# Modeling new exotic XYZ states


Alessandro Pilloni

Jefferson Lab

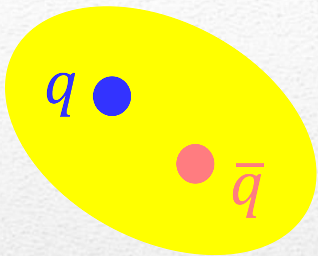

Johannes Gutenberg University, Mainz – February 5th, 2015

in coll. w/ Esposito, Faccini, Filaci, Guerrieri, Maiani, Papinutto, Piccinini, Polosa, Riquer, Tantalo

# Outline

- «Exotic landscape»
- Compact tetraquarks
- Other models
- Production of exotics at LHC
- Feshbach resonances
- Conclusions

# 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

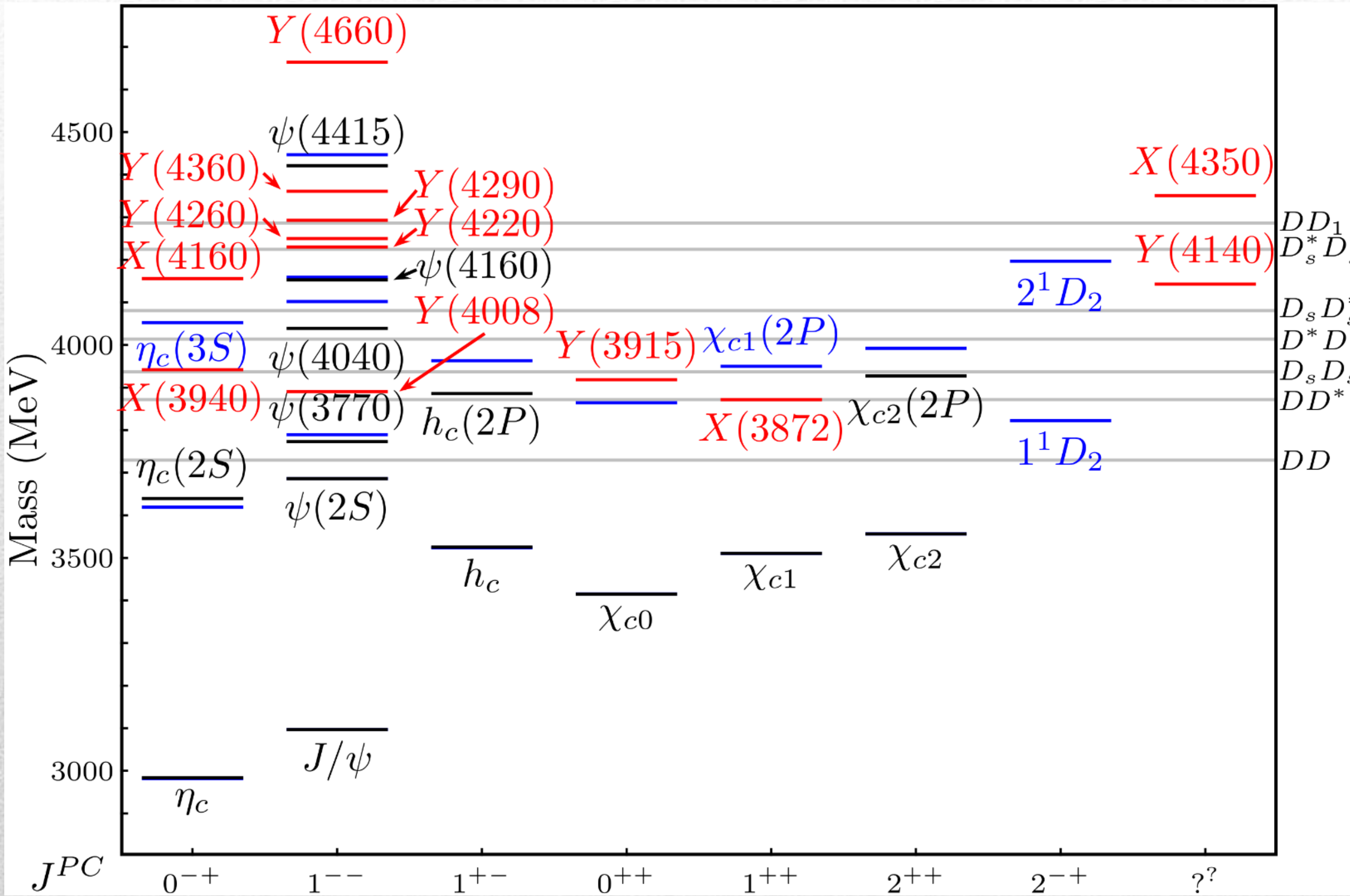
(HQET, NRQCD...)

Integrate out heavy DOF

↓

(spectrum), decay & production rates

# Quarkonium orthodoxy?

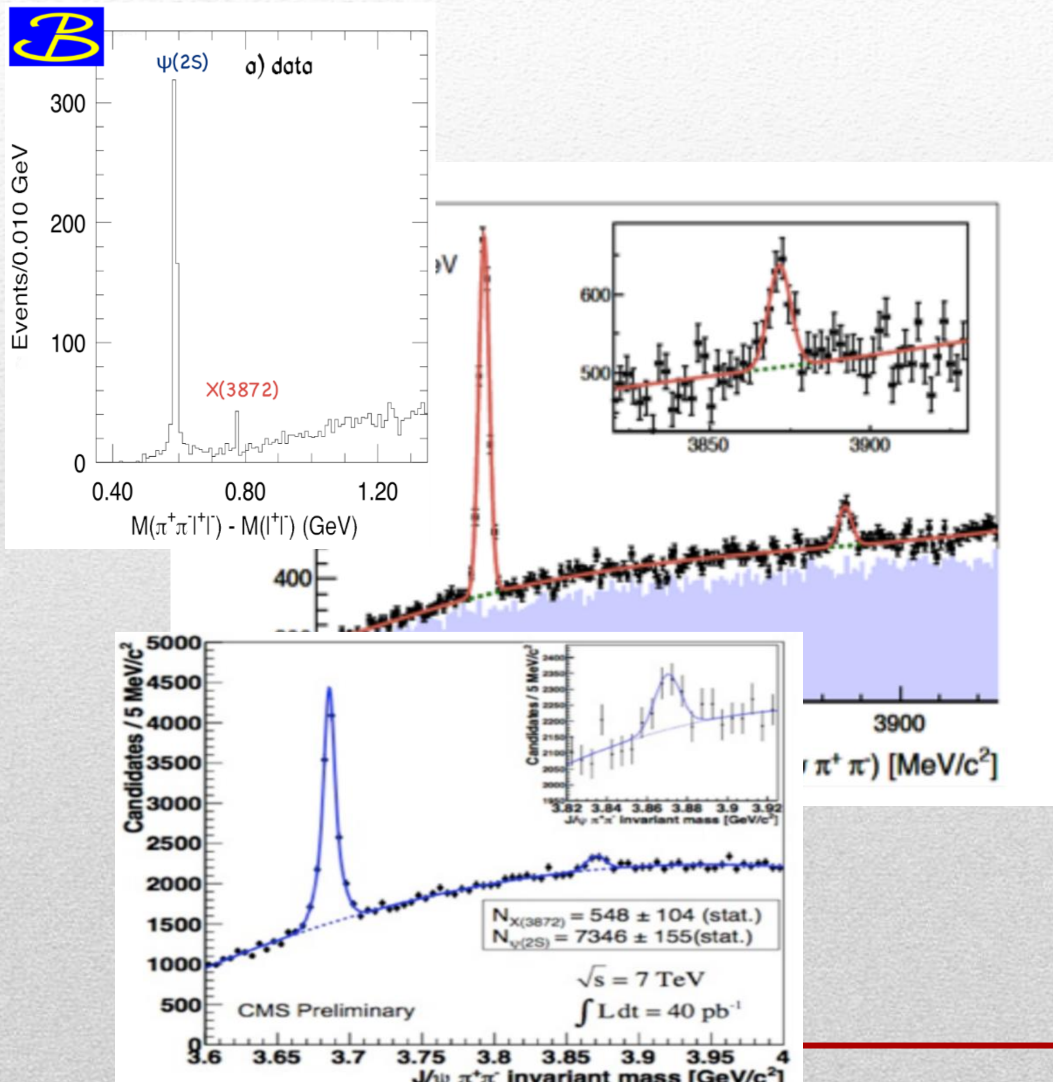



A host of unexpected resonances have appeared

decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

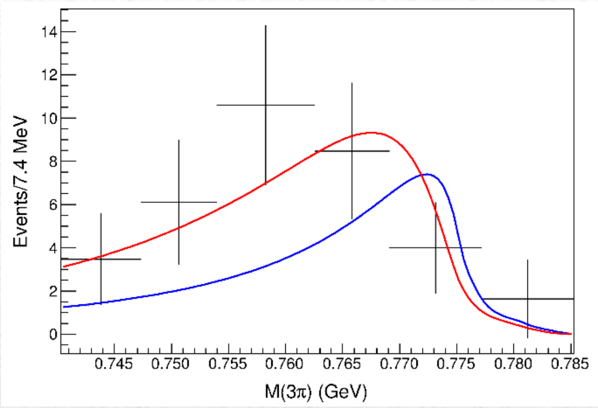
# $X(3872)$




- 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 $\chi_{c1}(2P)$

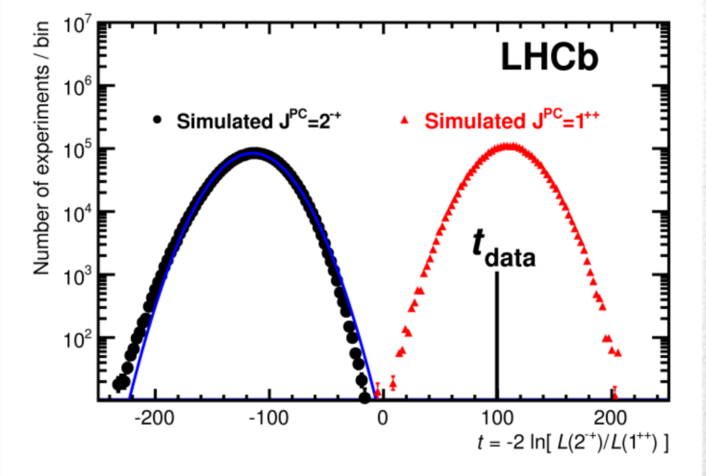
$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90%

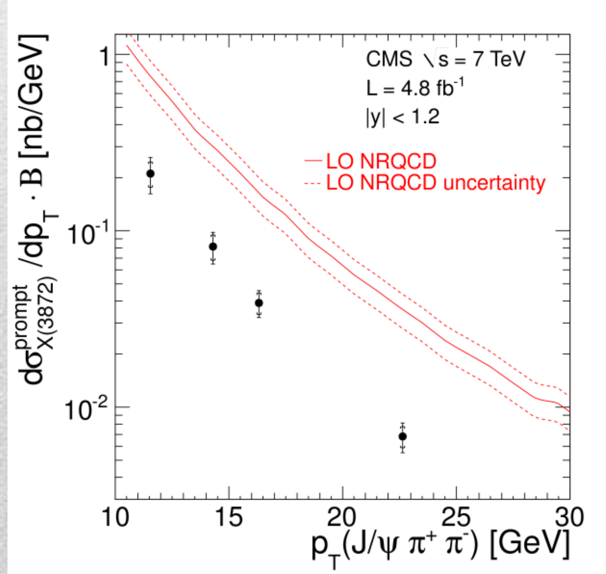
# $X(3872)$




BaBar data in $X \to J/\psi\, \omega$ favor $J^{PC} = 2^{-+}$, but LHCb in $X \to J/\psi\, \rho$ measures $1^{++}$ at $8\sigma$

Faccini, AP, Piccinini, Polosa
PRD 86, 054012
LHCb, PRL 110, 222001



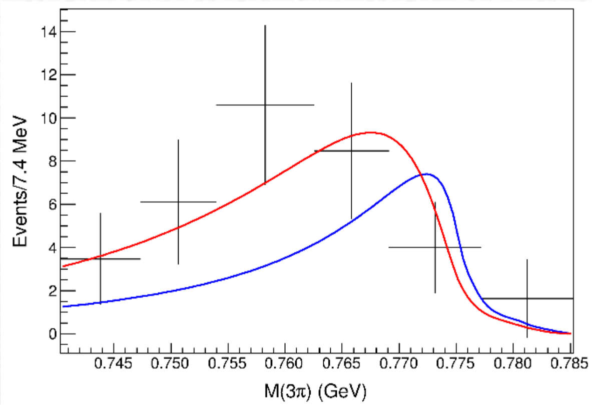

Large prompt production at hadron colliders

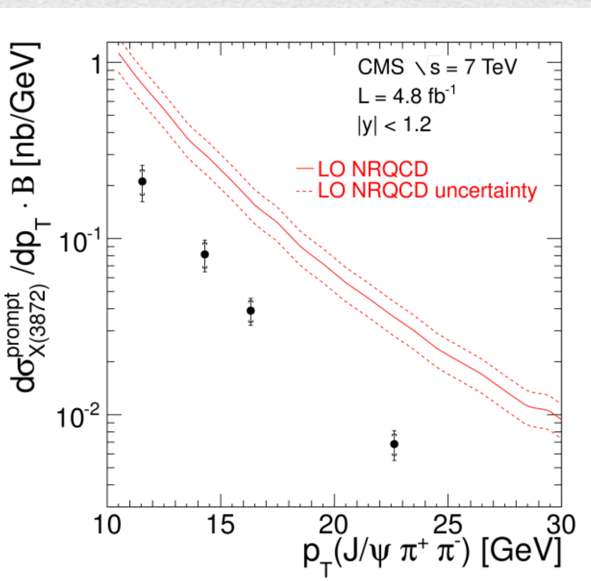
$$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$$

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

CMS, JHEP 1304, 154

# $X(3872)$

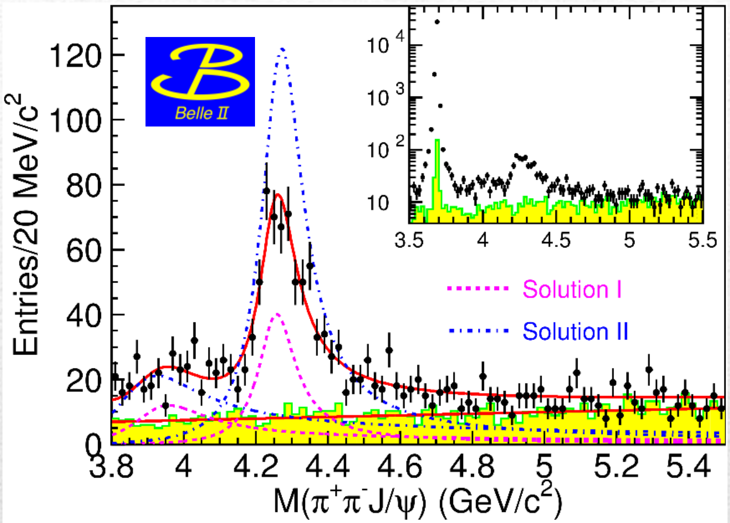



| $B$ decay mode | $X$ decay mode | product branching fraction ($\times 10^5$) | | $B_{fit}$ | $R_{fit}$ |
|---|---|---|---|---|---|
| $K^+X$ | $X \to \pi\pi J/\psi$ | $\mathbf{0.86 \pm 0.08}$ | (*BABAR*,[26] Belle[25]) | $0.081^{+0.019}_{-0.031}$ | 1 |
| | | $0.84 \pm 0.15 \pm 0.07$ | *BABAR*[26] |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

# Vector $Y$ states

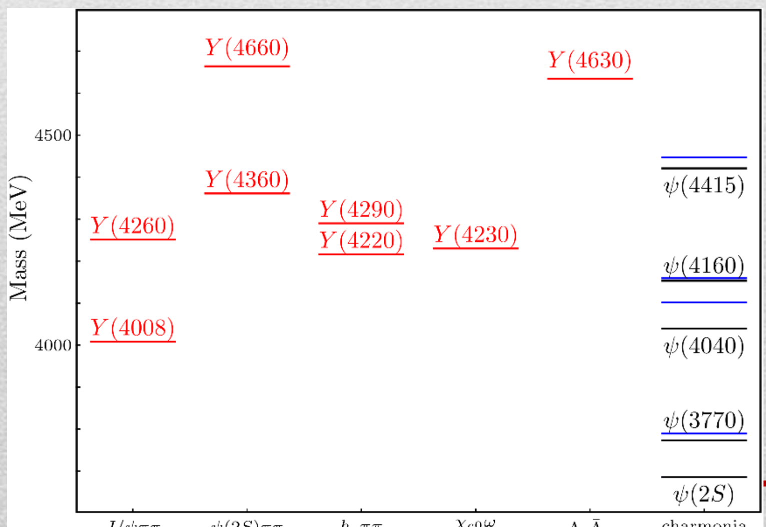
Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR analyses (and nowhere else!)

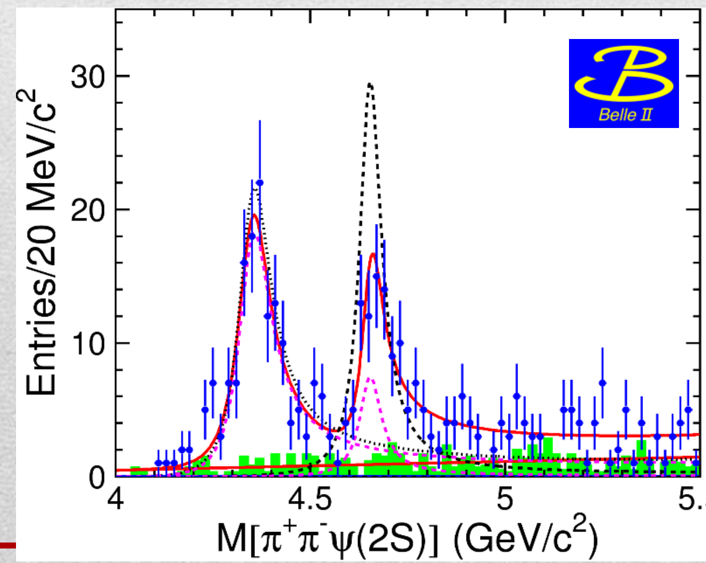



Seen in few final states,
mostly $J/\psi\,\pi\pi$ and $\psi(2S)\,\pi\pi$

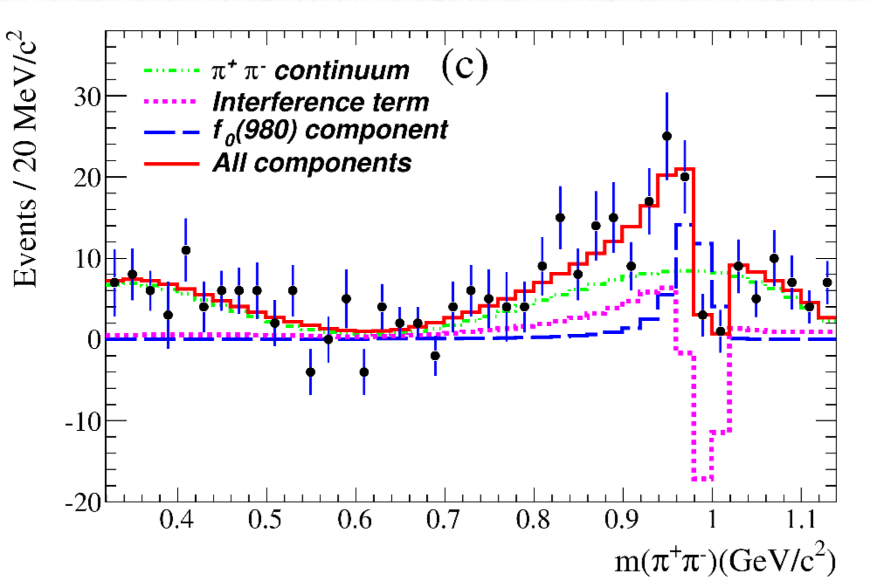
Not seen decaying into open charm pairs,
to compare with

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

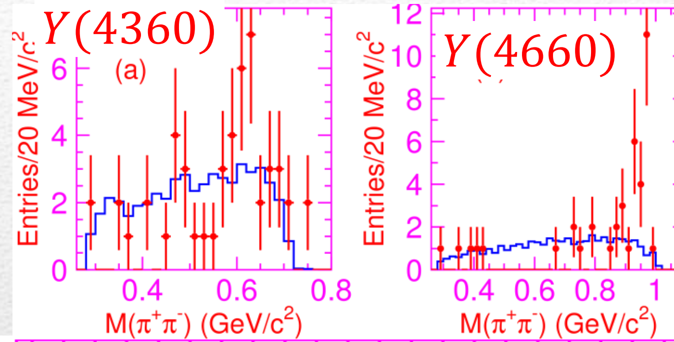


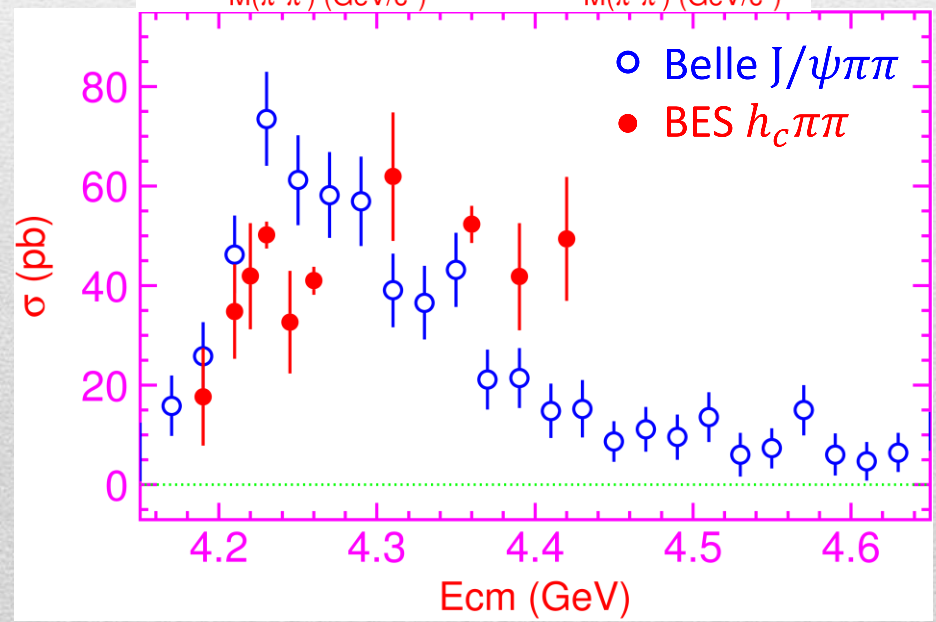



# Vector $Y$ states




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

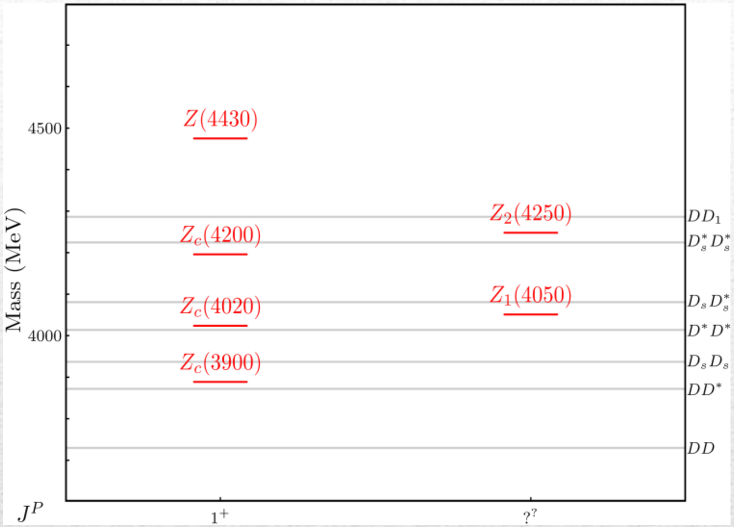



The lineshape in $h_c\,\pi\pi$ looks pretty different
Different states contributing?

# Charged $Z$ states: $Z_c(3900), Z_c'(4020)$

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




Two states $J^{PC} = 1^{+-}$ appear

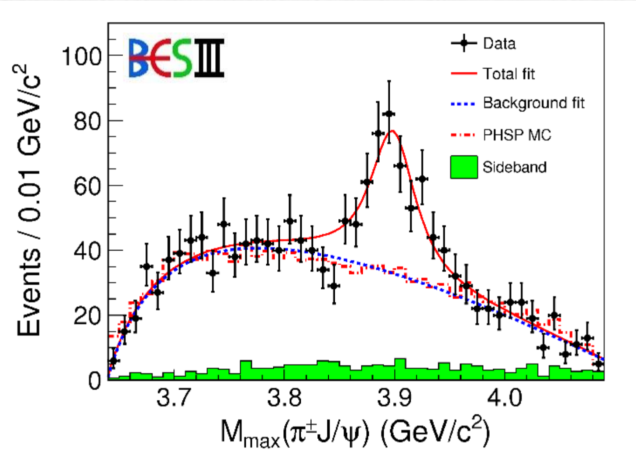
slightly above $D^{(*)}D^*$ thresholds

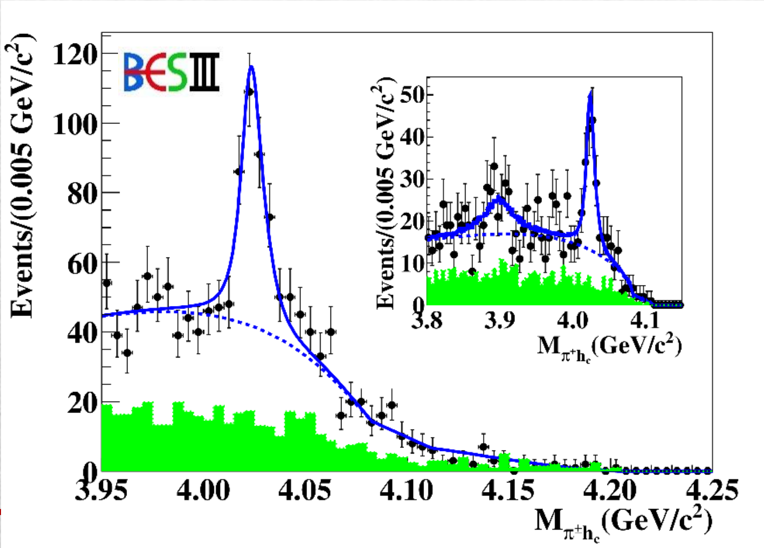
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$

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

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

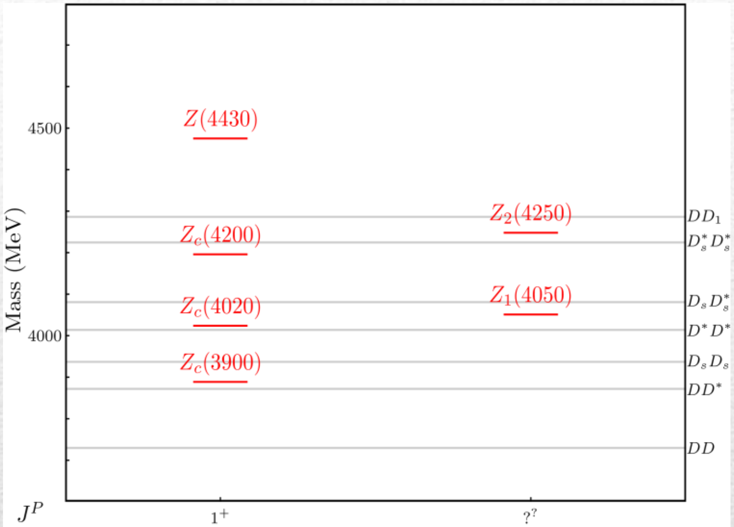
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV

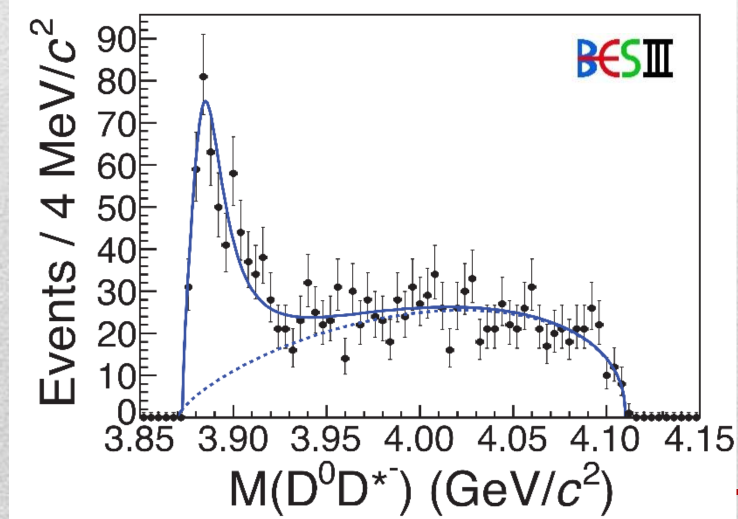


# Charged $Z$ states: $Z_c(3900), Z_c'(4020)$

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

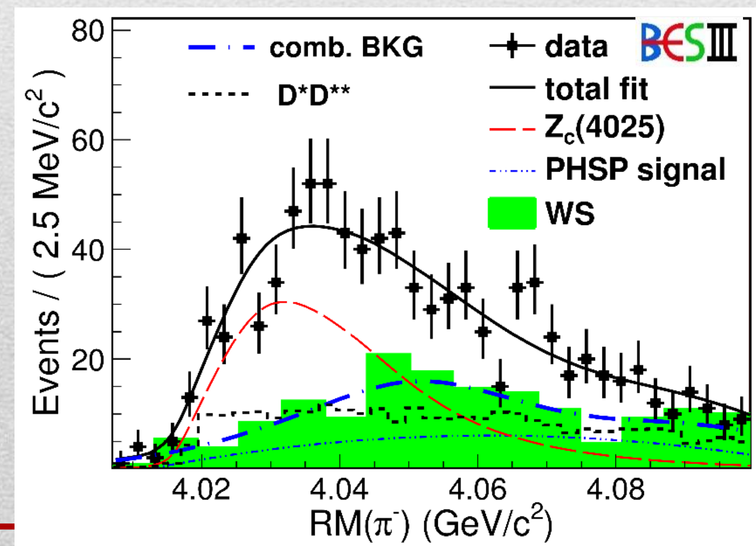


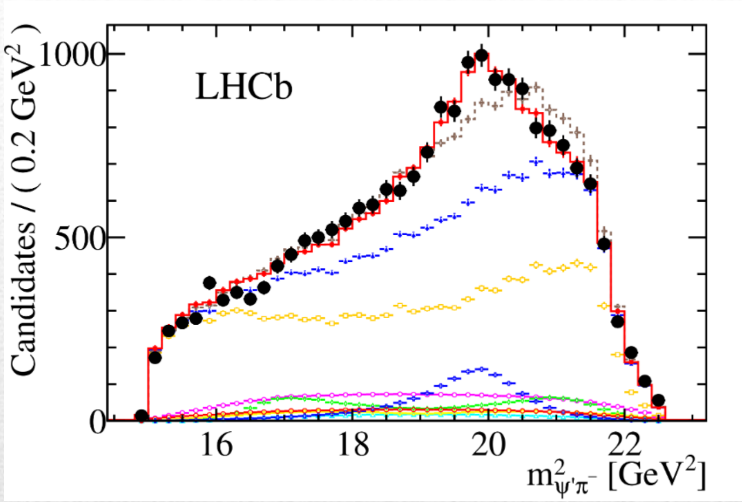

Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

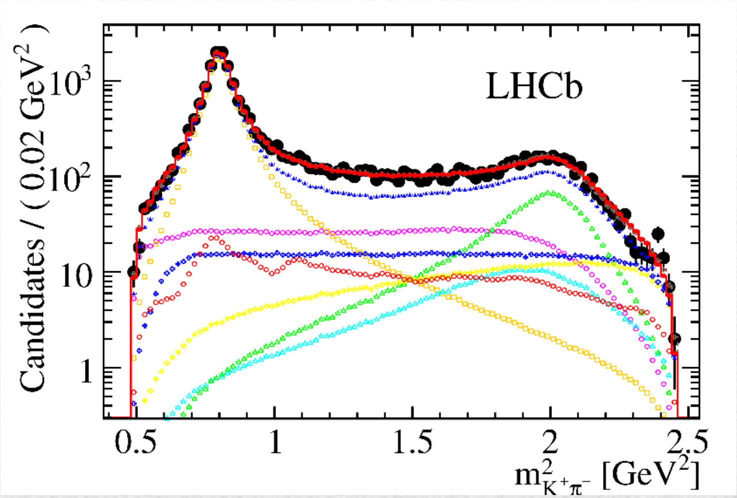
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV



# Charged $Z$ states: $Z(4430)$

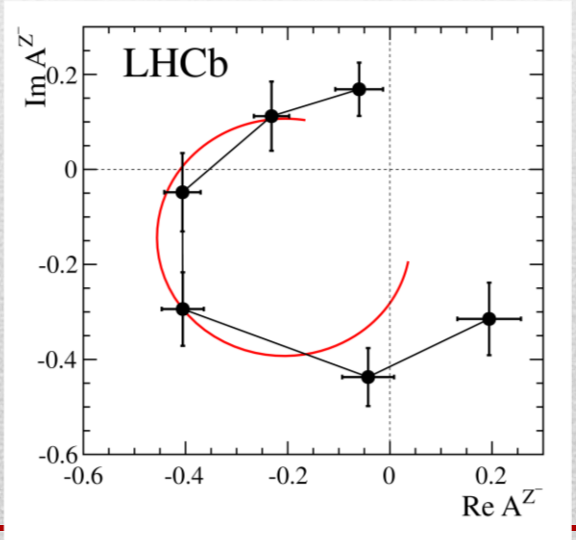



$$Z(4430)^+ \to \psi(2S)\,\pi^+$$
$$I^G J^{PC} = 1^+ 1^{+-}$$

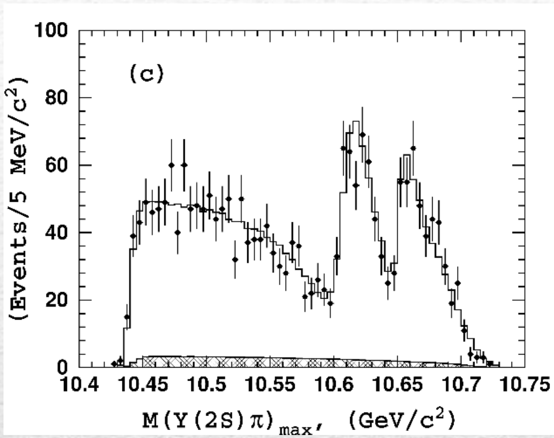
$$M = 4475 \pm 7^{+15}_{-25}\text{ MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

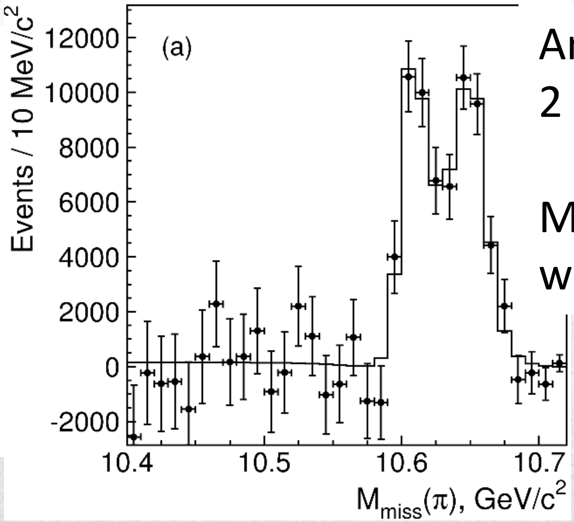
Far from open charm thresholds




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 $\Upsilon(nS)$

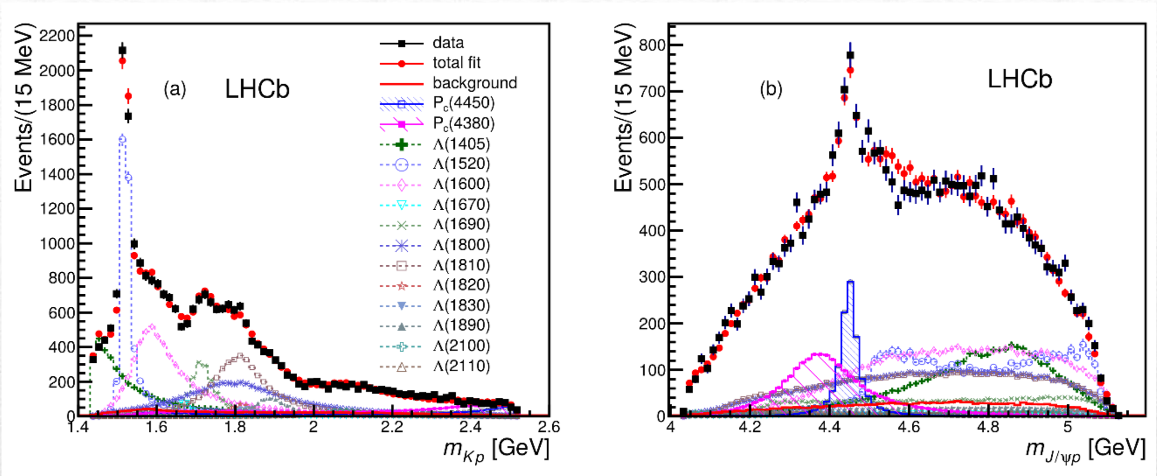
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$
which violates HQSS

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

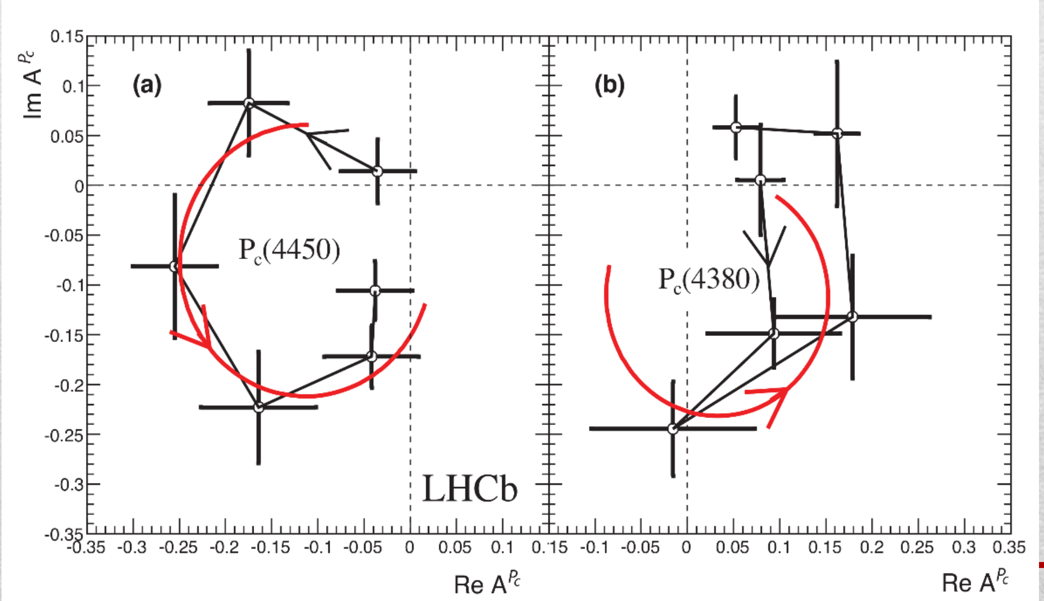
# Pentaquarks… and so on




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

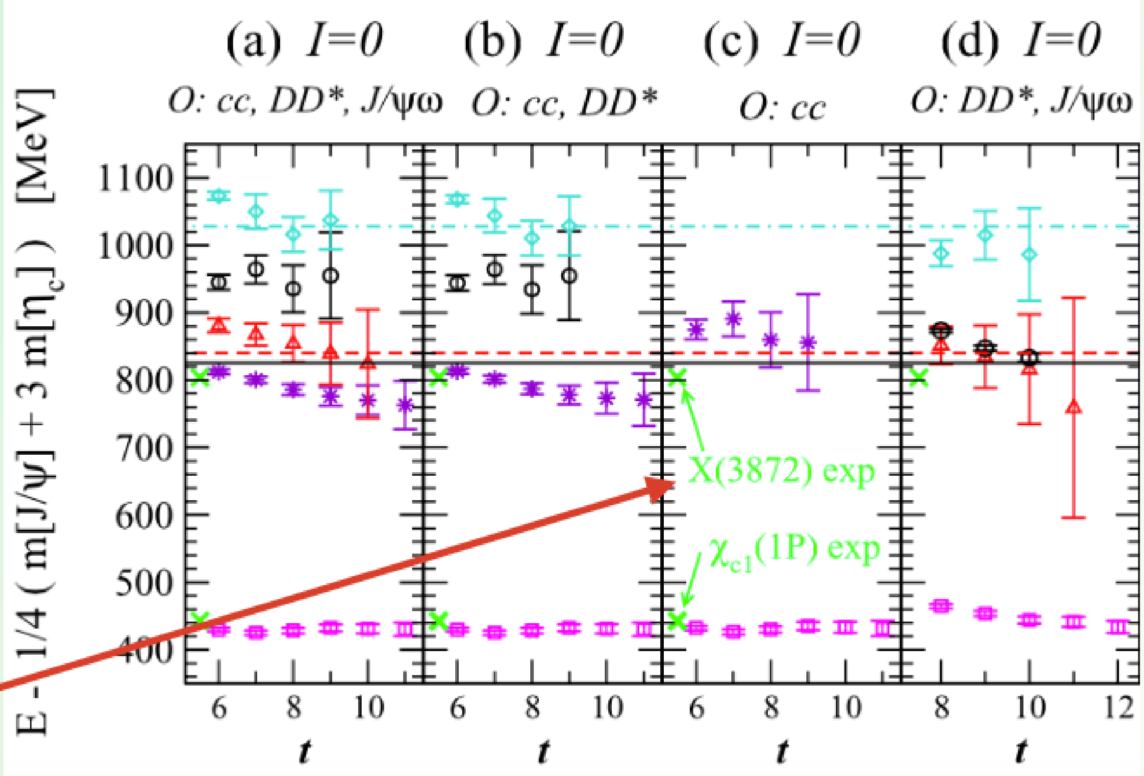
| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment ($\#\sigma$) |
|---|---|---|---|---|---|
| $X(3823)$ | $3823.1 \pm 1.9$ | $< 24$ | $?^{?-}$ | $B \to K(\chi_{c1}\gamma)$ | Belle[23] (4.0) |
| $X(3872)$ | $3871.68 \pm 0.17$ | $< 1.2$ | $1^{++}$ | $B \to K(\pi^+\pi^- J/\psi)$ | 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) |
| $Z_c(3900)^+$ | $3888.7 \pm 3.4$ | $35 \pm 7$ | $1^{+-}$ | $Y(4260) \to \pi^-(D\bar{D}^*)^+$ | BES III[39] (np) |
| | | | | $Y(4260) \to \pi^-(\pi^+ J/\psi)$ | BES III[40] (8), Belle[41] (5.2) |
| | | | | | CLEO data[42] (>5) |
| $Z_c(4020)^+$ | $4023.9 \pm 2.4$ | $10 \pm 6$ | $1^{+-}$ | $Y(4260) \to \pi^-(\pi^+ h_c)$ | BES III[43] (8.9) |
| | | | | $Y(4260) \to \pi^-(D^*\bar{D}^*)^+$ | BES III[44] (10) |
| $Y(3915)$ | $3918.4 \pm 1.9$ | $20 \pm 5$ | $0^{++}$ | $B \to K(\omega J/\psi)$ | Belle[45] (8), *BABAR*[33,46] (19) |
| | | | | $e^+e^- \to e^+e^-(\omega J/\psi)$ | Belle[47] (7.7), *BABAR*[48] (7.6) |
| $Z(3930)$ | $3927.2 \pm 2.6$ | $24 \pm 6$ | $2^{++}$ | $e^+e^- \to e^+e^-(D\bar{D})$ | 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) |
| $Y(4008)$ | $3891 \pm 42$ | $255 \pm 42$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- J/\psi)$ | 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) |
| $Y(4140)$ | $4145.6 \pm 3.6$ | $14.3 \pm 5.9$ | $?^{?+}$ | $B^+ \to K^+(\phi J/\psi)$ | 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) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment ($\#\sigma$) |
|---|---|---|---|---|---|
| $Y(4220)$ | $4196^{+35}_{-30}$ | $39 \pm 32$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- h_c)$ | BES III data[63,64] (4.5) |
| $Y(4230)$ | $4230 \pm 8$ | $38 \pm 12$ | $1^{--}$ | $e^+e^- \to (\chi_{c0}\omega)$ | 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) |
| $Y(4260)$ | $4250 \pm 9$ | $108 \pm 12$ | $1^{--}$ | $e^+e^- \to (\pi\pi J/\psi)$ | *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) |
| $Y(4290)$ | $4293 \pm 9$ | $222 \pm 67$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- h_c)$ | 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) |
| $Y(4360)$ | $4354 \pm 11$ | $78 \pm 16$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^-\psi(2S))$ | Belle[71] (8), *BABAR*[72] (np) |
| $Z(4430)^+$ | $4478 \pm 17$ | $180 \pm 31$ | $1^{+-}$ | $\bar{B}^0 \to K^-(\pi^+\psi(2S))$ | 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) |
| $Y(4660)$ | $4665 \pm 10$ | $53 \pm 14$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^-\psi(2S))$ | Belle[71] (5.8), *BABAR*[72] (5) |
| $Z_b(10610)^+$ | $10607.2 \pm 2.0$ | $18.4 \pm 2.4$ | $1^{+-}$ | $\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$ | 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) |
| $Z_b(10650)^+$ | $10652.2 \pm 1.5$ | $11.5 \pm 2.2$ | $1^{+-}$ | $\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$ | 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

A. Guerrieri

# X(3872) on the lattice: spectrum



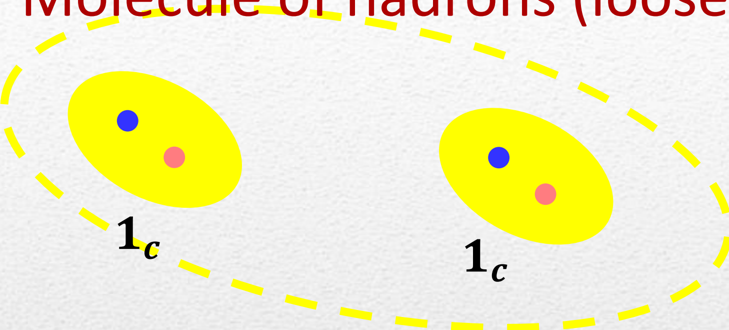

Where is the $\chi_{c1}(2P)$ ?

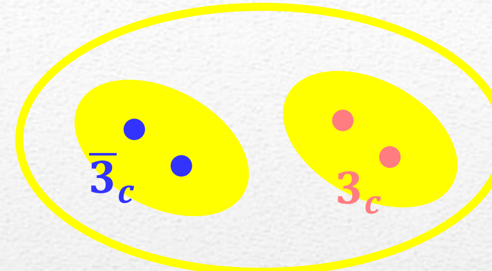
$J^{PC} = 1^{++}$ $I = 0$ channel

Prelovsek *et al.* PRL 111 (2013) 192001 arXiv: 1307.5172

# Proposed models

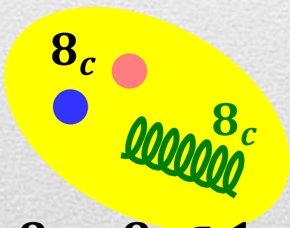
Molecule of hadrons (loosely bound)




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

Diquark-antidiquark (tetraquark)

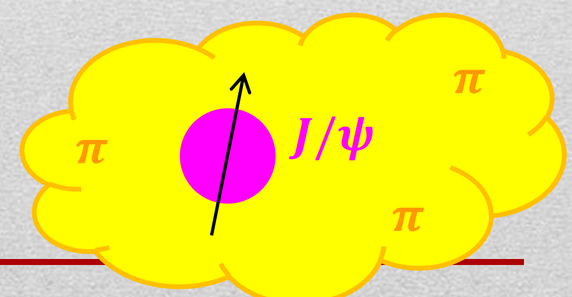



$\mathbf{8}_c \times \mathbf{8}_c \in \mathbf{1}_c$

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

Hadrocharmonium (Van der Waals forces)

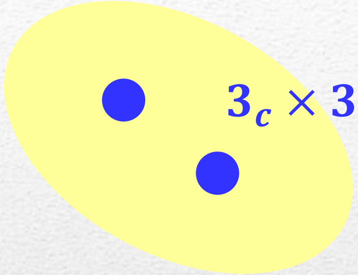

Cusp (kinematical effect)



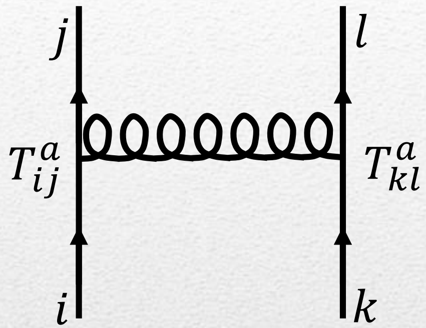

$\mathbf{1}_c \times \mathbf{1}_c \in \mathbf{1}_c$

# Diquarks

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



$$\mathbf{3}_c \times \mathbf{3}_c \in \overline{\mathbf{3}}_c$$



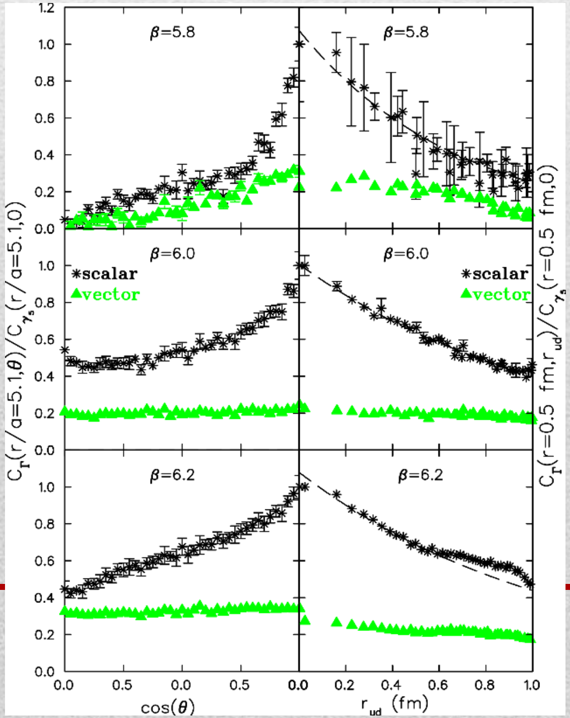

$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

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

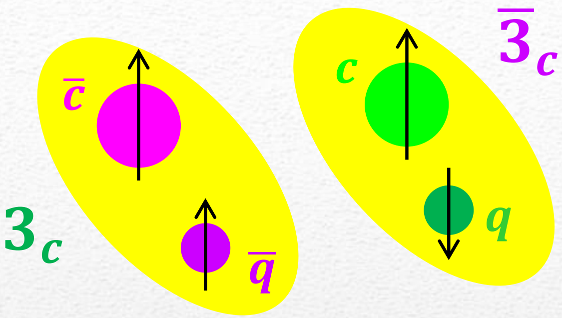
$$R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}$$

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



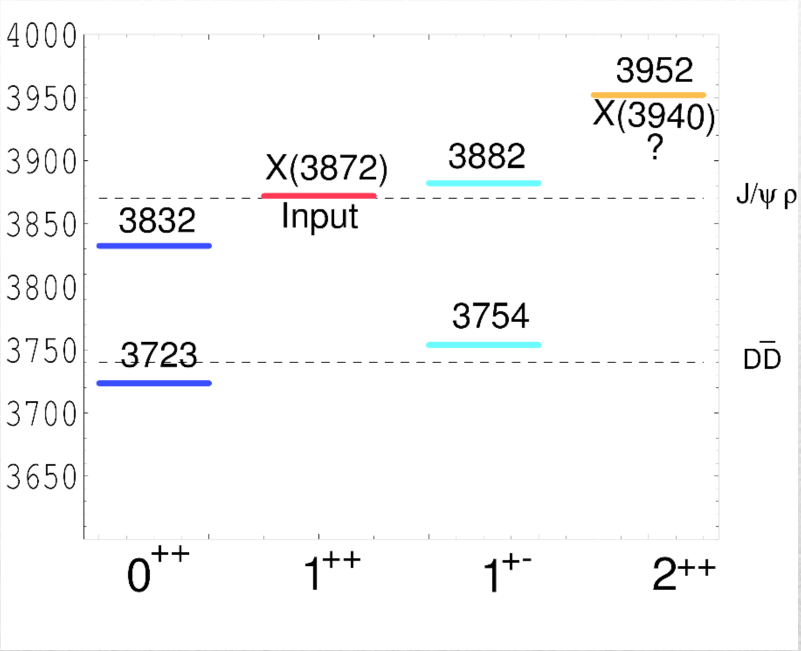

In a constituent quark model, we can think of a **diquark-antidiquark compact state**

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

Maiani, Piccinini, Polosa, Riquer PRD71 014028

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

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



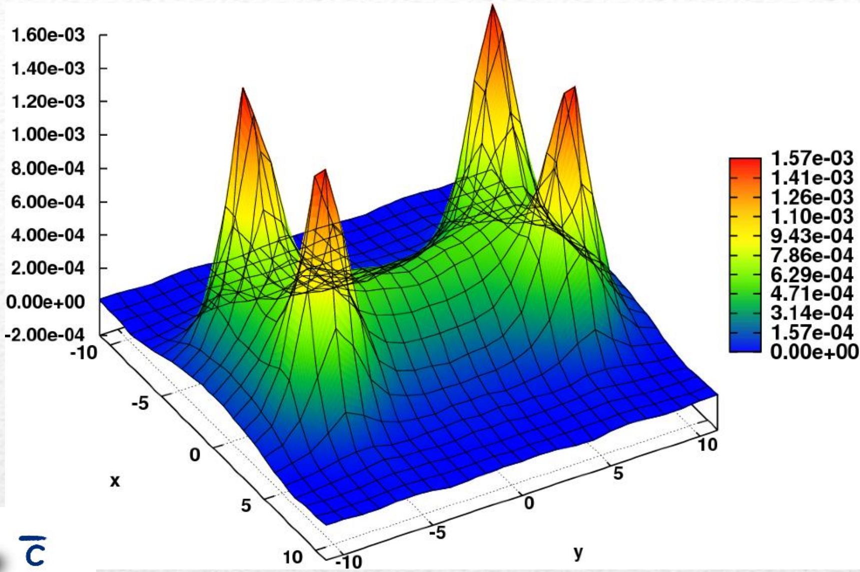

Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

$$\kappa_{q\bar{q}} = 315 \text{ MeV},\ \kappa_{c\bar{c}} = 59 \text{ MeV},$$
$$\kappa_{cq} = 22 \text{ MeV},\ \kappa_{c\bar{q}} = 72 \text{ MeV}$$

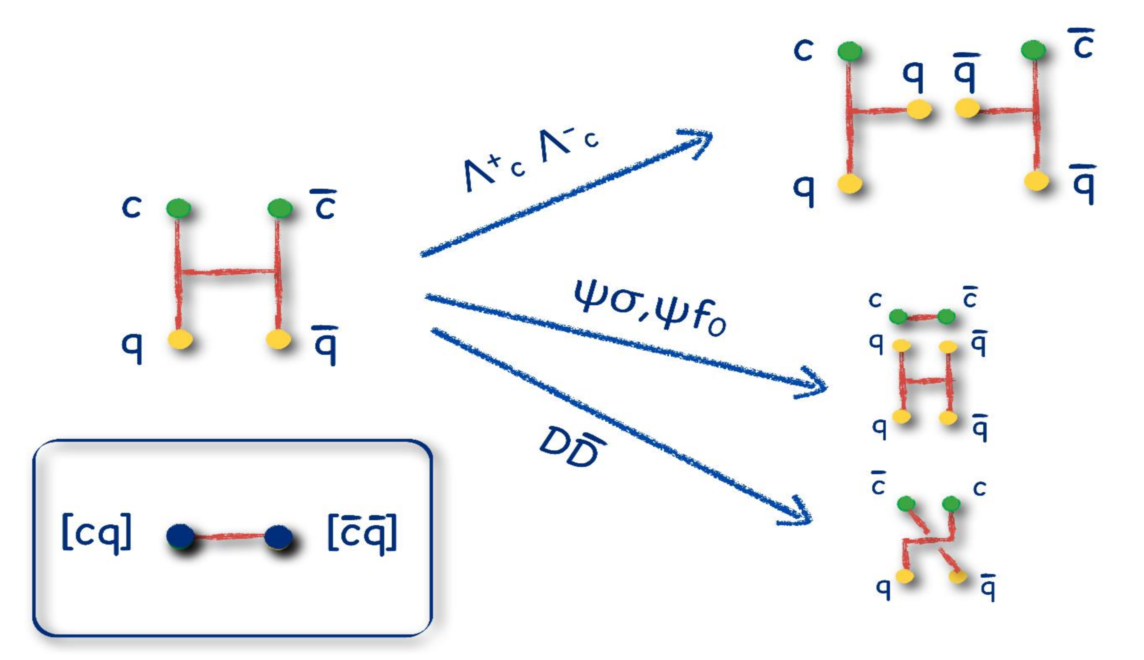
# Baryonium

a structure $[Qq][\bar{Q}\bar{q}]$ exhibits an «H» shape, as considered by baryonium models

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



Cardoso, Cardoso, Bicudo, PRD84, 054508

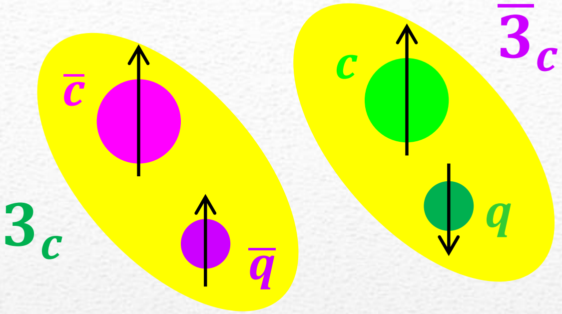



Isospin violation expected, $\alpha_s(m_c) \ll 1$

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

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

# Tetraquark: new ansatz

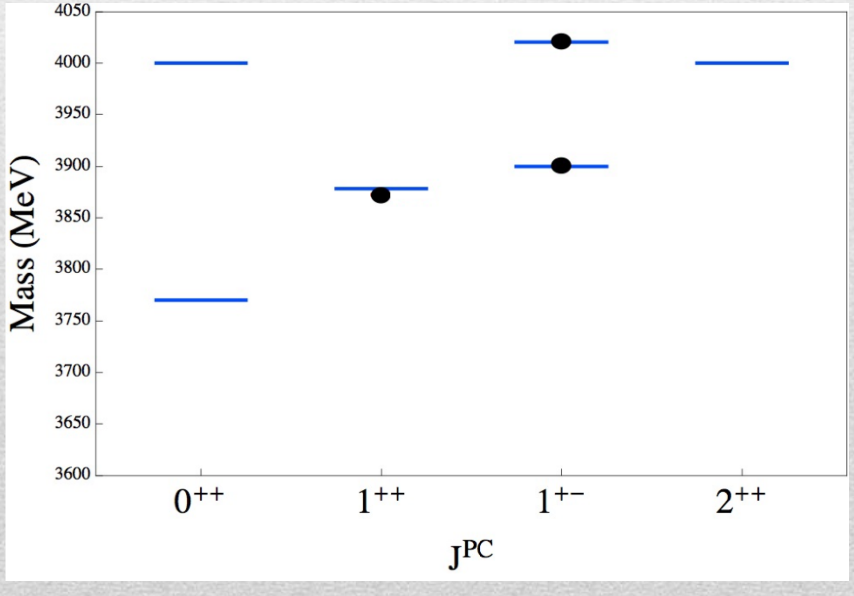



Type I-model predicts no $Z_c'(4020)$, and disfavors $Z_c(3900) \to J/\psi\pi$

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



# 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 |
|---|---|---|---|---|
| $0^{++}$ | $\|0,0\rangle$ | $1/2\|0,0\rangle + \sqrt{3}/2\|1,1\rangle_0$ | $X_0(\sim 3770\text{ MeV})$ | $\eta_c, J/\psi$ + light mesons |
| $0^{++}$ | $\|1,1\rangle_0$ | $\sqrt{3}/2\|0,0\rangle - 1/2\|1,1\rangle_0$ | $X_0'(\sim 4000\text{ MeV})$ | $\eta_c, J/\psi$ + light mesons |
| $1^{++}$ | $1/\sqrt{2}(\|1,0\rangle + \|0,1\rangle)$ | $\|1,1\rangle_1$ | $X_1 = X(3872)$ | $J/\psi + \rho/\omega,\ DD^*$ |
| $1^{+-}$ | $1/\sqrt{2}(\|1,0\rangle - \|0,1\rangle)$ | $1/\sqrt{2}(\|1,0\rangle - \|0,1\rangle)$ | $Z = Z(3900)$ | $J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$ |
| $1^{+-}$ | $\|1,1\rangle_1$ | $1/\sqrt{2}(\|1,0\rangle + \|0,1\rangle)$ | $Z' = Z(4020)$ | $J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$ |
| $2^{++}$ | $\|1,1\rangle_2$ | $\|1,1\rangle_2$ | $X_2(\sim 4000\text{ MeV})$ | $J/\psi$ + light mesons |

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

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

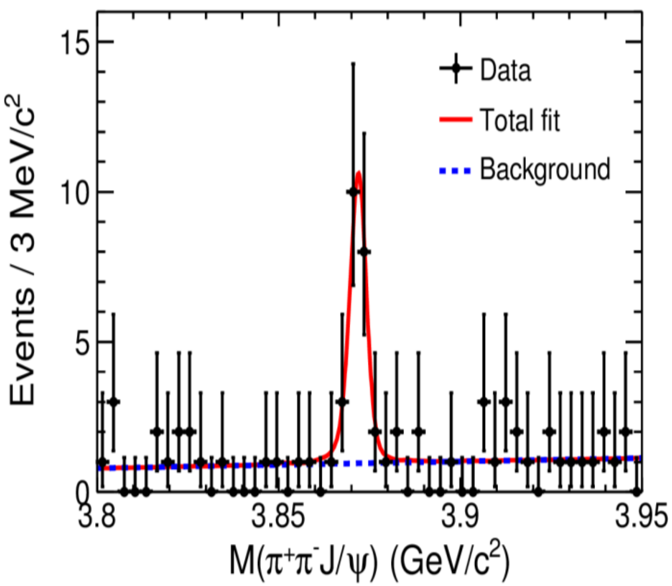
$$H = 2m_{dq} - 2\kappa_{cq}\left(\overrightarrow{S_c}\cdot\overrightarrow{S_q} + \overrightarrow{S_{\bar{c}}}\cdot\overrightarrow{S_{\bar{q}}}\right) + \frac{B_c\vec{L}^2}{2} - 2a\,\vec{L}\cdot\vec{S}$$

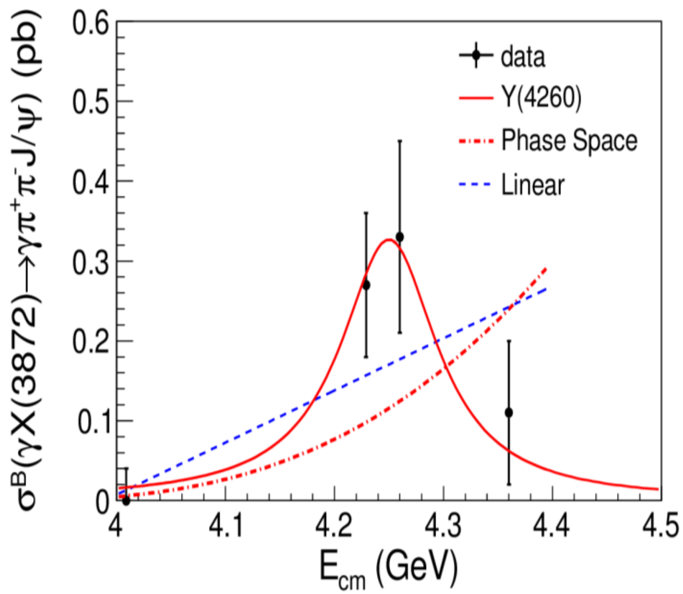
# $Y(4260) \to \gamma X(3872)$

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

F. Piccinini

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



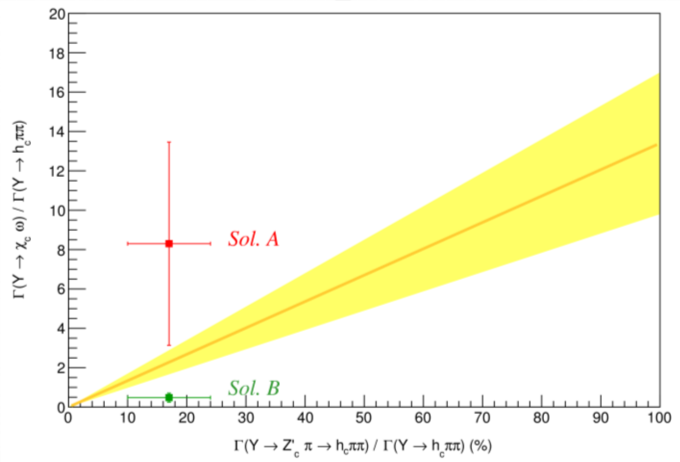




With $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$

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

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

# Tetraquark: the $Y(4220)$



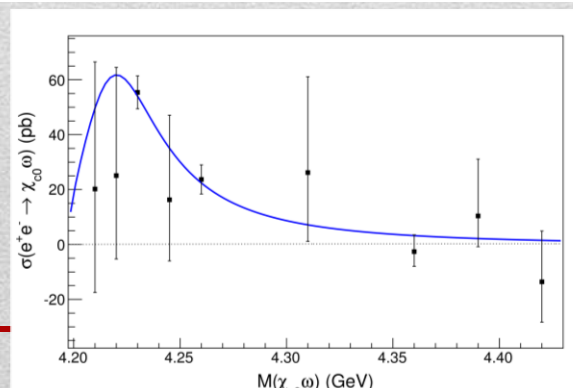

$$\langle \chi_{c0}(p)\,\omega(\eta,q)|Y(\lambda,P)\rangle = g_\chi\,\eta\cdot\lambda,$$
$$\langle Z'_c(\eta,q)\,\pi(p)|Y(\lambda,P)\rangle = g_Z\,\eta\cdot\lambda\frac{P\cdot p}{f_\pi M_Y},$$
$$\langle h_c(\eta,q)\,\sigma(p)|Y(\lambda,P)\rangle = g_h\,\varepsilon_{\mu\nu\rho\sigma}\eta^\mu\lambda^\nu\frac{P^\rho q^\sigma}{P\cdot q},$$
$$\langle \pi(q)\pi(p)|\sigma(P)\rangle = \frac{P^2}{2f_\pi},$$

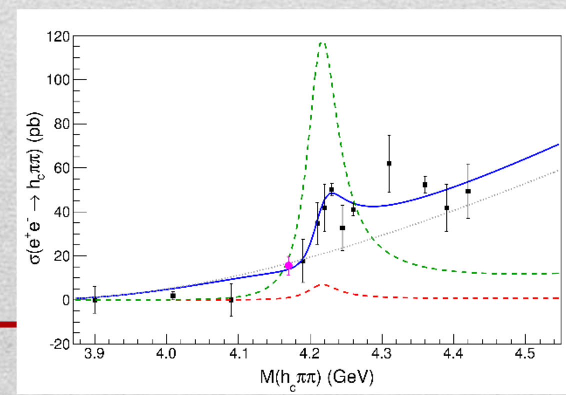
$$\frac{\Gamma\left(Y(4220)\to\chi_{c0}\omega\right)}{\Gamma(Y(4220)\to h_c\pi^+\pi^-)} = (13.4\pm3.6)\times R_{YZ} = 2.3\pm1.2.$$
$$\frac{\Gamma\left(Y(4220)\to Z_c'^{\pm}\pi^{\mp}\to h_c\pi^+\pi^-\right)}{\Gamma\left(Y(4220)\to h_c\sigma\to h_c\pi^+\pi^-\right)} = 4.8\pm3.5,$$

A state apparently breaking HQSS has been observed

Compatible to be the $Y_3$ state

Faccini, Filaci, Guerrieri, AP, Polosa, PRD 91, 117501



# Tetraquark: radial excitations

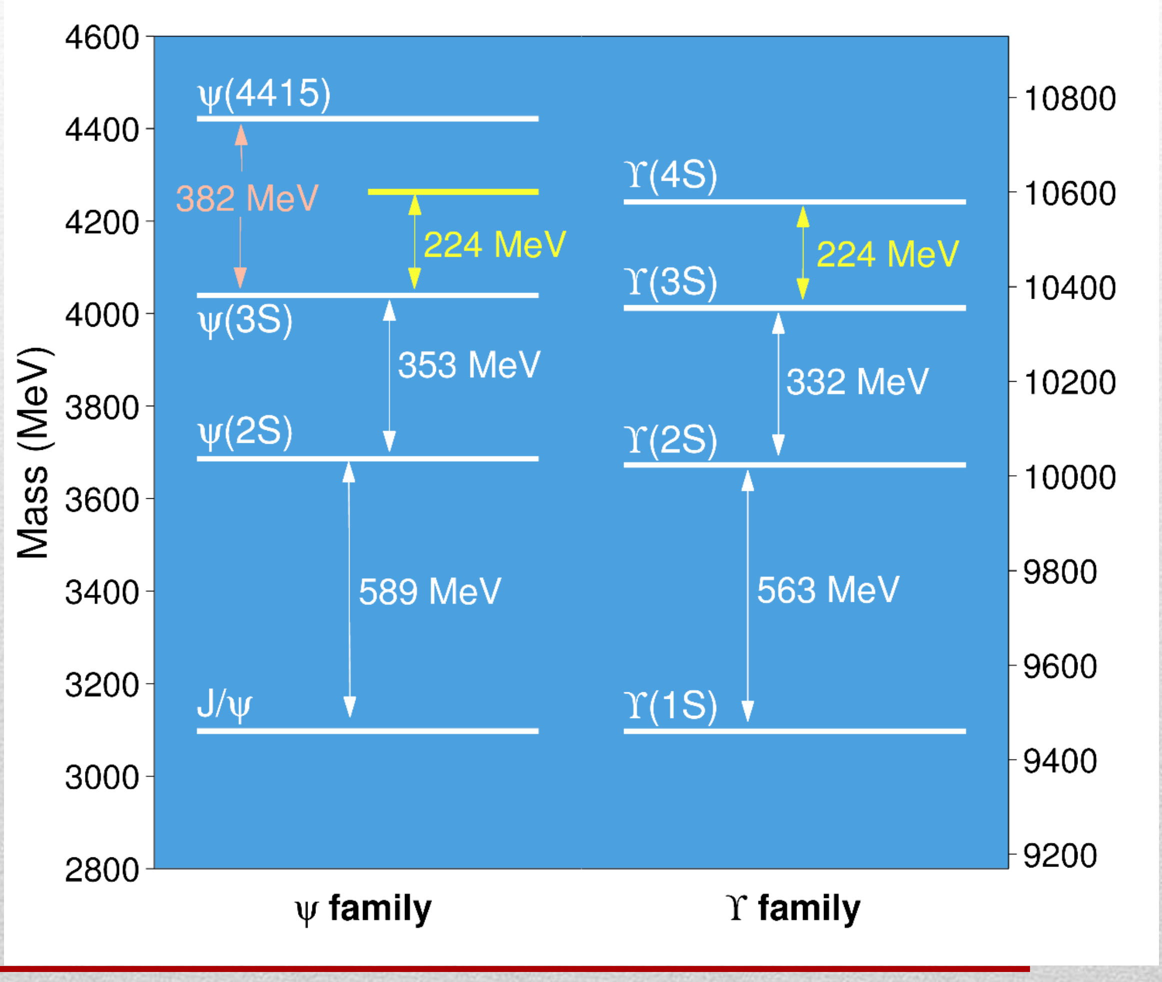
Maiani, Piccinini, Polosa, Riquer PRD89 114010

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



# Tetraquark: the $b$ sector

Ali, Maiani, Piccinini, Polosa, Riquer PRD91 017502

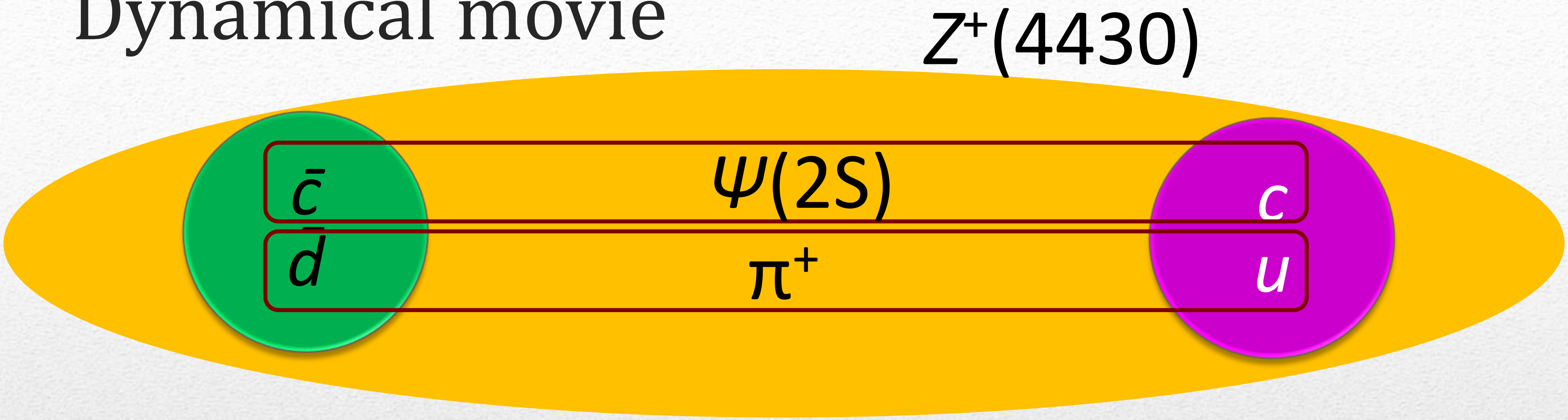
$$M(Z_b') - M(Z_b) = 2\kappa_b$$
$$M(Z_c') - M(Z_c) = 2\kappa_c \sim 120 \text{ MeV}$$
$$\kappa_b : \kappa_c = M_c : M_b \sim 0.30$$

$2\kappa_b \sim 36$ MeV, vs. 45 MeV (exp.)

$$Z_b = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle - \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$
$$Z_b' = \frac{\alpha \left|1_{q\bar{q}} 0_{b\bar{b}}\right\rangle + \beta \left|0_{q\bar{q}} 1_{b\bar{b}}\right\rangle}{\sqrt{2}}$$

Data on $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ and $\Upsilon(5S) \to \mathrm{h_b}(nP)\pi\pi$ strongly favor $\alpha = \beta$

# Dynamical movie




Brodsky, Hwang, Lebed PRL 113 112001

- Since this is still a $\mathbf{3} \leftrightarrow \overline{\mathbf{3}}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_{cq}^2}\left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2}\mathbf{S}_{cq}\cdot\mathbf{S}_{\overline{cq}},$$

e.g. Barnes *et al.*, PRD 72, 054026

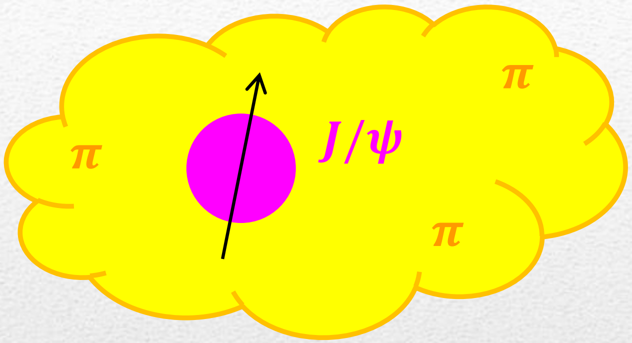
- Use that the kinetic energy released in $\overline{B}^0 \longrightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

$r_Z = 1.16\text{ fm}, \langle r_{\psi(2S)}\rangle = 0.80\text{ fm}, \langle r_{J/\psi}\rangle = 0.39\text{ fm}$

$$\frac{B(Z^+(4430)\to\psi(2S)\pi^+)}{B(Z^+(4430)\to J/\psi\,\pi^+)} \sim 72$$

$(> 10\text{ exp.})$

# Hadro-charmonium




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

Born in the context of QCD multipole expansion

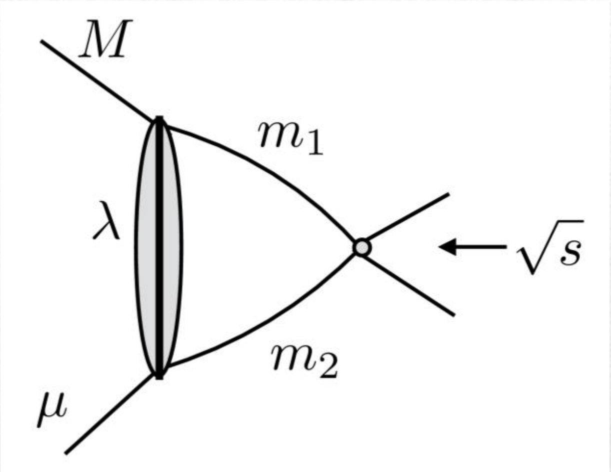
$$H_{eff} = -\frac{1}{2} a_\psi E_i^a E_i^a$$
$$a_\psi = \langle\psi|(t_c^a - t_{\bar{c}}^a) r_i\, G\, r_i (t_c^a - t_{\bar{c}}^a)|\psi\rangle$$

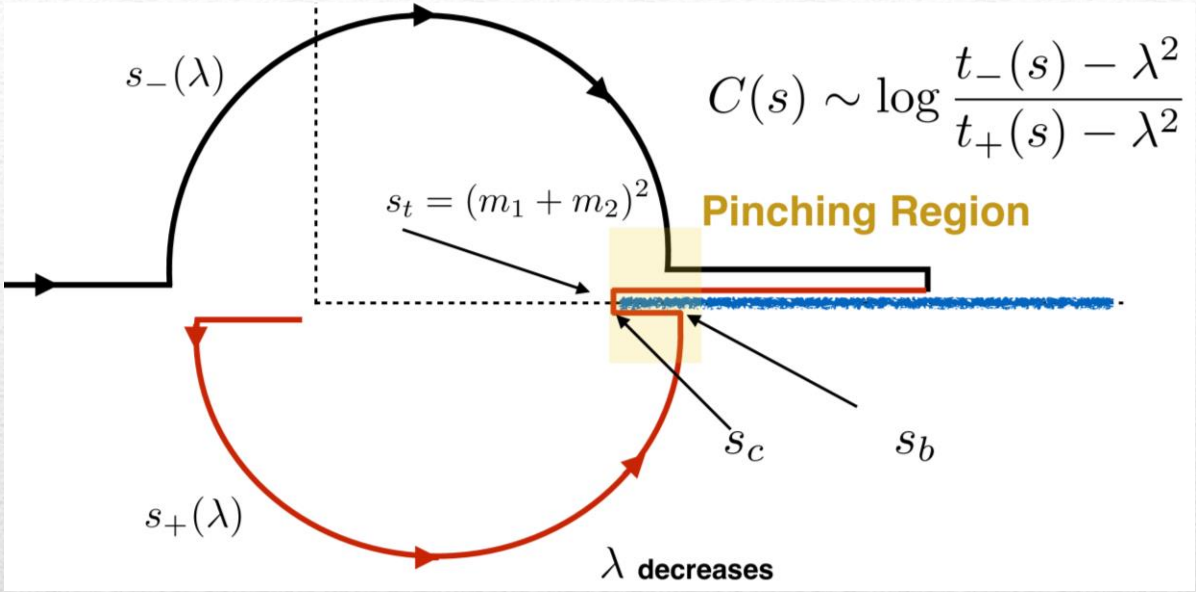
the chromoelectric field interacts with soft light matter (highly excited light hadrons)

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

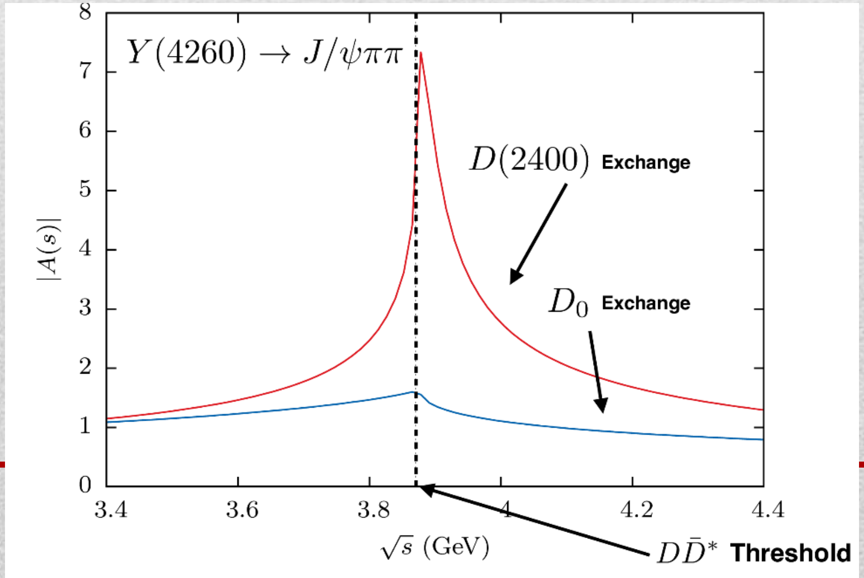
Expected to decay into core charmonium + light hadrons,
Decay into open charm exponentially suppressed

# Triangle singularity (cusps)



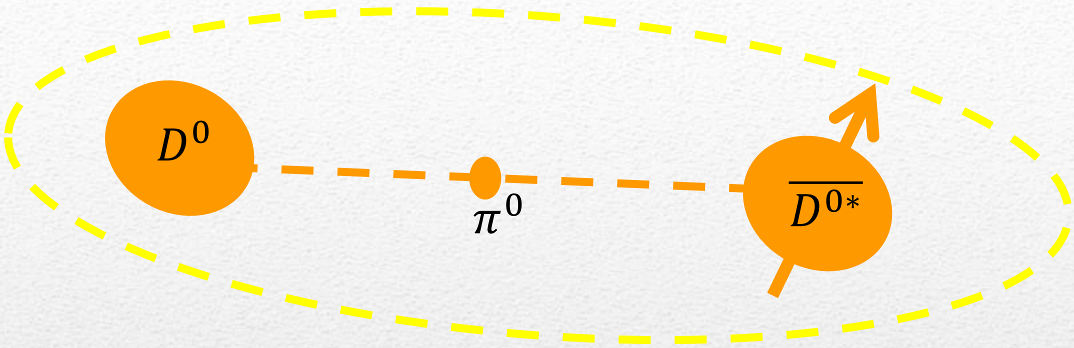




Bugg, PLB598, 8-14
Szczepaniak, PLB747, 410-416
Szczepaniak, 1510.01789



# 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

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

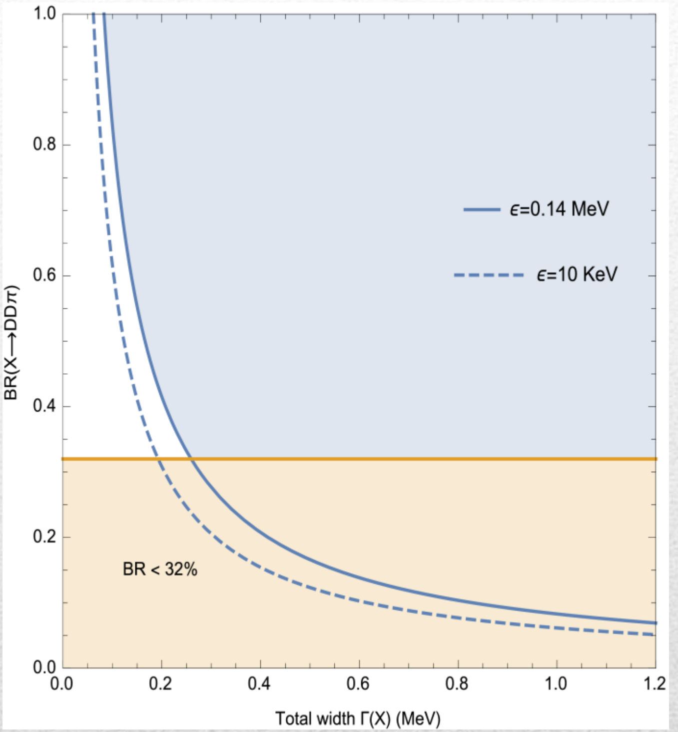
with $m_c = m_a + m_b - B$, and $B, T \ll m_{a,b}$

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

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 $-B$

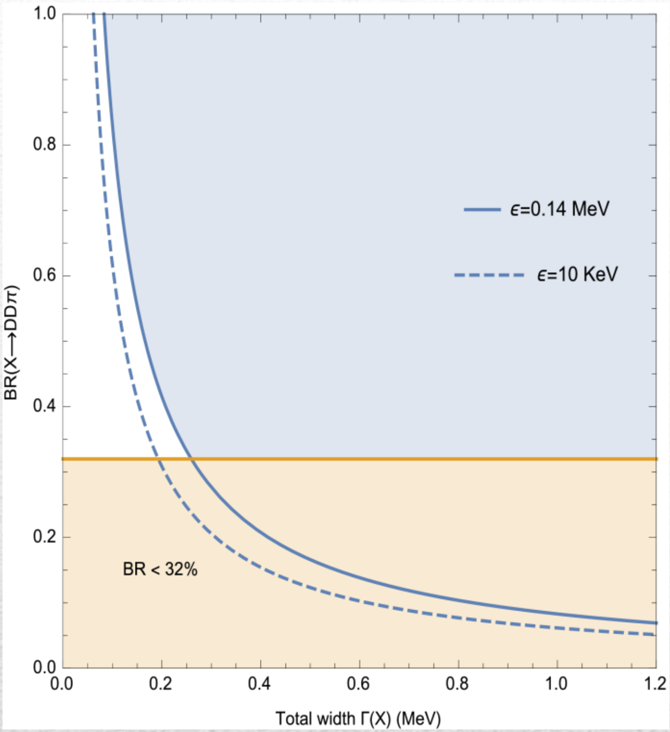
$$f(ab \to ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B} - i\sqrt{T}}{B + T}$$

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




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:

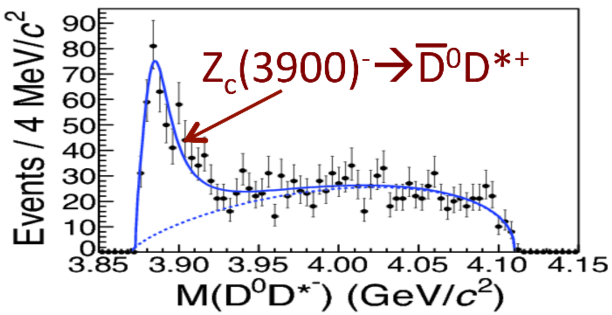
- $X(3872), B = 0, g \neq 0$
- $Zs, B < 0$, repulsive interaction!
- $Y(4260), kR \sim 1.4$

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

# $Y(4260) \to \bar{D}D_1$?

**$e^+e^- \to Y(4260) \to \pi^-\bar{D}^0D^{*+}$**

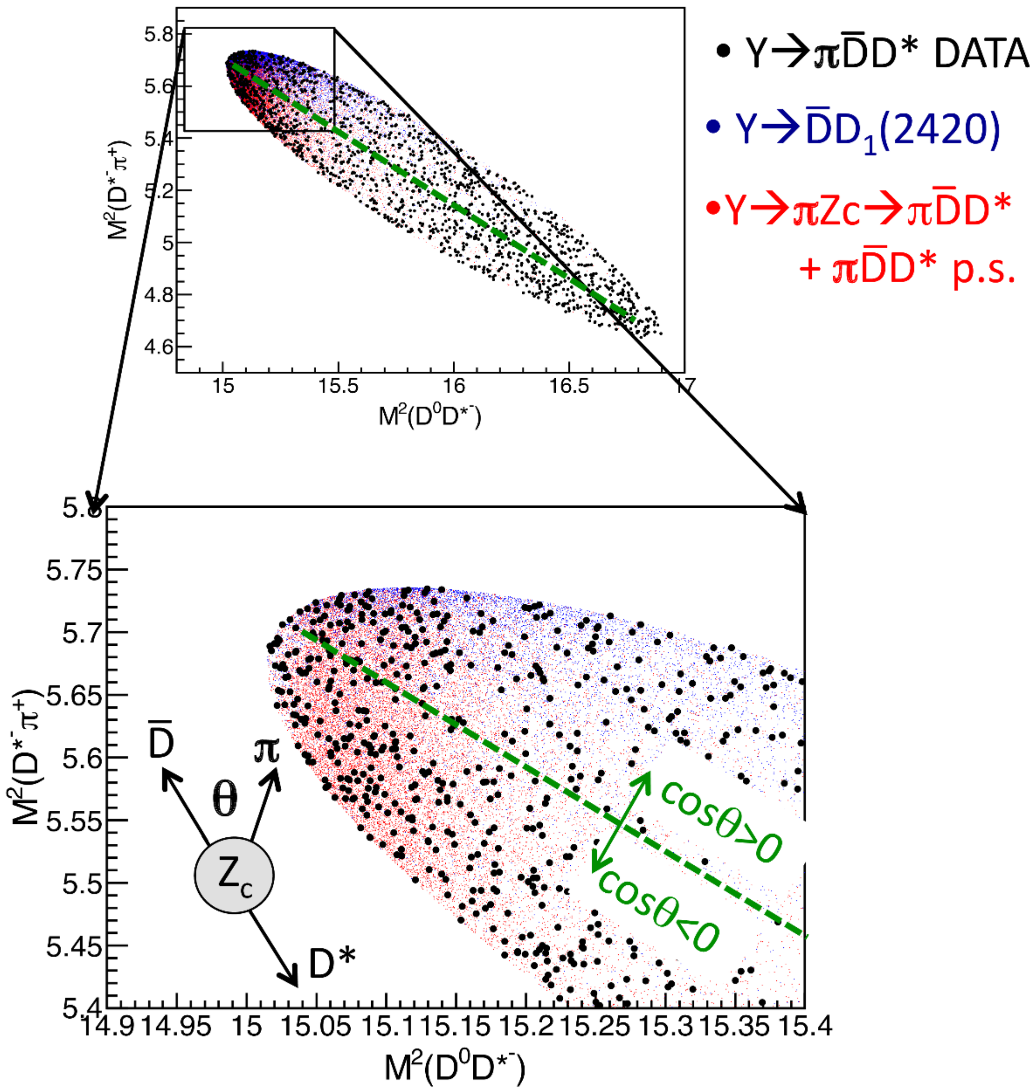
BESIII PRL 112, 022001




$$\mathcal{A} = \frac{N_{|\cos\theta|>0.5} - N_{|\cos\theta|<0.5}}{N_{|\cos\theta|>0.5} + N_{|\cos\theta|<0.5}}$$

| | $DD_1$ MC | $Z_c$+ps MC | data |
|---|---|---|---|
| $\mathcal{A}$ | 0.43±0.04 | 0.02±0.02 | 0.12+0.06 |

Not a lot of room for $\bar{D}D_1(2410)$



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

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

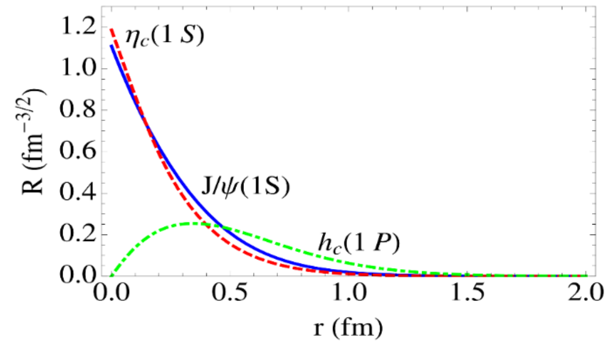
## If tetraquark

Kinematics with HQSS, dynamics estimated according to Brodsky et al., PRL113, 112001

$$A = \langle \chi_{c\bar{c}} | \chi_c \otimes \chi_{\bar{c}} \rangle \langle \phi_{c\bar{c}} | \hat{T}_{\perp HQS} | \phi[cq][\bar{c}\bar{q}] \rangle + O\left(\frac{\Lambda_{QCD}}{m_c}\right)$$

Clebsch-Gordan

Uncertainty $\sim 25\%$




Reduced matrix element

- approximated as a constant
- or $\propto \psi_{c\bar{c}}(r_Z)$

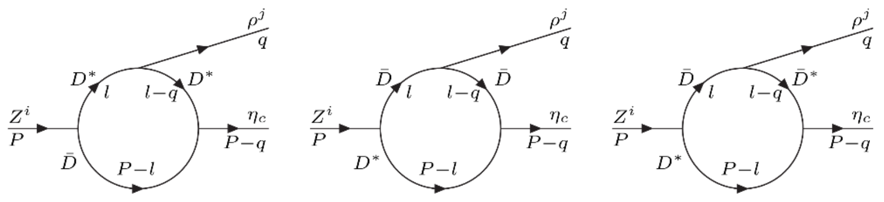
| | Kinematics only | | Dynamics included | |
|---|---|---|---|---|
| | type I | type II | type I | type II |
| $\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi\, \pi)}$ | $\left(3.3^{+7.9}_{-1.4}\right) \times 10^2$ | $0.41^{+0.96}_{-0.17}$ | $\left(2.3^{+3.3}_{-1.4}\right) \times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

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

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

## If molecule

Non-Relativistic Effective Theory, HQET+NRQCD and Hidden gauge Lagrangian
Uncertainty estimated with power counting at NLO



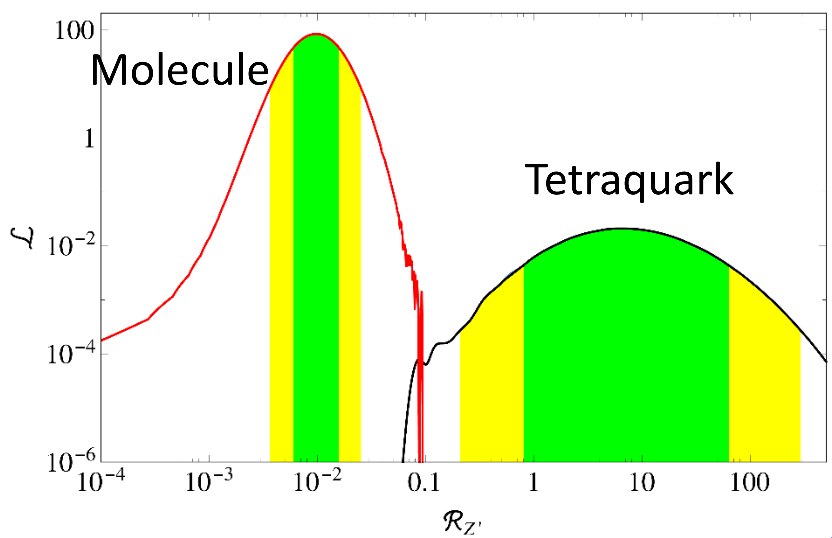
$$\mathcal{L}_{Z_c^{(\prime)}} = \frac{z^{(\prime)}}{2} \left\langle \mathcal{Z}^{(\prime)}_{\mu,ab} \bar{H}_{2b} \gamma^\mu \bar{H}_{1a} \right\rangle + h.c.,$$

$$\mathcal{L}_{c\bar{c}} = \frac{g_2}{2} \left\langle \bar{\Psi} H_{1a} \overleftrightarrow{\not\partial} H_{2a} \right\rangle + \frac{g_1}{2} \left\langle \bar{\chi}_\mu H_{1a} \gamma^\mu H_{2a} \right\rangle + h.c.,$$

$$\mathcal{L}_{\rho D D^*} = i\beta \left\langle H_{1b} v^\mu \left( \mathcal{V}_\mu - \rho_\mu \right)_{ba} \bar{H}_{1a} \right\rangle + i\lambda \left\langle H_{1b} \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ba} \bar{H}_{1a} \right\rangle + h.c.,$$

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

$$\frac{\mathcal{BR}(Z_c \to h_c\, \pi)}{\mathcal{BR}(Z_c' \to h_c\, \pi)} = 0.34^{+0.21}_{-0.13}; \quad \frac{\mathcal{BR}(Z_c \to J/\psi\, \pi)}{\mathcal{BR}(Z_c' \to J/\psi\, \pi)} = 0.35^{+0.49}_{-0.21}$$

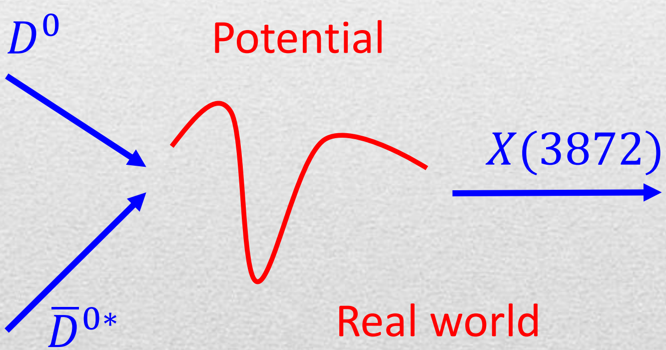


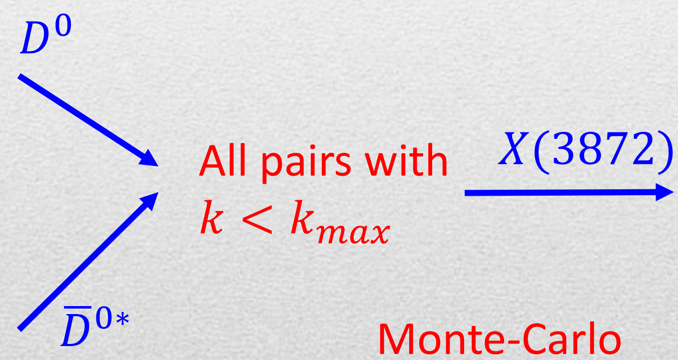
# Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\overline{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

**Q.** What is a molecule in MC? **A.** «Coalescence» model




$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k\ |\langle X|D\overline{D}^*\rangle\langle D\overline{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k\ |\langle D\overline{D}^*|p\bar{p}\rangle|^2$$

This should provide an upper bound for the cross section

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001
Kadastic, Raidan, Strumia PLB683 (2010) 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:

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

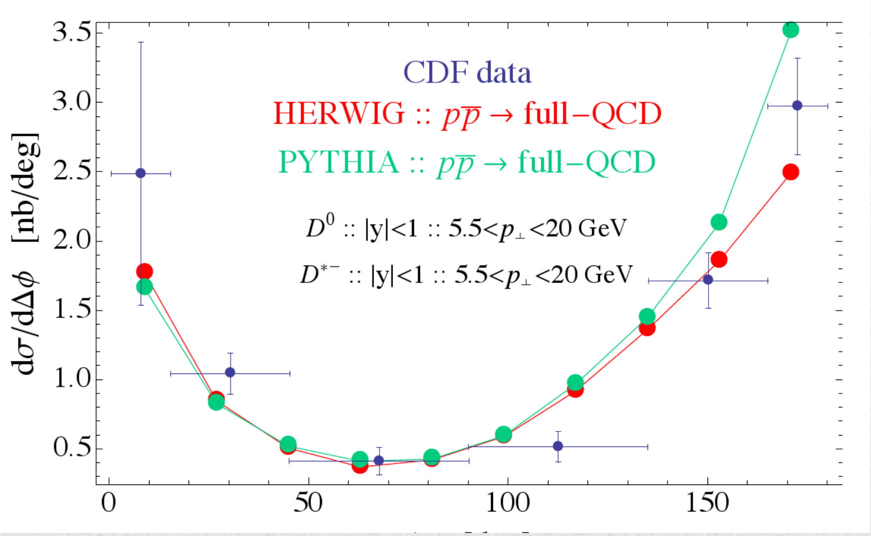
$$\left( \begin{array}{c} \text{binding energy reported by NU, PRD91, 011102} \\ E_B \approx -0.003 \pm 0.192 \text{ MeV: } \sqrt{\langle k^2 \rangle} \approx 20 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 60 \text{ fm} \end{array} \right)$$

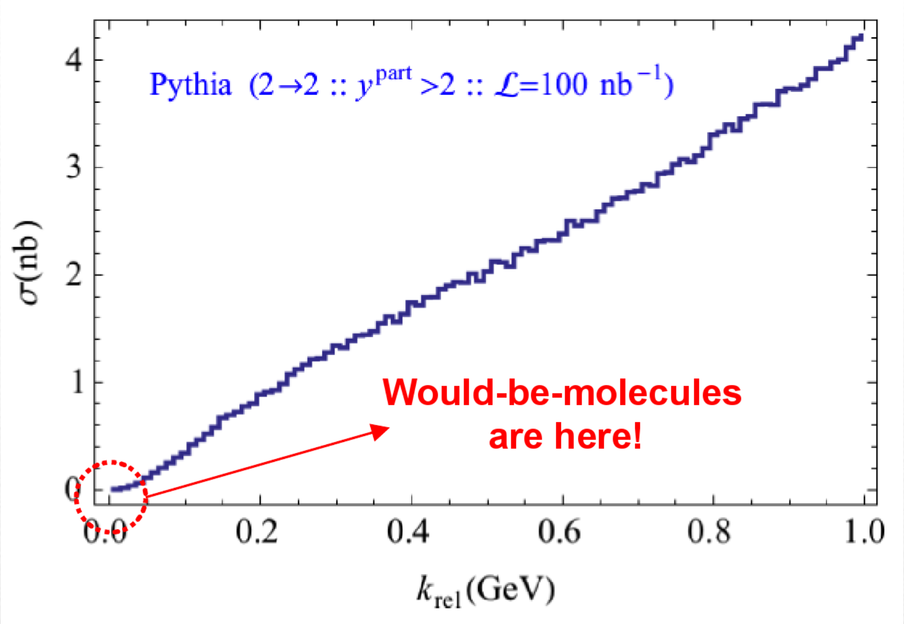
to compare with deuteron: $E_B = -2.2$ MeV

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

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

# Results



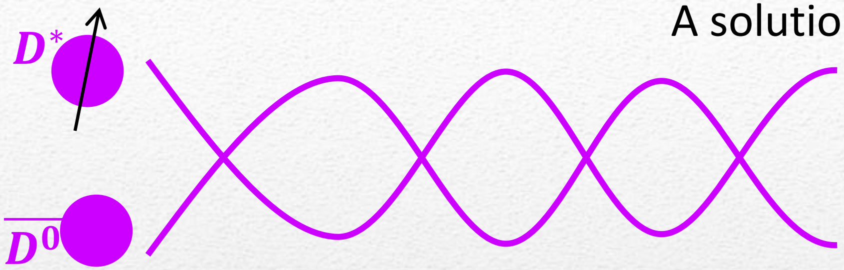

We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

We get $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1$ nb $@\sqrt{s} = 1.96$ TeV

Experimentally $\sigma(p\bar{p} \to X(3872)) \approx 30 - 70$ nb!!!

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

# 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

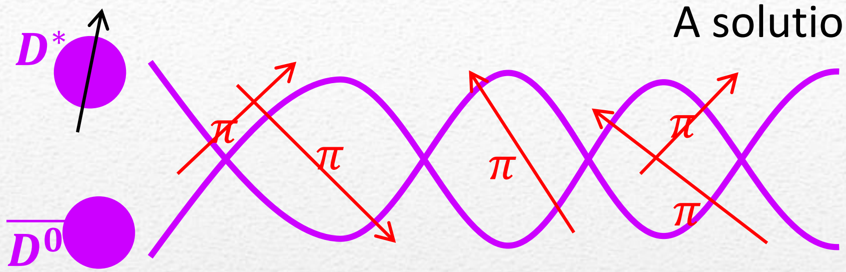
$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

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

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

# 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

However, the applicability of Watson theorem 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

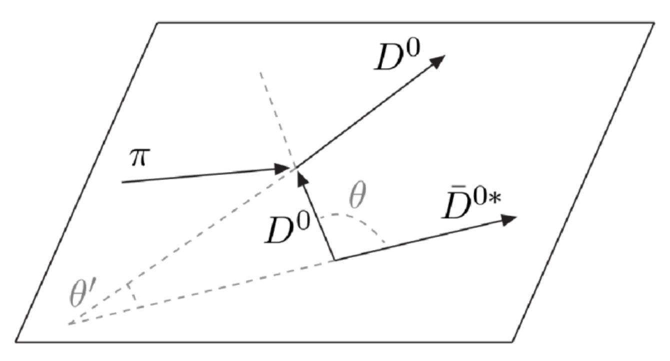
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354
use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,
limits on predictive power

# A new mechanism?

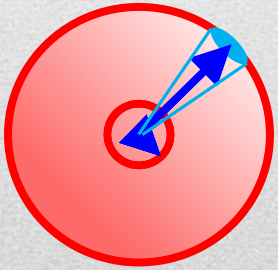
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the $DD^*$ pairs

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

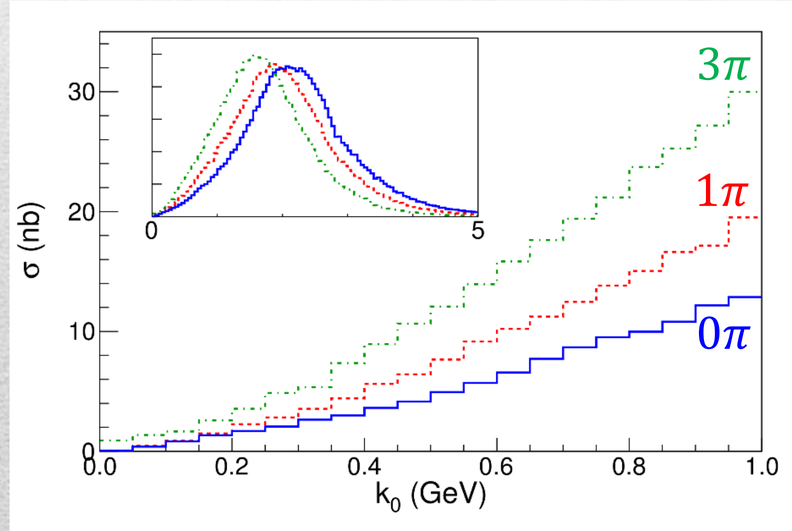



The mechanism also implies: $D$ mesons actually "pushed" inside the potential well (the classical 3-body problem!)

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



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

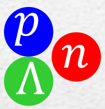



We get $\sigma\left(p\bar{p} \to X(3872)\right) \sim 5$ nb, still not sufficient to explain all the experimental cross section

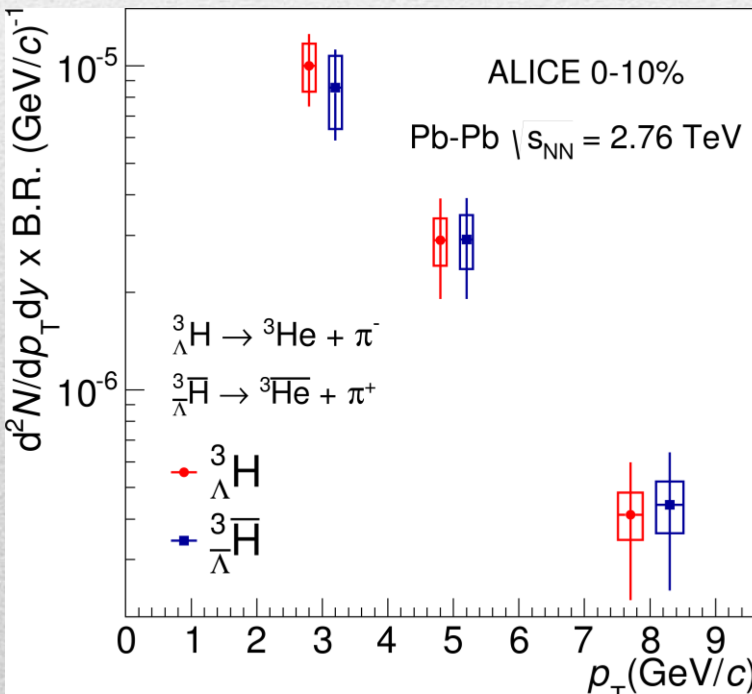
# Light nuclei at ALICE

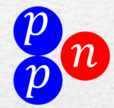
Recently, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

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

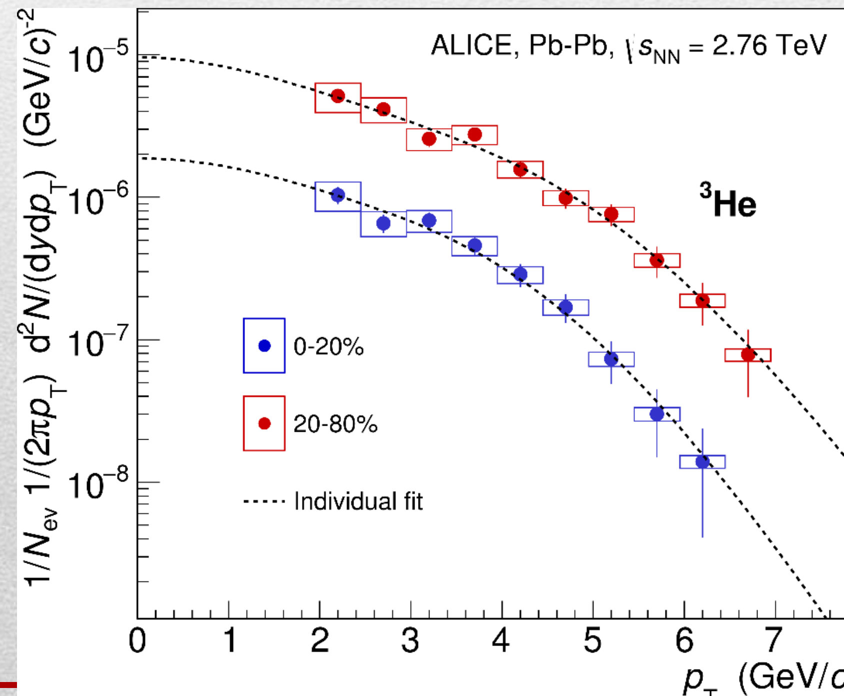



Hypertriton
arXiv:1506.08453

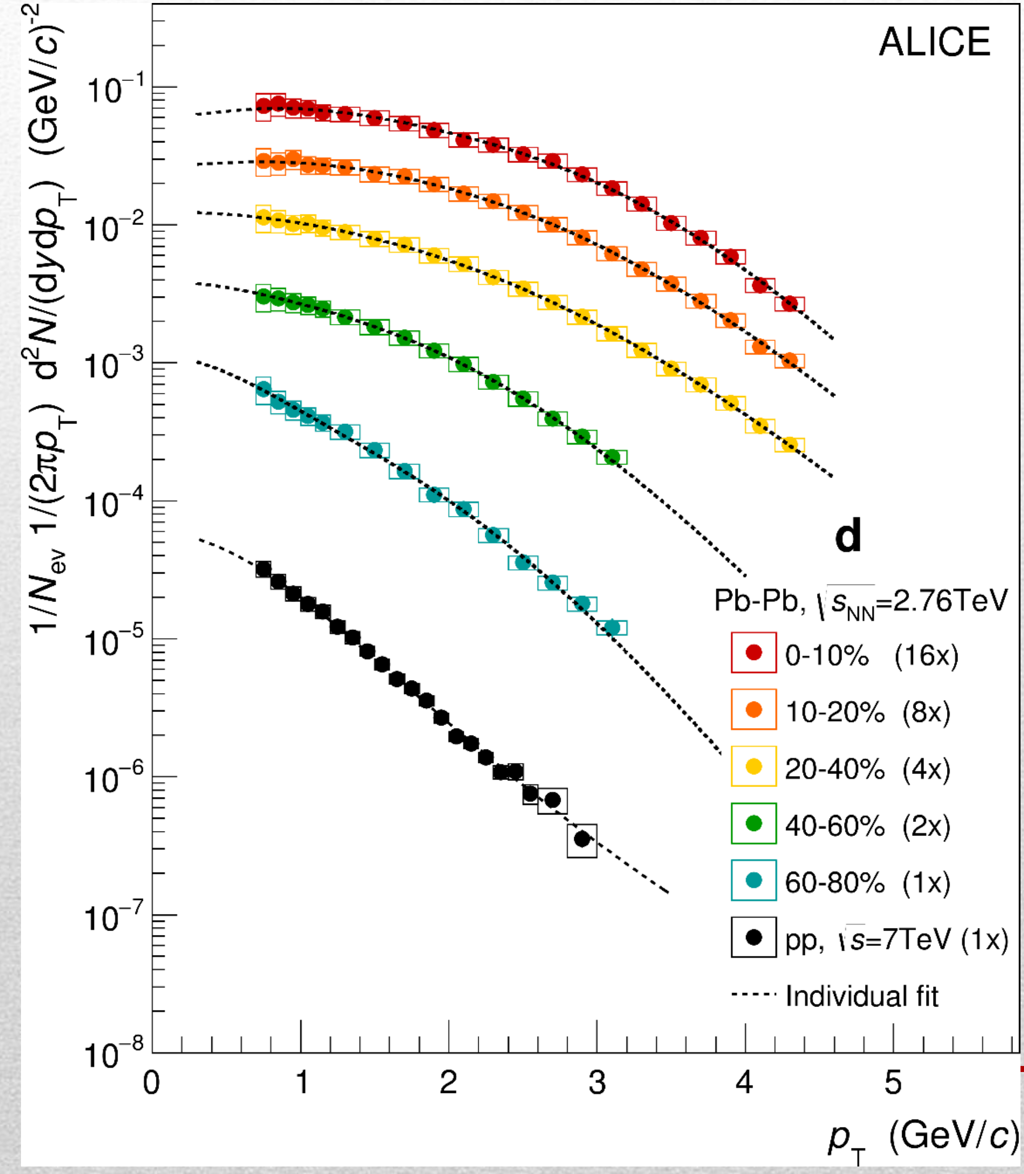


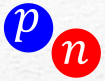




Helium-3
arXiv:1506.08951



# Light nuclei at ALICE



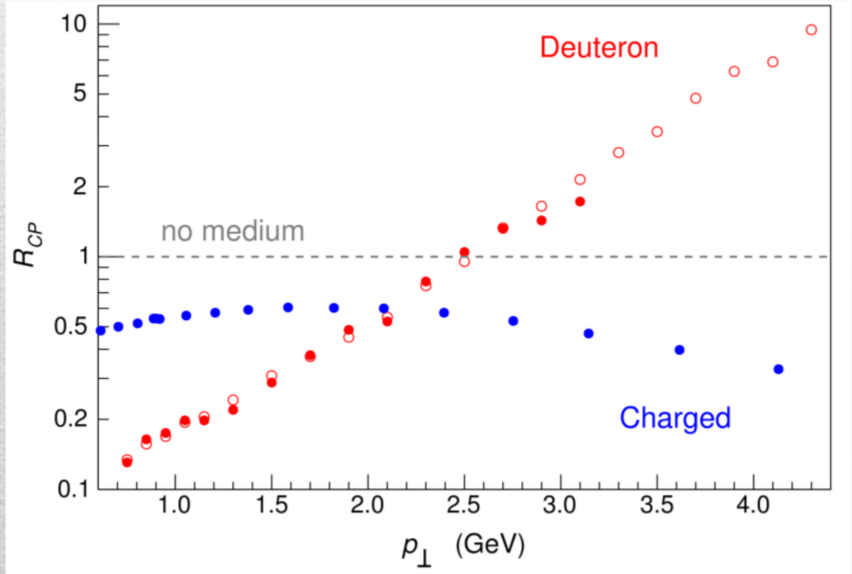

Deuteron
arXiv:1506.08951

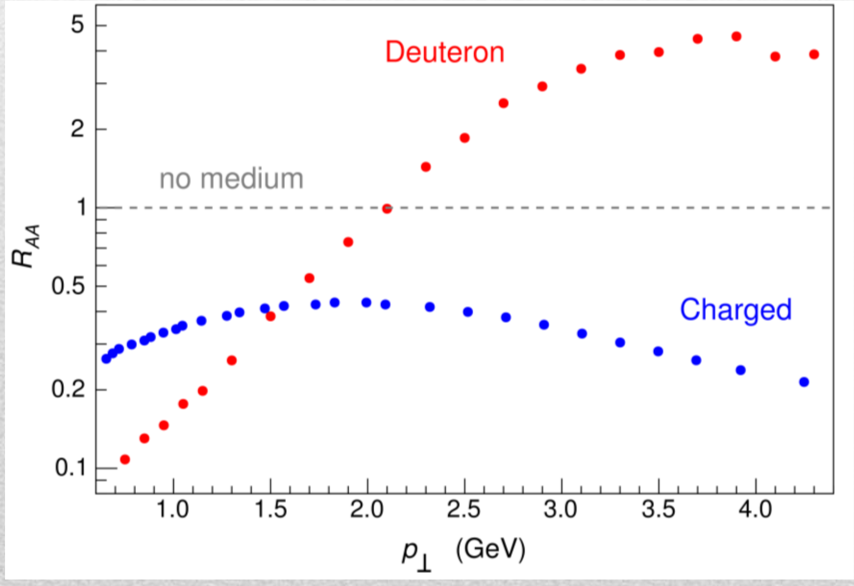
# Nuclear modification factors

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

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

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



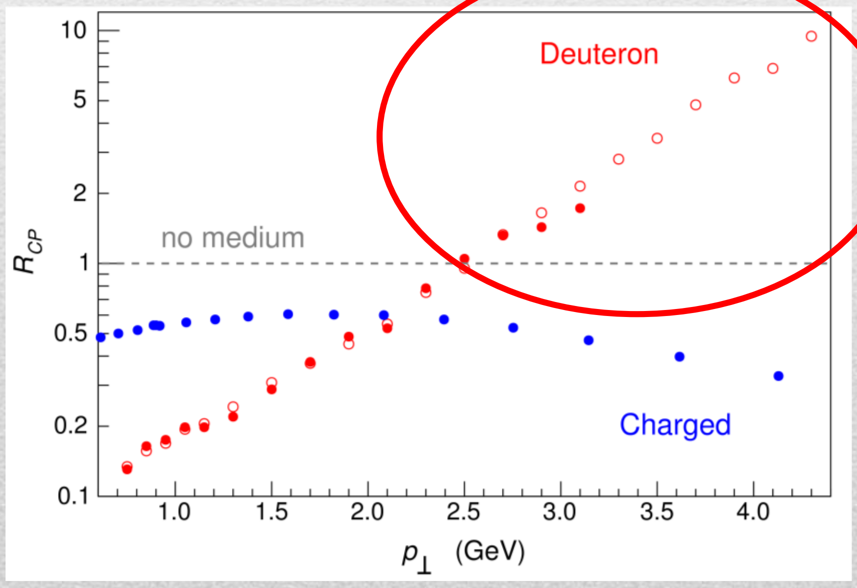



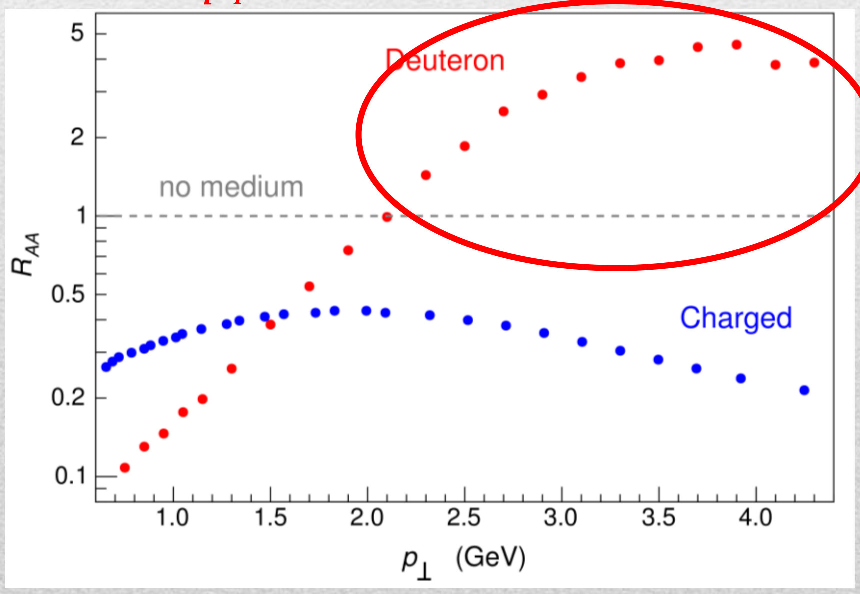
# Nuclear modification factors

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

$$R_{CP} = \frac{N_{coll}^{P}\left(\frac{dN}{dp_T}\right)_C}{N_{coll}^{C}\left(\frac{dN}{dp_T}\right)_P} \qquad R_{AA} = \frac{\left(\frac{dN}{dp_T}\right)_{\mathrm{Pb-Pb}}}{N_{coll}\left(\frac{dN}{dp_T}\right)_{pp}}$$

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

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

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

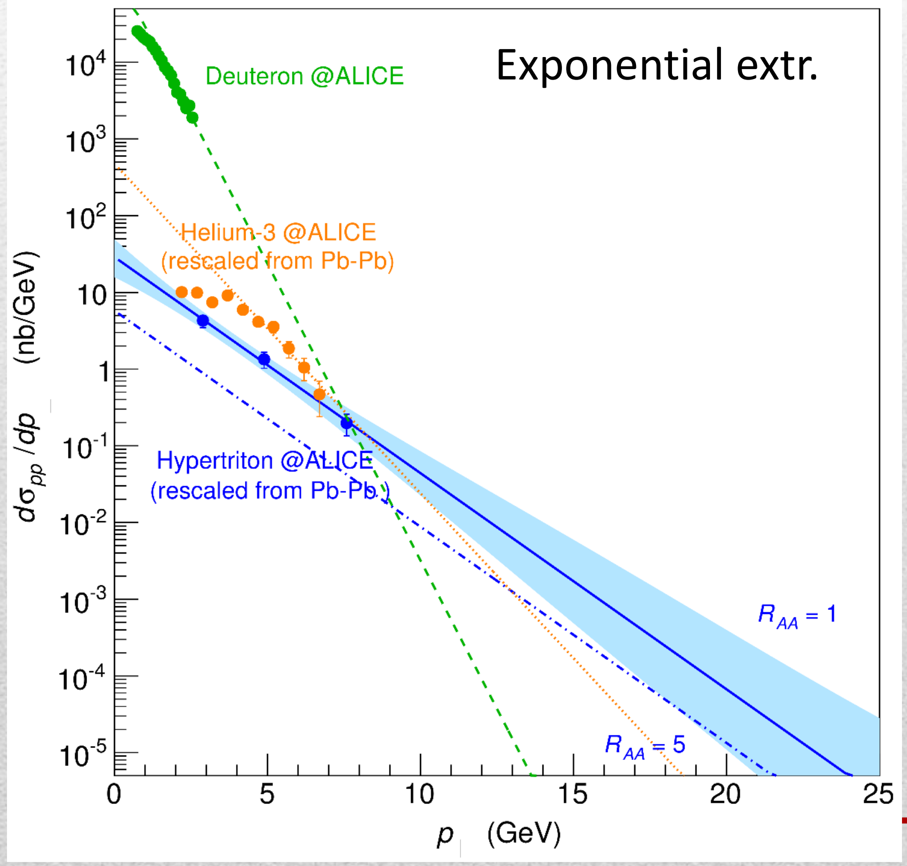
$$\frac{dN}{dp_\perp} \propto p_\perp \int_0^R r dr\, m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\mathrm{kin}}}\right),$$

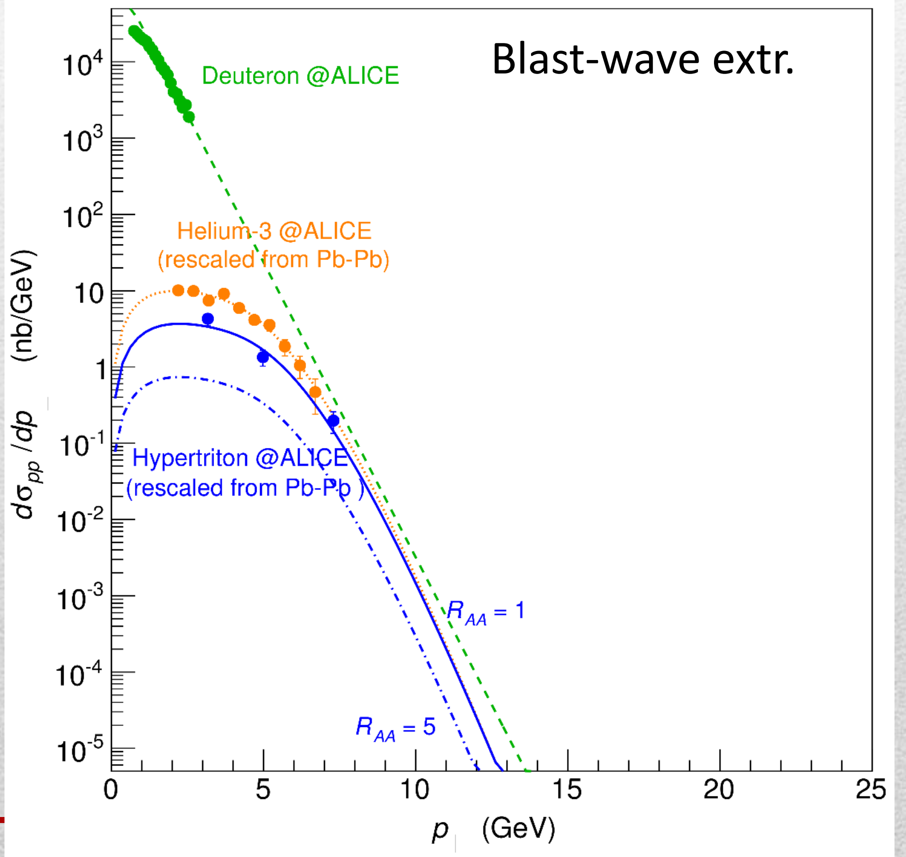
where $m_\perp$ is the transverse mass, $R$ is the radius of the fireball, $I_0$ and $K_1$ are the Bessel functions, $\rho = \tanh^{-1}\left(\frac{(n+2)\langle\beta\rangle}{2}(r/R)^n\right)$, and $\langle\beta\rangle$ the averaged speed of the particles in the medium.

# Light nuclei at ALICE

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



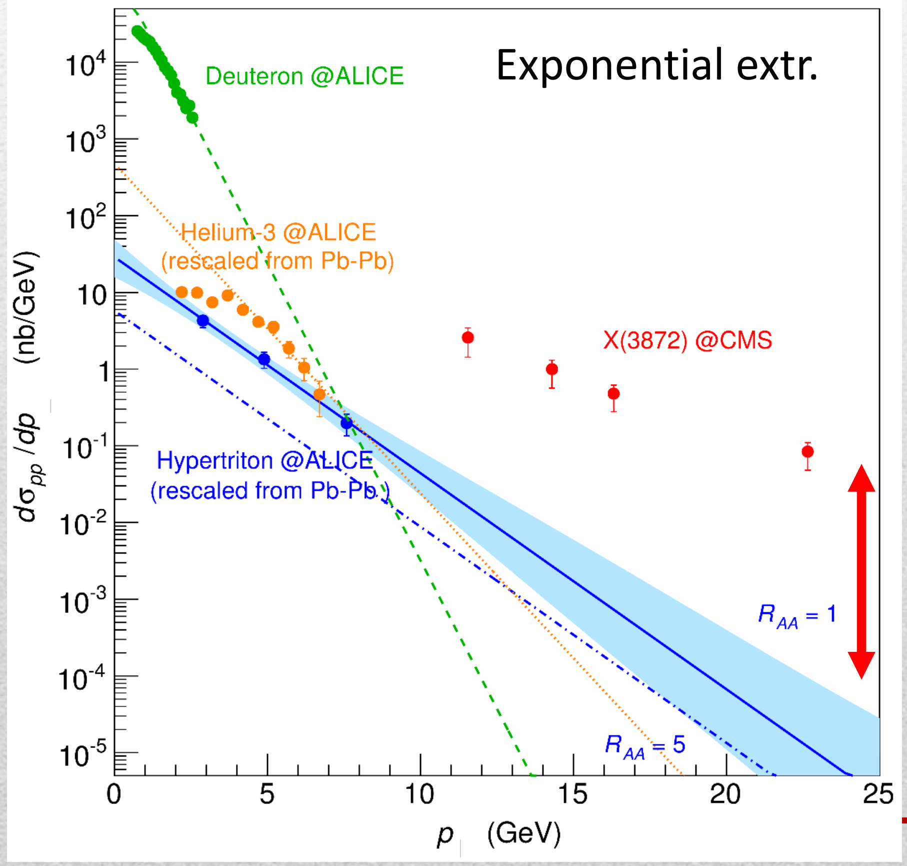



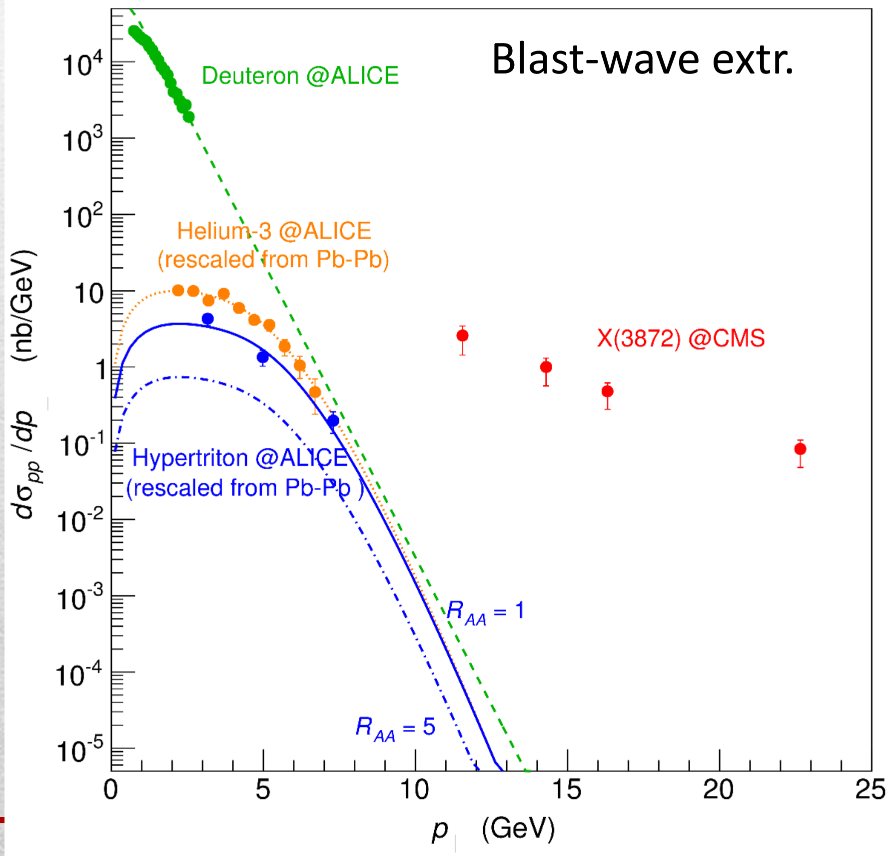
# Light nuclei at ALICE vs. $X(3872)$

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



# Feshbach resonances

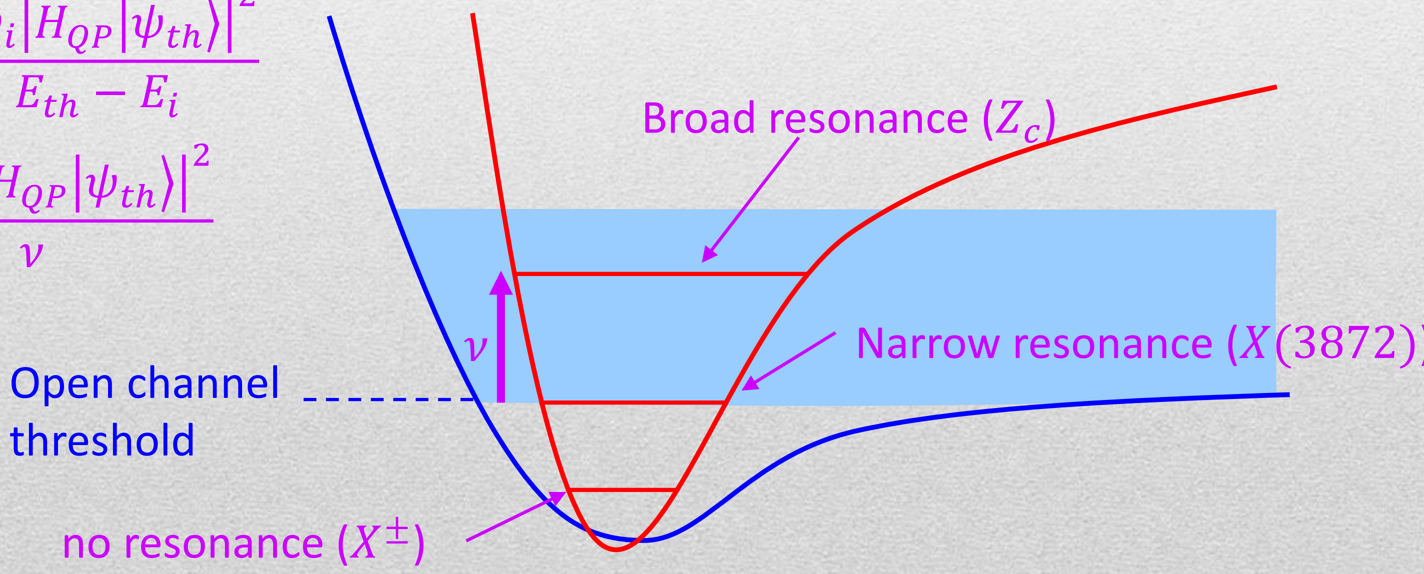
Braaten and Kusunoki, PRD69, 074005
Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

In cold atoms there is a mechanism that occurs when two atoms can interact with two potentials, resp. with continuum (molecule) and discrete (4q) spectrum
*e.g.* $DD^*$ has the same quantum numbers as $[cu][\bar{c}\bar{u}]$, the operators mix under renormalization

We add an interaction Hamiltonian $H_{QP}$

$$a \simeq a_P + C \sum \frac{\left|\langle \psi_i | H_{QP} | \psi_{th} \rangle\right|^2}{E_{th} - E_i}$$

$$\simeq a_{NR} - C \frac{\left|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle\right|^2}{\nu}$$



# Feshbach resonances

We impose a cutoff on $\nu < 100$ MeV
$X(3872)$ should be a $I = 0$ state, but $M(1^{++}) < M(D^{+*}D^{-})$
No charged component, isospin violation!

If we assume $\Gamma = A\sqrt{\nu}$, we can use $Z_c(3900)$ as input to extract $A = 10 \pm 5\ \mathrm{MeV}^{1/2}$
This value is compatible for all resonances (caveat: still large errors...)

| Open channel | $M_{4q}$ (MeV) | $\nu$ (MeV) | $\Gamma$ (MeV) | $I^G J^{PC}$ | name |
|---|---|---|---|---|---|
| $D^{*0}\bar{D}^0$ | 3872 | 0 | 0 | $1^-1^{++}$ | $X(3872)$ |
| $D^{*+}\bar{D}^0$ | 3900 | 24 | 53 | $1^+1^{+-}$ | $Z_c(3900)$ |
| $D^{*+}\bar{D}^0$ | 4025 | 8 | 24 | $1^+1^{+-}$ | $Z_c'(4025)$ |
| $\eta_c(2S)\rho^+$ | 4475 | 75 | >150 | $1^+1^{+-}$ | $Z(4430)$ |
| $B^{*+}\bar{B}^0$ | 10610 | 3 | 18 | $1^+1^{+-}$ | $Z_b(10610)$ |
| $B^{*+}\bar{B}^{*0}$ | 10650 | 1.8 | 11 | $1^+1^{+-}$ | $Z_b'(10650)$ |

We remark that $\Gamma(Z_b')/\Gamma(Z_b) \approx 0.63, \sqrt{\nu(Z_b')/\nu(Z_b)} \approx 0.77$

# 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!

For example, we compare the at-threshold $X(3872)$ with the below-threshold $Y(4260)$
CMS $X(3872)$ data: JHEP 1304, 154

$$\frac{\sigma\big(pp \to X(3872)\big) \times BR\big(X(3872) \to J/\psi\, \pi^+\pi^-\big)}{\sigma\big(pp \to Y(4260)\big) \times BR\big(Y(4260) \to J/\psi\, \pi^+\pi^-\big)} \sim 10^2$$

# Conclusions & prospects

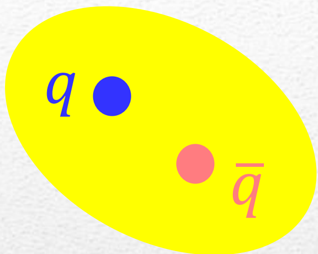
The study of exotic heavy quark sector is a challenging task
Experiments are very prolific! Constant feedback on predictions

- Study of spectra and decay patterns will improve our understanding, new data expected by BESIII, LHCb, Belle II, Jlab
- More detailed amplitude analyses will be needed to distinguish actual resonances from other (kinematical) singularities
- Nuclei observation at hadron colliders can give an unexpected help in testing some phenomenological hypotheses for the XYZ states
- Feshbach mechanism might be effective in reducing the number of states predicted by the tetraquark picture, and adds some interesting features of molecular description

**Thank you**

# BACKUP

# Dictionary – Quark model




$L$ = orbital angular momentum
$S$ = spin $q + \bar{q}$

$J$ = total angular momentum
= exp. measured spin

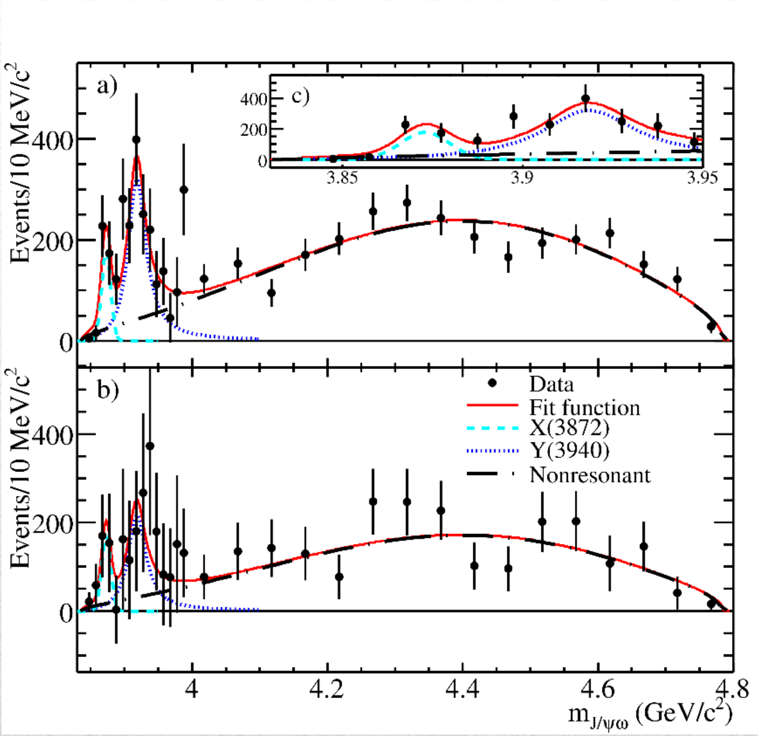
$I$ = isospin = 0 for quarkonia

$$L - S \leq J \leq L + S$$
$$P = (-1)^{L+1}, C = (-1)^{L+S}$$
$$G = (-1)^{L+S+I}$$

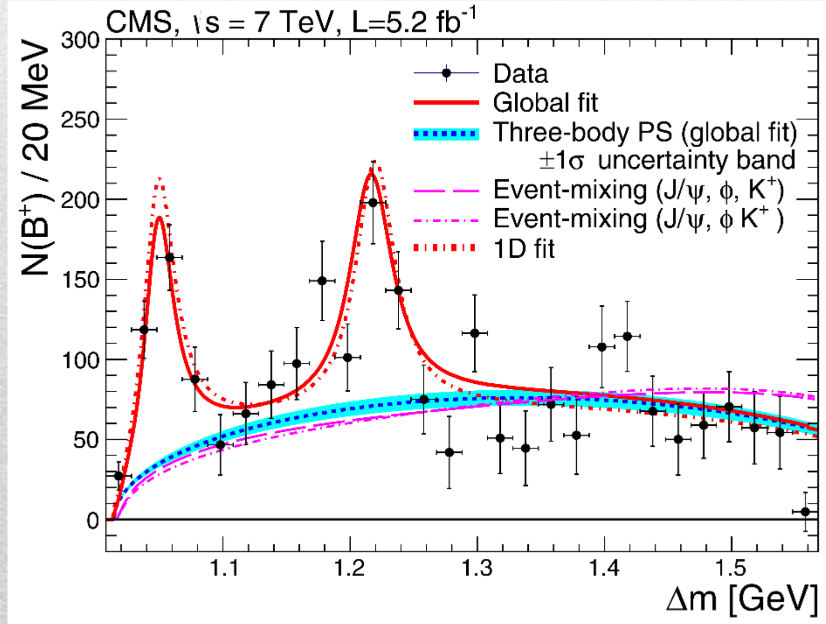
| $J^{PC}$ | $L$ | $S$ | Charmonium ($c\bar{c}$) | Bottomonium ($b\bar{b}$) |
|---|---|---|---|---|
| $0^{-+}$ | 0 ($S$-wave) | 0 | $\eta_c(nS)$ | $\eta_b(nS)$ |
| $1^{--}$ | | 1 | $\psi(nS)$ | $\Upsilon(nS)$ |
| $1^{+-}$ | 1 ($P$-wave) | 0 | $h_c(nP)$ | $h_b(nP)$ |
| $0^{++}$ | | 1 | $\chi_{c0}(nP)$ | $\chi_{b0}(nP)$ |
| $1^{++}$ | | 1 | $\chi_{c1}(nP)$ | $\chi_{b1}(nP)$ |
| $2^{++}$ | | 1 | $\chi_{c2}(nP)$ | $\chi_{b2}(nP)$ |

But $J/\psi = \psi(1S)$, $\psi' = \psi(2S)$

# 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 $X(3915) \nrightarrow D\bar{D}$ as expected,
and the hyperfine splitting
$\mathrm{M}(2^{++}) - \mathrm{M}(0^{++})$ too small



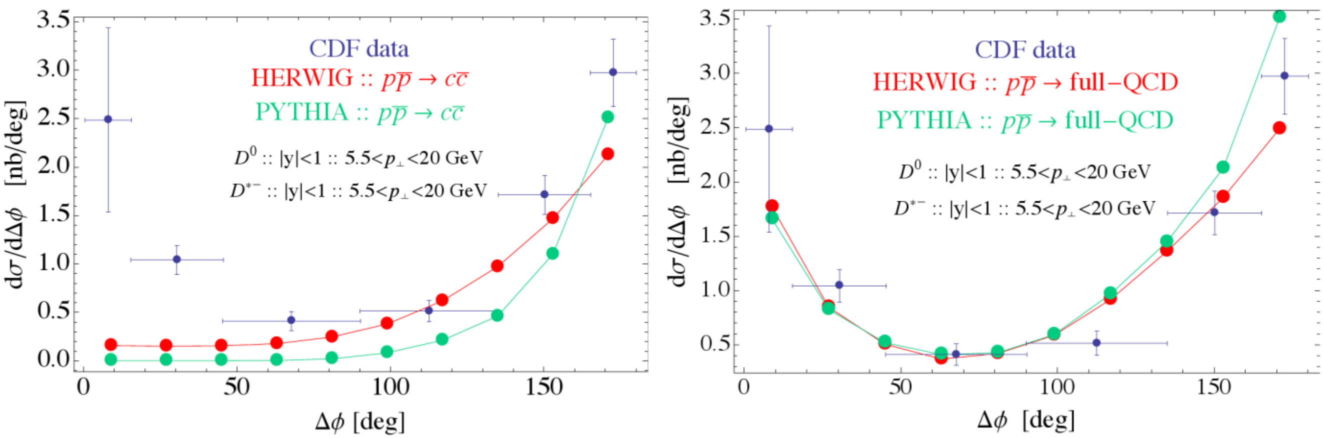

One/two peaks seen in $B \to XK \to J/\psi\,\phi\,K$, close to threshold

# 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

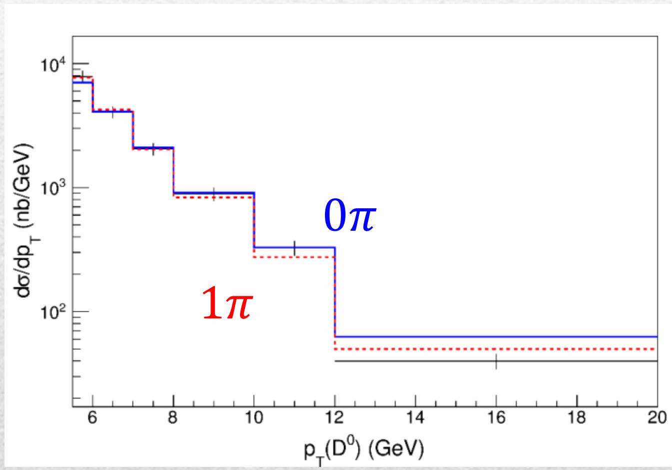
No distribution has been published (yet) at LHC

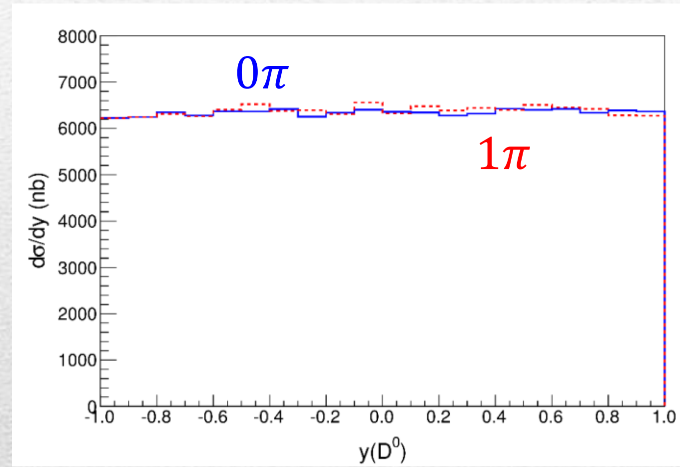
# Tuning pions

This picture could spoil existing meson distributions used to tune MC
We verify this is not the case up to an overall $K$ factor

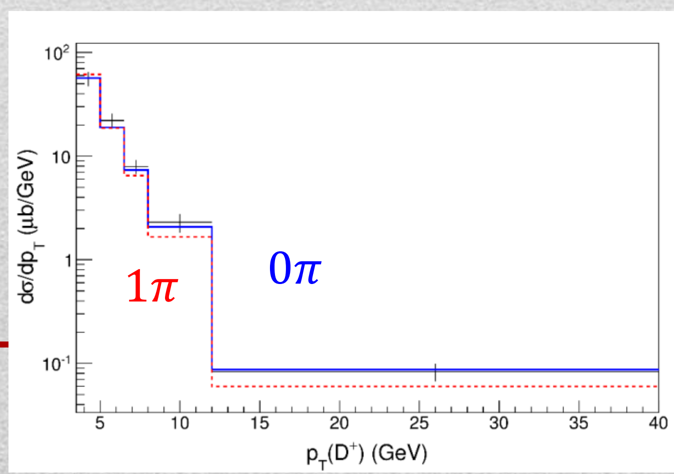
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

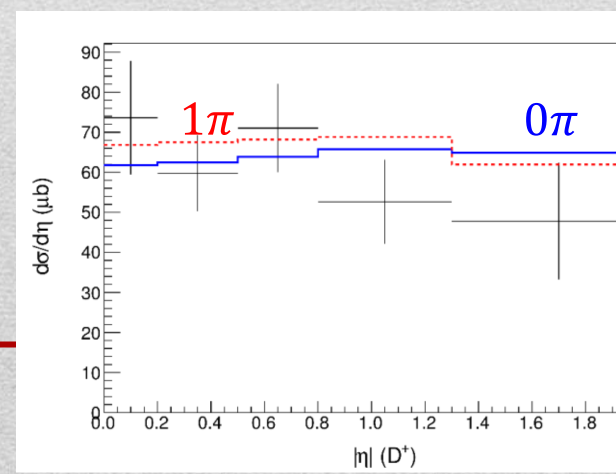
Neither at CDF...




...nor at ATLAS



# $Z_c(3900)$

Physics
spotlighting exceptional research

Home | About | Browse | APS Journals

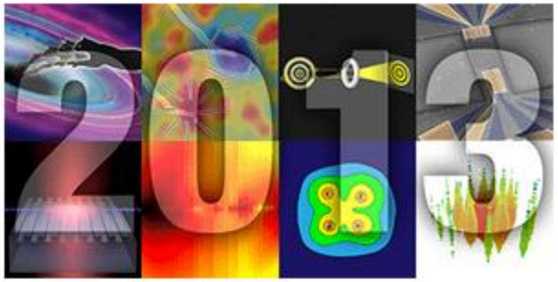
## Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

### Four-Quark Matter

mysterious particle

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

# Counting rules

Brodsky, Lebed, PRD91, 114025

- Exotic states can be produced in threshold regions in $e^+e^-$ (BES, Belle), electroproduction (JLab 12), hadronic beam facilities ($\bar{\text{P}}$ANDA at FAIR, AFTER@LHC) and are best characterized by cross section ratios
- Two examples:

1) $\frac{\sigma(e^+e^-\to Z_c^+\,\pi^-)}{\sigma(e^+e^-\to\mu^+\mu^-)} \propto \frac{1}{s^6}$ as $s\to\infty$

2) $\frac{\sigma(e^+e^-\to Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\to\Lambda_c(cud)+\bar{\Lambda}_c(\bar{c}\,\bar{u}\bar{d}))} \to const$ as $s\to\infty$

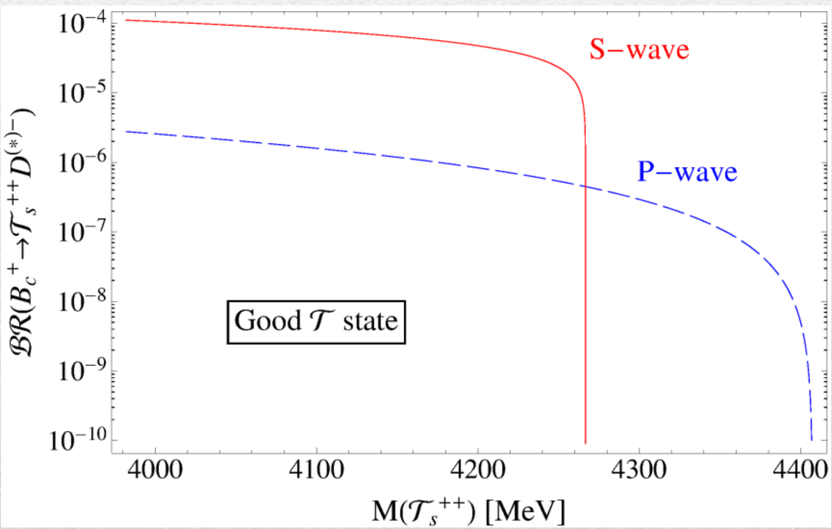
  - Ratio numerically smaller if $Z_c$ behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces

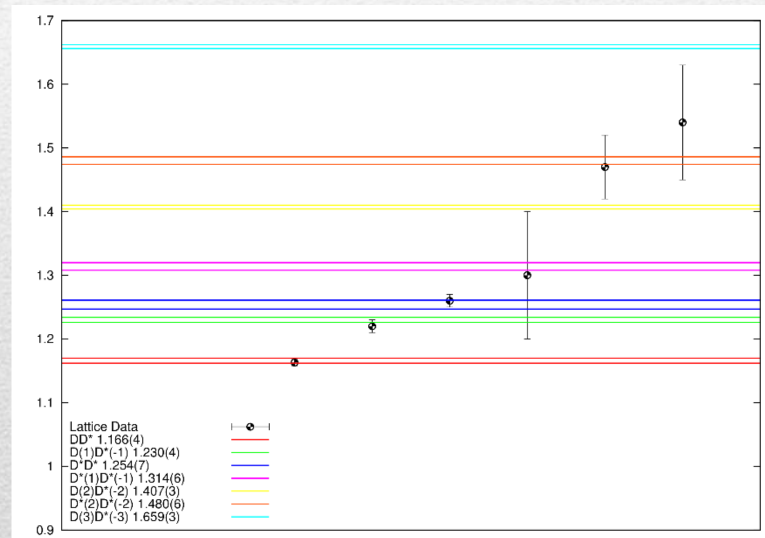
# Doubly charmed states

For example, we proposed to look for doubly charmed states, which in tetraquark model are $[cc]_{S=1}[\bar{q}\bar{q}]_{S=0,1}$

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

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

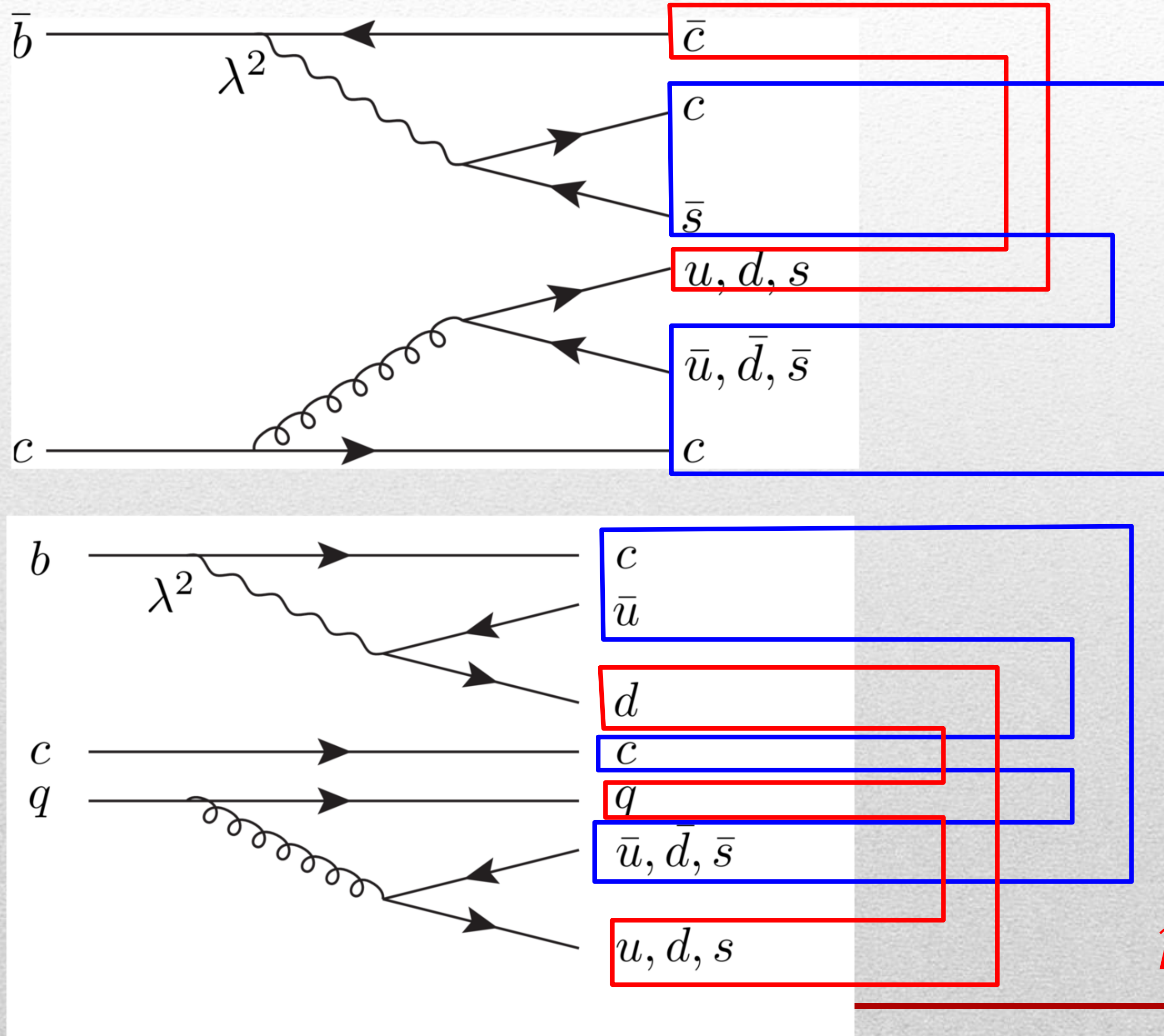



Preliminary results on spectrum for $m_\pi = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

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

# $T$ states production




$\overline{D^0}, D^-, D_s^-$

$T_s^+, T_s^{++}, T_{ss}^{++}$

$T^0, T^+, T_s^+$

$p, n, \Lambda, \Sigma, \Xi \ldots$