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

Multiquark hadrons as Feshbach resonances

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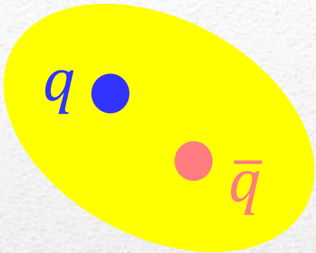
in coll. w/ A. Guerrieri, F. Piccinini, A.D. Polosa

Outline

- «Exotic landscape»
- Main models: tetraquarks and molecules
- The production paradox
- Feshbach resonances
- Conclusions

Quarkonium orthodoxy



Heavy quarkonium sector is extremely useful for the understanding of QCD

$\alpha_s(M_Q) \sim 0.3$
(asymptotic freedom)
OZI-rule

Potential models

(meaningful when $M_Q \to \infty$)

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

(Cornell potential)

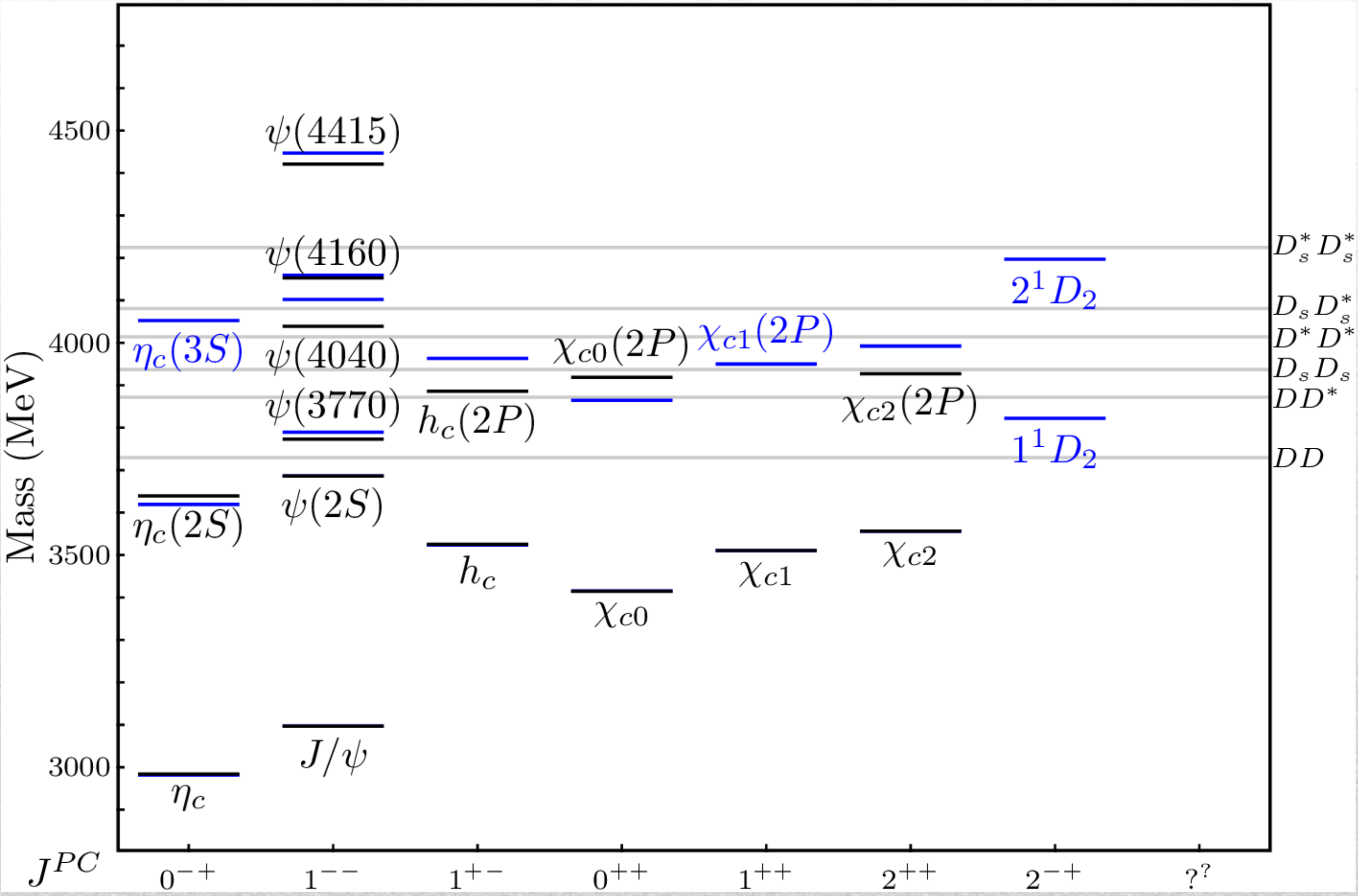
Solve NR Schrödinger eq. → spectrum

Effective theories

(HQET, NRQCD...)

Integrate out heavy DOF
↓
(spectrum), decay & production rates

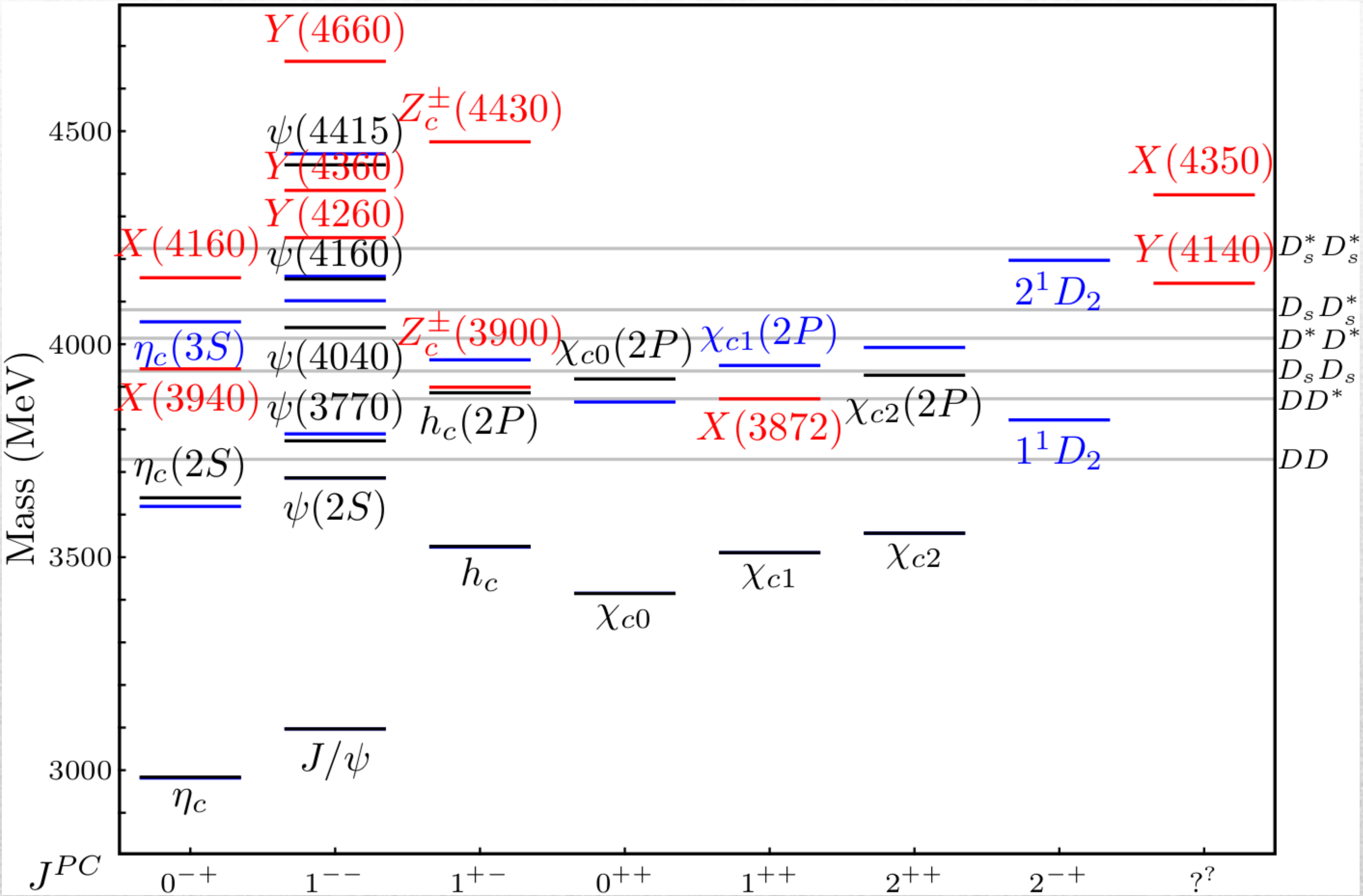
Quarkonium orthodoxy



Above thresholds, some discrepancy with predictions

Still good understanding of spectrum and decay pattern

Quarkonium orthodoxy?

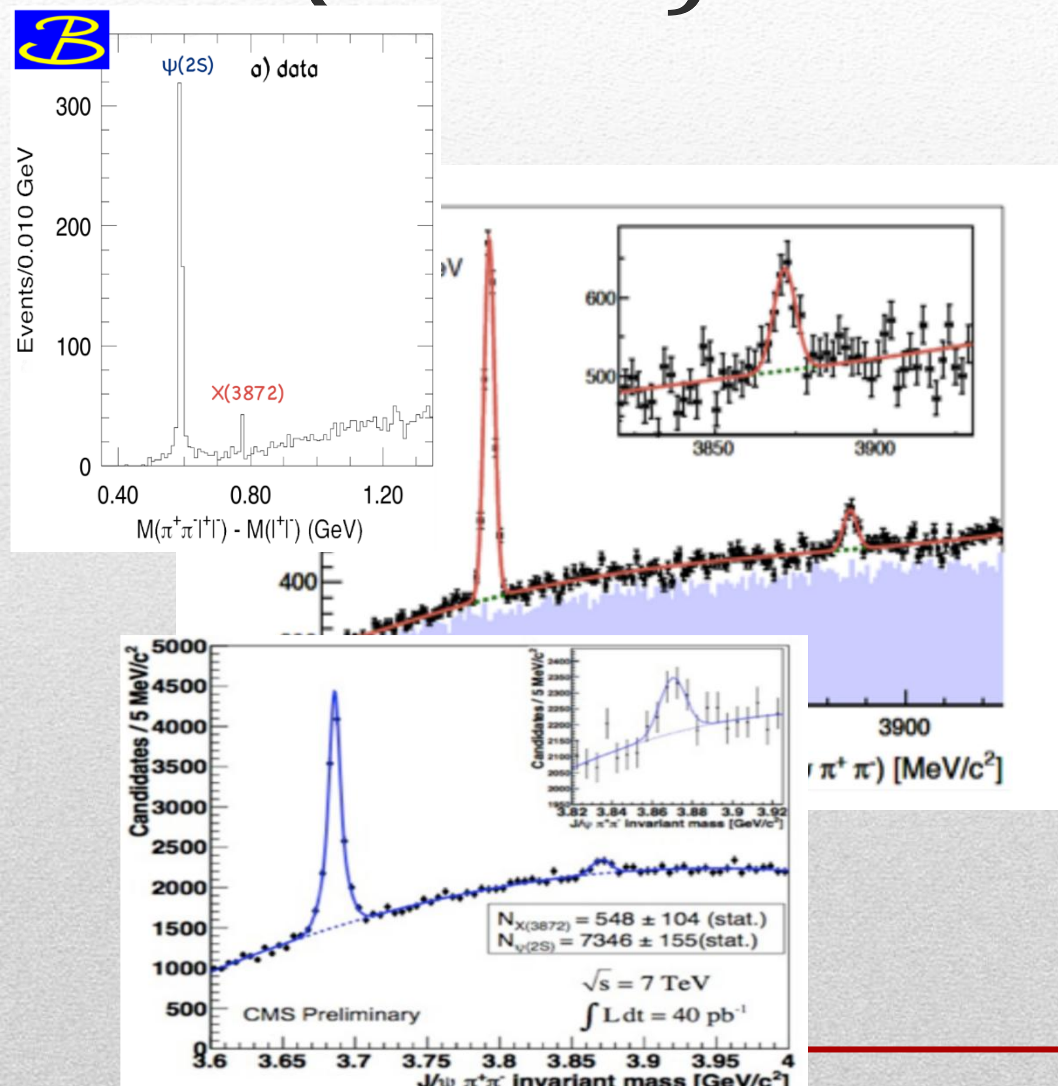


A host of unexpected resonances have appeared

decaying into charmonium + light

Hardly reconciled with usual charmonium interpretation

X(3872)



- 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 $\chi_{c1}(2P)$

$$M = 3871.68 \pm 0.17\ \text{MeV}$$
$$M_X - M_{DD^*} = -0.14 \pm 0.22\ \text{MeV}$$
$$\Gamma < 1.2\ \text{MeV}\ @90\%$$
$$J^{PC} = 1^{++}$$

$Z_c(3900)$

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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 to… and the Belle Collaboration in Japan reported they had sorted through th… seen a mysterious particle that appeared to contain four quarks. Though… $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining tra… that appear to contain four quarks.

mysterious particle

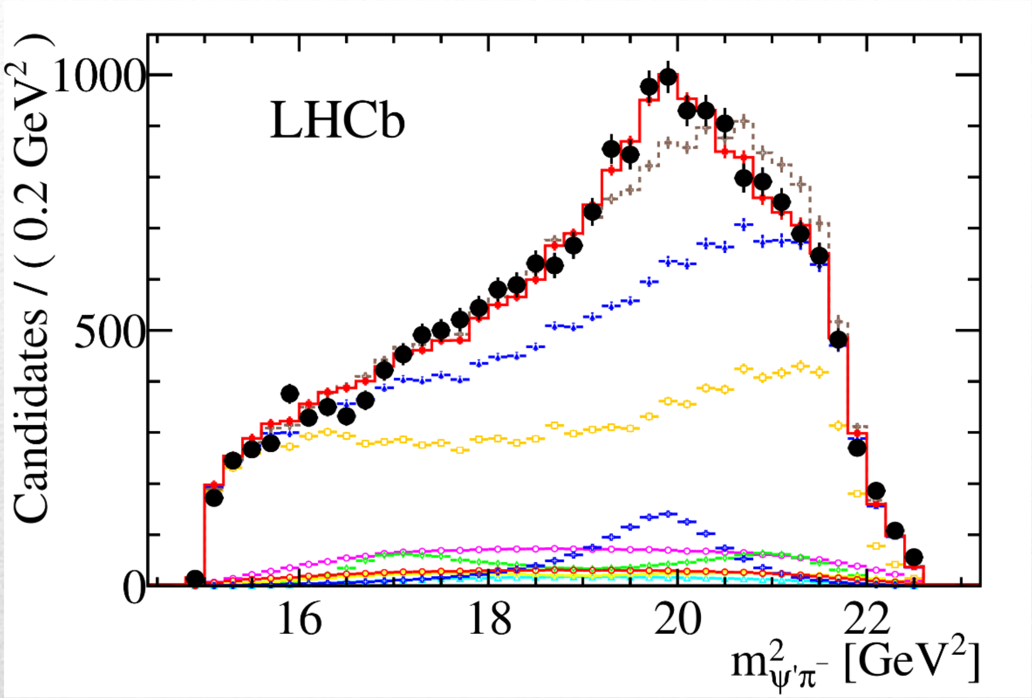
BESIII, PRL110 (2013) 252001
Belle, PRL110 (2013) 252002

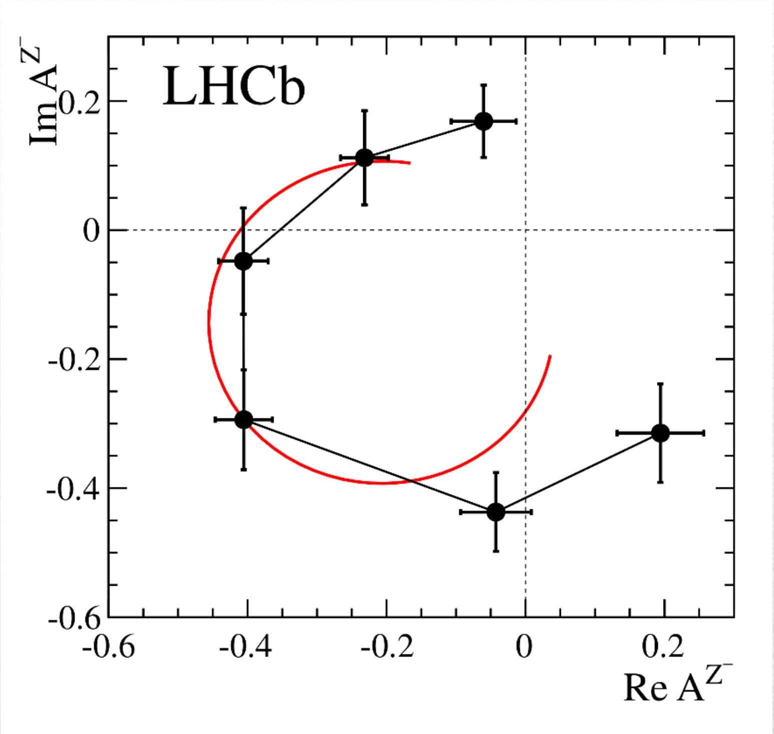
$Z_c^+(3900) \to J/\psi\,\pi^+$, 4q needed!
$I^G J^{PC} = 1^+1^{+-}$ (tbc)

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

Close to DD^* threshold

$Z(4430)$





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

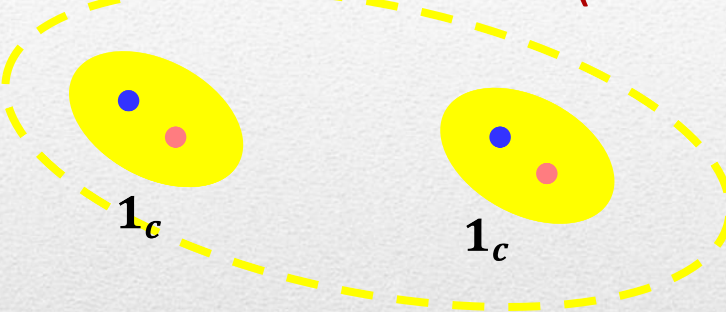
$$M = 4475 \pm 7^{+15}_{-25}\ \text{MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

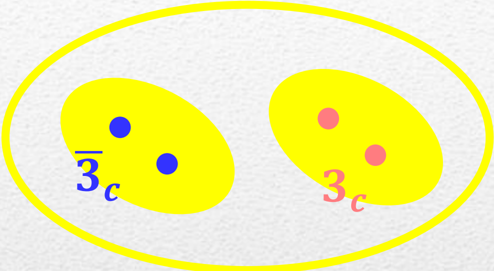
Far from open charm thresholds

Discovered by Belle, PRL100 (2008) 142001
Not confirmed by BaBar, PRD79 (2009) 112001
Confirmed by LHCb, 1404.1903 at 15σ level

Proposed models

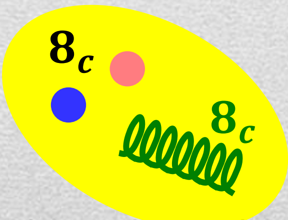
Molecule of hadrons (loosely bound)





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

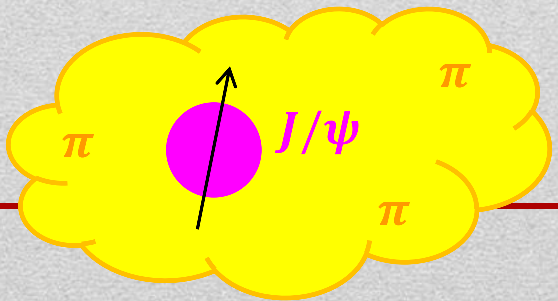
Diquark-antidiquark (tetraquark)



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

Glueball & Hybrids (with valence gluons)

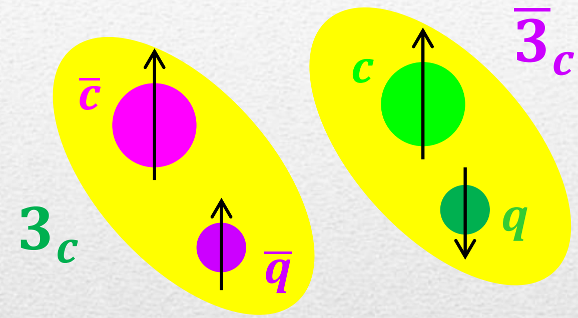
Hadrocharmonium (Van der Waals forces)



Tetraquark

One of the models is a compact
diquark-antidiquark bound state

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

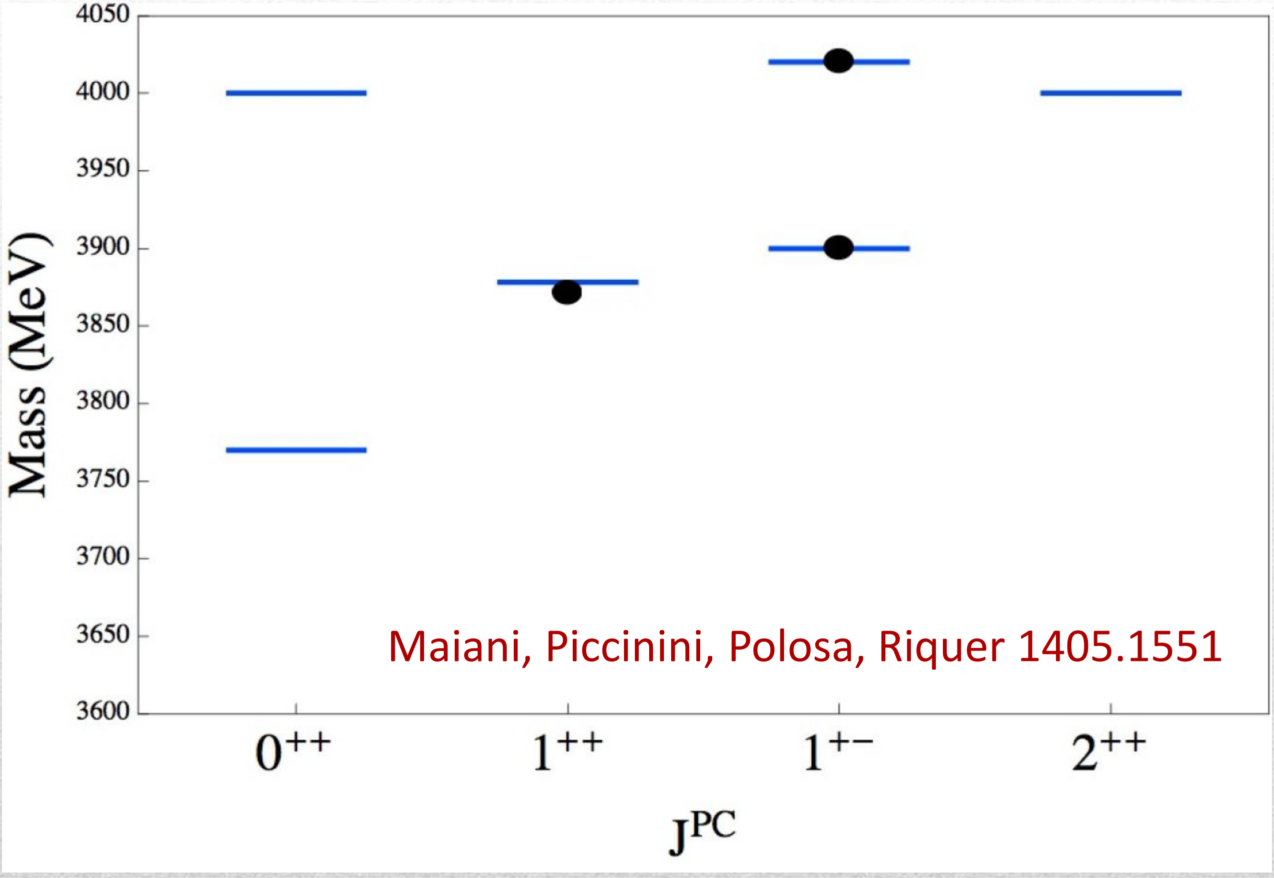


Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 11, 111102

We can evaluate mass spectrum in a constituent quark model

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

Tetraquark

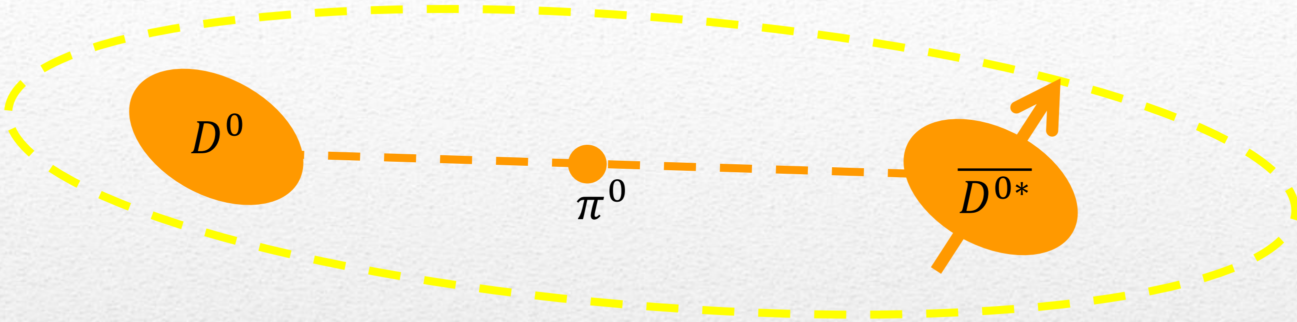


The pattern of $X(3872)$, $Z_c(3900)$, $Z_c'(4020)$, is understood

Prediction for radial excitation $Z(4430)$ ✓

A full nonet for each level is expected ✗

Molecule



Tornqvist, Z.Phys. C61, 525 (1994)

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

Two scales:
- $R{\sim}1$ fm radius of the mesons
- $R{\sim}10$ fm radius of the molecule

Good description of decay patterns and $\mathrm{X}(3872)$ isospin violation ✓

States appear close to thresholds ✓ (but $Z(4430)$ ✗)

Binding energy is often small, or positive (repulsive interaction) ✗

Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances

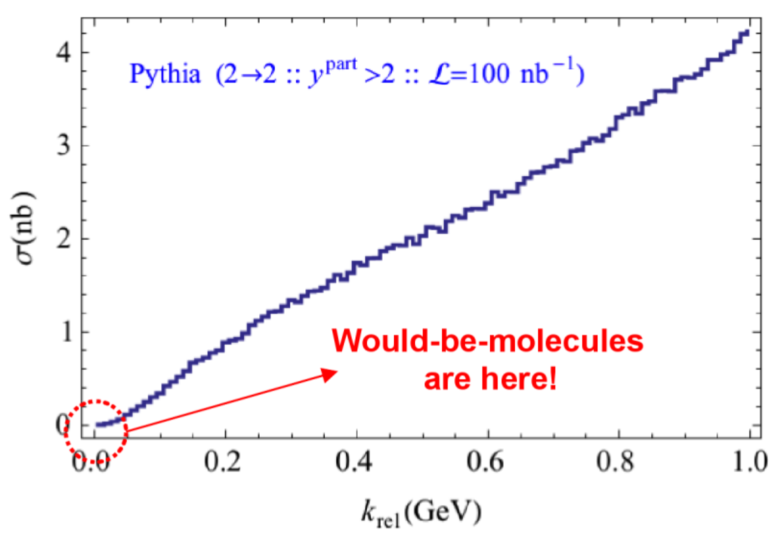
The most popular interpretation is a $D^0\bar{D}^{0*}$ molecule

But the binding energy is $E_B \approx -0.14 \pm 0.22$ MeV: very small!

A simple square well model shows that $k_{\text{rel}} \approx 50$ MeV

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

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



We obtain with MC simulations

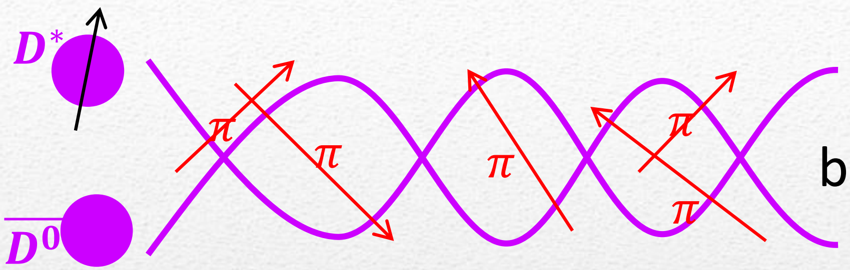
$\sigma(p\bar{p} \to DD^*) \approx 0.1$ nb $@\sqrt{s} = 1.96$ TeV

Experimentally

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

Molecule challenged!!!

Prompt production of $X(3872)$

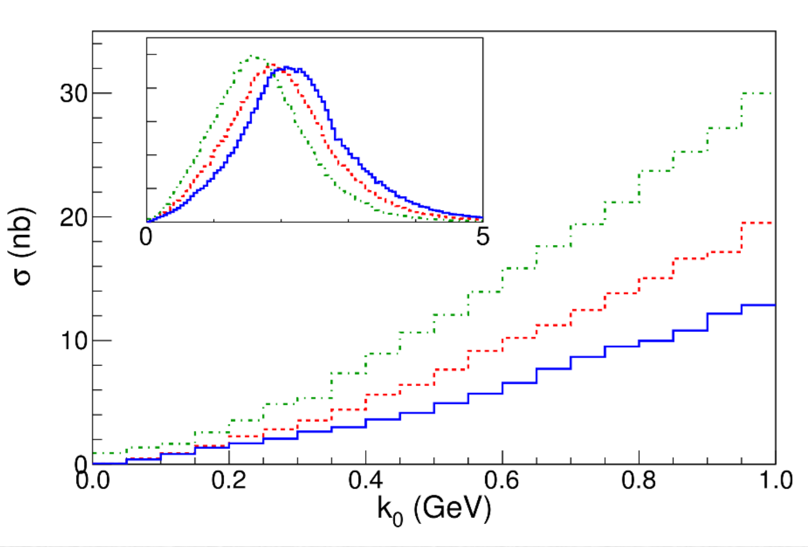


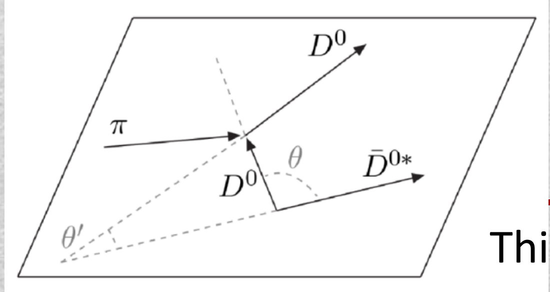
A solution can be FSI (rescattering of DD^*)
Artoisenet and Braaten PRD81 (2010) 114018

but it is spoiled by the presence of pions that interfere with DD^* propagation
Bignamini, Grinstein, Piccinini, Polosa, Sabelli PLB684 (2010) 228-230

We proposed a mechanism which makes use of these pions
Esposito, Piccinini, AP, Polosa JMP 4, 1569

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





This mechanism does not affect known open charm distributions
Guerrieri, Piccinini, AP, Polosa, to appear

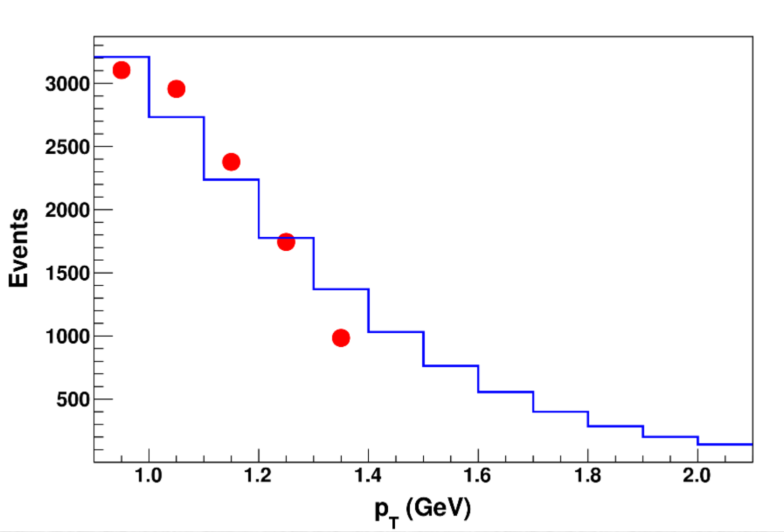
$X(3872) \sim$ Deuteron?

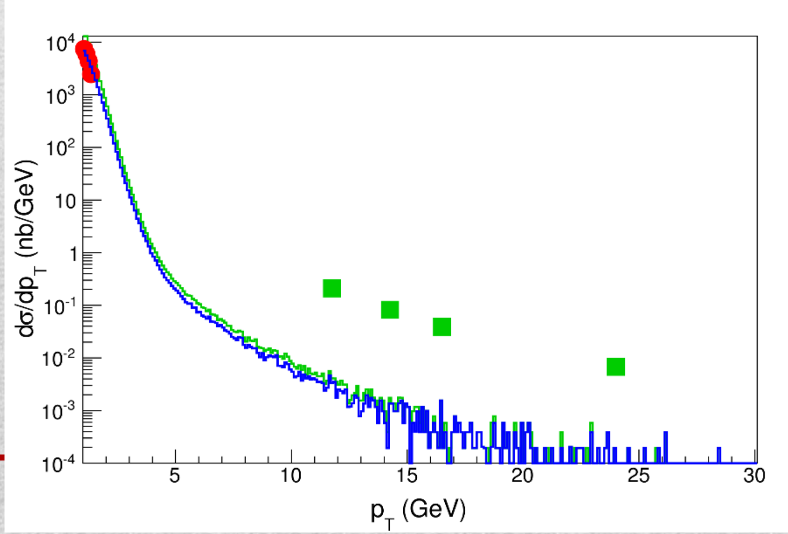
Guerrieri, Piccinini, AP, Polosa, to appear

If $X(3872)$ is a deuteron-like molecule, we can compare production cross sections

We use antideuteron ALICE data and use MC simulations to extrapolate at high p_T, 3 orders of magnitude smaller than CMS $X(3872)$ data!

Are they similar objects?





$X(3872) \sim$ Deuteron?

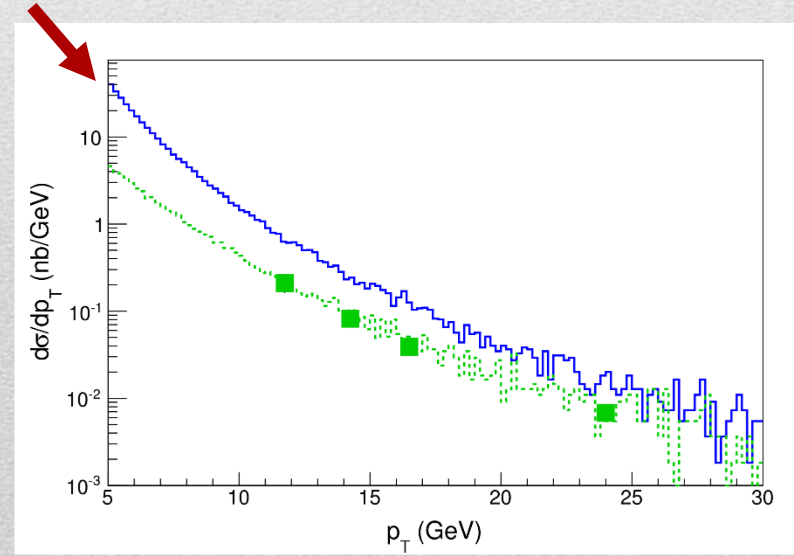
Guerrieri, Piccinini, AP, Polosa, to appear

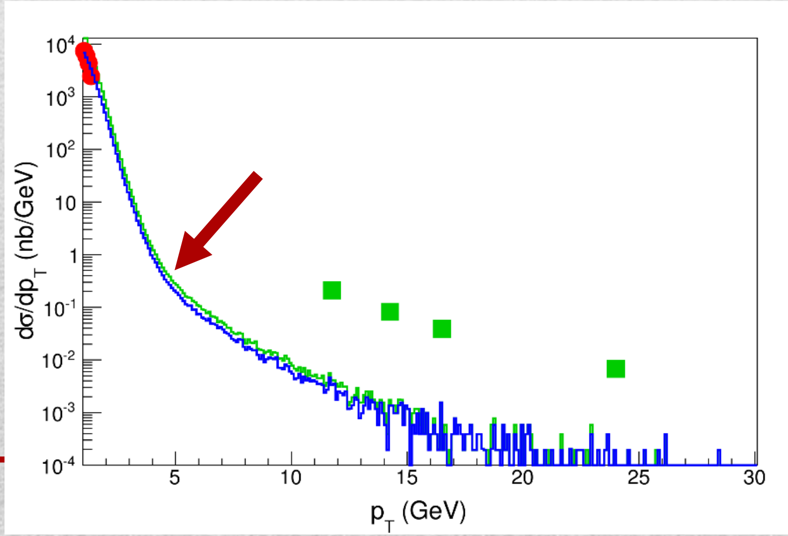
We can go backwards by normalizing to CMS $X(3872)$ data prediction for antideuteron is much larger than previous one

Caveat: more data needed

- ALICE data are preliminary
- MC is not very reliable in the $p_T \sim 1$ GeV
- Dependence on hadronization models

Are they similar objects?





Summary

Molecule

- ✓ The states are near thresholds
- ✓ Large decay into open charm
- ✗ Production paradox
- ✗ Z(4430)?
- ✗ How to justify bound states with positive binding energy?

Tetraquark

- ✓ The pattern is simple, based on $SU(3)$
- ✓ Good predictions for spectra
- ✓ Some indications on decays
- ✗ Many states are missing, in particular charged partners of $X(3872)$

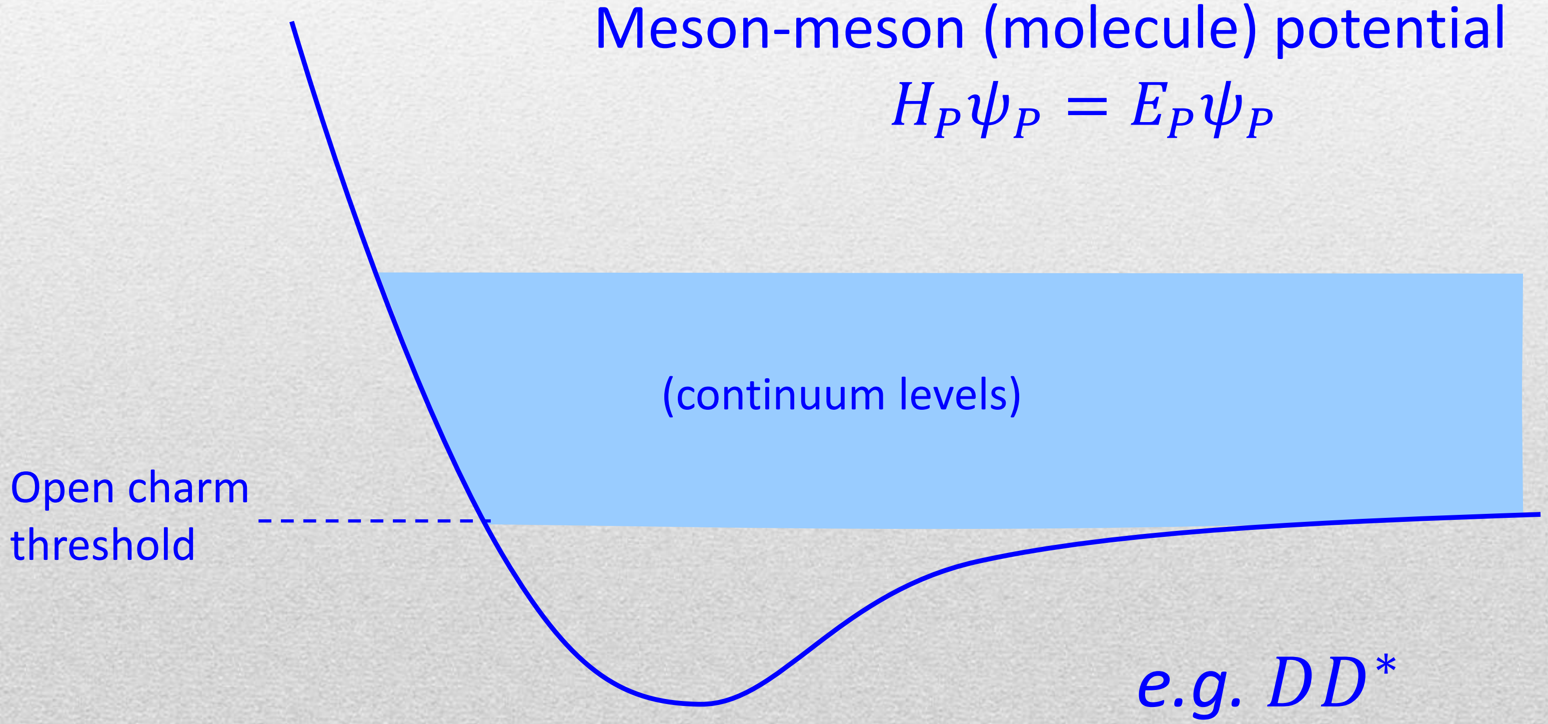
Feshbach resonances

Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374
Guerrieri, Piccinini, AP, Polosa, to appear

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

Meson-meson (molecule) potential

$$H_P \psi_P = E_P \psi_P$$



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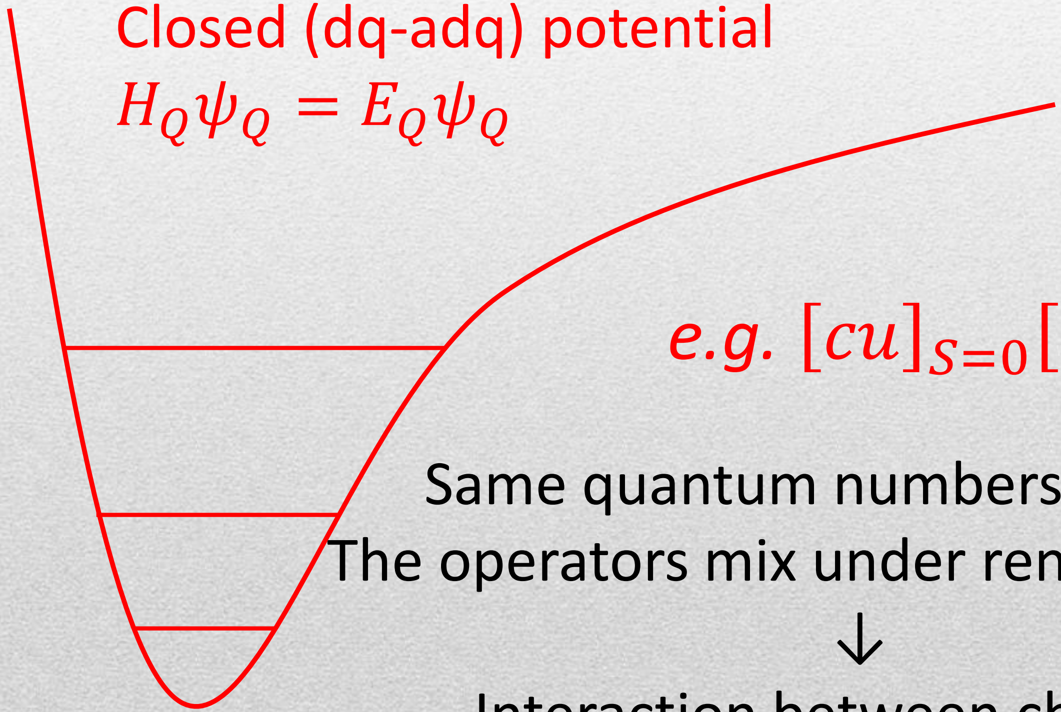


Closed (dq-adq) potential

$H_Q \psi_Q = E_Q \psi_Q$

$e.g.\ [cu]_{S=0}[\bar{c}\bar{u}]_{S=1}$

Same quantum numbers as DD^*,
The operators mix under renormalization

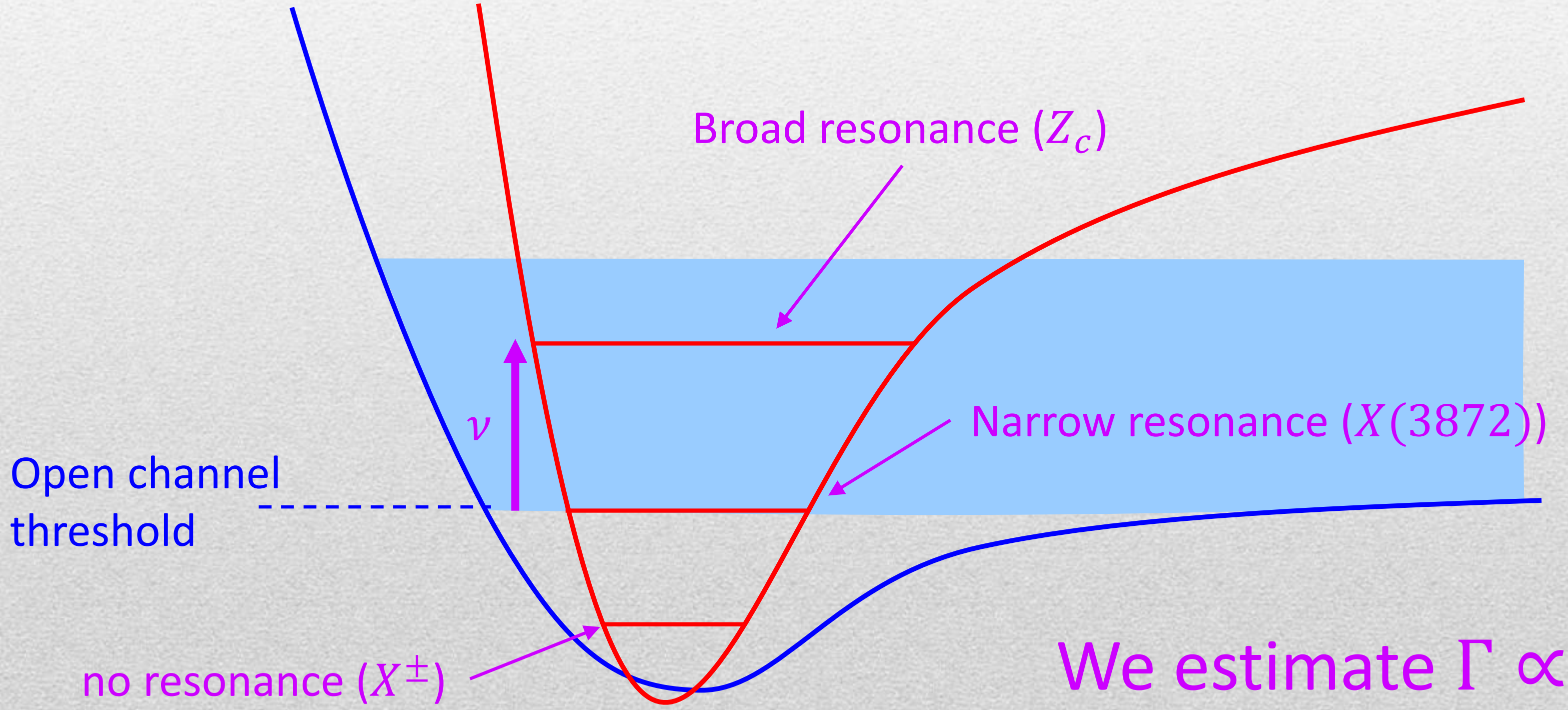
$\downarrow$

Interaction between channels

Feshbach resonances

We add an interaction Hamiltonian H_{QP} so that

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



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

Feshbach resonances

We impose a cutoff on $\nu < 100$ MeV
$X(3872)$ should be a $I = 1$ state, but $M(1^{++}) < M(D^{+*}\overline{D}^0)$
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 (caveat: still large errors...)

Open channel	M_{4q} (MeV)	ν (MeV)	Γ (MeV)	$I^G J^{PC}$	name
$D^{*0}\overline{D}^0$	3872	0	0	1^-1^{++}	$X(3872)$
$D^{*+}\overline{D}^0$	3900	24	53	1^+1^{+-}	$Z_c(3900)$
$D^{*+}\overline{D}^0$	4025	8	24	1^+1^{+-}	$Z_c'(4025)$
$\eta_c(2S)\rho^+$	4475	75	>150	1^+1^{+-}	$Z(3900)$
$B^{*+}\bar{B}^0$	10610	3	18	1^+1^{+-}	$Z_b(10610)$
$B^{*+}\bar{B}^{*0}$	10650	1.8	11	1^+1^{+-}	$Z_b'(10650)$

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

Prompt production cross sections

Guerrieri, Piccinini, AP, Polosa, to appear

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)

Prompt production cross sections

Guerrieri, Piccinini, AP, Polosa, to appear

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

No prompt production without Feshbach resonances!

For example, we compare the at-threshold $X(3872)$ with the below-threshold $Y(4260)$
CMS $X(3872)$ data: JHEP 1304, 154
Model-independent prediction for the $Y(4260)$: Ali and Wang, PRL106 192001

$$\frac{\sigma\big(pp \to X(3872)\big) \times BR(X(3872) \to J/\psi\, \pi^+\pi^-)}{\sigma(pp \to Y(4260)) \times BR(Y(4260) \to J/\psi\, \pi^+\pi^-)} \sim 10^2$$

Conclusions

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

- Feshbach mechanism is effective in reducing the number of states predicted by tetraquark picture, and adds some interesting features of molecular description
- 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
- Measure prompt production cross sections to improve our understanding of hadronization

Thank you

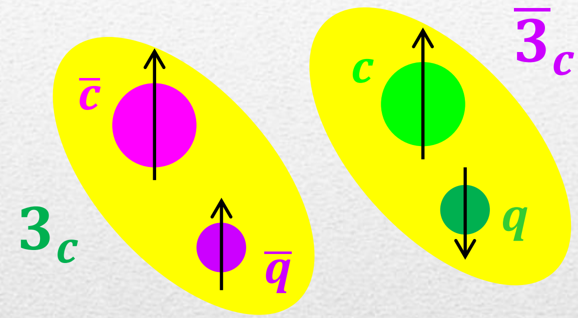
BACKUP

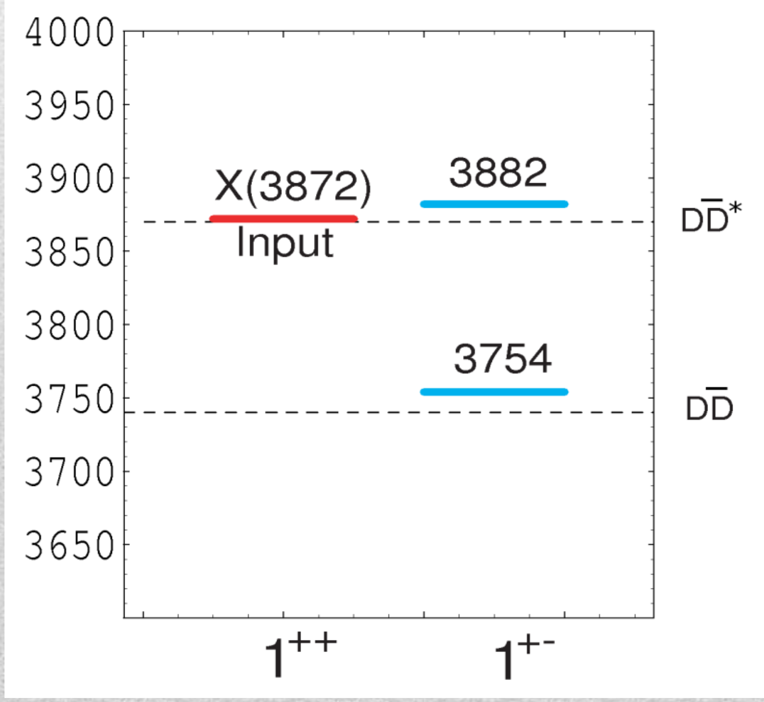
Tetraquark

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

Maiani, Piccinini, Polosa, Riquer PRD71 014028

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





Constituent mass of the diquark is unknown

↓

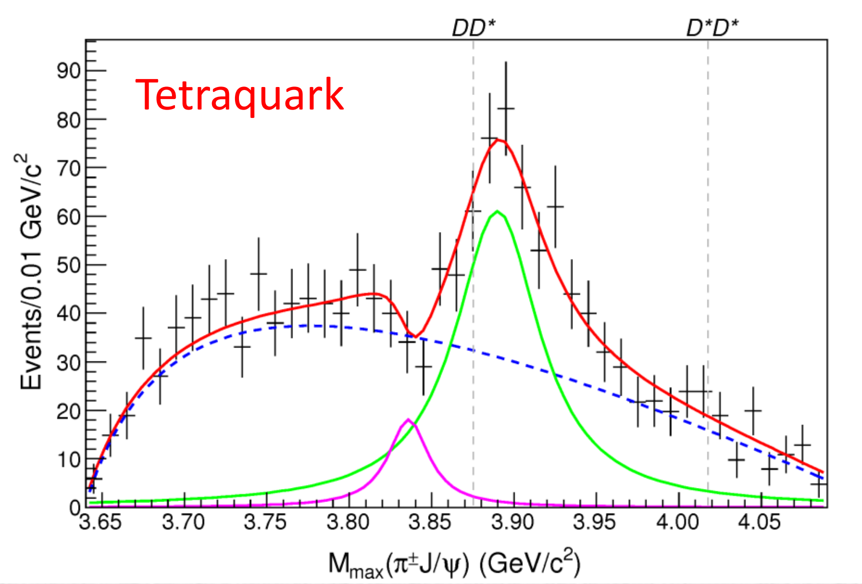
We can use $X(3872)$ as the seed to predict masses of mesons made up of the same diquarks

↓

$Z_c(3900)$ predicted + a ligther state

Combined BES-Belle fit

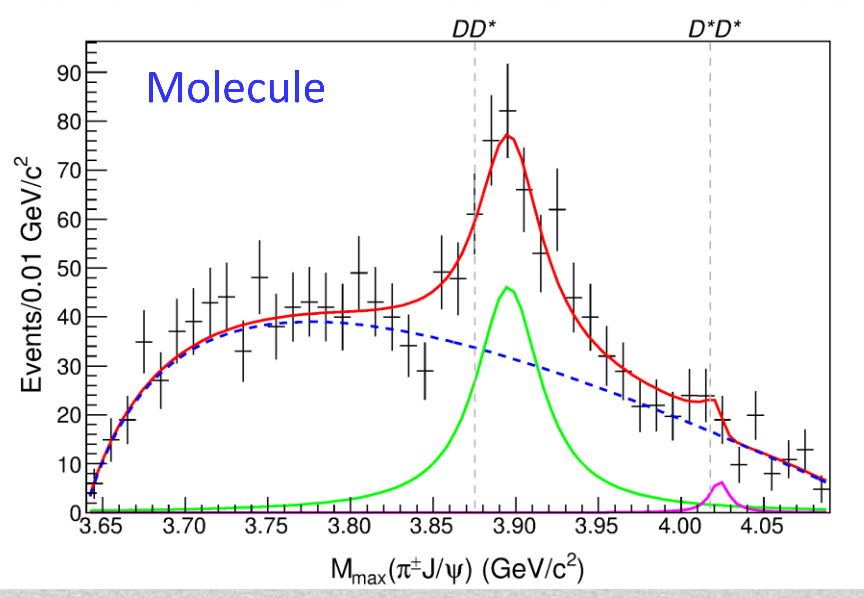
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 (2013) 111102



Z_c' $M' = 3836 \pm 13$ MeV

$\Gamma' = 30 \pm 18$ MeV

χ^2/DOF=41/65, $CL = 99.0\%$



Z_c' $M' = 4023 \pm 6$ MeV

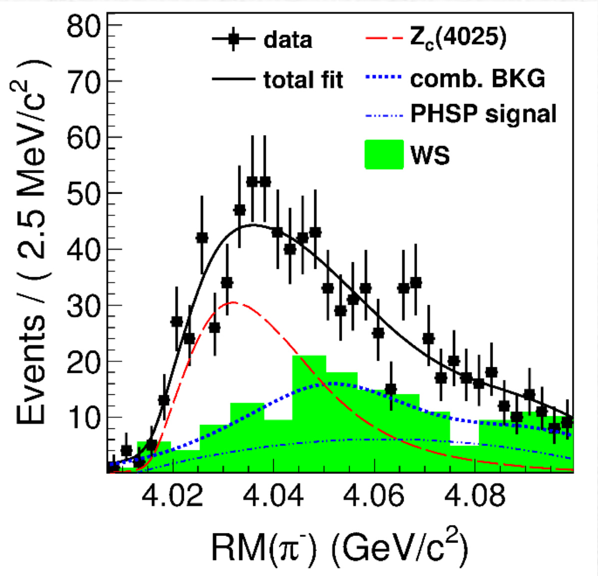
$\Gamma' = 13 \pm 26$ MeV

χ^2/DOF=47/65, $CL = 95.0\%$

But Nature is malicious…

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

BESIII, PRL112, 022001



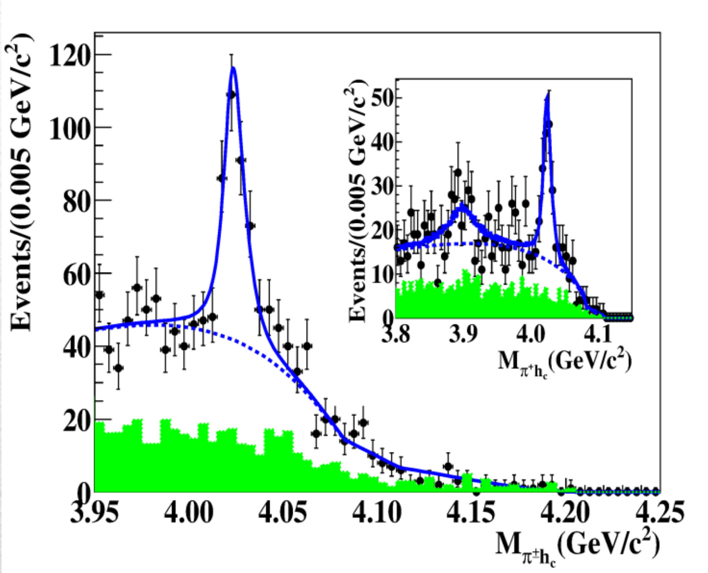
$Z_c'(4025) \to D^* D^*$

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

$M = 4026.3 \pm 4.5$ MeV

$\Gamma = 24.8 \pm 9.5$ MeV

BESIII, PRL111, 242001



$Z_c'(4020) \to h_c \pi$

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

$M = 4022.9 \pm 2.8$ MeV

$\Gamma = 7.9 \pm 3.7$ MeV

- Tetraquark picture for the moment lacks an interpretation for this state...
- Molecular picture predicts a state at (below) $D^* D^*$ threshold, but why $Z_c'(4025) \nrightarrow J/\psi\, \pi$?

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

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?

In fact, $Z_b(10610)$ and $Z_b'(10650)$ decay into both $\Upsilon(nS)$ and $h_b(nP)$

A simple PHS evaluation leads to

$$\frac{\sigma(e^+e^- \to Z_c'\pi \to \eta_c\pi\pi)}{\sigma(e^+e^- \to Z_c'\pi \to h_c\pi\pi)} \sim 270, \qquad \frac{\sigma(e^+e^- \to Z_c'\pi \to J/\psi\,\pi\pi)}{\sigma(e^+e^- \to Z_c'\pi \to h_c\pi\pi)} \sim 226$$

Although precise evaluation of meson loops can severely modify these values,
still $Z_c'\pi \to J/\psi\,\pi$ should be observed

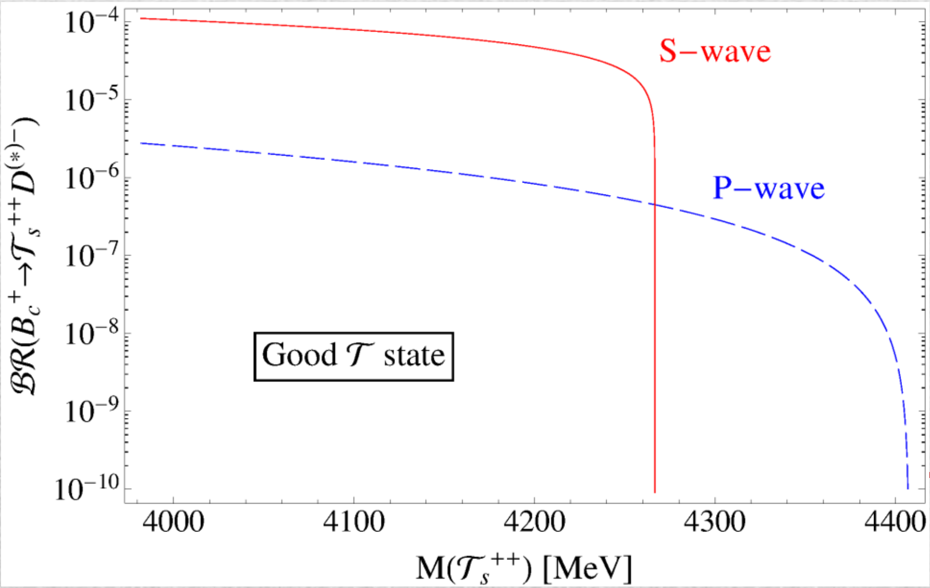
Doubly charmed states

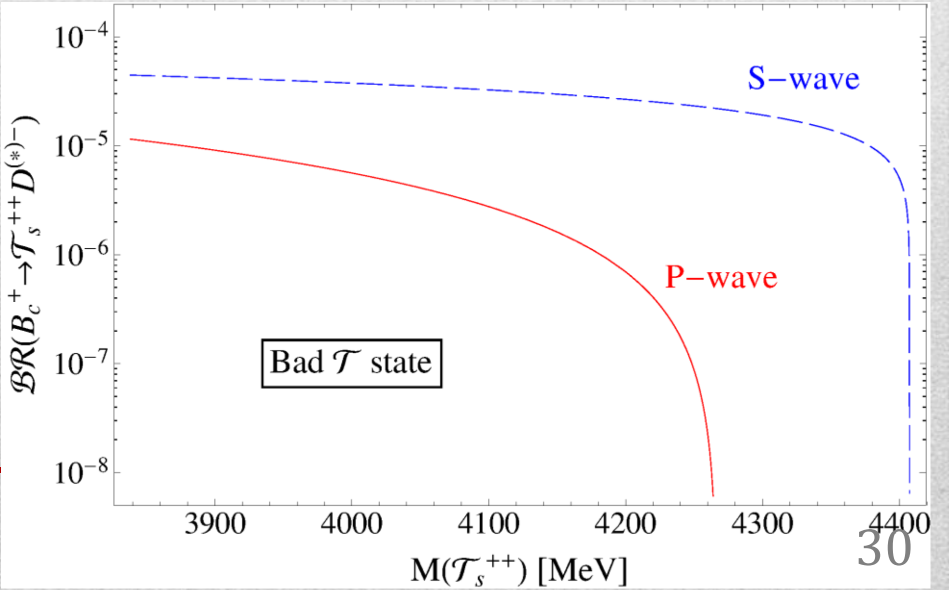
Another approach to choose among models, is to predict states who fit only in one model

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

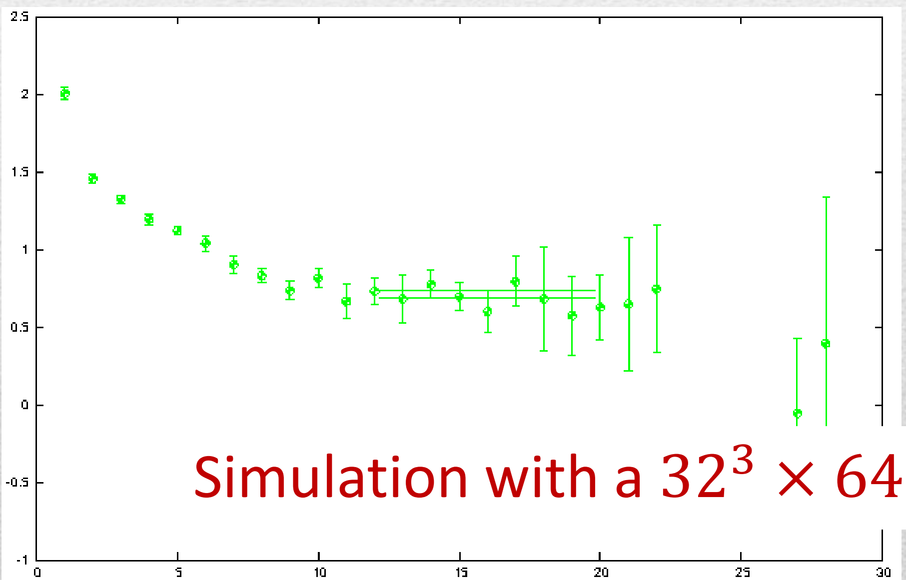
This state is particularly well-defined on the lattice, because no disconnected diagrams are involved.

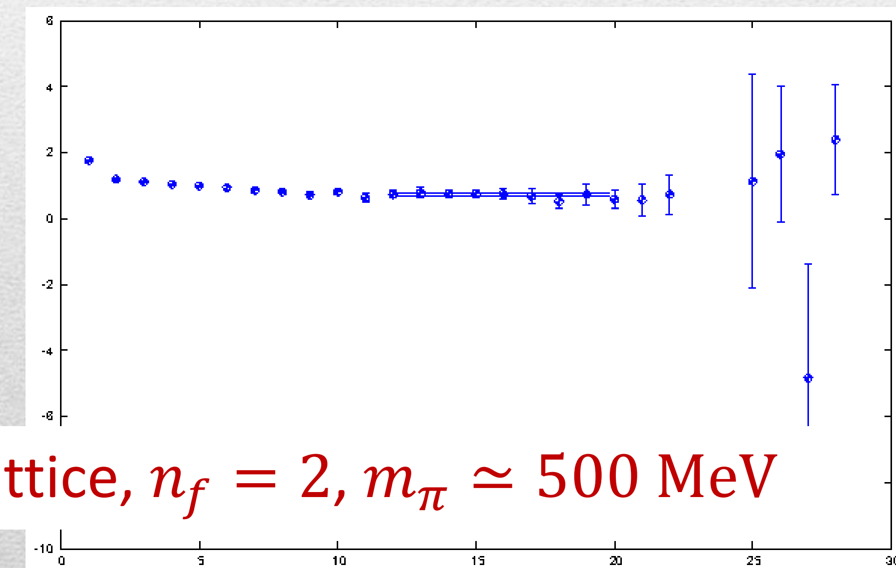
The calculation is ongoing…

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





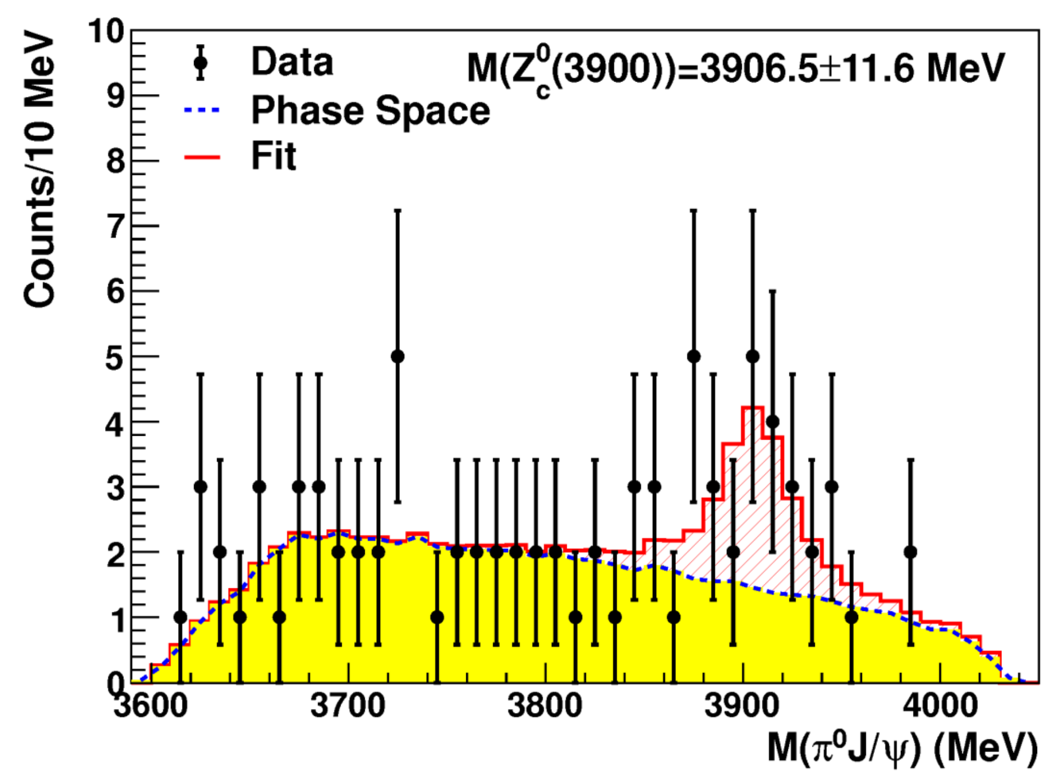
Simulation with a $32^3 \times 64$ lattice, $n_f = 2, m_\pi \simeq 500$ MeV

Lüscher's method is to be implemented

$Z_c^0(3900)$ 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.*
PLB767, 366-370

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

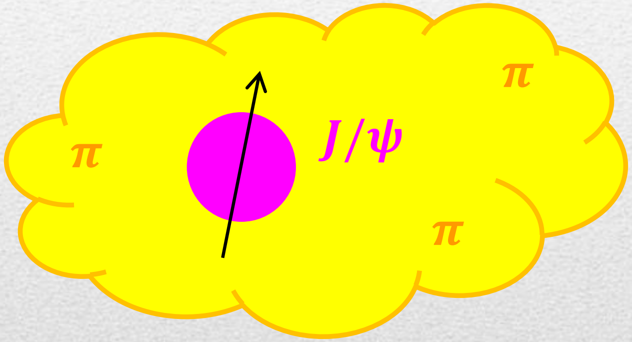
Isospin violation?
Look for $Z_c^0 \to J/\psi\,\eta$

Hanhart *et al.*
arXiv:1312.5621

Other models

Hadro-charmonium

Voloshin PRD87 9, 091501



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

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

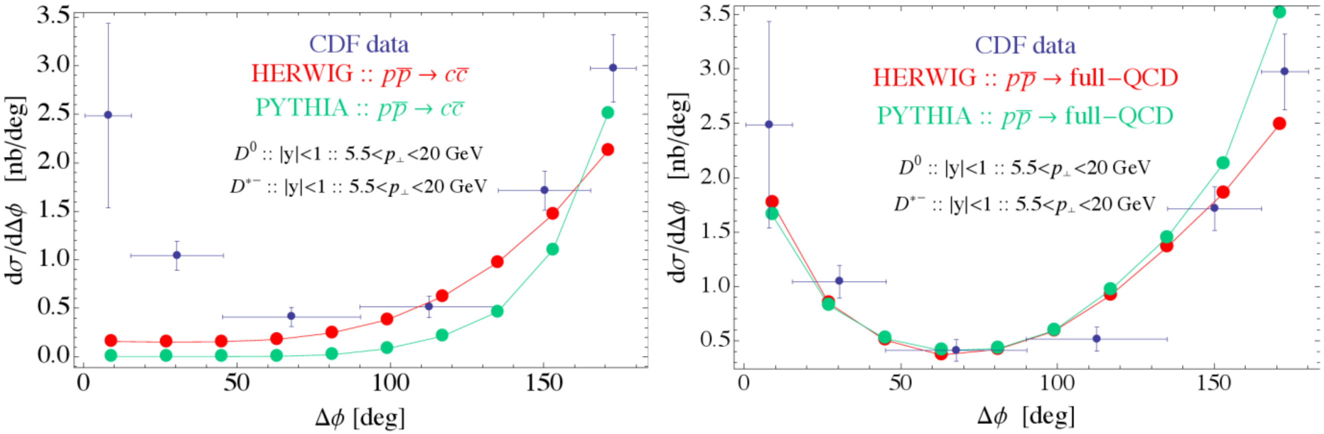
A light $Z_c'(3785)$ expected with $I^G J^{PC} = 1^- 0^{++}$
(not visible in $J/\psi\ \pi$ channel)

Tuning of MC

Monte Carlo simulations

A. Esposito

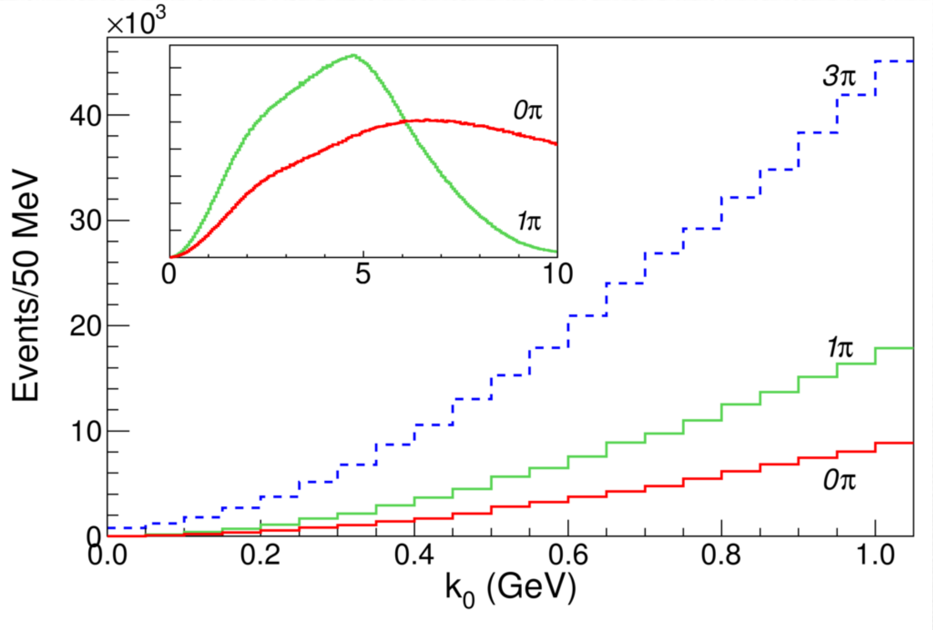
- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:

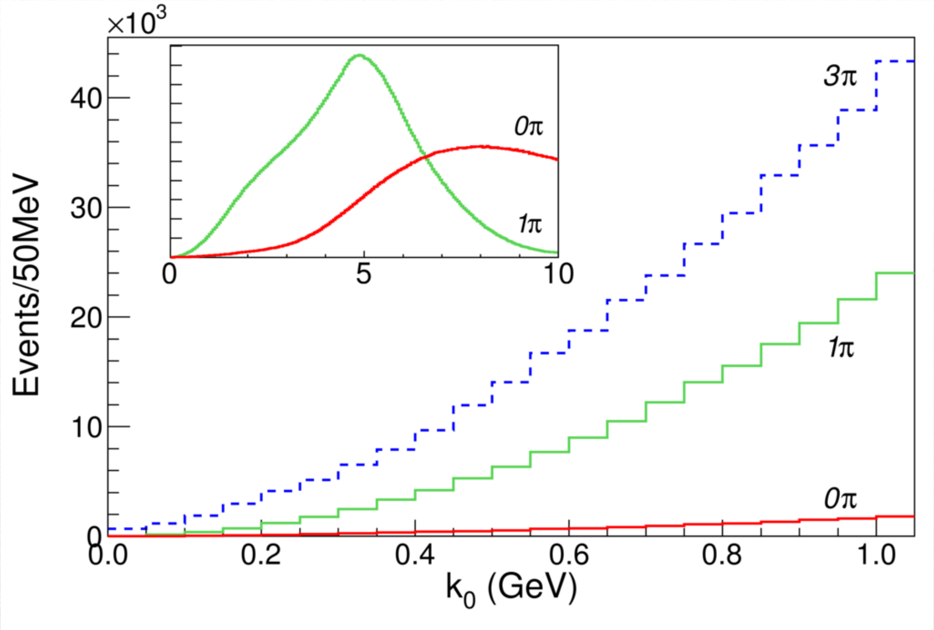


The c-cbar run understimate the low angles (low-k_0) region!

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

$p\bar{p} \rightarrow c\bar{c}$





#events	Herwig	Pythia
0π	10	3
1π	19	21
3π	802	814

The enhancement is impressive because first bins are almost empty

T states production