Modeling XYZ states at JPAC

Alessandro Pilloni

Kielce, Jan Kochanowski University, October 19th, 2016

Outline

- Joint Physics Analysis Center
- The exotic landscape: XYZ
- Compact tetraquarks
- Other models
- Production of exotics at LHC
- Hybridized Tetraquarks
- Conclusions

Joint Physics Analysis Center

- JPAC was funded to support the extraction of physics results from analysis of experimental data from JLab12 and other accelerator laboratories
- This is achieved through work on theoretical, phenomenological and data analysis tools
- JPAC aims to facilitate close collaboration between theorists, phenomenologists, and experimentalists worldwide
- It is engaged in education of further generation of hadron physics practitioners

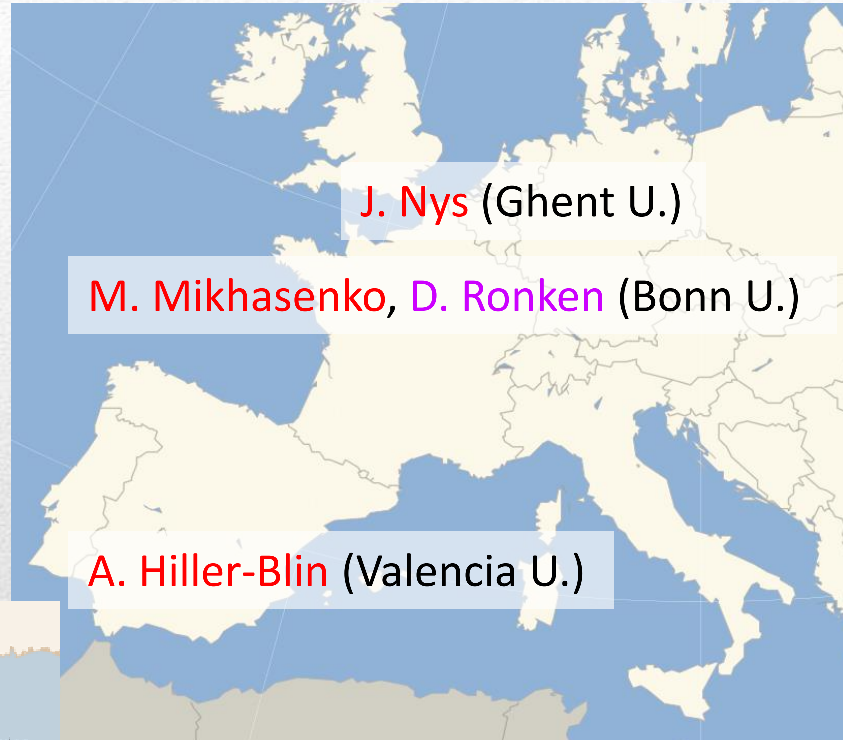
Joint Physics Analysis Center

E. Alexeev, A. Jackura, I. Lorenz,
V. Mathieu, G. Fox, T. Londergan,
E. Passemar (IU), A. Szczepaniak (IU/JLab)

B. Hu, M. Döring, R. Workman (GWU)

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

C. Fernandez-Ramirez (UNAM)



J. Nys (Ghent U.)

M. Mikhasenko, D. Ronken (Bonn U.)

A. Hiller-Blin (Valencia U.)

Former members:
L. Dai (Bonn), I. Danilkin (Mainz),
P. Guo (Cal. State), M. Shi (Peking)

Students, Postdocs, Faculties

Production

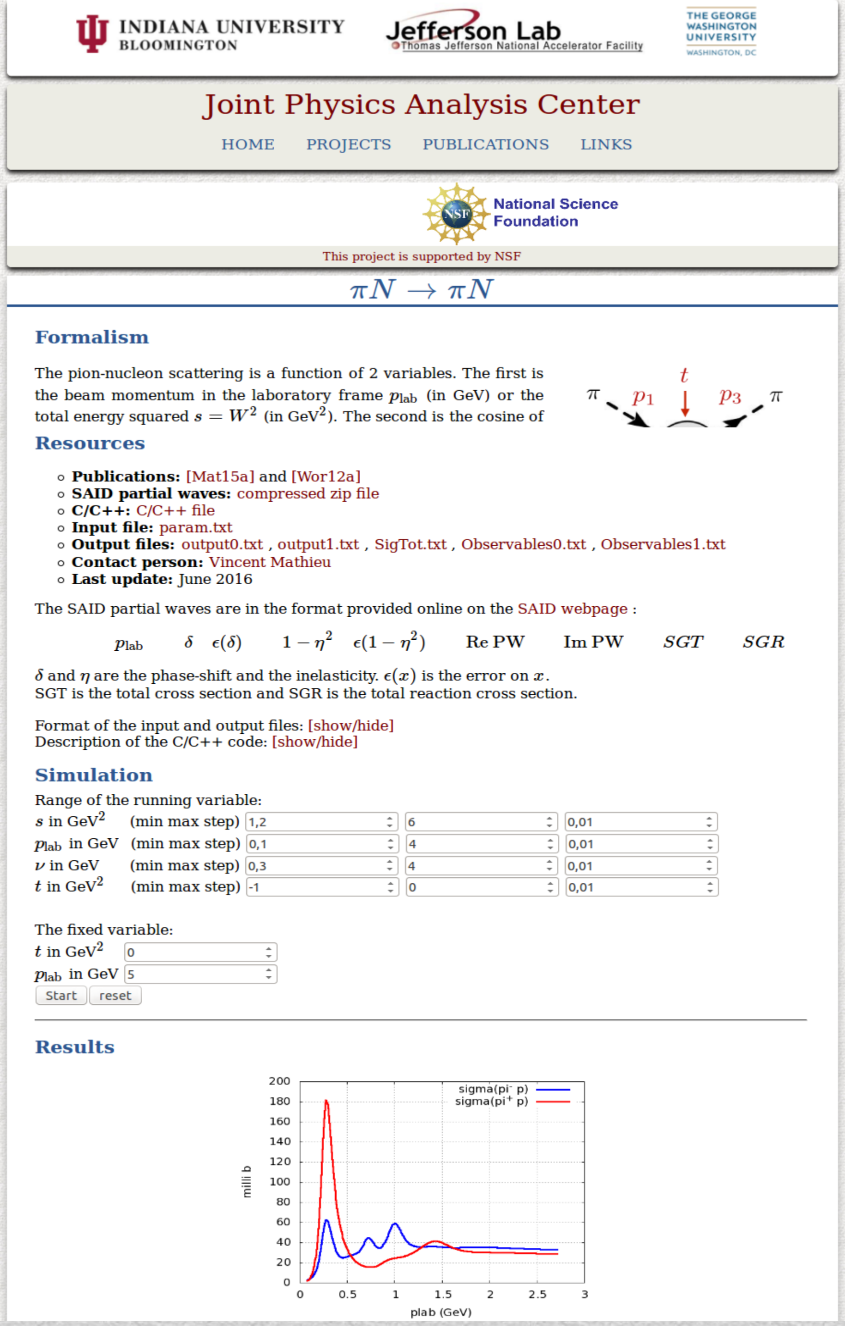
- $>$ 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.)
- $\sim$120 Invited Talks and Seminars
- $O(10)$ ongoing analyses
- Summer School on Reaction Theory (IU, 2015)
- Workshop “Future Directions in Hadron Spectroscopy” (JLab, 2014)

$P_c(4450)$	A. Blin *et al.*,	PRD94, 034002
$\Lambda(1405)$	C. Fernandez-Ramirez *et al.*,	PRD93, 074015
$K\,N \to K\,N$	C. Fernandez-Ramirez *et al.*,	PRD93, 034029
$\pi\,N \to \pi\,N$	V. Mathieu *et al.*,	PRD92, 074004
$\gamma\,p \to \pi^0\,p$	V. Mathieu *et al.*,	PRD92, 074013
$\eta \to \pi^+\,\pi^-\,\pi^0$	P. Guo *et al.*,	PRD92, 054016; arXiv:1608.01447
$\omega,\phi \to \pi^+\,\pi^-\,\pi^0$	I. Danilkin *et al.*,	PRD91, 094029
$\gamma\,p \to K^+\,K^-\,p$	M. Shi *et al.*,	PRD91, 034007

Data → Amplitude analysis (JPAC) → Spectrum and properties

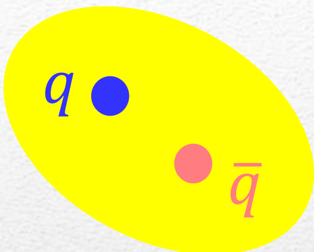
Interactive tools

- 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/

Dictionary – Quark model



L = orbital angular momentum
S = spin $q + \bar{q}$

J = total angular momentum
= exp. measured spin

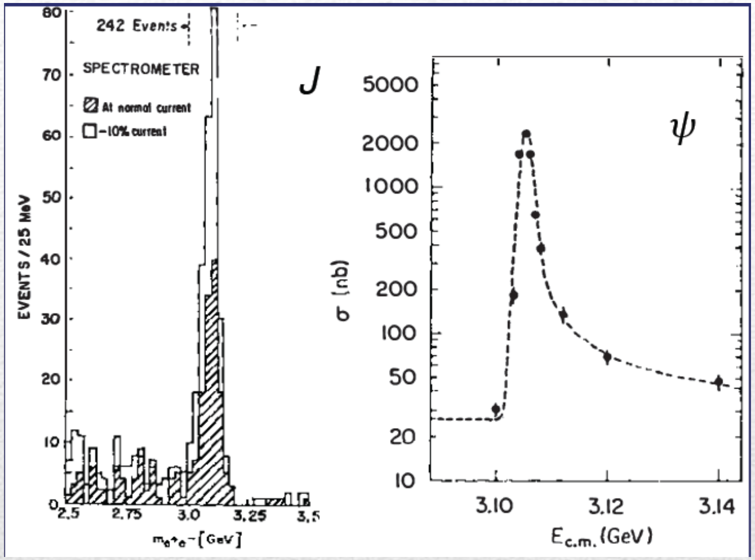
I = isospin = 0 for quarkonia

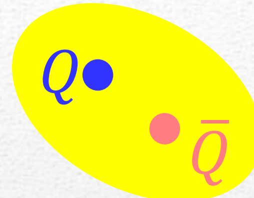
$$L - S \leq J \leq L + S$$
$$P = (-1)^{L+1}, C = (-1)^{L+S}$$
$$G = (-1)^{L+S+I}$$

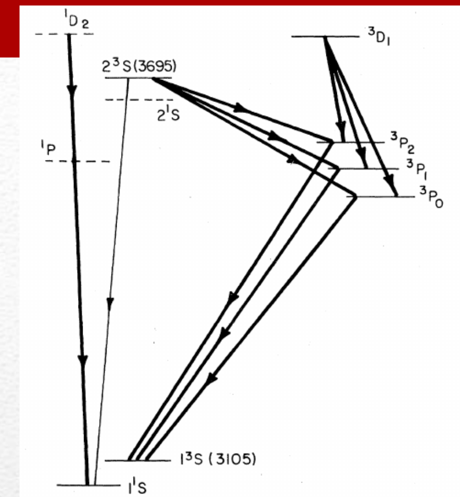
J^{PC}	L	S	Charmonium ($c\bar{c}$)	Bottomonium ($b\bar{b}$)
0^{-+}	0 (S-wave)	0	$\eta_c(nS)$	$\eta_b(nS)$
1^{--}		1	$\psi(nS)$	$\Upsilon(nS)$
1^{+-}	1 (P-wave)	0	$h_c(nP)$	$h_b(nP)$
0^{++}		1	$\chi_{c0}(nP)$	$\chi_{b0}(nP)$
1^{++}		1	$\chi_{c1}(nP)$	$\chi_{b1}(nP)$
2^{++}		1	$\chi_{c2}(nP)$	$\chi_{b2}(nP)$

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

Quarkonium orthodoxy







$\alpha_s(M_Q) \sim 0.3$

(perturbative regime)

OZI-rule, QCD multipole

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

Potential models

(meaningful when $M_Q \to \infty$)

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

(Cornell potential)

Solve NR Schrödinger eq. → spectrum

Effective theories

(HQET, NRQCD, pNRQCD...)

Integrate out heavy DOF

↓

(spectrum), decay & production rates

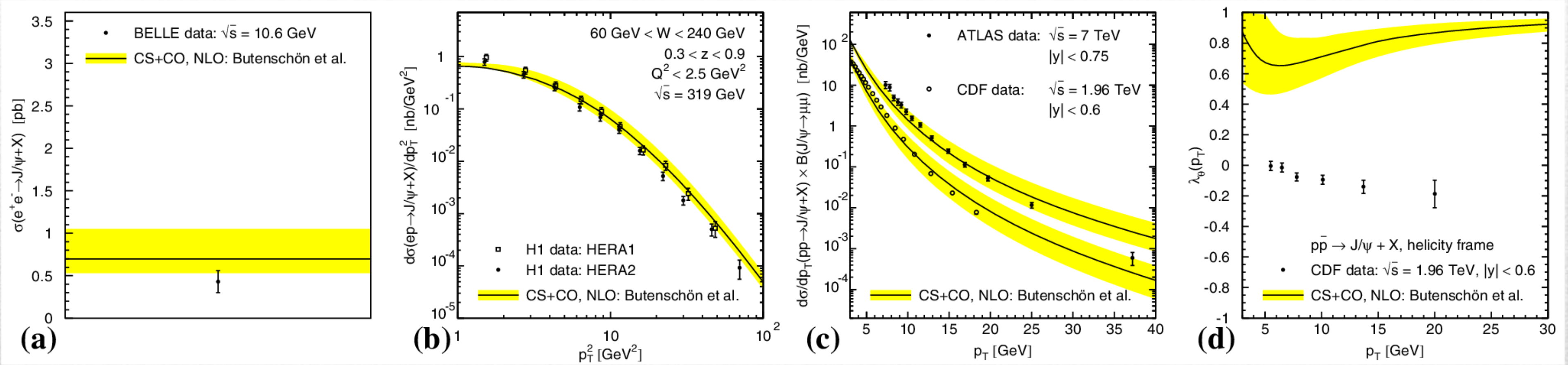
Multiscale system

Systematically integrate out the heavy scale, $m_Q \gg \Lambda_{QCD}$

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

Full QCD → NRQCD → pNRQCD

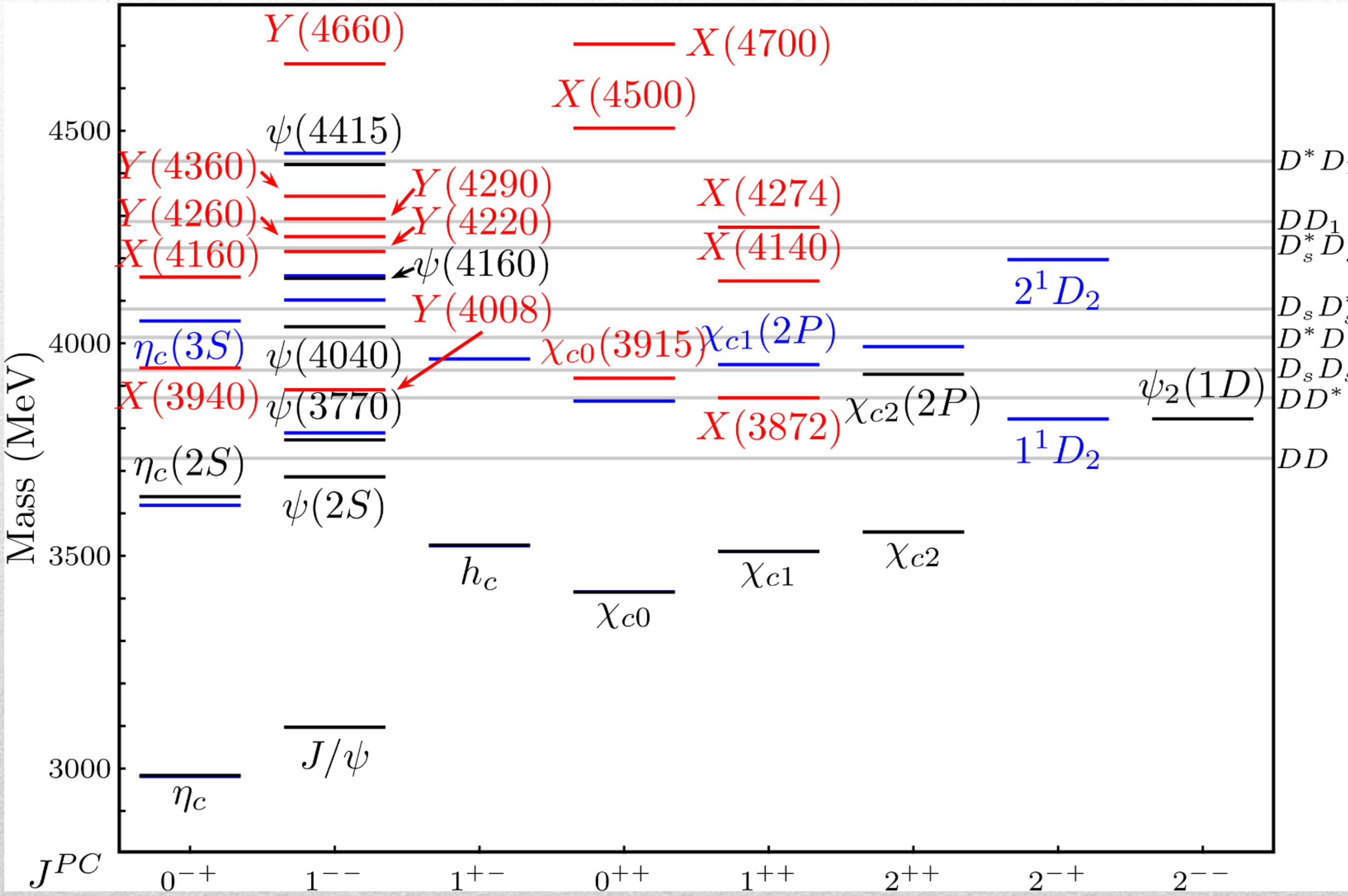
$m_b \sim 5\text{ GeV}, m_c \sim 1.5\text{ GeV}$
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$



Factorization (to be proved) of universal LDMEs

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

Exotic landscape

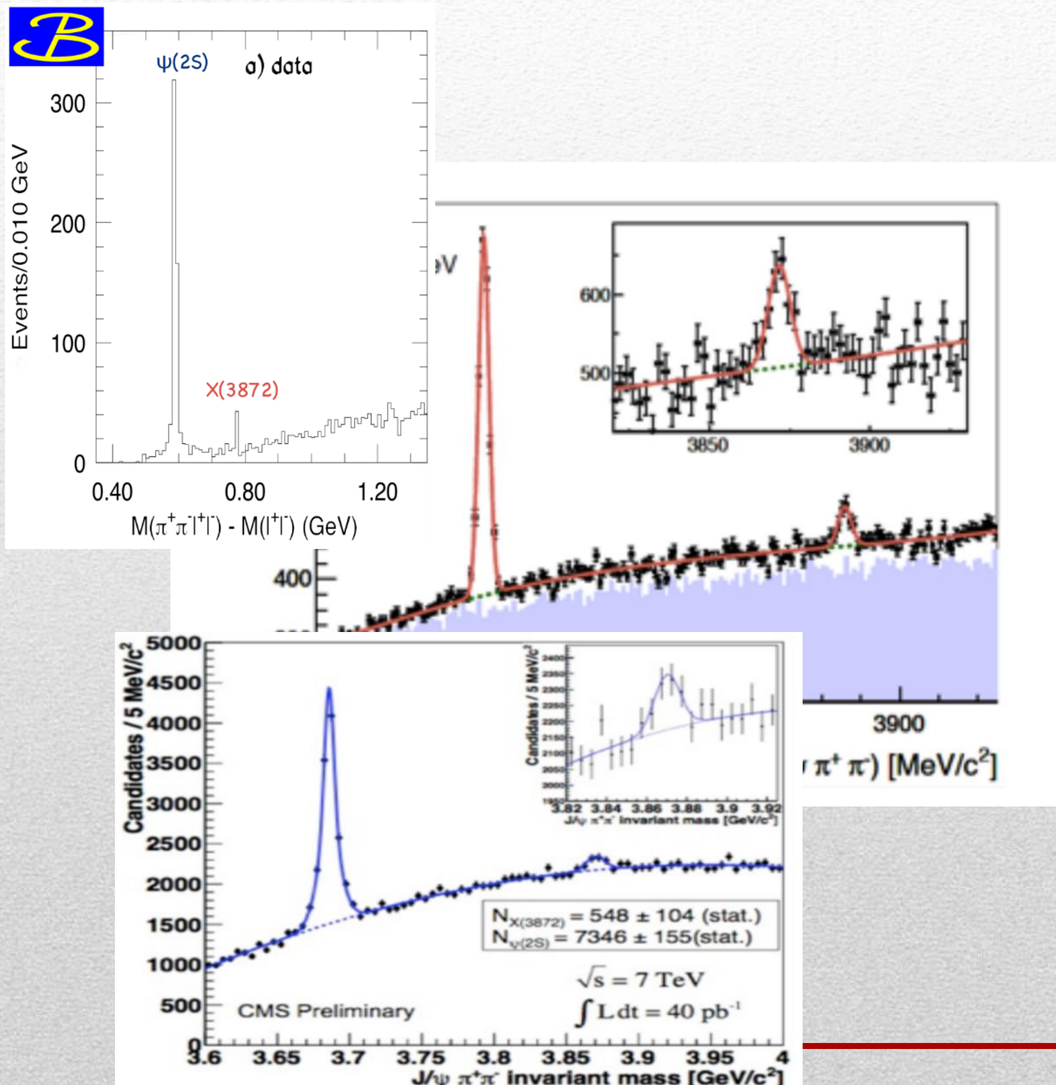


A host of unexpected resonances have appeared

decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

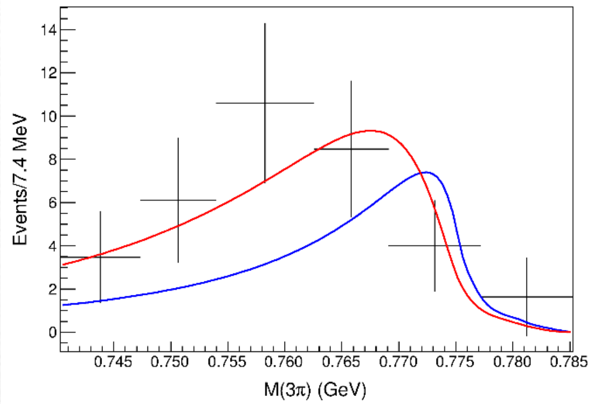
$X(3872)$



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

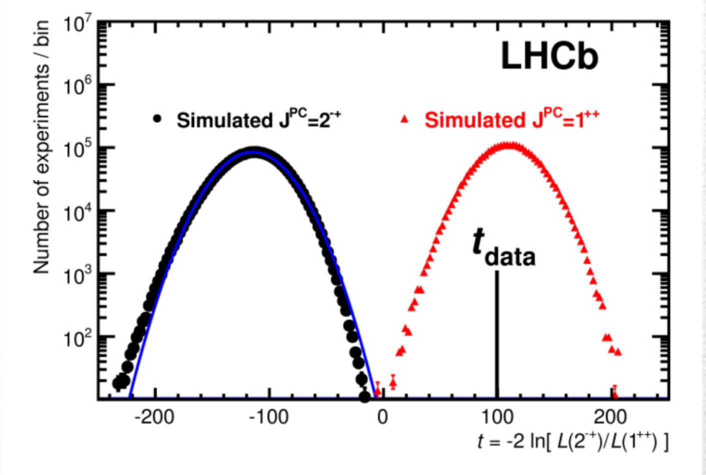
$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90%

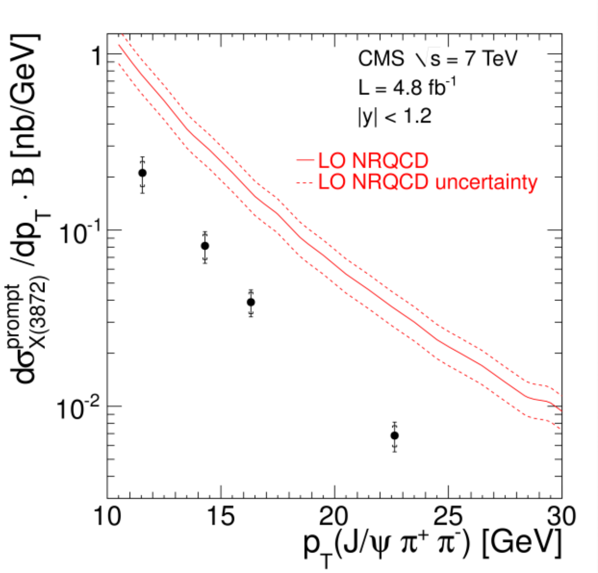
$X(3872)$



BaBar data in $X \to J/\psi\,\omega$ favor $J^{PC} = 2^{-+}$, but LHCb in $X \to J/\psi\,\rho$ measures 1^{++} at 8σ

Faccini, AP, Piccinini, Polosa
PRD 86, 054012
LHCb, PRL 110, 222001





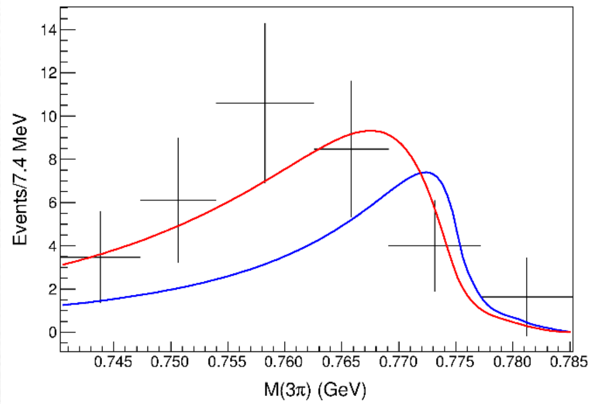
Large prompt production at hadron colliders

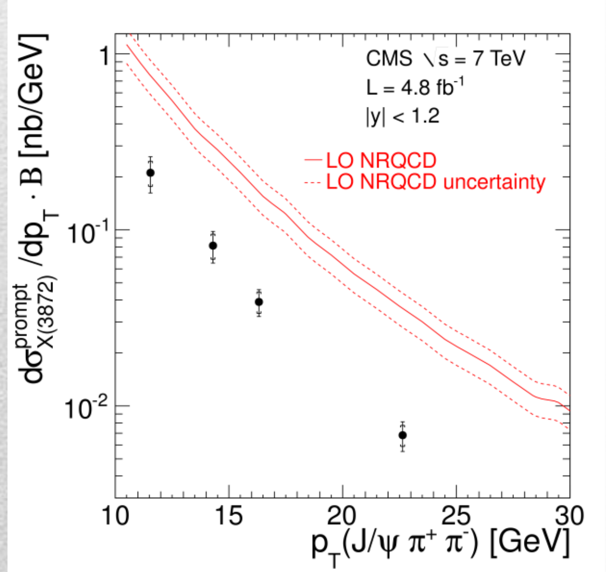
$$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$$

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

CMS, JHEP 1304, 154

$X(3872)$

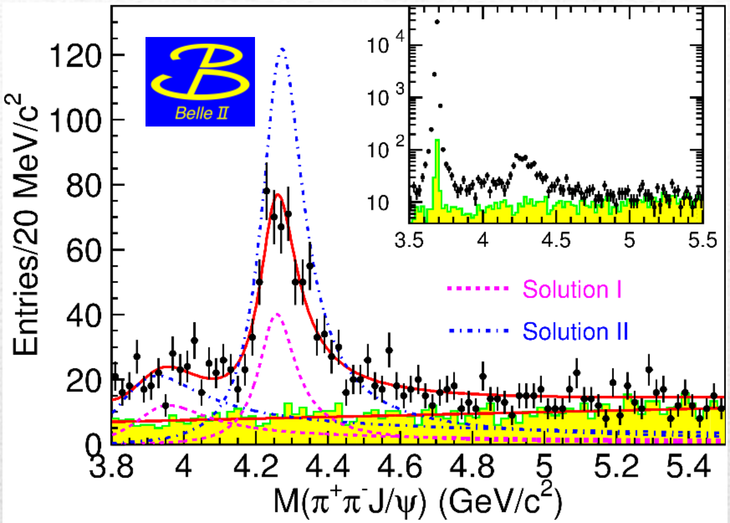




B decay mode	X decay mode	product branching fraction $(\times 10^5)$		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	($BABAR$[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	$BABAR$[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	($BABAR$[26] Belle[25])		
		$0.35 \pm 0.19 \pm 0.04$	$BABAR$[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle[25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle[106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle[106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	$BABAR$[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	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle[32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	($BABAR$[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	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	($BABAR$[38] Belle[37])		
		$22 \pm 10 \pm 4$	$BABAR$[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	($BABAR$[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]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle[34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	$BABAR$[35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle[34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	$BABAR$[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]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb[36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	$BABAR$[35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle[34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle[23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	$BABAR$[112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Vector Y states

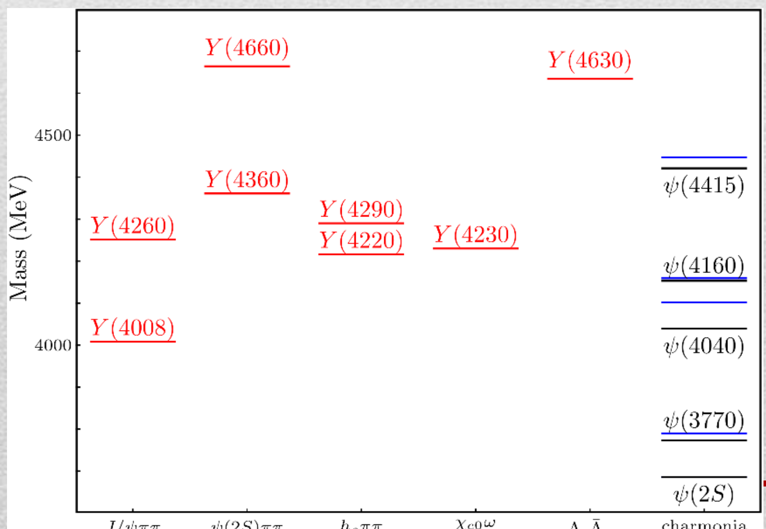
Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR analyses (and nowhere else!)

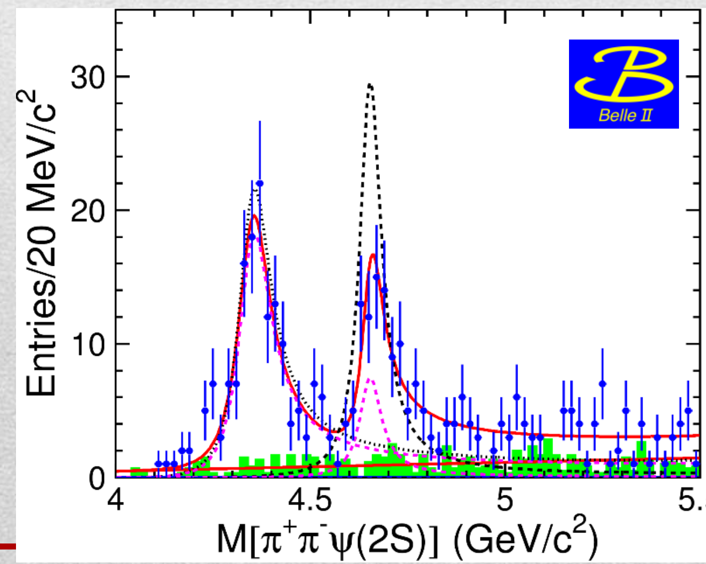


Seen in few final states,
mostly $J/\psi\,\pi\pi$ and $\psi(2S)\,\pi\pi$

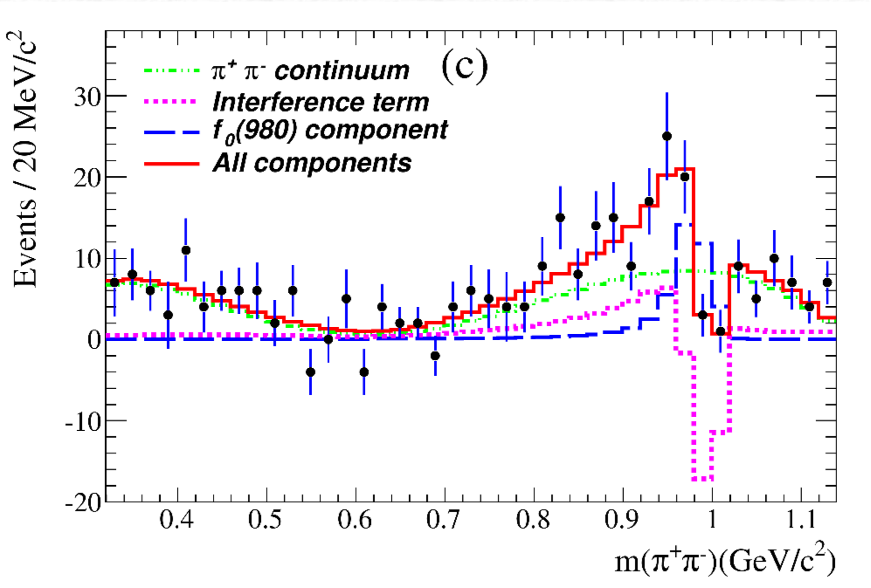
Not seen decaying into open charm pairs,
to compare with

$$\frac{B(\psi(3770) \to D\bar{D})}{B(\psi(3770) \to J/\psi\pi\pi)} > 480$$

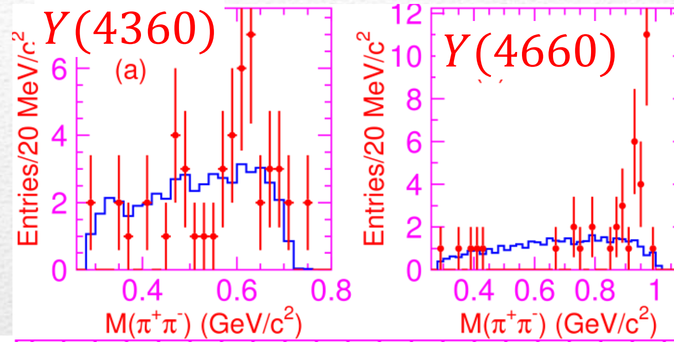


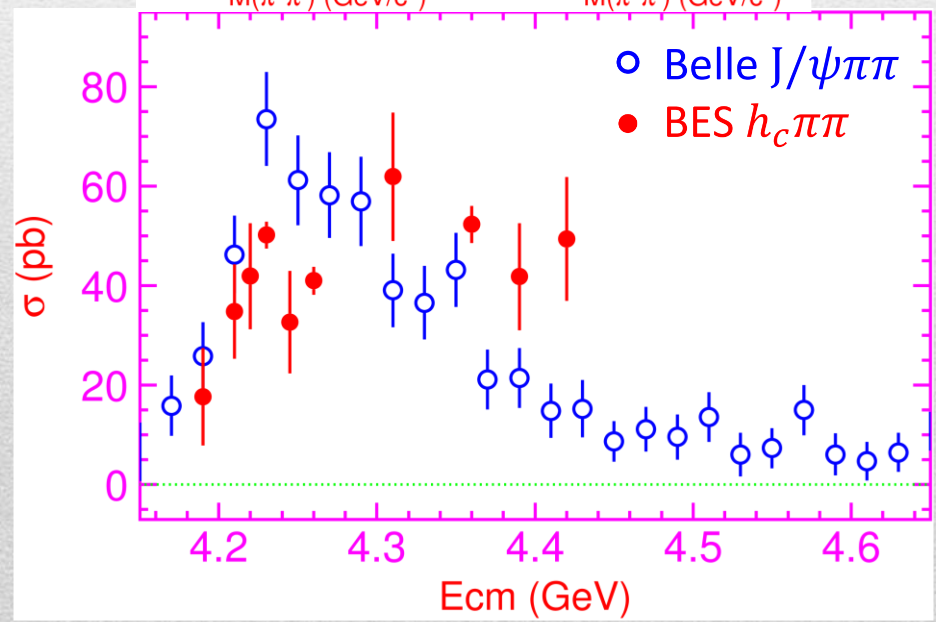


Vector Y states



A component $Y(4260) \to J/\psi\ f_0(980)$ might explain why $Y(4260) \to \psi(2S)\pi\pi$

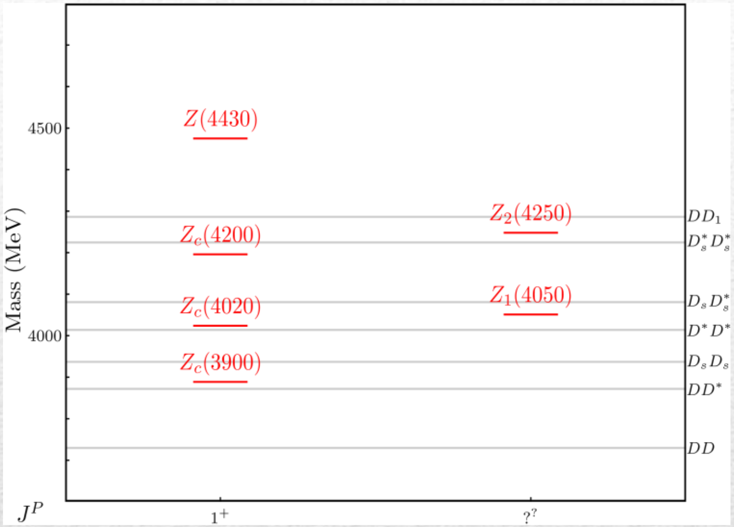




The lineshape in $h_c\ \pi\pi$ looks pretty different
Different states contributing?

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

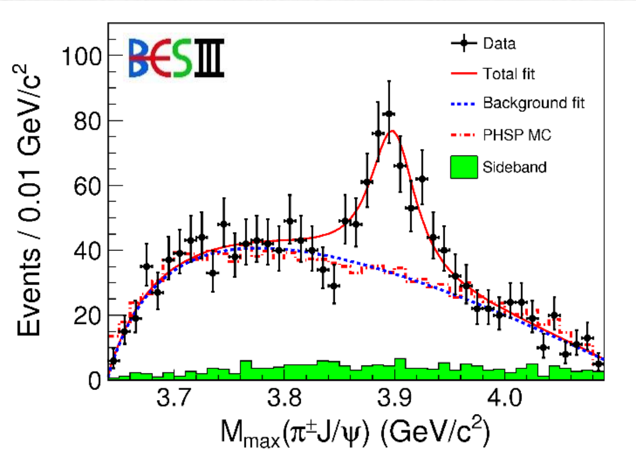
Charged quarkonium-like resonances have been found, **4q needed**

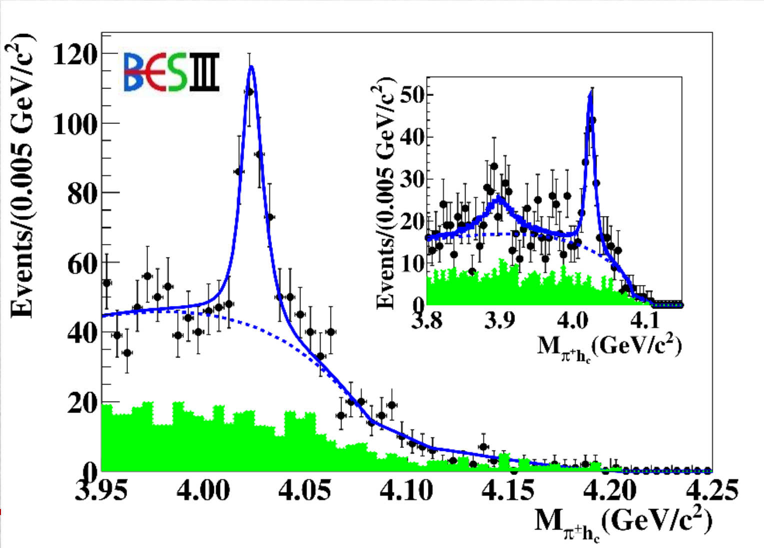


Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

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

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





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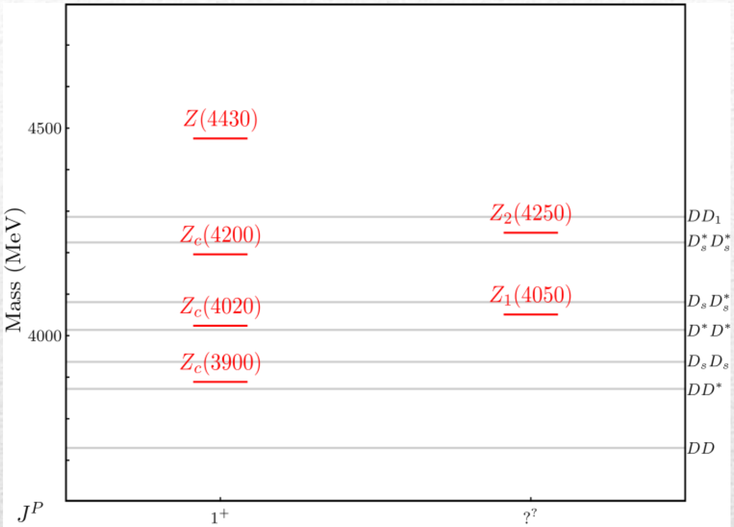

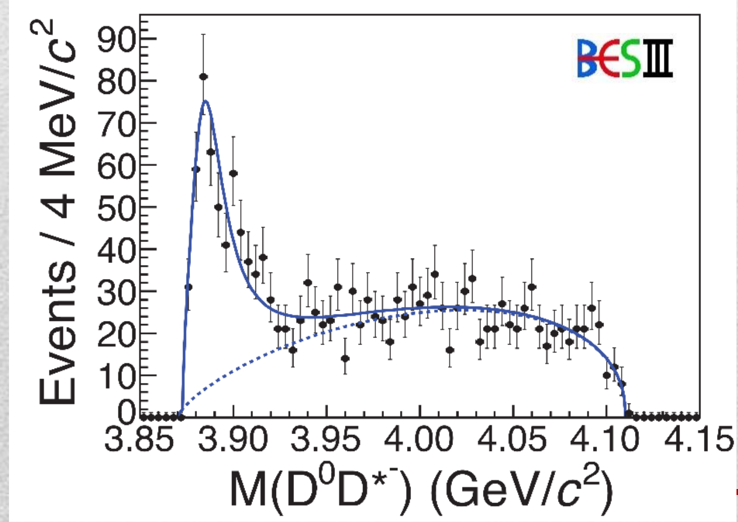

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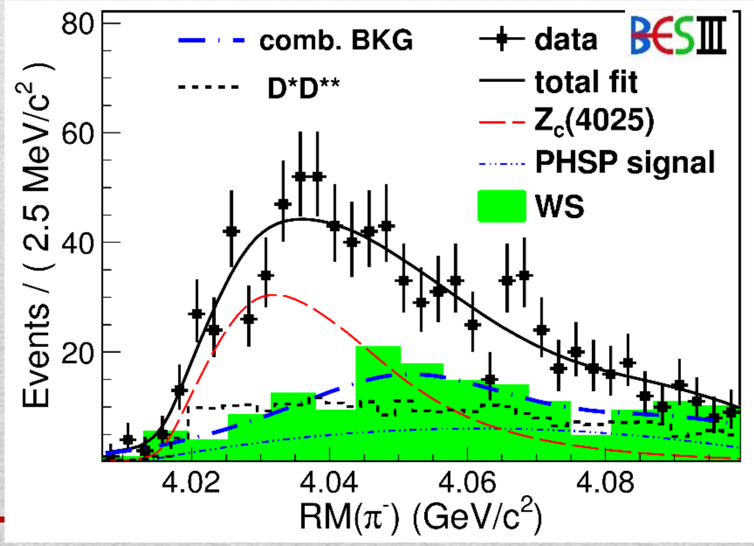
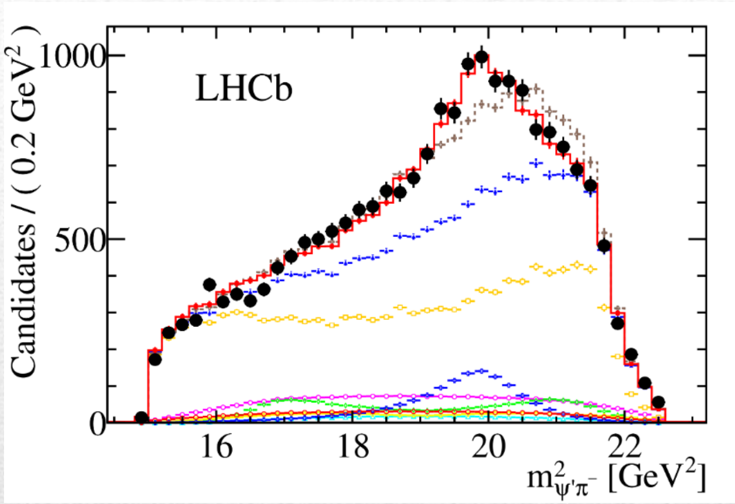
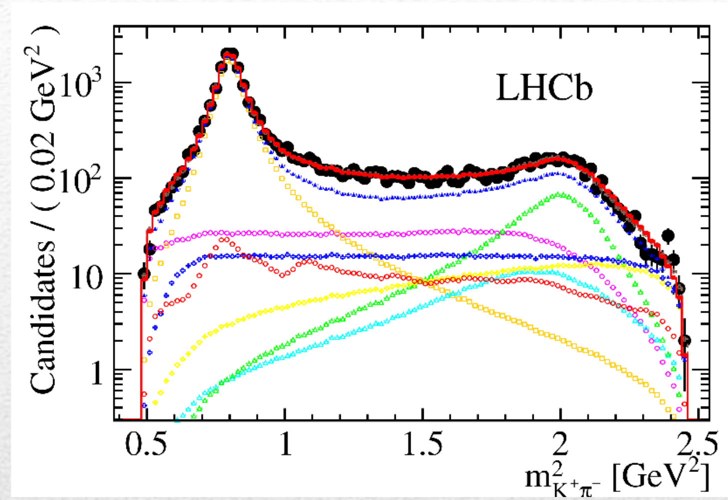


Charged Z states: $Z(4430)$

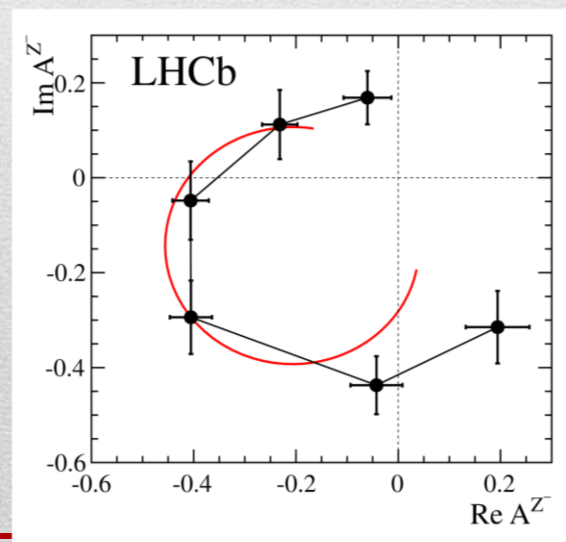




$Z(4430)^+ \to \psi(2S)\,\pi^+$
$I^G J^{PC} = 1^+ 1^{+-}$

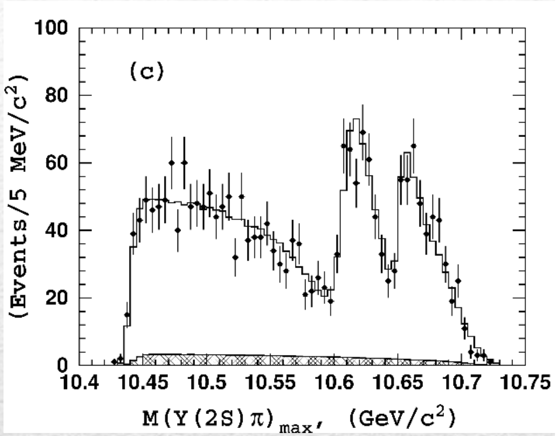
$M = 4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma = 172 \pm 13^{+37}_{-34}$MeV

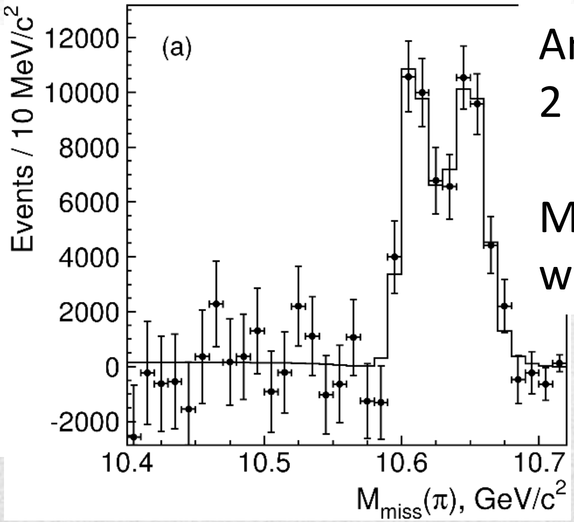
Far from open charm thresholds



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

Charged Z states: $Z_b(106010), Z_b'(10650)$





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

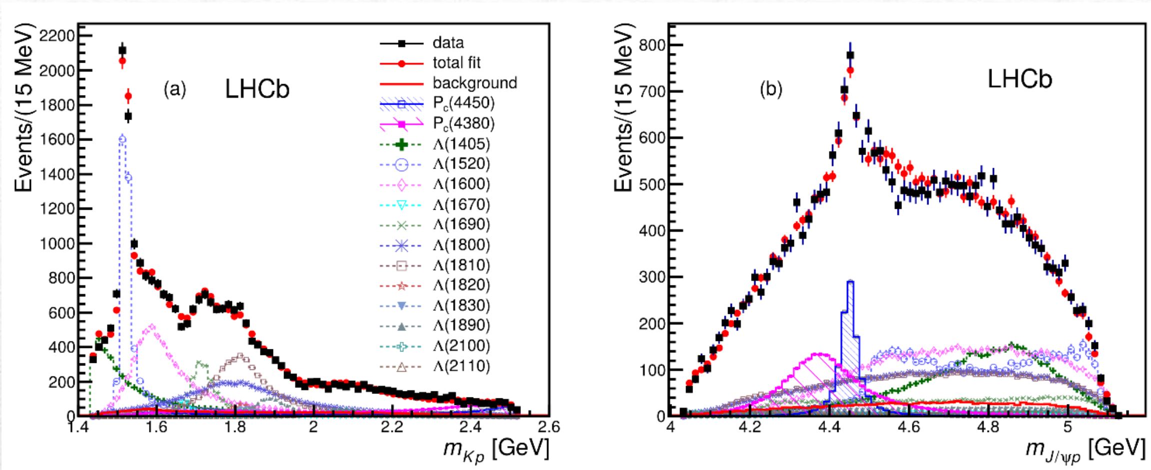
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$
which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

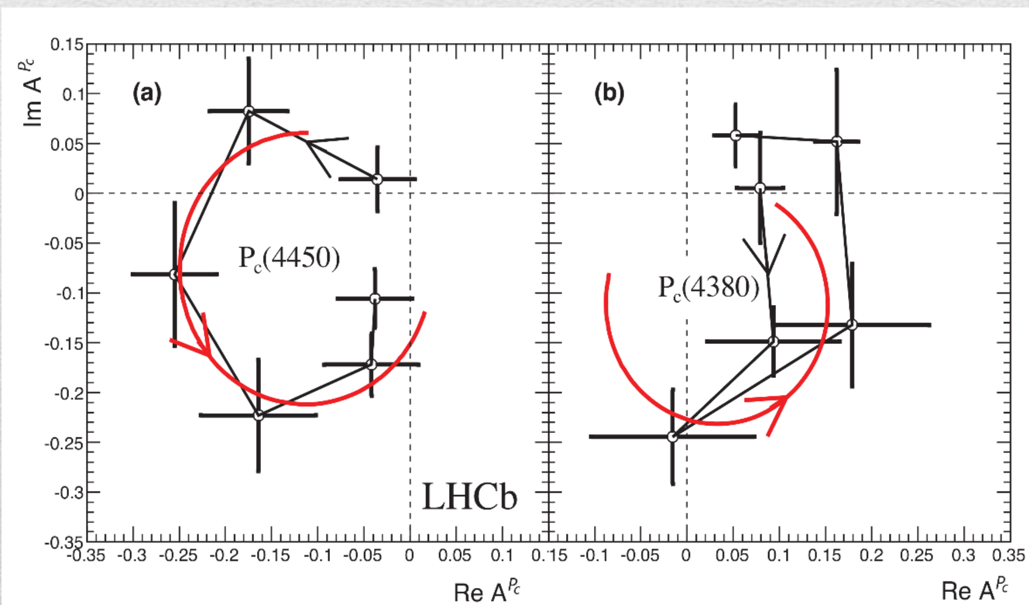
Pentaquarks



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

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

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



Quantum numbers

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

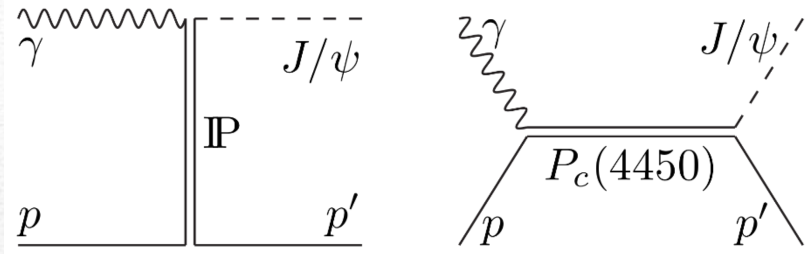
Opposite parities needed for the interference to correctly describe angular distributions

No obvious threshold nearby

Pentaquark photoproduction

We propose to search the $P_c(4450)$ state in photoproduction

Q. Wang *et al.* PRD92, 034022
M. Karliner *et al.* PLB752, 329-332
Kubarovsky *et al.* PRD92, 031502

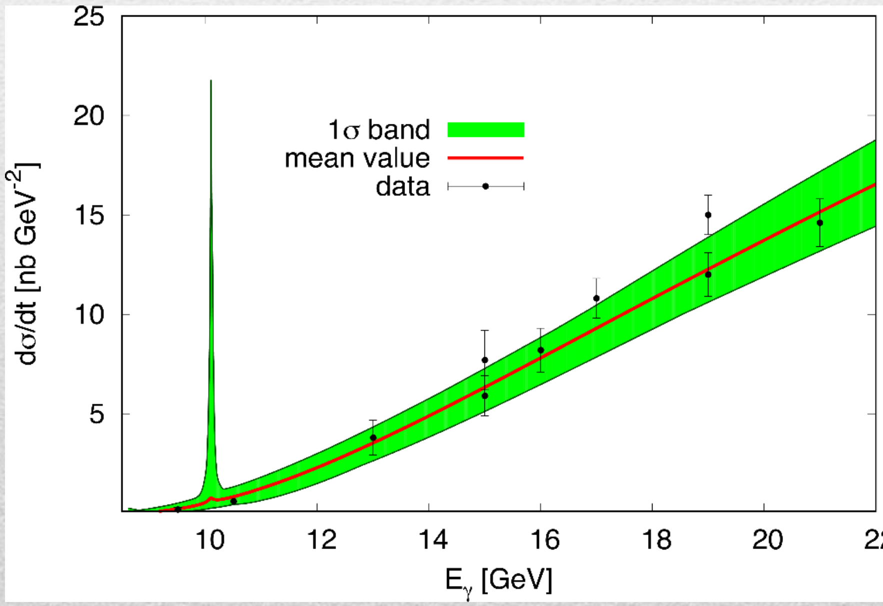


(a) Pomeron exchange (b) Resonant contribution

We use the (few) existing data and
VMD + pomeron inspired bkg
to estimate the cross section

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

σ_s (MeV)	0	60	120
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$	$0.157^{+0.037}_{-0.022}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$	$1.150^{+0.015}_{-0.023}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$	$0.111^{+0.038}_{-0.054}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$	$16.9^{+2.0}_{-1.1}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$	$1.03^{+0.49}_{-0.31}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %	≤ 23 %



A. Blin *et al.* (JPAC), PRD94, 034002

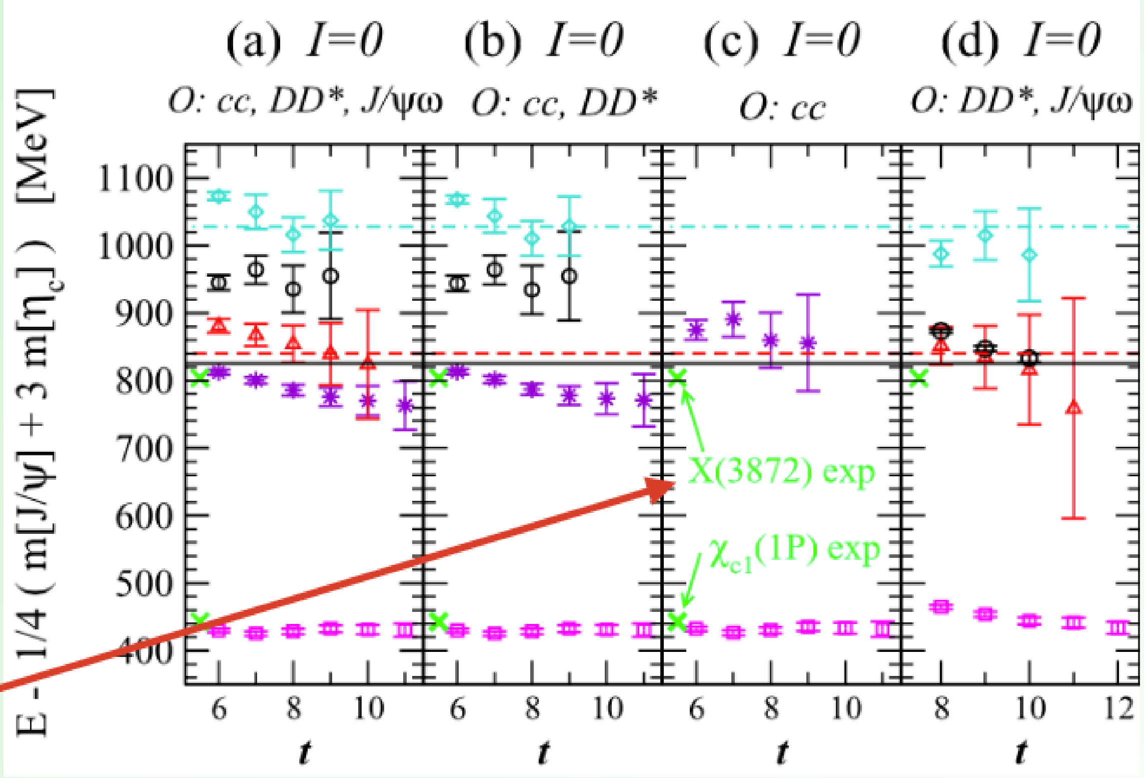
State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle[23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle[24,25] (>10), *BABAR*[26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF[27,28]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

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

Guerrieri, AP, Piccinini, Polosa,
IJMPA 30, 1530002

A. Guerrieri

X(3872) on the lattice: spectrum



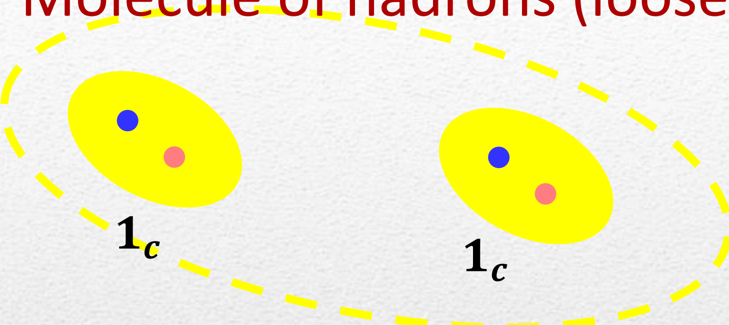
Where is the $\chi_{c1}(2P)$?

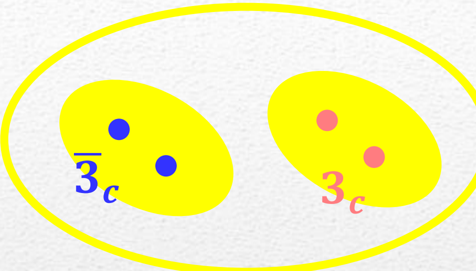
$J^{PC} = 1^{++}\ I = 0$ channel

Prelovsek *et al.* PRL 111 (2013) 192001 arXiv: 1307.5172

Proposed models

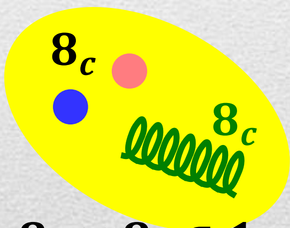
Molecule of hadrons (loosely bound)





$\mathbf{3}_c \times \bar{\mathbf{3}}_c \in \mathbf{1}_c$

Diquark-antidiquark
(tetraquark)

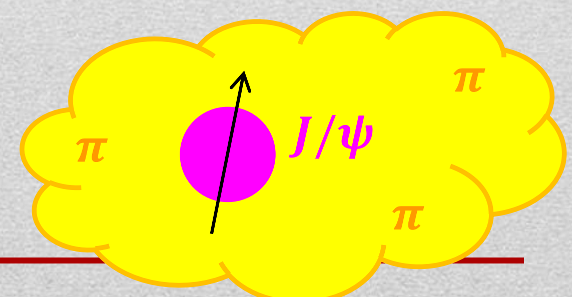


$\mathbf{8}_c \times \mathbf{8}_c \in \mathbf{1}_c$

Glueball, Hybrids
(with valence gluons),
Born-Oppenheimer 4q

Hadrocharmonium
(Van der Waals forces)

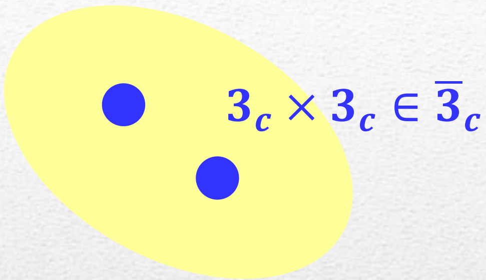
Cusp (kinematical effect)

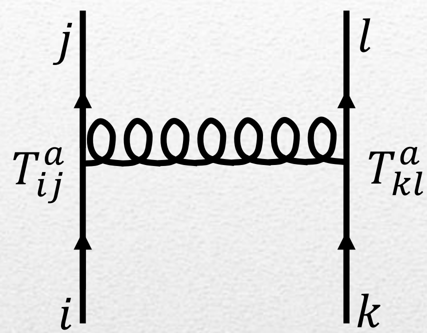


$\mathbf{1}_c \times \mathbf{1}_c \in \mathbf{1}_c$

Diquarks

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





$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

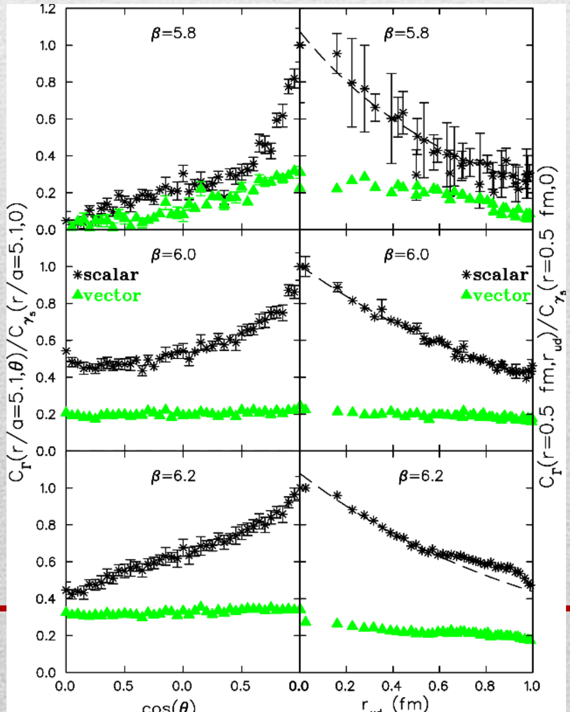
$$R_1 = -\frac{4}{3}, R_8 = +\frac{1}{6}$$

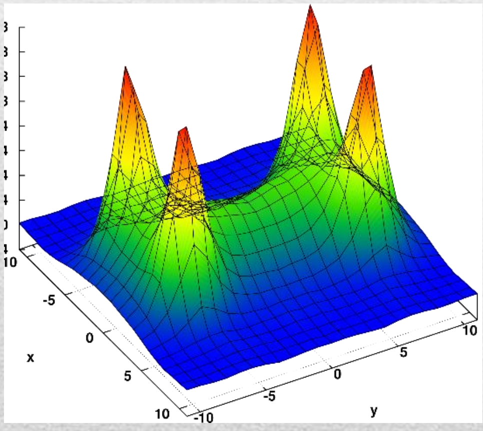
$$R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}$$

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





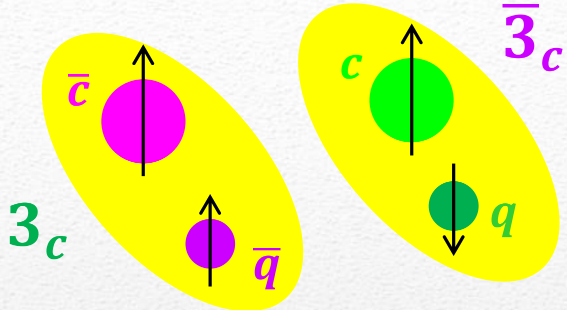
H-shape with a 4 quark system

Cardoso, Cardoso, Bicudo, PRD84, 054508

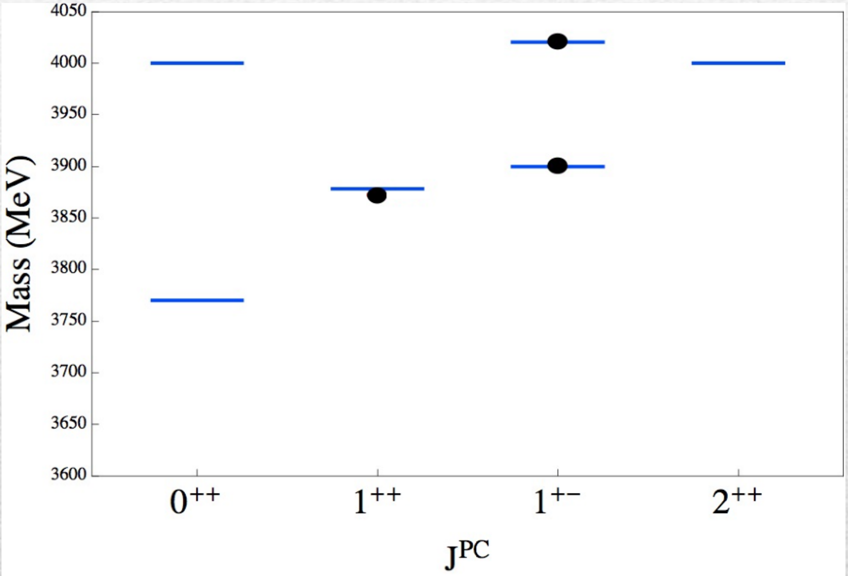
Tetraquark

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 spacially separated from each other, only $\kappa_{cq} \neq 0$
Existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

Tetraquark: new ansatz

Maiani, Piccinini, Polosa, Riquer PRD89 114010

J^{PC}	$cq\,\bar{c}\bar{q}$	$c\bar{c}\,q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\|0,0\rangle$	$1/2\|0,0\rangle + \sqrt{3}/2\|1,1\rangle_0$	$X_0(\sim 3770\text{ MeV})$	$\eta_c, J/\psi$ + light mesons
0^{++}	$\|1,1\rangle_0$	$\sqrt{3}/2\|0,0\rangle - 1/2\|1,1\rangle_0$	$X_0'(\sim 4000\text{ MeV})$	$\eta_c, J/\psi$ + 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/ψ + light mesons

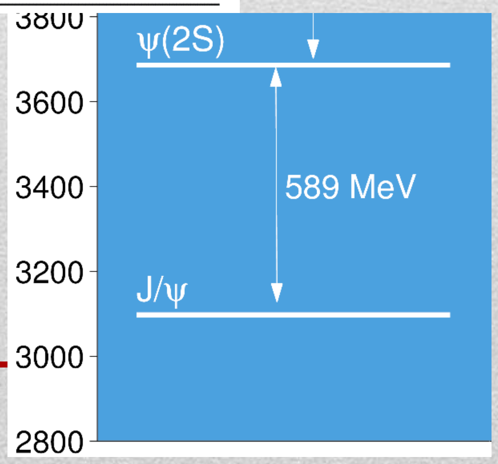
$$\Delta H = \frac{B_c \vec{L}^2}{2} - 2a\,\vec{L}\cdot\vec{S}$$

	$L = 1$	$P(S_{c\bar{c}}=1) : P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
$J/\psi\,\pi\pi$	Y_1	3:1	$Y(4008)$	$\gamma + X_0$
$J/\psi\,\pi\pi$	Y_2	1:0	$Y(4260)$	$\gamma + X$
$h_c\,\pi\pi$	Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
$\Lambda_c^+\Lambda_c^-$	Y_4	1:0	$Y(4630)$	$\gamma + X_2$

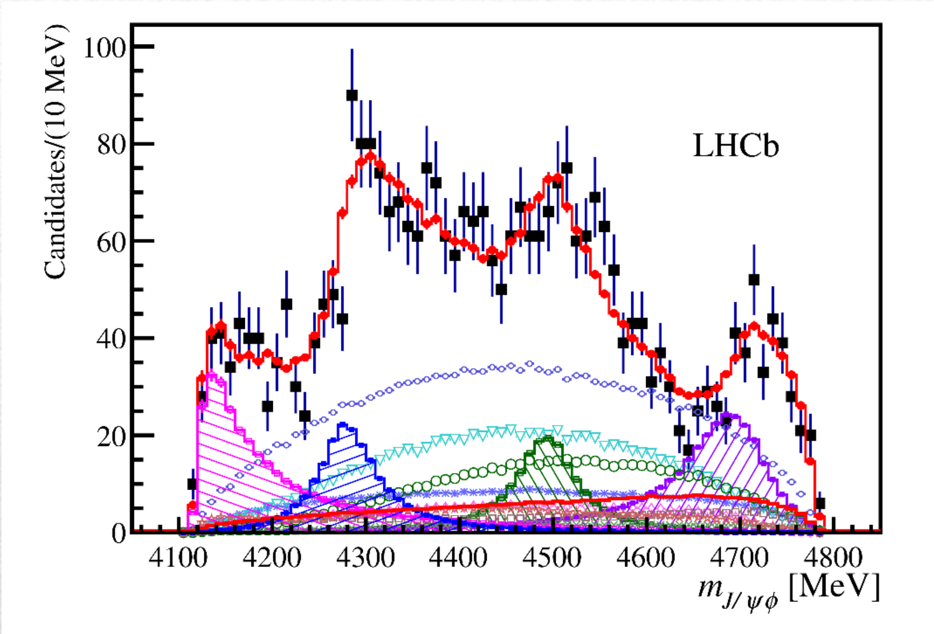
actually observed BESIII PRL 112, 092001

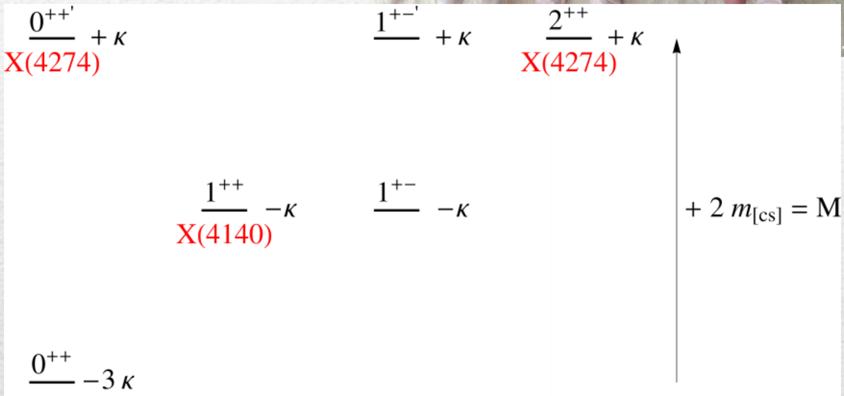
Radial excitations
$Z(2S) = Z(4430)$
$Y_1(2P) = Y(4360)$
$Y_2(2P) = Y(4660)$
Decay in $\psi(2S)$ preferably

$M_{Z(4430)} - M_{Z_c} = 586^{+17}_{-26}$ MeV
to compare with charmonium



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





$$J^{PC} = 0^{++} \quad X_0 = |0,0\rangle_0, \;\; X_0' = |1,1\rangle_0$$

$$J^{PC} = 2^{++} \quad X_2 = |1,1\rangle_2$$

$$J^{PC} = 1^{++} \quad X = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 + |0,1\rangle_1\right)$$

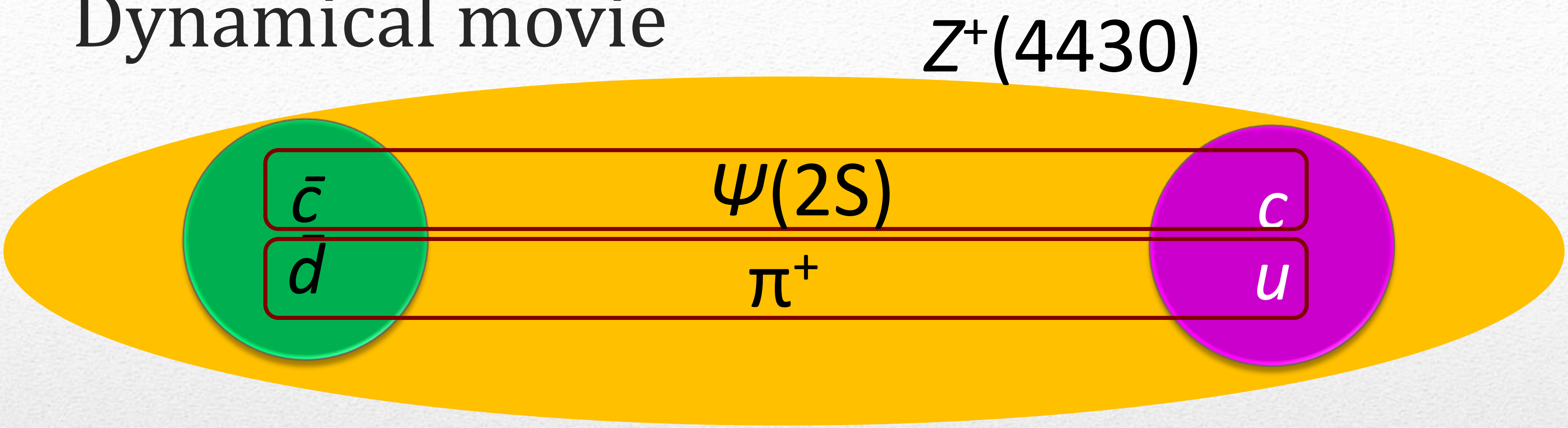
$$J^{PC} = 1^{+-} \quad Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 - |0,1\rangle_1\right)$$

$$Z' = |1,1\rangle_1$$

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, arXiv:1607.02405
Esposito, AP, Polosa, to appear

Dynamical movie



Brodsky, Hwang, Lebed PRL 113 112001

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

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

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

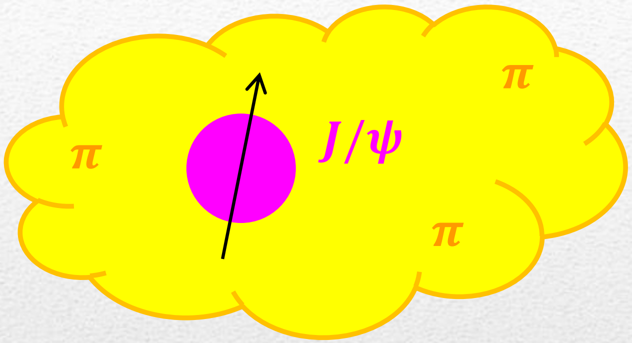
- Use that the kinetic energy released in $\overline{B}^0 \longrightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

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

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

$(> 10\text{ exp.})$

Hadro-charmonium



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

Born in the context of QCD multipole expansion

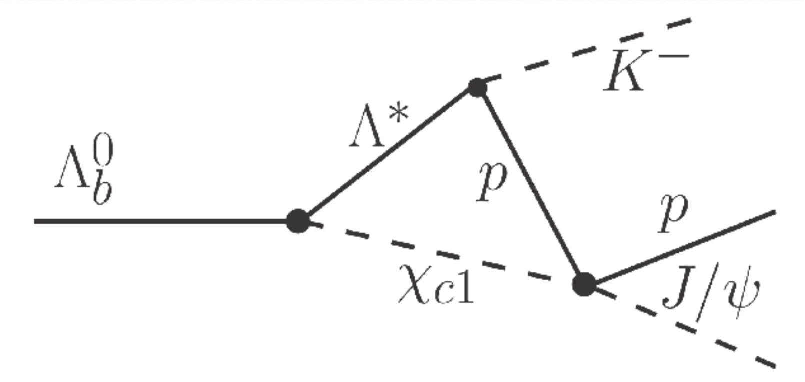
$$H_{eff} = -\frac{1}{2} a_\psi E_i^a E_i^a$$
$$a_\psi = \langle \psi | (t_c^a - t_{\bar{c}}^a) r_i \, G \, r_i (t_c^a - t_{\bar{c}}^a) | \psi \rangle$$

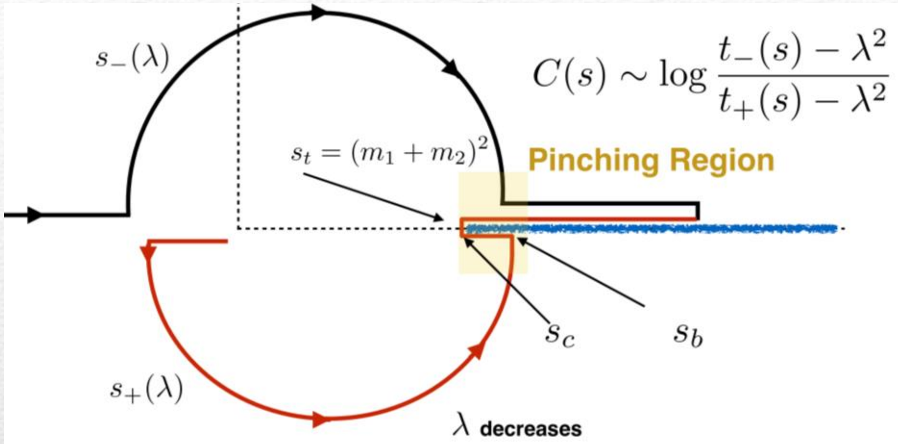
the chromoelectric field interacts with soft light matter (highly excited light hadrons)

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

Triangle singularity (kinematics)





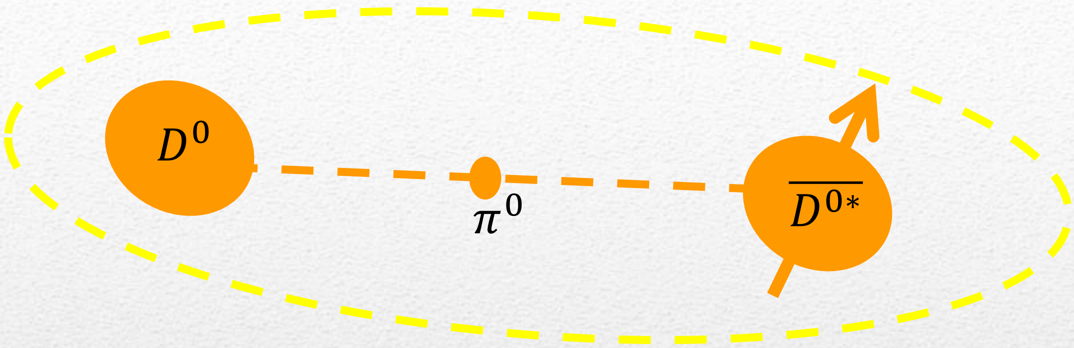
Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in very special kinematical conditions (Coleman and Norton, Nuovo Cim. 38, 438), However, this effects cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363)

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

...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

Molecule



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

$$X(3872) \sim \bar{D}^0 D^{*0}$$
$$Z_c(3900) \sim \bar{D}^0 D^{*+}$$
$$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$$
$$Y(4260) \sim \bar{D} D_1$$

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 $\mathrm{X}(3872)$ isospin violation ✓
- States appear close to thresholds ✓ (but $Z(4430)$ ✗)
- Lifetime of costituents has to be $\gg 1/m\_\pi$, (but why $\Gamma_Y \gg \Gamma_{D\_1}$?)
- 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 ✗

$$V_\pi(r) = \frac{g_{\pi N}^2}{3}(\overrightarrow{\tau_1}\cdot\overrightarrow{\tau_2})\left\{[3(\overrightarrow{\sigma_1}\cdot\hat{r})(\overrightarrow{\sigma_2}\cdot\hat{r}) - (\overrightarrow{\sigma_1}\cdot\overrightarrow{\sigma_2})]\left(1+\frac{3}{(m_\pi r)^2}+\frac{3}{m_\pi r}\right)+(\overrightarrow{\sigma_1}\cdot\overrightarrow{\sigma_2})\right\}\frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

Weinberg theorem

Resonant scattering amplitude

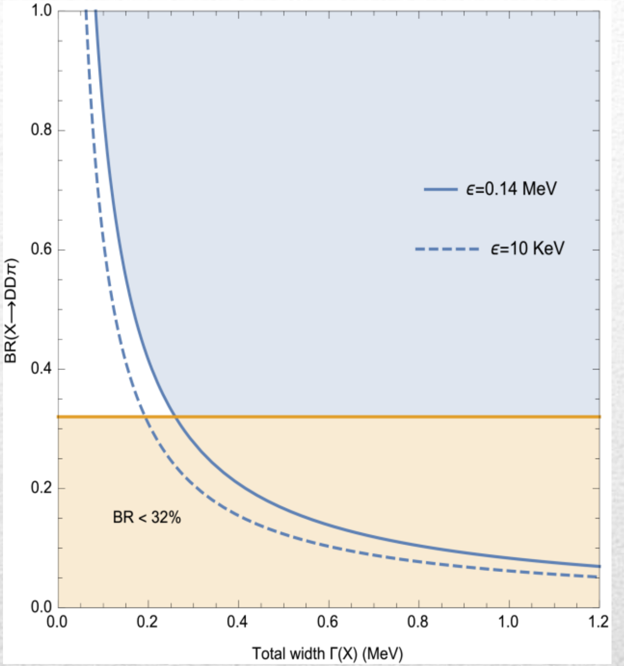
$$f(ab \to c \to ab) = -\frac{1}{8\pi\, E_{CM}} g^2 \frac{1}{(p_a+p_b)^2 - m_c^2}$$

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

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

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 $-B$

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

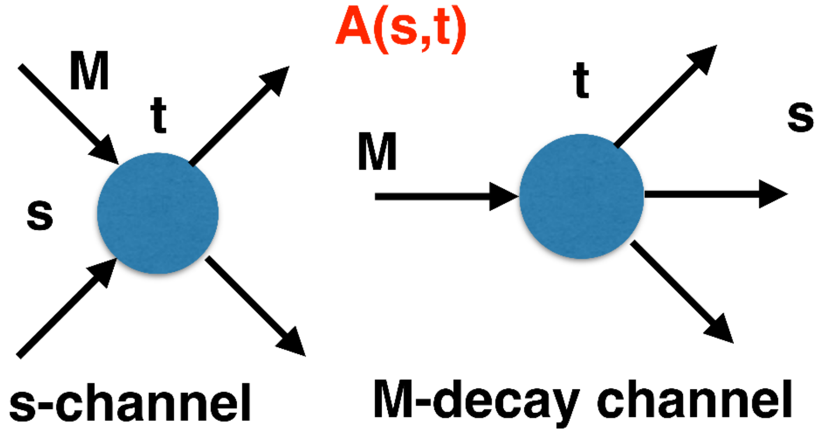


This has to be fulfilled by EVERY molecular state, but:

- $X(3872), B = 0, g \neq 0$
- $Zs, B < 0$, repulsive interaction!
- $Y(4260), kR \sim 1.4$

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

S-Matrix principles



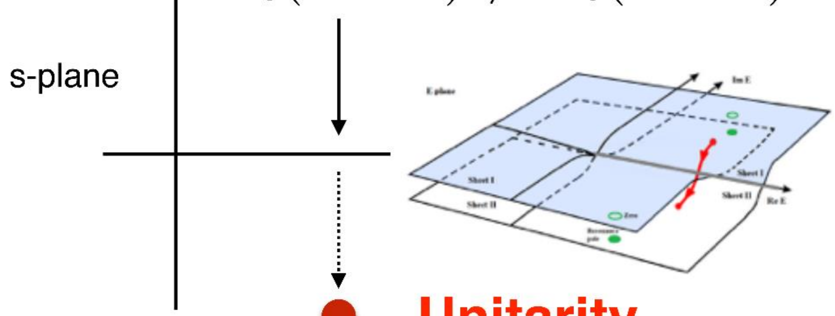
Crossing

$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$

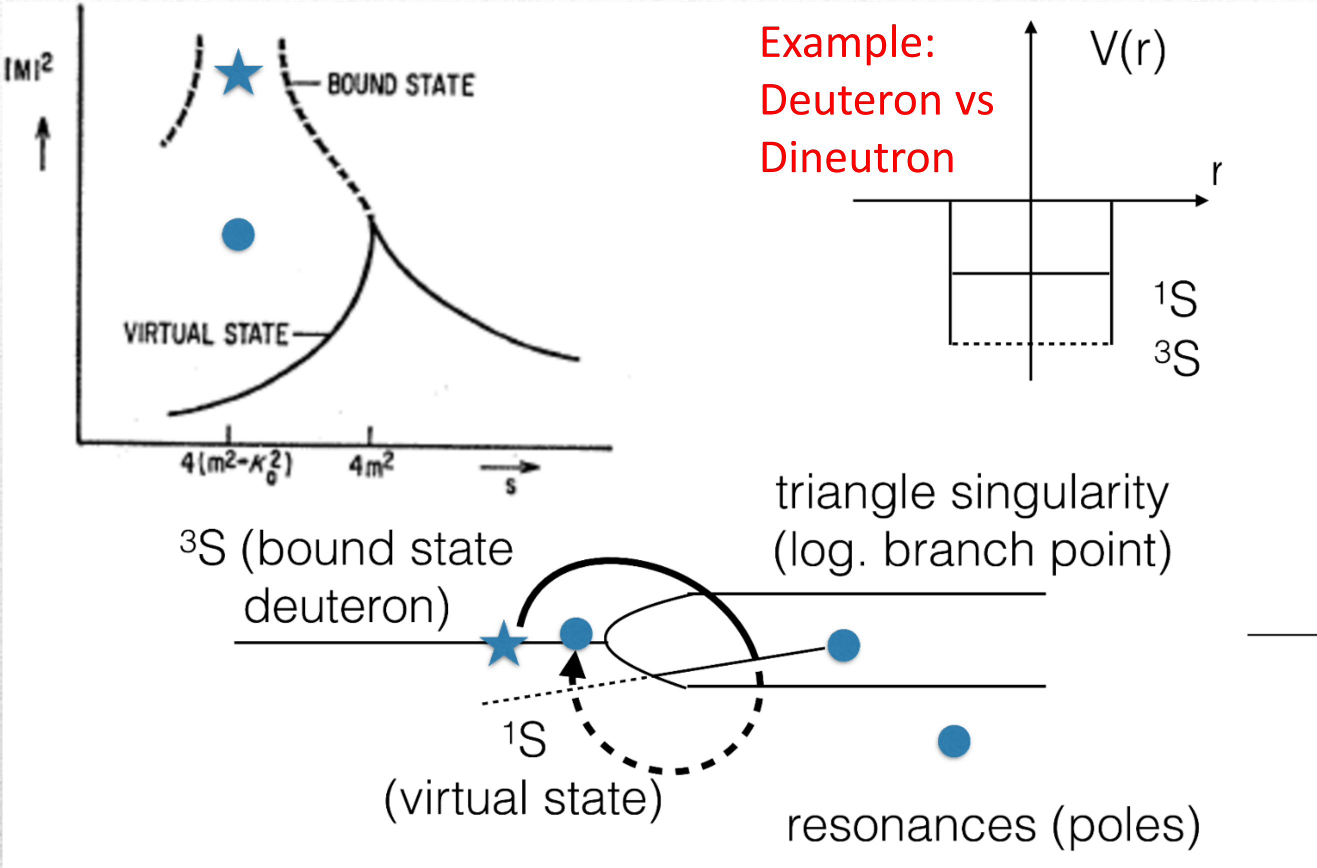


Unitarity

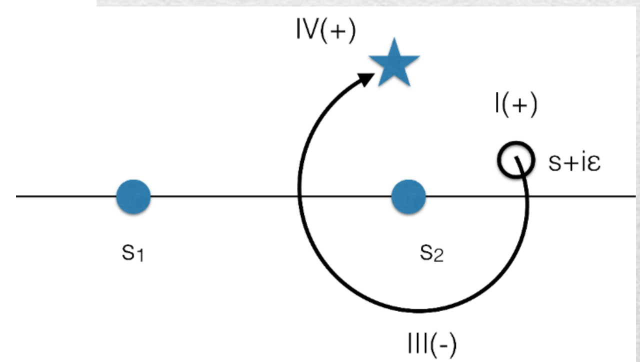
These are constraints the amplitudes have to satisfy, but do not fix the dynamics

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

Pole hunting



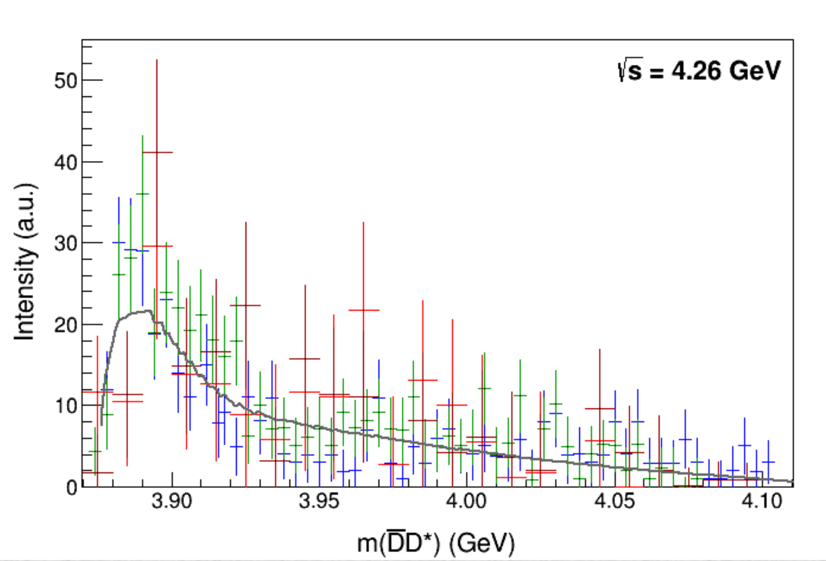
More complicated structure when more thresholds arise: two sheets for each new threshold

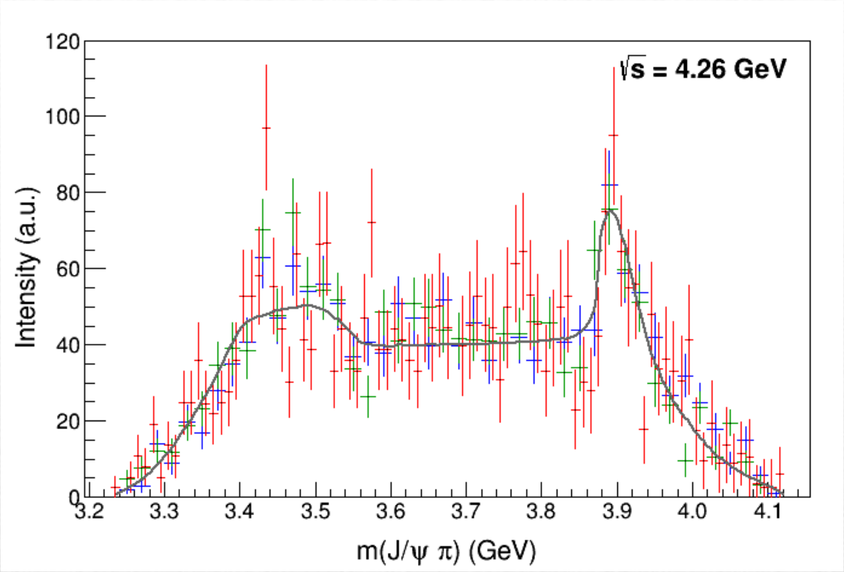


III sheet: usual resonances
IV sheet: cusps (virtual states)

Case study, $Z_c(3900)$

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



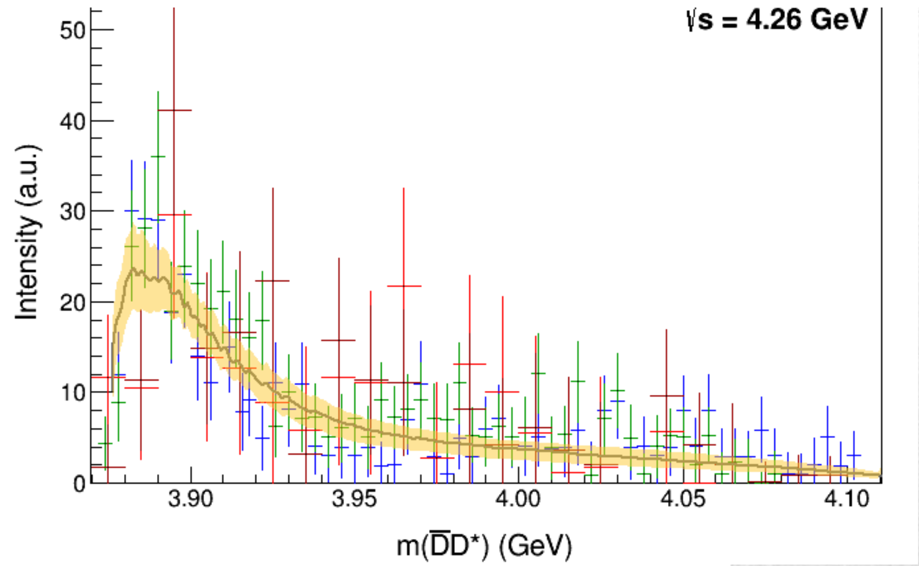


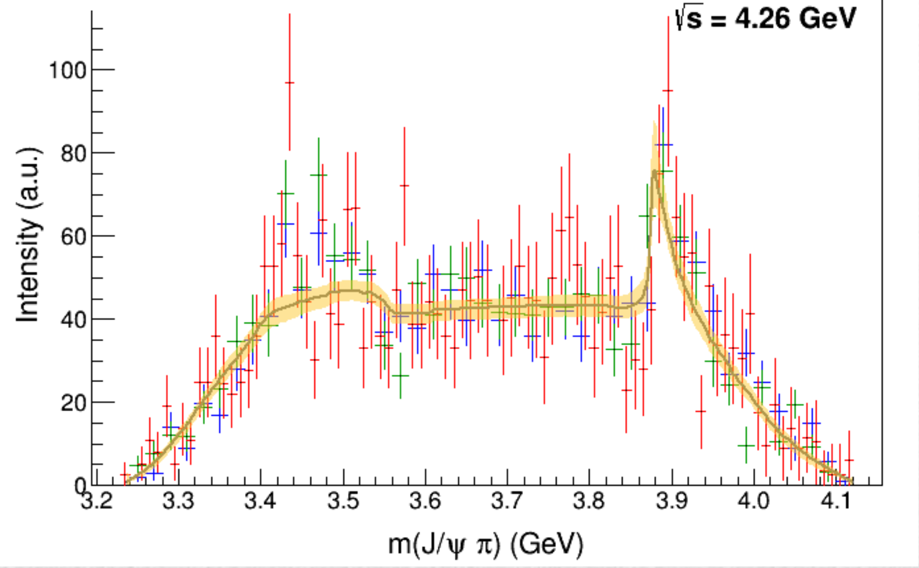
Case 1: Breit-Wigner-like singularity, $\chi^2/\mathrm{DOF} = 641/533$

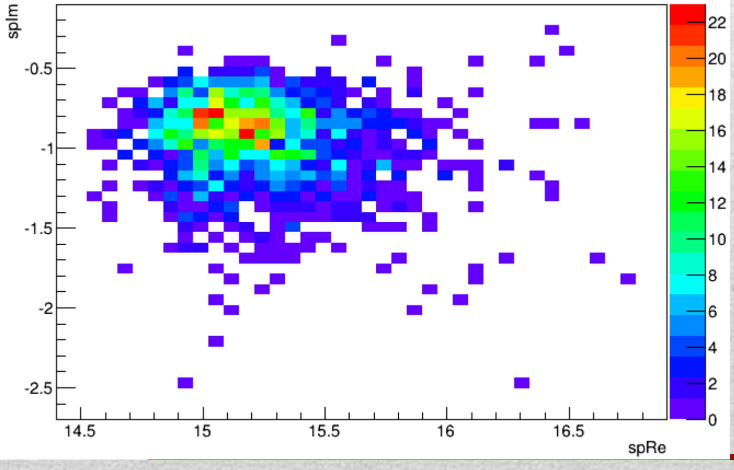
AP and A. Szczepaniak (JPAC), in progress

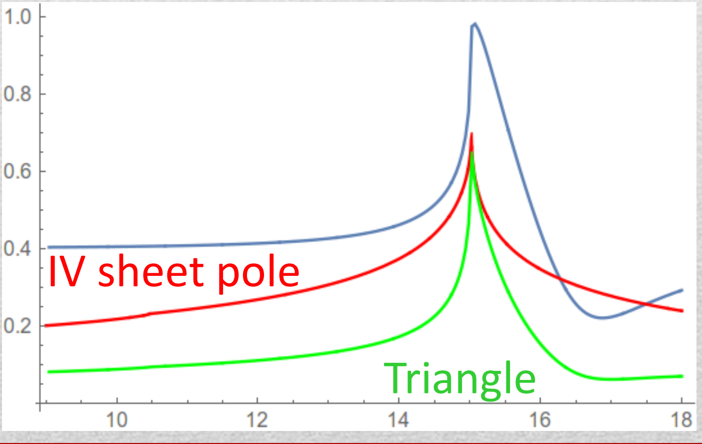
Case study, $Z_c(3900)$

Case 2: 4° sheet singularity (virtual state), $\chi^2/\mathrm{DOF} = 665/533$

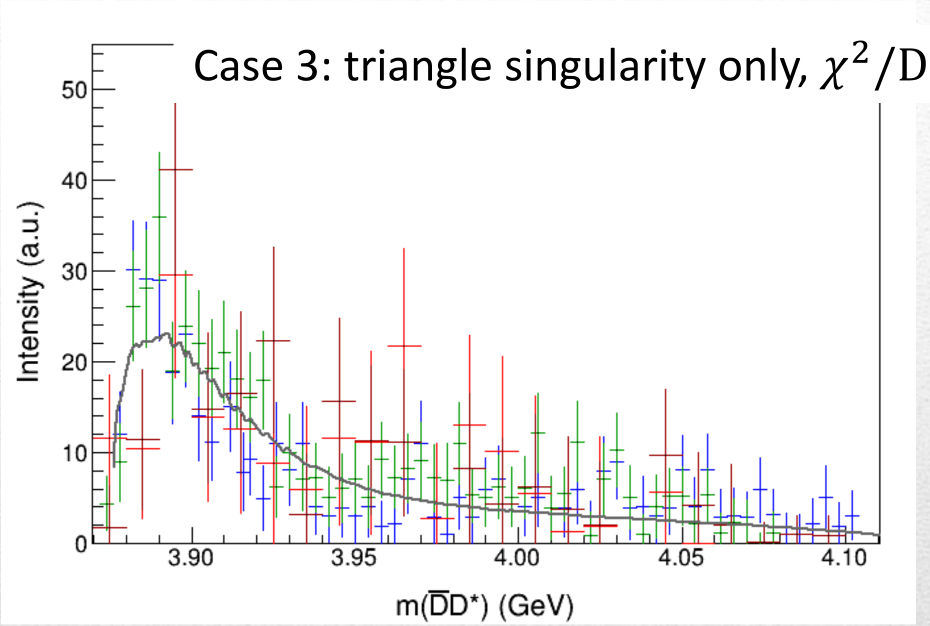


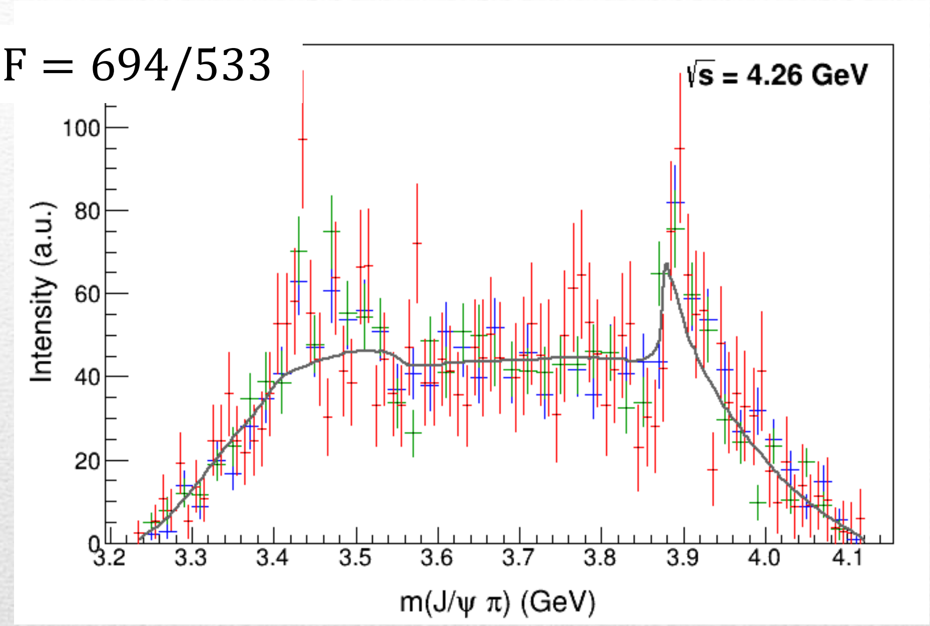


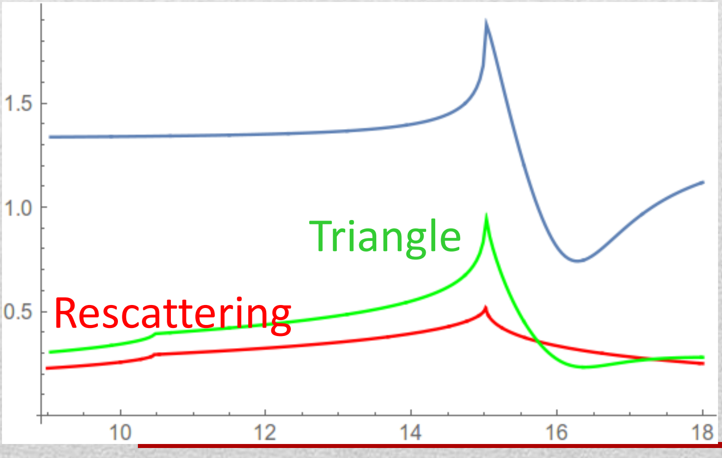




Case study, $Z_c(3900)$





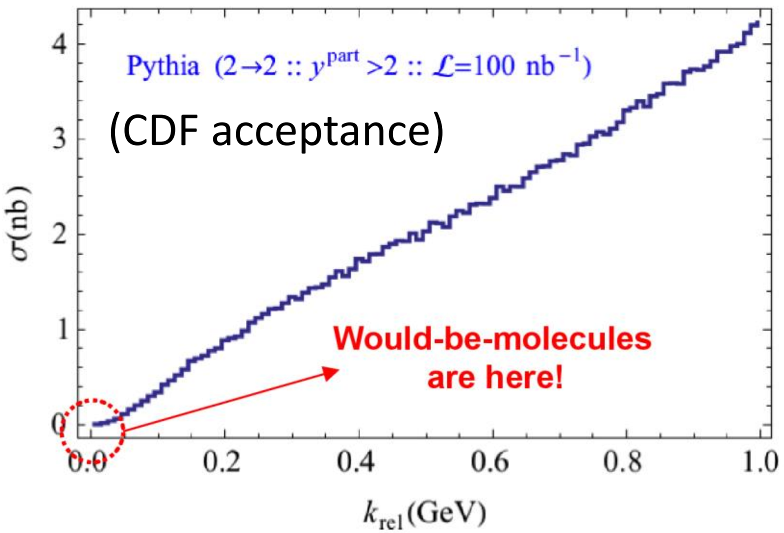


No strong conclusion can be driven yet, but we are establishing the method to use when higher statistics will be available

AP and A. Szczepaniak (JPAC), in progress

Prompt production of $X(3872)$

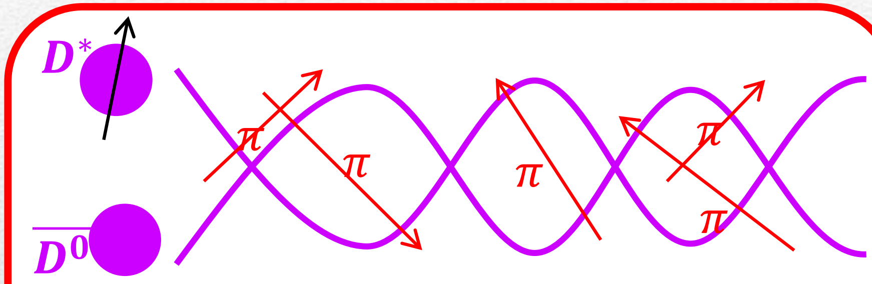
$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders



$$\sigma_{MC}(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1 \text{ nb}$$

$$\sigma_{exp}(p\bar{p} \to X(3872)) \approx 30 - 70 \text{ nb!!!}$$

Bignamini *et al.* PRL103 (2009) 162001



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi$,
$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with DD^* propagation. Estimating the effect of these pions increases σ, but not enough

Bignamini *et al.* PLB684, 228-230
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

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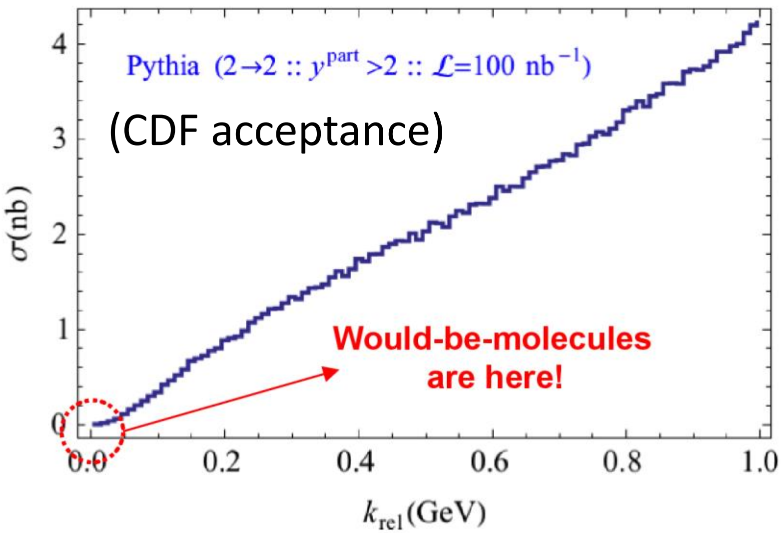

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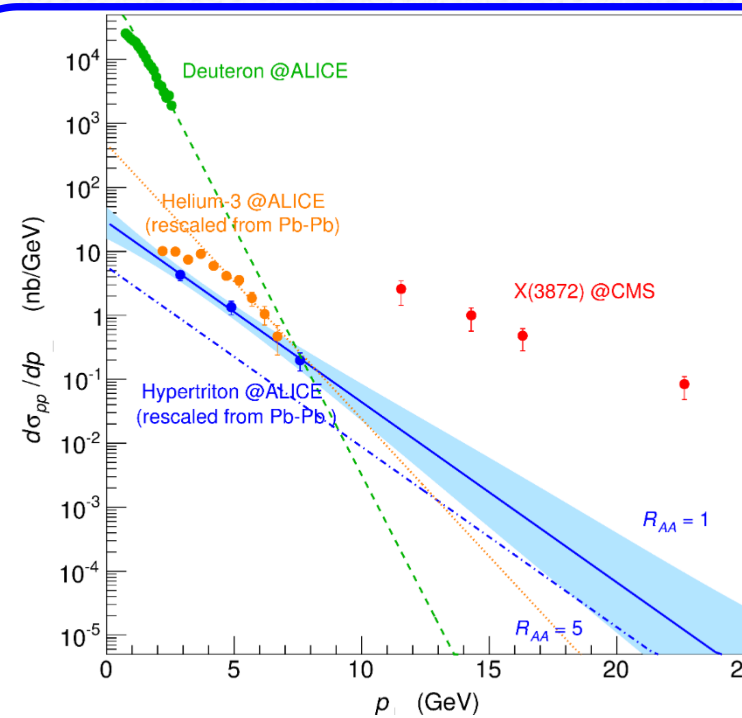
Bignamini *et al.* PRL103 (2009) 162001



Also, a comparison to light nuclei does not favor the $X(3872)$ to share the same nature

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

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:

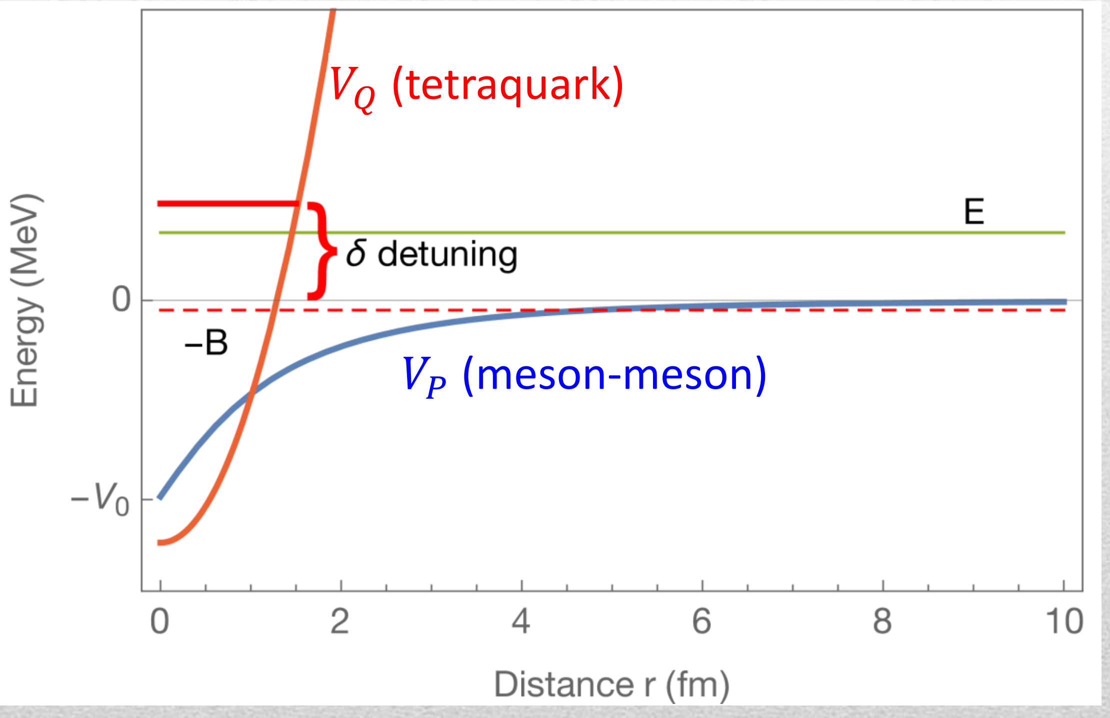
	Thr.	δ (MeV)	$A\sqrt{\delta}$ (MeV)	Γ (MeV)
$X(3872)$	$\bar{D}^0 D^{*0}$	$0^\dagger$	$0^\dagger$	$0^\dagger$
$Z_c(3900)$	$\bar{D}^0 D^{*+}$	7.8	27.9	27.9
$Z_c'(4020)$	$\bar{D}^{*0} D^{*+}$	6.7	25.9	$24.8^\P$
$X(4140)$	$J/\psi\,\phi$	*a*) 31.6	52.7	28.0
		b) 30.1	54.7	83.0
$Z_b(10610)$	$\bar{B}^0 B^{*+}$	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

Feshbach mechanism occurs when two atoms can interact with two potentials, resp. with continuum (meson-meson) and discrete (4q) spectrum → hybridization



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}

$$a = a_P - C \sum \frac{\left|\langle \psi_n | H_{QP} | \psi_P \rangle\right|^2}{E_n - E + i\epsilon}$$

$$\simeq a_P \left(1 - \frac{\kappa}{\delta + i\epsilon}\right)$$

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

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

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

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

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

$X(3872)$ should be a $I = 0$ state, but $M(1^{++}) < M(D^{+*}D^-)$

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

No charged component, isospin violation!

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 Ys or the $Z(4430)$)

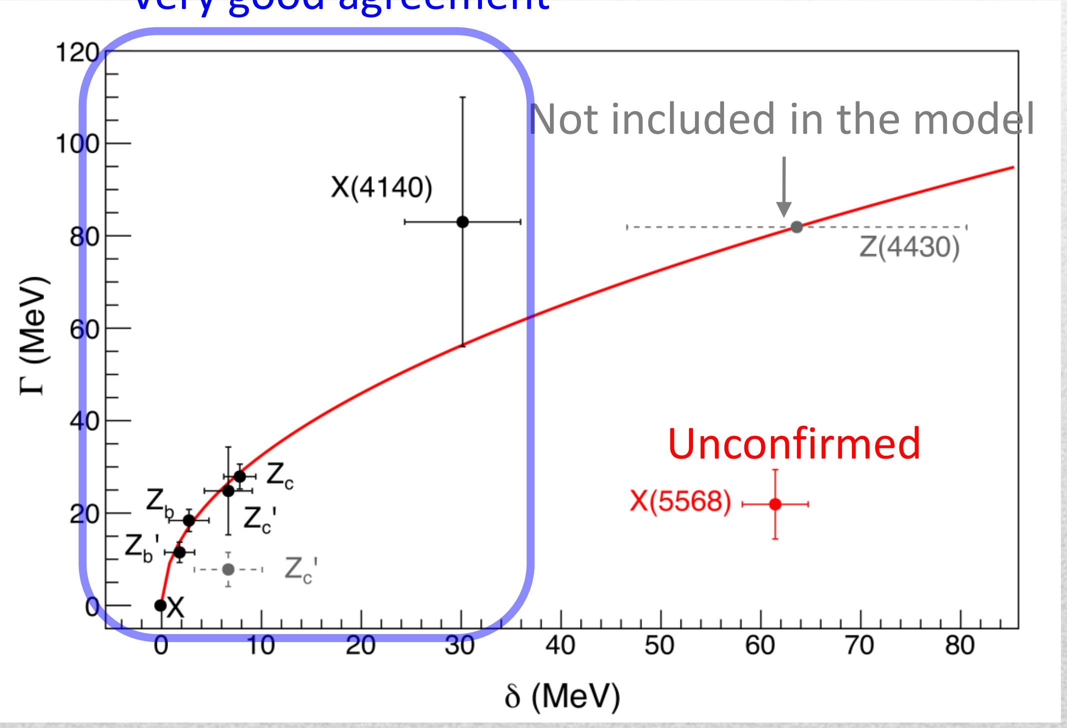
In this picture, a $[bu][\bar{s}\bar{d}]$ state with resonance parameters of the $X(5568)$ observed by D0 is not likely

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

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

Very good agreement



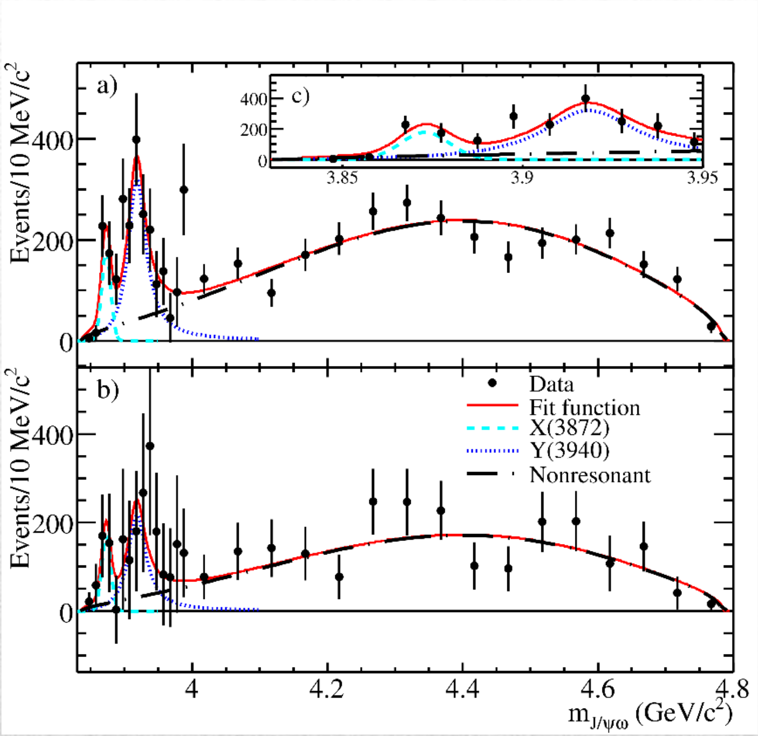
Conclusions & prospects

- The discovery of exotic states has challenged the well established Charmonium framework
- Some fantasy needed, many phenomenological models introduced.
- Experiments are very prolific! Constant feedback on predictions
- Nuclei observation at hadron colliders can give an unexpected help in testing some phenomenological hypotheses for the XYZ states
- Search for exotic states in prompt production is a necessary step to improve our understanding of the sector
- Feshbach mechanism might be effective in reducing the number of states predicted by the tetraquark picture
- Thorough amplitude anlyses might shed some light on the microscopic nature of the new states

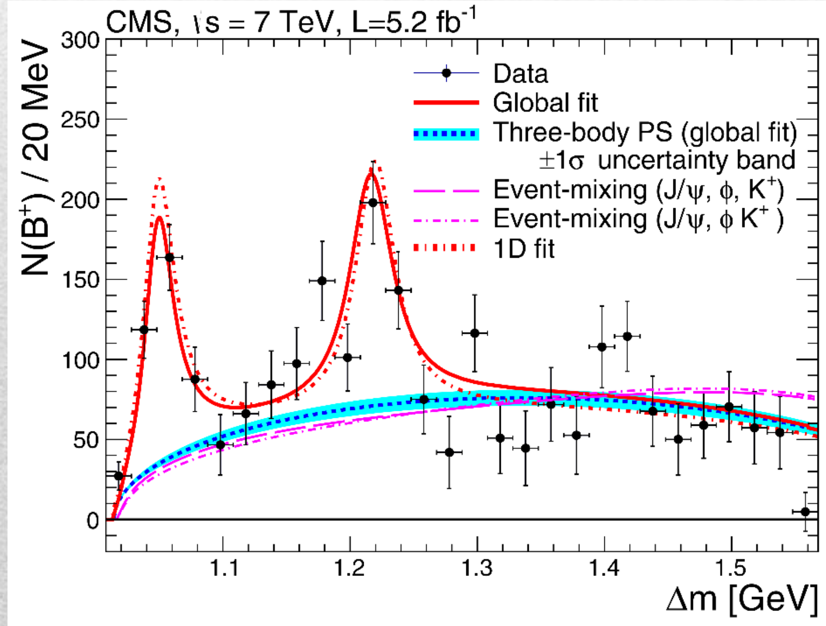
Thank you

BACKUP

Other beasts



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

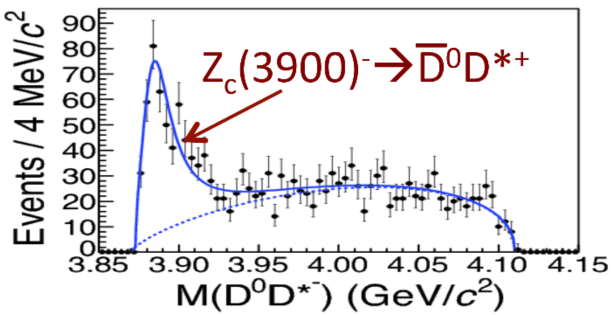


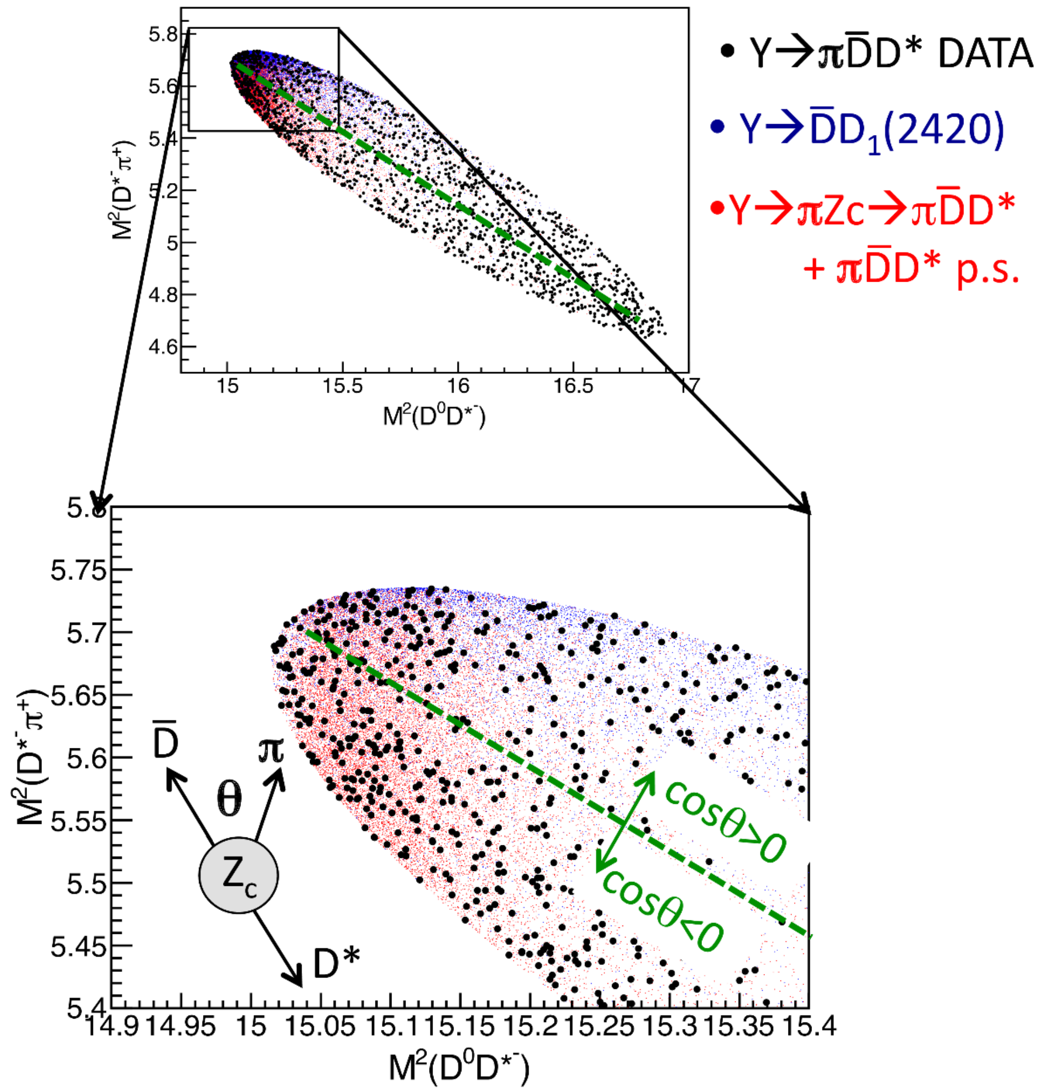
One/two peaks seen in $B \to XK \to J/\psi\, \phi\, K$, close to threshold

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

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

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 $\bar{D}D_1(2410)$

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

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

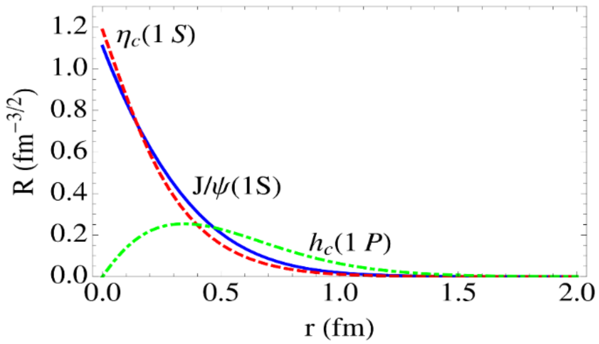
If tetraquark

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 $\sim 25\%$



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

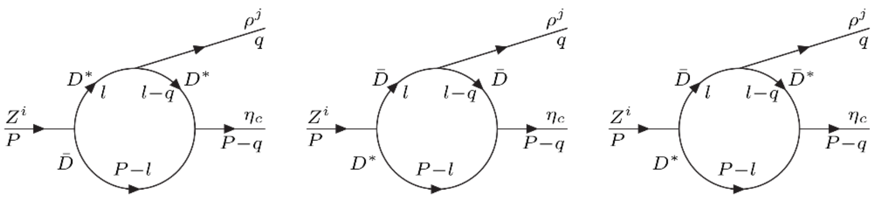
	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi \pi)}$	$\left(3.3^{+7.9}_{-1.4}\right) \times 10^2$	$0.41^{+0.96}_{-0.17}$	$\left(2.3^{+3.3}_{-1.4}\right) \times 10^2$	$0.27^{+0.40}_{-0.17}$
$\frac{\mathcal{BR}(Z'_c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

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

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



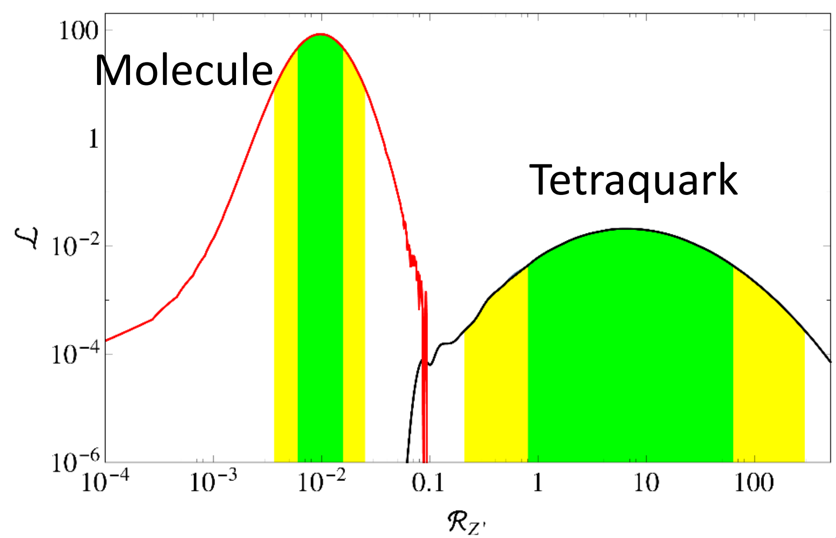
$$\mathcal{L}_{Z_c^{(\prime)}} = \frac{z^{(\prime)}}{2}\left\langle \mathcal{Z}^{(\prime)}_{\mu,ab}\bar{H}_{2b}\gamma^\mu \bar{H}_{1a}\right\rangle + h.c.,$$

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

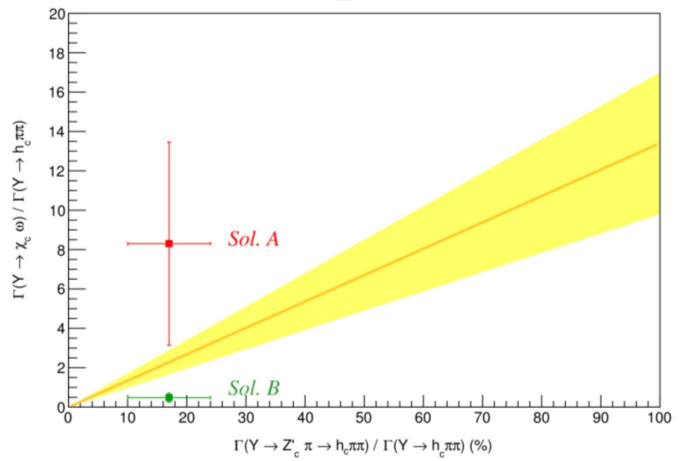
$$\mathcal{L}_{\rho DD^*} = i\beta \left\langle H_{1b} v^\mu \left(\mathcal{V}_\mu - \rho_\mu\right)_{ba} \bar{H}_{1a}\right\rangle + i\lambda\left\langle H_{1b}\sigma^{\mu\nu}F_{\mu\nu}(\rho)_{ba}\bar{H}_{1a}\right\rangle + h.c.,$$

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

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



Tetraquark: the $Y(4220)$



$$\langle \chi_{c0}(p)\,\omega(\eta,q)|Y(\lambda,P)\rangle = g_\chi\,\eta\cdot\lambda,$$
$$\langle Z_c'(\eta,q)\,\pi(p)|Y(\lambda,P)\rangle = g_Z\,\eta\cdot\lambda\frac{P\cdot p}{f_\pi M_Y},$$
$$\langle h_c(\eta,q)\,\sigma(p)|Y(\lambda,P)\rangle = g_h\,\varepsilon_{\mu\nu\rho\sigma}\eta^\mu\lambda^\nu\frac{P^\rho q^\sigma}{P\cdot q},$$
$$\langle \pi(q)\pi(p)|\sigma(P)\rangle = \frac{P^2}{2f_\pi},$$

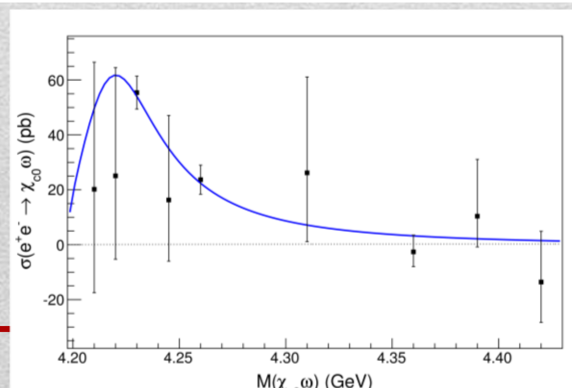
$$\frac{\Gamma\left(Y(4220)\to\chi_{c0}\omega\right)}{\Gamma(Y(4220)\to h_c\pi^+\pi^-)} = (13.4\pm3.6)\times R_{YZ} = 2.3\pm1.2.$$

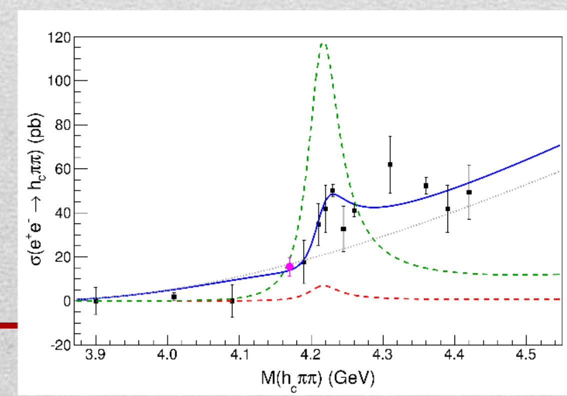
$$\frac{\Gamma\left(Y(4220)\to Z_c'^{\pm}\pi^{\mp}\to h_c\pi^+\pi^-\right)}{\Gamma\left(Y(4220)\to h_c\sigma\to h_c\pi^+\pi^-\right)} = 4.8\pm3.5,$$

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

$$M(Z_b') - M(Z_b) = 2\kappa_b$$
$$M(Z_c') - M(Z_c) = 2\kappa_c \sim 120 \text{ MeV}$$
$$\kappa_b : \kappa_c = M_c : M_b \sim 0.30$$

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

$$Z_b = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle - \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$
$$Z_b' = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle + \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$

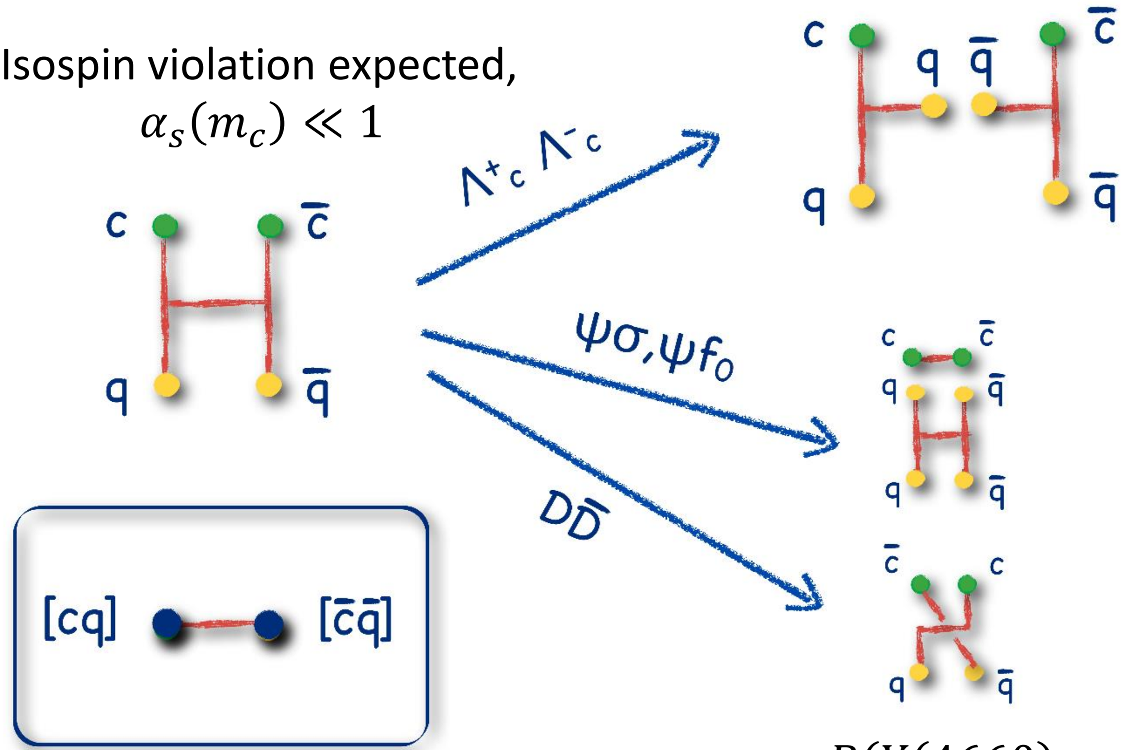
Data on $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ and $\Upsilon(5S) \to \mathrm{h_b}(nP)\pi\pi$ strongly favor $\alpha = \beta$

Baryonium

C. Sabelli

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

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



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

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

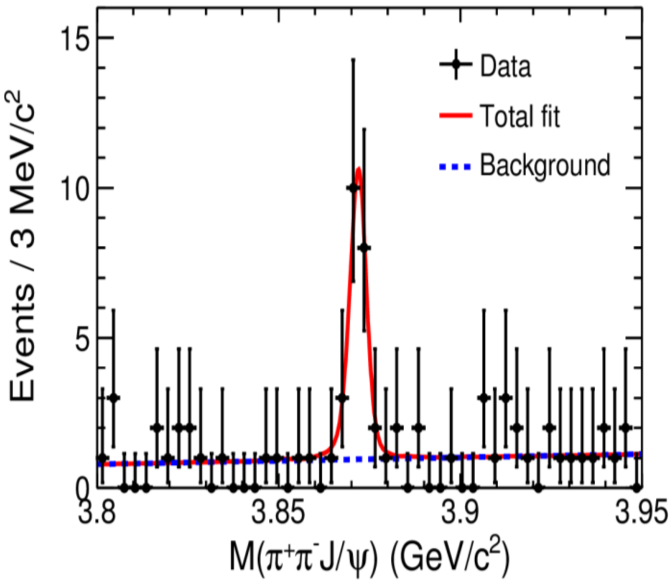
Cotugno, Faccini, Polosa, Sabelli,
PRL 104, 132005

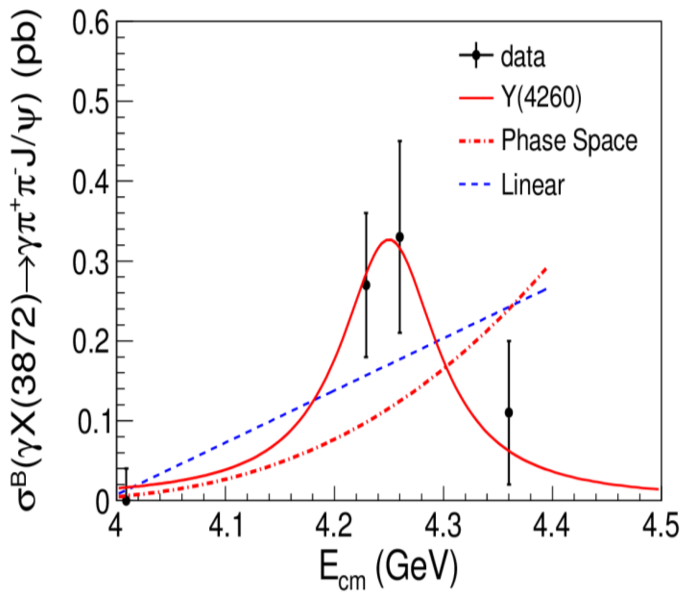
$Y(4260) \rightarrow \gamma X(3872)$

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

F. Piccinini

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





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

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

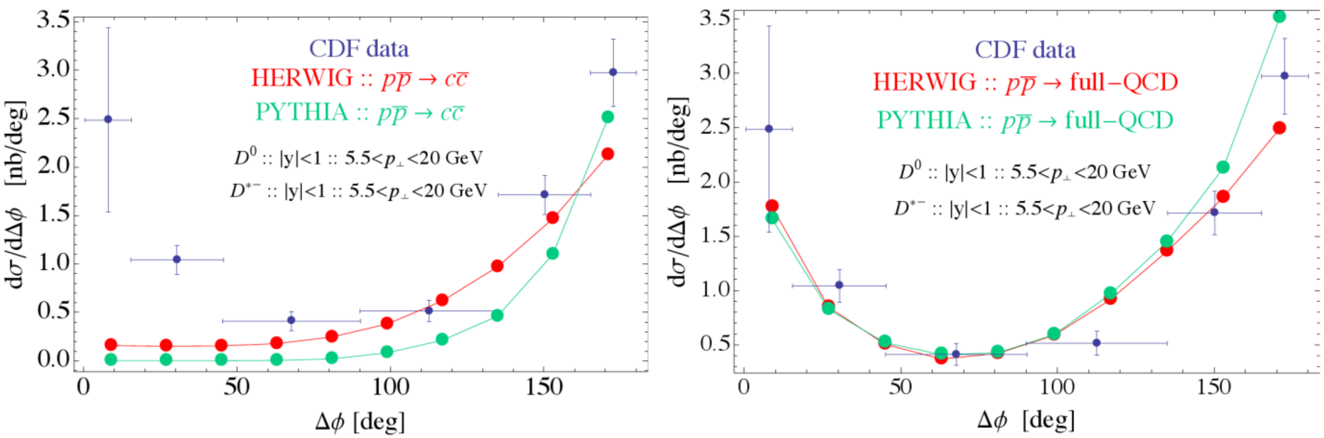
Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure

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 understimate the low angles (low-k_0) region!

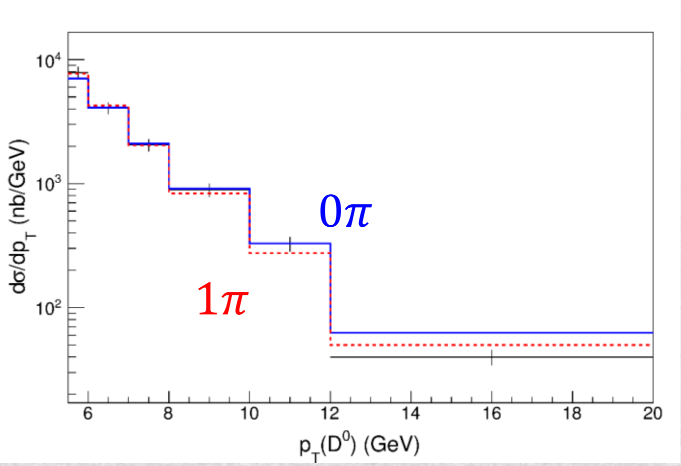
Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

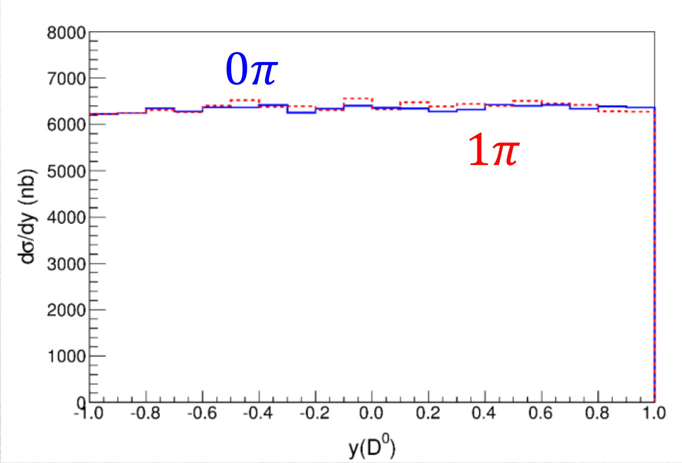
Tuning pions

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

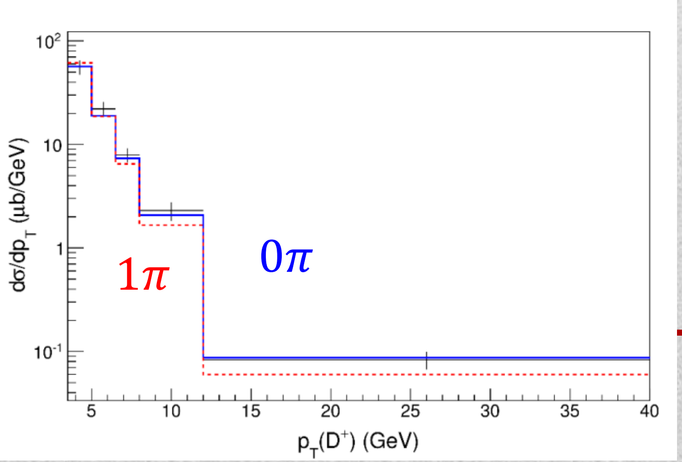
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

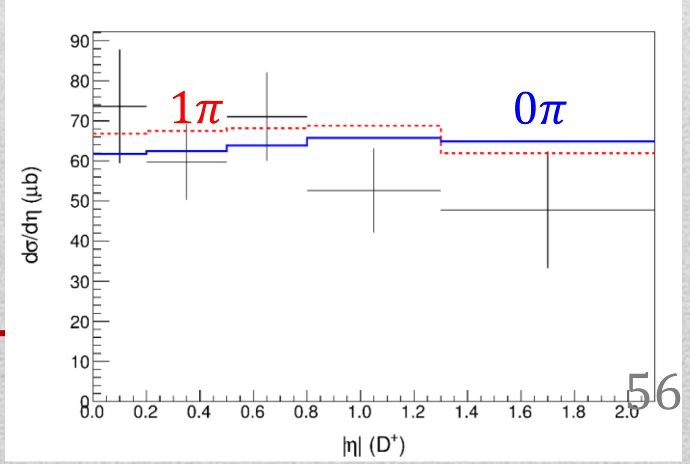
Neither at CDF...





...nor at ATLAS





$Z_c(3900)$

mysterious particle

Physics
spotlighting exceptional research

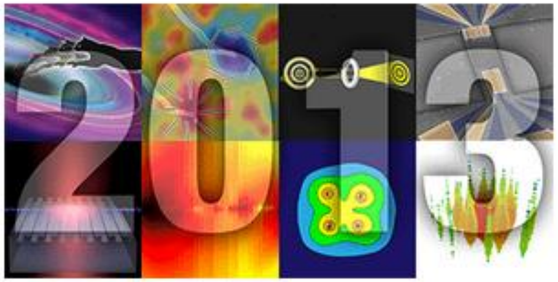
Notes from the Editors: Highlights of the Year

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



Images from popular *Physics* stories in 2013.

Four-Quark Matter

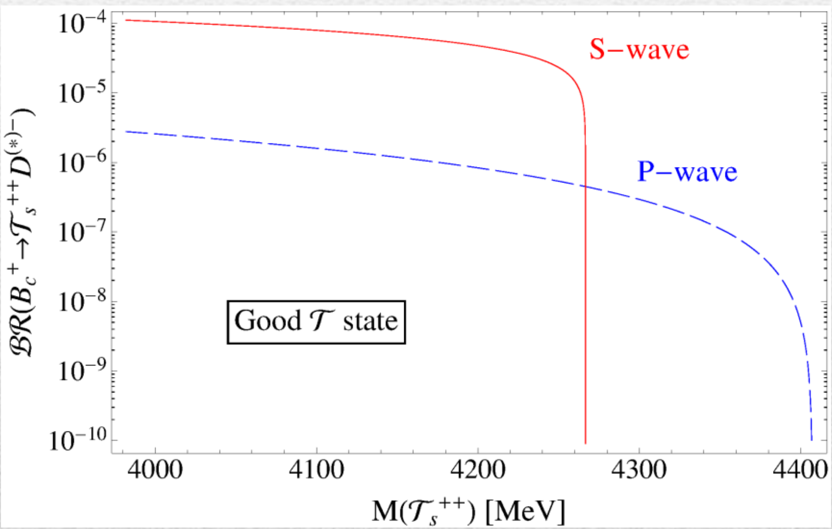
Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain 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.

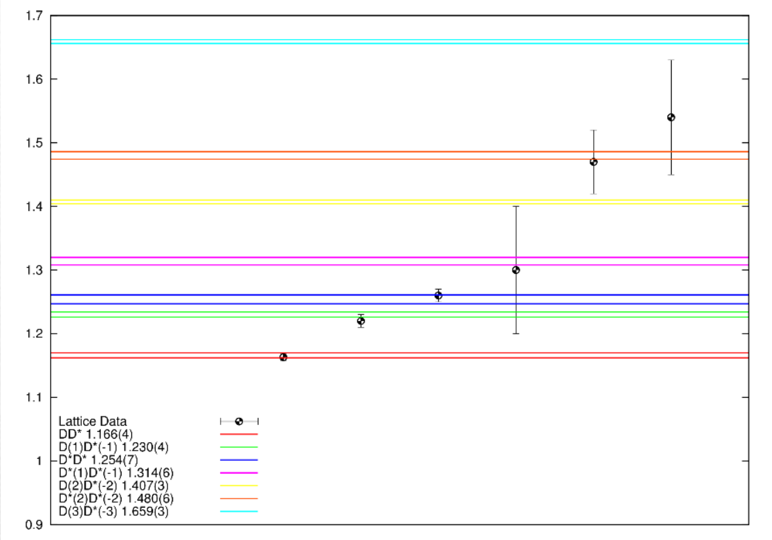
Doubly charmed states

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, Tantalo, PRD88 (2013) 054029

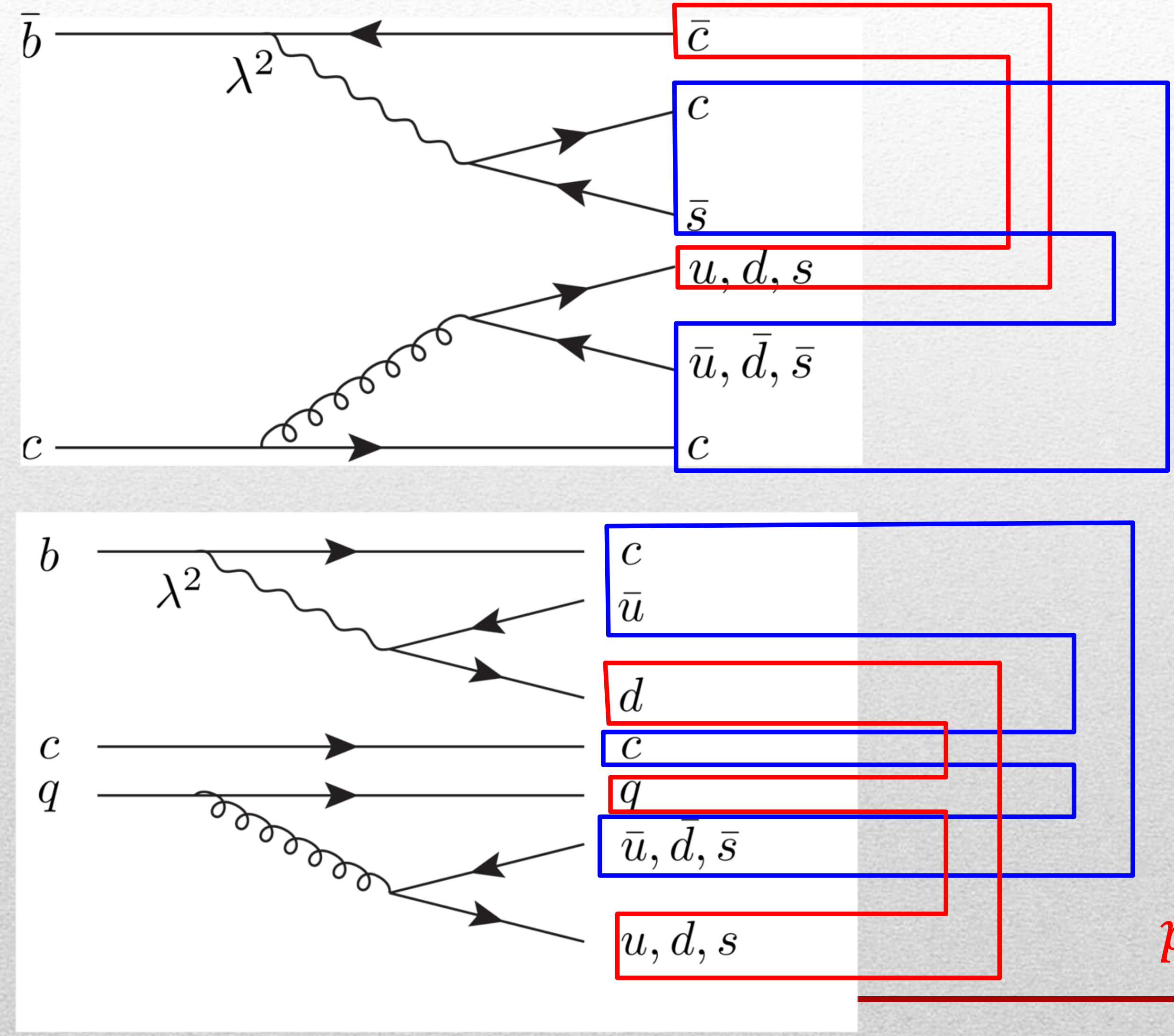




Preliminary results on spectrum for $m_\pi = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

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

T states production



$\overline{D^0}, D^-, D_s^-$

$T_s^+, T_s^{++}, T_{ss}^{++}$

T^0, T^+, T_s^+

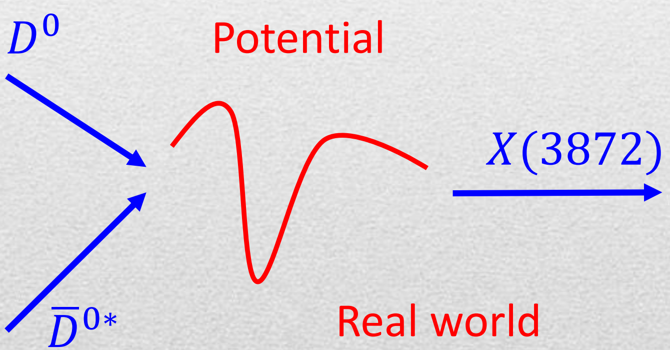
$p, n, \Lambda, \Sigma, \Xi \ldots$

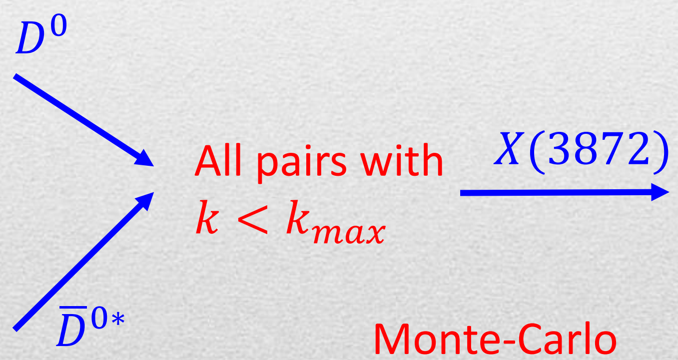
Prompt production of $X(3872)$

$X(3872)$ 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





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

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 $E_B \approx -0.16 \pm 0.31\ \text{MeV}$: very small!
In a simple square well model this corresponds to:

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

(binding energy reported in Kamal Seth's talk is $E_B \approx -0.013 \pm 0.192\ \text{MeV}$:

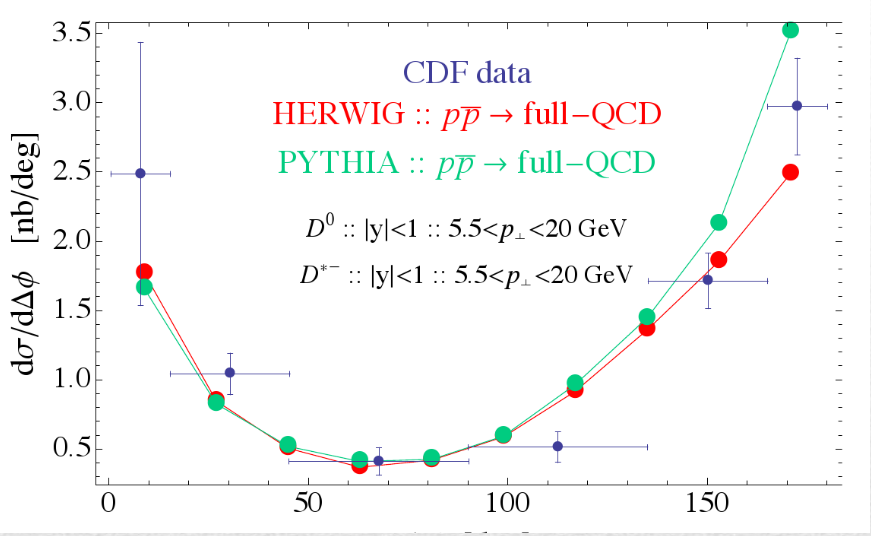
$$\sqrt{\langle k^2 \rangle} \approx 30\ \text{MeV}, \sqrt{\langle r^2 \rangle} \approx 30\ \text{fm}$$)

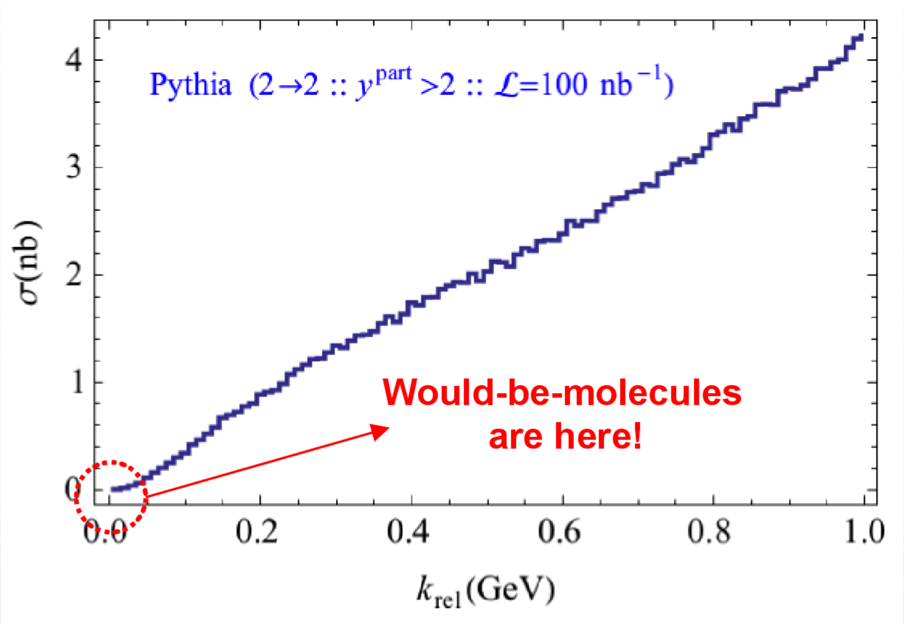
to compare with deuteron: $E_B = -2.2\ \text{MeV}$

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

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

2009 results





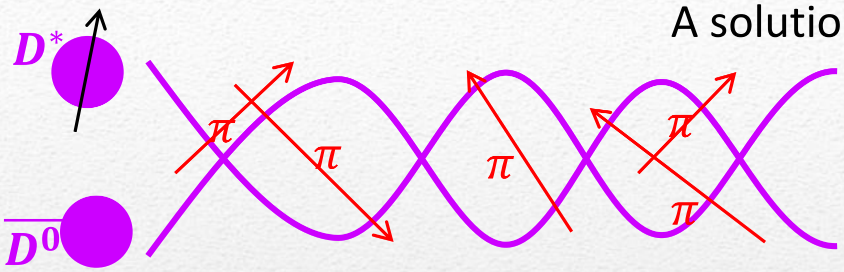
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

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

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

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

Estimating k_{max}



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

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

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

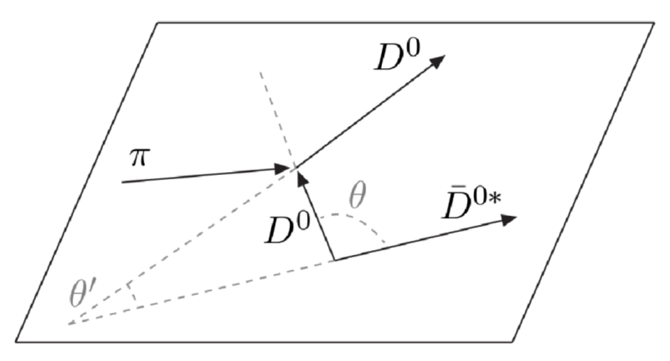
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354
use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

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

A new mechanism?

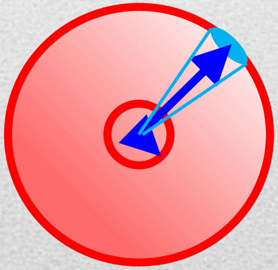
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the pairs DD^*

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

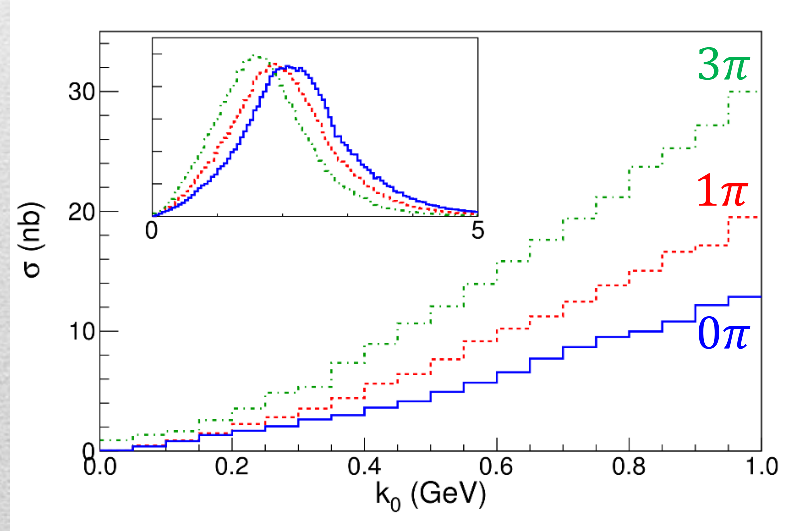


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100\ \mathrm{keV}$



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



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

Counting rules

Brodsky, Lebed, 1505.00803

- Exotic states can be produced in threshold regions in e^+e^- (BES, Belle), electroproduction (JLab 12), hadronic beam facilities ($\bar{\text{P}}$ANDA at FAIR, AFTER@LHC) and are best characterized by cross section ratios
- Two examples:

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

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

  - 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

Production & Feshbach?

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

No prompt production without Feshbach resonances!

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**

SELECTION RULES

ISOSPIN VIOLATION OF THE X(3872)

- An example of selection rule:
- Consider the down quark part of the *X(3872)* in the diquarkonium picture:

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

Fierz rearrangement

- The <u>closest threshold from below</u> 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)*:

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

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

- Only X_d is produced via this mechanism $\longrightarrow$ isospin violation
  $\longrightarrow$ no hyperfine neutral doublet

SELECTION RULES

THE $X^{\pm}$ *AND THE* X_b

- The procedure can be applied to other cases:

- X^+ *(A)* Diquark model predicts $M(X^{\pm}) \simeq M(X^0)$
  (B) Closest orthogonal threshold is $D^+\bar{D}^{*0},\ \bar{D}^0 D^{*+}$
  (C) Detuning is negative $\delta \simeq -5\ \mathrm{MeV} < 0 \longrightarrow$ the state is not formed!

- X_b *(A)* Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)\ \mathrm{MeV}$
  (B) The closest orthogonal threshold is $M(B^0 B^{*0}) = (10604.4 \pm 0.3)\ \mathrm{MeV}$
  (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*:

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

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