

Spectroscopy at the Electron Ion Collider

Alessandro Pilloni

w/ M. Battaglieri and A. Szczepaniak

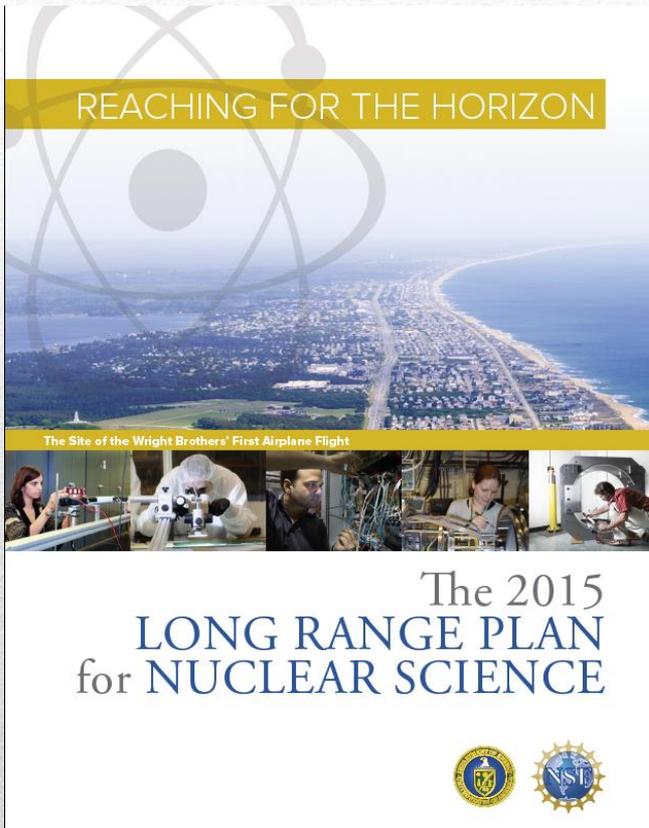
Genova, June 20th, 2018



Outline

- The Electron Ion Collider
- Spectroscopy at the EIC
- Production of exotics at colliders

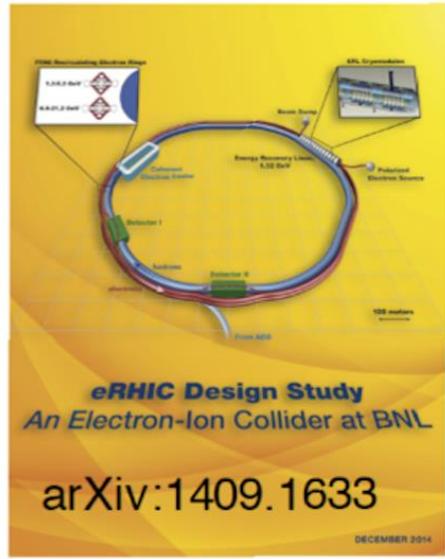
DOE-NP Long range plan



Recommendations:

- The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made. [...]
- Gluons...generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain.... These can only be answered with a powerful new electron ion collider (EIC). **We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. [...]**

Two options for the EIC



eRHIC

arXiv:1409.1633

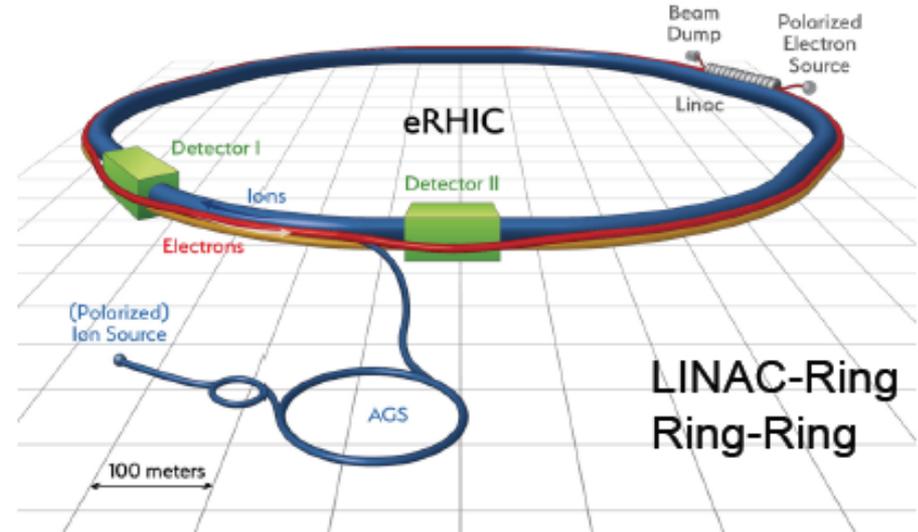
Energy range:

e⁻: 15-20 GeV

p: 100-250 GeV

W: 40-120 GeV

eRHIC



MEIC Design Summary

January 20, 2015

Author List

S. Abeyaratne⁶, D. Barber⁴, A. Bogacz², P. Brindza¹, Y. Cai¹, A. Camsonne¹, A. Castilla¹, P. Chevtsov¹⁰, E. Daly¹, Y. S. Derbenev¹, D. Douglas¹, V. Dudnikov¹¹, R. Ent¹, B. Erdelyi¹, Y. Filatov⁴, D. Gaskell¹, J. Grames¹, J. Guo¹, L. Harwood¹, A. Hutton¹, C. Hyde¹, K. Jordan¹, A. Kimber¹, G. A. Krafft¹² (editor), A. Kondratenko¹, M. Kondratenko¹, R. Li¹, F. Lin¹, T. Mann¹, P. McIntyre¹, T. Michalaki¹, V.S. Morozov¹, P. Nadel-Turonski¹, Y.M. Nosochkov¹, P. N. Ostroumov¹, K. Park¹, F. Pilat¹, M. Poelker¹, N. J. Pogue¹, R. Rimmer¹, Y. Robin¹, T. Satogata¹, A. Sattarov¹, M. Spata¹, R. Suleiman¹, M. Sullivan¹, A. Sy¹, C. Tennant¹, H. Wang¹, M-H Wang¹, S. Wang¹, U. Wienands¹, H. Zhang¹, Y. Zhang¹, Z. Zhao¹

Author Institutions

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⁹Texas A&M University, College Station, TX 77843 USA

¹⁰Paul Scherrer Institute, Villigen, Switzerland

¹¹Muons, Incorporated, Batavia, IL 60510 USA

JLEIC

arXiv:1504.07961

Energy range:

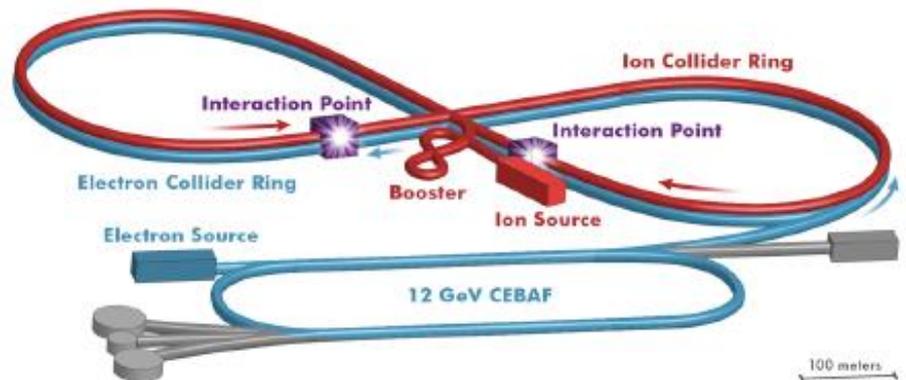
e⁻: 3-10 GeV

p : 20-100 GeV

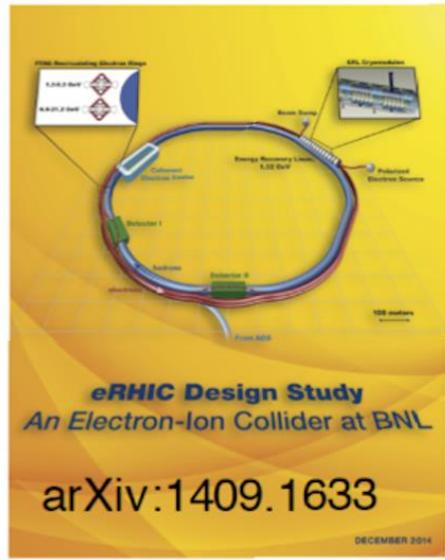
W: 20-100 GeV

JLEIC

Ring-Ring



Two options for the EIC



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JLEIC

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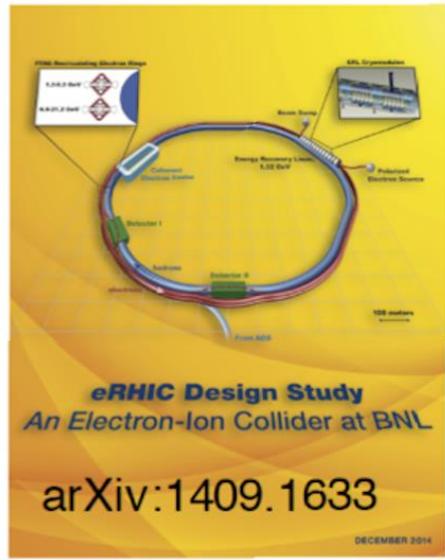
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Two options for the EIC



eRHIC

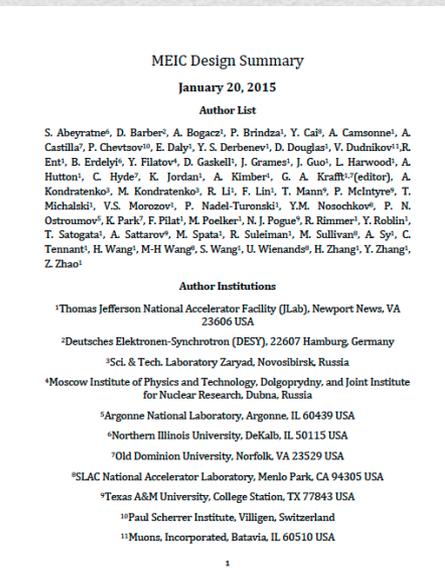
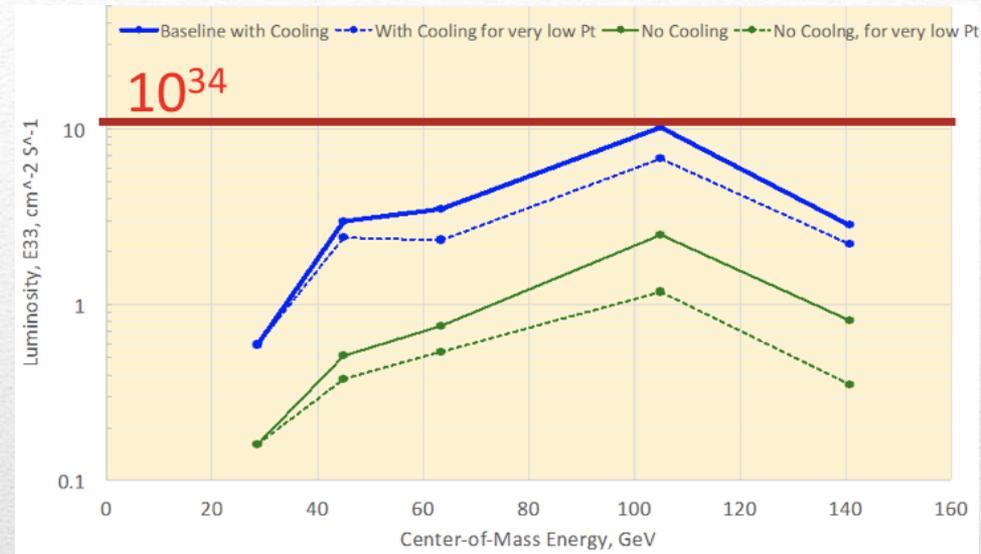
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JLEIC

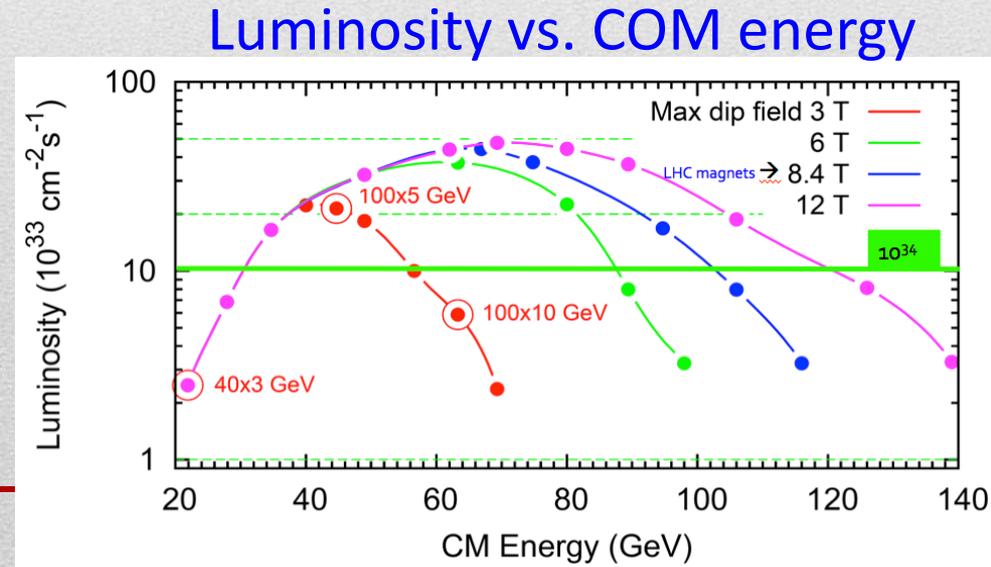
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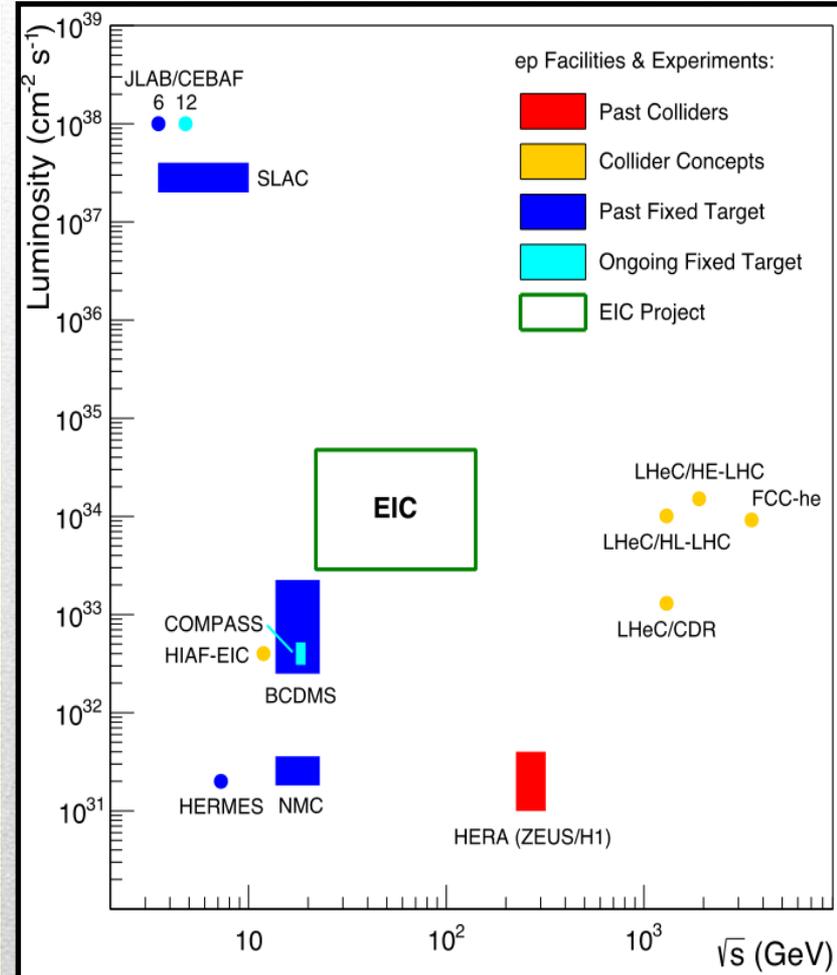
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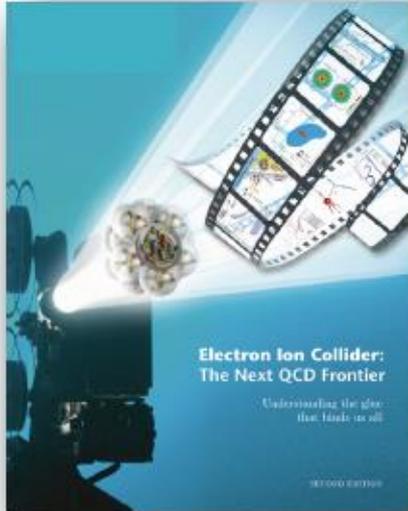
EIC vs. rest of the world

- **Luminosity 100-1000 times that of HERA**
Enable 3D tomography of gluons and sea quarks in protons
- **Polarized protons and light nuclear beams**
Critical to all spin physics related studies, including precise knowledge of gluon's spin & angular momentum contributions from partons to the nucleon's spin
- **Nuclear beams of all A (p→U)**
to study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test universality
- **Centre of mass variability with minimal loss of luminosity**
Critical to study onset of interesting QCD phenomena
- **Detector & IR designs mindful of "Lessons learned from HERA"**
No bends in e-beam, maximal forward acceptance....

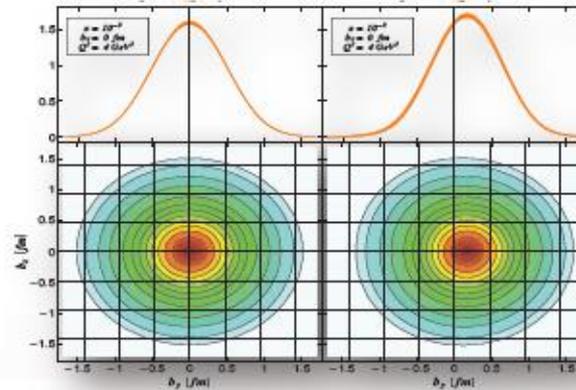


EIC physics so far

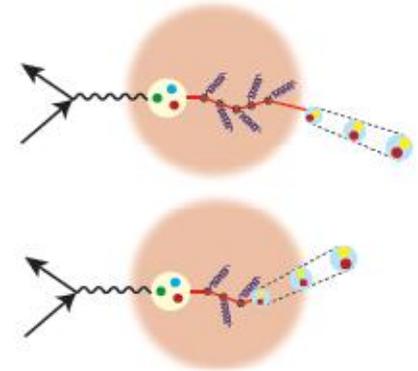
Accardi et al., Eur. Phys. J. A (2016) 52: 268 arXiv: 1212.1701.v3



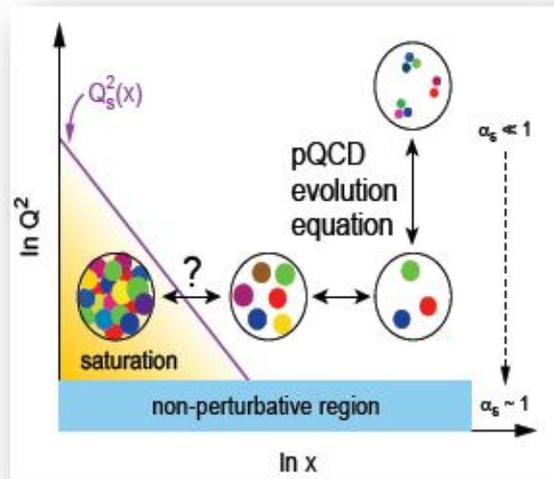
3D Imaging of Nucleon Structure



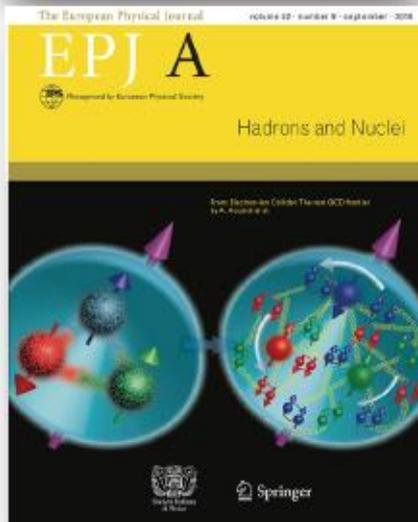
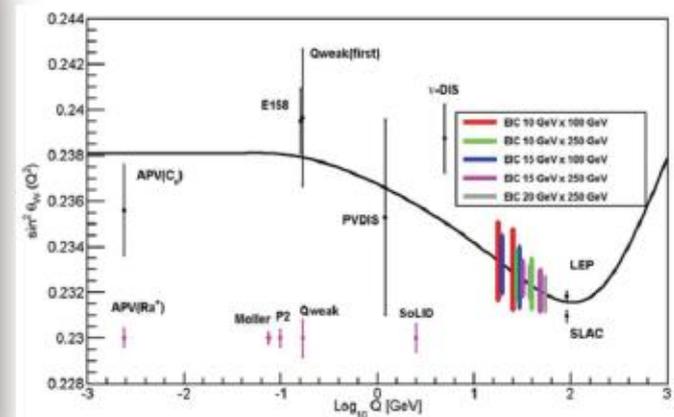
Hadronization in cold QCD matter



Gluon Saturation

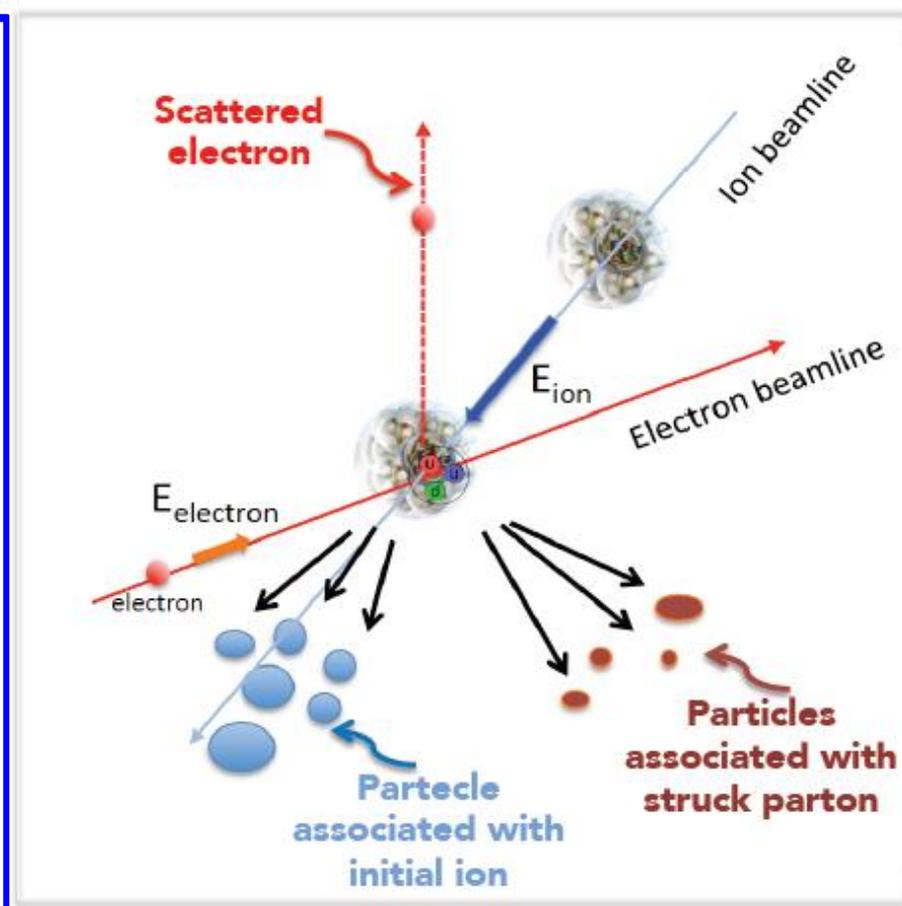


EW Physics



EIC detector challenges

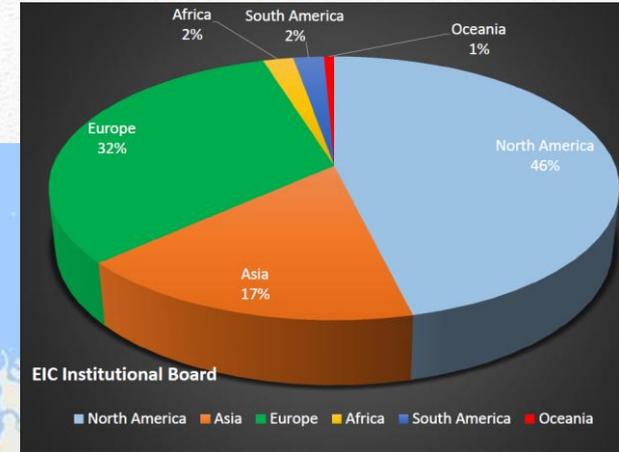
- Resolve partons in nucleons
 - high beam energies and luminosities
 - Q^2 up to $\sim 1000 \text{ GeV}^2$
- Need to resolve quantities (k_T, b_T) of the order a few hundred MeV in the proton
 - Correlated quantities, multi-dim analyses
 - High Granularity, wide dynamic range
- Need to detect all types of remnants to seek for correlations:
 - scattered electron
 - particles associated with initial ion
 - particles associated with struck parton
- Large acceptance, Forward particle detection, Excellent PID



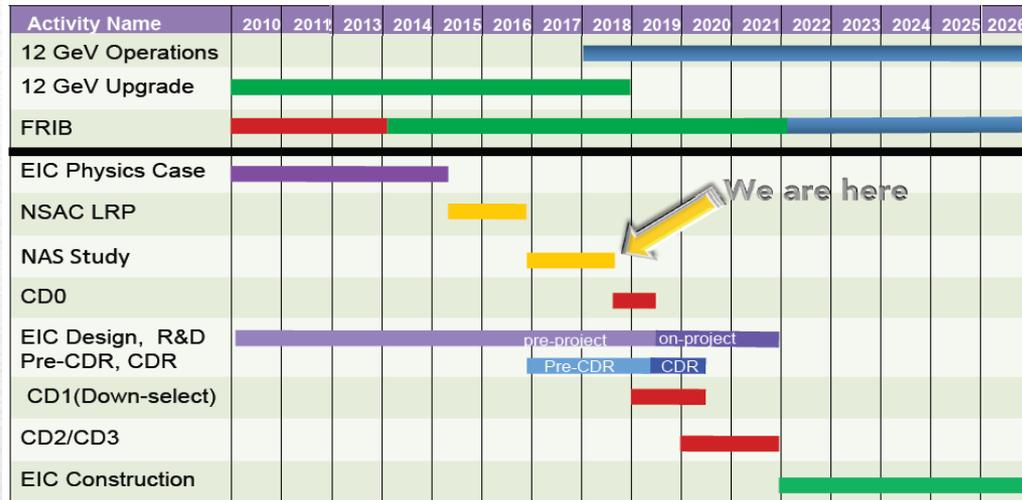
EIC community worldwide



734 collaborators, 29 countries, 167 institutions... (February 24, 2018)



EIC timeline

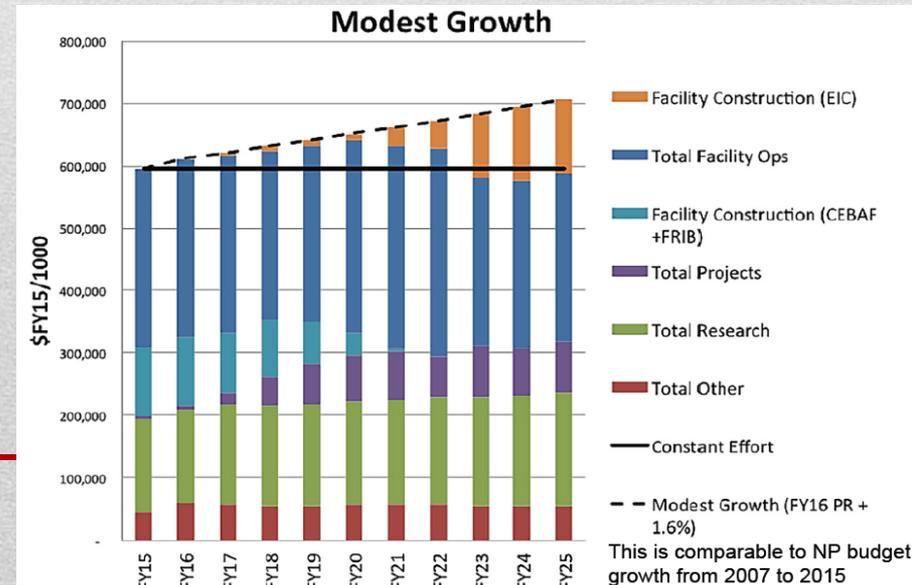


CD0 = DOE "Mission Need" statement; CD1 = design choice and site selection (VA/NY)
 CD2/CD3 = establish project baseline cost and schedule

It is the right time to propose a spectroscopy program for EIC!

- **July 30th-August 3rd**
EIC user group meeting
- **December 19th-21st:**
Workshop in Trento
- **Spring 2019:**
White book

- So far detectors just sketched (eRHIC vs JLEIC)
- They will be finalised for the CDR (site-dependent)
- We have a chance to propose a spectroscopy program at EIC to be included in the next EIC-Physics Book

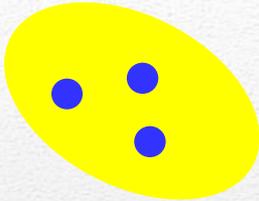


Hadron Spectroscopy at EIC

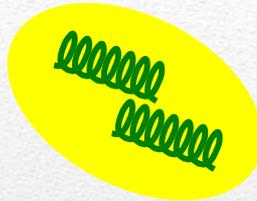
Meson



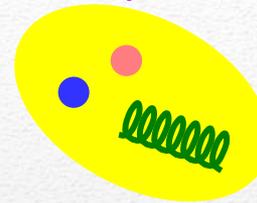
Baryon



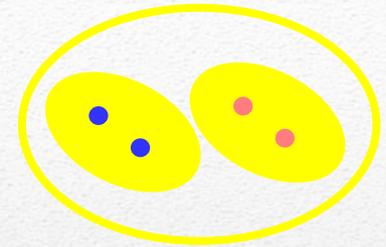
Glueball



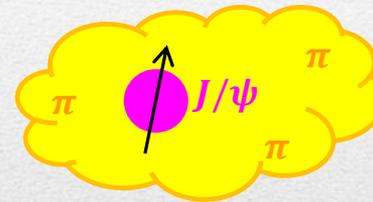
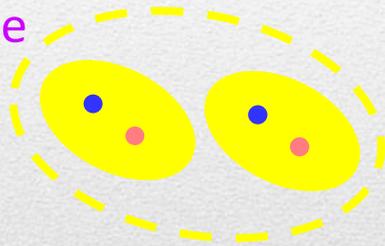
Hybrids



Tetraquark



Molecule

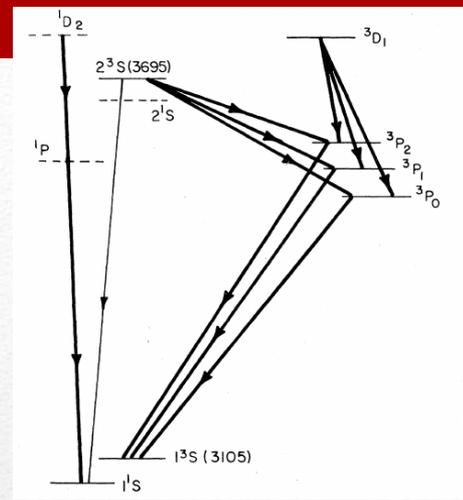
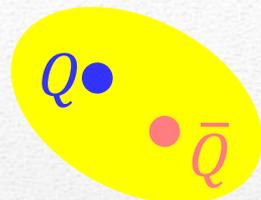
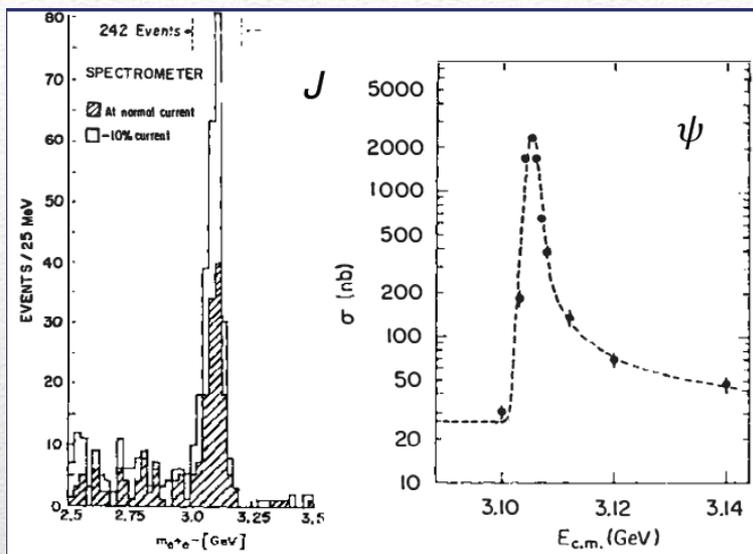


Hadroquarkonium

«The Electron Ion Collider will act like an enormous microscope»

We want to use it to study «human-size» hadrons!

Quarkonium orthodoxy



Potential models

(meaningful when $M_Q \rightarrow \infty$)

$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

(Cornell potential)

Solve NR Schrödinger eq. \rightarrow spectrum

Effective theories

(HQET, NRQCD, pNRQCD...)

Integrate out heavy DOF



(spectrum), decay & production rates

$$\alpha_s(M_Q) \sim 0.3$$

(perturbative regime)

OZI-rule, QCD multipole

Heavy quark spin flip suppressed by quark mass, approximate heavy quark spin symmetry (HQSS)

Multiscale system

Systematically integrate out the heavy scale,

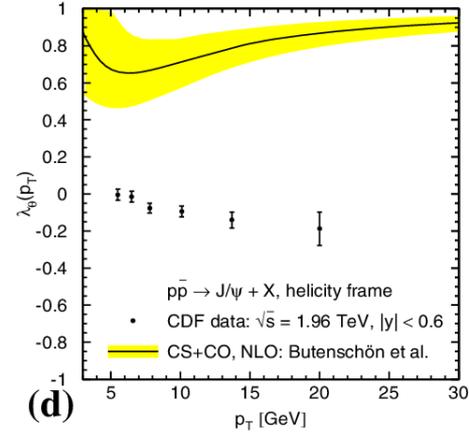
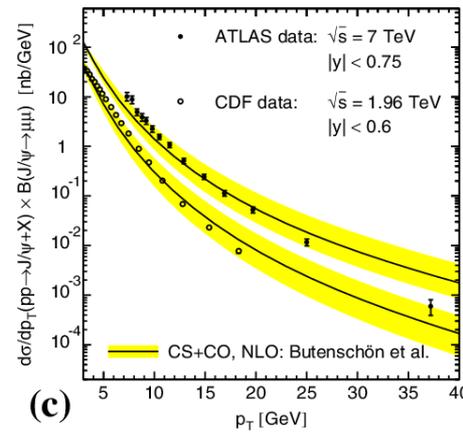
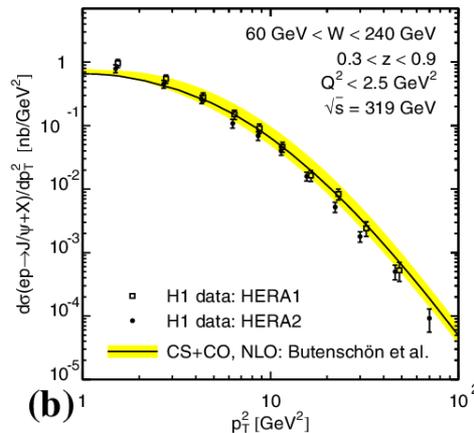
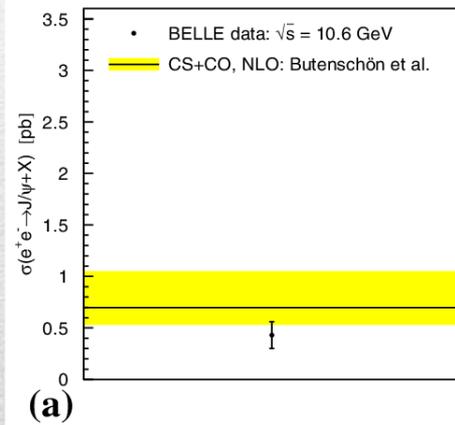
$$m_Q \gg \Lambda_{QCD}$$

$$m_Q \gg m_Q v \gg m_Q v^2$$

Full QCD \longrightarrow NRQCD \longrightarrow pNRQCD

$$m_b \sim 5 \text{ GeV}, m_c \sim 1.5 \text{ GeV}$$

$$v_b^2 \sim 0.1, v_c^2 \sim 0.3$$

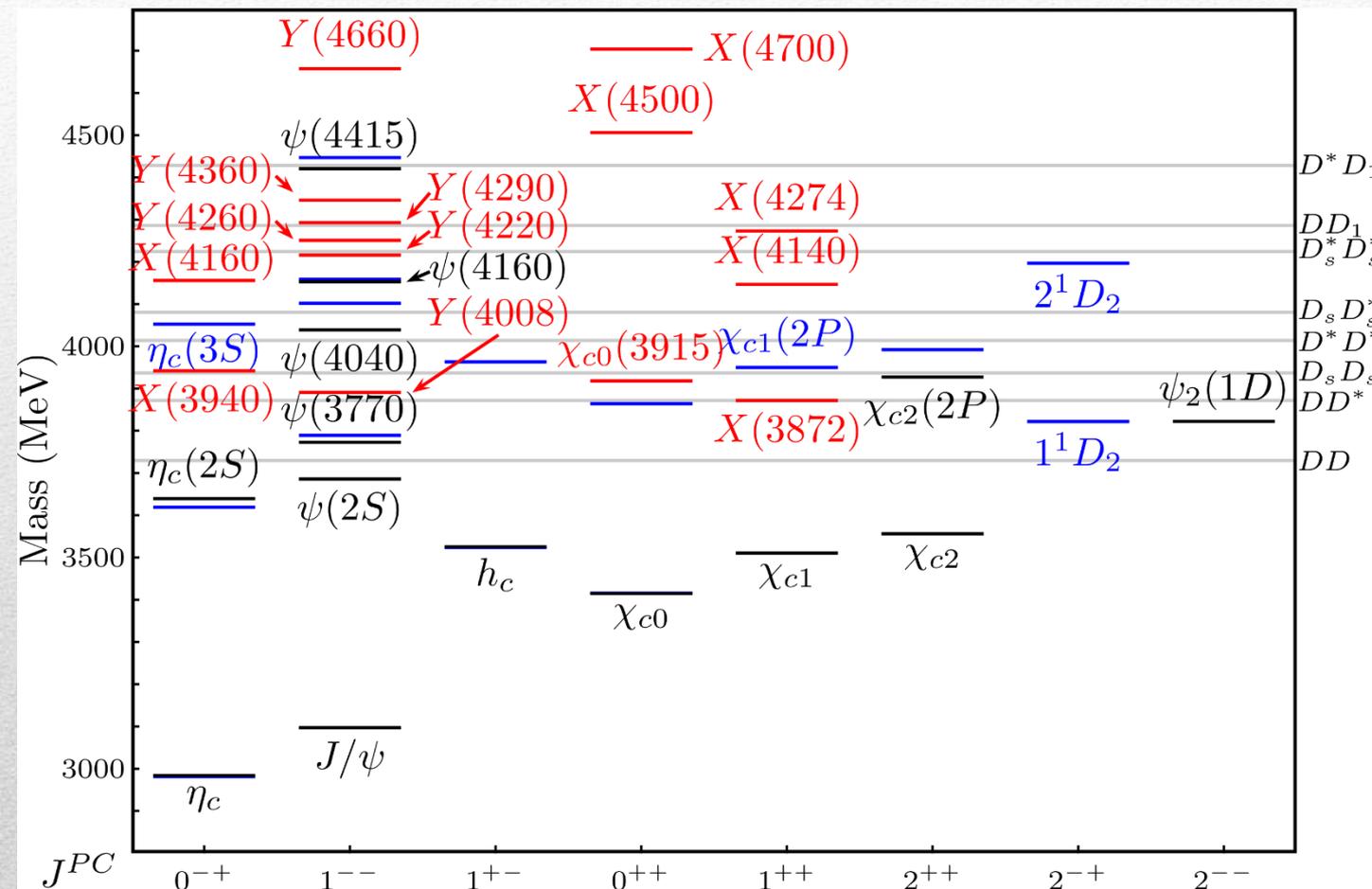


Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)

Exotic landscape

Esposito, AP, Polosa, Phys.Rept. 668

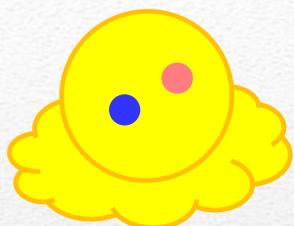


A host of **unexpected resonances** have appeared

decaying mostly into charmonium + light

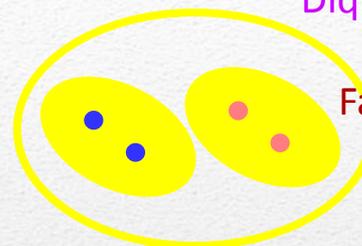
Hardly reconciled with usual charmonium interpretation

Models



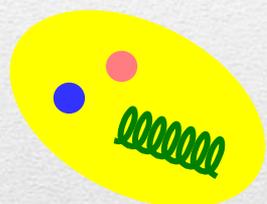
Meson/Baryon+continuum

Ferretti *et al.*, PRC88, 015207
Ferretti *et al.*, PRD90, 094022
Ferretti *et al.*, 1806.02489



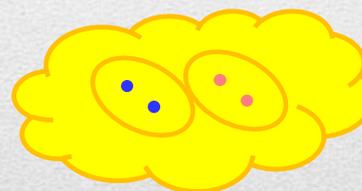
Diquark-Antidiquark

Maiani, *et al.* PRD71, 014028
Faccini, AP, *et al.* PRD87, 111102
Maiani, *et al.* PRD89, 114010
Maiani, *et al.*, PLB778, 247



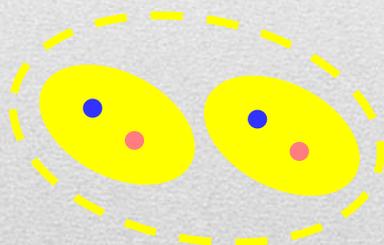
Hybrids/BO tetraquarks

Kou and Pene, PLB631, 164
Braaten, PRL111, 162003
Berwein *et al.*, PRD92, 114019



Hybridized Tetraquarks

Esposito, AP, Polosa
PLB758, 292



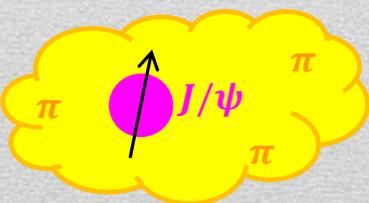
Molecule

Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305



Kinematical effects

Szczepaniak, PLB747, 410
Szczepaniak, PLB757, 61
Guo *et al.*, PRD92, 071502
Swanson, IJMPE25, 1642010



Hadroquarkonium

Dubynskiy *et al.*, PLB 666, 344
Dubynskiy and Voloshin, PLB 671, 82
Li and Voloshin, MPLA29, 1450060

Comparison: EIC vs. others

Too late (?) for charm physics ✗



Flexibility in the production mechanism ✓

Flexibility in energy (no Λ_b) ✓

Less clean environment ✗



Same luminosity ✓

Lower cross sections ✗

Better efficiencies for neutrals (?) ✓



Polarized electron & ion beams ✓

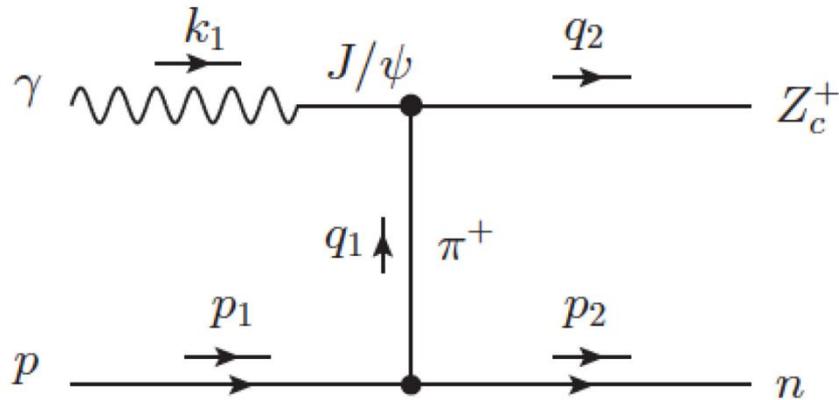
What for?

- High energy in the COM, possibility to study heavy flavors
 - Meson(-like) spectroscopy: $X_b, Z_b, (?)_b$
 - Baryon(-like) spectroscopy: $P_b, (?)_b$
 - Doubly heavy: $\Xi_{cc}, \Xi_{bc}; T_{bb}, T_{cc}$
 - Gluon-rich (small-x): heavy hybrids production?
- Diffractive production (photon-pomeron fusion, Primakoff)
- Interaction of heavy flavor with nuclear media
-

Need for cross section estimates
(NRQCD? Regge models?)

XYZ states in photoproduction

Justin Stevens,
APS 2015



PRD 88 (2013) 114009

$$\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu$$

$$\mathcal{L}_{Z\psi\pi} = \frac{g_{Z\psi\pi}}{M_Z} (\partial^\mu \psi^\nu \partial_\mu \pi Z_\nu - \partial^\mu \psi^\nu \partial_\nu \pi Z_\mu)$$

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N} \bar{N} \gamma_5 \gamma_\mu (\vec{\tau} \cdot \partial^\mu \vec{\pi}) N$$

* Several proposals to study XYZ states in photoproduction

* $\gamma p \rightarrow Z_c^+(3900)n, Z_c^+ \rightarrow J/\psi \pi^+$ PRD 88 (2013) 114009

* $\gamma p \rightarrow Z_c^+(4430)n, Z_c^+ \rightarrow \psi' \pi^+$ PRD 77 (2008) 094005, PRC 83 (2011) 065203 

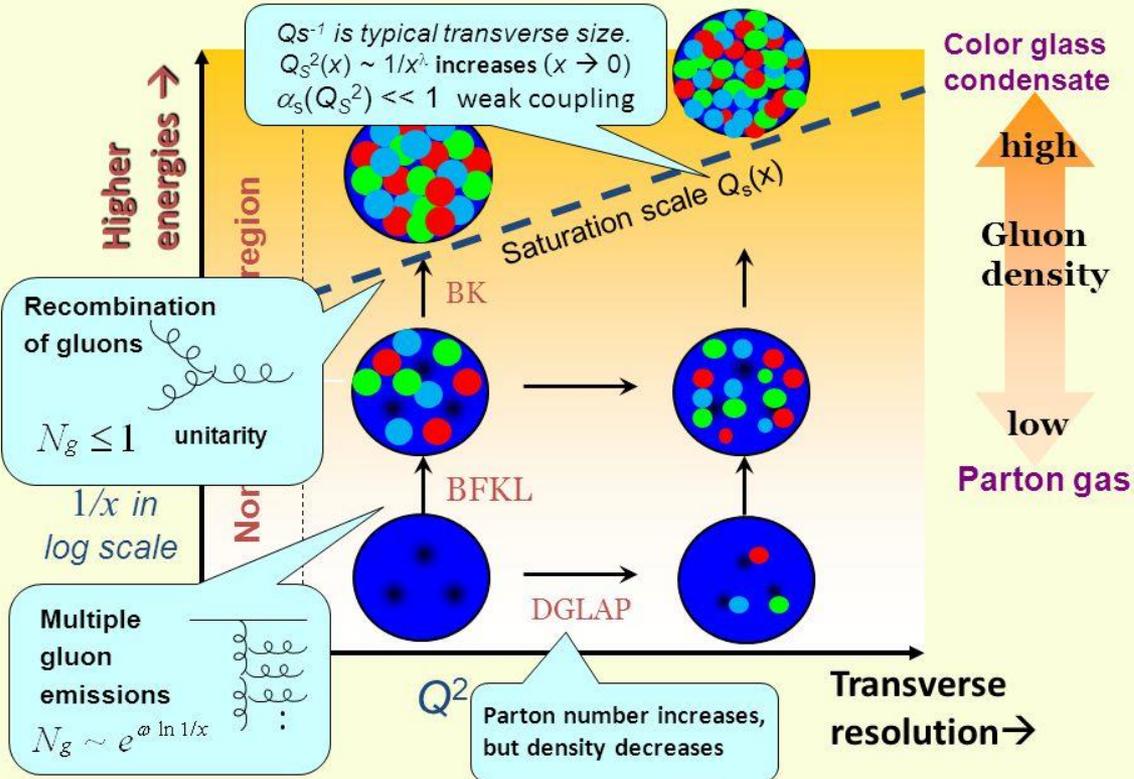
* $\gamma p \rightarrow Z_c^+(4200)n, Z_c^+ \rightarrow J/\psi \pi^+$ arXiv:1503:02125 (incl. Regge trajectories in model)

* $\gamma p \rightarrow Y(3940)p, Y(3940) \rightarrow J/\psi \omega$ PRD 80 (2009) 114007

* Use an Effective Lagrangian approach with Vector Meson Dominance

Hybrid production

Phase diagram of a proton as seen in DIS

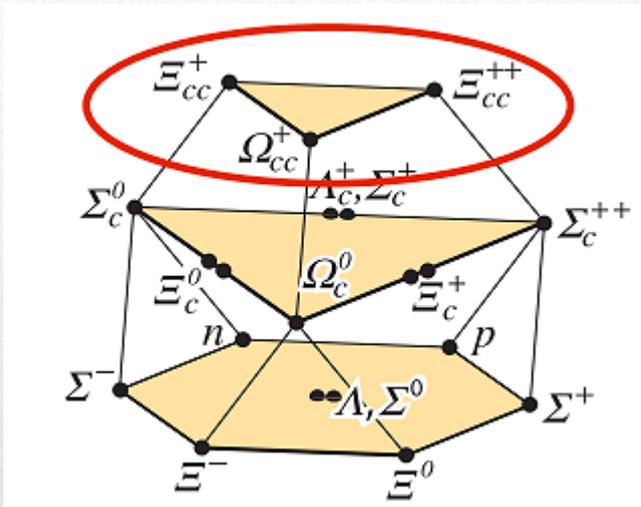


Surprisingly, no calculation for heavy hybrid production has been carried out so far

The only example for B decays is [Petrov et al. PRD58, 034013](#)

Room for improvement and inclusion of the large number of gluons at small x

Doubly heavy



Lots of attention recently on tetraquark and baryons with two heavy quarks, driven by LHCb and lattice results

Quigg and Eichten, PRL119, 202002
Esposito, AP et al. PRD88, 054029
Karliner and Rosner, PRD90, 094007
Karliner and Rosner, PRL119, 202001
Francis et al. PRL118, 142001

MC code available, [GENXICC2.0](#), which implements the heavy diquark in Pythia NRQCD approach in e^+e^- collisions in [Chen et al. JHEP1412, 018](#)

MC Tools specific for EIC

- PYTHIA8 + DIRE (for ep collisions), HERWIG
- PYTHIAeRHIC, nuclear PDFs included
- BeAGLE (nuclear shadowing, PS+hadr. w/ PYTHIA)
- SARTRE (diffractive VM production)

- <https://wiki.bnl.gov/eic/index.php/Simulations>

Working group

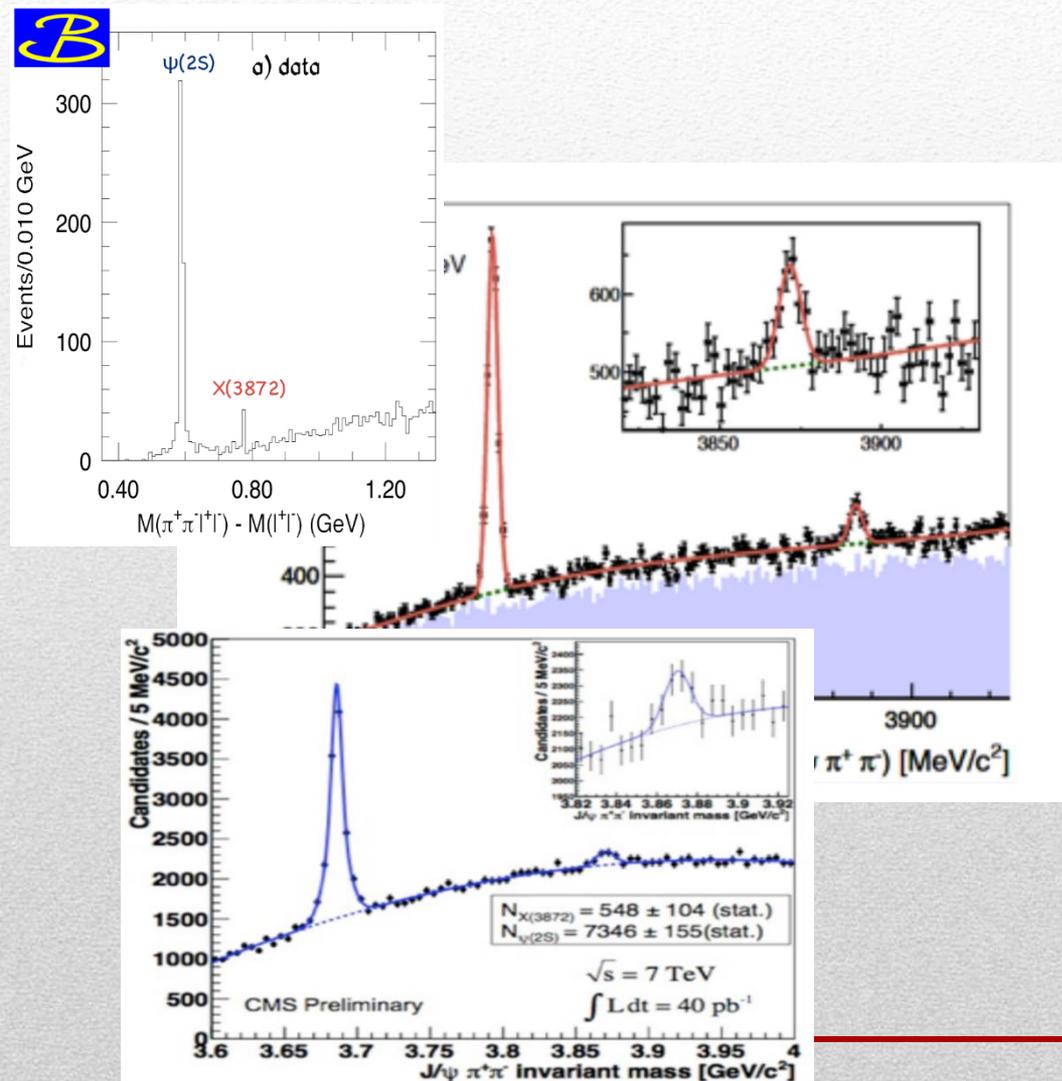
- **Theorists:**

F.K. Guo (CAS), T. Mehen + student (Duke), A. Pilloni (JLab), A. Szczepaniak (IU/JLab), N. Brambilla, A. Vairo (TUM), E. Santopinto (INFN-GE)

- **Experimentalists:**

M. Battaglieri (INFN-GE), Y. Furletova (JLab), J. Stevens (W&M)

X(3872)



- Discovered in
 $B \rightarrow K X \rightarrow K J/\psi \pi \pi$
- Quantum numbers 1^{++}
- **Very close** to DD^* threshold
- **Too narrow** for an above-threshold charmonium
- **Isospin violation** too big
 $\frac{\Gamma(X \rightarrow J/\psi \omega)}{\Gamma(X \rightarrow J/\psi \rho)} \sim 0.8 \pm 0.3$
- **Mass** prediction not compatible with $\chi_{c1}(2P)$

$$M = 3871.68 \pm 0.17 \text{ MeV}$$

$$M_X - M_{DD^*} = -3 \pm 192 \text{ keV}$$

$$\Gamma < 1.2 \text{ MeV @90\%}$$

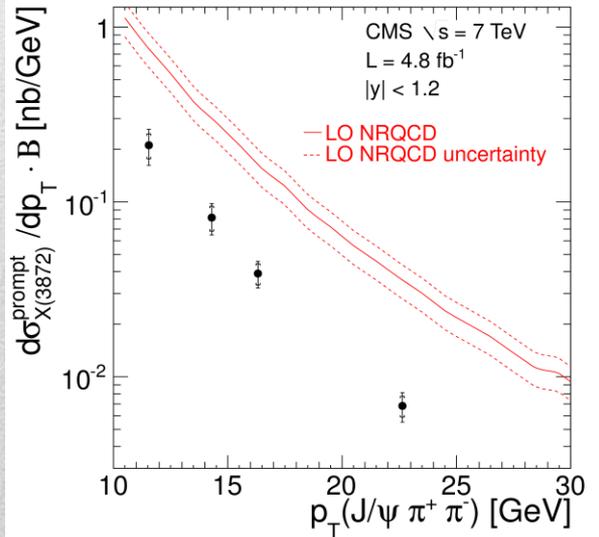
X(3872)

Large prompt production
at hadron colliders

$$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$$

$$\sigma_{PR} \times B(X \rightarrow J/\psi\pi\pi) = (1.06 \pm 0.11 \pm 0.15) \text{ nb}$$

CMS, JHEP 1304, 154

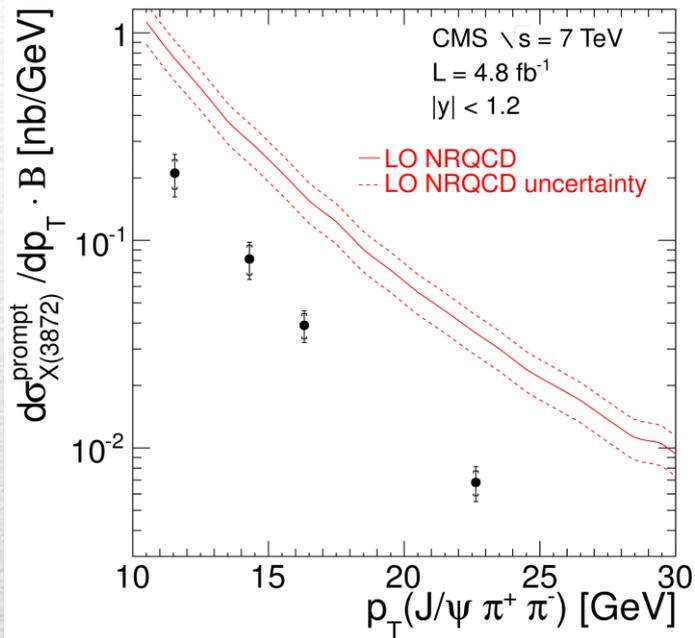


B decay mode	X decay mode	product branching fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \rightarrow \pi\pi J/\psi$	0.86 ± 0.08	(BABAR, ^[26] Belle ^[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	BABAR ^[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle ^[25]		
K^0X	$X \rightarrow \pi\pi J/\psi$	0.41 ± 0.11	(BABAR, ^[26] Belle ^[25])		
		$0.35 \pm 0.19 \pm 0.04$	BABAR ^[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle ^[25]		
$(K^+\pi^-)_{NR}X$	$X \rightarrow \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle ^[106]		
$K^{*0}X$	$X \rightarrow \pi\pi J/\psi$	< 0.34 , 90% C.L.	Belle ^[106]		
KX	$X \rightarrow \omega J/\psi$	$R = 0.8 \pm 0.3$	BABAR ^[33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	BABAR ^[33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	BABAR ^[33]		
KX	$X \rightarrow \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle ^[32]		
K^+X	$X \rightarrow D^{*0}\bar{D}^0$	8.5 ± 2.6	(BABAR, ^[38] Belle ^[37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	BABAR ^[38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle ^[37]		
K^0X	$X \rightarrow D^{*0}\bar{D}^0$	12 ± 4	(BABAR, ^[38] Belle ^[37])		
		$22 \pm 10 \pm 4$	BABAR ^[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle ^[37]		
K^+X	$X \rightarrow \gamma J/\psi$	0.202 ± 0.038	(BABAR, ^[35] Belle ^[34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	BABAR ^[35]		
K^0X		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle ^[34]		
K^0X	$X \rightarrow \gamma\psi(2S)$	$0.26 \pm 0.18 \pm 0.02$	BABAR ^[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle ^[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb ^[36]		
K^+X	$X \rightarrow \gamma\psi(2S)$	0.44 ± 0.12	BABAR ^[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	BABAR ^[35]		
K^0X		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle ^[34]		
K^+X	$X \rightarrow \gamma\chi_{c1}$	$1.14 \pm 0.55 \pm 0.10$	BABAR ^[35]	$< 1.0 \times 10^{-3}$	< 0.014
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle ^[34]		
K^+X	$X \rightarrow \gamma\chi_{c2}$	$< 9.6 \times 10^{-3}$	Belle ^[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \rightarrow \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle ^[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \rightarrow \eta J/\psi$	< 1.05	BABAR ^[112]	< 0.11	< 1.55
K^+X	$X \rightarrow p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb ^[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Prompt production of $X(3872)$

The question is:

«Are **large prompt production cross sections** at hadron colliders **compatible** with a **loosely bound** molecule interpretation?»



CMS, JHEP 1304 (2013) 154

$$M = 3871.69 \pm 0.17 \text{ MeV}$$

$$E_B = M_{DD^*} - M_X = 10 \pm 200 \text{ keV (PDG)}$$

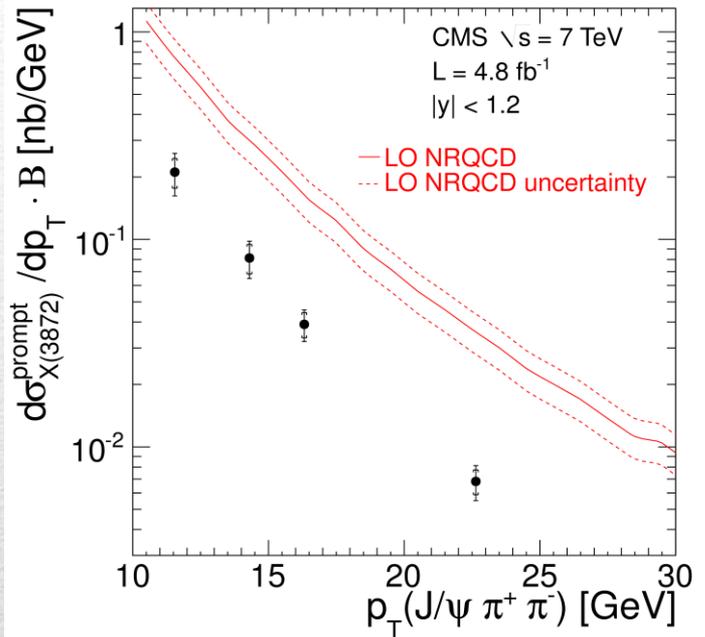
$$\Gamma < 1.2 \text{ MeV @90\%}$$

The width of the D^* and of the $X(3872)$ are neglected, according to Weinberg's spirit
The $X(3872)$ is considered a (stable) bound state of (stable) $\bar{D}^0 D^{*0}$

Prompt production of $X(3872)$

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$$\Gamma < 1.2 \text{ MeV @90\%}$$

$$k_B = \sqrt{2\mu E_B} \sim 20 \text{ MeV}, \quad R = \frac{1}{k_B} \sim 10 \text{ fm}$$

Hadronic molecules with MC simulations

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model

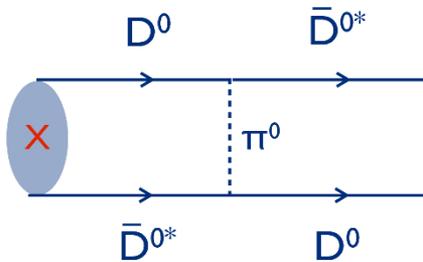


$$\sigma(p\bar{p} \rightarrow X(3872)) \sim \int d^3k |\langle X | D\bar{D}^* \rangle \langle D\bar{D}^* | p\bar{p} \rangle|^2 < \int_{k < k_{max}} d^3k |\langle D\bar{D}^* | p\bar{p} \rangle|^2$$

Estimating k_{max}

The choice of k_{max} is crucial. By phase space argument, the cross section scales as k_{max}^3 , small changes have huge impacts on the results

D mesons interact via π^0 -exchange:



$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi} \frac{e^{-m_\pi r_0}}{r_0} = |E_B| \simeq 0.25 \text{ MeV}$$

using the fact that $g^2/4\pi \sim 10$ we find a characteristic size

$$(1) \quad r_0 \simeq 8 \text{ fm} \quad \Rightarrow \quad \Delta k \sim 1/2r_0 \simeq 20 \text{ MeV}$$

(uncertainty principle)

$$(2) \quad k_0 = \frac{\sqrt{\lambda(m_X^2, m_D^2, m_{D^*}^2)}}{2m_X} \simeq 30 \text{ MeV}$$

C. Sabelli
(2009)

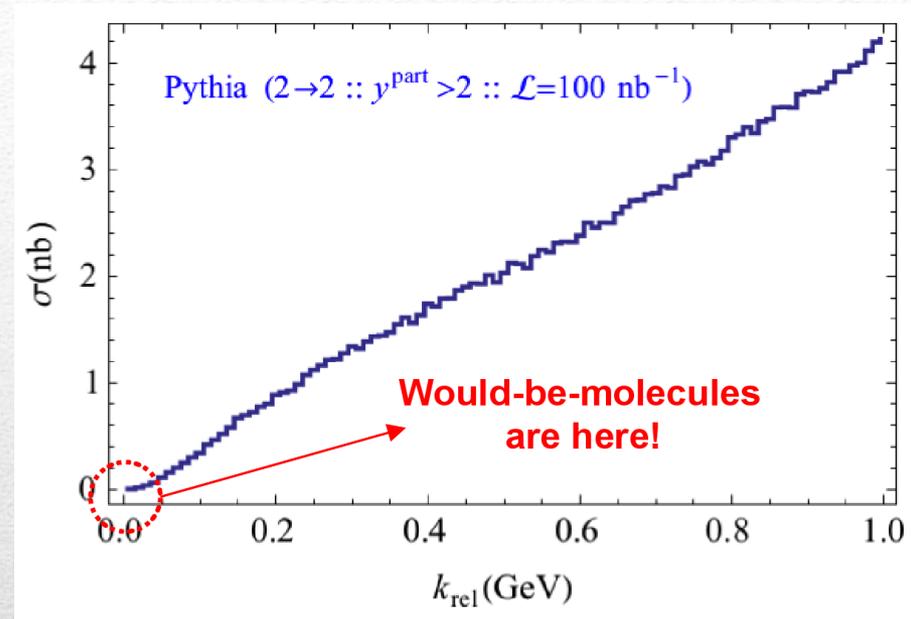
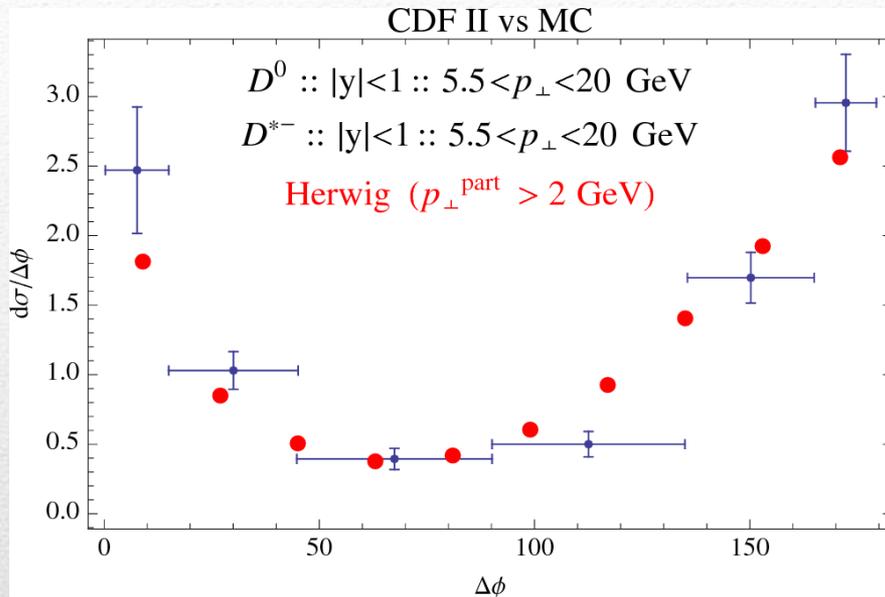
Alternative, one can model the binding potential.

For example, a simple square well with this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV},$$

$$\sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

2009 Results



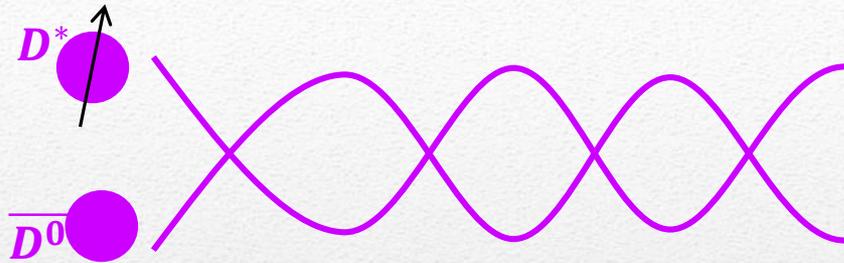
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi} (p\bar{p} \rightarrow D^0 D^{*-})$

We get $\sigma(p\bar{p} \rightarrow DD^* | k < k_{max}) \approx 0.1 \text{ nb} @ \sqrt{s} = 1.96 \text{ TeV}$

Experimentally $\sigma(p\bar{p} \rightarrow X(3872)) \approx 30 - 70 \text{ nb}!!!$

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max} -- Part II



A solution can be Final State Interactions
(rescattering of DD^*)

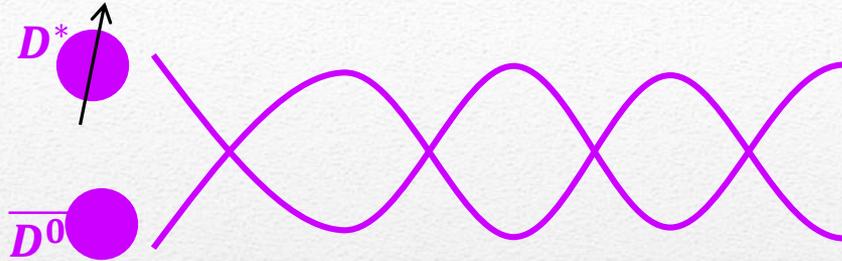
Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -N A_{prod}^{on} \cdot \frac{e^{i\delta} \sin \delta}{ka_{NN}}$$

Watson-Migdal model for FSI, the on-shell elastic scattering matrix multiplies the production amplitude

$$\sigma(p\bar{p} \rightarrow X(3872)) \rightarrow \sigma(p\bar{p} \rightarrow DD^* | k < k_{max}) \times \frac{6\pi\sqrt{2\mu E_B}}{k_{max}}$$

Estimating k_{max} -- Part II

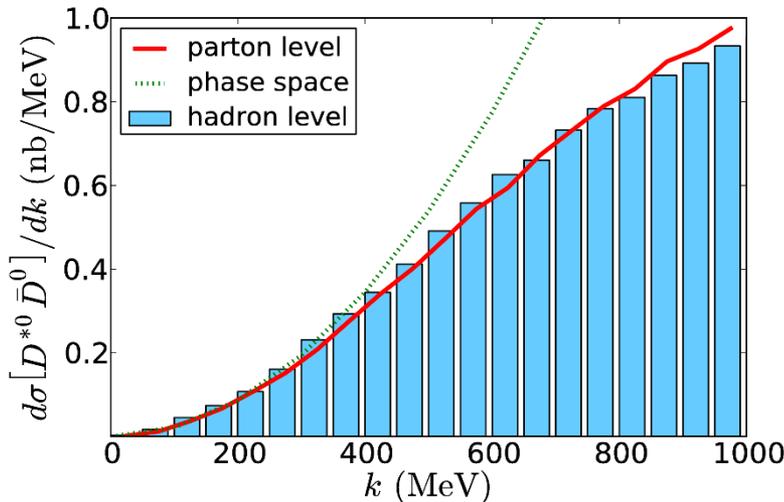


A solution can be Final State Interactions
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Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -N A_{prod}^{on} \cdot \frac{e^{i\delta} \sin \delta}{ka_{NN}}$$

Watson-Migdal model for FSI, the on-shell elastic scattering matrix multiplies the production amplitude

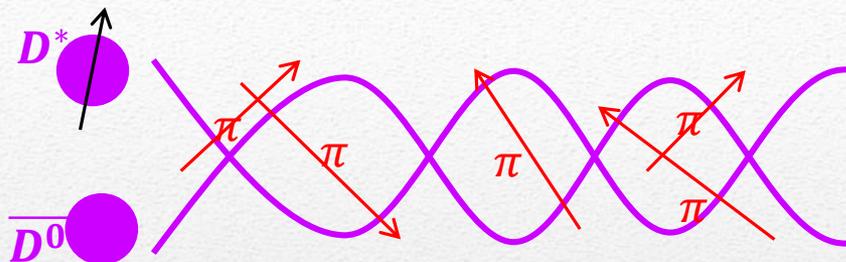


To take into account the rescattering correctly, one needs to integrate up to the scale of the mediator,

$$\sigma_{FSI}(p\bar{p} \rightarrow DD^* | k < 2m_\pi) \approx 23 \text{ nb}$$

$$\sigma(p\bar{p} \rightarrow DD^* | k < 5m_\pi) \approx 230 \text{ nb}$$

Estimating k_{max} -- Part III & IV



Watson-Migdal approach requires the DD^* to recoil onto some debrys. The theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound, the D and D^* only talk with each other

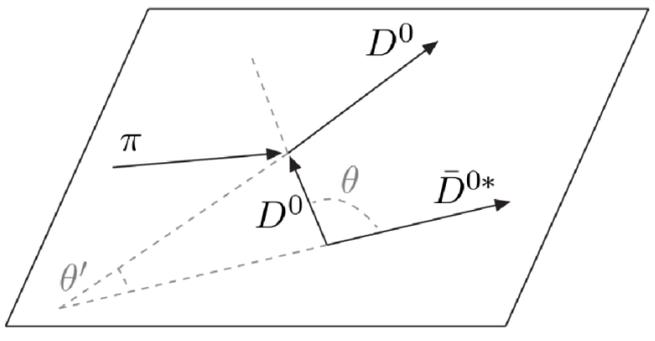
Artoisenet and Braaten, PRD83, 014019

What is the role of 2-body unitarity in a 100-body high energy collision?

A new mechanism?

In a more **billiard-like** point of view, the comoving pions can **elastically interact** with $D(D^*)$, and **slow down** the DD^* pairs

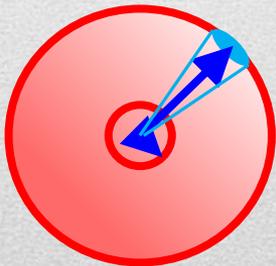
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003



The mechanism also implies: D mesons actually **“pushed”** **inside** the potential well (the **classical 3-body problem!**)

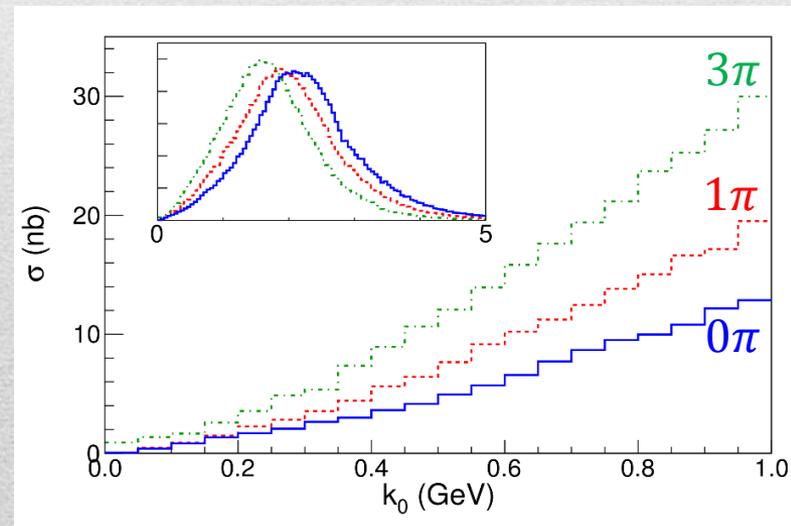
$X(3872)$ is a **real, negative energy bound state** (stable)

It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100$ keV



By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart

We get $\sigma(p\bar{p} \rightarrow X(3872)) \sim 5$ nb, **still not sufficient** to explain all the experimental cross section



Estimating k_{max} -- Part V

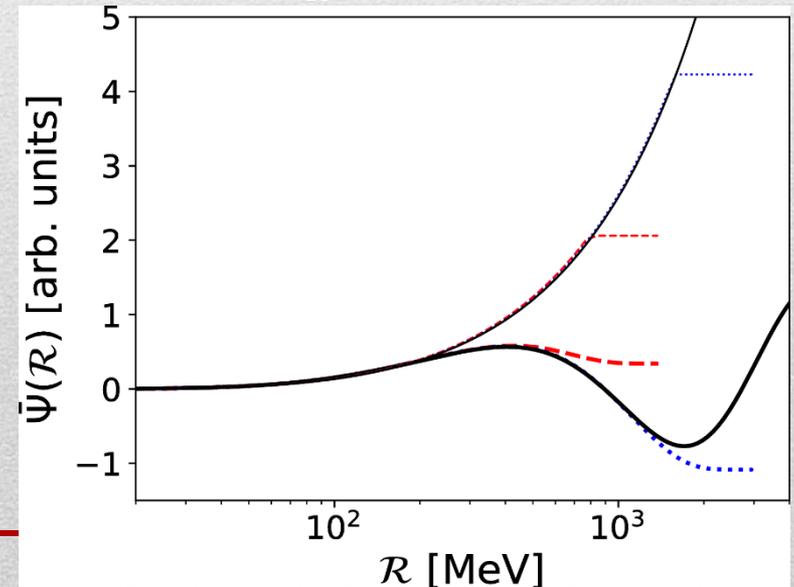
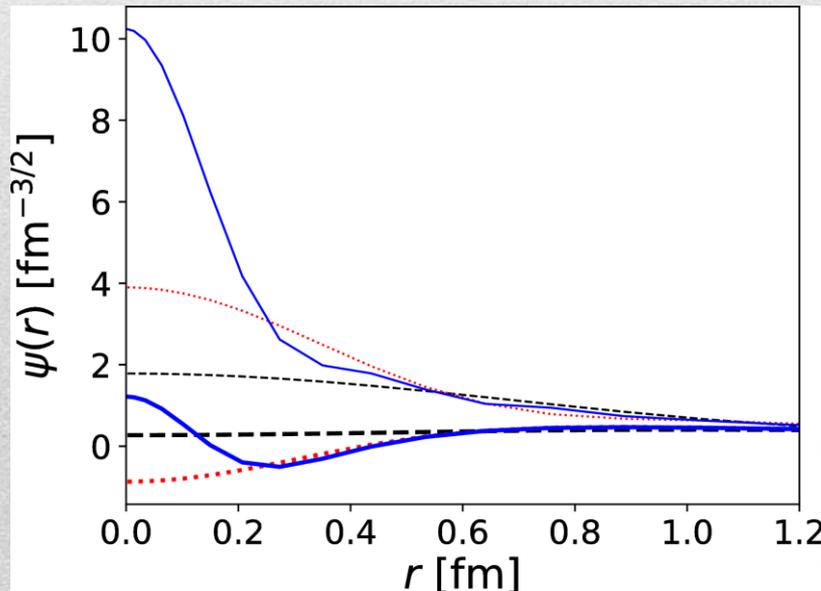
$$\begin{aligned}
 \sigma(\bar{p}p \rightarrow X) &\sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
 &\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
 &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2 \\
 &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2
 \end{aligned}$$

The estimate of the k_{max} has been brought back

Albaladejo et al. arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_{\mathcal{R}} d^3\mathbf{k} \psi(\mathbf{k})$$



Estimating k_{max} -- Part VI

However, the integral of the wave function may not be well defined.

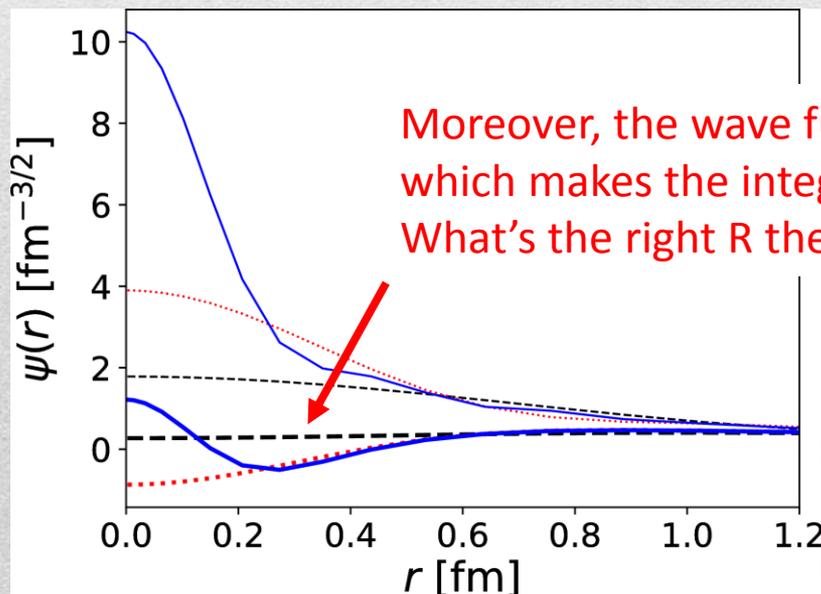
For example, if one considers the wave function in the scattering length approximation,

$$\psi(\mathbf{k}) = \frac{1}{\pi} \frac{a^{3/2}}{a^2 k^2 + 1} \quad \text{it's not integrable}$$

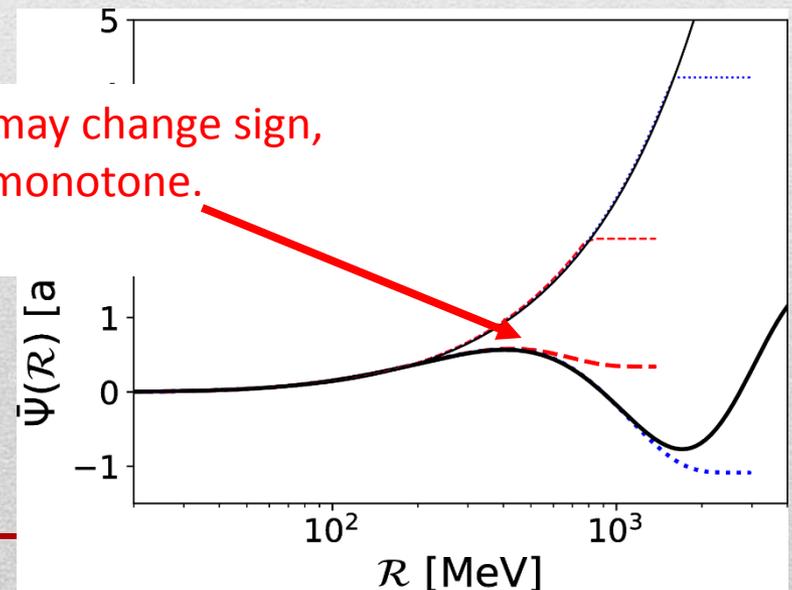
Esposito, AP *et al.* arXiv:1709.09631

A physical value should rather be based on expectation values which involve $|\psi(\mathbf{k})|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron



Moreover, the wave function may change sign,
which makes the integral nonmonotone.
What's the right R then?

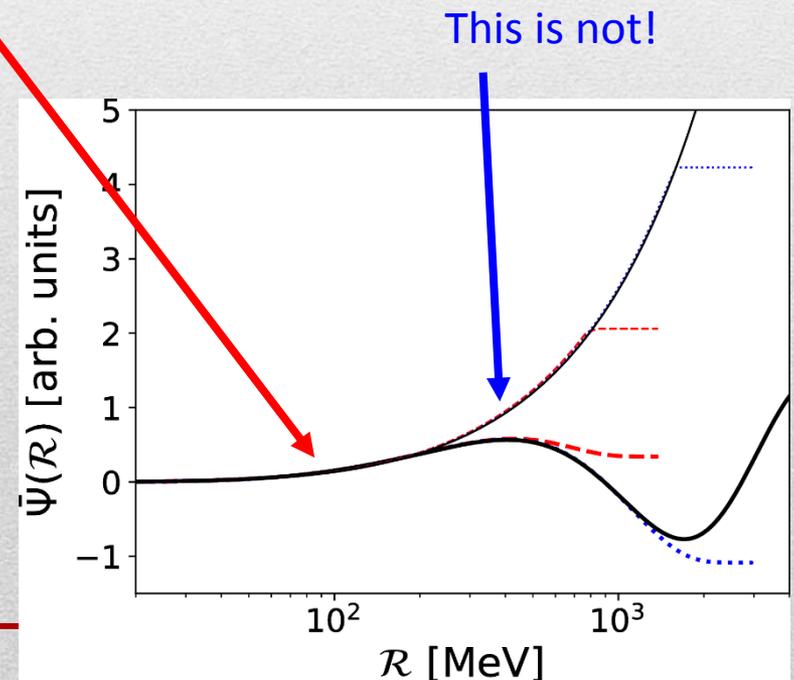
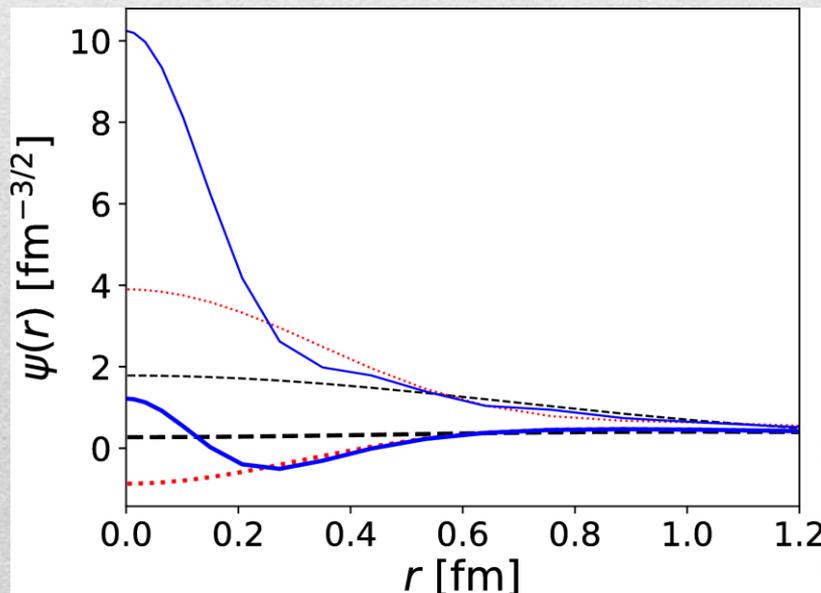


Estimating k_{max} -- Part VI

An accurate calculation using several deuteron S-wave functions available on the market (for example <https://www.phy.anl.gov/theory/research/av18/deut.wfk>) give

$$\int_R d^3\mathbf{k} |\psi(\mathbf{k})|^2 = 90\% \text{ for } k_{max} = 110 \text{ MeV}$$

This also show that this region is well controlled by pion exchange - universal



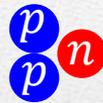
Light nuclei at ALICE

In 2015, ALICE published data on production of light nuclei in Pb-Pb and pp collisions

These might provide a benchmark for $X(3872)$ production



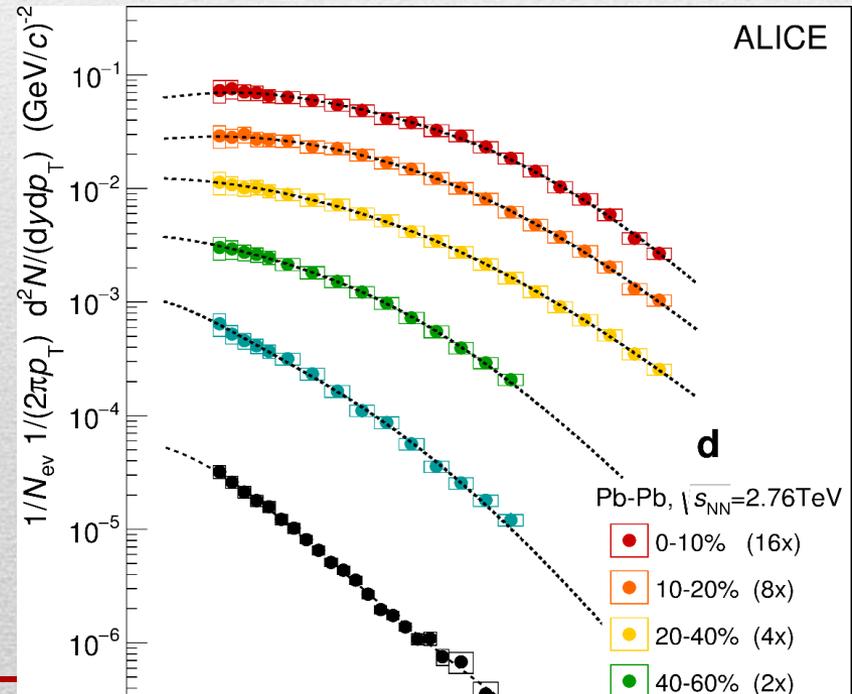
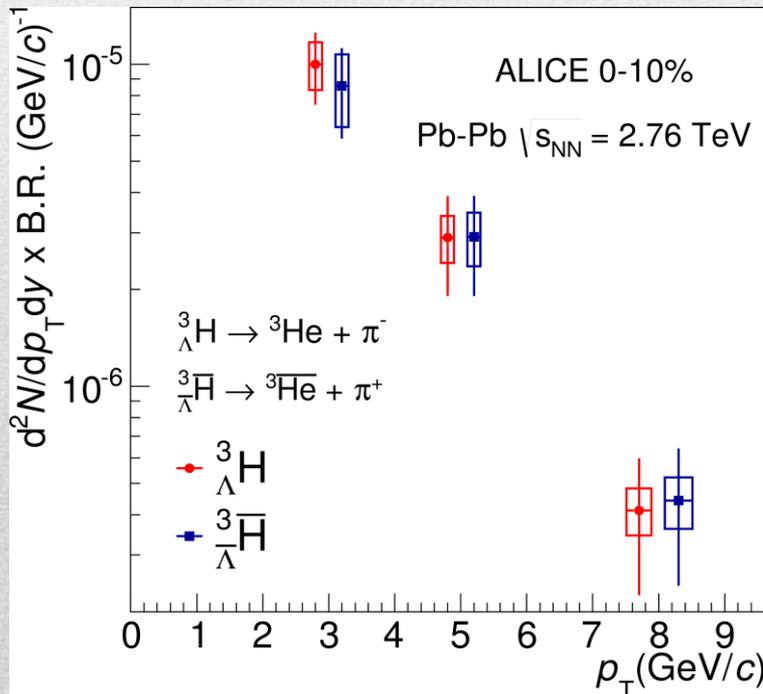
Hypertriton
arXiv:1506.08453



Helium-3
arXiv:1506.08951



Deuteron
arXiv:1506.08951

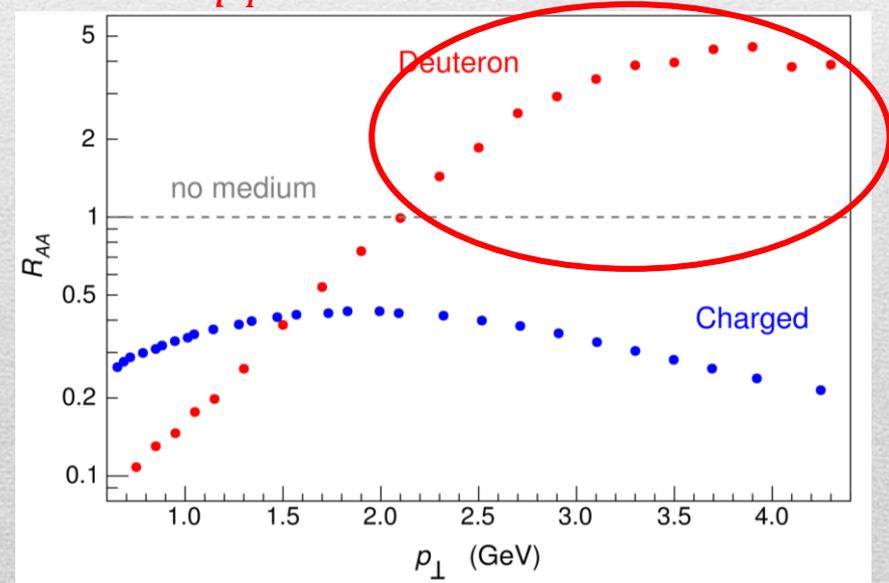
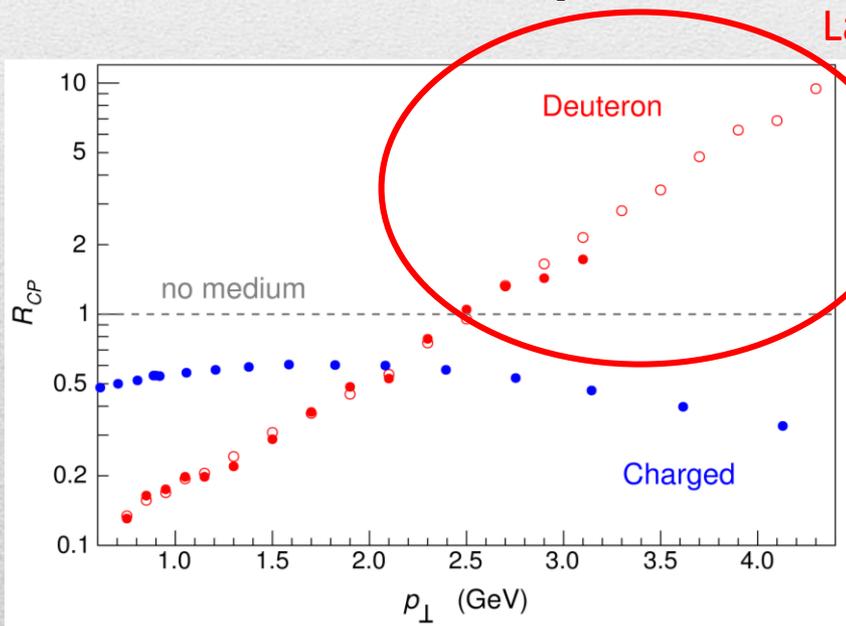


Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different \sqrt{s})

$$R_{CP} = \frac{N_{coll}^P \left(\frac{dN}{dp_T} \right)_C}{N_{coll}^C \left(\frac{dN}{dp_T} \right)_P}$$

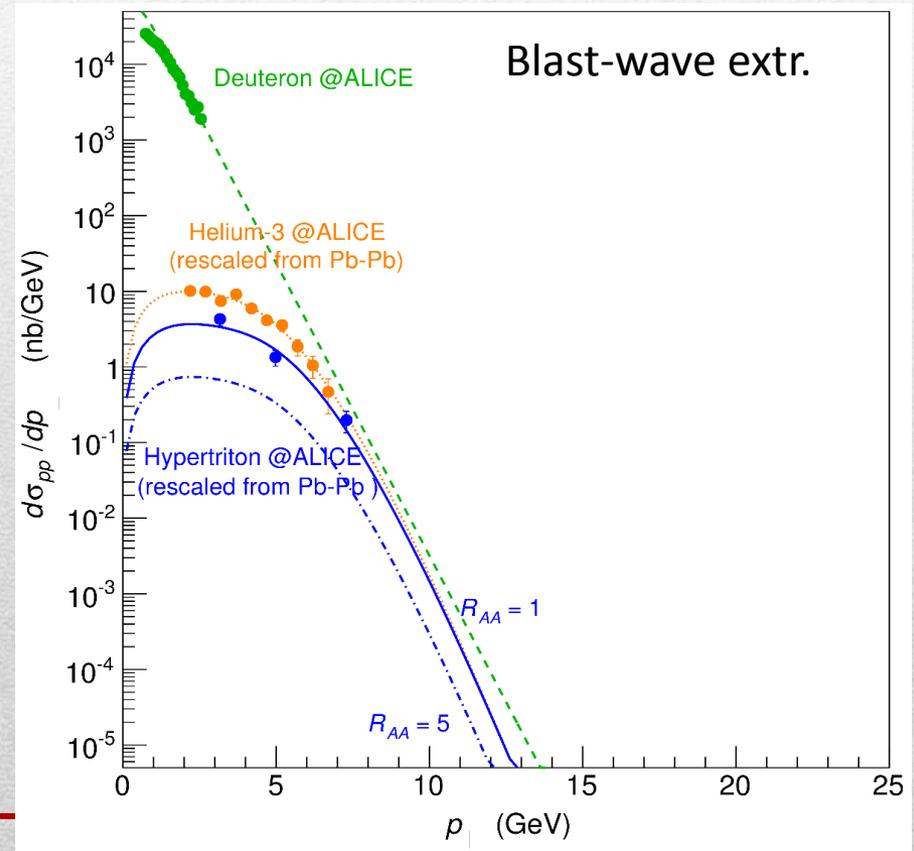
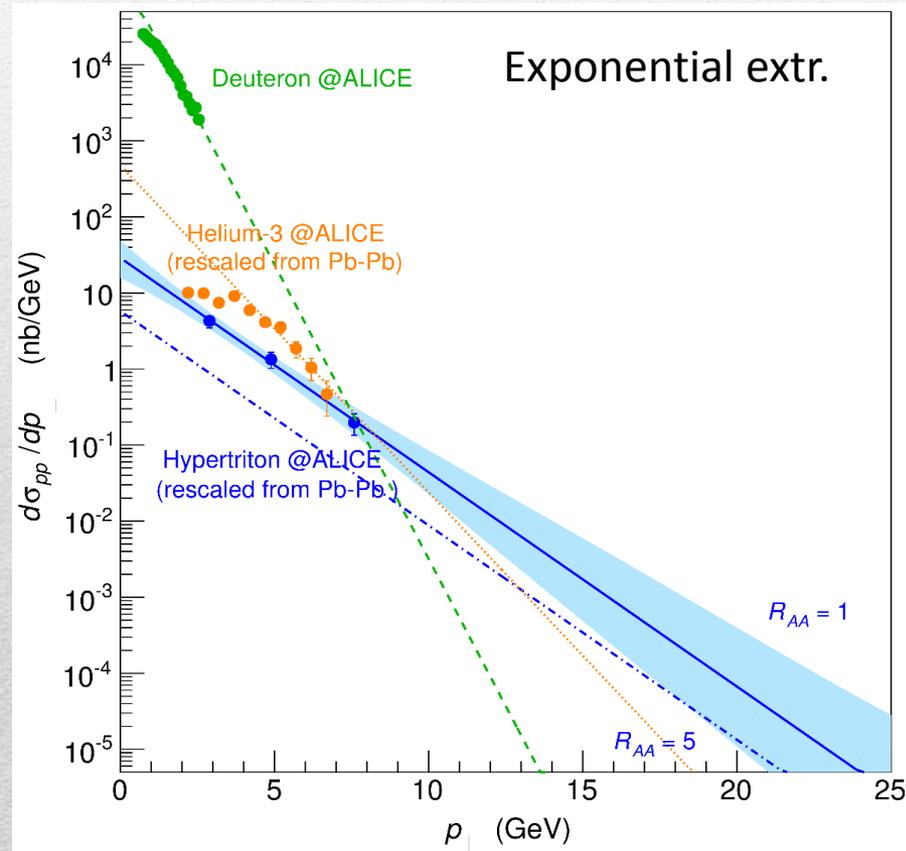
$$R_{AA} = \frac{\left(\frac{dN}{dp_T} \right)_{Pb-Pb}}{N_{coll} \left(\frac{dN}{dp_T} \right)_{pp}}$$



Light nuclei at ALICE

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model ($R_{AA} = 1$) and a value $R_{AA} = 5$ to rescale Pb-Pb data to pp

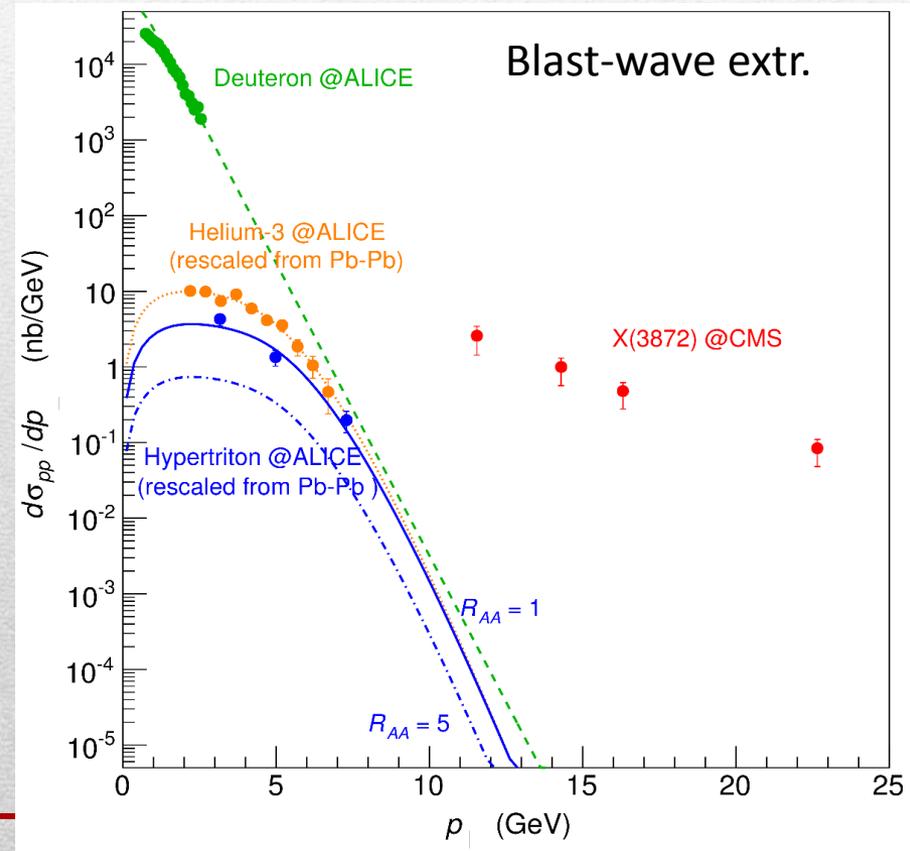
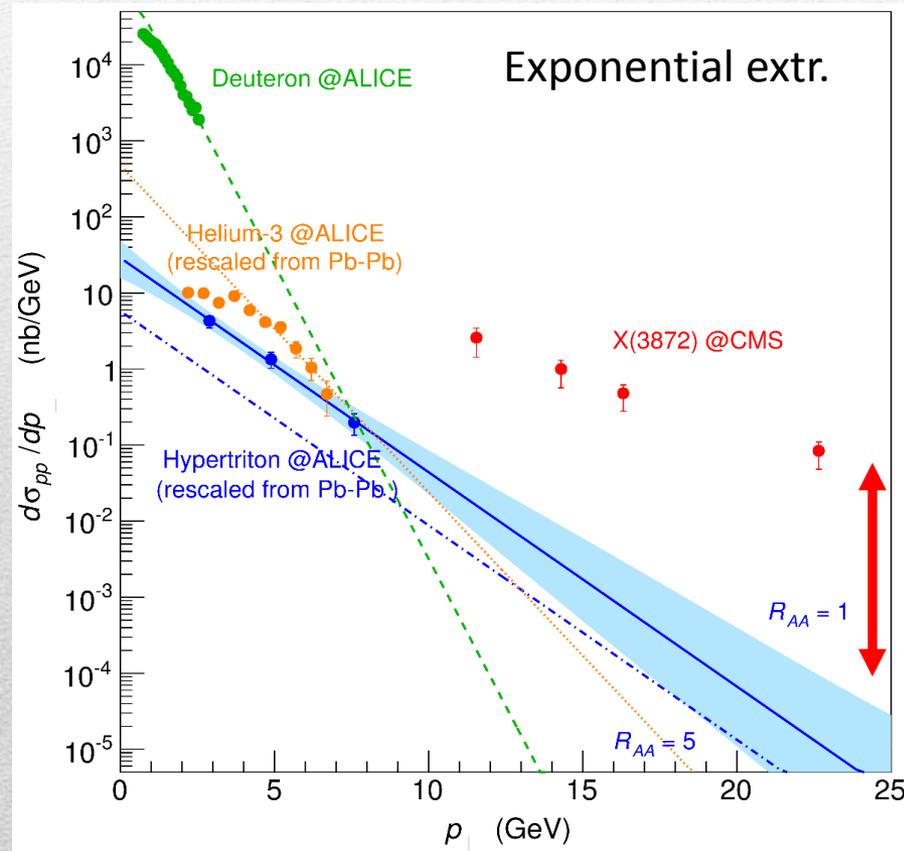


Light nuclei at ALICE vs. $X(3872)$

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model ($R_{AA} = 1$) and a value $R_{AA} = 5$ to rescale Pb-Pb data to pp

The $X(3872)$ is way larger than the extrapolated cross section



Light nuclei at ALICE vs. $X(3872)$

If the production is long-distance dominated, that's pretty much it.

If it's short-distance dominated, one can think on an effect related to the number of quarks involved, in the spirit of constituent counting rules

Brodsky and Lebed, PRD91, 114025

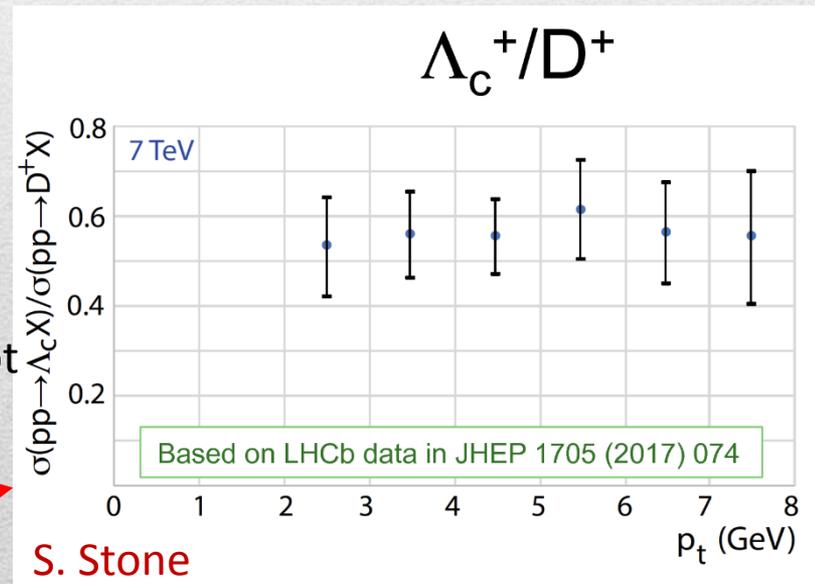
Guo et al., CPC41, 053108

Voloshin, PRD94, 074042

Wang, CPC42, 043103

However, it is not easy to make sense of constituent counting rules in **inclusive reactions**, where you cannot track the energy carried by each quark

They seem to spectacularly fail



Production of other exotics

Other cross sections have been estimated, generally quite large

Guo et al. EPJC74, 9, 3063

Guo et al. CTP, 61, 354

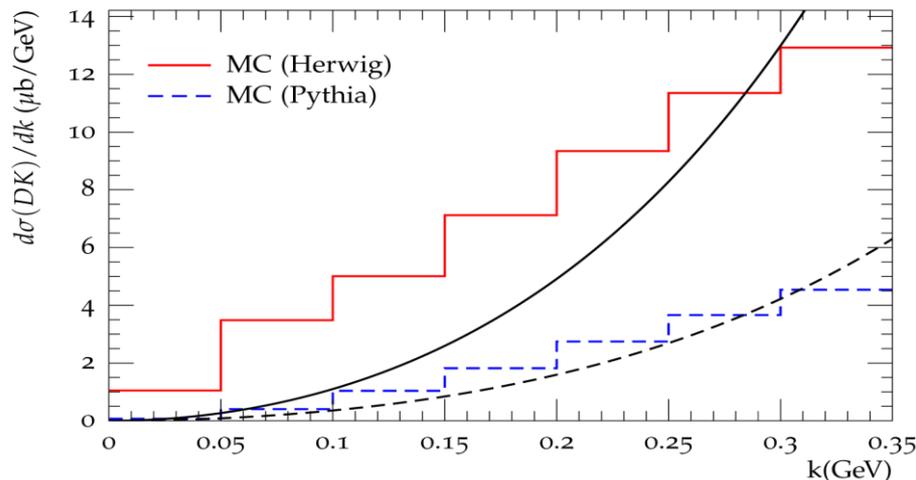
	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)

(nb)

X_b	$E_{X_b} = 24 \text{ MeV} (\Lambda = 0.5 \text{ GeV})$	$E_{X_b} = 66 \text{ MeV} (\Lambda = 1 \text{ GeV})$
Tevatron	0.08(0.18)	0.61(1.4)
LHC 7	1.5(3.1)	12(23)
LHCb 7	0.25(0.49)	1.9(3.7)
LHC 8	1.8(3.6)	14(27)
LHCb 8	0.3(0.62)	2.2(4.7)
LHC 14	3.2(6.8)	24(51)
LHCb 14	0.65(1.3)	4.9(9.7)

(nb)

Guo et al. JHEP 1405, 138



$$\sigma[D_{sJ}] = \left| \frac{F^2}{2} g_{\text{eff}} \right|^2 \left(\frac{d\sigma[HK(\mathbf{k})]}{dk} \right)_{\text{MC}} \frac{4\pi^2 \mu}{k^2 E_K^2 m_H^2}$$

	$D_{s0}^*(2317)$	$D_{s1}(2460)$	$D_{sJ}(2860)$	$D_{s2}(2910)$
LHC 7	2.5(0.83)	2.1(0.91)	0.21(-)	0.27(-)
LHCb 7	0.61(0.15)	0.5(0.17)	0.05(-)	0.06(-)
LHC 8	2.9(0.94)	2.4(1.0)	0.24(-)	0.32(-)
LHCb 8	0.74(0.18)	0.61(0.2)	0.06(-)	0.08(-)
LHC 14	5.5(1.6)	4.7(1.7)	0.5(-)	0.65(-)
LHCb 14	1.6(0.35)	1.3(0.38)	0.13(-)	0.17(-)

(μb)

Production of $Y(4260)$ and $P_c(4450)$

Given the new lineshape by BESIII, we need to rethink the binding energy of the $Y(4260)$

J. Nys and AP, to appear

	Constituents	Bind. Energy	Bind. Mom.	Mediator
$X(3872)$	$\bar{D}^0 D^{*0}$	~ 100 keV	~ 50 MeV	1π (~ 300 MeV)
$Y(4260)$	$\bar{D} D_1$	~ 70 MeV	~ 400 MeV	2π (~ 600 MeV)
$P_c(4450)$	$\bar{D}^* \Sigma_c$	~ 10 MeV	~ 150 MeV	1π (~ 300 MeV)

If the states are purely hadron molecule, all the properties depend on the position of the pole with respect to threshold – all the features are universal

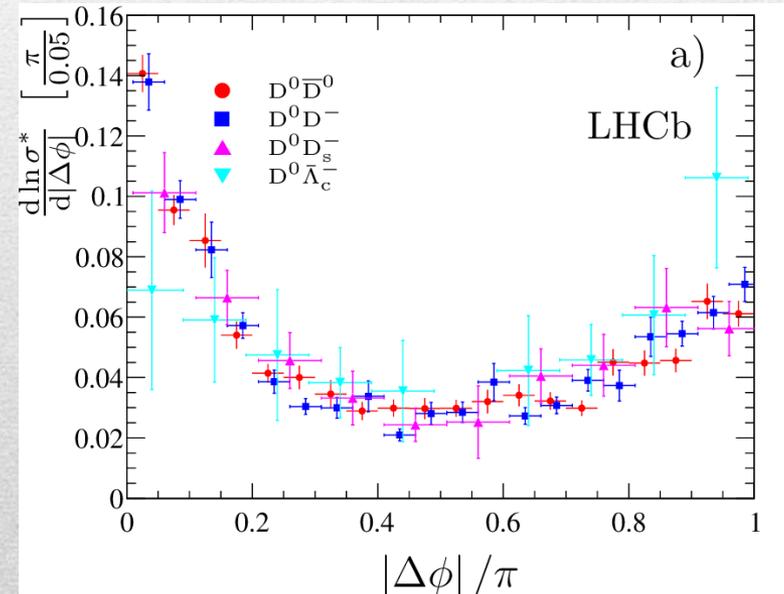
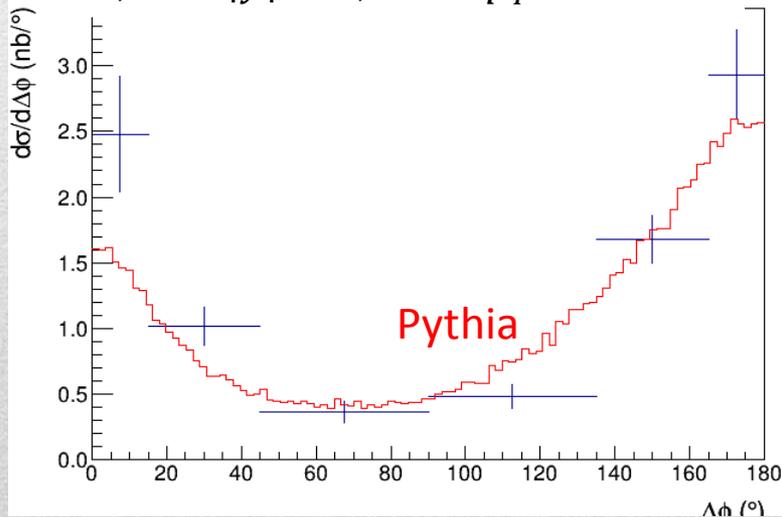
Production of $Y(4260)$ and $P_c(4450)$

We can use Pythia to simulate the production of event, and calculate the relative production of $Y(4260)$ and $P_c(4450)$ with respect to the $X(3872)$ J. Nys and AP, to appear

We tune our MC on charm pair production For baryons we can double check with LHCb data

CDF data, $\sqrt{s} = 1.96$ TeV

D^0, D^{*-} : $|y| < 1, 5.5 < p_T < 20$ GeV



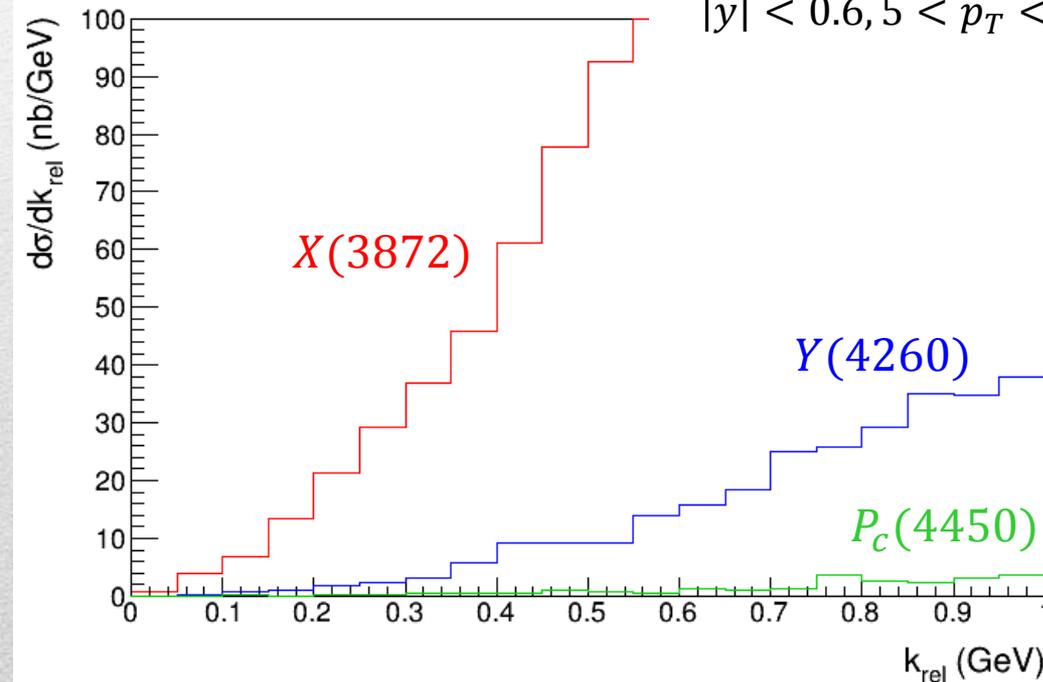
LHCb, $\sqrt{s} = 7$ TeV, **JHEP 1206, 141**
all: $2 < y < 4, 3 < p_T < 12$ GeV

Production of $Y(4260)$ and $P_c(4450)$

Naively, the fragmentation function of the D_1 is 1/10 of the D^* ,
but the cross section scales as k_{max}^3

J. Nys and AP, to appear

Pythia $p\bar{p}$, $\sqrt{s} = 1.96$ TeV
 $|y| < 0.6, 5 < p_T < 20$ GeV



	No FSI	With FSI
$Y(4260)/X$	23	0.75
$P_c(4450)/X$	1.0	0.01

The production of $Y(4260)$
is expected to be at worse comparable
with the $X(3872)$

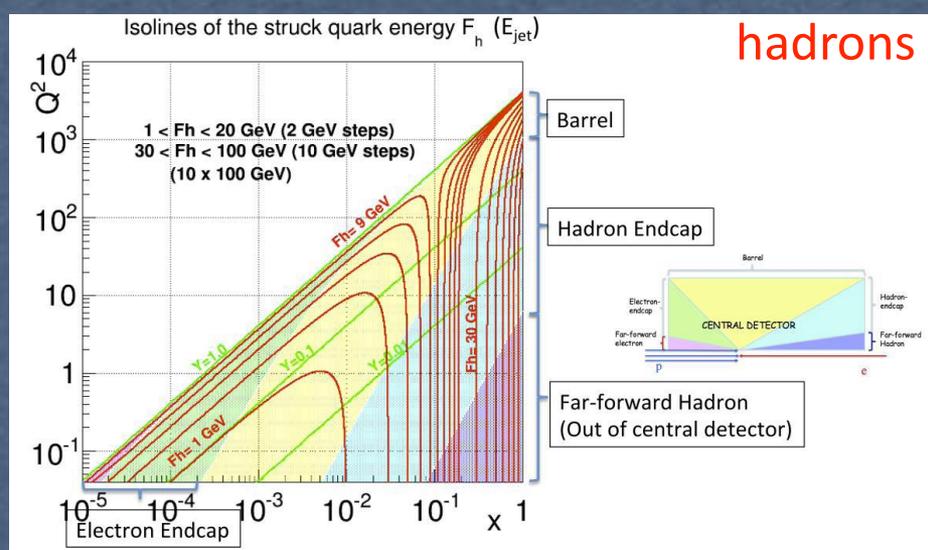
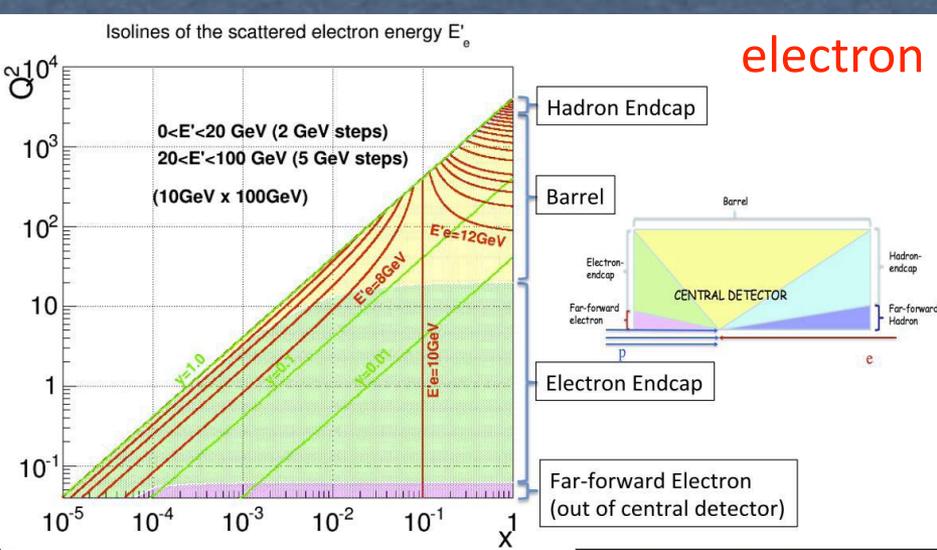
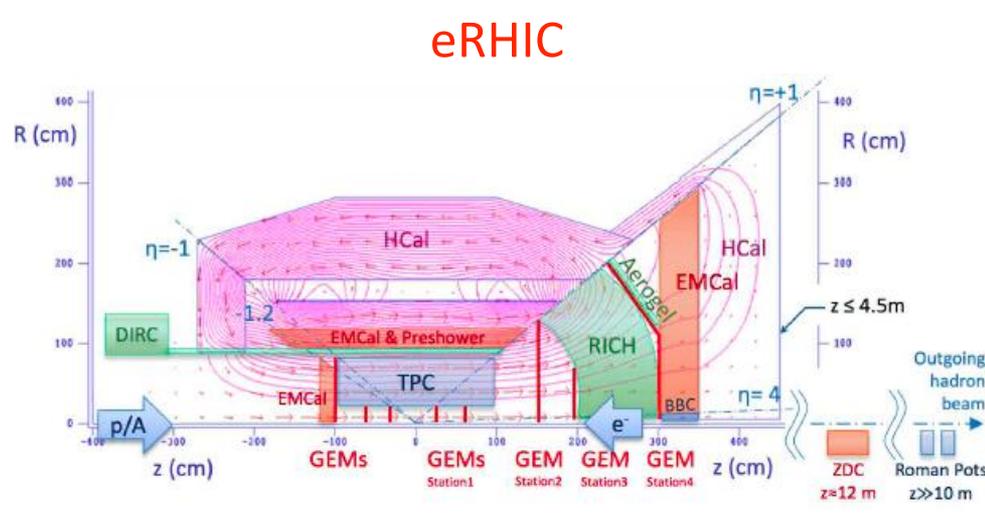
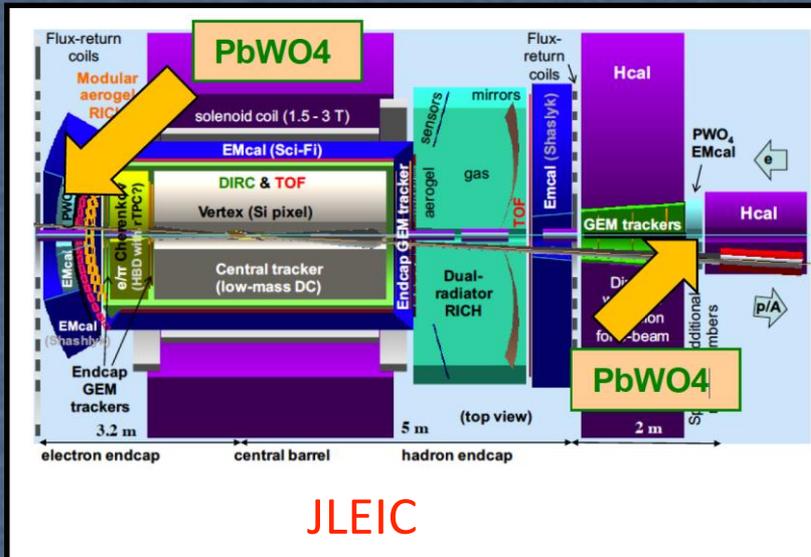
Conclusions

- An **Electron Ion Collider** is going to be a **challenge** from any point of view
- The spectroscopy program requires an **intense effort from the theory** side, to exploit all the unique features of the new machine
- The working group just started working, some estimates are on the way.
We need people and ideas!
- We aim to have a workshop in December, and to wrap up the white book in ~ 1 year from now

Thank you

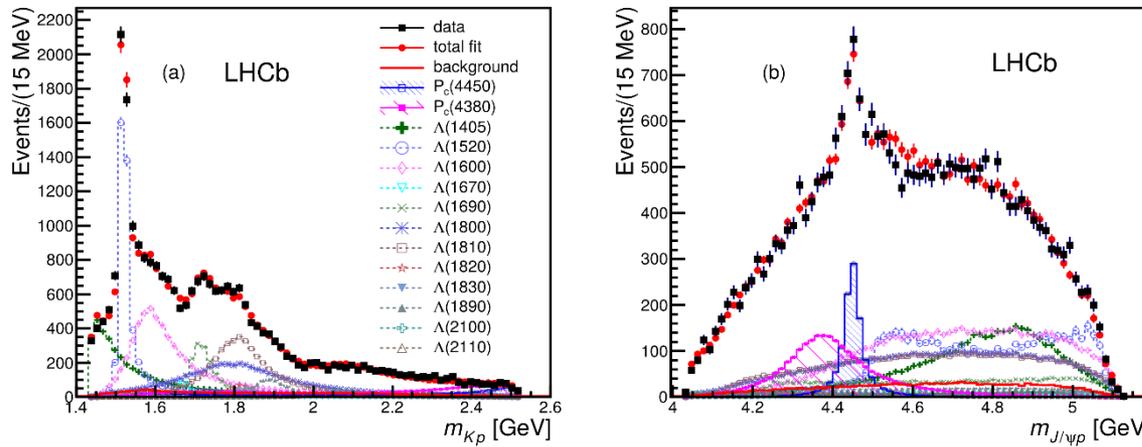
BACKUP

EIC detectors



Pentaquarks!

LHCb, PRL 115, 072001
LHCb, PRL 117, 082003



Two states seen in $\Lambda_b \rightarrow (J/\psi p) K^-$,
evidence in $\Lambda_b \rightarrow (J/\psi p) \pi^-$

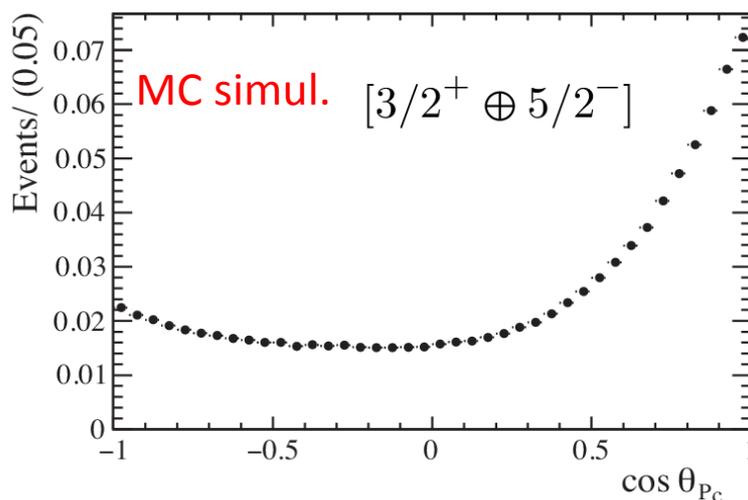
$M_1 = 4380 \pm 8 \pm 29$ MeV
 $\Gamma_1 = 205 \pm 18 \pm 86$ MeV
 $M_2 = 4449.8 \pm 1.7 \pm 2.5$ MeV
 $\Gamma_2 = 39 \pm 5 \pm 19$ MeV

Quantum numbers

$$J^P = \left(\frac{3^-}{2}, \frac{5^+}{2} \right) \text{ or } \left(\frac{3^+}{2}, \frac{5^-}{2} \right) \text{ or } \left(\frac{5^+}{2}, \frac{3^-}{2} \right)$$

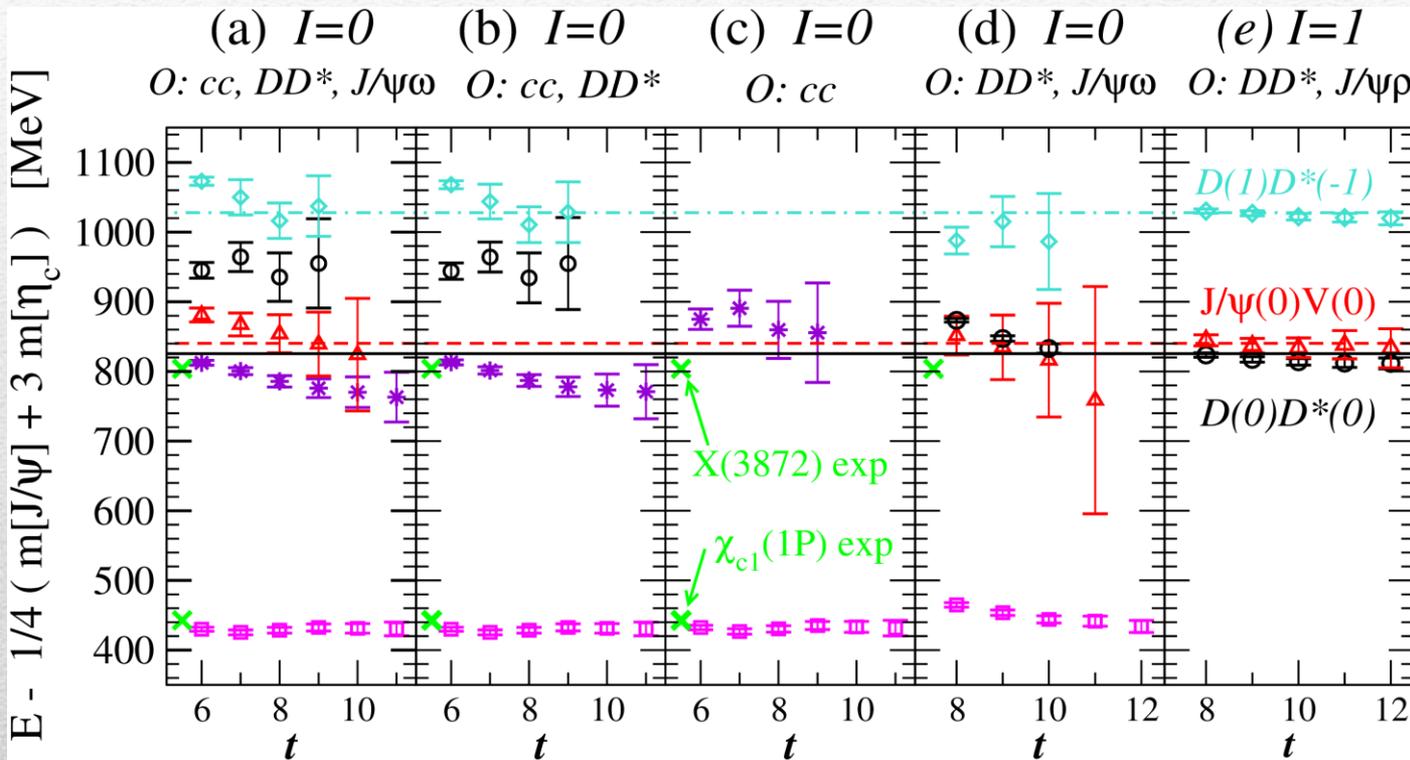
Opposite parities needed for the interference to correctly describe angular distributions, **low mass region contaminated by Λ^* (model dependence?)**

No obvious threshold nearby



$X(3872)$ on the lattice

There is only evidence (?) for the $X(3872)$ in the $I^G J^{PC} = 0^+ 1^{++}$ channel



Caveats:

- Small lattices, large artifacts
- Three body dynamics may play a role
- Interpretation of the overlap coefficients is questionable

Status of other XYZ on the lattice is even less clear

S. Prelovsek, L. Leskovec, PRL111, 192001

Dictionary – Quark model

L = orbital angular momentum

S = spin $q + \bar{q}$

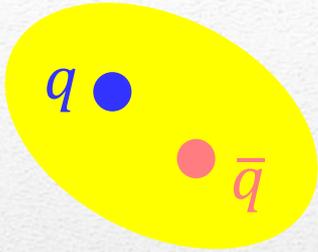
J = total angular momentum
= exp. measured spin

I = isospin = 0 for quarkonia

$$L - S \leq J \leq L + S$$

$$P = (-1)^{L+1}, C = (-1)^{L+S}$$

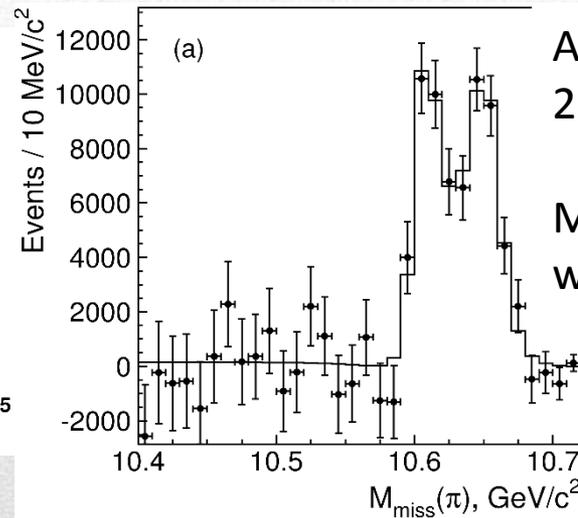
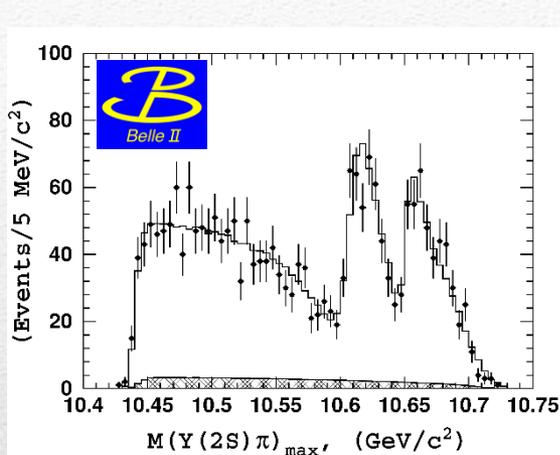
$$G = (-1)^{L+S+I}$$



J^{PC}	L	S	Charmonium ($c\bar{c}$)	Bottomonium ($b\bar{b}$)
0^{-+}	0 (S -wave)	0	$\eta_c(nS)$	$\eta_b(nS)$
1^{--}		1	$\psi(nS)$	$\Upsilon(nS)$
1^{+-}	1 (P -wave)	0	$h_c(nP)$	$h_b(nP)$
0^{++}		1	$\chi_{c0}(nP)$	$\chi_{b0}(nP)$
1^{++}		1	$\chi_{c1}(nP)$	$\chi_{b1}(nP)$
2^{++}		1	$\chi_{c2}(nP)$	$\chi_{b2}(nP)$

But $J/\psi = \psi(1S)$, $\psi' = \psi(2S)$

Charged Z states: $Z_b(10610)$, $Z'_b(10650)$



Anomalous dipion width in $\Upsilon(5S)$,
2 orders of magnitude larger than $\Upsilon(nS)$

Moreover, observed $\Upsilon(5S) \rightarrow h_b(nP)\pi\pi$
which violates HQSS

2 twin resonances!

$$\Upsilon(5S) \rightarrow Z_b(10610)^+\pi^- \rightarrow \Upsilon(nS)\pi^+\pi^-, h_b(nP)\pi^+\pi^-$$

$$\text{and } \rightarrow (BB^*)^+\pi^-$$

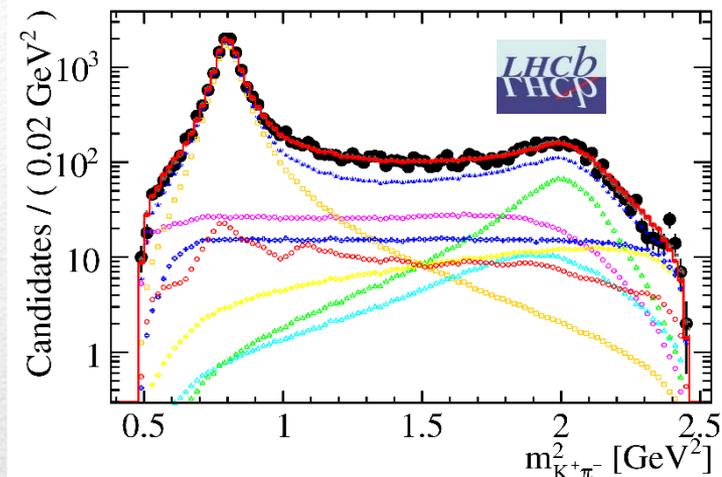
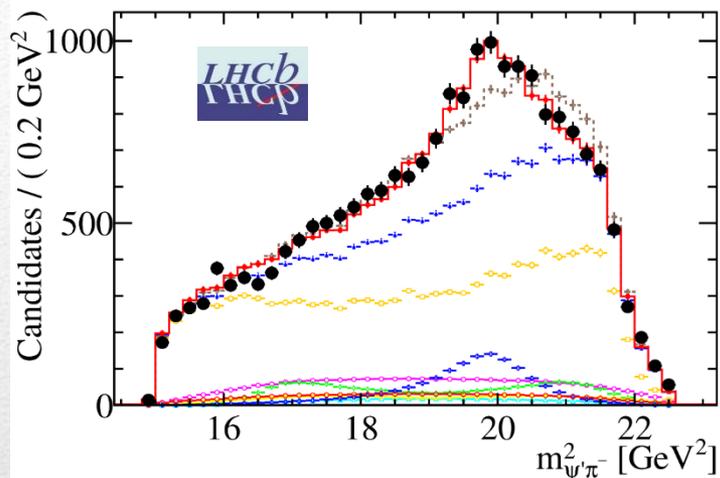
$$M = 10607.2 \pm 2.0 \text{ MeV}, \Gamma = 18.4 \pm 2.4 \text{ MeV}$$

$$\Upsilon(5S) \rightarrow Z'_b(10650)^+\pi^- \rightarrow \Upsilon(nS)\pi^+\pi^-, h_b(nP)\pi^+\pi^-$$

$$\text{and } \rightarrow \bar{B}^{*0}B^{*+}\pi^-$$

$$M = 10652.2 \pm 1.5 \text{ MeV}, \Gamma = 11.5 \pm 2.2 \text{ MeV}$$

Charged Z states: Z(4430)



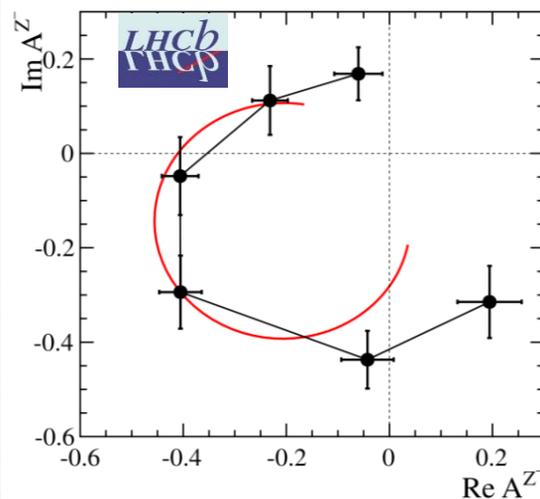
$$Z(4430)^+ \rightarrow \psi(2S) \pi^+$$

$$I^G J^{PC} = 1^+ 1^{+-}$$

$$M = 4475 \pm 7_{-25}^{+15} \text{ MeV}$$

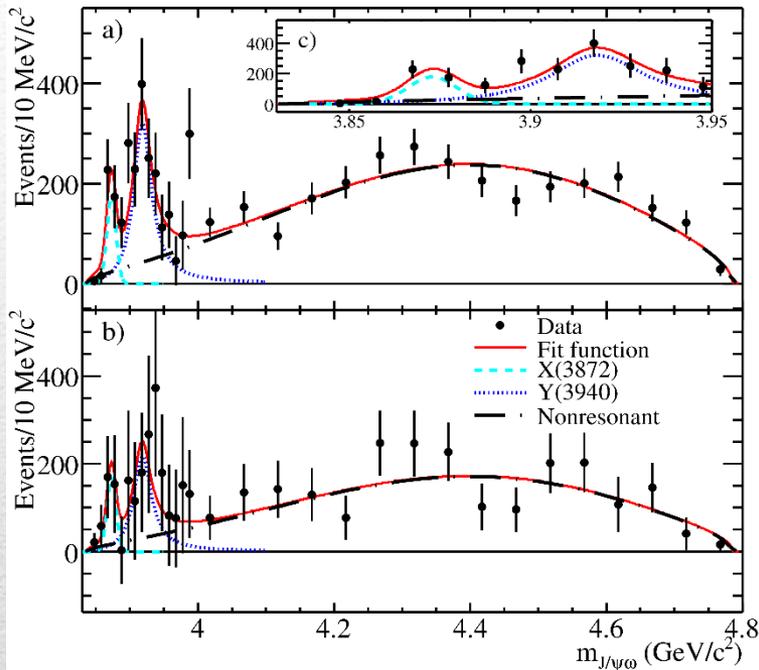
$$\Gamma = 172 \pm 13_{-34}^{+37} \text{ MeV}$$

Far from open charm thresholds



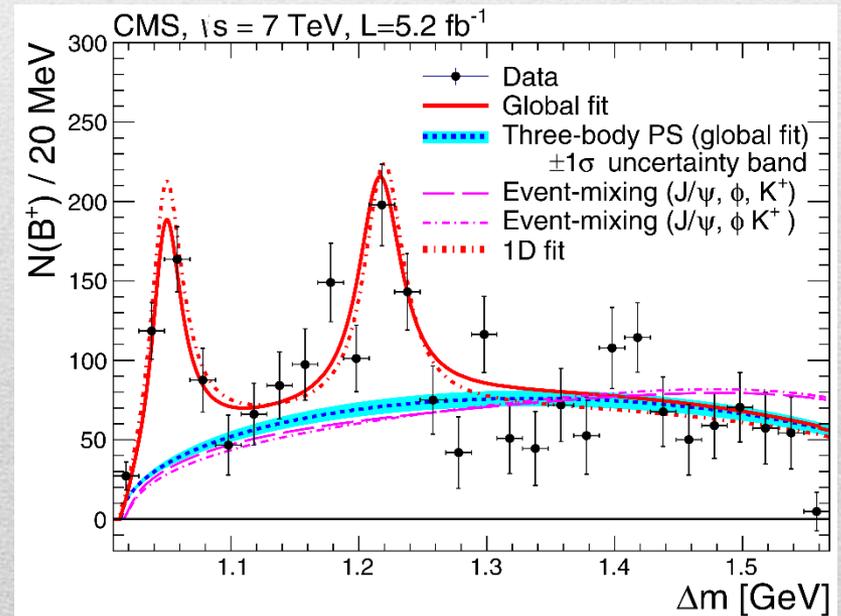
If the amplitude is a free complex number, in each bin of $m_{\psi\pi^-}^2$, the resonant behaviour appears as well

Other beasts



One/two peaks seen in $B \rightarrow XK \rightarrow J/\psi \phi K$, close to threshold

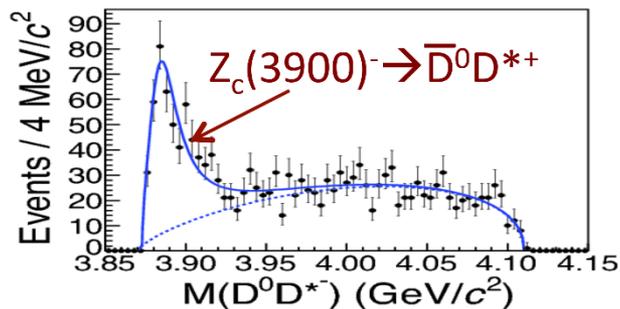
$X(3915)$, seen in $B \rightarrow XK \rightarrow J/\psi \omega$
 and $\gamma\gamma \rightarrow X \rightarrow J/\psi \omega$
 $J^{PC} = 0^{++}$, candidate for $\chi_{c0}(2P)$
 But $X(3915) \not\rightarrow D\bar{D}$ as expected,
 and the hyperfine splitting
 $M(2^{++}) - M(0^{++})$ too small



$Y(4260) \rightarrow \bar{D}D_1?$

$e^+e^- \rightarrow Y(4260) \rightarrow \pi^-\bar{D}^0D^{*+}$

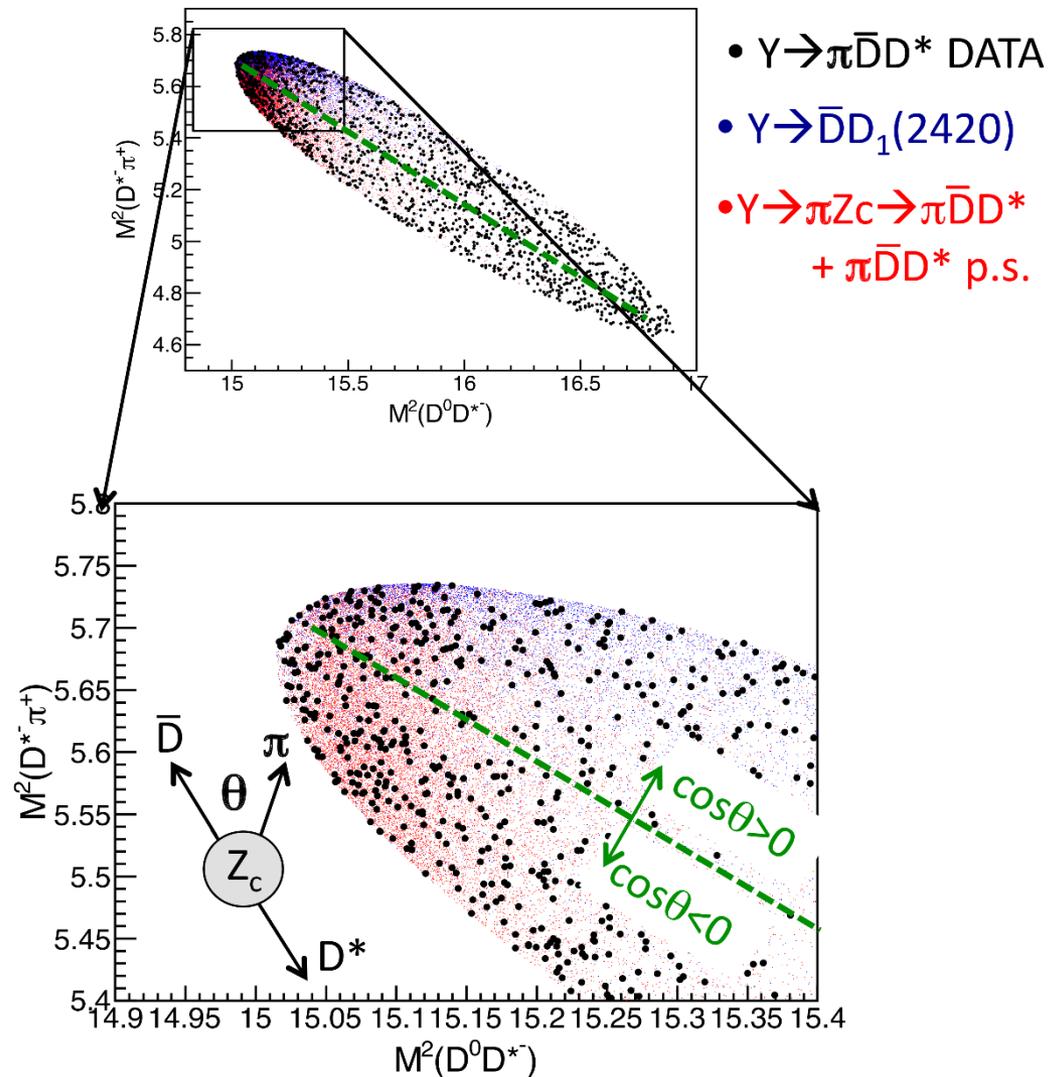
BESIII PRL 112, 022001



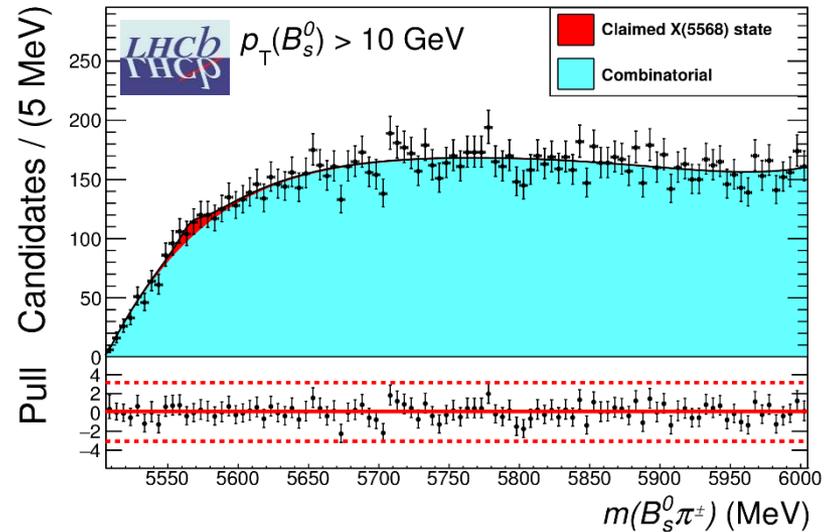
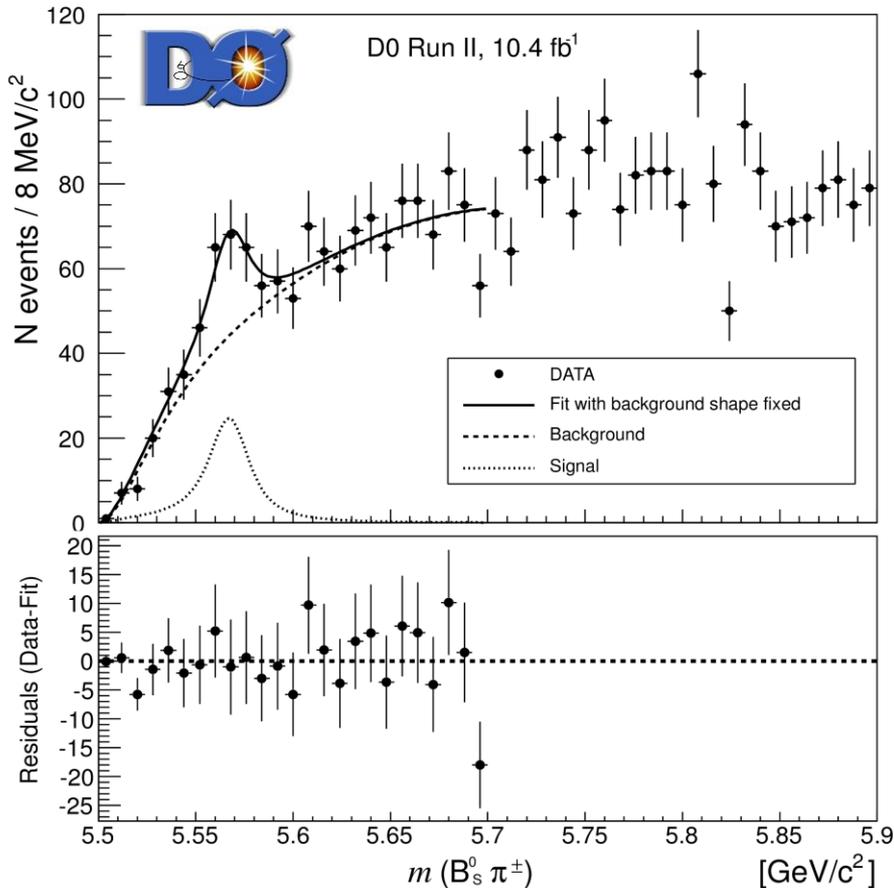
$$\mathcal{A} = \frac{N_{|\cos\theta|>0.5} - N_{|\cos\theta|<0.5}}{N_{|\cos\theta|>0.5} + N_{|\cos\theta|<0.5}}$$

	DD ₁ MC	Z _c +ps MC	data
\mathcal{A}	0.43±0.04	0.02±0.02	0.12±0.06

Not a lot of room for $\bar{D}D_1(2410)$



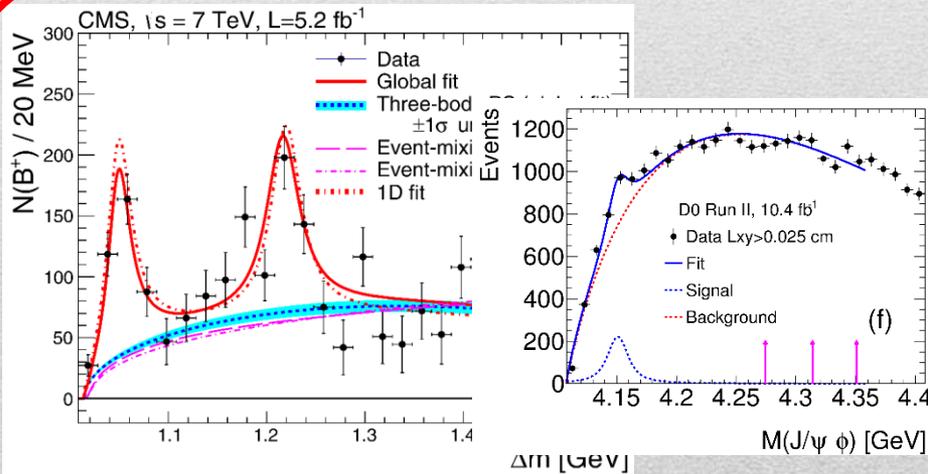
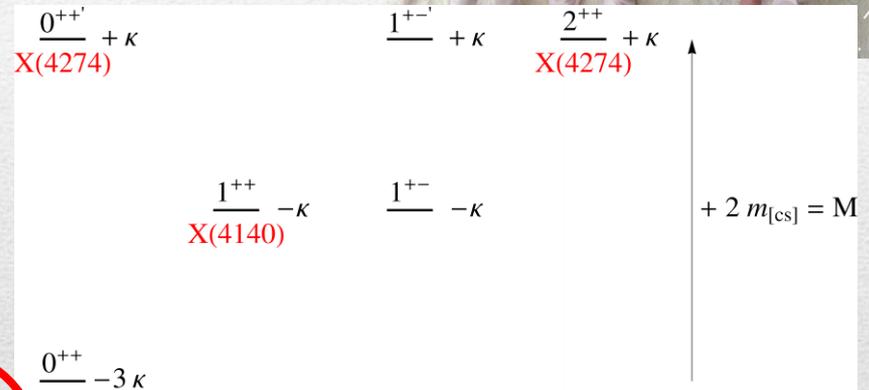
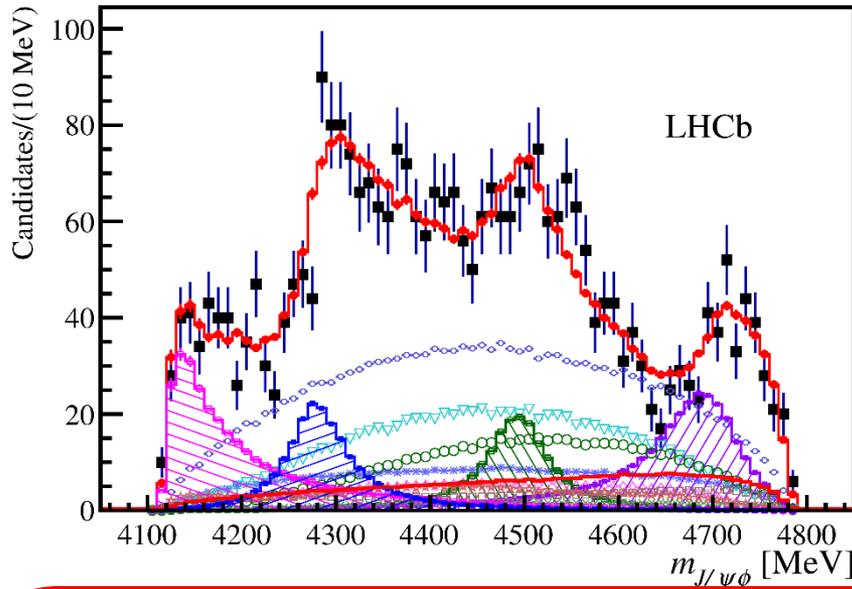
Flavored X(5568)



- A **flavored state** seen in $B_s^0 \pi$ invariant mass by D0 (both $B_s^0 \rightarrow J/\psi \phi$ and $\rightarrow D_s \mu \nu$),
- **not conformed** by LHCb or CMS
- (different kinematics? Compare differential distributions)

Controversy to be solved

Tetraquark: the $c\bar{c}s\bar{s}$ states



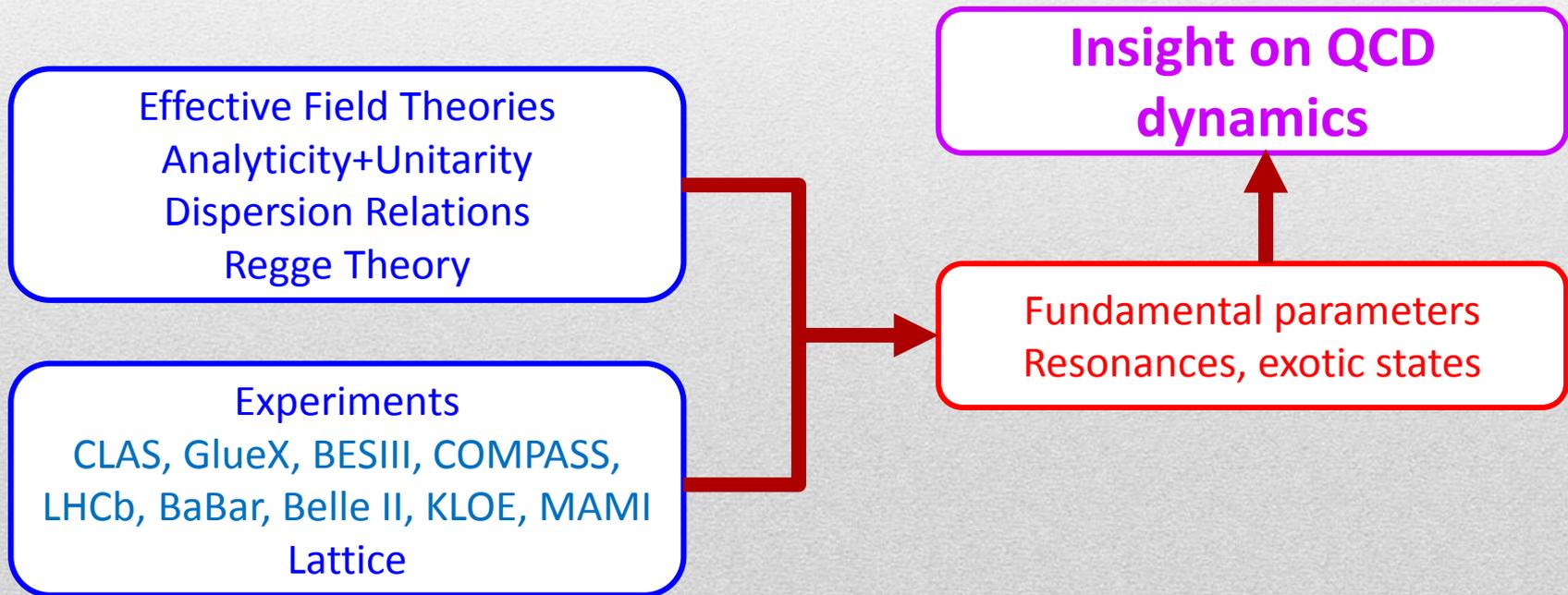
Much narrower than LHCb! Look for prompt!

Good description of the spectrum **but** one has to assume the axial assignment for the X(4274) to be incorrect (two unresolved states with 0^{++} and 2^{++})

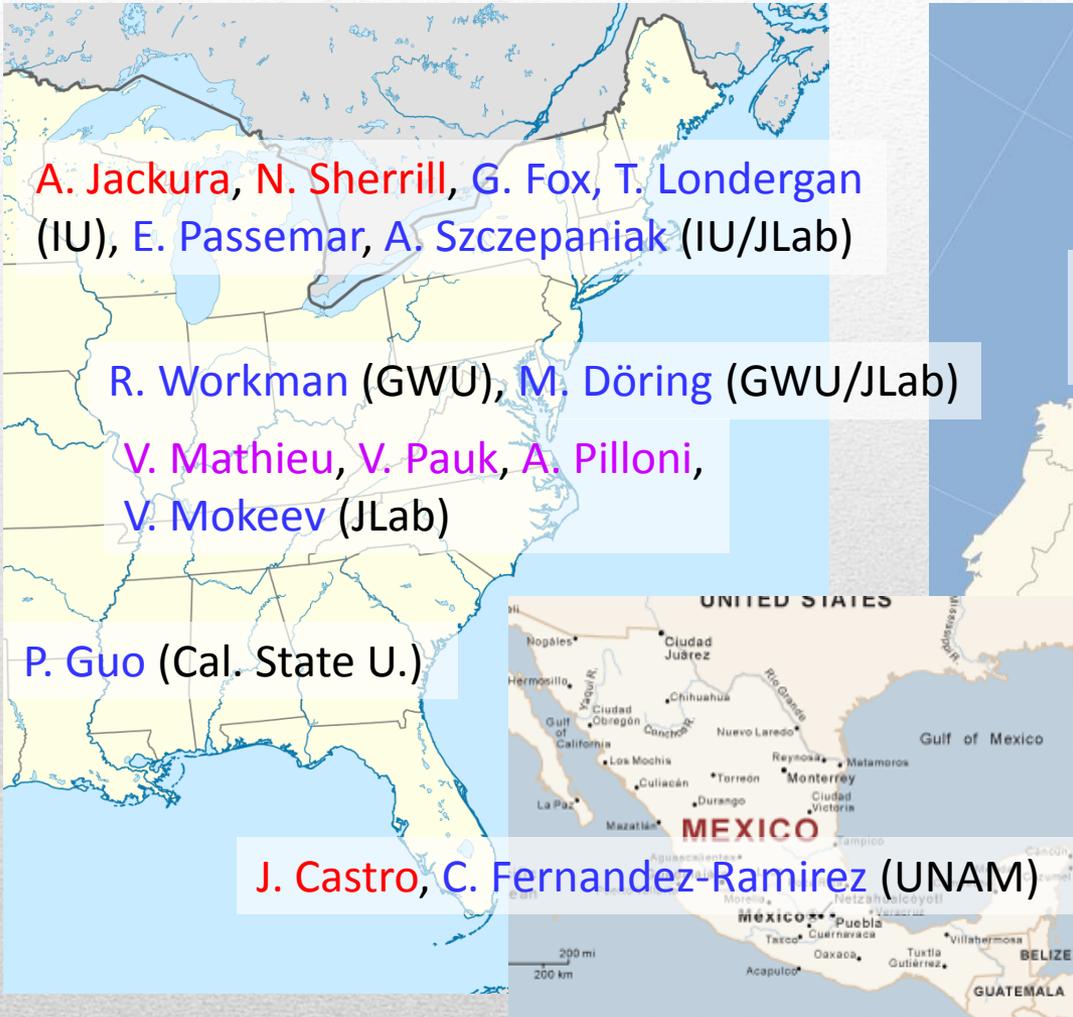
Maiani, Polosa and Riquer, PRD 94, 054026

Joint Physics Analysis Center

- **Joint effort** between **theorists** and **experimentalists** to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Created in 2013 by JLab & IU agreement
- It is engaged in **education** of further generations of hadron physics practitioners



Joint Physics Analysis Center



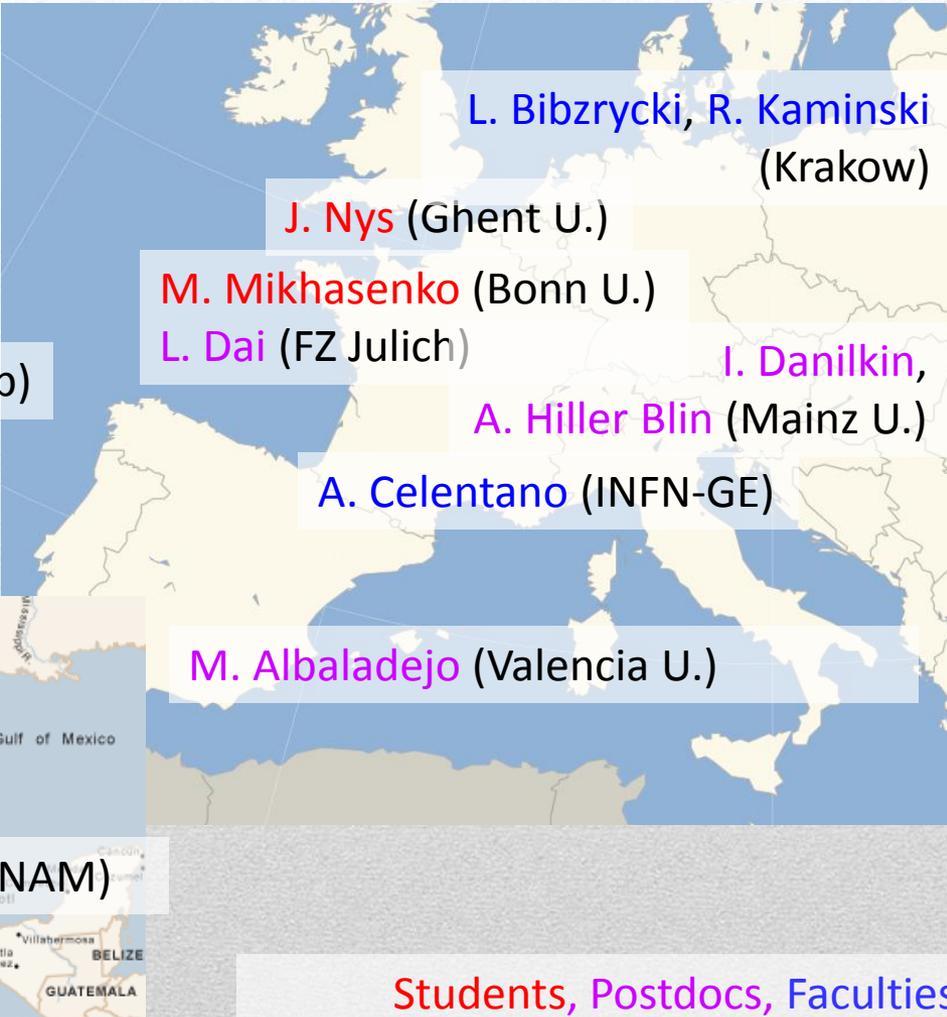
A. Jackura, N. Sherrill, G. Fox, T. Londergan
(IU), E. Passemar, A. Szczepaniak (IU/JLab)

R. Workman (GWU), M. Döring (GWU/JLab)

V. Mathieu, V. Pauk, A. Pilloni,
V. Mokeev (JLab)

P. Guo (Cal. State U.)

J. Castro, C. Fernandez-Ramirez (UNAM)



L. Bibzrycki, R. Kaminski
(Krakow)

J. Nys (Ghent U.)

M. Mikhasenko (Bonn U.)

L. Dai (FZ Julich)

I. Danilkin,

A. Hiller Blin (Mainz U.)

A. Celentano (INFN-GE)

M. Albaladejo (Valencia U.)

Students, Postdocs, Faculties

Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.

<http://www.indiana.edu/~jpac/>

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

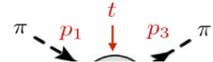


This project is supported by NSF

$$\pi N \rightarrow \pi N$$

Formalism

The pion-nucleon scattering is a function of 2 variables. The first is the beam momentum in the laboratory frame p_{lab} (in GeV) or the total energy squared $s = W^2$ (in GeV^2). The second is the cosine of



Resources

- Publications: [Mat15a] and [Wor12a]
- SAID partial waves: compressed zip file
- C/C++: C/C++ file
- Input file: param.txt
- Output files: output0.txt, output1.txt, SigTot.txt, Observables0.txt, Observables1.txt
- Contact person: Vincent Mathieu
- Last update: June 2016

The SAID partial waves are in the format provided online on the SAID webpage :

p_{lab} δ $\epsilon(\delta)$ $1 - \eta^2$ $\epsilon(1 - \eta^2)$ Re PW Im PW SGT SGR

δ and η are the phase-shift and the inelasticity. $\epsilon(x)$ is the error on x .
SGT is the total cross section and SGR is the total reaction cross section.

Format of the input and output files: [show/hide]
Description of the C/C++ code: [show/hide]

Simulation

Range of the running variable:

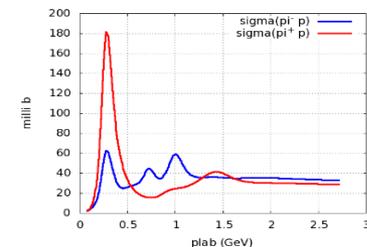
s in GeV^2 (min max step)	1,2	:	6	:	0,01
p_{lab} in GeV (min max step)	0,1	:	4	:	0,01
ν in GeV (min max step)	0,3	:	4	:	0,01
t in GeV^2 (min max step)	-1	:	0	:	0,01

The fixed variable:

t in GeV^2

p_{lab} in GeV

Results



Strategy

AP *et al.* (JPAC), arXiv:1612.06490

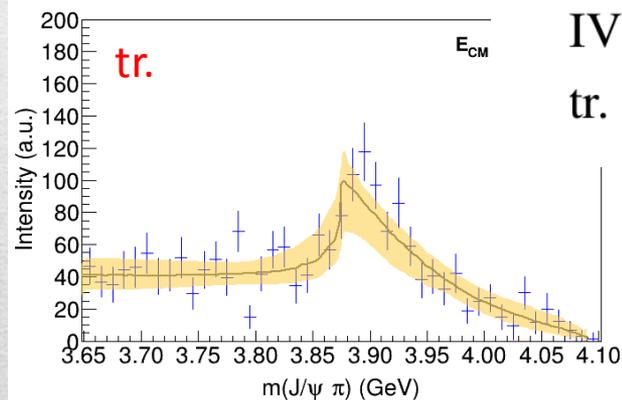
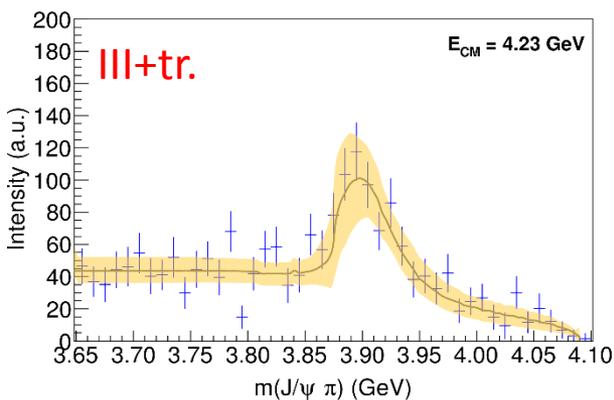
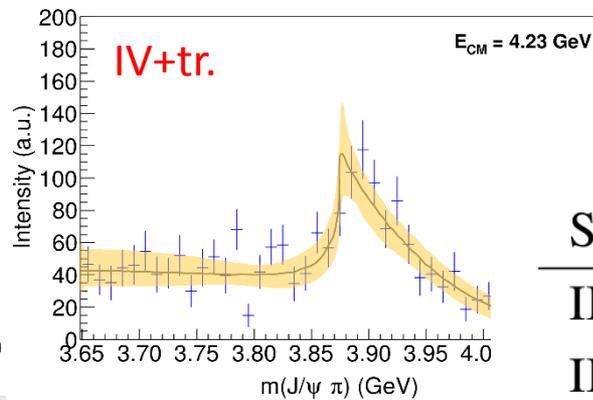
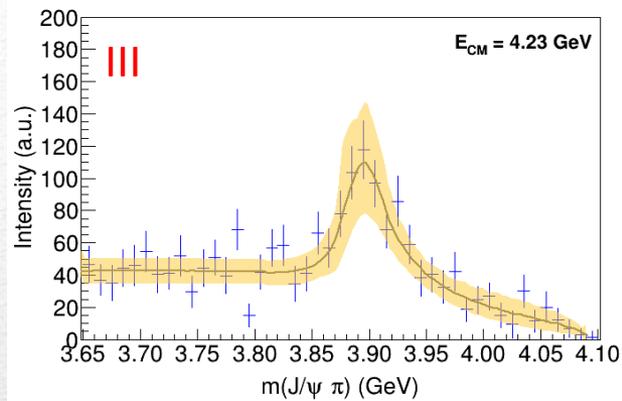
- We fit the following **invariant mass distributions**:
 - BESIII PRL110, 252001 $J/\psi \pi^+, J/\psi \pi^-, \pi^+ \pi^-$ at $E_{CM} = 4.26$ GeV
 - BESIII PRL110, 252001 $J/\psi \pi^0$ at $E_{CM} = 4.23, 4.26, 4.36$ GeV
 - BESIII PRD92, 092006 $\overline{D^0} D^{*+}, \overline{D^{*0}} D^+$ (double tag) at $E_{CM} = 4.23, 4.26$ GeV
 - BESIII PRL115, 222002 $\overline{D^0} D^{*0}, \overline{D^{*0}} D^0$ at $E_{CM} = 4.23, 4.26$ GeV
 - ~~BESIII PRL112, 022001 $\overline{D^0} D^{*+}, \overline{D^{*0}} D^+$ (single tag) at $E_{CM} = 4.26$ GeV~~
 - ~~Belle PRL110, 252002 $J/\psi \pi^\pm$ at $E_{CM} = 4.26$ GeV~~
 - ~~CLEO-c data PLB727, 366 $J/\psi \pi^\pm, J/\psi \pi^0$ at $E_{CM} = 4.17$ GeV~~
- Published data are not efficiency/acceptance corrected,
→ we are **not able to give the absolute normalization** of the amplitudes
- No given dependence on E_{CM} is assumed – the couplings at different E_{CM} are independent parameters

Strategy

AP *et al.* (JPAC), arXiv:1612.06490

- **Reducible** (incoherent) **backgrounds are pretty flat** and do not influence the analysis, except the peaking background in $\overline{D^0}D^{*0}, \overline{D^{*0}}D^0$ (subtracted)
- Some information about **angular distributions** has been published, but it's **not constraining** enough → we do not include in the fit
- Because of that, **we approximate all the particles to be scalar** – this affects the value of couplings, which are not normalized anyway – but not the position of singularities. This also limits the number of free parameters

Fit summary

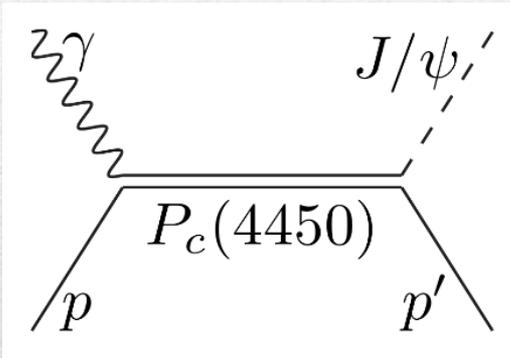


Scenario	χ^2	DOF	χ^2/DOF
III	644	532	1.21
III+tr.	642	532	1.21
IV+tr.	666	532	1.25
tr.	695	532	1.31

Naive loglikelihood ratio test give a $\sim 4\sigma$ significance of the scenario III+tr. over IV+tr., looking at plots it looks too much – better using some more solid test

P_c photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in **photoproduction**.



Vector meson dominance relates the radiative width to the hadronic width

$$\langle \lambda_\psi \lambda_{p'} | T_r | \lambda_\gamma \lambda_p \rangle = \frac{\langle \lambda_\psi \lambda_{p'} | T_{\text{dec}} | \lambda_R \rangle \langle \lambda_R | T_{\text{em}}^\dagger | \lambda_\gamma \lambda_p \rangle}{M_r^2 - W^2 - i\Gamma_r M_r}$$

Hadronic vertex EM vertex

Hadronic part

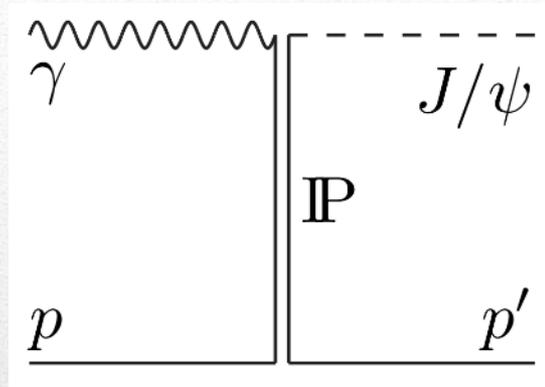
- 3 independent helicity couplings,
→ approx. equal, $g_{\lambda_\psi, \lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

$$\Gamma_\gamma = 4\pi\alpha \Gamma_{\psi p} \left(\frac{f_\psi}{M_\psi} \right)^2 \left(\frac{\bar{p}_i}{\bar{p}_f} \right)^{2\ell+1} \times \frac{4}{6}$$

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Background parameterization

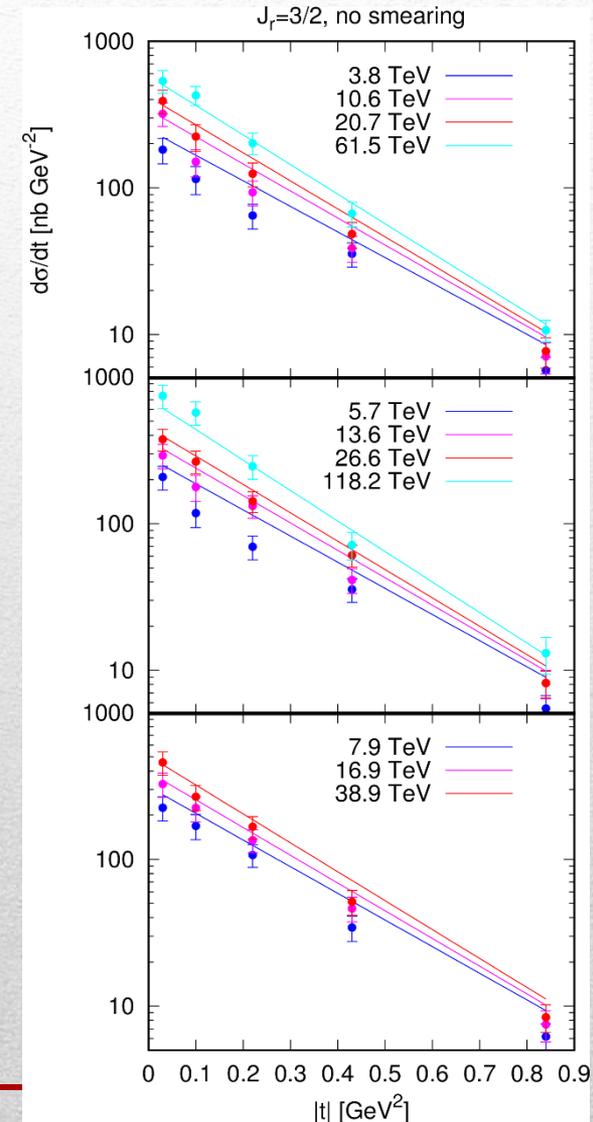
The background is described via an **Effective Pomeron**, whose parameters are fitted to high energy data from Hera



$$\langle \lambda_\psi \lambda_{p'} | T_P | \lambda_\gamma \lambda_p \rangle = iA \left(\frac{s - s_t}{s_0} \right)^{\alpha(t)} e^{b_0(t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

Asymptotic + Effective threshold

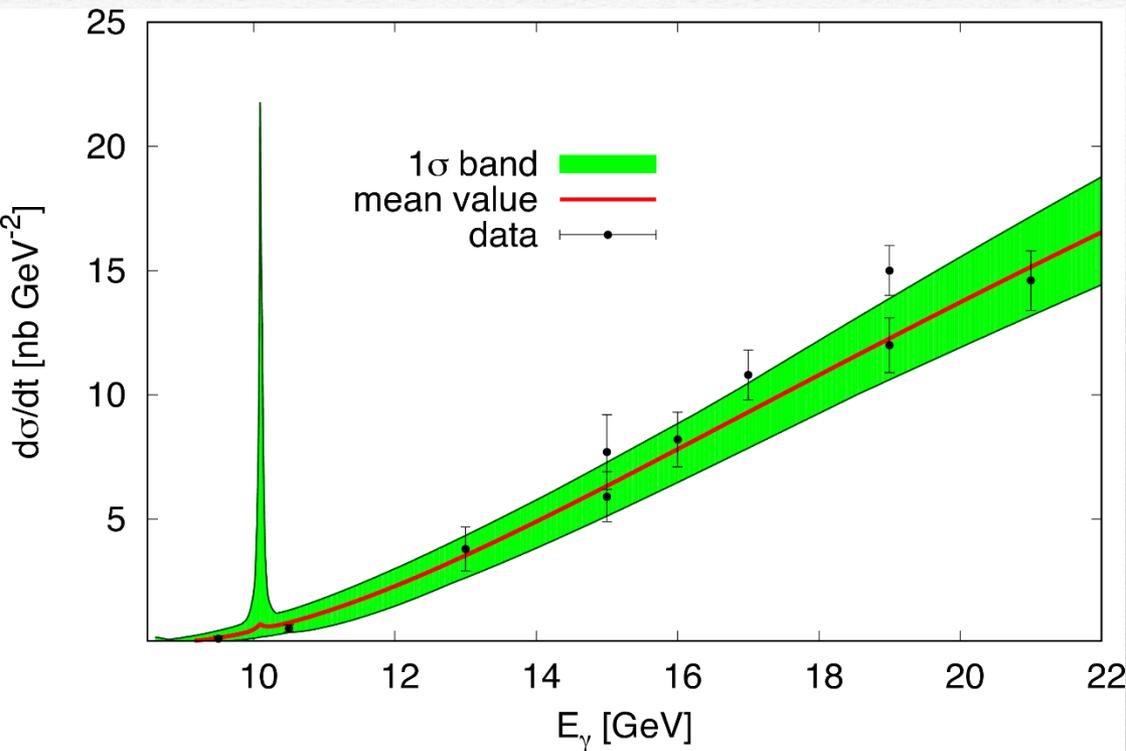
Helicity conservation



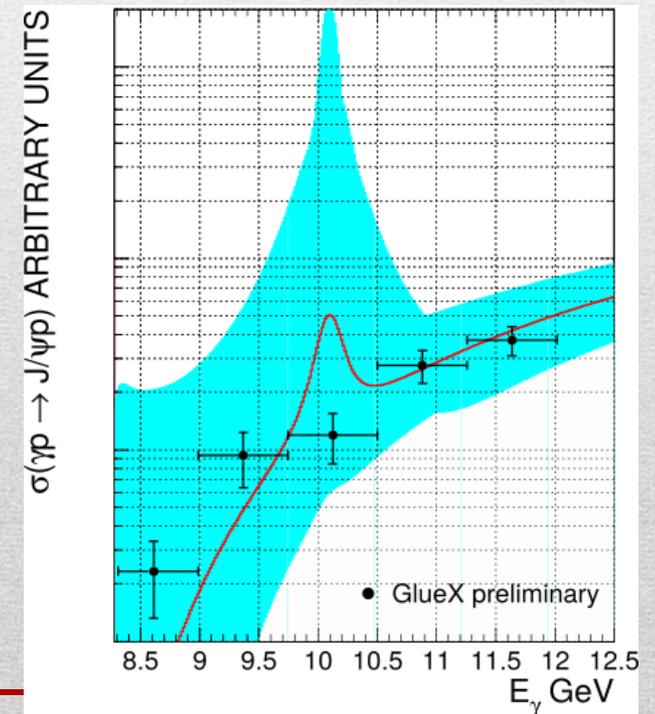
Hiller Blin, *AP et al.* (JPAC), PRD94, 034002

Pentaquark photoproduction

$$J^P = (3/2)^-$$



σ_s (MeV)	0	60
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$
$\mathcal{B}_{\psi p}$ (95% CL)	$\leq 29\%$	$\leq 30\%$



Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Lineshapes at 4260

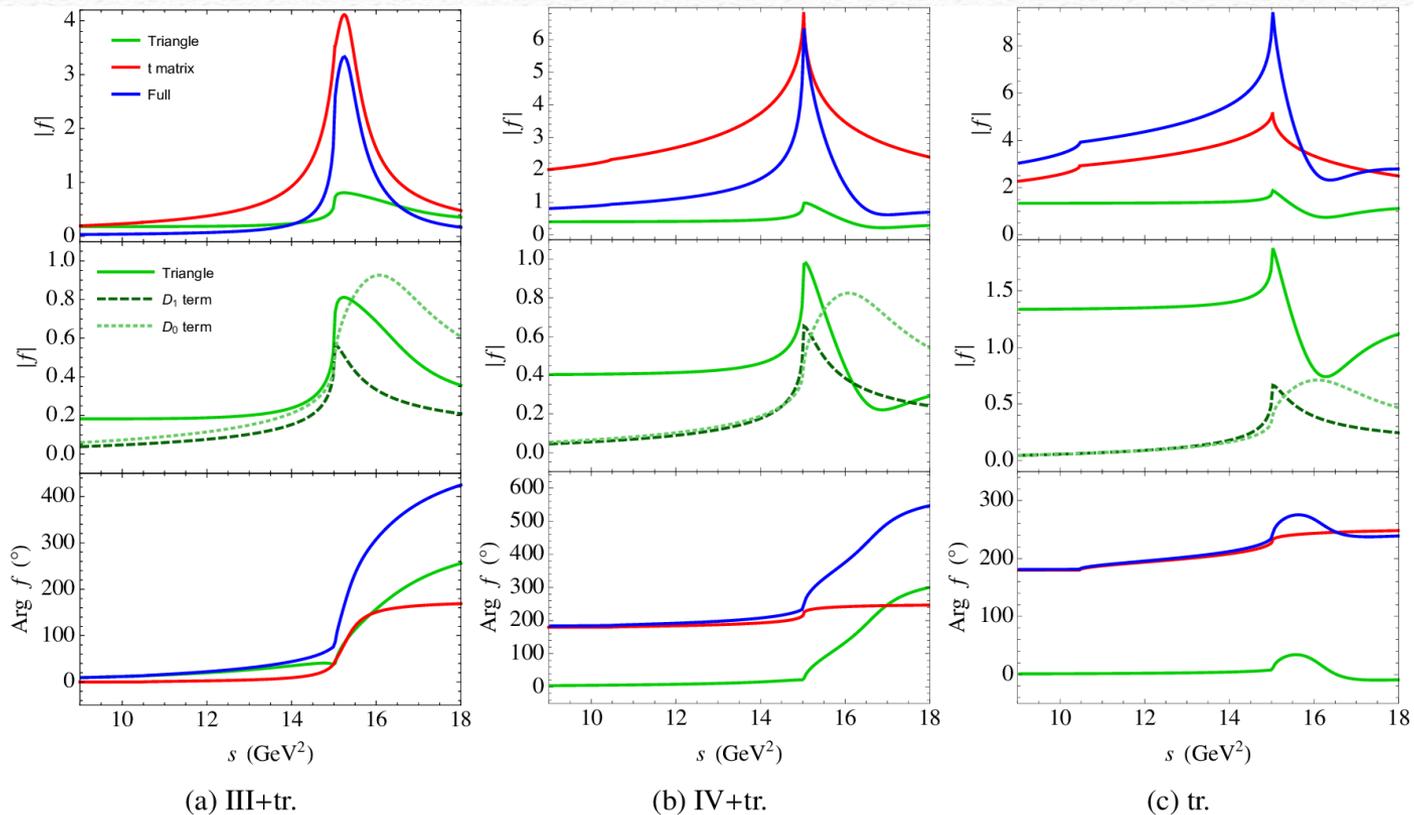


Figure 7: Interplay of scattering amplitude poles and triangle singularity to reconstruct the peak. We focus on the $J/\psi\pi\pi$ channel, at $E_{CM} = 4.26$ GeV. The red curve is the t_{12} scattering amplitude, the green curve is the $c_1 + H(s, D_1) + H(s, D_0)$ term in Eq. (9), and the blue curve is the product of the two. The upper plots show the magnitudes of these terms, the lower plots the phases. The middle row shows the contributions to the unitarized term due to the D_1 (dashed) and the D_0 (dotted). Only for D_1 the singularity is close enough to the physical region to generate a large peak. (a) The pole on the III sheet generates a narrow Breit-Wigner-like peak. The contribution of the triangle is not particularly relevant. (b) The sharp cusp in the scattering amplitude is due to the IV sheet pole close by; the triangle contributes to make the peak sharper. (c) The scattering amplitude has a small cusp due to the threshold factor, and the triangle is needed to make it sharp enough to fit the data.

Lineshapes at 4230

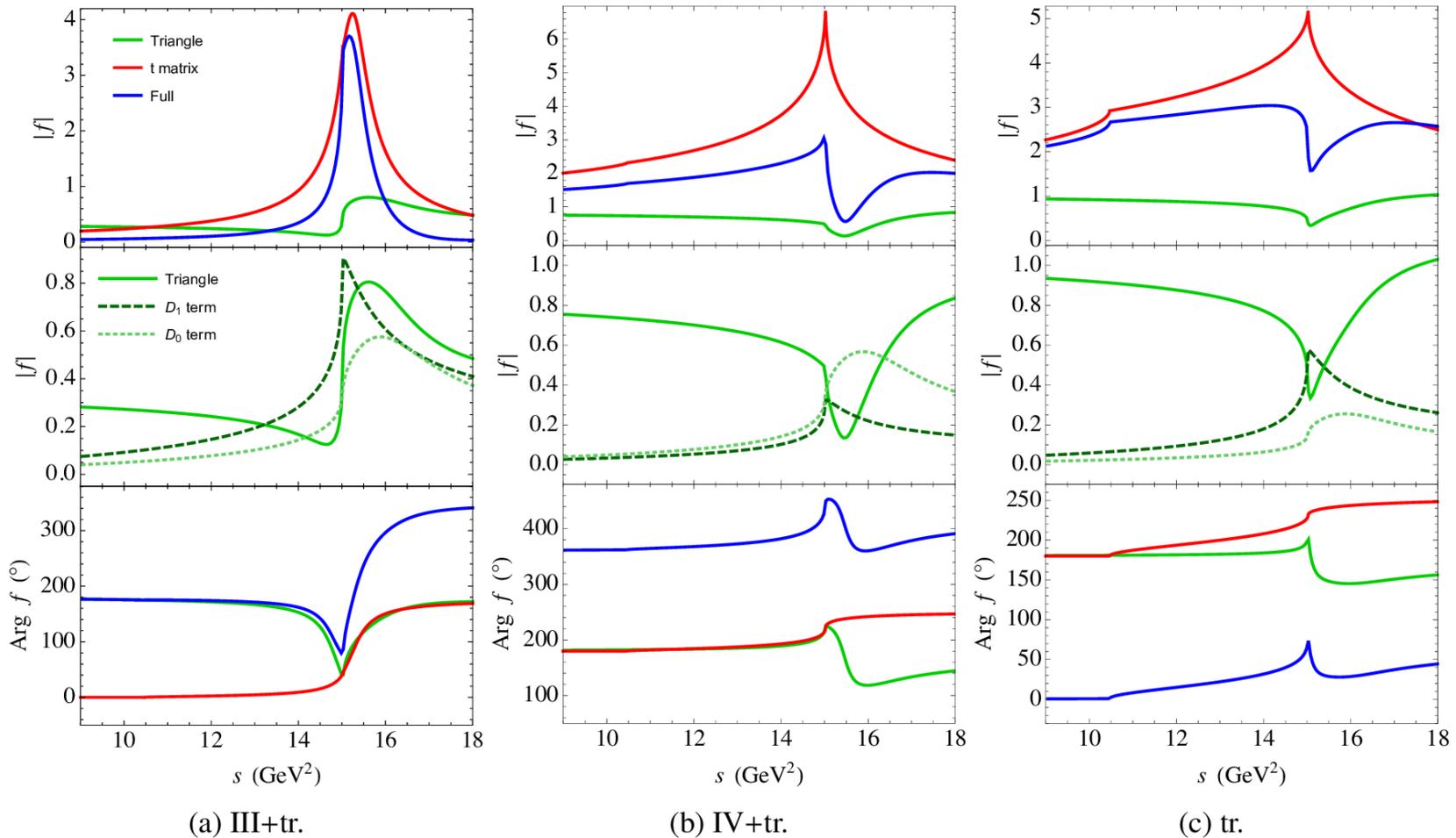
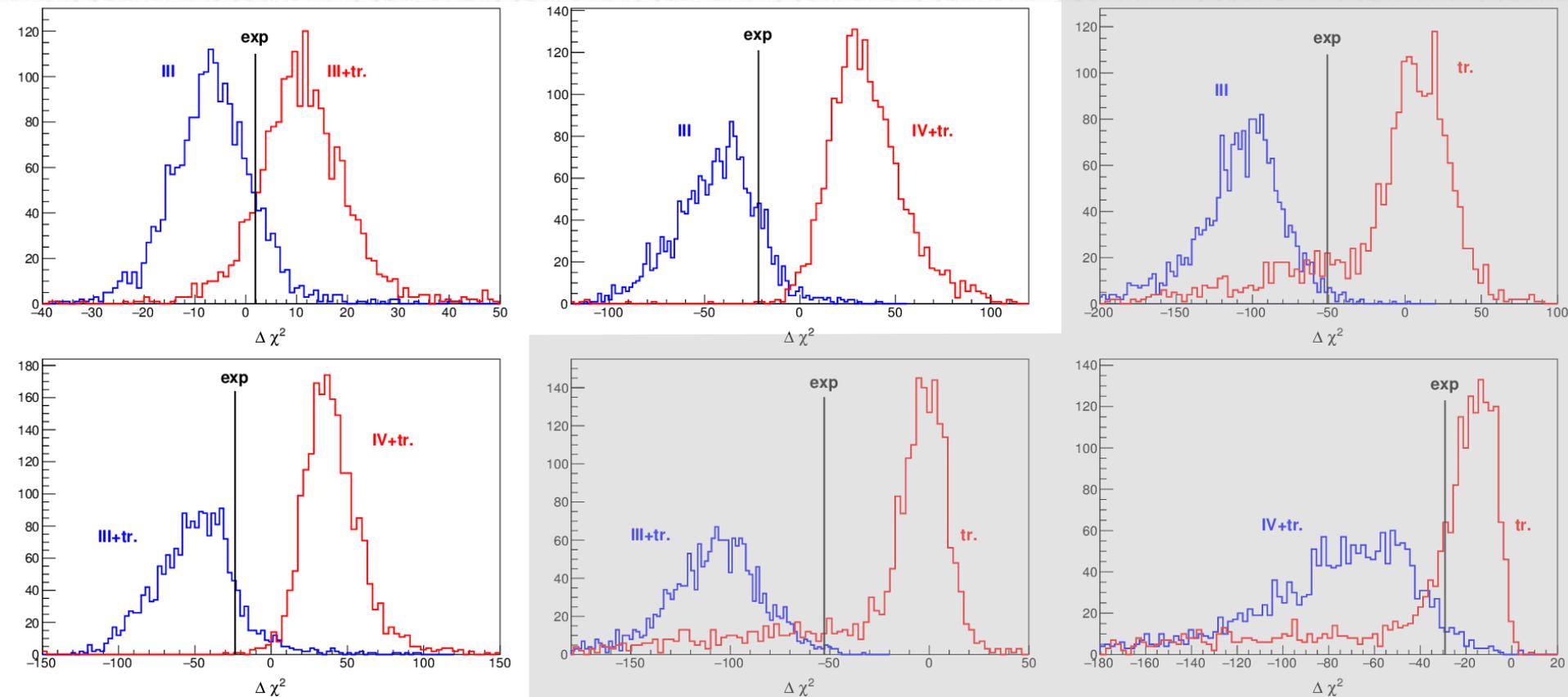


Figure 8: Same as Figure 7, but for $E_{CM} = 4.23$ GeV.

Statistical analysis



Toy experiments according to the different hypotheses, to estimate the relative rejection of various scenarios

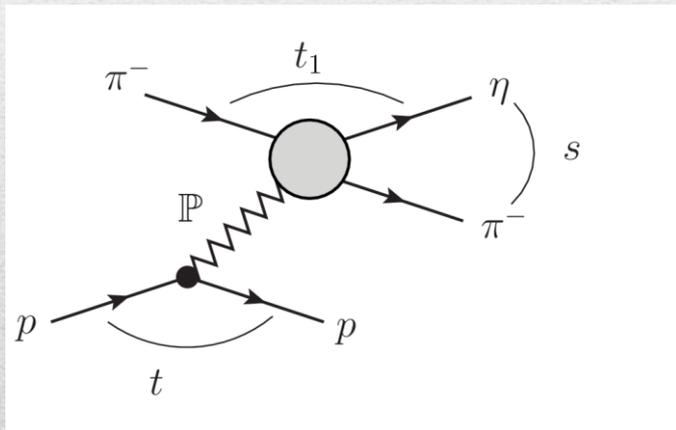
Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	" 2.4σ " (" 1.4σ ")
III+tr.	—	1.5σ (3.1σ)	" 2.6σ " (" 1.3σ ")
IV+tr.			" 2.1σ " (" 0.9σ ")

Not conclusive at this stage

Searching for resonances in $\eta\pi$

- The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons
- We build the partial wave amplitudes according to the N/D method
- We test against the D -wave data, where the a_2 and the a'_2 show up

A. Jackura, M. Mikhasenko, *AP et al.* (JPAC & COMPASS), PLB779, 464-472



Production amplitude

$$\text{Im} \mathbb{P} = \sum_n \text{Im} \mathbb{P} \cdot \text{Im} \mathbb{P}^*$$

Scattering amplitude

$$\text{Im} \mathbb{P} = \sum_n \text{Im} \mathbb{P} \cdot \text{Im} \mathbb{P}^*$$

Searching for resonances in $\eta\pi$

- The $\eta\pi$ system is one of the golden modes for hunting **hybrid mesons**
- We build the partial wave amplitudes according to the **N/D method**
- We test against the D -wave data, where the a_2 and the a'_2 show up

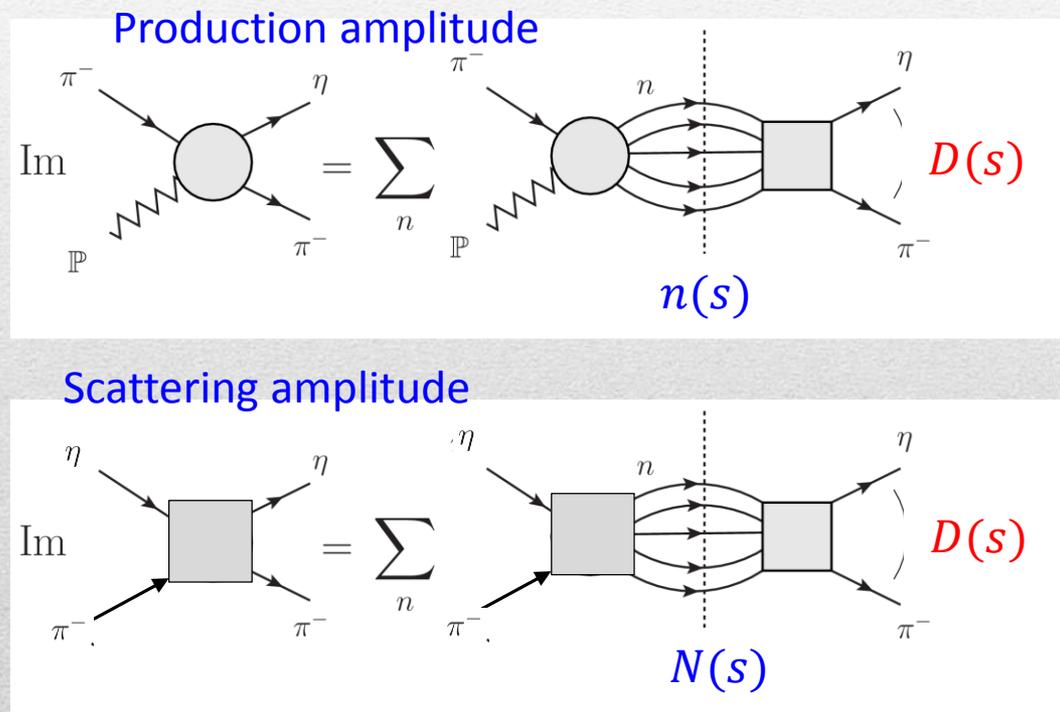
A. Jackura, M. Mikhasenko, *AP et al.* (JPAC & COMPASS), PLB779, 464-472

$$t(s) = \frac{N(s)}{D(s)}$$



The $D(s)$ has **only right hand cuts**;
it contains all the Final State Interactions
constrained by unitarity \rightarrow **universal**

$$\text{Im } D(s) = -\rho N(s)$$



Searching for resonances in $\eta\pi$

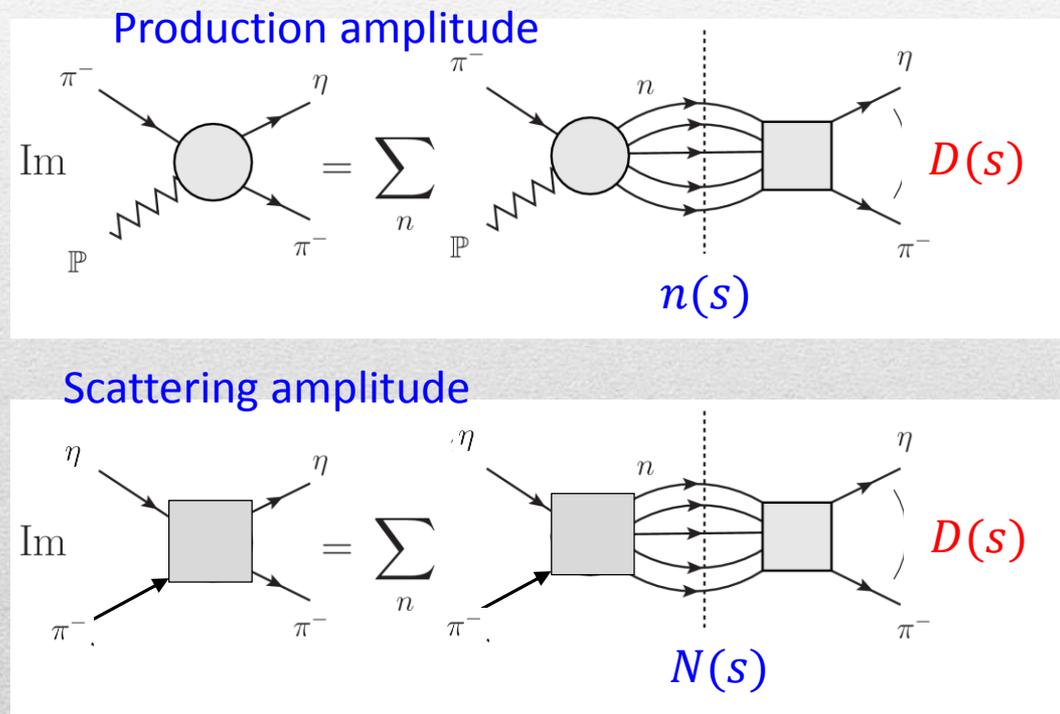
- The $\eta\pi$ system is one of the golden modes for hunting **hybrid mesons**
- We build the partial wave amplitudes according to the **N/D method**
- We test against the D -wave data, where the a_2 and the a'_2 show up

A. Jackura, M. Mikhasenko, *AP et al.* (JPAC & COMPASS), PLB779, 464-472

$$t(s) = \frac{N(s)}{D(s)}$$



The $n(s), N(s)$ have **left hand cuts only**, they depend on the exchanges \rightarrow **process-dependent, smooth**



Searching for resonances in $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity \rightarrow **universal**

$$D(s)_{ij} = (K^{-1})_{ij}(s) - \frac{s}{\pi} \int_{s_i}^{\infty} \frac{\rho_i(s') N_{ij}(s')}{s' (s' - s)} ds'$$

$$K_{ij}(s) = \sum_R \frac{g_i^R g_j^R}{M_R^2 - s} \quad \text{OR} \quad K_{ij}^{-1}(s) = c_0 - c_1 s + \sum_i \frac{c_i}{M_i^2 - s}$$

$$\rho_i(s) N_{ij}(s) = g \frac{\lambda^{(2l+1)/2} (s, m_\pi^2, m_\eta^2)}{(s + \Lambda)^7}$$

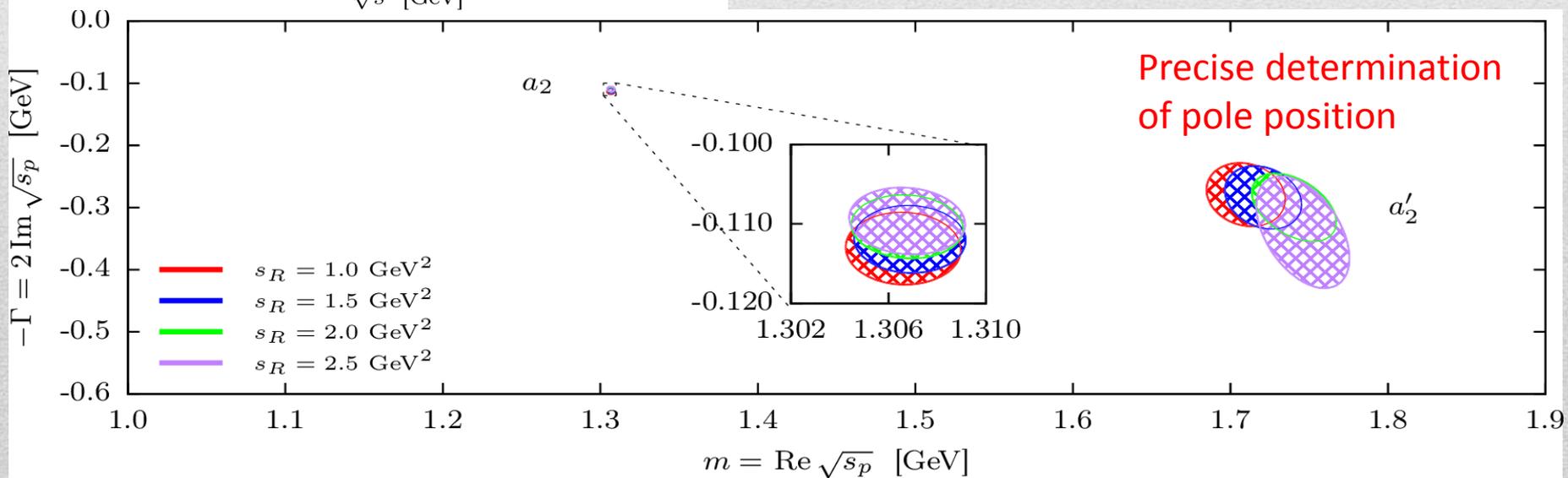
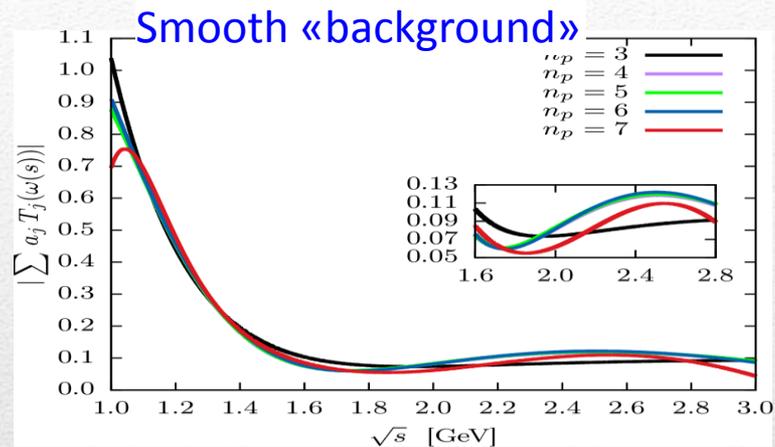
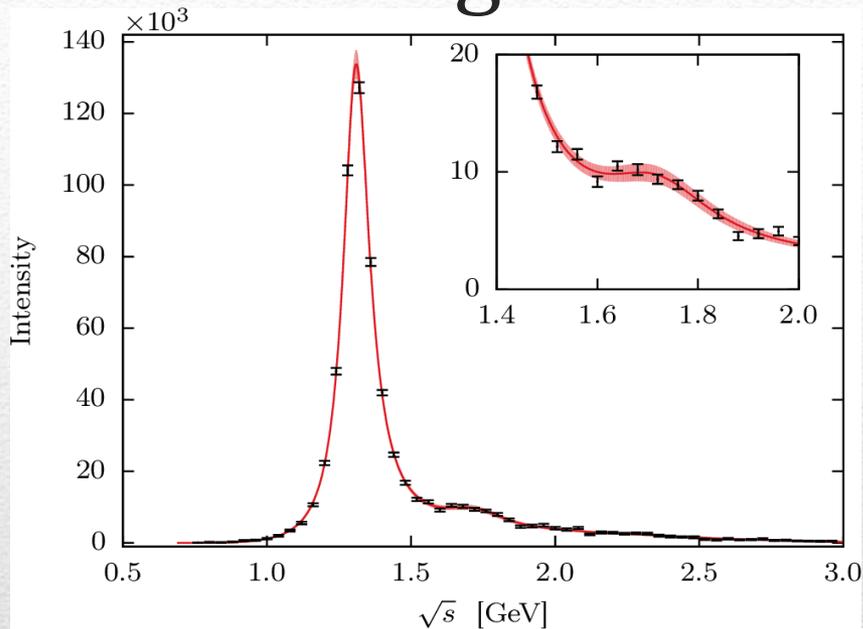
Searching for resonances in $\eta\pi$

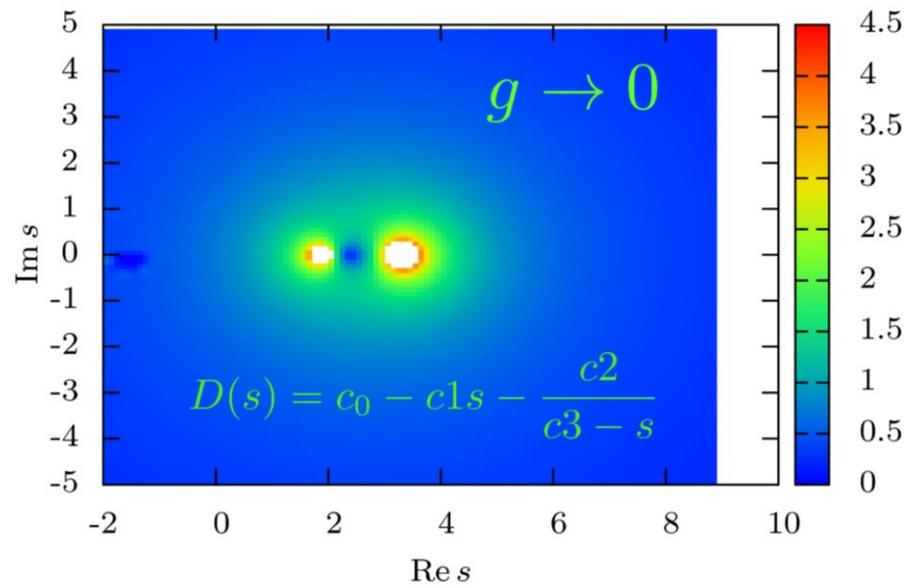
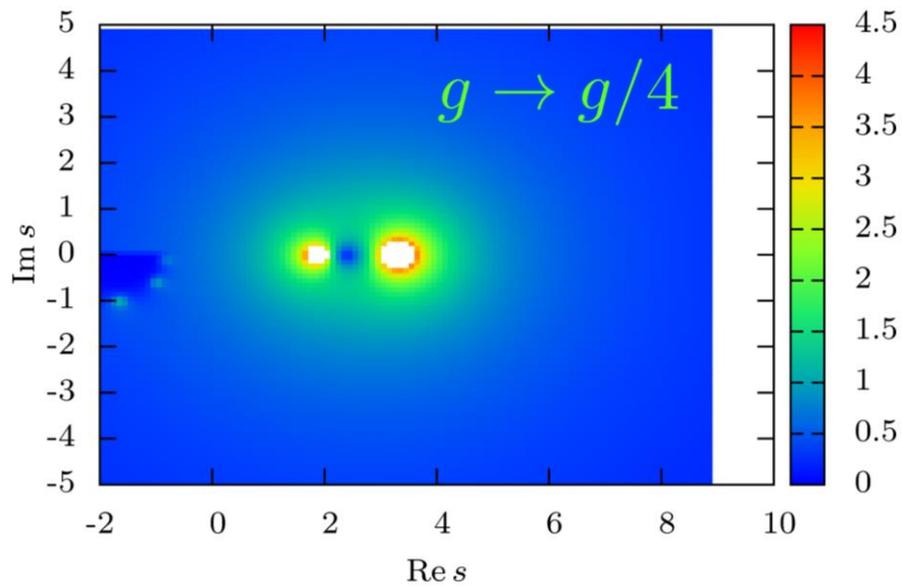
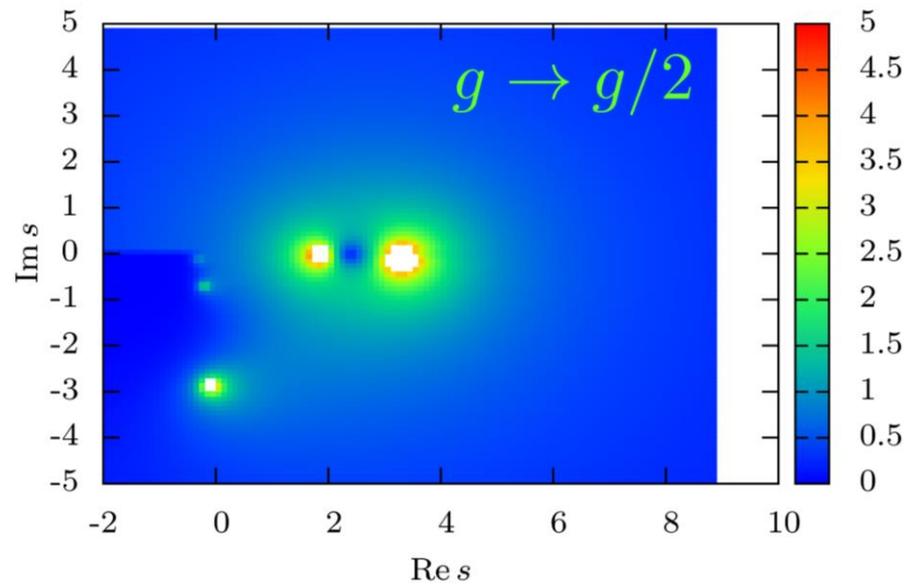
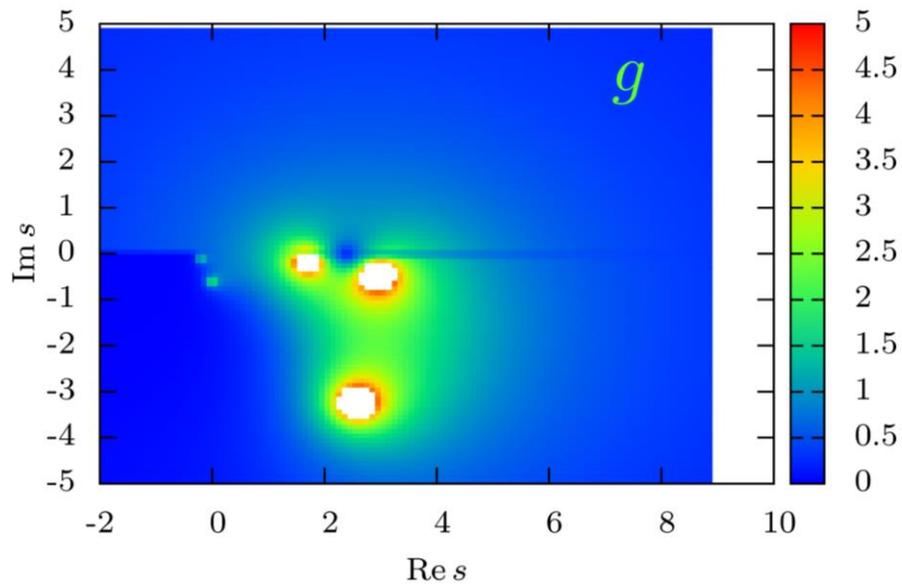
The $n(s)$ is process-dependent, smooth

$$n(s) = \sum_j a_j \omega^j(s)$$

$$\omega(s) = \frac{s}{s + s_0}$$

Searching for resonances in $\eta\pi$

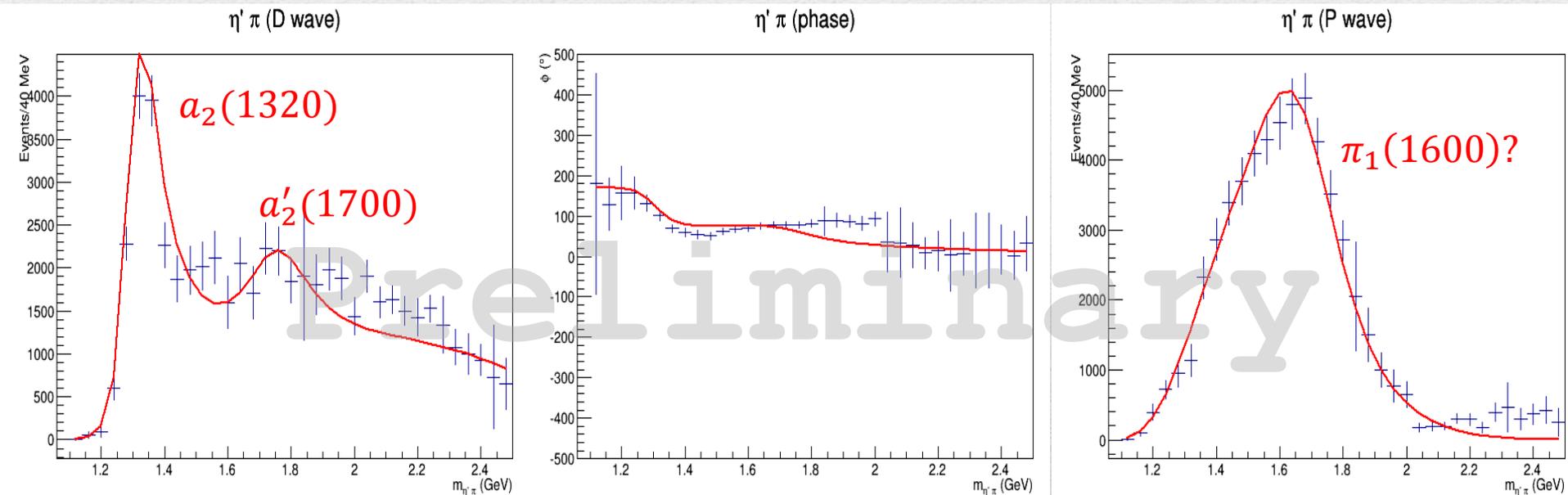




Searching for resonances in $\eta\pi$

$$m(a_2) = (1307 \pm 1 \pm 6) \text{ MeV} \quad m(a'_2) = (1720 \pm 10 \pm 60) \text{ MeV}$$
$$\Gamma(a_2) = (112 \pm 1 \pm 8) \text{ MeV} \quad \Gamma(a'_2) = (280 \pm 10 \pm 70) \text{ MeV}$$

- The **coupled channel analysis** involving the **exotic P -wave** is **ongoing**, as well as the extension to the GlueX production mechanism and kinematics



The $Y(4260)$

A. Amor, C. Fernandez-Ramirez, AP, U. Tamponi, in preparation

$$f(s) = \frac{N(s)}{K^{-1}(s) - \frac{i}{2}\rho_3(s)},$$

Same game,
we start analyzing the single channel
 $e^+e^- \rightarrow J/\psi \pi\pi$ data

$$i\rho_3(s) = \sum_{k=0}^{n-1} a_k (s - s_0)^k + \frac{(s - s_0)^n}{\pi} \int_{(2m_\pi + M_\psi)^2}^{\infty} \frac{\rho_2(s')}{(s' - s)(s' - s_0)^n} ds'$$

$$\rho_2(s') = \int_{4m_\pi^2}^{(\sqrt{s'} - M_\psi)^2} \frac{ds_{\pi\pi}}{2\pi} \frac{\lambda^{1/2}(s', s_{\pi\pi}, m_{J/\psi}^2)}{8\pi s'} \frac{\lambda^{1/2}(s_{\pi\pi}, m_\pi^2, m_\pi^2)}{8\pi s_{\pi\pi}} |t_{2 \rightarrow 2}(s_{\pi\pi})|^2$$


We consider the amplitude in the
elastic, quasi two-body
approximation

Need model for the Dalitz distribution

Weinberg theorem

Resonant scattering amplitude

$$f(ab \rightarrow c \rightarrow ab) = -\frac{1}{8\pi E_{CM}} g^2 \frac{1}{(p_a + p_b)^2 - m_c^2}$$

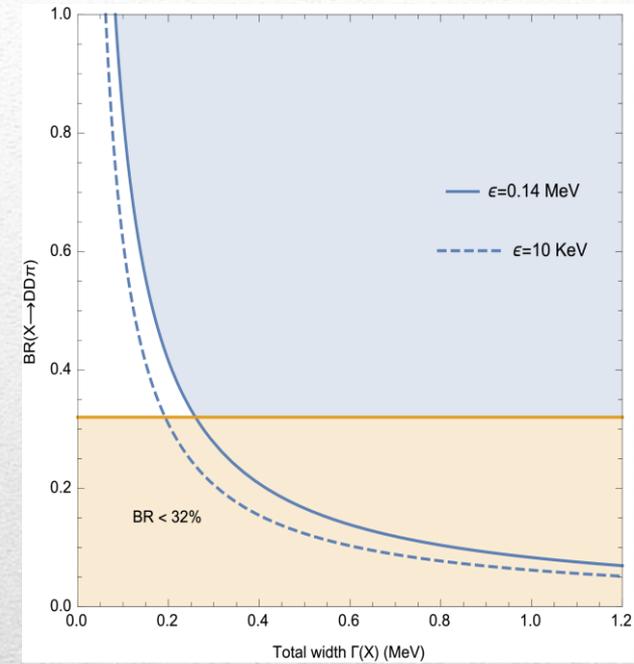
with $m_c = m_a + m_b - B$, and $B, T \ll m_{a,b}$

$$f(ab \rightarrow c \rightarrow ab) = -\frac{1}{16\pi(m_a + m_b)^2} g^2 \frac{1}{B + T}$$

This has to be compared with the potential scattering for slow particles ($kR \ll 1$, being $R \sim 1/m_\pi$ the range of interaction) in an attractive potential U with a superficial level at $-B$

$$f(ab \rightarrow ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B} - i\sqrt{T}}{B + T}, \quad B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}$$

This corresponds to the pure molecular interpretation of the $X(3872)$

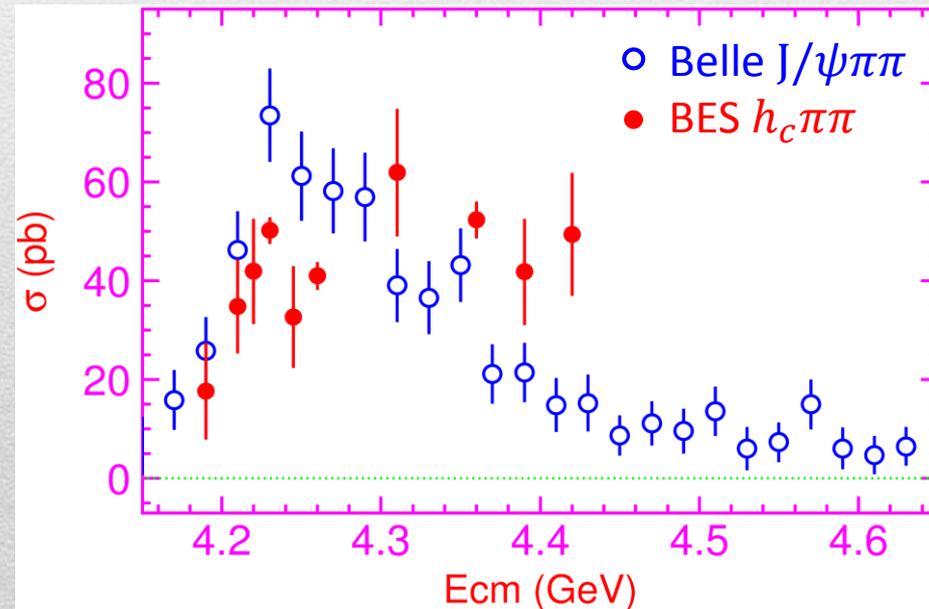
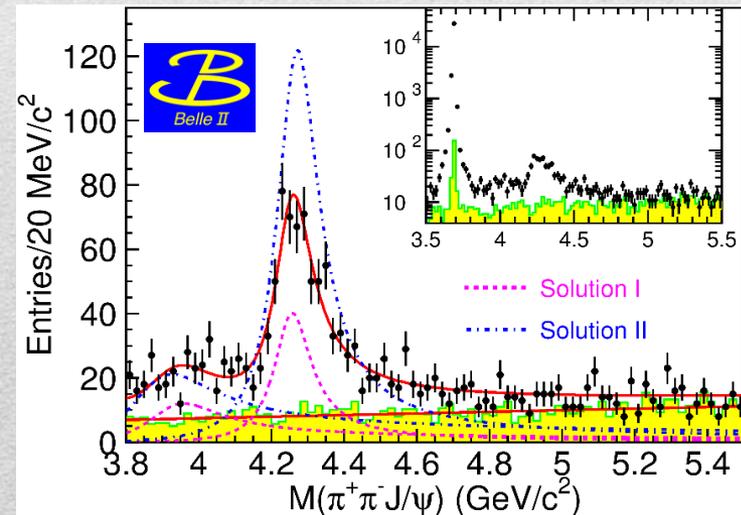
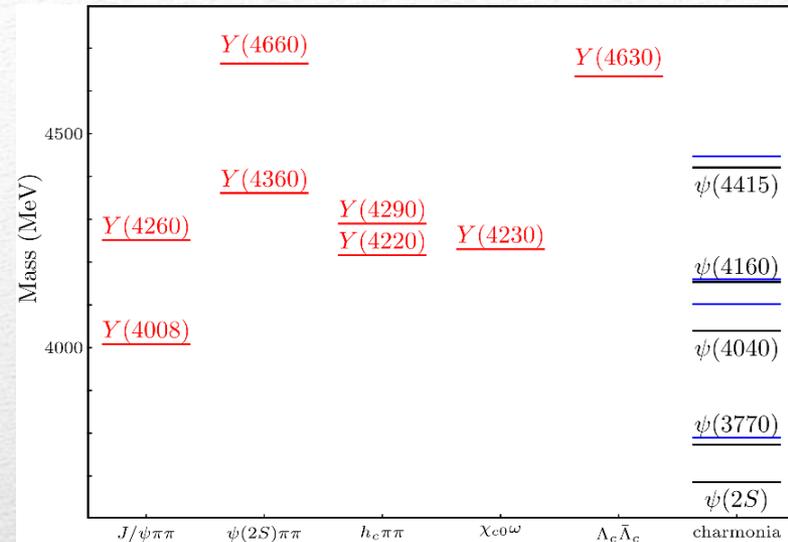


Weinberg, PR 130, 776
 Weinberg, PR 137, B672
 Polosa, PLB 746, 248

Vector Y states

Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR/direct production (and nowhere else!)
 Seen in few final states, mostly $J/\psi \pi\pi$ and $\psi(2S) \pi\pi$

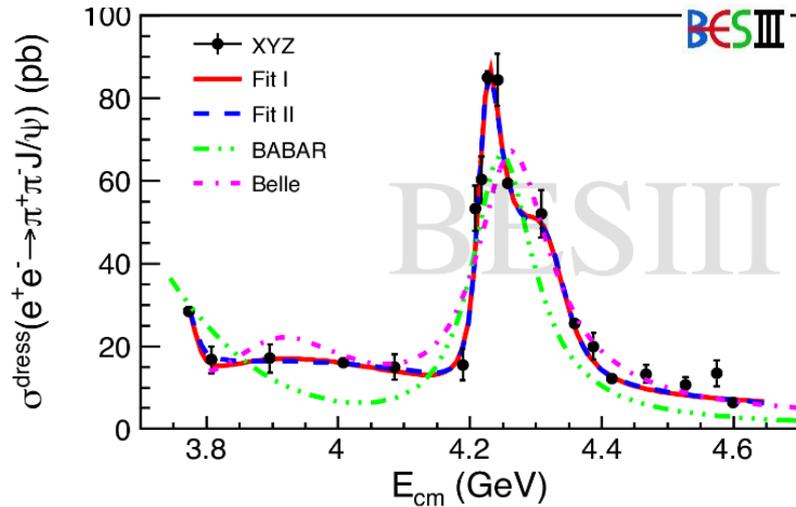
Not seen decaying into open charm pairs
 Large HQSS violation



Vector Y states in BESIII

BESIII, PRL118, 092002 (2017)

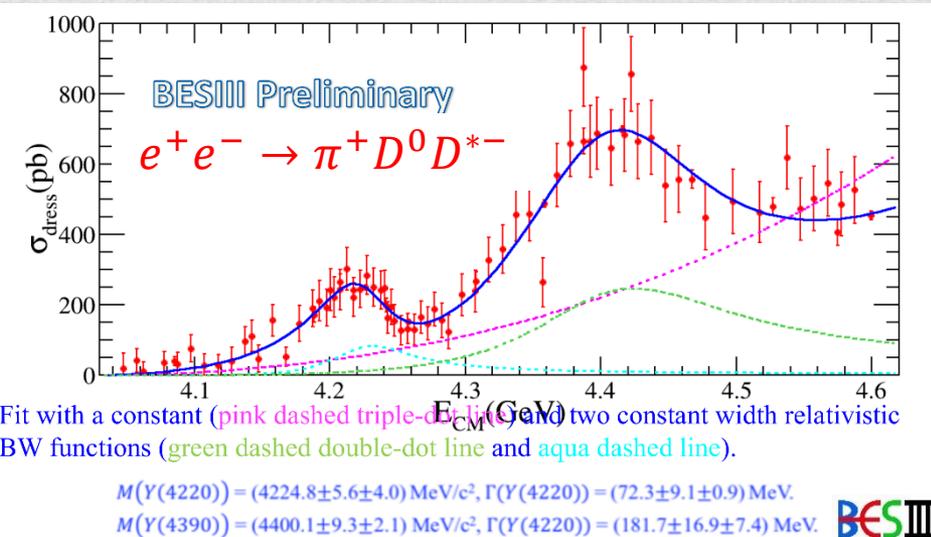
BESIII, PRL118, 092001 (2017) $e^+e^- \rightarrow J/\psi \pi\pi$



Parameters	Solution I	Solution II
$\Gamma_{e^+e^-} \mathcal{B}[\psi(3770) \rightarrow \pi^+\pi^- J/\psi]$		0.5 ± 0.1 (0)
$\Gamma_{e^+e^-} \mathcal{B}(R_1 \rightarrow \pi^+\pi^- J/\psi)$	$8.8_{-2.2}^{+1.5}$ (\dots)	$6.8_{-1.5}^{+1.1}$ (\dots)
$\Gamma_{e^+e^-} \mathcal{B}(R_2 \rightarrow \pi^+\pi^- J/\psi)$	13.3 ± 1.4 (12.0 ± 1.0)	9.2 ± 0.7 (8.9 ± 0.6)
$\Gamma_{e^+e^-} \mathcal{B}(R_3 \rightarrow \pi^+\pi^- J/\psi)$	21.1 ± 3.9 (17.9 ± 3.3)	$1.7_{-0.6}^{+0.8}$ ($1.1_{-0.4}^{+0.5}$)
ϕ_1	-58 ± 11 (-33 ± 8)	-116_{-10}^{+9} (-81_{-8}^{+7})
ϕ_2	-156 ± 5 (-132 ± 3)	68 ± 24 (107 ± 20)

New BESIII data show a peculiar lineshape for the $Y(4260)$

The state appear lighter and narrower, compatible with the ones in $h_c \pi\pi$ and $\chi_{c0} \omega$
 A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^* \pi$, maybe indicating a $\bar{D}D_1$ dominance



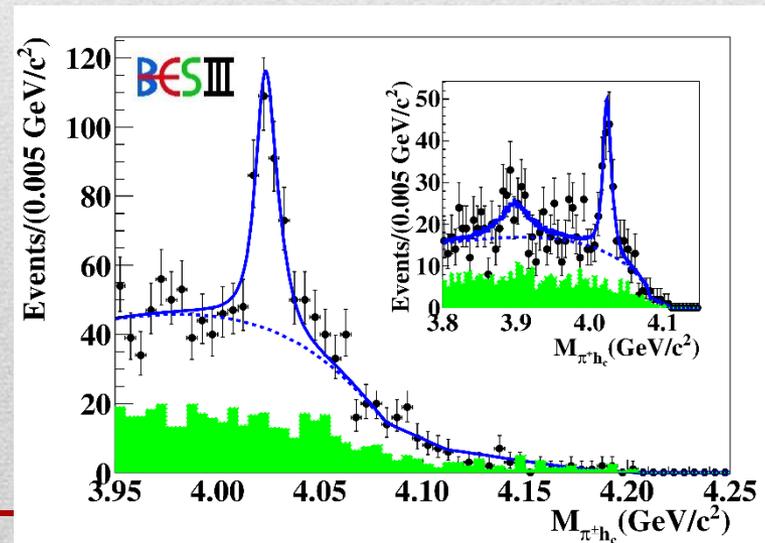
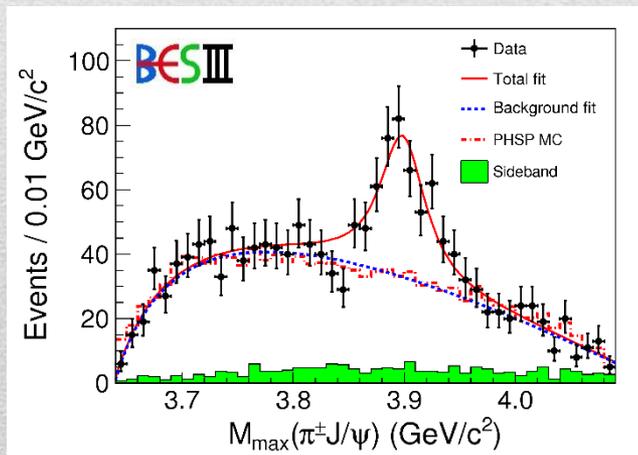
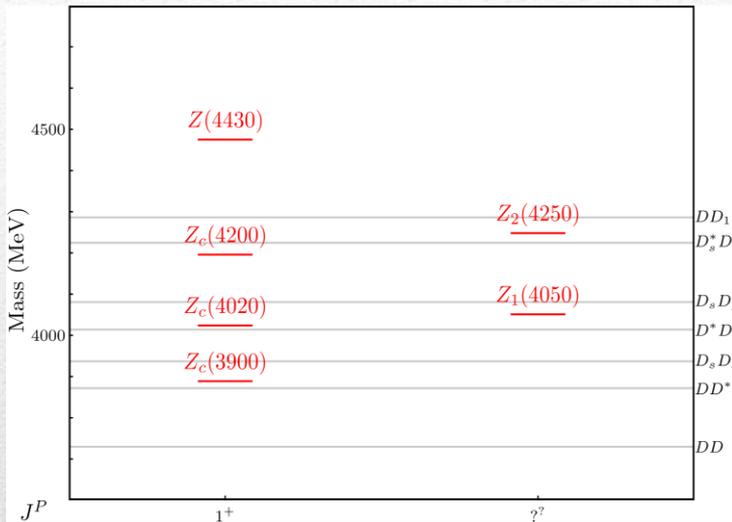
Charged Z states: $Z_c(3900)$, $Z_c(4020)$

Charged quarkonium-like resonances have been found, **4q needed**

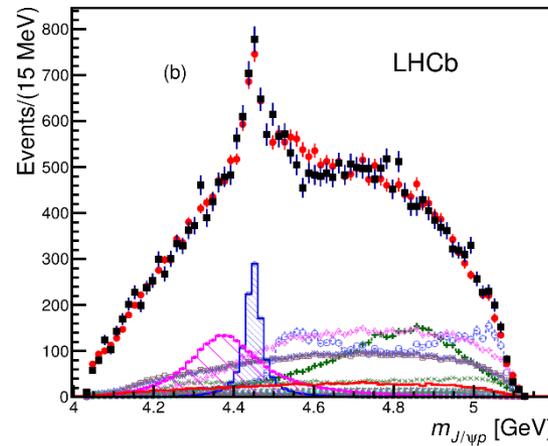
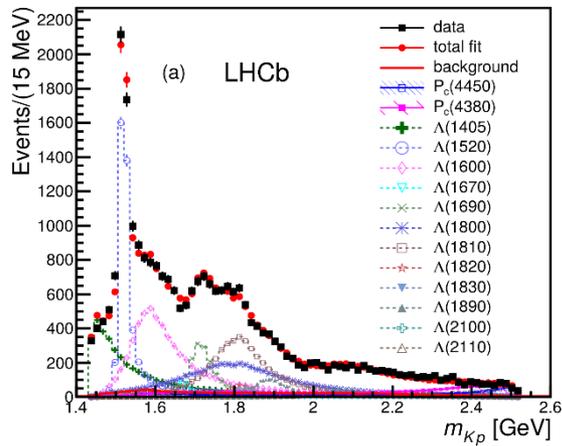
Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

$e^+e^- \rightarrow Z_c(3900)^+\pi^- \rightarrow J/\psi \pi^+\pi^-$ and $\rightarrow (DD^*)^+\pi^-$
 $M = 3888.7 \pm 3.4 \text{ MeV}, \Gamma = 35 \pm 7 \text{ MeV}$

$e^+e^- \rightarrow Z_c'(4020)^+\pi^- \rightarrow h_c \pi^+\pi^-$ and $\rightarrow \bar{D}^{*0}D^{*+}\pi^-$
 $M = 4023.9 \pm 2.4 \text{ MeV}, \Gamma = 10 \pm 6 \text{ MeV}$



Pentaquarks!



LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

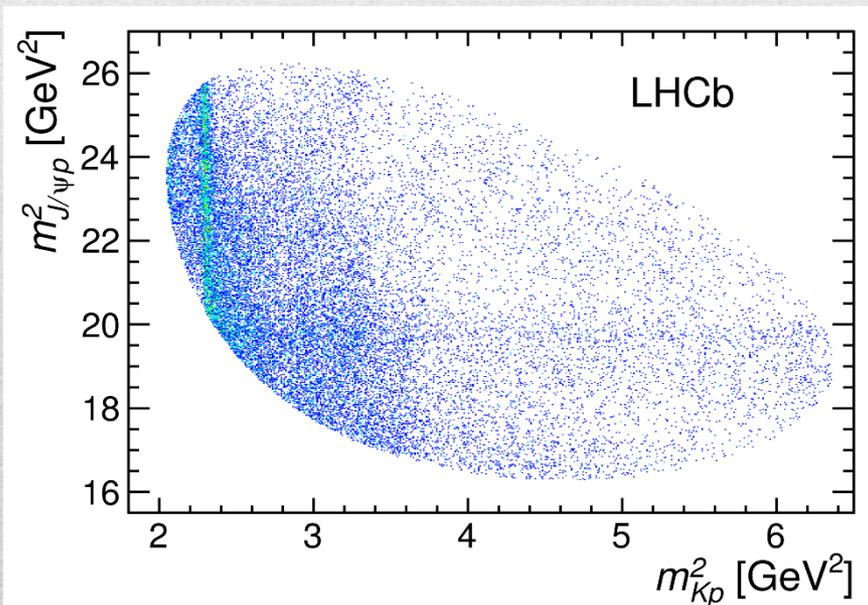
Two states seen in $\Lambda_b \rightarrow (J/\psi p) K^-$,
evidence in $\Lambda_b \rightarrow (J/\psi p) \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$

$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$

$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$

$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$



Quantum numbers

$$J^P = \left(\frac{3^-}{2}, \frac{5^+}{2} \right) \text{ or } \left(\frac{3^+}{2}, \frac{5^-}{2} \right) \text{ or } \left(\frac{5^+}{2}, \frac{3^-}{2} \right)$$

Opposite parities needed for the
interference to correctly describe angular
distributions, **low mass region**
contaminated by Λ^* (model dependence?)

No obvious threshold nearby

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (# σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{? -}$	$B \rightarrow K(\chi_{c1}\gamma)$	Belle ^[23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \rightarrow K(\pi^+\pi^-J/\psi)$	Belle ^[24,25] (>10), BABAR ^[26] (8.6)
				$p\bar{p} \rightarrow (\pi^+\pi^-J/\psi) \dots$	CDF ^[27,28] (11.6), D0 ^[29] (5.2)
				$pp \rightarrow (\pi^+\pi^-J/\psi) \dots$	LHCb ^[30,31] (np)
				$B \rightarrow K(\pi^+\pi^-\pi^0J/\psi)$	Belle ^[32] (4.3), BABAR ^[33] (4.0)
				$B \rightarrow K(\gamma J/\psi)$	Belle ^[34] (5.5), BABAR ^[35] (3.5)
					LHCb ^[36] (>10)
				$B \rightarrow K(\gamma\psi(2S))$	BABAR ^[35] (3.6), Belle ^[34] (0.2)
					LHCb ^[36] (4.4)
				$B \rightarrow K(D\bar{D}^*)$	Belle ^[37] (6.4), BABAR ^[38] (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \rightarrow \pi^-(D\bar{D}^*)^+$	BES III ^[39] (np)
				$Y(4260) \rightarrow \pi^-(\pi^+J/\psi)$	BES III ^[40] (8), Belle ^[41] (5.2)
					CLEO data ^[42] (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \rightarrow \pi^-(\pi^+h_c)$	BES III ^[43] (8.9)
				$Y(4260) \rightarrow \pi^-(D^*\bar{D}^*)^+$	BES III ^[44] (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \rightarrow K(\omega J/\psi)$	Belle ^[45] (8), BABAR ^[33,46] (19)
				$e^+e^- \rightarrow e^+e^-(\omega J/\psi)$	Belle ^[47] (7.7), BABAR ^[48] (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \rightarrow e^+e^-(D\bar{D})$	Belle ^[49] (5.3), BABAR ^[50] (5.8)
$X(3940)$	3942_{-8}^{+9}	37_{-17}^{+27}	$?^{?+}$	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle ^[51,52] (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \rightarrow (\pi^+\pi^-J/\psi)$	Belle ^[41,53] (7.4)
$Z(4050)^+$	4051_{-43}^{+24}	82_{-55}^{+51}	$?^{?+}$	$\bar{B}^0 \rightarrow K^-(\pi^+\chi_{c1})$	Belle ^[54] (5.0), BABAR ^[55] (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \rightarrow K^+(\phi J/\psi)$	CDF ^[56,57] (5.0), Belle ^[58] (1.9), LHCb ^[59] (1.4), CMS ^[60] (>5) D0 ^[61] (3.1)
$X(4160)$	4156_{-25}^{+29}	139_{-65}^{+113}	$?^{?+}$	$e^+e^- \rightarrow J/\psi(D^*\bar{D}^*)$	Belle ^[52] (5.5)
$Z(4200)^+$	4196_{-30}^{+35}	370_{-110}^{+99}	1^{+-}	$\bar{B}^0 \rightarrow K^-(\pi^+J/\psi)$	Belle ^[62] (7.2)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (# σ)
$Y(4220)$	4196_{-30}^{+35}	39 ± 32	1^{--}	$e^+e^- \rightarrow (\pi^+\pi^-h_c)$	BES III data ^[63,64] (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \rightarrow (\chi_{c0}\omega)$	BES III ^[65] (>9)
$Z(4250)^+$	4248_{-45}^{+185}	177_{-72}^{+321}	$?^{?+}$	$\bar{B}^0 \rightarrow K^-(\pi^+\chi_{c1})$	Belle ^[54] (5.0), BABAR ^[55] (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \rightarrow (\pi\pi J/\psi)$	BABAR ^[66,67] (8), CLEC ^[68,69] (11) Belle ^[41,53] (15), BES III ^[40] (np)
				$e^+e^- \rightarrow (f_0(980)J/\psi)$	BABAR ^[67] (np), Belle ^[41] (np)
				$e^+e^- \rightarrow (\pi^-Z_c(3900)^+)$	BES III ^[40] (8), Belle ^[41] (5.2)
				$e^+e^- \rightarrow (\gamma X(3872))$	BES II ^[70] (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \rightarrow (\pi^+\pi^-h_c)$	BES III data ^[63,64] (np)
$X(4350)$	$4350.6_{-5.1}^{+4.6}$	13_{-10}^{+18}	$0/2^{?+}$	$e^+e^- \rightarrow e^+e^-(\phi J/\psi)$	Belle ^[58] (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \rightarrow (\pi^+\pi^- \psi(2S))$	Belle ^[71] (8), BABAR ^[72] (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \rightarrow K^-(\pi^+\psi(2S))$	Belle ^[73,74] (6.4), BABAR ^[75] (2.4) LHCb ^[76] (13.9)
				$\bar{B}^0 \rightarrow K^-(\pi^+J/\psi)$	Belle ^[62] (4.0)
$Y(4630)$	4634_{-11}^{+9}	92_{-32}^{+41}	1^{--}	$e^+e^- \rightarrow (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle ^[77] (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \rightarrow (\pi^+\pi^- \psi(2S))$	Belle ^[71] (5.8), BABAR ^[72] (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \rightarrow \pi(\pi\Upsilon(nS))$	Belle ^[78,79] (>10)
				$\Upsilon(5S) \rightarrow \pi^-(\pi^+h_b(nP))$	Belle ^[78] (16)
				$\Upsilon(5S) \rightarrow \pi^-(B\bar{B}^*)^+$	Belle ^[80] (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \rightarrow \pi^-(\pi^+\Upsilon(nS))$	Belle ^[78] (>10)
				$\Upsilon(5S) \rightarrow \pi^-(\pi^+h_b(nP))$	Belle ^[78] (16)
				$\Upsilon(5S) \rightarrow \pi^-(B^*\bar{B}^*)^+$	Belle ^[80] (6.8)

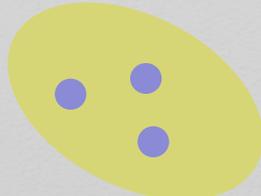
Esposito, AP, Polosa, Phys.Rept. 668
Guerrieri, AP, Piccinini, Polosa, IJMPA 30, 1530002

Hadron Spectroscopy

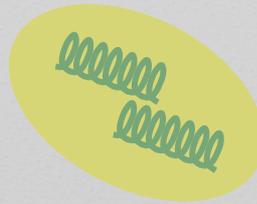
Meson



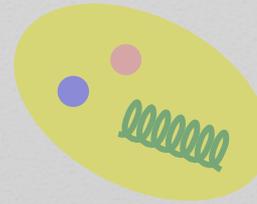
Baryon



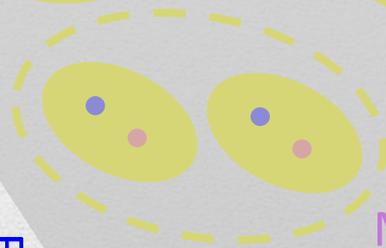
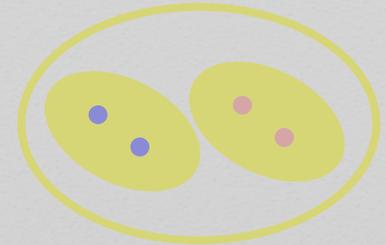
Glueball



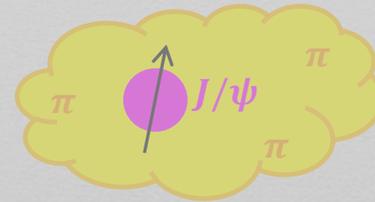
Hybrids



Tetraquark



Molecule



Hadroquarkonium



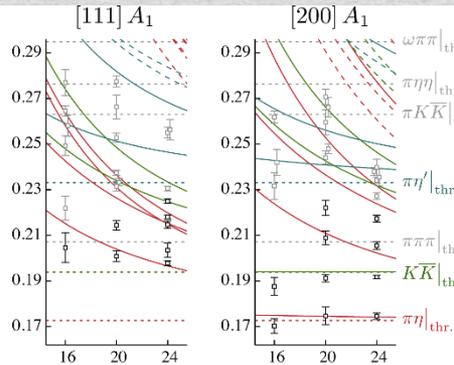
Experiment

Lattice QCD

Data

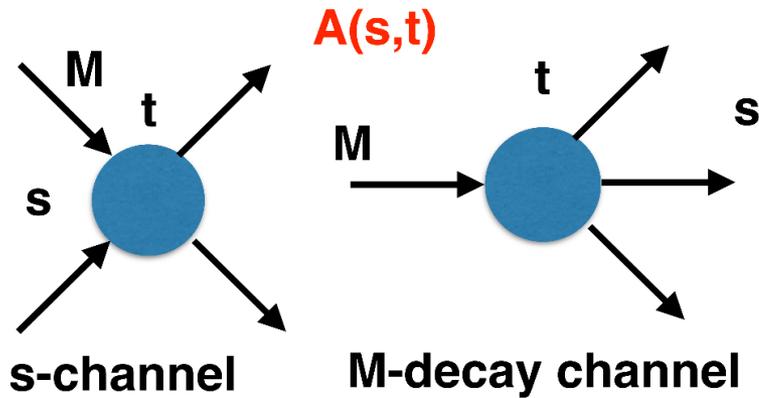
Amplitude analysis

Properties, Model building

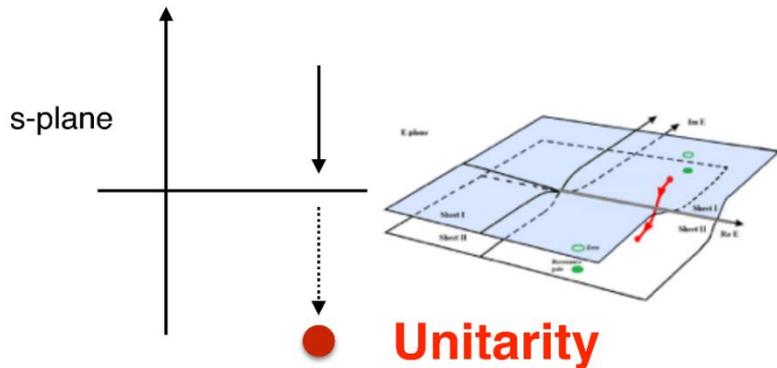
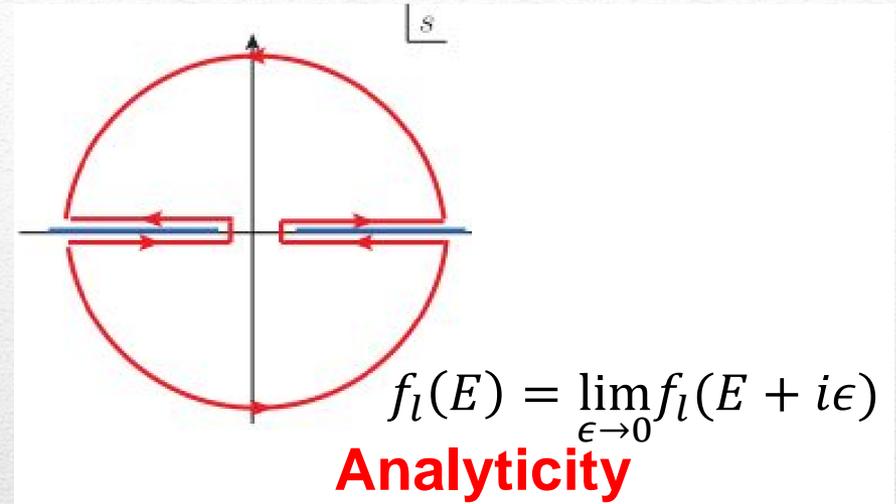


Interpretations on the spectrum leads to understanding fundamental laws of nature

S-Matrix principles



Crossing



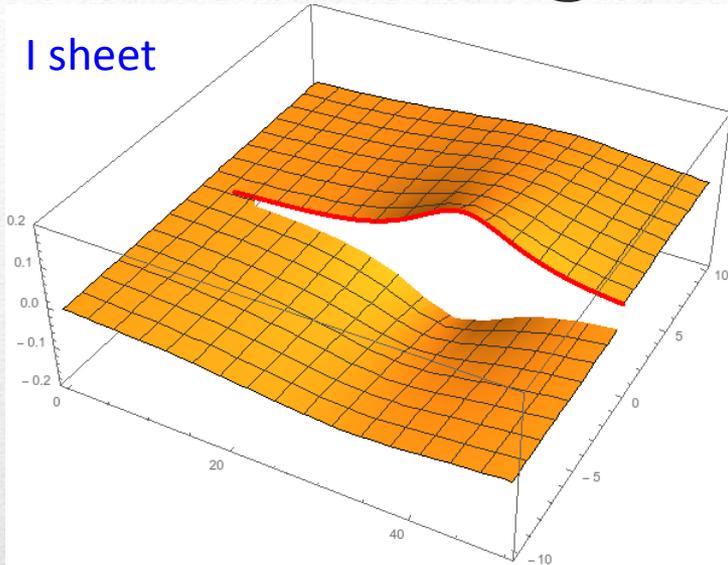
These are constraints the amplitudes have to satisfy, but do not fix the dynamics

Resonances (QCD states) are poles in the unphysical Riemann sheets

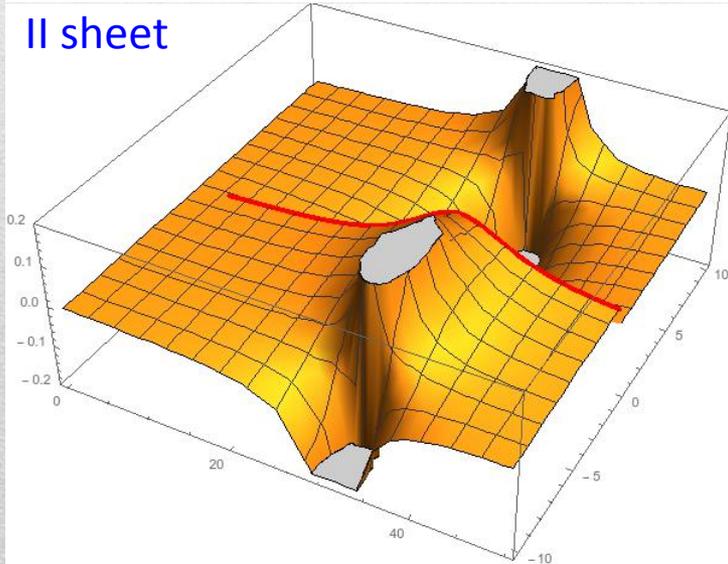
+ Lorentz, discrete & global symmetries

Pole hunting

I sheet

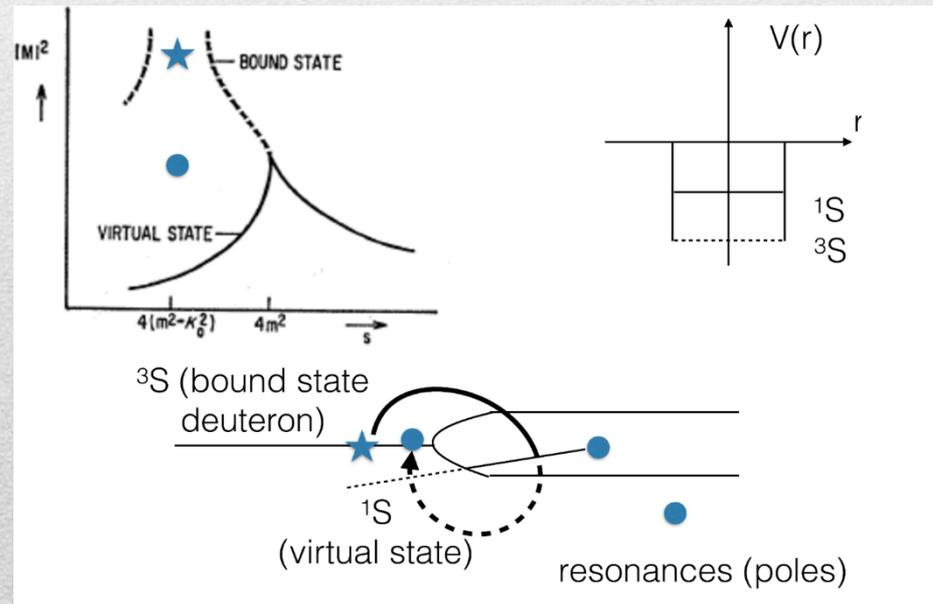


II sheet



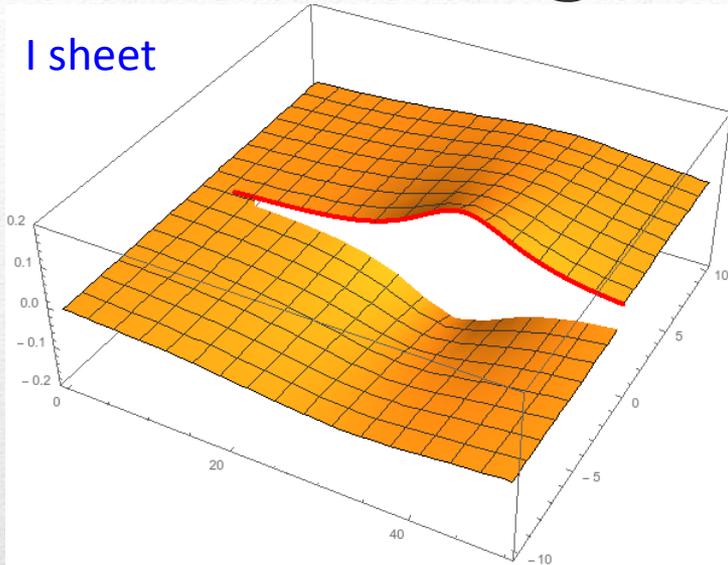
Bound states on the real axis 1st sheet

Not-so-bound (virtual) states on the real axis 2nd sheet

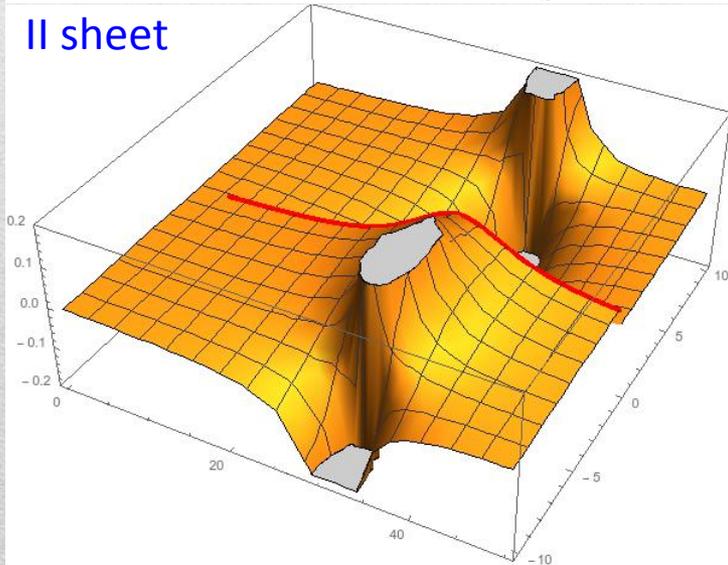


Pole hunting

I sheet

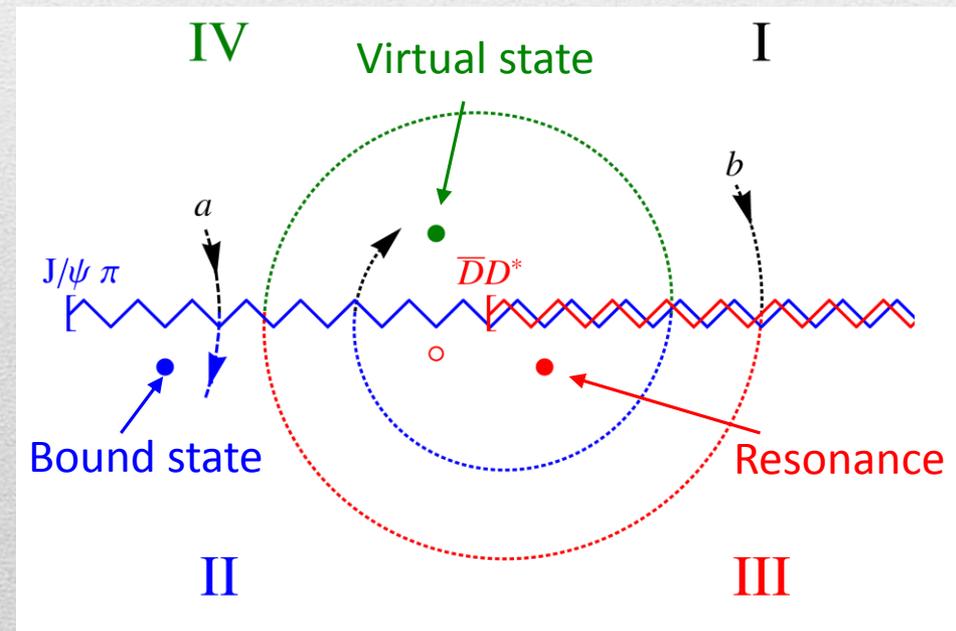


II sheet

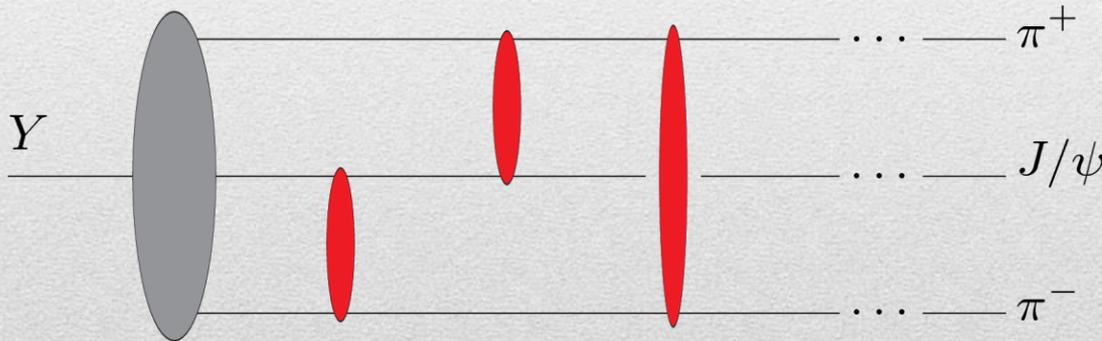
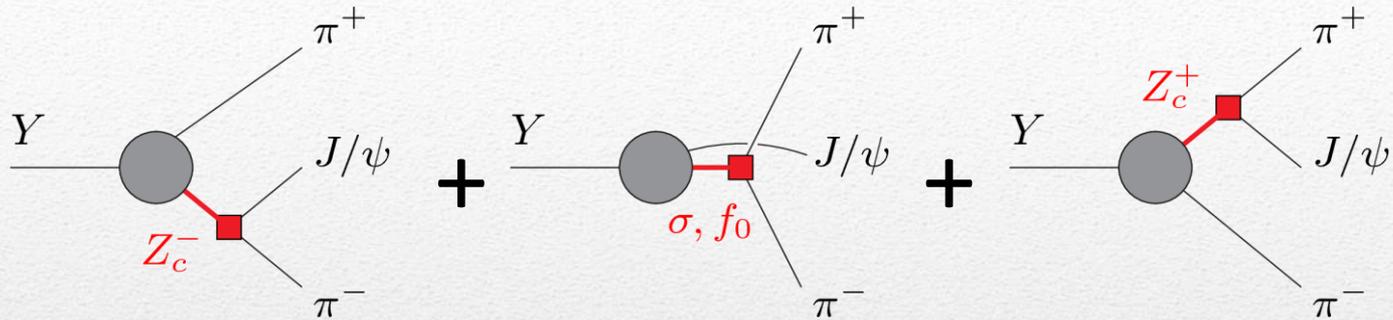


More complicated structure when more thresholds arise:
two sheets for each new threshold

III sheet: usual resonances
IV sheet: cusps (virtual states)



The isobar model



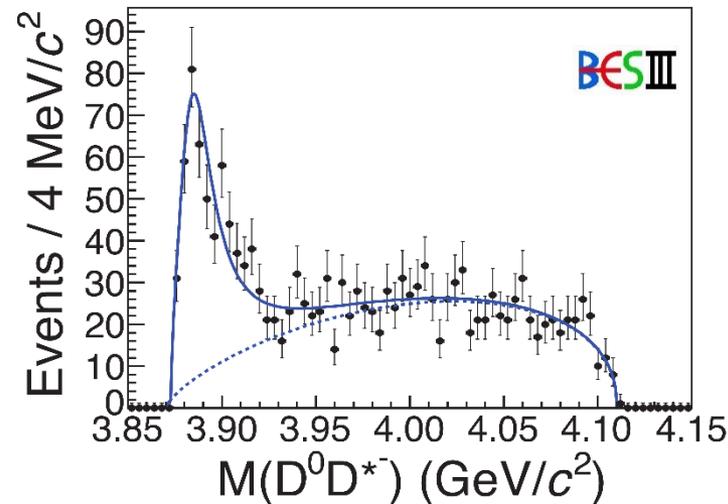
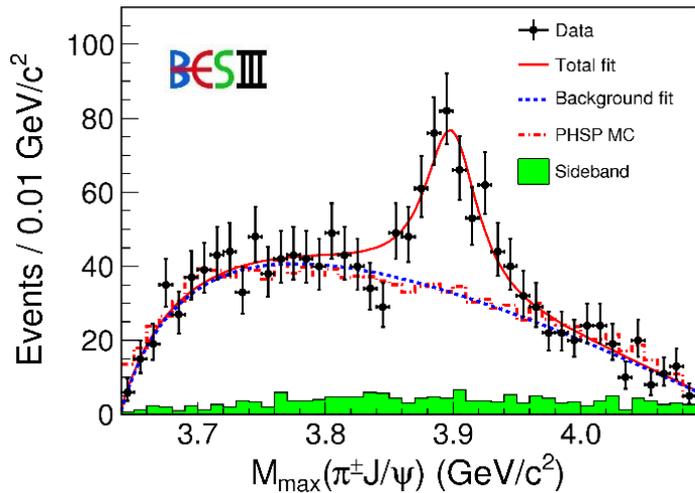
The formalism implements the all-order rescattering in **all the 3 channels at once**

Khuri-Treiman formalism was introduced to describe $K \rightarrow 3\pi$
 Khuri and Treiman, PR119, 1115

Used recently for several reactions,
 Niecknig and Kubis, JHEP 10, 142
 Colangelo, *et al.*, PRL118, 022001
 AP *et al.* [JPAC], PLB772, 200
 Albaladejo, AP *et al.* [JPAC], 1803.06027

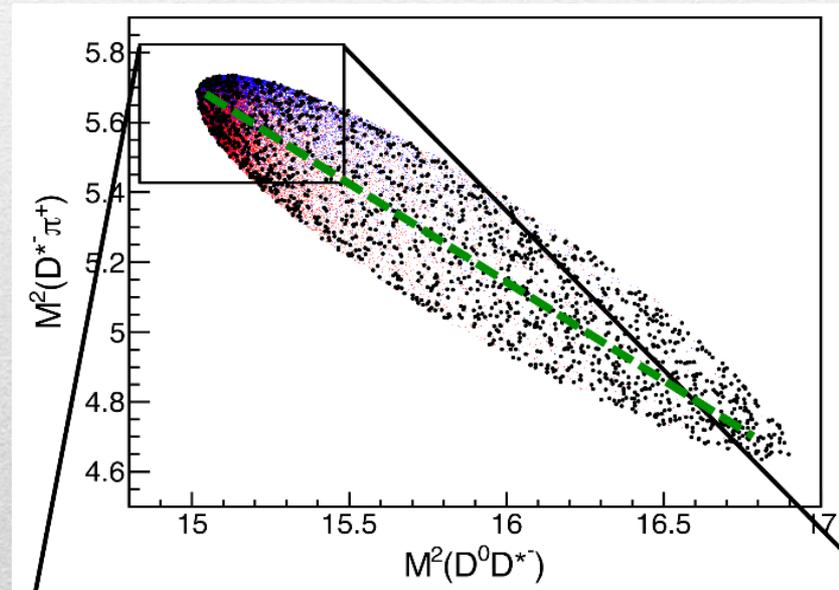
Example: The charged $Z_c(3900)$

A **charged charmonium-like** resonance has been claimed by BESIII in 2013.



$$e^+e^- \rightarrow Z_c(3900)^+\pi^- \rightarrow J/\psi \pi^+\pi^- \text{ and } \rightarrow (DD^*)^+\pi^-$$

$$M = 3888.7 \pm 3.4 \text{ MeV}, \Gamma = 35 \pm 7 \text{ MeV}$$

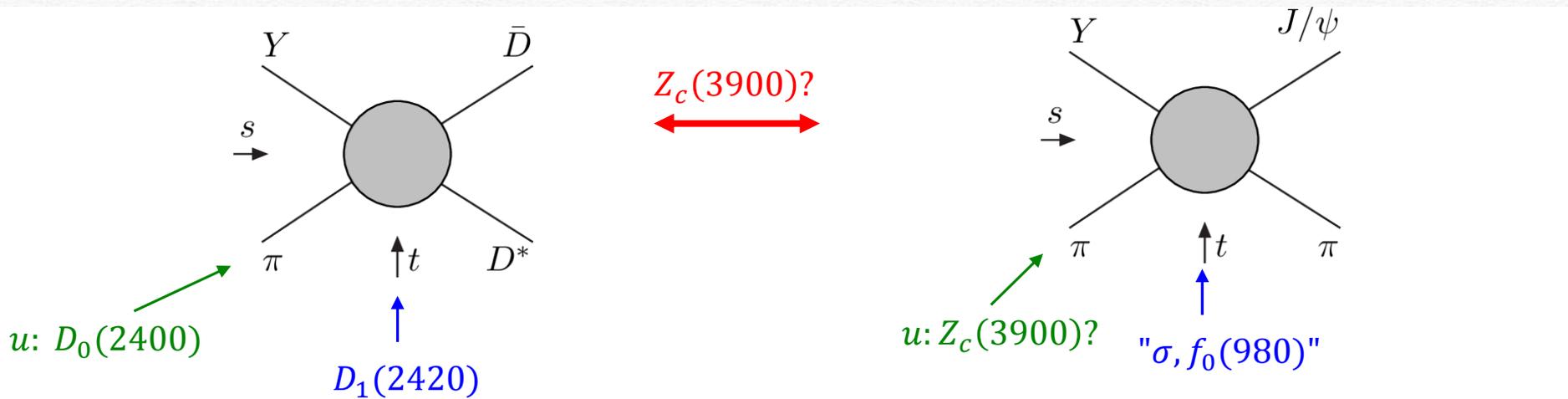


Such a state would require a **minimal 4q content** and would be manifestly exotic

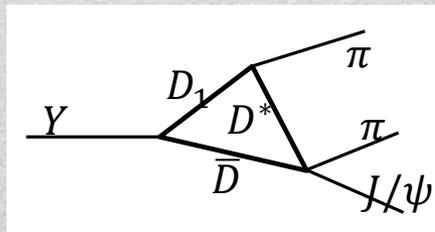
Amplitude analysis for $Z_c(3900)$

One can test different parametrizations of the amplitude, which correspond to different singularities \rightarrow different natures

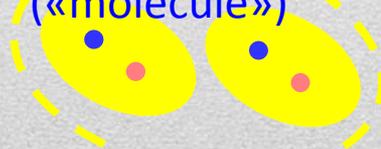
AP *et al.* (JPAC), PLB772, 200



Triangle rescattering,
logarithmic branching point

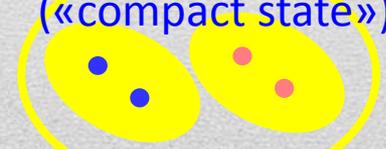


(anti)bound state,
II/IV sheet pole
(«molecule»)



Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

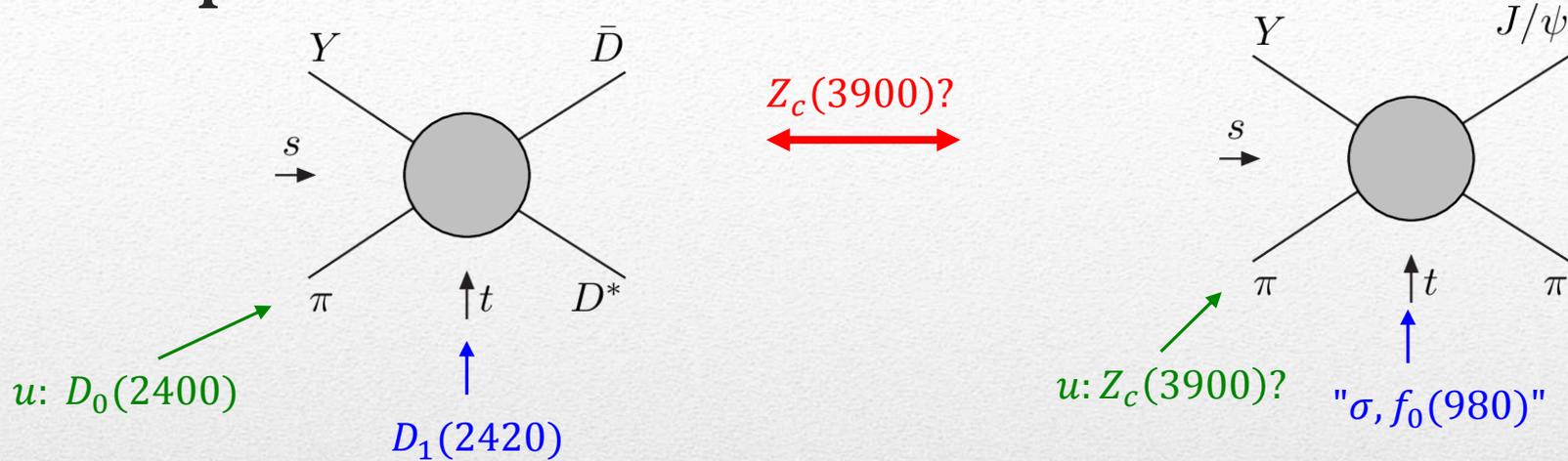
Resonance,
III sheet pole
(«compact state»)



Maiani *et al.*, PRD71, 014028
Faccini *et al.*, PRD87, 111102
Esposito *et al.*, Phys.Rept. 668

Szczepaniak, PLB747, 410

Amplitude model



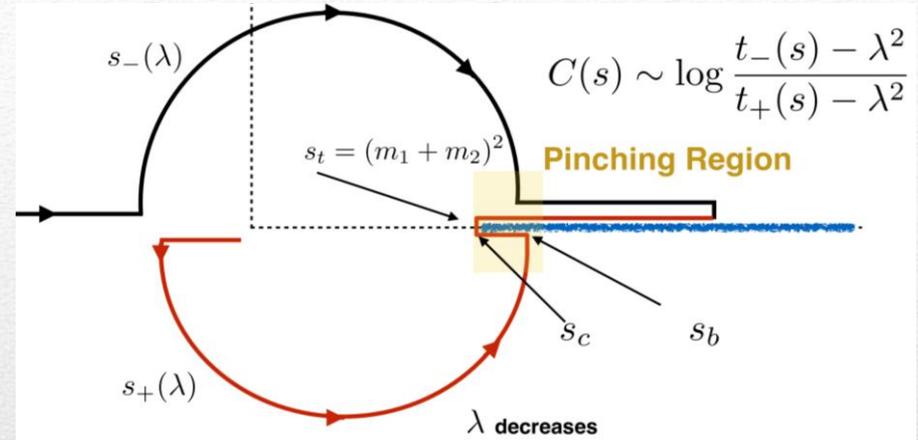
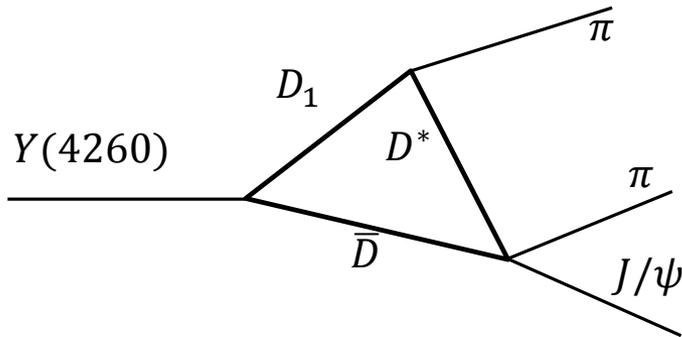
$$f_i(s, t, u) = 16\pi \sum_{l=0}^{L_{\max}} (2l+1) \left(a_{l,i}^{(s)}(s) P_l(z_s) + a_{l,i}^{(t)}(t) P_l(z_t) + a_{l,i}^{(u)}(u) P_l(z_u) \right)$$

$$f_{0,i}(s) = \frac{1}{32\pi} \int_{-1}^1 dz_s f_i(s, t(s, z_s), u(s, z_s)) = a_{0,i}^{(s)} + \frac{1}{32\pi} \int_{-1}^1 dz_s \left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) \right) \equiv a_{0,i}^{(s)} + b_{0,i}(s)$$

$$f_{l,i}(s) = \frac{1}{32\pi} \int_{-1}^1 dz_s P_l(z_s) \left(a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) \right) \equiv b_{l,i}(s) \quad \text{for } l > 0. \quad f_{0,i}(s) = b_{0,i}(s) + \sum_j t_{ij}(s) \frac{1}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' - s},$$

$$f_i(s, t, u) = 16\pi \left[a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s) \left(c_j + \frac{s}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' (s' - s)} \right) \right],$$

Triangle singularity



Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in **very special kinematical conditions** (Coleman and Norton, Nuovo Cim. 38, 438), However, this effects **cancel in Dalitz projections, no peaks** (Schmid, Phys.Rev. 154, 1363)

$$f_{0,i}(s) = b_{0,i}(s) + \frac{t_{ij}}{\pi} \int_{s_i}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' - s}$$

...but the cancellation can be spread in different channels, you might still see peaks in other channels only!

Szczepaniak, PLB747, 410-416

Szczepaniak, PLB757, 61-64

Guo, Meissner, Wang, Yang PRD92, 071502

Testing scenarios

- We approximate all the particles to be scalar – this affects the value of couplings, which are not normalized anyway – but not the position of singularities. This also limits the number of free parameters

$$f_i(s, t, u) = 16\pi \left[a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s) \left(c_j + \frac{s}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' (s' - s)} \right) \right],$$

The scattering matrix is parametrized as $(t^{-1})_{ij} = K_{ij} - i \rho_i \delta_{ij}$

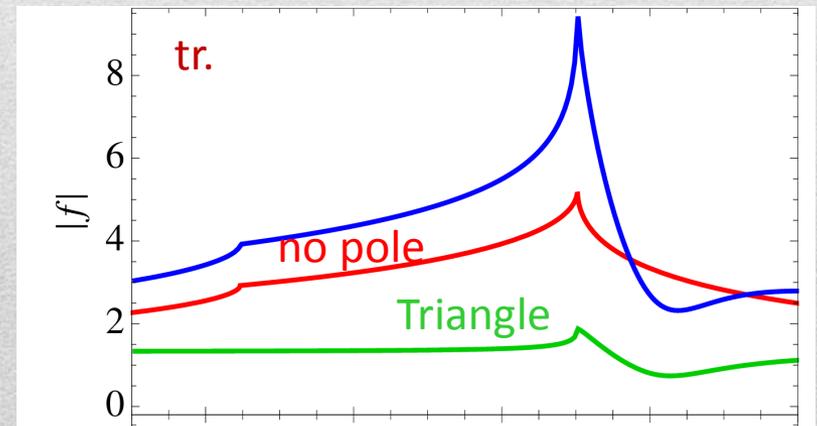
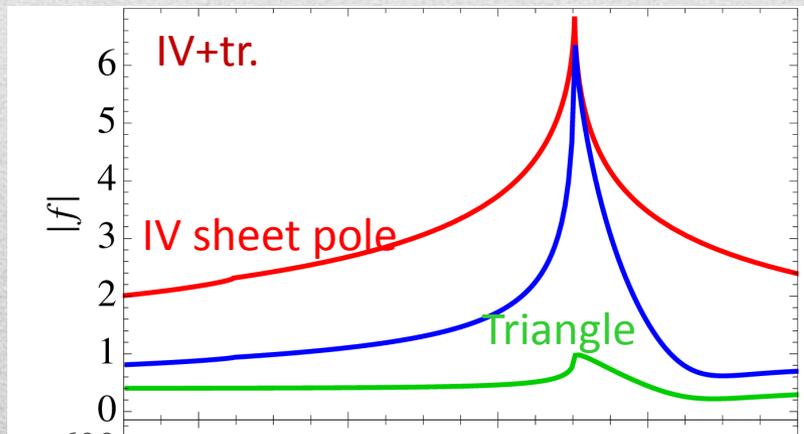
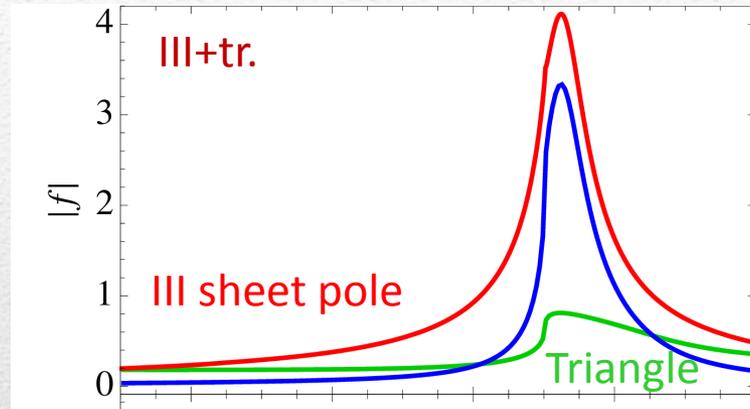
Four different scenarios considered:

- «III»: the K matrix is $\frac{g_i g_j}{M^2 - s}$, this generates a pole in the closest unphysical sheet the rescattering integral is set to zero
- «III+tr.»: same, but with the correct value of the rescattering integral
- «IV+tr.»: the K matrix is constant, this generates a pole in the IV sheet
- «tr.»: same, but the pole is pushed far away by adding a penalty in the χ^2

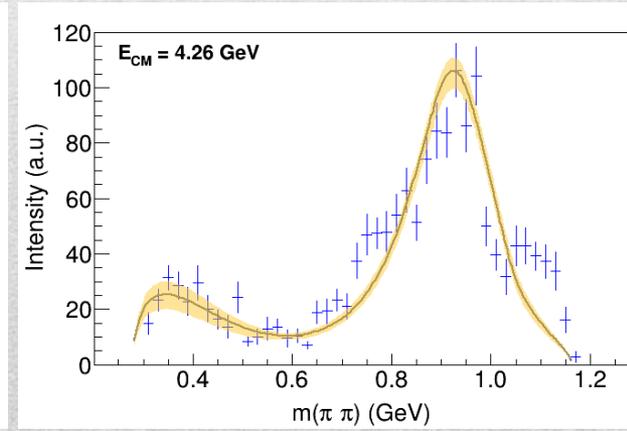
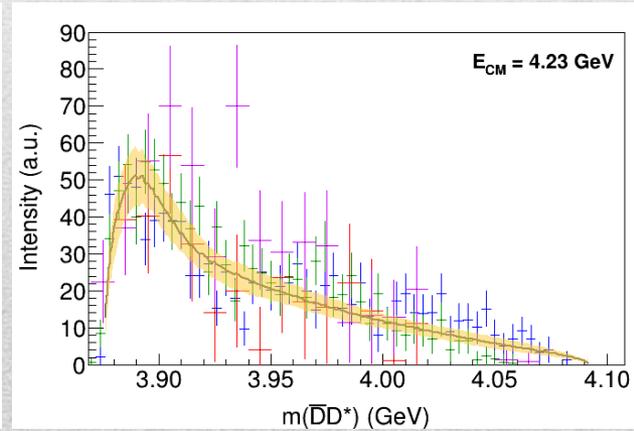
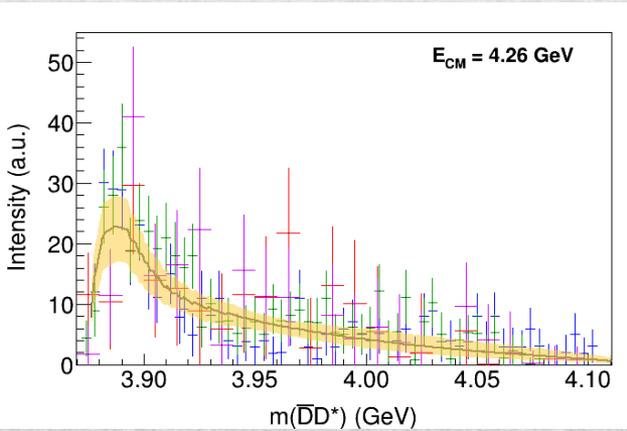
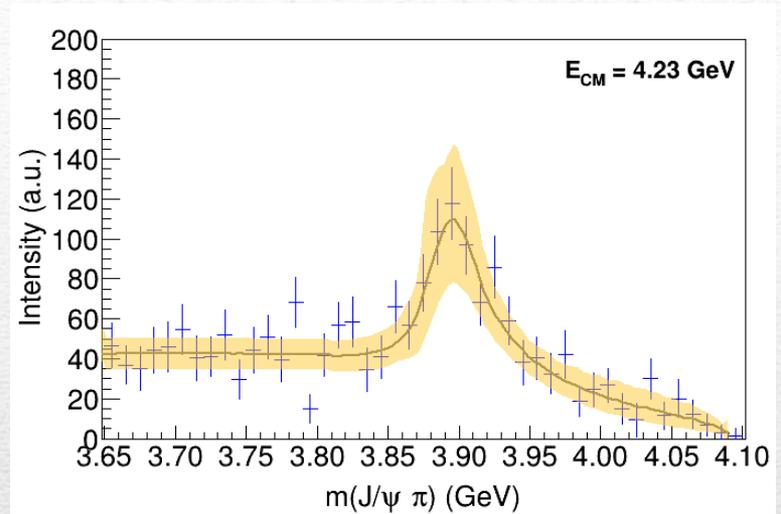
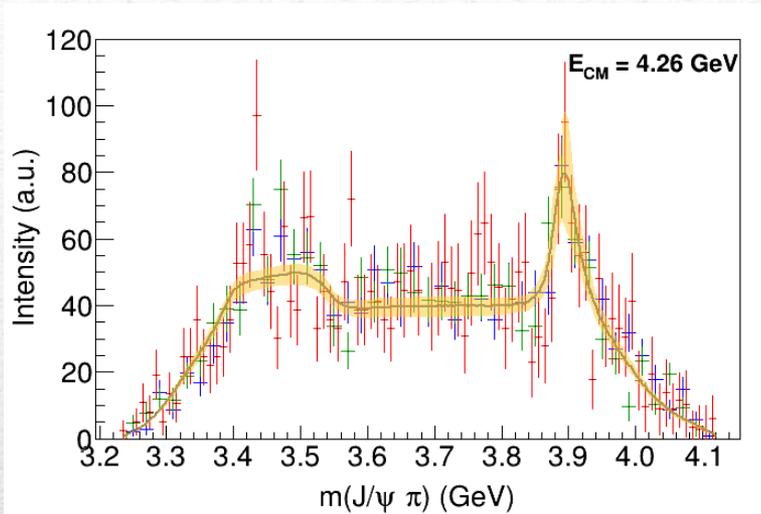
Singularities and lineshapes

Different lineshapes according to different singularities

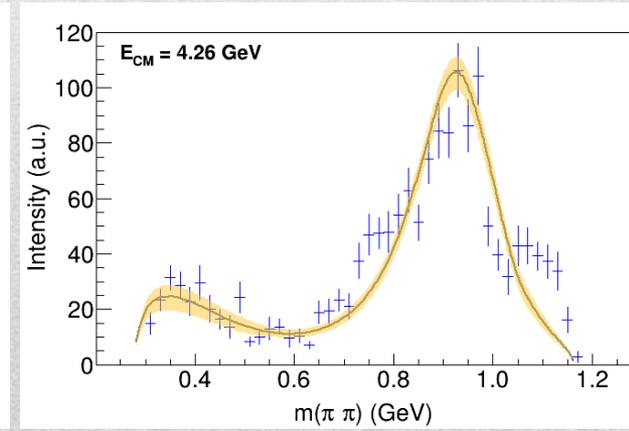
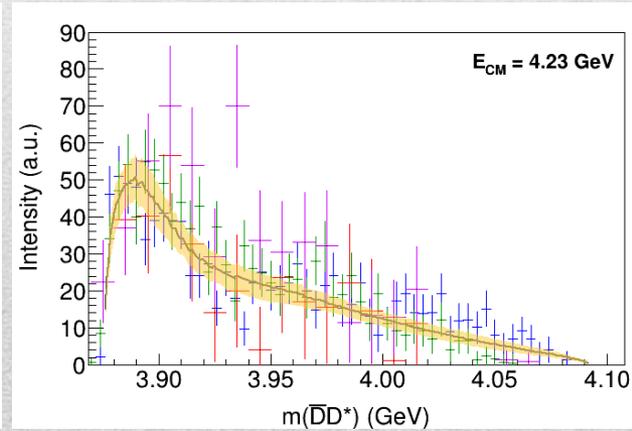
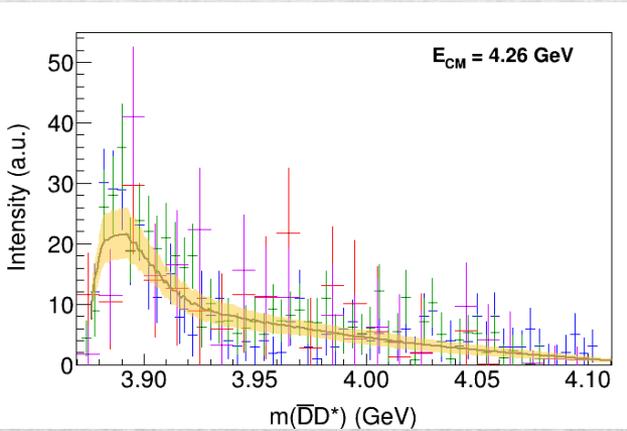
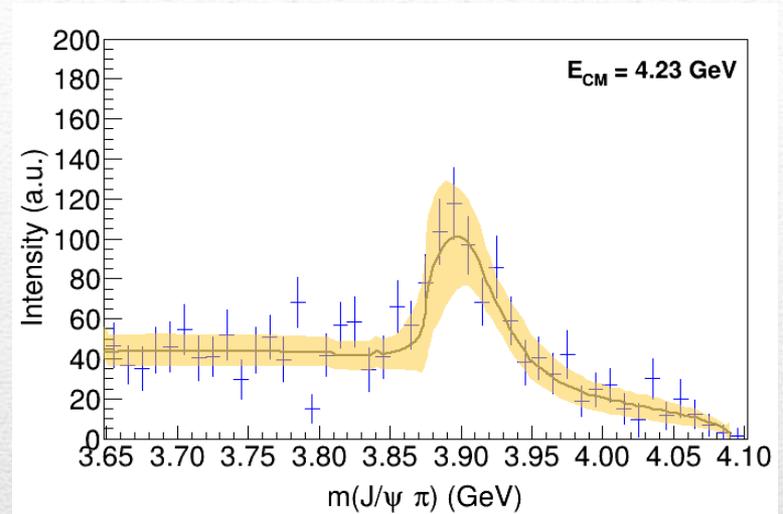
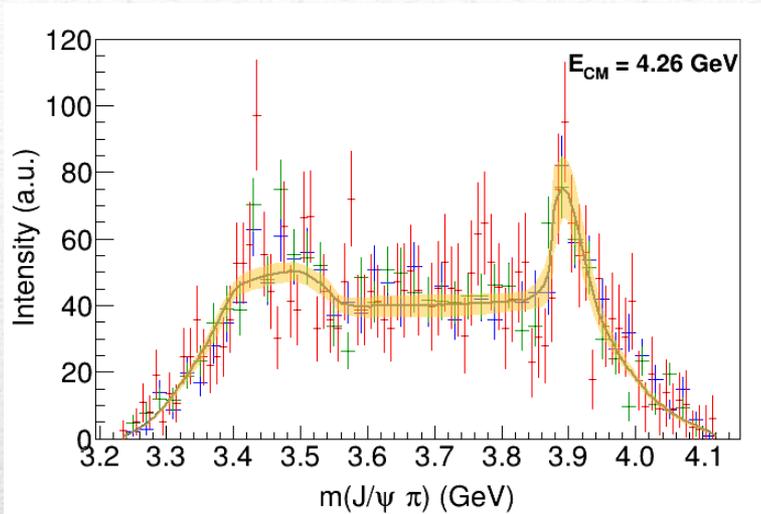
— Triangle
— t matrix
— Full



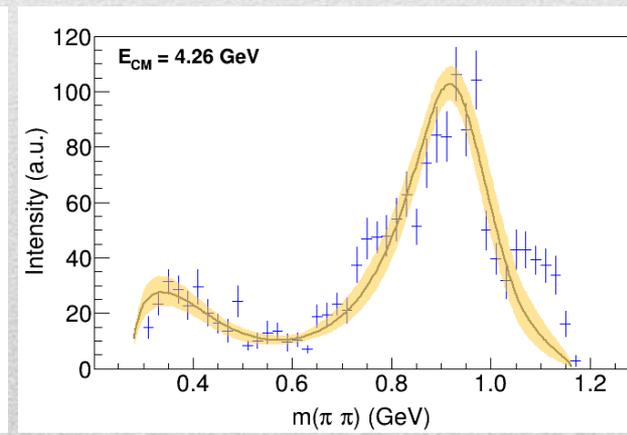
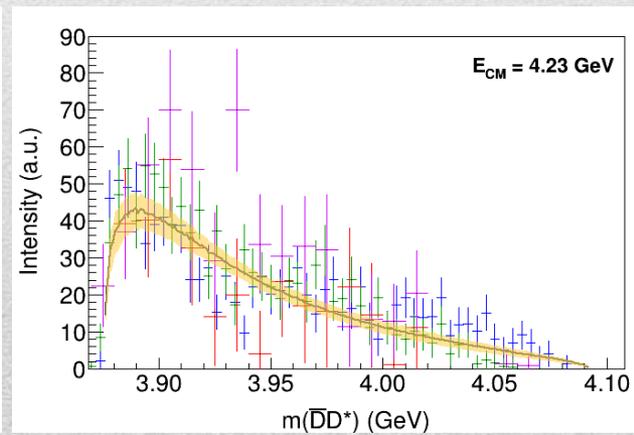
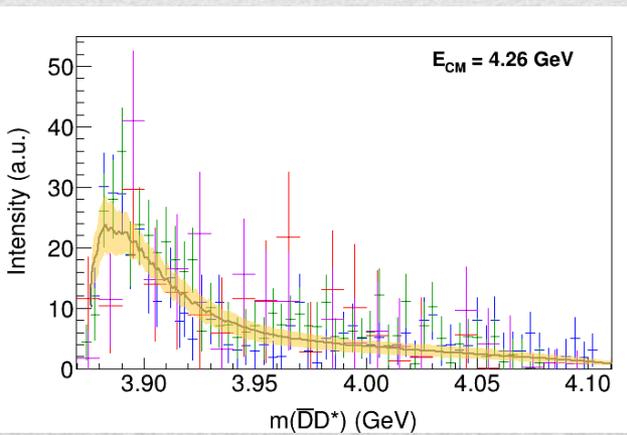
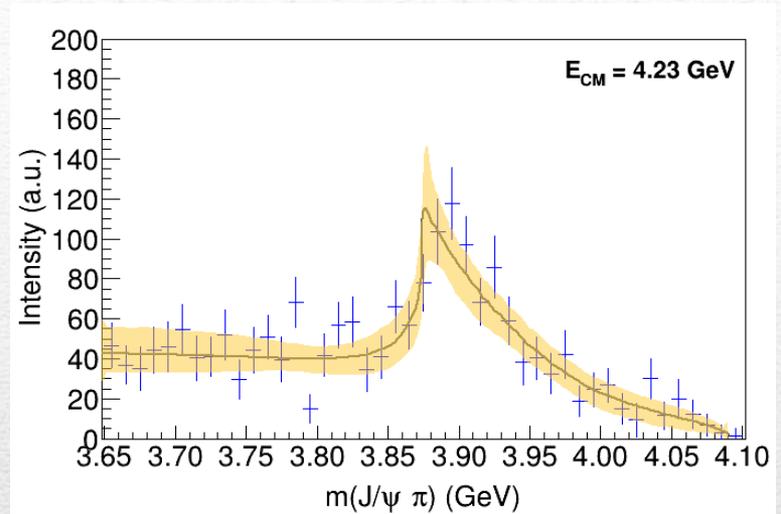
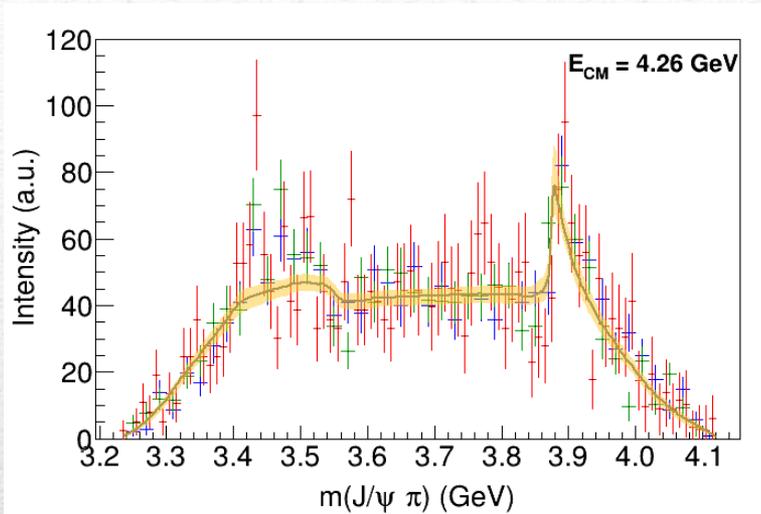
Fit: III



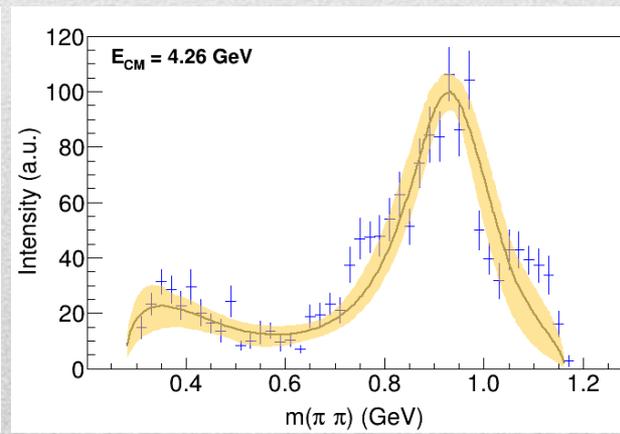
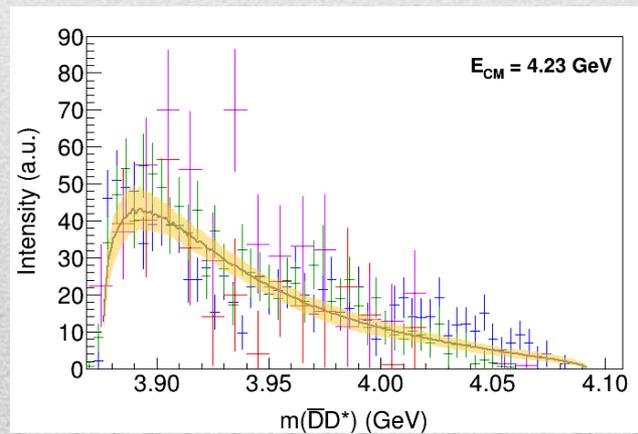
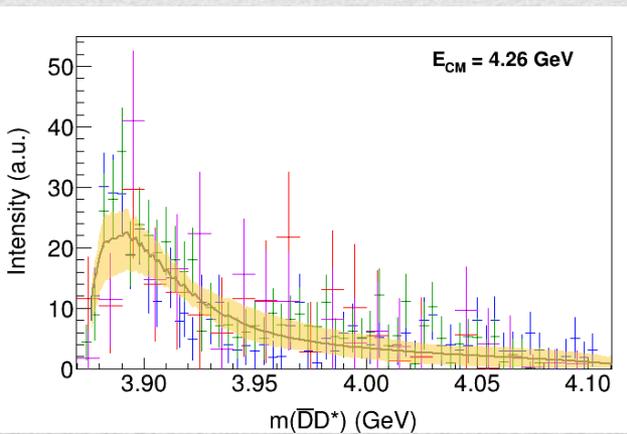
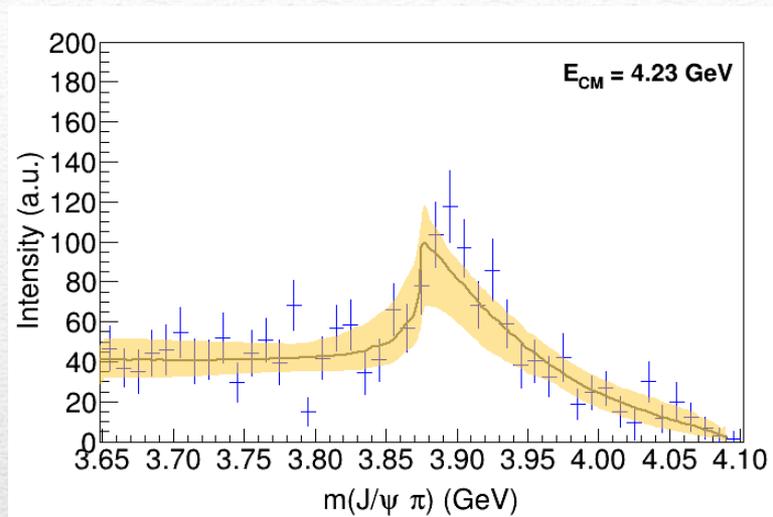
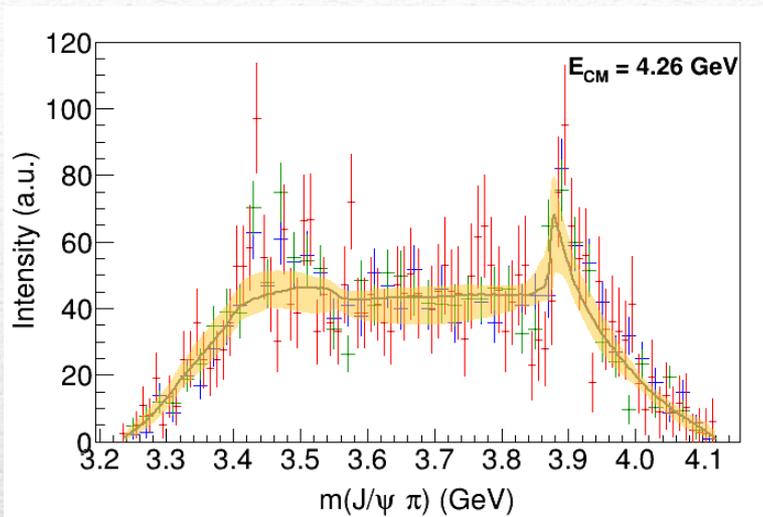
Fit: III+tr.



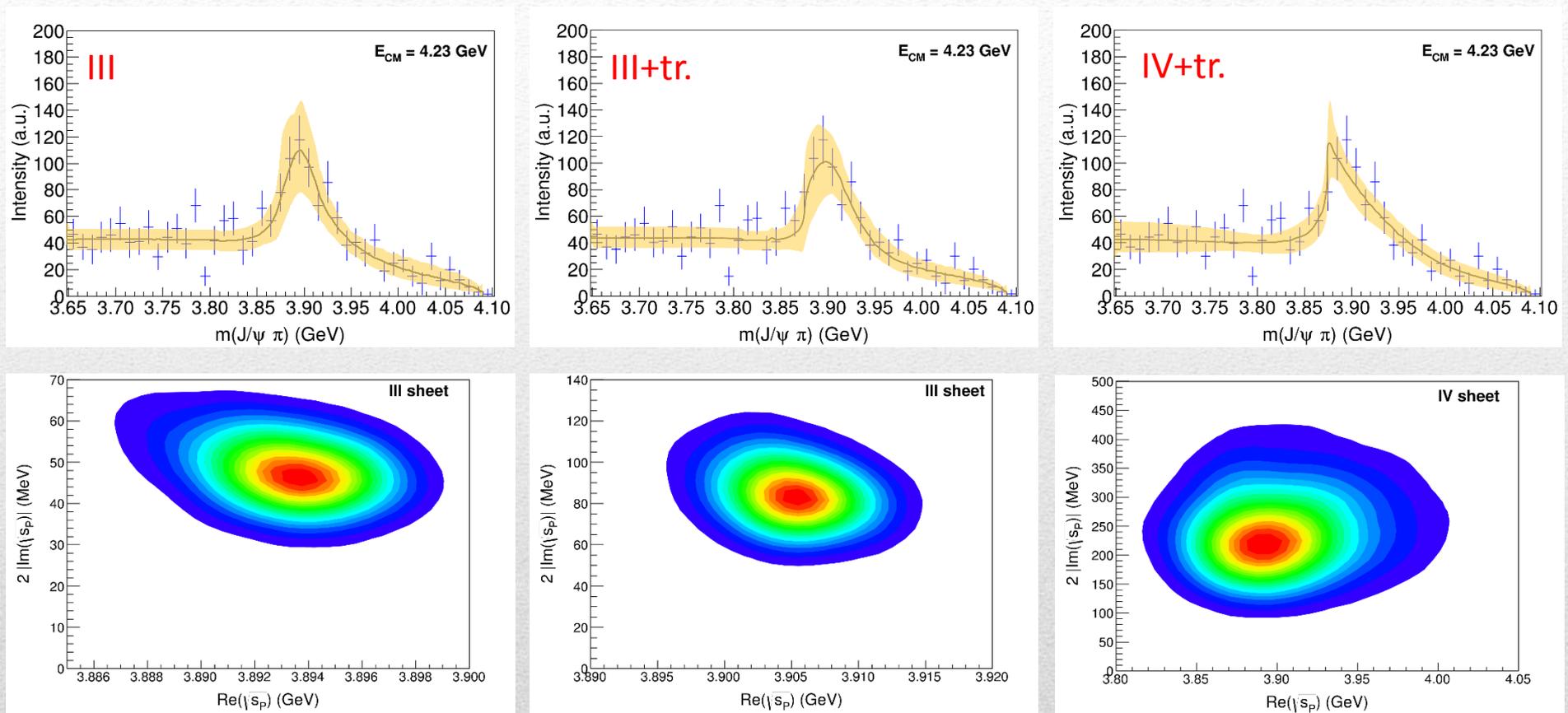
Fit: IV+tr.



Fit: tr.



Pole extraction



Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	“ 2.4σ ” (“ 1.4σ ”)
III+tr.	–	1.5σ (3.1σ)	“ 2.6σ ” (“ 1.3σ ”)
IV+tr.	–	–	“ 2.1σ ” (“ 0.9σ ”)

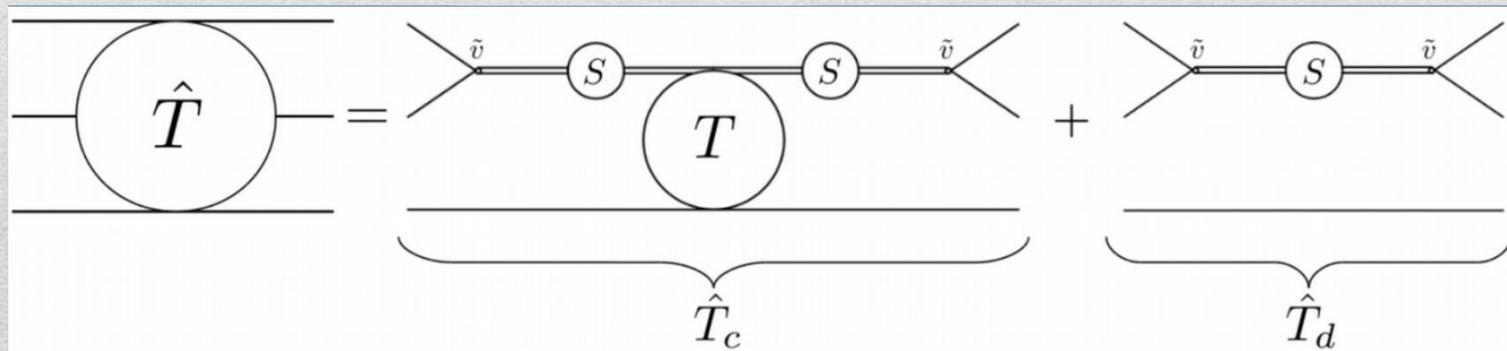
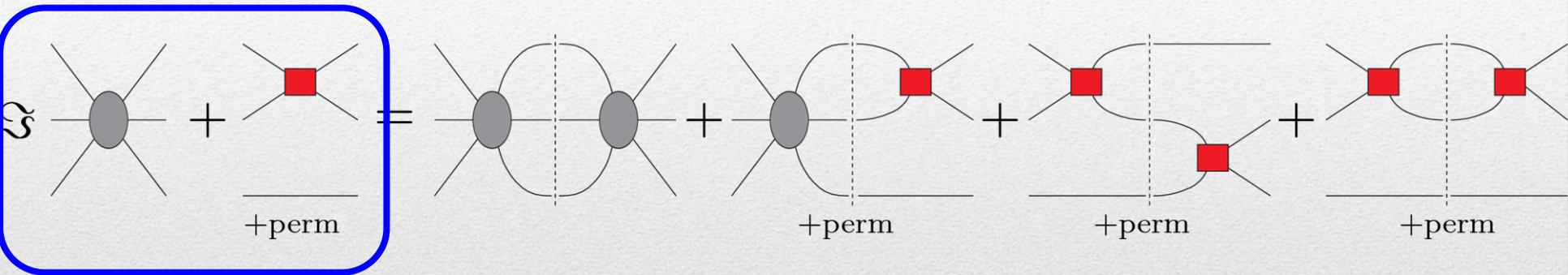
	III	III+tr.	IV+tr.
M (MeV)	$3893.2^{+5.5}_{-7.7}$	3905^{+11}_{-9}	3900^{+140}_{-90}
Γ (MeV)	48^{+19}_{-14}	85^{+45}_{-26}	240^{+230}_{-130}

Not conclusive at this stage

Three-Body Unitarity

Amado, Aaron, Young (1968)

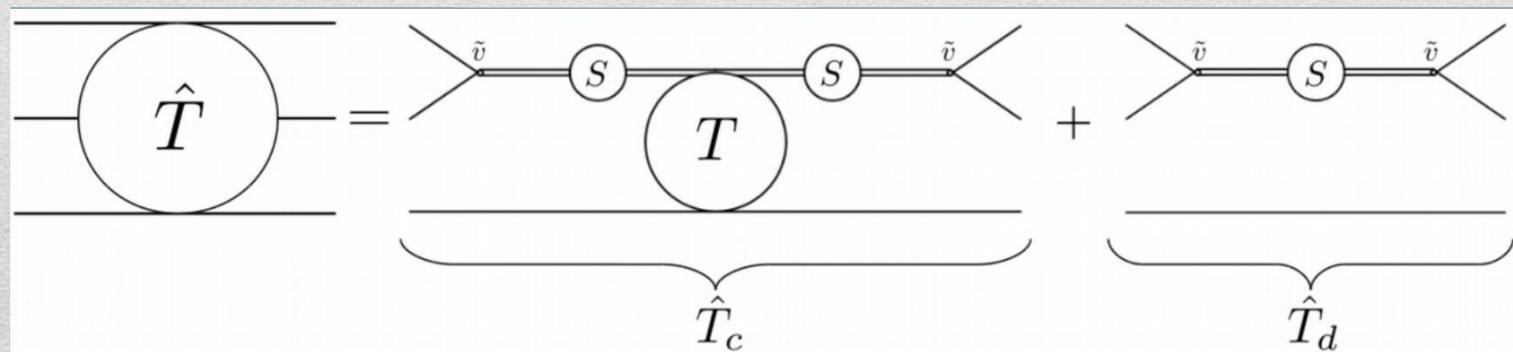
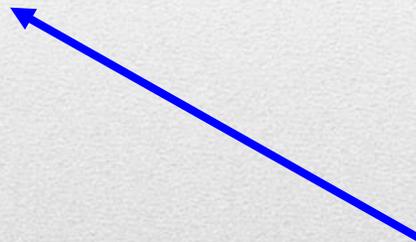
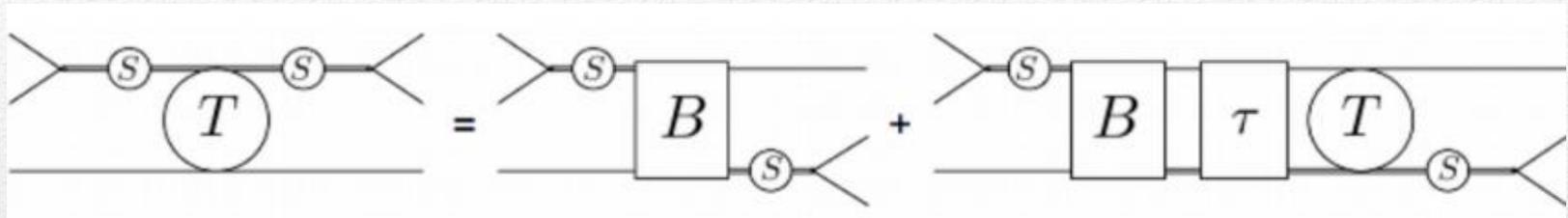
Mai, Hu, Doring, AP, Szczepaniak, EPJA53, 9, 177



Three-Body Unitarity

Amado, Aaron, Young (1968)

Mai, Hu, Doring, AP, Szczepaniak, EPJA53, 9, 177

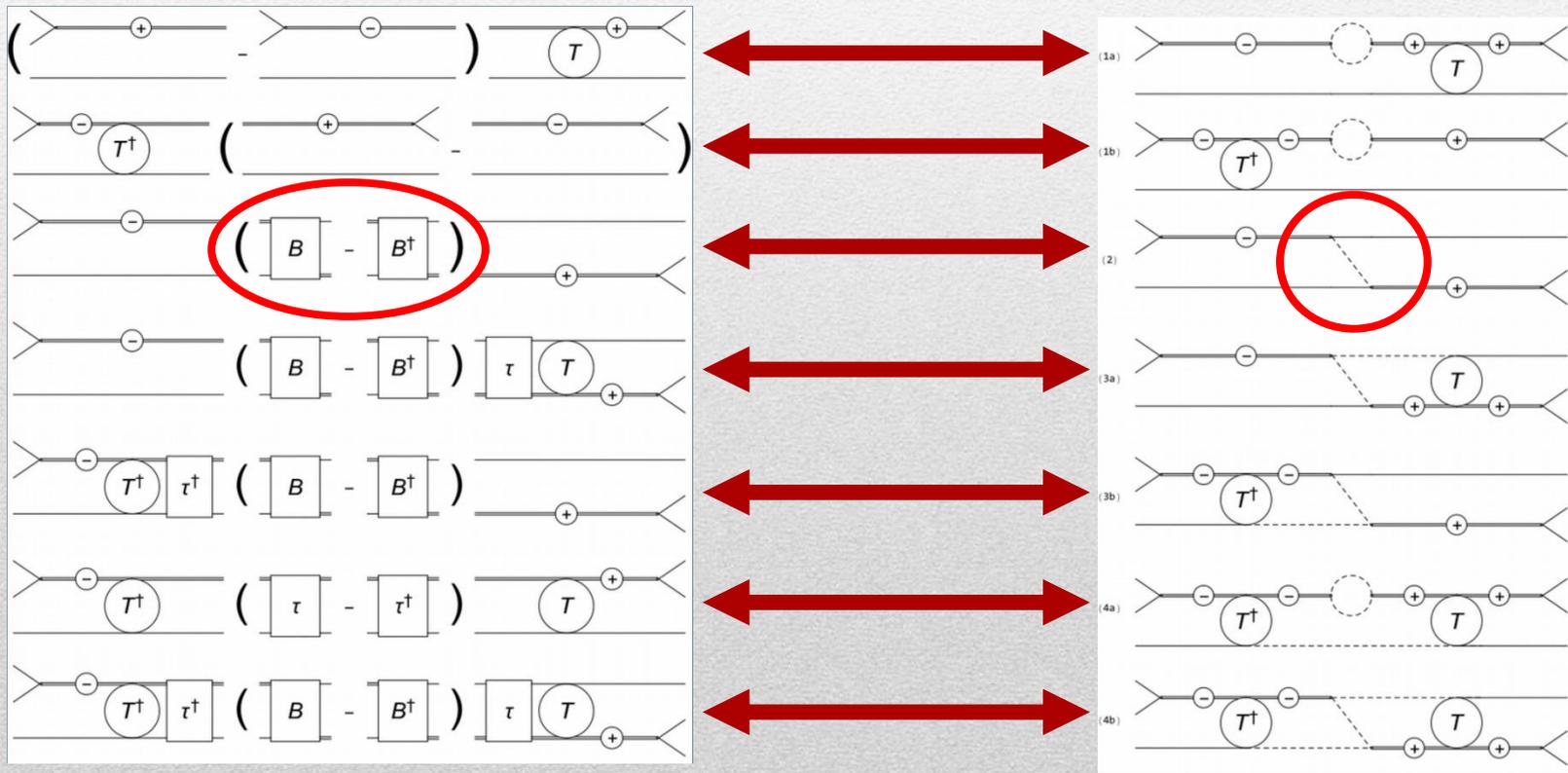


Three-Body Unitarity

$$\langle q_1, q_2, q_3 | (\hat{T} - \hat{T}^\dagger) | p_1, p_2, p_3 \rangle = i \int_P \langle q_1, q_2, q_3 | \hat{T}^\dagger | k_1, k_2, k_3 \rangle \langle k_1, k_2, k_3 | \hat{T} | p_1, p_2, p_3 \rangle$$

BS ansatz

Product of disconnected terms are source for the connected amplitude

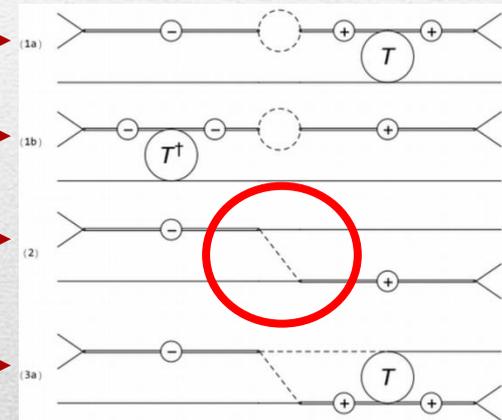
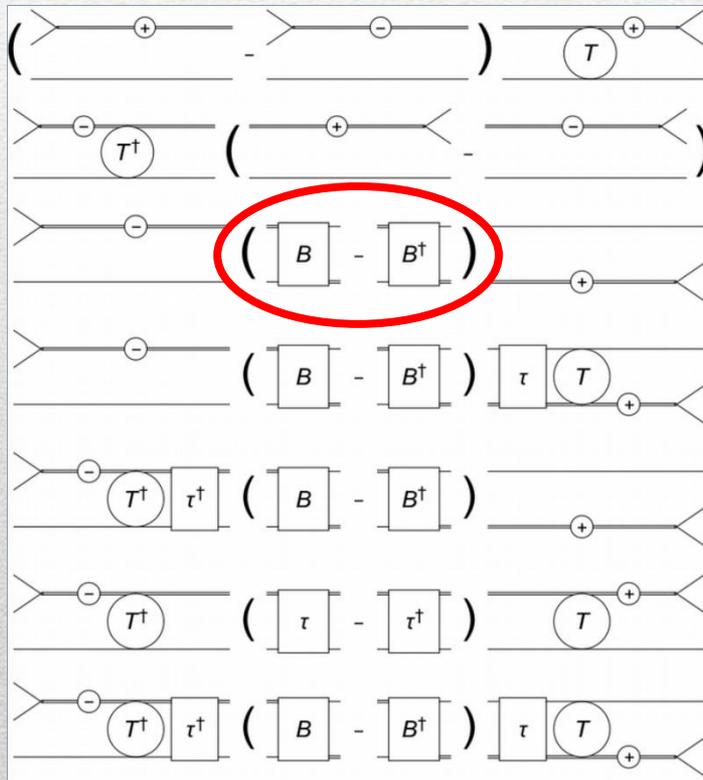


Three-Body Unitarity

$$\langle q_1, q_2, q_3 | (\hat{T} - \hat{T}^\dagger) | p_1, p_2, p_3 \rangle = i \int_P \langle q_1, q_2, q_3 | \hat{T}^\dagger | k_1, k_2, k_3 \rangle \langle k_1, k_2, k_3 | \hat{T} | p_1, p_2, p_3 \rangle$$

BS ansatz

Product of disconnected terms are source for the connected amplitude



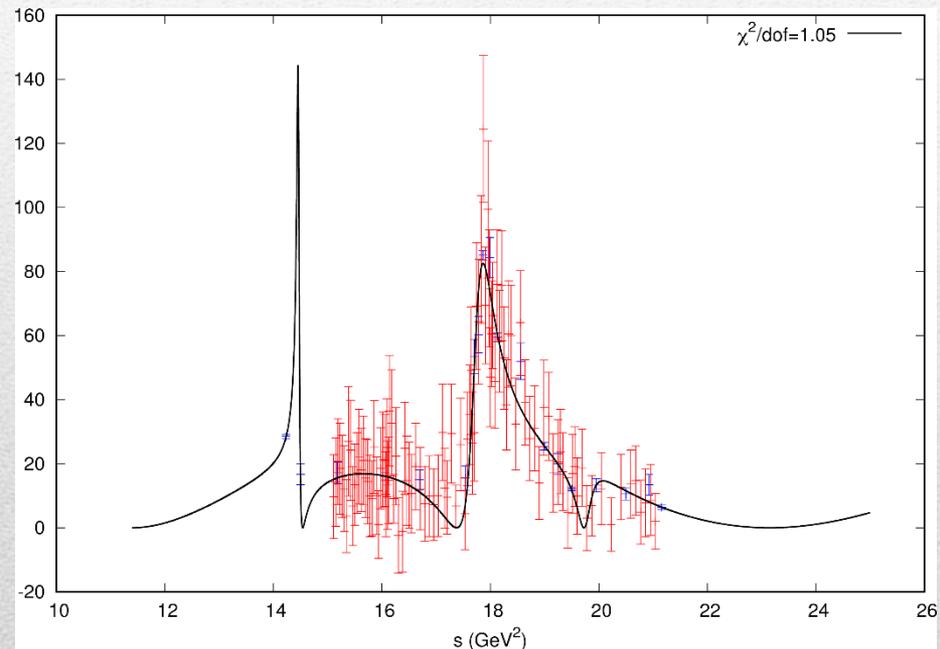
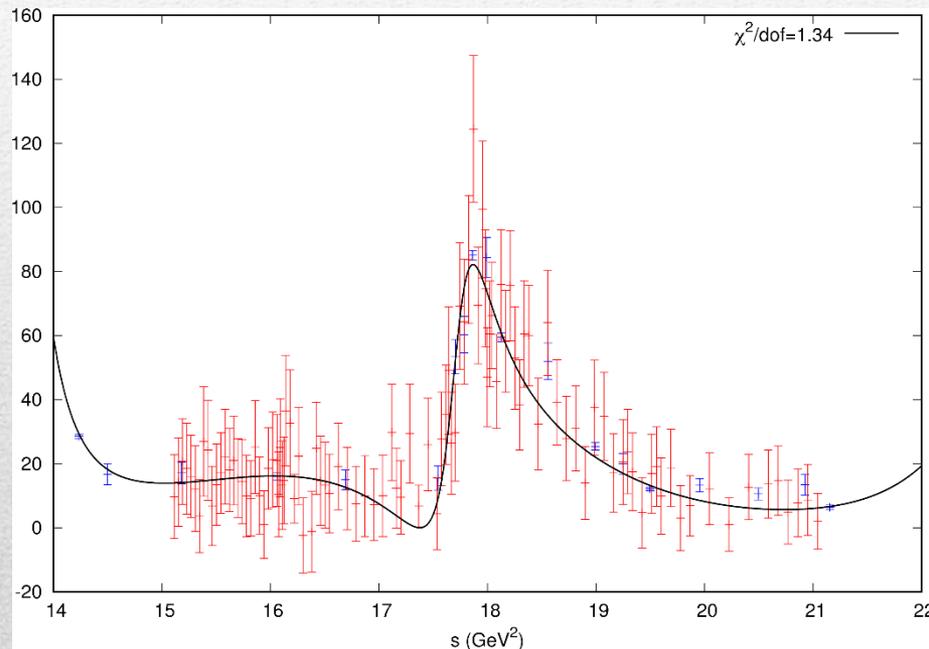
$$\langle q | B(s) | p \rangle = - \frac{\lambda^2}{2\sqrt{m^2 + Q^2} (E_Q - \sqrt{m^2 + Q^2} + i\epsilon)}$$

The $Y(4260)$

A. Amor, C. Fernandez-Ramirez, AP, U. Tamponi, in preparation

We start analyzing the single channel $e^+e^- \rightarrow J/\psi \pi\pi$

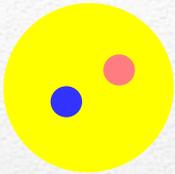
We consider the amplitude in the elastic, quasi two-body approximation



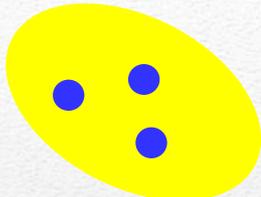
LASSO method (linear penalization in the χ^2) is helpful in constraining the number of resonances and parameters in the numerator

Hadron Spectroscopy

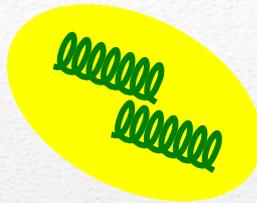
Meson



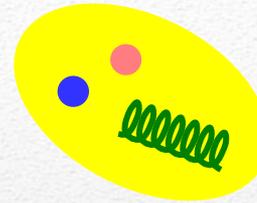
Baryon



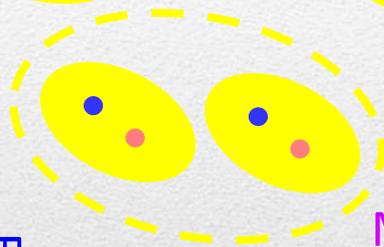
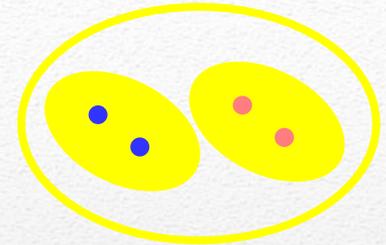
Glueball



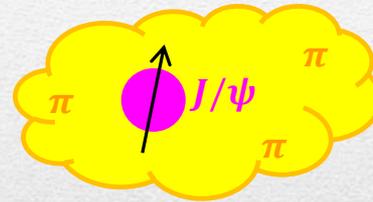
Hybrids



Tetraquark



Molecule



Hadroquarkonium

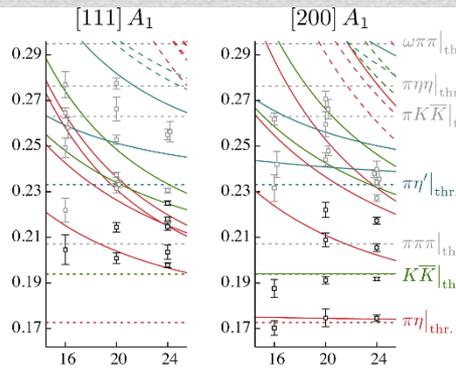


Experiment

Lattice QCD

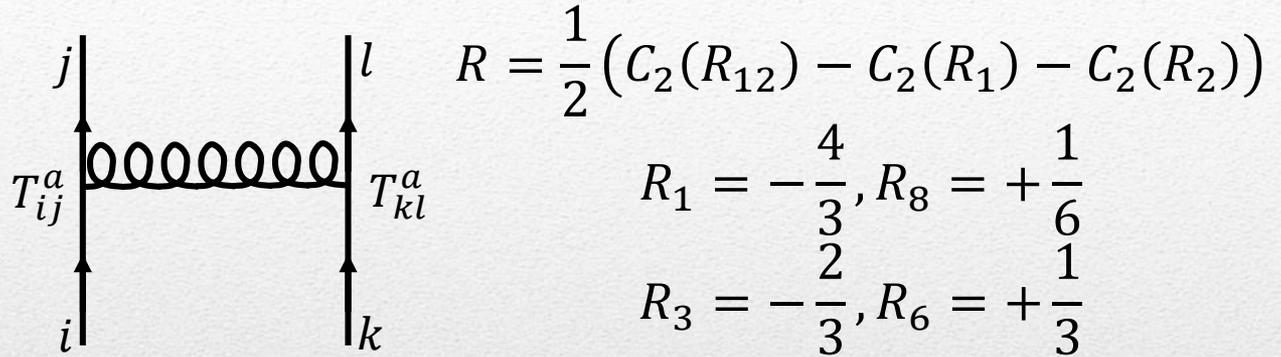
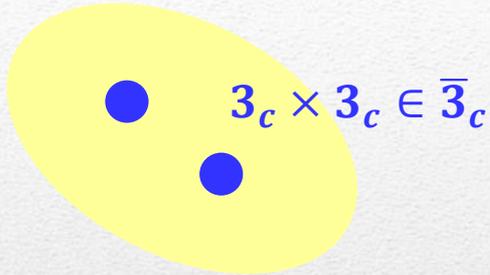


Interpretations on the spectrum leads to understanding fundamental laws of nature



Diquarks

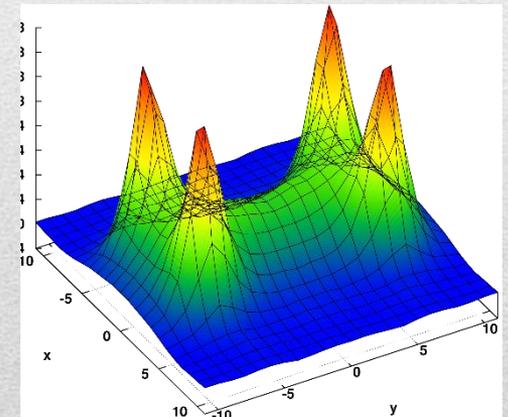
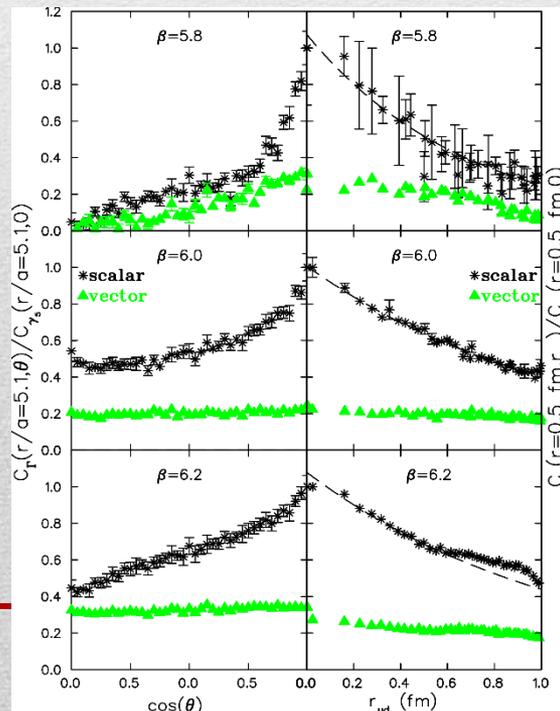
Attraction and repulsion in 1-gluon exchange approximation is given by



The singlet $\mathbf{1}_c$ is attractive

A diquark in $\bar{\mathbf{3}}_c$ is attractive

Evidence (?) of diquarks in LQCD,
Alexandrou, de Forcrand, Lucini,
PRL 97, 222002



H-shape with a 4 quark system
Cardoso, Cardoso, Bicudo,
PRD84, 054508

Tetraquark

In a constituent (di)quark model, we can think of a **diquark-antidiquark compact state**

$$[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} + h.c.$$

Maiani, Piccinini, Polosa, Riquer PRD71 014028

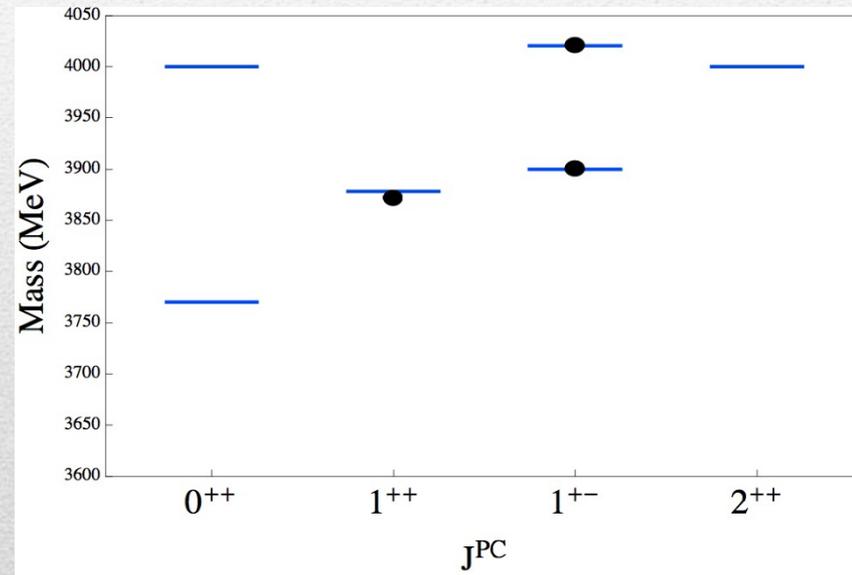
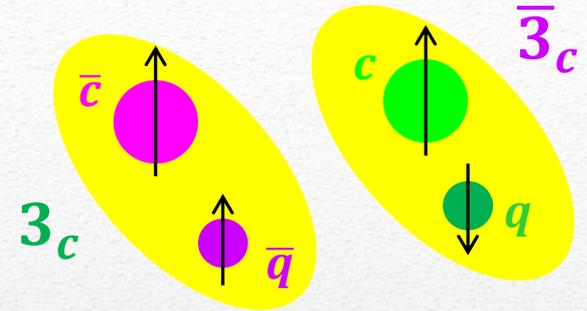
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102

Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to **color-spin hamiltonian**
(all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

$$H = \sum_{dq} m_{dq} + 2 \sum_{i < j} \kappa_{ij} \vec{S}_i \cdot \vec{S}_j \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$

- Decay pattern mostly driven by **HQSS** ✓
- Fair understanding of existing spectrum ✓
- A full nonet for each level is expected ✗



New ansatz: the diquarks are compact objects spatially separated from each other,
only $\kappa_{cq} \neq 0$

Existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

Tetraquark

Maiani, Piccinini, Polosa, Riquer PRD89 114010

J^{PC}	$cq \bar{c}\bar{q}$	$c\bar{c} q\bar{q}$	Resonance Assig.	Decays
0^{++}	$ 0, 0\rangle$	$1/2 0, 0\rangle + \sqrt{3}/2 1, 1\rangle_0$	$X_0(\sim 3770 \text{ MeV})$	$\eta_c, J/\psi + \text{light mesons}$
0^{++}	$ 1, 1\rangle_0$	$\sqrt{3}/2 0, 0\rangle - 1/2 1, 1\rangle_0$	$X'_0(\sim 4000 \text{ MeV})$	$\eta_c, J/\psi + \text{light mesons}$
1^{++}	$1/\sqrt{2}(1, 0\rangle + 0, 1\rangle)$	$ 1, 1\rangle_1$	$X_1 = X(3872)$	$J/\psi + \rho/\omega, DD^*$
1^{+-}	$1/\sqrt{2}(1, 0\rangle - 0, 1\rangle)$	$1/\sqrt{2}(1, 0\rangle - 0, 1\rangle)$	$Z = Z(3900)$	$J/\psi + \pi, h_c/\eta_c + \pi/\rho$
1^{+-}	$ 1, 1\rangle_1$	$1/\sqrt{2}(1, 0\rangle + 0, 1\rangle)$	$Z' = Z(4020)$	$J/\psi + \pi, h_c/\eta_c + \pi/\rho$
2^{++}	$ 1, 1\rangle_2$	$ 1, 1\rangle_2$	$X_2(\sim 4000 \text{ MeV})$	$J/\psi + \text{light mesons}$

$$H_{\text{eff}} = 2m_Q + \frac{B_Q}{2} \mathbf{L}^2 - 3\kappa_{cq} + 2a_Y \mathbf{L} \cdot \mathbf{S} + b_Y \frac{\langle S_{12} \rangle}{4} + \kappa_{cq} [2(\mathbf{S}_q \cdot \mathbf{S}_c + \mathbf{S}_{\bar{q}} \cdot \mathbf{S}_{\bar{c}}) + 3]$$

Ali, et al. EPJC78, 1, 29

Maiani, Polosa, Riquer, PLB778, 247-251

Two different mass scenarios

$$M_1 = 4008 \pm 40_{-28}^{+114}, \quad M_2 = 4230 \pm 8, \\ M_3 = 4341 \pm 8, \quad M_4 = 4643 \pm 9.$$

$$M_1 = 4219.6 \pm 3.3 \pm 5.1, \quad M_2 = 4333.2 \pm 19.9, \\ M_3 = 4391.5 \pm 6.3, \quad M_4 = 4643 \pm 9,$$

Prediction for a high Y_5

$$M_5 = \begin{cases} 6539 \text{ MeV} & \text{SI(c1)} \\ 6589 \text{ MeV} & \text{SI(c2)} \\ 6862 \text{ MeV} & \text{SII(c1)} \\ 6899 \text{ MeV} & \text{SII(c2)} \end{cases}$$

Label	$ S_Q, S_{\bar{Q}}; S, L\rangle_J$
Y_1	$ 0, 0; 0, 1\rangle_1$
Y_2	$(1, 0; 1, 1\rangle_1 + 0, 1; 1, 1\rangle_1)/\sqrt{2}$
Y_3	$ 1, 1; 0, 1\rangle_1$
Y_4	$ 1, 1; 2, 1\rangle_1$
Y_5	$ 1, 1; 2, 3\rangle_1$

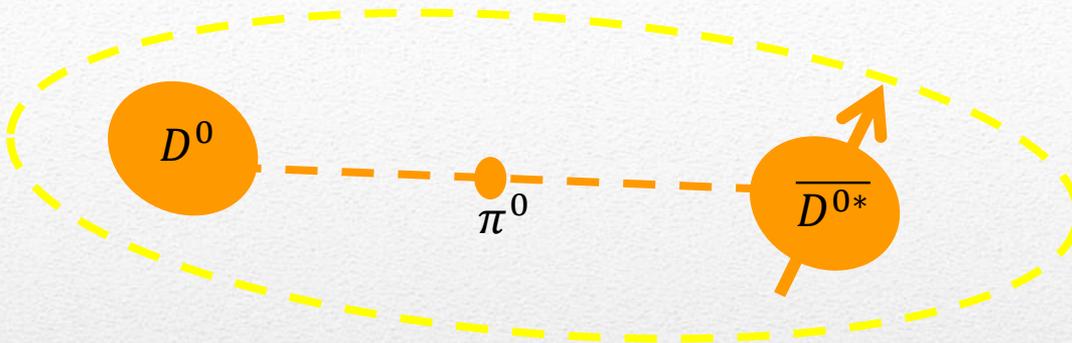
Other models: Molecule

Tornqvist, Z.Phys. C61, 525

Braaten and Kusunoki, PRD69 074005

Swanson, Phys.Rept. 429 243-305

$$\begin{aligned} X(3872) &\sim \bar{D}^0 D^{*0} \\ Z_c(3900) &\sim \bar{D}^0 D^{*+} \\ Z'_c(4020) &\sim \bar{D}^{*0} D^{*+} \\ Y(4260) &\sim \bar{D} D_1 \end{aligned}$$



A **deuteron-like meson pair**, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (**Weinberg's theorem**) ✓
- Good description of **decay patterns** (mostly to constituents) and X(3872) **isospin violation** ✓
- States appear **close to thresholds** ✓ (but **Z(4430)** ✗)
- Lifetime of constituents has to be $\gg 1/m_\pi$
- Binding energy varies from -70 to -0.1 MeV, or even **positive** (repulsive interaction) ✗
- **Unclear spectrum** (a state for each threshold?) – **depends on potential models** ✗

$$V_\pi(r) = \frac{g_{\pi N}^2}{3} (\vec{\tau}_1 \cdot \vec{\tau}_2) \left\{ [3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)] \left(1 + \frac{3}{(m_\pi r)^2} + \frac{3}{m_\pi r} \right) + (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \right\} \frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

Three-Body Unitarity

Imaginary parts of B, τ, S are fixed by unitarity and matching
(for simplicity $v = \lambda$)

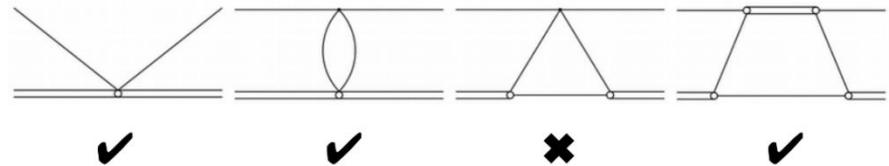
$$\tau(\sigma(k)) = (2\pi)\delta^+(k^2 - m^2)S(\sigma(k))$$

$$-\frac{1}{S(P^2)} = \sigma(k) - M_0^2 - \frac{1}{(2\pi)^3} \int d^3\ell \frac{\lambda^2}{2E_\ell(\sigma(k) - 4E_\ell^2 + i\epsilon)}$$

- in the rest-frame of isobar (**Lorentz invariance!**)
- twice subtracted dispersion relation in $\sigma(k)=(P-k)^2$

$$\langle q|B(s)|p\rangle = -\frac{\lambda^2}{2\sqrt{m^2+Q^2}(E_Q - \sqrt{m^2+Q^2} + i\epsilon)}$$

- un-subtracted dispersion relation
- one- π exchange in TOPT
- real contributions can be added to B



The freedom of adding real terms to B allows us to use this solution as a flexible parametrization

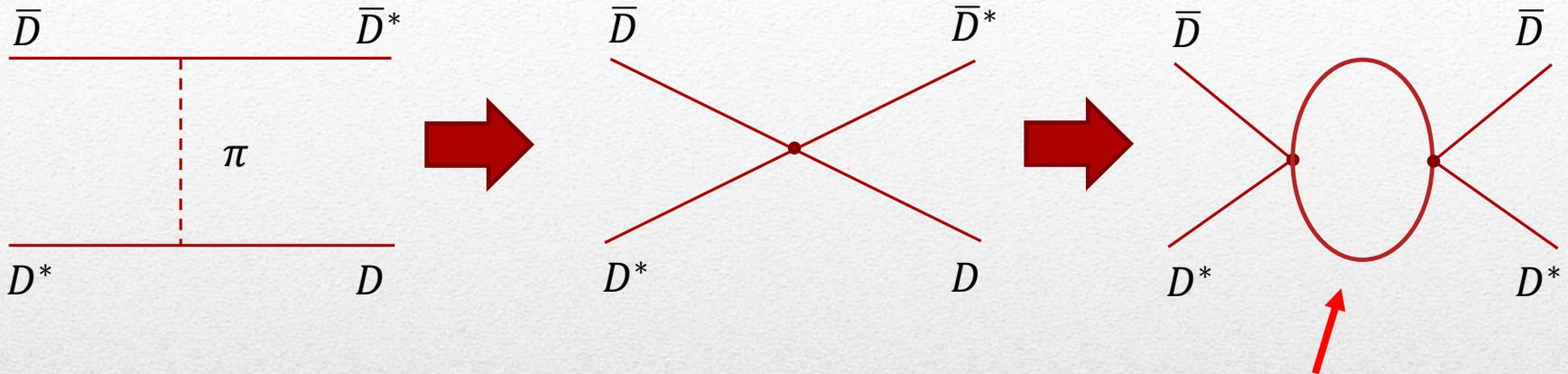
Numerics in progress:

- D. Sadasivan, M. Mai, AP, M. Doring, A. Szczepaniak for the $a_1(1260)$ and $a_1(1420)$

Alternative approach based on N/D :

- A. Jackura, AP et al. (JPAC) for the $X(3872)$
- J.M. Alarcon, E. Passemar, AP, C. Weiss for the nucleon isoscalar vector form factor

Weinberg and amplitudes



This means that IF you can consider the pion exchange as a contact interaction, the amplitude is determined by the pole close to threshold

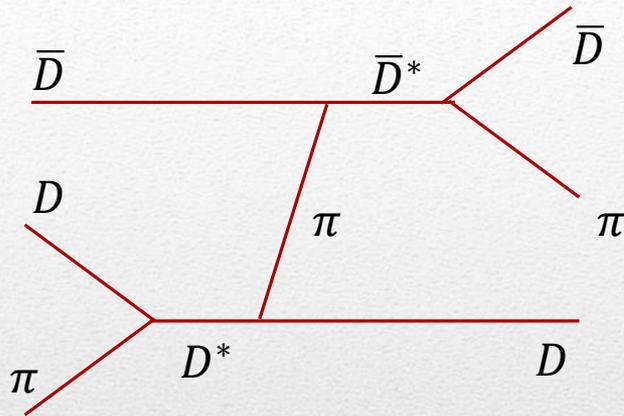
This loop is now divergent, I need to renormalize the integral I can put the pole where I want

Complex s



Weinberg and amplitudes

A. Jackura, AP et al., in progress



BUT the D^* actually decays into $D\pi$ and the system is constrained by 3-body unitarity

The position of the pole can be calculated given a model for the simple pion exchange

The simplest model leads to a convergent dispersion relation, the pole position is determined
One can check whether this purely molecular amplitude is consistent or not with data

Complex s

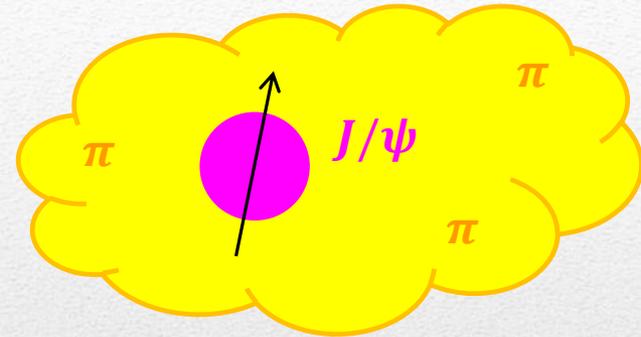
Short cut of real pion exchange



pole?

Hadro-charmonium

Dubynskiy, Voloshin, PLB 666, 344
Dubynskiy, Voloshin, PLB 671, 82
Li, Voloshin, MPLA29, 1450060



Born in the context of QCD multipole expansion

$$H_{eff} = -\frac{1}{2} a_\psi E_i^a E_i^a$$
$$a_\psi = \langle \psi | (t_c^a - t_{\bar{c}}^a) r_i G r_i (t_c^a - t_{\bar{c}}^a) | \psi \rangle$$

the chromoelectric field interacts with soft light matter (highly excited light hadrons)

A bound state can occur via Van der Waals-like interactions

Expected to decay into core charmonium + light hadrons,
Decay into open charm exponentially suppressed

Counting rules

Brodsky, Lebed PRD91, 114025

- Exotic states can be produced in threshold regions in e^+e^- , electroproduction, hadronic beam facilities and are best characterized by cross section ratios
- Two examples:

$$1) \frac{\sigma(e^+e^- \rightarrow Z_c^+ \pi^-)}{\sigma(e^+e^- \rightarrow \mu^+ \mu^-)} \propto \frac{1}{s^6} \text{ as } s \rightarrow \infty$$

$$2) \frac{\sigma(e^+e^- \rightarrow Z_c^+(\bar{c}c\bar{d}u) + \pi^-(\bar{u}d))}{\sigma(e^+e^- \rightarrow \Lambda_c(cud) + \bar{\Lambda}_c(\bar{c}\bar{u}\bar{d}))} \rightarrow \text{const as } s \rightarrow \infty$$

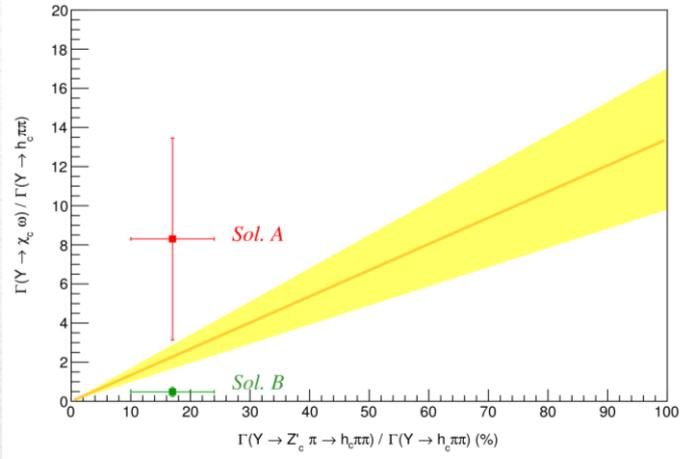
- Ratio numerically smaller if Z_c behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces

Different estimates close to thresholds, and in presence of annihilating $q \bar{q}$

Guo, Meissner, Wang, Yang, 1607.04020

Voloshin PRD94, 074042

Tetraquark: the $Y(4220)$



$$\langle \chi_{c0}(p) \omega(\eta, q) | Y(\lambda, P) \rangle = g_\chi \eta \cdot \lambda,$$

$$\langle Z'_c(\eta, q) \pi(p) | Y(\lambda, P) \rangle = g_Z \eta \cdot \lambda \frac{P \cdot p}{f_\pi M_Y},$$

$$\langle h_c(\eta, q) \sigma(p) | Y(\lambda, P) \rangle = g_h \varepsilon_{\mu\nu\rho\sigma} \eta^\mu \lambda^\nu \frac{P^\rho q^\sigma}{P \cdot q},$$

$$\langle \pi(q) \pi(p) | \sigma(P) \rangle = \frac{P^2}{2f_\pi},$$

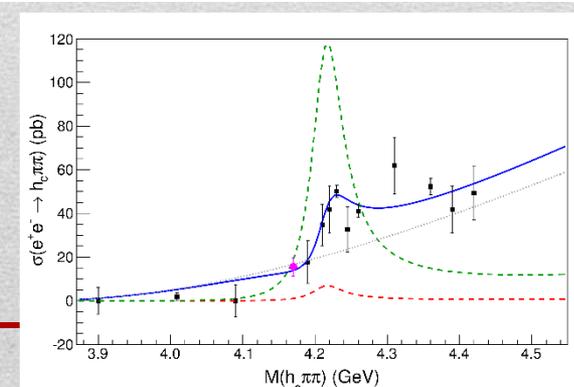
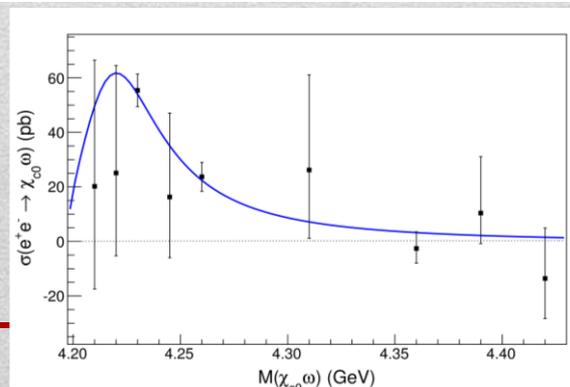
$$\frac{\Gamma(Y(4220) \rightarrow \chi_{c0} \omega)}{\Gamma(Y(4220) \rightarrow h_c \pi^+ \pi^-)} = (13.4 \pm 3.6) \times R_{YZ} = 2.3 \pm 1.2.$$

$$\frac{\Gamma(Y(4220) \rightarrow Z'_c{}^\pm \pi^\mp \rightarrow h_c \pi^+ \pi^-)}{\Gamma(Y(4220) \rightarrow h_c \sigma \rightarrow h_c \pi^+ \pi^-)} = 4.8 \pm 3.5,$$

A state apparently breaking HQSS has been observed

Compatible to be the Y_3 state

Faccini, Filaci, Guerrieri, AP, Polosa, PRD 91, 117501



Tetraquark: the b sector

Ali, Maiani, Piccinini, Polosa, Riquer PRD91 017502

$$\begin{aligned}M(Z'_b) - M(Z_b) &= 2\kappa_b \\M(Z'_c) - M(Z_c) &= 2\kappa_c \sim 120 \text{ MeV} \\ \kappa_b : \kappa_c &= M_c : M_b \sim 0.30\end{aligned}$$

$$2\kappa_b \sim 36 \text{ MeV, vs. } 45 \text{ MeV (exp.)}$$

$$\begin{aligned}Z_b &= \frac{\alpha |1_{q\bar{q}}0_{b\bar{b}}\rangle - \beta |0_{q\bar{q}}1_{b\bar{b}}\rangle}{\sqrt{2}} \\ Z'_b &= \frac{\alpha |1_{q\bar{q}}0_{b\bar{b}}\rangle + \beta |0_{q\bar{q}}1_{b\bar{b}}\rangle}{\sqrt{2}}\end{aligned}$$

Data on $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ and $\Upsilon(5S) \rightarrow h_b(nP)\pi\pi$ strongly favor $\alpha = \beta$

$$Z_c(3900) \rightarrow \eta_c \rho$$

Esposito, Guerrieri, AP, PLB 746, 194-201

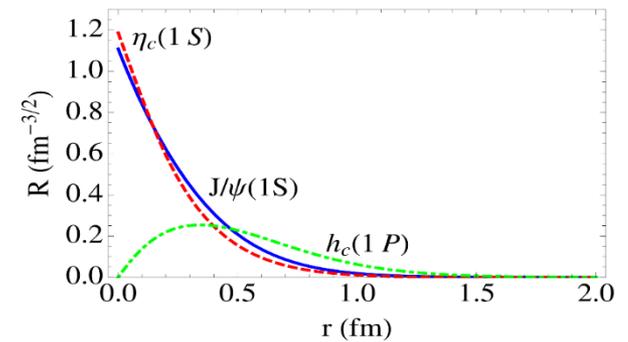
If tetraquark

Kinematics with HQSS, dynamics estimated according to Brodsky et al., PRL113, 112001

$$A = \langle \chi_{c\bar{c}} | \chi_c \otimes \chi_{\bar{c}} \rangle \langle \phi_{c\bar{c}} | \hat{T}_{\perp HQS} | \phi[cq][\bar{c}\bar{q}] \rangle + O\left(\frac{\Lambda_{QCD}}{m_c}\right)$$

Clebsch-Gordan

Uncertainty
~ 25%



Reduced matrix element

- approximated as a constant
- or $\propto \psi_{c\bar{c}}(r_Z)$

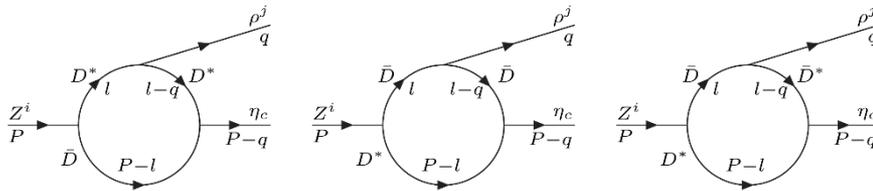
	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z_c \rightarrow J/\psi \pi)}$	$(3.3^{+7.9}_{-1.4}) \times 10^2$	$0.41^{+0.96}_{-0.17}$	$(2.3^{+3.3}_{-1.4}) \times 10^2$	$0.27^{+0.40}_{-0.17}$
$\frac{\mathcal{BR}(Z'_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z'_c \rightarrow h_c \pi)}$	$(1.2^{+2.8}_{-0.5}) \times 10^2$		$6.6^{+56.8}_{-5.8}$	

$$Z_c(3900) \rightarrow \eta_c \rho$$

Esposito, Guerrieri, AP, PLB 746, 194-201

If molecule

Non-Relativistic Effective Theory, HQET+NRQCD and Hidden gauge Lagrangian
Uncertainty estimated with power counting at NLO



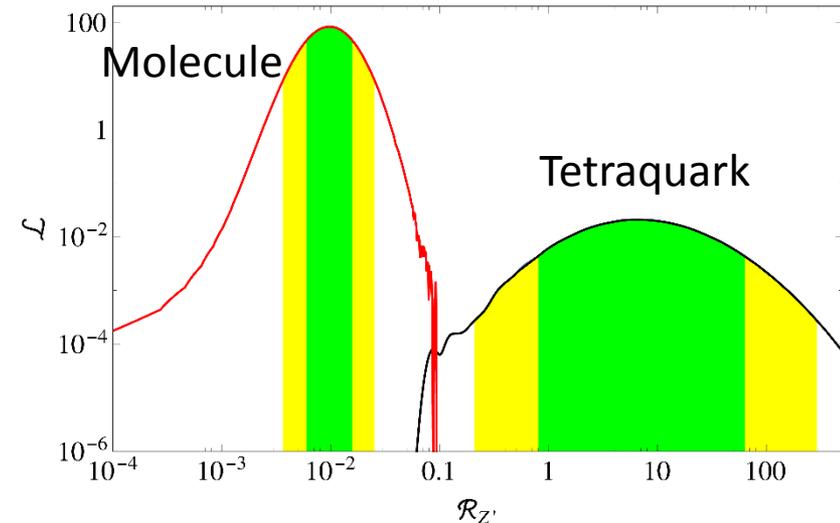
$$\mathcal{L}_{Z_c^{(\prime)}} = \frac{z^{(\prime)}}{2} \langle Z_{\mu,ab}^{(\prime)} \bar{H}_{2b} \gamma^\mu \bar{H}_{1a} \rangle + h.c.,$$

$$\mathcal{L}_{c\bar{c}} = \frac{g_2}{2} \langle \bar{\Psi} H_{1a} \overleftrightarrow{\not{D}} H_{2a} \rangle + \frac{g_1}{2} \langle \bar{\chi}_\mu H_{1a} \gamma^\mu H_{2a} \rangle + h.c.,$$

$$\mathcal{L}_{\rho DD^*} = i\beta \langle H_{1b} v^\mu (\mathcal{V}_\mu - \rho_\mu)_{ba} \bar{H}_{1a} \rangle + i\lambda \langle H_{1b} \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ba} \bar{H}_{1a} \rangle + h.c.,$$

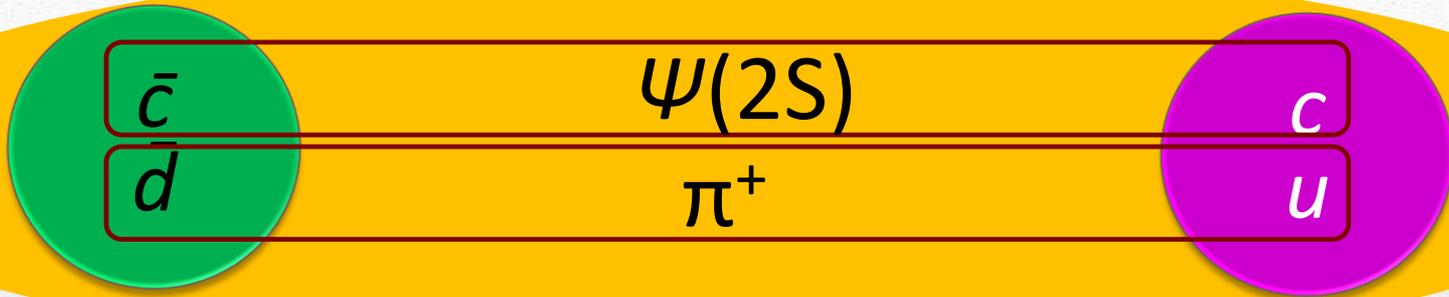
$$\frac{\mathcal{BR}(Z_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z_c \rightarrow J/\psi \pi)} = (4.6_{-1.7}^{+2.5}) \times 10^{-2}; \quad \frac{\mathcal{BR}(Z_c' \rightarrow \eta_c \rho)}{\mathcal{BR}(Z_c' \rightarrow h_c \pi)} = (1.0_{-0.4}^{+0.6}) \times 10^{-2}.$$

$$\frac{\mathcal{BR}(Z_c \rightarrow h_c \pi)}{\mathcal{BR}(Z_c' \rightarrow h_c \pi)} = 0.34_{-0.13}^{+0.21}; \quad \frac{\mathcal{BR}(Z_c \rightarrow J/\psi \pi)}{\mathcal{BR}(Z_c' \rightarrow J/\psi \pi)} = 0.35_{-0.21}^{+0.49}$$



Dynamical movie

$Z^+(4430)$



Brodsky, Hwang, Lebed PRL 113 112001

- Since this is still a $\mathbf{3} \leftrightarrow \bar{\mathbf{3}}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_{cq}^2} \left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2} \mathbf{S}_{cq} \cdot \mathbf{S}_{\bar{c}\bar{q}},$$

e.g. Barnes *et al.*, PRD 72, 054026

- Use that the kinetic energy released in $\bar{B}^0 \rightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

$$r_Z = 1.16 \text{ fm}, \langle r_{\psi(2S)} \rangle = 0.80 \text{ fm}, \langle r_{J/\psi} \rangle = 0.39 \text{ fm}$$

$$\frac{B(Z^+(4430) \rightarrow \psi(2S)\pi^+)}{B(Z^+(4430) \rightarrow J/\psi \pi^+)} \sim 72$$

(> 10 exp.)

Towards hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

The absence of many of the predicted states might point to the need for **selection rules**

It is unlikely that the **many close-by thresholds** play no role whatsoever

All the well assessed 4-quark resonances lie close and **above** some meson-meson thresholds:

We introduce a **mechanism** that might provide “dynamical selection rules” to explain the presence/absence of resc

	Thr.	δ (MeV)	$A \sqrt{\delta}$ (MeV)	Γ (MeV)
$X(3872)$	$\bar{D}^0 D^{*0}$	0^\dagger	0^\dagger	0^\dagger
$Z_c(3900)$	$\bar{D}^0 D^{*+}$	7.8	27.9	27.9
$Z'_c(4020)$	$\bar{D}^{*0} D^{*+}$	6.7	25.9	24.8 [¶]
$X(4140)$	$J/\psi \phi$	a) 31.6	52.7	28.0
		b) 30.1	54.7	83.0
$Z_b(10610)$	$\bar{B}^0 B^{*+}$	2.7	16.6	18.4
$Z'_b(10650)$	$\bar{B}^{*0} B^{*+}$	1.8	13.4	11.5
$X(5568)$	$B_s^0 \pi^+$	61.4	78.4	21.9
X_{bs}	$B^+ \bar{K}^0$	5.8	24.1	—

We introduce a **mechanism** that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.

Hybridized tetraquarks

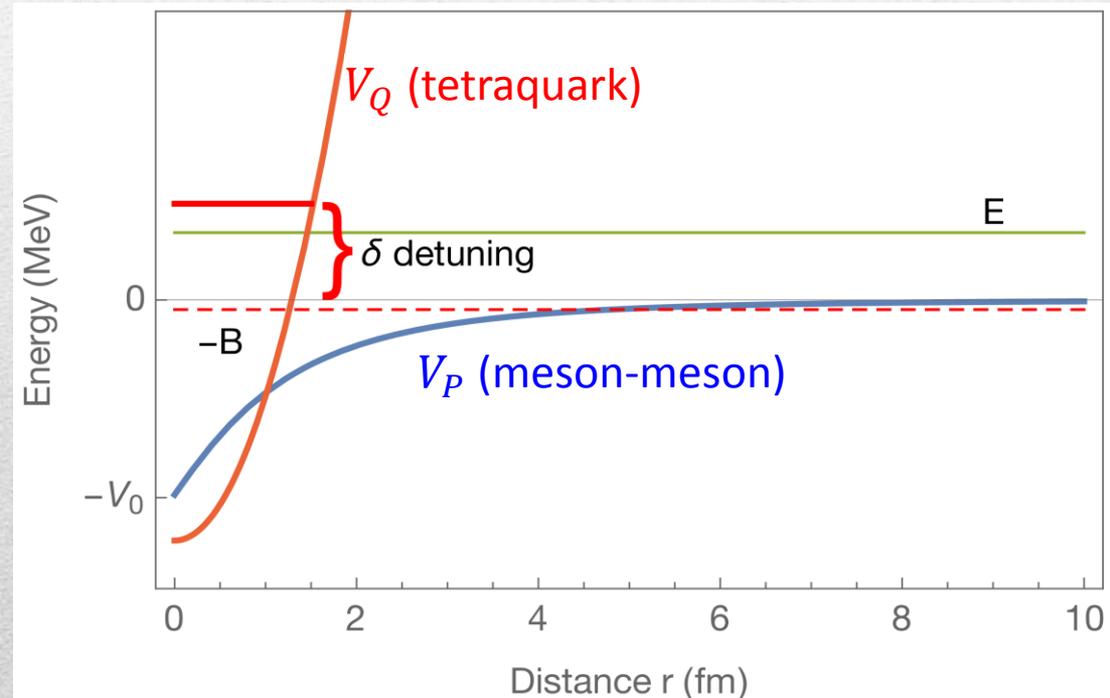
Esposito, AP, Polosa, PLB758, 292

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Let P and Q be orthogonal subspaces of the Hilbert space

$$H = H_{PP} + H_{QQ}$$

We have the (weak) scattering length a_P in the open channel.

We add an off-diagonal H_{QP} which connects the two subspaces

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

$$\Gamma = -16\pi^3 \rho \Im(T) \sim 16\pi^4 \rho |H_{PQ}|^2 \delta \left(\frac{p_1^2}{2M} + \frac{p_2^2}{2M} - \delta \right)$$

The expected width is the average **over momenta that allow for the existence of a tetraquark** $p < \bar{p} = 50 \div 100$ MeV

$$\Gamma \sim A\sqrt{\delta}$$

We therefore expect to see a level if:

- $\delta > 0$ the state **lies above threshold**
- $\delta < \frac{\bar{p}^2}{2M}$, only the **closest threshold** contributes
- The states ψ_Q and ψ_P are **orthogonal**

$X(3872)^+$ falls below threshold, $M(1^{++}) < M(D^{+*}\bar{D}^0)$

$\delta < 0$, so $a > 0 \rightarrow$ **Repulsive interaction**

No charged partners of the $X(3872)$!

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

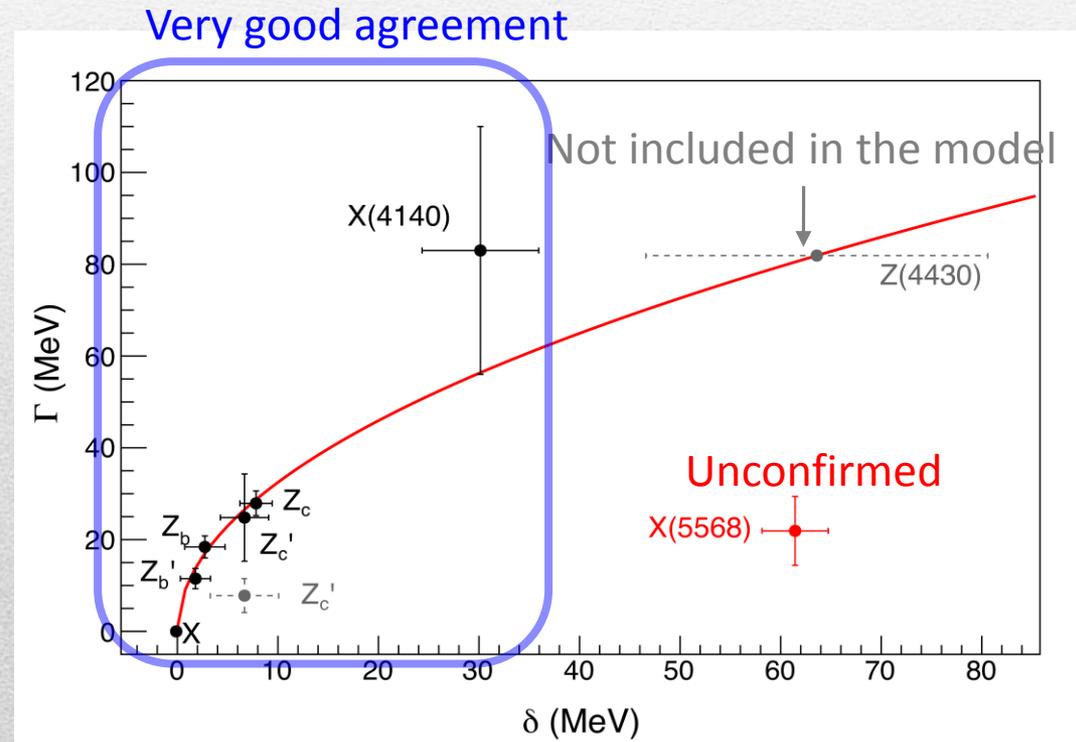
The model works only if no direct transition between closed channel levels can occur
This prevents the straightforward generalization to $L = 1$ and radially excited states
(like the Y s or the $Z(4430)$)

In this picture, a $[bu][\bar{s}\bar{d}]$ state with resonance parameters of the $X(5568)$ observed by D0 is not likely

Also, one has to ensure the orthogonality between the two Hilbert subspaces P and Q .
This might affect the estimate for the $X(4140)$

All the resonances can be fitted with

$$A = (10.3 \pm 1.3) \text{ MeV}^{1/2}$$
$$\chi^2/\text{DOF} = 1.2/5$$

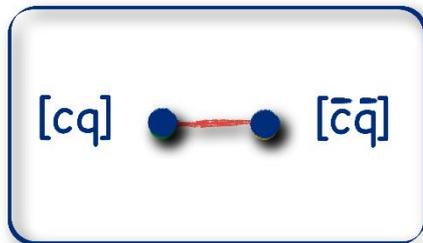
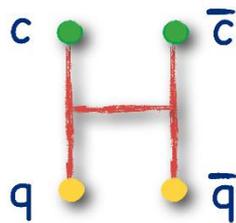


Baryonium

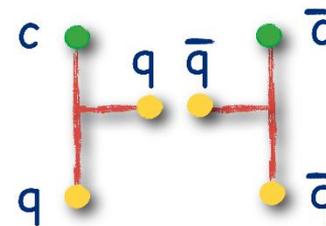
C. Sabelli

a structure $[cq][\bar{c}\bar{q}]$ can explain the dominance of baryon channel

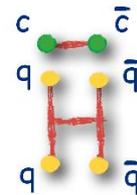
Isospin violation expected,
 $\alpha_s(m_c) \ll 1$



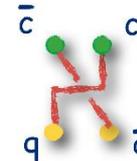
$\Lambda_c^+ \Lambda_c^-$



$\psi\sigma, \psi f_0$



$D\bar{D}$



Rossi, Veneziano,
 NPB 123, 507;
 Phys.Rept. 63, 149;
 PLB70, 255

$$\frac{B(Y(4660) \rightarrow \Lambda_c^+ \Lambda_c^-)}{B(Y(4660) \rightarrow \psi(2S)\pi\pi)} = 25 \pm 7$$

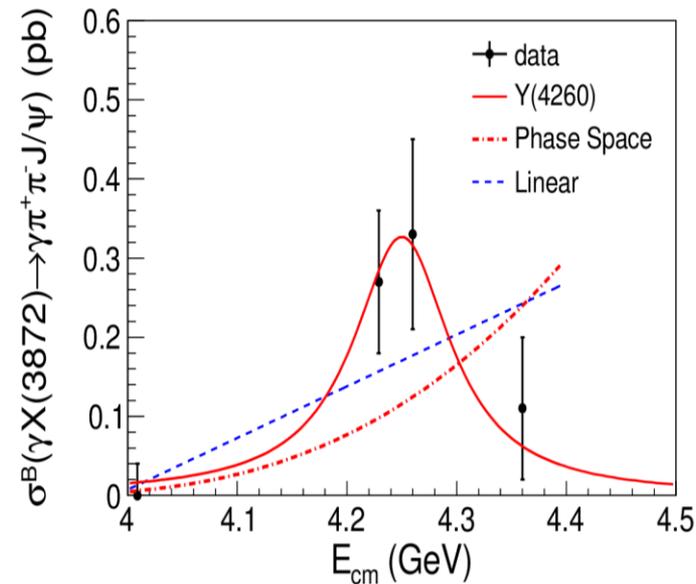
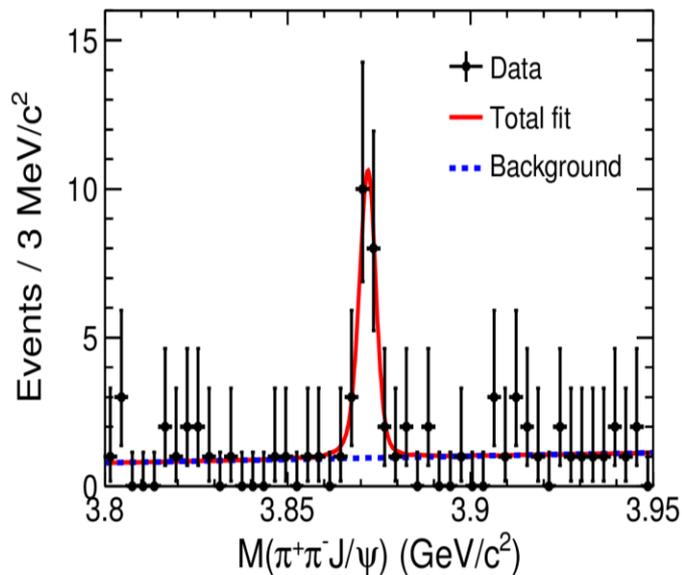
Cotugno, Faccini, Polosa, Sabelli,
 PRL 104, 132005

$Y(4260) \rightarrow \gamma X(3872)$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 092001

F. Piccinini

BESIII: $e^+e^- \rightarrow Y(4260) \rightarrow X(3872)\gamma$



With $\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi] = 5\%$

$$\frac{\mathcal{B}[Y(4260) \rightarrow \gamma X(3872)]}{\mathcal{B}[Y(4260) \rightarrow \pi^+\pi^-J/\psi]} = 0.1$$

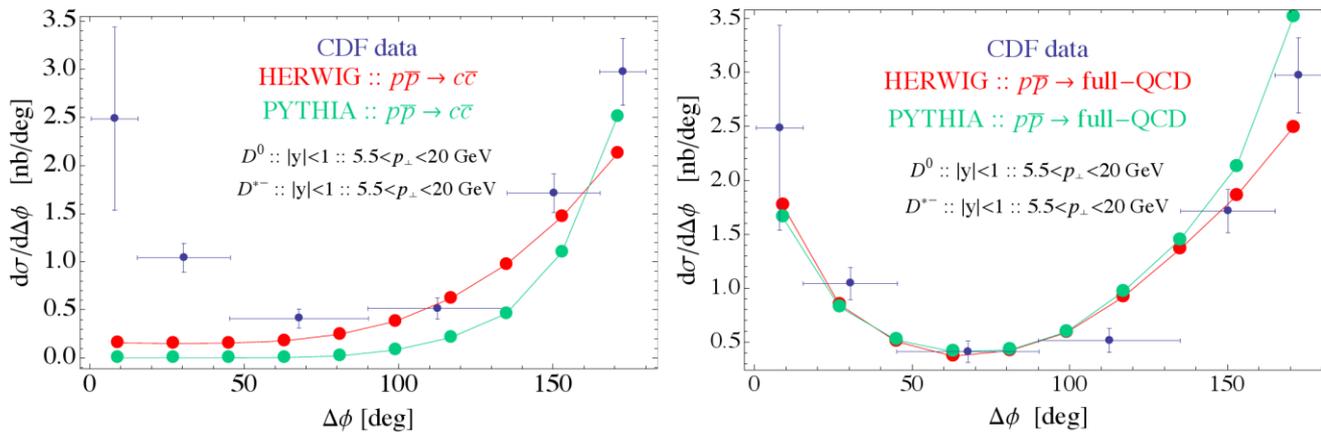
Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure

Tuning of MC

Monte Carlo simulations

A. Esposito

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:



The c-cbar run underestimate the low angles (low- k_{θ}) region!

Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

Prompt production of $X(3872)$

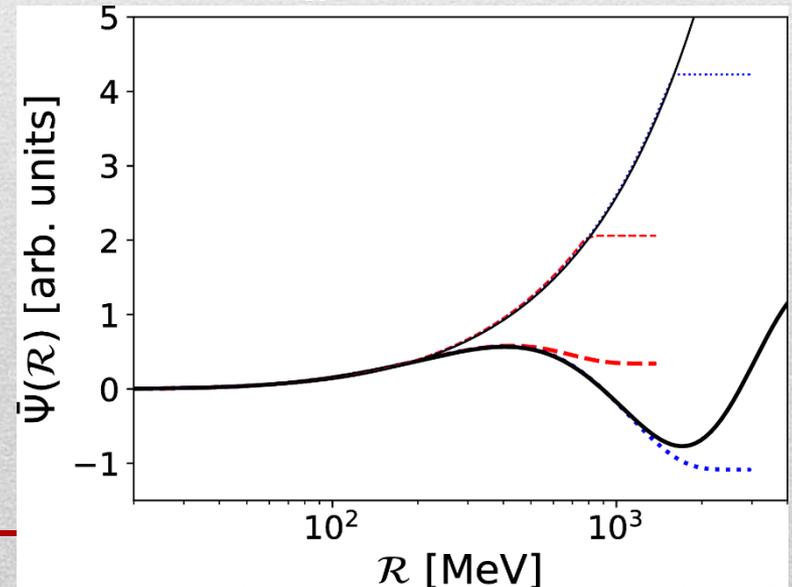
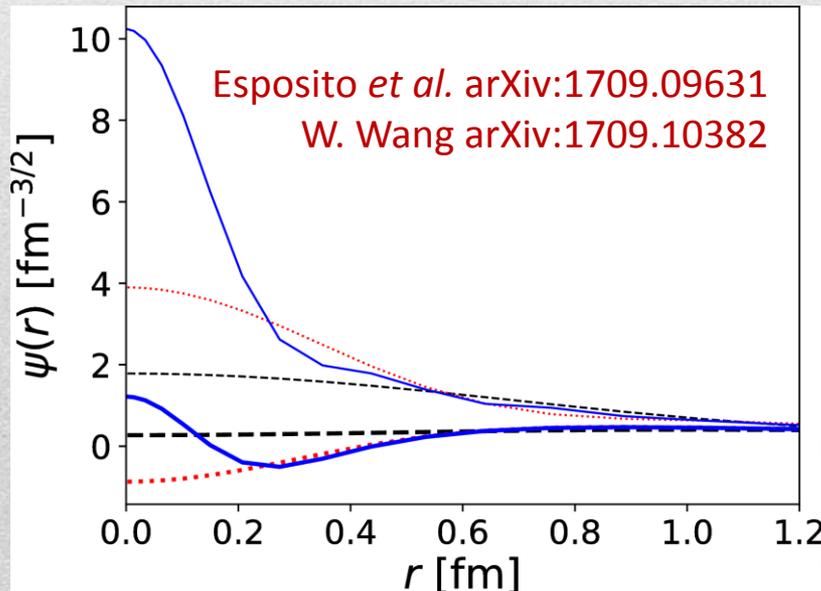
$$\begin{aligned}
 \sigma(\bar{p}p \rightarrow X) &\sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
 &\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
 &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2 \\
 &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle|^2
 \end{aligned}$$

The estimate of the k_{max} has been brought back

Albaladejo et al. arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_{\mathcal{R}} d^3\mathbf{k} \psi(\mathbf{k})$$



Prompt production of $X(3872)$

However, the integral of the wave function may not be well defined.

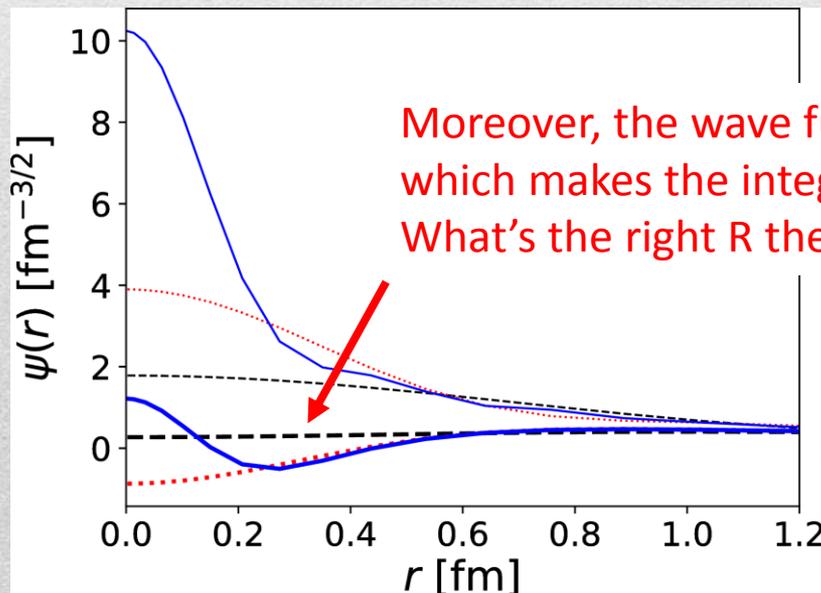
For example, if one considers the wave function in the scattering length approximation,

$$\psi(\mathbf{k}) = \frac{1}{\pi} \frac{a^{3/2}}{a^2 k^2 + 1} \quad \text{it's not integrable}$$

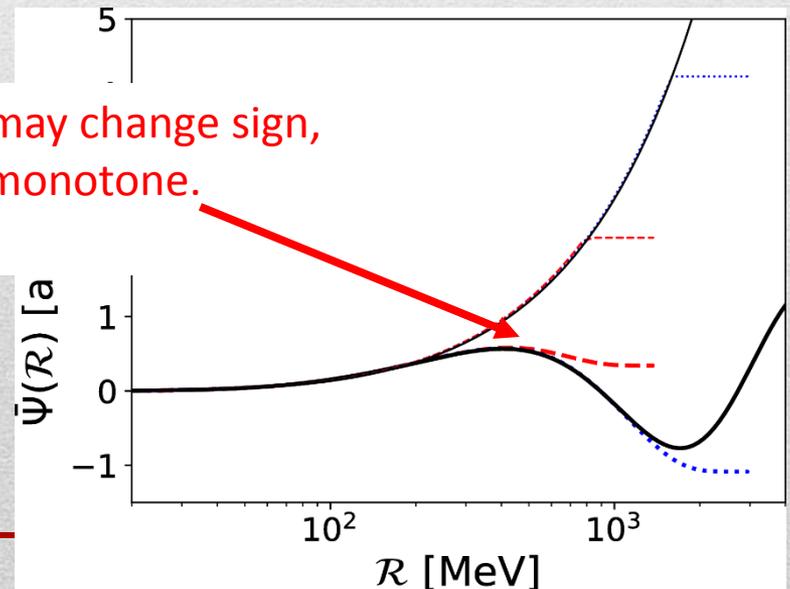
Esposito *et al.* arXiv:1709.09631

A physical value should rather be based on expectation values which involve $|\psi(\mathbf{k})|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron



Moreover, the wave function may change sign, which makes the integral nonmonotone. What's the right R then?



Note on $X(3872)$ production at hadron colliders and its molecular structure

Miguel Albaladejo,¹ Feng-Kun Guo,^{2,3} Christoph Hanhart,⁴

Ulf-G. Meißner,^{5,4} Juan Nieves,⁶ Andreas Nogga,⁴ and Zhi Yang⁵

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Universität Bonn, D-53115 Bonn, Germany

⁶*Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Uiversitat de València,*

Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain



The production of the $X(3872)$ as a hadronic molecule in hadron colliders is clarified. We show that the conclusion of Bignamini *et al.*, Phys. Rev. Lett. **103** (2009) 162001, that the production of the $X(3872)$ at high p_T implies a non-molecular structure, does not hold. In particular, using the well understood properties of the deuteron wave function as an example, we identify the relevant scales in the production process.

The argument is about the value of a nonnormalizable wave function. Any argument about where the wave function is localized must be calculated for the modulus square

A widespread argument against the interpretation of the $X(3872)$ as a hadronic molecule is its copious production at hadron colliders. Based on the inequality¹

$$\sigma(\bar{p}p \rightarrow X) \sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

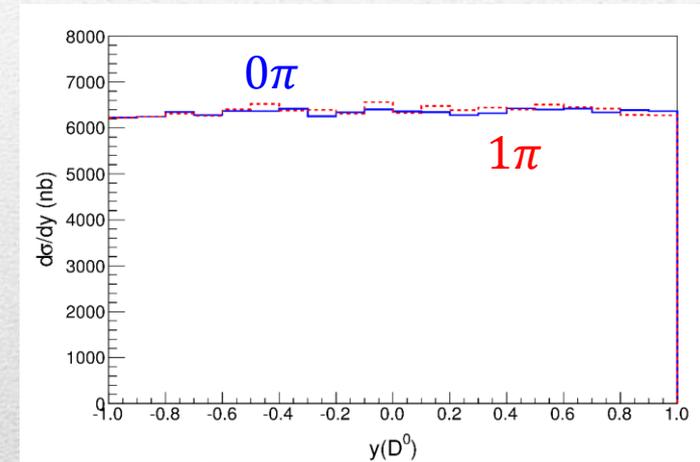
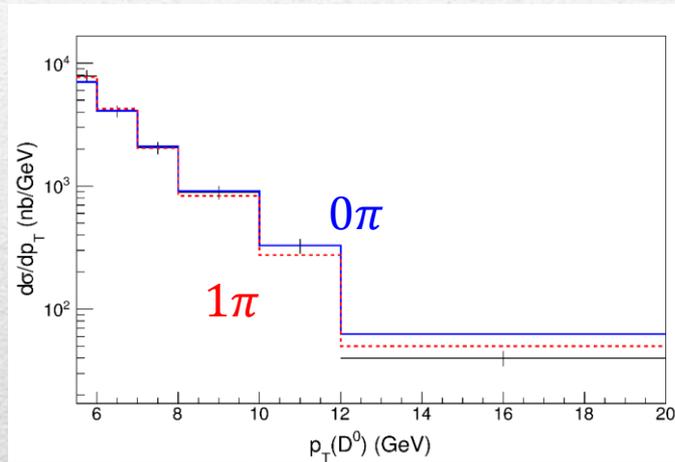
v:1709.09101v1 [hep-ph] 26 Sep 2017

Tuning pions

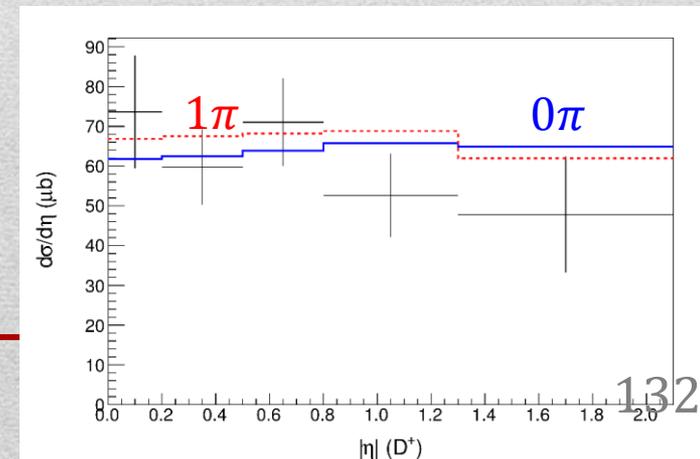
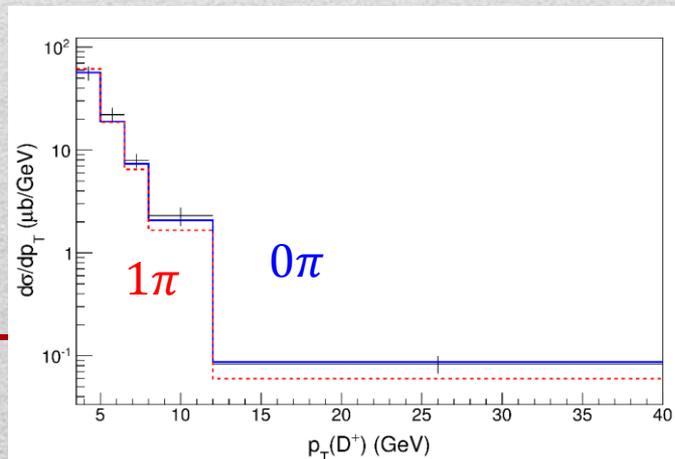
This picture could spoil existing meson distributions used to tune MC
We verify this is not the case up to an overall K factor

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

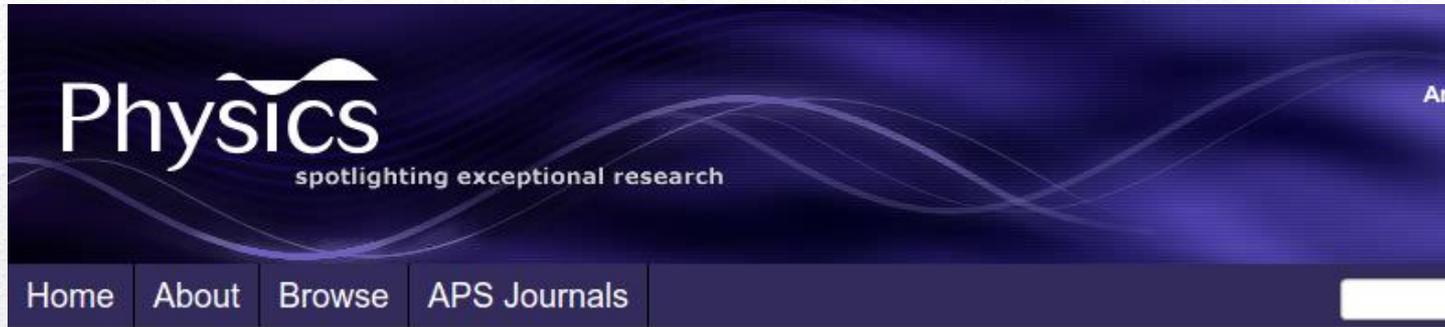
Neither at CDF...



...nor at ATLAS



$$Z_c(3900)$$



Notes from the Editors: Highlights of the Year

Published December 30, 2013 | *Physics* 6, 139 (2013) | DOI: 10.1103/Physics.6.139

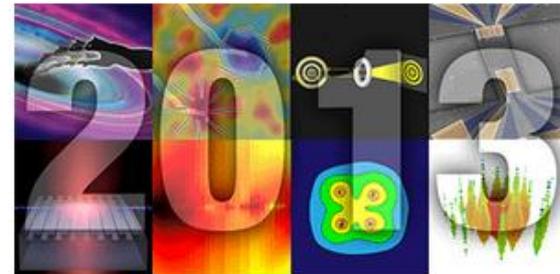
***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

— Matteo Rini and Jessica Thomas

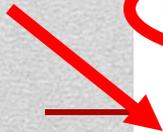
Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a **mysterious particle** that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the “tetraquark” interpretation may be gaining traction: BESIII has since **seen** a series of other particles that appear to contain four quarks.



Images from popular *Physics* stories in 2013.

mysterious particle

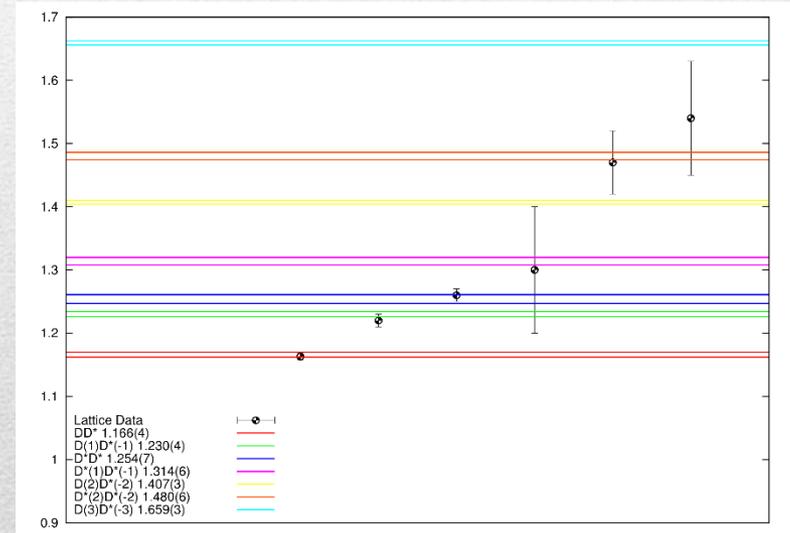
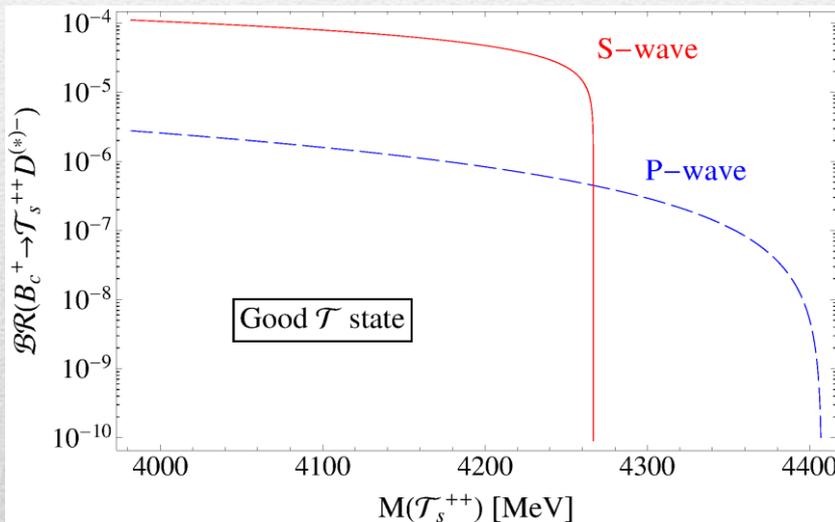


Doubly charmed states

For example, we proposed to look for **doubly charmed states**, which in tetraquark model are $[cc]_{S=1}[\bar{q}\bar{q}]_{S=0,1}$

These states could be observed in B_c decays @LHC and sought on the lattice

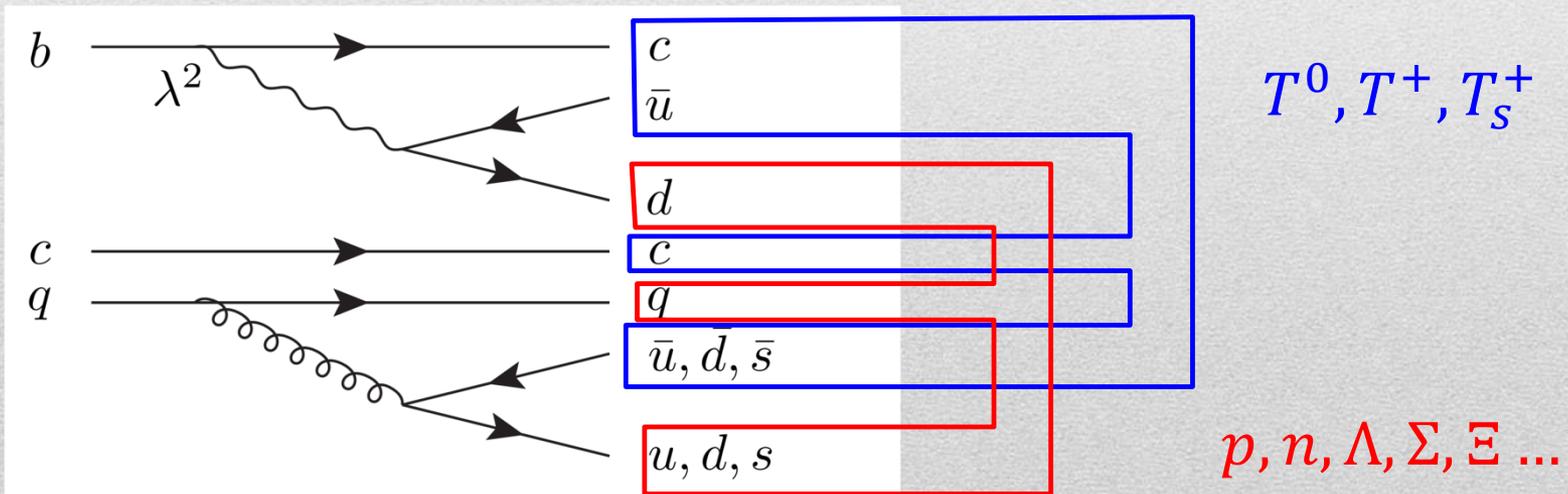
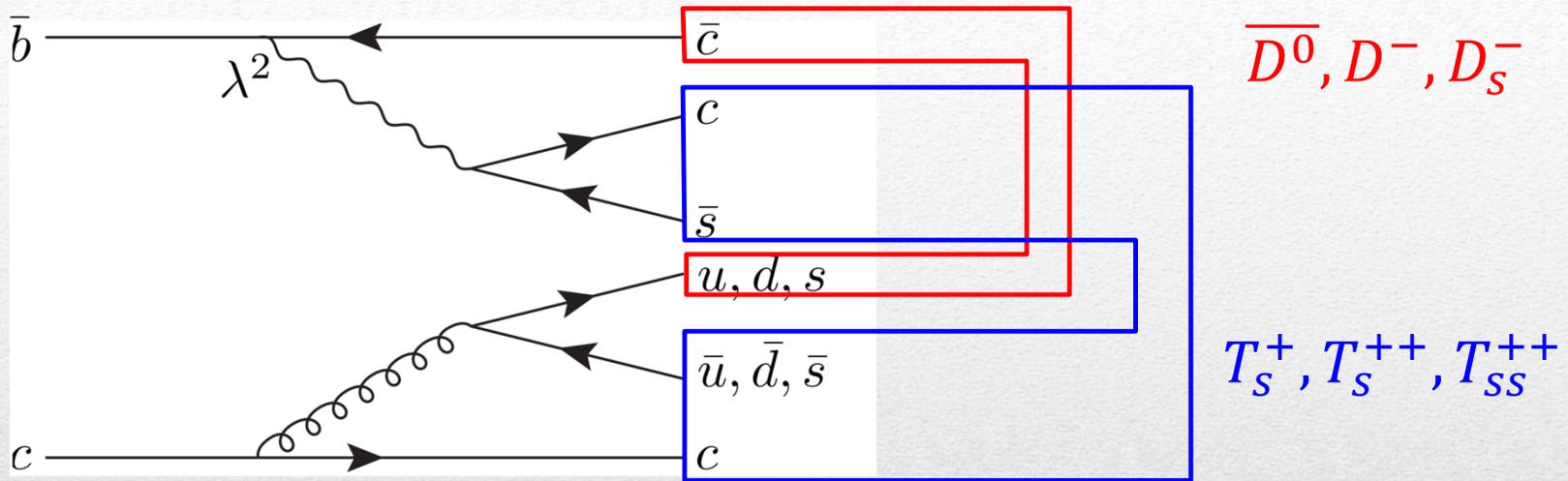
Esposito, Papinutto, AP, Polosa, Tantalò, PRD88 (2013) 054029



Preliminary results on spectrum for $m_\pi = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

Guerrieri, Papinutto, AP, Polosa, Tantalò, PoS LATTICE2014 106

T states production



Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model



$$\sigma(p\bar{p} \rightarrow X(3872)) \sim \int d^3k |\langle X | D\bar{D}^* \rangle \langle D\bar{D}^* | p\bar{p} \rangle|^2 < \int_{k < k_{max}} d^3k |\langle D\bar{D}^* | p\bar{p} \rangle|^2$$

This should provide an upper bound for the cross section

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Kadastic, Raidan, Strumia PLB683 (2010) 248

Estimating k_{max}

The binding energy is $E_B \approx -0.16 \pm 0.31$ MeV: **very small!**

In a simple square well model this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

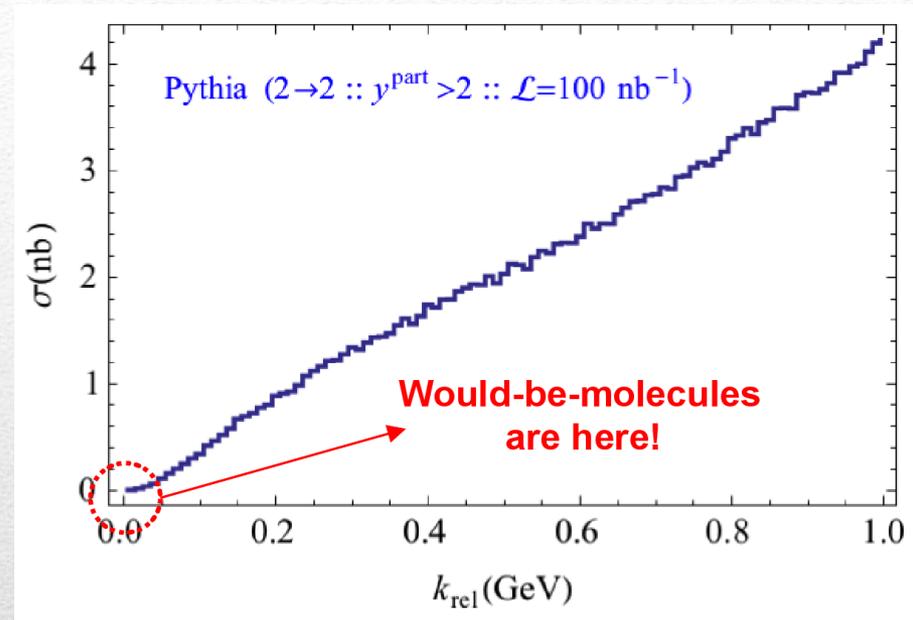
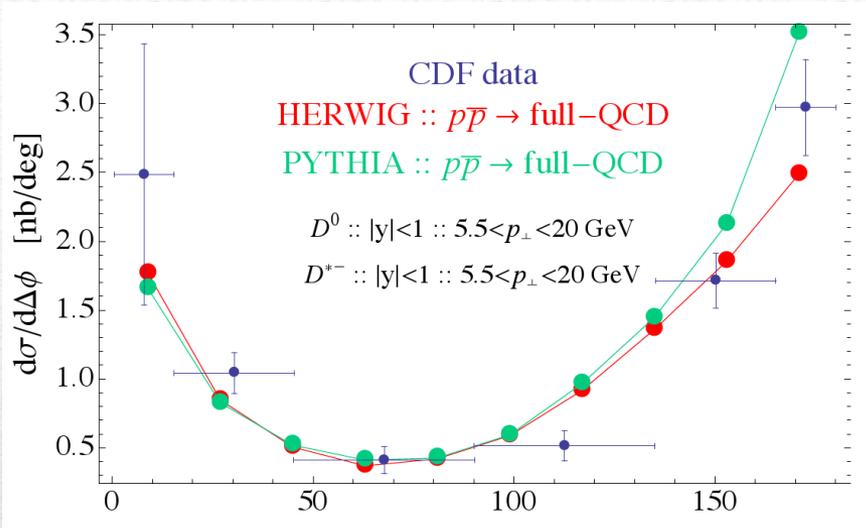
$$\left(\begin{array}{l} \text{binding energy reported in Kamal Seth's talk is } E_B \approx -0.013 \pm 0.192 \text{ MeV:} \\ \sqrt{\langle k^2 \rangle} \approx 30 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 30 \text{ fm} \end{array} \right)$$

to compare with deuteron: $E_B = -2.2$ MeV

$$\sqrt{\langle k^2 \rangle} \approx 80 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 4 \text{ fm}$$

We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50$ MeV, some other choices are commented later

2009 results

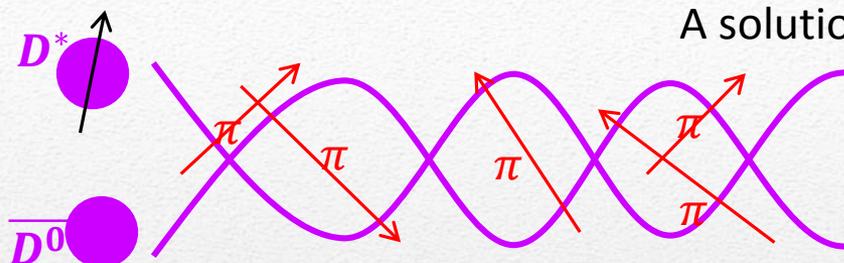


We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi} (p\bar{p} \rightarrow D^0 D^{*-})$

We get $\sigma(p\bar{p} \rightarrow DD^* | k < k_{max}) \approx 0.1 \text{ nb}$ @ $\sqrt{s} = 1.96 \text{ TeV}$

Experimentally $\sigma(p\bar{p} \rightarrow X(3872)) \approx 30 - 70 \text{ nb}!!!$

Estimating k_{max}



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi \sim 700$ MeV

$$\sigma(p\bar{p} \rightarrow DD^* | k < k_{max}) \approx 230 \text{ nb}$$

Artoisenet and Braaten, PRD81, 114018

However, the applicability of Watson theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

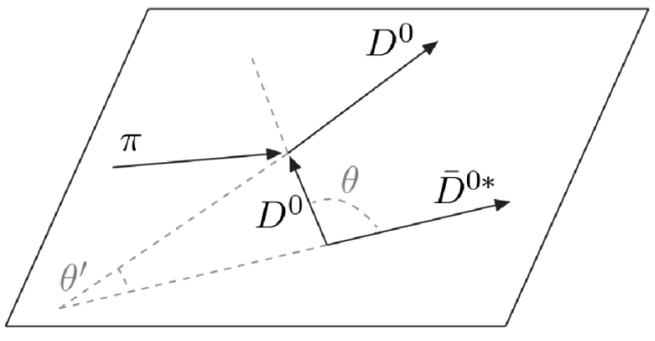
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354
use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,
limits on predictive power

A new mechanism?

In a more **billiard-like** point of view, the comoving pions can **elastically interact** with $D(D^*)$, and **slow down** the pairs DD^*

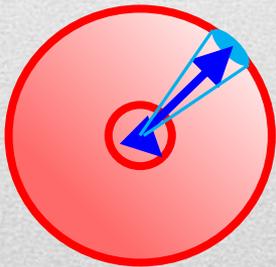
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003



The mechanism also implies: D mesons actually **“pushed”** **inside** the potential well (the **classical 3-body problem!**)

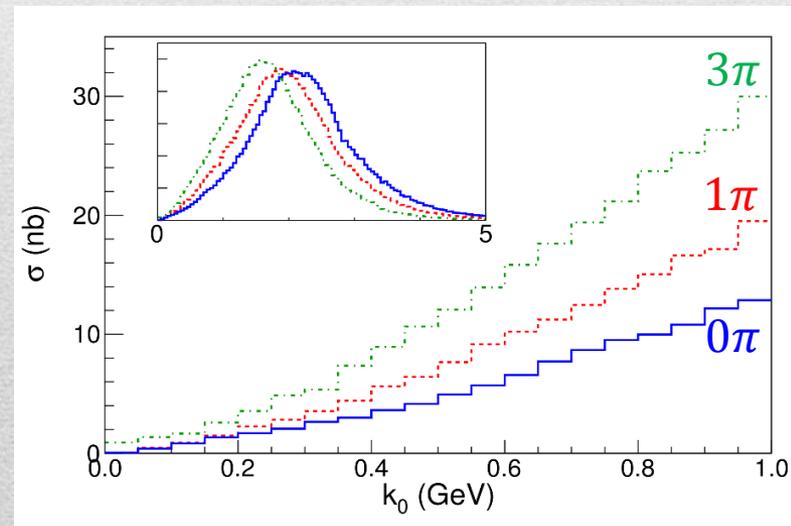
$X(3872)$ is a **real, negative energy bound state** (stable)

It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100$ keV



By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart

We get $\sigma(p\bar{p} \rightarrow X(3872)) \sim 5$ nb, **still not sufficient** to explain all the experimental cross section



Hybridized tetraquarks – Selection rules

- Consider the **down quark part of the $X(3872)$** in the diquarkonium picture:

$$\Psi_{\mathbf{d}} = X_{\mathbf{d}} = [cd]_0[\bar{c}\bar{d}]_1 + [cd]_1[\bar{c}\bar{d}]_0 \sim (D^{*-}D^+ - D^{*+}D^-) + i(\psi \times \rho^0 - \psi \times \omega^0)$$

↑
Fierz rearrangement

- The closest threshold from below is $\Psi_m \sim \bar{D}^0 D^{*0} \longrightarrow \Psi_{\mathbf{d}} \perp \Psi_m$ ✓

- But if we consider the **up quark part of the $X(3872)$** :

$$\Psi_{\mathbf{d}} = X_{\mathbf{u}} = [cu]_0[\bar{c}\bar{u}]_1 + [cu]_1[\bar{c}\bar{u}]_0 \sim (\bar{D}^{*0}D^0 - D^{*0}\bar{D}^0) - i(\psi \times \rho^0 + \psi \times \omega^0)$$

- But then $\longrightarrow \Psi_{\mathbf{d}} \not\perp \Psi_m$ ✗

- Only $X_{\mathbf{d}}$ is produced via this mechanism
 - isospin violation
 - no hyperfine neutral doublet

- X_b (A) Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)$ MeV
 (B) The closest orthogonal threshold is $M(B^0 B^{*0}) = (10604.4 \pm 0.3)$ MeV
 (C) This could either be **above threshold (very narrow state)** or **below (no state at all)**
 (D) Experimentally the diquark model overpredicts the mass of the X :

$$M(Z_c) - M(X) \simeq 32 \text{ MeV}$$

- (E) We favor the below threshold scenario \longrightarrow no X_b should be seen

A. Esposito

Production of hybridized tetraquarks

Going back to $pp(\bar{p})$ collisions, we can imagine hadronization to produce a state

$$|\psi\rangle = \alpha|[qQ][\bar{q}\bar{Q}]\rangle_c + \beta|(\bar{q}q)(\bar{Q}Q)\rangle_o + \gamma|(\bar{q}Q)(\bar{Q}q)\rangle_o$$

If $\beta, \gamma \gg \alpha$, an initial tetraquark state is not likely to be produced
The open channel mesons fly apart
(see MC simulations)



If hybridization mechanism is at work, an open state can resonate in a closed one

α expected to be small in Large N limit, [Maiani, Polosa, Riquer JHEP 1606, 160](#)

No prompt production without hybridization mechanism!

Note that only the $X(3872)$ has been observed promptly so far...

...and a narrow $X(4140)$ not compatible with the LHCb one → **needs confirmation**