

# Tetraquarks and $XYZ$ states

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37th Course

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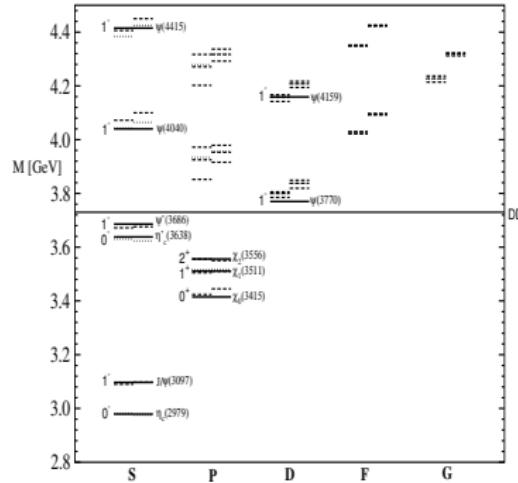
*based on work with A. Esposito, A. Guerrieri, L. Maiani, A. Pilloni, A.D. Polosa and V. Riquer*

# Introduction

- Charmonium as a  $c\bar{c}$  bound state: the “hydrogen atom” of meson spectroscopy
- spectrum and transitions predicted by potential models

## main ingredients

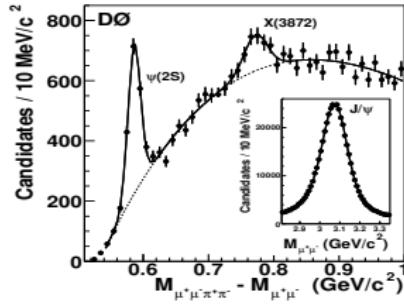
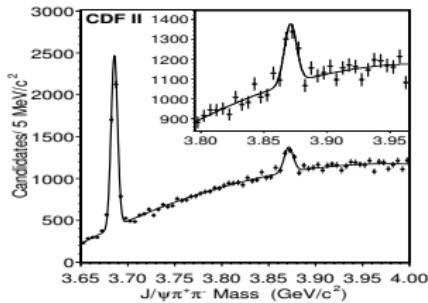
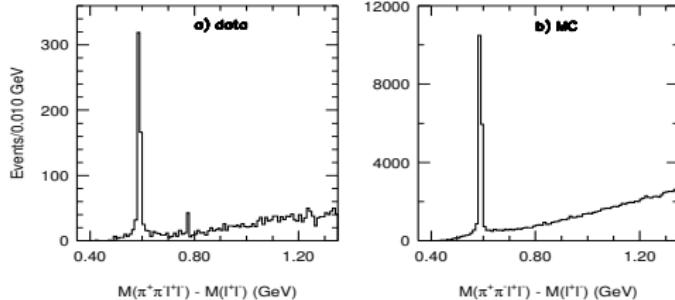
- color Coulomb term
- linear scalar confining term
- spin dependent terms
- relativistic corrections



Barnes, Godfrey and Swanson, hep-ph/0505002

# 2003 and the opening of $XYZ$ spectroscopy

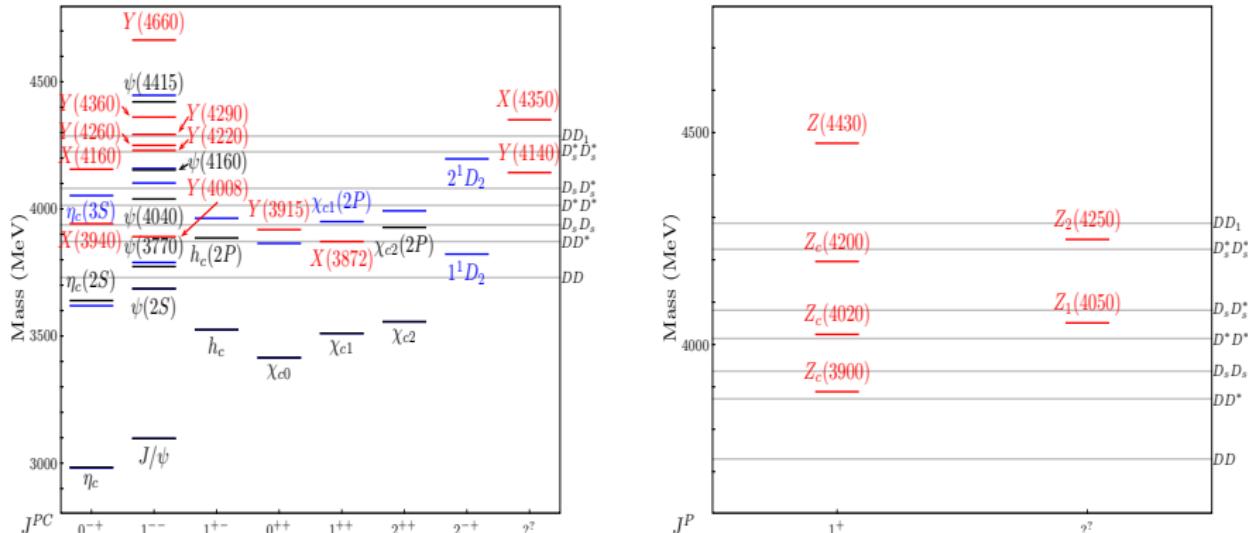
BELLE



- Phys.Rev.Lett. 91 (2003) 262001, most cited paper of Belle Collaboration

# $c\bar{c}$ spectrum 12 years after $X(3872)$ discovery

A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, IJMPA30 (2014) 04n05, 1530002



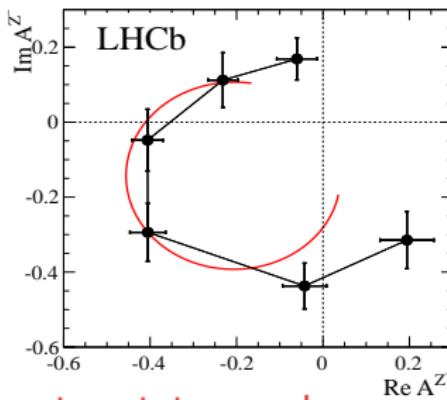
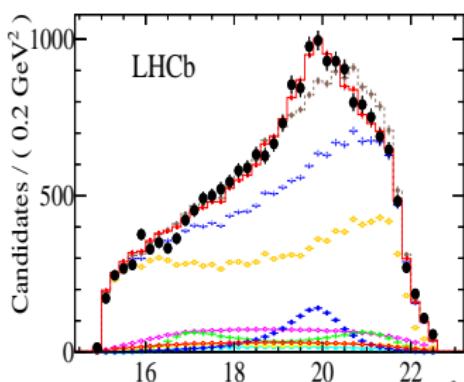
- All  $c\bar{c}$  states below open  $c$  threshold identified
- All  $J^{PC} = 1^{--}$   $c\bar{c}$  states filled
- New neutral and charged particles above threshold
- Some may be charmonia, others not (exotica,  $X$ ,  $Y$ ,  $Z$ ), in particular the charged ones (the neutral ones have quantum numbers compatible with charmonia)

# $XYZ$ : naming scheme convention

- $X$ : neutral states which decay in  $S$ -wave, with  $P = +$
  - $Y$ : neutral states seen in  $e^+e^-$  annihilations, with  $J^{PC} = 1^{--}$
  - $Z$ : charged states, with  $P = +$  for  $S$ -wave decay to  $J/\psi\pi^\pm$
- 
- for complete experimental information and more detailed discussions on molecular approaches see the talks by
    - T. Iijima
    - Y. Guo
    - Y. Dong
    - U. Uwer

# Few recent clue measurements: LHCb confirmed BELLE on $Z(4430)$ and measured $J^P = 1^+$

- $B^0 \rightarrow K^+ Z^- \rightarrow K^+ \psi(2S) \pi^-$  (LHCb)  
 $M = 4485^{+22+28}_{-22-11}$  MeV,  $\Gamma = 200^{+41+26}_{-46-35}$  MeV,  $J^P = 1^+$   
 PRL112 (2014) 222002
- $B^0 \rightarrow K^\mp \psi(2S) \pi^\pm$  Belle  
 $M = 4443^{+15+19}_{-12-13}$  MeV,  $\Gamma = 107^{+86+74}_{-43-56}$  MeV  
 PRL100 (2008) 142001; PRD80 (2009) 031104, PRD88 (2013) 074026

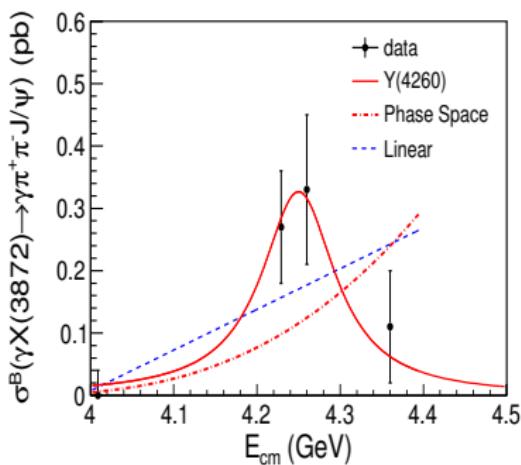
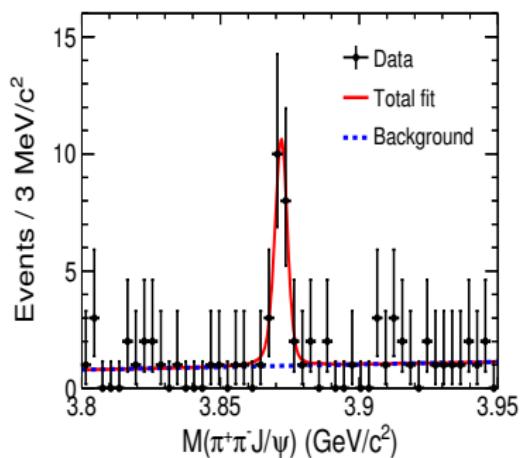


- valence structure  $cc\bar{u}\bar{d}$  required  $\Rightarrow$  true tetraquark
- $\frac{\pi}{2}$  phase shift with energy crossing the mass  $\Rightarrow$  true resonance
- mass not close to a meson pair threshold

# $Y(4260)$ radiative decay to $X(3872)$

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

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

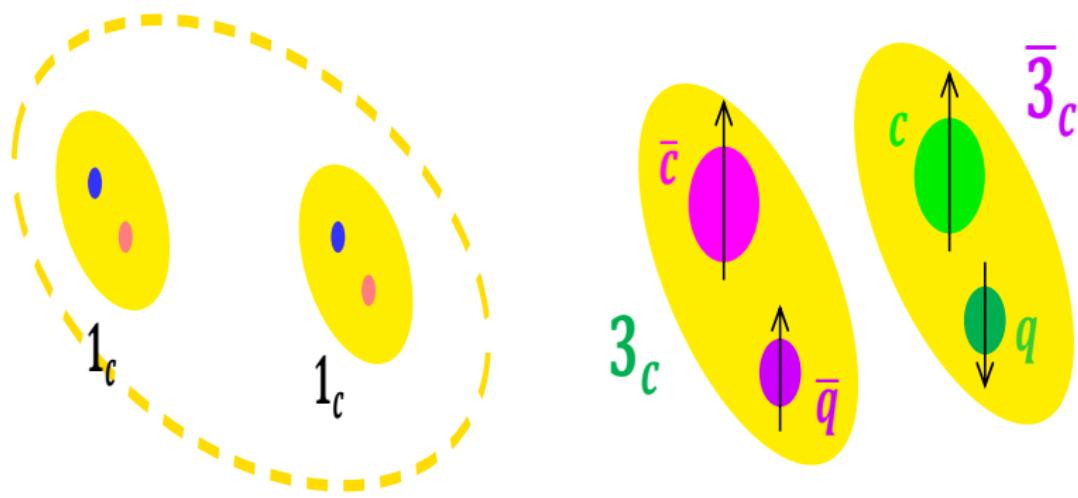


With  $\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi] = 5\%$

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

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

# main th. phenomenological models for exotica



overall picture still not clear

# Idea of light diquarks

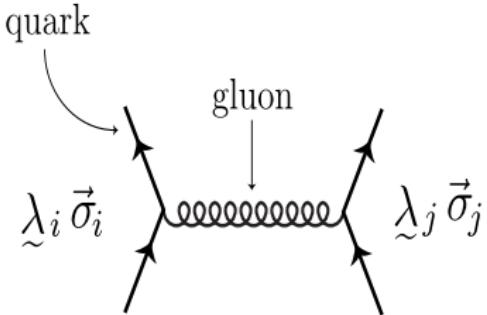
A. De Rujula, H. Georgi, S.L. Glashow, PRD12, (1975) 147

From QCD Breit interaction

$$\begin{aligned}\mathcal{H}_{\text{eff}} &\propto - \sum_{i \neq j} \tilde{\lambda}_i \cdot \tilde{\lambda}_j \vec{\sigma}_i \cdot \vec{\sigma}_j \\ &= 4P_{12}^F + \frac{4}{3}P_{12}^S + 2P_{12}^C - \frac{2}{3}\end{aligned}$$

$P_{12}^X$  are  $C, F, S$  exchange operator with eigenvalue  $(-) + 1$  for states (anti)symmetric under exchange

Flavor	Spin	Color	$\Delta E$
$\bar{3}(A)$	$1(A)$	$\bar{3}(A)$	-8
$\bar{3}(A)$	$3(S)$	$6(S)$	$-4/3$
$6(S)$	$3(S)$	$\bar{3}(A)$	$8/3$
$6(S)$	$1(A)$	$6(S)$	4

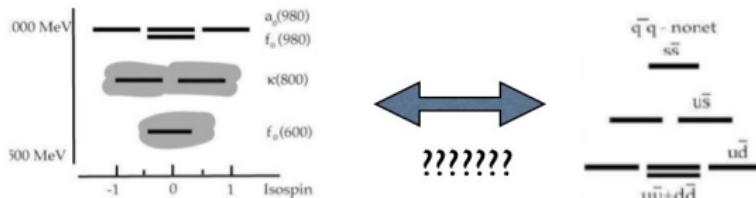


- Diquarks  $[qq']$  can be the basic building blocks of new hadrons

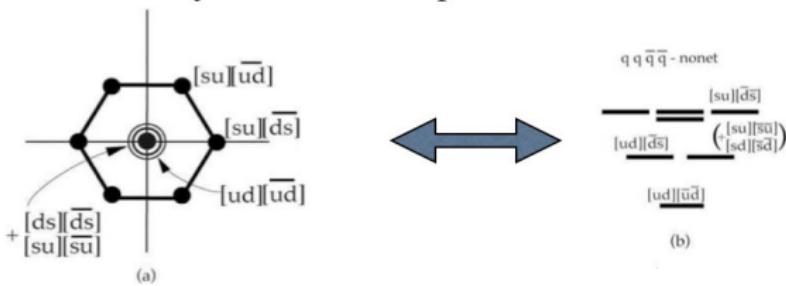
R.L. Jaffe, hep-ph/0001123

# Diquarks applied to the light scalar meson sector

D. Black, A.H. Fariborz, F. Sannino, J. Schechter, PRD 59 074026 (1999)



Antisymmetric tetraquarks work better



from L. Maiani lectures in Erice 2014

- a diquark based model for light scalar mesons developed in

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRL93 (2004) 212002  
G. 't Hooft, G. Isidori, L. Maiani, A.D. Polosa, V. Riquer, PLB662 (2008) 424

# Heavy diquarks as building blocks

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRD 71 (2005) 014028

- A natural extension of the diquark model is the inclusion of diquarks involving one heavy constituent ( $[cq][\bar{c}\bar{q}']$ ), *assuming*  $[cq]$  is binding
- For  $[cq][\bar{c}\bar{q}]$  the near spin independence of heavy quark interactions (exact in the limit  $m_c \rightarrow \infty$ ) implies the presence of both **spin zero** and **spin one diquarks**.
- As a consequence, a reach spectrum is implied, with states with  $J = 0, 1, 2$  and both natural and unnatural  $J^{PC}$   
( $C = (-1)^{L+S_{q\bar{q}}+S_{c\bar{c}}}$ )
- mass spectrum calculated in terms of
  - constituent diquark masses
  - spin-spin interactions

# Evolution of the tetraquark model

- The absence of charged partners of the  $X(3872)$  made many people skeptical on the original model
- however

$$\mathcal{B}(B^+ \rightarrow K^+ X) \times \mathcal{B}(X \rightarrow \rho^0 J/\psi)$$

$$= (8.4 \pm 1.5 \pm 0.7) \times 10^{-6} \quad (\text{BaBar})$$

$$= (8.6 \pm 0.8 \pm 0.5) \times 10^{-6} \quad (\text{Belle})$$

$$\mathcal{B}(\bar{B}^0 \rightarrow K^- X^+) \times \mathcal{B}(X^+ \rightarrow \rho^+ J/\psi) < 5.4 \times 10^{-6} \quad (\text{BaBar}),$$
$$< 4.2 \times 10^{-6} \quad (\text{Belle}),$$

$$\mathcal{B}(B^+ \rightarrow K^0 X^+) \times \mathcal{B}(X^+ \rightarrow \rho^+ J/\psi) < 22 \times 10^{-6} \quad (\text{BaBar})$$
$$< 6.1 \times 10^{-6} \quad (\text{Belle})$$

- after discovering new charged states, there is now renewed interest in the tetraquark model e.g. S. Brodsky, R. Lebed et al. 2014, 2015
- studying the tetraquark in large- $N$  QCD, S. Weinberg showed
  - ① that the Coleman theorem (tetraquark correlators reduce to disconnected propagators) does not apply if the connected tetraquark correlator develops a pole
  - ② that the decay amplitude  $\sim \frac{1}{\sqrt{N}}$

S. Weinberg, PRL 110 (2013) 261601

# Diquark-antidiquark / tetraquark model

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRD 71 (2005) 014028

- in the original version a “democratic” hypothesis was made on spin-spin interactions

$$H = \sum_i m_i + \sum_{i < j} 2\kappa_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

From conventional  $S$ -wave mesons and baryons

$$H \approx 2\kappa_{q\bar{q}} \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}}$$

- with the accumulated data it has been necessary to revisit the model, w.r.t. the hierarchy within the spin interactions

# From type-I to type-II diquark-antidiquark model

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRD 89 (2014) 114010

- new ansatz: only spin-spin coupling inside the diquark is leading

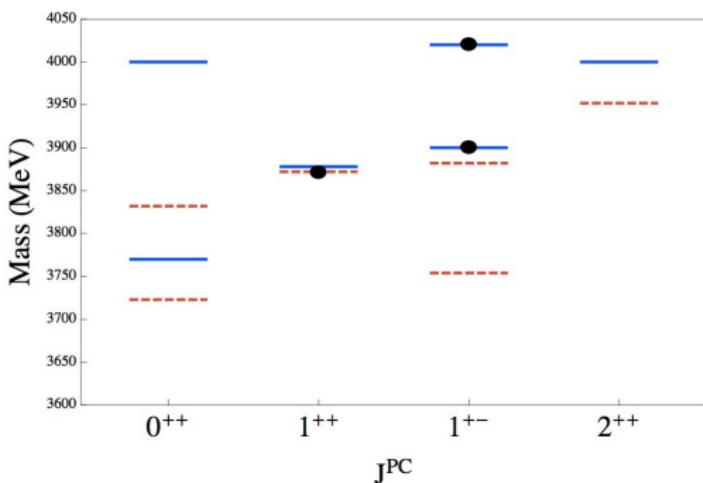
$$H \approx 2\kappa_{qc} (\mathbf{S}_q \cdot \mathbf{S}_c + \mathbf{S}_{\bar{q}} \cdot \mathbf{S}_{\bar{c}})$$

$J^{PC}$	$cq \bar{c}\bar{q}$	$c\bar{c} q\bar{q}$	Resonance Assig.	Decays
$0^{++}$	$ 0, 0\rangle$	$1/2 0, 0\rangle + \sqrt{3}/2 1, 1\rangle_0$	$X_0(\sim 3770 \text{ MeV})$	$\eta_c, J/\psi + \text{light mesons}$
$0^{++}$	$ 1, 1\rangle_0$	$\sqrt{3}/2 0, 0\rangle - 1/2 1, 1\rangle_0$	$X'_0(\sim 4000 \text{ MeV})$	$\eta_c, J/\psi + \text{light mesons}$
$1^{++}$	$1/\sqrt{2}( 1, 0\rangle +  0, 1\rangle)$	$ 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$	$X_2(\sim 4000 \text{ MeV})$	$J/\psi + \text{light mesons}$

with a value of the coupling  $\kappa_{qc} = 67 \text{ MeV}$  (cfr. 22 MeV of type I)

- $M(X_1) \sim M(Z)$
- $M(Z') - M(Z) \sim 2\kappa_{qc} = 134 \text{ MeV}$
- $M(X_2) \sim M(X'_0) \sim 4000 \text{ MeV}$
- $M(X_0) \sim 3770 \text{ MeV}$

## Type-II diquark-antidiquark model (cnt'd)



- in this scheme  $Z(4430)$  is the first radial excitation of  $Z(3900)$ 
  - note that  $M(Z(4430)) - M(Z(3900)) = 593 \text{ MeV} \sim M(\psi(2S)) - M(J/\psi) = 589 \text{ MeV}$
- both  $Z(3900)$  and  $Z(4020)$  have  $s_{c\bar{c}} = 1, 0$ 
  - $\Rightarrow Z(4020) \rightarrow \pi h_c(^1P_1)$

# $Y$ states: tetraquarks with $L = 1$

- 

$$H \approx 2\kappa'(\mathbf{S}_q \cdot \mathbf{S}_c + \mathbf{S}_{\bar{q}} \cdot \mathbf{S}_{\bar{c}}) - 2A \mathbf{S} \cdot \mathbf{L} + \frac{1}{2}B \mathbf{L}^2$$

State	$P(S_{c\bar{c}} = 1) : P(S_{c\bar{c}} = 0)$	Assignment	Radiative Decay
$Y_1$	3:1	$Y(4008)$	$\gamma + X_0$
$Y_2$	1:0	$Y(4260)$	$\gamma + X$
$Y_3$	1:3	$Y(4290)/Y(4220)$	$\gamma + X'_0$
$Y_4$	1:0	$Y(4630)$	$\gamma + X_2$

- $Y(4360)$ : radial excitation of  $Y(4008)$ ;  $Y(4660)$ : radial excitation of  $Y(4260)$ , since both decay to  $\psi(2S)$
- $Y(4260)$  and  $X(3872)$  have the same spin structure  $\implies$  the observed radiative decay  $Y(4260) \rightarrow \gamma X(3872)$  is an  $E1$  transition ( $\Delta L = 1$  and  $\Delta S = 0$ ) as in radiative decays of  $\chi$  states

# some predictions on radiative decays

- type-II tetraquark model seems to capture several features making also additional predictions

$Y_4 = Y(4630) \rightarrow \gamma + X_2 \quad (J^{PC} = 2^{++}) = \gamma + X(3940), ??$

$Y_3 = Y(4290/4220) \rightarrow \gamma + X'_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3916), ??$

$Y_2 = Y(4260) \rightarrow \gamma + X_1 \quad (J^{PC} = 1^{++}) = \gamma + X(3872), \text{ seen}$

$Y_1 = Y(4008) \rightarrow \gamma + X_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3770 ??), ??$

# molecules vs. compact tetraquarks: where are we?

- brief summary of the present situation
  - molecular model is the most economic one but no firm predictions to be tested
  - on the contrary, for tetraquarks models two many predictions
- $Z(4430)$ , with  $J^P = 1^+$ , challenges the molecular interpretation
- closest threshold  $D^*(2010)\bar{D}_1(2420)$  would imply negative parity

J. Rosner, PRD76 (2007) 114002

- other molecular hypothesis would require unlikely excited components  $D^*\bar{D}(1S, 2S)$  or  $P$ -wave  $D^*\bar{D}_1$
- T. Barnes, F.E. Close and E.S. Swanson, Phys.Rev. D91 (2015) 1, 014004
- on the other hand tetraquark models predict charged states, not necessarily close to thresholds

L. Maiani, F.P., A.D. Polosa, V. Riquer, Phys.Rev. D71 (2005) 014028

- many new data still required to clarify the picture
- on the theory side: point out whether there are distinctive signatures able to distinguish between different models

# $X(3872)$ , the oldest and still debated one

- $M(X(3872)) = 3871.68 \pm 0.17 \text{ MeV}$      $\Gamma_X \lesssim 1.2 \text{ MeV}$   
 $J^{PC} = 1^{++}$

LHCb 2014

- $\Delta M \equiv M(X(3872)) - (M_{D^0} + M_{D^{*0}}) = -3 \pm 192 \text{ keV}$

Tomaradze et al. 2015

- production
  - production through  $B$  decays at  $e^+e^-$  and  $p\bar{p}/pp$  colliders
- decay

- $J/\psi\rho \rightarrow J/\psi\pi^+\pi^-$

- $J/\psi\omega \rightarrow J/\psi\pi^+\pi^-\pi^0$

- $D^0\bar{D}^{0*} \rightarrow D^0\bar{D}^0\pi^0$

(large isospin violation)

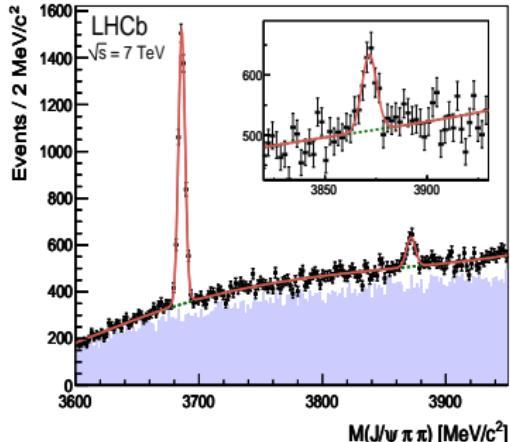
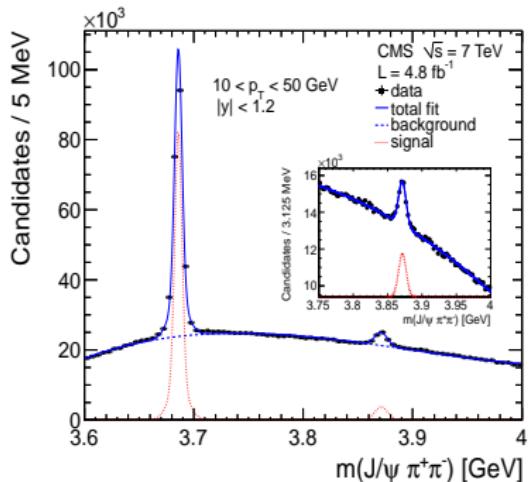
- $D^0\bar{D}^{0*} \rightarrow \bar{D}^0\gamma$

- $J/\psi\gamma, \psi'\gamma$

$$\frac{\mathcal{BR}(\psi'\gamma)}{\mathcal{BR}(J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29 \text{ (LHCb)}$$

- $\Delta M \lesssim 0 \implies \text{molecular interpretation natural}$
- isospin violation explained with the distance of  $D^+D^{*-}$  and  $D^0\bar{D}^{0*}$  thresholds of  $\sim 8 \text{ MeV}$
- $R = \frac{\hbar c}{\sqrt{2\mu(-\Delta M)}} \implies R \geq 10 \text{ fm}$

# $X(3872)$ and the production cross section issue



- large production cross section
- detected at large  $p_T$
- prompt production dominant over  $B$  decay ( $\sim 84\%$  @Tevatron)
- features at odds with a loosely bound molecule

# Prompt $X(3872)$ production: upper theoretical bounds

Bignamini, Grinstein, F.P., Polosa, Sabelli: Phys. Rev. Lett. 103, 162001, 2009

hypothesis:  $X(3872)$  as an  $S$ -wave bound state of two  $D$  mesons

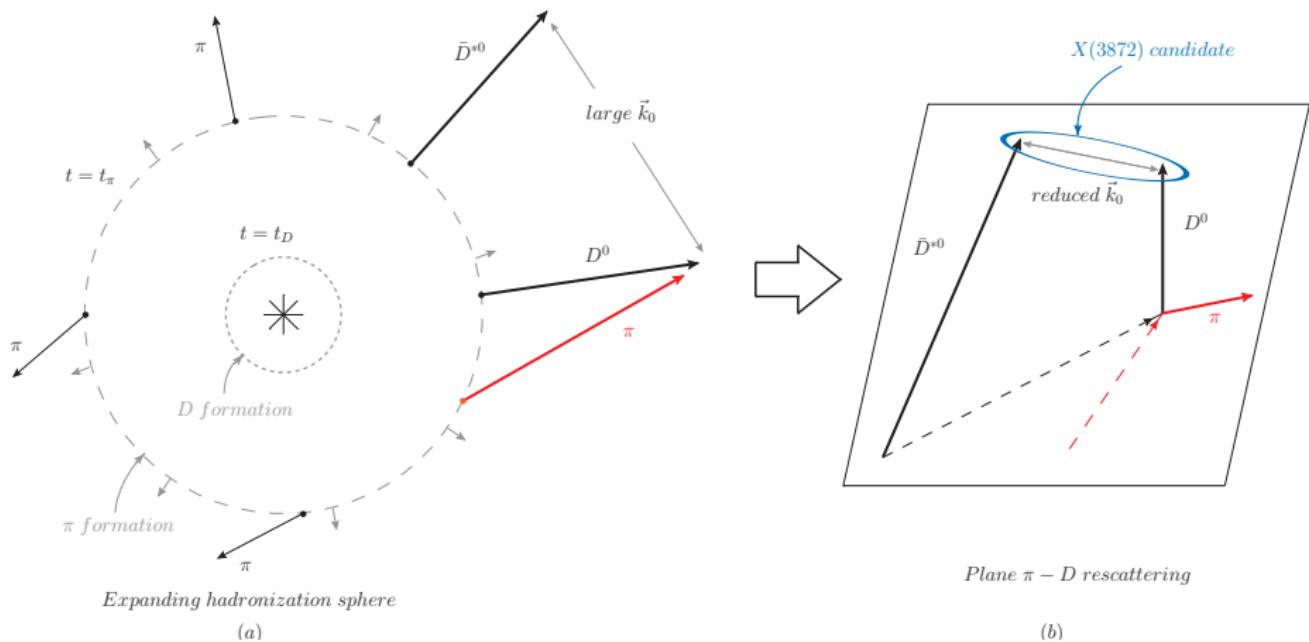
$$\begin{aligned}\sigma(p\bar{p} \rightarrow X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \rightarrow X(3872))_{\text{prompt}}^{\max}\end{aligned}$$

- $\mathbf{k}$  is the rest-frame relative 3-momentum between the  $D$  and  $D^*$
- $|\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$  can be computed with MC simulations
- result: measured prompt cross section  $\ll$  upper estimate by more than 2 orders of magnitude unless integration over  $|\mathbf{k}|$  extended up to  $\sim 400$  MeV
- this could be made possible by FSI Artoisenet and Braaten, PRD81 (2010) 114018
- actually the large hadronic activity (mainly  $\pi$ ) close to  $D$  and  $D^*$  could prevent the effectiveness of FSI (Bignamini et al., PLB684 (2010) 228)
- but the same  $\pi$  could give an alternative contribution

# Possible mechanism alternative to FSI

A. Esposito, F.P., A. Pilloni and A.D. Polosa, J.Mod.Phys. 4 (2013) 1569

A.L. Guerrieri, F.P., A. Pilloni and A.D. Polosa, PRD90 (2014) 3, 034003



Expanding hadronization sphere

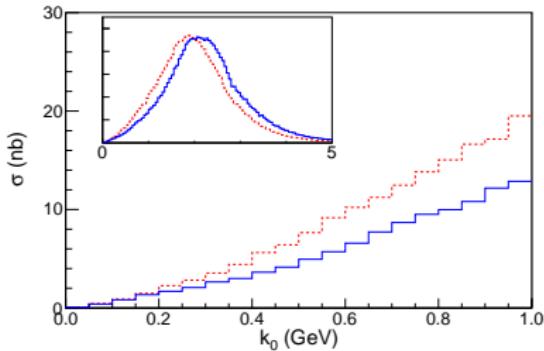
(a)

Plane  $\pi - D$  rescattering

(b)

# results

- additional pions close to  $D^0(*)$  in momentum space can interact elastically and change the rel. momentum between  $D^0$  and  $D^{0*}$
- given the initial asymmetric distribution in  $k_{\text{rel}}$  there could be a feed-down process from larger relative momenta to lower ones and bring  $D$  pairs from positive to negative energies (bound state)

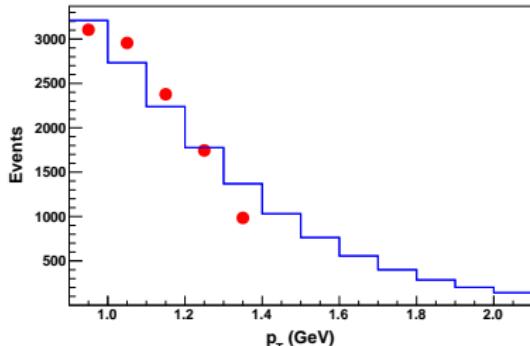
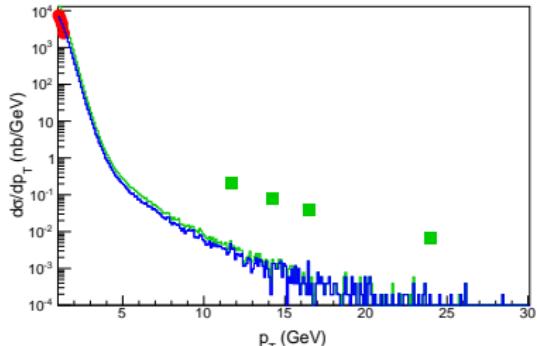


- there is a contribution but not enough
- additional ways to check the molecular hypothesis?

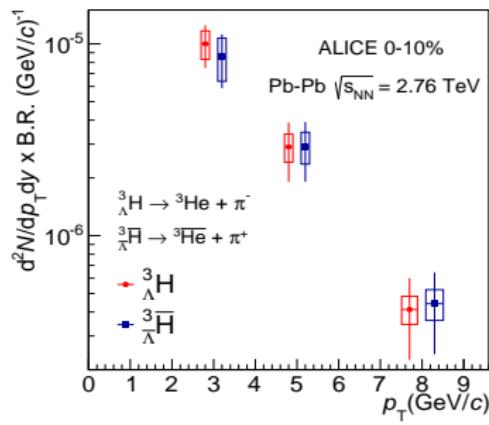
# Antideuterium - $X(3872)$

A.L. Guerrieri, F.P., A. Pilloni, A.D. Polosa, PRD90 (2014) 3, 034003

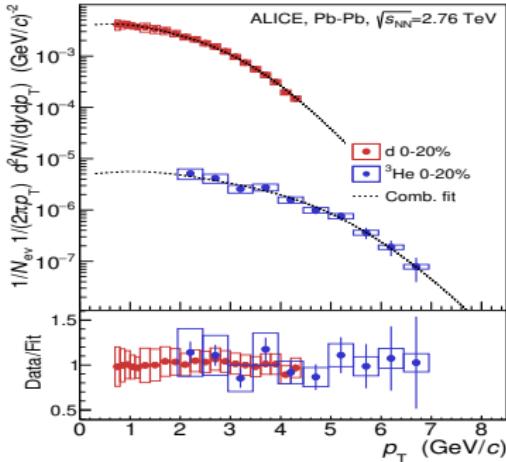
- deuterium is the known hadronic molecule, would be analog of  $X(3872)$
- antideuterium production is measured at ALICE (in particular  $pp$ )
- we could study the relation indicated by data between antideuterium and  $X(3872)$  production
- unfortunately, up to now, they are measured in two completely different  $p_{\perp}$  regimes. We can only have a qualitative idea through MC, referring to the coalescence model



# Alice measured $^3\text{He}$ and $^3\Lambda$ He in Pb-Pb@2.76 TeV



ALICE, arXiv:1506.08453



ALICE, arXiv:1506.08951

- can we use this information to give an estimate of the cross section in  $p p$  collisions?
- ... yes, under certain hypothesis       $\implies$

# $^3\text{He}$ and ${}_{\Lambda}^3\text{He}$ from Pb-Pb to p-p collisions

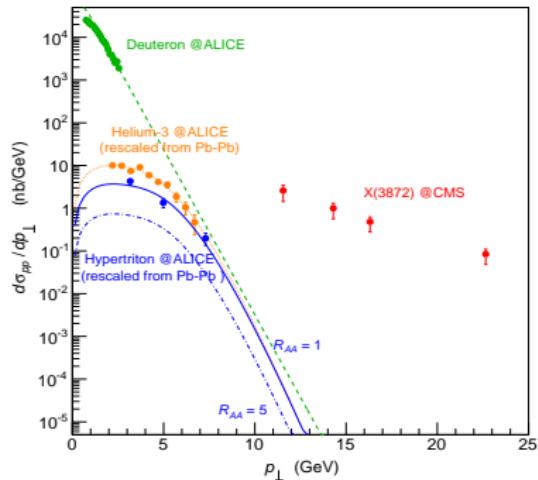
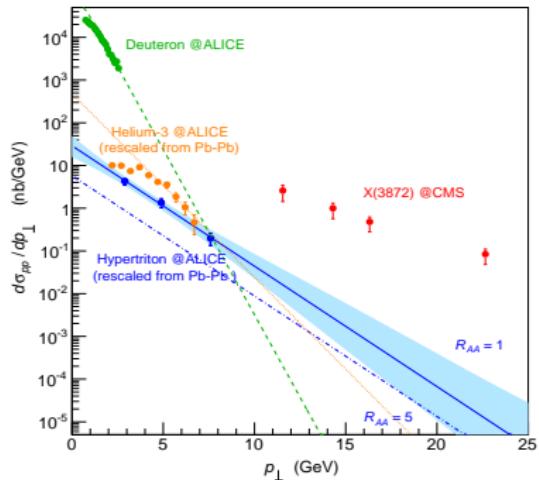
A. Esposito, A. Guerrieri, L. Maiani, F.P., A. Pilloni, A.D. Polosa, V. Riquer, arXiv:1508.00295

## Approximations

- no medium effects on the production of light nuclei, *i.e.* each Pb-Pb collision is an independent product of  $N_{\text{coll}}$  collisions  
( $N_{\text{coll}}$  function of the centrality class through a Glauber MC calculation)
- data @2.76 TeV can be rescaled to  $\sqrt{s} = 7\text{TeV}$  through the ratio of total inelastic  $pp$  cross sections
- no coalescence/recombination effects in Pb-Pb collisions, which usually favor the production of many-body hadrons in medium w.r.t. vacuum

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

# $^3\text{He}$ and $^3\Lambda\text{He}$ from Pb-Pb to p-p collisions



- neglecting possible medium effects, the production cross sections for  $^3\text{H}$  and  $^3\text{He}$  at  $pp$  collisions are several order of magnitudes smaller than the  $X(3872)$  production cross section
- medium effects are expected to further decrease the cross section
- a conclusive statement should come from direct measurements at  $pp$  collisions

# A check with future precision measurements

- by considering the scattering amplitude  $f(DD^* \rightarrow DD^*)$ , assuming it proceeds through a pole  $f(DD^* \rightarrow X \rightarrow DD^*)$  in the soft limit,

$$f \sim \frac{g^2}{\varepsilon + T}$$

- in NRQM the amplitude for the scattering of two slow particles interacting through an attractive potential with superficial discrete level  $-\varepsilon$  has the universal form

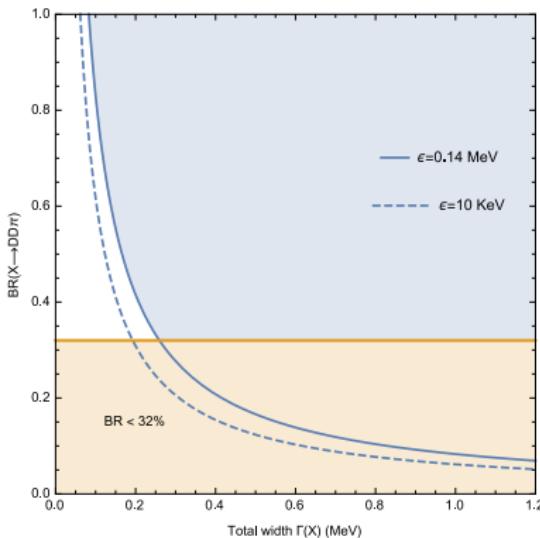
$$f \sim \frac{\sqrt{\varepsilon} - i\sqrt{T}}{\varepsilon + T}$$

⇒

$$\varepsilon = \frac{g^4}{512\pi^2} \frac{\mu^5}{M_D^4 M_{D^*}^4}$$

with  $g$  the coupling  $XDD^*$

A. Polosa arXiv:1505.03083[hep-ph]



future measurements of  $\Delta M$ ,  $\Gamma_X$ ,  $\mathcal{BR}(X \rightarrow DD^*)$  at LHC and BELLEII, crucial to test the molecular hypothesis

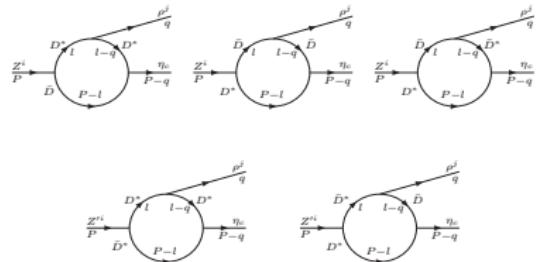
# $Z_c^{(\prime)} \rightarrow \eta_c \rho$ : a channel able to discriminate between molecule and tetraquark

A. Esposito, A. Guerrieri and A. Pilloni, arXiv:1409.3551[hep-ph]

- according to tetraquark models

	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z_c \rightarrow J/\psi \pi)}$	554	1/1.48	387	1/2.12
$\frac{\mathcal{BR}(Z'_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z'_c \rightarrow h_c \pi)}$	199	199	4.05	4.05

- according to molecular model



$$\frac{\mathcal{BR}(Z_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z_c \rightarrow J/\psi \pi)} \simeq 0.053$$

$$\frac{\mathcal{BR}(Z'_c \rightarrow \eta_c \rho)}{\mathcal{BR}(Z'_c \rightarrow h_c \pi)} \simeq 0.012.$$

# To be improved: threshold distances for charged $Z$

- $Z_b^+(10610) \rightarrow \Upsilon(nS)\pi^+$  ( $n = 1, 2, 3$ )
  - $M_Z = 10607.2 \pm 2.0$  MeV,  $\Gamma_Z = 18.4 \pm 2.4$  MeV
  - $M_B + M_{B^*} = 10604.46 \pm 0.43$  MeV  $\Delta M \sim 3 \pm 2$  MeV
- $Z_b^+(10650) \rightarrow h_B(nP)\pi^+$  ( $n = 1, 2$ )
  - $M_Z = 10652.2 \pm 1.5$  MeV,  $\Gamma_Z = 11.5 \pm 2.2$  MeV
  - $M_{B^*} + M_{B^{*+}} = 10650.4 \pm 0.6$  MeV  $\Delta M \sim 2 \pm 2$  MeV
- $Z_c(3900) \rightarrow J/\psi\pi^+$ 
  - $M_Z = 3899.0 \pm 6.1$  (MeV),  $\Gamma_Z = 46 \pm 22$  MeV (in  $J/\psi\pi^\pm$ );  
 $M_Z = 3883.9 \pm 4.5$  (MeV),  $\Gamma_Z = 24.8 \pm 12$  MeV (in  $D\bar{D}^*$ )
  - $M_{D^0} + M_{D^{*+}} = 3875.15 \pm 0.18$  MeV;  
 $M_{D^\pm} + M_{D^{*0}} = 3876.61 \pm 0.21$  MeV  $\Delta M \sim 24/8 \pm 5$  MeV
- $Z'_c(4020) \rightarrow h_c(1P)\pi^+$ 
  - $M_Z(h_c\pi) = 4022.9 \pm 1.8$  MeV,  $\Gamma_Z = 7.9 \pm 3.8$  MeV;  
 $M_{D^{*+}} + M_{D^{*0}} = 4017.28 \pm 0.20$   $\Delta M \sim 6 \pm 2$  MeV
- $Z'_c(4025) \rightarrow D^*\bar{D}^*$ 
  - $M_Z(D^*\bar{D}^*) = 4026.3 \pm 4.5$  MeV,  $\Gamma_Z = 24.5 \pm 9.5$  MeV

$\Delta M_Z > 0$  (even if higher experimental precision needed)

# Ab initio approach with LQCD

- What we name as exotic is actually contained within the QCD Lagrangian
- In principle, every bound structure should come out from a first principle calculation, as in LQCD
- recently first attempts to investigate tetraquarks with heavy quarks on the lattice.

see e.g. S. Prelovsek at CHARM2015 arXiv:1508.07322

A. Guerrieri, M. Papinutto, A. Pilloni, A.D. Polosa, N. Tantalo, arXiv:1411.2247

- not yet firm conclusions because of several difficulties, e.g.
  - difficult the separation of the diquark-antidiquark contribution from the meson-meson one
  - lattices with dimensions of few fm's not suited for the simulation of extended objects such as the  $X(3872)$
  - extrapolation from few hundreds MeV to the physical point can be critical
- Work in progress by several groups