“Sapienza” Università di Roma – INFN sez. Roma 1

Exotic Hadron Spectroscopy

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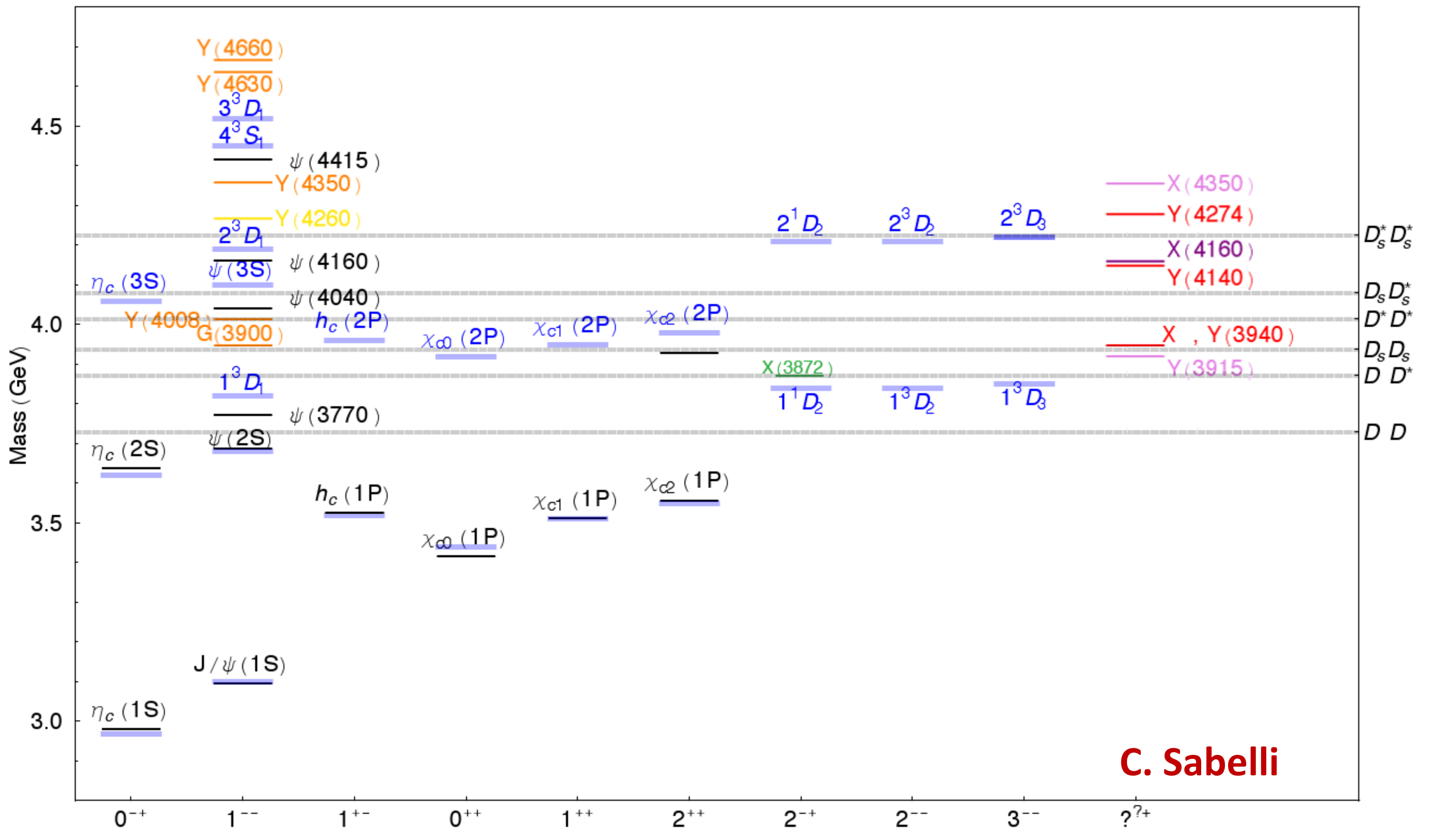
Lattice QCD and Hadron physics, ECT* Trento – January 14th, 2014

in coll. w/ Esposito, Faccini, Maiani, Papinutto, Piccinini, Polosa, Riquer, Tantalo

Outline

- «Exotic landscape»
- $Z_c(3900)$ and $Z'_c(4025)$: tetraquarks?
- Feshbach resonances
- Doubly charmed tetraquarks
- Conclusions

Exotic landscape



Exotic landscape

In last ten years a lot of **exotic resonances** that do not fit the quarkonium model have appeared

Nowadays, the most assessed are

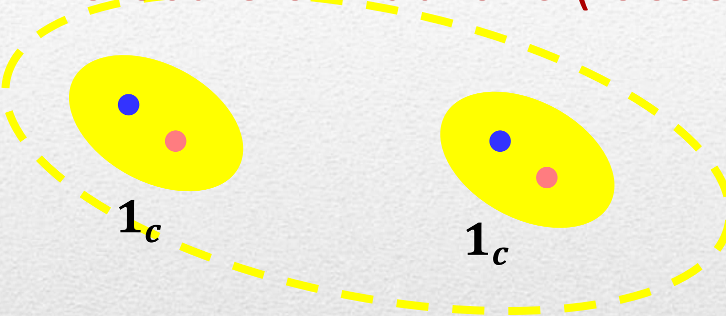
- $X(3872)$, $J^{PC} = 1^{++}$, no charged partners, huge isospin violation
- $Z_c(3900)$, $J^{PC} = 1^{+-}$, charged state
- $Y(4260)$, $J^{PC} = 1^{--}$, no charged partners

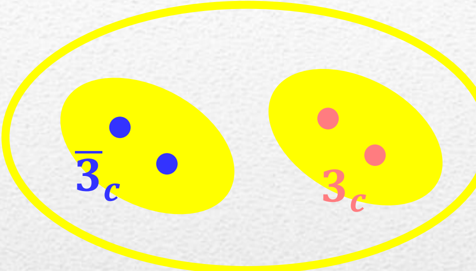
- $Z_b(10610)$ with $J^{PC} = 1^{+-}$, charged state
- $Z_b'(10650)$ with $J^{PC} = 1^{+-}$, charged state

A convincing comprehensive framework which includes all these states is still missing

Proposed models

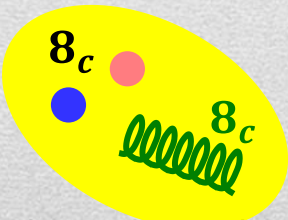
Molecule of hadrons (loosely bound)





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

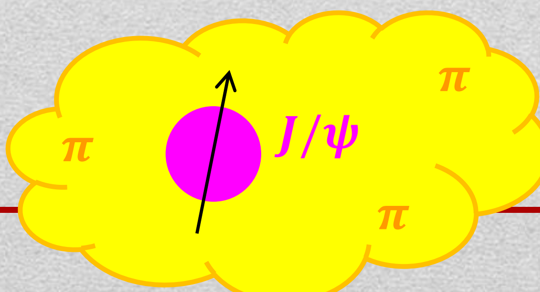
Diquark-antidiquark
(tetraquark)



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

Glueball & Hybrids
(with valence gluons)

Hadrocharmonium
(Van der Waals forces)



…or a superposition of all these

$Z_c(3900)$

Found in $Y(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp} \to J/\psi\,\pi^{\pm}\,\pi^{\mp}$

Exotic charged charmonium-like state! $I^G J^{PC} = 1^+ 1^{+-}$ (tbc)

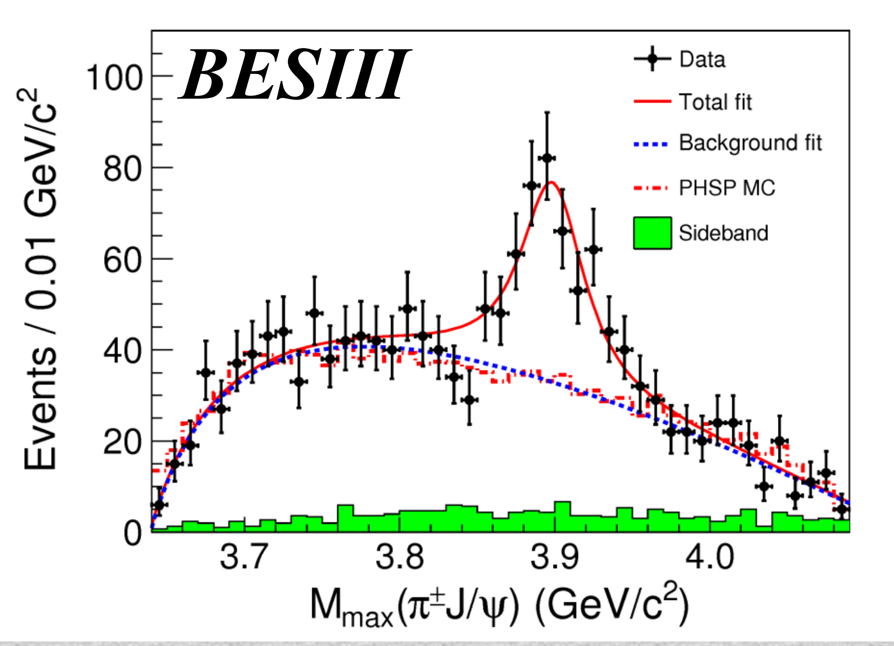
(note that the DD^* threshold is at 3876 MeV)

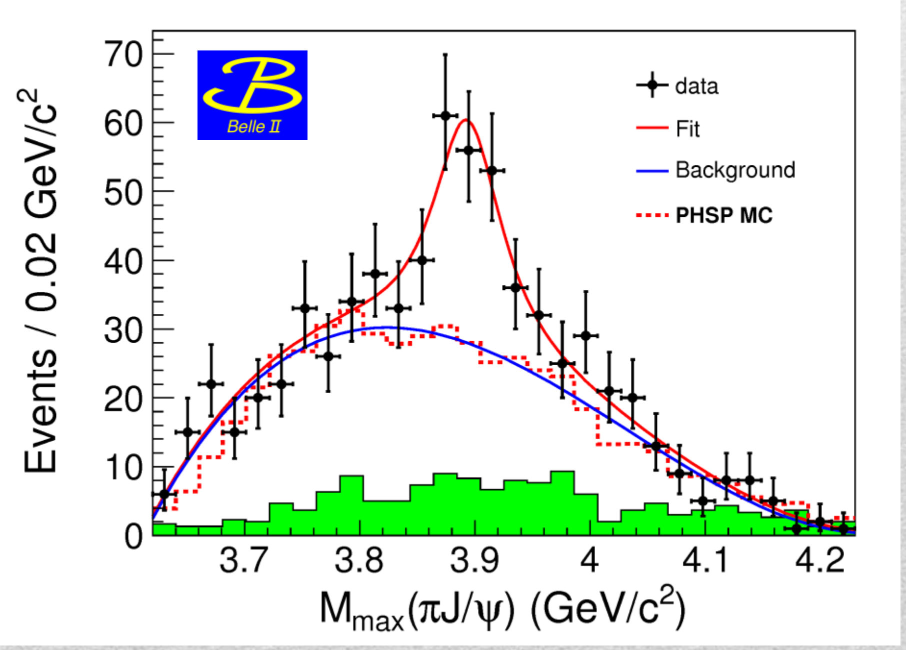
BESIII, PRL110 (2013) 252001

$M = 3899.0 \pm 3.6 \pm 4.9$ MeV
$\Gamma = 46 \pm 10 \pm 20$ MeV

Belle, PRL110 (2013) 252002

$M = 3894.5 \pm 6.6 \pm 4.5$ MeV
$\Gamma = 63 \pm 24 \pm 26$ MeV





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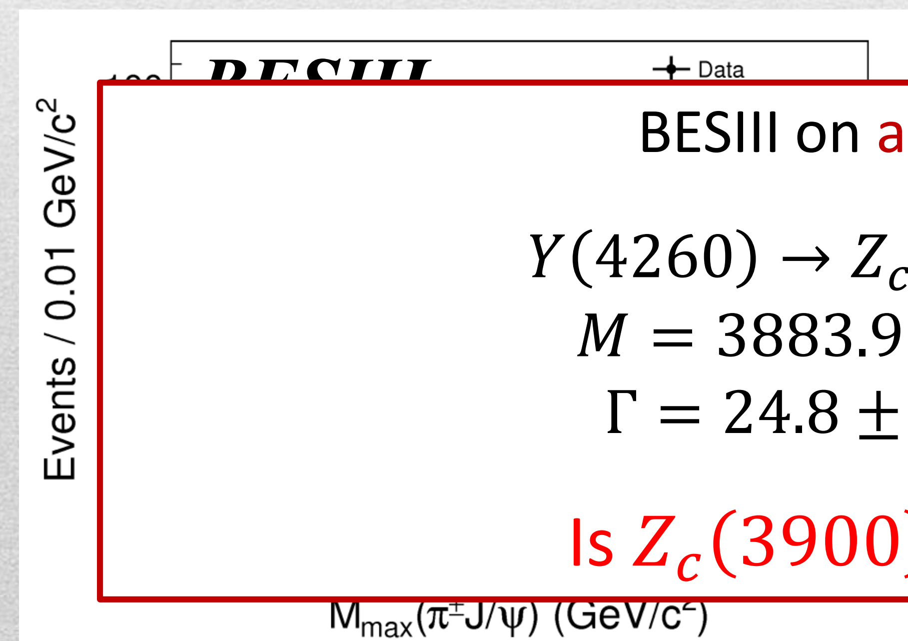
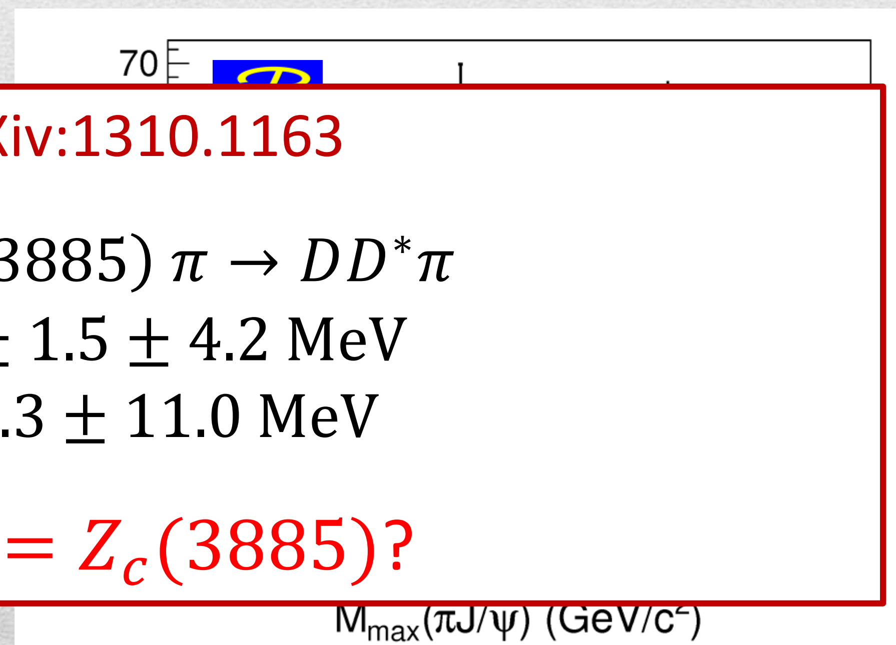




BESIII on arXiv:1310.1163

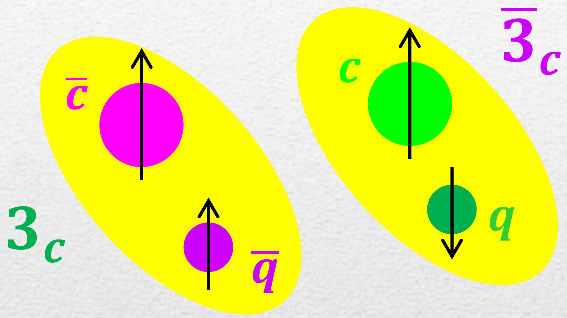
$$Y(4260) \to Z_c(3885)\,\pi \to DD^*\pi$$
$$M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$$
$$\Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$

Is $Z_c(3900) = Z_c(3885)$?

Tetraquark

One of the models for the **X(3872)** is a compact **diquark-antidiquark bound state**

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

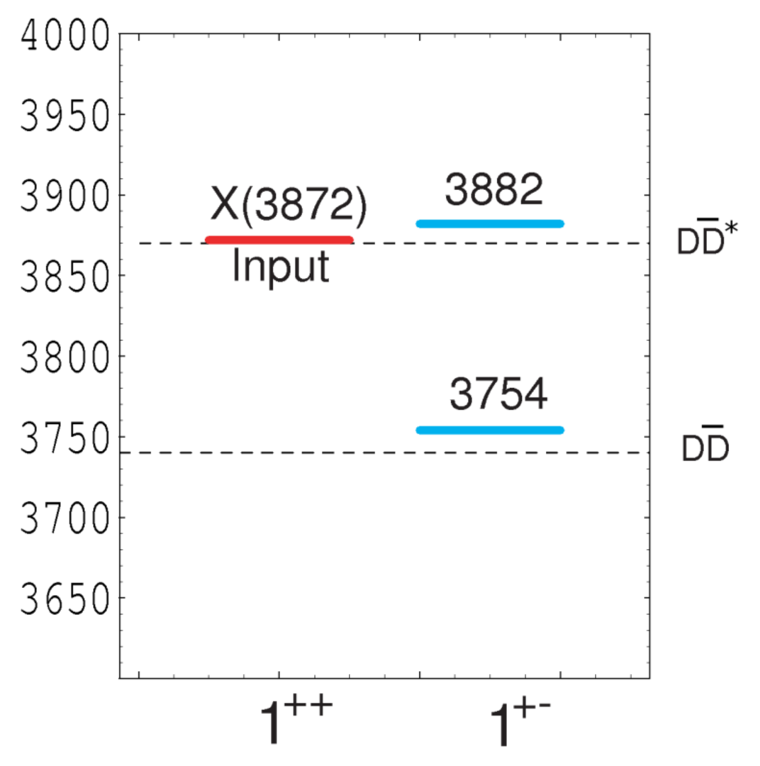


Maiani *et al.* PRD71 014028

We can evaluate mass spectrum in a constituent quark model

$$H = -2\sum_{i<j} \kappa_{ij}\, \vec{S_i} \cdot \vec{S_j}\, \frac{\lambda_i^a}{2}\frac{\lambda_j^a}{2}$$

Tetraquark



1^{+-} state at 3882 MeV compatible with $Z_c(3900)$!

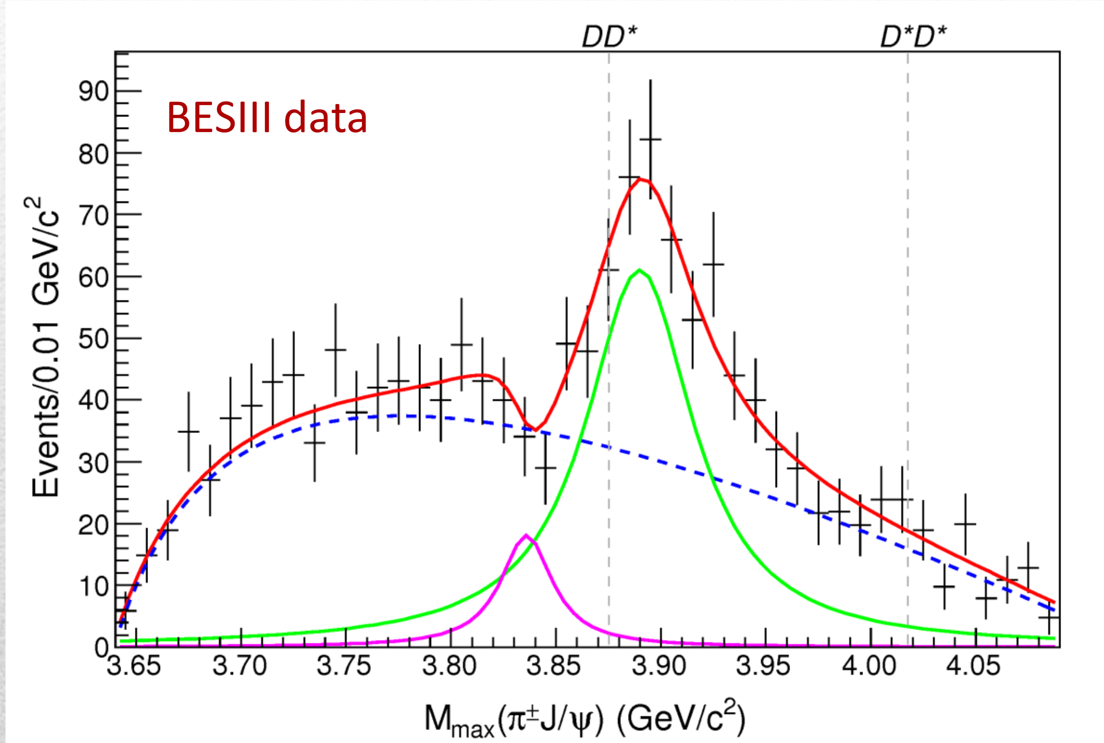
Prevision for other states:

- Neutral $I^G = 1^+$ partner ~ 3900 MeV
- Neutral $I^G = 0^-$ partner ~ 3900 MeV
- Charged/neutral 1^{+-} states ~ 3755 MeV

- Look for a $Z_c'(3760)$ about ~ 100 MeV below $Z_c(3900)$
- Look for the prominent decay $Z_c(3900) \to \eta_c \rho$

Combined BES-Belle fit

Is there room for a lighter resonance?



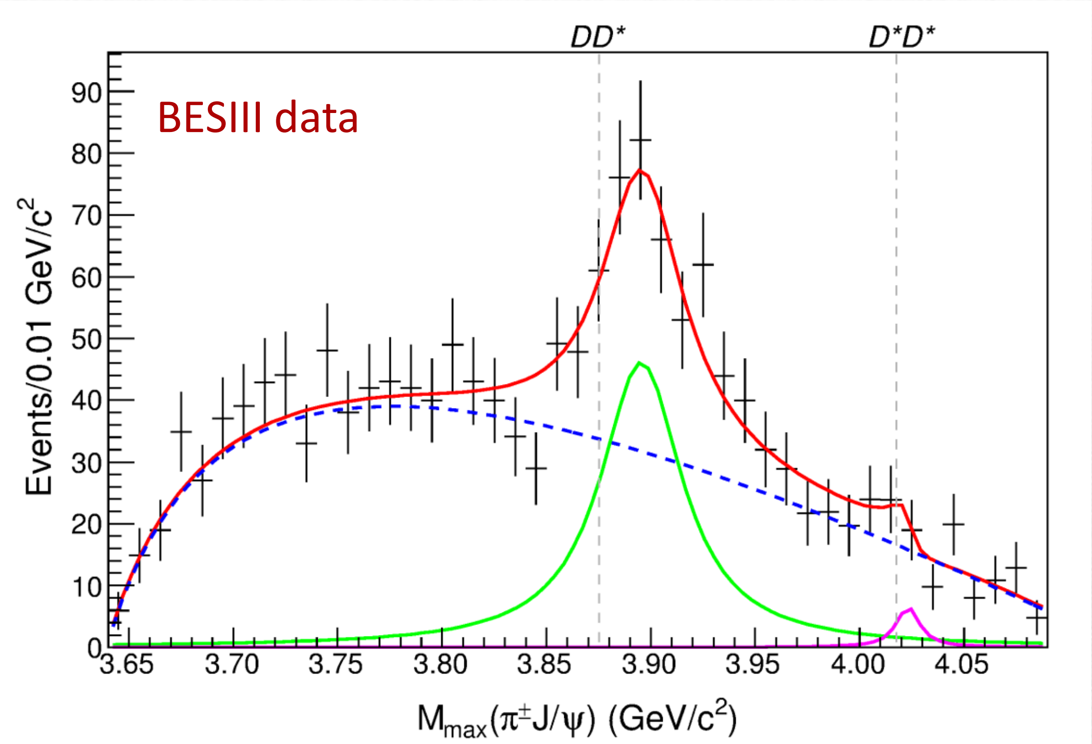
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 (2013) 111102

Z_c	$M = 3890 \pm 6$ MeV $\Gamma = 62 \pm 12$ MeV
Z_c'	$M' = 3836 \pm 13$ MeV $\Gamma' = 30 \pm 18$ MeV
	$\Delta\phi = (109 \pm 30)^\circ$

$$\chi^2/\mathrm{DOF}=41/65,\ CL = 99.0\%$$

Combined BES-Belle fit

What about the D^*D^* molecule?



Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 (2013) 111102

Z_c	$M = 3895 \pm 3$ MeV
	$\Gamma = 48 \pm 8$ MeV
Z_c'	$M' = 4023 \pm 6$ MeV
	$\Gamma' = 13 \pm 26$ MeV
	$\Delta\phi = (196 \pm 77)^\circ$

$$\chi^2/\text{DOF}=47/65, CL = 95.0\%$$

But Nature is malicious…

$Z_c'(4020), Z_c'(4025)$

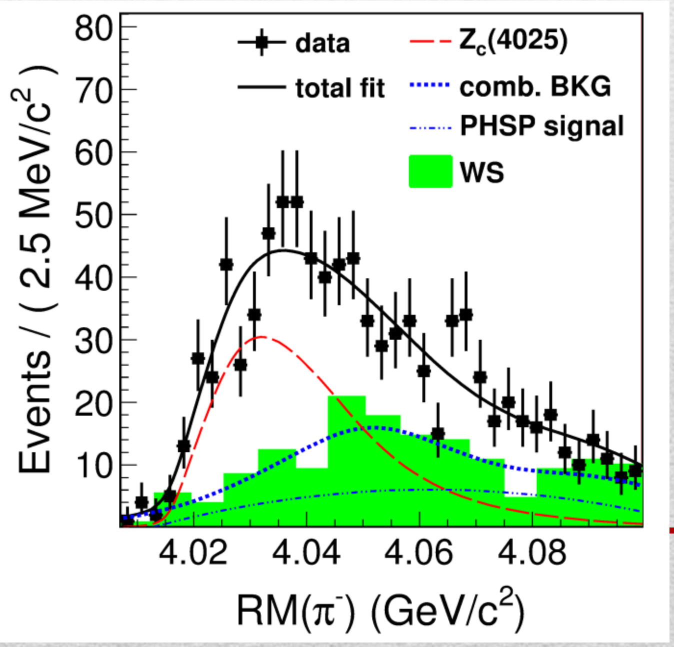
BESIII, arXiv:1308.2760

$$Y(4260) \to Z_c'(4025)\,\pi \to D^*D^*\pi$$

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

$$M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}$$

$$\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$$



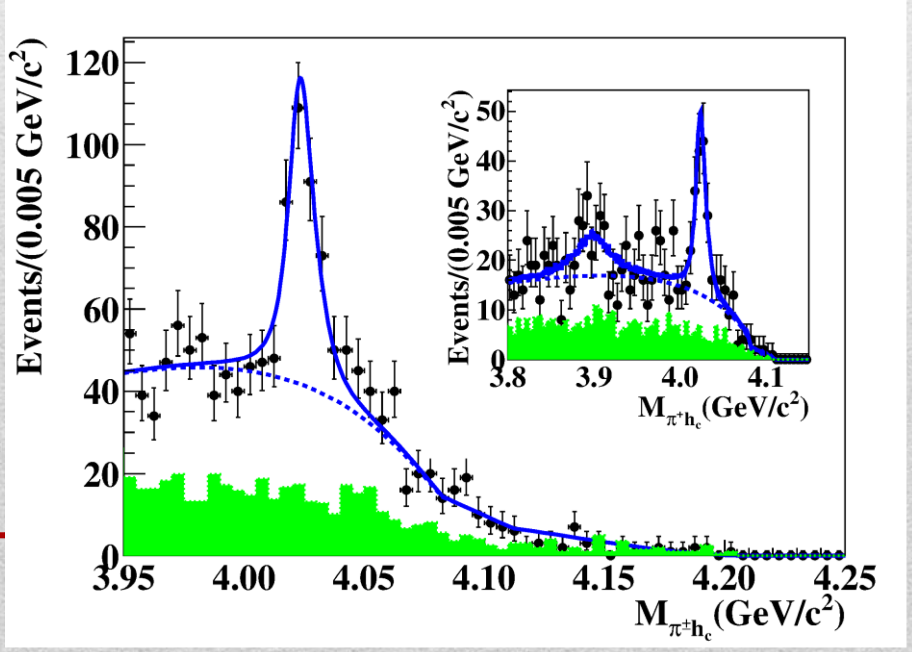
BESIII, arXiv:1309.1896

$$Y(4260) \to Z_c'(4020)\,\pi \to h_c\pi\pi$$

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

$$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$$

$$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$



$Z_c'(4020), Z_c'(4025)$

BESIII, arXiv:1308.2760

$Y(4260) \to Z_c'(4025)\,\pi \to D^* D^* \pi$

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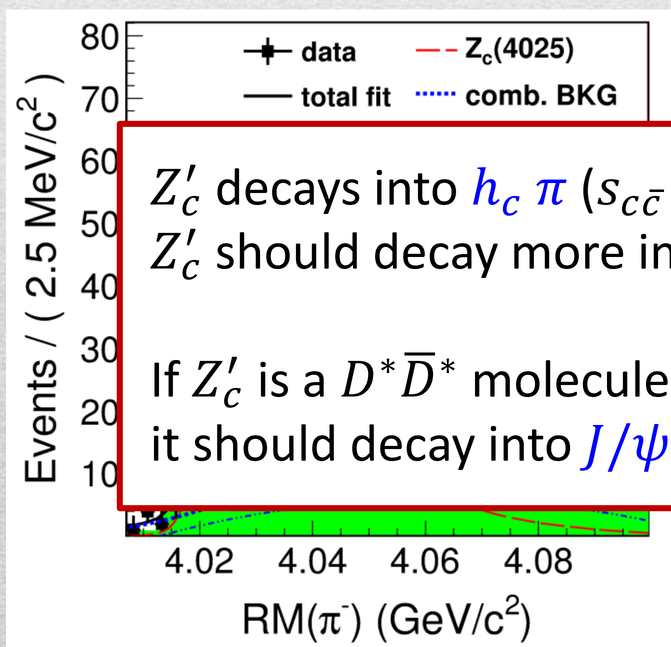
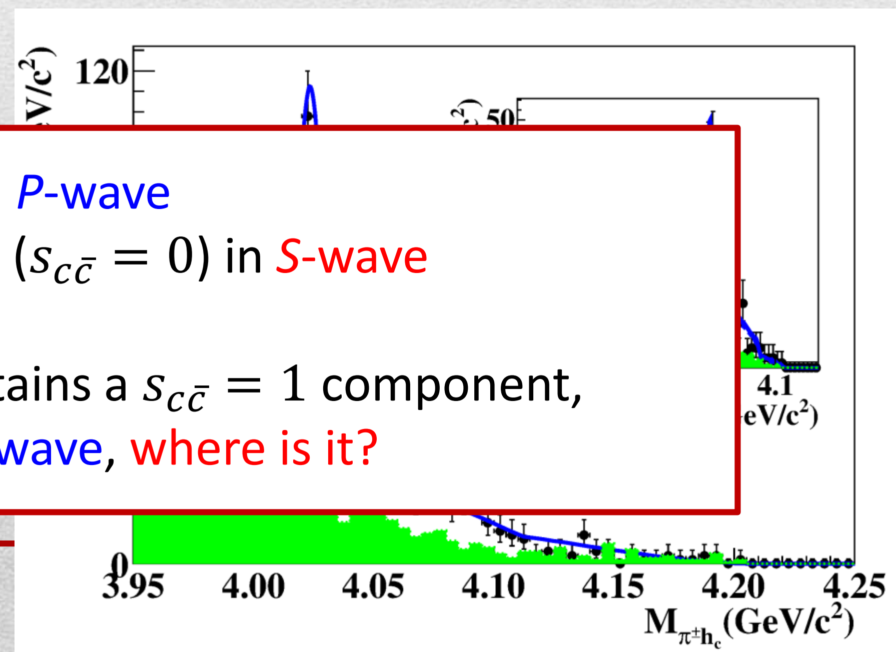




Z_c' decays into $h_c\,\pi$ ($s_{c\bar{c}} = 0$) in P-wave
Z_c' should decay more into $\eta_c\,\rho$ ($s_{c\bar{c}} = 0$) in S-wave

If Z_c' is a $D^*\overline{D}^*$ molecule, it contains a $s_{c\bar{c}} = 1$ component,
it should decay into $J/\psi\,\pi$ in S-wave, where is it?

X, Z_c, Z_c': summary

Molecule

- ✓ The states are near thresholds
- ✓ Large decay into open charm
- × Dynamical effects make the pattern obscure
- × How to justify bound states with positive binding energy?

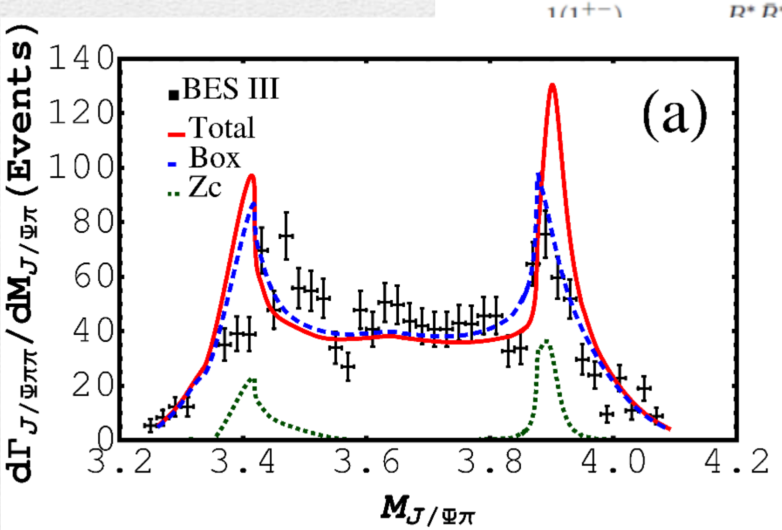
Tetraquark

- ✓ The pattern is simple, based on $SU(3)$
- × Many states are missing, in particular charged partners of $X(3872)$
- × Who is $Z_c'(4025)$?

X, Z_c, Z_c': summary

V_C	$I(J^{PC})$	States	Thresholds	Masses ($\Lambda = 0.5$ GeV)	Masses ($\Lambda = 1$ GeV)	Measurements
C_{0X}	$0(1^{++})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$	3875.87	3871.68 (input)	3871.68 (input)	3871.68 ± 0.17 [33]
	$0(2^{++})$	$D^*\bar{D}^*$	4017.3	4012^{+4}_{-5}	4012^{+5}_{-12}	?
	$0(1^{++})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})$	10604.4	10580^{+9}_{-8}	10539^{+25}_{-27}	?
	$0(2^{++})$	$B^*\bar{B}^*$	10650.2	10626^{+8}_{-9}	10584^{+25}_{-27}	?
	$0(2^{+})$	D^*B^*	7333.7	7322^{+6}_{-7}	7308^{+16}_{-20}	?
C_{0Z}	$1(1^{+-})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})$	10604.4	10602.4 ± 2.0 (input)	10602.4 ± 2.0 (input)	10607.2 ± 2.0 [5]
						10597 ± 9 [34]
	$1(1^{+-})$	$B^*\bar{B}^*$	10650.2	10648.1 ± 2.1	$10648.1^{+2.1}_{-2.5}$	10652.2 ± 1.5 [5]
						10649 ± 12 [34]
		$D^*\bar{D})$	3875.87	3871^{+4}_{-12} (V)	3837^{+17}_{-35} (V)	$3899.0 \pm 3.6 \pm 4.9$ [24]
						$3894.5 \pm 6.6 \pm 4.5$ [25]
			4017.3	4013^{+4}_{-11} (V)	3983^{+17}_{-32} (V)	?
			7333.7	$7333.6^{\dagger}_{-4.2}$ (V)	7328^{+5}_{-14} (V)	?

Nieves *et al.* PRD88 (2013) 054007



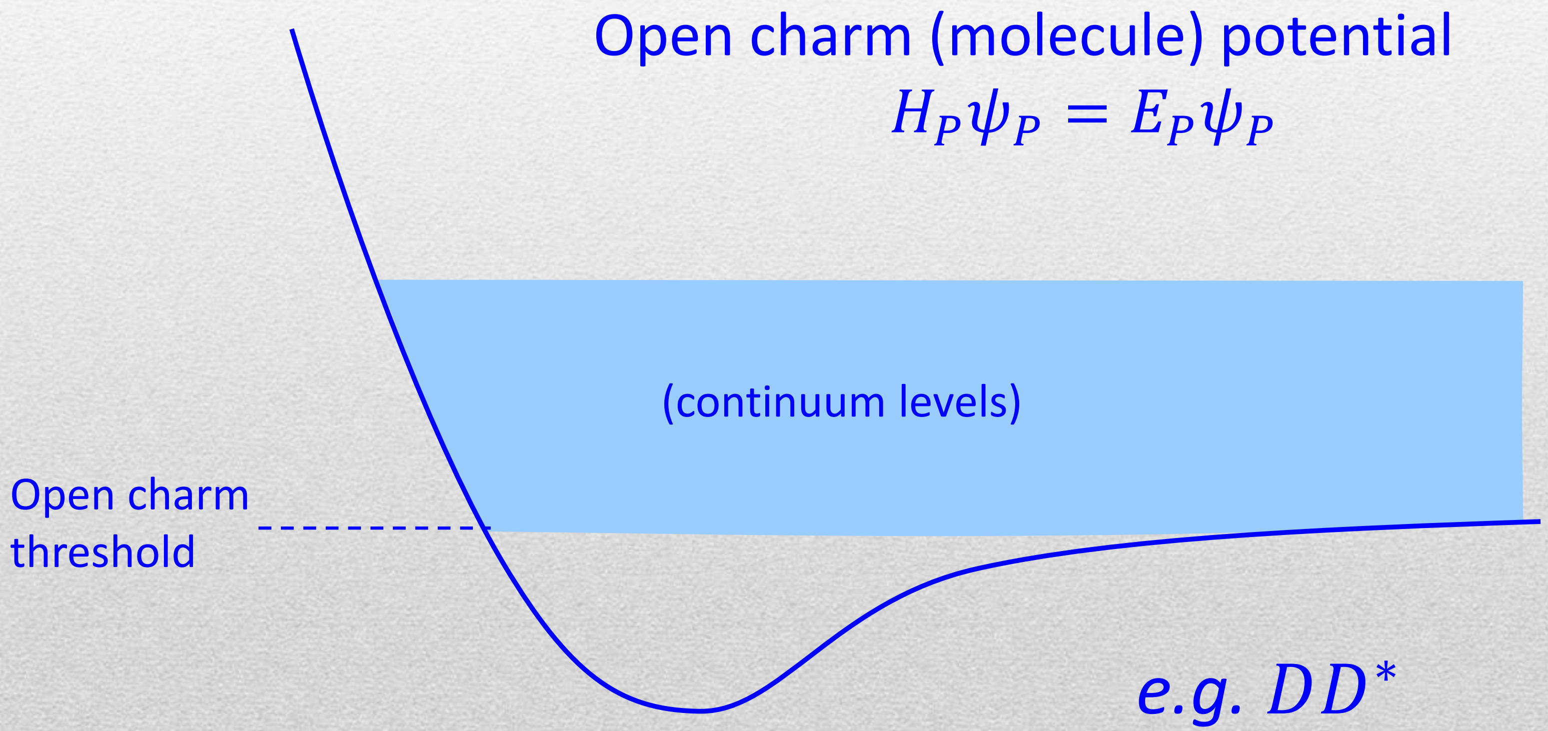
Hanhart *et al.* PRL111 (2013) 132003

In all calculations, molecular resonances are at or below threshold.
Is there a mechanism to push a bound state above threshold?

Feshbach resonances

Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374

In cold atoms there is a mechanism that occurs when two atoms can interact with two potentials, resp. with continuum and discrete spectrum



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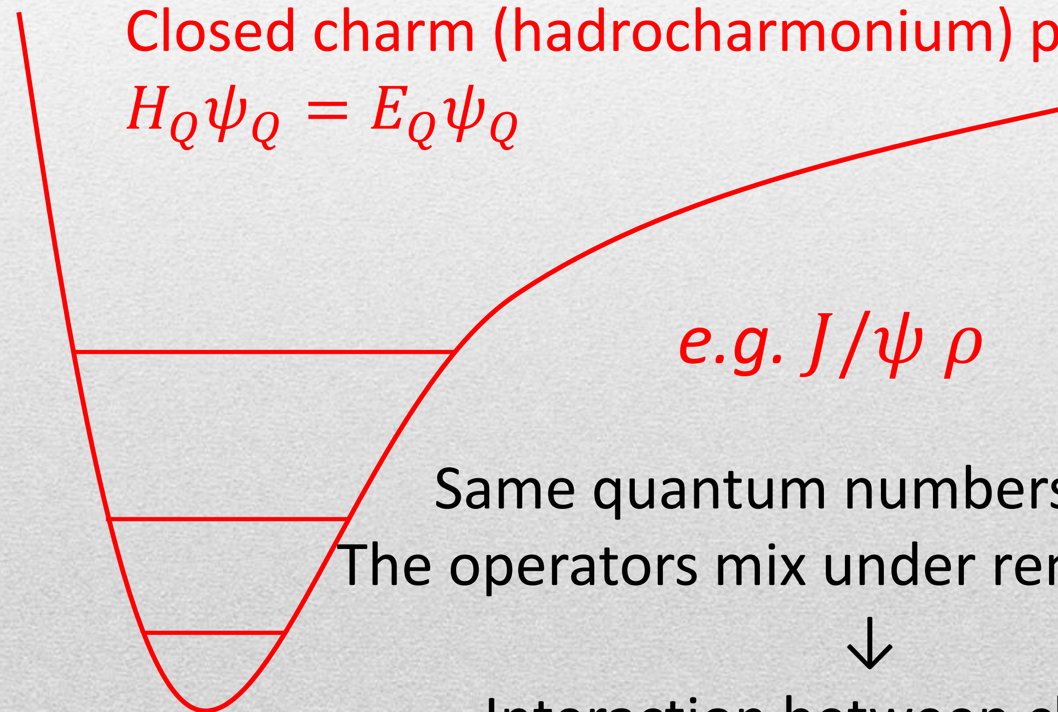


Closed charm (hadrocharmonium) potential

$H_Q \psi_Q = E_Q \psi_Q$

e.g. $J/\psi\ \rho$

Same quantum numbers as DD^*,

The operators mix under renormalization

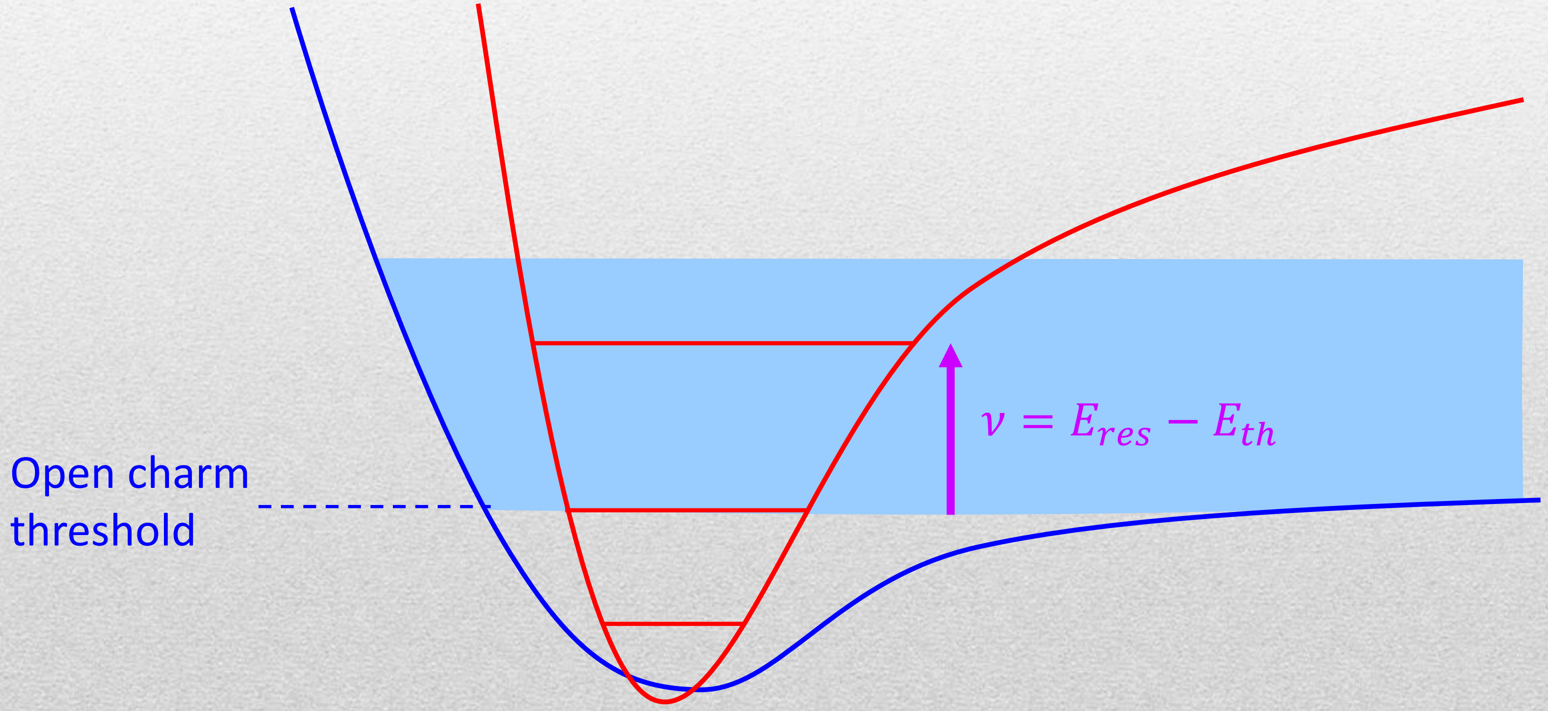
↓

Interaction between channels

Feshbach resonances

We add an interaction Hamiltonian H_{QP} so that

$$a \simeq a_P + C \sum \frac{\left|\langle \psi_i | H_{QP} | \psi_{th} \rangle\right|^2}{E_{th} - E_i} \simeq a_{NR} - C \frac{\left|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle\right|^2}{\nu}$$



Feshbach resonances

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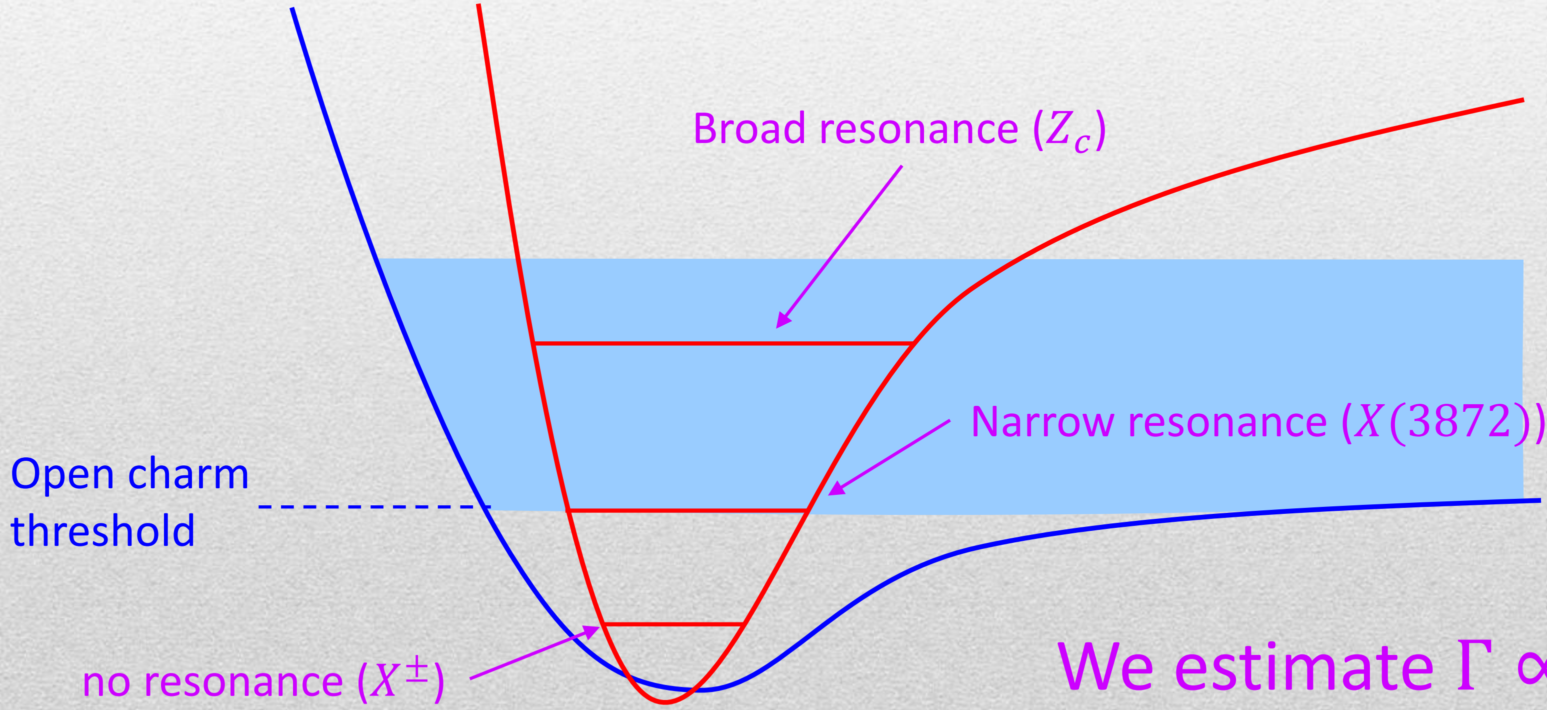


We estimate $\Gamma \propto \sqrt{\nu}$

Feshbach resonances

The Hadrocharmonium spectrum is unknown,
it can be deduced from the mass of the resonance,
otherwise one can naively expect $M_{\text{Hch}} \approx M_{c\bar{c}} + M_{\text{light}}$

We impose a cutoff on ν and $\Gamma_D < \nu$

Charm sector

Open channel	Hadroch.	M_{Hch} (MeV)	ν (MeV)	$I^G J^{PC}$	name
$D^{*0}\overline{D}^0$	$J/\psi\ \ \rho^0$	3872	0	$1^- 1^{++}$	$X(3872)$
$D^{*+}\overline{D}^0$	$\psi(3770)\ \ \pi^+$	3900	24	$1^+ 1^{+-}$	$Z_c(3900)$
$D^{*+}\overline{D}^0$	$h_c(2P)\ \ \pi^+$ (P-wave)	4025	8	$1^+ 1^{+-}$	$Z_c'(4025)$

The vector state $Y(4260)$ does not fit this scheme → Hybrid?
Hadron Spectrum coll. JHEP 1207 (2012) 126, see also Santopinto et al. PRD78 (2008) 056003

Feshbach resonances

$X(3872)$ should be a $I = 1$ state, but $M(J/\psi\,\rho^+) < M(D^{+*}\overline{D}^0)$

No charged states, isospin violation!

If we assume $\Gamma = A\sqrt{\nu}$, we can use $Z_c(3900)$ as input to extract $A = 10 \pm 5\ \mathrm{MeV}^{1/2}$

This value is compatible for all resonances

(still large errors...)

Bottom sector

Open channel	Hadrobott.	M_{Hbt} (MeV)	ν (MeV)	$I^G J^{PC}$	name
$B^{*+}\bar{B}^0$	$\chi_{b0}(1P)\ \rho^+$ (P-wave)	10610	3	1^+1^{+-}	$Z_b(10610)$
$B^{*+}\bar{B}^{*0}$	$\chi_{b0}(1P)\ \rho^+$ (P-wave)	10650	1.8	1^+1^{+-}	$Z_b'(10650)$

We remark that $\Gamma(Z_b')/\Gamma(Z_b) \approx 0.63$, $\nu(Z_b')/\nu(Z_b) \approx 0.77$

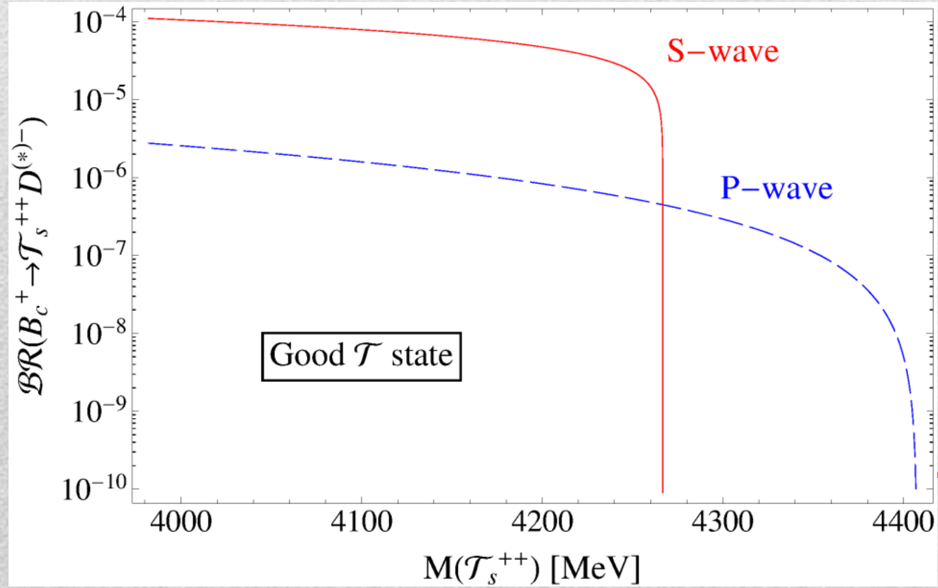
Doubly charmed states

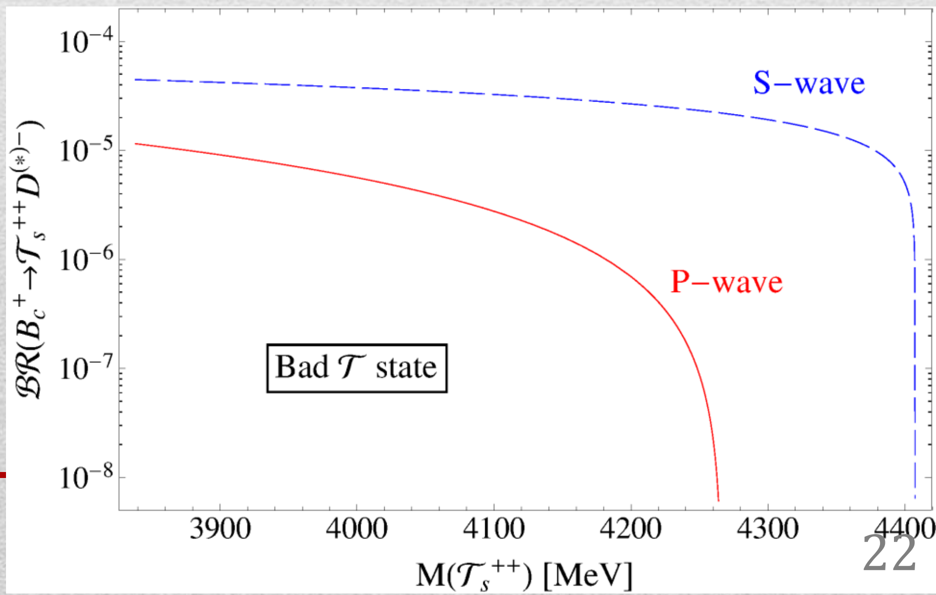
Another approach to choose among models,
is to predict states who fit only in one model

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

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





Doubly charmed states

Another approach to choose among models,
is to predict states who fit only in one model

The doubly charged state $T_s^{++} = [cc]_{S=1}\left[\bar{d}\bar{s}\right]_{S=0}$
could not be explained in the molecular picture
because of the Coulombian repulsion.

If $M(T_s^{++}) > 3979$ MeV the state could decay into $D^{*+}D_s^+$
and could be seen @LHC

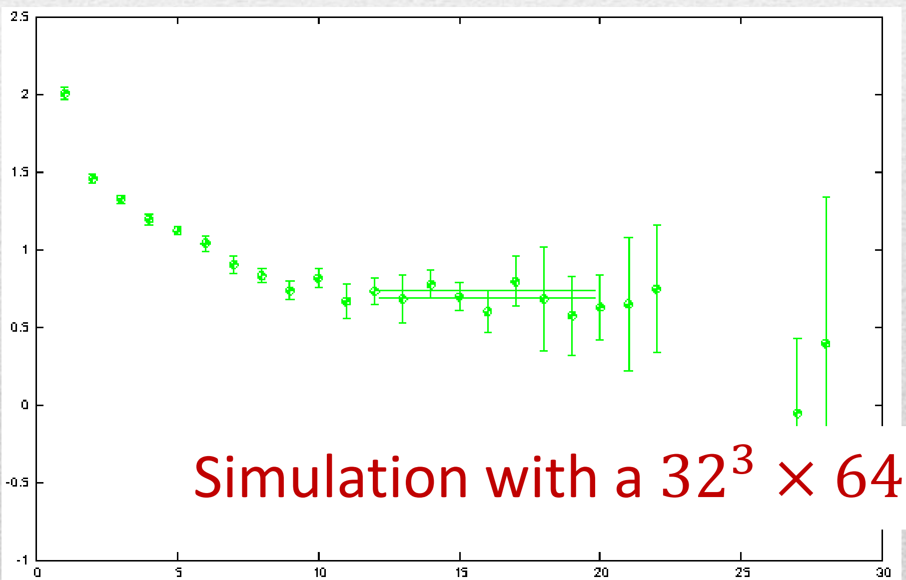
This state is particularly well-defined on the lattice,
because no disconnected diagrams are involved.

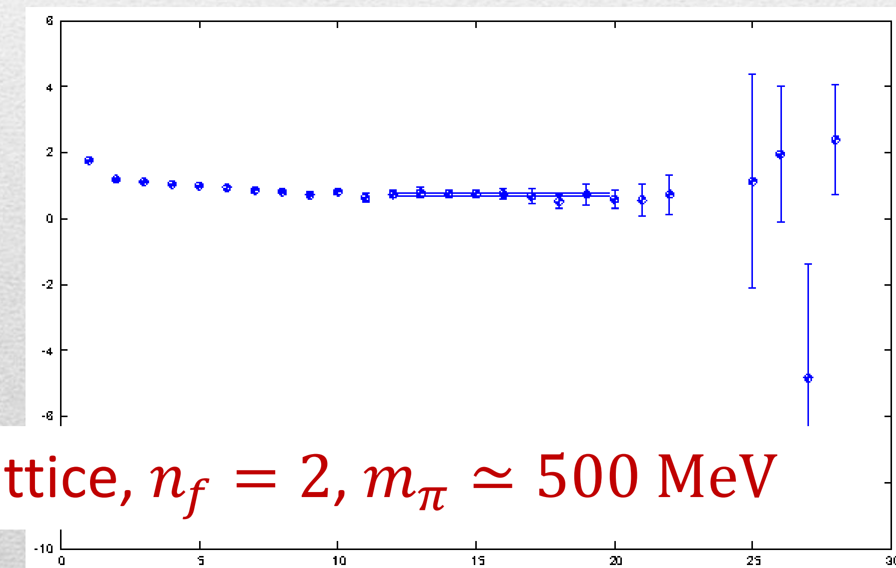
The calculation is ongoing…

Doubly charmed states

Just started the analysis of correlators $\langle O_1(x) O_1^\dagger(0) \rangle$
where $O_1 = \epsilon_{ABK} \bar{c}_c^A \gamma^i c^B \epsilon_{CDK} (\bar{d}^C \gamma^5 s_c^D - \bar{s}^C \gamma^5 d_c^D)$
is the interpolating operator of a $J^P = 1^+$ tetraquark

Guerrieri, Papinutto, AP, Polosa, Tantalo, work in progress





Simulation with a $32^3 \times 64$ lattice, $n_f = 2$, $m_\pi \simeq 500$ MeV

Lüscher's method is to be implemented

Conclusions

The study of exotic resonances in heavy quark sector
is still puzzling

- The tetraquark picture predicts $Z_c(3900)$, but misses $Z_c'(4025)$
- The molecular picture has troubles with above-threshold states and production mechanisms

- Look for missing states and decay modes who can help in excluding models
- Explore new production mechanisms to take into account at- and above-threshold states (see F.Piccinini's talk!)
- Propose and search new states who can falsify some models

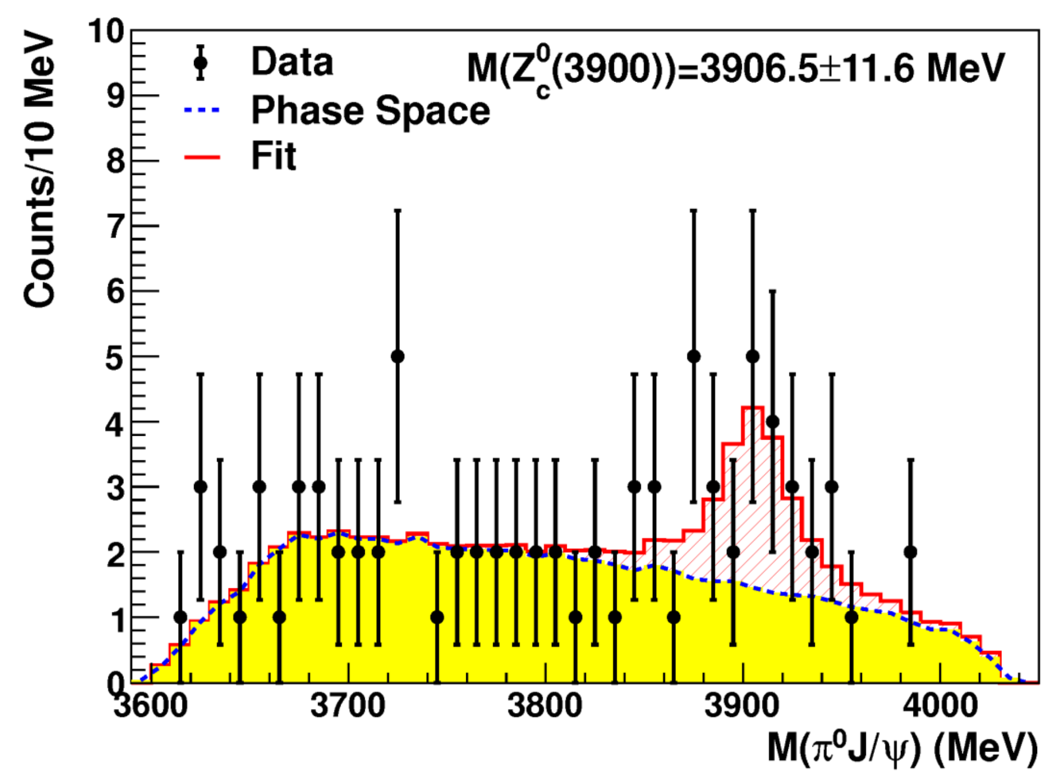
Thank you

BACKUP

$Z_c^0(3900)$ at CLEO?

A reanalysis of CLEO data shows a 3σ neutral resonance in

$$\psi(4160) \to \pi^0 Z_c^0 \to J/\psi\, \pi^0\, \pi^0$$



Xiao et al.
arXiv:1304.3036

$$M = 3907 \pm 12 \text{ MeV}$$
$$\Gamma = 34 \pm 29 \text{ MeV}$$

Isospin violation?
Look for $Z_c^0 \to J/\psi\, \eta$

Decay channels

Two questions:

- What can $Z_c(3900)$ decay into?
- Why is $Z_c(3900)$ much broader than $X(3872)$?

- $J/\psi\,\pi^+$
- $\psi(2S)\pi^+$
- $D^+\,\overline{D^{*0}}, D^{*+}\,\overline{D^0} \sim 4\text{ MeV}$
- $\eta_c\,\rho^+$
- $h_c\,\pi^+$ in P-wave
- Radiative decays

We suppose

$$g_{DD^*X(3872)} = g_{DD^*Z(3900)}$$

Decay channels

Two questions:

- What can $Z_c(3900)$ decay into?
- Why is $Z_c(3900)$ much broader than $X(3872)$?

- $J/\psi\,\pi^+ \sim 29\text{ MeV}$
- $\psi(2S)\pi^+ \sim 6\text{ MeV}$
- $D^+\,\overline{D^{*0}}, D^{*+}\,\overline{D^0} \sim 4\text{ MeV}$
- $\eta_c\,\rho^+ \sim 19\text{ MeV}$
- $h_c\,\pi^+$ in P-wave
- Radiative decays

No grounds for other couplings
We only suppose

$$g = M_{Z_c}$$

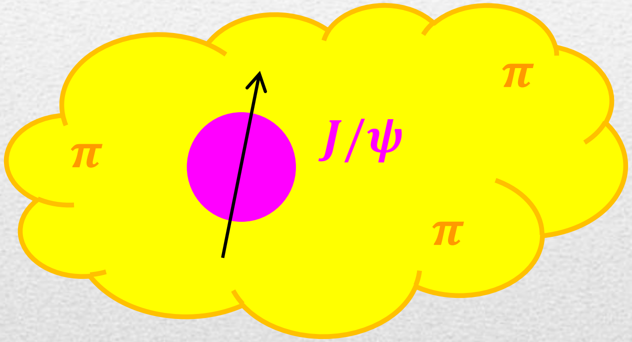
Some agreement with QCD sum rules
Dias *et al.* arXiv:1304.6433

$\Gamma \sim 60\text{ MeV}$, agrees with experimental value

Other models

Hadro-charmonium

Voloshin arXiv:1304.0380



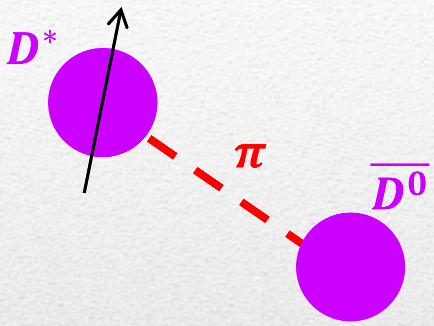
A $c\bar{c}$ state surrounded by light matter

Decay into $\eta_c\ \rho$ forbidden by HQSS

A light $Z_c'(3785)$ expected with $I^G J^{PC} = 1^- 0^{++}$
(not visible in $J/\psi\ \pi$ channel)

Other models

Molecule



Wang *et al.* arXiv:1303.6355

DD^* loosely bound molecule
1-π exchange attractive in $I^C = 1^-$ channel, although less than in $I^C = 0^+$ ($X(3872)$)

Tornqvist Z.Phys. C61 525-537

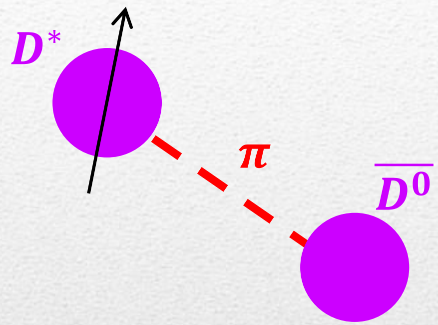
A molecule decays mostly into its constituents (long range decay)

Decays into charmonium + light mesons suppressed by $1/a$ (short range decay) Braaten *et al.* PRD69, 074005

e.g. $BR(X(3872) \to DD^*) \sim 70\%$, $BR(X(3872) \to J/\psi\, \rho) \sim 5\%$

Other models

Molecule



Wang *et al.* arXiv:1303.6355

DD^* loosely bound molecule
1-π exchange attractive in $I^C = 1^-$ channel,
although less than in $I^C = 0^+$ ($X(3872)$)

Tornqvist Z.Phys. C61 525-537

Expected with $\mathrm{BR}(\mathrm{Z_c} \to DD^*) \sim$ 70-80%
But we estimated $\Gamma(\mathrm{Z_c} \to DD^*) \sim 4$ MeV,
How to reach $\Gamma = 40$ MeV?

A light $Z_c'(3760)$ expected with $I^G J^{PC} = 1^- 0^{++}$
A heavy $Z_c''(4020)$ expected at $D^* D^*$ threshold

Voloshin
PRD 84, 031502

Other models

Molecule

$Z_c^0(3900)$ could violate isospin just like $X(3872)$

A $\Upsilon(4260) \to Z_c^0\, \pi^0 \to J/\psi\, \eta\, \pi^0$ could occur

If so, it cannot be accomodated into molecular picture:

In X(3872) isospin violation is due to

$\Delta = \mathrm{M}(\mathrm{D}^+\mathrm{D}^{-*}) - \mathrm{M}(\mathrm{D}^0\mathrm{D}^{0*}) \sim 8\ \mathrm{MeV}$

Hanhart *et al.* PRD85 011501

Z_c^0 is above both thresholds, and $\Delta \ll \Gamma$

In molecular picture Z_c^0 should be a pure isovector

Strong couplings

How do we evaluate $g_{DD^*X(3872)}$?

$$g^2_{DD^*X(3872)} = BR(X \to DD^*)\,\Gamma_X \left(\frac{p^*}{8\pi M_x^2} \overline{|M(X \to DD^*)|^2} \right)^{-1}$$

But if $M_X < M_D + M_{D^*}$ the decay momentum p^* is undefined

We average over a random set $(M_X)_i$, distributed as a Breit-Wigner, centered at $M_X = 3872$ MeV and with a width $\Gamma_X = 1.2$ MeV respecting the kinematical limits

$$M_D + M_{D^*} < (M_X)_i < \mathrm{M_B} - \mathrm{M_K}$$

We get $g_{DD^*X(3872)} = 2.5$ GeV

Strong couplings

The matrix element can be evaluated in an effective theory

$$\langle D(p)\, D^*(\eta, q)|X(\lambda, P)\rangle = g_{DD^*X}\, \eta\cdot\lambda$$

$$\frac{1}{3}\sum_{\text{pol}} |\langle D(p)\, D^*(\eta, q)|X(\lambda, P)\rangle|^2 = \frac{1}{3} g_{DD^*X}^2 \left(3 + \frac{p^{*2}}{M_X^2}\right)$$

The D-wave componenent is negligible with respect to the S-wave one

We get $g_{DD^*X(3872)} = 2.5\ \text{GeV}$

Strong couplings

What about other couplings?

We cannot relate $g_{X\psi\rho}$ to $g_{Z_c\psi\pi}$
(no chiral symmetry or HQSS)

But we are talking about S-wave decays
and we need couplings with the dimension of a mass

The main mass scale is the mass of the $Z_c(3900)$
So we estimate

$$g \sim M_{Z_c} \sim 3900 \text{ MeV}$$

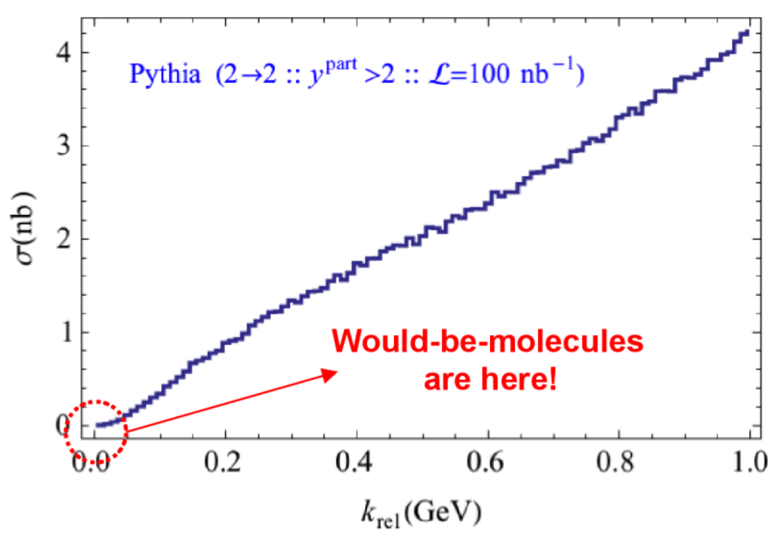
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances
The most popular interpretation is a $D^0\bar{D}^{0*}$ molecule

But the binding energy is $E_B \approx -0.14 \pm 0.22$ MeV: very small!
A simple square well model shows that $k_{\rm rel} \approx 50$ MeV

How many pairs can we produce at hadron colliders with such a small relative momentum?

Bignamini *et al.* PRL103 (2009) 162001



We obtain
$$\sigma(p\bar{p} \to DD^*) \approx 0.1 \text{ nb} @\sqrt{s} = 1.96 \text{ TeV}$$

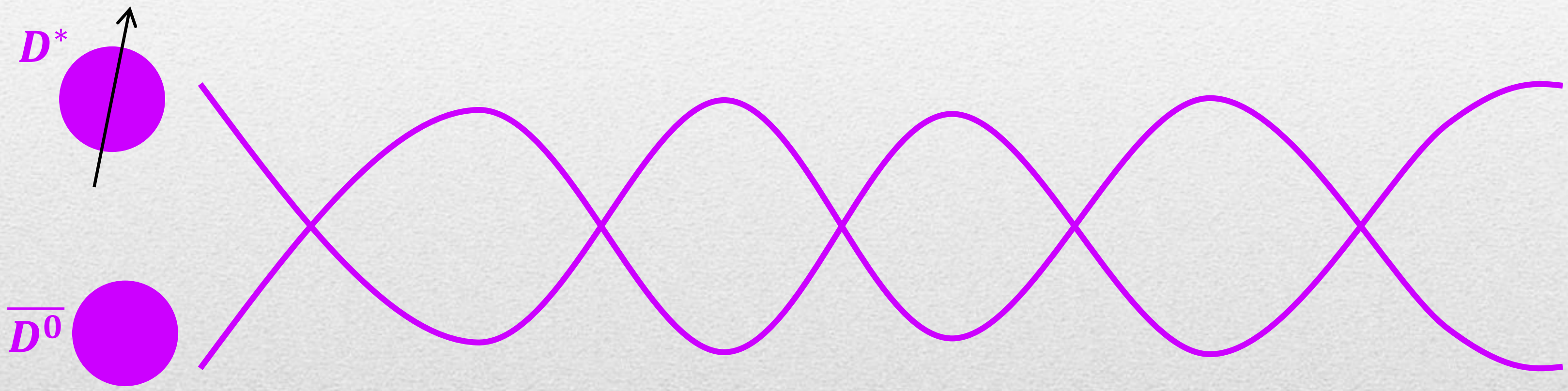
Experimentally
$$\sigma(p\bar{p} \to X(3872)) \approx 30 \text{ nb!!!}$$

Molecule challenged!!!

Prompt production of $X(3872)$

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

Artoisenet and Braaten PRD81 (2010) 114018



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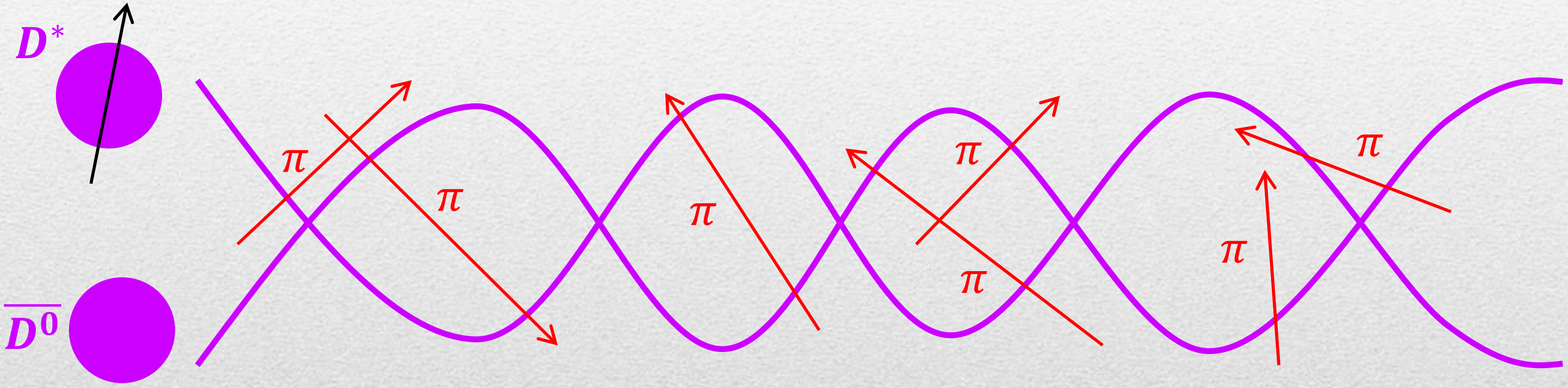
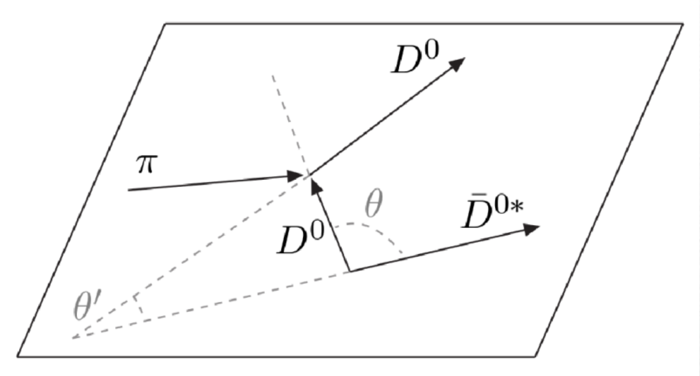


…but the application of Watson Theorem is spoiled by the presence of pions that interfere with DD^* propagation, Bignamini *et al.* PLB684 (2010) 228-230

(FSI have been used also by Meissner *et al.* arXiv:1308.0193 to estimate Z_c and Z_b prompt xsects, but the application to above-threshold states is unclear)

A new mechanism?

However, these pions can elastically interact with $D(D^*)$, and slow down the pairs DD^*

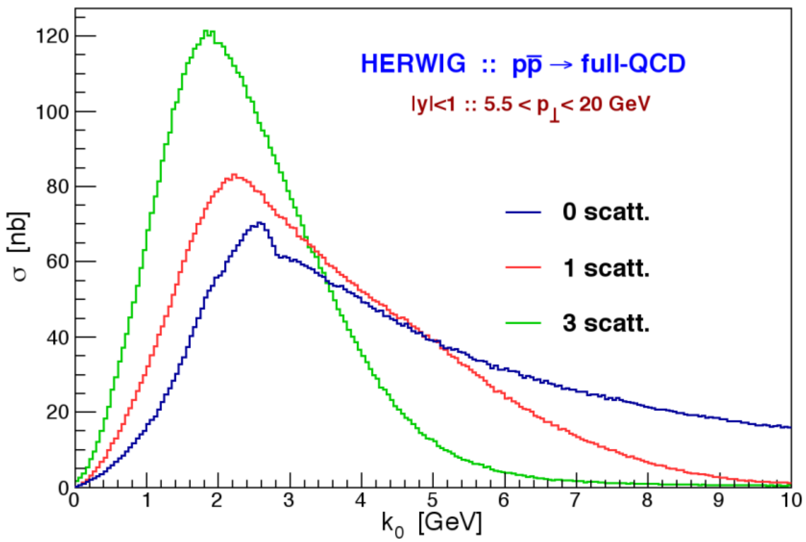


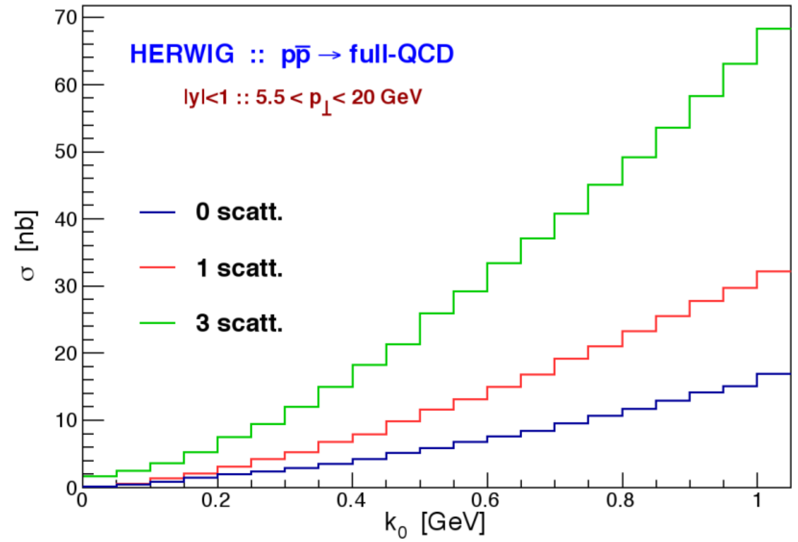
Esposito, Piccinini, AP, Polosa arXiv:1305.0527

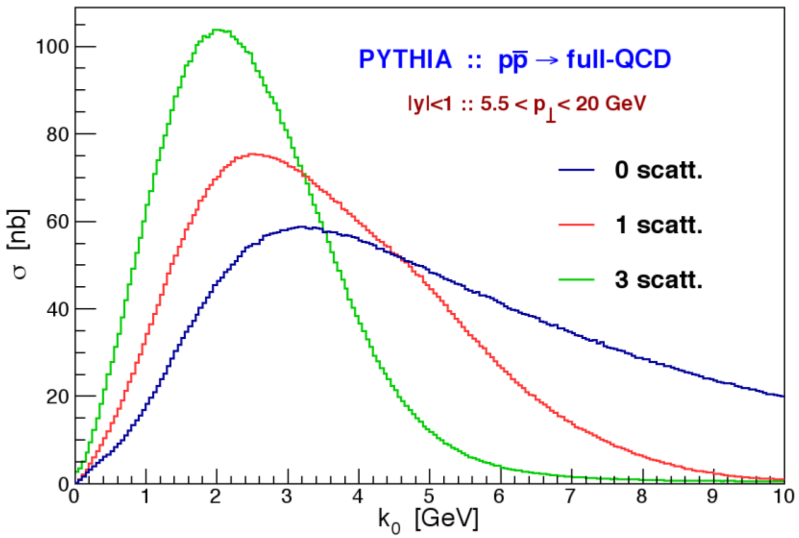
The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

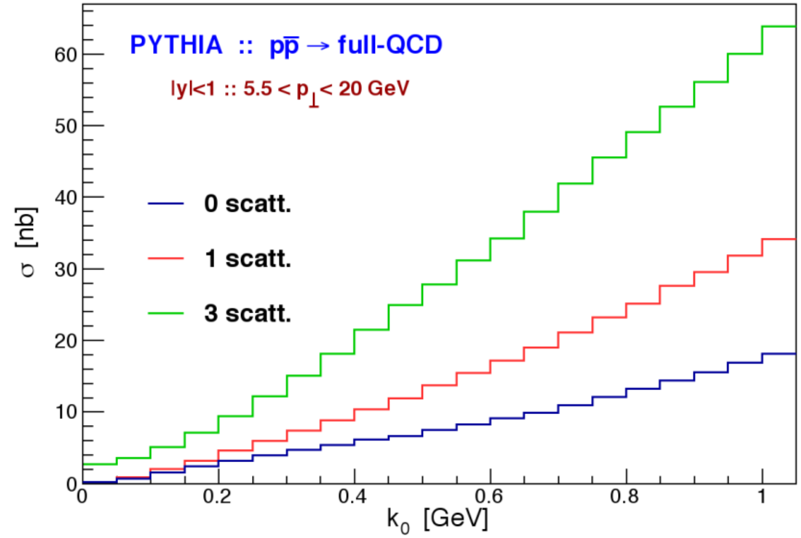
$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100$ keV

A new mechanism?









A new mechanism?

A. Esposito		Herwig		Pythia	
$k_0^{\max}$		50 MeV	100 MeV	50 MeV	100 MeV
No. of events	0 scatt.	52	253	240	1560
	1 scatt.	44	299	283	1984
	3 scatt.	843	2069	4843	11679
	4 scatt.	1166	2802	6489	14916
	5 scatt.	1689	4167	7770	18284
σ [nb]	0 scatt.	0.10	0.50	0.13	0.83
	1 scatt.	0.09	0.59	0.15	1.05
	3 scatt.	1.67	4.10	2.57	6.20
	4 scatt.	2.31	5.55	3.44	7.92
	5 scatt.	3.34	8.25	4.12	9.71

Striking increase of σ after each scattering!

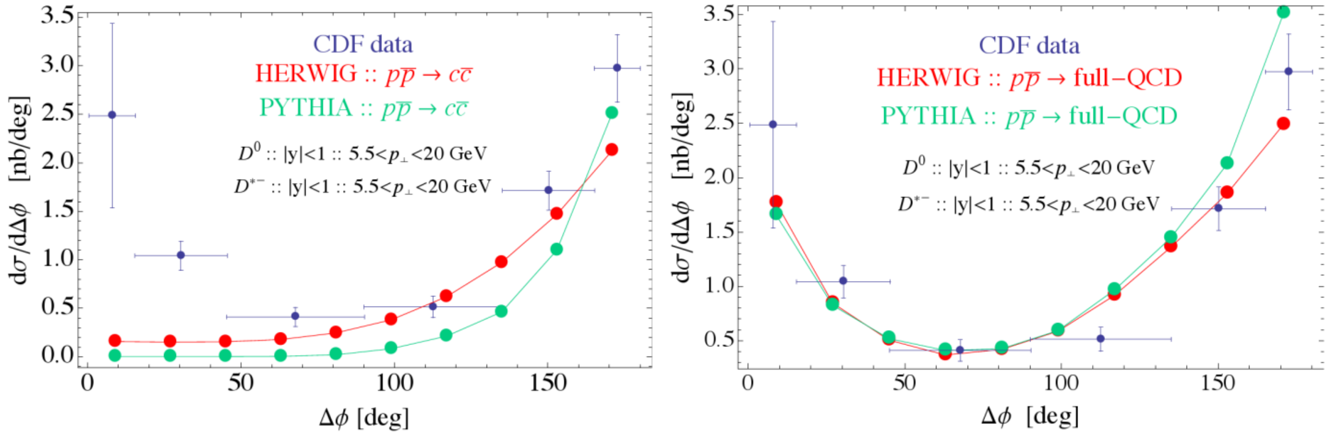
Down by a factor 5-7 wrt $\sigma_{\rm exp} \approx 30$ nb, further increases with 4-5 scatterings

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