Multiquark Resonances

AD Polosa
Cern and Sapienza University of Rome

EXOTIC RESONANCES

— $X^0(3872)$ — No charged partners observed: $X^\pm$?
1^{++} — Isospin violations: $X \to \psi\rho / X \to \psi\omega \sim 1$
Very narrow $\Gamma < 1$ MeV
Almost degenerate w/ $\bar{D}^0 D^{*0}$ & $\psi\rho$

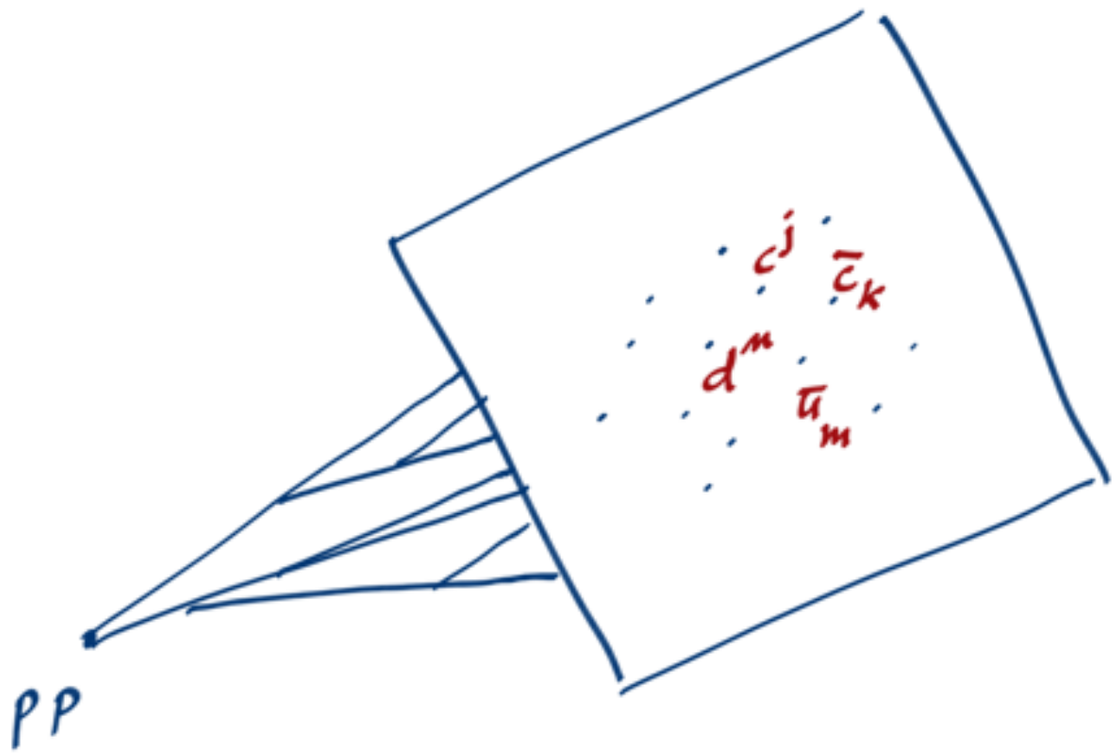
— $Z_c^{0,\pm}(3900)$ — Charged & neutral!
$Z_c'^{\pm}(4020)$ — The lowest is very close in mass to X^0
1^{+-}

— $Z_b(10610)$ — There is no X_b^0 (≈ 10600)
$Z_b(10650)$
1^{+-}

— $X^0(4140)$ — Together w/ $X(4274)$, $X(4500)$, $X(4700)$
1^{++} — recently observed by LHCb.

HADRONIZATION OF EXOTIC RESONANCES

All should be searched in prompt pp collisions at LHC



The relative motion must be compatible with the formation of a <u>compact tetraquark</u>

$$\epsilon_{ijn}\, c^j d^n \;\; \epsilon^{ikm}\, \bar{c}_k\, \bar{u}_m$$

(Virial theorem $\bar{T}(=-\bar{E}) = \frac{1}{2} m_c \alpha_s^2(2m_c) \approx 50\,\mathrm{MeV}$)

'HADRONIZATION STATE'

Superposition with unknown coefficients

$$\Psi = [cd]_S[\bar{c}\bar{u}]_{S'} + \psi\pi^- + \psi'\pi^- + \eta_c\rho + \bar{D}D^* + \bar{D}^*\bar{D}^*$$

$$= \Psi_d + \sum_i \Psi_{m_i}$$

$$\boxed{\Psi = \Psi_Q + \Psi_P = Q\Psi + P\Psi}$$

$$Q + P = \mathbb{1} \quad \& \quad Q \cdot P = PQ = 0$$

$$H\Psi = E\Psi \quad \begin{cases} (E - H_{PP})\Psi_P = H_{PQ}\Psi_Q \\ (E - H_{QQ})\Psi_Q = H_{QP}\Psi_P \end{cases}$$

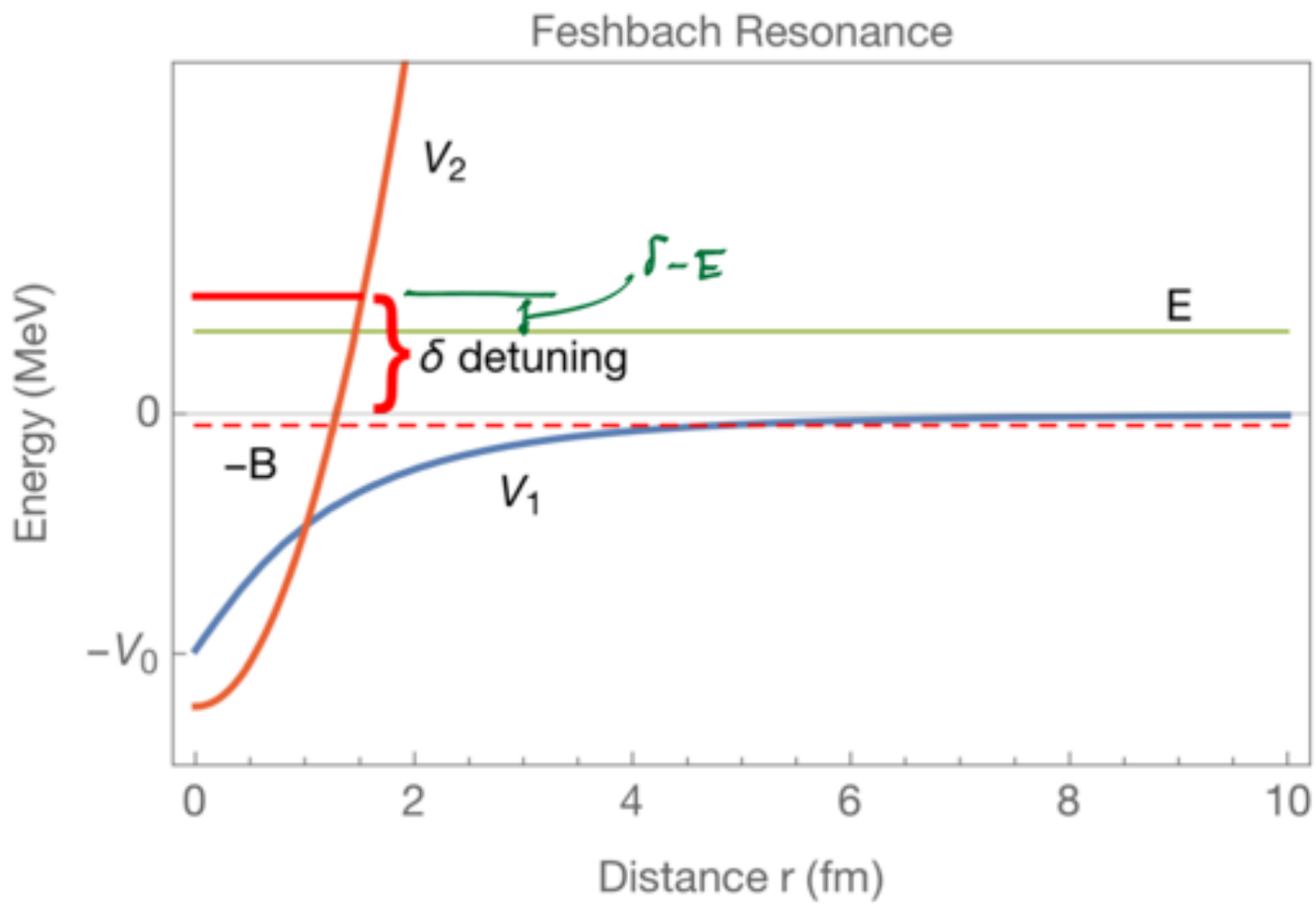
$$H_{PP} = H_0 + V_1$$
$$H_{QQ} = H_0 + V_2$$

$$\& \quad \boxed{(E - H_{PP} - V_I)\Psi_P = 0}$$

EFFECTIVE INT. IN THE P SPACE ($P \to Q \to P$)

$$V_I = H_{PQ}\frac{1}{E - H_{QQ} + i\epsilon}H_{QP}$$

OPEN & CLOSED CHANNELS



Because of V_I the scattering length in P is

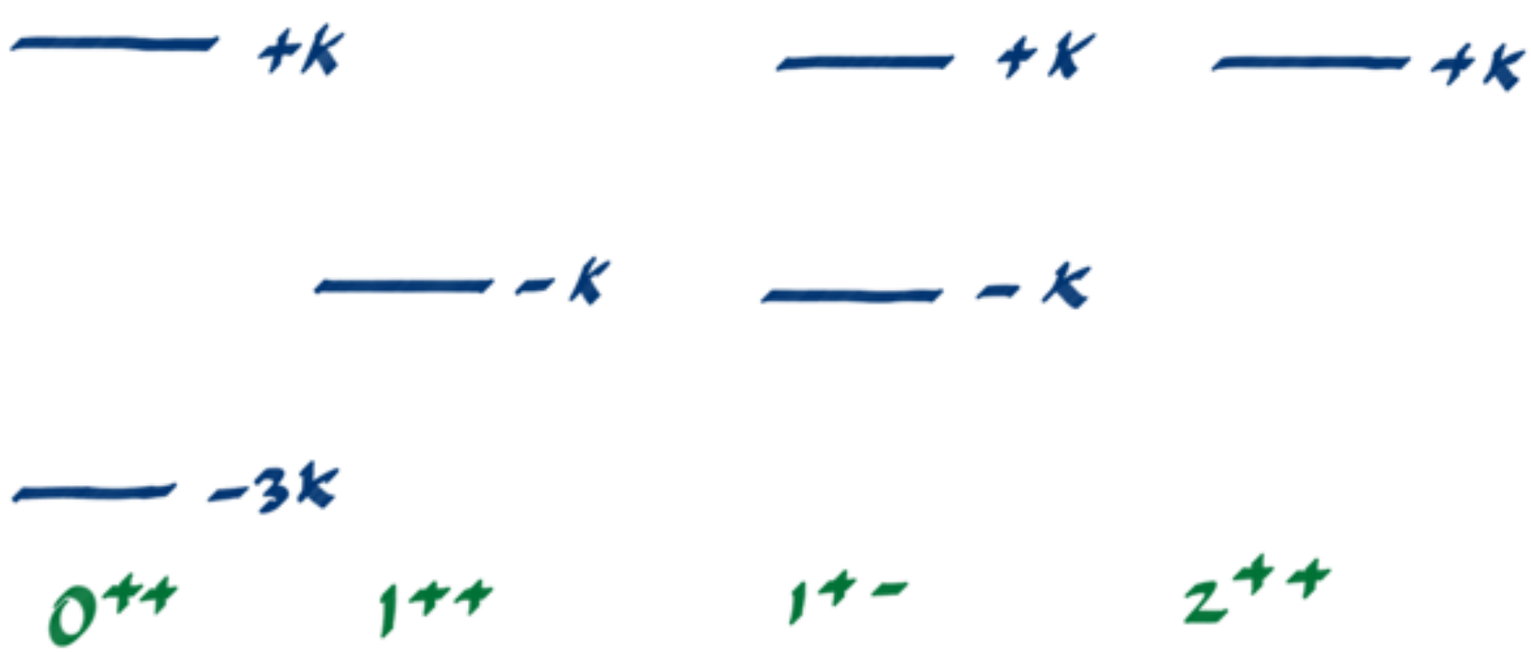
$$a = a_p - c\,\frac{|\langle \Psi_n | H_{QP} \Psi_\alpha \rangle|^2}{E_n - E_\alpha + i\epsilon} \qquad (c>0)$$

$$\equiv \left(1 - \frac{x}{\delta - E + i\epsilon}\right) a_p$$

DIQUARKONIUM MASSES (Q-SPACE)

$$H \approx 2k\left(\vec{S}_Q \cdot \vec{S}_q + \vec{S}_{\bar{Q}} \cdot \vec{S}_{\bar{q}}\right)$$

The spectrum is as follows



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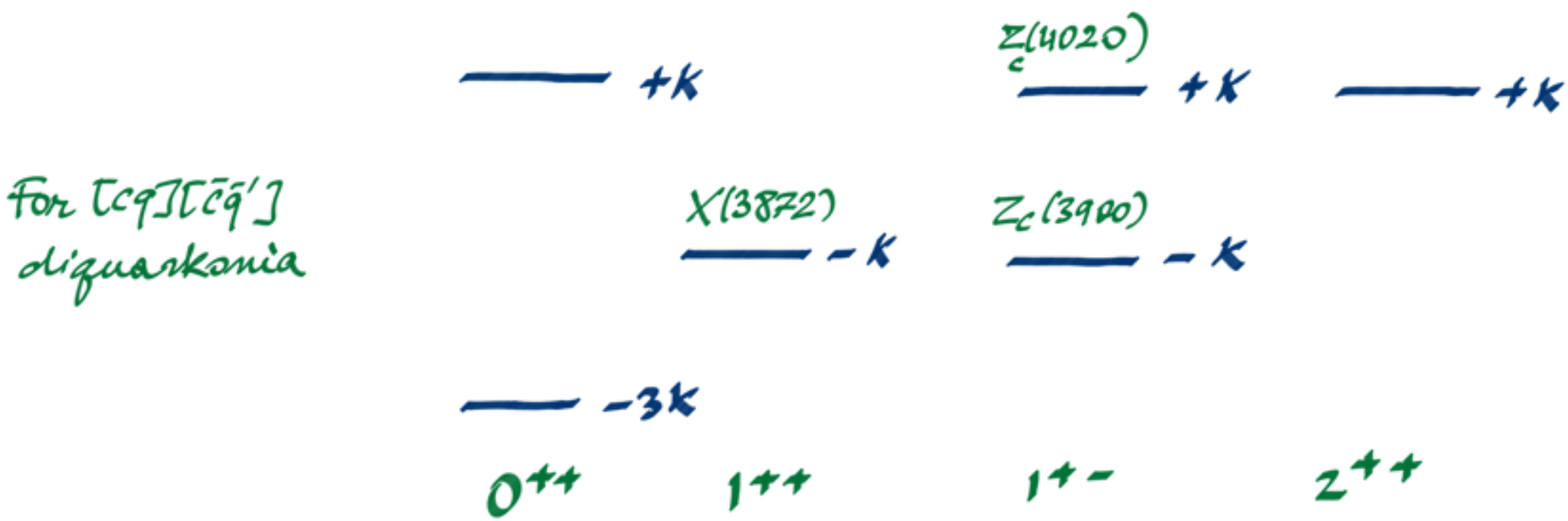
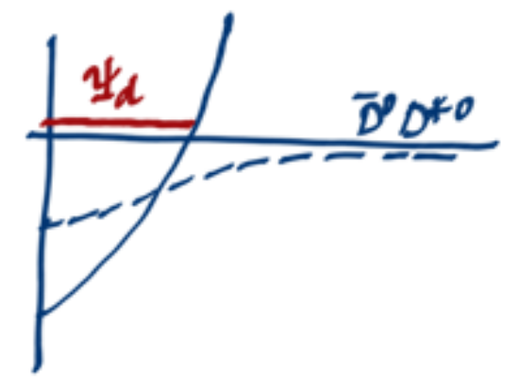


DIQUARKONIA & MOLECULES

'CLOSED' SPACE Q	'OPEN' SPACE P
$\Psi_d(X_d^0) \equiv [cd]_0[\bar{c}\bar{d}]_1 + [cd]_1[\bar{c}\bar{d}]_0$ $\sim \frac{\bar{D}^{*-}D^+ - D^{*+}\bar{D}^-}{\sqrt{2}} + i\,\frac{\psi\wedge\rho^0}{\sqrt{2}}$ $\Psi_d(X_4^0)$ does not work $\rightarrow$ I violation $M(X^+) \simeq M(X^0) < M(D^+\bar{D}^{*0}) \rightarrow$ no $X^\pm$	$\Psi_m \sim \bar{D}^0 D^{*0}$ 
$\Psi_d(Z_c^+) \sim \frac{\eta_c\rho^+ - \psi\pi^+}{\sqrt{2}} - i\,\frac{\bar{D}^{*0}\wedge D^{*+}}{\sqrt{2}}$ $M(Z_c^+) > M(D^+\bar{D}^{*0}) \rightarrow$ yes Z^+	$\Psi_m \sim \bar{D}^0 D^{*0}$
$\Psi_d(Z_c'^+) \sim \frac{\eta_c\rho^+ + \psi\pi^+}{\sqrt{2}} - \frac{\bar{D}^0 D^{*+} + D^+\bar{D}^{*0}}{\sqrt{2}}$ $M(Z_c'^+) > M(D^{*+}\bar{D}^{*0}) \rightarrow$ yes Z'^+	$\Psi_m \sim D^{*0}\bar{D}^{*0}$

SAME FOR Z_b RESONANCES BUT $M(X_b^0)$ IS ESTIMATED $< M(\bar{B}^0 B^{*0})$
(deduced from the splitting $Z_c - X$)

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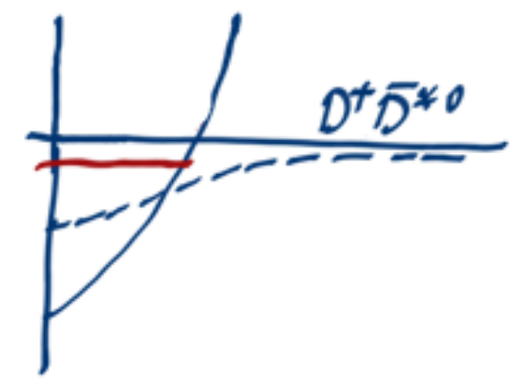
$\Psi_d(X_d^0) \equiv [cd]_0[\bar{c}\bar{d}]_1 + [cd]_1[\bar{c}\bar{d}]_0$ $\sim \dfrac{\bar{D}^{*-}D^+ - D^{*+}\bar{D}^-}{\sqrt{2}} + i\,\dfrac{\psi\wedge\rho^0}{\sqrt{2}}$ $\Psi_d(X_4^0)$ does not work $\rightarrow$ I violation $M(X^+) \simeq M(X^0) < M(D^+\bar{D}^{*0}) \rightarrow$ no $X^\pm$	$\Psi_m \sim \bar{D}^0 D^{*0}$ 
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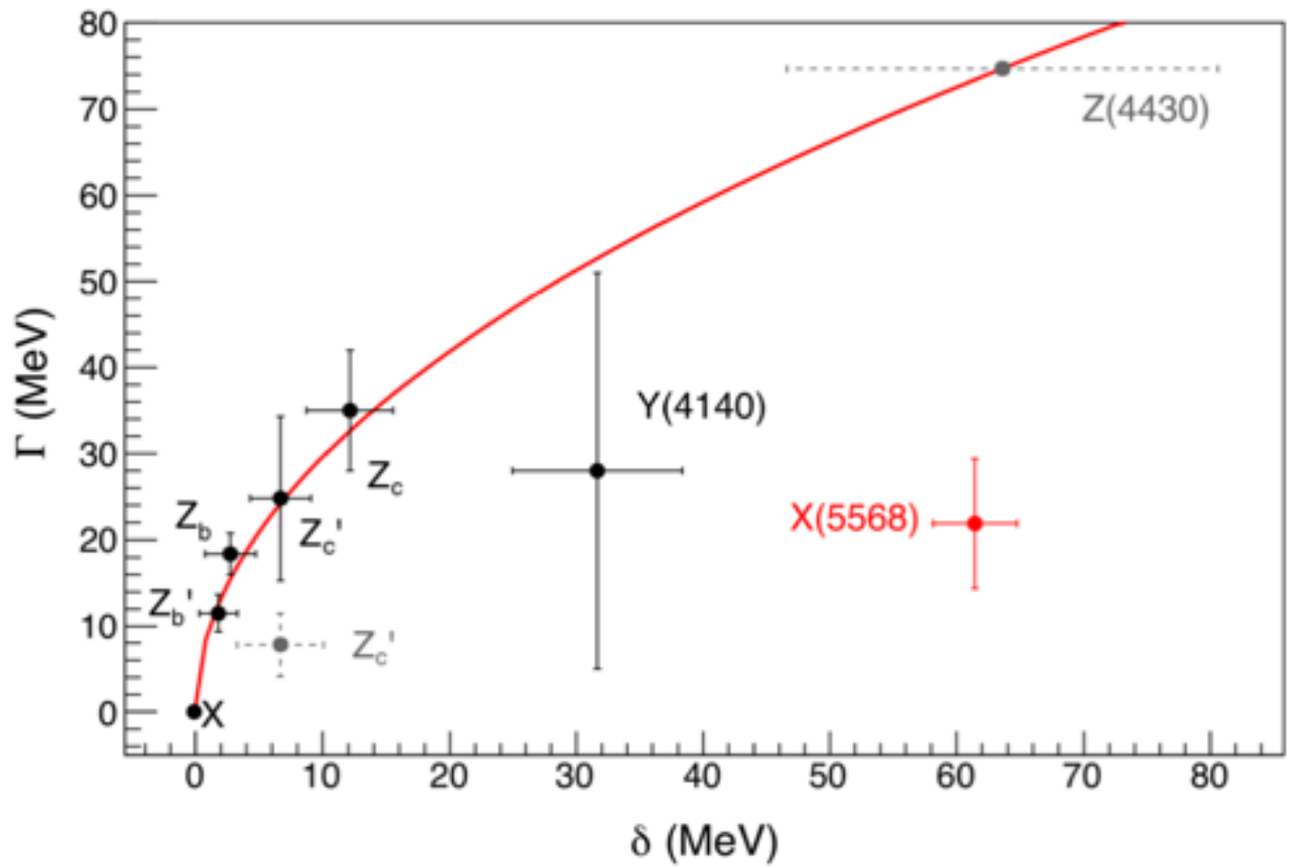
TOTAL WIDTHS

N.B. δ (detuning) = distance of the level in Q from the CLOSEST molecular threshold from BELOW.

$$\Gamma \sim (2m)^{1/2} \, |\varkappa a_p| \sqrt{\delta}$$



X(5568) claimed by D0 in $B_s^0 \pi^+$ in FEB 2016

A. ESPOSITO, A. PILLONI, ADP 1603.07667 (PLB)

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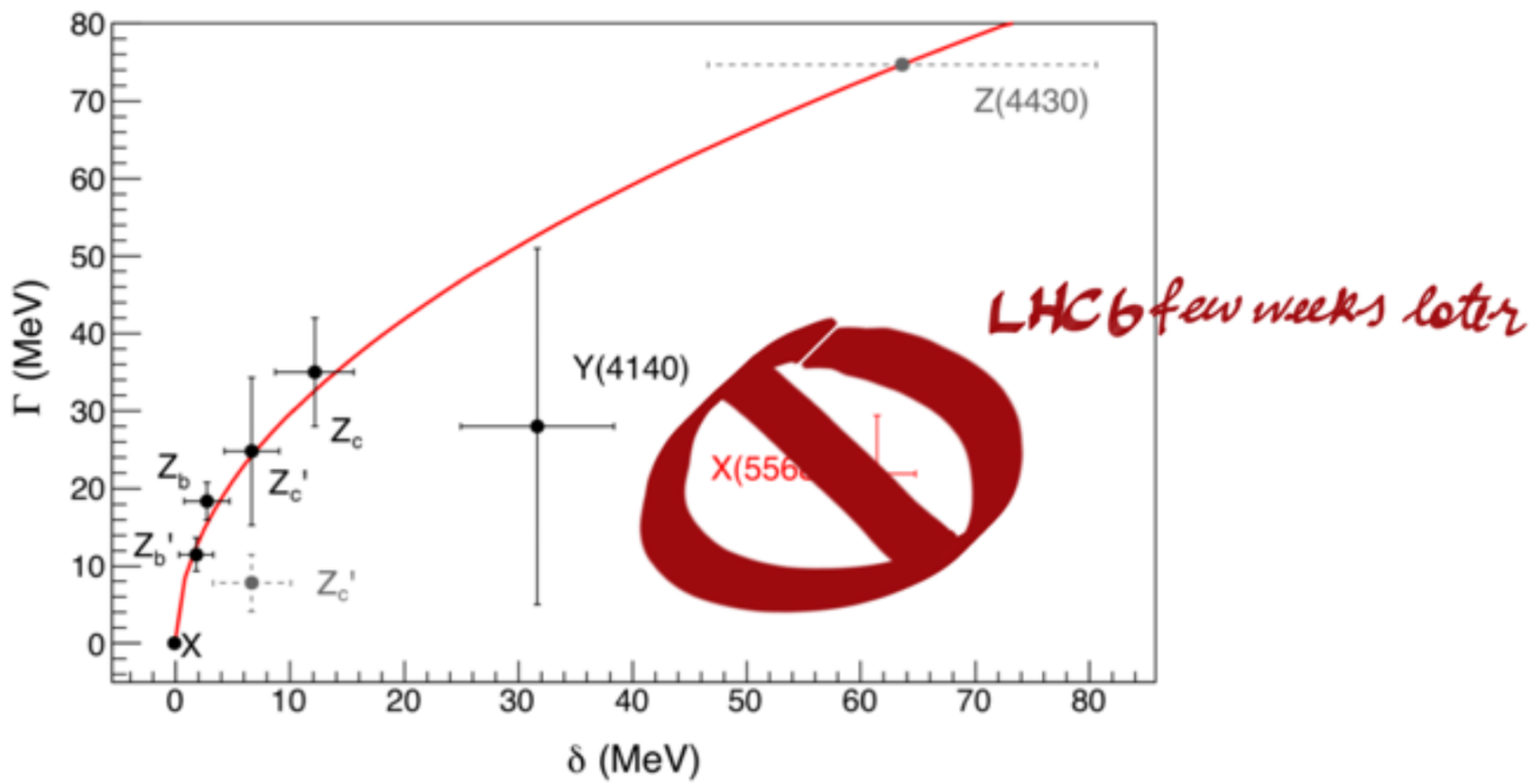
$0 < \delta < E_{max} < T$ in [Q9][Q9]



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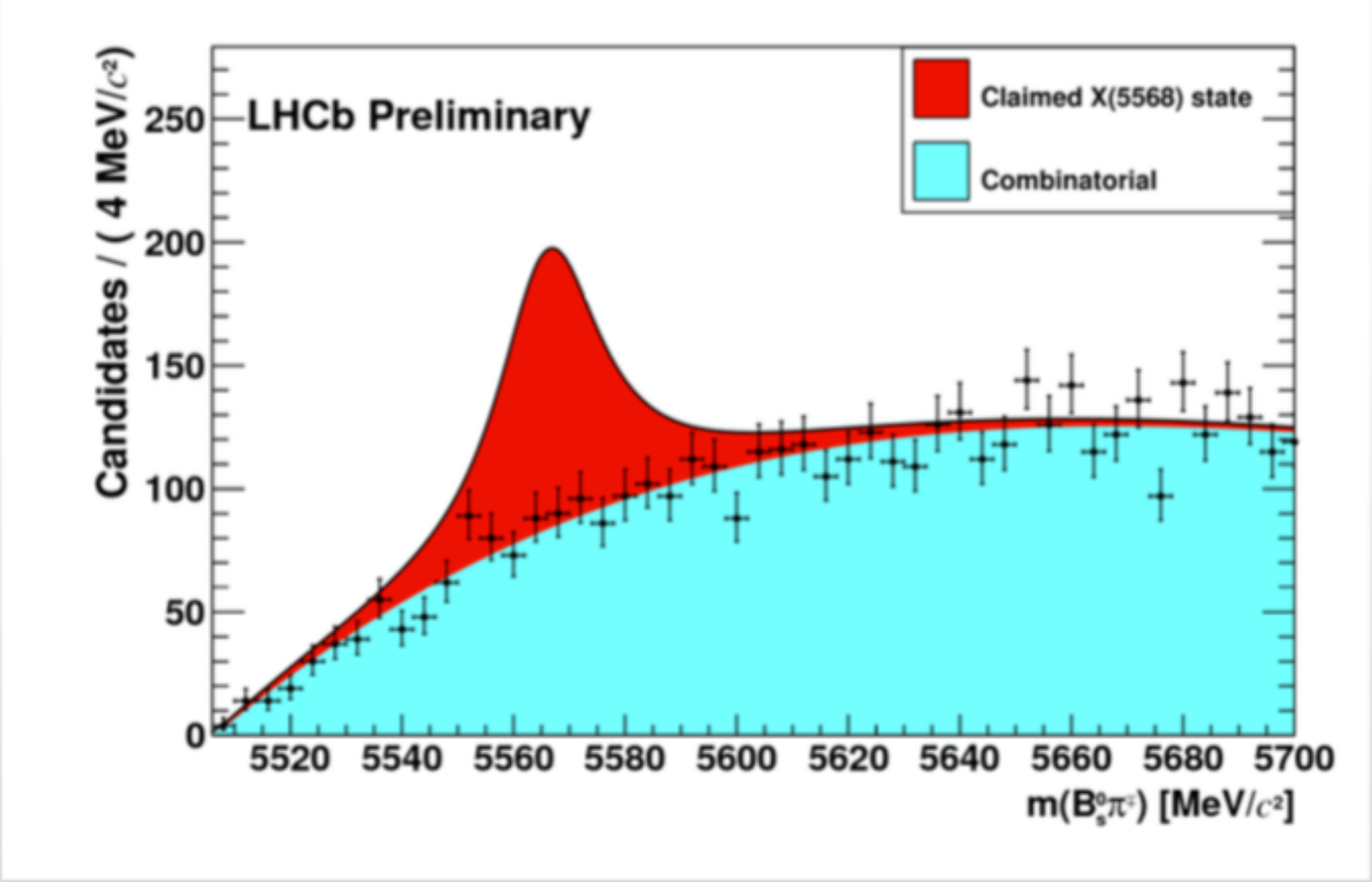
JUST FOR CURIOSITY…

LHCb-CONF-2016-004

If $\rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D\emptyset}} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(B_s) > 10$ GeV/c)



DIQUARKONIUM & $X_b(5568)$

$$M_{Z_b'} - M_{Z_b} = 2k_{bq}$$

$$M_{Z_b'} + M_{Z_b} = 4m_{[bq]}$$

$$M(X_b[\bar{b}\bar{q}][sq']) = m_{[bq]} + m_{[sq]} + 2k_{bq}\,\vec{S}_{\bar{b}}\cdot\vec{S}_{\bar{q}} + 2k_{sq}\,\vec{S}_s\cdot\vec{S}_q$$

both diquarks w/ $S=0$
0^{++}

$$= m_{[bq]} - 3/2\,k_{bq} + \underbrace{(m_{[sq]} - 3/2\,k_{sq})}_{m_{a_0}/2}$$

$$\simeq \underline{5771\ \text{MeV}}$$

— Too large detuning δ wrt $B_s\pi$ threshold ($\delta > E_{max}$)

— Very close to BK threshold. If underestimated by a few MeVs, a resonance might appear just above the BK (same quark content).

SEARCH IN BK^+!

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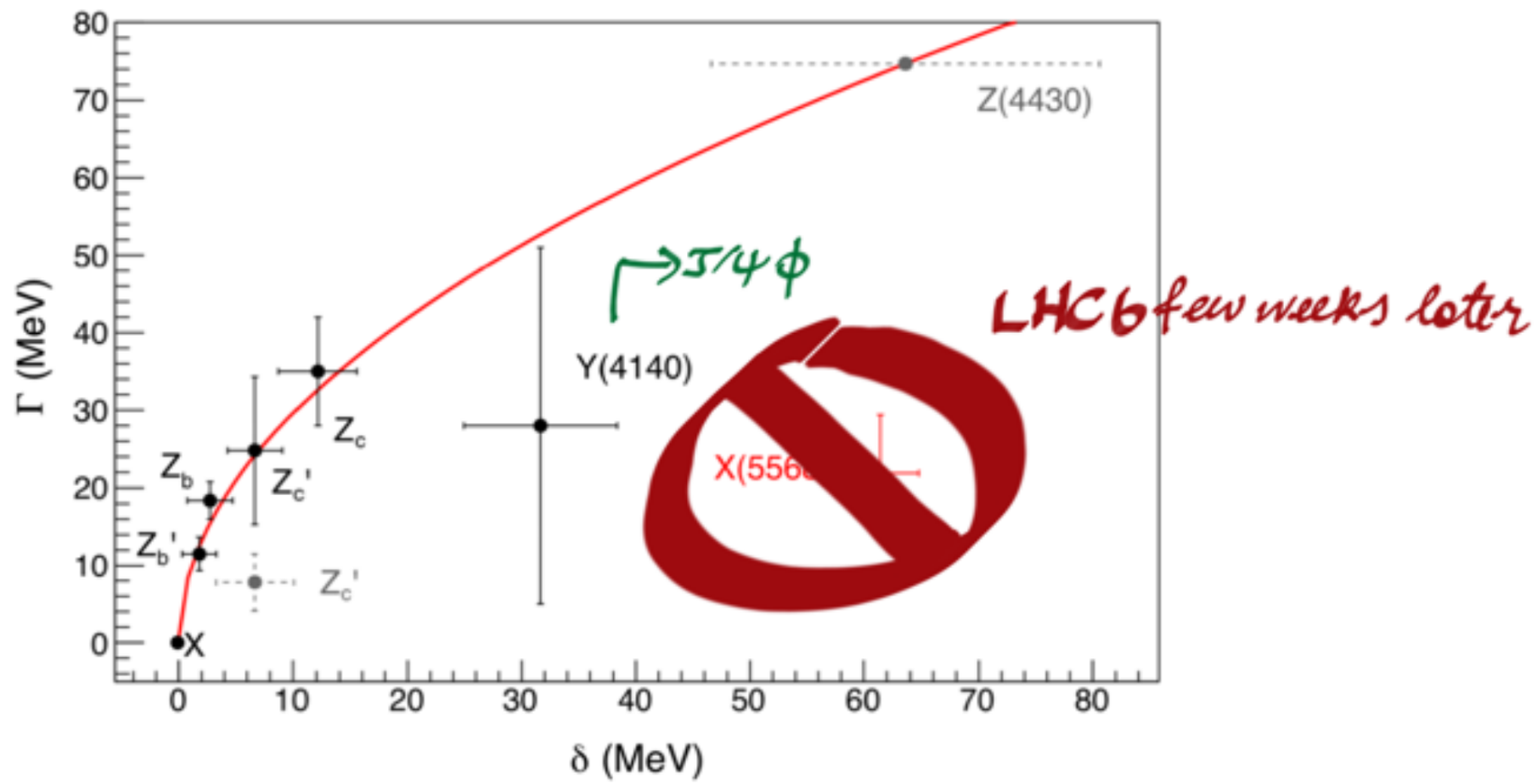
$0 < \delta < E_{max} < T$ in [Q9][Q9]



$$\Psi_d(X(4140)) \sim \frac{\bar{D}_s^{*-} D_s^{+} - D_s^{*+} \bar{D}_s^{-}}{\sqrt{2}} + i \frac{\psi \wedge \phi}{\sqrt{2}}$$

Ψ_m might be taken orthogonal but there will be no single threshold dominance: δ from the lower $\bar{D}_s^{*-} D_s^{+}$

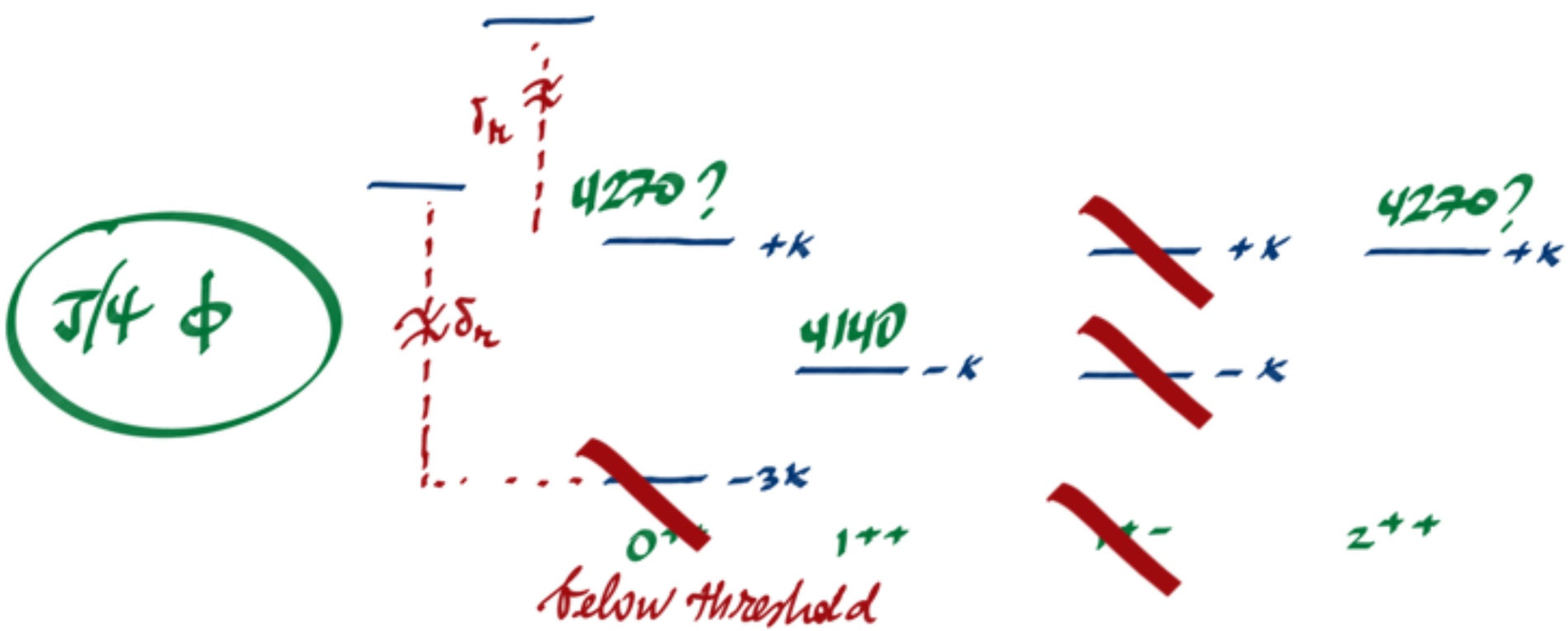
X(4140), X(4274), X(4500), X(4700)

as from LHCb @ BLOIS (see S. Stone)

28 Recontres de Blois, June 2, 2016

$$X(4140) = [cs]_0[\bar{c}\bar{s}]_1 + [cs]_1[\bar{c}\bar{s}]_0$$

$X(4140)$	1^{++}	$2m_{[cs]} - K$
$X(4270)$	$0^{++} \vee 2^{++}$	$2m_{[cs]} + K$
$X(4500)$	0^{++}	$2m_{[cs]} - 3K + \delta_R$
$X(4700)$	0^{++}	$2m_{[cs]} + K + \delta_R$



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$X(4140)$	1^{++}	$2m_{[cs]} - K$	4146	
$X(4270)$	$0^{++} \vee 2^{++}$	$2m_{[cs]} + K$	4273	(MeV)
$X(4500)$	0^{++}	$2m_{[cs]} - 3K + \delta_r$	4506	
$X(4700)$	0^{++}	$2m_{[cs]} + K + \delta_r$	4704	

with
$$m_{[cs]} = 2100 \text{ MeV}$$
$$K_{cs} = 54 \text{ MeV}$$
$$\delta_r = 460 \text{ MeV}$$

N.B.
$$m_{[cs]} = m_{[cq]} + \underbrace{(m_s - m_q)}_{120 \text{ MeV from } \underline{10} \text{ of } SU(3)} \simeq 2100 \text{ MeV}$$

$$K_{cs} = K_{cq} \frac{m_q}{m_s} \simeq 45 \pm 3 \text{ MeV}$$

EXOTIC RESONANCES

— $X^0(3872)$ 1^{++}

No charged partners observed: $X^\pm$ ✓

Isospin violations: $X \to \psi\rho / X \to \psi\omega \sim 1$ ✓

Very narrow $\Gamma < 1$ MeV ✓

Almost degenerate w/ $\bar{D}^0 D^{*0}$ & $\psi\rho$ related

— $Z_c^{0,\pm}(3900)$
$Z_c'^{\pm}(4020)$
1^{+-}

Charged & neutral! ✓

The lowest is very close in mass to X^0 ✓

— $Z_b(10610)$
$Z_b(10650)$
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There is no X_b^0 (≈ 10600) ✓

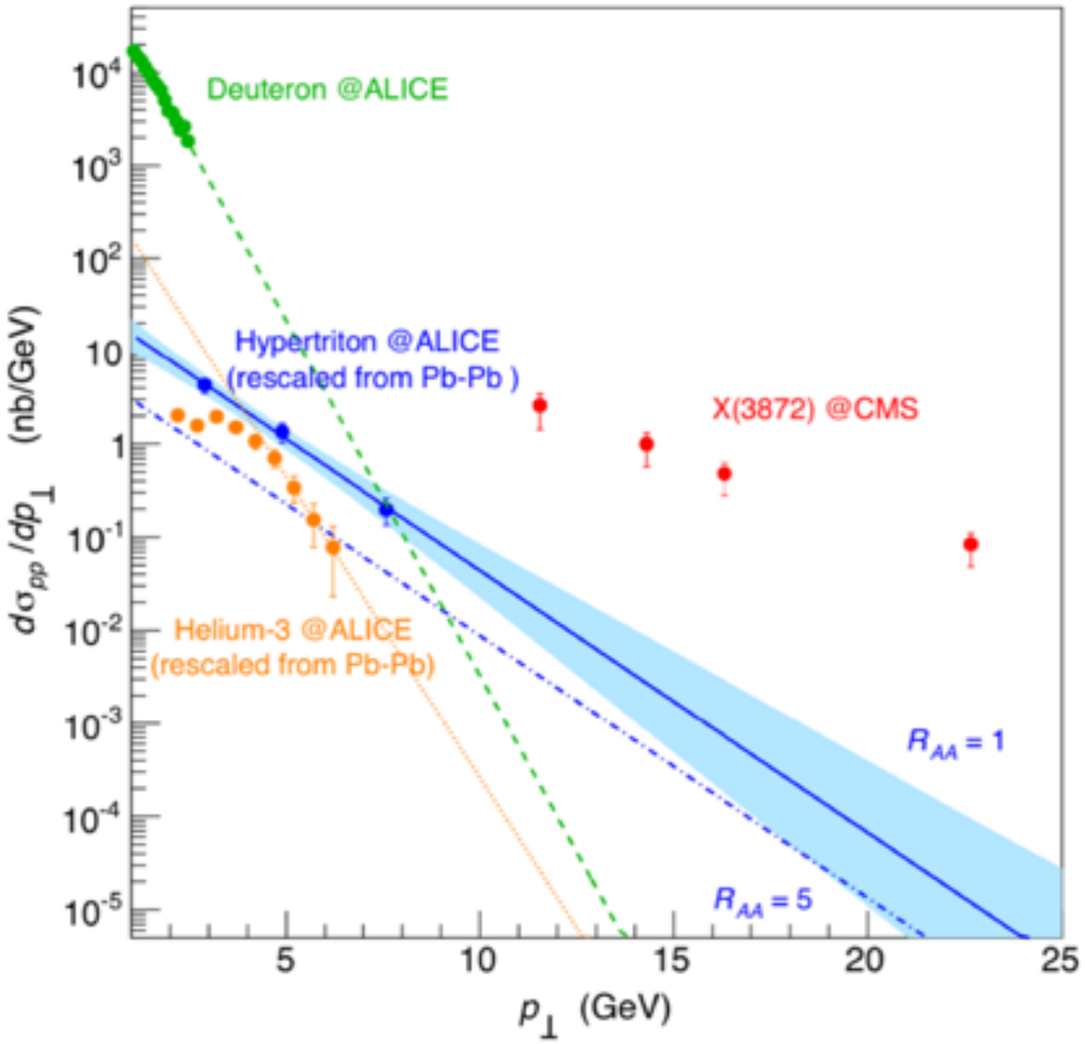
— $X^0(4140)$ 1^{++}

Together w/ $X(4274)$, $X(4500)$, $X(4700)$ ✓
recently observed by LHCb.

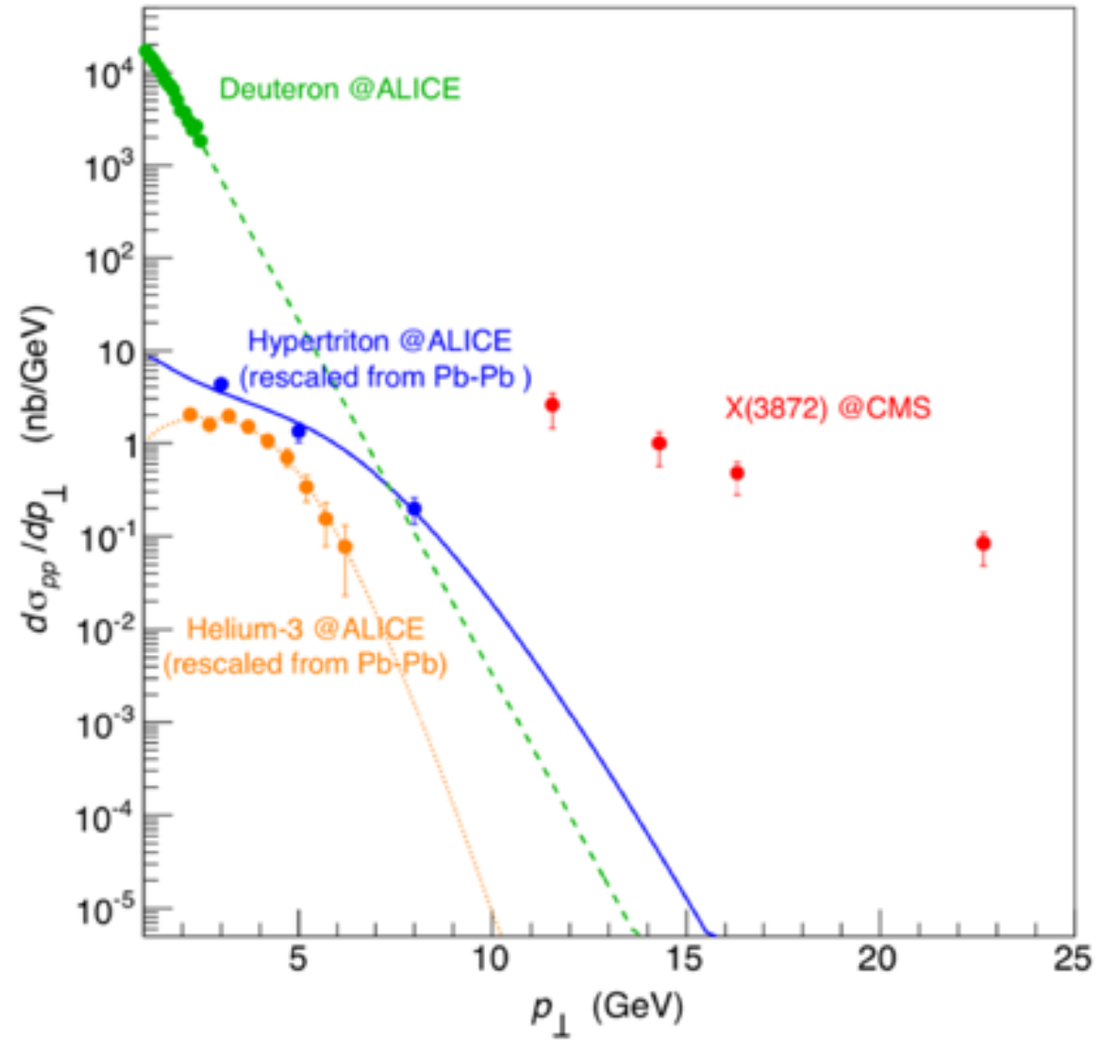
but: one of 1^{++} states is 0^{++} or 2^{++}.

DATA FROM ALICE

For those who think that we are observing only hadron molecules



Exponential fit –



'Blastwave' fit –

A Esposito et al. PRD 92 (2015) 034028

Pentaquarks

based on 1507.04980 with L. Maiani and V. Riquer (Sapienza U.)

THE PENTAQUARK

Highly undesirable option for molecules (before discovery)
Perfect molecule (after discovery)

LHCb 2015

$$\Lambda_b(bud) \to K^- \mathbb{P}^+$$
$$\hookrightarrow J/\psi\, p$$

$$\mathbb{P}^+ = \bar{c}\, c\, u\, u\, d \Rightarrow \text{negative parity}$$

TWO STATES OBSERVED

$$J^P = 3/2^- \quad @ \quad 4380 \text{ MeV}$$

$$J^P = 5/2^+ \quad @ \quad 4550 \text{ MeV}$$

$L=0$ & $L=1$ Pentaquarks?

Note: Lower baryons have $P=+$ / pentaq. have $P=-$!
Lower mesons have $P=-$ / tetraq. have $P=+$

MASS DIFFERENCE

ISN'T $\Delta M = 170$ MeV too SMALL for one unit of L?

($\Delta M = 300$ MeV for $\Lambda(1405) - \Lambda(1116)$)

On the other hand, from $\Sigma_c - \Lambda_c$ we find

$$M_{[qq']_{S=1}} - M_{[qq']_{S=0}} \simeq 200 \text{ MeV}$$

So

$$\mathbb{P}(3/2^-) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=1} \quad @\ L=0$$

$$\mathbb{P}(5/2^+) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=0} \quad @\ L=1$$

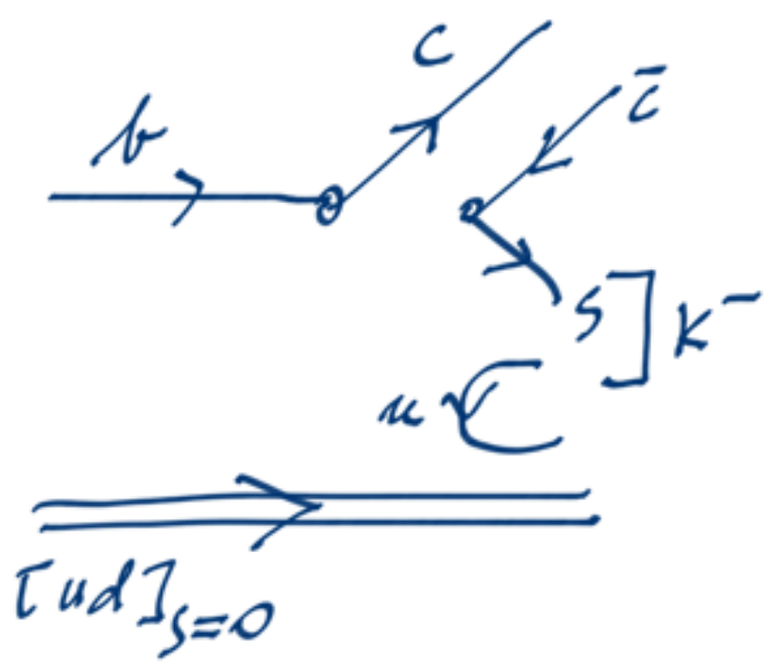
... combine diquark spin & orbital angular momentum –

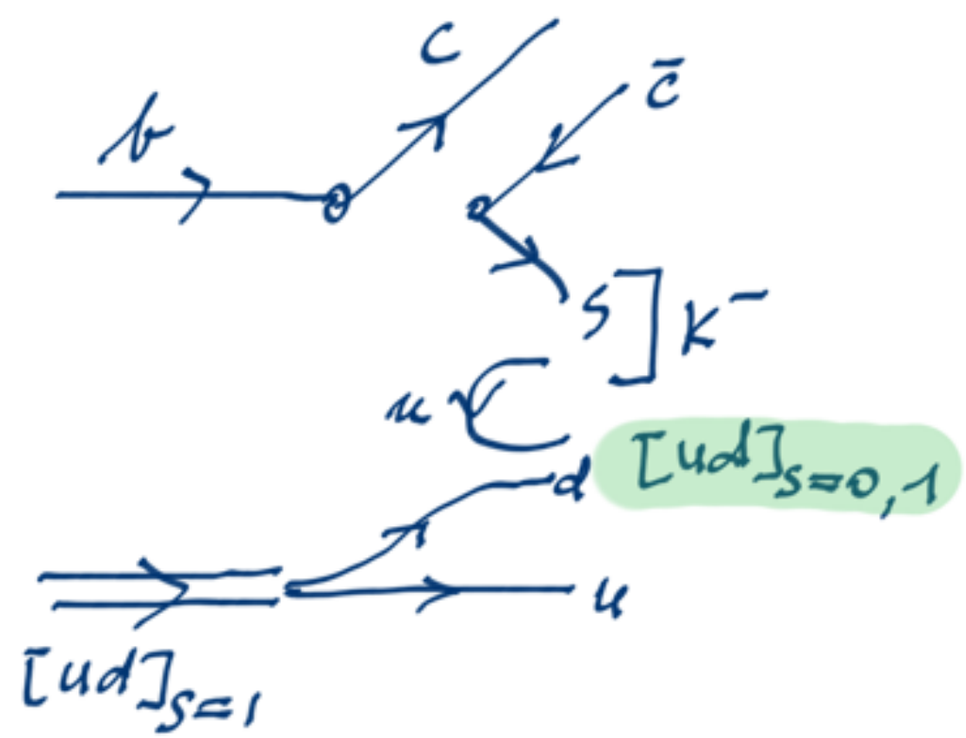
Other states?

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

$\Lambda \to K^- p^+$

Λ_b baryon might contain a $[ud]_{S=0}$, "good" diquark. But $P(3/2^-)$ should contain $[ud]_{S=1}$, whereas $P(5/2^+)$ has $[ud]_{S=0}$.





One can show that both pentaquarks have $S_{c\bar{c}} = 1$ so that HQ spin cons. allows decay into J/ψ.

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

Flavor

$$\langle \mathbb{P}, M | H_w (\Delta I = 0, \Delta S = -1) | \Lambda_b \rangle$$

8_F $\quad$ 3_F (from s,d,u) $\quad$ $\bar{3}_F$ (from [ud])

therefore $\mathbb{P}$ is either 8 or 10 (*)

We might expect

$$\Lambda_b \to \pi \mathbb{P}_{10}^{S=-1} \to \pi\, J/\psi\, \Sigma(1385)$$

$$\Lambda_b \to K \mathbb{P}_{10}^{S=-2} \to K\, J/\psi\, \Xi(1530)$$

or even

$$\Omega_b \to \phi \mathbb{P}_{10}^{S=-3} \to \phi\, J/\psi\, \Omega^-(1672)$$

(*) $\begin{cases} 8 \otimes 10 = 8 \oplus 10 \oplus 27 \oplus 35 \\ 8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27 \end{cases}$