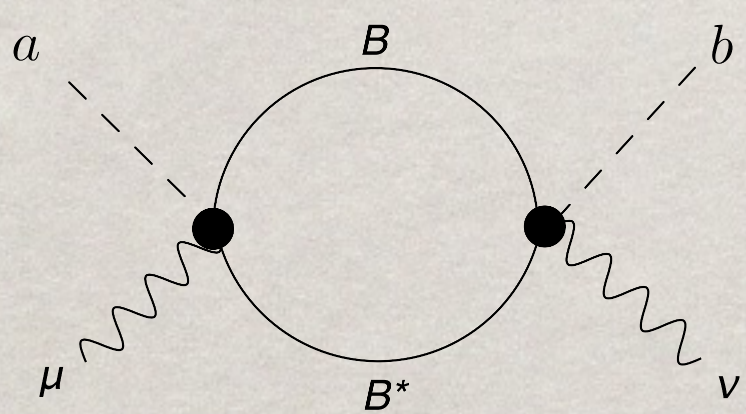
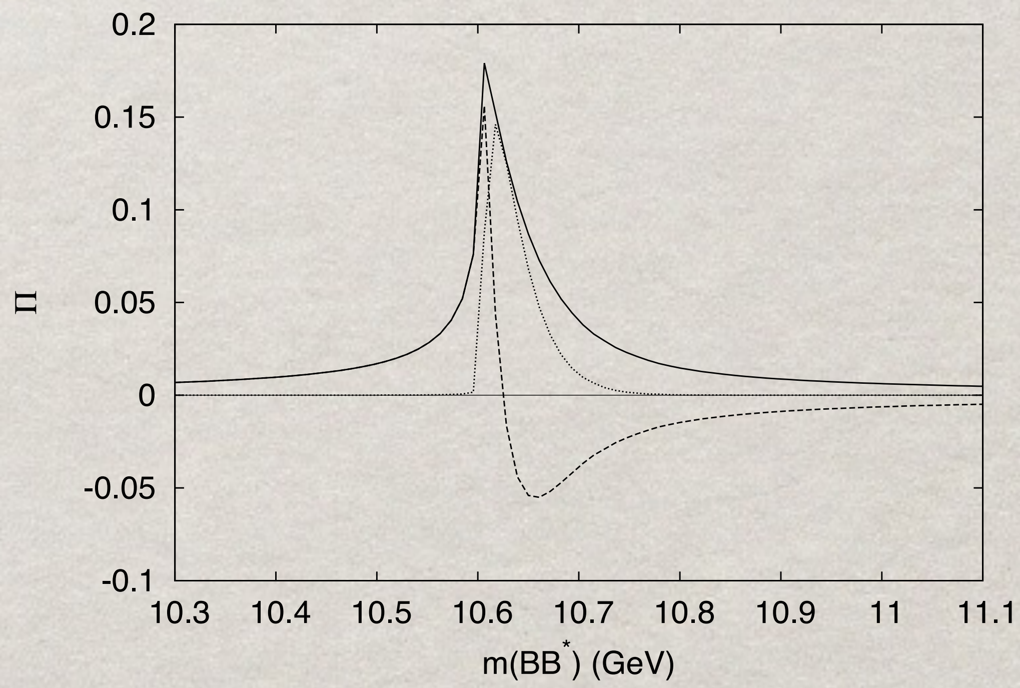
Round table on Z_c and Z_b states (and related issues)…

Eric Swanson [arXiv:1409.6651, arXiv:1409.3291]
Antonello Polosa [arXiv:1405.1551]
Timofey Uglov [arXiv:1408.5295]
Christoph Hanhart
Rudolf Faustov [arXiv:1111.0454]
Roman Mizuk [Belle-II, above 4S running]
Marco Pappogallo [LHCb, Z(4430) + future plans]

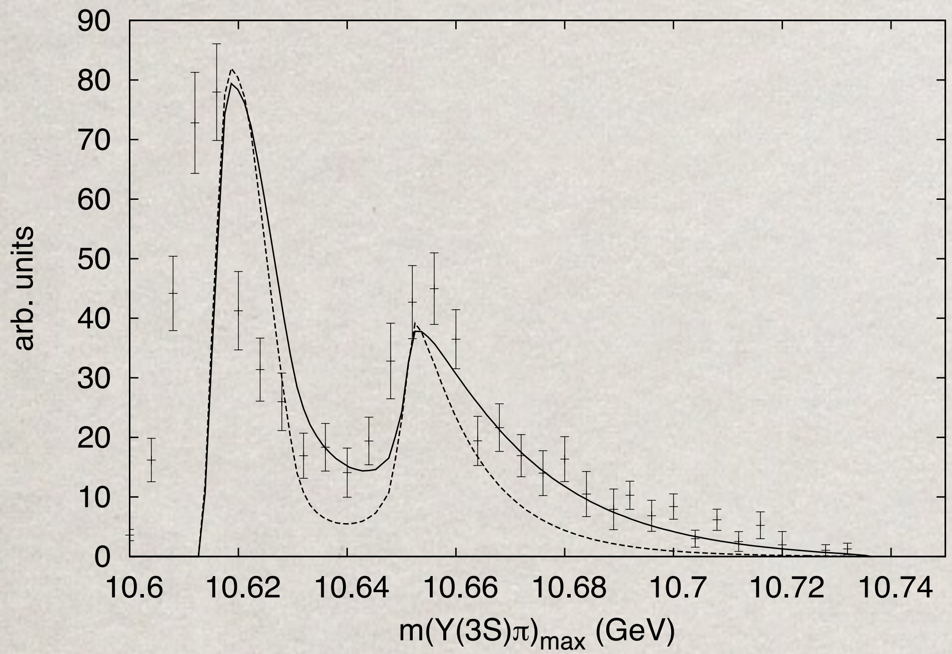
Z_b and Z_c as Threshold Cusps

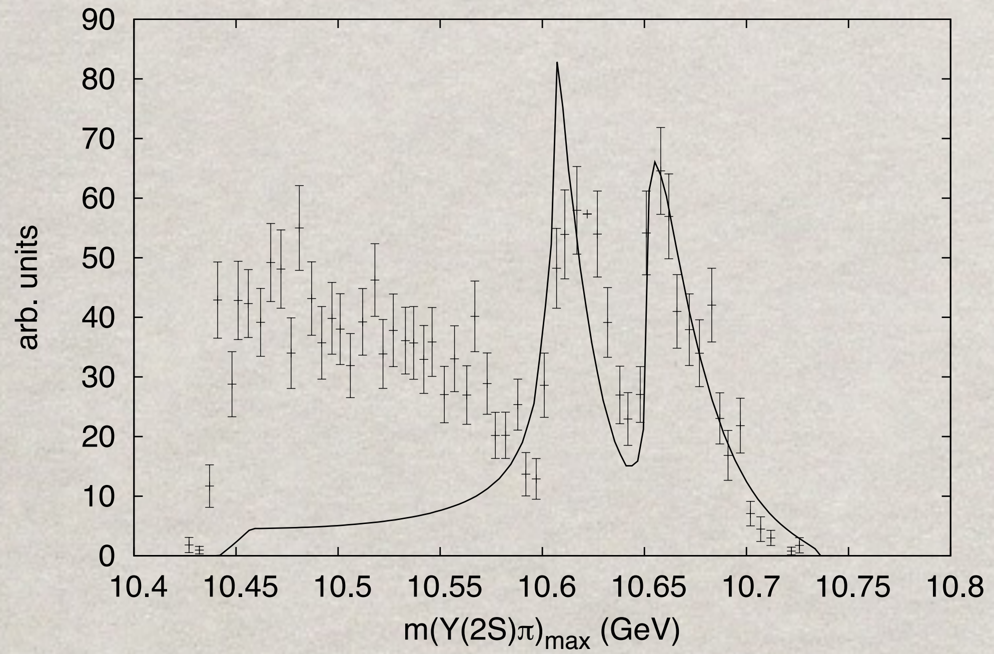
Eric Swanson

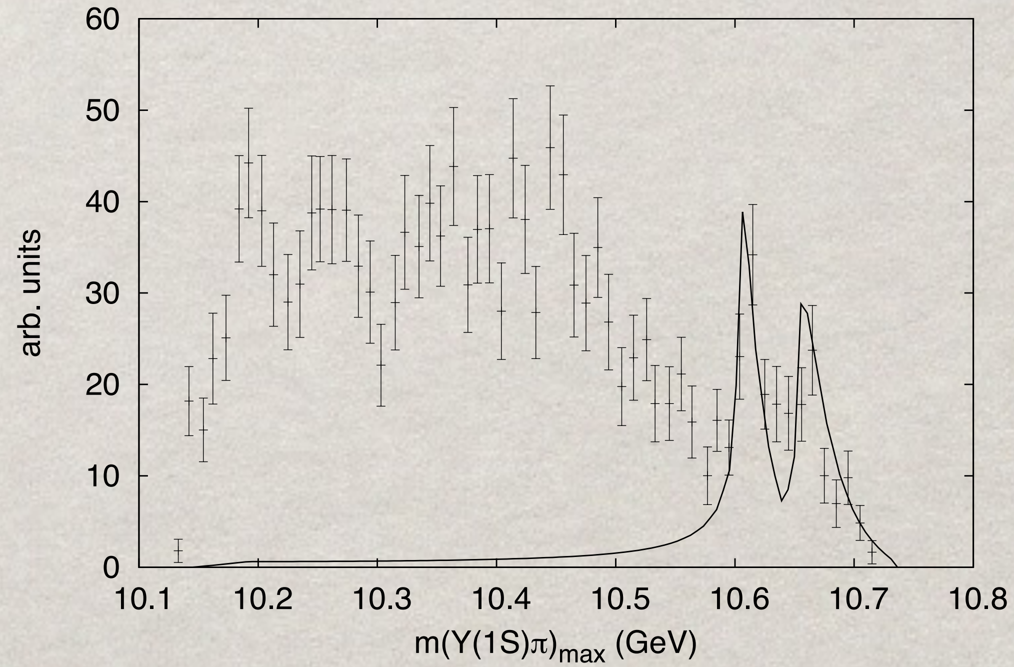




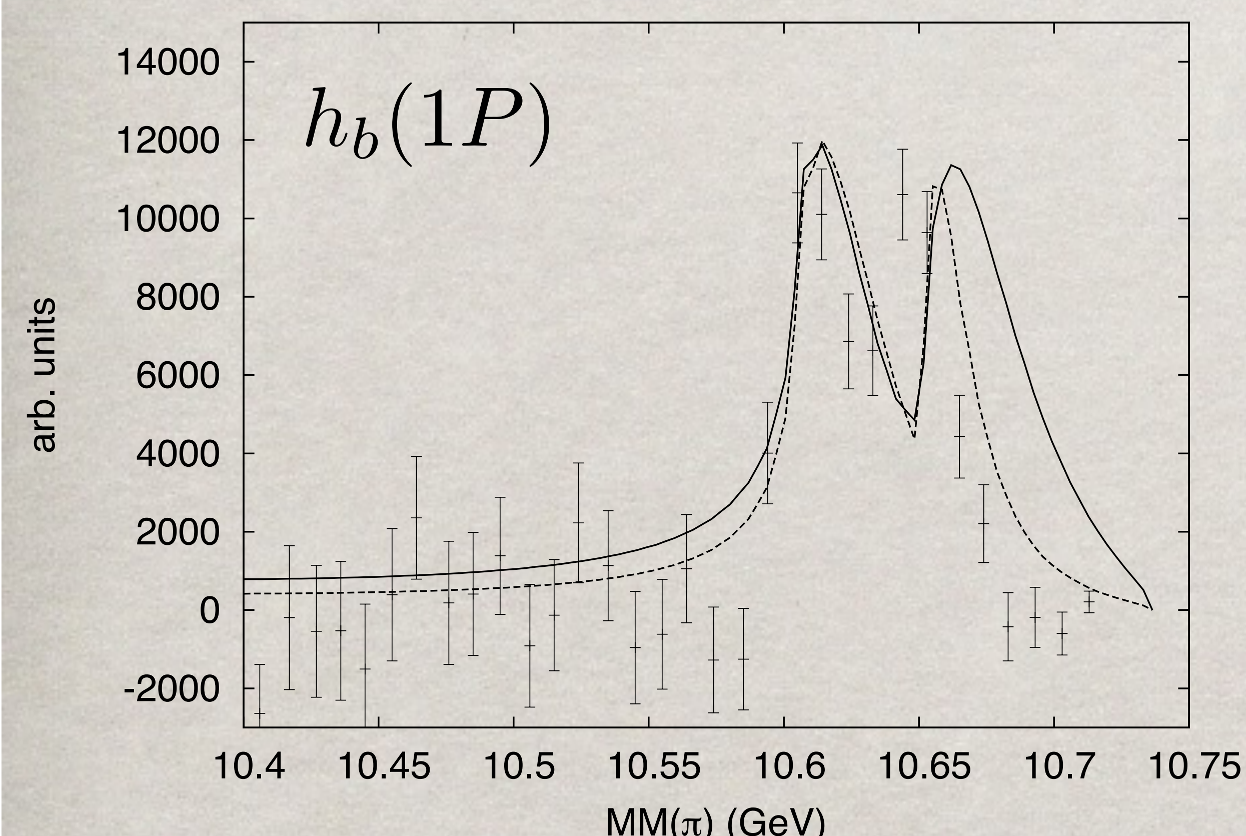
$$\Upsilon(5S) \to \Upsilon(nS)\pi\pi$$

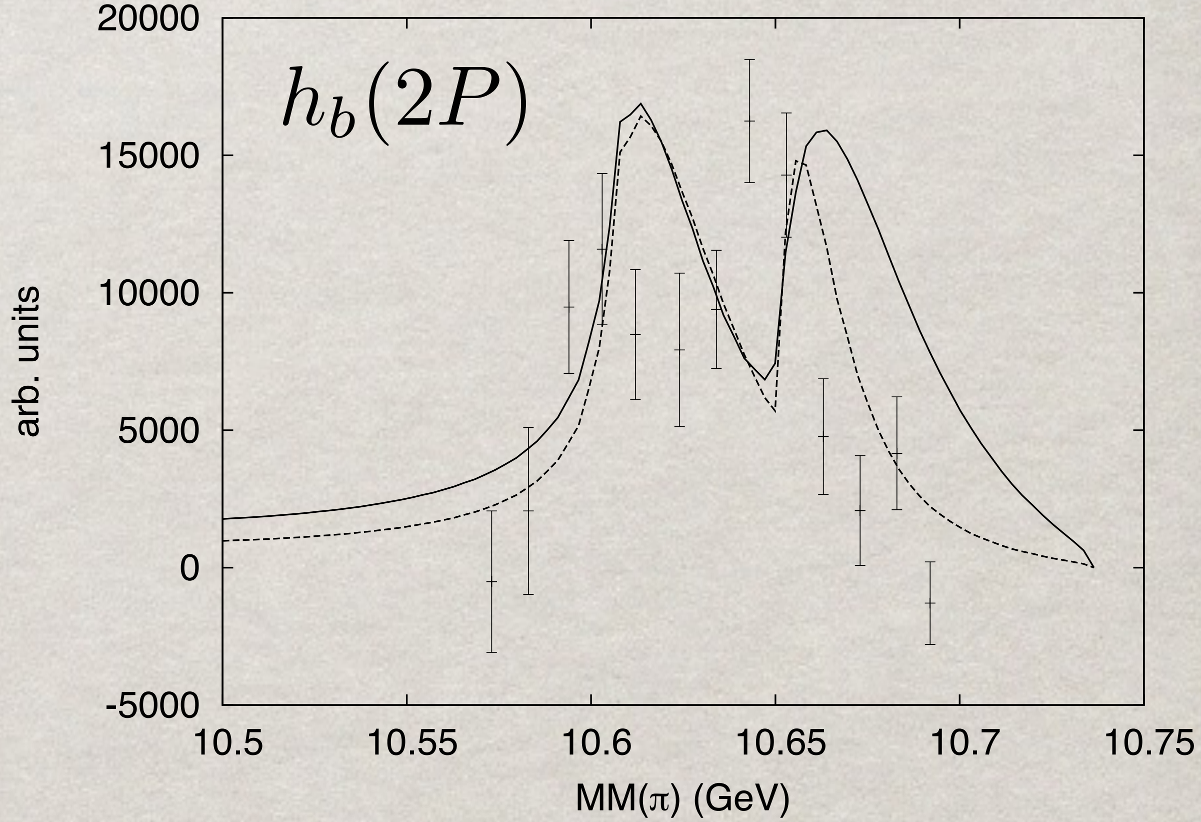




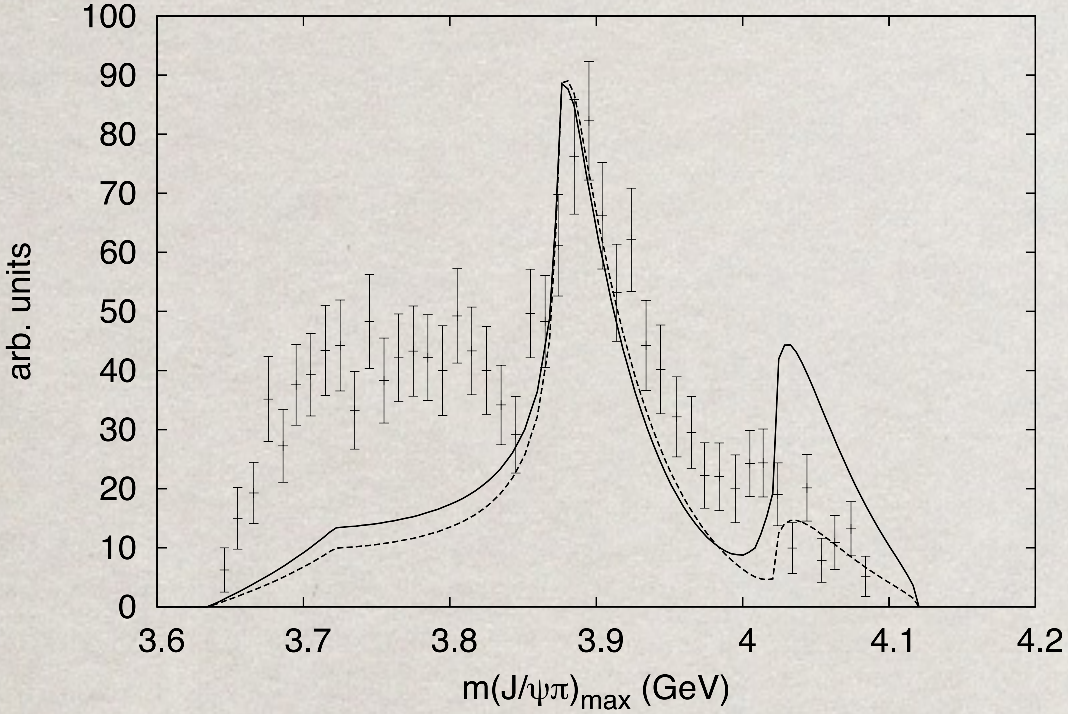


$$\Upsilon(5S) \to h_b(nP)\pi\pi$$

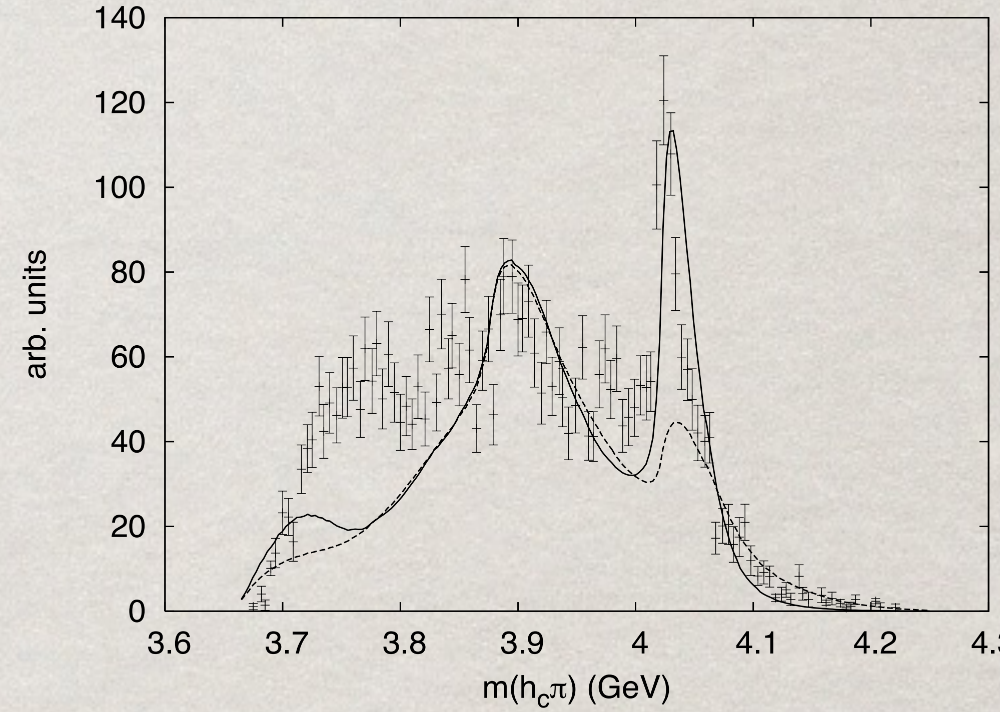


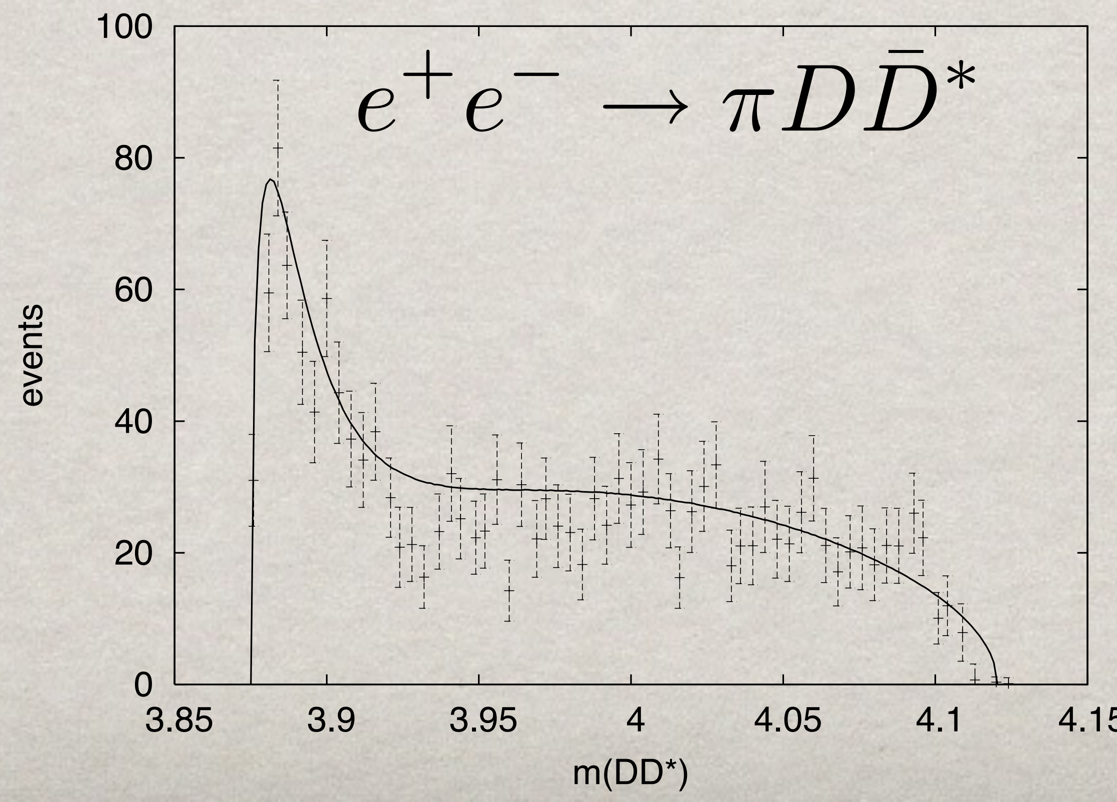


$Y(4260) \rightarrow J/\psi\pi\pi$



$e^+e^- \rightarrow h_c\pi\pi$





Cusp Diagnostics

- lie just above thresholds
- S-wave quantum numbers
- partner states of similar width – widths will depend on channel
- the reaction $\Upsilon(5S) \to K\bar{K}\Upsilon(nS)$ should reveal "states" at 10695 ($B\bar{B}_s^* + B^*\bar{B}_s$) and 10745 ($B^*\bar{B}_s^*$)

Tetraquarks

AD Polosa
Sapienza Università di Roma

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

See Maiani's Talk

Spin

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

Mass

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

$$(H)_{1^{+-}} = \begin{pmatrix} -\kappa & 0 \\ 0 & \kappa \end{pmatrix}$$

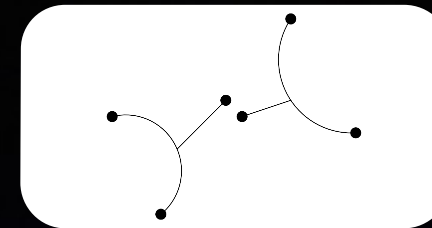
$$(H)_{1^{++}} = -\kappa$$

$$(H)_{2^{++}} = \kappa$$

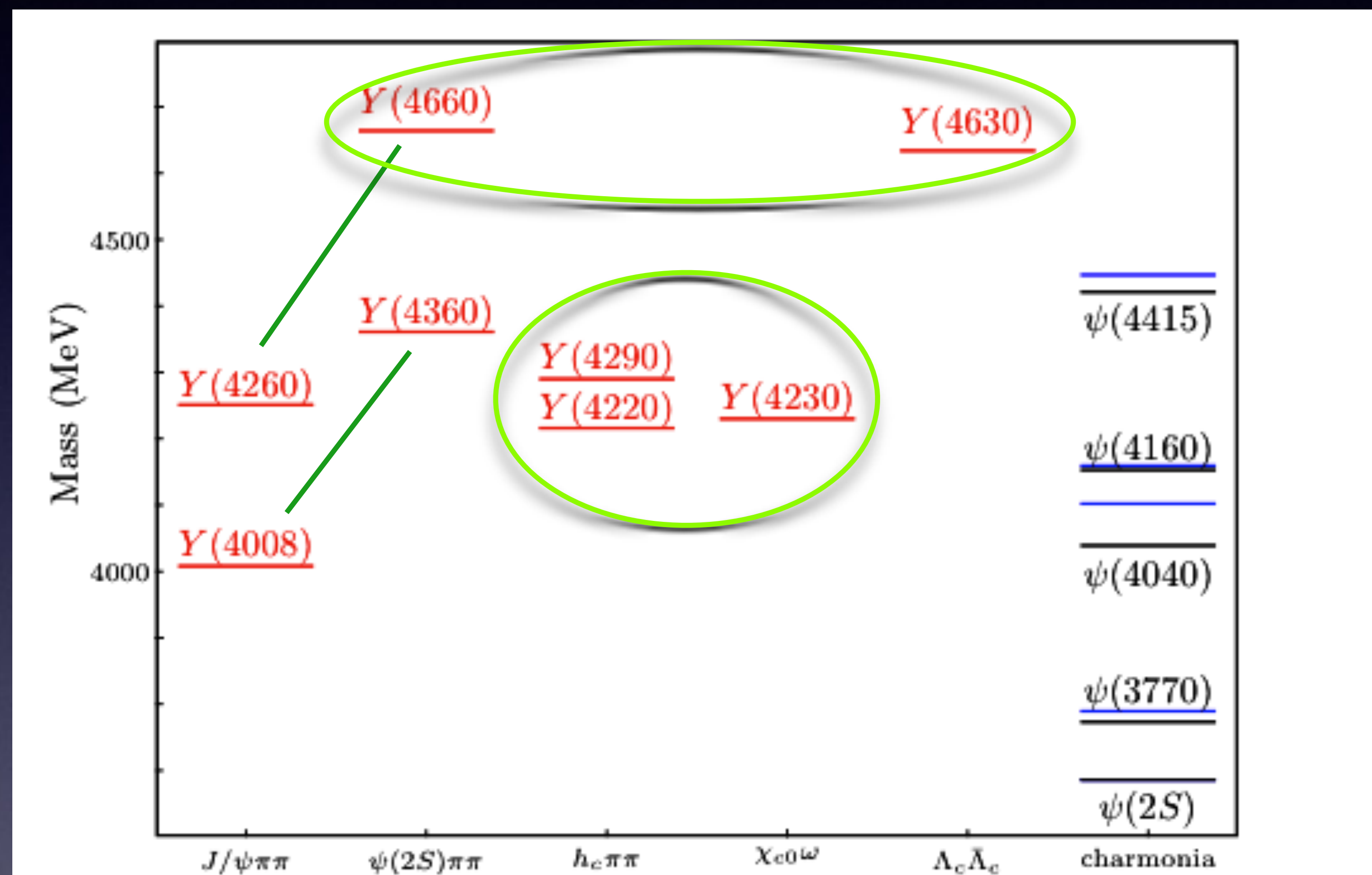
$$(H)_{0^{++}} = -3\kappa$$

$$(H)_{0^{++\prime}} = \kappa$$

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



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



Negative parity (L=1)

Spin (dq basis)

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

$$Y_2 = \frac{|1,0\rangle + |0,1\rangle}{\sqrt{2}}$$ Like the X; Mass difference due to L

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

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

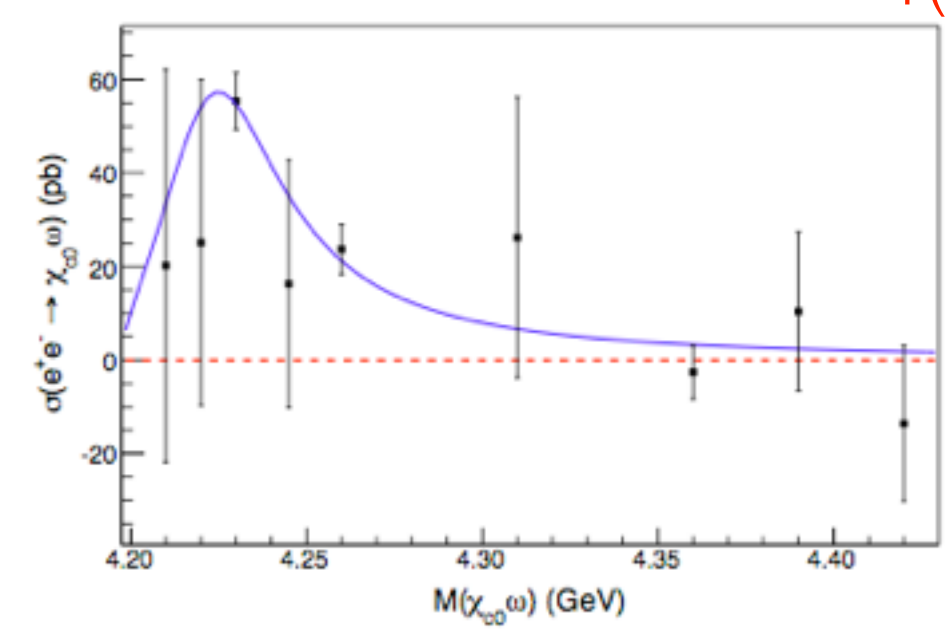
State	$P(S_{c\bar{c}}=1) : P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
Y_1	3:1	$Y(4008)$	$\gamma + X_0$
Y_2	1:0	$Y(4260)$	$\gamma + X$
Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
Y_4	1:0	$Y(4630)$	$\gamma + X_2$

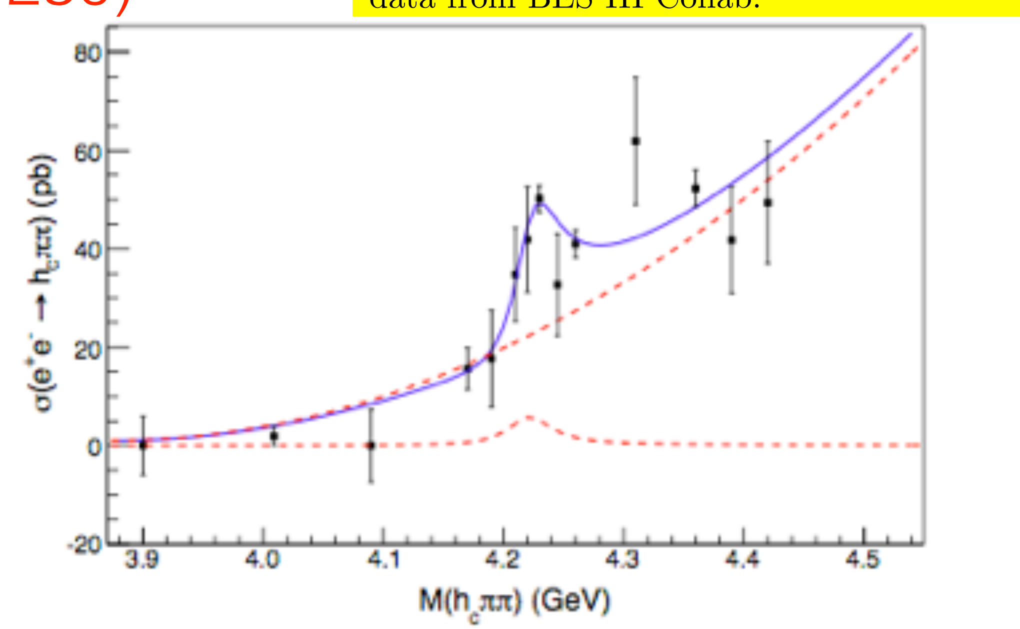
We identify Y(4360) and Y(4660) decaying into ψ(2S)π as radial excitations of Y(4008) and Y(4260).

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.

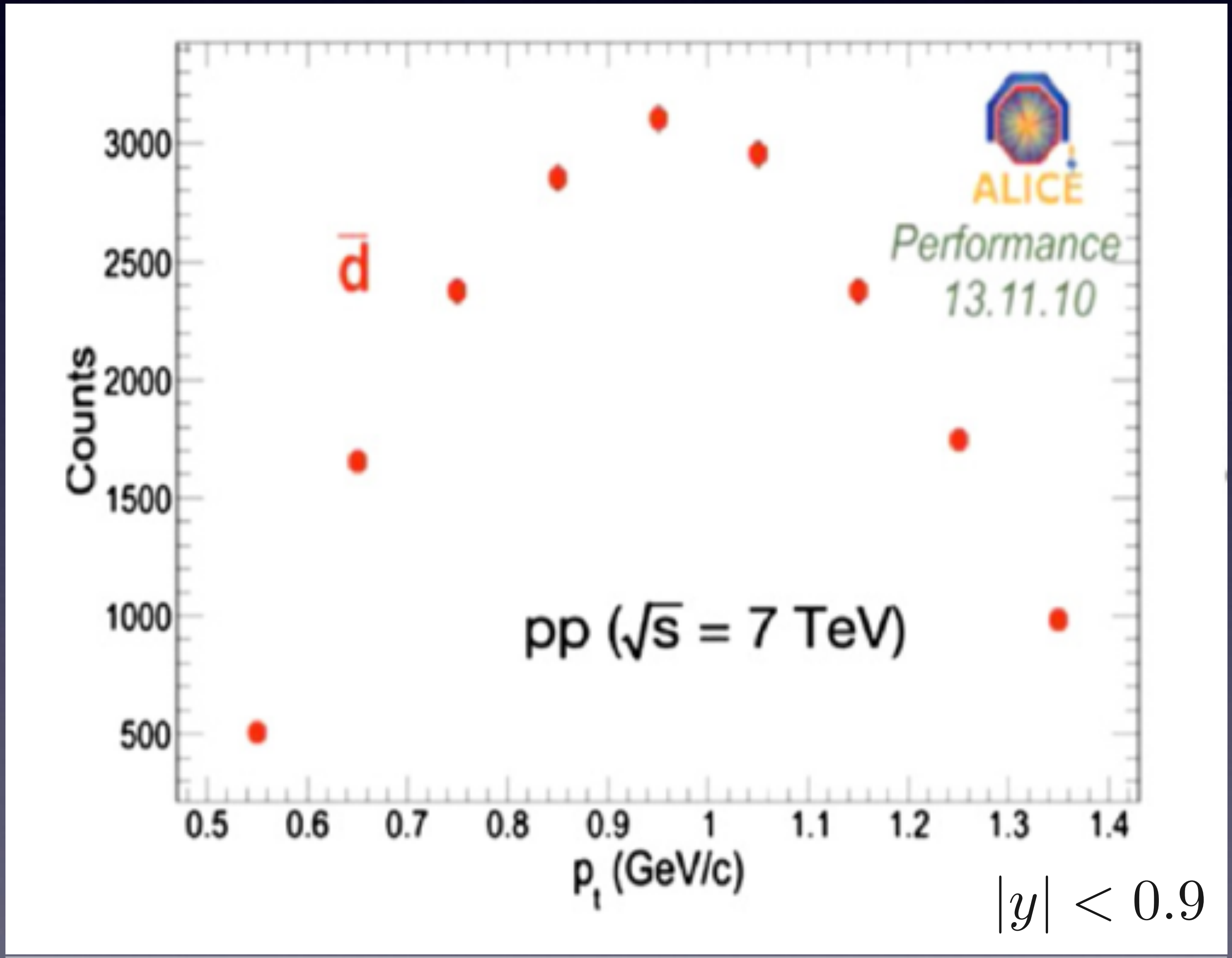




See Pilloni's talk

Anti-deuteron at LHC?

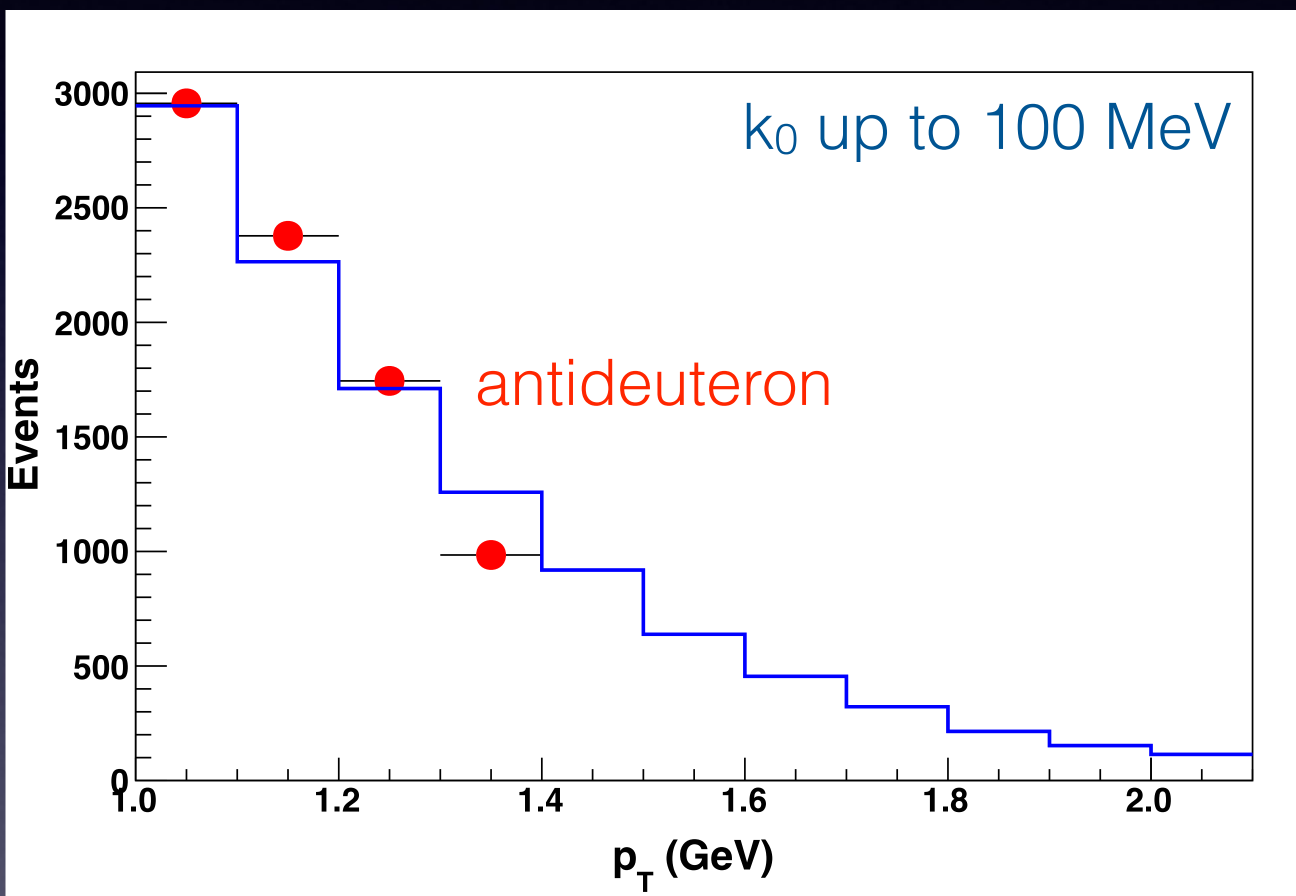
A lot!!…
Indeed Alice has 30K antideuterons.
— In which p_T range though?

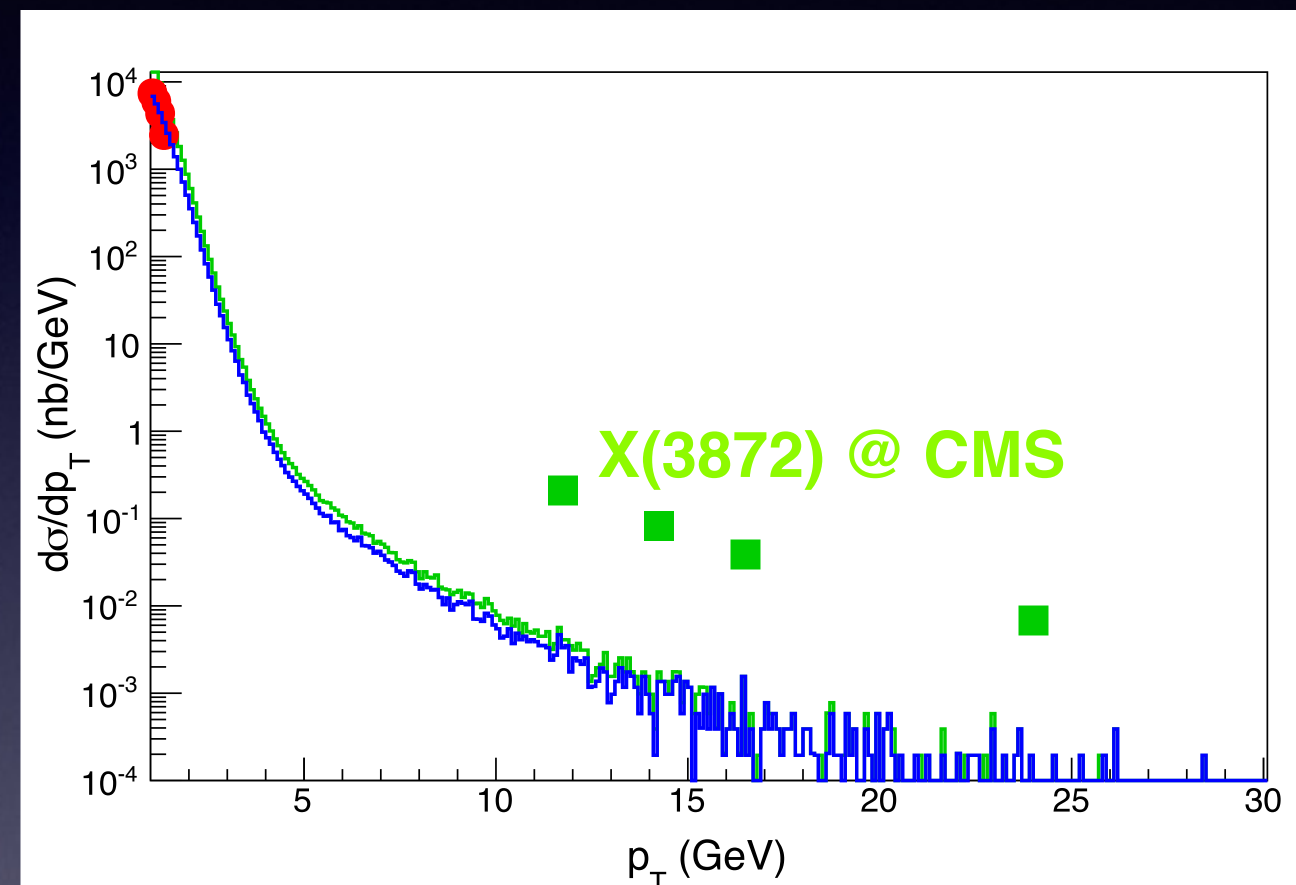


Recall that X has been observed with a p_T>5.5 GeV!

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

Binding Energy

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

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

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

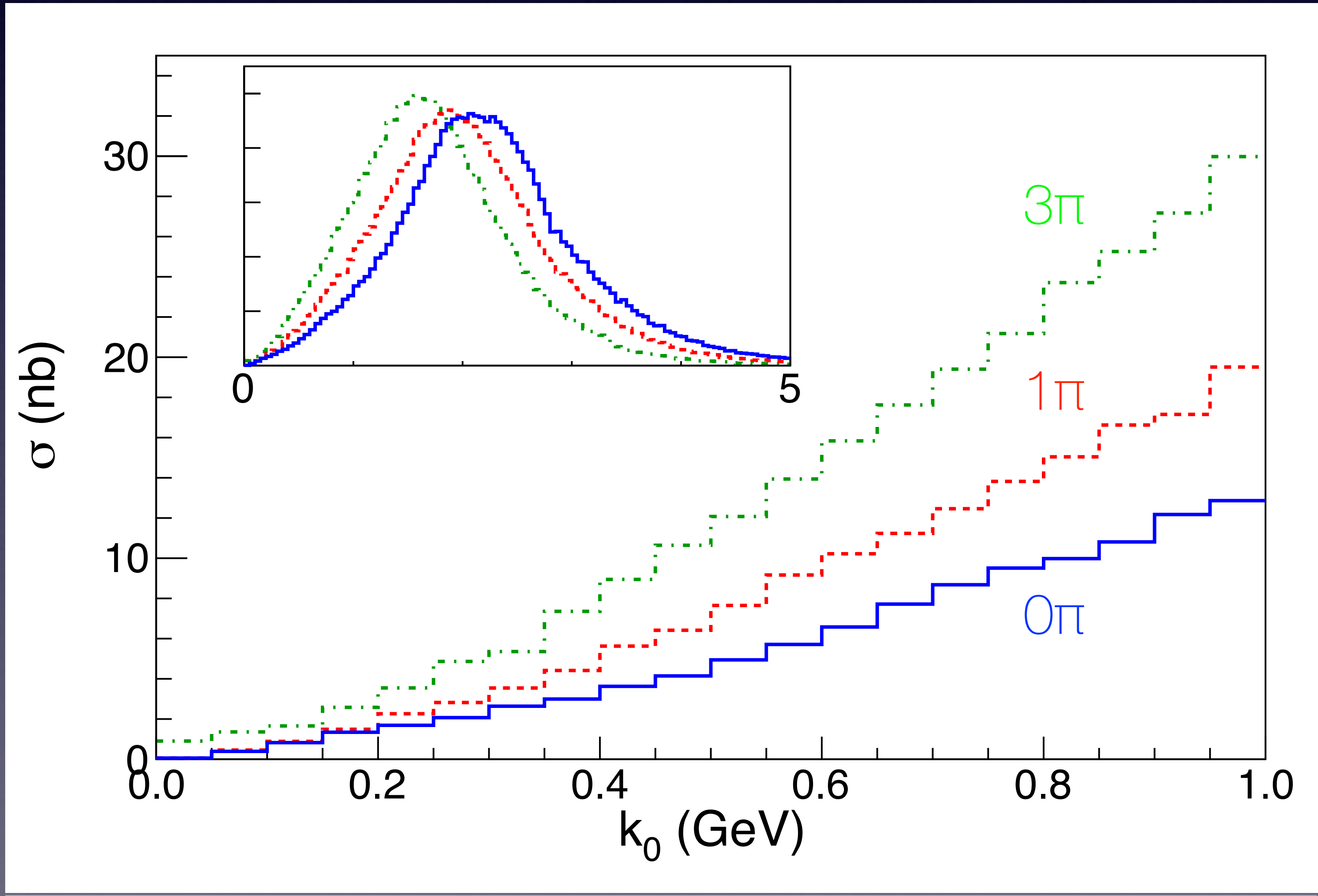
$$g^2 \to g^2\,\frac{1}{3}\left(2 + \frac{(M_X^2 + M_{D^*}^2 - M_D^2)^2}{4M_X^2 M_{D^*}^2}\right)$$

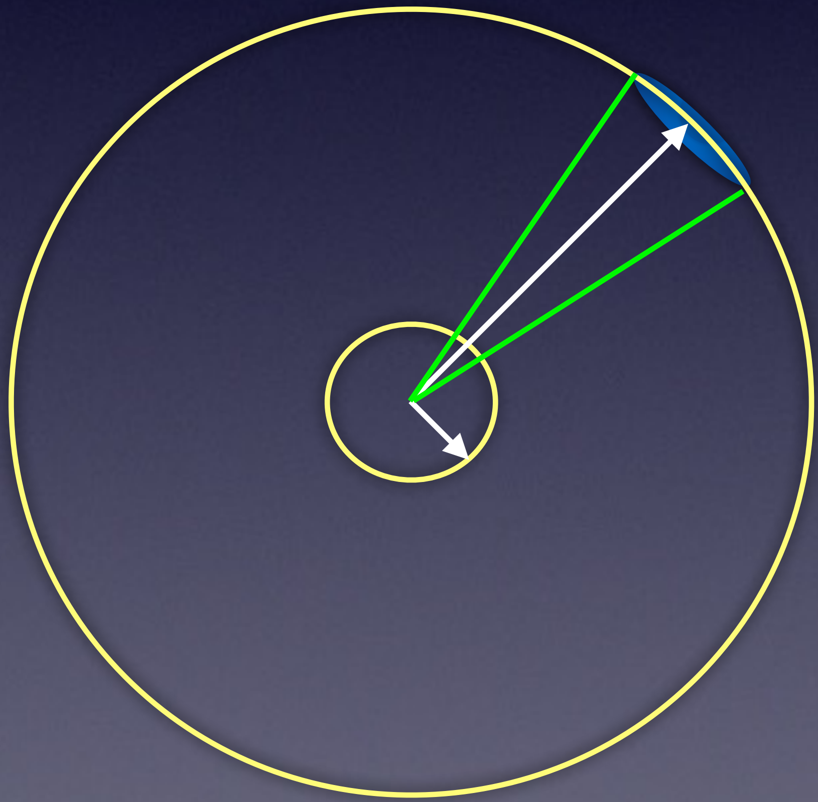
$$|\epsilon|_{\rm exp} \approx 0.1 \text{ MeV vs. } |\epsilon| \approx 0.4 \text{ MeV}$$

with the basic assumption that the barycentric energy is as small as the binding one

Rescattering 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

4q Hadronization

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

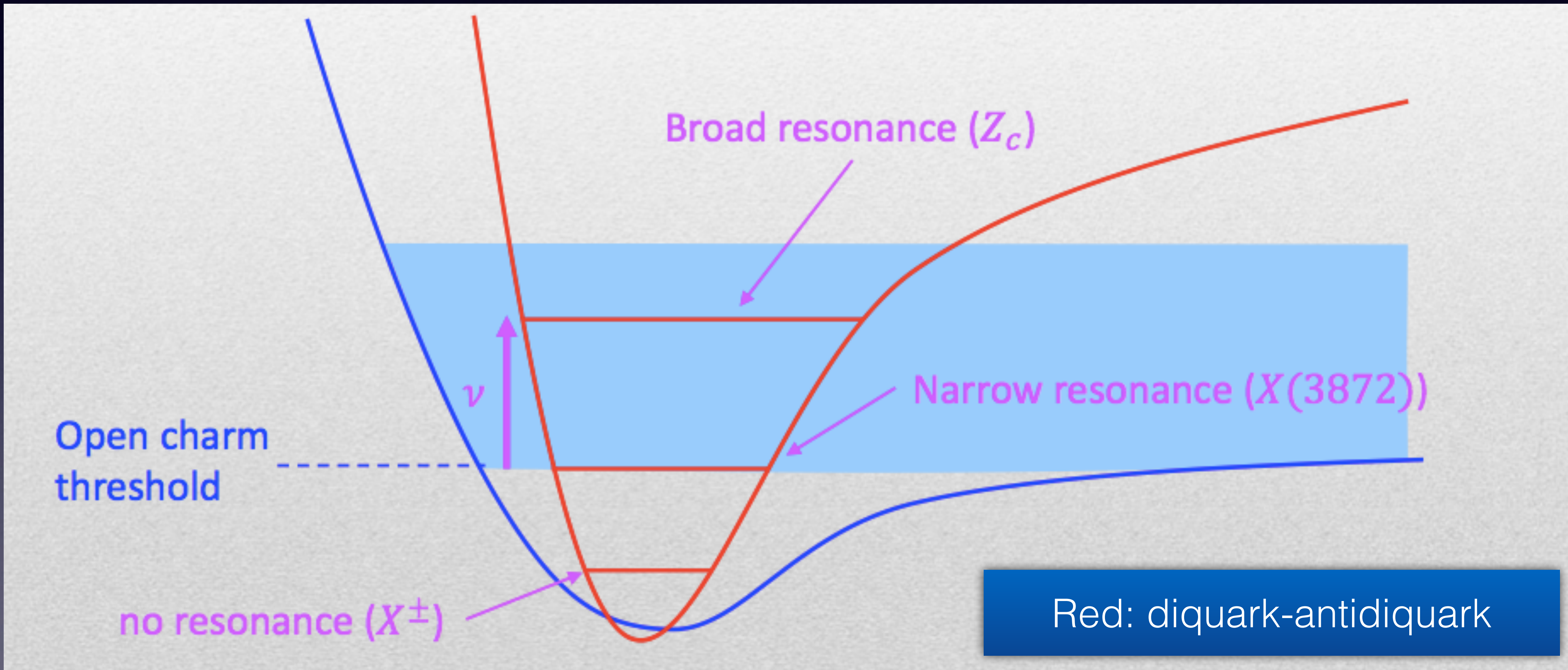
— All 'woud-be' loosely bound molecules do not form any bound state.
— Sometimes a compact 4-quark state is formed, but it could be that $|\alpha| < |\beta|,|\gamma|$
— An amplification mechanism might be at work when the closed channel level matches the onset of the continuum spectrum of two mesons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

Do we know 'amplification' mechanisms between open/closed channels?

The two hadrons in one open channel can undergo an elastic scattering, altered by the presence of the near closed channel level.

Feshbach Mechanism?

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



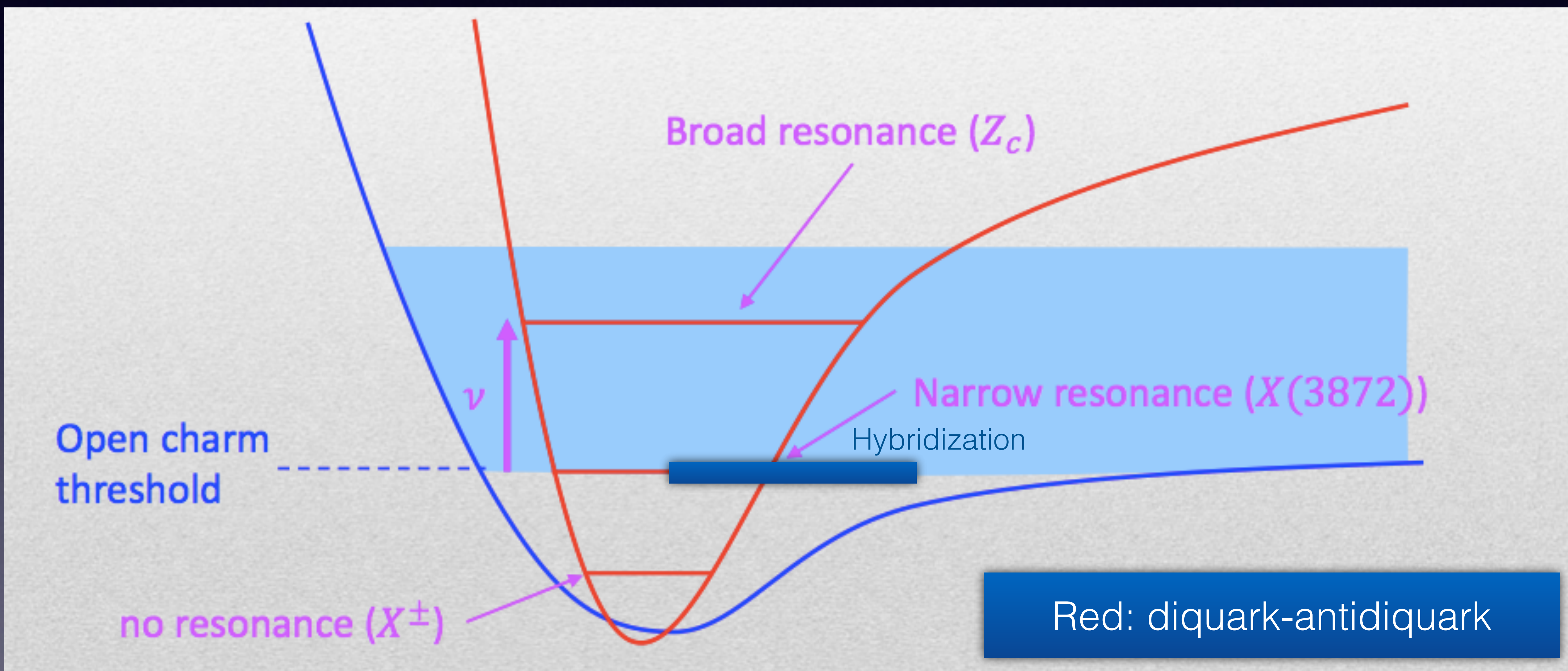
Red: diquark-antidiquark

Blue: loose molecule

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

Feshbach 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

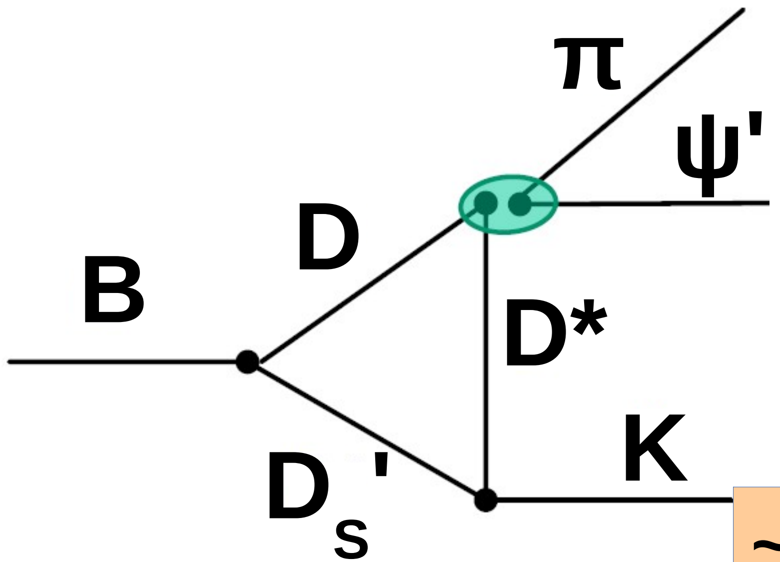
$$a \sim |C| \sum_n \frac{c\langle [Qq]_{\bar{\mathbf{3}}_c}[\bar{Q}\bar{q}]_{\mathbf{3}_c}, n | H_{\mathcal{CO}} | (Q\bar{q})_{\mathbf{1}_c}(\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}}{E_{\mathcal{O}} - E_n}$$

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

Z(4430) as a rescattering effect

T.Uglov (ITEP)

P.Pakhlov, T.Uglov arXiv: 1408.5295



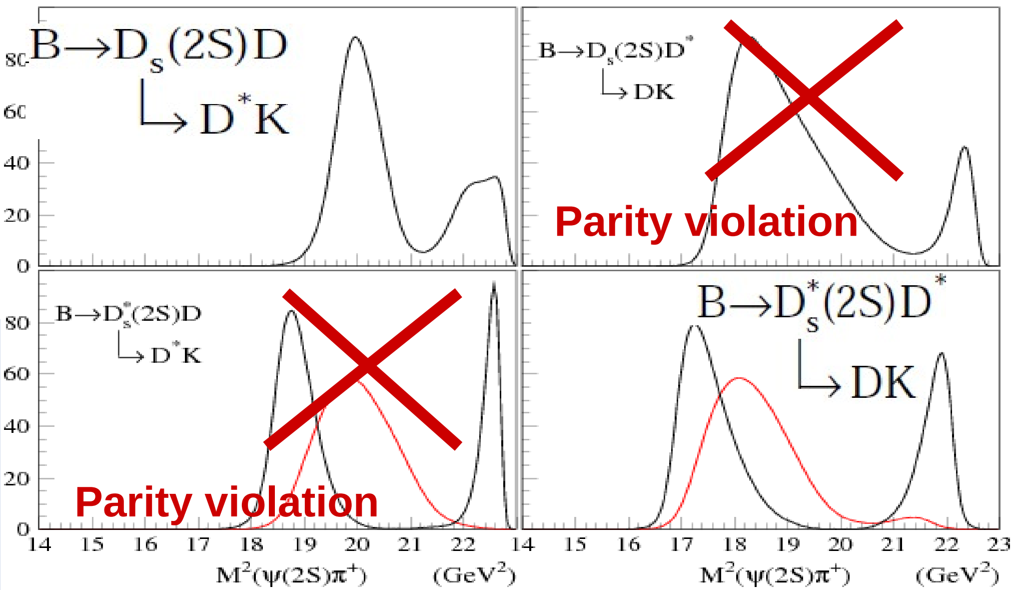
~1

Assumptions:

- S-wave domination in DD*→ Ψ' π
- On-shell approximation works

A ~ BW(Ds'->D*K) x A(Ds' decay) x

x A (D* spin rotation) x A (Z formation)



$\sim d^1_{00}(\theta')$

θ' is angle btw. Ds' and Z in D* frame

$\sim d^1_{00}(\theta'')$

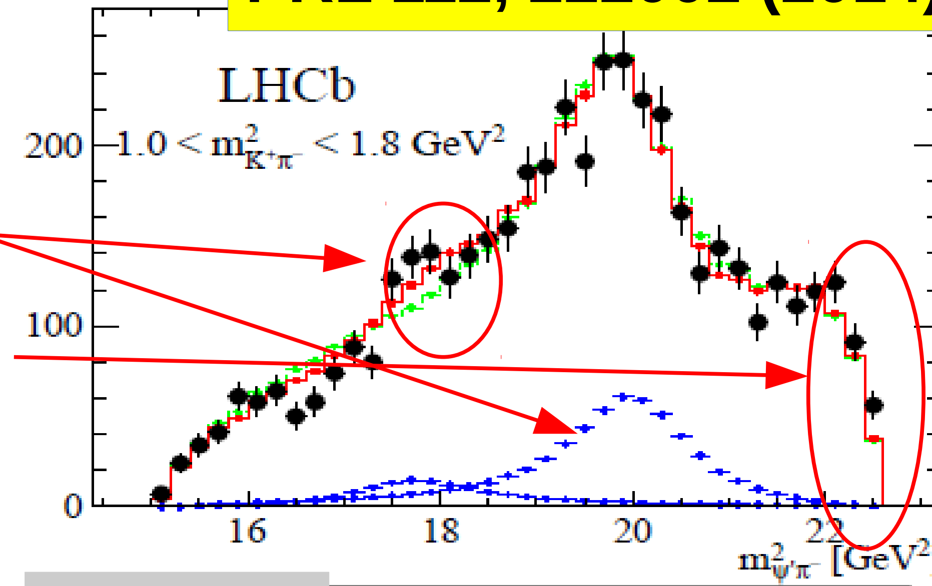
θ'' is D* helicity in Z frame

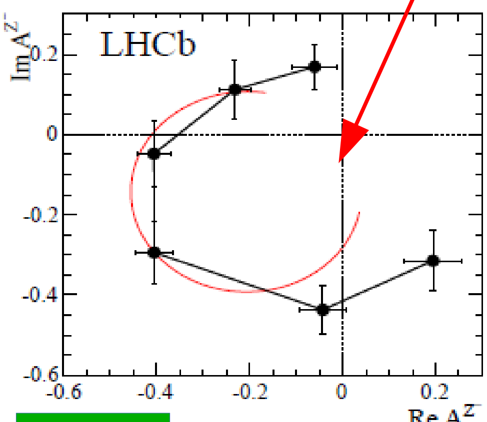
Check with LHCb data

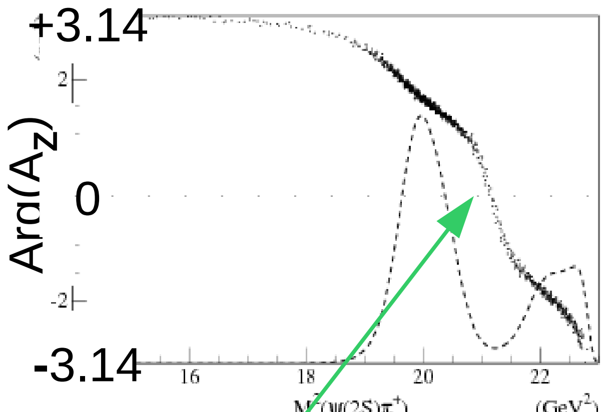
Key features of the LHCb fit:

PRL 112, 222002 (2014)

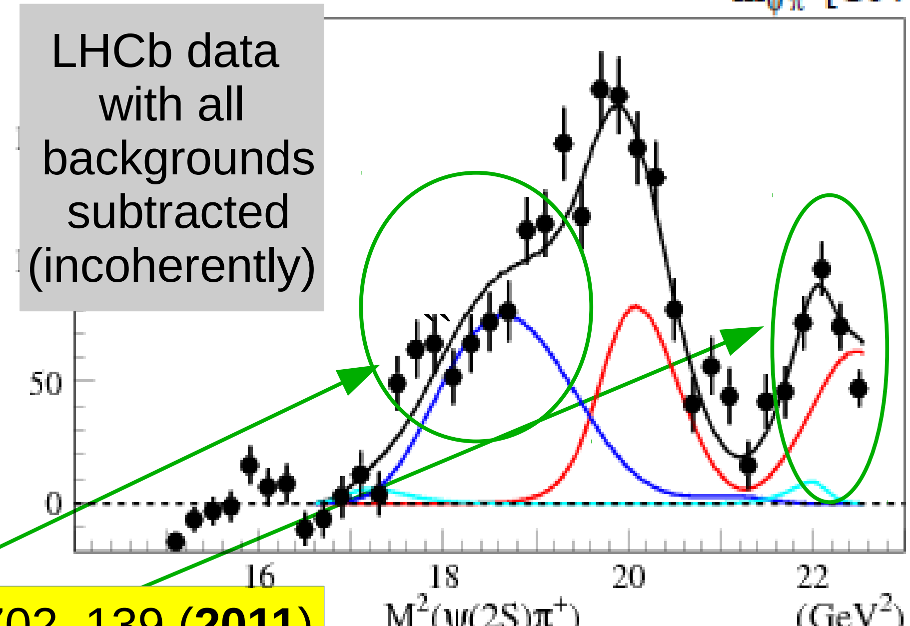
- Z(4430) quantum numbers: **1^+**
- ~5σ peak at ~4200 MeV
- Underestimated event number at the end of the spectrum (some point are excluded “*to improve modeling of the detector efficiency*”)
- Resonance-like Z(4430) phase behavior







LHCb data with all backgrounds subtracted (incoherently)



Z(4430) from rescattering

- ✔ BW-like phase change (*in opposite direction, though*)
- ✔ Z(4430) quantim numbers: **1^+**
- ✔ Broad peak around 4200 MeV
- ✔ Excess at the end of the spectrum

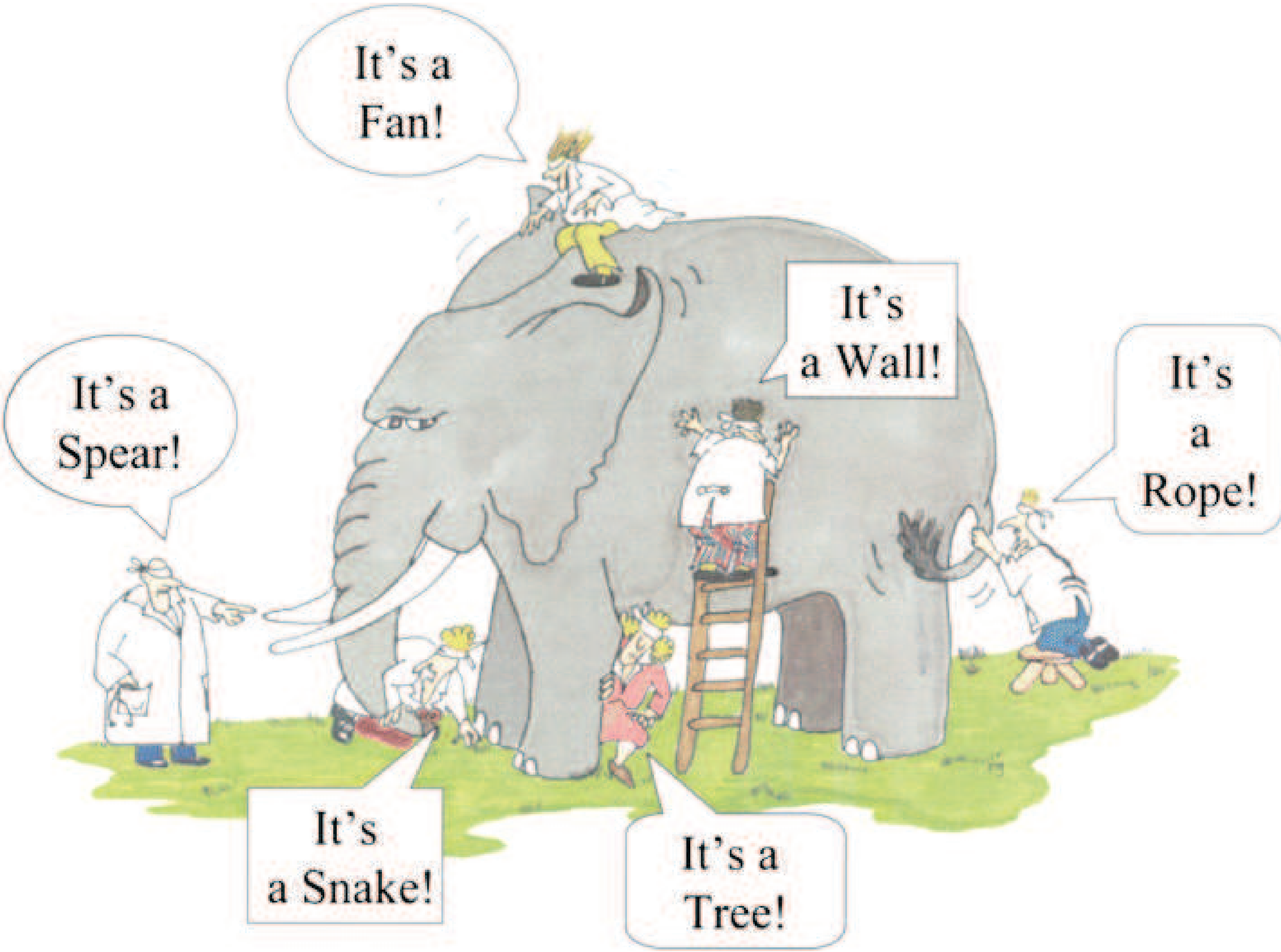
} PLB 702, 139 (**2011**) predictions, made well before Z (4430) quantum number measurements by Belle and LHCb

Are there hadronic molecules amongst the XYZ states?

Christoph Hanhart

Forschungszentrum Jülich

Eric's elephant



artwork by G. R. Guzlas

Better: if it is a tree, there must be branches ...

What is a molecule?

A mostly molecule state is a physical state with a two hadron state prominent in the wave function

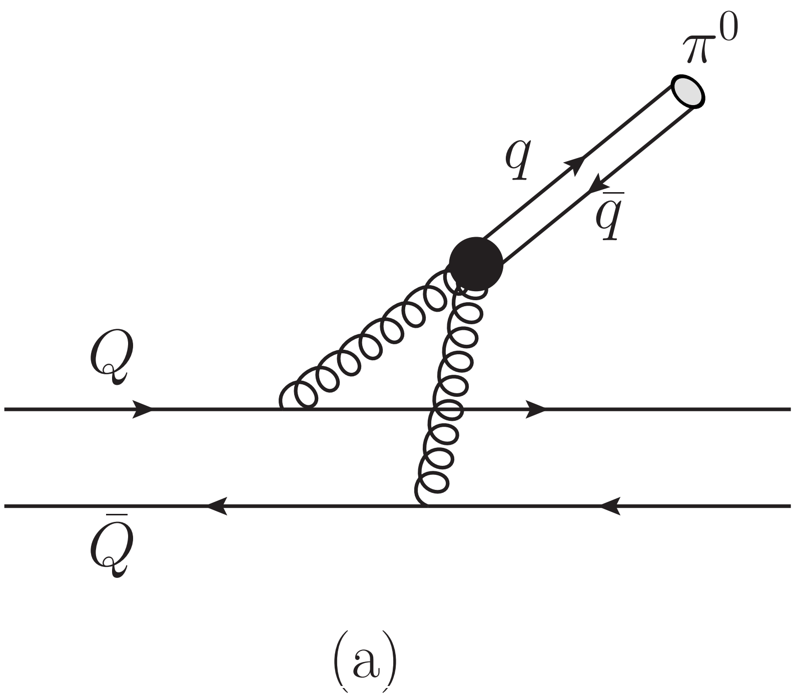
$\rightarrow$ large coupling to the continuum states

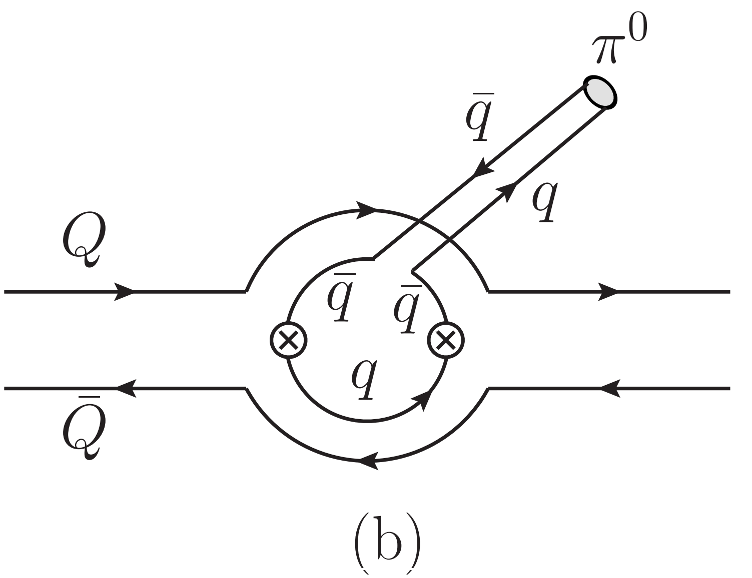
$\rightarrow$ for near threshold bound states coupling calculable from binding energy

Weinberg 1963

$\rightarrow$ goes beyond QCDME

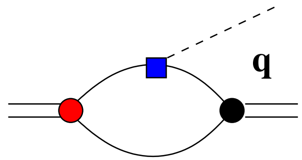
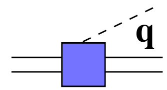
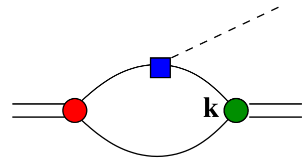
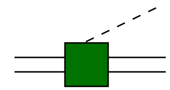
Moxhay (1989); Zhou and Kuang (1991)





Formal considerations

Transition from a pos. parity state to a light neg. parity state and

transition	a pos. parity $\bar{Q}Q$		a neg. parity $\bar{Q}Q$	
	 convergent		 divergent	
compact state	N^2LO	LO	N^2LO	LO
molecule	LO	NLO	LO	LO

Only those transitions are sensitive to the molecular nature that are dominated by the loops!

Mehen/Springer, PRD83 (2011), Guo/Meißner, PRL109 (2012), Cleven et al., PRD87 (2013)

A X, Y, Z story

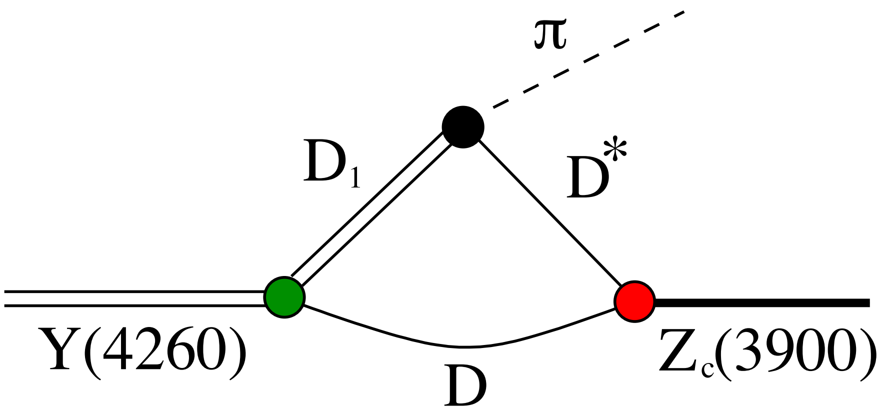
We proposed:

→ $Y(4260)$ is a $D_1(2420)\bar{D}$–molecule

→ $Z_c(3900)$ is a $D^*\bar{D}$ molecule

A molecule decays via its constituents

Within this picture Z_c was found in $Y(4260)$ decays
since the decay $D_1 \to D\pi$ provides many slow D^*D pairs



Q. Wang, CH and Q. Zhao, Phys. Rev. Lett. 111 (2013) 132003

Consequence

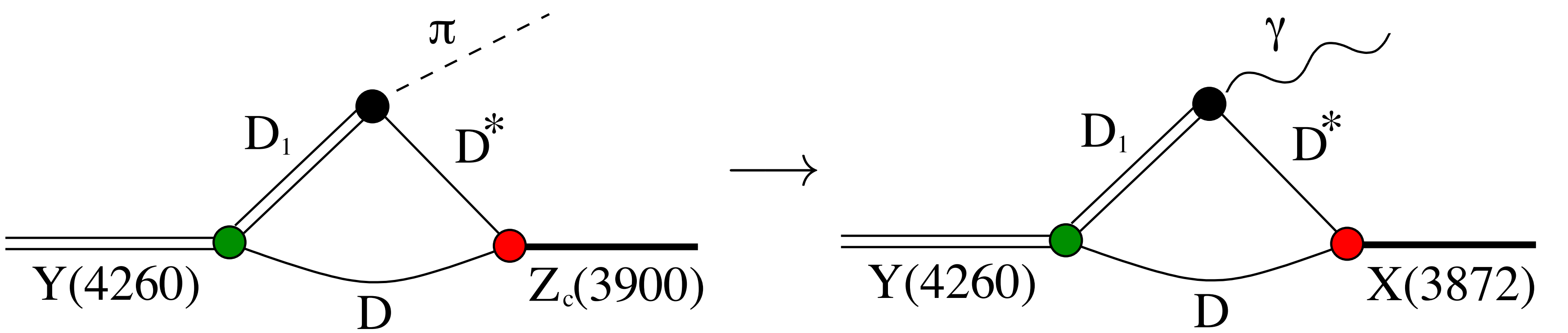
We claim that Z_c ($I(J^{PC} = 1(1^{+-})$) is a $(\bar{D}^* D + D^* \bar{D})$ state with

$$Z_c^+ \sim D^{*+}\bar{D}^0 \,, \quad Z_c^0 \sim \frac{1}{\sqrt{2}}(D^{*+}D^- - D^{*0}\bar{D}^0) \,, \quad Z_c^- \sim D^{*0}D^-$$

If now $X(3872)$ ($I(J^{PC} = 0(1^{++})$) is a $(\bar{D}^* D - D^* \bar{D})$ state with

$$X \sim \frac{1}{\sqrt{2}}(D^{*+}D^- + D^{*0}\bar{D}^0)$$

there must be $Y(4260) \to \gamma X(3872)$ F.-K. Guo et al., PLB 725 (2013) 127-133



For more: see talk by Qian Wang - this afternoon

SPECTROSCOPY AND REGGE TRAJECTORIES OF HEAVY QUARKONIA

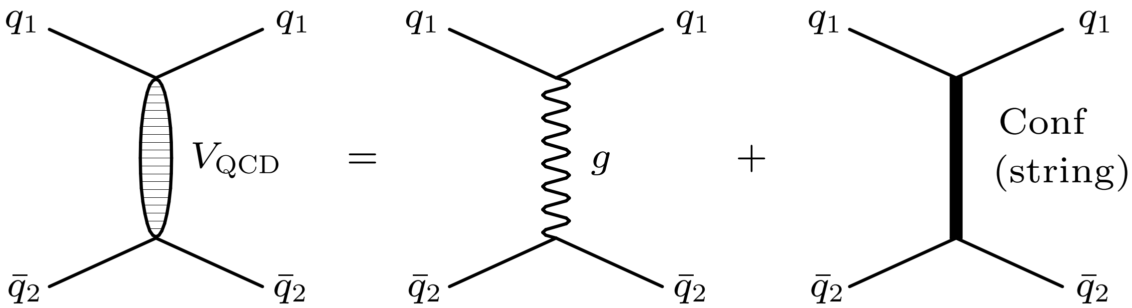
Rudolf Faustov

Dorodnicyn Computing Centre, RAS, Moscow

(in collaboration with Dietmar Ebert and Vladimir Galkin)

10th International Workshop on Heavy Quarkonium
10-14 November 2014, CERN

- **Relativistic Schrödinger-like equation with $Q\bar{Q}$ quasipotential**



$$V(\mathbf{p},\mathbf{q};M)=\bar{u}_1(p)\bar{u}_2(-p)\left\{\frac{4}{3}\alpha_s D_{\mu\nu}(\mathbf{k})\gamma_1^{\mu}\gamma_2^{\nu}+V^V_{\rm conf}(\mathbf{k})\Gamma_1^{\mu}\Gamma_{2;\mu}+V^S_{\rm conf}(\mathbf{k})\right\}u_1(q)u_2(-q)$$

$\mathbf{k}=\mathbf{p}-\mathbf{q}$; $D_{\mu\nu}(\mathbf{k})$ - (perturbative) gluon propagator
$\Gamma_{\mu}(\mathbf{k})$ - effective long-range vertex with Pauli term:

$$\Gamma_{\mu}(\mathbf{k})=\gamma_{\mu}+\frac{i\kappa}{2m}\sigma_{\mu\nu}k^{\nu},$$

κ - anomalous chromomagnetic moment of quark,

- Lorentz structure of $V_{\rm conf}=V^V_{\rm conf}+V^S_{\rm conf}$

  In nonrelativistic limit

$$\left.\begin{array}{lcc} V^V_{\rm conf}(r) & = & (1-\varepsilon)(Ar+B) \\ V^S_{\rm conf}(r) & = & \varepsilon(Ar+B) \end{array}\right\} \quad \text{Sum}: \quad V_{\rm conf}(r)=Ar+B$$

ε - mixing parameter

$$V_{\rm NR}(r)=V_{\rm Coul}(r)+V_{\rm conf}(r)$$
$$V_{\rm Coul}(r)=-\frac{4}{3}\frac{\alpha_s}{r}$$

Parameters A, B, κ, ε and quark masses fixed from analysis of meson masses and radiative decays:

$\varepsilon = -1$ from heavy quarkonium radiative decays ($J/\psi \to \eta_c + \gamma$) and HQET

$\kappa = -1$ from fine splitting of heavy quarkonium ${}^3P_J$ states and HQET

$(1+\kappa) = 0 \Longrightarrow$ vanishing long-range chromomagnetic interaction ! (flux tube model)

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln\frac{\mu^2}{\Lambda^2}}, \quad \beta_0 = 11 - \frac{2}{3}n_f, \quad \mu = \frac{2m_1m_2}{m_1+m_2},$$

Quasipotential parameters:

$A = 0.18$ GeV^2, $B = -0.30$ GeV,

$\Lambda = 0.169$ GeV

Quark masses:

$m_b = 4.88$ GeV $m_s = 0.50$ GeV

$m_c = 1.55$ GeV $m_{u,d} = 0.33$ GeV

Table 1: Charmonium mass spectrum (in MeV).

State $n^{2S+1}L_J$	J^{PC}	Theory	Experiment meson	Experiment mass	State $n^{2S+1}L_J$	J^{PC}	Theory	Experiment meson	Experiment mass
1^1S_0	0^{-+}	2981	$\eta_c(1S)$	2980.3(1.2)	2^3D_1	1^{--}	4150	$\psi(4160)$	4191(5)
1^3S_1	1^{--}	3096	$J/\psi(1S)$	3096.916(11)	2^3D_2	2^{--}	4190		
2^1S_0	0^{-+}	3635	$\eta_c(2S)$	3637(4)	2^3D_3	3^{--}	4220		
2^3S_1	1^{--}	3685	$\psi(2S)$	3686.09(4)	2^1D_2	2^{-+}	4196	$X(4160)$?	$4156(^{29}_{25})$
3^1S_0	0^{-+}	3989			3^3D_1	1^{--}	4507		
3^3S_1	1^{--}	4039	$\psi(4040)$	4039(1)	3^3D_2	2^{--}	4544		
4^1S_0	0^{-+}	4401			3^3D_3	3^{--}	4574		
4^3S_1	1^{--}	4427	$\psi(4415)$	4421(4)	3^1D_2	2^{-+}	4549		
5^1S_0	0^{-+}	4811			4^3D_1	1^{--}	4857		
5^3S_1	1^{--}	4837			4^3D_2	2^{--}	4896		
6^1S_0	0^{-+}	5155			4^3D_3	3^{--}	4920		
6^3S_1	1^{--}	5167			4^1D_2	2^{-+}	4898		
1^3P_0	0^{++}	3413	$\chi_{c0}(1P)$	3414.75(31)	1^3F_2	2^{++}	4041		
1^3P_1	1^{++}	3511	$\chi_{c1}(1P)$	3510.66(7)	1^3F_3	3^{++}	4068		
1^3P_2	2^{++}	3555	$\chi_{c2}(1P)$	3556.20(9)	1^3F_4	4^{++}	4093		
1^1P_1	1^{+-}	3525	$h_c(1P)$	3525.41(16)	1^1F_3	3^{+-}	4071		
2^3P_0	0^{++}	3870	$\chi_{c0}(2P)$	3918.4(1.9)	2^3F_2	2^{++}	4361		
2^3P_1	1^{++}	3906			2^3F_3	3^{++}	4400		
2^3P_2	2^{++}	3949	$\chi_{c2}(2P)$	3927.2(2.6)	2^3F_4	4^{++}	4434		
2^1P_1	1^{+-}	3926			2^1F_3	3^{+-}	4406		
3^3P_0	0^{++}	4301			1^3G_3	3^{--}	4321		
3^3P_1	1^{++}	4319			1^3G_4	4^{--}	4343		
3^3P_2	2^{++}	4354	$X(4350)$?	4351(5)	1^3G_5	5^{--}	4357		

Table 1: (continued)

State $n^{2S+1}L_J$	J^{PC}	Theory	Experiment meson	Experiment mass	State $n^{2S+1}L_J$	J^{PC}	Theory	Experiment meson	Experiment mass
3^1P_1	1^{+-}	4337			1^1G_4	4^{-+}	4345		
4^3P_0	0^{++}	4698			1^3H_4	4^{++}	4572		
4^3P_1	1^{++}	4728			1^3H_5	5^{++}	4592		
4^3P_2	2^{++}	4763			1^3H_6	6^{++}	4608		
4^1P_1	1^{+-}	4744			1^3H_5	5^{+-}	4594		
1^3D_1	1^{--}	3783	$\psi(3770)$	3773.15(33)					
1^3D_2	2^{--}	3795	$X(3823)$	3823.1(1.9)					
1^3D_3	3^{--}	3813							
1^1D_2	2^{-+}	3807							

Table 2: Bottomonium mass spectrum (in MeV).

State $n^{2S+1}L_J$	J^{PC}	Theory	Experiment meson	Experiment mass	State $n^{2S+1}L_J$	J^{PC}	Theory
1^1S_0	0^{-+}	9398	$\eta_b(1S)$	9398.0(3.2)	2^3D_1	1^{--}	10435
1^3S_1	1^{--}	9460	$\Upsilon(1S)$	9460.30(26)	2^3D_2	2^{--}	10443
2^1S_0	0^{-+}	9990	$\eta_b(2S)$	9999.0(4.5)	2^3D_3	3^{--}	10449
2^3S_1	1^{--}	10023	$\Upsilon(2S)$	10023.26(31)	2^1D_2	2^{-+}	10445
3^1S_0	0^{-+}	10329			3^3D_1	1^{--}	10704
3^3S_1	1^{--}	10355	$\Upsilon(3S)$	10355.2(5)	3^3D_2	2^{--}	10711
4^1S_0	0^{-+}	10573			3^3D_3	3^{--}	10717
4^3S_1	1^{--}	10586	$\Upsilon(4S)$	10579.4(1.2)	3^1D_2	2^{-+}	10713
5^1S_0	0^{-+}	10851			4^3D_1	1^{--}	10949

State		Theory	Experiment		State		Theory
$n^{2S+1}L_J$	J^{PC}		meson	mass	$n^{2S+1}L_J$	J^{PC}	
5^3S_1	1^{--}	10869	$\Upsilon(10860)$	10876(1)	4^3D_2	2^{--}	10957
6^1S_0	0^{-+}	11061			4^3D_3	3^{--}	10963
6^3S_1	1^{--}	11088	$\Upsilon(11020)$	11019(8)	4^1D_2	2^{-+}	10959
1^3P_0	0^{++}	9859	$\chi_{b0}(1P)$	9859.44(52)	1^3F_2	2^{++}	10343
1^3P_1	1^{++}	9892	$\chi_{b1}(1P)$	9892.78(40)	1^3F_3	3^{++}	10346
1^3P_2	2^{++}	9912	$\chi_{b2}(1P)$	9912.21(40)	1^3F_4	4^{++}	10349
1^1P_1	1^{+-}	9900	$h_b(1P)$	9899.3(1.0)	1^1F_3	3^{+-}	10347
2^3P_0	0^{++}	10233	$\chi_{b0}(2P)$	10232.5(6)	2^3F_2	2^{++}	10610
2^3P_1	1^{++}	10255	$\chi_{b1}(2P)$	10255.46(55)	2^3F_3	3^{++}	10614
2^3P_2	2^{++}	10268	$\chi_{b2}(2P)$	10268.65(55)	2^3F_4	4^{++}	10617
2^1P_1	1^{+-}	10260	$h_b(2P)$	10259.8(1.2)	2^1F_3	3^{+-}	10615
3^3P_0	0^{++}	10521			1^3G_3	3^{--}	10511
3^3P_1	1^{++}	10541	$\chi_b(3P)$	{ 10534(9)PDG 10516(4)LHCb	1^3G_4	4^{--}	10512
3^3P_2	2^{++}	10550			1^3G_5	5^{--}	10514
3^1P_1	1^{+-}	10544			1^1G_4	4^{-+}	10513
4^3P_0	0^{++}	10781			1^3H_4	4^{++}	10670
4^3P_1	1^{++}	10802			1^3H_5	5^{++}	10671
4^3P_2	2^{++}	10812			1^3H_6	6^{++}	10672
4^1P_1	1^{+-}	10804			1^3H_5	5^{+-}	10671
1^3D_1	1^{--}	10154					
1^3D_2	2^{--}	10161	$\Upsilon(1D)$	10163.7(1.4)			
1^3D_3	3^{--}	10166					

Bottomonium hyperfine splittings:

- $1S$ and $2S$ states

$$\Delta M_{\rm hfs}(nS) \equiv M_{\Upsilon(nS)} - M_{\eta_b(nS)}$$

⋆ $1S$ states

$$\Delta M^{\rm exp}_{\rm hfs}(1S) = 62.3 \pm 3.2 \ \ {\rm MeV} \qquad \Delta M^{\rm theor}_{\rm hfs}(1S) = 62 \ {\rm MeV}$$

⋆ $2S$ states

$$\Delta M^{\rm exp}_{\rm hfs}(2S) = 24 \pm 4 \ \ {\rm MeV} \qquad \Delta M^{\rm theor}_{\rm hfs}(2S) = 33 \ {\rm MeV}$$

- $1P$ and $2P$ states

$$\Delta M_{\rm hfs}(nP) \equiv \langle M(n^3P_J)\rangle - M(n^1P_1),$$

where spin-averaged centroid of the triplet states

$$\langle M(^3P_J)\rangle = [M(\chi_{b0}) + 3M(\chi_{b1}) + 5M(\chi_{b2})]/9 \qquad M(^1P_1) = M(h_b)$$

⋆ $1P$ states

$$\Delta M^{\rm exp}_{\rm hfs}(1P) = (0.8 \pm 1.1) \ {\rm MeV} \qquad \Delta M^{\rm theor}_{\rm hfs}(1P) = 0$$

⋆ $2P$ states

$$\Delta M^{\rm exp}_{\rm hfs}(2P) = (0.5 \pm 1.2) \ {\rm MeV} \qquad \Delta M^{\rm theor}_{\rm hfs}(1P) = 0$$

$\Longrightarrow$ vanishing of the long-range chromomagnetic interaction in heavy quarkonia (e.g. flux tube model)

REGGE TRAJECTORIES

(a) The (J, M^2) Regge trajectory:

$$J = \alpha M^2 + \alpha_0$$

(b) The (n_r, M^2) Regge trajectory:

$$n_r = \beta M^2 + \beta_0,$$

α, β – slopes
α_0, β_0 – intercepts.

$P = (-1)^J$ – natural parity
$P = (-1)^{J-1}$ – unnatural parity

Nonlinear Regge trajectories:
(a) for the parent trajectory in the (J, M^2) plane

$$M^2 = \left(J - \frac{\gamma_1}{(J+2)^2} + \gamma_0 \right) / \gamma,$$

(b) for the $J = 1$ trajectory in the (n_r, M^2) plane

$$M^2 = \left(n_r - \frac{\tau_1}{(n_r+2)^2} + \tau_0 \right) / \tau,$$

γ, τ – slopes, γ_0, τ_0 – intercepts, γ_1, τ_1 – nonlinearity.

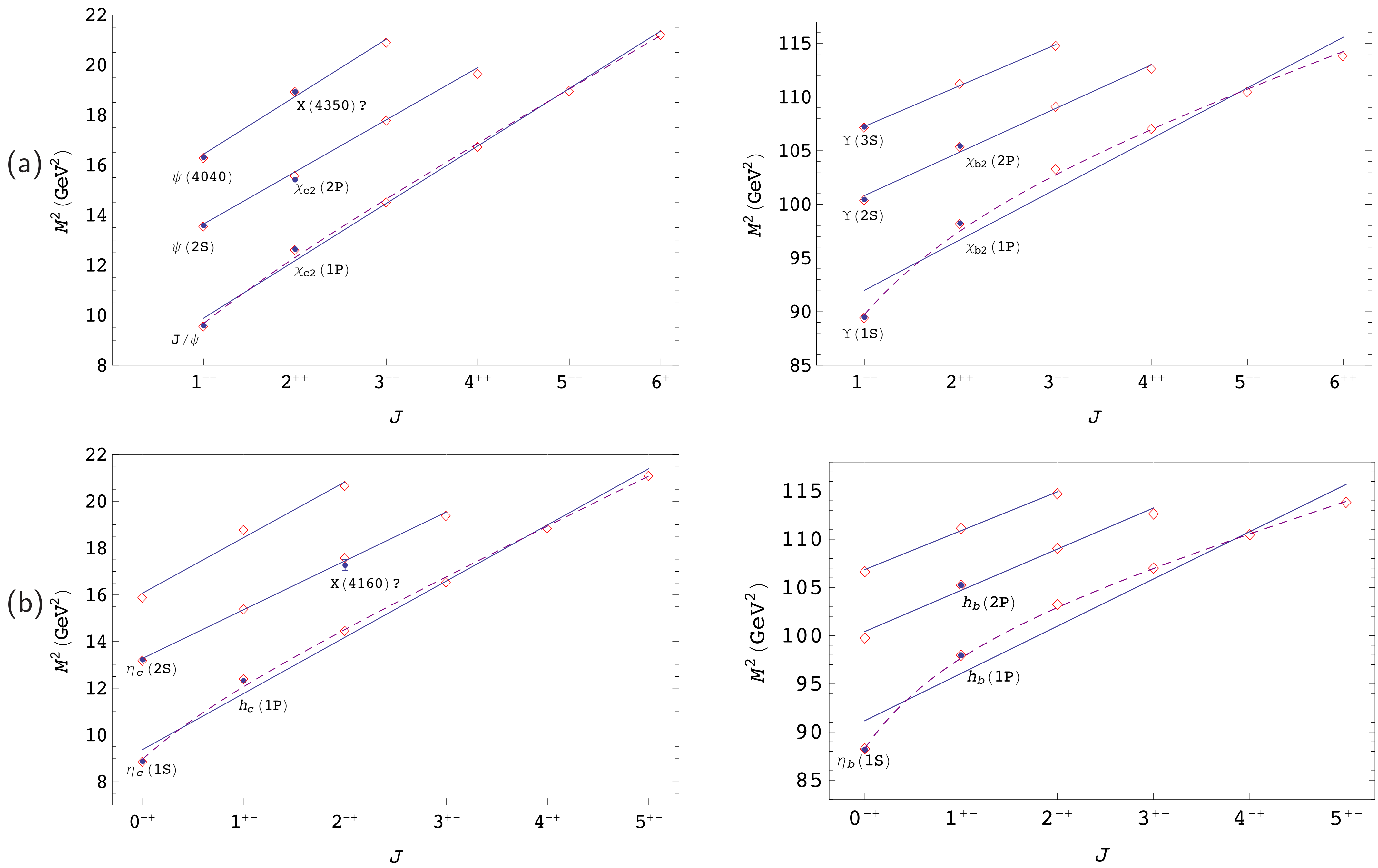


Figure 1: Parent and daughter (J, M^2) Regge trajectories for charmonium and bottomonium state with natural (a) and unnatural (b) parity. Diamonds are predicted masses. Available experimental data are given by dots with error bars and particle names. The dashed line corresponds to a nonlinear fit.

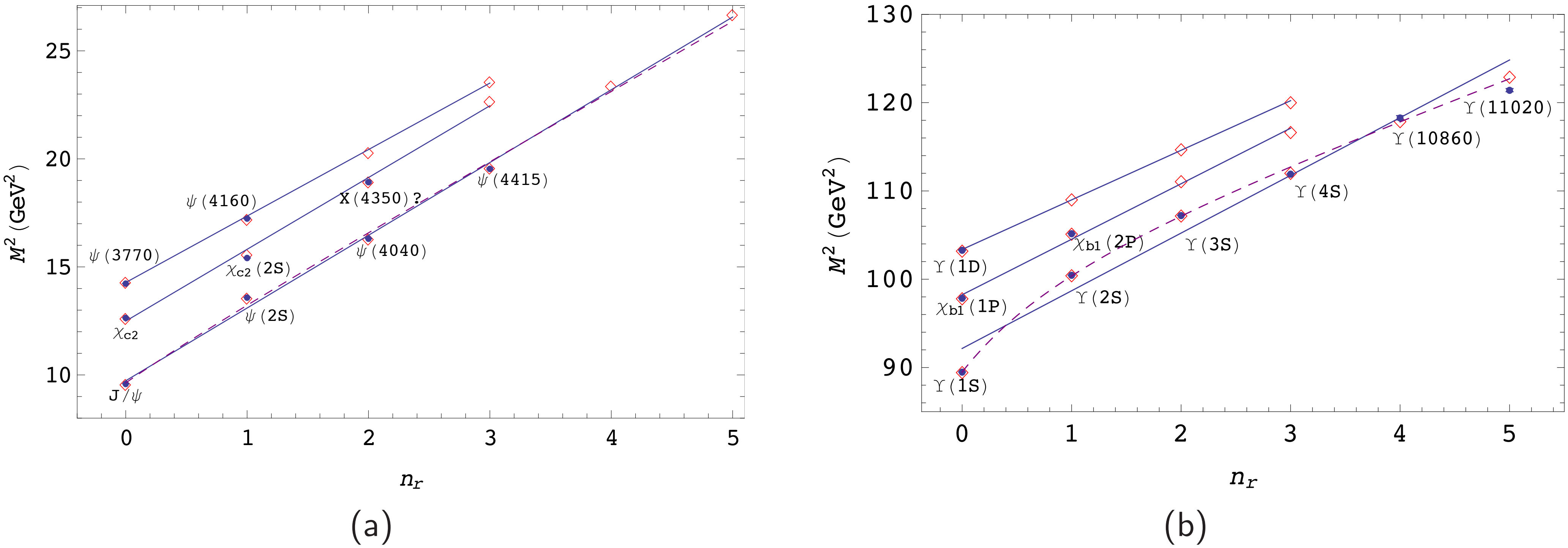


Figure 2: The (n_r, M^2) Regge trajectories for vector (S-wave), tensor and vector (D-wave) charmonium (a) and bottomonium (b) states (from bottom to top).

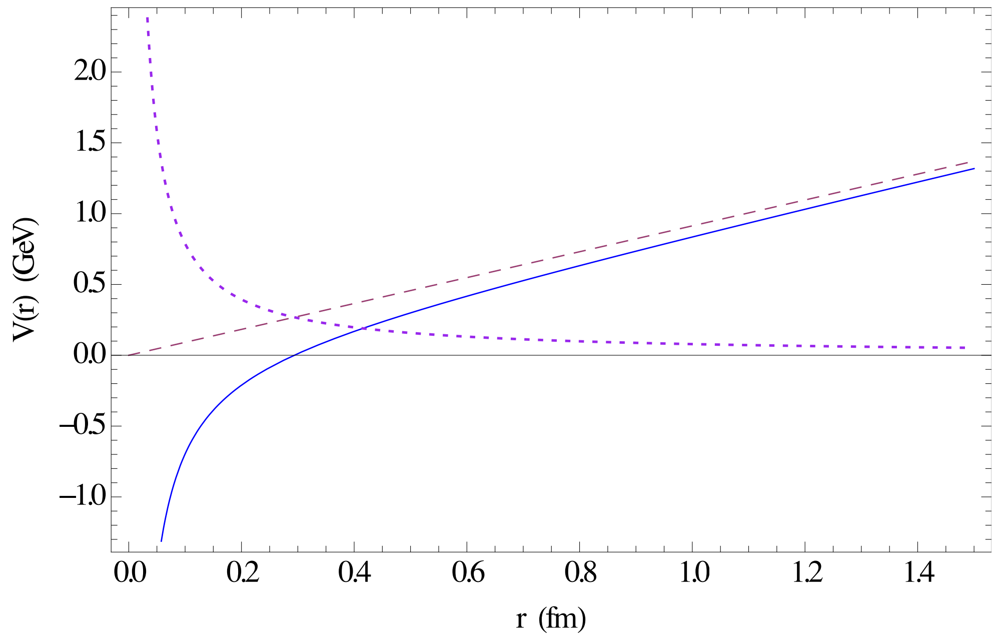


Figure 3: Static potential of the quark-antiquark interaction without the constant term (solid line). Dashed line shows the linear confining potential, dotted line corresponds to the modulus of the Coulomb potential.

Table 3: Mean square radii $\sqrt{\langle r^2 \rangle}$ for the spin-singlet ground and excited states of charmonia, B_c mesons and bottomonia (in fm).

State	$\sqrt{\langle r^2 \rangle_\psi}$	$\sqrt{\langle r^2 \rangle_{B_c}}$	$\sqrt{\langle r^2 \rangle_\Upsilon}$
$1S$	0.37	0.33	0.22
$1P$	0.59	0.53	0.41
$2S$	0.71	0.63	0.50
$1D$	0.74	0.67	0.54
$2P$	0.87	0.79	0.65
$1F$	0.87	0.79	0.65
$3S$	0.94	0.87	0.72
$1G$	0.98	0.89	0.75

Voloshin PRD84, 031502 (2011)

$$\left|Z_b'\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar b} \otimes 1^-_{Q\bar q} - \frac{1}{\sqrt{2}} 1^-_{b\bar b} \otimes 0^-_{Q\bar q}$$

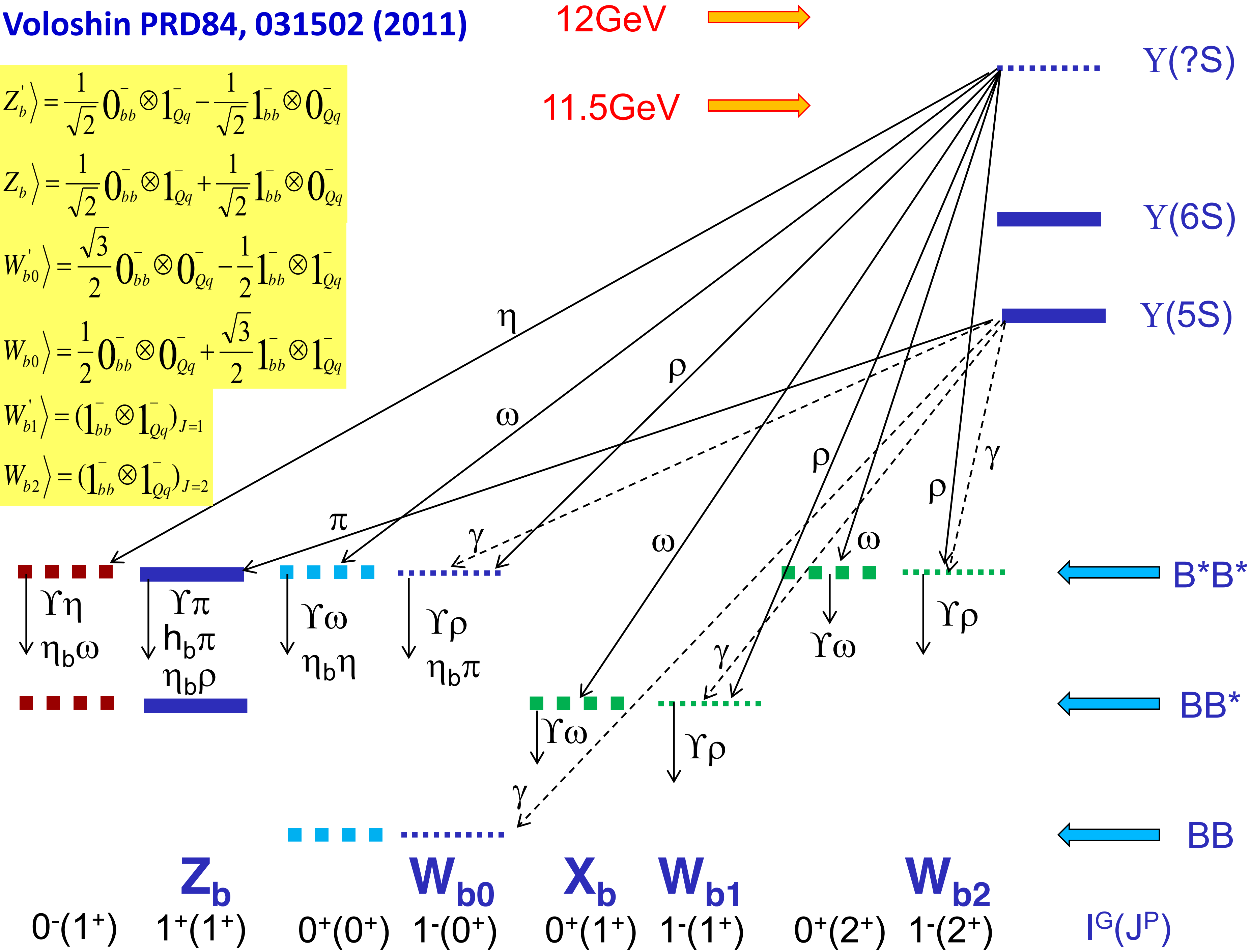
$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar b} \otimes 1^-_{Q\bar q} + \frac{1}{\sqrt{2}} 1^-_{b\bar b} \otimes 0^-_{Q\bar q}$$

$$\left|W_{b0}'\right\rangle = \frac{\sqrt{3}}{2} 0^-_{b\bar b} \otimes 0^-_{Q\bar q} - \frac{1}{2} 1^-_{b\bar b} \otimes 1^-_{Q\bar q}$$

$$\left|W_{b0}\right\rangle = \frac{1}{2} 0^-_{b\bar b} \otimes 0^-_{Q\bar q} + \frac{\sqrt{3}}{2} 1^-_{b\bar b} \otimes 1^-_{Q\bar q}$$

$$\left|W_{b1}'\right\rangle = (1^-_{b\bar b} \otimes 1^-_{Q\bar q})_{J=1}$$

$$\left|W_{b2}\right\rangle = (1^-_{b\bar b} \otimes 1^-_{Q\bar q})_{J=2}$$



High energy scans at Belle II

All transitions are kinematically allowed: $2m_{B*} + m_{\omega} = 11.43$ GeV

Are cross-sections resonating? Peaks in the BB** thresholds region?

Thresholds (GeV)	B	Bs
B**B	11.01	11.20
B**B**	11.46	11.68 GeV

Are there molecules at baryon thresholds ?

$2m_{\Lambda b} = 11.24$, $m_{\Lambda b**} + m_{\Lambda b} = 11.54$, $m_{\Lambda b**} + m_{\Lambda b**} = 11.84$ GeV

we need energy up to ~12GeV

Possible data taking scenario (E_{max}=12GeV):

Scan with 10MeV step 10fb^{-1} per point (~1.3ab^{-1} total), take 500fb^{-1} at Υ(5S), Υ(6S),..

Present limitation E_{max}=11.25GeV (injection system). Phase-I data taking (no VXD):

Scan 10.95-11.25GeV region with 10MeV step 1fb^{-1} per point, take 100fb^{-1} at Υ(6S).

Motivation for taking data at $\Upsilon(6S)$

Resonant structure of $\Upsilon(6S) \to \Upsilon(nS)\,\pi^+\pi^-$

$h_b(nP)\,\pi^+\pi^-$

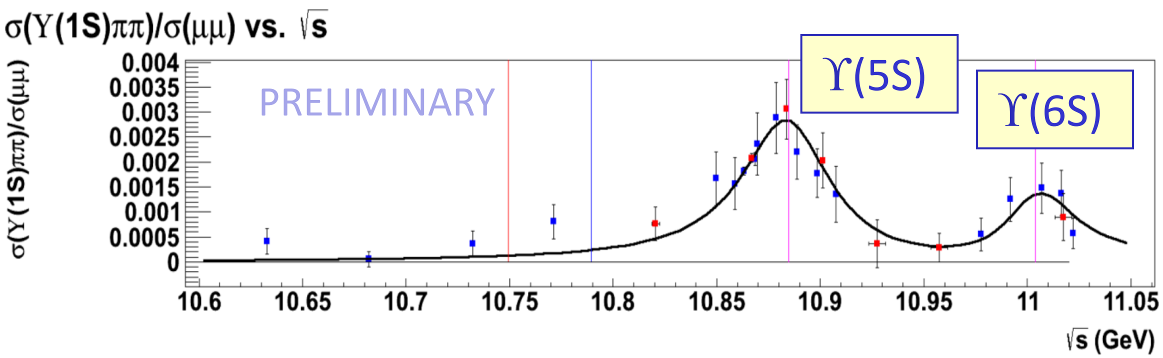
Is $\Upsilon(6S)$ similar to $\Upsilon(5S)$ or to Y(4260)?

Search for $\Upsilon(6S) \to X_b\,\gamma$

$W_{b0}\,\rho$

Hadronic transitions to lower bottomonia, their spectroscopy.

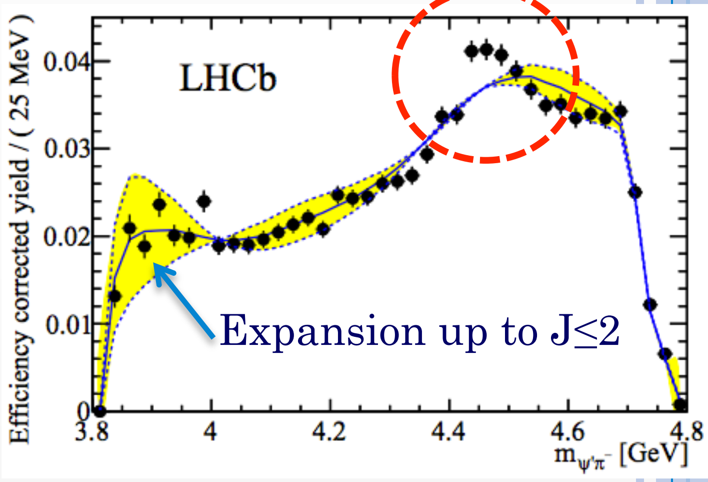
Access to 2D and 1F multiplets?



Belle data at $\Upsilon(6S)$: 6fb^{-1} – inconclusive. Need similar to $\Upsilon(5S)$ sample of ~100fb^{-1}.

$Z(4430)^+$ & Future Plans

- ✧ *$Z(4430)^+$ "long paper"*
  - ✓ Model independent analysis
  - ✓ Amplitude analysis details
  - ✓ Test on the nature of Z(4430)?
- ✧ *Search for Z's in B→J/ ψ K π*
- ✧ *Search for X(4140)/X(4274)*
  - ✓ Amplitude analysis of B→J/ψϕ K



Data taking run is upcoming (RUN I + RUN II ~ 10 fb^{-1})

- ✓ *X(3872)*: Search for new decay modes/measurements of BR's
- ✓ Studies of charmonium(-like) states from *b* decays
- ✓ Search for bottomonium(-like) states

Do you think we are missing some important measurements?

Naming Scheme for Hadrons

November 10, 2014 | Christoph Hanhart | IKP and IAS

The PDG Meson Team: unstable mesons

Unstable wrt. strong decay (not π, η, K, D, B)

Person	Affiliation	Responsibilities
Claude Amsler	Bern	Notes
Michael Doser	CERN	Management, notes
Simon Eidelman	Novosibirsk	Literature, notes
Thomas Gutsche	Tübingen	Theory, notes
Christoph Hanhart	Jülich	Theory, notes
Brian Heltsley	Cornell	Notes
Juan-Jose Hernández-Rey	Valencia	Notes
Alberto Masoni	Cagliari	Notes
Sergio Navas	Granada	$c\bar{c}$ fit, notes
Claudia Patrignani	Genova	$c\bar{c}$ fit, notes
Stefan Spanier	Knoxville	Notes
Nils Törnqvist	Helsinki	Theory, notes
Graziano Venanzoni	Frascati	Notes

If you have comments on the listings: Just approach any us

The current Naming Scheme

PDG pages $\rightarrow$ Reviews Tables Plots
$\rightarrow$ Constants, Units, Atomic and Nuclear Properties
$\rightarrow$ Naming Scheme For Hadrons (Roos & Wohl, 2004)

Rules

- As long as quantum numbers unknown use $X(mass)$
- When Quantum numbers known: use Quark Model Name and
  - put quark level, if spectroscopic identity known (e.g. $\Upsilon(2S)$)
  - put mass in brackets otherwise (e.g. $\Upsilon(11020)$)

(Potential) Problems

- Rules tell us to change various names, e.g.
  $X(3872) \to \chi_{c1}(3872)$
  $Y(4260) \to \psi(4260)$

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

$f_0(500)$ or σ was $f_0(600)$	$I^G(J^{PC}) = 0^+(0^{++})$

A REVIEW GOES HERE – Check our WWW List of Reviews

- One has to decide when an identity is known, e.g.
  $\psi(2S)$ or $\psi(3686)$

- There is no suggestion for a name for the charged states
  Name should tell quantum numbers ....