Multiquark resonances

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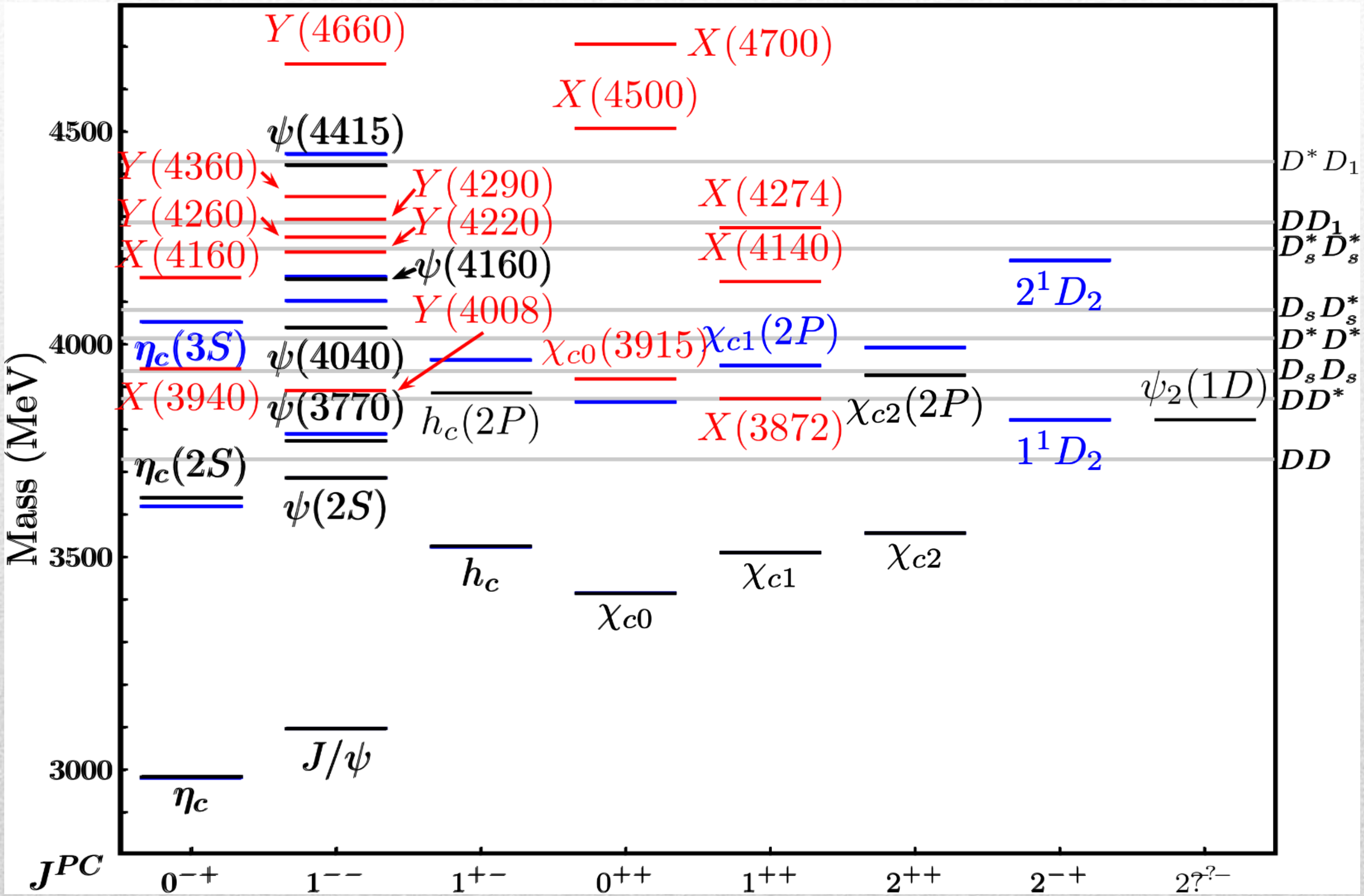
Outline

- Compact tetraquarks
- Production of exotics at LHC
- Hybridized tetraquarks
- Conclusions

Exotic landscape



A host of unexpected resonances have appeared

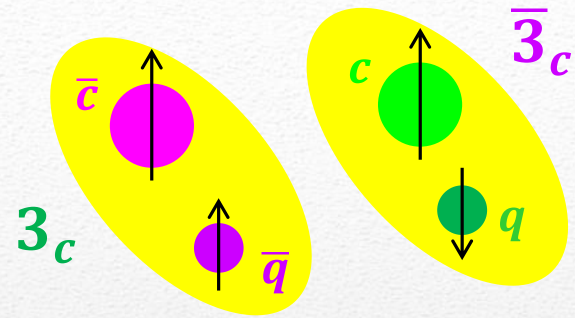
decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Tetraquark

In a constituent quark model, we can think of a **diquark-antidiquark compact state**

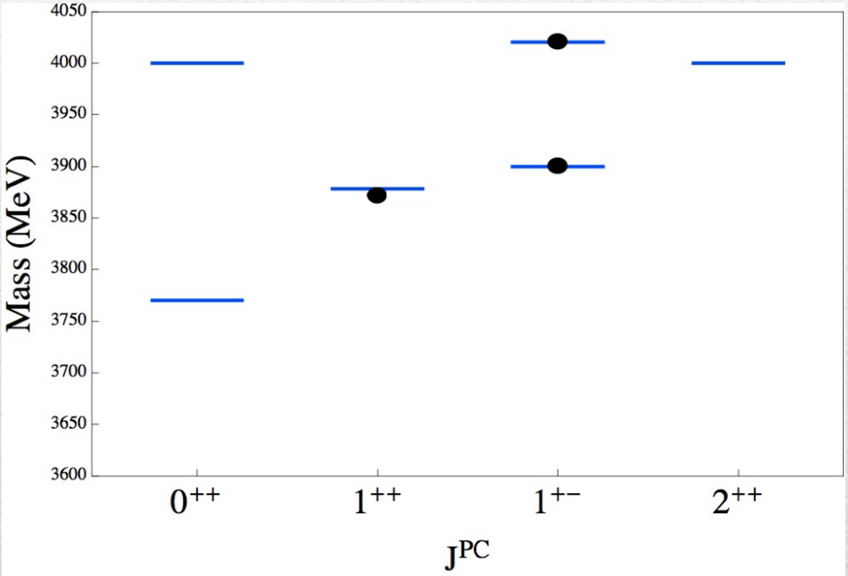
$$[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} + h.c.$$



Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to color-spin hamiltonian (all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

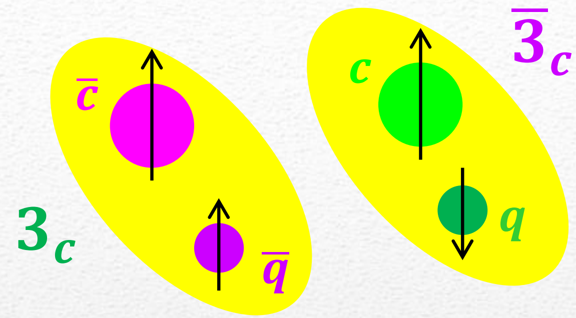
$$H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij}\, \vec{S_i} \cdot \vec{S_j}\, \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$



Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

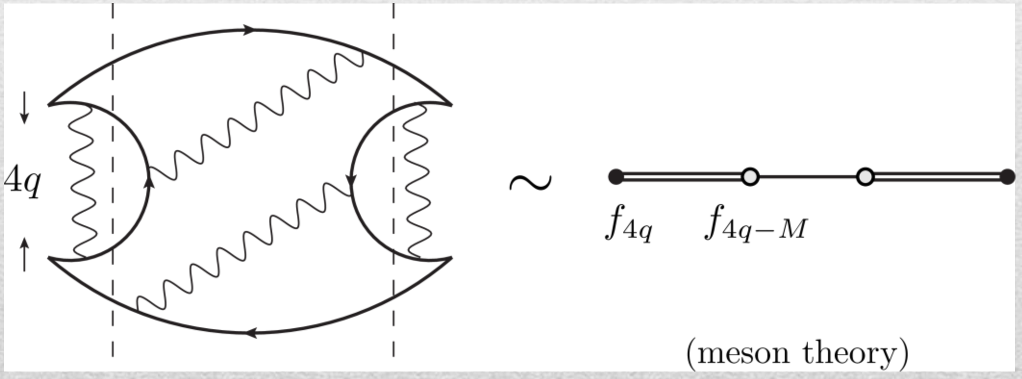
New ansatz: the diquarks are compact objects spacially separated from each other, only $\kappa_{cq} \neq 0$
Existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

Tetraquark at large-N



Some discussions about the existence of tetraquark poles in the large-N limit have been recently raised

S. Weinberg, PRL110 261601
Kencht and Peris, PRD88, 036016
Cohen and Lebed, PRD89, 054018
Cohen and Lebed, PRD90, 016001
Maiani, Polosa, Riquer, JHEP1606, 160



The poles can appear at subleading order (nonplanar diagrams), and give rise to narrow objects

See T. Cohen's talk on Tuesday 17:30

Tetraquark: new ansatz

Maiani, Piccinini, Polosa, Riquer PRD89 114010

J^{PC}	$cq\,\bar{c}\bar{q}$	$c\bar{c}\,q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\vert 0,0\rangle$	$1/2\vert 0,0\rangle + \sqrt{3}/2\vert 1,1\rangle_0$	$X_0(\sim 3770\text{ MeV})$	$\eta_c, J/\psi$ + light mesons
0^{++}	$\vert 1,1\rangle_0$	$\sqrt{3}/2\vert 0,0\rangle - 1/2\vert 1,1\rangle_0$	$X_0'(\sim 4000\text{ MeV})$	$\eta_c, J/\psi$ + light mesons
1^{++}	$1/\sqrt{2}(\vert 1,0\rangle + \vert 0,1\rangle)$	$\vert 1,1\rangle_1$	$X_1 = X(3872)$	$J/\psi + \rho/\omega,\ DD^*$
1^{+-}	$1/\sqrt{2}(\vert 1,0\rangle - \vert 0,1\rangle)$	$1/\sqrt{2}(\vert 1,0\rangle - \vert 0,1\rangle)$	$Z = Z(3900)$	$J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$
1^{+-}	$\vert 1,1\rangle_1$	$1/\sqrt{2}(\vert 1,0\rangle + \vert 0,1\rangle)$	$Z' = Z(4020)$	$J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$
2^{++}	$\vert 1,1\rangle_2$	$\vert 1,1\rangle_2$	$X_2(\sim 4000\text{ MeV})$	J/ψ + light mesons

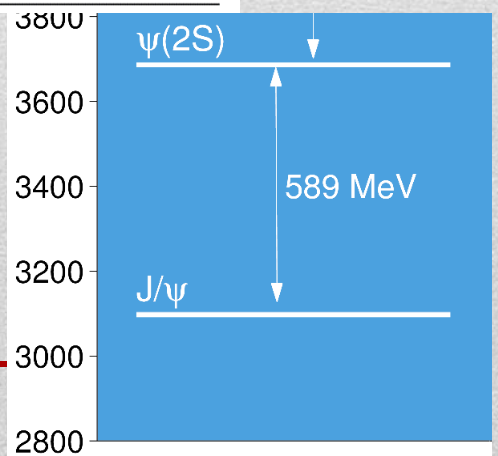
$$\Delta H = \frac{B_c \vec{L}^2}{2} - 2a\,\vec{L}\cdot\vec{S}$$

	$L = 1$	$P(S_{c\bar{c}} = 1) : P(S_{c\bar{c}} = 0)$	Assignment	Radiative Decay
$J/\psi\,\pi\pi$	Y_1	3:1	$Y(4008)$	$\gamma + X_0$
$J/\psi\,\pi\pi$	Y_2	1:0	$Y(4260)$	$\gamma + X$
$h_c\,\pi\pi$	Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
$\Lambda_c^+\Lambda_c^-$	Y_4	1:0	$Y(4630)$	$\gamma + X_2$

actually observed BESIII PRL 112, 092001

Radial excitations
$Z(2S) = Z(4430)$
$Y_1(2P) = Y(4360)$
$Y_2(2P) = Y(4660)$
Decay in $\psi(2S)$ preferably

$M_{Z(4430)} - M_{Z_c} = 586^{+17}_{-26}$ MeV
to compare with charmonium



Tetraquark: the Y states

	$L=1$	$P(S_{c\bar{c}}=1) : P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
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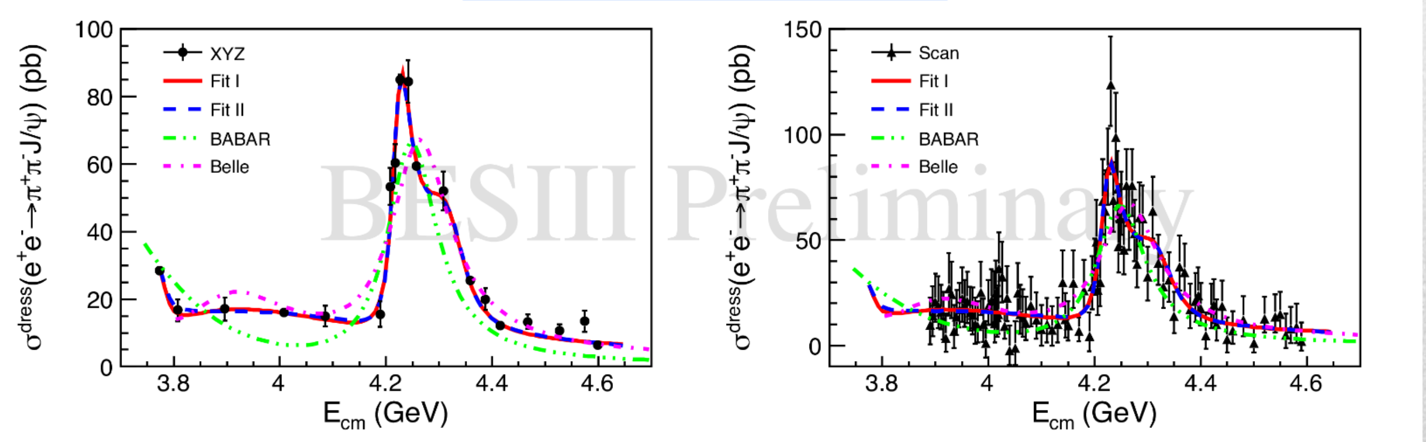
$\Lambda_c^+\Lambda_c^-$	Y_4	1:0	$Y(4630)$	$\gamma + X_2$

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)

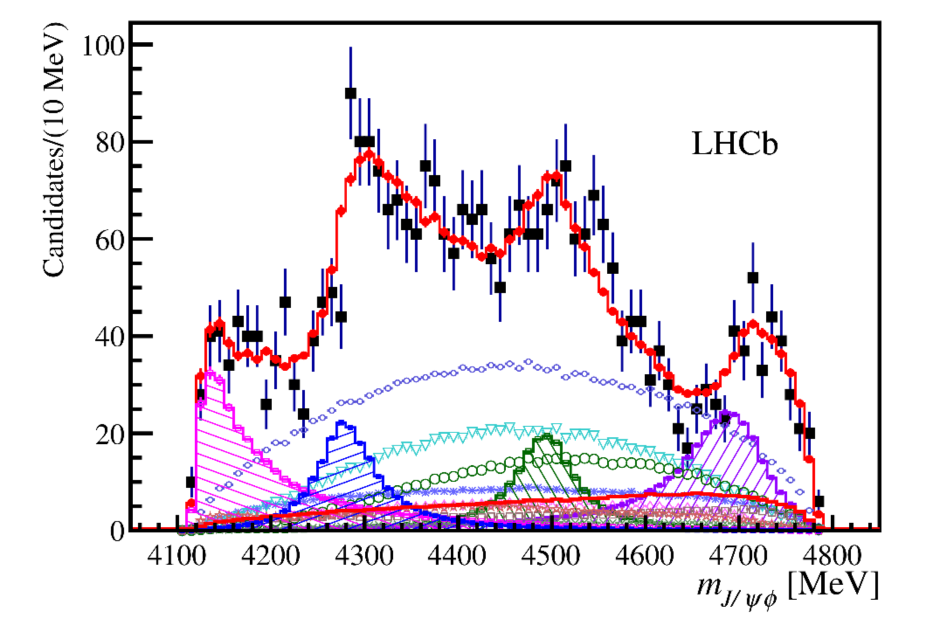
BESIII Preliminary (NEW!)

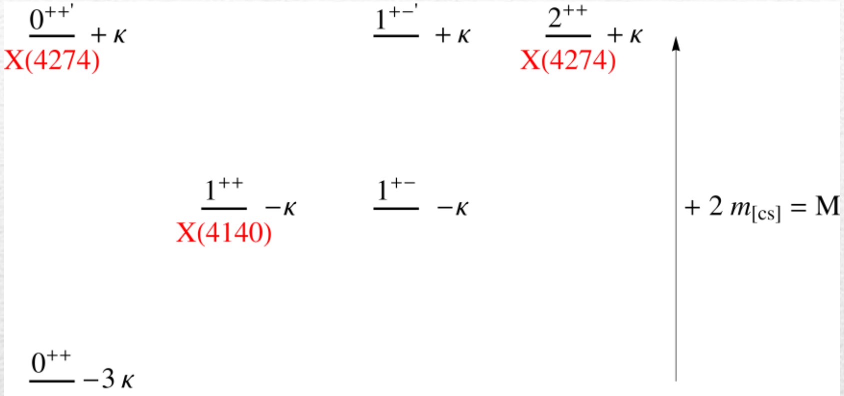
R. Mitchell for BESIII, ICHEP



New data on the Y states are going to change this picture, waiting for a clarification

Tetraquark: the $c\bar{c}s\bar{s}$ states





$$J^{PC} = 0^{++} \quad X_0 = |0,0\rangle_0,\ \ X_0' = |1,1\rangle_0$$

$$J^{PC} = 2^{++} \quad X_2 = |1,1\rangle_2$$

$$J^{PC} = 1^{++} \quad X = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 + |0,1\rangle_1\right)$$

$$J^{PC} = 1^{+-} \quad Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 - |0,1\rangle_1\right)$$

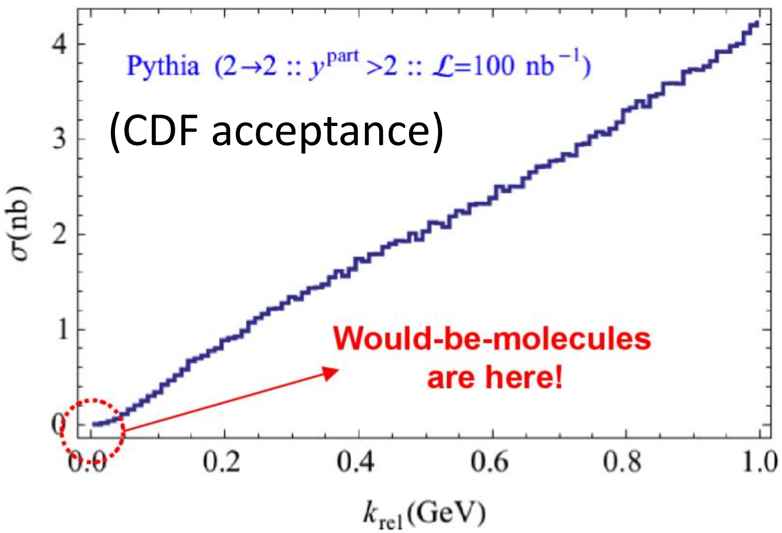
$$Z' = |1,1\rangle_1$$

Good description of the spectrum **but** one has to assume the axial assignment for the $X(4274)$ to be incorrect (two unresolved states with 0^{++} and 2^{++})

Maiani, Polosa and Riquer, arXiv:1607.02405
Esposito, AP, Polosa, to appear

Prompt production of $X(3872)$

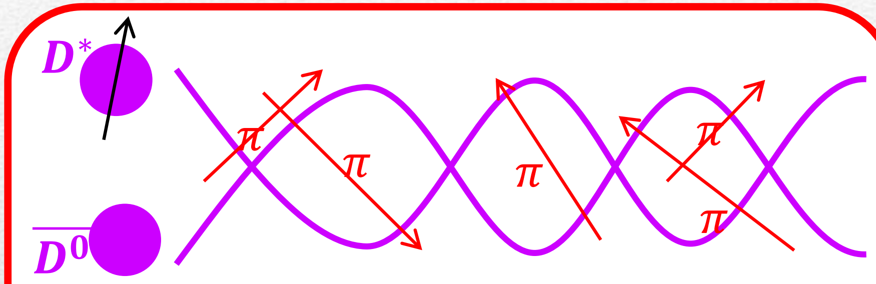
$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders



$$\sigma_{MC}(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1 \text{ nb}$$

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

Bignamini *et al.* PRL103 (2009) 162001



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi$, $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with DD^* propagation. Estimating the effect of these pions increases σ, but not enough

Bignamini *et al.* PLB684, 228-230
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

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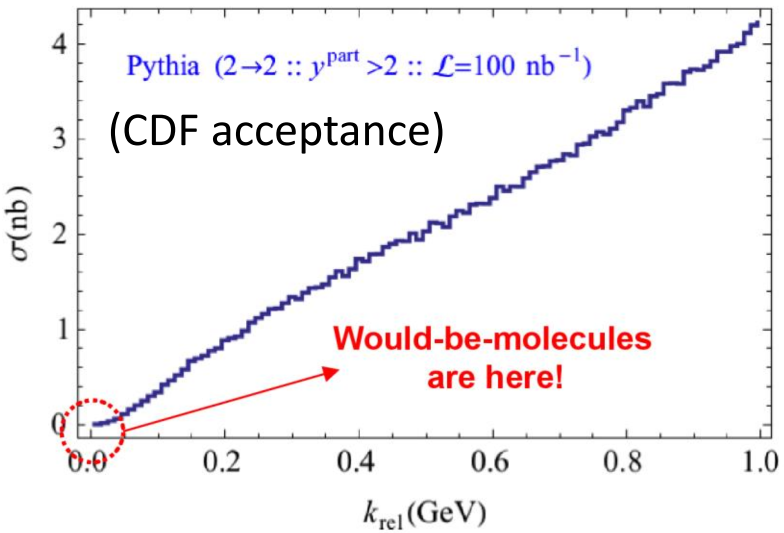

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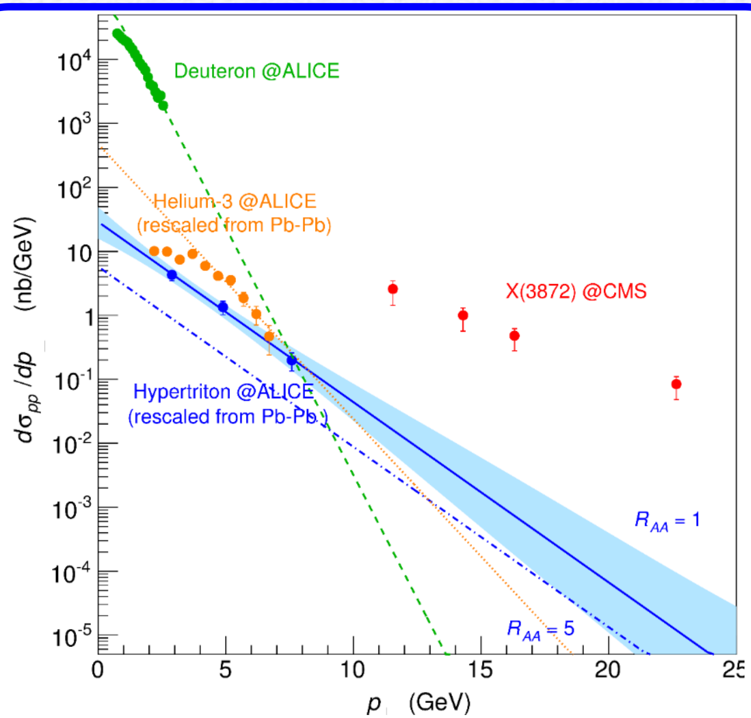


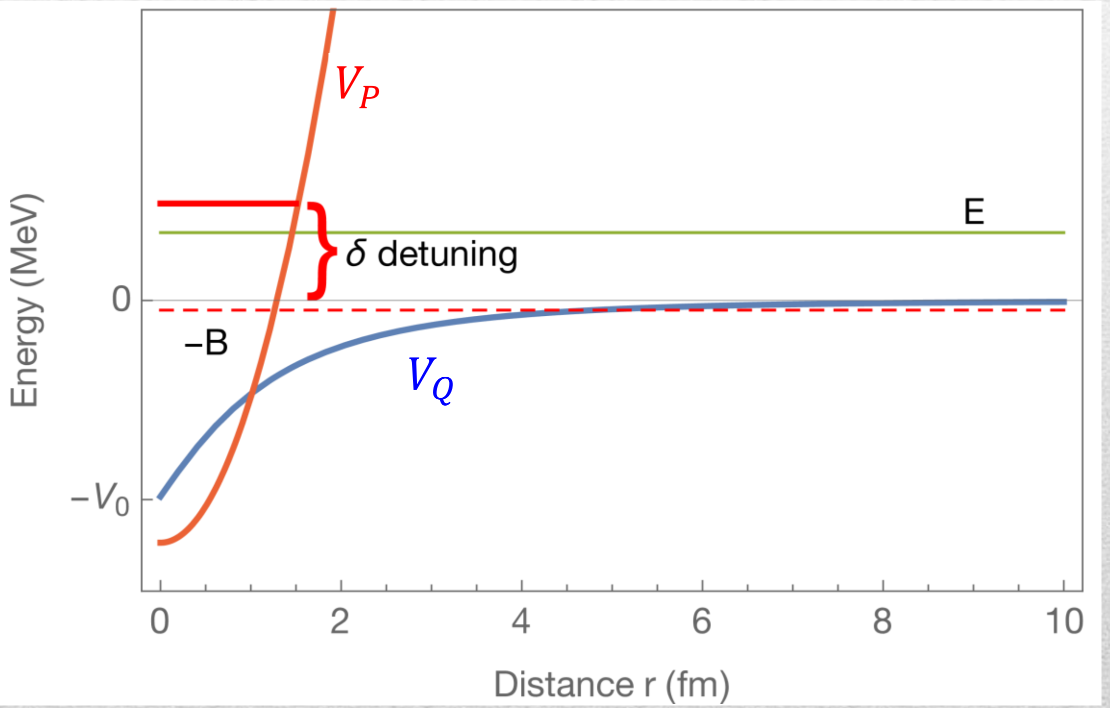
Also, a comparison to light nuclei does not favor the $X(3872)$ to share the same nature

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

Feshbach mechanism occurs when two atoms can interact with two potentials, resp. with continuum ("molecule") and discrete (4q) spectrum → hybridization



Let P and Q be orthogonal subspaces of the Hilbert space

$$H = H_{PP} + H_{QQ}$$

We have the (weak) scattering length a_P in the open channel.

We add an off-diagonal H_{QP}

$$a = a_P - C \sum \frac{\left|\langle \psi_n | H_{QP} | \psi_P \rangle\right|^2}{E_n - E + i\epsilon}$$

$$\simeq a_P \left(1 - \frac{\kappa}{\delta - E + i\epsilon}\right)$$

Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

$X(3872)$ should be a $I = 0$ state, but $M(1^{++}) < M(D^{+*}D^{-})$

$\delta < 0$, so $a > 0$ → Repulsive interaction

No charged component, isospin violation!

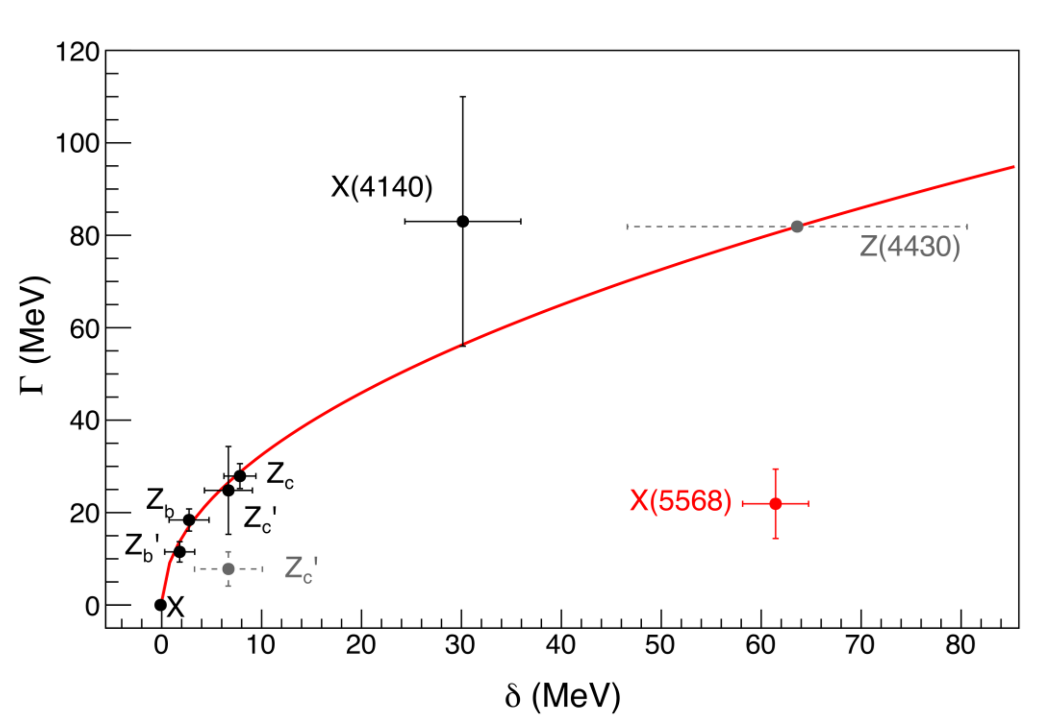
$$d\Gamma = \rho\, v\, \sigma_{inel} \sim \delta(E-\delta)|\kappa a_P| \frac{d^3p}{m}$$

$$\Gamma \sim \sqrt{2m}|\kappa a_P|\,\sqrt{\delta} \equiv A\sqrt{\delta}$$

$E < E_{max}$, with E_{max} estimated by diqurkonium potential to be

- ~ 20 MeV for charmonium
- ~ 40 MeV for bottomonium

The closest threshold below the state dominates the interaction

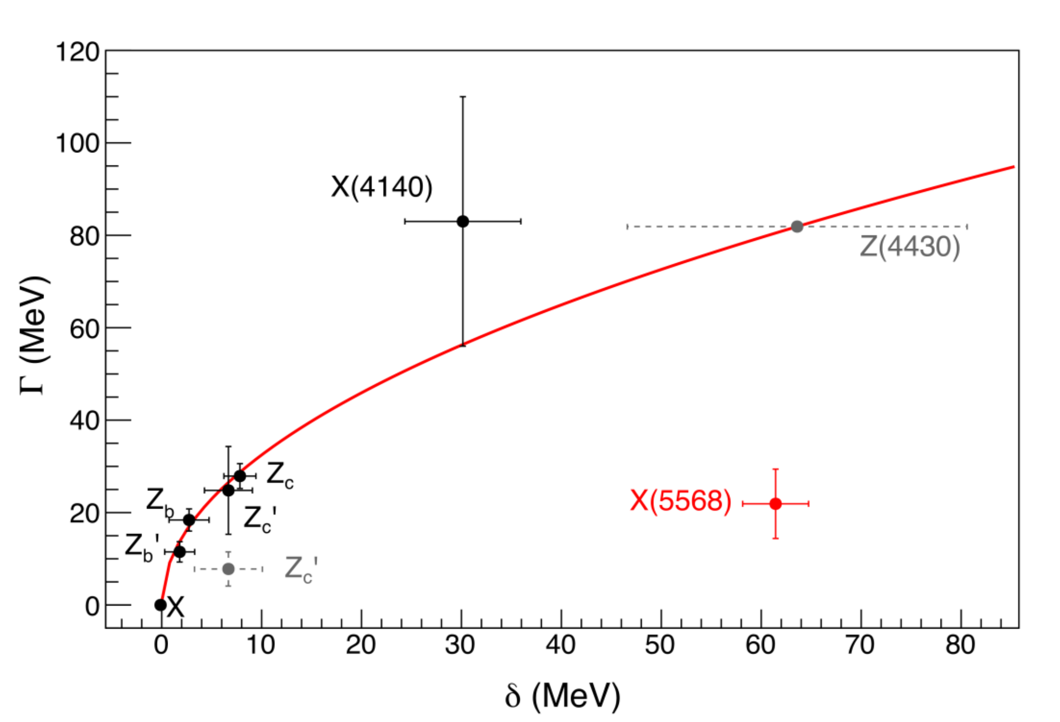


Hybridized tetraquarks

Esposito, AP, Polosa, PLB758, 292

The model works only if no direct transition between closed channel levels can occur
This prevents the straightforward generalization to $L = 1$ and radially excited states (like the Ys or the $Z(4430)$)

In this picture, a $[bu][\bar{s}\bar{d}]$ state with resonance parameters of the $X(5568)$ observed by D0 is not likely



Also, one has to ensure the orthogonality between the two Hilbert subspaces P and Q.
This might affect the estimate for the X(4140)

Production & Feshbach?

Going back to $pp(\bar{p})$ collisions, we can imagine hadronization to produce a state

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

If $\beta, \gamma \gg \alpha$, an initial tetraquark state is not likely to be produced
The open channel mesons fly apart
(see MC simulations)

If Feshbach mechanism is at work, an open state can resonate in a closed one

No prompt production without Feshbach resonances!

Note that only the $X(3872)$ has been observed promptly so far...

...and a narrow $X(4140)$ not compatible with the LHCb one → **needs confirmation**

Conclusions & prospects

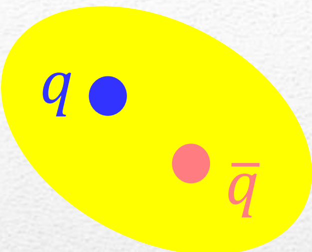
The study of exotic heavy quark sector is a challenging task
Experiments are very prolific! Constant feedback on predictions

- Study of spectra and decay patterns will improve our understanding, new data expected by BESIII, LHCb, Belle II, JLab
- Nuclei observation at hadron colliders can give an unexpected help in testing some phenomenological hypotheses for the XYZ states
- Search for exotic states in prompt production is a necessary step to improve our understanding of the sector
- Feshbach mechanism might be effective in reducing the number of states predicted by the tetraquark picture

Thank you

BACKUP

Quarkonium orthodoxy



Heavy quarkonium sector is extremely useful for the understanding of QCD

$\alpha_s(M_Q) \sim 0.3$
(perturbative regime)
OZI-rule, QCD multipole

Heavy quark spin flip suppressed by quark mass, approximate heavy quark spin symmetry (HQSS)

Potential models

(meaningful when $M_Q \to \infty$)

$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

(Cornell potential)

Solve NR Schrödinger eq. → spectrum

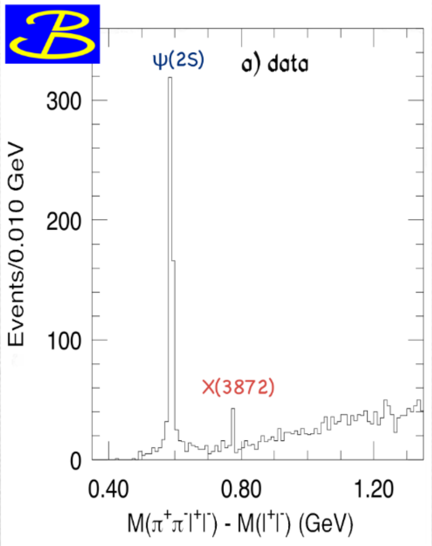
Effective theories

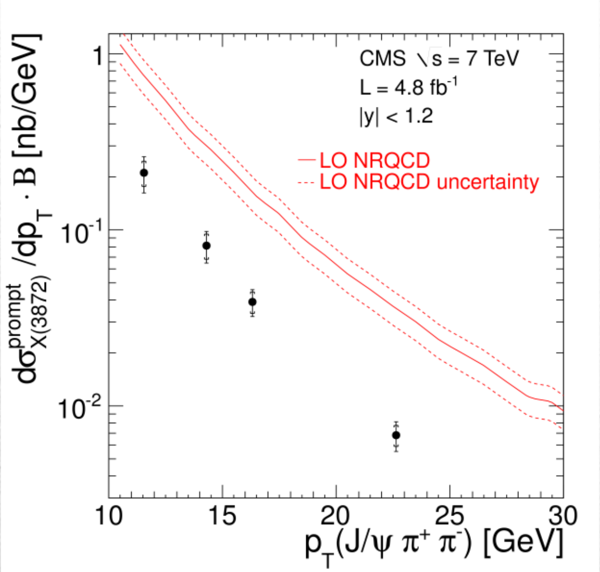
(HQET, NRQCD...)

Integrate out heavy DOF
↓
(spectrum), decay & production rates

$X(3872)$

- Discovered in
  $B \to K\,X \to J/\psi\,\pi\pi$
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \omega)}{\Gamma(X\to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$





Unexpected large prompt production at hadron colliders

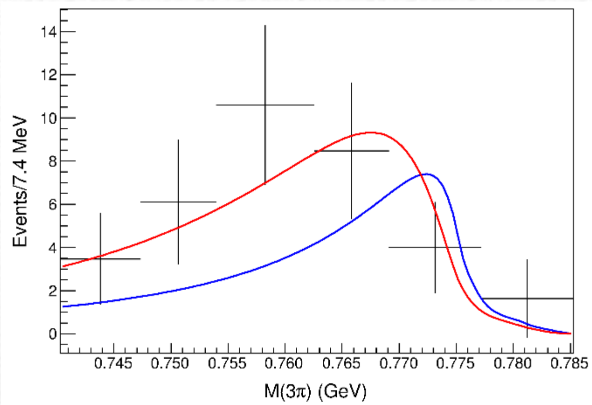
$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$

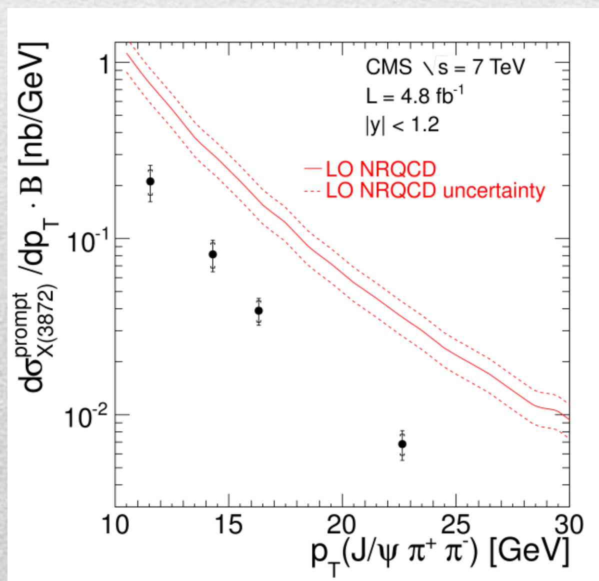
$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90% , $J^{PC} = 1^{++}$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi) = (1.06 \pm 0.11 \pm 0.15)$ nb

CMS, JHEP 1304, 154

$X(3872)$

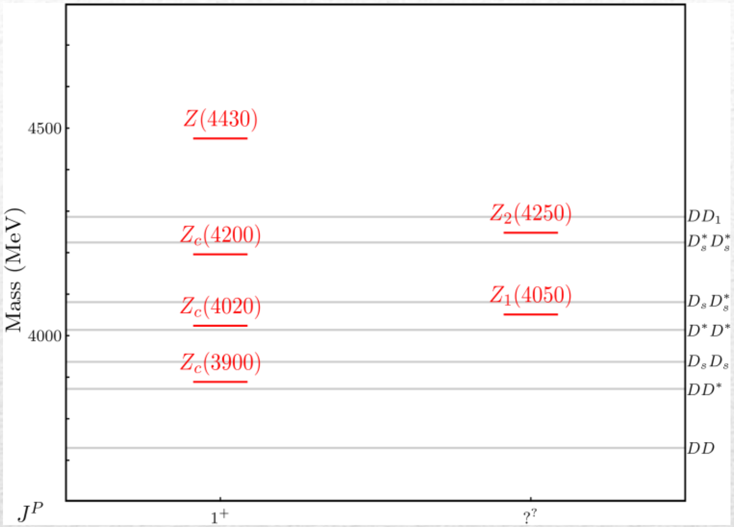




B decay mode	X decay mode	product branching fraction $(\times 10^5)$		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(*BABAR* [26] Belle [25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	*BABAR* [26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle [25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(*BABAR* [26] Belle [25])		
		$0.35 \pm 0.19 \pm 0.04$	*BABAR* [26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle [25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle [106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle [106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	*BABAR* [33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	*BABAR* [33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	*BABAR* [33]		
KX	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle [32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	(*BABAR* [38] Belle [37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	*BABAR* [38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle [37]		
K^0X	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	(*BABAR* [38] Belle [37])		
		$22 \pm 10 \pm 4$	*BABAR* [38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle [37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	(*BABAR* [35] Belle [34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	*BABAR* [35]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle [34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	*BABAR* [35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle [34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	*BABAR* [35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	*BABAR* [35]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle [34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb [36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	*BABAR* [35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle [34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle [23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle [23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle [111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	*BABAR* [112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb [110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Charged Z states...

Charged quarkonium-like resonances have been found, **4q needed**



Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$

$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$

$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV

Similar system in bottomonium

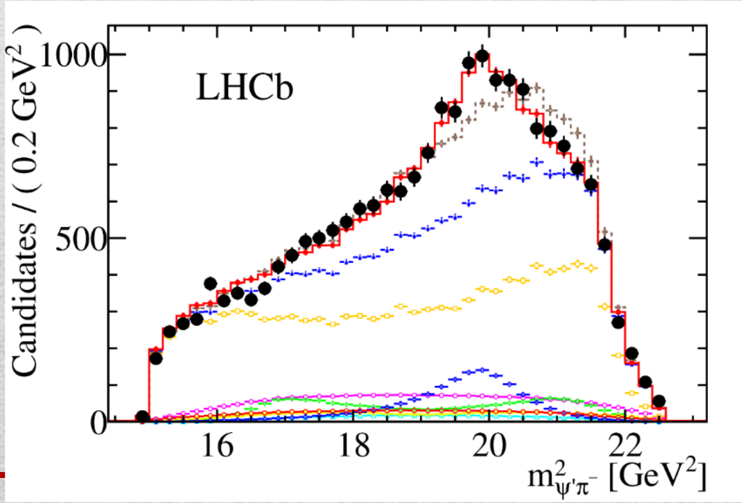
$Z(4430)^+ \to \psi(2S)\,\pi^+$

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

$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$MeV

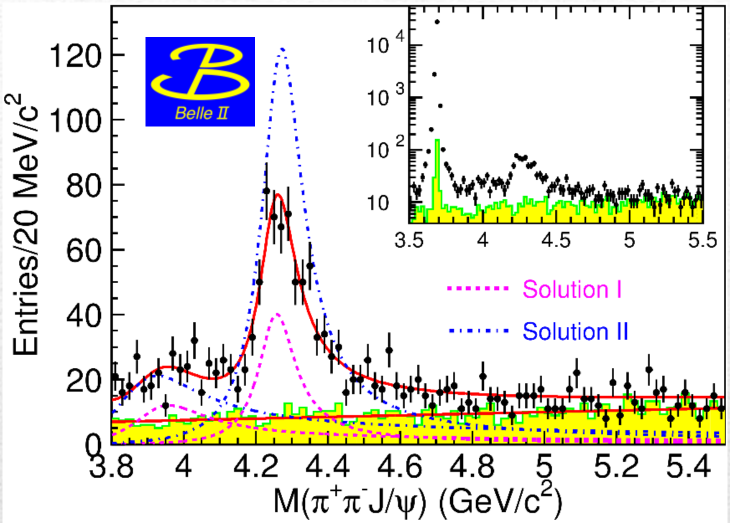
Far from open charm thresholds



...Y vectors, pentaquarks...

Vector Y states

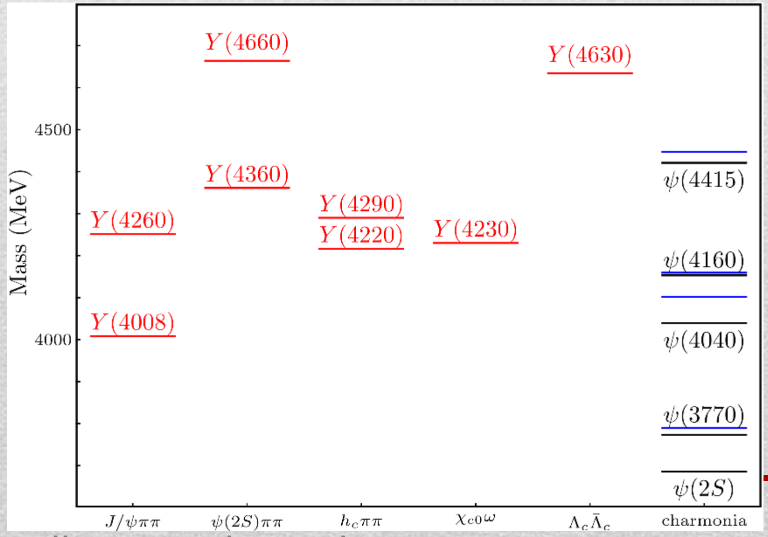
Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR analyses (and nowhere else!)

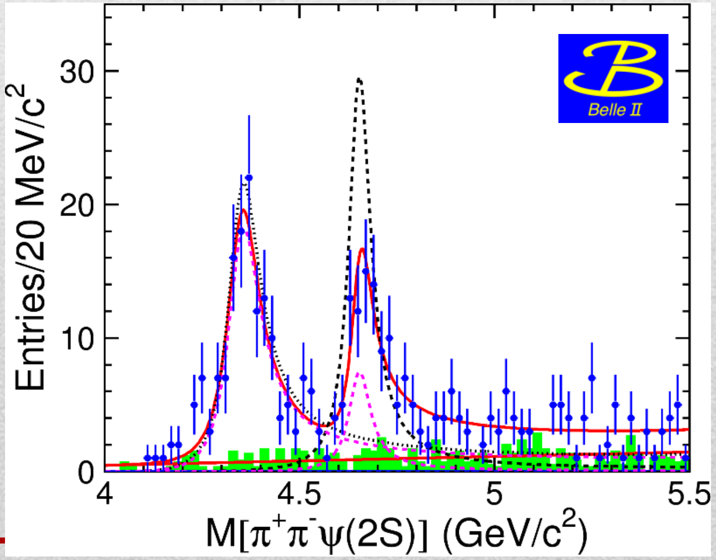


Seen in few final states,
mostly $J/\psi\,\pi\pi$ and $\psi(2S)\,\pi\pi$

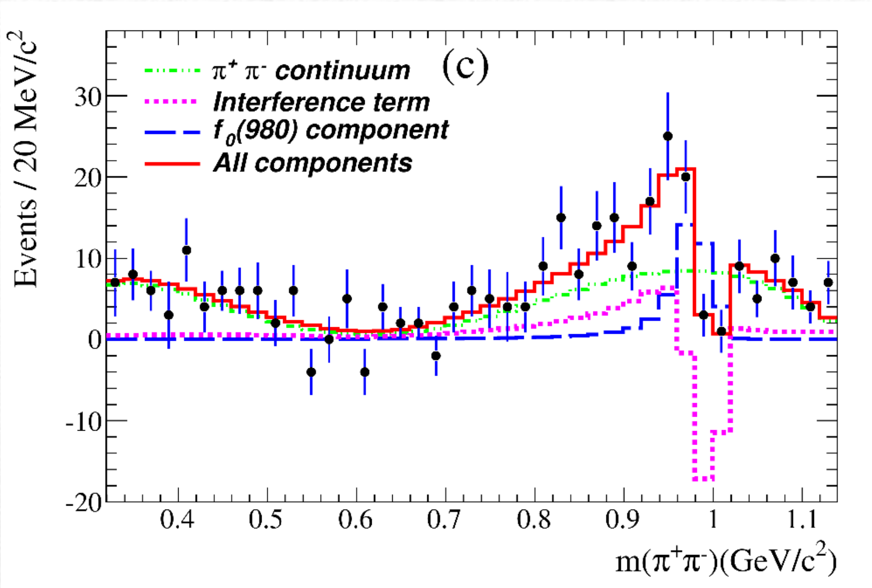
Not seen decaying into open charm pairs,
to compare with

$$\frac{B(\psi(3770) \to D\bar{D})}{B(\psi(3770) \to J/\psi\pi\pi)} > 480$$

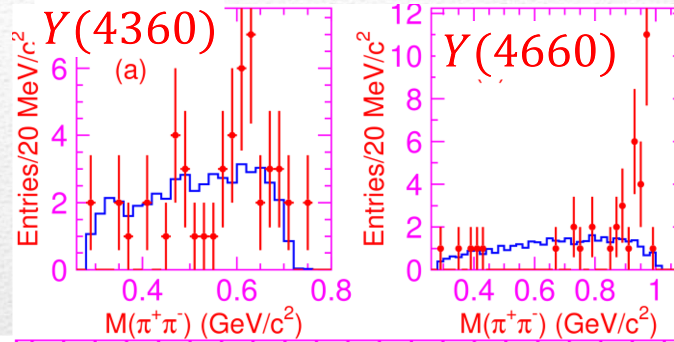


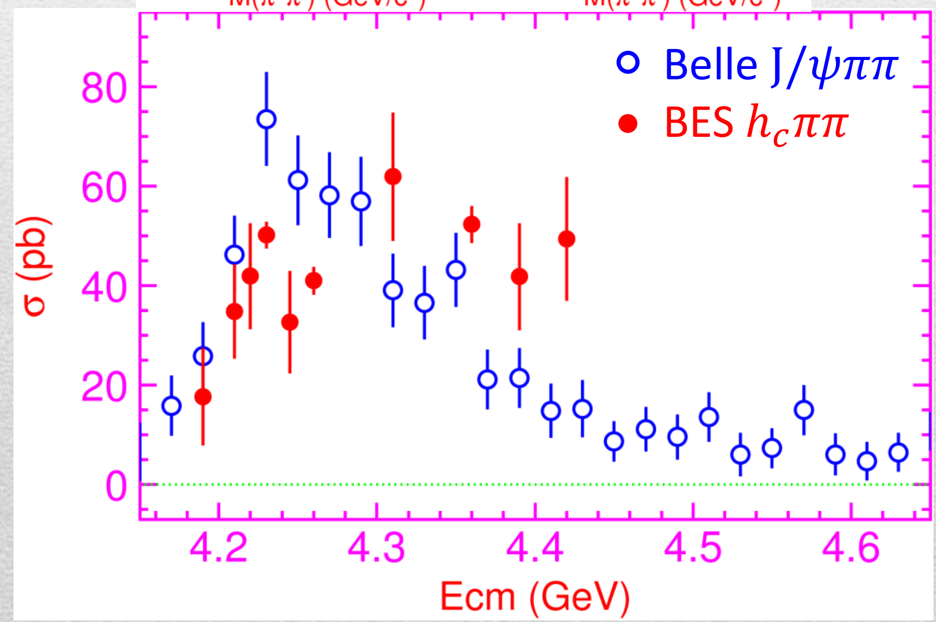


Vector Y states



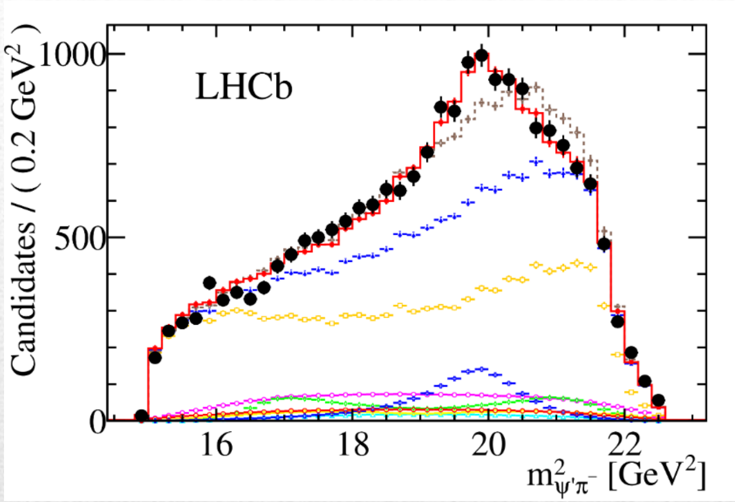
A component $Y(4260) \to J/\psi\ f_0(980)$ might explain why $Y(4260) \to \psi(2S)\pi\pi$

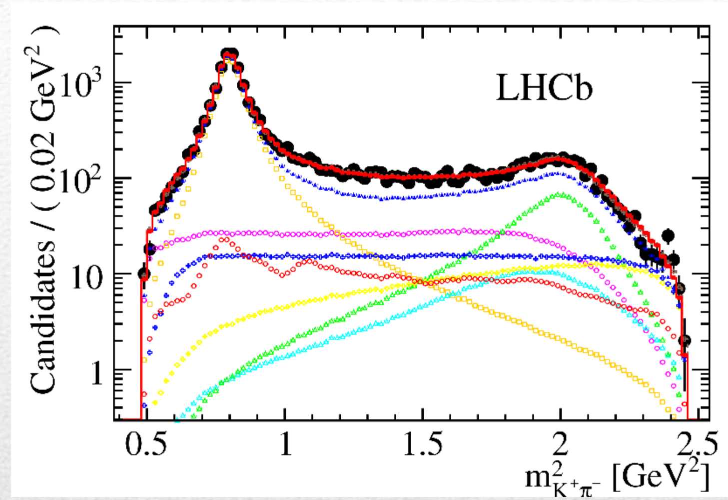




The lineshape in $h_c\ \pi\pi$ looks pretty different
Different states contributing?

Charged Z states: $Z(4430)$

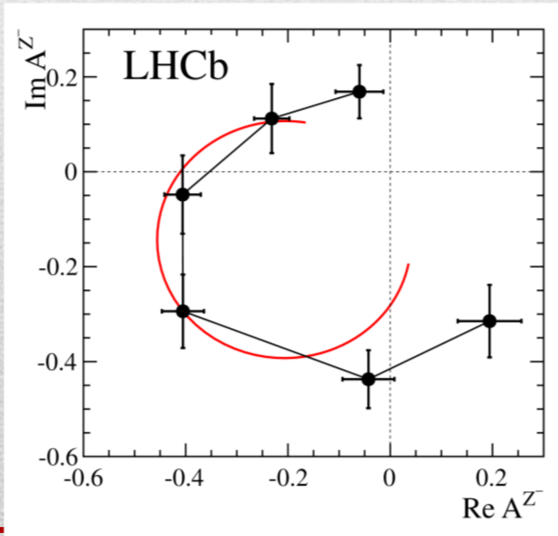




$$Z(4430)^+ \to \psi(2S)\,\pi^+$$
$$I^G J^{PC} = 1^+ 1^{+-}$$

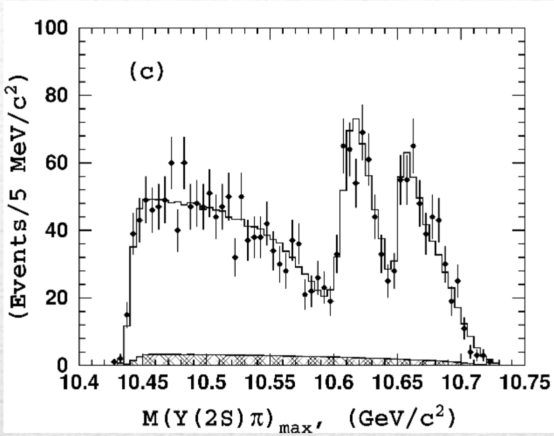
$$M = 4475 \pm 7^{+15}_{-25}\text{ MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

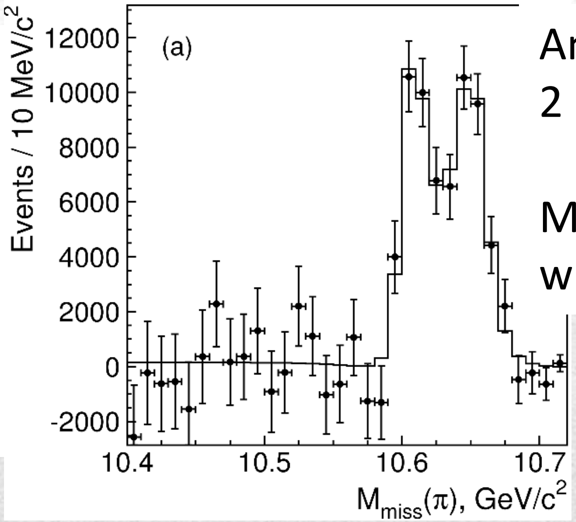
Far from open charm thresholds



If the amplitude is a free complex number, in each bin of $m^2_{\psi'\pi^-}$, the resonant behaviour appears as well

Charged Z states: $Z_b(106010), Z_b'(10650)$





Anomalous dipion width in $\Upsilon(5S)$, 2 orders of magnitude larger than $\Upsilon(nS)$

Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$ which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

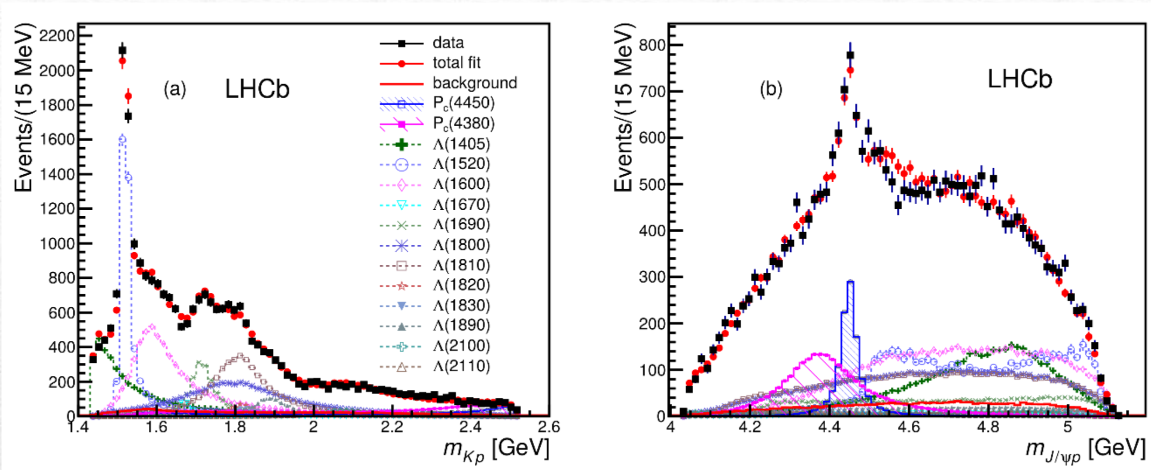
$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle[23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle[24,25] (>10), *BABAR*[26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF[27,28] (11.6), D0[29] (5.2)
				$pp \to (\pi^+\pi^- J/\psi) \ldots$	LHCb[30,31] (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle[32] (4.3), *BABAR*[33] (4.0)
				$B \to K(\gamma J/\psi)$	Belle[34] (5.5), *BABAR*[35] (3.5)
					LHCb[36] (> 10)
				$B \to K(\gamma\psi(2S))$	*BABAR*[35] (3.6), Belle[34] (0.2)
					LHCb[36] (4.4)
				$B \to K(D\bar{D}^*)$	Belle[37] (6.4), *BABAR*[38] (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III[39] (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III[40] (8), Belle[41] (5.2)
					CLEO data[42] (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III[43] (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III[44] (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle[45] (8), *BABAR*[33,46] (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle[47] (7.7), *BABAR*[48] (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle[49] (5.3), *BABAR*[50] (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle[51,52] (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle[41,53] (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle[54] (5.0), *BABAR*[55] (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF[56,57] (5.0), Belle[58] (1.9),
					LHCb[59] (1.4), CMS[60] (>5)
					DØ[61] (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle[52] (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle[62] (7.2)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$Y(4220)$	4196^{+35}_{-30}	39 ± 32	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data[63,64] (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \to (\chi_{c0}\omega)$	BES III[65] (>9)
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle[54] (5.0), *BABAR*[55] (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	*BABAR*[66,67] (8), CLEO[68,69] (11)
					Belle[41,53] (15), BES III[40] (np)
				$e^+e^- \to (f_0(980) J/\psi)$	*BABAR*[67] (np), Belle[41] (np)
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III[40] (8), Belle[41] (5.2)
				$e^+e^- \to (\gamma X(3872))$	BES III[70] (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data[63,64] (np)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle[58] (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle[71] (8), *BABAR*[72] (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle[73,74] (6.4), *BABAR*[75] (2.4)
					LHCb[76] (13.9)
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle[62] (4.0)
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle[77] (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle[71] (5.8), *BABAR*[72] (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$	Belle[78,79] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle[78] (16)
				$\Upsilon(5S) \to \pi^-(B\bar{B}^*)^+$	Belle[80] (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$	Belle[78] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle[78] (16)
				$\Upsilon(5S) \to \pi^-(B^*\bar{B}^*)^+$	Belle[80] (6.8)

Guerrieri, AP, Piccinini, Polosa,
IJMPA 30, 1530002

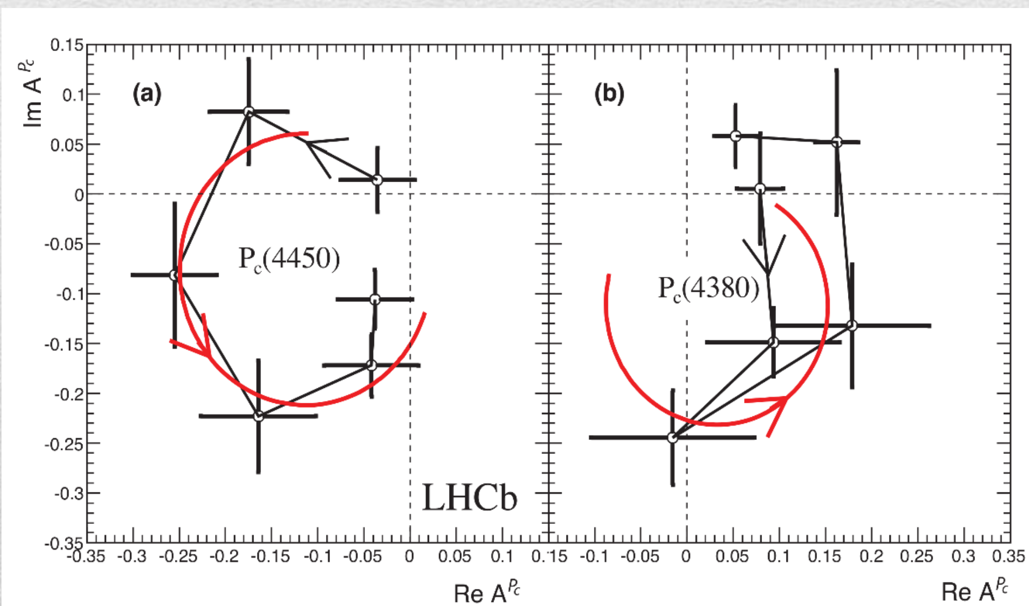
Pentaquarks... and so on



LHCb, PRL 115, 072001

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$



Quantum numbers

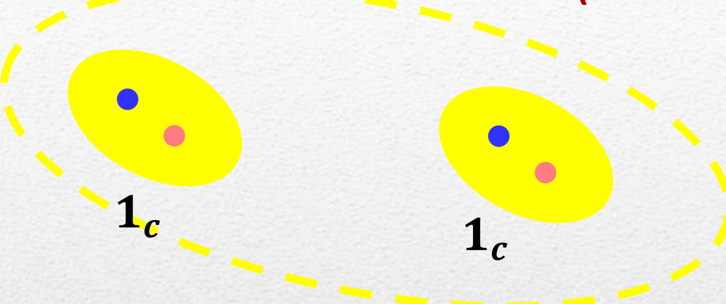
$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

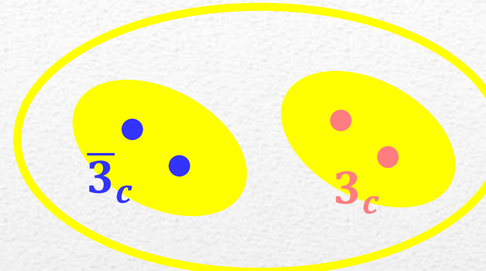
Opposite parities needed for the interference to correctly describe angular distributions

No obvious threshold nearby

Proposed models

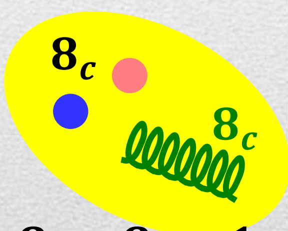
Molecule of hadrons (loosely bound)





$\mathbf{3}_c \times \bar{\mathbf{3}}_c \in \mathbf{1}_c$

Diquark-antidiquark (tetraquark)

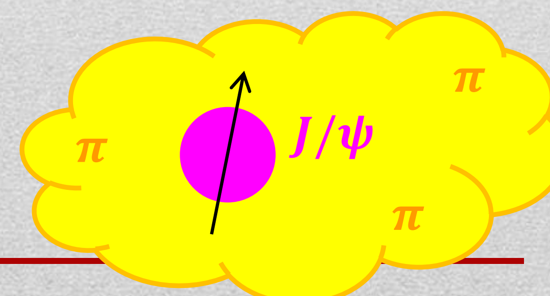


$\mathbf{8}_c \times \mathbf{8}_c \in \mathbf{1}_c$

Glueball, Hybrids (with valence gluons), Born-Oppenheimer 4q

Hadrocharmonium (Van der Waals forces)

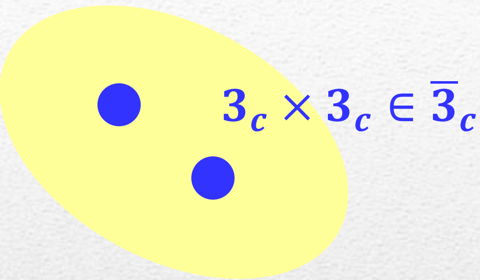
Cusp (kinematical effect)

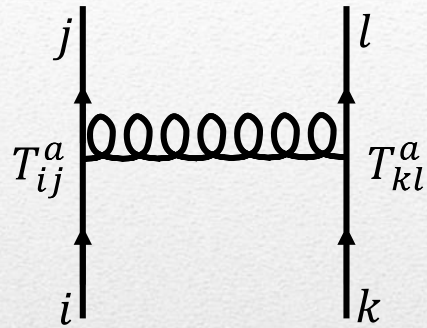


$\mathbf{1}_c \times \mathbf{1}_c \in \mathbf{1}_c$

Diquarks

Attraction and repulsion in 1-gluon exchange approximation is given by





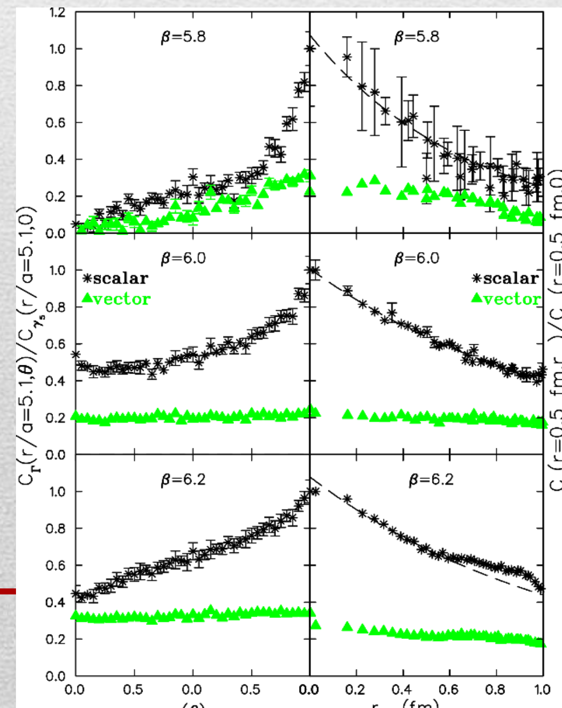
$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

$$R_1 = -\frac{4}{3}, R_8 = +\frac{1}{6}$$

$$R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}$$

The singlet $\mathbf{1}_c$ is an attractive combination

A diquark in $\overline{\mathbf{3}}_c$ is an attractive combination
A diquark is colored, so it can stay into hadrons but cannot be an asymptotic state
Evidence (?) of diquarks in lattice QCD,
Alexandrou, de Forcrand, Lucini, PRL 97, 222002

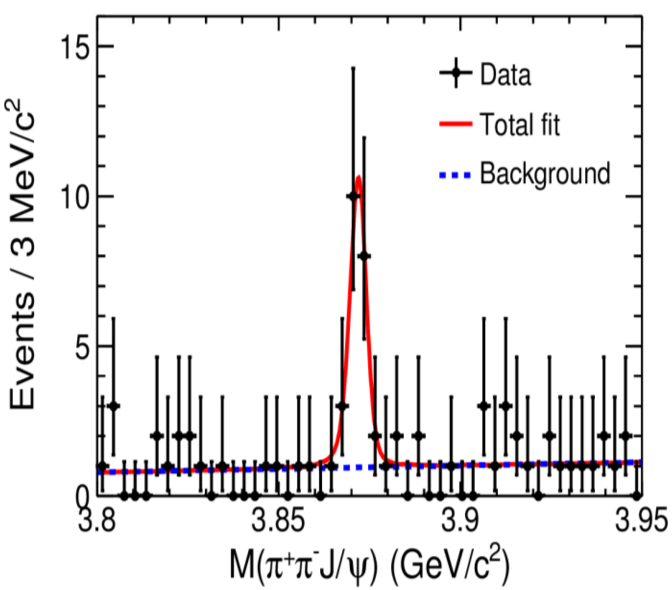


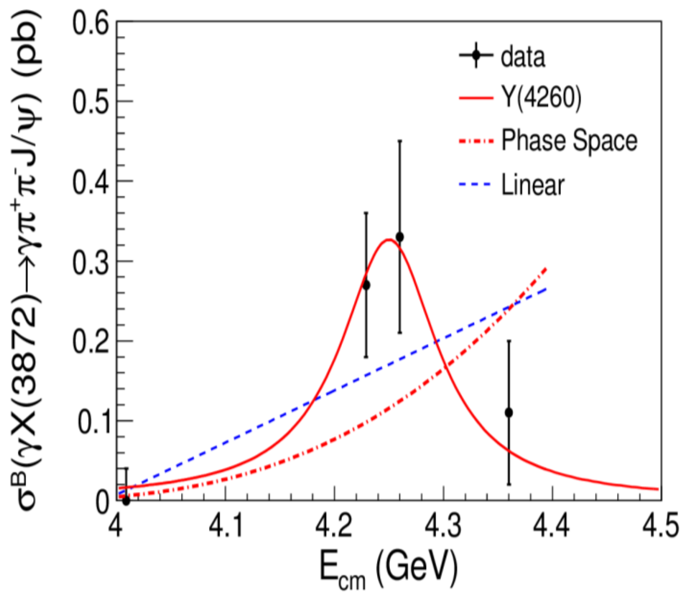
$Y(4260) \to \gamma X(3872)$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 092001

F. Piccinini

BESIII: $e^+e^- \to Y(4260) \to X(3872)\gamma$





With $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$

$$\frac{\mathcal{B}[Y(4260) \to \gamma X(3872)]}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} = 0.1$$

Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure

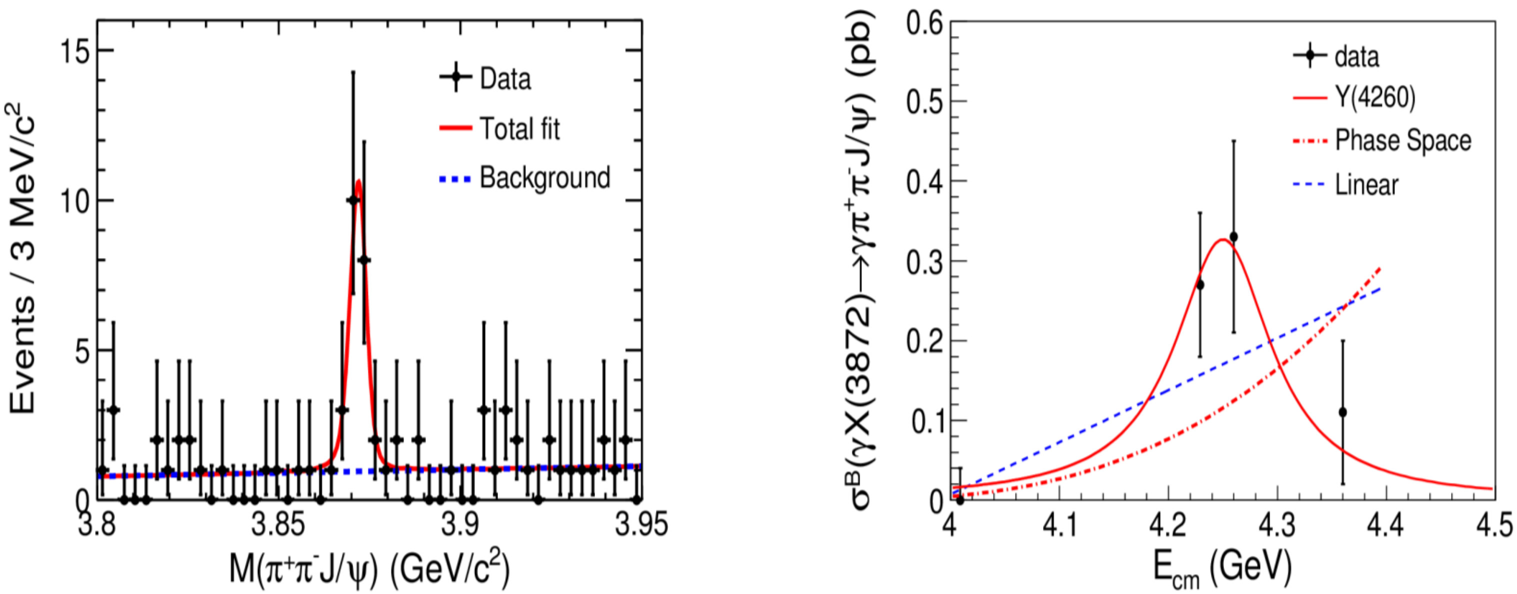
Chen, Maiani, Polosa, Riquer EPJC75 11, 550

$Y(4260) \to \gamma X(3872)$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 092001

F. Piccinini

BESIII: $e^+e^- \to Y(4260) \to X(3872)\gamma$

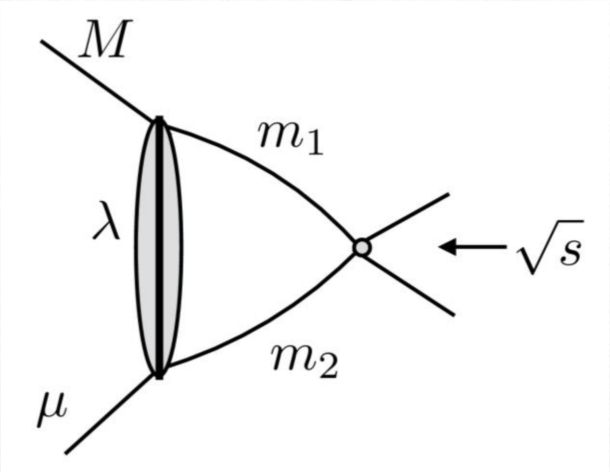


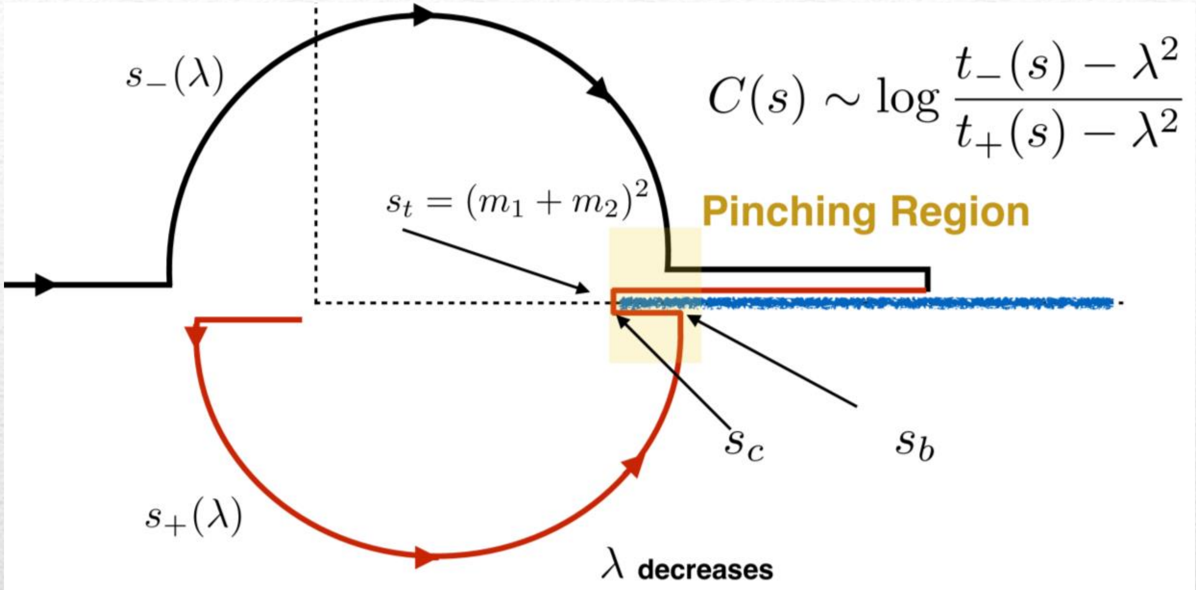
With $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$

$$\frac{\mathcal{B}[Y(4260) \to \gamma X(3872)]}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} = 0.1$$

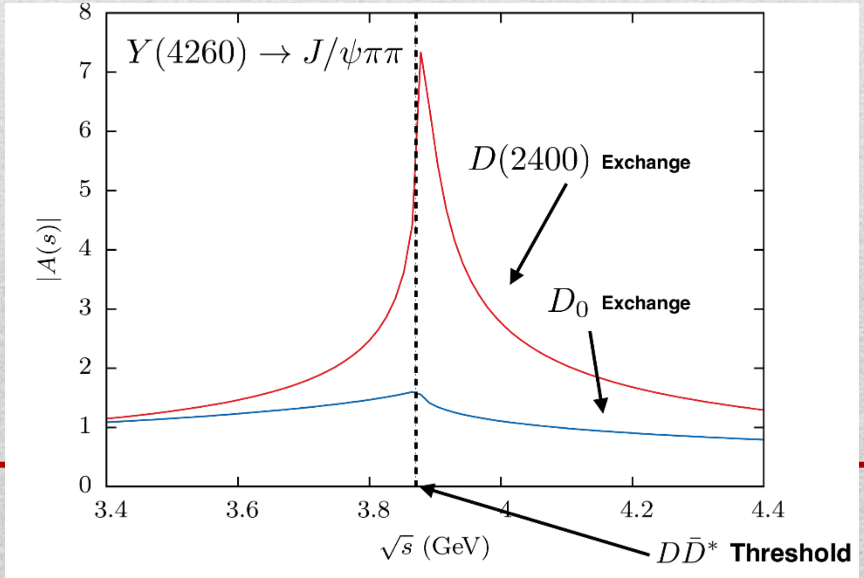
Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure

Triangle singularity (cusps)



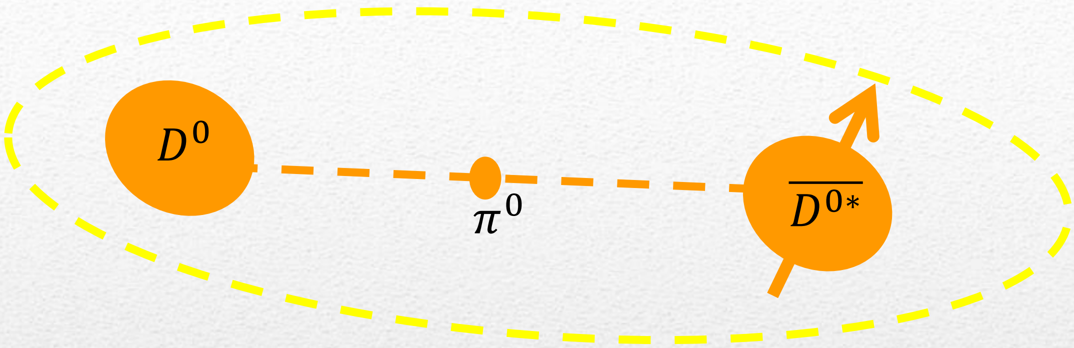


Bugg, PLB598, 8-14
Szczepaniak, PLB747, 410-416
Szczepaniak, 1510.01789



Molecule

Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305



$X(3872) \sim \bar{D}^0 D^{*0}$
$Z_c(3900) \sim \bar{D}^0 D^{*+}$
$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$
$Y(4260) \sim \bar{D} D_1$

A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (Weinberg's theorem) ✓
- Good description of decay patterns (mostly to constituents) and $\mathrm{X}(3872)$ isospin violation ✓
- States appear close to thresholds ✓ (but $Z(4430)$ ✗)
- Lifetime of costituents has to be $\gg 1/m\_\pi$, (but why $\Gamma_Y \gg \Gamma_{D\_1}$?)
- Binding energy varies from -70 to -0.1 MeV, or even positive (repulsive interaction) ✗
- Unclear spectrum (a state for each threshold?) – depends on potential models ✗

$$V_\pi(r) = \frac{g_{\pi N}^2}{3}(\vec{\tau_1}\cdot\vec{\tau_2})\left\{[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r}) - (\vec{\sigma_1}\cdot\vec{\sigma_2})]\left(1 + \frac{3}{(m_\pi r)^2} + \frac{3}{m_\pi r}\right) + (\vec{\sigma_1}\cdot\vec{\sigma_2})\right\}\frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

Weinberg theorem

Resonant scattering amplitude

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

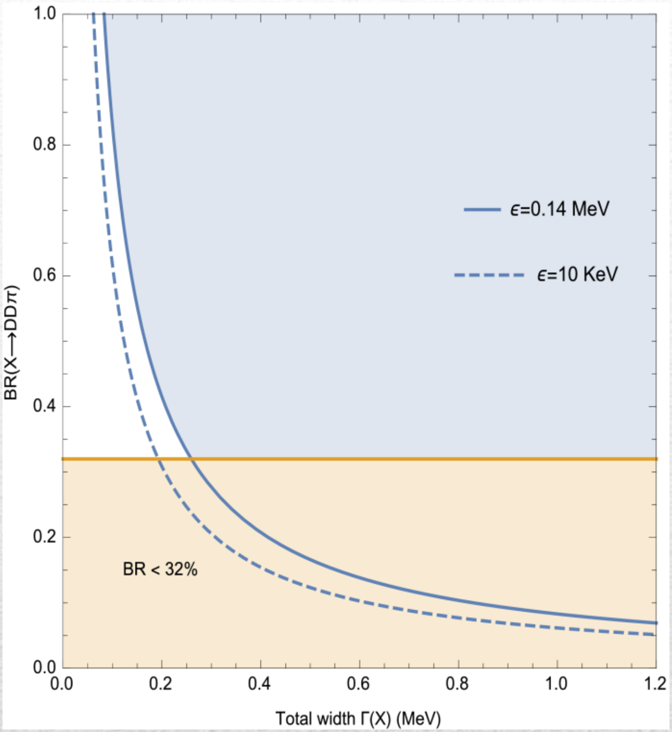
with $m_c = m_a + m_b - B$, and $B, T \ll m_{a,b}$

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

This has to be compared with the potential scattering for slow particles ($kR \ll 1$, being $R \sim 1/m_\pi$ the range of interaction) in an attractive potential U with a superficial level at $-B$

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

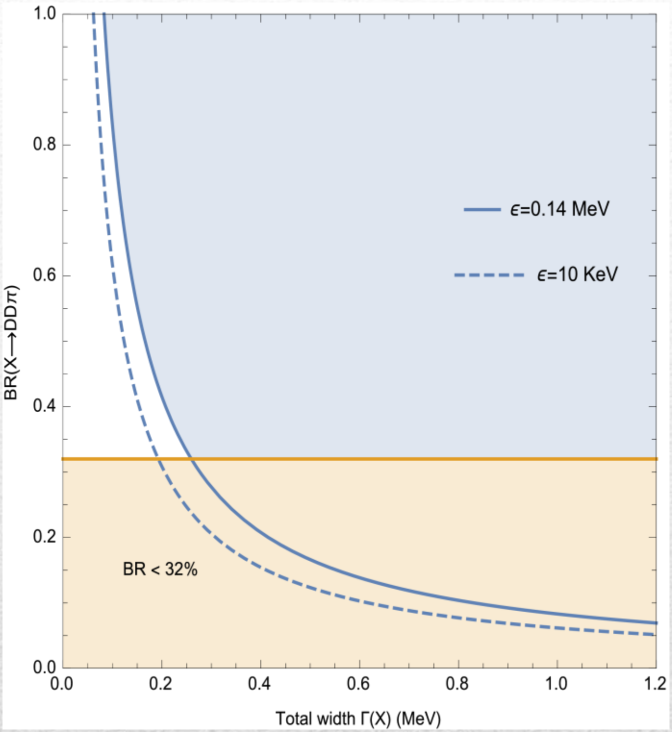
$$B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}$$



Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248

Weinberg theorem

$$B = \frac{g^4}{512\pi^2}\frac{\mu^5}{(m_a m_b)^2}, \qquad kR \ll 1$$



This has to be fulfilled by EVERY molecular state, but:

- $X(3872), B = 0, g \neq 0$
- Zs, $B < 0$, repulsive interaction!
- $Y(4260), kR \sim 1.4$

Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248

Estimating k_{max}

The binding energy is $E_B \approx -0.16 \pm 0.31$ MeV (PDG): very small!
In a simple square well model this corresponds to:

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

(binding energy reported by NU, PRD91, 011102

$$E_B \approx -0.003 \pm 0.192 \text{ MeV}: \sqrt{\langle k^2 \rangle} \approx 20 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 60 \text{ fm}$$)

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

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

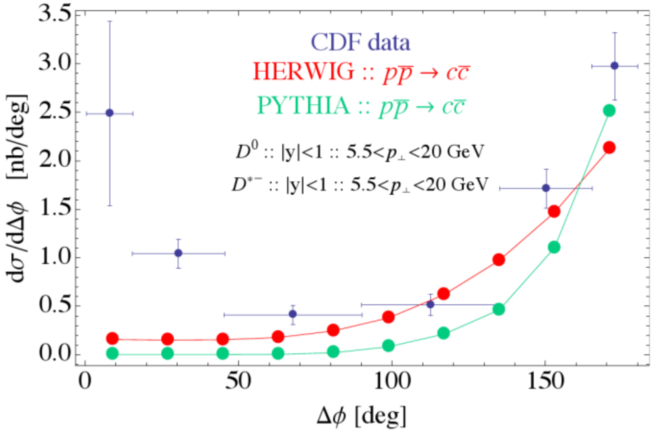
We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50$ MeV, some other choices are commented later

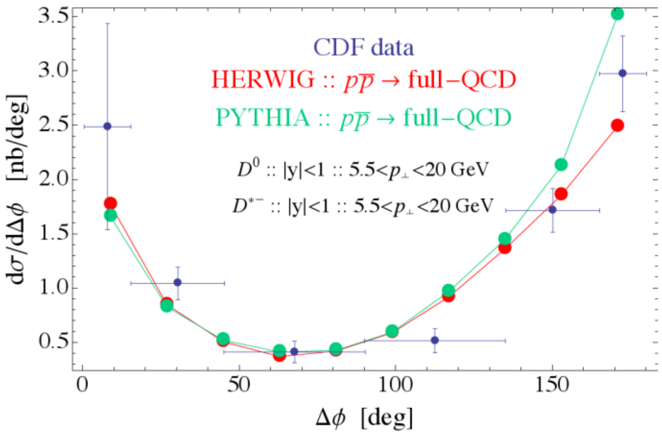
Tuning of MC

Monte Carlo simulations

A. Esposito

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:





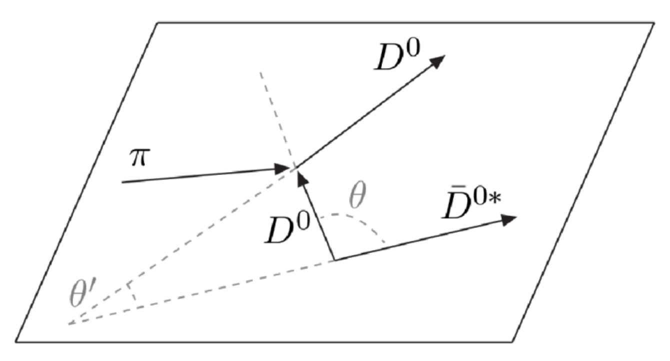
The c-cbar run understimate the low angles (low-k_0) region!

Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

A new mechanism?

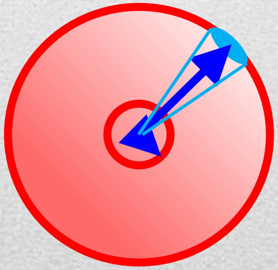
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the DD^* pairs

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

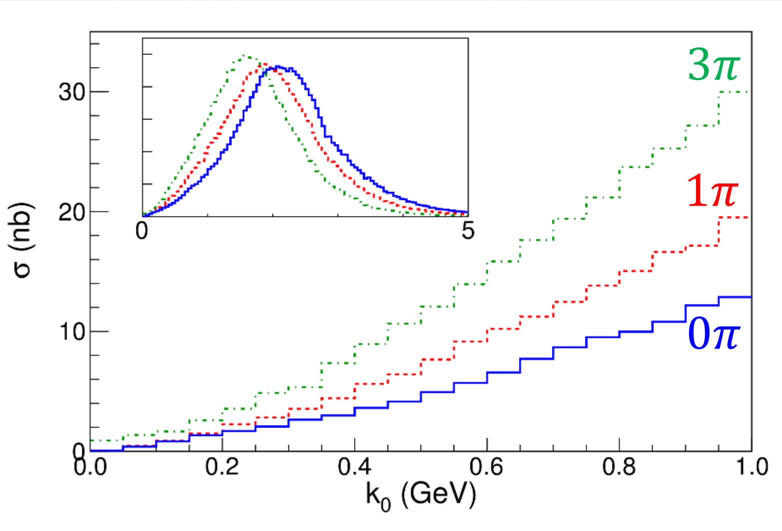


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

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



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

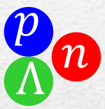


We get $\sigma\left(p\bar{p} \to X(3872)\right) \sim 5\ \text{nb}$, still not sufficient to explain all the experimental cross section

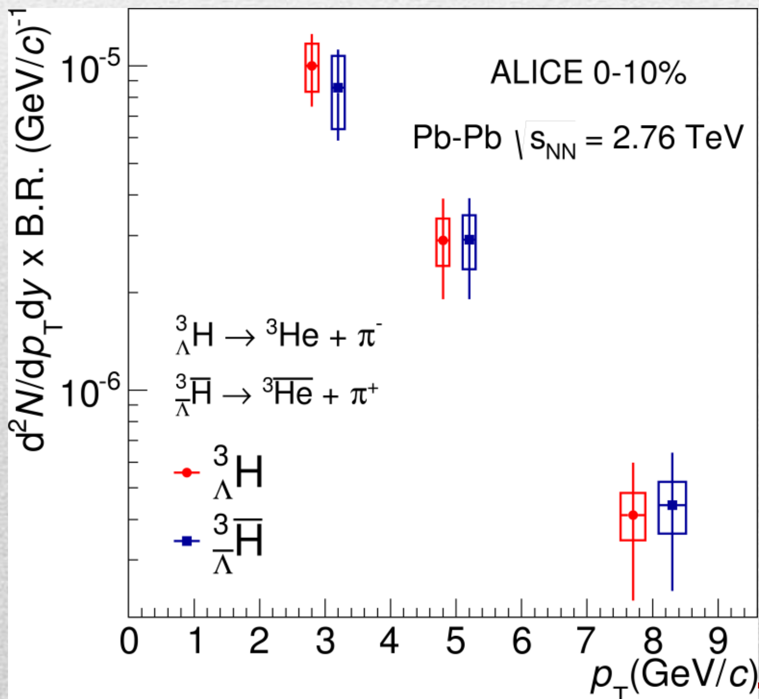
Light nuclei at ALICE

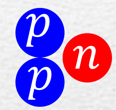
Recently, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

These might provide a benchmark for $X(3872)$ production

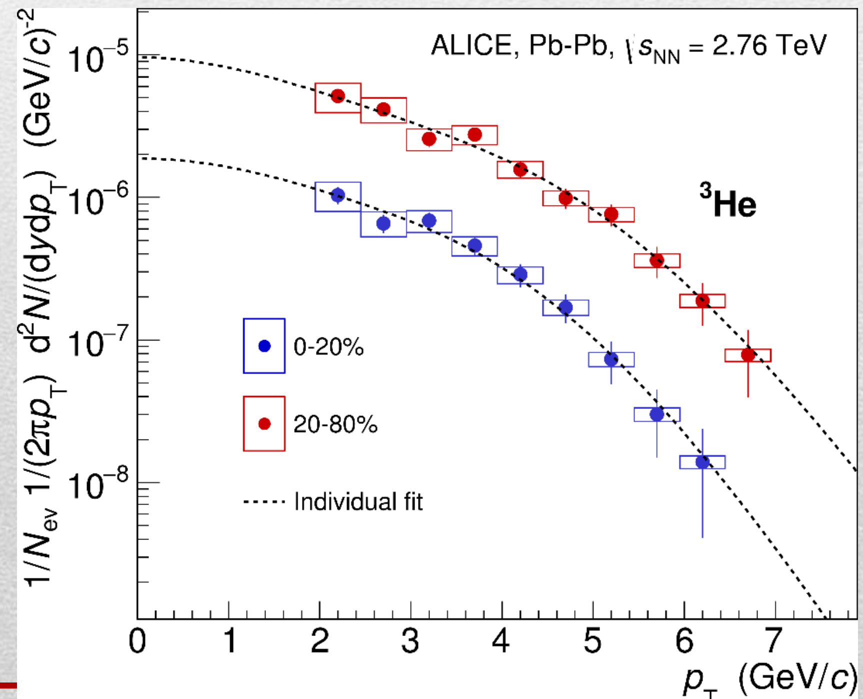


Hypertriton
arXiv:1506.08453

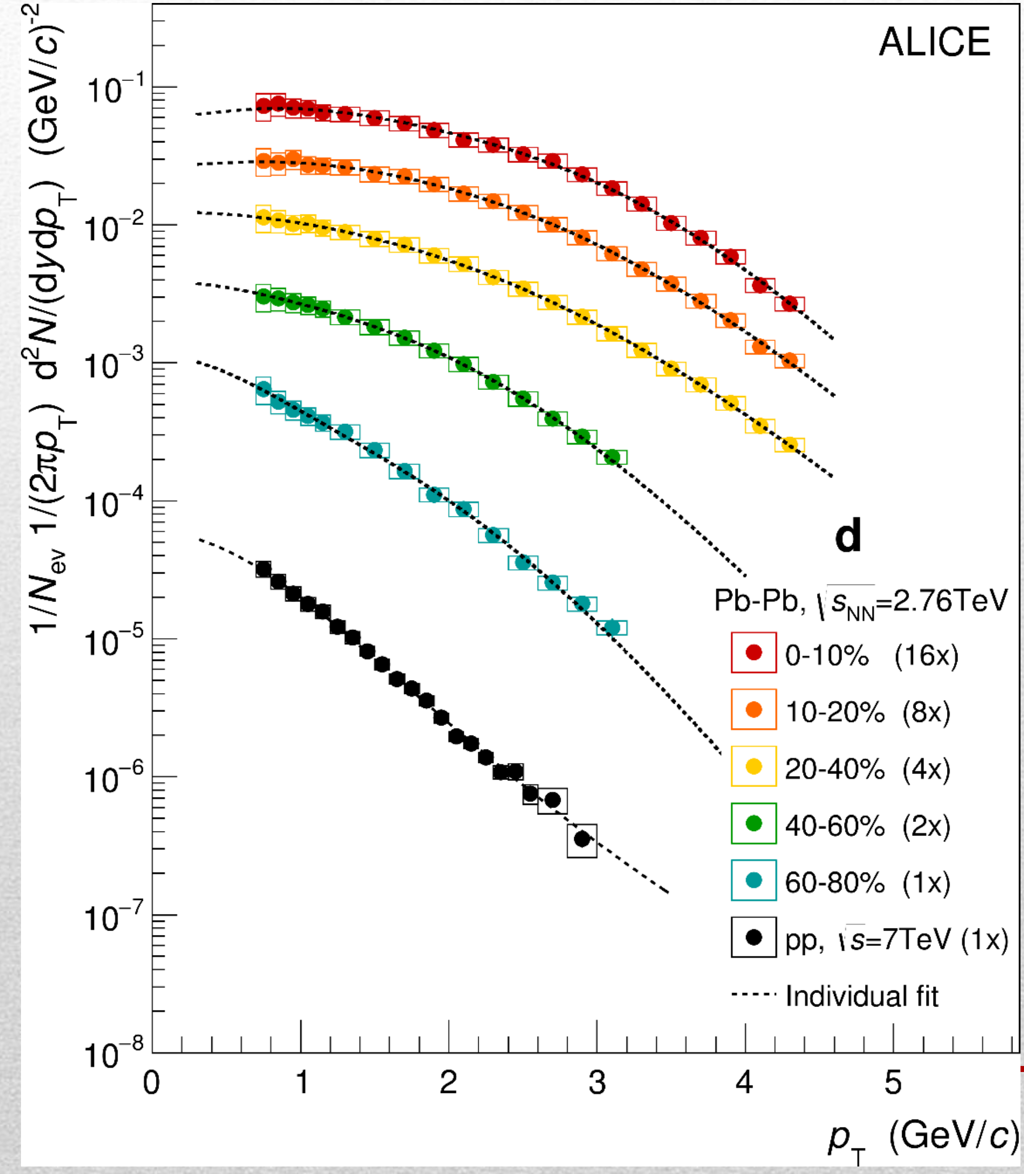


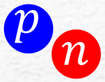


Helium-3
arXiv:1506.08951



Light nuclei at ALICE





Deuteron

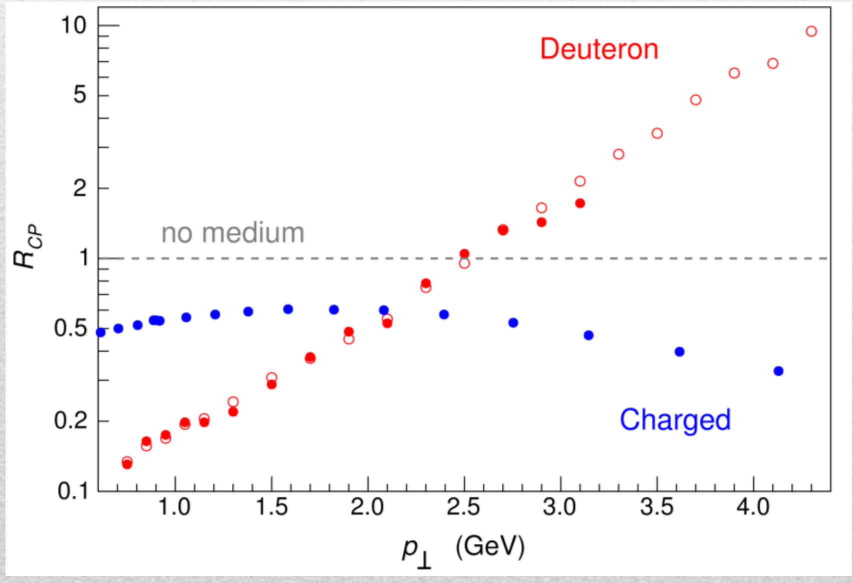
arXiv:1506.08951

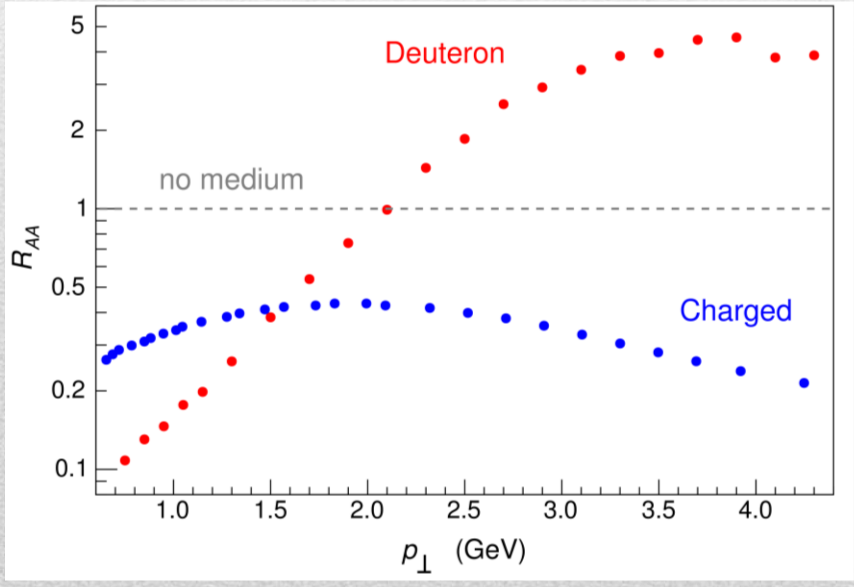
Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$$R_{CP} = \frac{N_{coll}^{P} \left(\frac{dN}{dp_T}\right)_C}{N_{coll}^{C} \left(\frac{dN}{dp_T}\right)_P}$$

$$R_{AA} = \frac{\left(\frac{dN}{dp_T}\right)_{\text{Pb-Pb}}}{N_{coll} \left(\frac{dN}{dp_T}\right)_{pp}}$$





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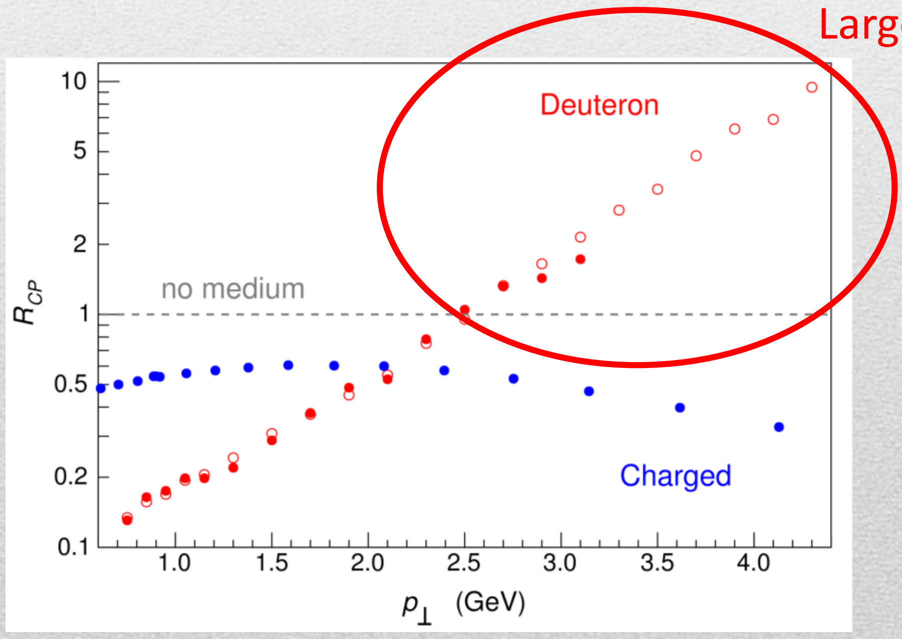
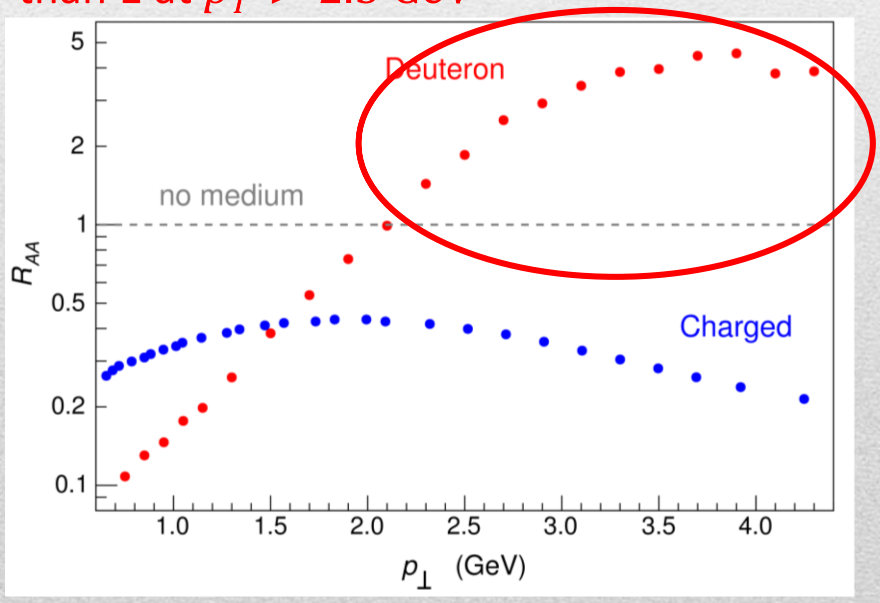
Larger than 1 at $p_T > 2.5$ GeV





Light nuclei at ALICE

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

Constant RAA → same shape in Pb-Pb and pp

$$\left(\frac{d\sigma\left({}^3_\Lambda\mathrm{H}\right)}{dp_\perp}\right)_{pp} = \frac{\Delta y}{\mathcal{B}({}^3\mathrm{He}\,\pi)} \times \frac{\sigma_{pp}^{\mathrm{inel}}}{N_{\mathrm{coll}}}\left(\frac{1}{N_{\mathrm{evt}}}\frac{d^2N({}^3\mathrm{He}\,\pi)}{dp_\perp dy}\right)_{\text{Pb-Pb}}$$

We extrapolate this data at higher p_T either by assuming an exponential law, or with a blast-wave function, which describes the emission of particles in an espanding medium

The blast-wave function is

$$\frac{dN}{dp_\perp} \propto p_\perp \int_0^R r dr\, m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\mathrm{kin}}}\right),$$

where $m_\perp$ is the transverse mass, R is the radius of the fireball, I_0 and K_1 are the Bessel functions, $\rho = \tanh^{-1}\left(\frac{(n+2)\langle\beta\rangle}{2}(r/R)^n\right)$, and $\langle\beta\rangle$ the averaged speed of the particles in the medium.

Light nuclei at ALICE vs. $X(3872)$

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

The $X(3872)$ is way larger than the extrapolated cross section