Tetraquarks

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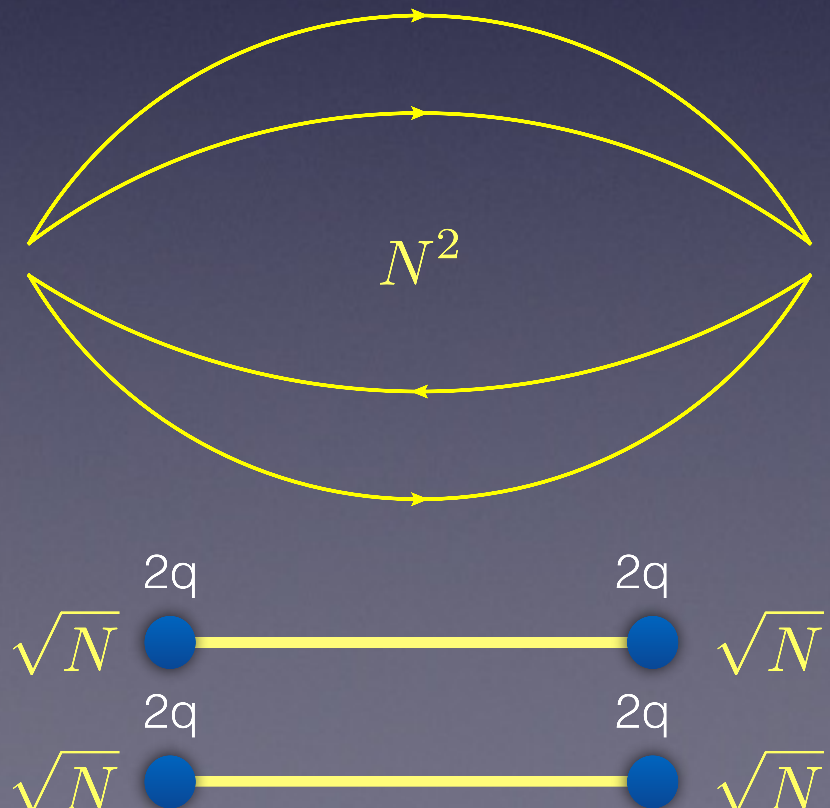
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

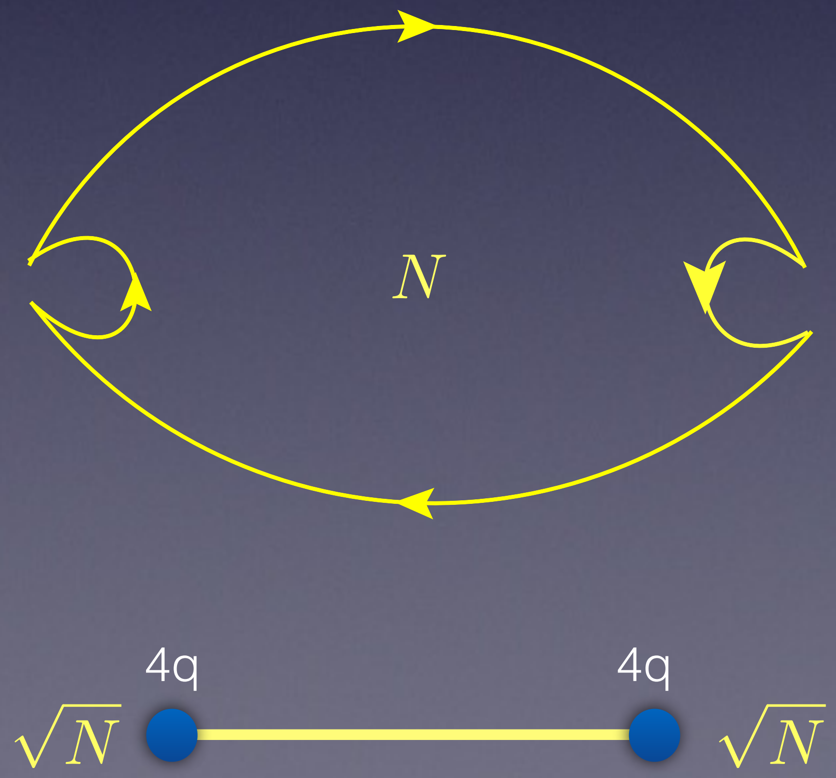
Taken from Gell-Mann's paper on quark model

Large N_c and Tetraquarks

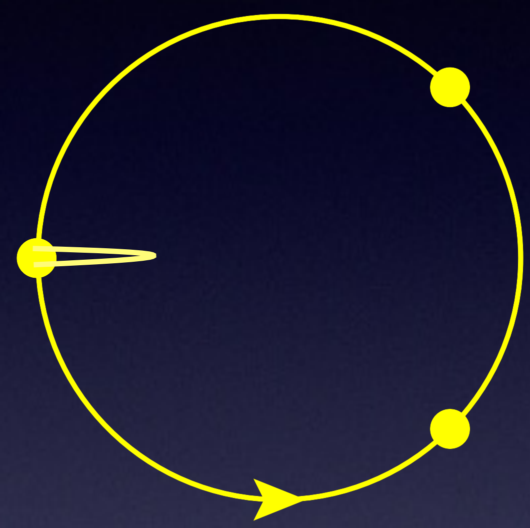
Following E. Witten's paper on 1/N and Baryons (see also S. Coleman's lectures), tetraquarks should instantly fall apart into mesons.

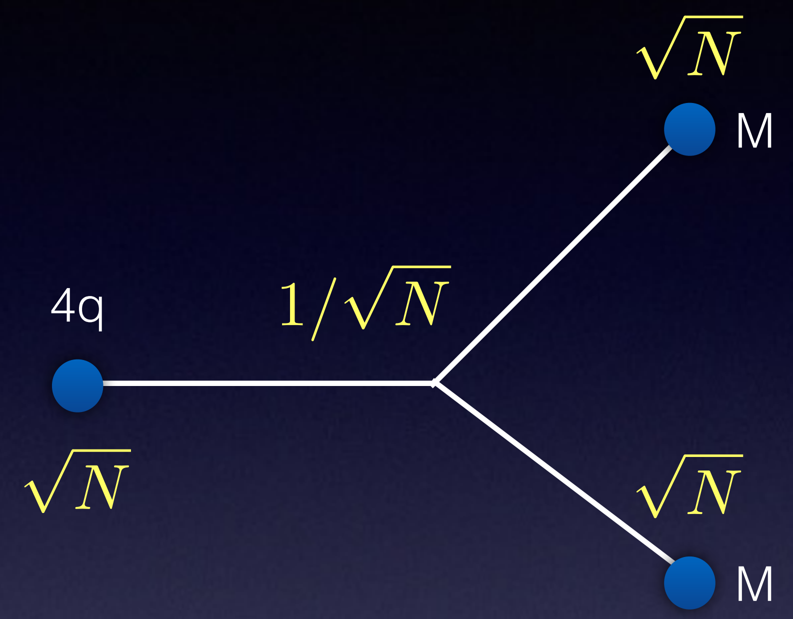
However, as pointed by S. Weinberg in a recent paper (PRL 110, 2013), this applies only at the leading order N^2 *disconnected* diagram. The leading order *connected* diagram has only one color loop and excludes the leading order of free two meson propagation.





Large N_c and Tetraquarks



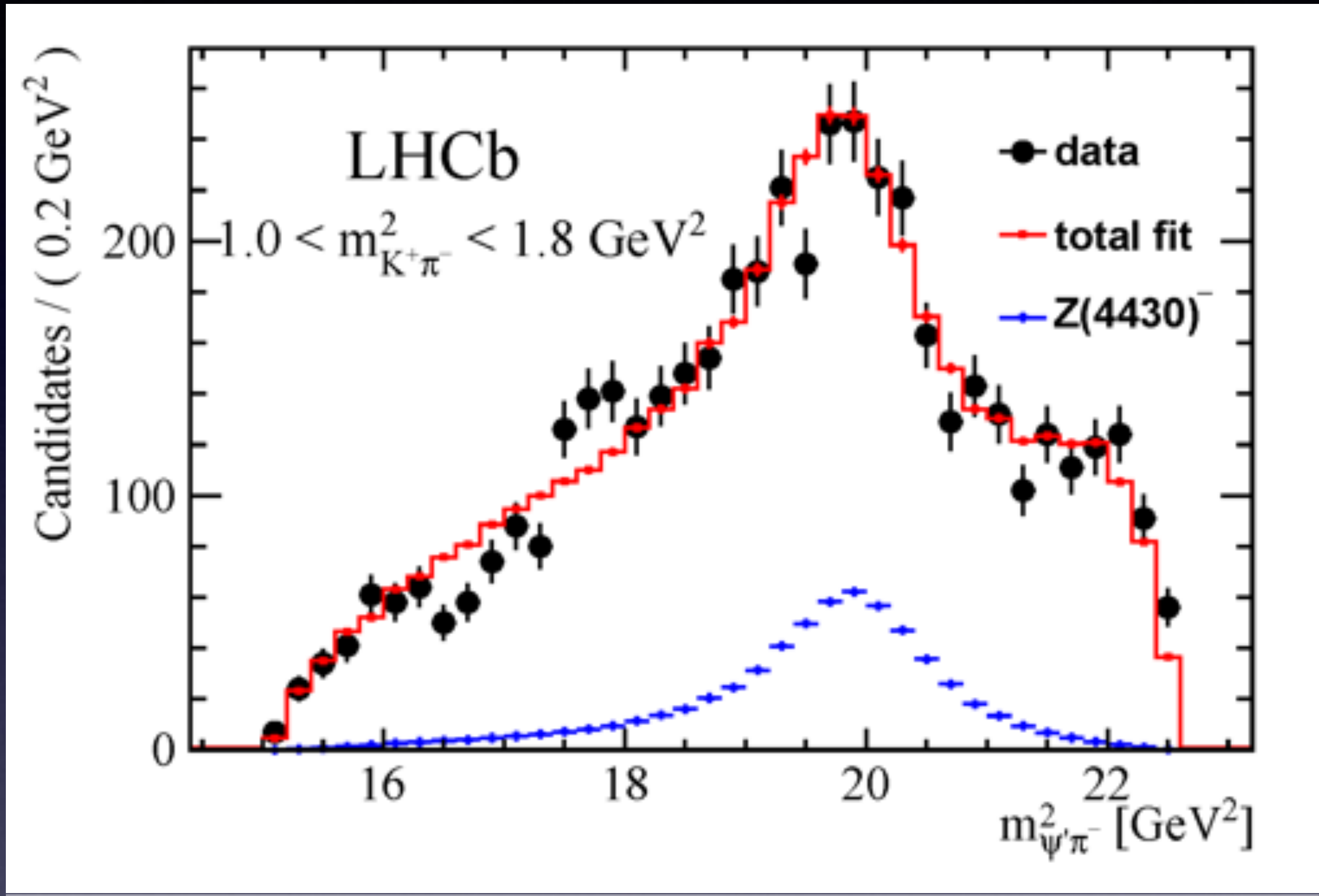


which implies that the 4q decay amplitude into two ordinary mesons can be $1/N^{1/2}$

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.

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 <u>not confirmed by BaBar</u>

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LHCb confirms existence of exotic hadrons

ABOUT CERN

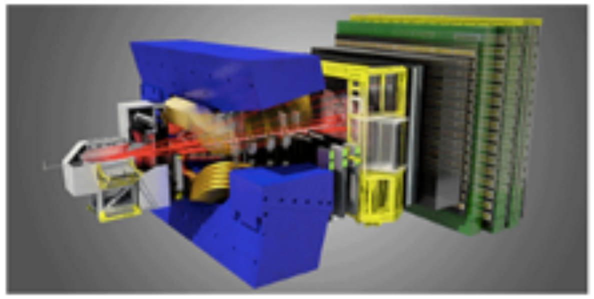
Cian O'Luanaigh

The Large Hadron Collider beauty (LHCb) collaboration today announced results that confirm the existence of exotic hadrons – a type of matter that cannot be classified within the traditional quark model.

NEWS AND COMMENTARY IN *PHYSICS*

Four-Quark State Confirmed

June 4, 2014



The LHCb experiment provides conclusive evidence for the existence of the four-quark particle called $Z(4430)$.

Synopsis on R. Aaij *et al.* (LHCb Collaboration) Phys. Rev. Lett. **112**, 222002 (2014)

Charged $Z_c(3900)$

$$G = G_\pi C_{J/\psi} = = -1(-1) = +1$$
$$P = +1 \ (S - \text{wave})$$
$$\Rightarrow Z_c^0 \text{ has } J^{PC} = 1^{+-}$$

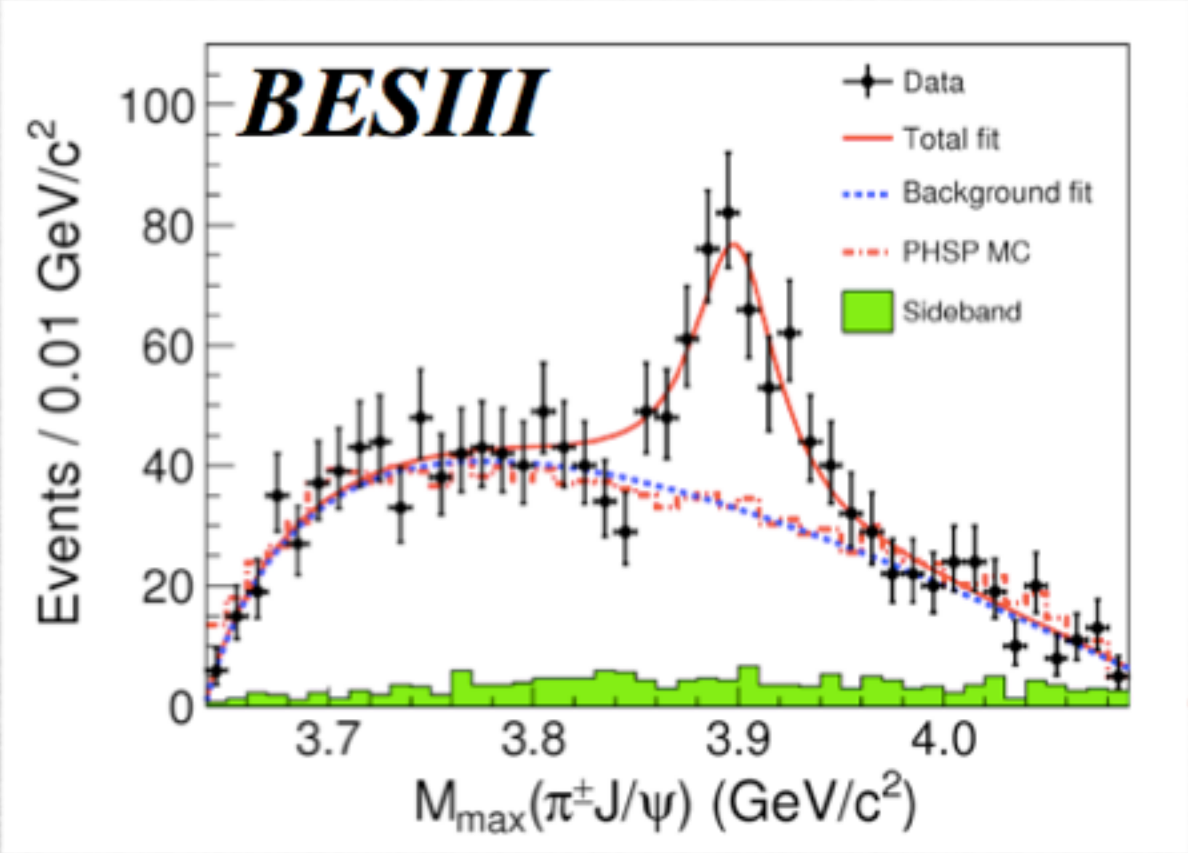
$$I^G J^{PC} = 1^+ 1^{+-}$$

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

Exotic charged charmonium-like state!

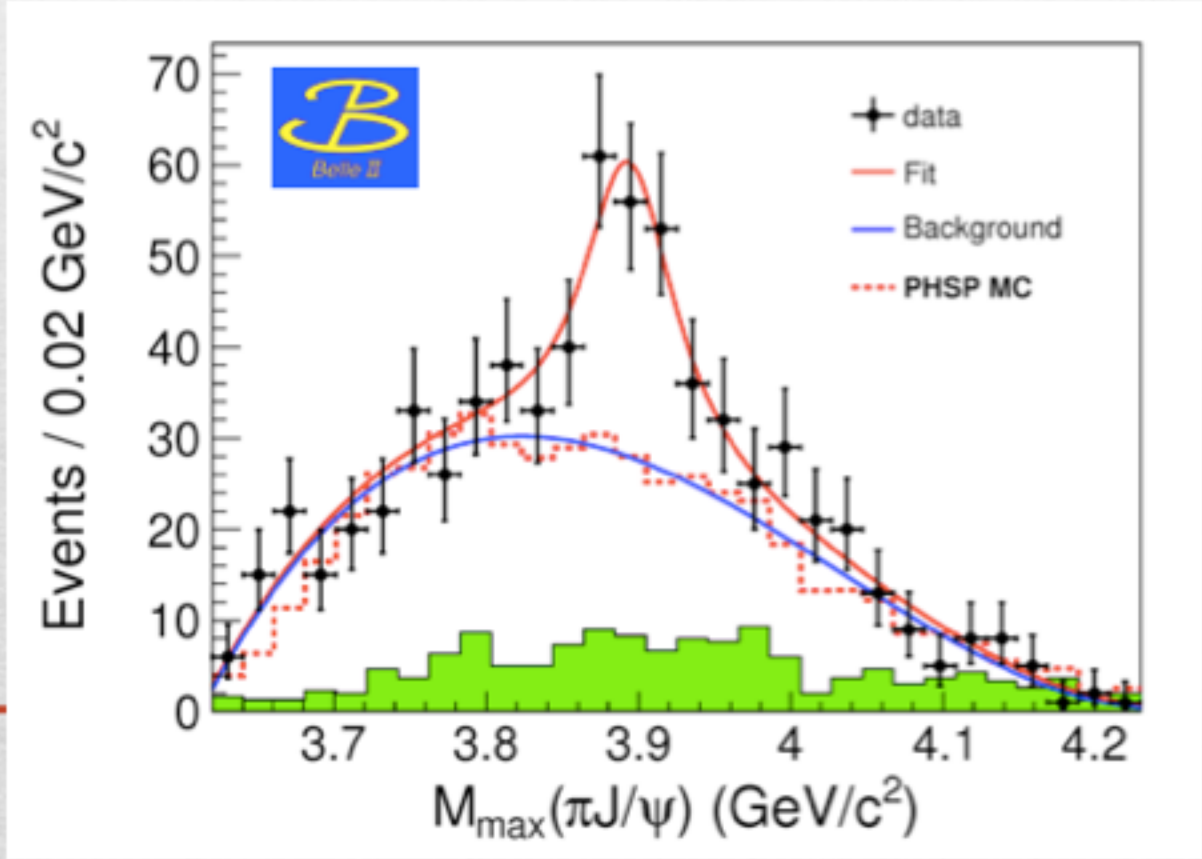
BESIII, arXiv:1303.5949

$M = 3899.0 \pm 3.6 \pm 4.9$ 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



$Z_c(3900)^{\pm 0}$

Physics
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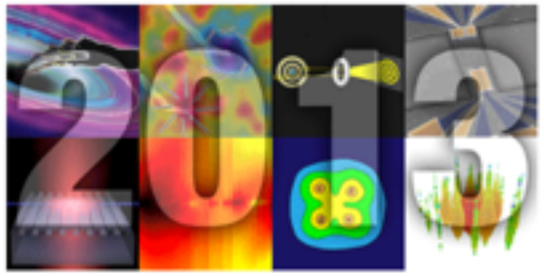
Notes from the Editors: Highlights of the Year

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



Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

Strangers from Beyond our Solar System

Detector experiments hunting for rare events can go years and never see anything out of the ordinary. So it was cause for excitement when IceCube, a giant neutrino telescope at the South Pole, reported the detection of two neutrinos with energies of around 1000 tera-electron-volts (TeV), roughly a billion times more energetic than those arriving from the Sun. Scientists at IceCube have since further analyzed their data and reported 26 more neutrinos with energies above 30 TeV. Researchers will need to observe many more of the neutrinos before they can be certain of their source, and that may require a larger detector. But they believe the particles were produced outside of the Solar System (experiments haven't detected neutrinos from so far away since 1987) and may be carrying information about astrophysical events, like gamma-ray bursts, in distant galaxies.

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New in Physics

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  Viewpoint | Mar 19, 2014
- The Smallest Shock Wave
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- An Untested Window into Nuclear Structure
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- Tuning in to the Smallest (Man-Made) Mechanical Resonator
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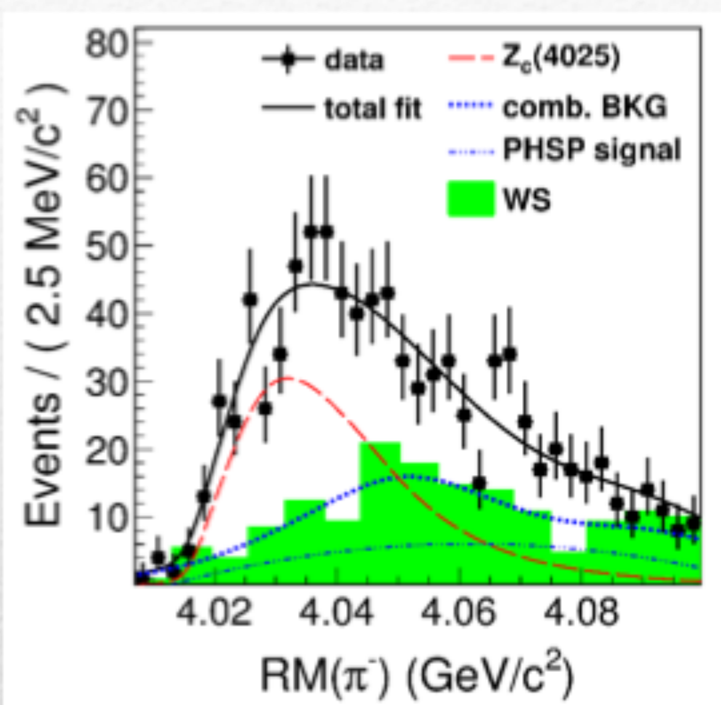
- Snapshots from the March Meeting—No-Photon Lasers, Hyperbolic Metamaterials, and More
  Editorial | Mar 17, 2014
- Earth as Giant Gravitational Wave Detector
  Synopsis | Mar 13, 2014

One or two Z'?

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

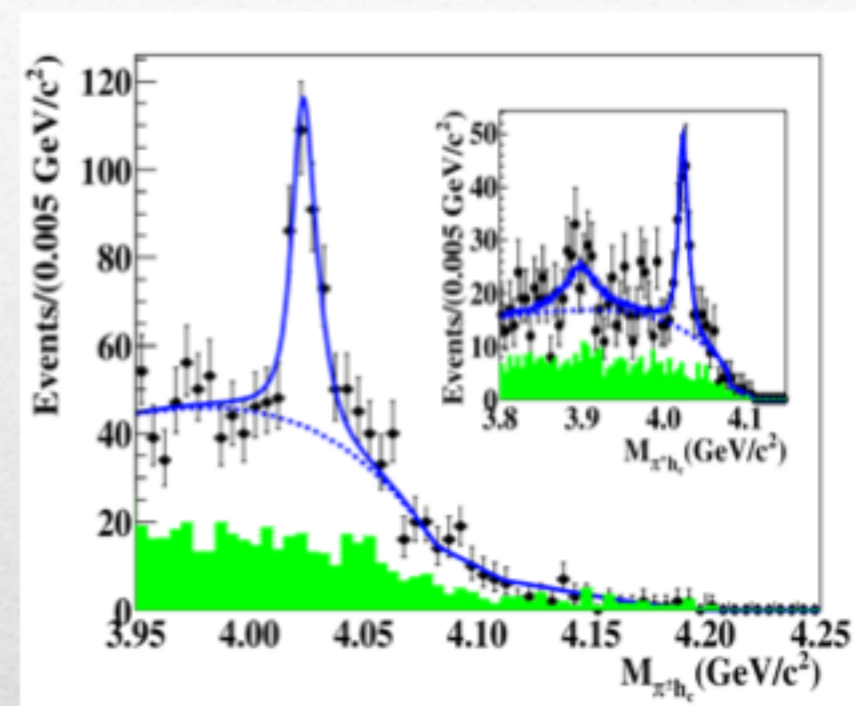
$Z'_c(4020) \to h_c \pi$

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

$M = 4022.9 \pm 2.8$ MeV

$\Gamma = 7.9 \pm 3.7$ MeV

BESIII, PRL111, 242001



Radial Excitations?

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

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

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 $\eta_c + \rho^{\pm}$) <u>should be found</u> around 3880 MeV'

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

$$Z_c(4025) \to h_c(S_{c\bar{c}} = 0)\pi^-$$

Does this pattern fit in an any extended quark model?

Since 2003/4 new Charmonium-Like States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st 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

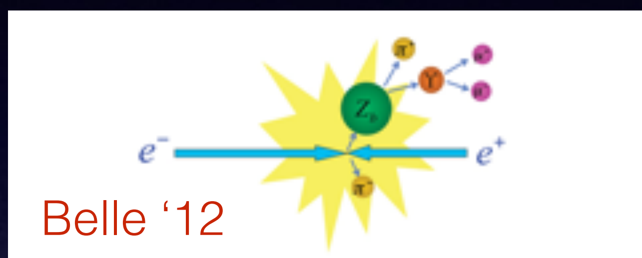
[a] Not included in the averages for M and Γ.

New Charmonium & Bottomonium Like States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st 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.

Mass Matchings

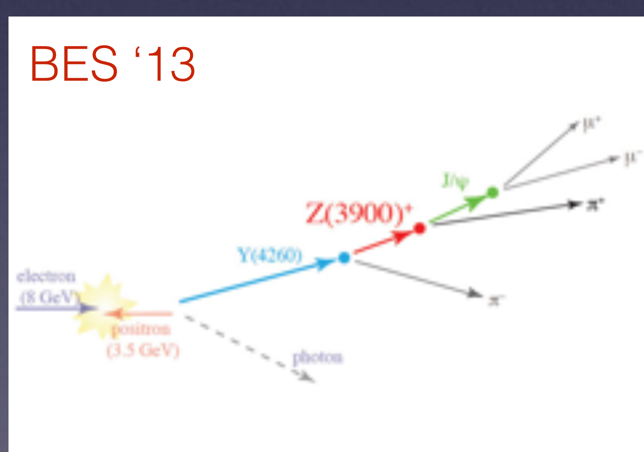


$$\Upsilon(5S) \to \pi^\pm Z_b^\mp(10610) \to \pi^\pm\pi^\mp\Upsilon(nS) \quad n = 1, 2, 3$$

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

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

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



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

$$Z_c'(4025) \to h_c\pi^\pm$$

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

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

$+24$ MeV

$+8$ MeV

No molecular matchings for the Z(4430)

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

Discovered by **Belle**, and soon confirmed by CDF, BaBar, D0. Later observed at CMS and ATLAS. Both produced in *B* meson decays and *prompt*, in hadron collisions. Four-Quark matter as well? Its isospin seems to be *I=0 — whereas the diquark model would naively predict I=1 (just change the flavors of light quarks q & q').*

CMS Collaboration arXiv:1302.3968

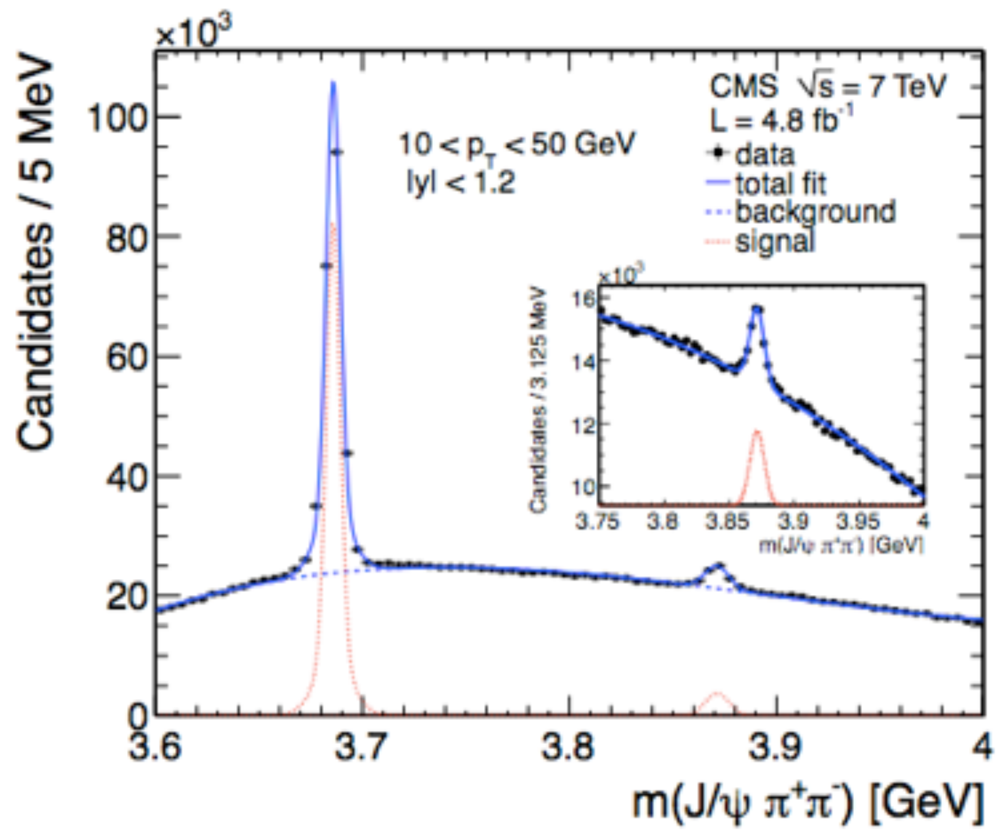


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.

X: Mass and Isospin Problems

Similarly to what happens to Z_c, Z_c' and Z_b, also the *X(3872)* appears to be very close to the the closeby (and quantum numbers allowed) open charm threshold

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

This time the coincidence is really striking because the value is just exactly there. Actually in terms of mass there is another surprising 'coincidence' in the *X* case

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

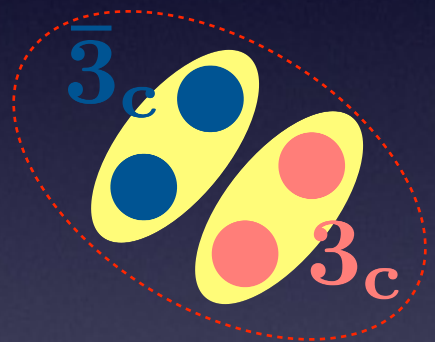
The X decays in both channels, preferring the first one, and also decays into J/ψ ω

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

which is an interesting hint of *isospin violation*

Extreme Interpretations of X

and of all other XYZ states



A compact ‘tetraquark’

Jaffe & Wilczek
Maiani, Piccinini, Polosa, Riquer ‘2005
Terasaki, Ali, Ebert…

Approach based on SU(3) symmetry

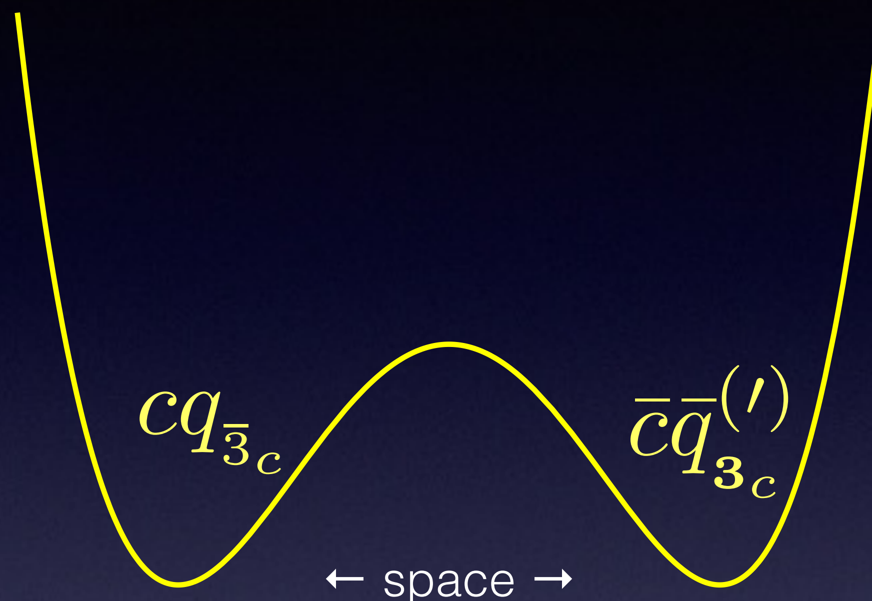
A loosely bound molecule

Tornqvist; Braaten, Kusinoki; Voloshin; Barnes;
Swanson; Close; Mehen, Fleming; Hanhart, Guo, Meissner
very long list…’2005 —

Based on strong hadron dynamics

Diquarks

Diquarks



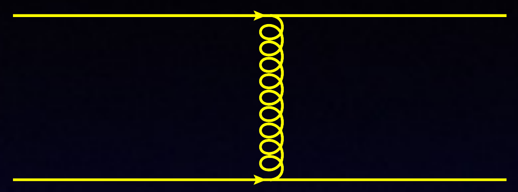
$$H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

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)

1-Gluon-Exchange



$$T^a_{R_1} \otimes T^a_{R_2} = \bigoplus_i \frac{1}{2}(C_{S_i} - C_{R_1} - C_{R_2})\mathbb{1}_{S_i}$$

$$T^a_{\mathbf{3}} \otimes T^a_{\mathbf{3}} = \frac{1}{2}(4/3 - 4/3 - 4/3)\mathbb{1}_{\bar{\mathbf{3}}} \oplus$$

$$\oplus \frac{1}{2}(10/3 - 4/3 - 4/3)\mathbb{1}_{\mathbf{6}} =$$

$$= -\frac{2}{3}\mathbb{1}_{\bar{\mathbf{3}}} \oplus \frac{1}{3}\mathbb{1}_{\mathbf{6}}$$

$$T^a_{\mathbf{3}} \otimes T^a_{\bar{\mathbf{3}}} = -\frac{4}{3}\mathbb{1}_{\mathbf{1}} \oplus \frac{1}{6}\mathbb{1}_{\mathbf{8}}$$

Diquark spin basis

$|s, \bar{s}\rangle_J$ notation

$\mathrm{J}^{\mathrm{P}} = 0^+ \quad C = + \quad X_0 = |0,0\rangle_0, \; X_0' = |1,1\rangle_0$ X(3915), X(3940) ?

$\mathrm{J}^{\mathrm{P}} = 1^+ \quad C = + \quad X_1 = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 + |0,1\rangle_1\right)$ X(3872)

$\mathrm{J}^{\mathrm{P}} = 1^+ \quad G = + \quad Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 - |0,1\rangle_1\right), \; Z' = |1,1\rangle_1$

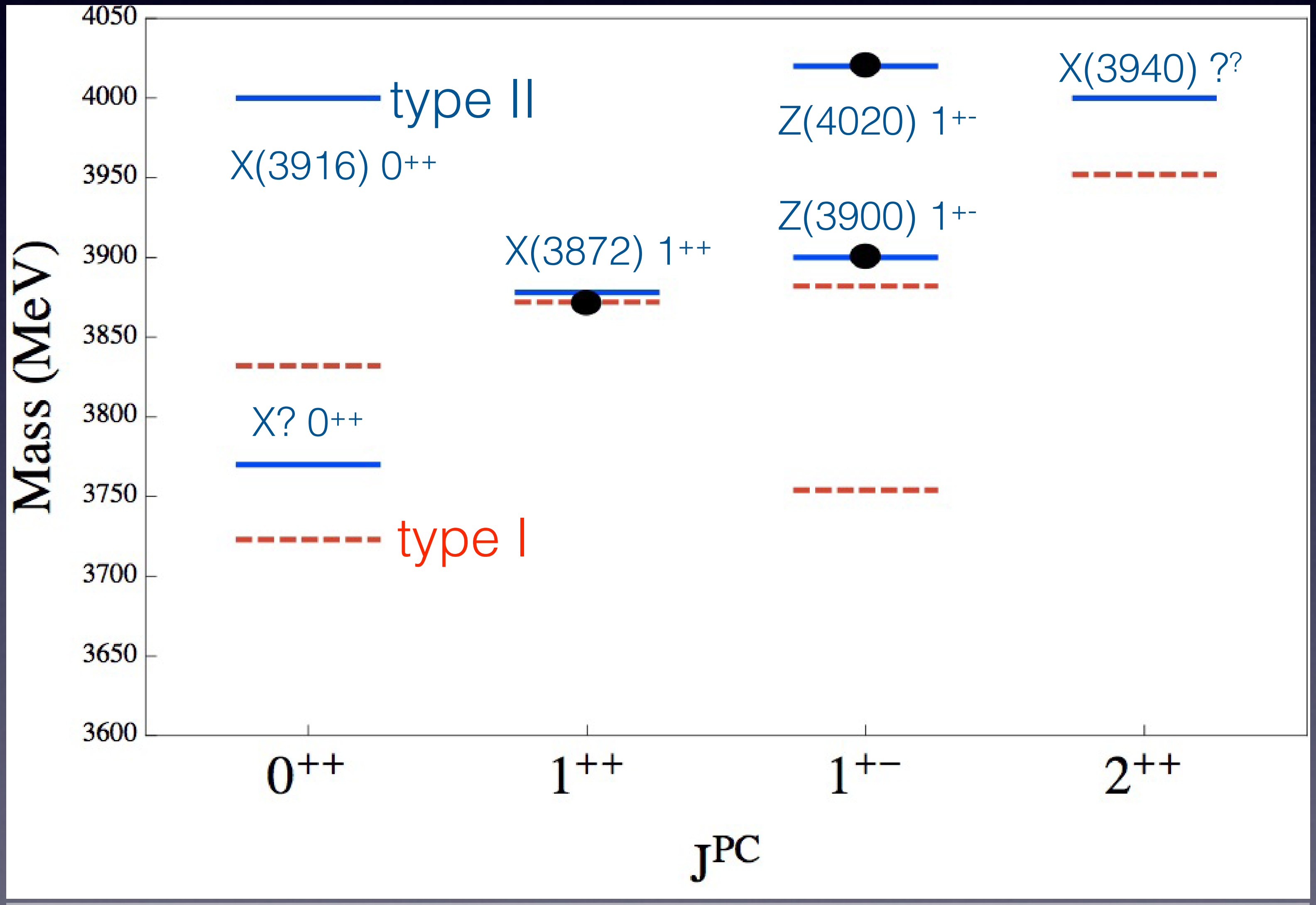
$\mathrm{J}^{\mathrm{P}} = 2^+ \quad C = + \quad X_2 = |1,1\rangle_2$ Linear combi Z,Z' to make Z_c's

The Hamiltonian, of the 'type I' diquark model, turns out to be diagonal on 1^{++} and 2^{++} states but *not* on 1^{+-} and 0^{++}.

In the 'type II' model the mass eigenvectors coincide with the listed states and **M(X_1)~M(Z)**, **M(Z') - M(Z)~134 MeV**.

Spectrum

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



The Y states (e^+e^- collisions)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment ($\#\sigma$)	1st observation
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
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				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	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)	
$\boldsymbol{X(3915)}$	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)	
$\boldsymbol{\chi_{c2}(2P)}$	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)	
$\boldsymbol{G(3900)}$	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
$\boldsymbol{Y(4140)}$	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.

The Y states (e^+e^- collisions)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$Y(4260)$	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
$Y(4360)$	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
$Z_c^+(3900)$	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.

Y States: One Unit of L

$|s, \bar{s}; S, L\rangle_{J=1}$

Y(4260) like X(3872) →

$$Y_1 = |0,0;0,1\rangle_1$$
$$Y_2 = \frac{1}{\sqrt{2}}(|1,0;1,1\rangle_1 + |0,1;1,1\rangle_1$$
$$Y_3 = |1,1;0,1\rangle_1$$
$$Y_4 = |1,1;2,1\rangle_1$$

Changing spin basis (quark-antiquark) one finds

		1^{--}
	$Y_1 :\ P(s_{c\bar{c}}=1) : P(s_{c\bar{c}}=0) = 3:1$	$Y(4008)$
$Y(4260) \to \gamma + X(3872)$ →	$Y_2 :\ P(s_{c\bar{c}}=1) = 1$	$Y(4260)$
$h_c(1P)$ →	$Y_3 :\ P(s_{c\bar{c}}=1) : P(s_{c\bar{c}}=0) = 1:3$	$Y(4290)$ or $Y(4220)$
	$Y_4 :\ P(s_{c\bar{c}}=1) = 1$	$Y(4630)$

which helps the given tentative assignation. We identify Y(4360) and Y(4660) decaying into ψ(2S) as <u>radial excitations</u> of Y(4008) and Y(4260).

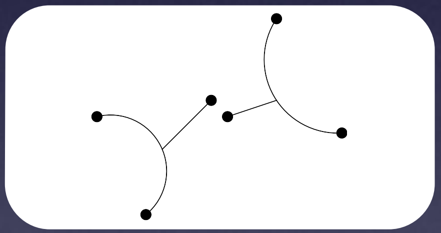
Charmed Baryonium

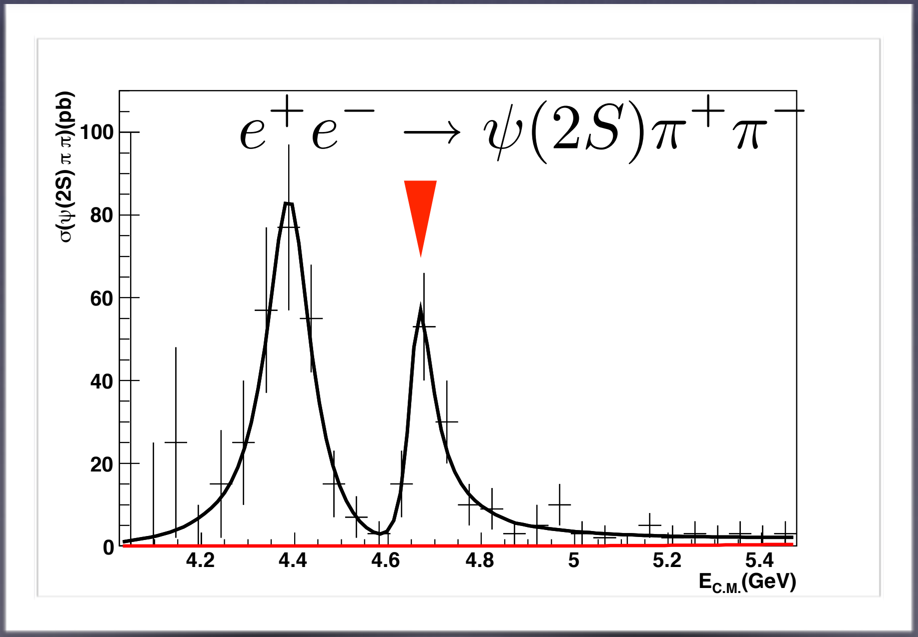
G. Cotugno, R. Faccini, ADP, C. Sabelli *Phys. Rev. Lett.* ***104***, *132005 (2010)*

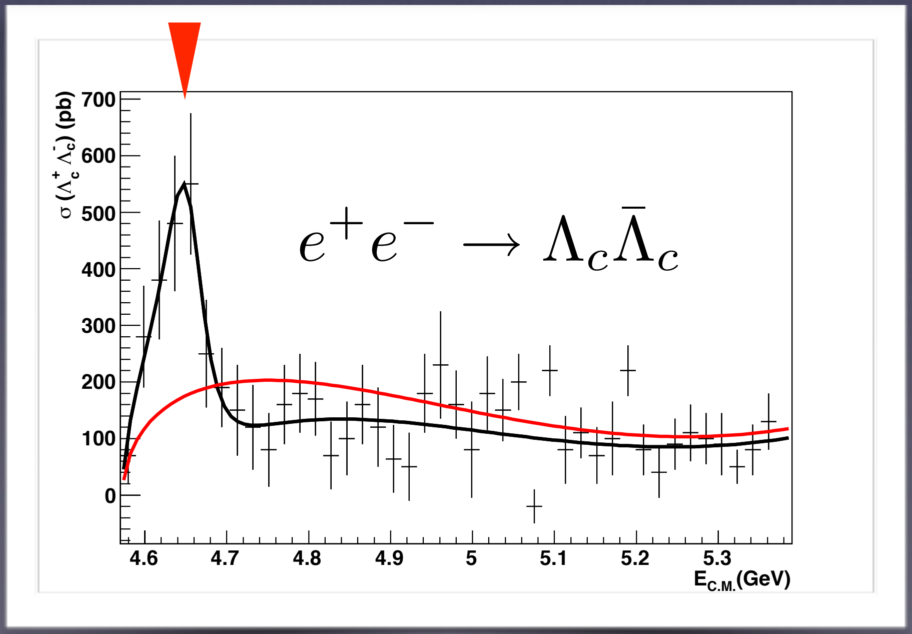
One may easily suspect that Y(4660) and Y(4630) are one and the same particle (call it Y_B) showing how this hypothesis improves the fit to Belle data.

Under this hypothesis we found the remarkable ratio

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







Molecules

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Molecular Charmonium: A New Spectroscopy?

Phys. Rev. Lett. **38**, 317 – Published 14 February 1977

A. De Rújula, Howard Georgi, and S. L. Glashow

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ABSTRACT
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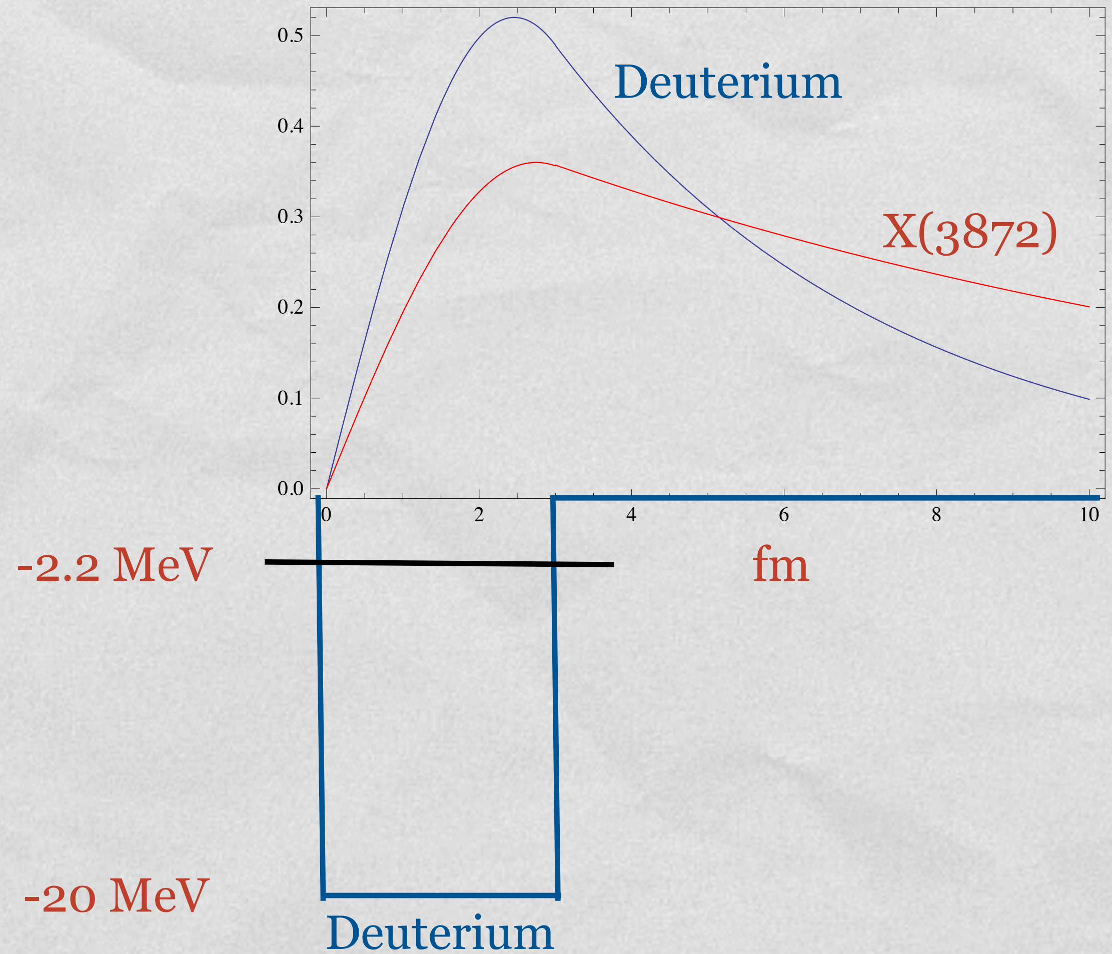
ABSTRACT

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

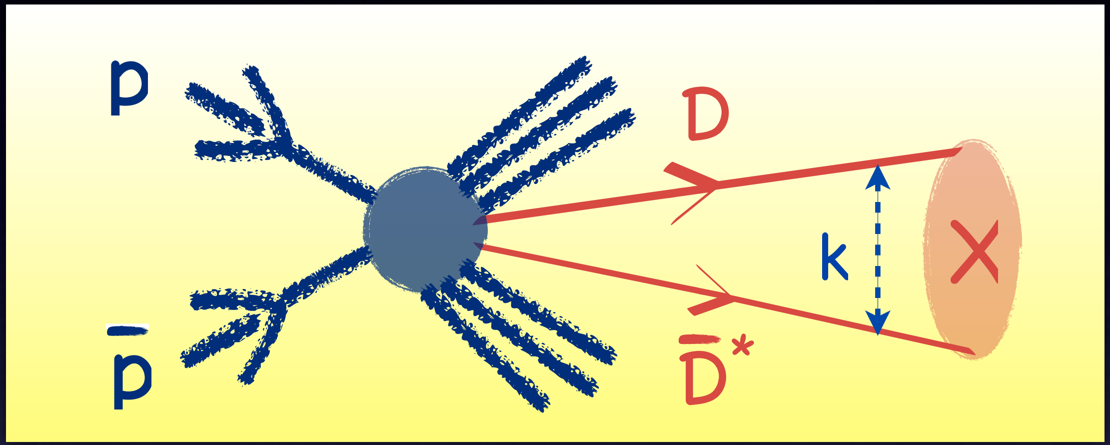
IS THE X(3872) SOME SORT OF DD* DEUTERON?



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

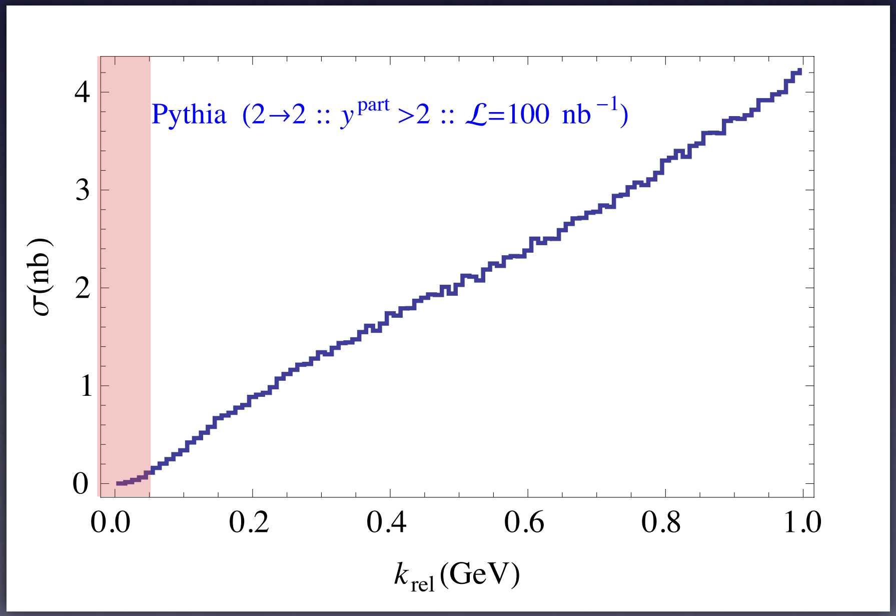
$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-\frac{m_\pi c}{\hbar}r_0}}{r_0} = \mathcal{E}_b = 0.14 \text{ MeV} \Rightarrow r_0 \approx 12 \text{ fm}$$

Barely Bound States in TeV Hadron Collisions?



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

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



Production xsect 300 times smaller than the observed one

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

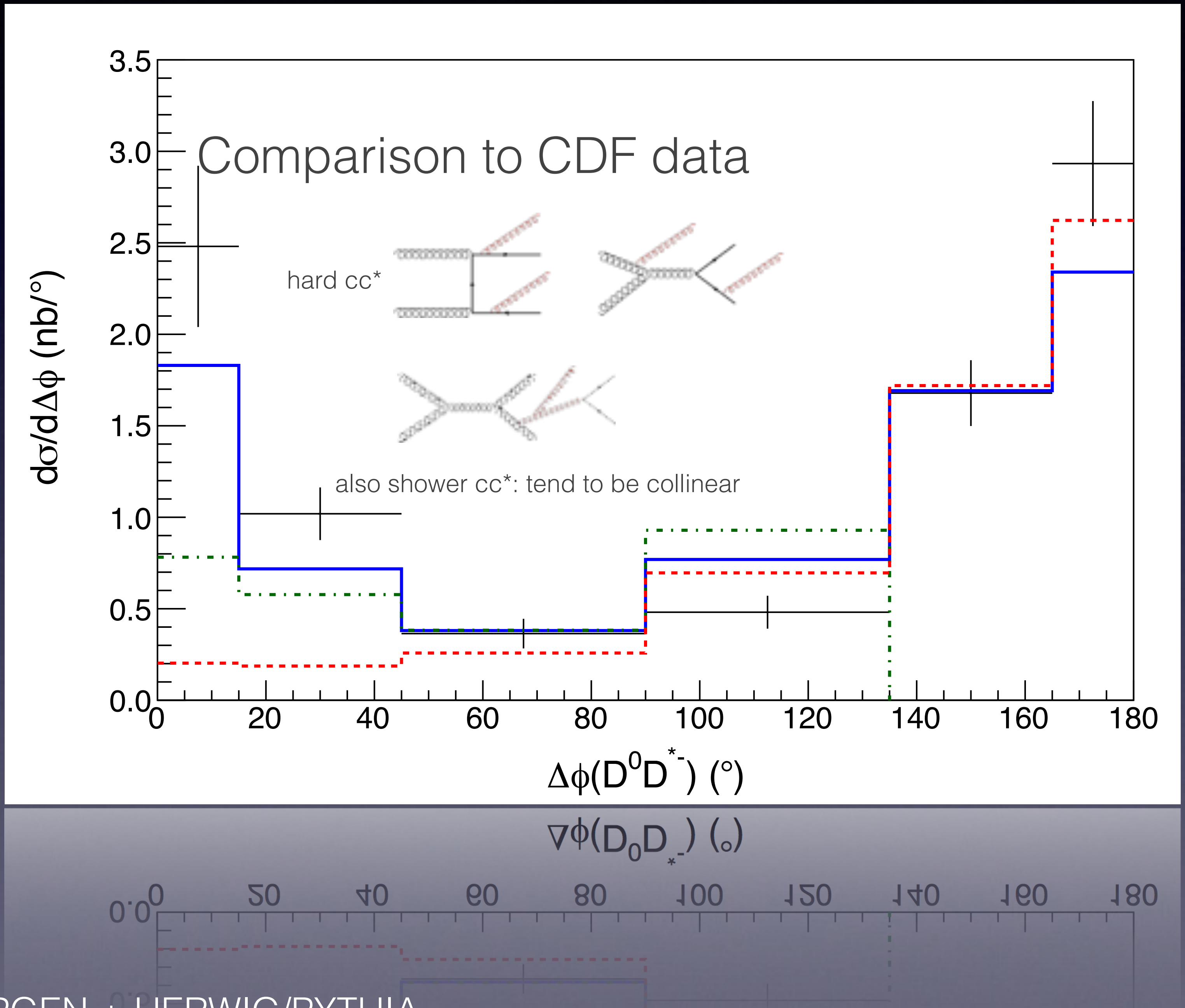
P. Artoisenet and E. Braaten, *Phys Rev* ***D81***, *114018 (2010)*

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 [. . .]

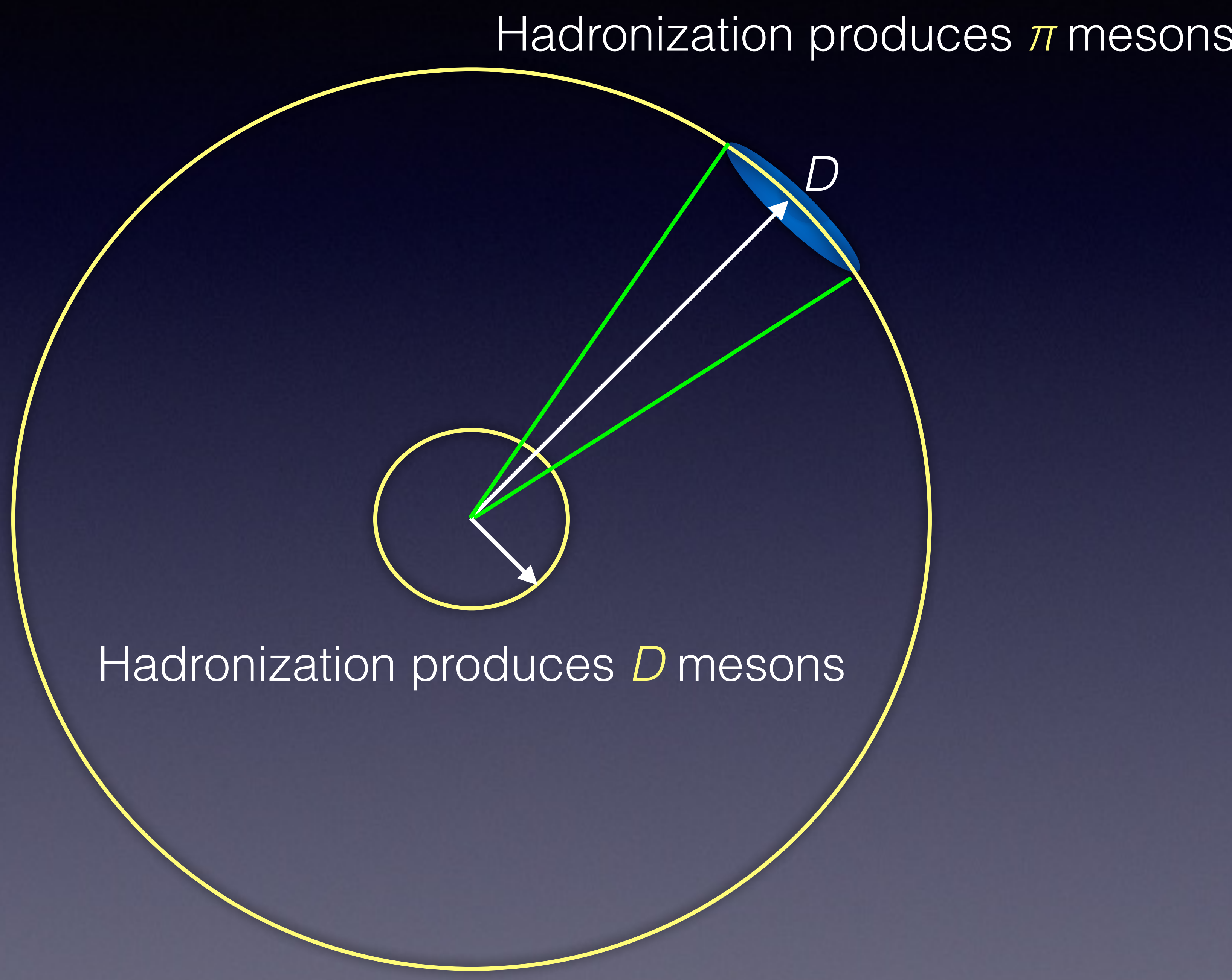
Production: MC Tuning



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

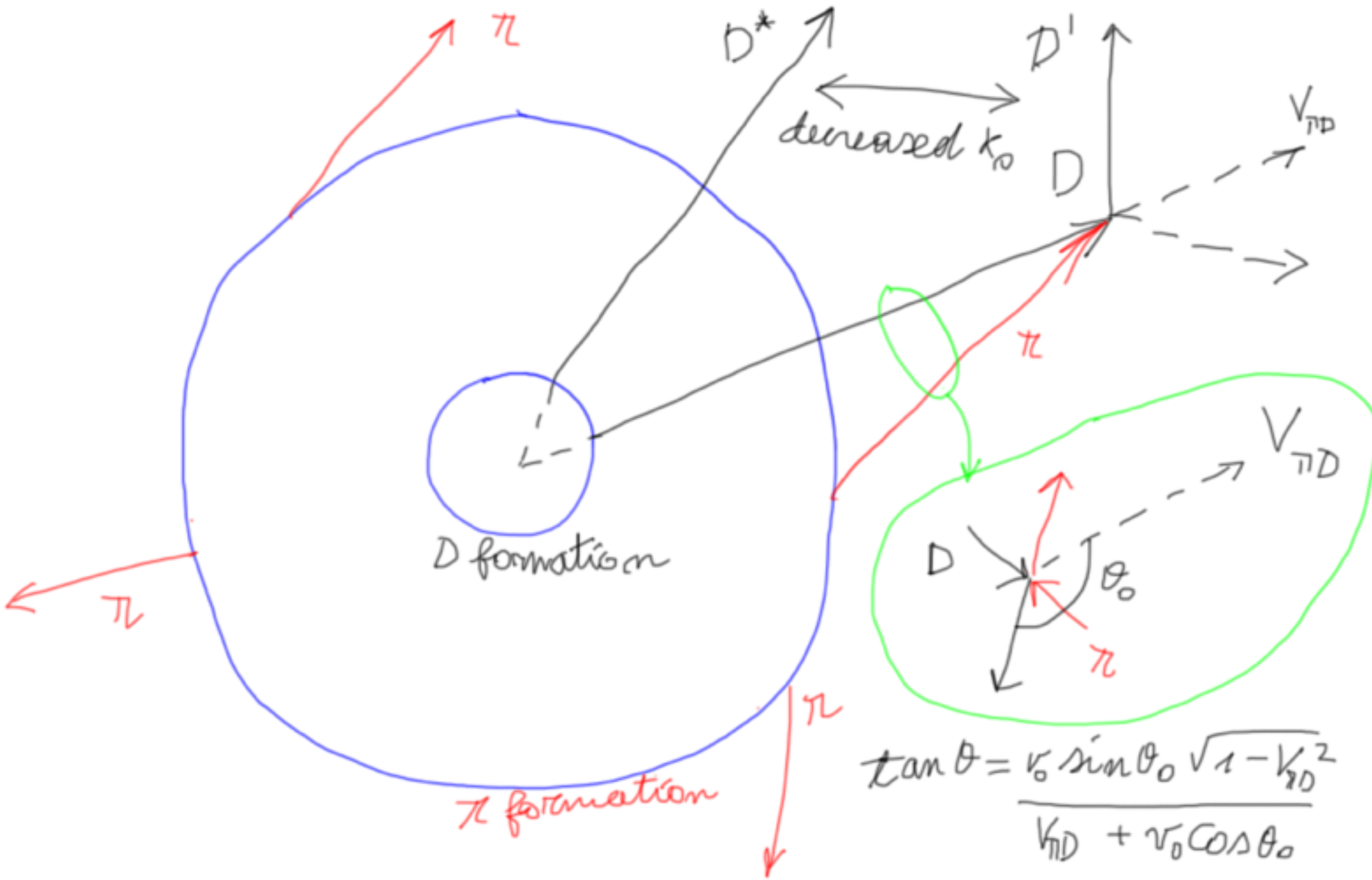
A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929

Final state πD scatterings?



How many π mesons in a spherical sector of 3 fm of base radius around *D*?
Possible multiple interactions to correct the k_0? Not many! Estimate ~3

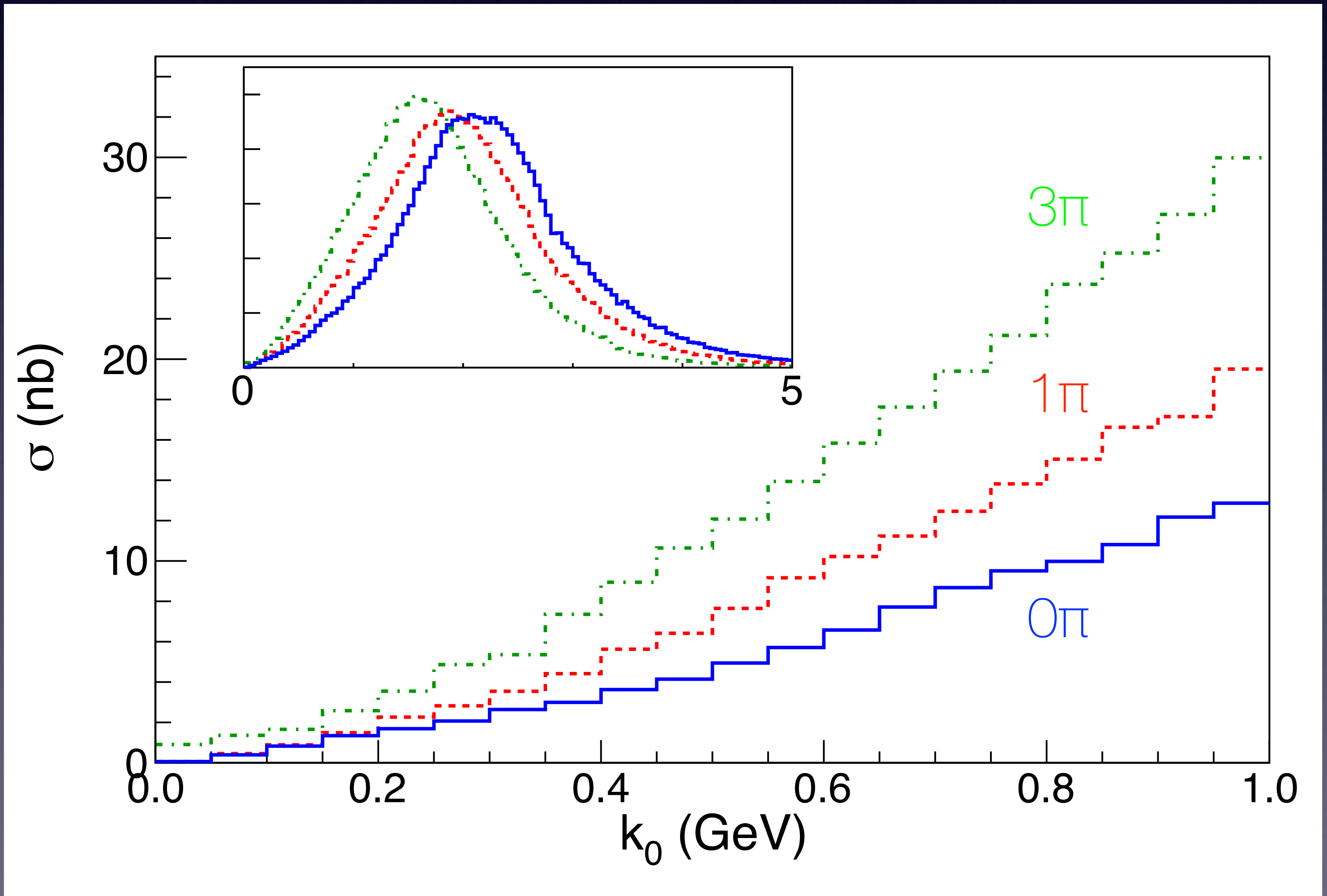
Complanar Pions



$$\tan\theta = \frac{v_0 \sin\theta_0 \sqrt{1 - V_{\pi D}^2}}{V_{\pi D} + v_0 \cos\theta_0}$$

Any Improvements?

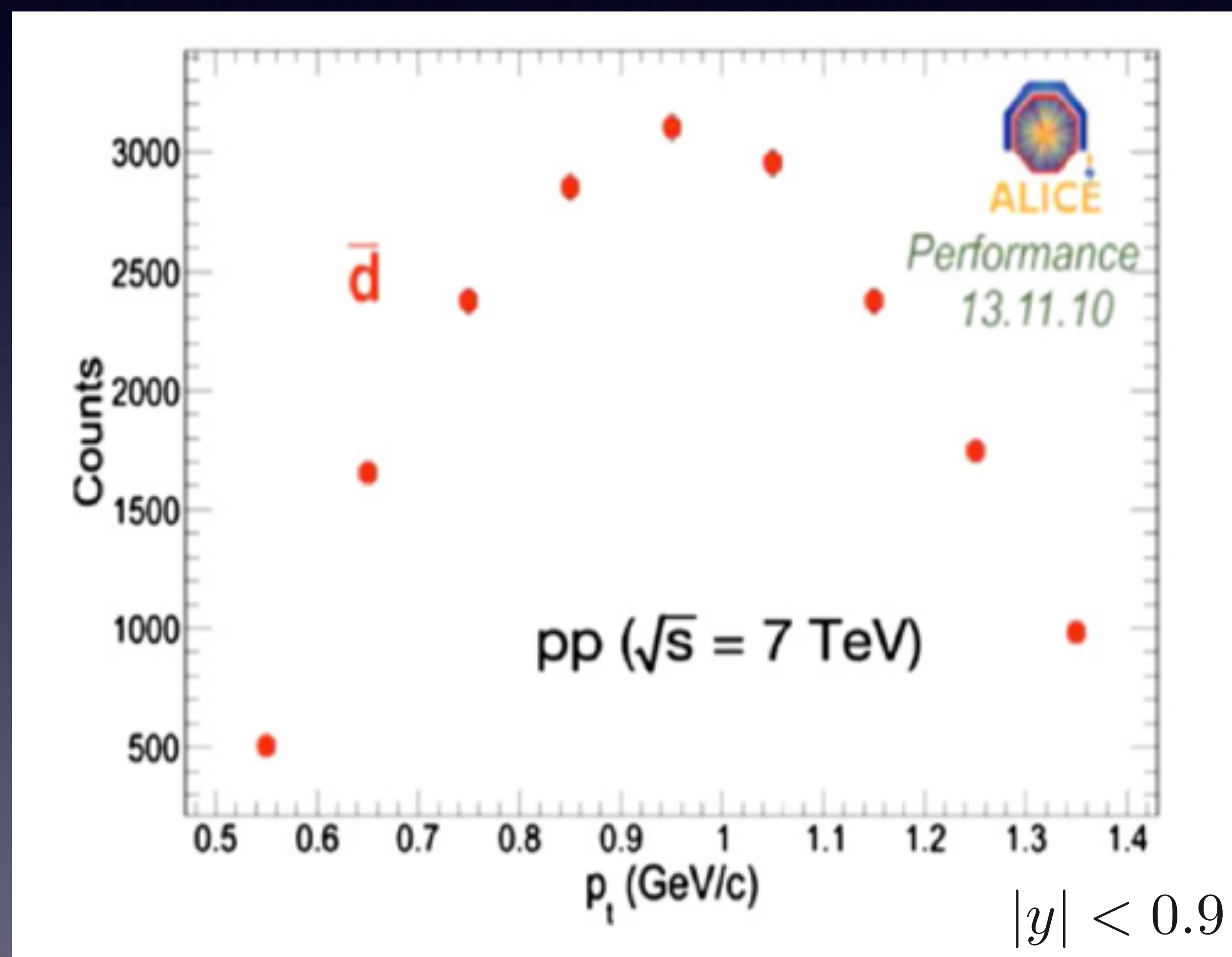
The mechanism works: *feed down* from higher bins — but it does not help in the *bins of interest* (up to 100 MeV for the com relative momentum in the wold-be-molecule, k_0)



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

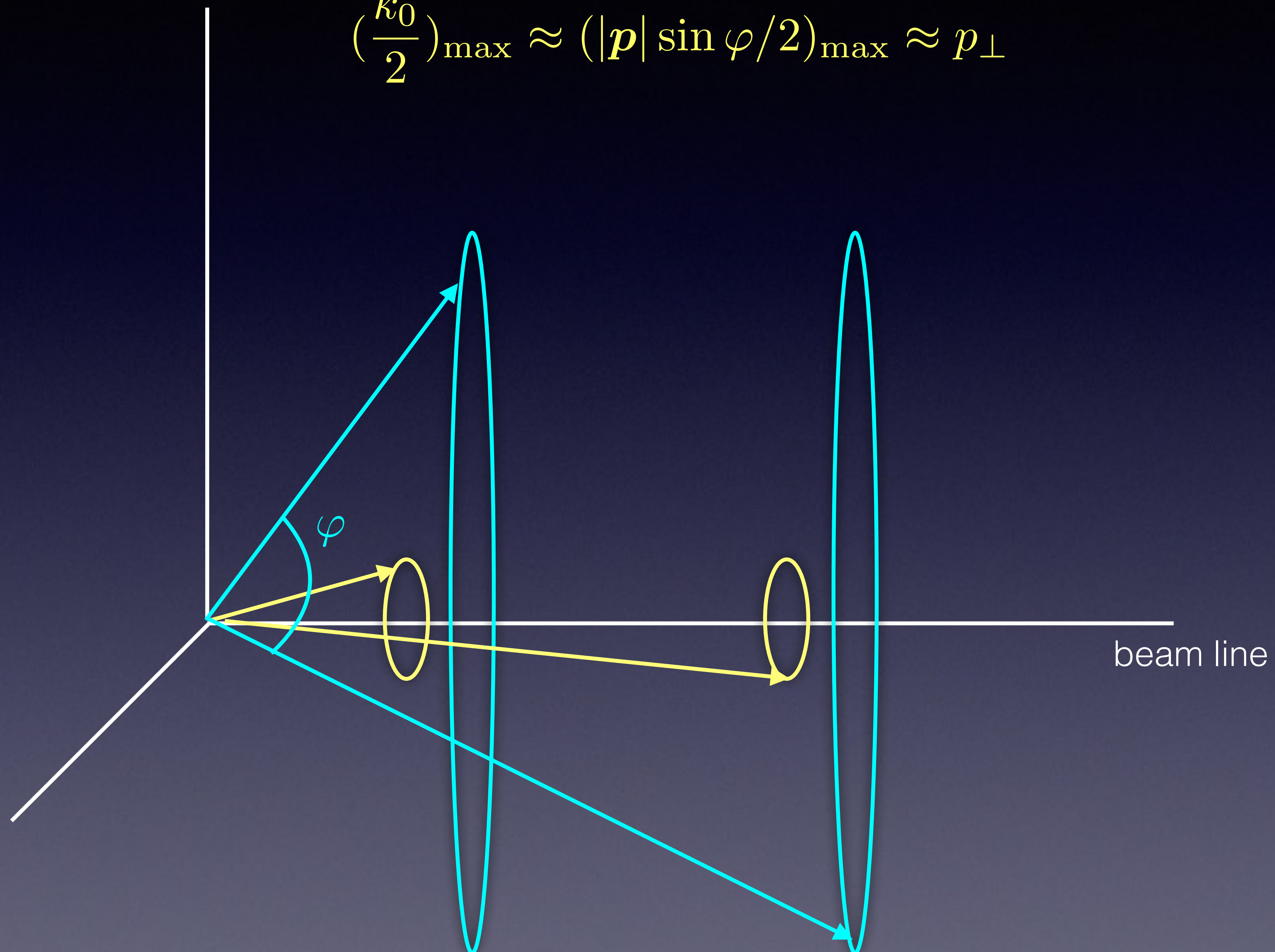
Deuteron at LHC?

Usual reply: A lot!!
Indeed Alice has 30K antideuterons.
— In which p_T range though?

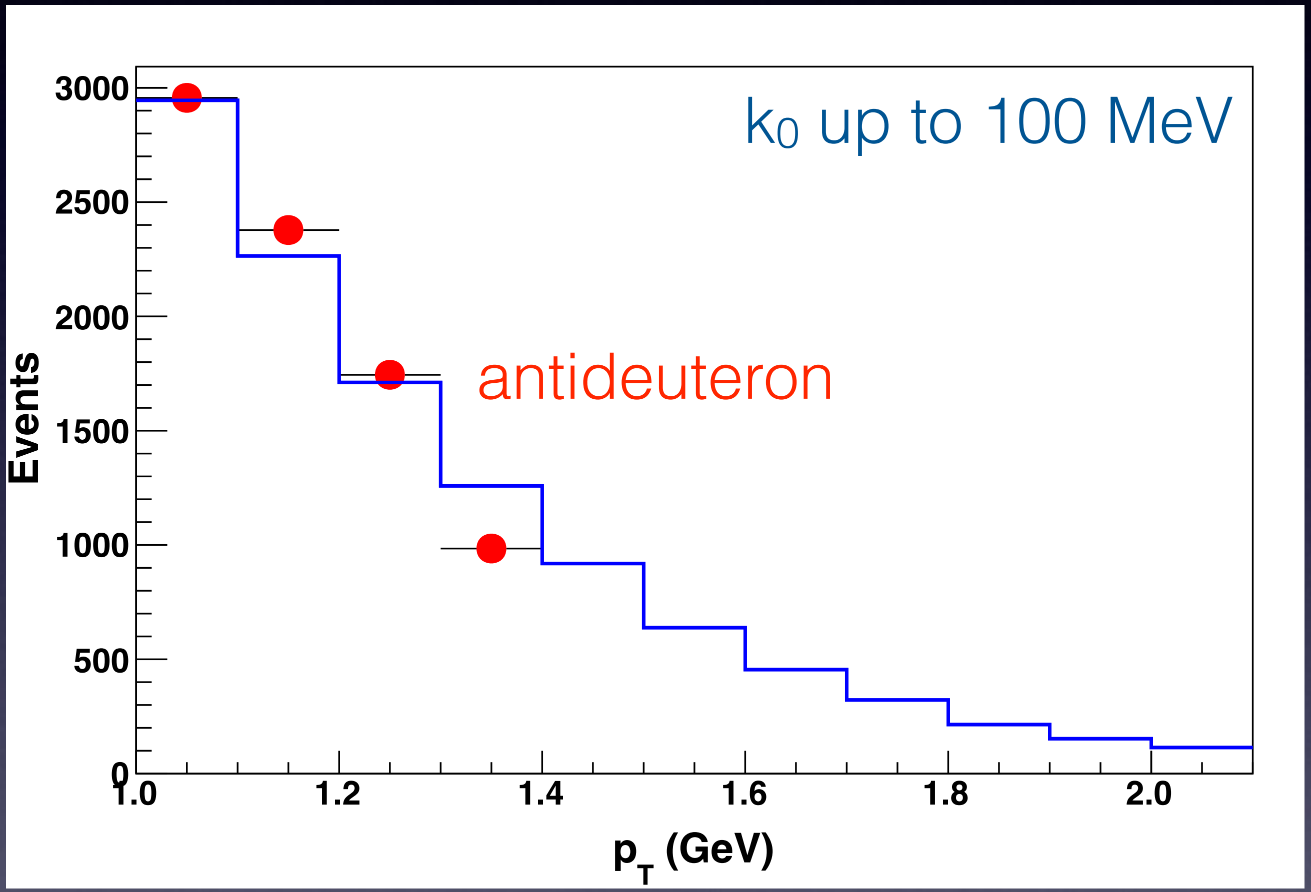


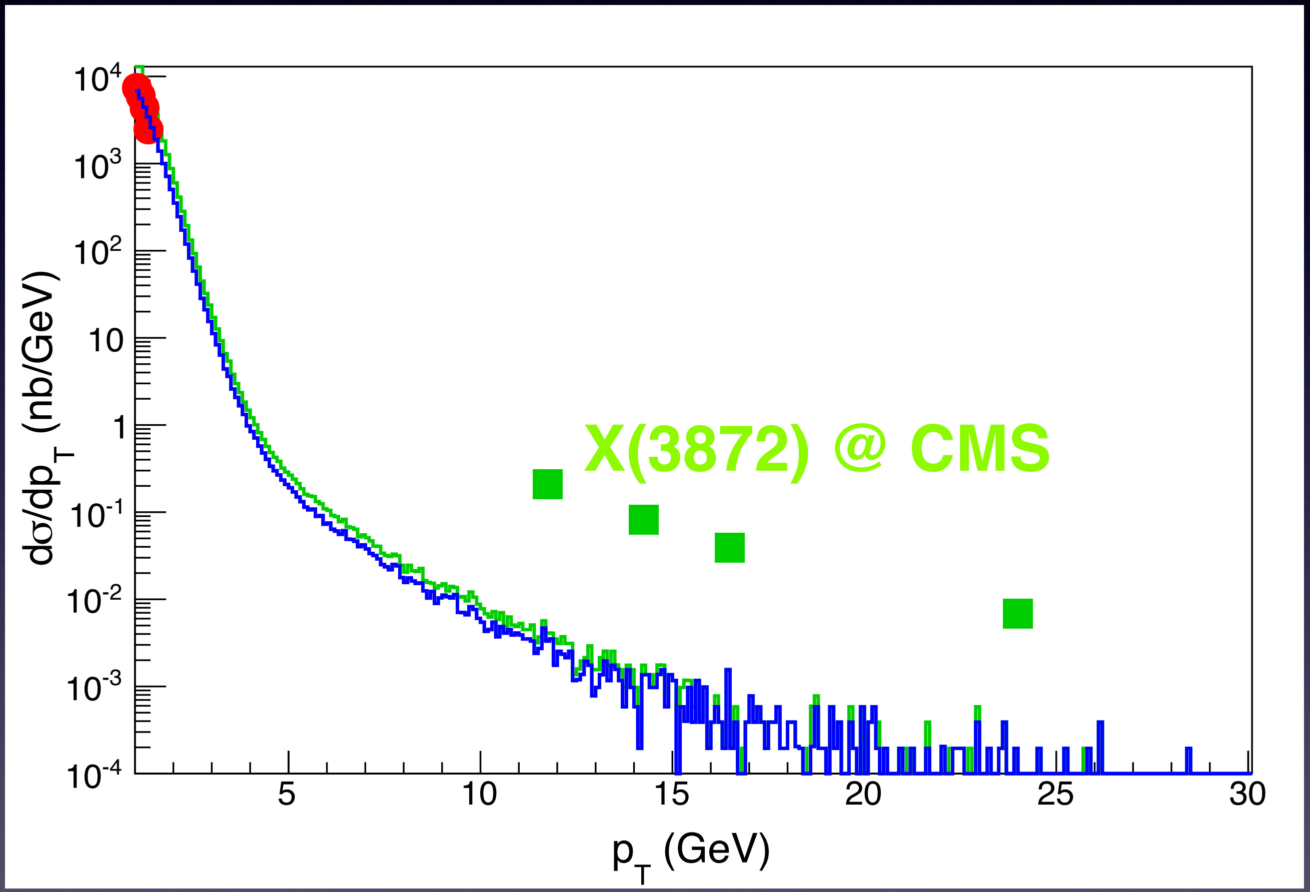
Recall that X has been observed with a p_T>5.5 GeV!

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



MC Extrapolation



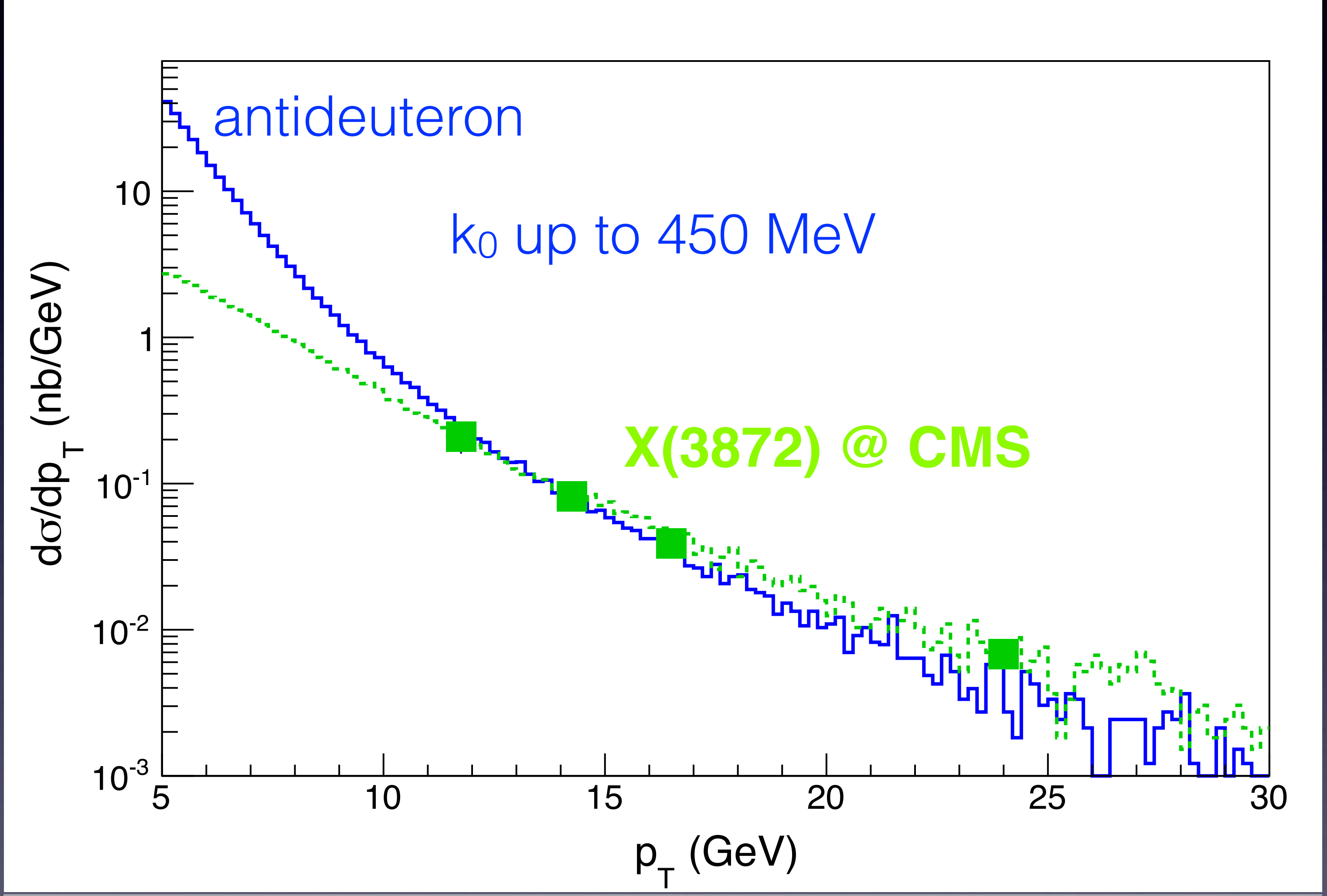


CMS cuts for the X: $10 < p_T < 50$ GeV

$|y| < 2$

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

Reverse MC Extrapolation



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

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Selection Rules

Hadronization must be 4q

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

— 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.

BTW observe that from an estimate by Ali & Wang

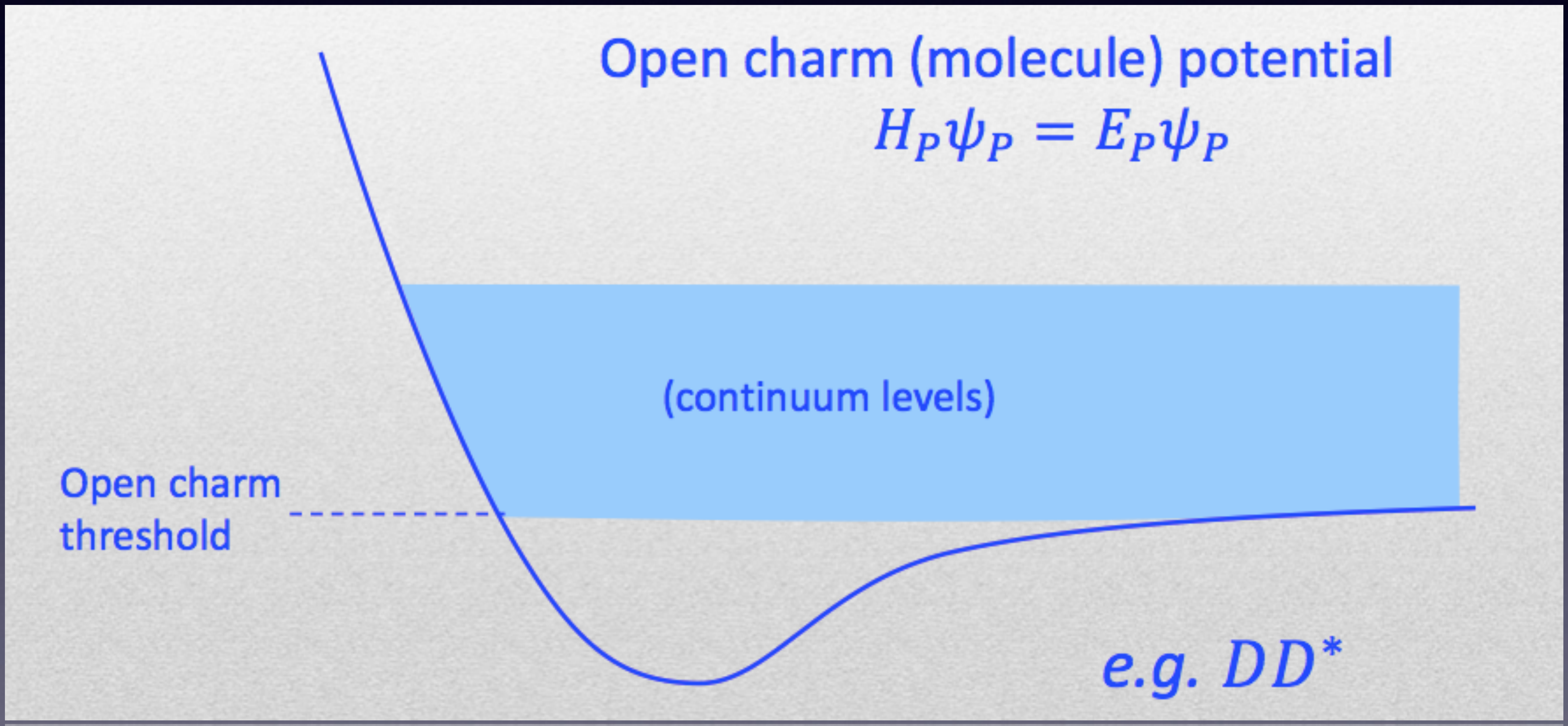
$$\frac{\sigma(pp \to Y(4260))}{\sigma(pp \to X(3872))} \gtrsim 10^{-2}$$

It would be very significant to directly measure this ratio.

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

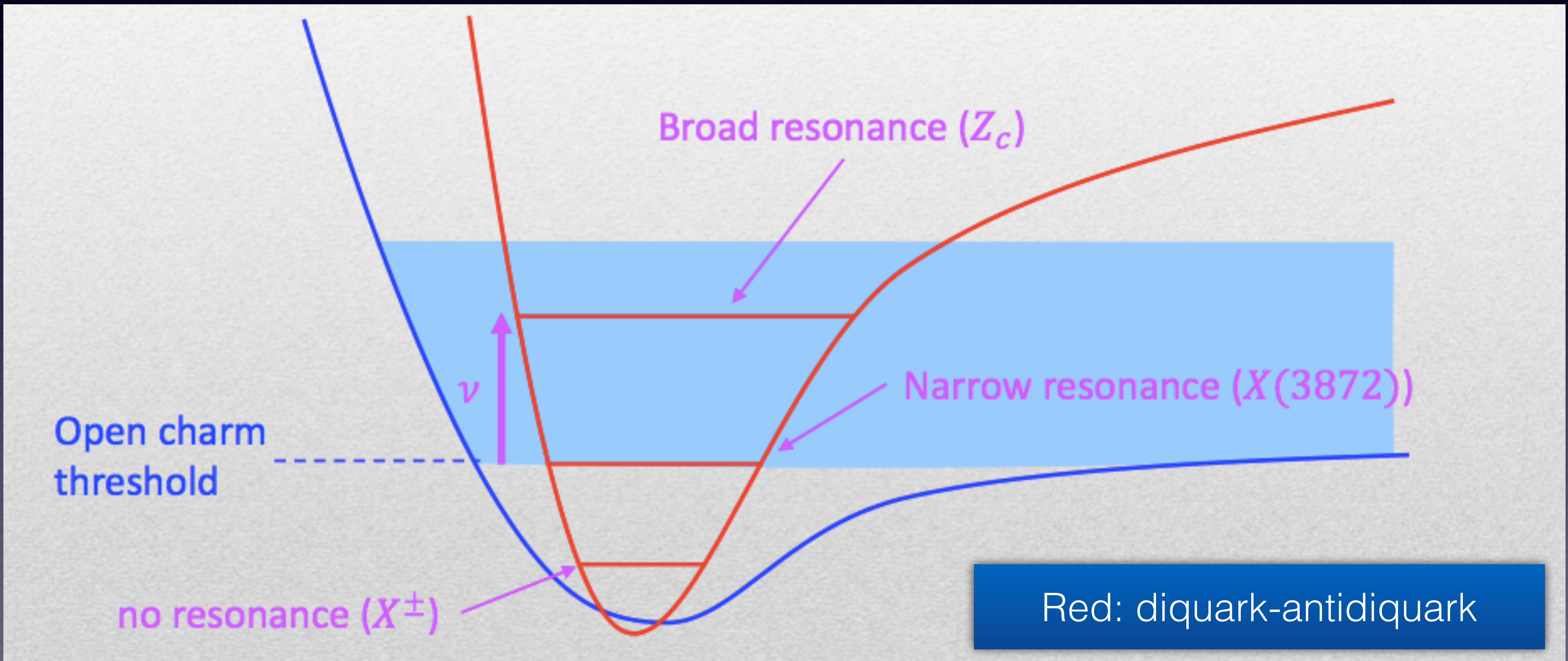
Another Mechanism

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



Another Mechanism

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



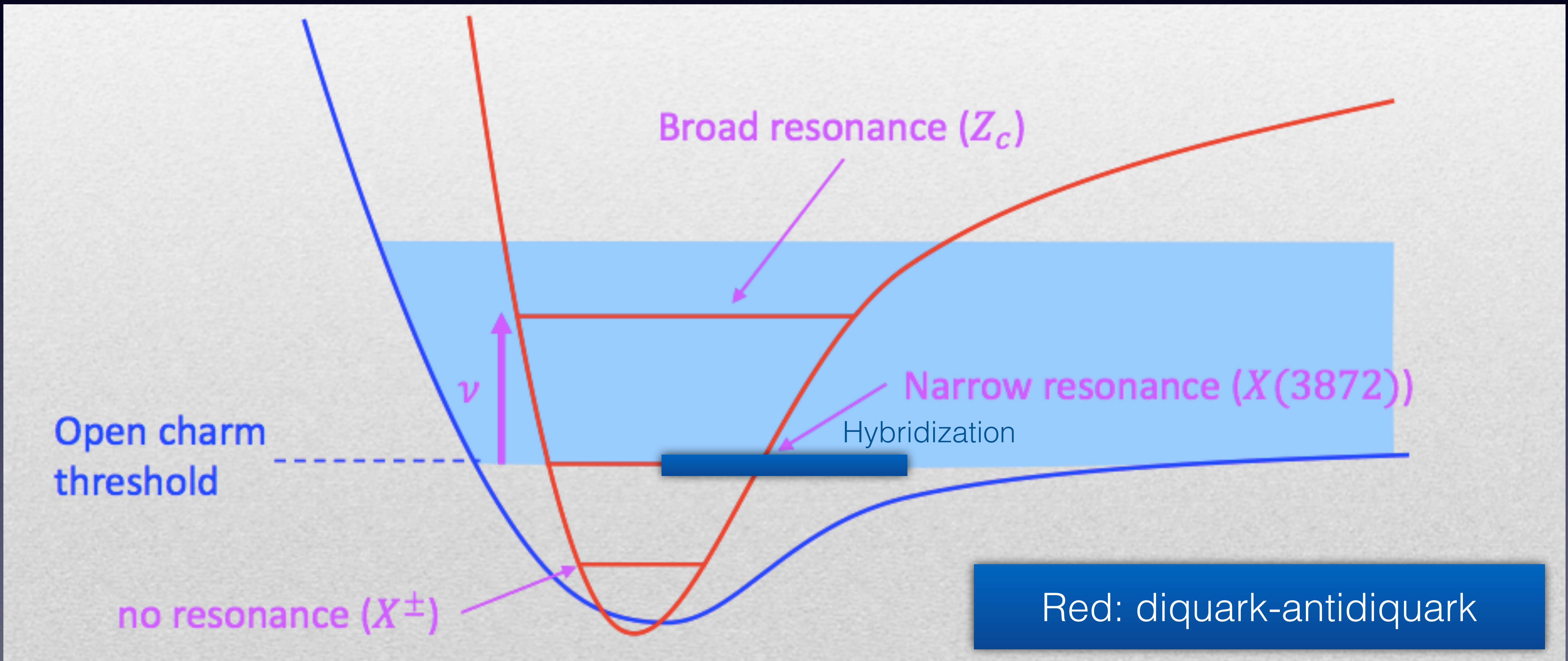
Red: diquark-antidiquark

Blue: loose molecule

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

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.



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

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

Lattice

4-quarks from lattice?

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

On simulating a proton on the lattice, the interpolating operators

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

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.

$$\mathcal{O}^1_{T^0} = \varepsilon^{ABC} c^B c^C \ \varepsilon^{ADE} \bar{u}^D \bar{u}^E$$
$$\mathcal{O}^2_{T^0} = \bar{u}^A c^A \ \bar{u}^B c^B$$
$$\mathcal{O}^3_{T^0} = \sum_a \bar{u}^A T_i^{AB} c^B \ \bar{u}^C T_a^{CD} c^D$$
$$\mathcal{O}^4_{T^0} = \bar{u}^A c^A \ \bar{u}^B c^B \ \bar{s}^C s^C$$

More Exotic States

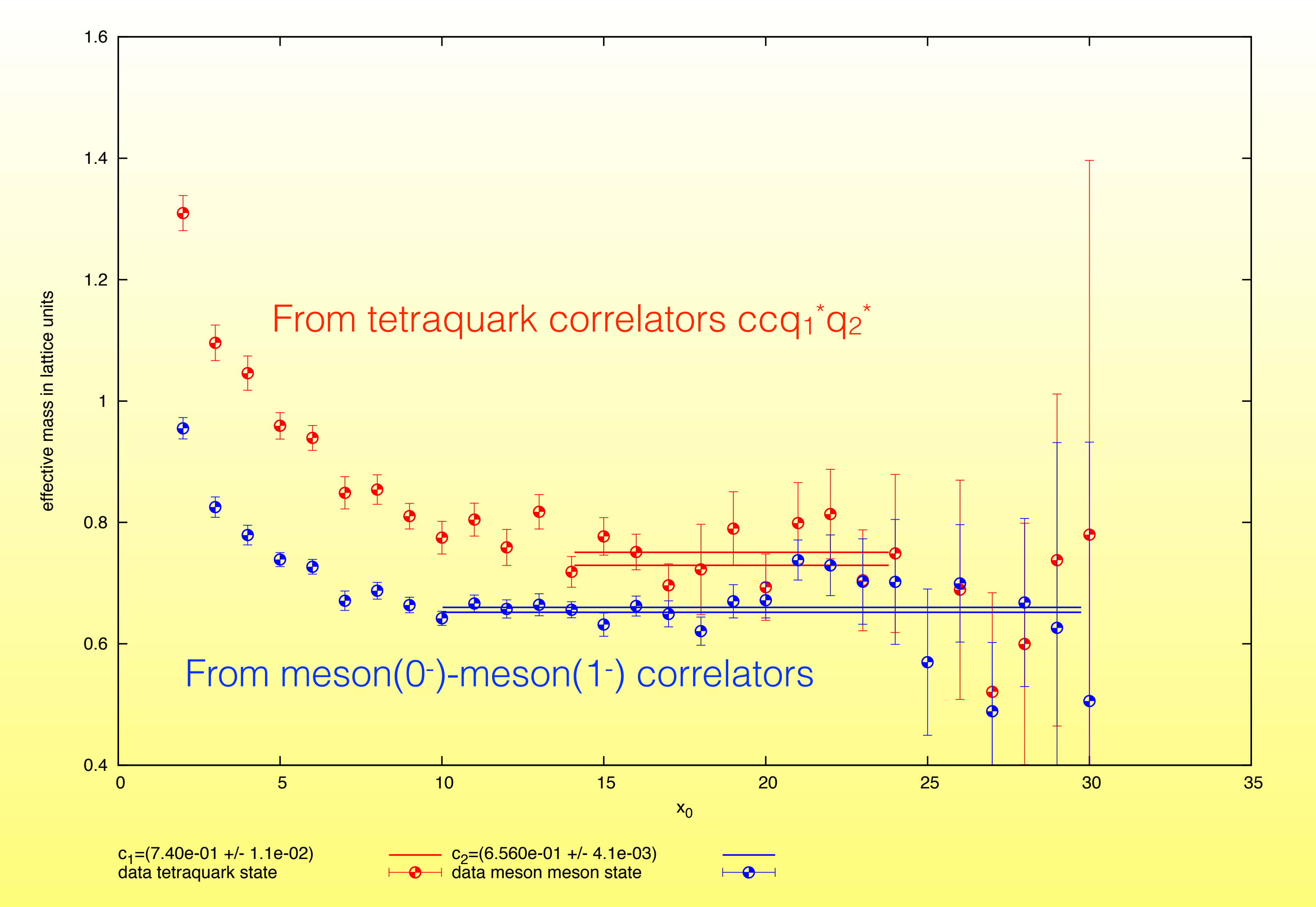
$$|T^0\rangle = |Q_u = -2, Q_c = +2\rangle$$
$$|T^+\rangle = |Q_u = -1, Q_d = -1, Q_c = +2\rangle$$
$$|T_s^+\rangle = |Q_u = -1, Q_s = -1, Q_c = +2\rangle$$
$$|T^{++}\rangle = |Q_d = -2, Q_c = +2\rangle$$
$$|T_s^{++}\rangle = |Q_s = -2, Q_c = +2\rangle$$

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 $d \leftrightarrow s$)	$\Omega^-\mathcal{T}_s^+ \to \Omega^-D_s^+D^0$

Lattice Spectrum Studies

$$m_{\text{eff}} = -\ln \frac{C(x_0+1)}{C(x_0)}$$



A. Guerrieri, M. Papinutto, A. Pilloni, N.Tantalo

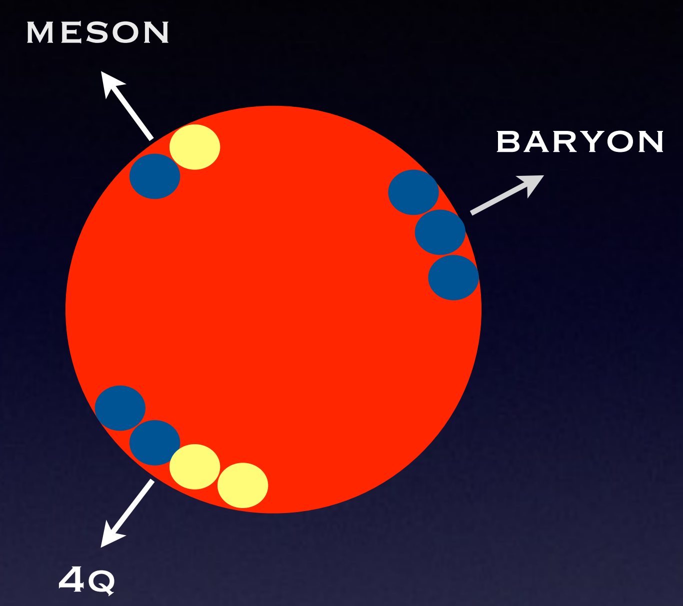
Conclusions

- **Multiquarks hadrons have been discovered!** We need a coherent description which aims to explain the largest number/totality of collected data.
- Loosely bound molecules promptly produced at high energy hadron colliders require a miracle in final state interactions.
- Diquark-antidiquark states give an easy understanding of prompt production but require a richer flavor structure induced by SU(3) symmetry.
- Is the quantum mechanics of Feshbach resonances a possible solution? Not with standard charmonia vs open charm molecules. Most likely the closed hannel has to be diquark-antidiquark.

Backup Slides

Can Alice add knowledge on X(3872)?

Let's consider the recombination mechanism (Muller et al.)



The phase space is densely populated of partons. The soft part of the spectrum of produced hadrons is assumed to be formed by the decay of a deconfined state of constituent quarks which 'recombine'. The hard part is instead described by pQCD with an implementation of the parton energy loss in medium. This simple picture turns out to be effective at explaining the observation of

$$\frac{\#p}{\#\pi^+} \geq 1 \text{ for } 1.5 \text{ GeV} \leq p_\perp \leq 4 \text{ GeV @ RHIC}$$

this cannot be explained with fragmentation functions (fitted at e+e-) where the number of expected pions is much higher.

I - The transverse momentum of partons is steeply falling with pT
II - Fragmentation functions favor the situation where the energy of the fragmenting parton is *not* concentrated in a *single hadron* but distributed amid all *radiated partons*.

Thus fragmentation is inefficient at producing high pT hadrons in general. In particular pions are favored with respect to baryons .

But if th phase space is highly populated with partons, then it can simply happen that

$$P_\pi = p_u + p_{\bar{d}}$$
$$P_p = p_u + p_u + p_d$$

Assume

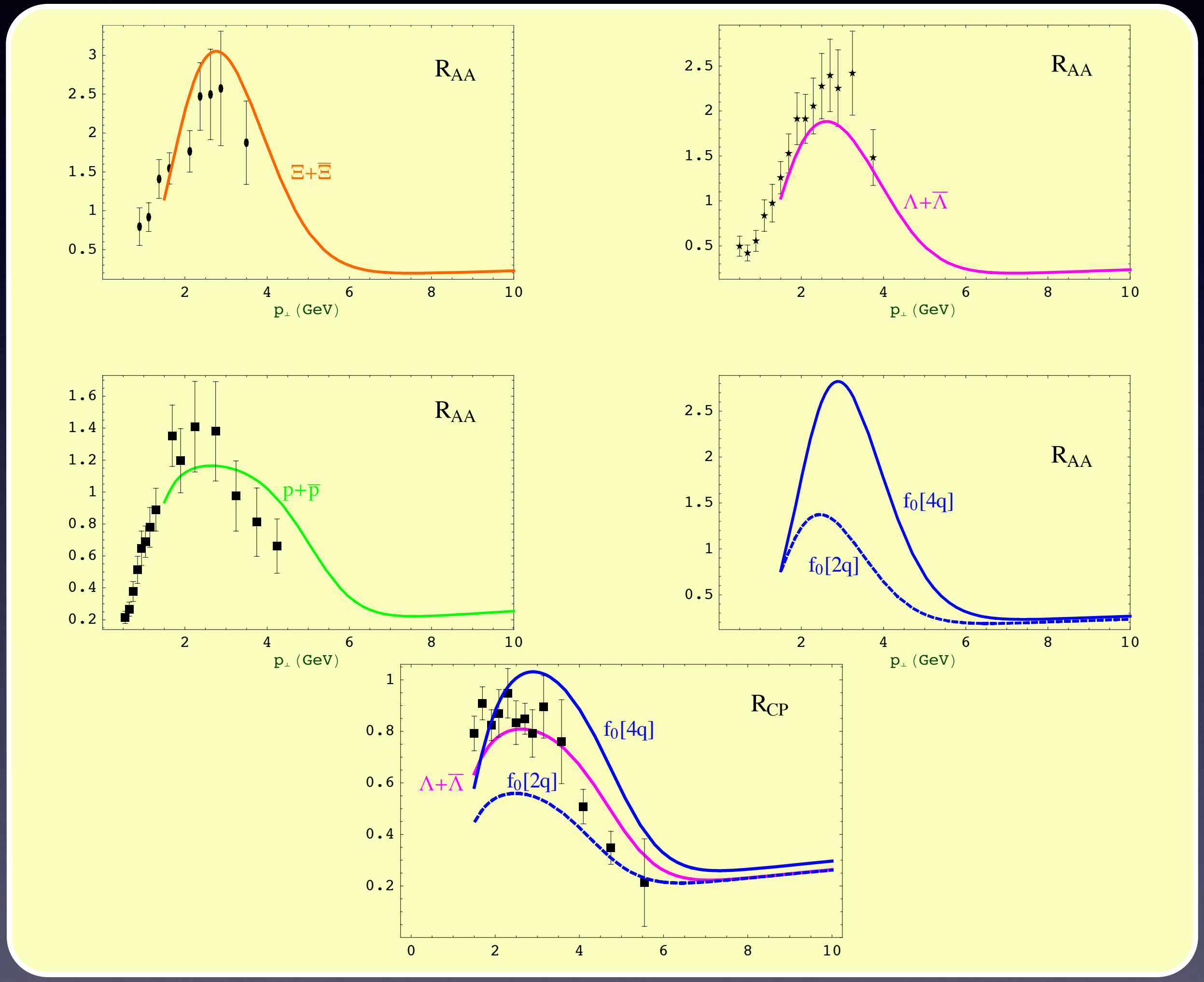
$$p_u \simeq p_d \simeq p_{\bar{d}} \simeq p$$

$$\text{Prob(N-quark hadron}(p)) \propto (\text{Prob(quark}(q)))^N$$

and assume also exponentially falling parton spectra: same yields at the same hadron transverse momenta

$$\#(\text{protons}) \propto (\exp(-p_T/3))^3 \quad \simeq \quad \#(\text{pions}) \propto (\exp(-p_T/2))^2$$

As for the recombination mechanism, we might expect the *X* should be produced with similar yields as other charmonia/bottomonia (either 4q or molecule interpretations are assumed). Charm enhancemet at ALICE? Then *X* enancement as well!

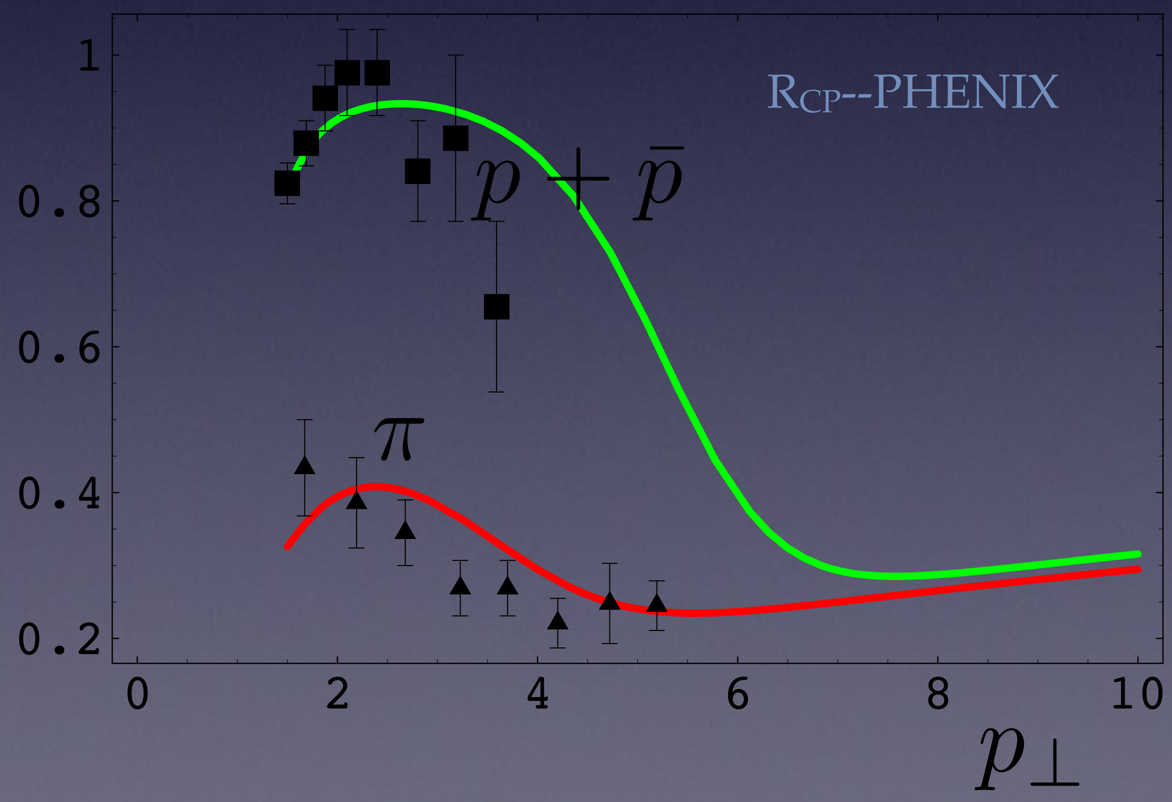


Maiani, Polosa, Riquer, Salgado arXiv:0707.4578 [hep-ph]

Fragmentation functions should be modified for a tetraquark *X* as diquarks are produced whereas the hard part of the spectrum should be left unchanged for the molecule.

Exotic hadrons and HIC

- Model the fragmentation functions of diquark-antidiquark mesons. Confronted with data from ALICE.



The numerators are dominated by the ‘coalescence’ mechanism (B. Muller et al). Molecule and tetraquark denominators should also be different

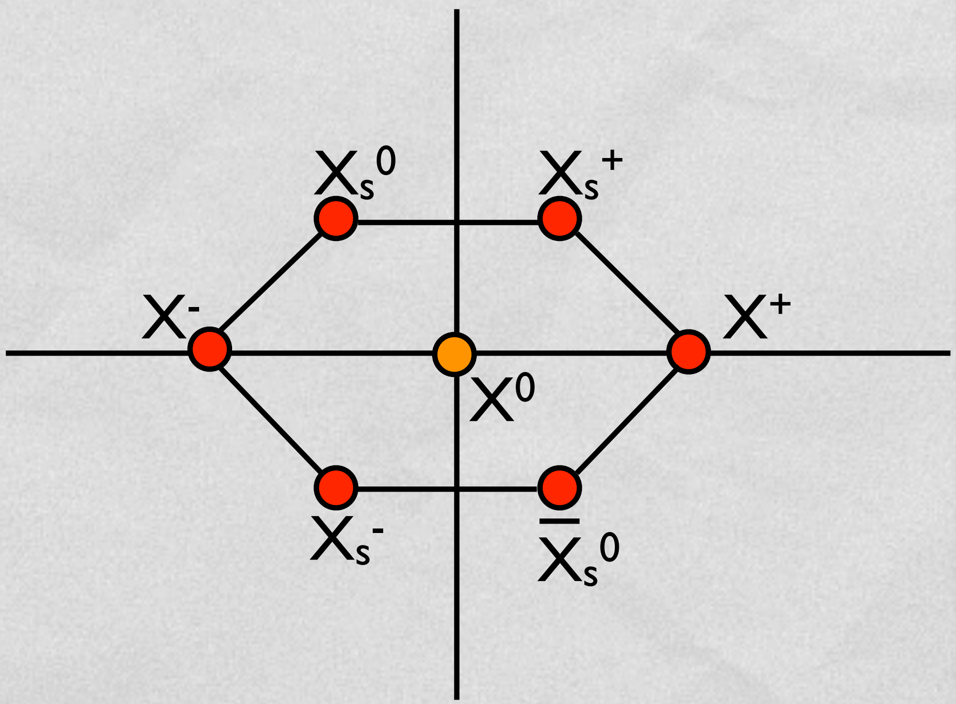
$$R_{CP} = \frac{N_{\rm coll}(b)}{N_{\rm coll}(b=0)} \left(\frac{dN_H/d^2p_\perp(b=0)}{dN_H/d^2p_\perp(b)} \right)$$

$$R_{AA} = \frac{1}{N_{\rm coll}(b=0)} \left(\frac{dN_H/d^2p_\perp(b=0)}{dN_H/d^2p_\perp|pp} \right)$$

L. Maiani, A.D. Polosa, V. Riquer, C. Salgado, *Phys Lett B 2007* (light mesons)

CHARMED DIQUARKS

The octet with diquarks - the 'azimuthal approach'



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

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

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^{++}	$([cq]_1[\bar{c}\bar{q}]_1)_2$

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

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

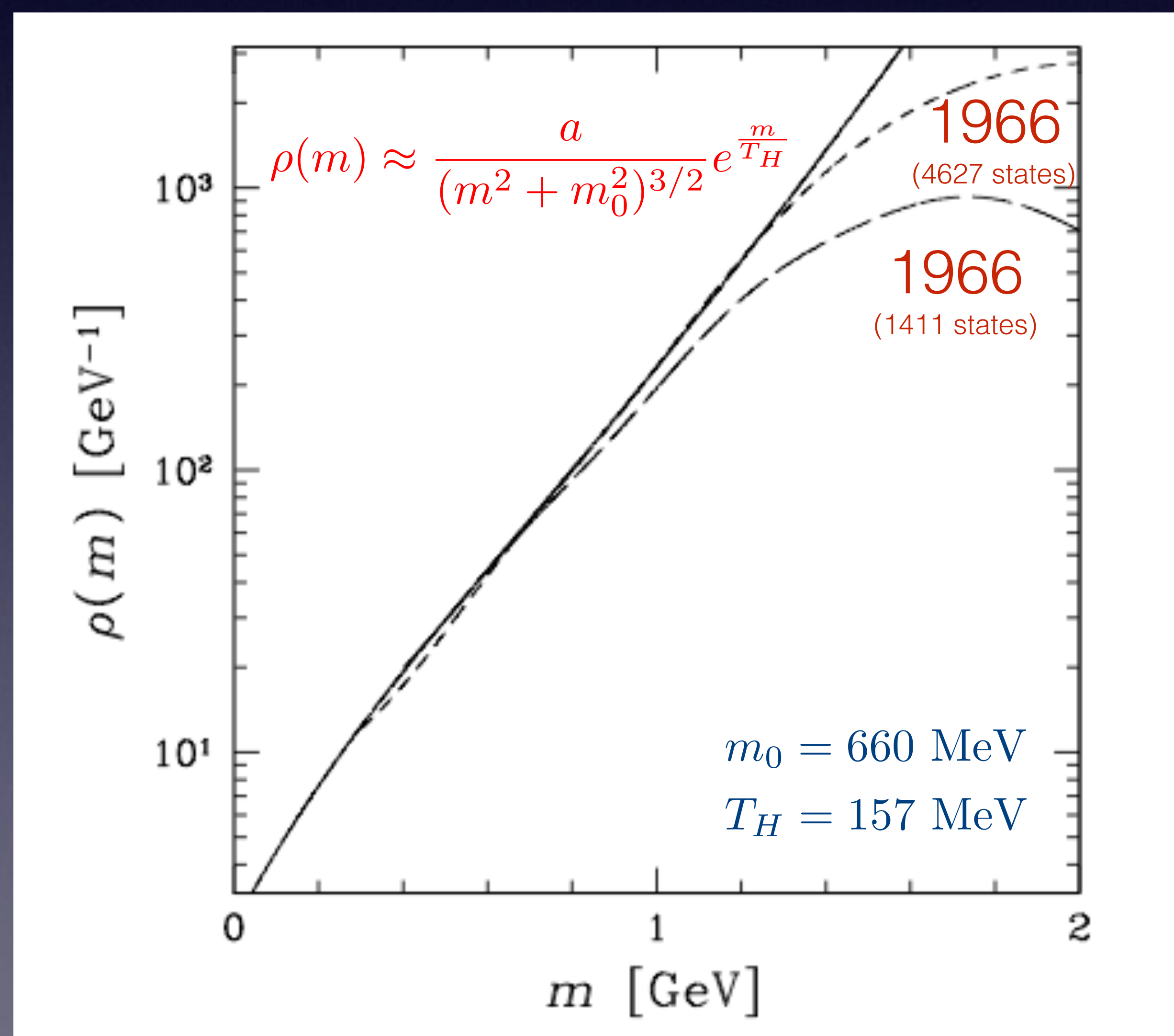
Learn from Hadron Multiplicity

$$\rho(m) = \#\text{ of states in (m,m+dm)} = \sum_{m^*} \delta(m - m^*) \rightarrow$$

$$\rightarrow \sum_{m^* = m_f, m_\rho, m_\omega, \ldots} \frac{g_{m^*}}{\sigma_{m^*}\sqrt{2\pi}} \exp(-(m - m^*)^2/2\sigma^2_{m^*})$$

1996 (4627 states)

$$\sigma_{m^*} = \Gamma_{m^*}/2 \sim O(100)\text{ MeV}$$



Hadron Gas

The partition function of a hot gas of hadrons could be written using the degeneracy factor as extrapolated by the exponential density of hadrons

$$Z = \sum_E \underbrace{g(E)}_{\text{degeneracy of } E} e^{-E/T} = \sum_m \rho(m) \sum_{\boldsymbol{p}} e^{-\frac{\sqrt{\boldsymbol{p}^2+m^2}}{T}}$$
$$\simeq \frac{V}{(2\pi)^3} \int dm\, \rho(m) e^{-\frac{m}{T}} \int dp\, p^2 e^{-\frac{p^2}{2mT}}$$
$$= V \left(\frac{T}{2\pi}\right)^{3/2} \int dm\, \frac{a}{(m^2+m_0^2)^{3/2}} m^{3/2} e^{m\left(\frac{T-T_H}{TT_H}\right)}$$
$$\approx A + B|T - T_H|^{1/2}$$

Hadron matter cannot exist at temperature $T>T_H$ (the partition function would not be convergent). As T approaches T_H, *from below*, heavier and heavier resonances *enter in the sum* — while their momenta do not increase.

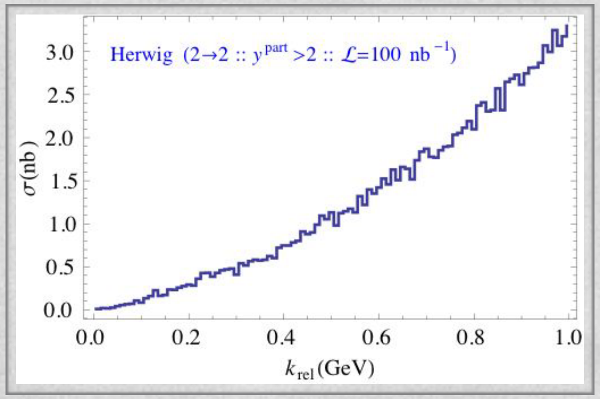
T_H must be the *ultimate temperature of hadronic matter*, where relevant dof must change (N. Cabibbo & G. Parisi 1975)

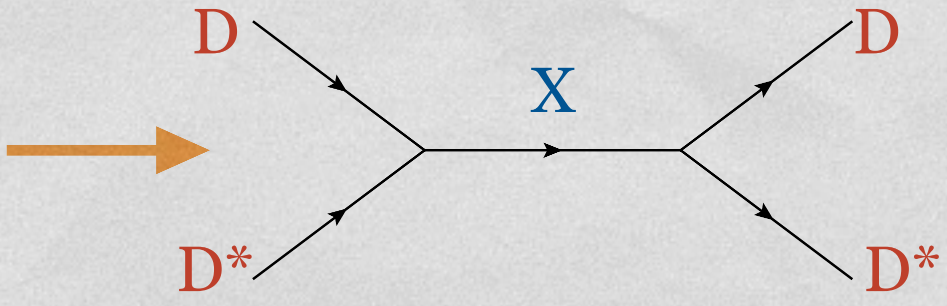
LOW EQUATION

When shallow bound states are allowed in low energy potential scattering it is possible a description of scattering leghts and phase shifts which does not require the precise knowledge of the scattering potential.

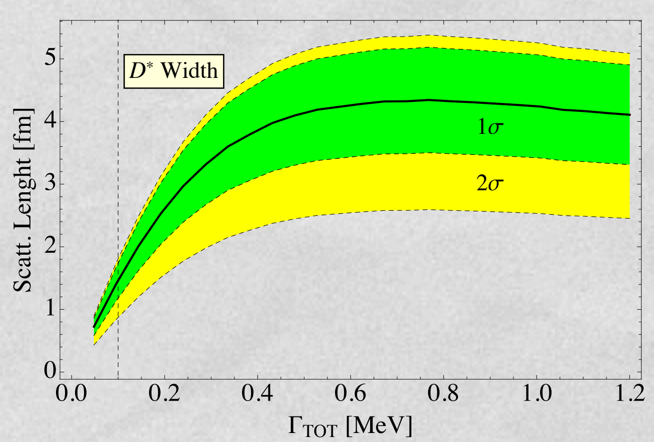
$$\sigma_{\mathrm{tot}} = \frac{2\pi\hbar^2}{\mu|E_b|}$$

DD* Luminosity; $k_0 < \Lambda$





vs. a ~12 fm from Low Eq.



The coupling is extracted from the *X* decay width into *DD** components; yet the binding energy is too low.

X at LHCb

LHCb arXiv:1404.0275

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\,\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 3.4 \pm 1.4$$

"…The measured value agrees with expectations for a pure charmonium interpretation of the X(3872) state and a mixture of charmonium and molecular interpretations. However, it does not support a pure DD* molecular interpretation of the X(3872) state …"

yet I wuold continue, citing Eichten, Lane & Quigg hep-ph/0511179

" …but the mass of X (3872) is too low to be gracefully identified with the 2^3P_1 charmonium state, especially if Z(3931) is to be identified as the 2^3P_2 level…"

btw charmonium violating isospin?…

Imperfect Matchings

The matchings shown above are valid only with *neutral* components though.
We know that the *two* following *thresholds do not match*

$$D^{\pm}\bar{D}^{*0}\ (\mathrm{or}\ D^0\bar{D}^{*\pm}) \neq J/\psi\ \rho^{\pm}$$

being that

$$m_{D^{\pm}} - m_{D^0} \approx 4.8 \pm 0.1\ \mathrm{MeV}$$
$$m_{D^{*\pm}} - m_{D^{*0}} \approx 3.3 \pm 0.3\ \mathrm{MeV}$$

Also the *D^+D^{*-}* threshold is pretty far away

$$m_{D^+D^{*-}} - m_{D^0\bar{D}^{*0}} \approx 8\ \mathrm{MeV}$$

According to this last fact, we someone concluded e.g. that the dd* component in the *X* has to be suppressed so that the *X cannot be a pure I=0 state* and this might be the seed of observed isospin violations. On the other hand the Z_c should be a *pure I=1* state and should not violate isospin as in $Z_c \to J/\psi\ \eta$ (not forbidden in 4q models).

Quantum Numbers

Let's refer to $Z_c^0(3900)$. It is a 1^{+-} particle. A simple way of building it is the following. Take two colored *positive parity* bosons (*diquarks*) in S-wave (L=0).

$$|s_{Qq}, s_{\bar{Q}\bar{q}}, S\rangle = |1_{cq}, 1_{\bar{c}\bar{q}}, 1\rangle$$

Indeed exchanging coordinates, spins and charges, in this two boson system we can make *C=-1*

$$(-1)^L(-1)^{2s+S}C = +1 \Rightarrow C = -1$$

Another *C=-1* state can be formed by taking simply

$$|1_{cq}, 0_{\bar{c}\bar{q}}, 1\rangle - |0_{cq}, 1_{\bar{c}\bar{q}}, 1\rangle$$

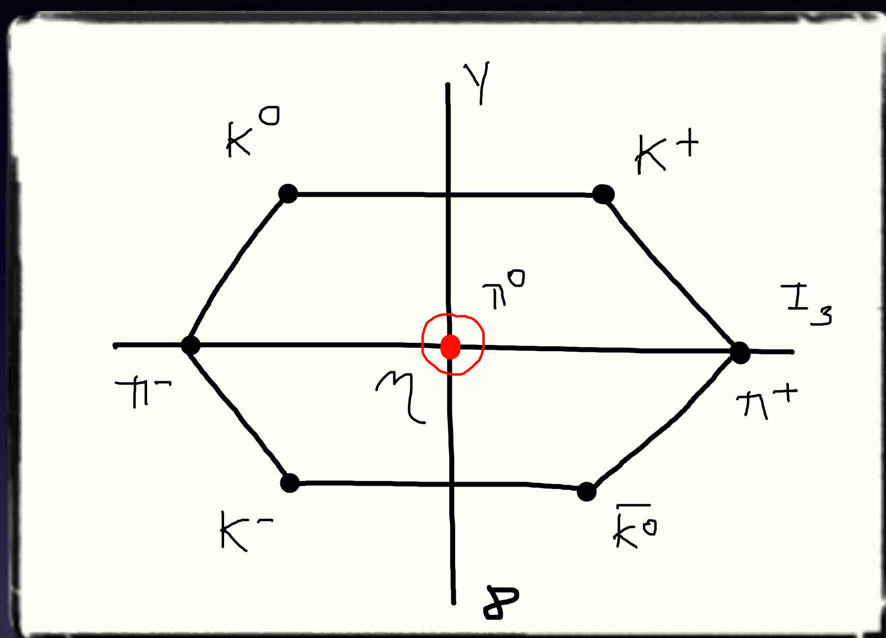
Thus we got two *$J^{PC}=1^{+-}$* states, and automatically one *$J^{PC}=1^{++}$* state

$$|1_{cq}, 0_{\bar{c}\bar{q}}, 1\rangle + |0_{cq}, 1_{\bar{c}\bar{q}}, 1\rangle$$

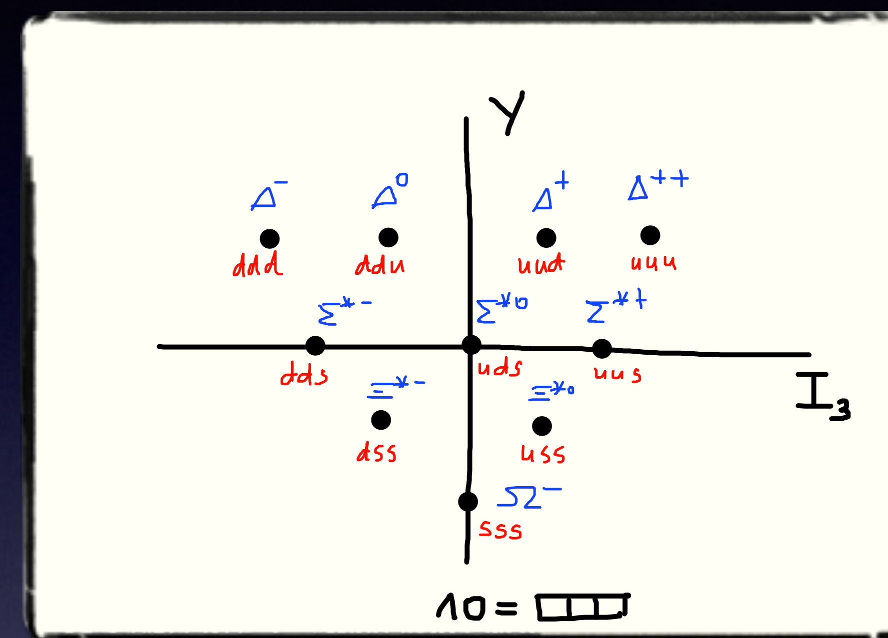
The latter could simply be the X(3872) the first one; discovered back in 2003

Eightfold Way

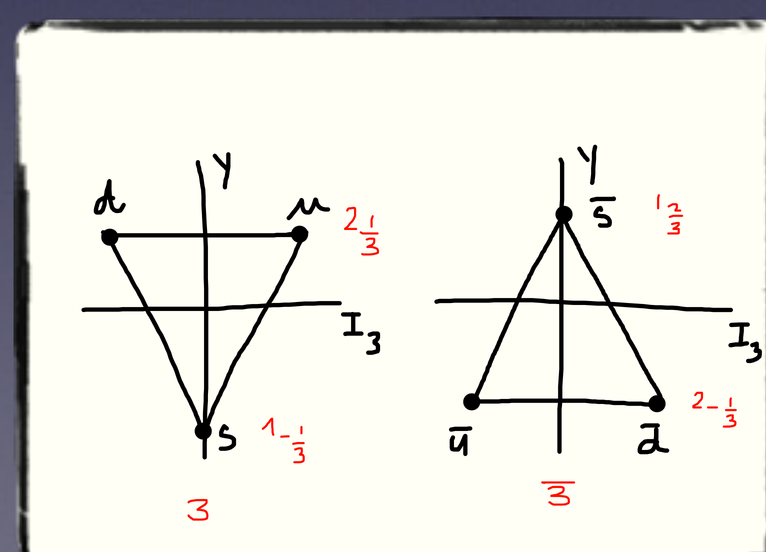
50 years of quark model



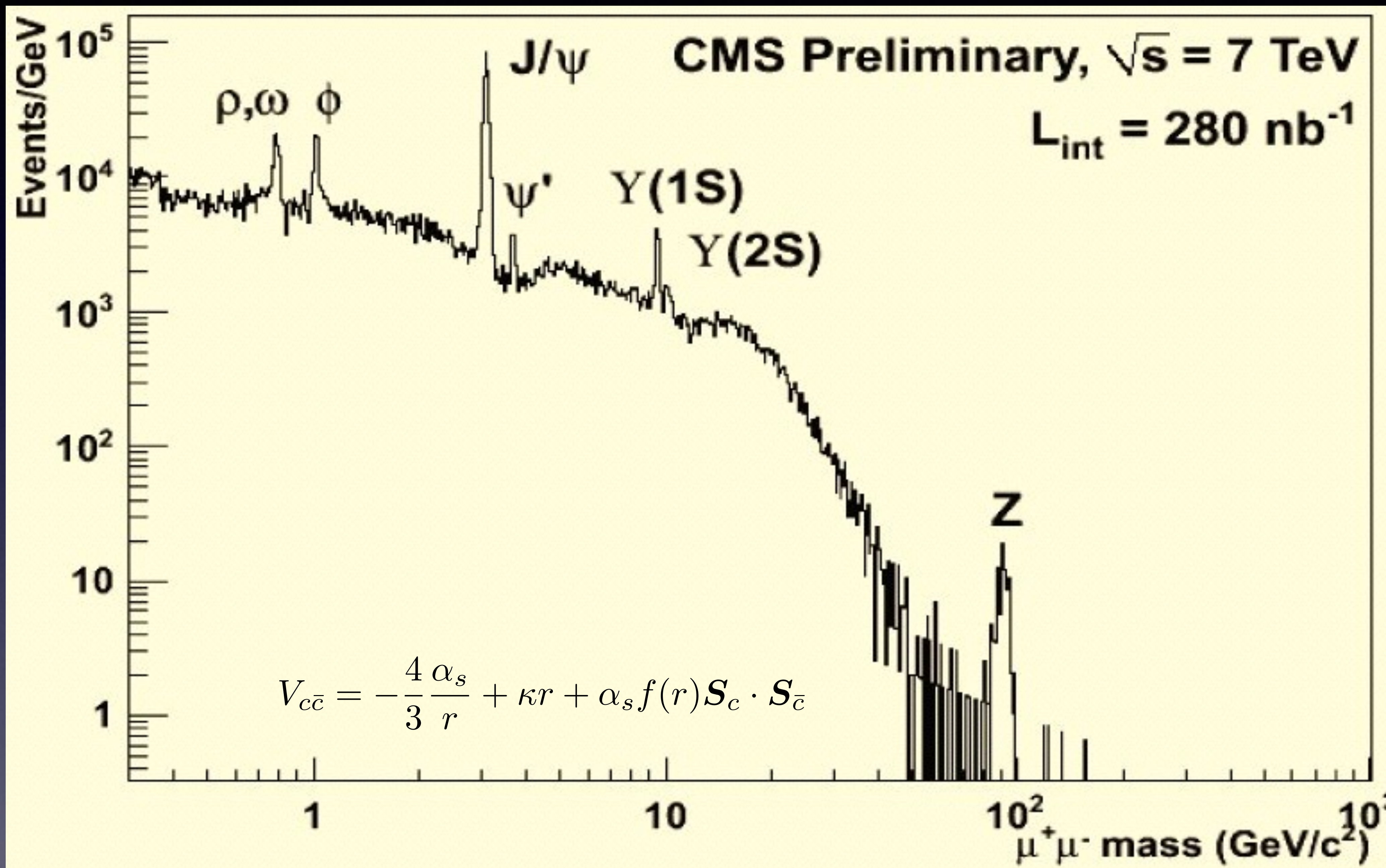
diagonalize simultaneously $T^3_{\mathbf{8}}, T^8_{\mathbf{8}}$



diagonalize simultaneously $T^3_{\mathbf{10}}, T^8_{\mathbf{10}}$

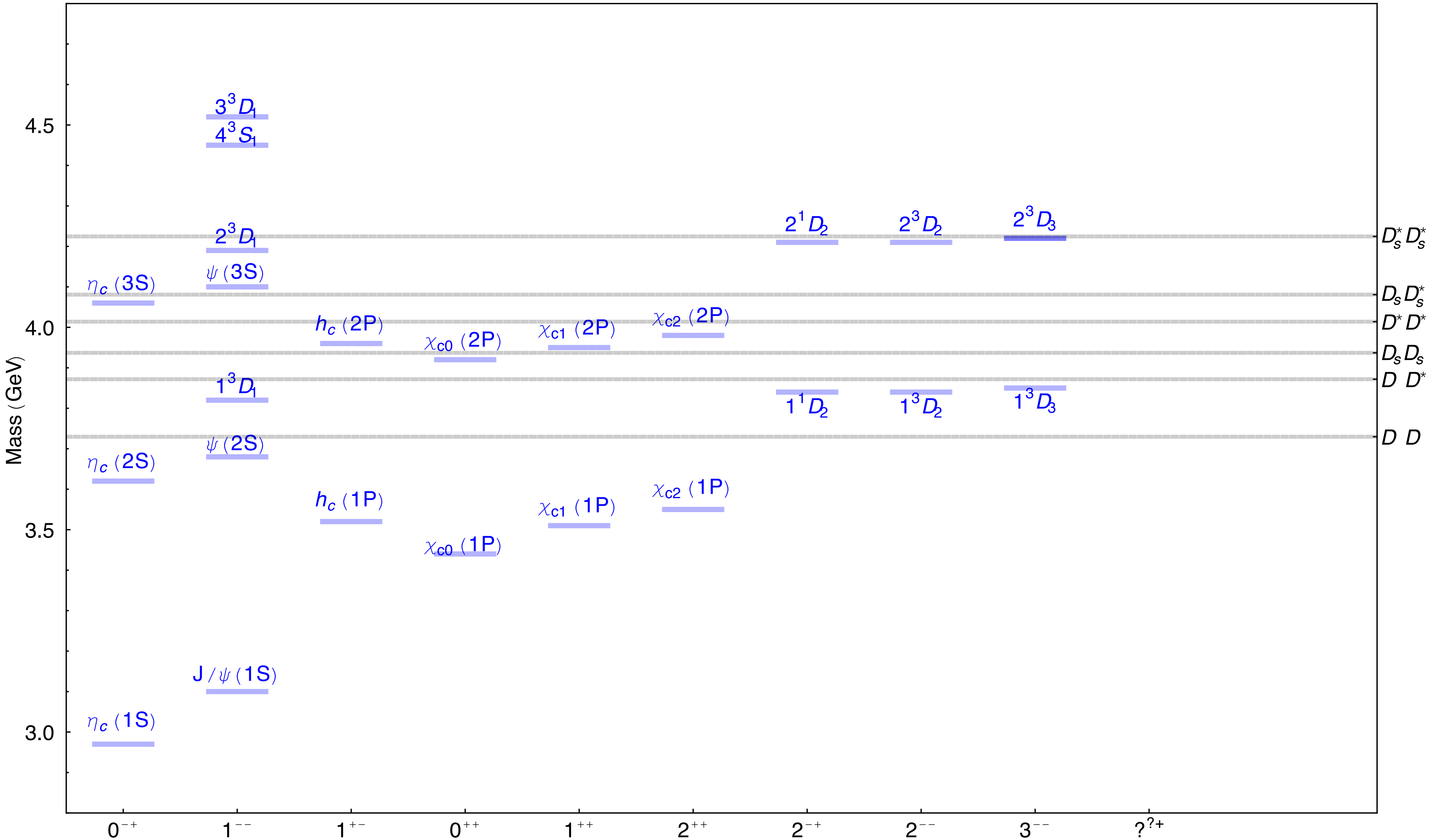


Three quarks in the fundamental. The list of *elementary* particles gets much shorter…

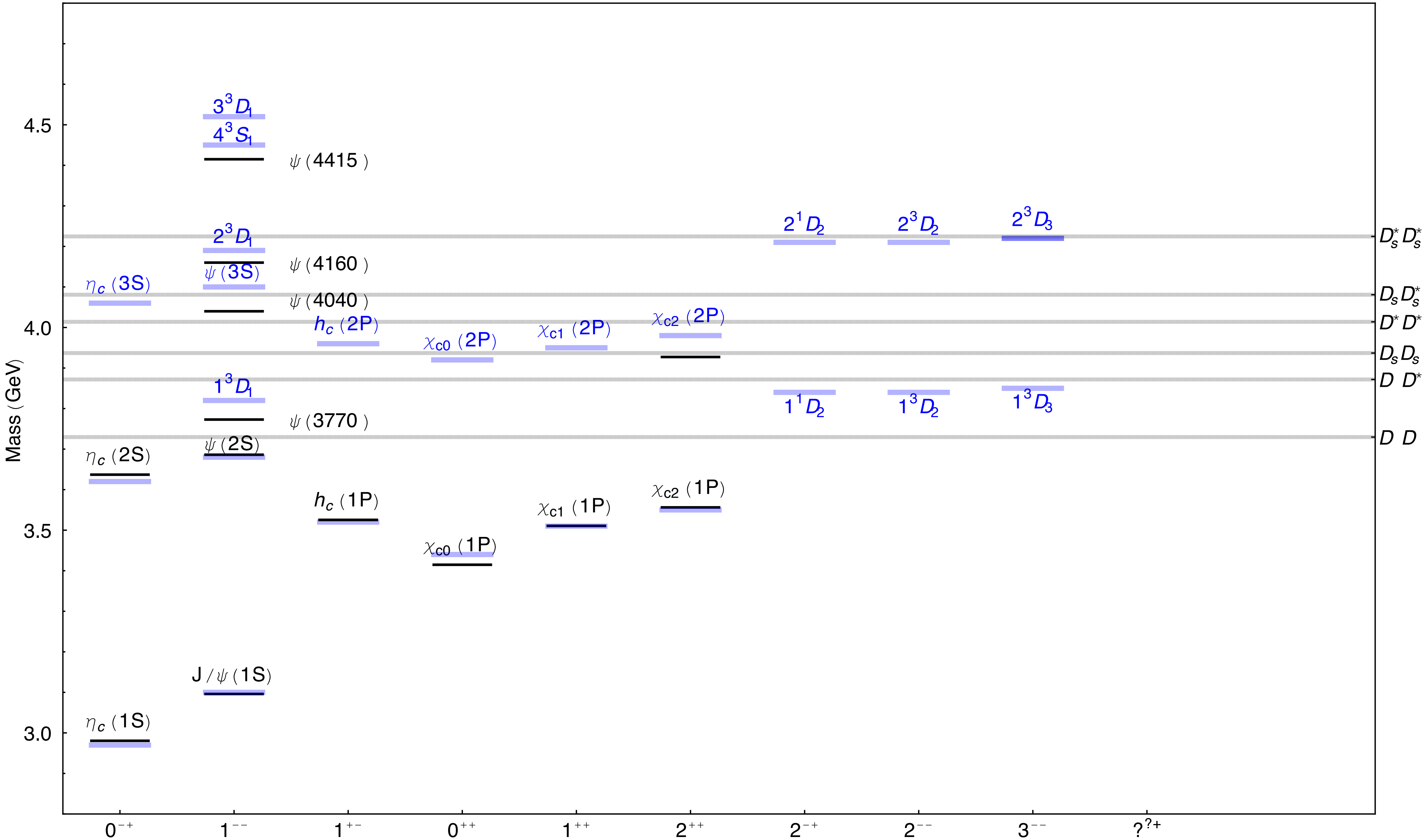


$$V_{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r + \alpha_s f(r) \boldsymbol{S}_c \cdot \boldsymbol{S}_{\bar{c}}$$

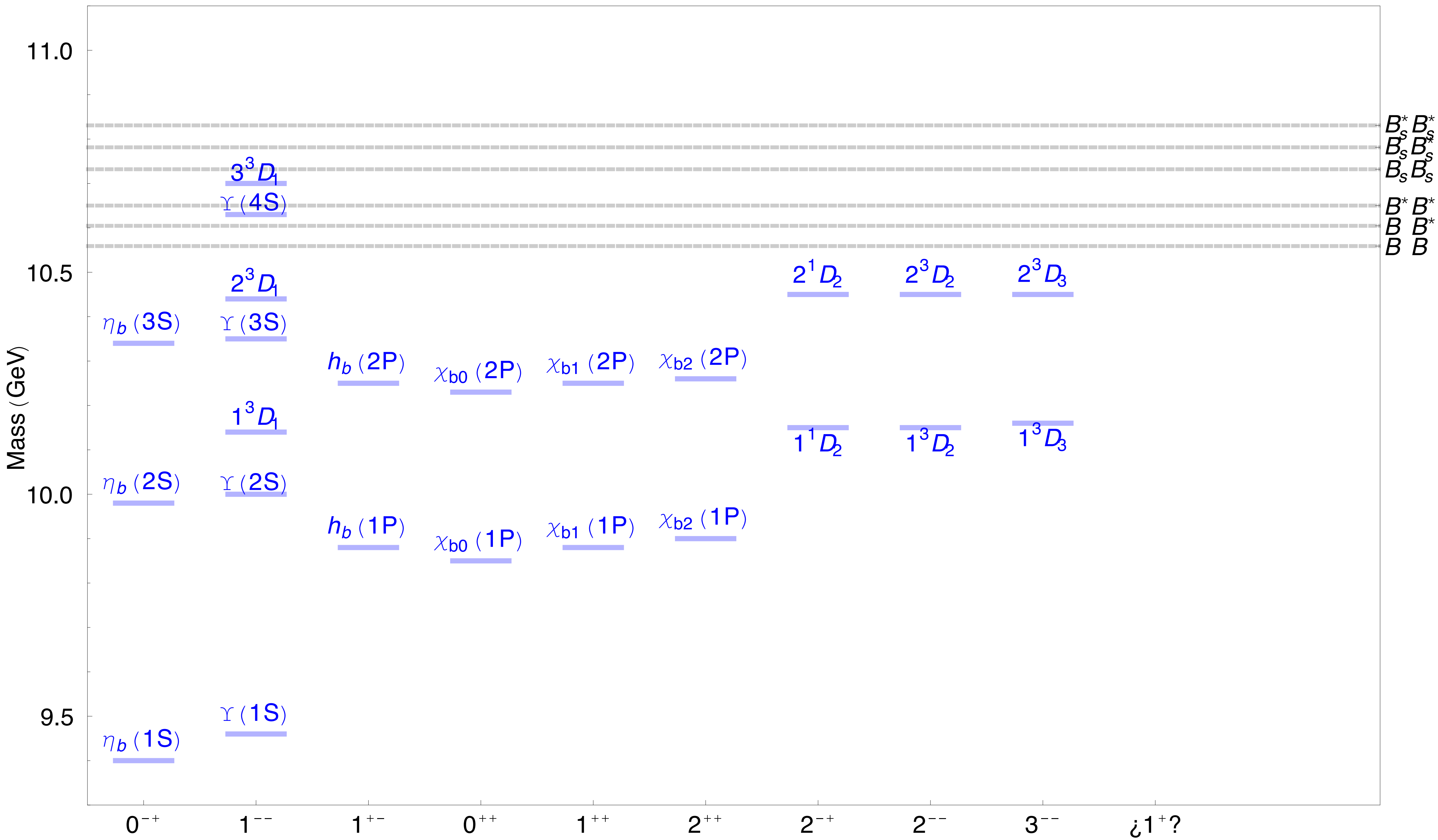
Charmonium Predictions



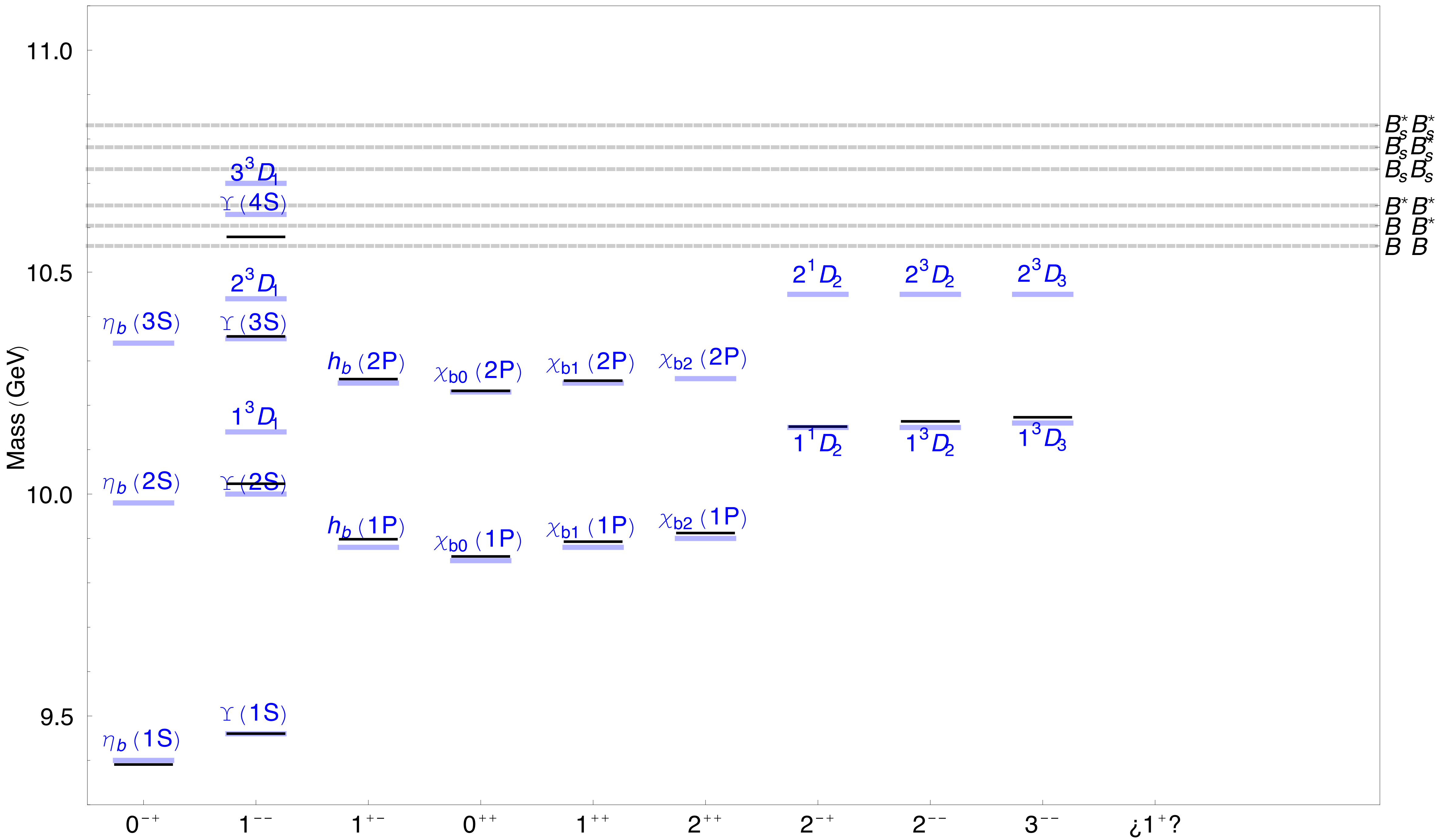
Charmonium Levels



Bottomonium Predictions



Bottomonium Levels



Diquarks

$$[cq]_i = \epsilon_{ijk}\bar{c}^j_{\boldsymbol{c}}\gamma_5 q^k \quad \text{spin } 0$$

$$[cq]_i = \epsilon_{ijk}\bar{c}^j_{\boldsymbol{c}}\boldsymbol{\gamma} q^k \quad \text{spin } 1$$

$|s, \bar{s}\rangle_J$ notation

$$|0,1\rangle_1 := \frac{1}{2}\sigma^2 \otimes \sigma^2\sigma^i$$

$$|1,0\rangle_1 := \frac{1}{2}\sigma^2\sigma^i \otimes \sigma^2$$

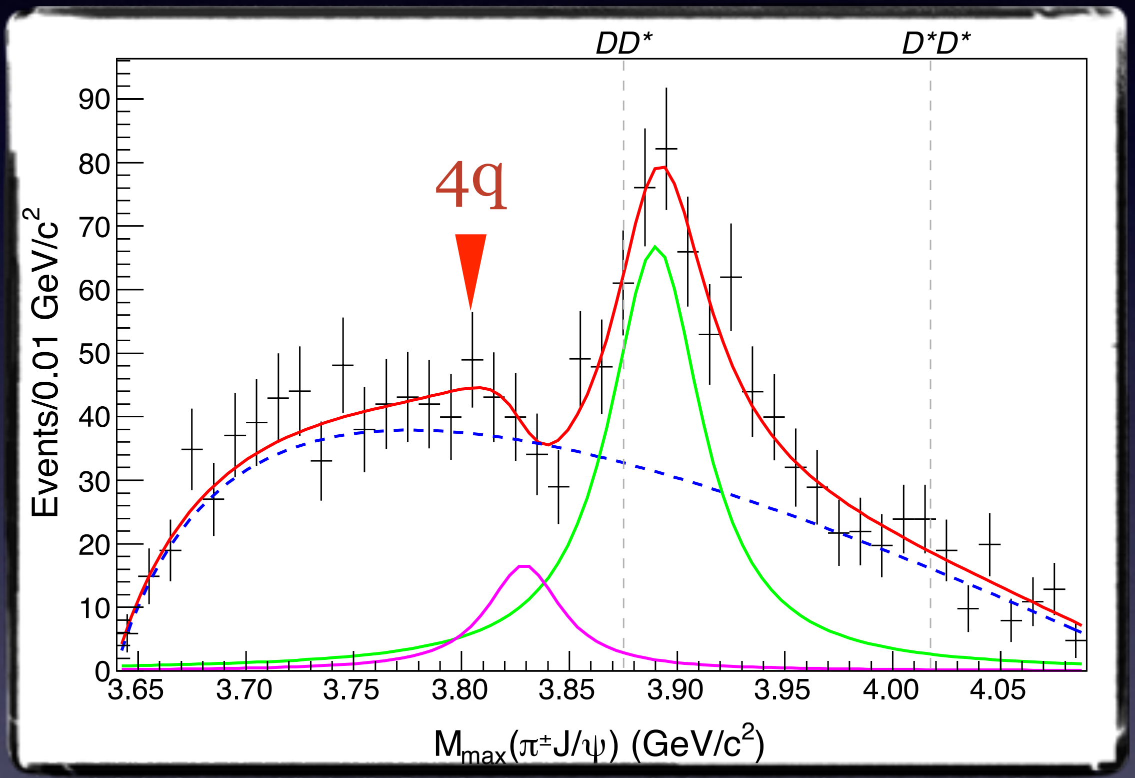
$$|1,1\rangle_0 := \frac{1}{2\sqrt{3}}\sigma^2\sigma^i \otimes \sigma^2\sigma^i$$

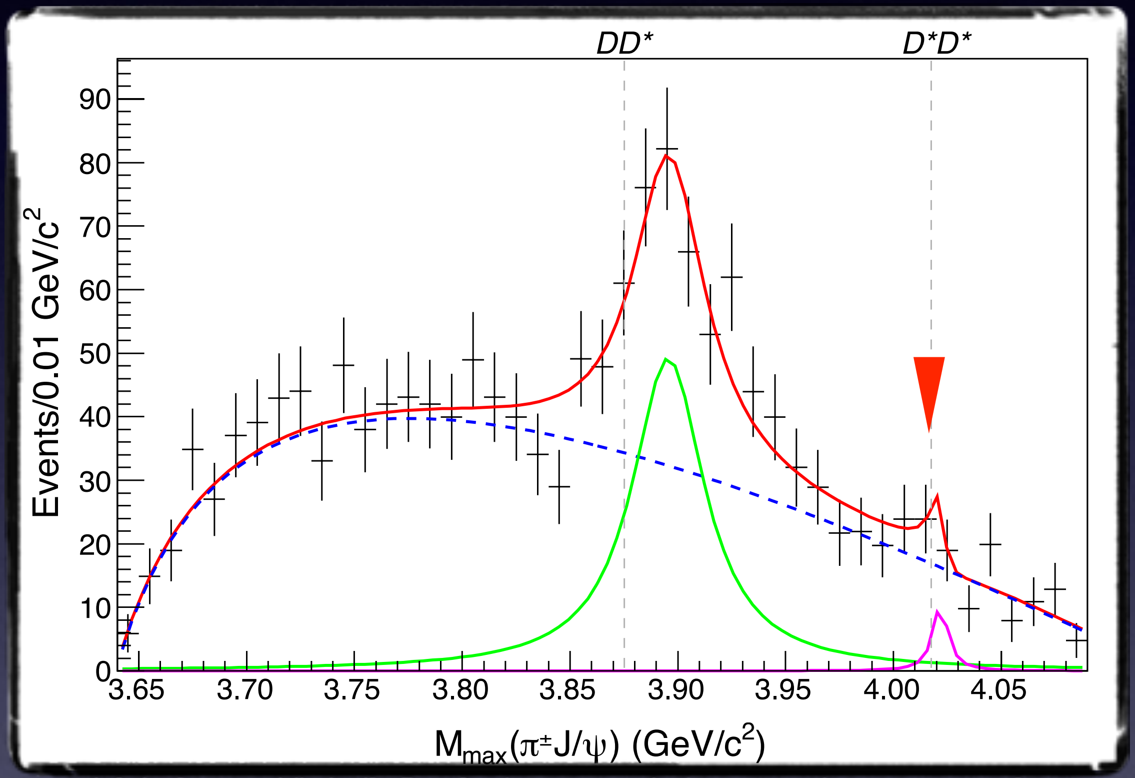
$$|1,1\rangle_1 := \frac{i}{2\sqrt{2}}\epsilon^{ijk}\sigma^2\sigma^j \otimes \sigma^2\sigma^k$$

...

Before $Z_c(4025)$ was found

Maiani, Piccinini, ADP, Riquer, PRD 2013 — type I model





Fit with <u>two</u> resonances with no further constraints. The second structure is a fluctuation P=12%

$$\chi^2/\mathrm{dof} = 41/65$$

Fit with <u>two</u> resonances with M(Z')>M(Z). The second structure is a fluctuation P=53%

$$\chi^2/\mathrm{dof} = 47/65$$

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.

Quark-antiquark spin basis

$$|s_{q\bar{q}}, s_{c\bar{c}}\rangle_J$$

$$X_0 = \frac{1}{2}|0_{q\bar{q}}, 0_{c\bar{c}}\rangle_0 + \frac{\sqrt{3}}{2}|1_{q\bar{q}}, 1_{c\bar{c}}\rangle_0,$$

$$X_0' = \frac{\sqrt{3}}{2}|0_{q\bar{q}}, 0_{c\bar{c}}\rangle_0 - \frac{1}{2}|1_{q\bar{q}}, 1_{c\bar{c}}\rangle_0$$

$$X_1 = |1_{q\bar{q}}, 1_{c\bar{c}}\rangle_1$$ decays into J/ψ

$$Z = \frac{1}{\sqrt{2}}\left(|1_{q\bar{q}}, 0_{c\bar{c}}\rangle_1 - |0_{q\bar{q}}, 1_{c\bar{c}}\rangle_1\right)$$

$$Z' = \frac{1}{\sqrt{2}}\left(|1_{q\bar{q}}, 0_{c\bar{c}}\rangle_1 + |0_{q\bar{q}}, 1_{c\bar{c}}\rangle_1\right)$$

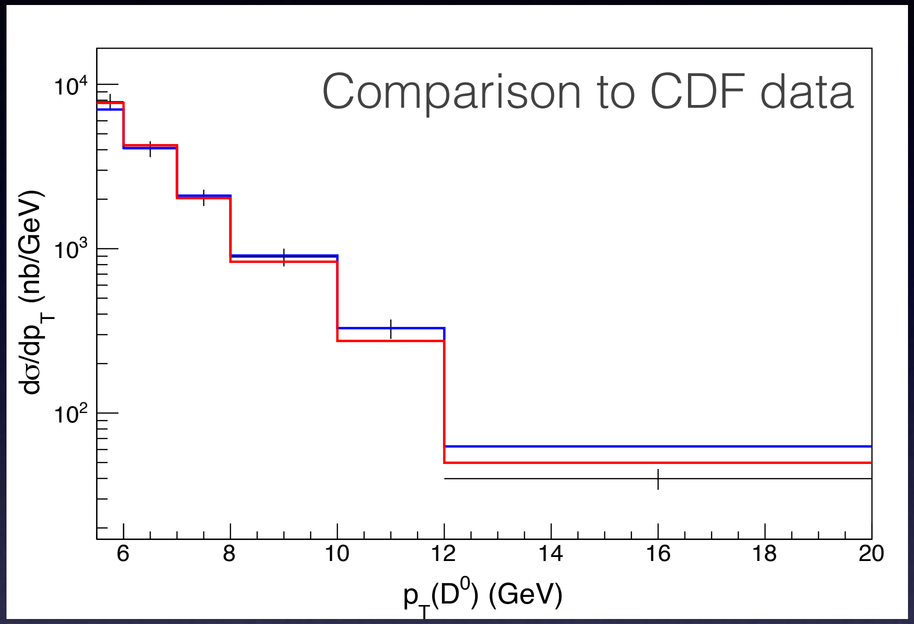
$$X_2 = |1_{q\bar{q}}, 1_{c\bar{c}}\rangle_2$$

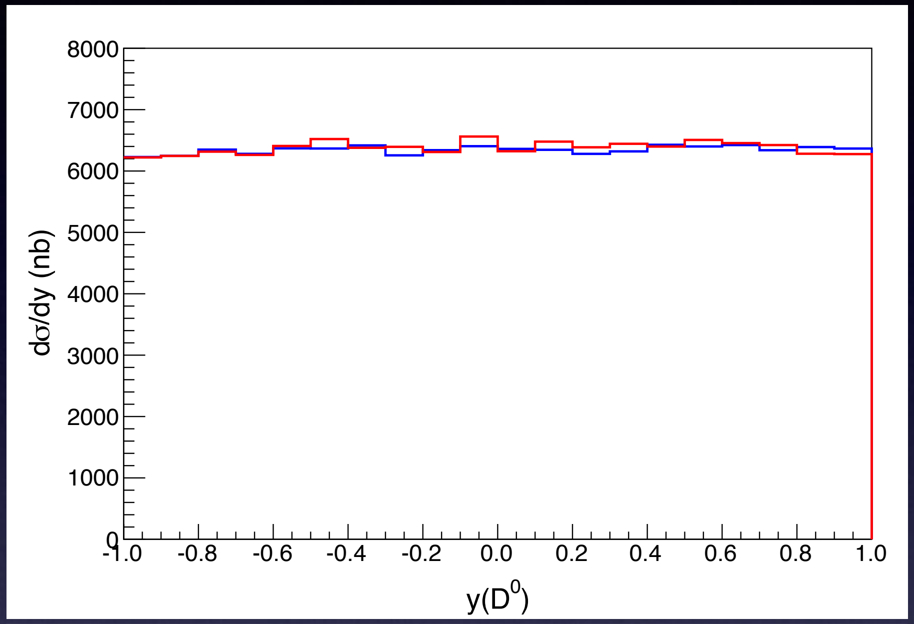
Seince in type II the mass eigenvectors correspond to those listed before, we can 'Fierz' them in the quark-antiquark spin basis, and realize that both Z and Z' have also a spin 0 component in agreement with the observed

$$Z(4020) \to \pi + h_c(1^1P_1),\ \text{seen}$$

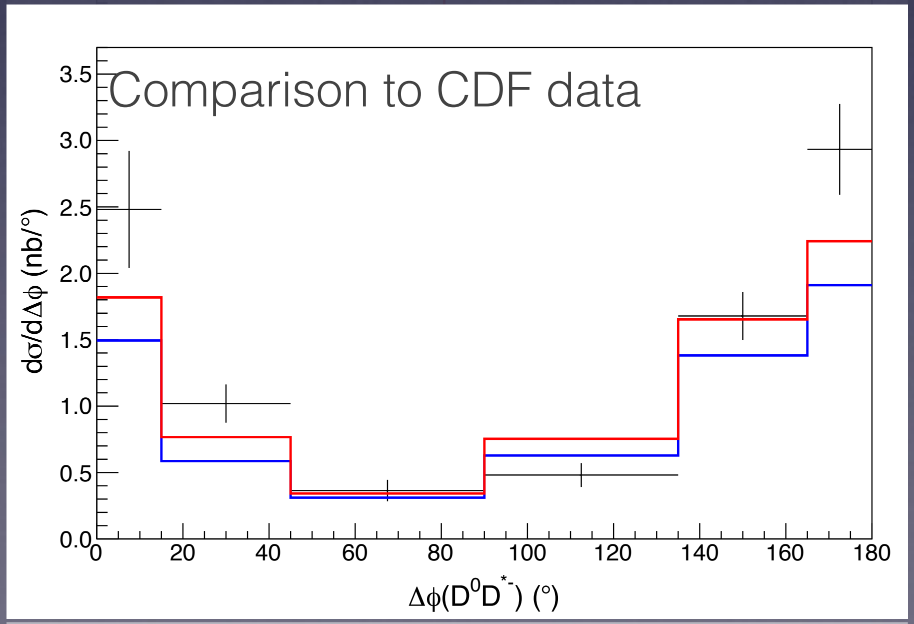
$$Z(3900) \to \pi + h_c(1^1P_1),\ \text{seen (?)}$$

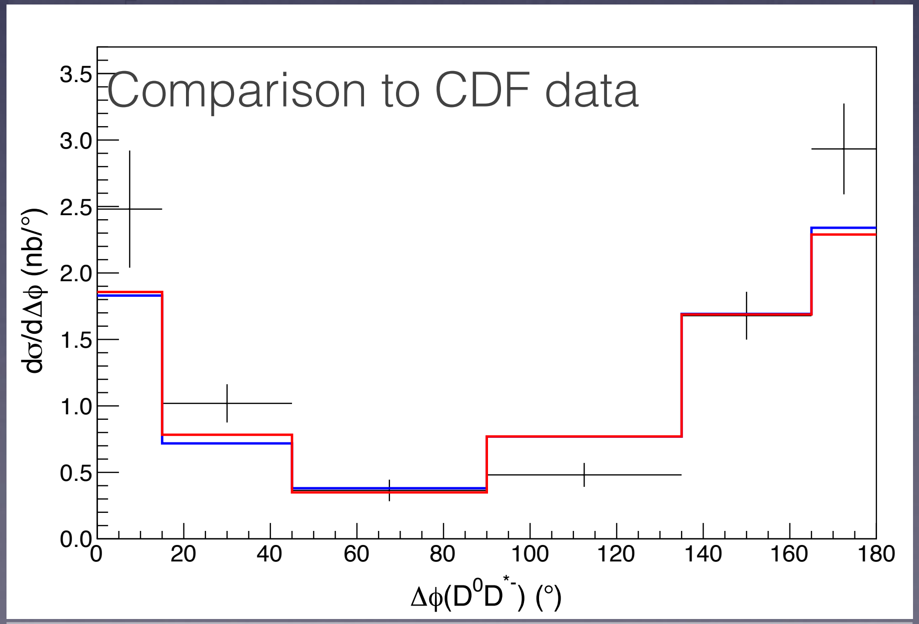
The 1π Correction





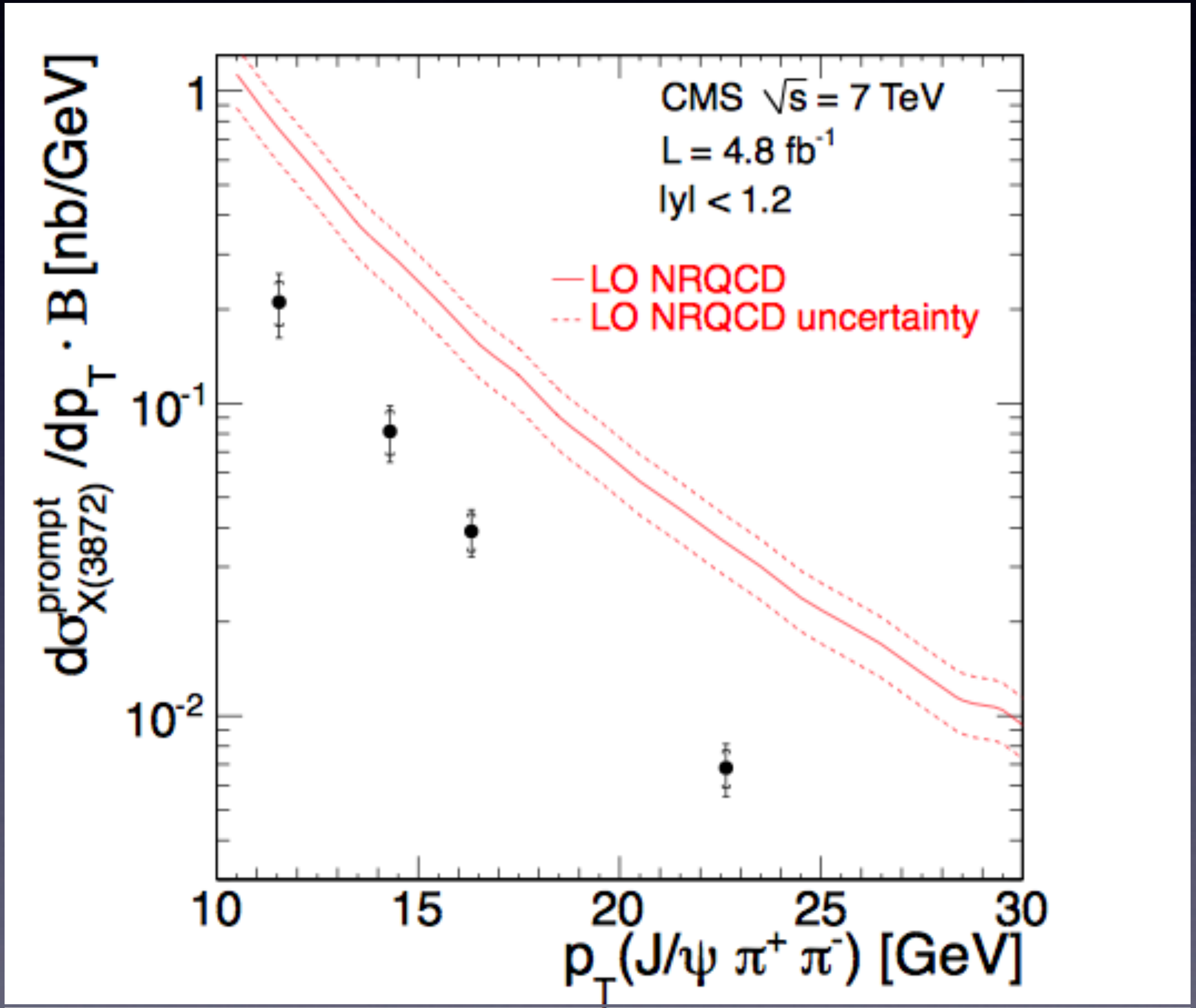
red: 1 pion
blue: 0 pions





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

X at LHC (CMS data)



Braaten & Artoisenet arXiv:1007.2868