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

Production of tetraquarks at the LHC

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10th Quarkonium Working Group, CERN – November 14th, 2014

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

Phys.Rev. D90, 034003 – arXiv:1405.7929

Outline

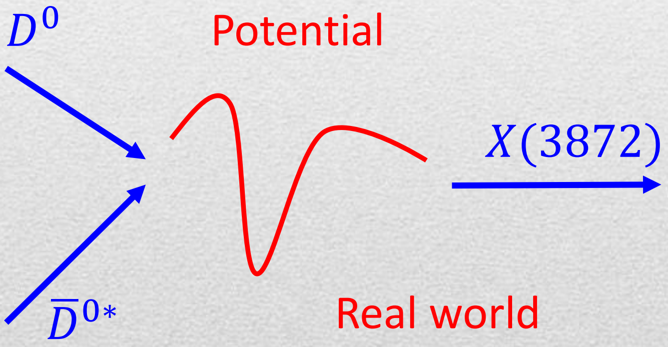
- Production of X(3872)
- A new mechanism?
- X(3872) vs. Deuteron production
- Hadronization and Feshbach mechanism
- Conclusions

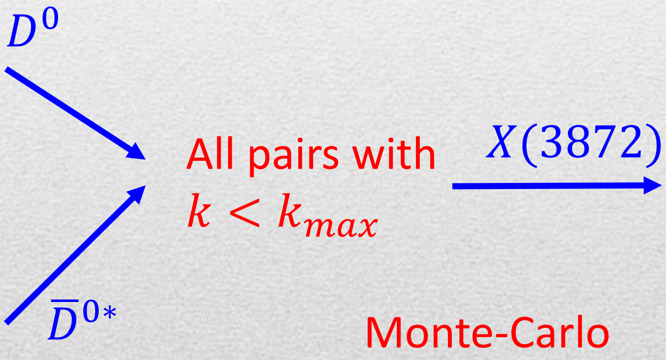
Prompt production of $X(3872)$

$X(3872)$ 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 $E_B \approx -0.16 \pm 0.31$ MeV: very small!
In a simple square well model this corresponds to:

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

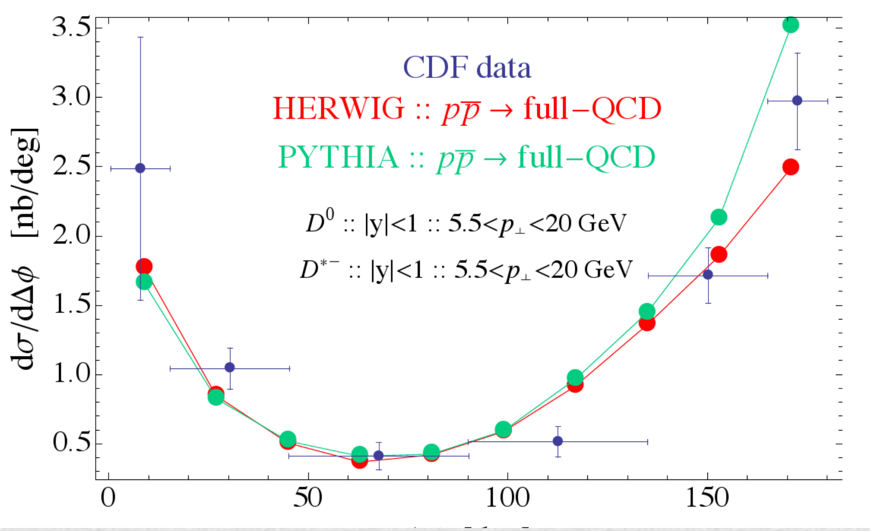
$$\left(\begin{array}{c} \text{binding energy reported in Kamal Seth's talk is } E_B \approx -0.013 \pm 0.192 \text{ MeV:} \\ \sqrt{\langle k^2 \rangle} \approx 30 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 30 \text{ fm} \end{array} \right)$$

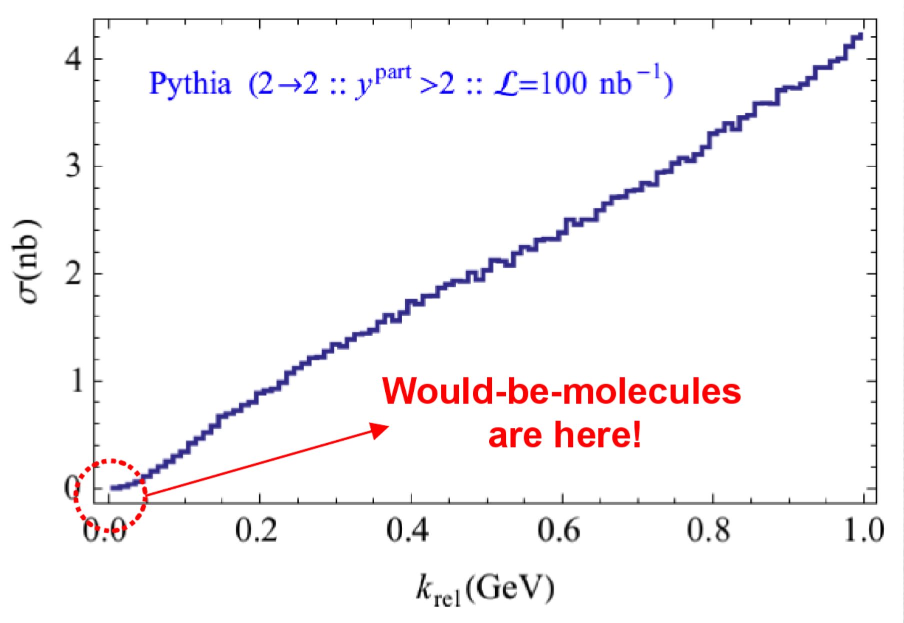
to compare with deuteron: $E_B = -2.2$ MeV

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

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

2009 results





Would-be-molecules are here!

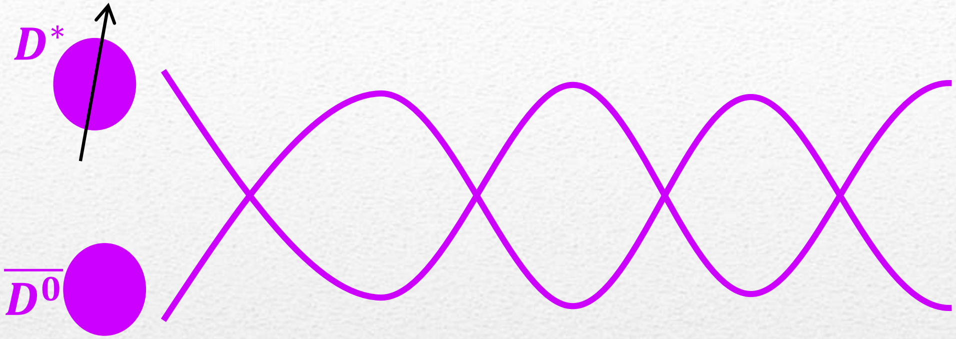
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

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

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

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

Estimating k_{max} (again)

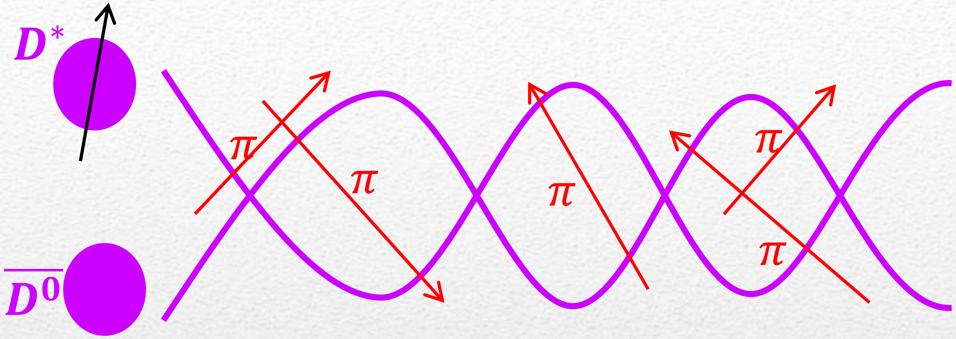


A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi \sim 700\text{ MeV}$

$$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230\text{ nb} > \sigma_{exp}(p\bar{p} \to X(3872))$$

Artoisenet and Braaten PRD81 (2010) 114018

Estimating k_{max} (again)



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Artoisenet and Braaten PRD81 (2010) 114018

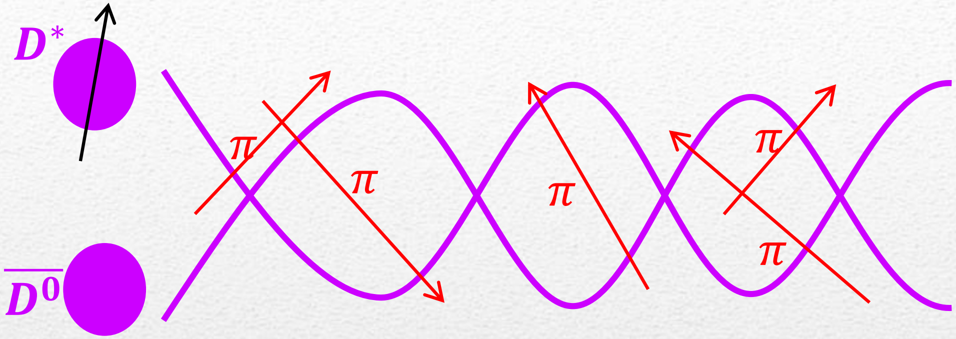
However, the applicability of Watson theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PLB684 (2010) 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten PRD83 (2011) 014019

Estimating k_{max} (again)



A solution can be FSI (rescattering of DD^*), which allow k

2010) 114018

Howe

e of

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

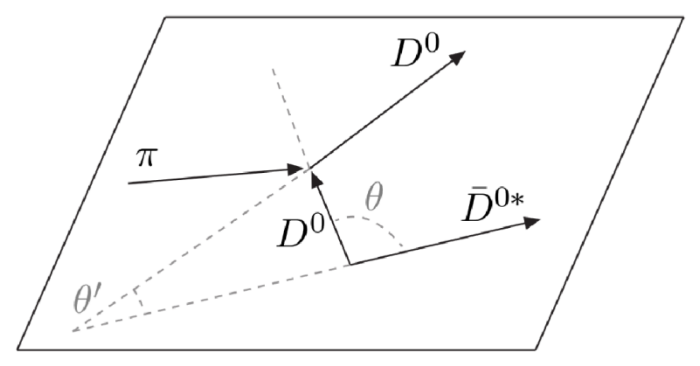
FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten PRD83 (2011) 014019

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



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

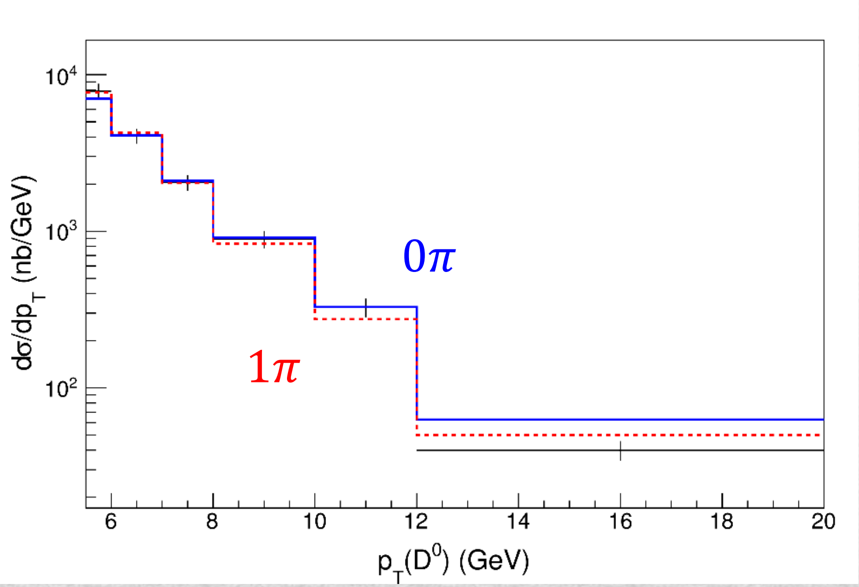
$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100\ \mathrm{keV}$

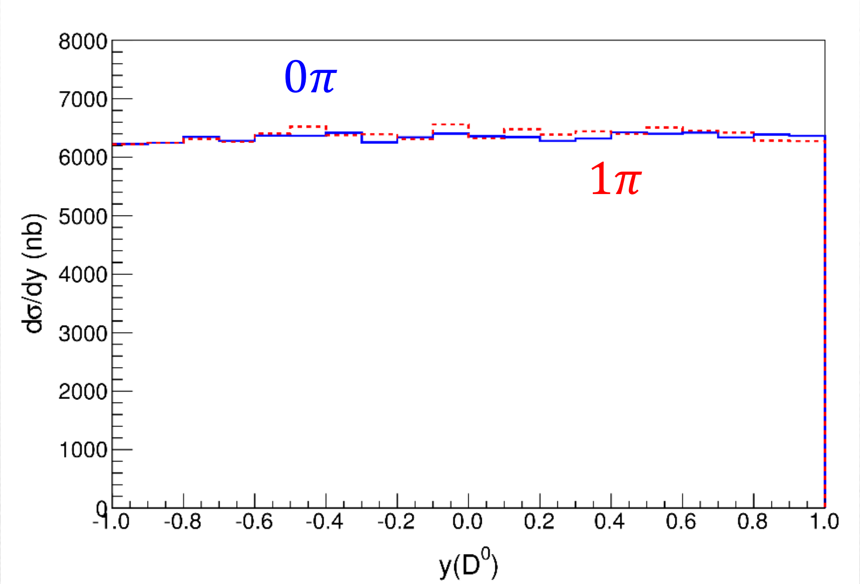
Tuning pions

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...

Tuning pions

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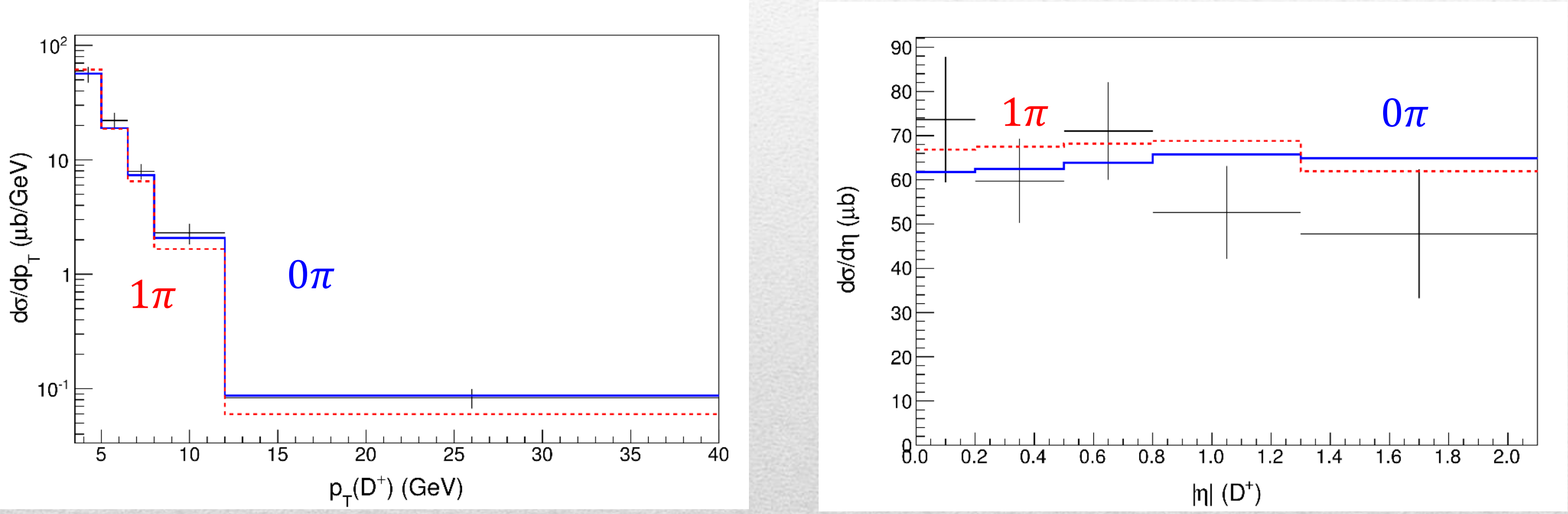
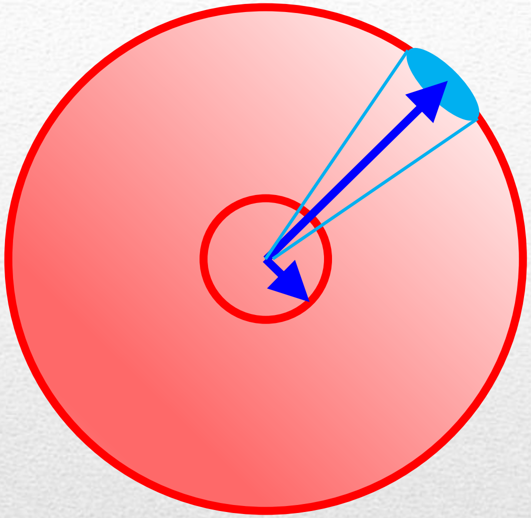
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

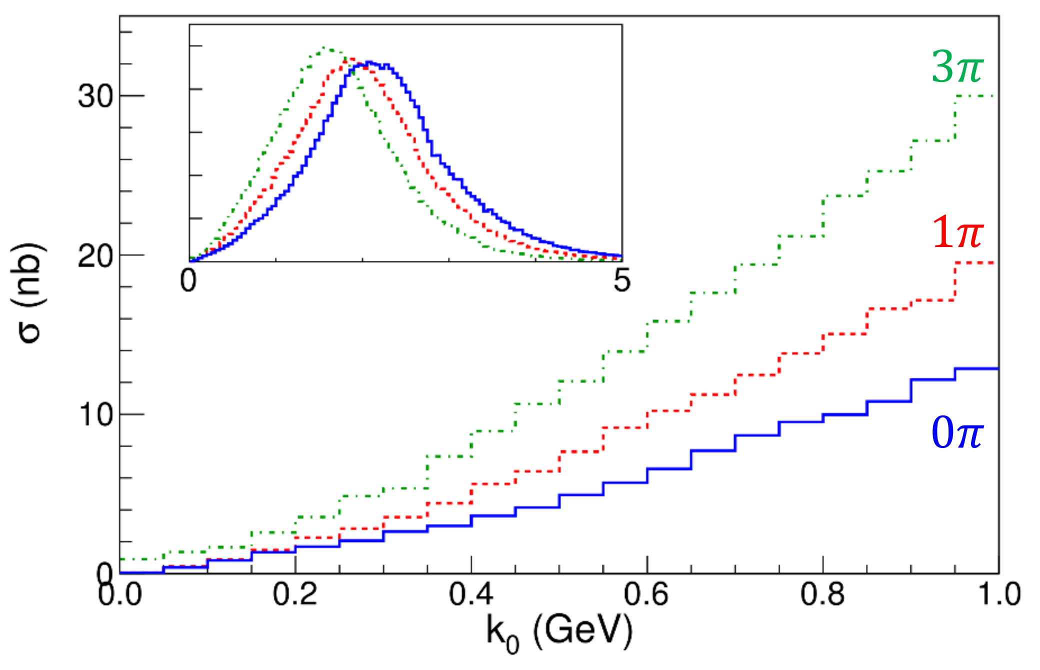


...nor at ATLAS

Results



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



We get $\sigma\left(p\bar{p} \rightarrow X(3872)\right) \sim 5$ nb,

still not sufficient to explain all the experimental cross section

$X(3872) \sim$ Deuteron?

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

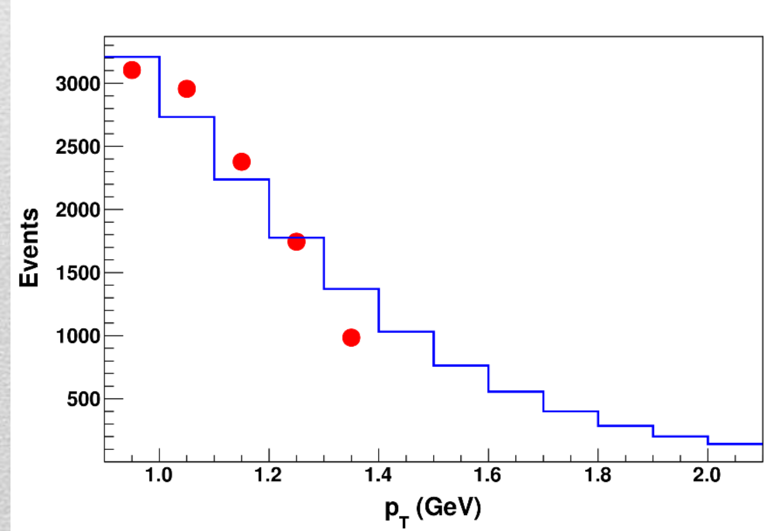
If $X(3872)$ is a deuteron-like molecule, we can compare production cross sections

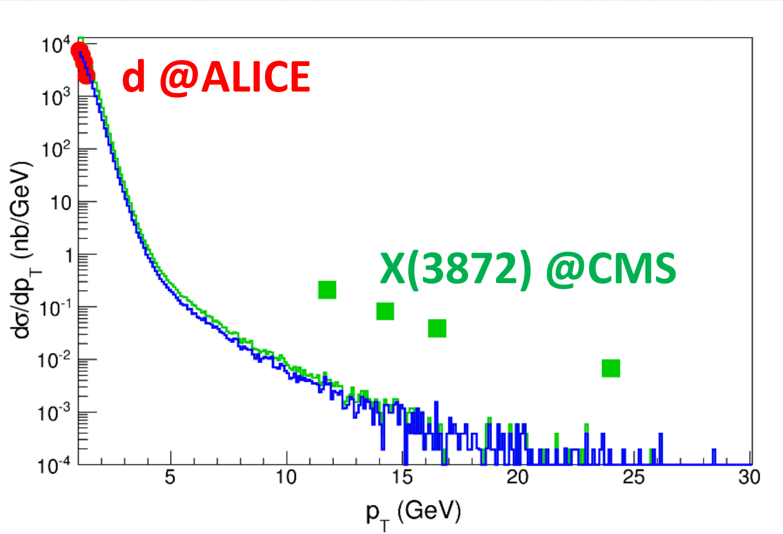
We use antideuteron ALICE data and use MC simulations to extrapolate at high p_T

Since $p_{Tmin} \sim 1\ \mathrm{GeV}$, total cross section is exploding, we cannot normalize data we choose a K factor to fit data: no dependence on k_{max}

3 orders of magnitude smaller than CMS $X(3872)$ data!

Are they similar objects?

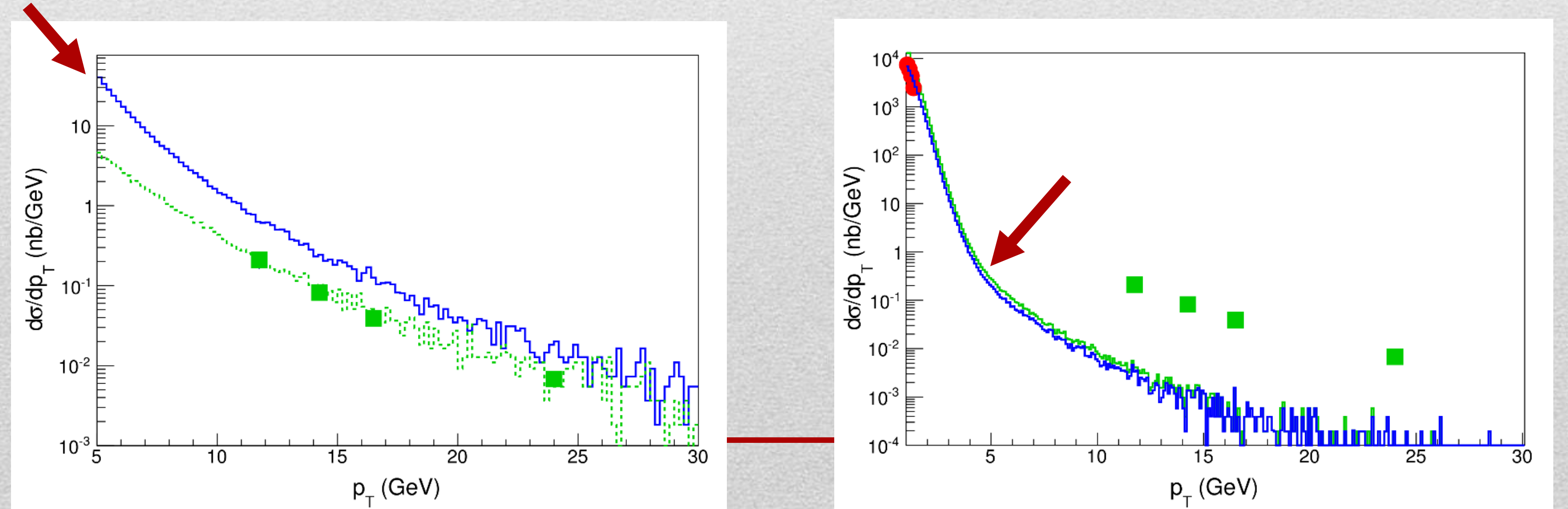




$X(3872) \sim$ Deuteron?

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

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



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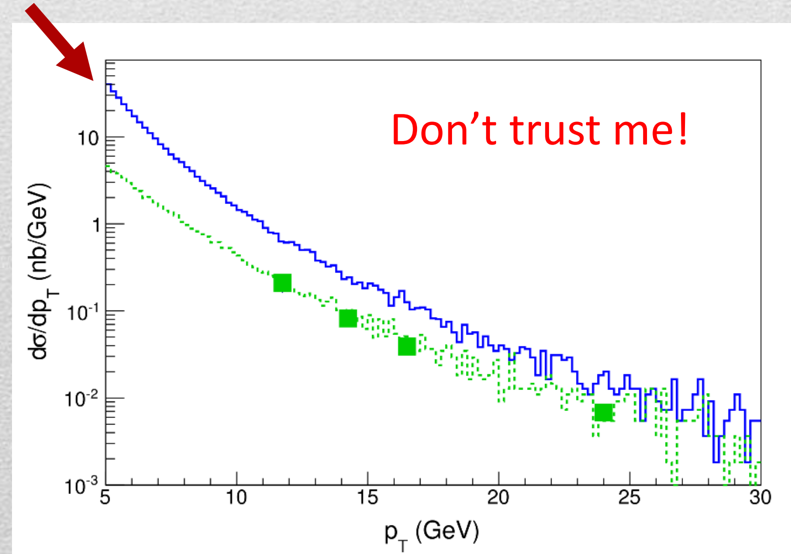
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

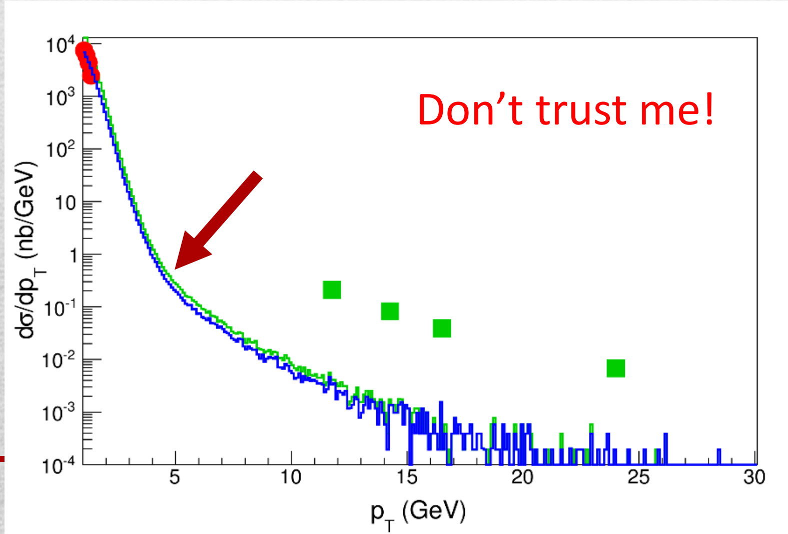
We can go backwards by normalizing to CMS $X(3872)$ data prediction for antideuteron is much larger than previous one

Do not trust MC!
We want data!!!

- ALICE data are preliminary
- MC is not reliable in the $\mathrm{p_T} \sim 1$ GeV
- Dependence on hadronization models
- Different fragmentation functions to be considered

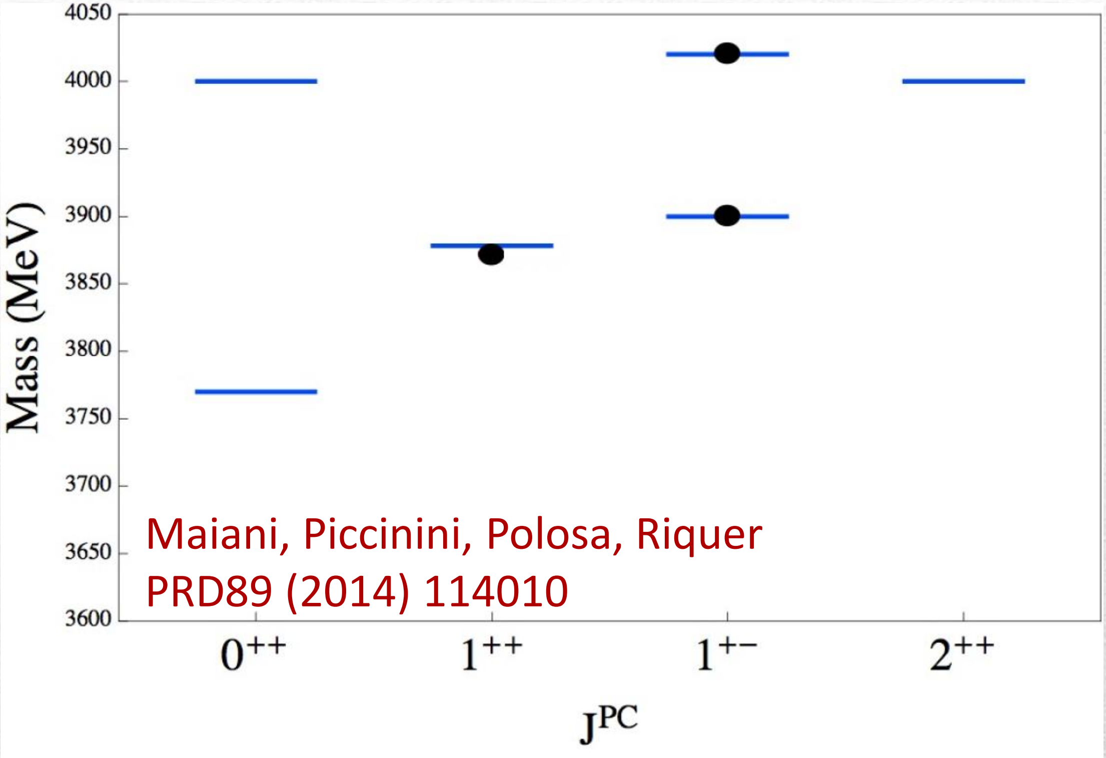


Don’t trust me!



Don’t trust me!

Tetraquark



Maiani, Piccinini, Polosa, Riquer
PRD89 (2014) 114010

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

Prediction for radial excitation $Z(4430)$ ✓

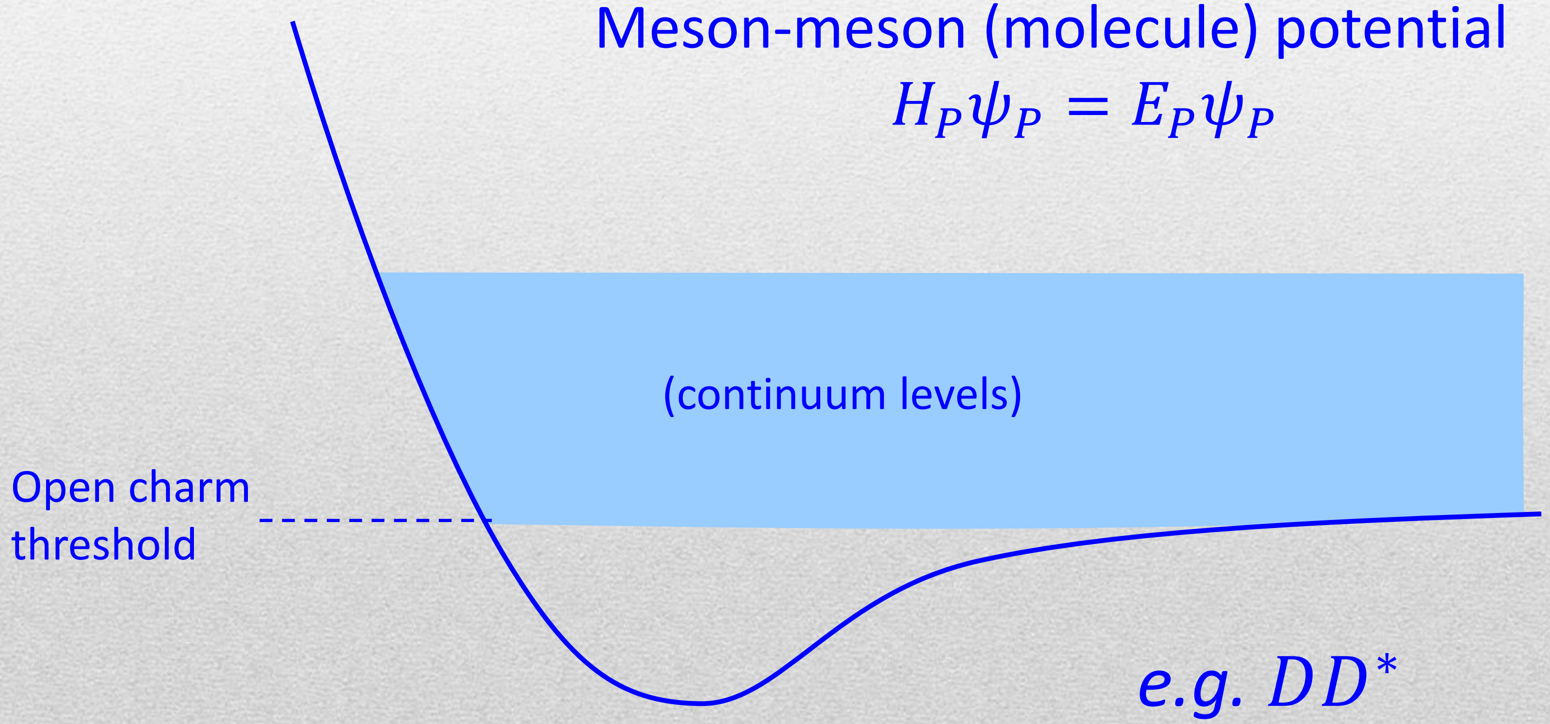
A full nonet for each level is expected ✗

We need a mechanism that disfavors the formation of the unobserved states

Feshbach resonances

Braaten and Kusunoki, PRD69, 074005
Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

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

$$H_P \psi_P = E_P \psi_P$$

Feshbach resonances

Braaten and Kusunoki, PRD69, 074005
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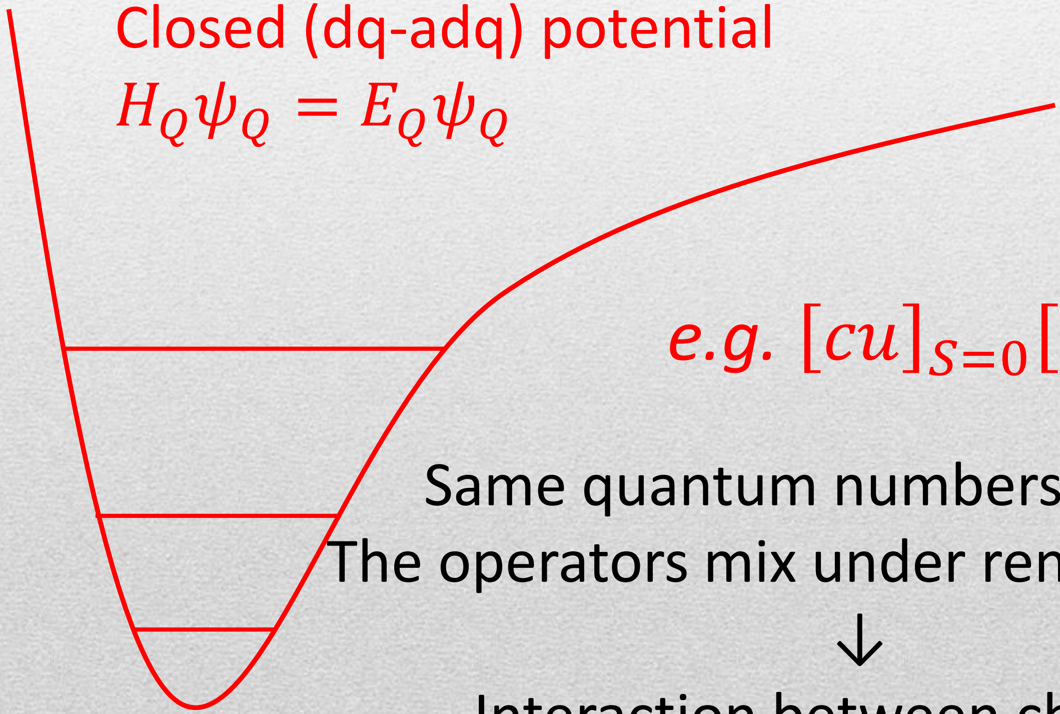


Closed (dq-adq) potential

$$H_Q\psi_Q = E_Q\psi_Q$$

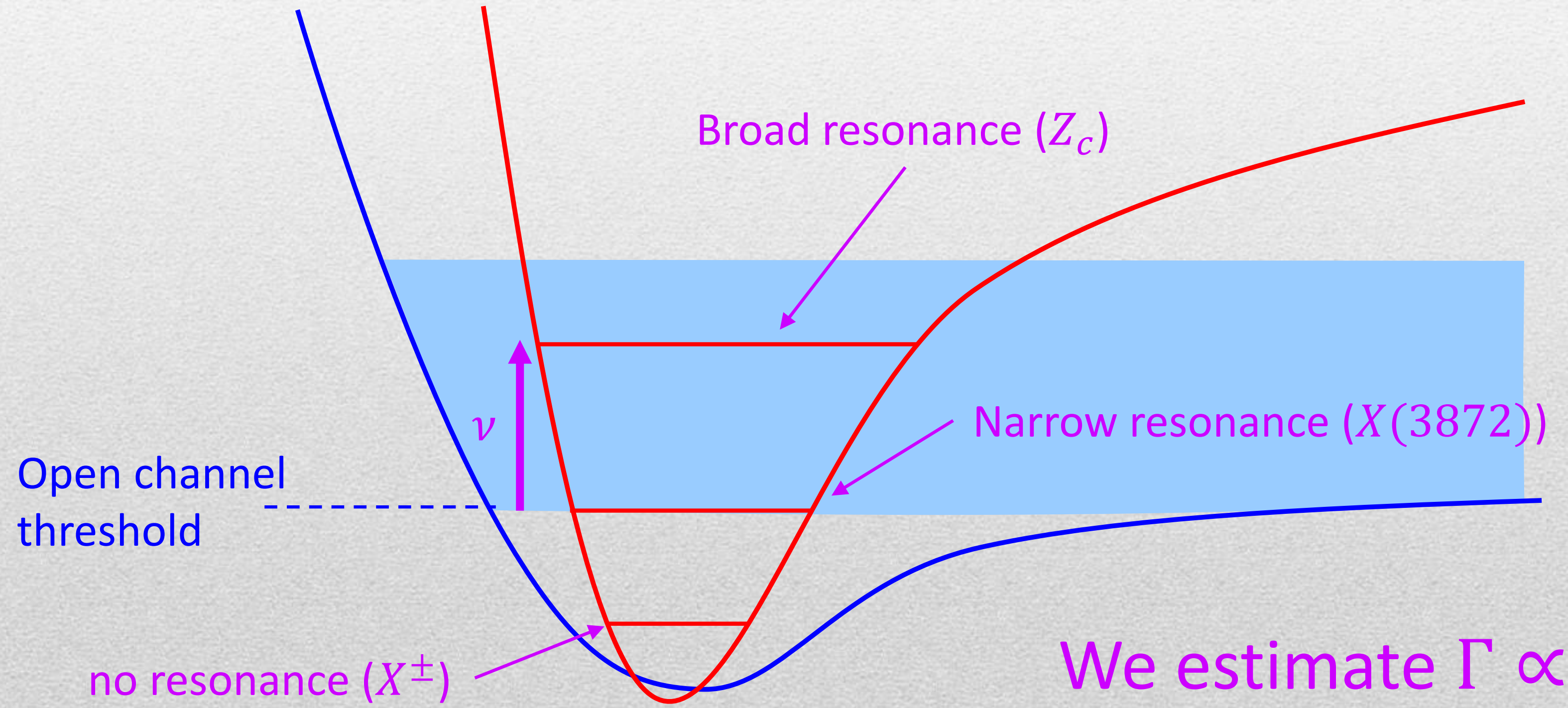
$$e.g.\ [cu]_{S=0}[\bar{c}\bar{u}]_{S=1}$$

Same quantum numbers as DD^*,
The operators mix under renormalization
↓
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 $I = 0$ state, but $M(1^{++}) < M(D^{+*}D^{-})$
No charged component, 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
$D^{*0}\bar{D}^0$	3872	0	0	1^-1^{++}	$X(3872)$
$D^{*+}\bar{D}^0$	3900	24	53	1^+1^{+-}	$Z_c(3900)$
$D^{*+}\bar{D}^0$	4025	8	24	1^+1^{+-}	$Z_c'(4025)$
$\eta_c(2S)\rho^+$	4475	75	>150	1^+1^{+-}	$Z(4430)$
$B^{*+}\bar{B}^0$	10610	3	18	1^+1^{+-}	$Z_b(10610)$
$B^{*+}\bar{B}^{*0}$	10650	1.8	11	1^+1^{+-}	$Z_b'(10650)$

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

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)

Production & Feshbach?

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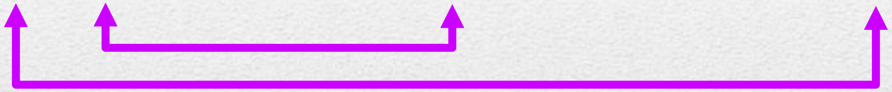
$$|\psi\rangle = \alpha|[qQ][\bar{q}\bar{Q}]\rangle_c + \beta|(\bar{q}q)(\bar{Q}Q)\rangle_o + \gamma|(\bar{q}Q)(\bar{Q}q)\rangle_o$$



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

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

Conclusions

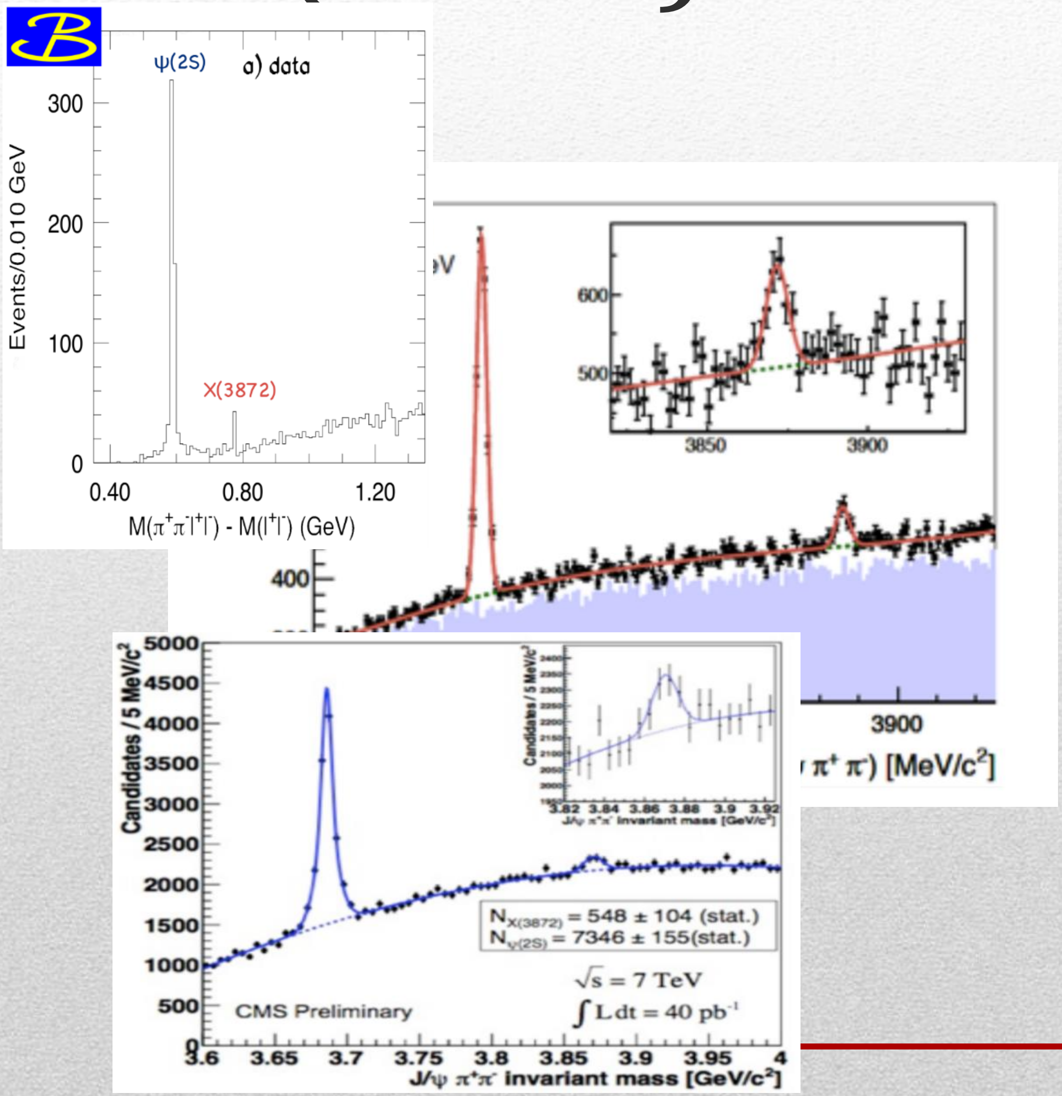
The study of exotic resonances in heavy quark sector
is still puzzling

- Measurement of prompt production cross sections could improve our understanding of hadronization
- Explore new production mechanisms having predictive power for at- and above-threshold states
- Feshbach mechanism could help in reducing the number of states predicted by tetraquark picture, and in adding some interesting features of molecular description

Thank you

BACKUP

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 $\chi_{c1}(2P)$

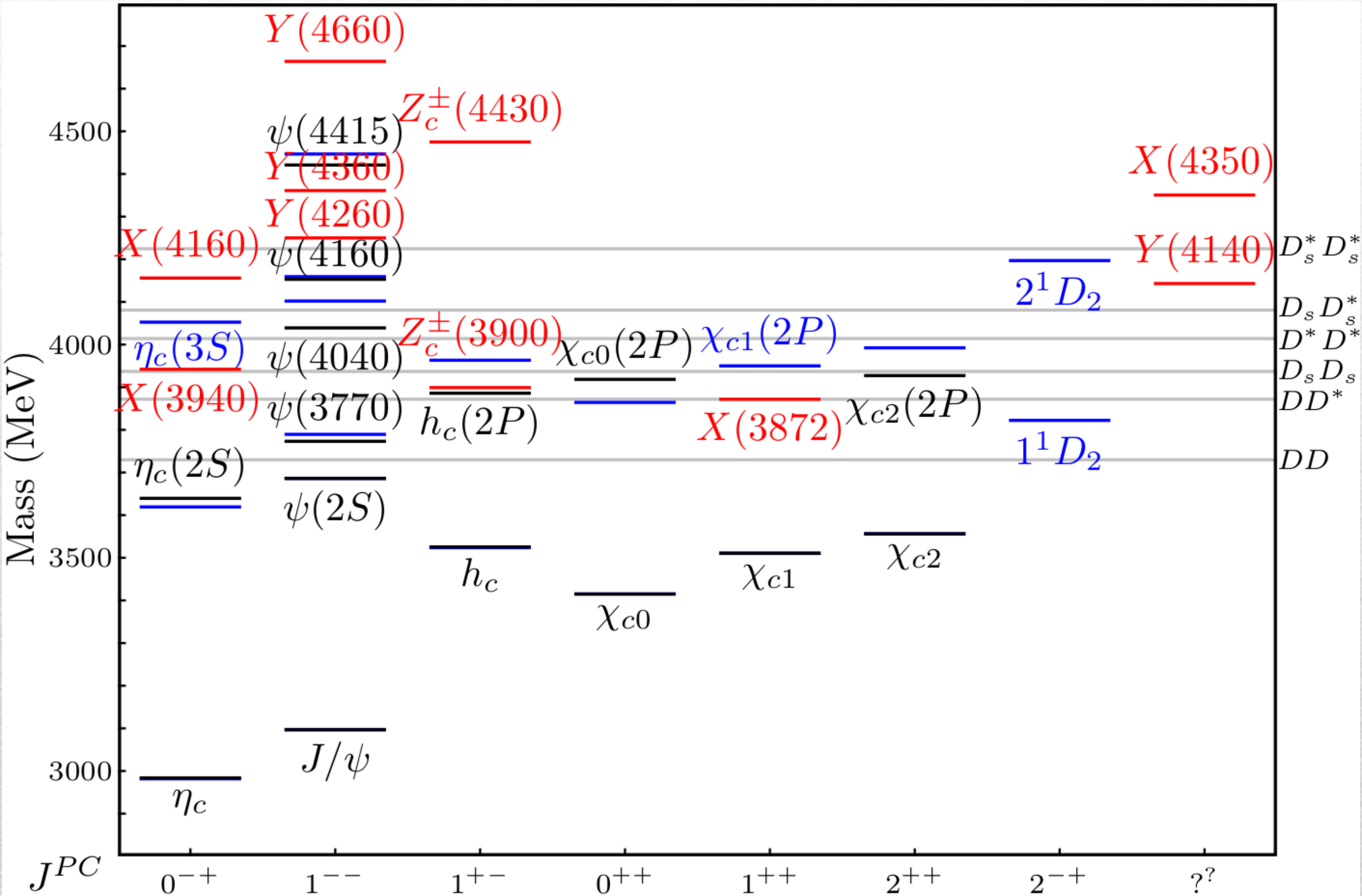
$M\ = 3871.68 \pm 0.17\ \mathrm{MeV}$

$M_X - M_{DD^*} = -0.14 \pm 0.22\ \mathrm{MeV}$

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

$J^{PC} = 1^{++}$

Quarkonium orthodoxy?



A host of unexpected resonances have appeared

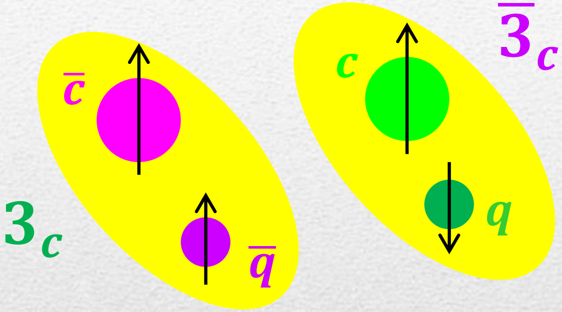
decaying into charmonium + light

Hardly reconciled with usual charmonium interpretation

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

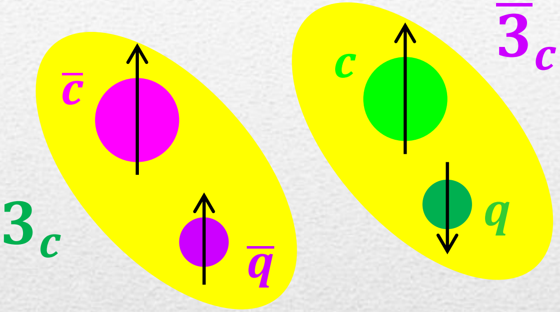
$$H = -2\sum_{i<j} \kappa_{ij}\, \overrightarrow{S_i} \cdot \overrightarrow{S_j}\, \frac{\lambda_i^a}{2}\frac{\lambda_j^a}{2}$$

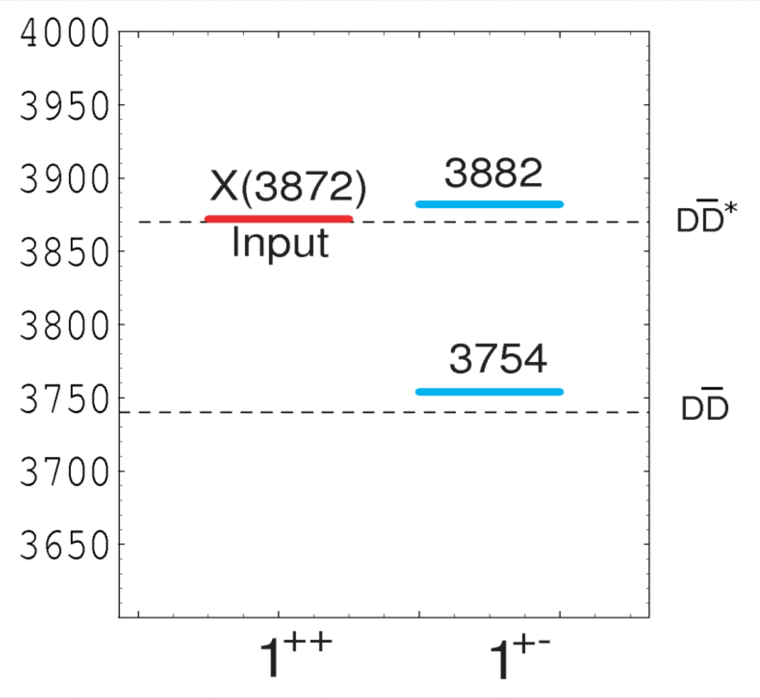
Tetraquark

One of the models for the $\boldsymbol{X(3872)}$ 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

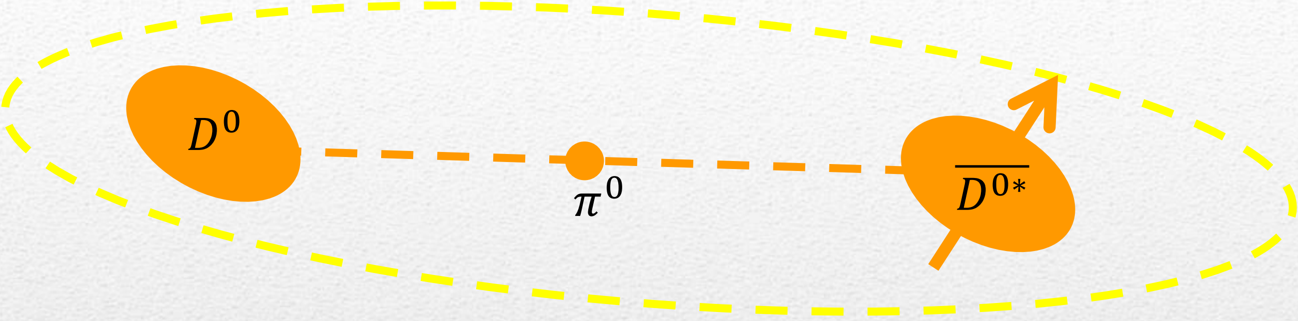
↓

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

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 $Z(4430)$ ✗)

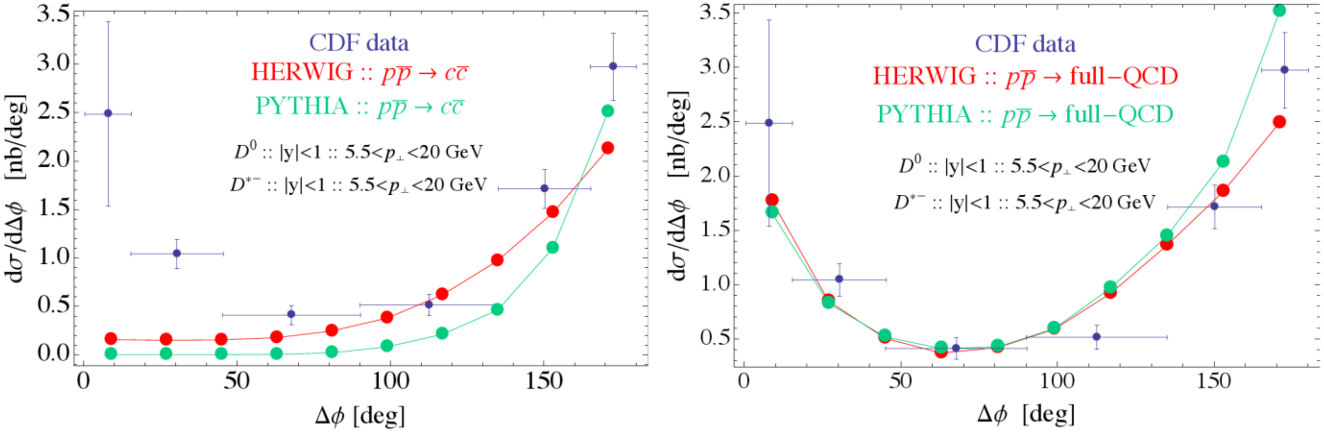
Binding energy is often small, or positive (repulsive interaction) ✗

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:

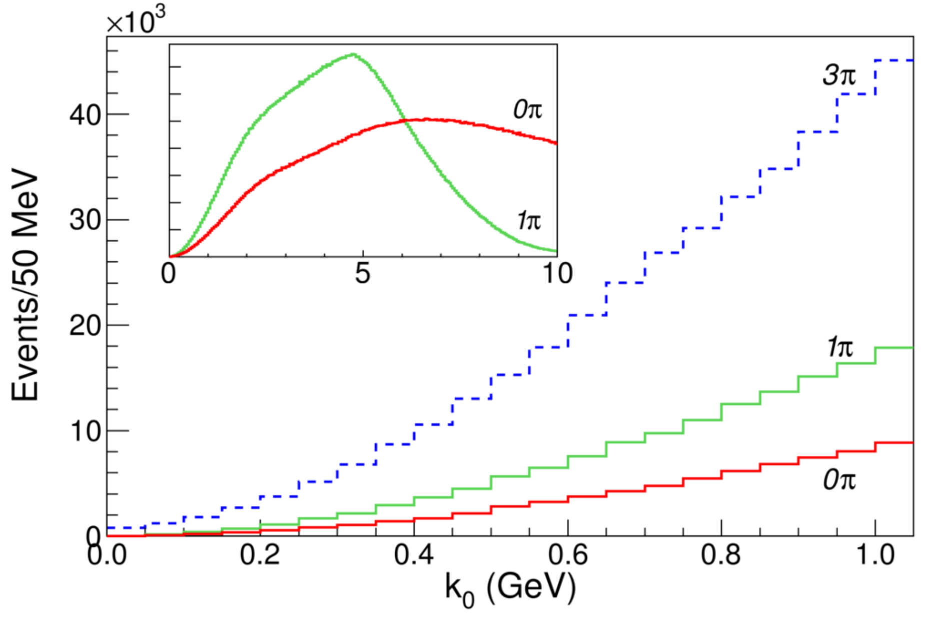


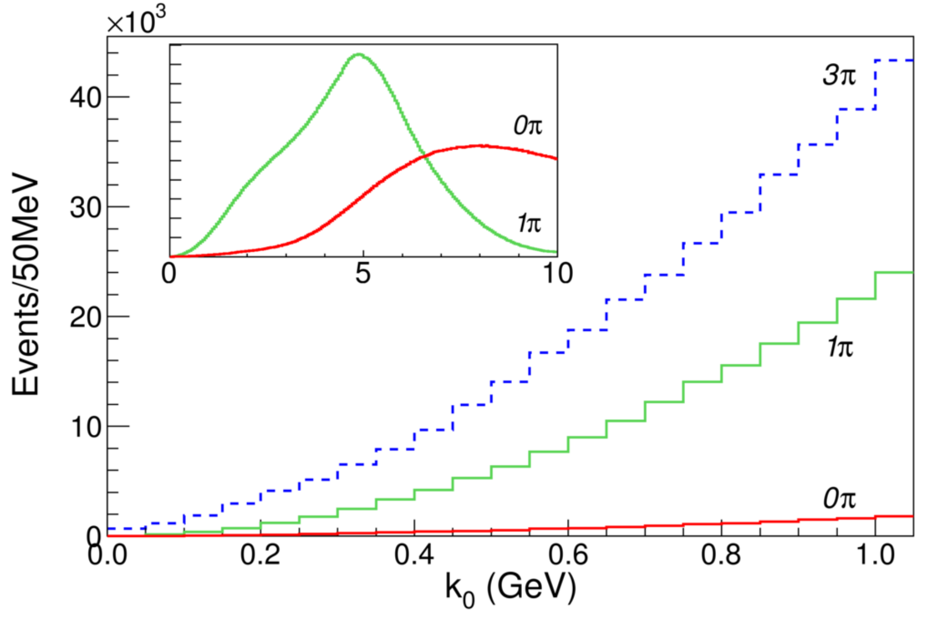
The c-cbar run understimate the low angles (low-k_0) region!

Such distributions of charm mesons are available at Tevatron

No distribution has been published (yet) at LHC

$p\bar{p} \to c\bar{c}$





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

The enhancement is impressive because first bins are almost empty