Theory Progress in Exotic Spectroscopy

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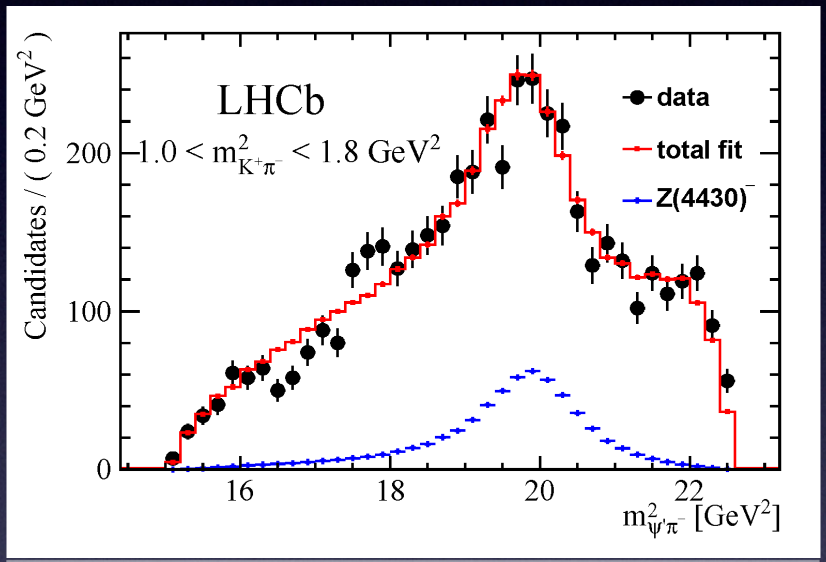
Fact: Tetraquark mesons do exist

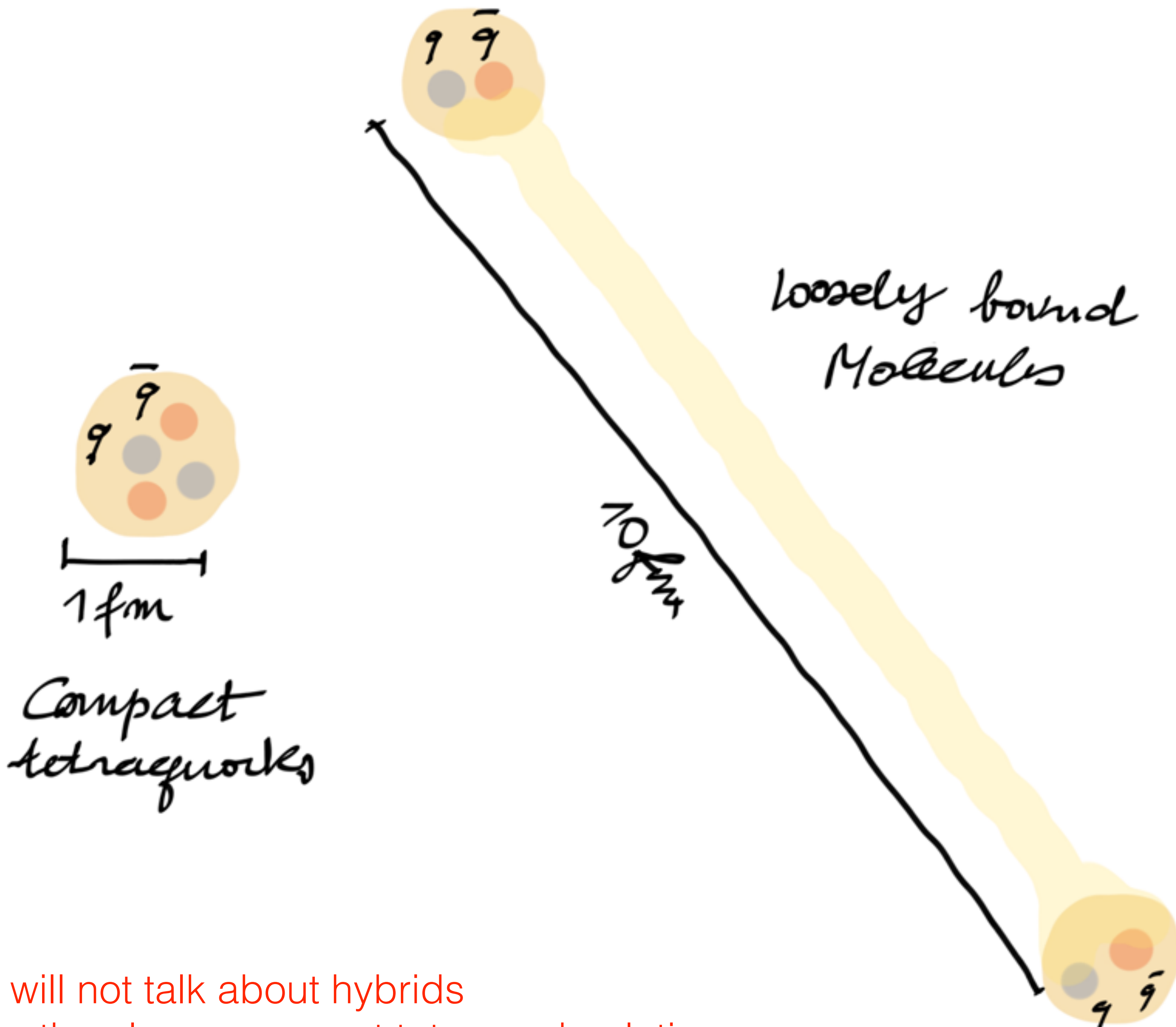
- Z(4.43) LHCb April 2014
- Z_c(3.9) BESIII & Belle 2013
- Z_c(4.02) BESIII 2013
- Z_b(10.61) & Z_b(10.65) Belle 2012

$B \to K^+(\psi(2S)\pi^-)_{J^{PG}=1^{++}}$



Some authors elaborated alternative explanations in terms of effects like kinematical cusps, coupled channels etc…
— the seminar proceeds under the hypothesis that they are wrong

Fancy: Compact or Extended?



I will not talk about hybrids
— the closer compact tetraquark relatives

Another couple of facts

- Compact tetraquark models predicted charged states ~10 years ago Maiani et al. hep-ph/0412098, PRD
  - But some of the predicted states have not (yet?) been found
- Molecular models do not provide predictions but provide explanations for supposedly tight, loose (and even unbound…) molecules
  - But no convincing description of their production at hadron collliders at high pT

Prototypical Example: X(3872), $J^{PC}=1^{++}$

Discovered by **Belle**, 2003, and soon confirmed by **CDF, BaBar, D0**. Later observed at **CMS** and **ATLAS**. Produced in *B* meson decays and ***prompt***, in hadron collisions.

4 CMS Collaboration arXiv:1302.3968 **4 Measurement of the cross section ratio**

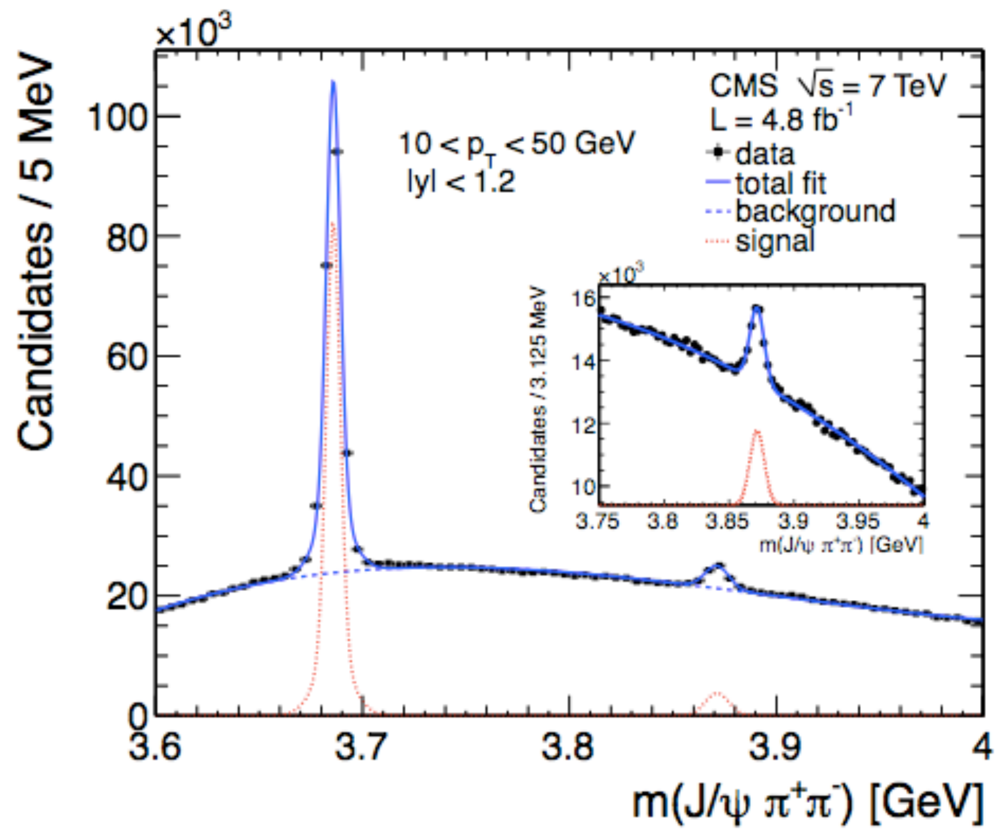


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.

The X(3872) `fine tunings`

The X(3872) appears to be very close to the DD* open charm threshold

$$m_{D^0} + m_{D^{*0}} = 3872 \text{ MeV}$$

The coincidence is really striking because the value is exactly matched.
Actually in terms of mass there is another surprising 'coincidence' in the X case

$$m_{J/\psi} + m_{\rho^0} = 3872 \text{ MeV}$$

The X decays in both channels, preferring the first one, and also decays into J/ψ ω

$$\frac{\mathcal{B}(X \to J/\psi\ \rho)}{\mathcal{B}(X \to J/\psi\ \omega)} \approx 1$$

which is an strong hint of ***isospin violation***

A loosely bound molecule

$$f(\alpha \to \beta) = -\frac{1}{8\pi E} A_{\beta\alpha}$$

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

$$m_c \simeq m_a + m_b - \varepsilon$$

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

This has to be compared with the potential scattering for slow particles (ka<<1) in an attractive potential U with a superficial level at -ε (ε>0) — here T~|ε|

$$f(ab \to ab) = -\frac{1}{\sqrt{2m}} \frac{\sqrt{\varepsilon} - i\sqrt{T}}{\varepsilon + T}$$

$$\varepsilon \simeq \frac{g^4}{512\pi^2} \frac{m^5}{m_a^4 m_b^4}$$

A loosely bound molecule

For slow (ka<<1) spinless particles whose scattering can be described by an attractive shallow potential U with a (superficial) discrete level at -ϵ (|ϵ|<<|U| within a, U(∞)→0)

$$\epsilon = \frac{g^4}{512\pi^2}\frac{M_D M_{D^*}}{(M_D + M_{D^*})^5}$$

If we consider a trasnition

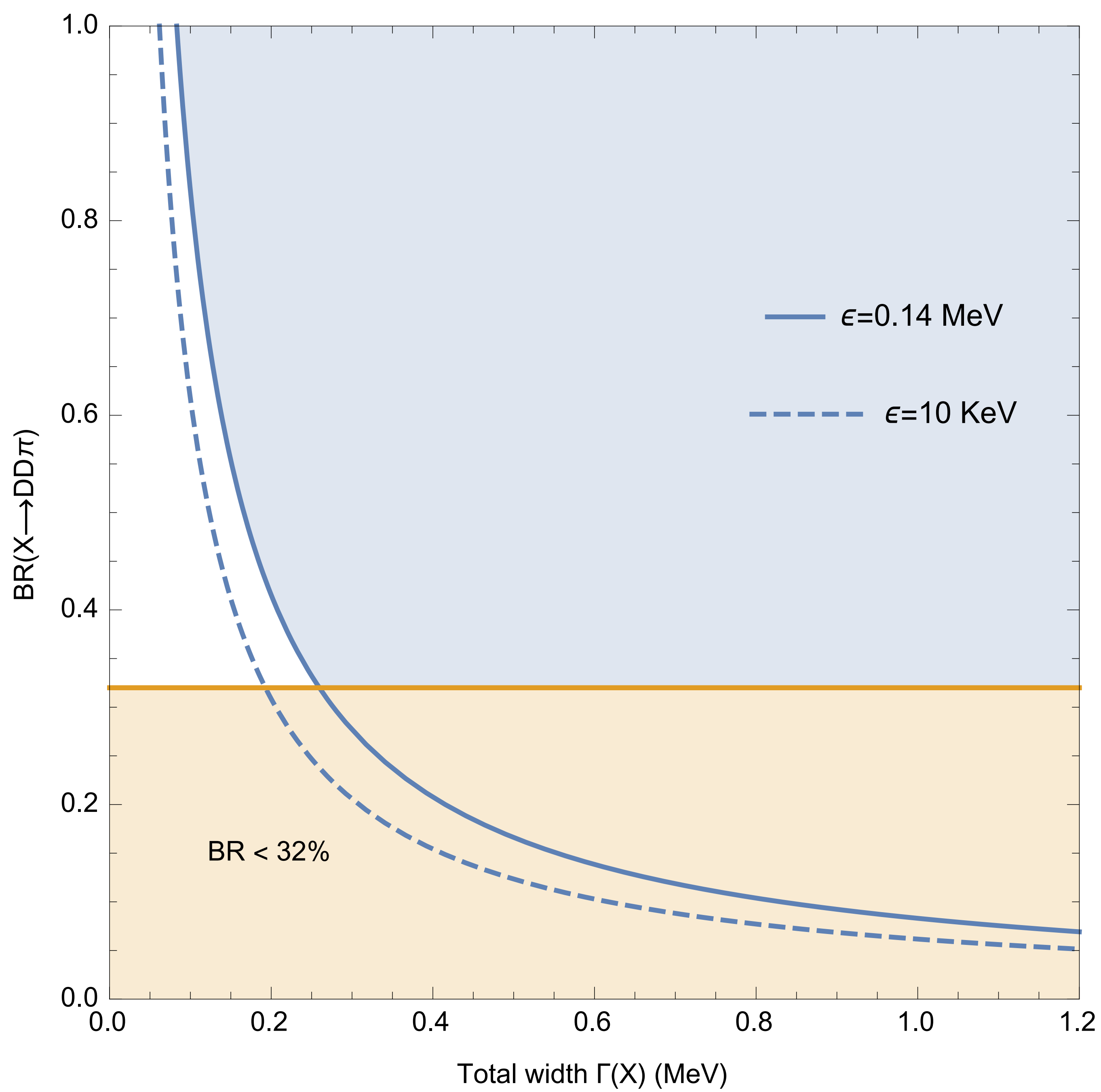
$$\langle D^0 \bar{D}^{0*}(\epsilon, q) | X(\lambda, P)\rangle = g\,\lambda\cdot\epsilon^*$$

in the formula for **ϵ** one can substitute

$$g^2 \to g^2\,\frac{1}{3}\left(2 + \frac{(M_X^2 + M_{D^*}^2 - M_D^2)^2}{4M_X^2 M_{D^*}^2}\right)$$

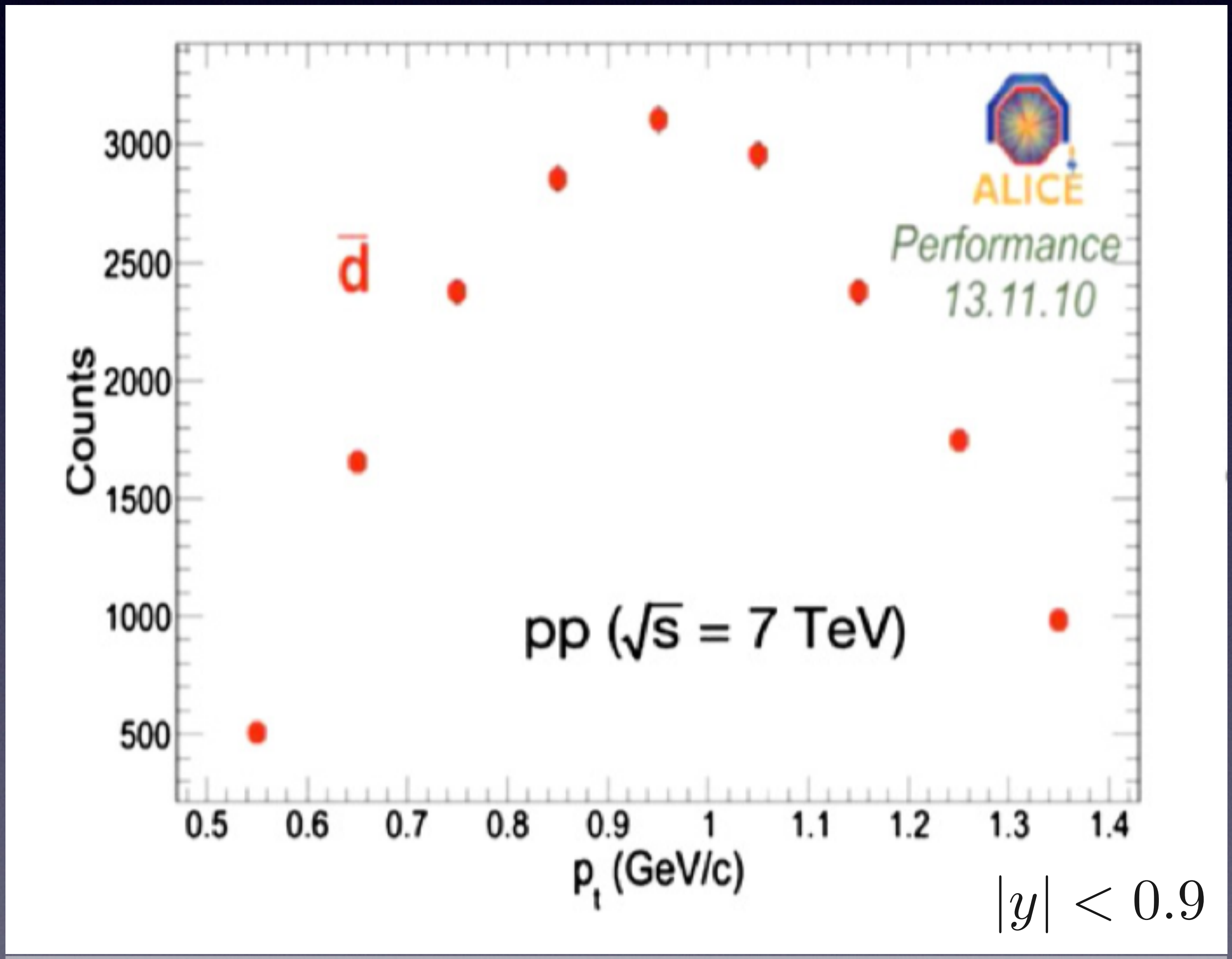
assuming that the **barycentric kin. energy** is **as small as the binding one**

Precision measurement of ε, Γ_X, $\mathcal{B}r(X \to \mathcal{D}\mathcal{D}^*)$



Any anti-deuteron at LHC?

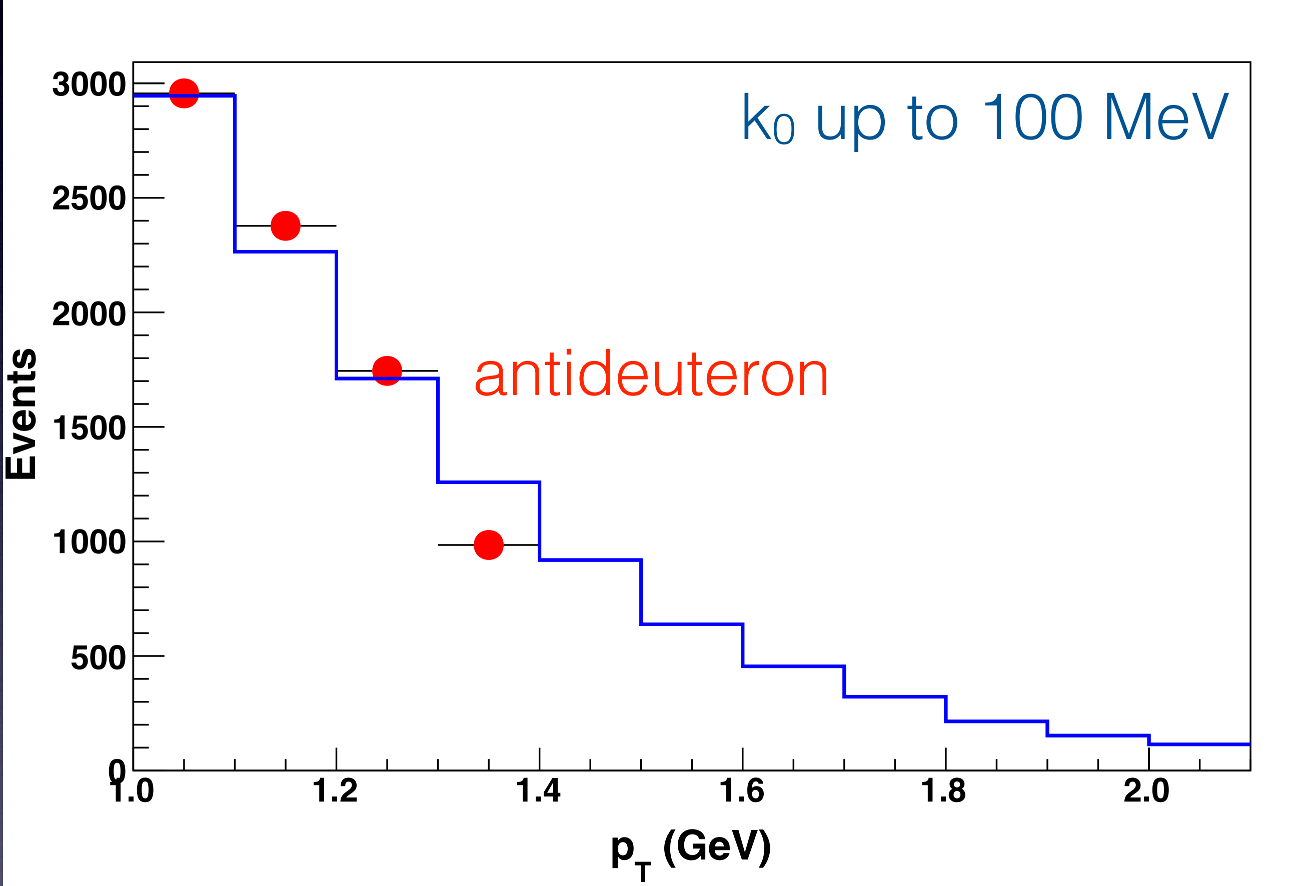
A lot!!…
Indeed Alice has 30K antideuterons — In which p_T range though?

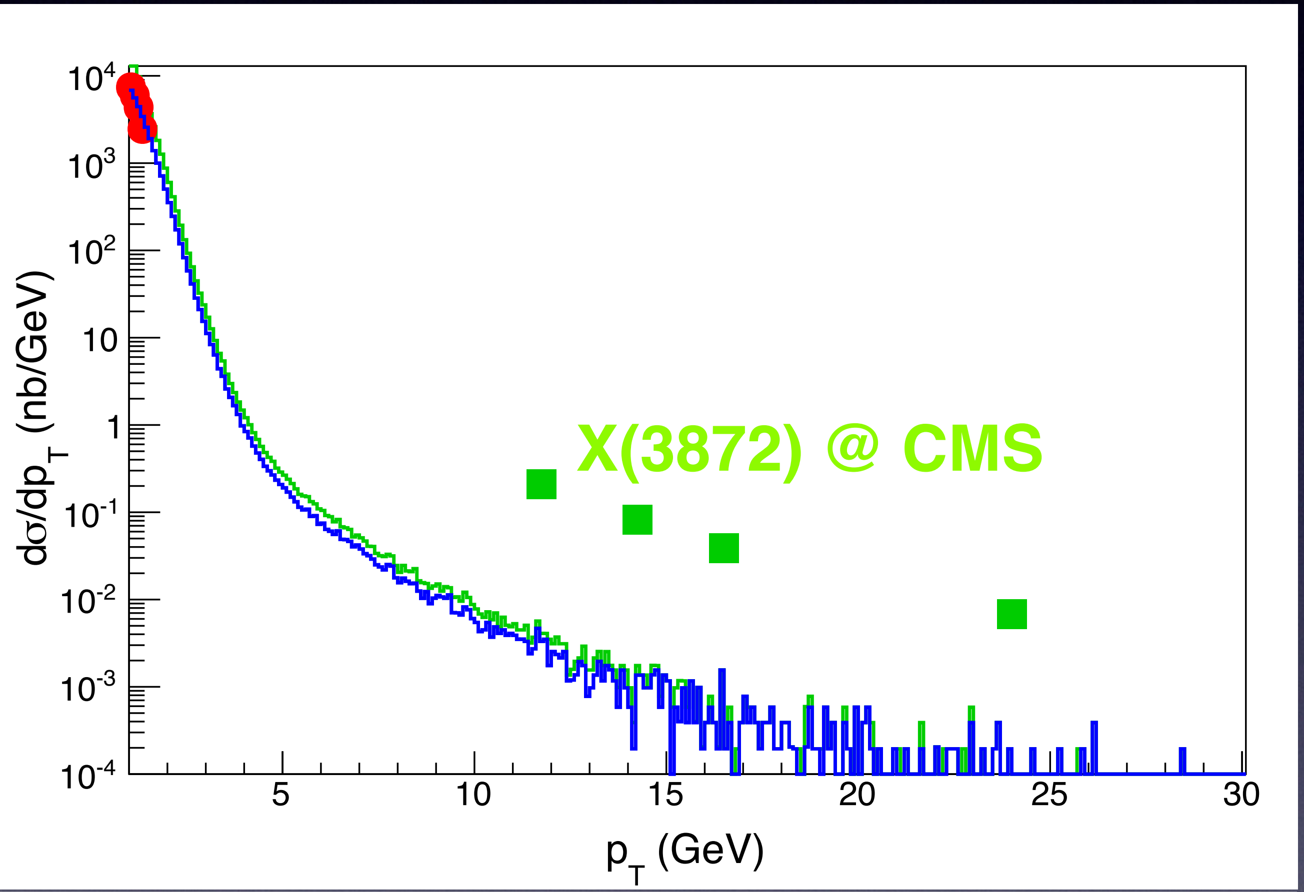


Recall that X has been observed with a **p_T>10 GeV!**

MC Extrapolation

More data at higher pT would be needed for we can't rely on qcd at pT~1GeV



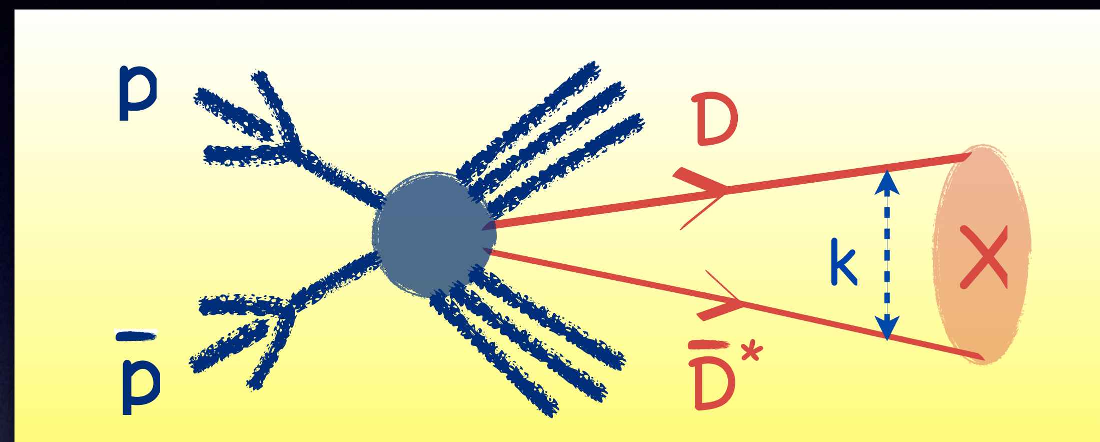


CMS cuts for the X: $10 < p_T < 50$ GeV

$|y| < 2$

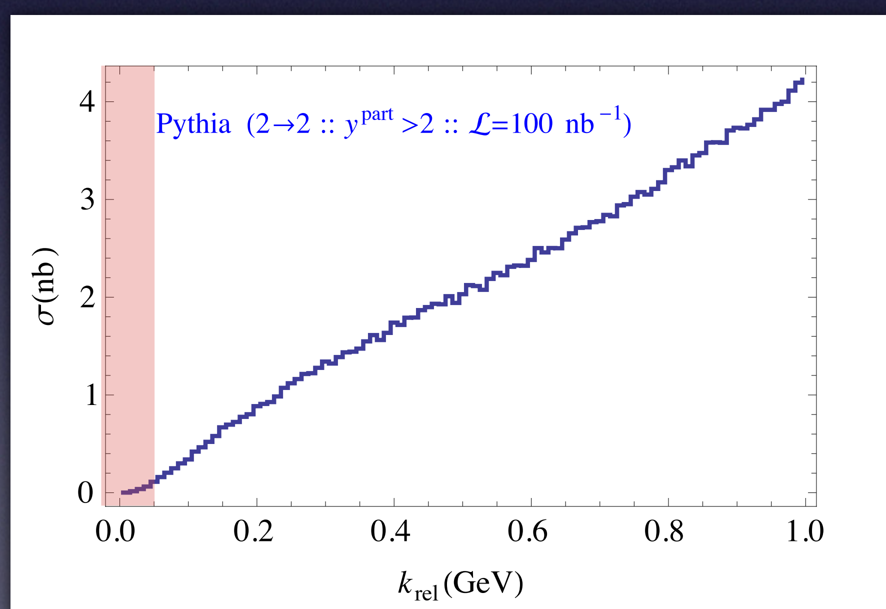
A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929, PRD

Barely Bound States in TeV Hadron Collisions?



$p_{\perp}^{\text{mol}} > 5.5$ GeV

$|y^{\text{mol}}| < 1$



k bounded by 50 MeV

Production xsect 300 times smaller than the observed one

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Rev Lett*, ***103***, *162001 (2009)*

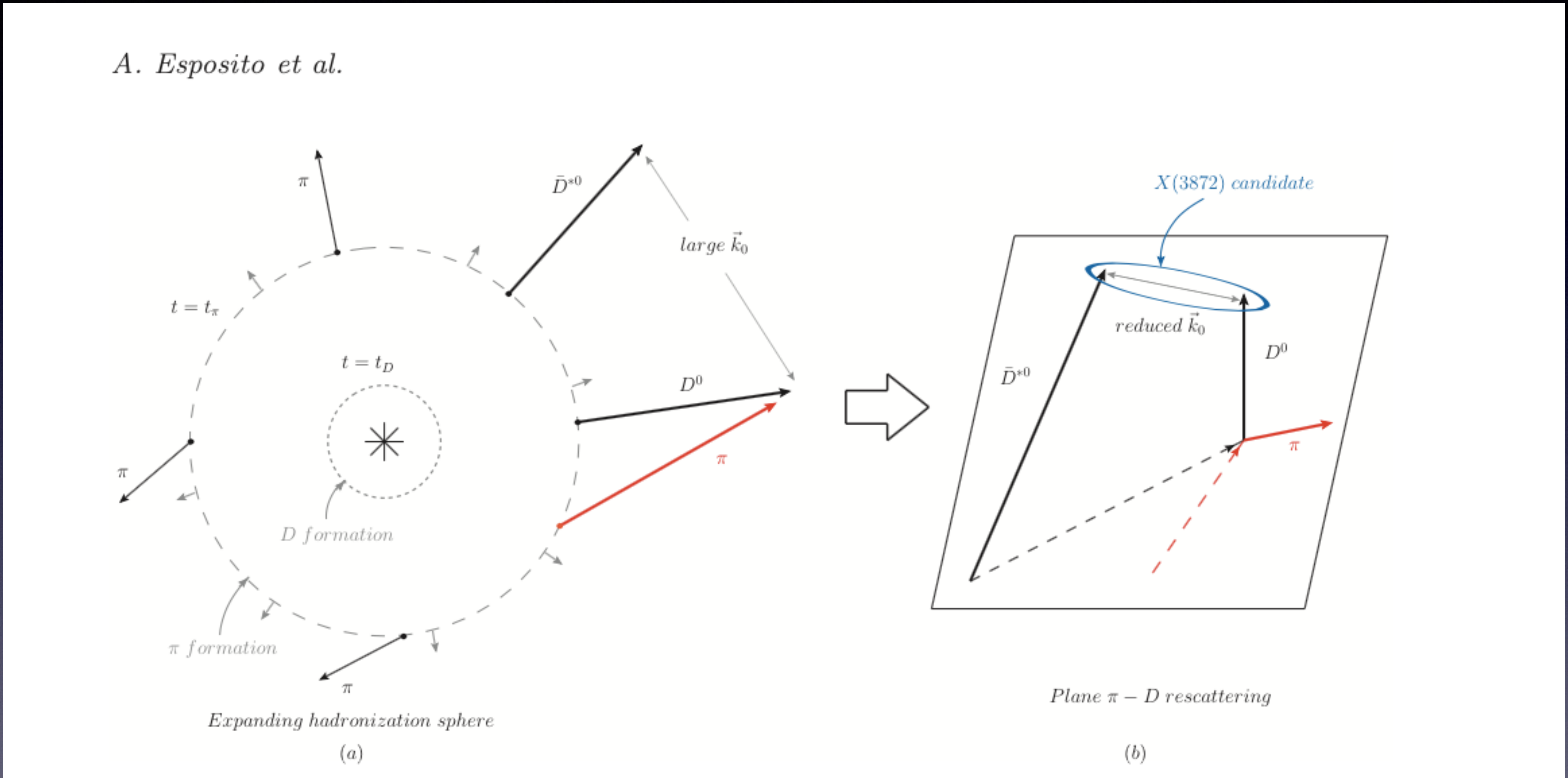
P. Artoisenet and E. Braaten, *Phys Rev* ***D81***, *114018 (2010)*

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Lett*, ***B684***, *228 (2010)*

A. Esposito, F. Piccinini, A. Pilloni, A.D. Polosa, *J. Mod. Phys. 4, 1569, (2013)*

F-K. Guo, U. Meissner and Wang, arXiv: 1308.0193, 1402.6236 [. . .]

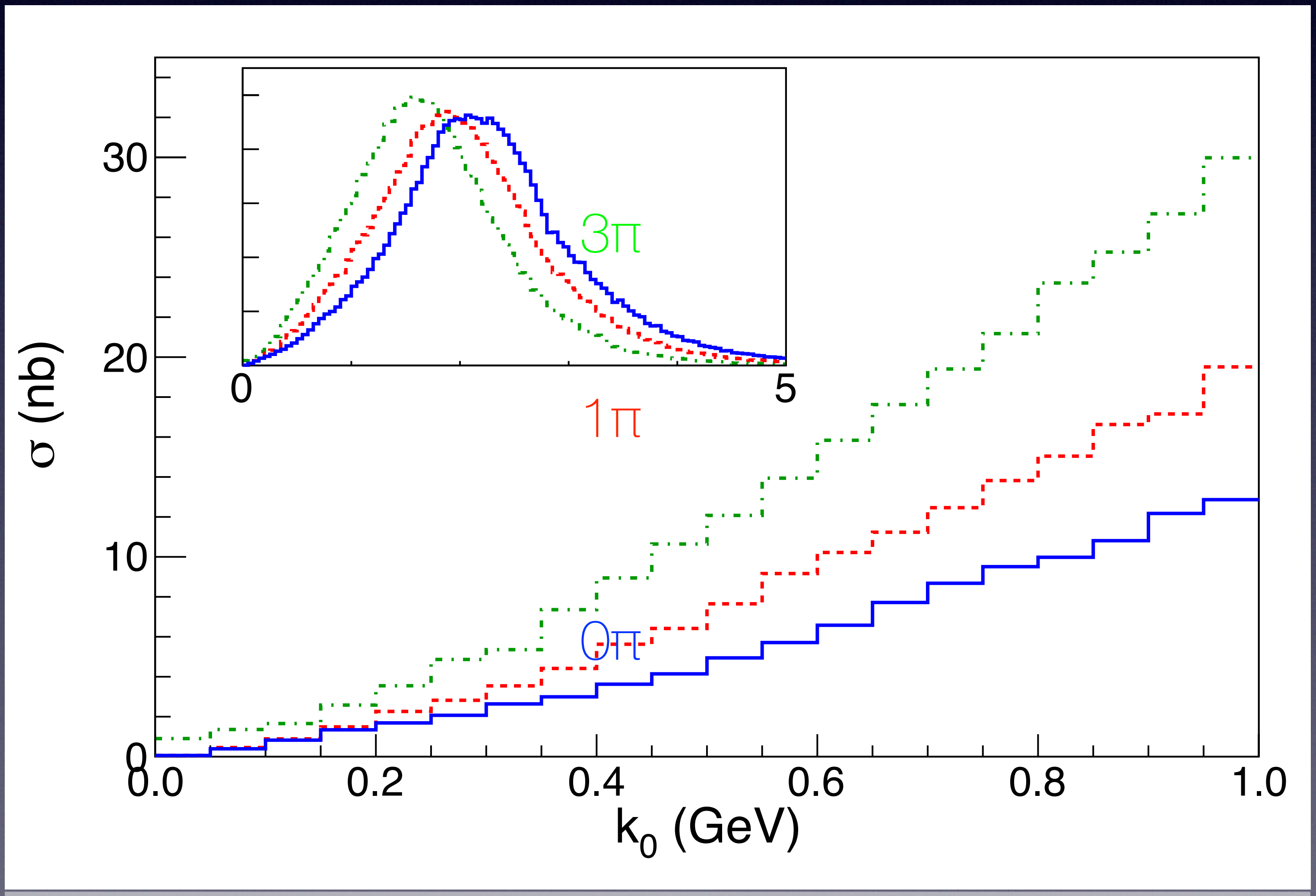
Rescattering (FSI) by Pions



A. Esposito, A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1411.5997, IJMP**A**

Rescattering (FSI) by Pions

The mechanism works: *feed down* from higher bins — but it does not help in the *bins of interest* (up to 100 MeV for the com relative momentum in the wold-be-molecule, k_0)



A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929, PRD

Compact Tetraquarks

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

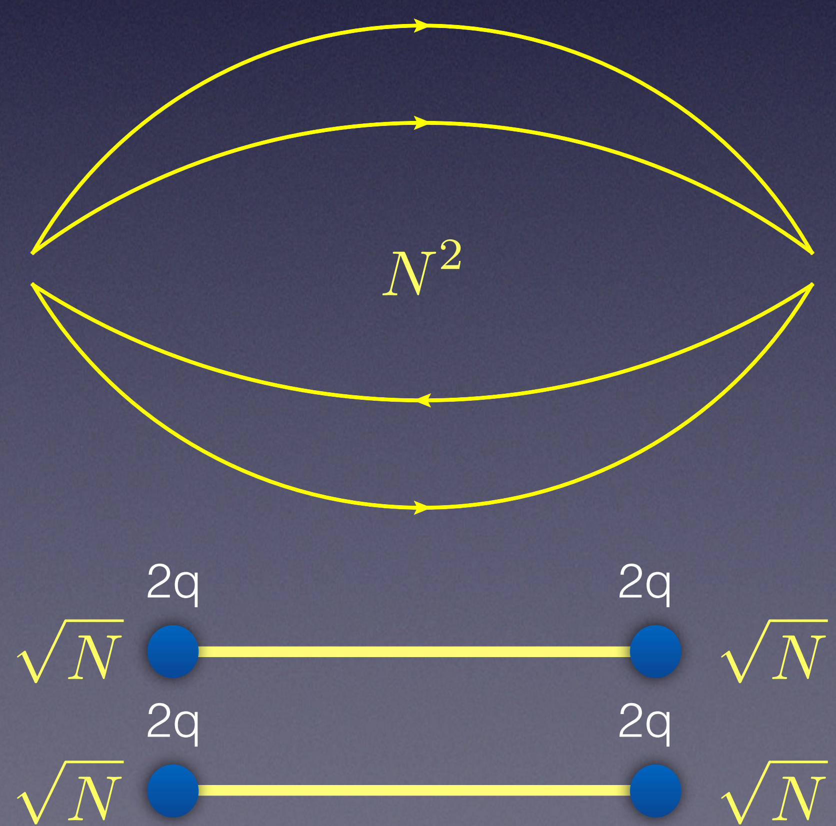
from a Gell-Mann's paper
on quark model

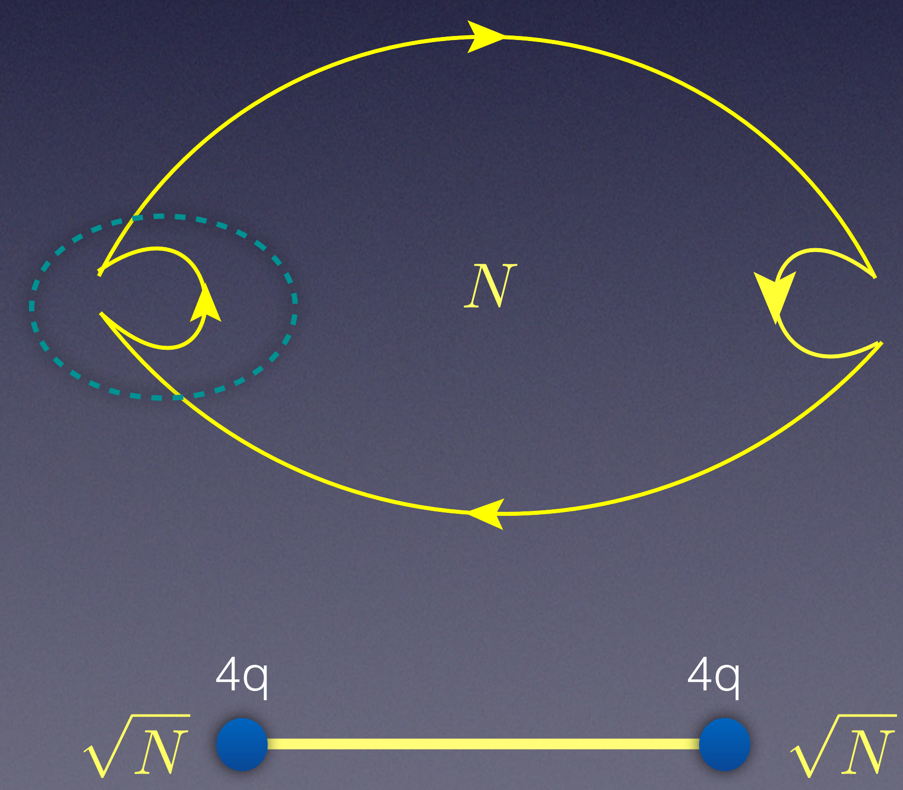
Large N_c and Tetraquarks

Following a paper by Witten on `1/N and Baryons` (see also S. Coleman's lectures), tetraquarks should **instantly fall apart into mesons**.

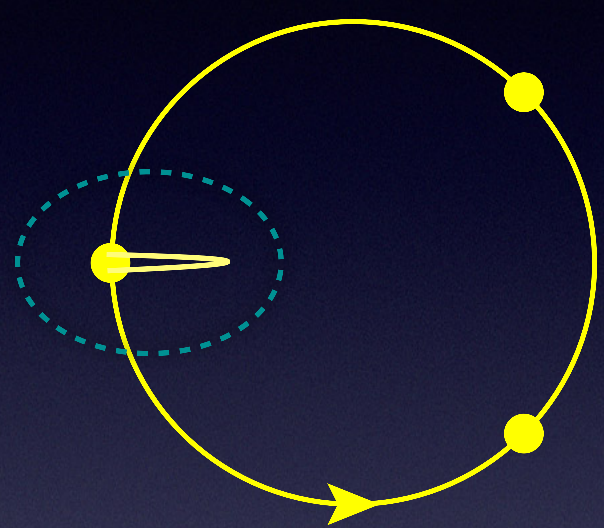
However, as commented by S. Weinberg in a recent paper (PRL 110, 2013), this applies only at the leading order N^2 *disconnected* diagram.

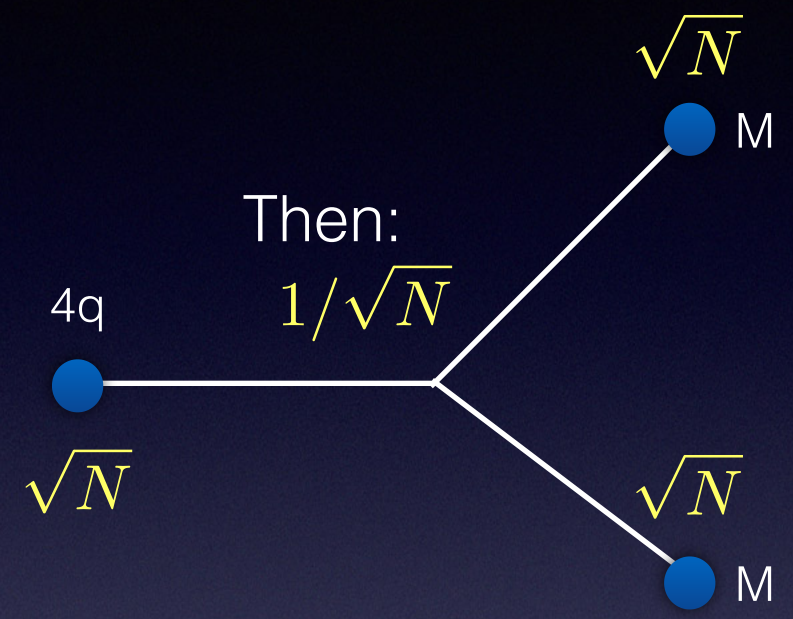
The leading order *connected* diagram has only one color loop.





Large N_c and Tetraquarks





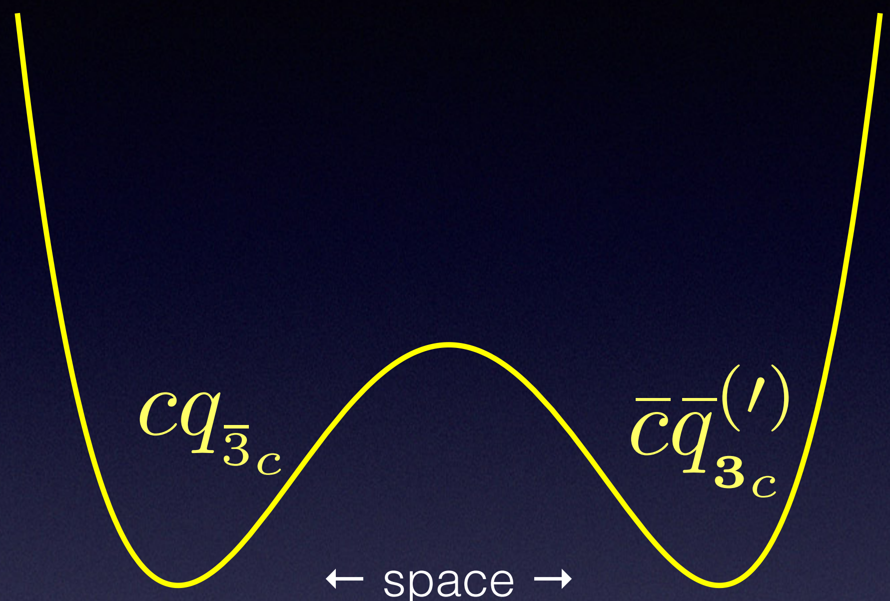
which implies that the 4q decay amplitude into two ordinary mesons can be $1/N^{1/2}$

This discussion has been enlarged by M. Knecht and S. Peris (arXiv:1307.1273) and further considered in three papers by T. Cohen and R. Lebed et al. (arXiv: 1401.1815, arXiv:1403.8090). According to them, tetraquark are not narrow because of 1/N counting but due to other effects.

On the other hand tetraquarks appear in the spectrum of QCD in the Corrigan-Ramond large N limit ('larks' in the antifundamental) as *narrow* hadrons.

A. Esposito, A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1411.5997, IJMP**A**

Diquarkonia



$$H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

In ‘type II’ model, the spin interactions inside the diquark are assumed to dominate over all other possible pairings.

$H \approx 2\kappa_{q\bar{q}}(s_q \cdot \boldsymbol{s}_{\bar{q}})$ type I Maiani, Piccinini, Polosa, Riquer, PRD71 (2005)

$H \approx 2\kappa_{q\bar{c}}(s_q \cdot \boldsymbol{s}_c + s_{\bar{q}} \cdot \boldsymbol{s}_{\bar{c}})$ type II Maiani, Piccinini, Polosa, Riquer, PRD89 (2014)

Charged states and diquarkonia

$$Z(4430) \to \psi(2S)\,\pi^-$$

$$Z(3900) \to J/\psi\,\pi^-$$

See also the calculation by S. Brodsky, D. Hwang & R. Lebed in a *diquark-antidiquark* model arXiv:1406.7281

$$m(\psi(2S)) - m(J/\psi) \simeq m(Z(4430)) - m(Z(3900))$$

'A crucial consequence of a Z(4430) charged particle is that a charged state decaying into $J/\psi + \pi^\pm$ (or $\eta_c + \rho^\pm$) should be found around 3880 MeV'

Taken from L. Maiani, A. D. P. and V. Riquer, arXiv:0708.3997 [hep-ph].
At that time there was no hint of Z_c(3900) in data.

There is another state in between — the Z_c(4025) — also required by the diquark-antidiquark model. Both of them have been discovered in 2013 (BES)

What is the S_{cc^*} in Z_c and Z_c'?

Focus on the **heavy quark (pair) spin**, which we assume to be **conserved** in strong interactions

$$Z_c(3900) \to J/\psi(S_{c\bar{c}} = 1)\,\pi^-$$
$$Z_c(4025) \to h_c(S_{c\bar{c}} = 0)\,\pi^-$$

Things get more complicated when light quarks are involved as in the D*D* decay.

One might conclude that the two light Z_c cannot be states with the heavy spin fixed to be equal to one but

$$Z_c, Z_c' = |S_{c\bar{c}}, S_{q\bar{q}}\rangle_J \neq |1,1\rangle_1$$
$$Z_c, Z_c' \sim |0,1\rangle \pm |1,0\rangle$$

Are there **|1,1>** states?

Tetraquarks made of diquarks

In our schemes tetraquarks could be described in terms of **heavy-light diquarks**

$$[cq]_i [\bar{c}\bar{q}]^i$$

Diquark-antidiquark states might be formed in different spin combinations

	$cq\ \bar{c}\bar{q}$	$c\bar{c}\ q\bar{q}$	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

One should build a **diquark** Hamiltonian with **degenerate eigenvalues** for X(3872) and Z_c(3900) - look at exp. mass values

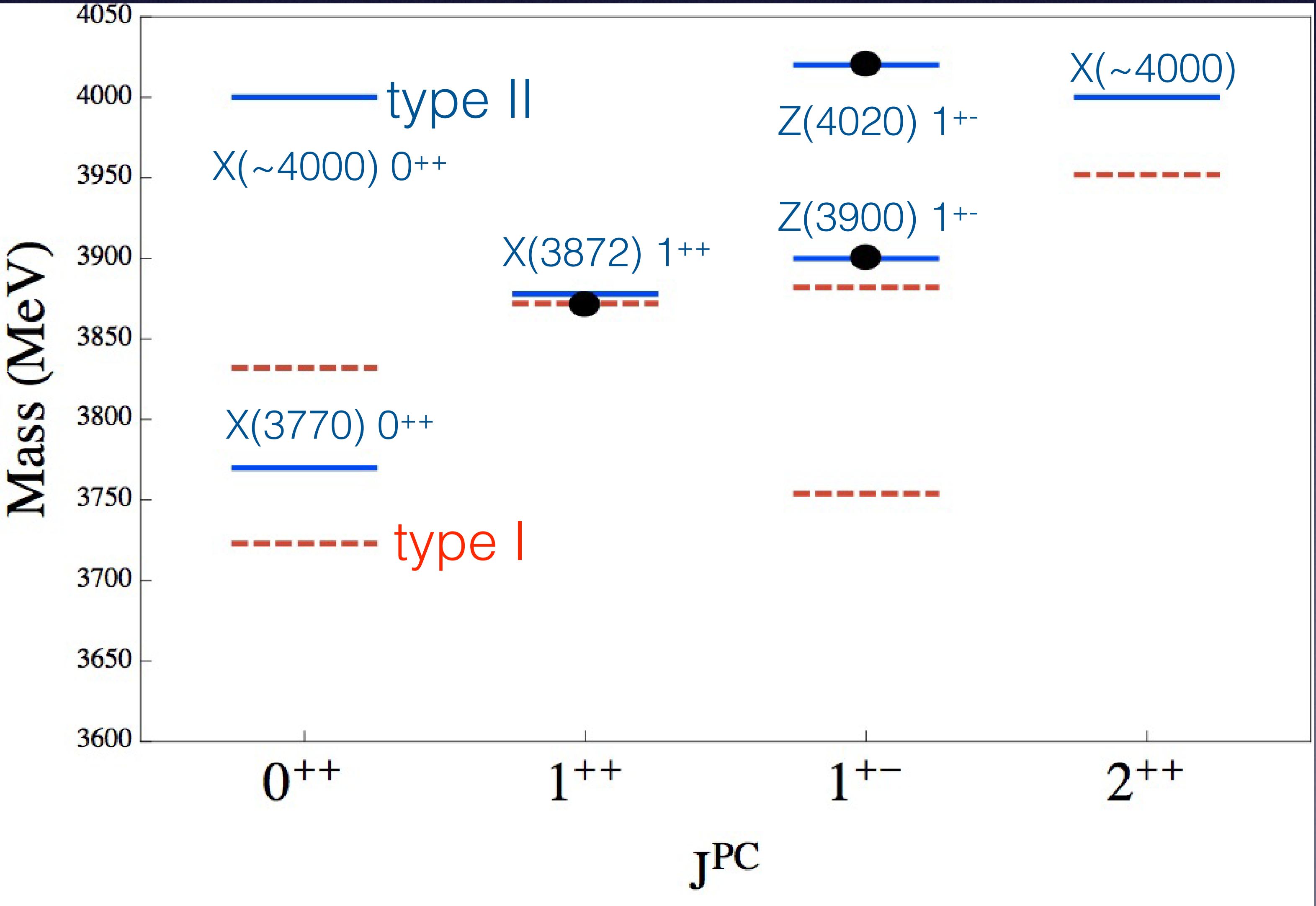
A. Esposito, A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1411.5997, IJMP**A**

Mass Spectrum

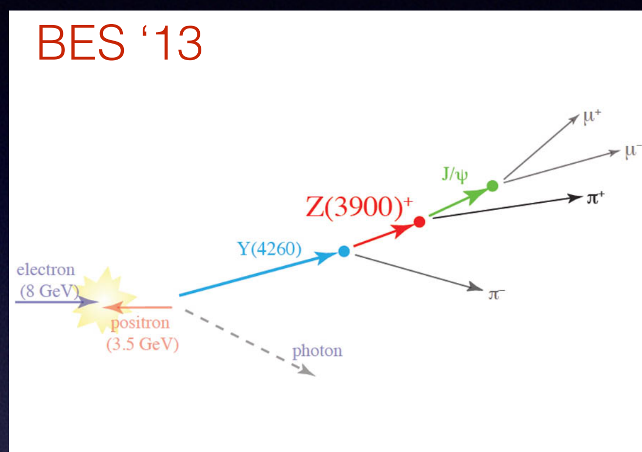
$$H \approx 2\kappa(\boldsymbol{S}_q \cdot \boldsymbol{S}_c + \boldsymbol{S}_{\bar{q}} \cdot \boldsymbol{S}_{\bar{c}})$$

$$(H)_{1^{+-}} = \begin{pmatrix} -\kappa & 0 \\ 0 & \kappa \end{pmatrix} \qquad (H)_{1^{++}} = -\kappa \quad (H)_{2^{++}} = \kappa \qquad (H)_{0^{++}} = -3\kappa \quad (H)_{0^{++\prime}} = \kappa$$

Maiani, Piccinini, Polosa, Riquer, PRD89 (2014) and TYPE II Model



Loosely bound $Z_{c,b}$'s?



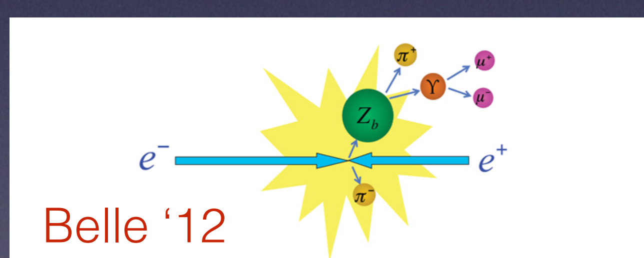
$$Z_c(3900) \to \pi^\pm J/\psi$$
$$Z_c'(4025) \to h_c \pi^\pm$$

$$m_{D^0} + m_{D^{*+}} = 3875 \text{ MeV}$$
$$m_{D^{*0}} + m_{D^{*+}} = 4017 \text{ MeV}$$

$+24$ MeV

$+8$ MeV

Better in the beauty sector



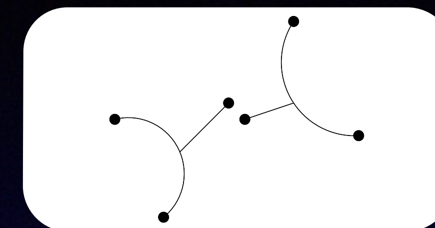
$$\Upsilon(5S) \to \pi^\pm Z_b^\mp(10610) \to \pi^\pm\pi^\mp\Upsilon(nS) \quad n = 1,2,3$$
$$\Upsilon(5S) \to \pi^\pm Z_b^\mp(10650) \to \pi^\pm\pi^\mp h_b(kP) \quad k = 1,2$$

$$m_B + m_{B^*} \simeq 10604 \text{ MeV}$$
$$2m_{B^*} \simeq 10650 \text{ MeV}$$

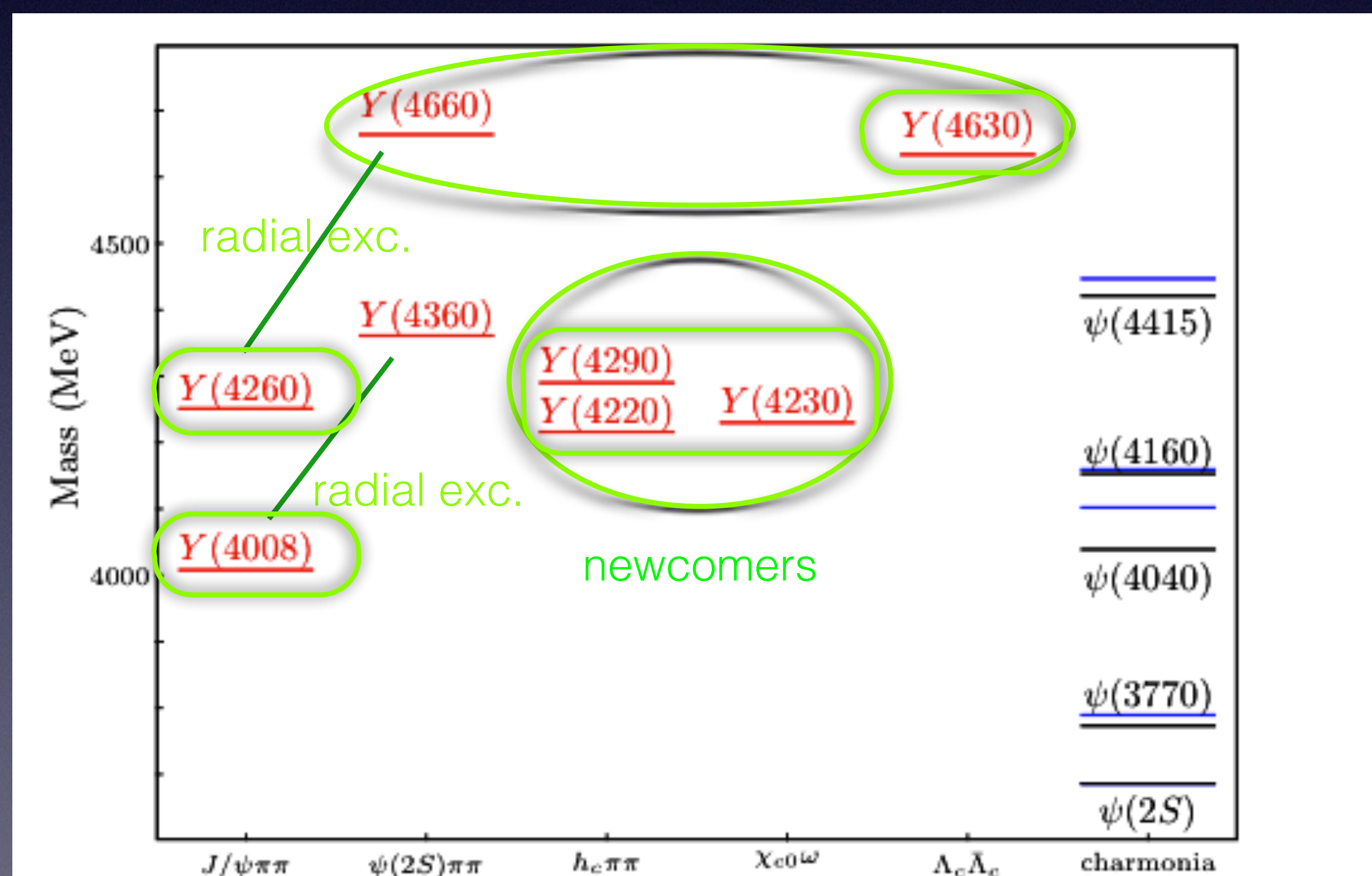
No molecular matchings for the Z(4430)

The Y(1⁻) resonances

$$\frac{\mathcal{B}(Y_B \to \Lambda_c \bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 24.6 \pm 6.6$$



G. Cotugno, R. Faccini, ADP, C. Sabelli *Phys. Rev. Lett.* ***104**, 132005 (2010)*



Negative Parity: L=1

Spin (dq basis)

$$Y_1 = |0,0\rangle$$

$$Y_2 = \frac{|1,0\rangle + |0,1\rangle}{\sqrt{2}}$$

$$Y_3 = |1,1\rangle_{S=0}$$

$$Y_4 = |1,1\rangle_{S=2}$$

Like the X; Mass difference due to L

We identify Y(4360) and Y(4660) decaying into ψ(2S)π as radial excitations of Y(4008) and Y(4260).

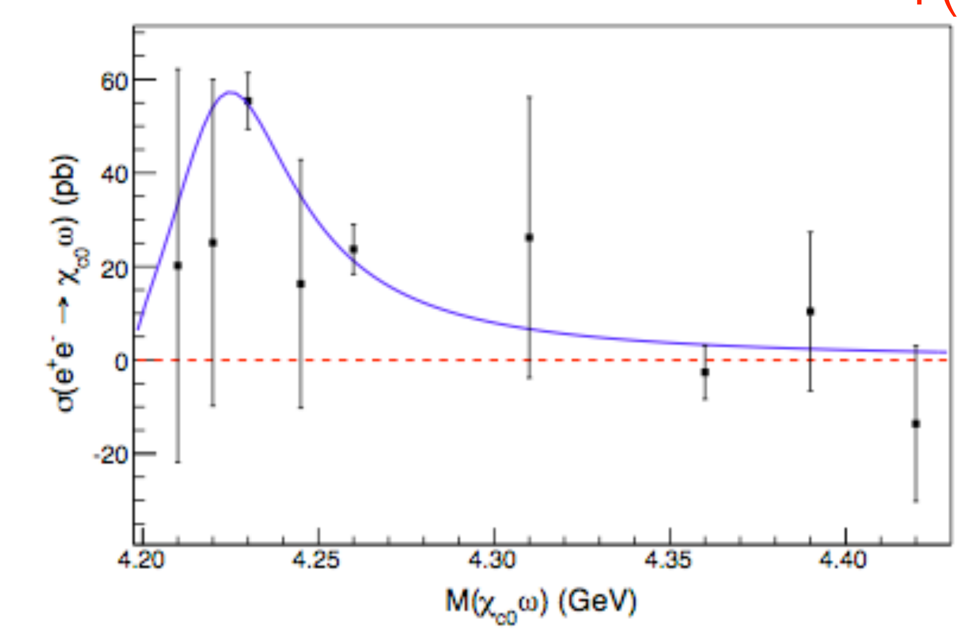
State	$P(S_{c\bar{c}}=1):P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
Y_1	3:1	$Y(4008)$	$\gamma + X_0$
Y_2	1:0	$Y(4260)$	$\gamma + X$
Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
Y_4	1:0	$Y(4630)$	$\gamma + X_2$

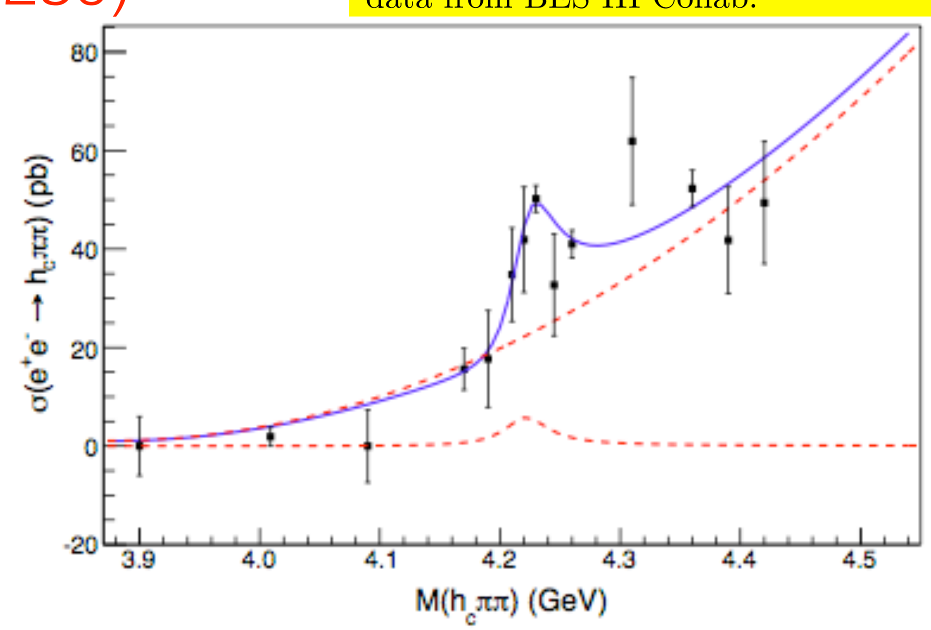
R. Faccini, G. Filaci, A. Guerrieri, A. Pilloni, ADP arXiv:1412.7196, IJMP**A**

M. Ablikim *et al.* [BESIII Collaboration], arXiv:1410.6538 [hep-ex].

Y(4230)

C. Z. Yuan, Chin. Phys. C **38** (2014) 043001 data from BES III Collab.





A brief tour in the beauty sector

A. Ali, L. Maiani, ADP, V. Riquer arXiv:1412.2049, PRD

1)

$$M(Z_b') - M(Z_b) = 2\kappa_b$$

$$M(Z_c') - M(Z_c) = 2\kappa_c = 120 \text{ MeV}$$

$$\kappa_b : k_c = M_c : M_b \approx 0.30$$

$$\Rightarrow 2\kappa_b \simeq 36 \text{ MeV vs. } 45 \text{ MeV (exp.)}$$

2)

$$\Upsilon(10890)(\Upsilon(5S)?) \to Z_b^{(\prime)}\pi \to h_b(nP)\pi\pi$$

$$Y(4260) \to Z_c(3900) + \pi$$

$S_{cc^*}=0$

$S_{cc^*}=1$

heavy spin violation?

but

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

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

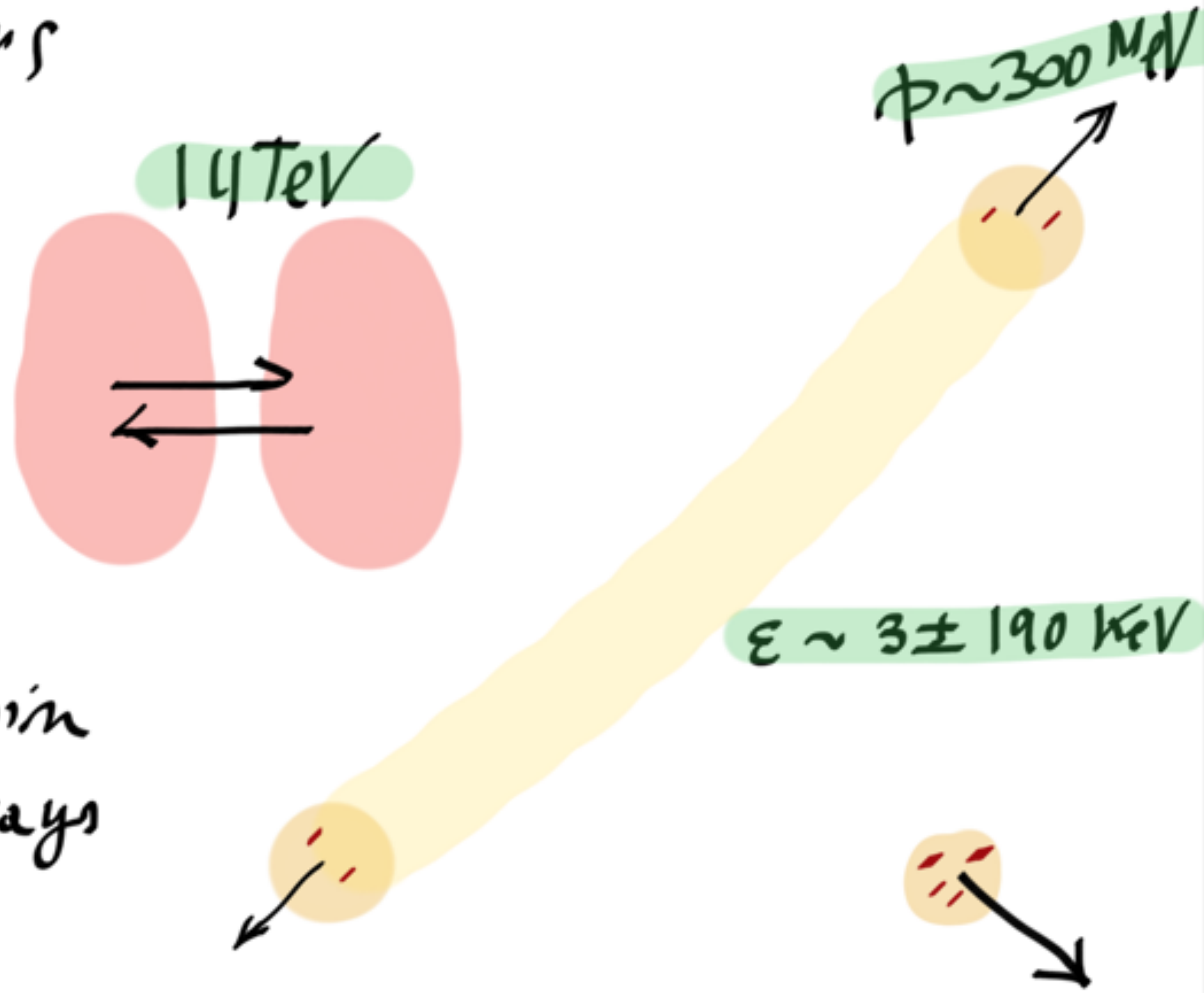
and data on 1—>0 and 1—>1 transitions strongly favor

$$\alpha = \beta$$

Conclusions

1. Seek antideuterons at high $p_\perp$

2. Precision measurem. of ε, $\mathcal{B}(X \to D\bar{D}^*)$, Γ_X
   similarly for Y, Z



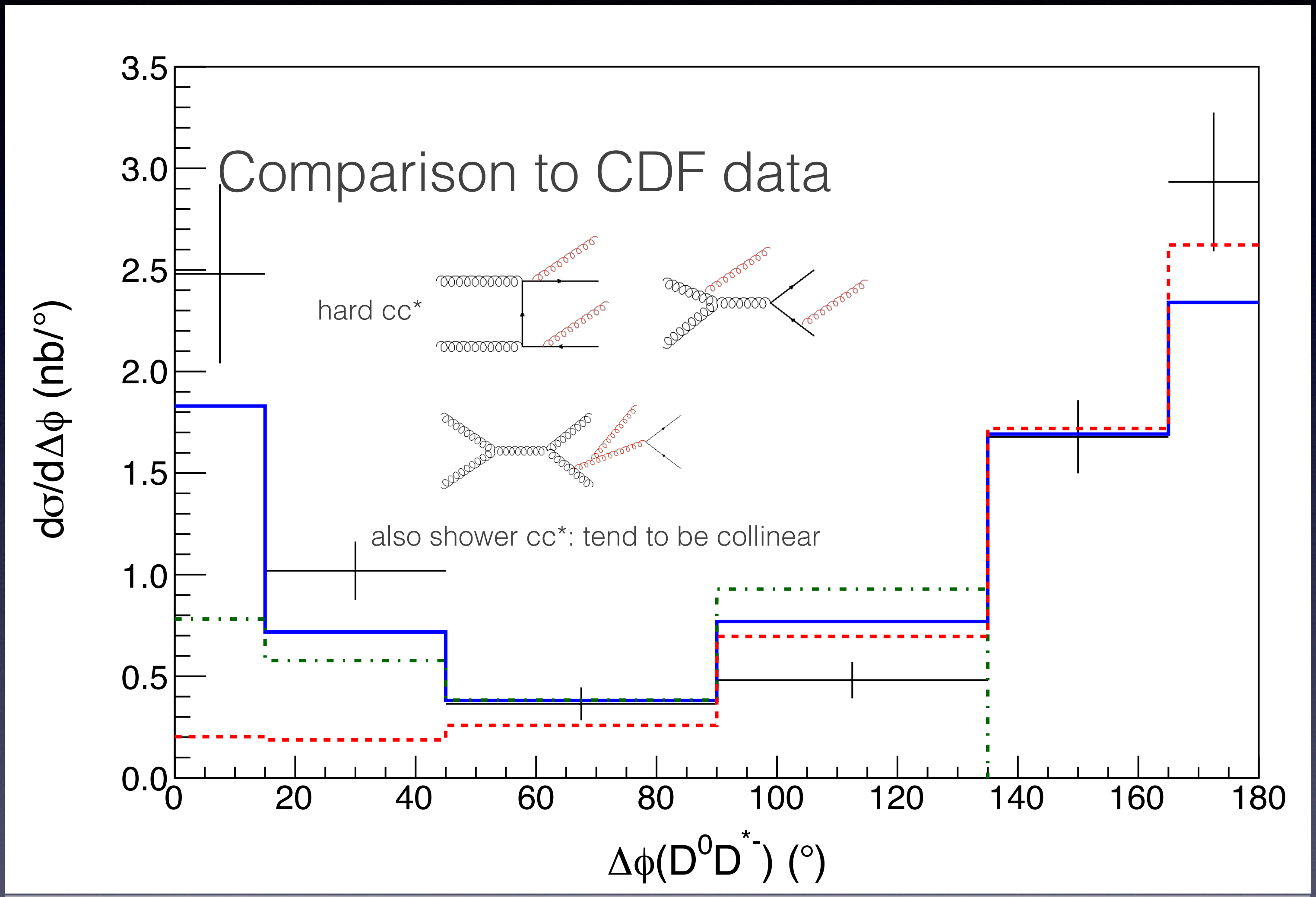
3. Apparent heavy spin violation in Υ decays (Belle II)

4. Look for the "missing ones"

5. Don't be fooled by the physics of effects; cusps & all that

Backup

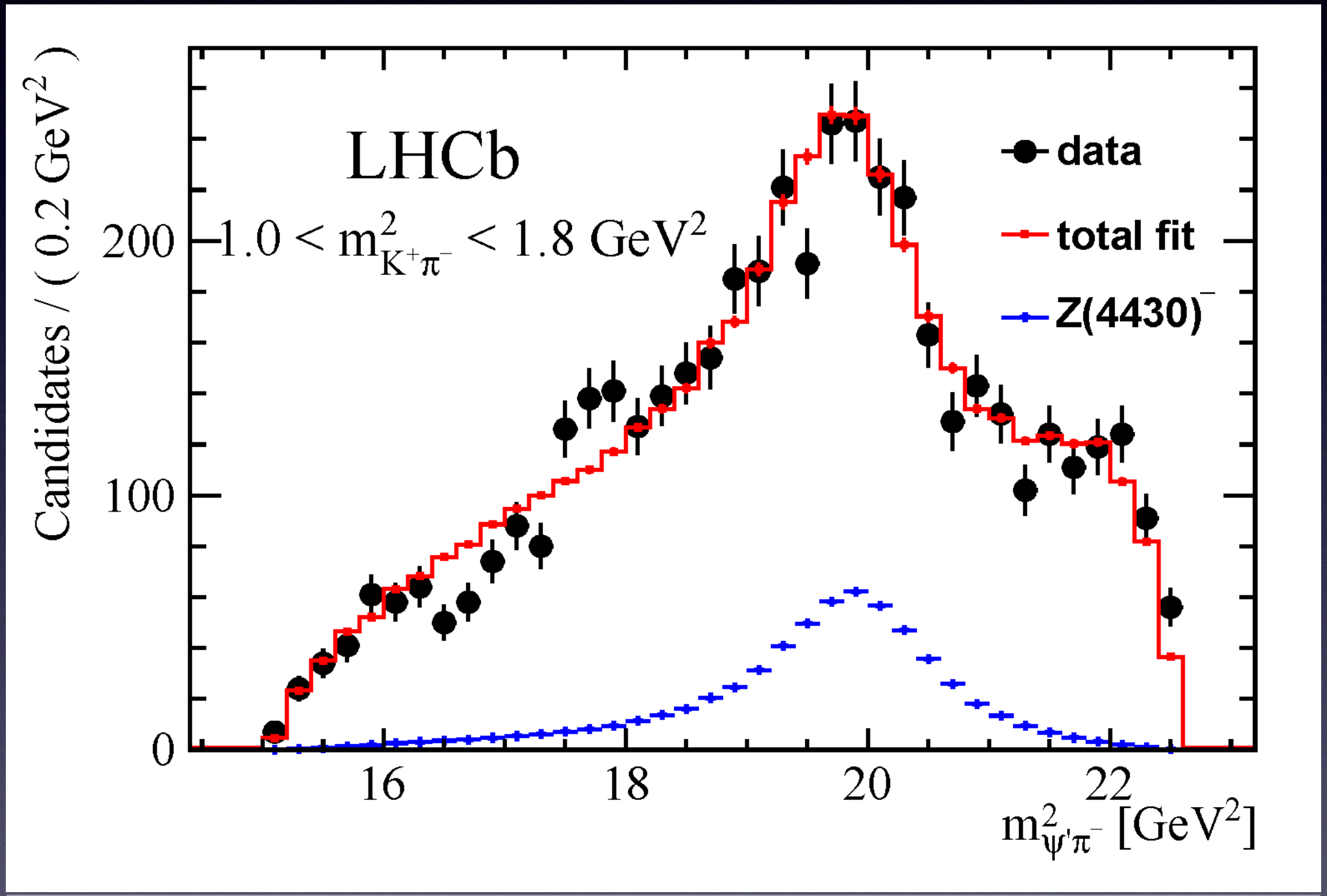
Production: MC Tuning



red: cc* HERWIG/PYTHIA
green: cc*g(recoiling) ALPGEN + HERWIG/PYTHIA
blue: full qcd HERWIG/PYTHIA

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929; PRD

Z(4430)⁻ at LHCb | April 2014



$$B \to K^+(\psi(2S)\pi^-)_{J^{PG}=1^{++}}$$

Signal: 13.9 σ
Other assignments ruled out at 9.7σ

First observed by BELLE in 2007 and not confirmed by BaBar at that time

courtesy of A Pilloni

Charged $Z_c(3900)$

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

Exotic charged charmonium-like state!

$$G = G_\pi C_{J/\psi} = \\ = -1(-1) = +1$$

$$P = +1\ (S-\text{wave})$$

$$\Rightarrow Z_c^0 \text{ has } J^{PC} = 1^{+-}$$

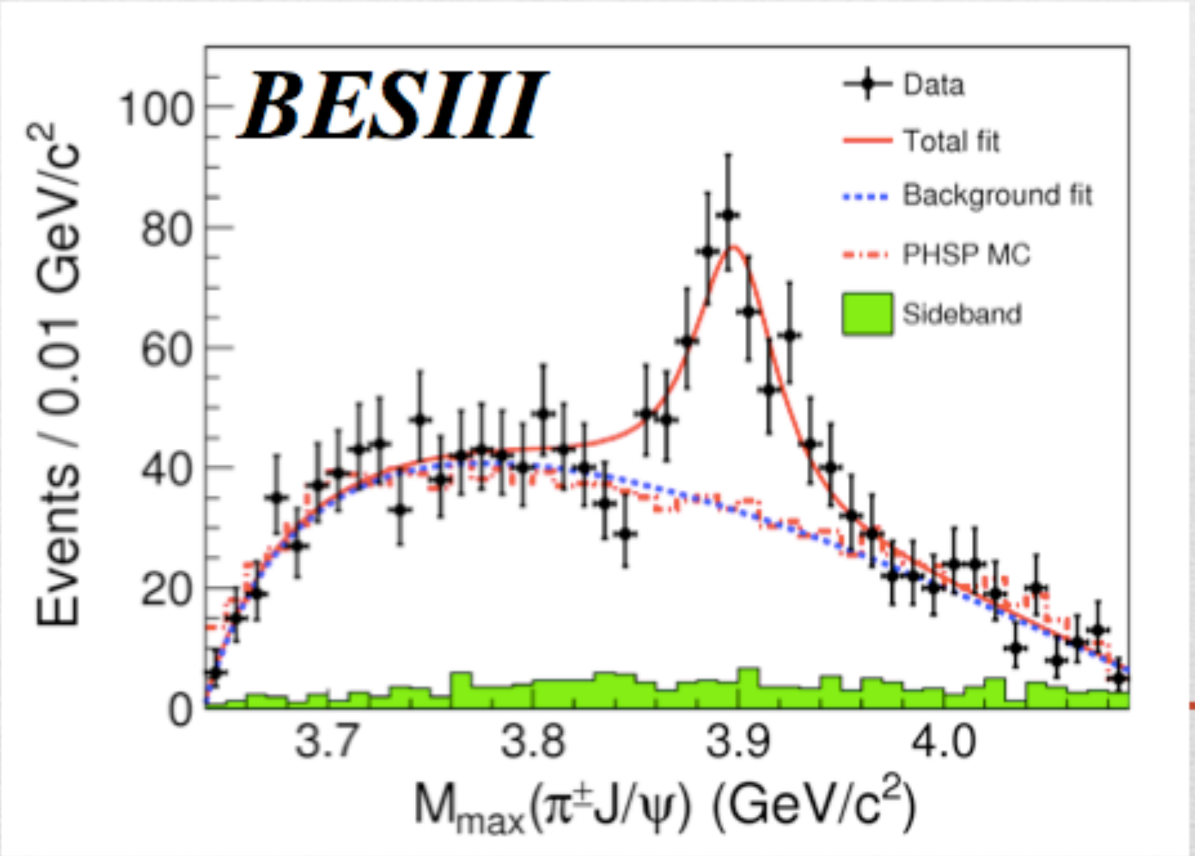
$$I^G J^{PC} = 1^+ 1^{+-}$$

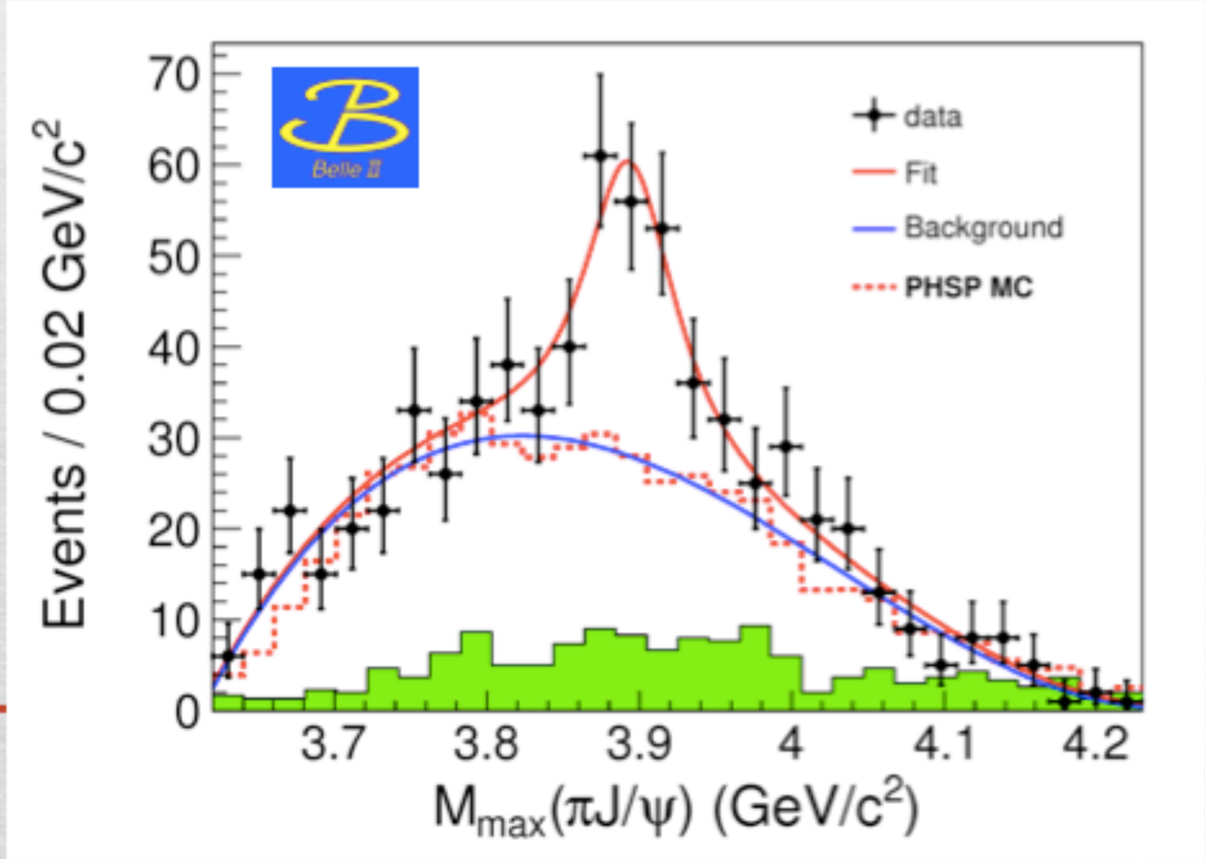
BESIII, arXiv:1303.5949

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

Belle, arXiv:1304.0121

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



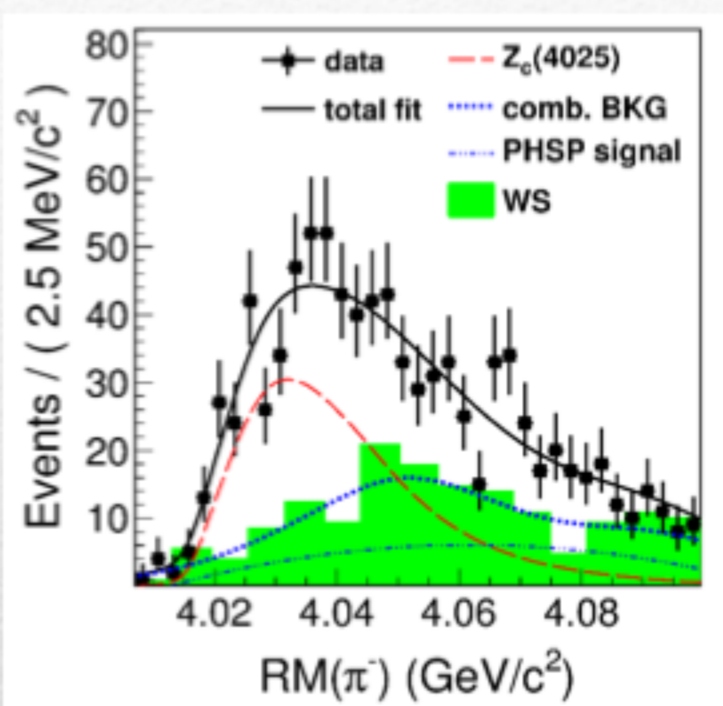


One more Z_c observed (or two?)

courtesy of A Pilloni

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

BESIII, PRL112, 022001



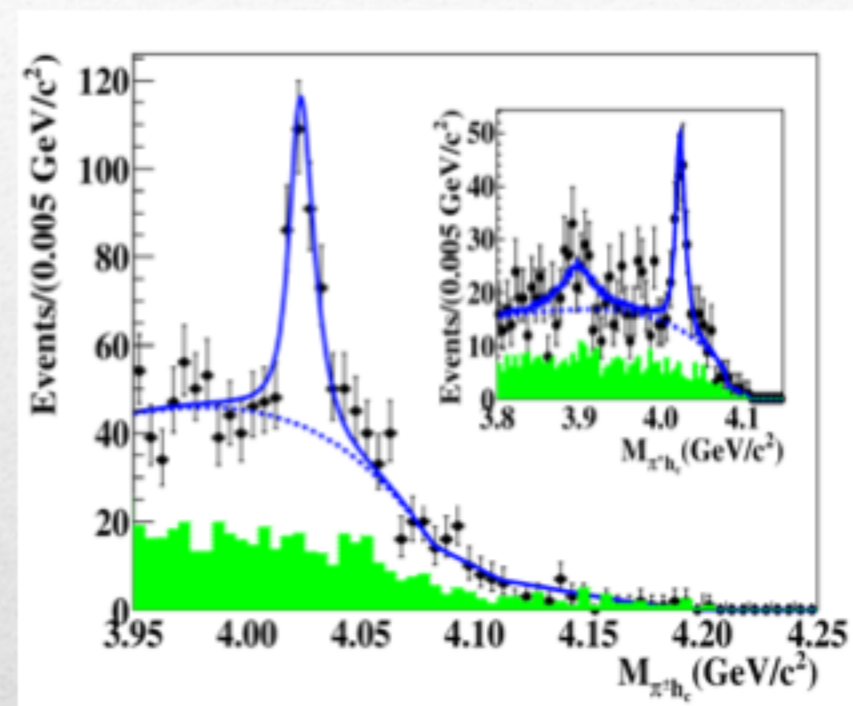
$Z_c'(4025) \to D^* D^*$

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

$M = 4026.3 \pm 4.5$ MeV

$\Gamma = 24.8 \pm 9.5$ MeV

BESIII, PRL111, 242001



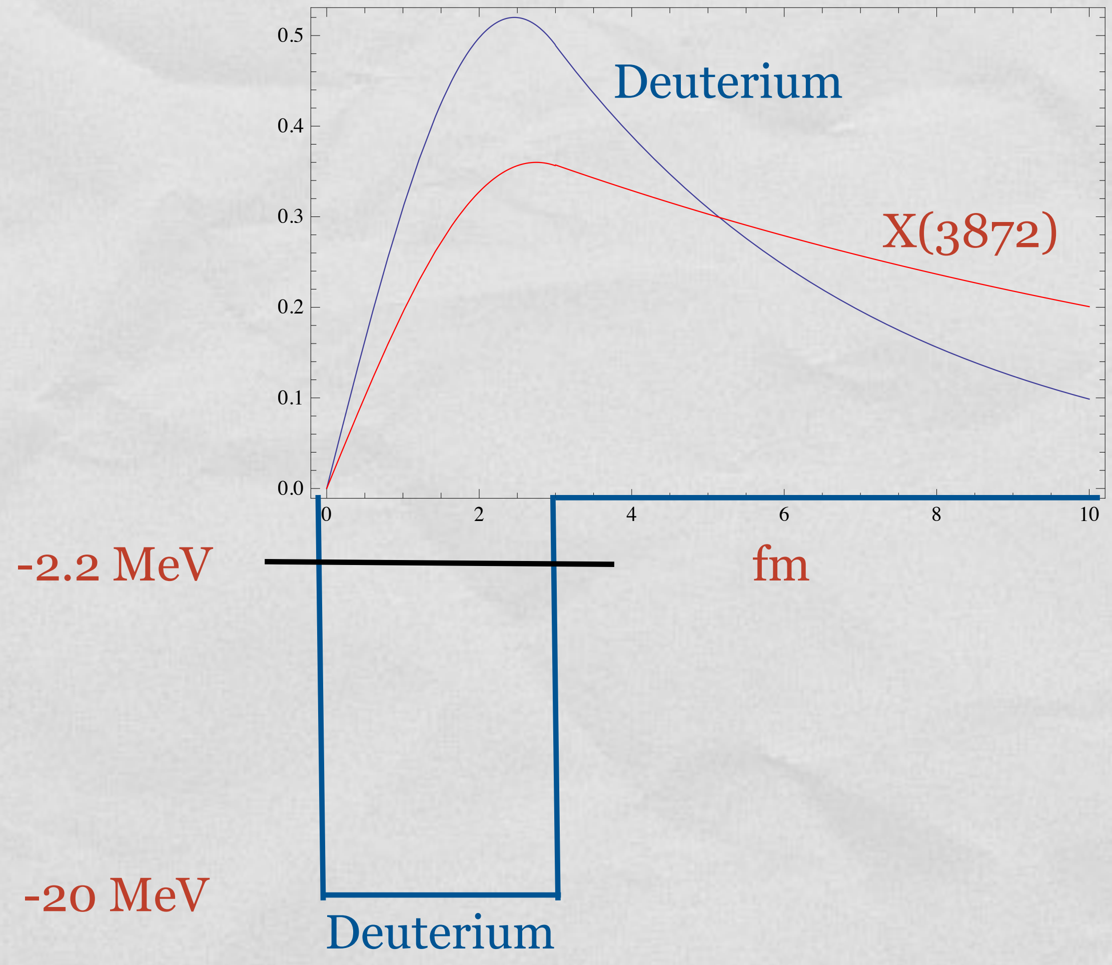
$Z_c'(4020) \to h_c \pi$

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

$M = 4022.9 \pm 2.8$ MeV

$\Gamma = 7.9 \pm 3.7$ MeV

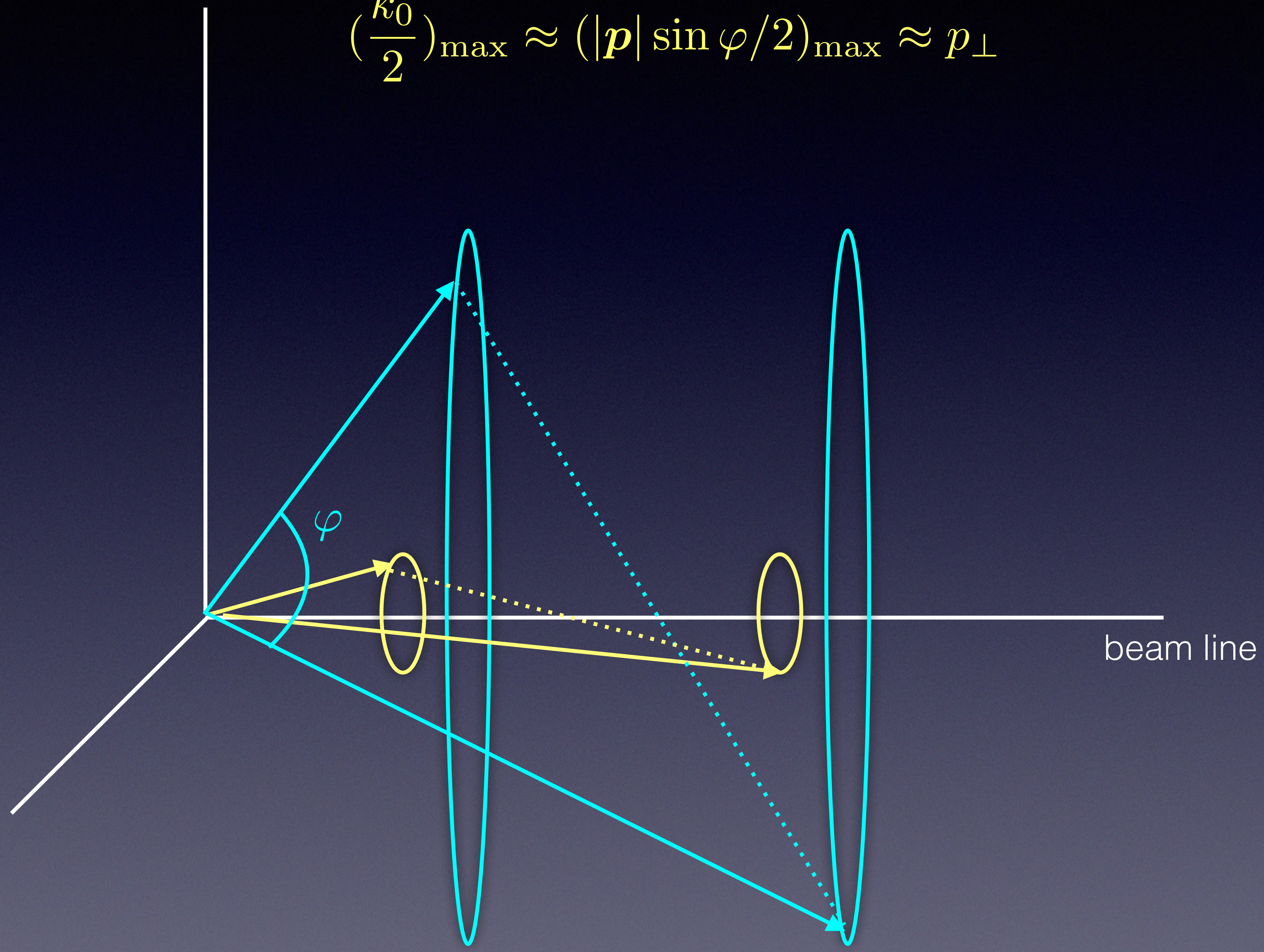
IS THE X(3872) SOME SORT OF DD* DEUTERON?



$$k_{\rm rel} = \sqrt{2\mu \langle T \rangle_\psi^2} \approx \begin{cases} 80 \text{ MeV} & \text{for deuterium} \\ 50 \text{ MeV} & \text{for } X; \quad U_0 \approx -7 \text{ MeV} \quad \mathcal{E}_b \approx -0.14 \text{ MeV} \end{cases}$$

$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi} \frac{e^{-\frac{m_\pi c}{\hbar} r_0}}{r_0} = \mathcal{E}_b = 0.14 \text{ MeV} \Rightarrow r_0 \approx 12 \text{ fm}$$

$$(\frac{k_0}{2})_{\max} \approx (|\boldsymbol{p}|\sin\varphi/2)_{\max} \approx p_\perp$$



exaggerating the differences between the momenta of D and D* (yellow / turquoise arrows)

Since 2003/4 new Charmonium-Like States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1[st] observation
$X(3823)$	3823.1±1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [5, 6] (12.8), *BABAR* [7] (8.6)	Belle 2003
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [8–10] (np), DØ [11] (5.2)	
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [12][a] (4.3), *BABAR* [13][a] (4.0)	
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9)	
				$B \to K + (J/\psi\,\gamma)$	Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6)	
				$B \to K + (\psi(2S)\,\gamma)$	*BABAR* [19][a] (3.5), Belle [17][a] (0.4)	
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [20] (np)	
$X(3915)$	3917.5 ± 1.9	20±5	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [21] (8.1), *BABAR* [22] (19)	Belle 2004
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [23] (7.7), *BABAR* [13, 24](7.6)	
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [25] (5.3), *BABAR* [26] (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27] (6.0)	Belle 2007
				$e^+e^- \to J/\psi + (...)$	Belle [28] (5.0)	
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	*BABAR* [29] (np), Belle [30] (np)	*BABAR* 2007
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [31] (7.4)	Belle 2007
$Y(4140)$	4144.5 ± 2.6	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [32, 33] (5.0), CMS [34] (>5)	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle [27] (5.5)	Belle 2007

[a] Not included in the averages for M and Γ.

New Charmonium & Bottomonium Like States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1[st] observation
$\boldsymbol{Y(4260)}$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	*BABAR* [35, 36] (8.0), CLEO [37] (5.4)	*BABAR* 2005
					Belle [31] (15)	
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [38] (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [38] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [33] (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [39] (3.2)	Belle 2009
$\boldsymbol{Y(4360)}$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	*BABAR* [40] (np), Belle [41] (8.0)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [42] (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle [41] (5.8)	Belle 2007
$\boldsymbol{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [43] (np), Belle [44] (5.2)	BESIII 2013
				$e^+e^- \to \pi^- + (J/\psi\,\pi^+)$	Xiao *et al.* [45][a] (6.1)	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (1.1)	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K + (\psi(2S)\,\pi^+)$	Belle [48, 49] (6.4), *BABAR* [50] (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [51, 52] (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	

[a]Not included in the averages for M and Γ.

Hadronization must be 4q

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929, PRD

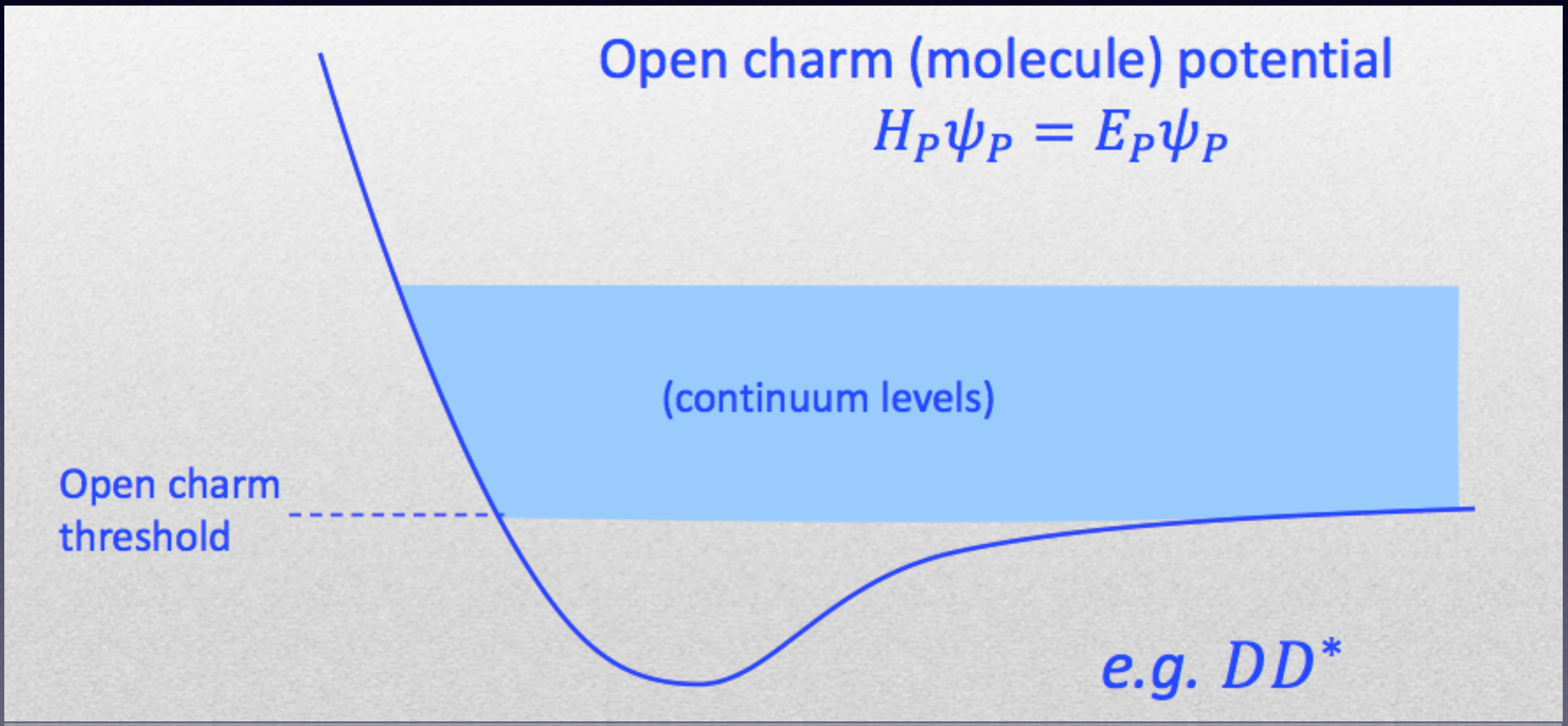
$$|\psi\rangle = \alpha|[Qq]_{\bar{\mathbf{3}}_c}[\bar{Q}\bar{q}]_{\mathbf{3}_c}\rangle_{\mathcal{C}} + \beta|(Q\bar{Q})_{\mathbf{1}_c}(q\bar{q})_{\mathbf{1}_c}\rangle_{\mathcal{O}} + \gamma|(Q\bar{q})_{\mathbf{1}_c}(\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}$$

— All ‘woud-be' loosely bound molecules do not form any bound state.
— Sometimes a compact 4quark state is formed, but it could be that $|\alpha| < |\beta|,|\gamma|$
— An amplification mechanism might be at work when the closed channel level matches the onset of the continuum spectrum of two mesons with the same quantum numbers.

Do we know ‘amplification’ mechanisms between open/closed channels?

Another Mechanism

Borrow some ideas from cold atom physics. The Fano-Feshbach mechanism.



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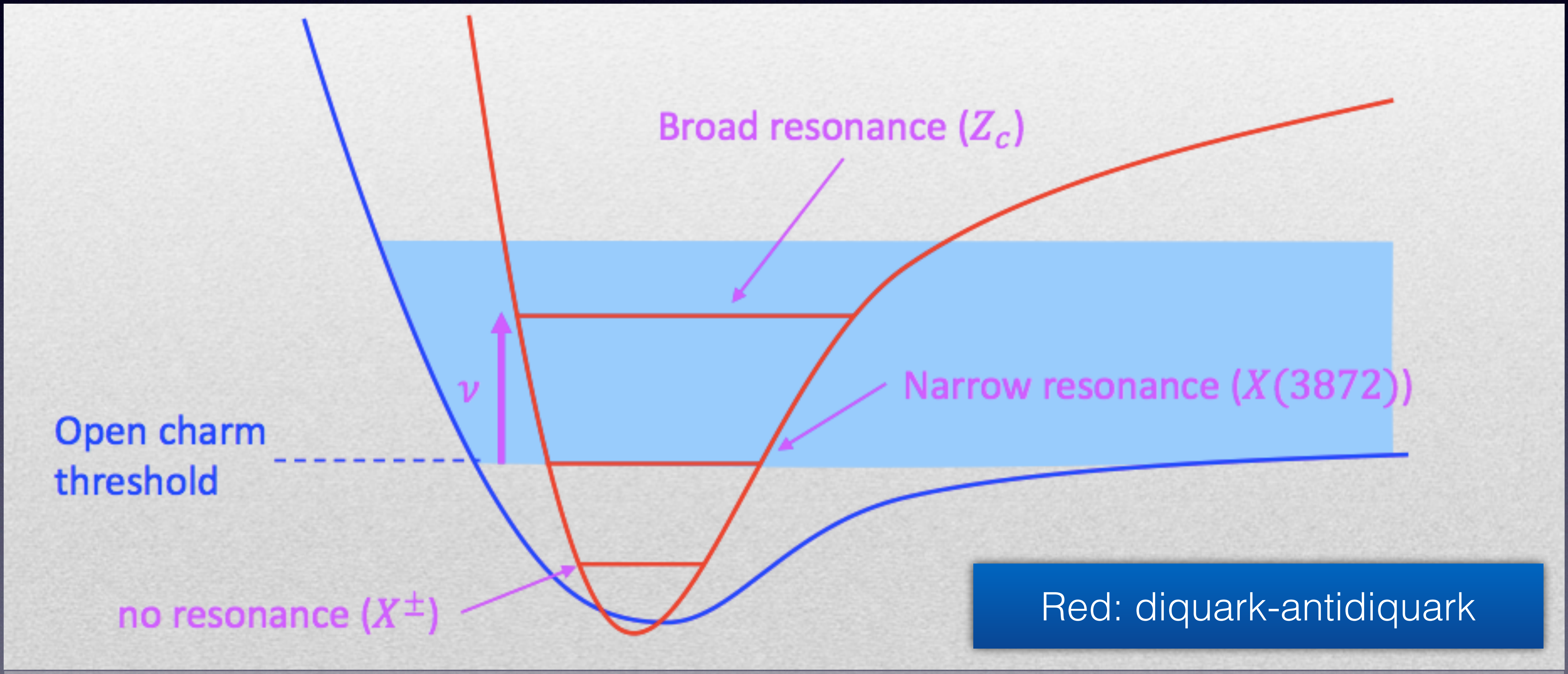


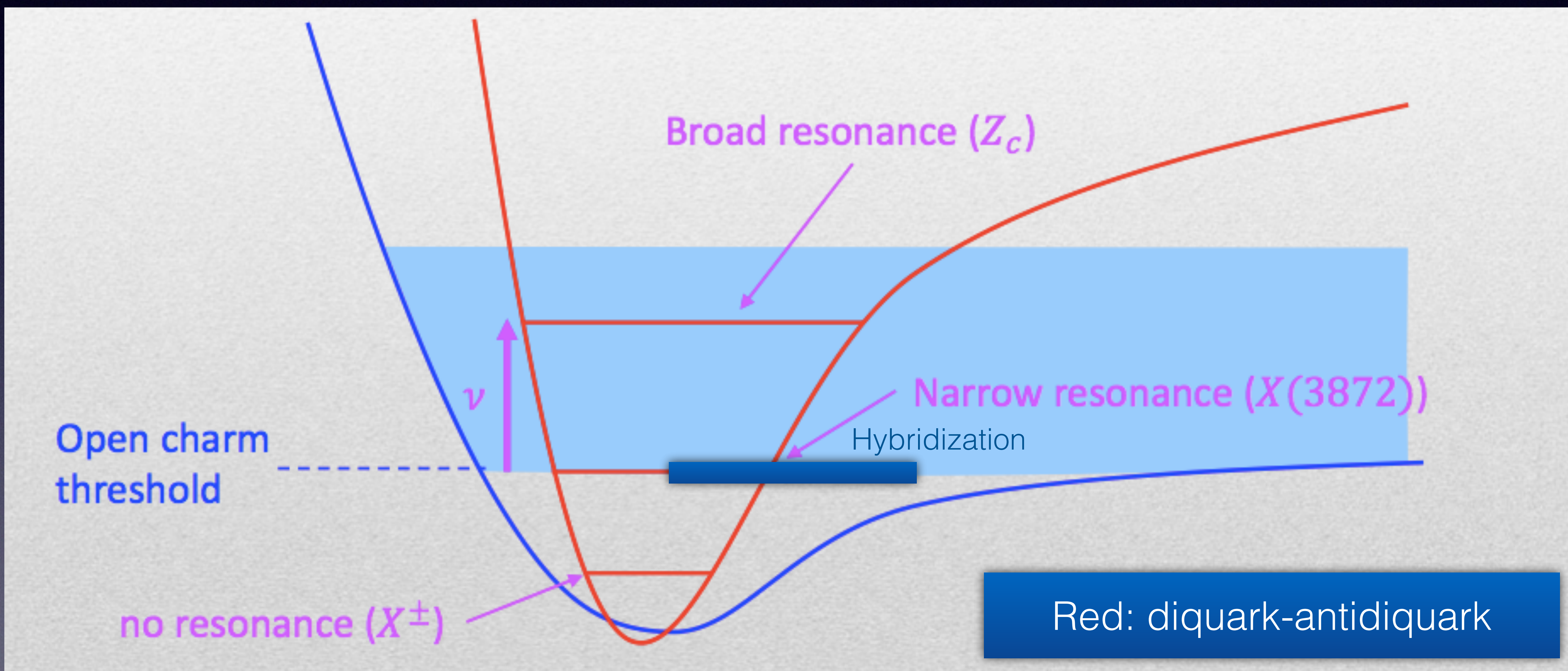
Red: diquark-antidiquark

Blue: loose molecule

$$a \sim |C| \sum_n \frac{c\langle [Qq]_{\bar{\mathbf{3}}_c} [\bar{Q}\bar{q}]_{\mathbf{3}_c}, n | H_{\mathcal{CO}} | (Q\bar{q})_{\mathbf{1}_c} (\bar{Q}q)_{\mathbf{1}_c} \rangle_{\mathcal{O}}}{E_{\mathcal{O}} - E_n}$$

Another Mechanism

Consider also that the J/ψ ρ⁺ is sensibly lower than the related open charm charged molecule. This could be why there is no charged X and *I*-violat.



Blue: loose molecule

$$a \sim |C| \sum_n \frac{c\langle [Qq]_{\bar{\mathbf{3}}_c}[\bar{Q}\bar{q}]_{\mathbf{3}_c}, n | H_{\mathcal{CO}} | (Q\bar{q})_{\mathbf{1}_c}(\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}}{E_{\mathcal{O}} - E_n}$$

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929

4-quarks from lattice?

Esposito, Papinutto, Pilloni, ADP, Tantalo Phys.Rev. D88 (2013) 054029

On simulating a proton on the lattice, the interpolating operators

$$O = \epsilon^{abc} u^a u^b d^c, \quad \epsilon^{abc} u^a u^b d^c \bar{s}^d s^d ...$$

are equally good. One might wonder if is there any chance of studying genuine tetraquark configurations on the lattice **as they might turn out not to be distinguishable from standard charmonia**.

On the other hand *states with* ***two charm quarks*** cannot mix with standard chamonia.

More Exotic States

$$|T^0\rangle = |Q_u = -2, Q_c = +2\rangle$$
$$|T^+\rangle = |Q_u = -1, Q_d = -1, Q_c = +2\rangle$$
$$|T_s^+\rangle = |Q_u = -1, Q_s = -1, Q_c = +2\rangle$$
$$|T^{++}\rangle = |Q_d = -2, Q_c = +2\rangle$$
$$|T_s^{++}\rangle = |Q_s = -2, Q_c = +2\rangle$$

Production from heavy baryons

	Bottom quark decays	
Starting baryon	$b \to c\bar{u}d \quad (O(\lambda^2))$	$b \to c\bar{u}s \quad (O(\lambda^3))$
Ξ_{bc}^+ $[bcu]$	$p\mathcal{T}^0 \to pD^0D^0$	$\Sigma^+\mathcal{T}^0 \to \Sigma^+D^0D^0$
	$n\mathcal{T}^+ \to nD^0D^+$	$\Lambda^0(\Sigma^0)\mathcal{T}^+ \to \Lambda^0(\Sigma^0)D^0D^+$
	$\Lambda^0(\Sigma^0)\mathcal{T}_s^+ \to \Lambda^0(\Sigma^0)D^0D_s^+$	$\Xi^0\mathcal{T}_s^+ \to \Xi^0D_s^+D^0$
Ξ_{bc}^0 $[bcd]$	$n\mathcal{T}^0 \to nD^0D^0$	$\Lambda^0(\Sigma^0)\mathcal{T}^0 \to \Lambda^0(\Sigma^0)D^0D^0$
	$\Delta^-\mathcal{T}^+ \to \Delta^-D^+D^0$	$\Sigma^-\mathcal{T}^+ \to \Sigma^-D^+D^0$
	$\Sigma^-\mathcal{T}_s^+ \to \Sigma^-D_s^+D^0$	$\Xi^-\mathcal{T}_s^+ \to \Xi^-D_s^+D^0$
Ξ_{bcs}^0 $[bcs]$	Same final states as $[bcd]$	$\Xi^0\mathcal{T}^0 \to \Xi^0D^0D^0$
	with $b \to c\bar{u}s$	$\Xi^-\mathcal{T}^+ \to \Xi^-D^+D^0$
	(they differ by just $d \leftrightarrow s$)	$\Omega^-\mathcal{T}_s^+ \to \Omega^-D_s^+D^0$

ISOSPIN VIOLATIONS

We set in the flavor basis X_u, X_d

$$M = \begin{pmatrix} 2m_u & 0 \\ 0 & 2m_d \end{pmatrix} + \delta \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

where the mixing matrix has a diagonal structure in the Isospin $I = 0, 1$ basis, its eigenvectors being

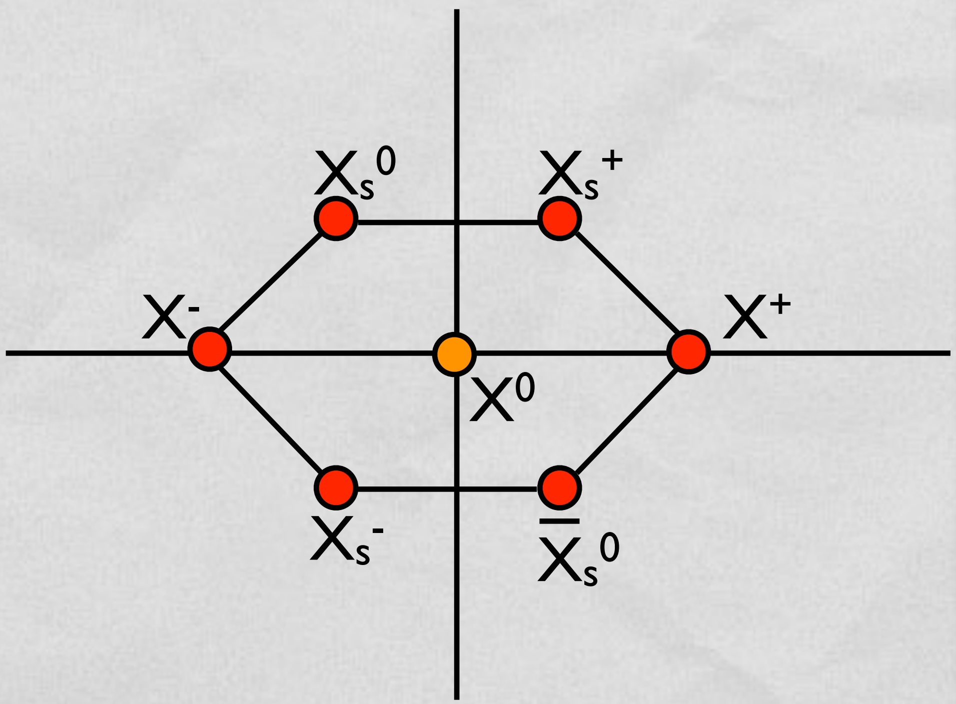
$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

At the charmonium scale we expect the annihilations to be small and quark mass to dominate - observed X -> ω/ρ isospin breaking

G.C. Rossi, G. Veneziano; L. Maiani, F. Piccinini, ADP, V.Riquer PRD 2005

CHARMED DIQUARKS

The octet with diquarks - the 'azimuthal approach'



$$\mathfrak{q}_{i\alpha} = \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}\bar{q}_C^{j\beta}\gamma_5 q^{k\gamma} = [qq]_0$$

$$\mathfrak{q}_{\alpha}^{jk} = \epsilon_{\alpha\beta\gamma}\bar{q}_C^{\beta(j}\vec{\gamma}q^{k)\gamma} = [qq]_1$$

J^{PC}	dq-dq*
0^{++}	$[cq]_0[\bar{c}\bar{q}]_0 \;\vee\; ([cq]_1[\bar{c}\bar{q}]_1)_0$
1^{++}	$\frac{[cq]_1[\bar{c}\bar{q}]_0 + [cq]_0[\bar{c}\bar{q}]_1}{\sqrt{2}}$
1^{+-}	$\frac{[cq]_1[\bar{c}\bar{q}]_0 - [cq]_0[\bar{c}\bar{q}]_1}{\sqrt{2}} \;\vee\; ([cq]_1[\bar{c}\bar{q}]_1)_1$
2^{++}	$([cq]_1[\bar{c}\bar{q}]_1)_2$

$$([\;]_s[\;]_s)_J$$

Spin problem in type I

In the type I diquark model we have two 1^{+-} states the heavier, Z, at about 3880 MeV

$$|Z^{(\prime)}\rangle = \alpha^{(\prime)}(|10\rangle_u - |01\rangle_u) + \beta^{(\prime)}|11\rangle_u + (u \to d)$$

The expected spin of the cc* pair being computed as

$$\ell_{c\bar{c}} = (3/2 + 2\langle Z^{(\prime)}|\boldsymbol{S}_c \cdot \boldsymbol{S}_{\bar{c}}|Z^{(\prime)}\rangle)^{1/2}$$

equal to √2 if S_{cc^*}=1, and 0 if S_{cc^*}=0. Contrary to the experimental fact that the Z is observed to decay predominantly in J/ψ, we found

$$\underbrace{\ell_{c\bar{c}}(Z')}_{\text{lighter}} \approx 3\ell_{c\bar{c}}(Z)$$

This problem is solved in the type II model in which the $S_q.S_{q^*}$ interaction is not the dominating one.