Charmonium and exotics on the continuum

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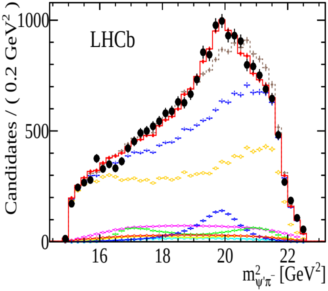
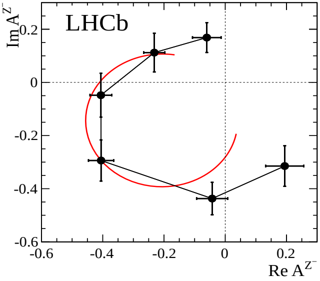
based on work with
A. Esposito, A. Guerrieri, L. Maiani,
A. Pilloni, A.D. Polosa and V. Riquer

Disclaimer: not intended to be an exhaustive review

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

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





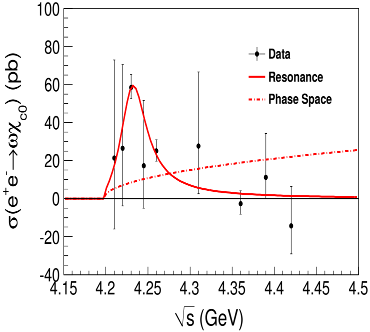
- valence structure $c\bar{c}u\bar{d}$ required $\Longrightarrow$ true tetraquark
- $\frac{\pi}{2}$ phase shift with energy crossing the mass $\Longrightarrow$ true resonance

and something also in the neutral sector

BESIII:

$e^+e^- \to \chi_{c0}\omega$

(and not χ_{c1}, χ_{c2})

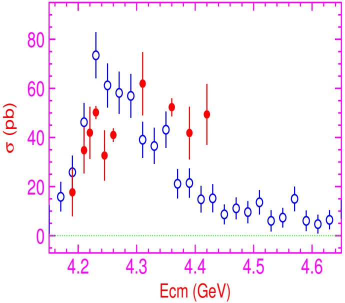


M. Ablikim et al., Phys. Rev. Lett. 114 (2015) 9, 092003

$$M = 4230 \pm 10\,\mathrm{MeV}$$
$$\Gamma = 38 \pm 12 MeV$$

BESIII/BELLE:

$e^+e^- \to h_c\pi^+\pi^-$



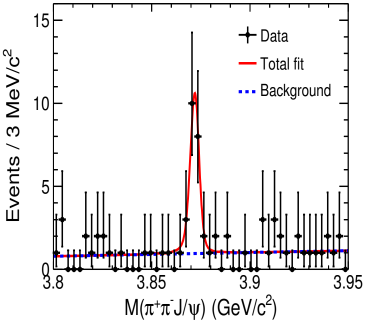
C.-Z. Yuan, Chin. Phys. C38 (2014) 043001

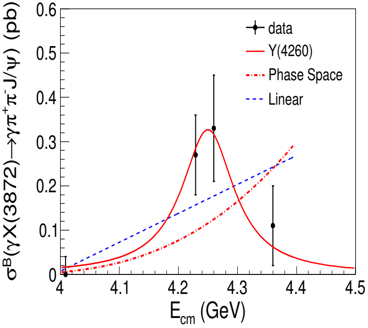
$$M_1 = 4216 \pm 18\,\mathrm{MeV}$$
$$\Gamma_2 = 39 \pm 22\mathrm{MeV}$$
$$M_2 = 4293 \pm 9\,\mathrm{MeV}$$
$$\Gamma_2 = 222 \pm 67\mathrm{MeV}$$

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

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

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





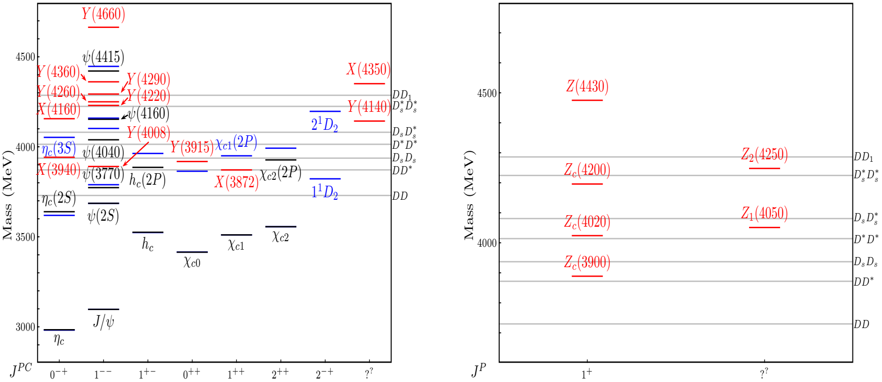
With $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = 5\%$

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

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

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

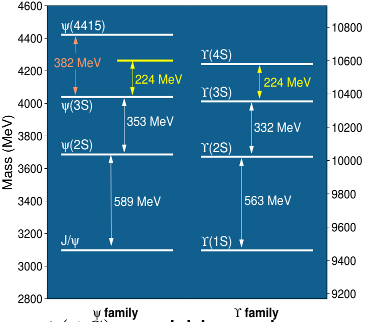
A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, IJMPA30 (2014) 04n05, 1530002



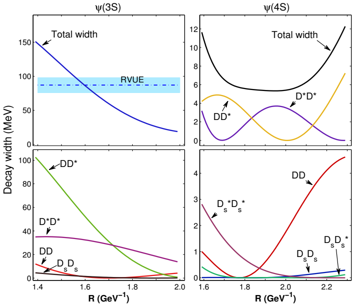
- All $c\bar{c}$ states below open c threshold identified
- All $J^{PC} = 1^{--}$ $c\bar{c}$ states filled
- New neutral and charged particles above threshold
- Some may be charmonia, others not (exotica, X, Y, Z), in particular the charged ones (the neutral ones have quantum numbers compatible with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

Recent development on charmonium

L.-P. He, D.-Y. Chen, X. Liu, T. Matsuki, EPJC 74 (2014) 12, 3208



- looking at the spacings in the b sector
- $M(\psi(4S)) \sim 4263$ MeV
- the width to open charm results to be small (even if model-dependent)



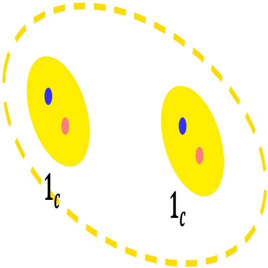
- $\psi(4S)$ could have been missed because too narrow for open charm searches and R energy scans
- $\psi(4415)$ could be $\psi(5S)$ (but too small calculated width)

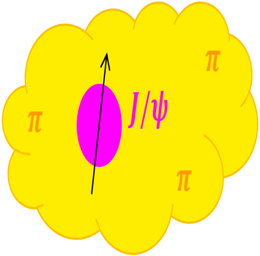
Recent development on charmonium (II)

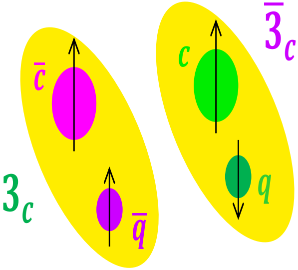
L.-P. He, D.-Y. Chen, X. Liu, T. Matsuki, arXiv:1411.5136[hep-ex]

- the authors propose that the cross section enhancement in $e^+e^- \to \omega\chi_{c0}$ is due to the $\psi(4S)$
- they propose to look also for the decay $\psi(4S) \to J/\psi\eta$
- following the same reasoning on the level spacings between $\eta_c(1S)$-$\eta_c(2S)$, very similar to $\psi(1S)$-$\psi(2S)$, they conclude that $X(3940)$ could be identified with $\eta_c(3S)$

main th. phenomenological models for exorica







overall picture still not clear

two extremes: molecules vs. tetraquarks

- 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
- new data still required to clarify the picture

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

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

LHCb 2014

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

Tomaradze et al. 2015

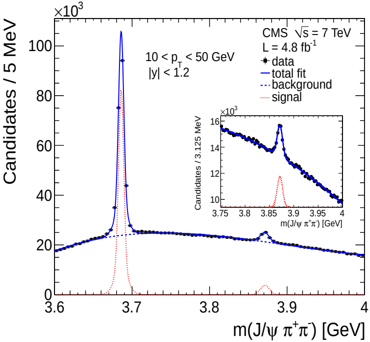
- production
  - production through B decays at e^+e^- and $p\bar{p}/pp$ colliders
- decay
  - $J/\psi\rho \to J/\psi\pi^+\pi^-$
  - $J/\psi\omega \to J/\psi\pi^+\pi^-\pi^0$
  - $D^0\bar{D}^{0*} \to D^0\bar{D}^0\pi^0$
  - $D^0\bar{D}^{0*} \to \bar{D}^0\gamma$
  - $J/\psi\gamma$, $\psi'\gamma$

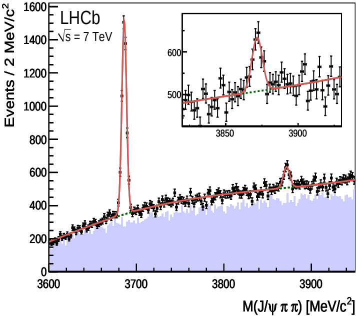
(large isospin violation)

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

- $\Delta M \lesssim 0 \Longrightarrow$ molecular interpretation natural
- isospin violation explained with the distance of D^+D^{*-} and $D^0\bar{D}^{0*}$ thresholds of ~ 8 MeV
- $R = \frac{1}{\sqrt{2\mu(-\Delta M)}} \Longrightarrow R \geq 10$ fm

$X(3872)$ at LHC





- 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

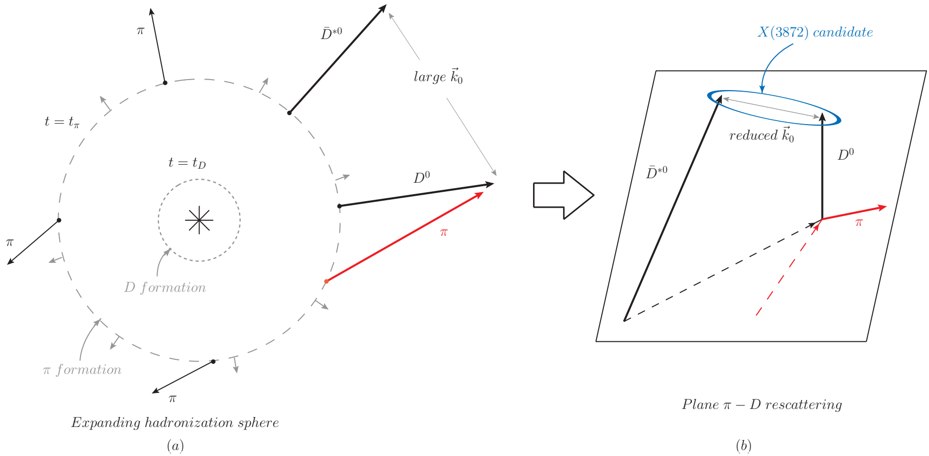
$$\begin{aligned}\sigma(p\bar{p} \to X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to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

- $\mathbf{k}$ 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 ~ 400 MeV
- this could be made possible by FSI Artoisenet and Braaten, PRD81 (2010) 114018
- actually the large hadronic activity (mainly π) close to D and D^* could prevent the effectiveness of FSI (Bignamini et al., PLB684 (2010) 228)
- but the same π could give an alternative contribution

Possible mechanism alternative to FSI

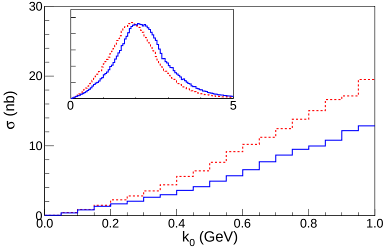
A. Esposito, F.P., A. Pilloni and A.D. Polosa, J.Mod.Phys. 4 (2013) 1569

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



results

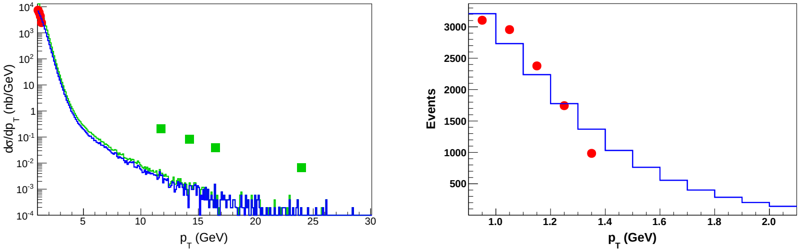
- additional pions close to $D^{0(*)}$ in momentum space can interact elastically and change the rel. momentum between D^0 and D^{0*}
- given the initial asymmetric distribution in $k_{\rm rel}$ there could be a feed-down process from larger relative momenta to lower ones and bring D pairs from positive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



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

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
- 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



A check with future precision measurements

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

A. Polosa arXiv:1505.03083[hep-ph]

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

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

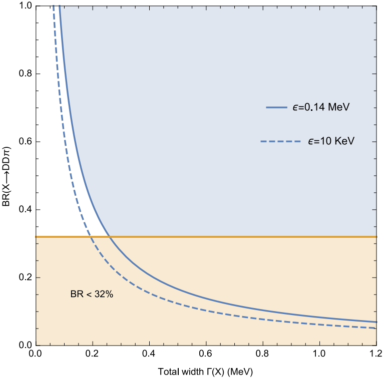
- in NRQM the amplitude for the scattering of two slow particles interacting through an attractive potential with superficial discrete level $-\mathcal{E}$ has the universal form

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

$\Longrightarrow$

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

with g the coupling XDD^*



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

Evolution of the tetraquark model

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

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

$$\mathcal{B}(B^+ \to K^+ X) \times \mathcal{B}(X \to \rho^0 J/\psi)$$
$$= (8.4 \pm 1.5 \pm 0.7) \times 10^{-6} \quad \text{(BaBaR)}$$
$$= (8.6 \pm 0.8 \pm 0.5) \times 10^{-6} \quad \text{(Belle)}$$
$$\mathcal{B}(\bar{B}^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 5.4 \times 10^{-6} \quad \text{(BaBar)},$$
$$< 4.2 \times 10^{-6} \quad \text{(Belle)},$$
$$\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 22 \times 10^{-6} \quad \text{(BaBar)}$$
$$< 6.1 \times 10^{-6} \quad \text{(Belle)}$$

- after discovering several new charged states, there is now renewed interest in the tetraquark model see the talk of R. Lebed
- 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 $\sim \frac{1}{\sqrt{N}}$

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

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

From conventional S-wave mesons and baryons

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

- 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

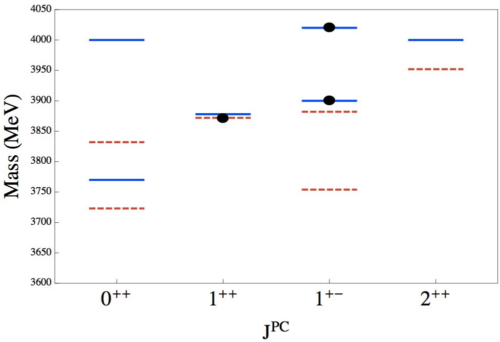
$$H \approx 2\kappa_{qc}\ (\boldsymbol{S}_q \cdot \boldsymbol{S}_c + \boldsymbol{S}_{\bar{q}} \cdot \boldsymbol{S}_{\bar{c}})$$

J^{PC}	$cq\ \bar{c}\bar{q}$	$c\bar{c}\ q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\|0,0\rangle$	$1/2\|0,0\rangle + \sqrt{3}/2\|1,1\rangle_0$	$X_0(\sim 3770\ \mathrm{MeV})$	$\eta_c,\ J/\psi$ + light mesons
0^{++}	$\|1,1\rangle_0$	$\sqrt{3}/2\|0,0\rangle - 1/2\|1,1\rangle_0$	$X_0'(\sim 4000\ \mathrm{MeV})$	$\eta_c,\ J/\psi$ + 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^{++}	$\|1,1\rangle_2$	$\|1,1\rangle_2$	$X_2(\sim 4000\ \mathrm{MeV})$	J/ψ + light mesons

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

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

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



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

Y states: tetraquarks with $L = 1$

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

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 $\Longrightarrow$ the observed radiative decay $Y(4260) \to \gamma X(3872)$ is an $E1$ transition ($\Delta L = 1$ and $\Delta S = 0$) as in radiative decays of χ states

some predictions on radiative decays

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

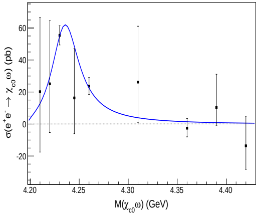
$$Y_4 = Y(4630) \to \gamma + X_2 \;\; (J^{PC} = 2^{++}) = \gamma + X(3940),\;\; ??$$
$$Y_3 = Y(4290/4220) \to \gamma + X_0' \;\; (J^{PC} = 0^{++}) = \gamma + X(3916),\;\; ??$$
$$Y_2 = Y(4260) \to \gamma + X_1 \;\; (J^{PC} = 1^{++}) = \gamma + X(3872),\;\; \text{seen}$$
$$Y_1 = Y(4008) \to \gamma + X_0 \;\; (J^{PC} = 0^{++}) = \gamma + X(3770\;??),\;\; ??$$

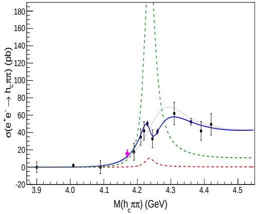
- important to select channels able to distinguish between models

see talk by A. Esposito

$Y(4220)$ phenomenology in the tetraquark model

R. Faccini, G. Filaci, A.L. Guerrieri, A. Pilloni, A.D. Polosa, arXiv:1412.7196





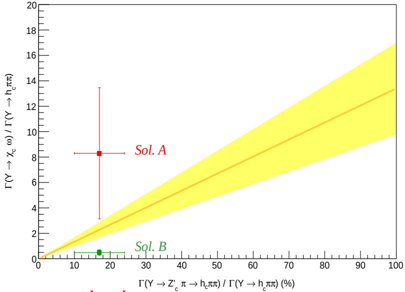
$$|Y(4220)\rangle = \frac{\sqrt{3}}{2}|0,0\rangle - \frac{1}{2}|1,1\rangle$$

$$|Z_c'\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$$

with

$$|h_c\rangle = |s_{c\bar{c}}\rangle{=}0$$

$$|\chi_{cJ}\rangle = |s_{c\bar{c}} = 1\rangle$$



more data needed

Ab initio approach with LQCD

- recently first attempts to investigate tetraquarks with heavy quarks on the lattice
- not yet firm conclusions because of several difficulties, e.g.
  - very 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

see the following talk by S. Prelovsek for un update