Modeling new exotic states

A. Pilloni

Director's seminar

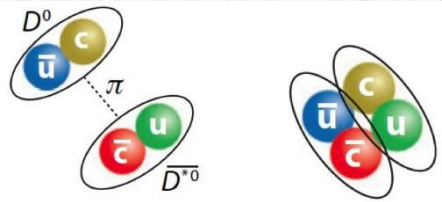
JLab, December 2nd, 2015

Jefferson Lab

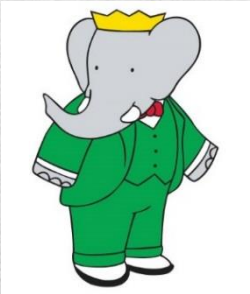
Chronology

2012-2015: Ph.D. student at «Sapienza» Università di Roma

Main research topic: Exotic Hadron Spectroscopy,
advisor Prof. A.D. Polosa
phenomenology of XYZ,
i.e. exotic charmonium-like states
within the diquark-antidiquark model,
detailed Monte-Carlo simulations
to estimate production of exotics at LHC,



Side projects in Large-N QCD

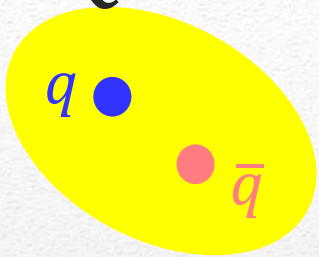


2013-: Member of the *BABAR* collaboration
ongoing analysis of *CP* violations in *SCS* Charm Decays

Nov 2015-now: Member of JPAC, my current projects are

- $3 \to 3$ scattering, focusing on $D\bar{D}\pi \to D\bar{D}\pi$
- $J/\psi \to \gamma\, \pi^0\pi^0$ amplitude analysis

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

Spin flip suppressed by heavy 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...)

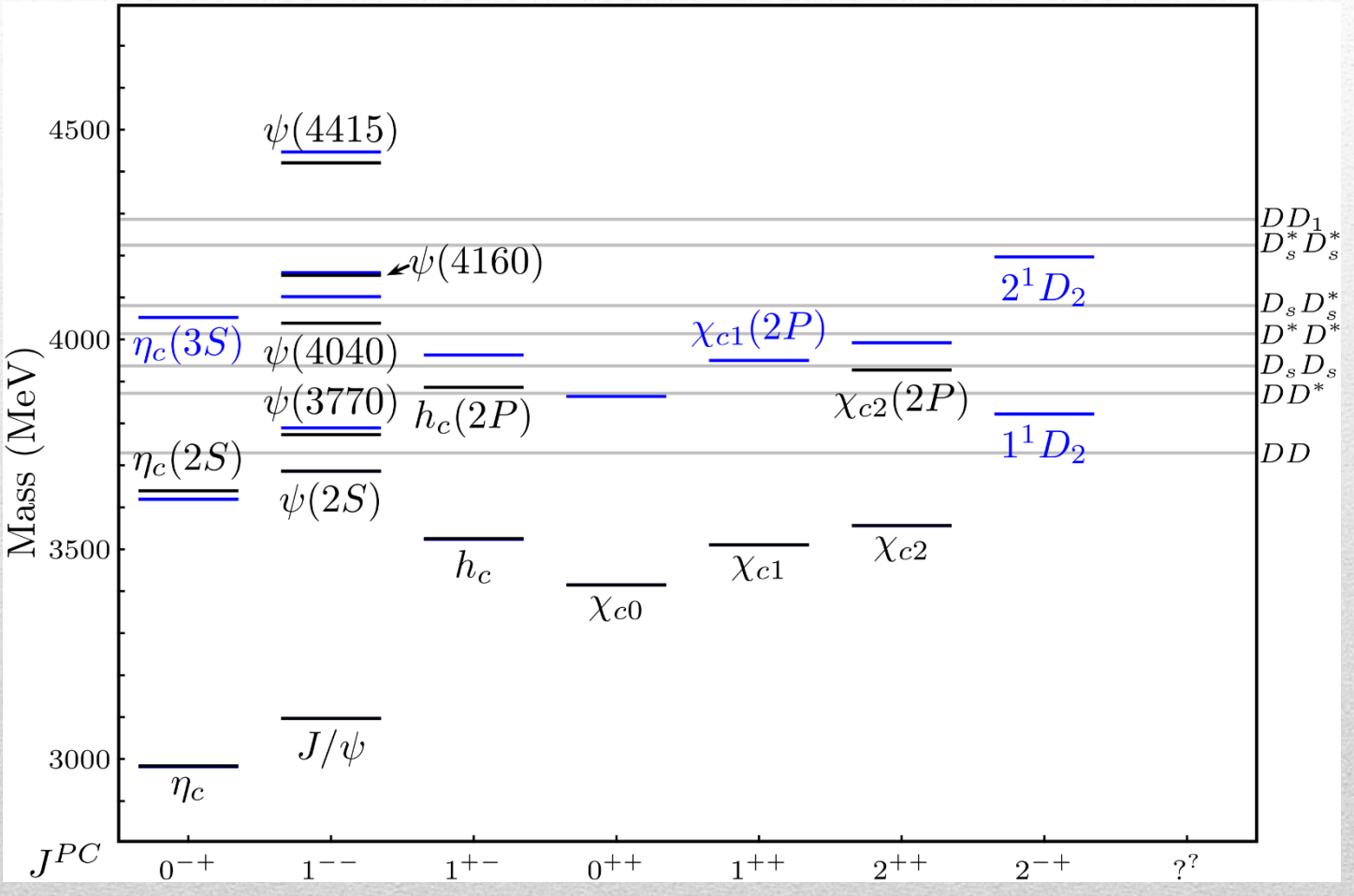
Integrate out heavy DOF

↓

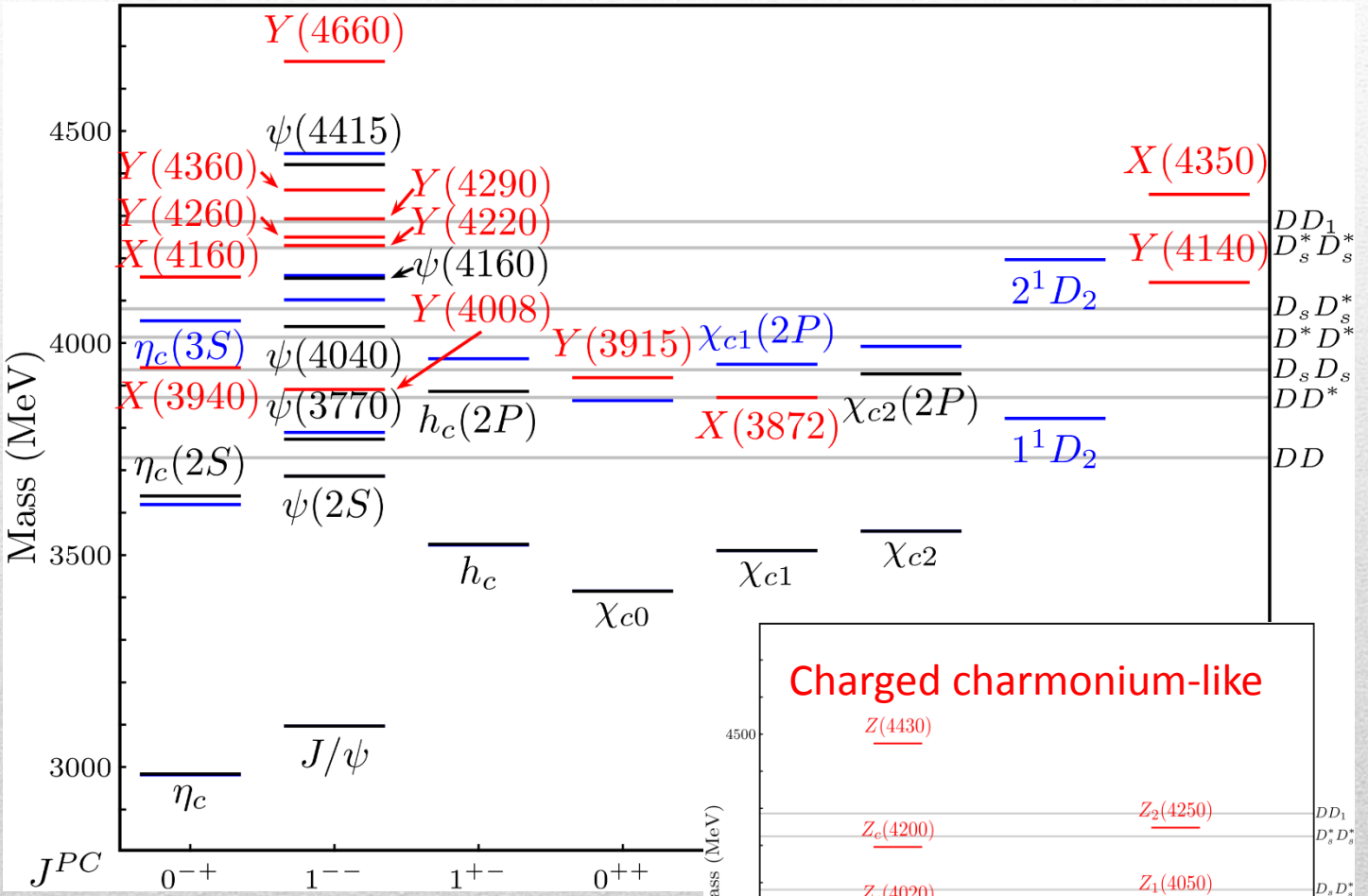
(spectrum), decay & production rates

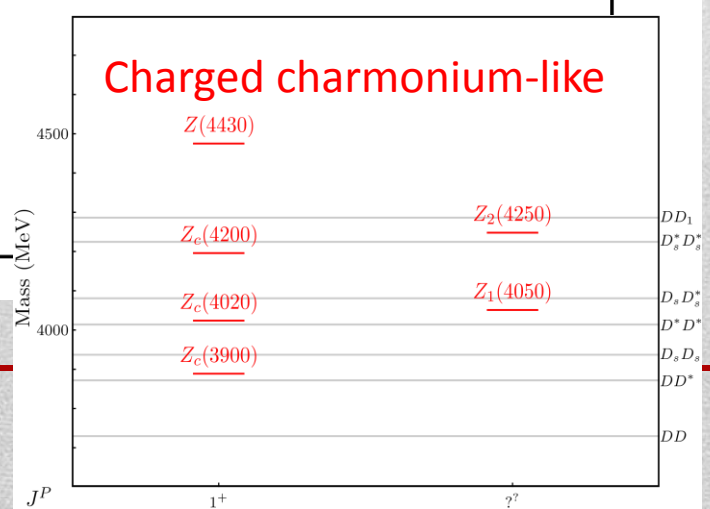
A precious training for understanding the strangeonia sector at JLab!

Quarkonium orthodoxy



Quarkonium orthodoxy?





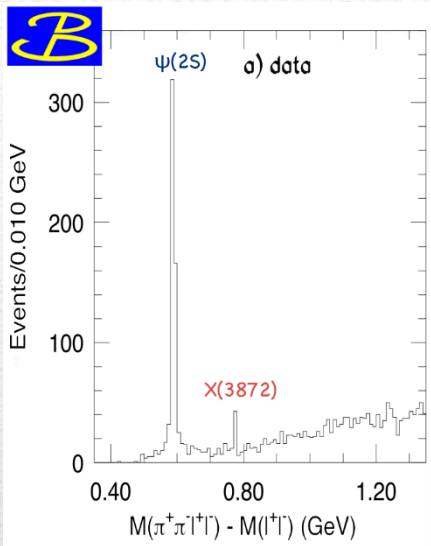
A host of unexpected peaks have appeared

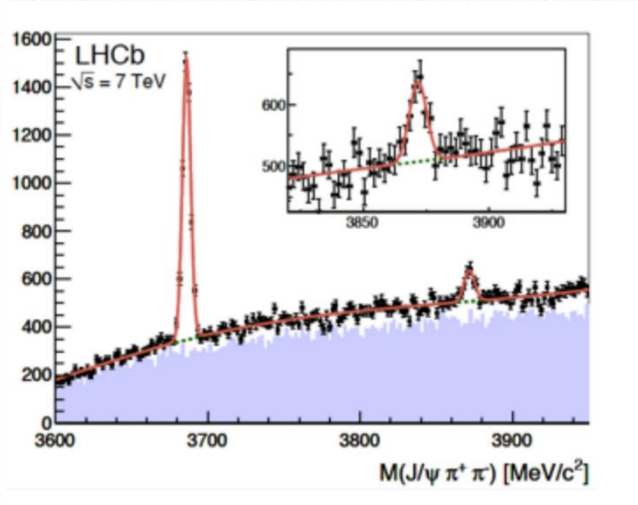
decaying mostly into charmonium + light

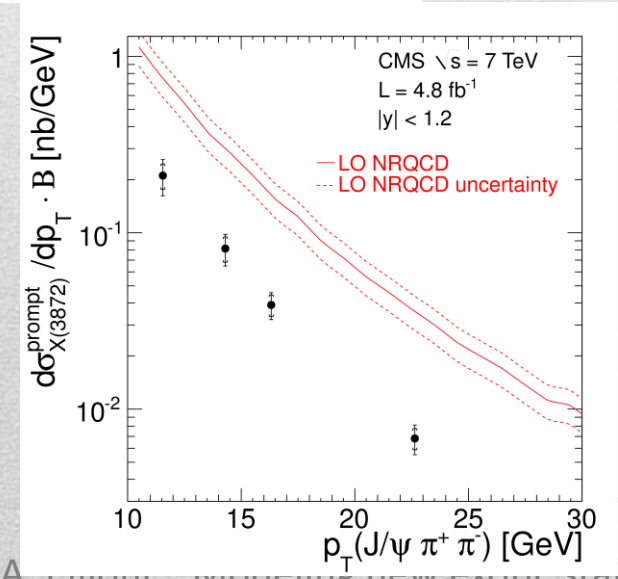
Quantum numbers allowed by quark model,
but hardly reconciled with the well-known charmonium phenomenology

«Who ordered that?»
– I. Rabi

$X(3872)$





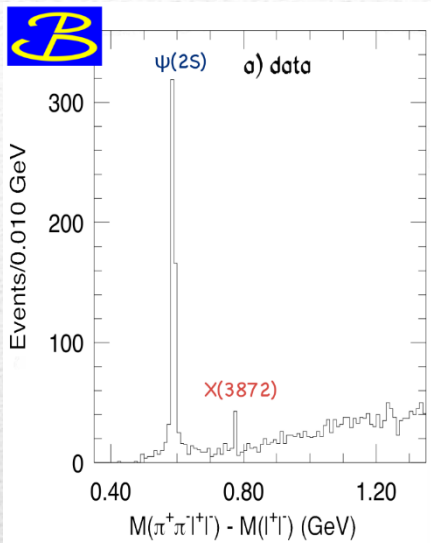


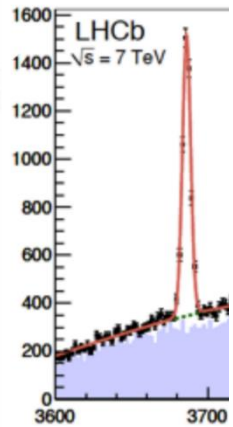
- Discovered in
  $B \to K\, X \to J/\psi\, \pi\pi$
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X \to J/\psi\ \omega)}{\Gamma(X \to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- $J^{PC} = 1^{++}$, but mass not compatible with $\chi_{c1}(2P)$

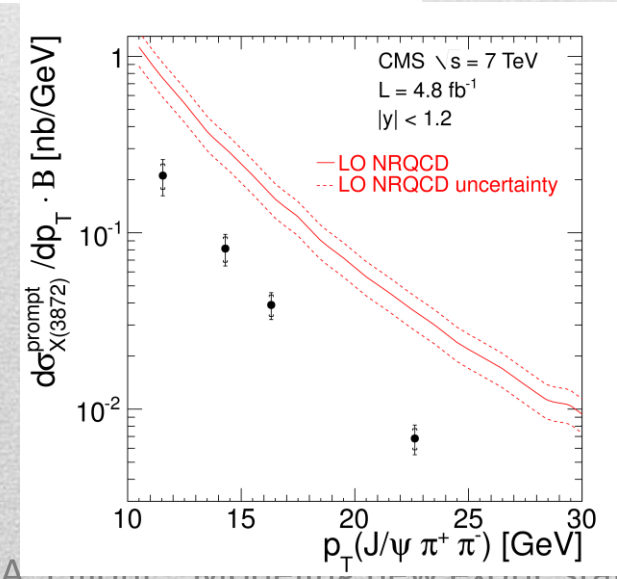
$$M = 3871.68 \pm 0.17 \text{ MeV}$$
$$M_X - M_{DD^*} = -3 \pm 192 \text{ keV}$$
$$\Gamma < 1.2 \text{ MeV @90\%}$$

Large prompt production, comparable to $\psi(2S)$

$X(3872)$



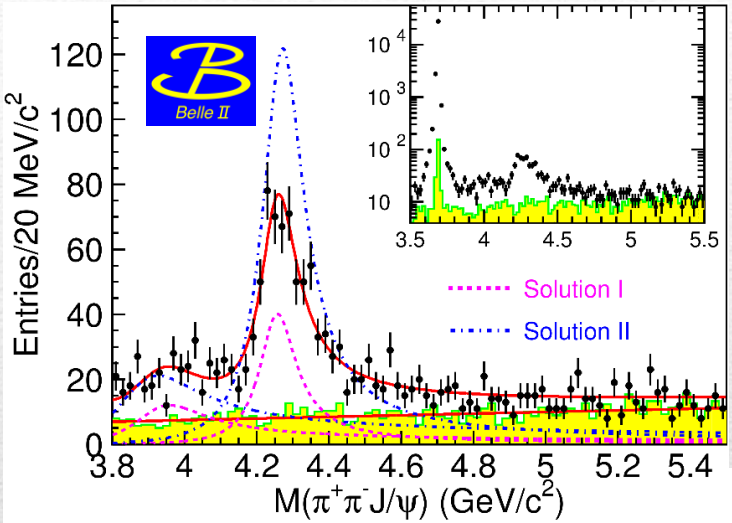




B decay mode	X decay mode	product branching fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(*BABAR*,[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	*BABAR*[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(*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]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Vector Y states

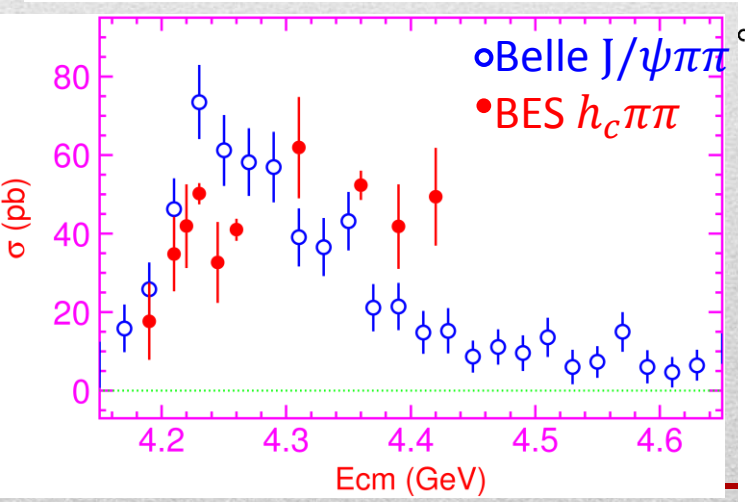
Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR analyses (and nowhere else!)

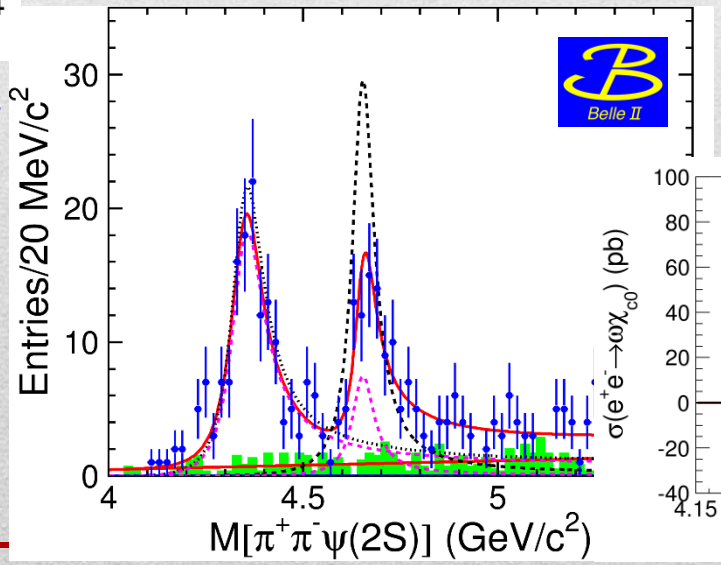


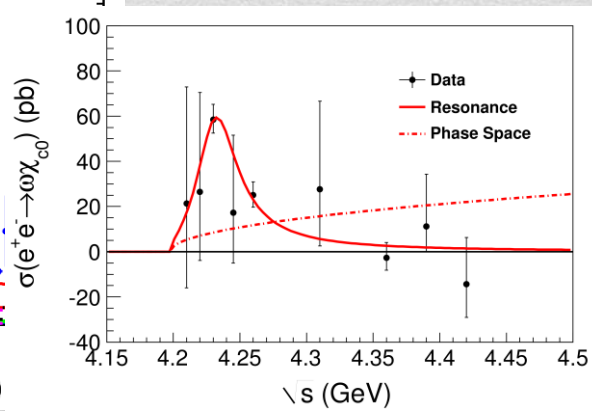
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

Not seen decaying into open charm pairs,
to compare with

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

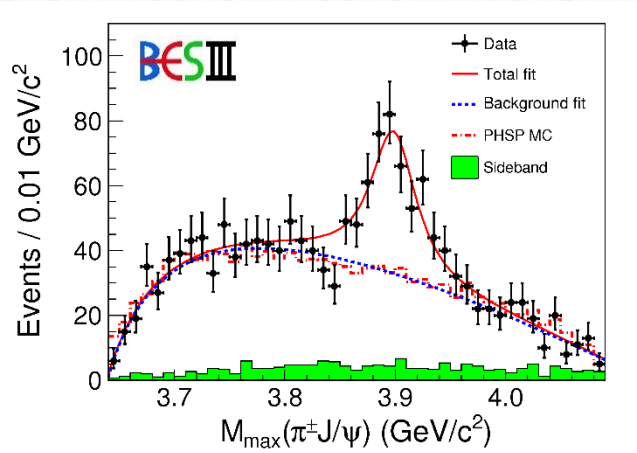






Charged Z states

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



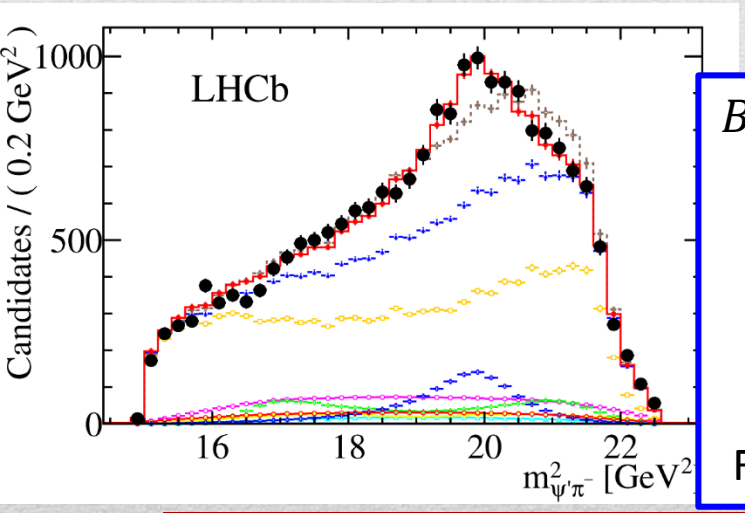
Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

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



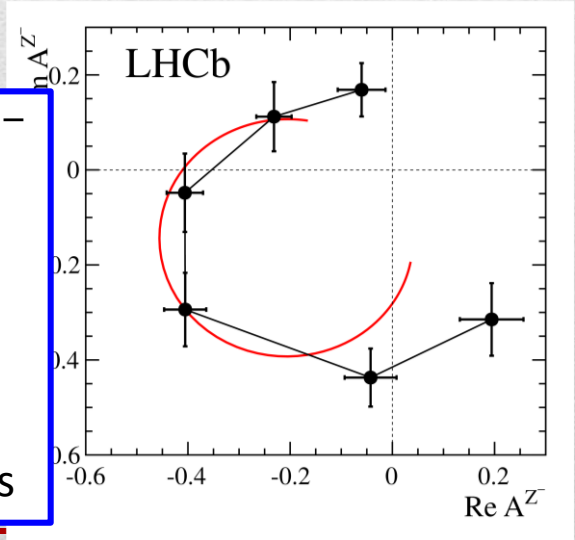
$B^0 \to K^+Z(4430)^- \to \psi(2S)\,\pi^-$

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

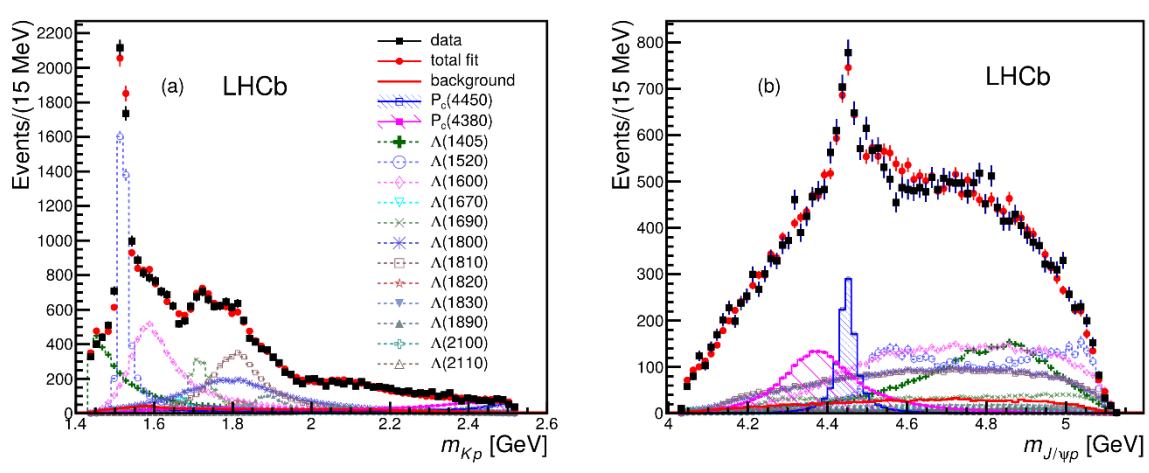
$M = 4475 \pm 7^{+15}_{-25}$ MeV

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

Far from open charm thresholds



Pentaquarks… and so on



LHCb, PRL 115, 072001

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

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

Opposite parities needed

…to be photoproduced at JLab@12 GeV

Usually, in the experimental analyses the amplitudes are parametrized with a coherent sum of Breit-Wigner functions (breaks unitarity)

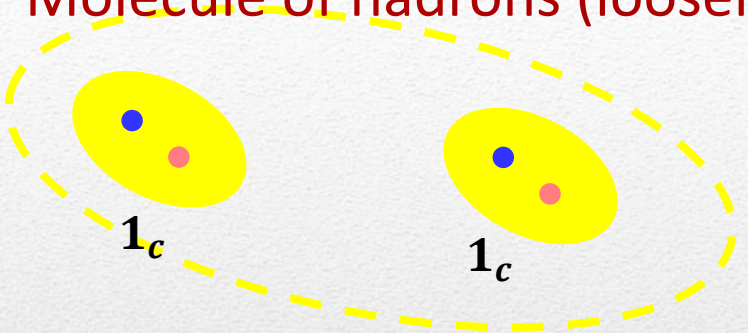
While this works when the resonances are well separated, a more accurate parametrization is needed to avoid premature discovery claims

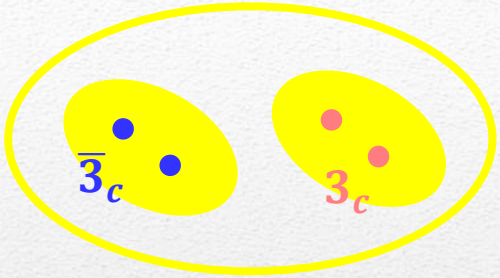
In this, the activity of JPAC plays a crucial role

see C. Fernandez-Ramirez et al., arXiv:1510.07065 on Λ^* states

Proposed models

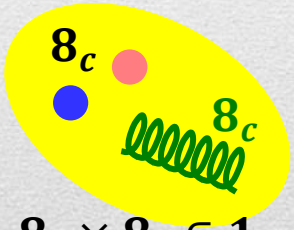
Molecule of hadrons (loosely bound)





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

Diquark-antidiquark (tetraquark)

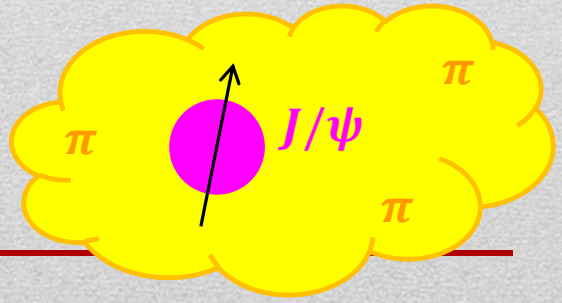


$\mathbf{8}_c \times \mathbf{8}_c \in \mathbf{1}_c$

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

Hadrocharmonium (Van der Waals forces)

Cusp, Rescattering effect (no actual resonance)

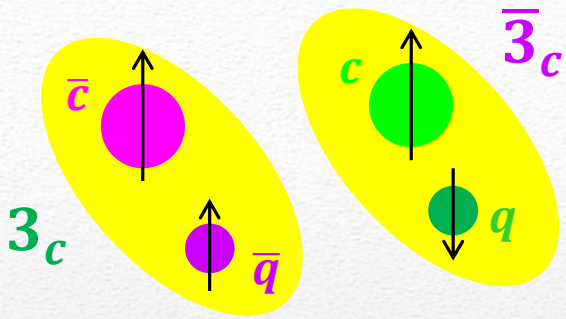


$\mathbf{1}_c \times \mathbf{1}_c \in \mathbf{1}_c$

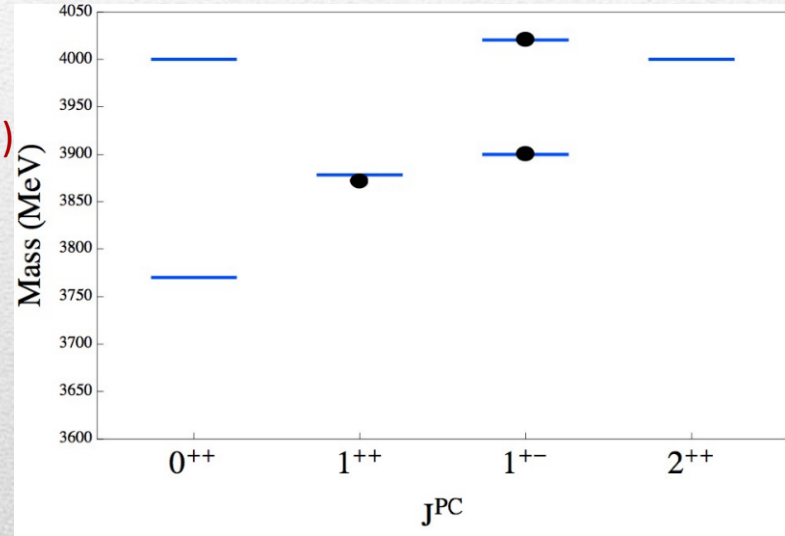
Tetraquark

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 (2005)
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87, 111102 (2013)
Maiani, Piccinini, Polosa, Riquer PRD89, 114010 (2014)



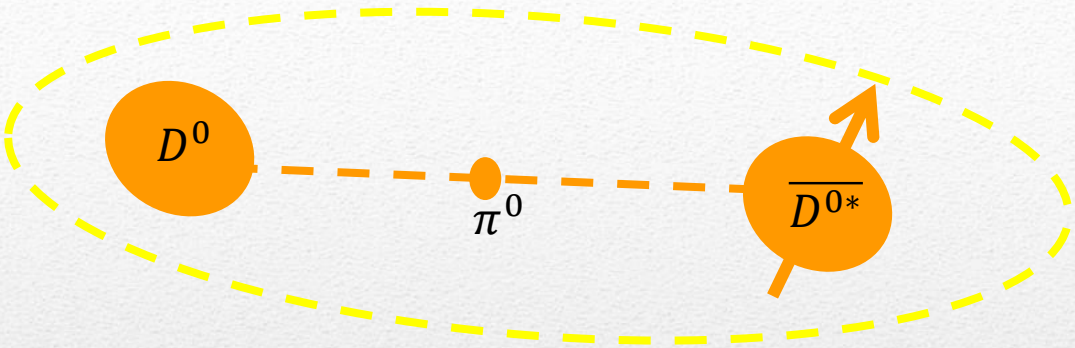
Spectrum according to color-spin hamiltonian:

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

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

✓ Decay pattern mostly driven by HQSS
✓ Fair understanding of existing spectrum (Ys and Z(4430))
✗ A full nonet for each level is expected

Molecule



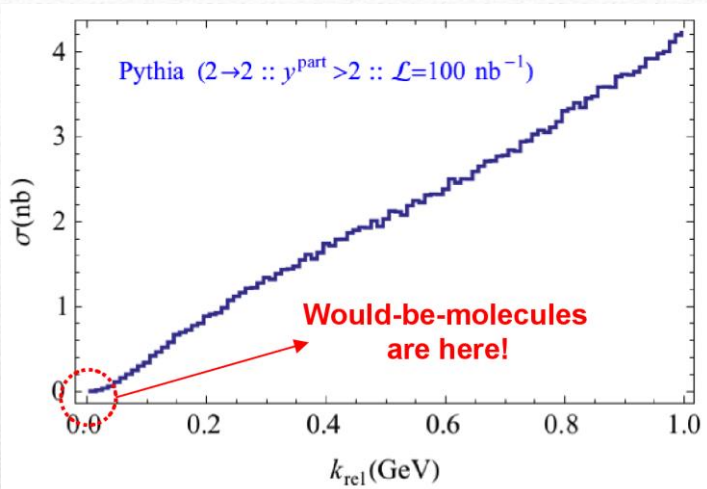
Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305

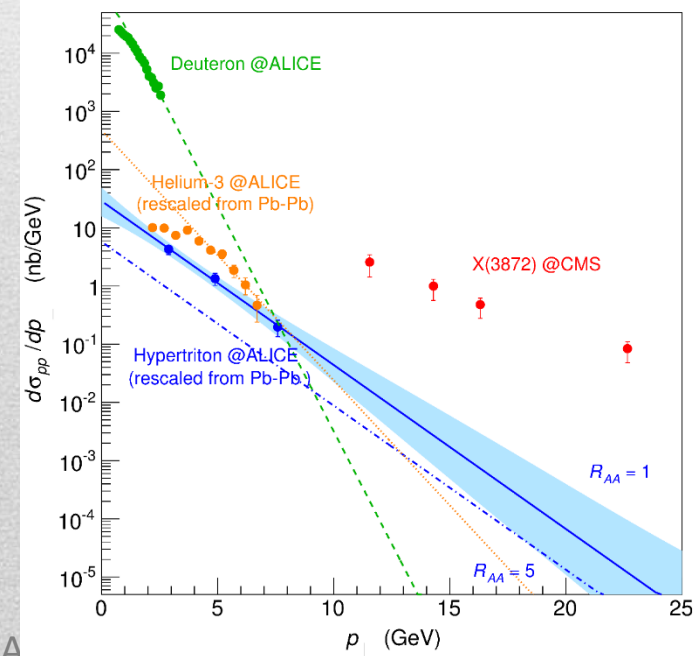
$$X(3872) \sim \bar{D}^0 D^{*0}$$
$$Z_c(3900) \sim \bar{D}^0 D^{*+}$$
$$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$$
$$Y(4260) \sim \bar{D} D_1$$

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 $Z(4430)$ ✗)
- 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 ✗

Prompt production of $X(3872)$





If the $X(3872)$ is a $D^0\bar{D}^{0*}$ molecule, the binding energy is $E_B \approx -0.14 \pm 0.22$ MeV, $k_{\rm rel} \approx 50$ MeV

How many pairs can we produce at hadron colliders?

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001
Esposito, Piccinini, AP, Polosa JMP 4 (2013), 1569-1573
Guerrieri, Piccinini, AP, Polosa PRD90 (2014), 034003

We obtain with MC simulations

$$\sigma(p\bar{p} \to DD^*) \approx 0.1 \text{ nb } @\sqrt{s} = 1.96 \text{ TeV}$$

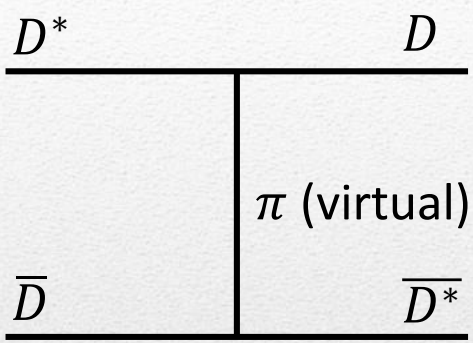
Experimentally

$$\sigma(p\bar{p} \to X(3872)) \approx 30 \text{ nb!!!}$$

Also the comparison with light nuclei production at ALICE seems not to favor a molecular interpretation

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer PRD92 (2015), 034028

One pion-exchange



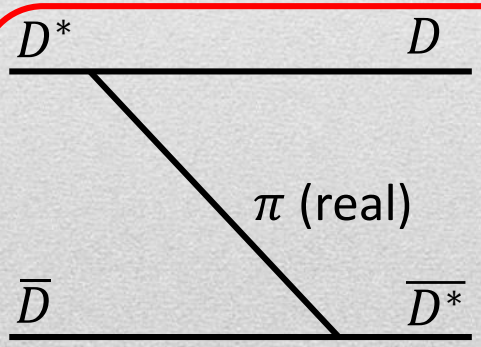
The dominant binding mechanism is expect to be the exchange of one- (two-...) pion in the *u* channel

In the literature, this has been evaluated in the static limit only

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

Solve Schrödinger equation, look for bound states

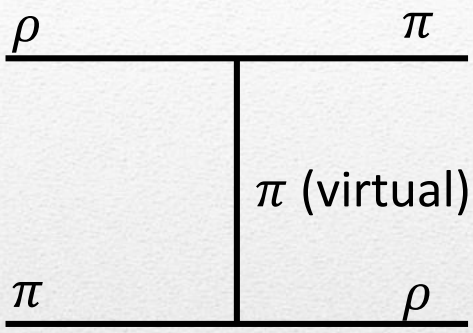
Yukawa-like potential, needs regularization



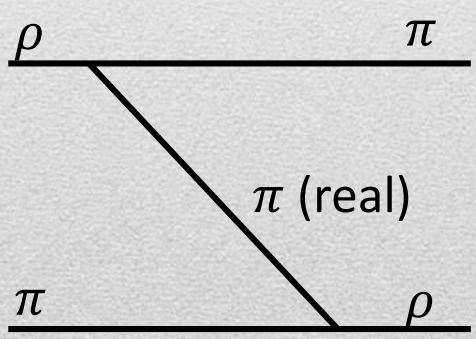
However, the π can happen to be on shell:
we aim to estimate this contribution, and check wether a (loosely) bound state can actually be formed

My current project

One pion-exchange



Once developed, the formalism will be extended to other $3 \to 3$ channels, like the $\rho\,\pi \to \rho\,\pi$, which JLab@12 GeV is going to produce with huge statistics



This is also connected with JLab Lattice QCD group activity on 3-body physics

Conclusions

The quarkonium sector was quite well understood,
until the XYZ states have challenged our beliefs

Quarkonium-like states are fairly narrow and exhibit
clean experimental signatures,
providing the ideal environment to test
new phenomenological models,
and different amplitude parametrizations,
which is the core activity of JPAC group

A better understanding of this sector will improve
our knowledge of strong interactions

Thank you

BACKUP

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COMPASS collaboration

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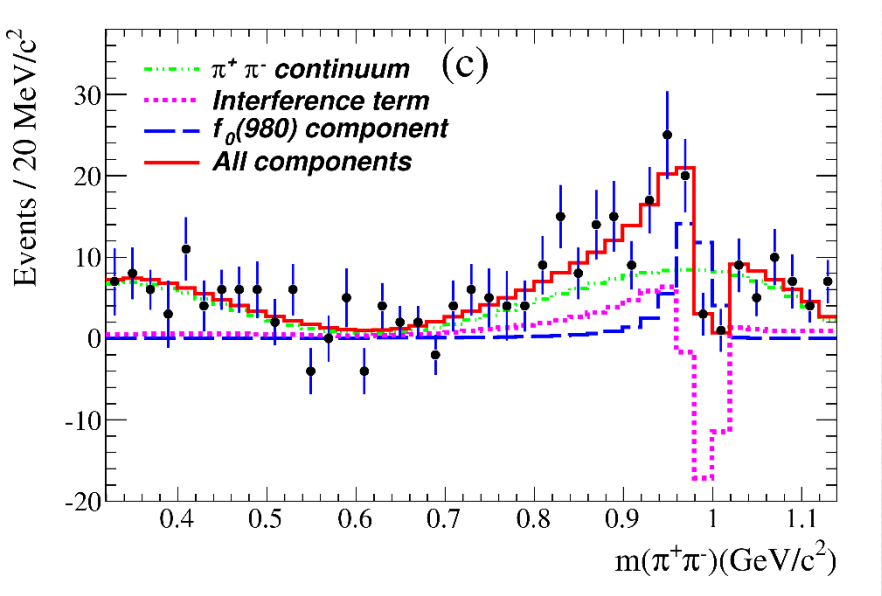
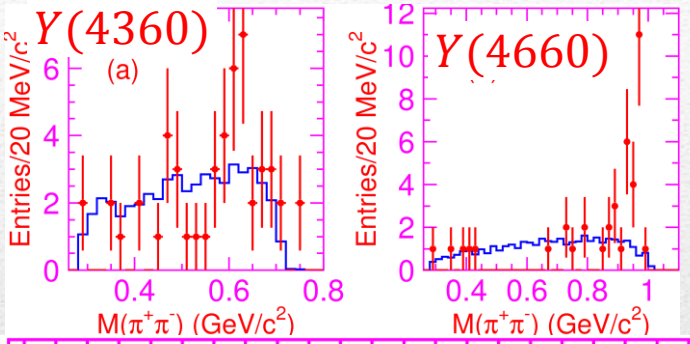
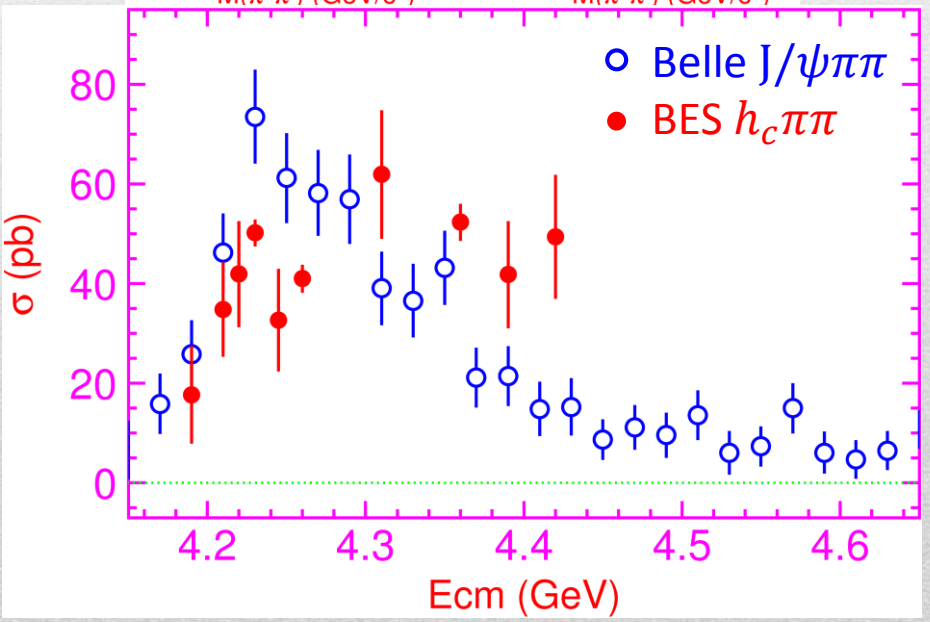
Fabian Krinner (TUM)
Boris Grube (TUM)
…

Vector Y states



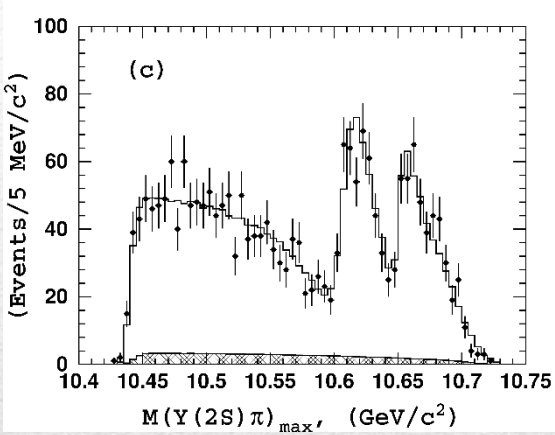
A component $Y(4260) \to J/\psi\, f_0(980)$ might explain why $Y(4260) \to \psi(2S)\pi\pi$

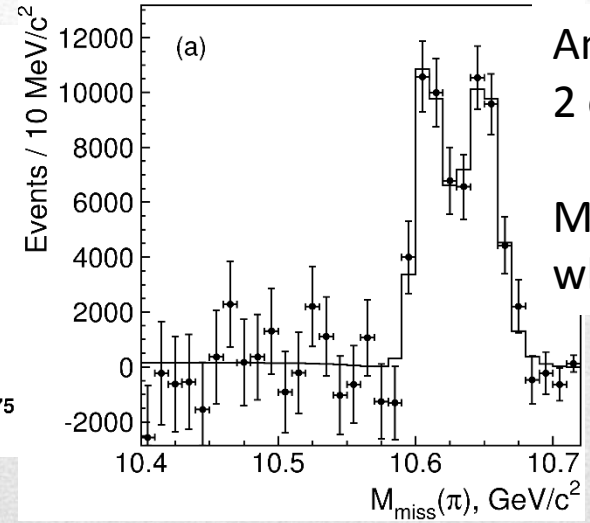




The lineshape in $h_c\ \pi\pi$ looks pretty different
Different states contributing?

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





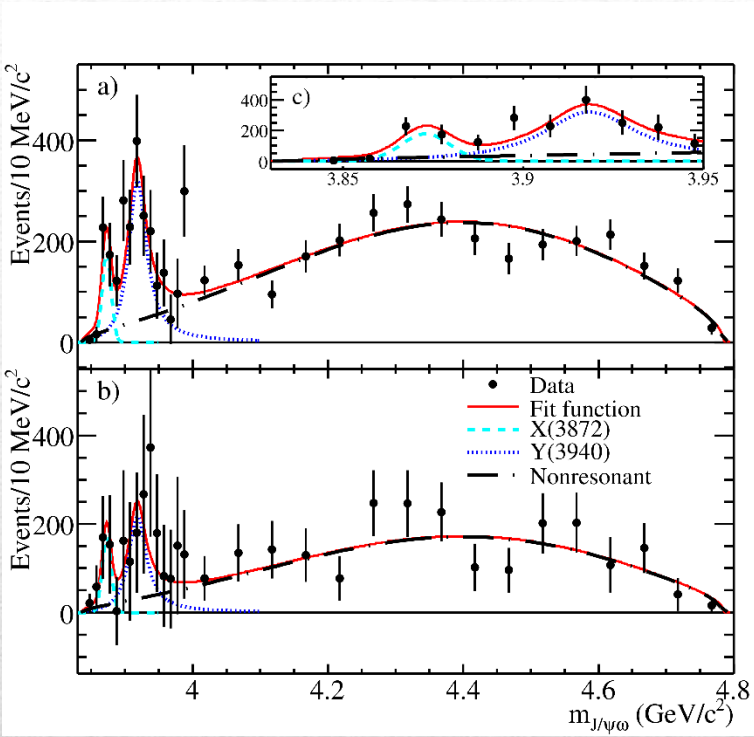
Anomalous dipion width in $\Upsilon(5S)$,
2 orders of magnitude larger than $\Upsilon(nS)$

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

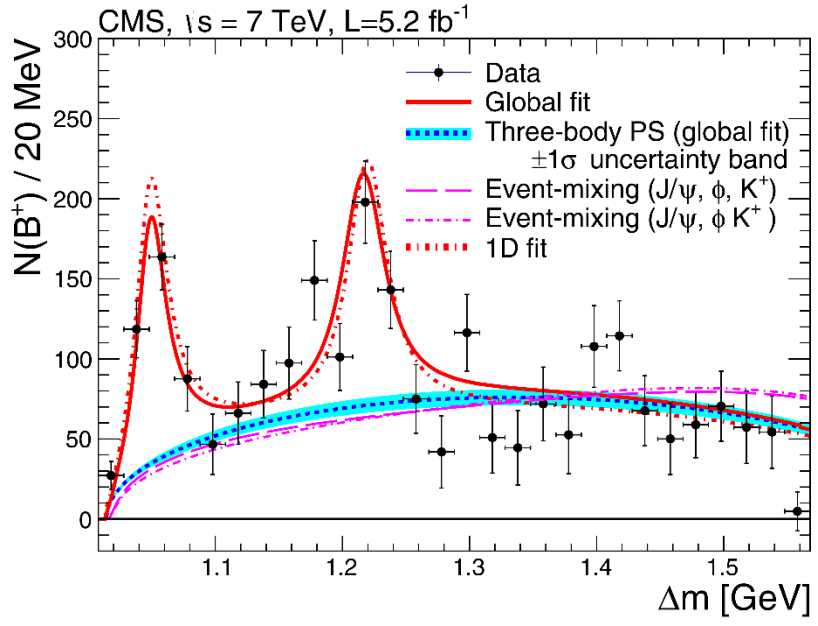
2 twin resonances!

$$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$$
$$\text{and} \to (BB^*)^+\pi^-$$
$$M = 10607.2 \pm 2.0 \text{ MeV}, \Gamma = 18.4 \pm 2.4 \text{ MeV}$$
$$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$$
$$\text{and} \to \bar{B}^{*0}B^{*+}\pi^-$$
$$M = 10652.2 \pm 1.5 \text{ MeV}, \Gamma = 11.5 \pm 2.2 \text{ MeV}$$

Other beasts



$X(3915)$, seen in $B \to X\,K \to J/\psi\,\omega$
and $\gamma\gamma \to X \to J/\psi\,\omega$
$J^{PC} = 0^{++}$, candidate for $\chi_{c0}(2P)$
But $X(3915) \not\to D\bar{D}$ as expected,
and the hyperfine splitting
$\mathrm{M}(2^{++}) - \mathrm{M}(0^{++})$ too small



One/two peaks seen in $B \to XK \to J/\psi\,\phi\,K$,
close to threshold

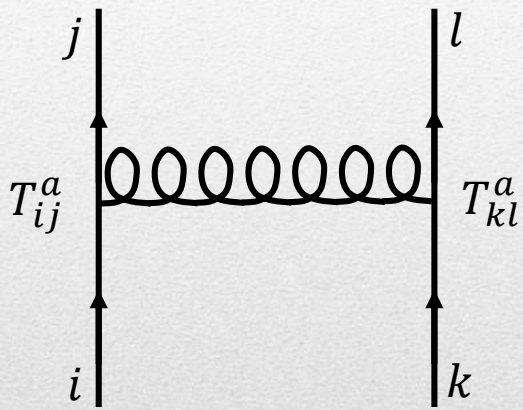
State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle[23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle[24,25] (>10), BABAR[26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF[27,28] (11.6), 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

Diquarks

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



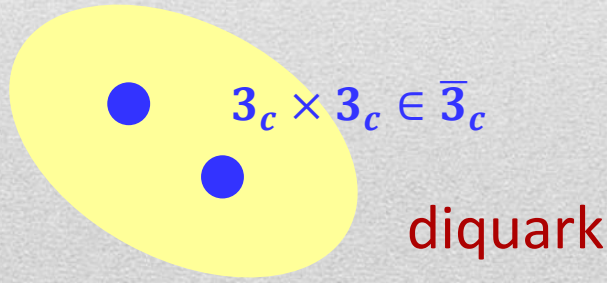
$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

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

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

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

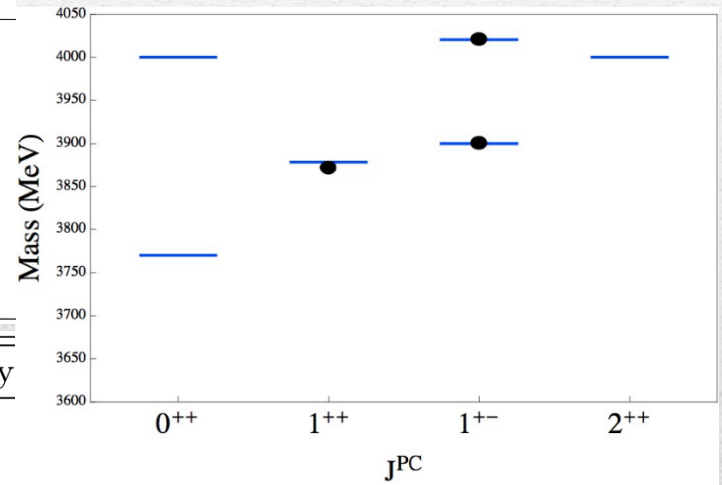


Tetraquark: new ansatz

Maiani, Piccinini, Polosa, Riquer PRD89 114010

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

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



State	$P(S_{c\bar{c}}=1) : P(S_{c\bar{c}}=0)$	$L = 1$ nt	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	$Y(4630)$	$\gamma + X_2$

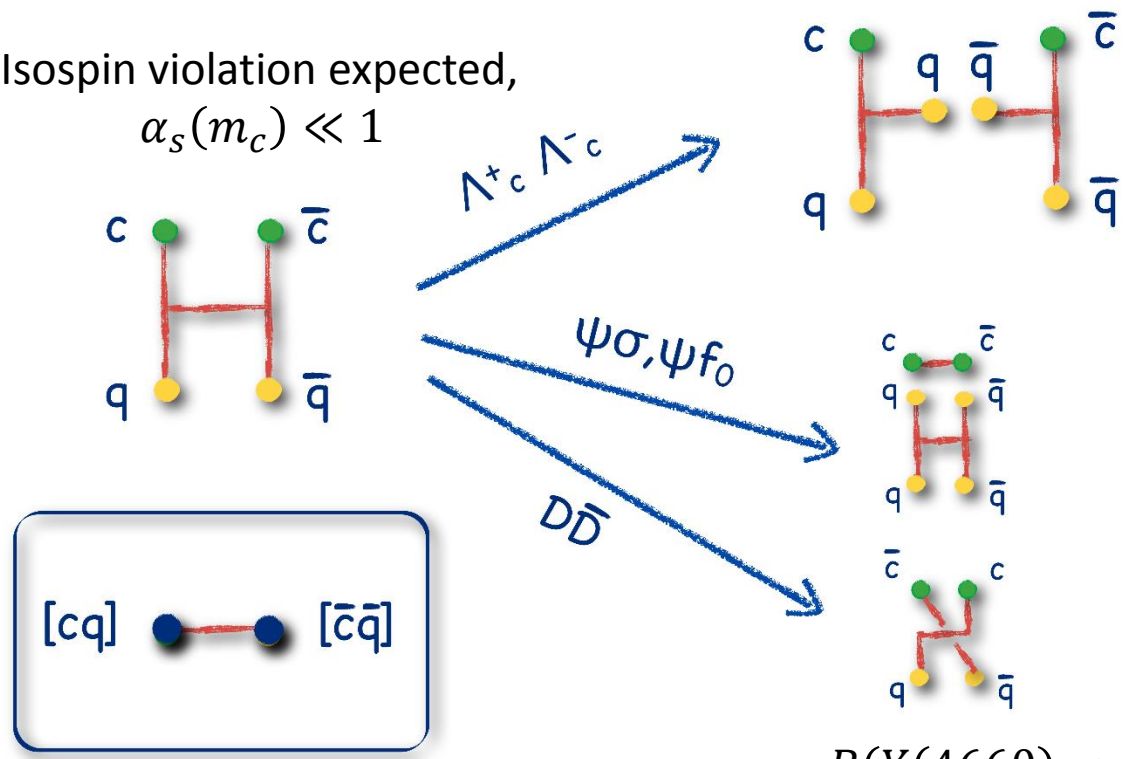
$$H = 2m_{dq} - 2\kappa_{cq}\left(\vec{S_c}\cdot\vec{S_q} + \vec{S_{\bar{c}}}\cdot\vec{S_{\bar{q}}}\right) + \frac{B_c\vec{L}^2}{2} - 2a\,\vec{L}\cdot\vec{S}$$

Baryonium

C. Sabelli

a structure $[cq][\bar{c}\bar{q}]$ can explain the dominance of baryon channel

Isospin violation expected,
$\alpha_s(m_c) \ll 1$



Rossi, Veneziano, NPB 123, 507; Phys.Rept. 63, 149; PLB70, 255

$$\frac{B(Y(4660) \to \Lambda_c^+ \Lambda_c^-)}{B(Y(4660) \to \psi(2S)\pi\pi)} = 25 \pm 7$$

Cotugno, Faccini, Polosa, Sabelli, PRL 104, 132005

Tetraquark: radial excitations

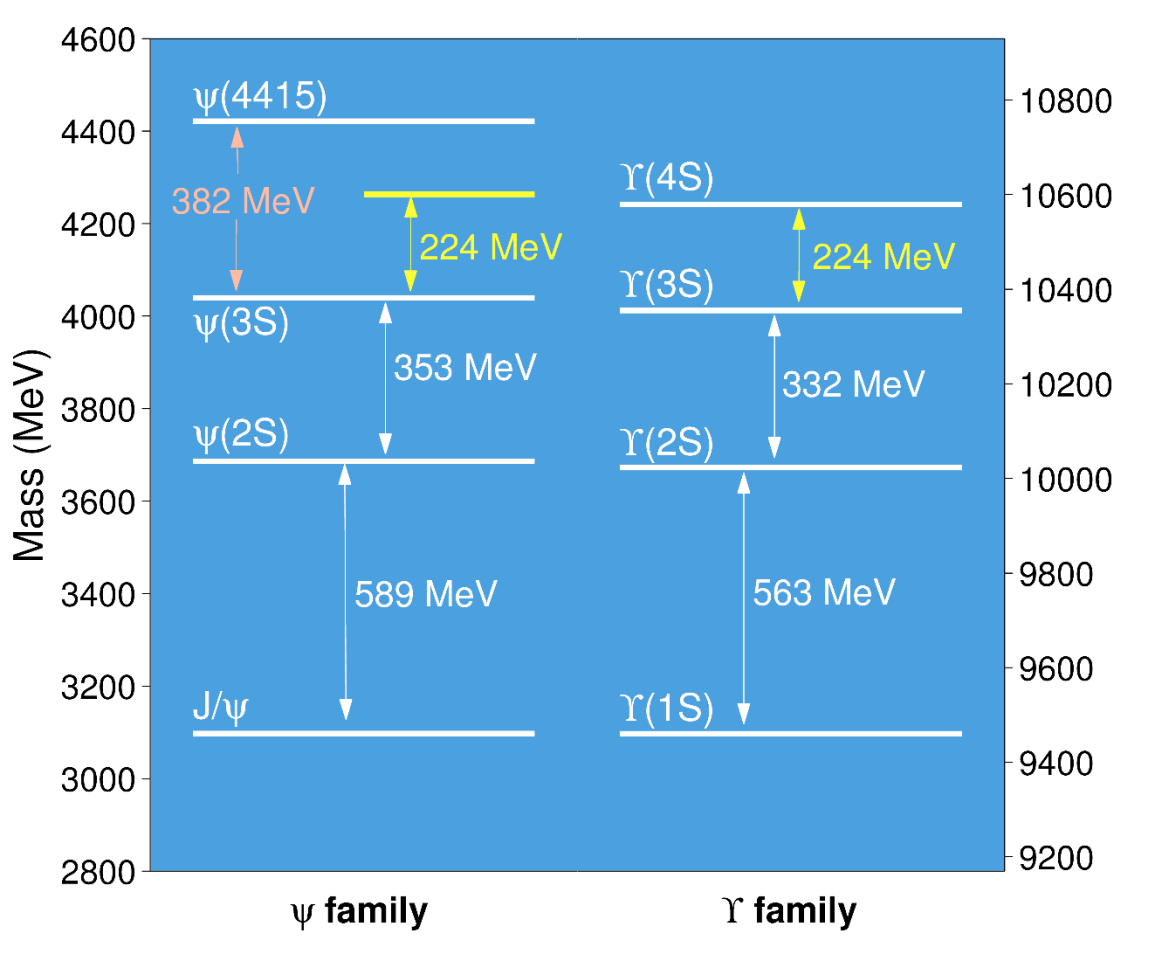
Maiani, Piccinini, Polosa, Riquer PRD89 114010

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

$\chi_{cJ}(2P) - \chi_{cJ}(1P) \sim 437$ MeV
$\chi_{bJ}(2P) - \chi_{bJ}(1P) \sim 360$ MeV

Use the same splittings for tetraquarks

$M\big(Z(4430)\big) - M(Z_c(3900)$
$= 586^{+17}_{-26}$ MeV



$Z_c(3900) \to \eta_c \rho$

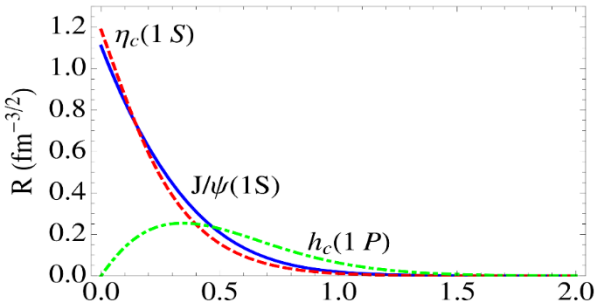
Esposito, Guerrieri, AP, PLB 746, 194-201

If tetraquark

Kinematics with PHS and HQSS

Dynamics estimated according to

Brodsky, Hwang, Lebed, PRL113, 112001

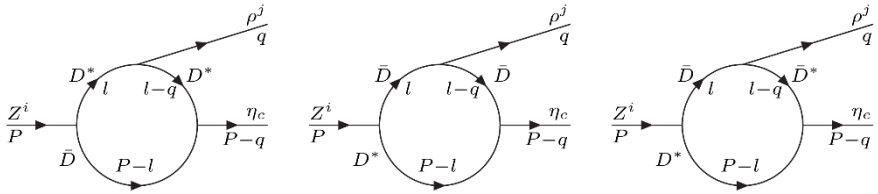


	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi\,\pi)}$	$\left(3.3^{+7.9}_{-1.4}\right) \times 10^2$	$0.41^{+0.96}_{-0.17}$	$\left(2.3^{+3.3}_{-1.4}\right) \times 10^2$	$0.27^{+0.40}_{-0.17}$
$\frac{\mathcal{BR}(Z_c' \to \eta_c \rho)}{\mathcal{BR}(Z_c' \to h_c \pi)}$	$\left(1.2^{+2.8}_{-0.5}\right) \times 10^2$		$6.6^{+56.8}_{-5.8}$	

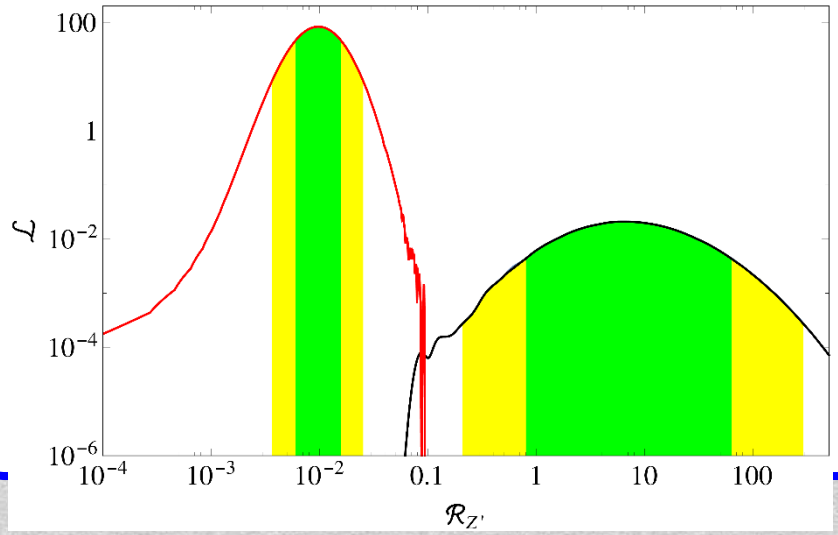
If molecule

Non-Relativistic Effective Theory

HQET and Hidden gauge Lagrangian



$$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi\,\pi)} = \left(4.6^{+2.5}_{-1.7}\right) \times 10^{-2}\,; \qquad \frac{\mathcal{BR}(Z_c' \to \eta_c \rho)}{\mathcal{BR}(Z_c' \to h_c\,\pi)} = \left(1.0^{+0.6}_{-0.4}\right) \times 10^{-2}\,.$$

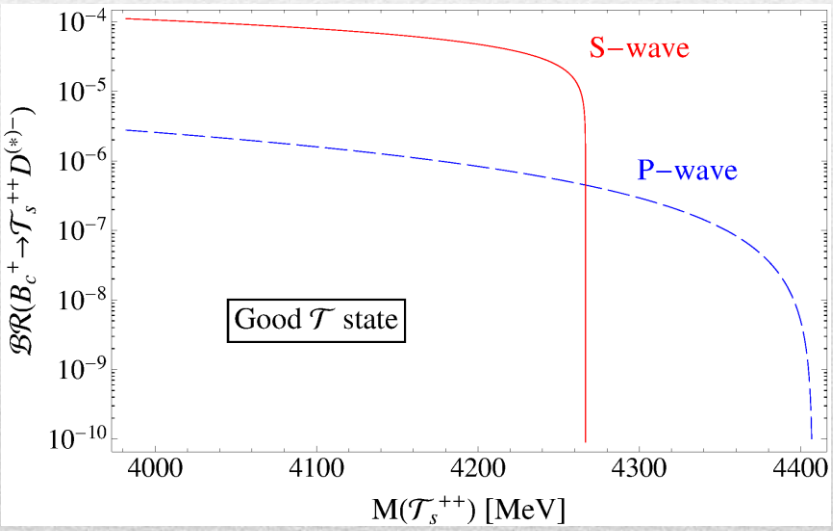


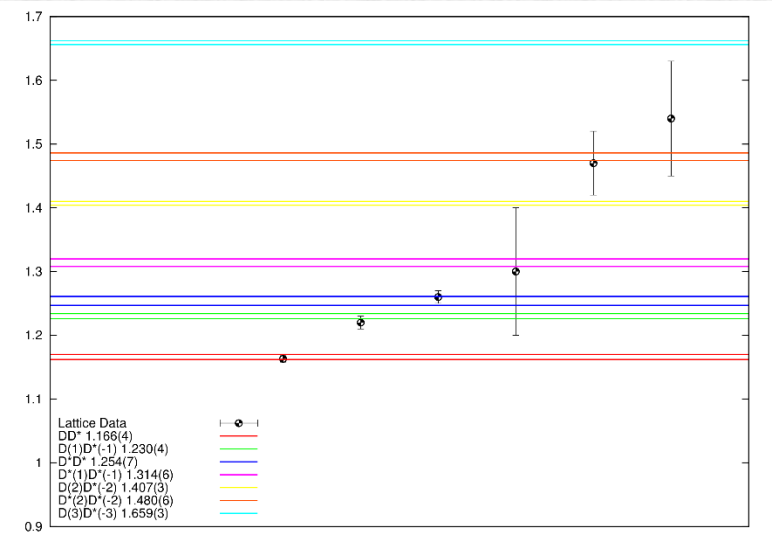
Doubly charmed states

We explored the phenomenology of doubly charmed states,
which in tetraquark model are $[cc]_{S=1}[\bar{q}\bar{q}]_{S=0,1}$
The doubly charged $cc\bar{d}\bar{d}$ partner cold not be interpreted as a molecule

These states might be observed in B_c decays @LHC and sought on the lattice

Esposito, Papinutto, AP, Polosa, Tantalo, PRD88 (2013) 054029





Preliminary results on spectrum for $m_\pi = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

Guerrieri, Papinutto, AP, Polosa, Tantalo, PoS LATTICE2014 106

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 $B, T \ll m_{a,b}$

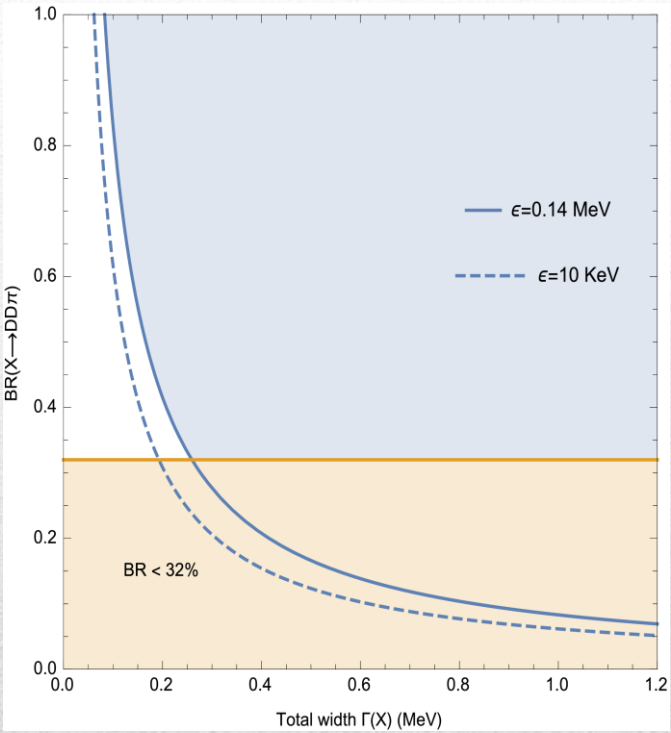
$$f(ab \to c \to ab) = -\frac{1}{16\pi (m_a + m_b)^2} g^2 \frac{1}{B + T}$$

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 $-B$

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

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

This holds if the constituents are stable!



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

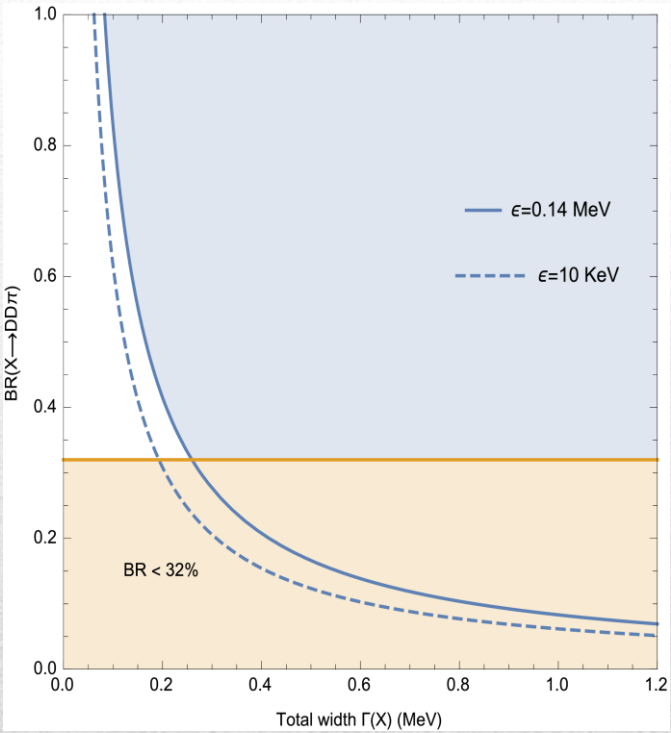
Weinberg theorem

$$Z = \sum_n |\langle n|X\rangle|^2 = \text{elementariness}$$

$$a = \frac{2(1-Z)}{2-Z}\frac{1}{\sqrt{2\mu B}}$$

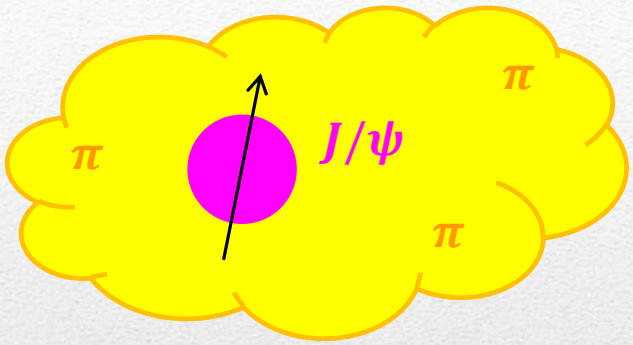
$$r_0 = -\frac{Z}{1-Z}\frac{1}{\sqrt{2\mu B}}$$

$$B = \frac{g^4}{512\pi^2}\frac{\mu^5}{(m_a m_b)^2}\frac{1}{(1-Z)^2}$$



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

Hadro-charmonium



Dubynskiy, Voloshin, PLB 666, 344
Dubynskiy, Voloshin, PLB 671, 82
Li, Voloshin, MPLA29, 1450060

Born in the context of QCD multipole expansion

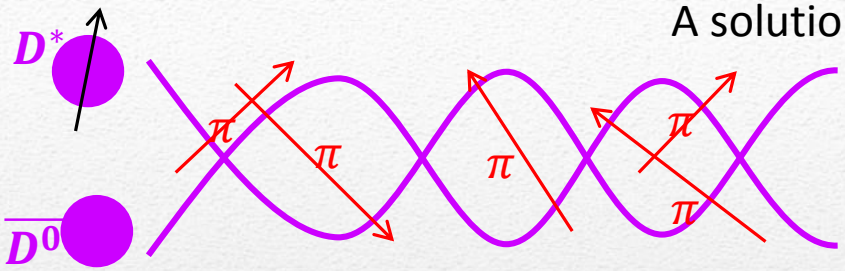
$$H_{eff} = -\frac{1}{2} a_\psi E_i^a E_i^a$$
$$a_\psi = \langle \psi | (t_c^a - t_{\bar{c}}^a) r_i \, G \, r_i (t_c^a - t_{\bar{c}}^a) | \psi \rangle$$

the chromoelectric field interacts with soft light matter (highly excited light hadrons)

A bound state can occur via Van der Waals-like interactions

Expected to decay into core charmonium + light hadrons,
Decay into open charm exponentially suppressed

Estimating k_{max}



A solution can be FSI (rescattering of DD^*) , which allow k_{max} to be as large as $5m_\pi \sim 700$ MeV

$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -NA^{on}_{prod} \cdot \frac{e^{i\delta}\sin\delta}{ka_{NN}}$$

$$\sigma\big(p\bar{p} \to X(3872)\big) \to \sigma(p\bar{p} \to DD^*|k < k_{max}) \times \frac{6\pi\sqrt{2\mu\, E_B}}{k_{max}}$$

However, the applicability of Watson-Migdal approach is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354

use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,

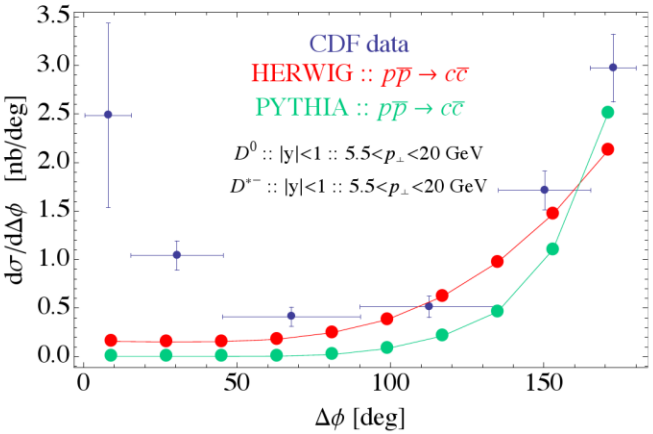
limits on predictive power

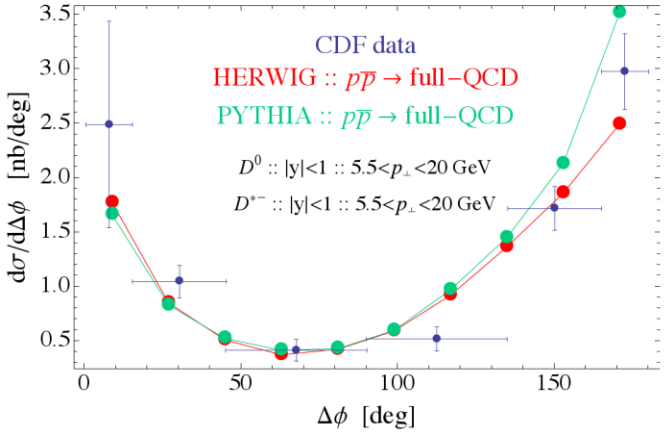
Tuning of MC

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

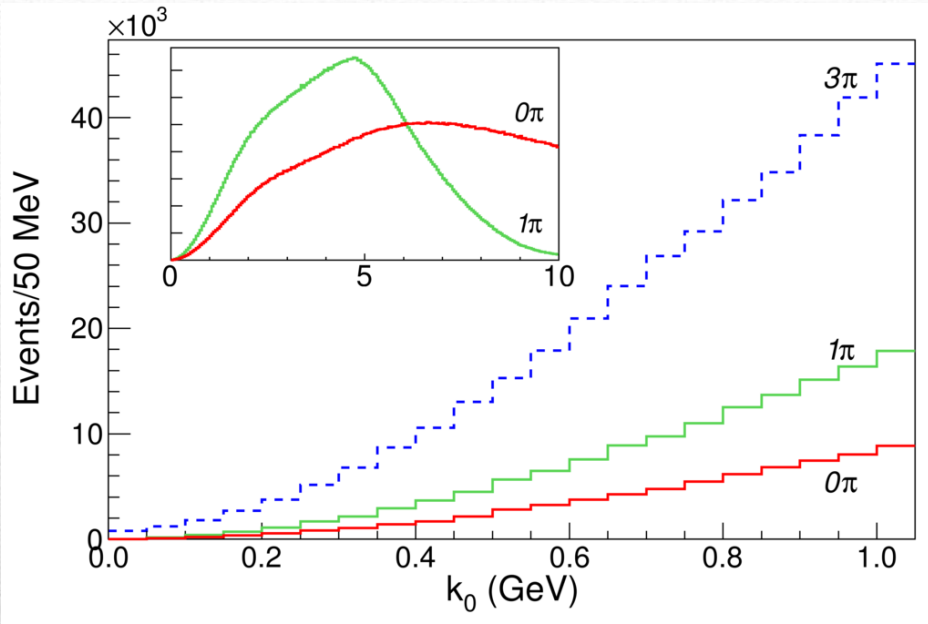
A new mechanism?

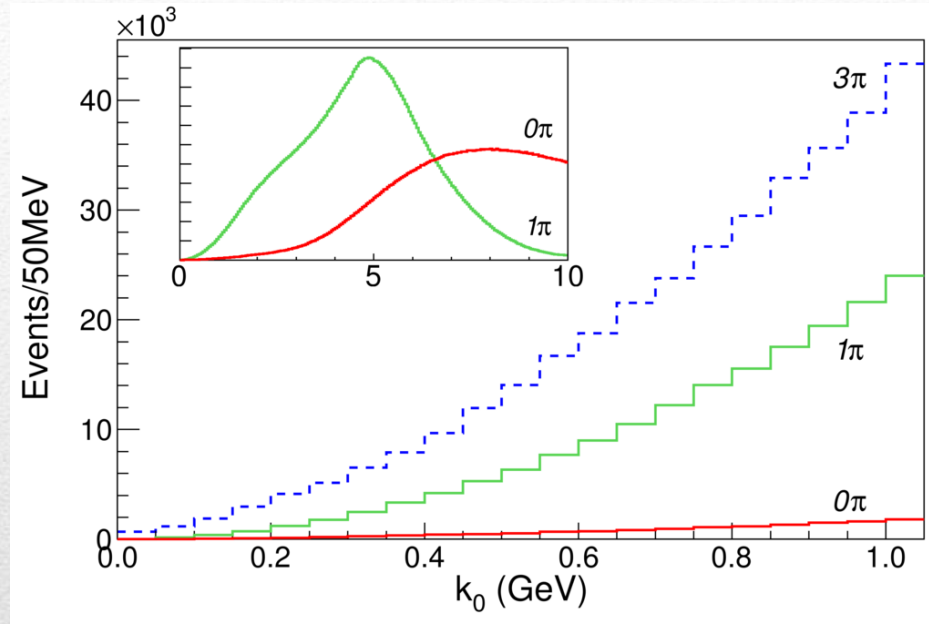
		HERWIG		PYTHIA	
$k_0^{\max}$		50 MeV	100 MeV	50 MeV	100 MeV
No. of events	0 scatt.	52	253	240	1560
	1 scatt.	44	299	283	1984
	3 scatt.	843	2069	4843	11679
	4 scatt.	1166	2802	6489	14916
	5 scatt.	1689	4167	7770	18284
σ [nb]	0 scatt.	0.10	0.50	0.13	0.83
	1 scatt.	0.09	0.59	0.15	1.05
	3 scatt.	1.67	4.10	2.57	6.20
	4 scatt.	2.31	5.55	3.44	7.92
	5 scatt.	3.34	8.25	4.12	9.71

Striking increase of σ after each scattering!

Down by a factor 5-7 wrt $\sigma_{\text{exp}} \approx 30$ nb,

$p\bar{p} \rightarrow c\bar{c}$





#events	Herwig	Pythia
0π	10	3
1π	19	21
3π	802	814

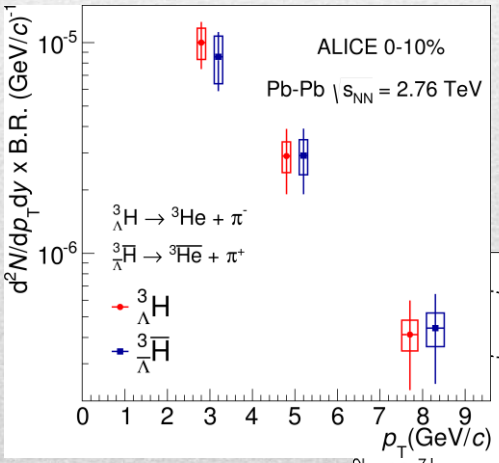
The enhancement is impressive because first bins are almost empty

Light nuclei at ALICE

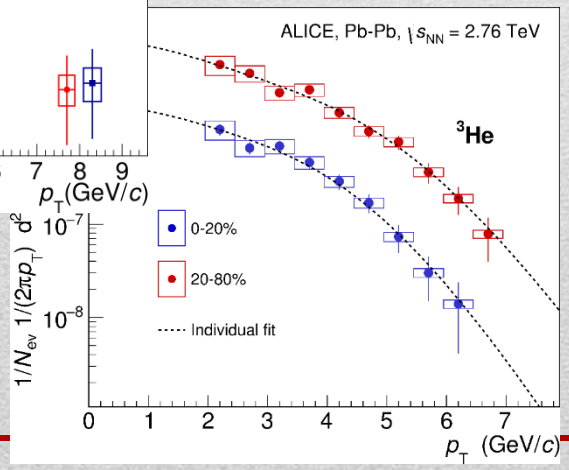
Recently, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

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

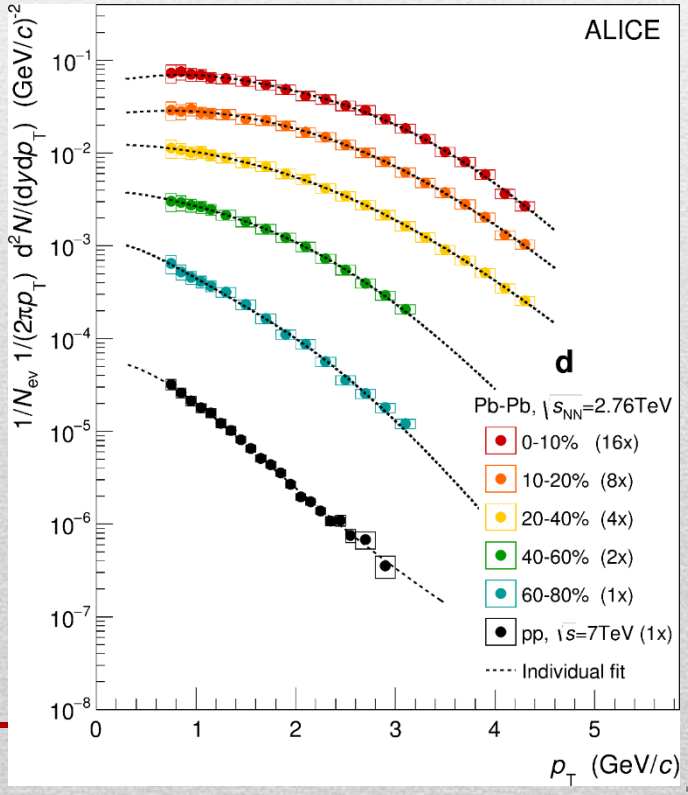
Hypertriton
arXiv:1506.08453



Helium-3
arXiv:1506.08951



Deuteron
arXiv:1506.08951



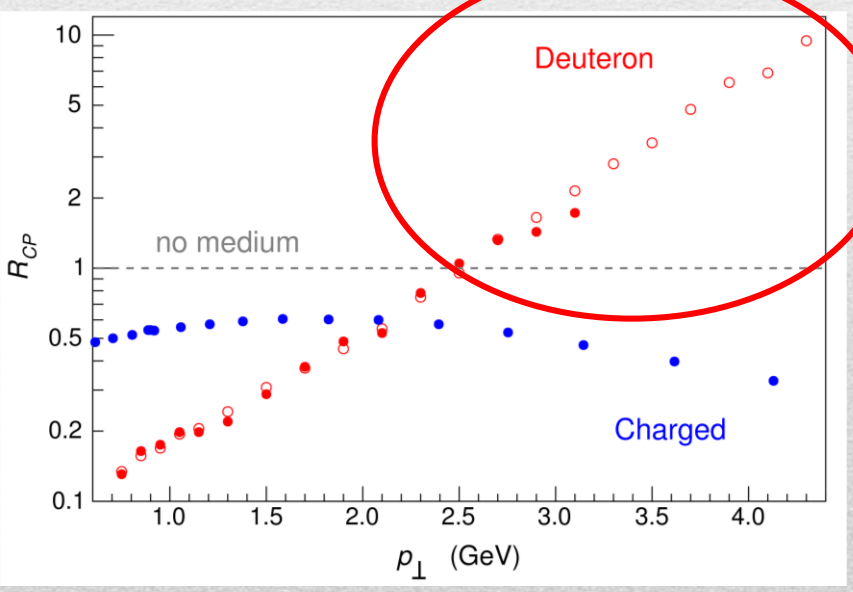
Nuclear modification factors

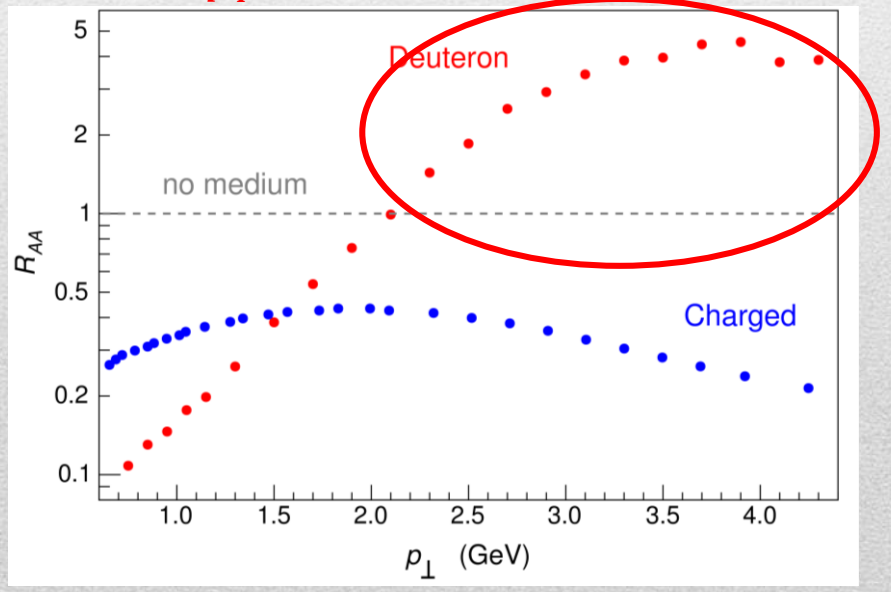
We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

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

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

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

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

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