Exotic Mesons, XYZ, as tetraquarks

DESY&Zeuthen, June 30-July1, 2015

Luciano Maiani, Universita' di Roma La Sapienza, and INFN, Roma, Italia

1. Introduction

Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc.

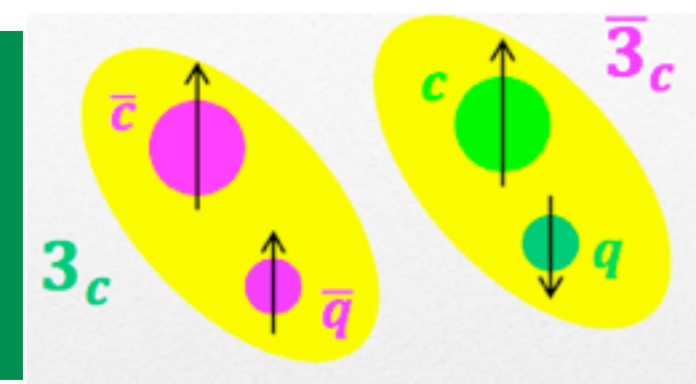
M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964

- For long, we lived with the simplest paradigm:

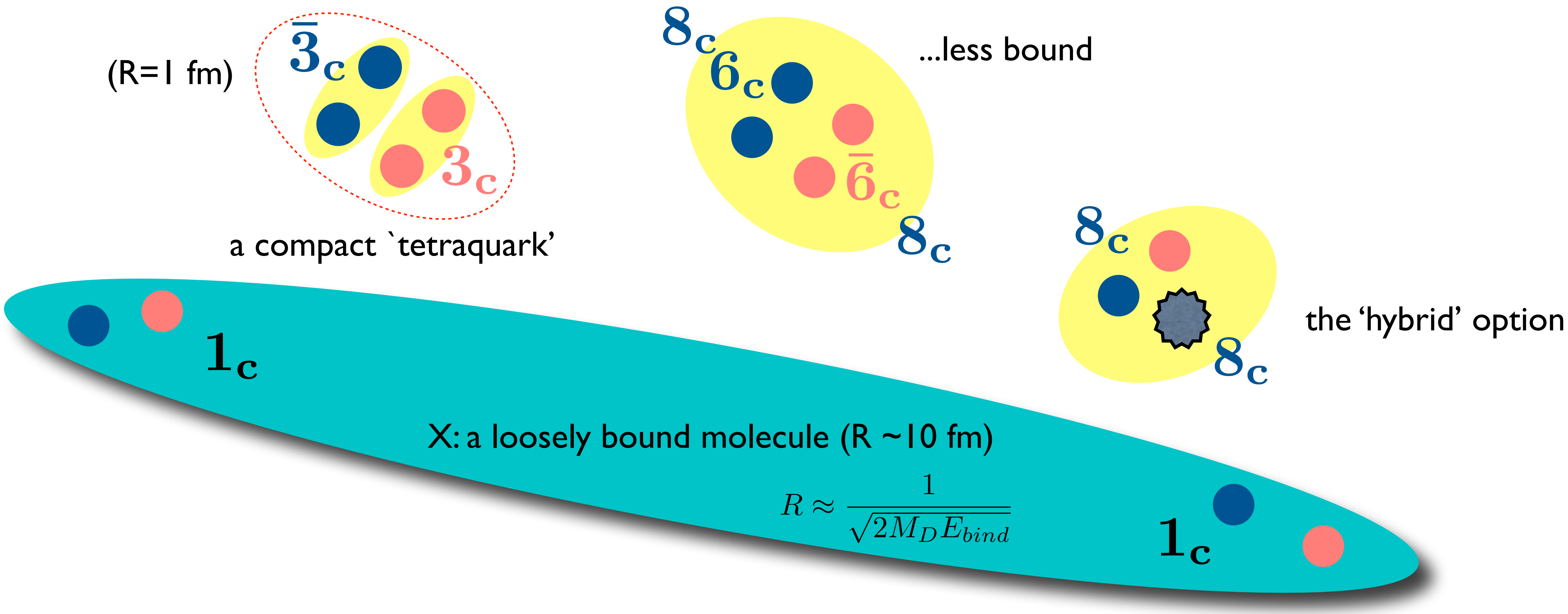
$$\text{mesons} = q\bar{q}, \quad \text{baryons} = qqq$$

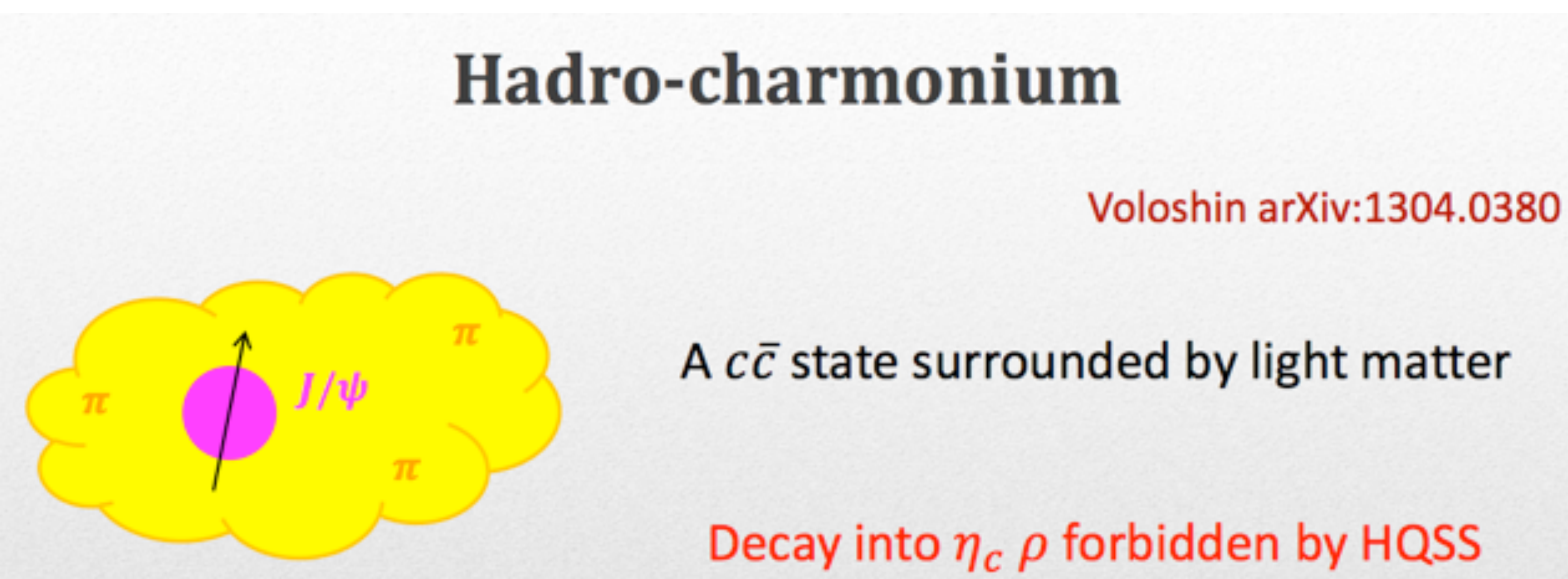
- Paradigm rested on the absence of I=2, ππ resonances and of S>0 baryons.
- The case had to be revisited, because the lowest lying, octet of scalar mesons- $f_0(980)$, $a_0(980)$, kappa(800) and sigma(600)- does not fit in the picture.
- The X(3872), narrow width, with decays into J/Psi+ 2π/3π, discovered by Belle in 2003, does not fit into the "charmonium" states,
- since then, Belle, BaBar, BES and LHcB have reported many other states that do not fit the charmonium picture, called X (1^{++}) and $Y(1^{--})$ states: molecules? hybrids? tetraquarks?
- In 2007, Belle observed a charged "charmonium", $Z^+(4430) \to \psi(2S)+\pi$, that could not be interpreted as molecule, but later Babar suggested it was simply a reflection of K* states
- LHCb has confirmed the $Z^+(4430)$ while other similar states, $Z^+(3900)$ and $Z^+(4020)$, have been established.

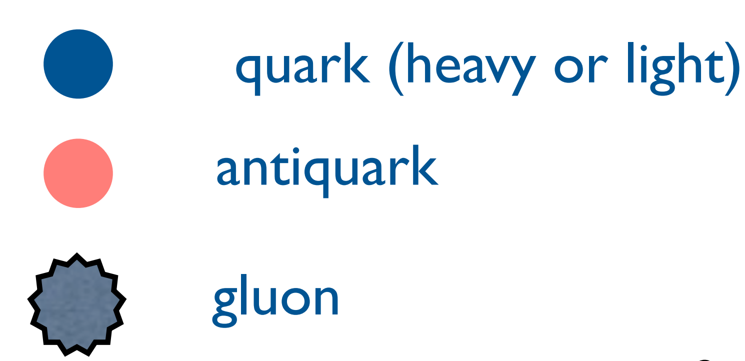
I shall follow the idea that X, Y, and Z states belong to a new spectroscopy of mesons, made by diquark-antidiquark pairs. For Beauty see also A. Ali, Belle II TIP, Krakov (slides available).



Models for X Y Z mesons





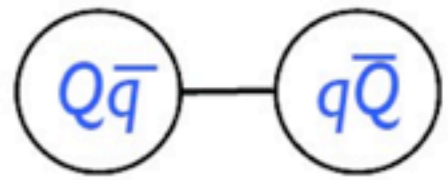


Models for XYZ Mesons

Quarkonium Tetraquarks

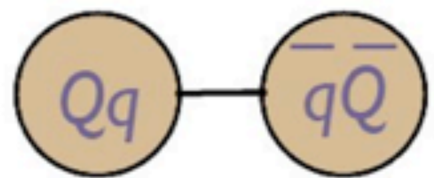
- compact tetraquark

- meson molecule



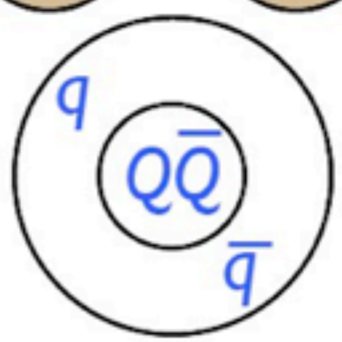
M.Cleven, F.K.Guo, C.Hanhart, Q.Wang and Q.Zhao, arXiv:1505.01771 and refs. therein

- diquark-onium



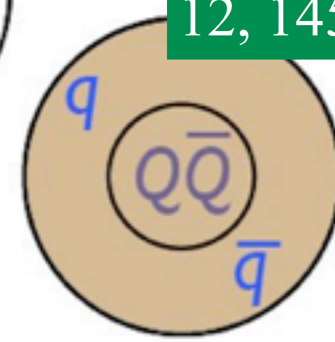
A. Ali, L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. D **91** (2015) 1, 017502 and refs. therein

- hadro-quarkonium



X.Li, M.B.Voloshin, Mod. Phys. Lett. **29**(2014) 12, 1450060 and refs. therein

- quarkonium adjoint meson



Ahmed Ali (DESY, Hamburg)

Few think X, Y, Z are only kinematic effects due to the opening of new channels. For one, see: E. S. Swanson, Cusps and Exotic Charmonia, arXiv:1504.07952 [hep-ph]
I think it takes a lot of unconventional dynamics to produce the X(3872) as a “cusp”
Also, the phase of Z(4430) seems to go at 90^0 at the peak, like a well-behaved Breit-Wigner resonance...

X(3872) production @ LHC

4 Measurement of the cross section rati

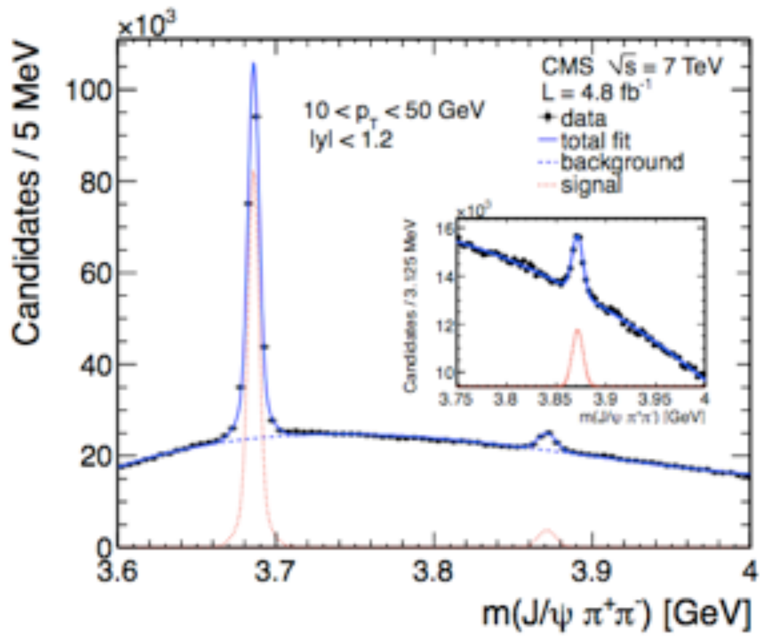
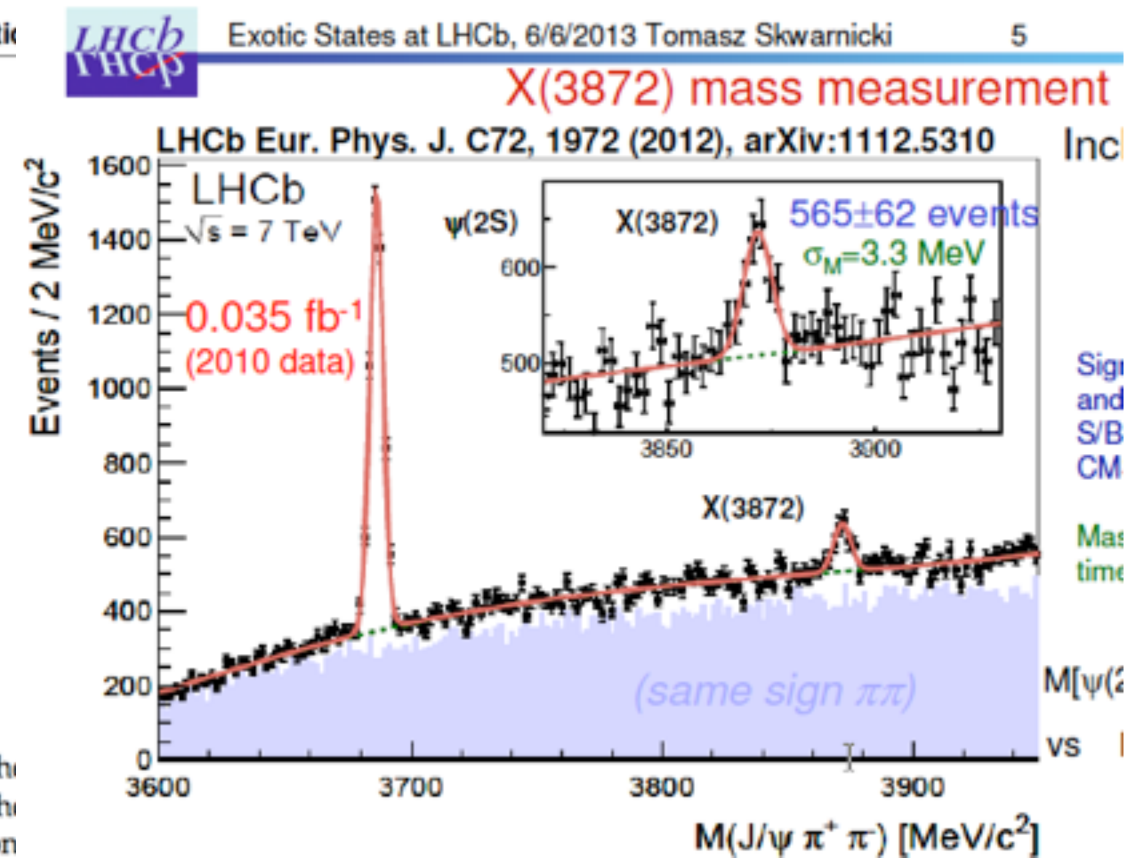
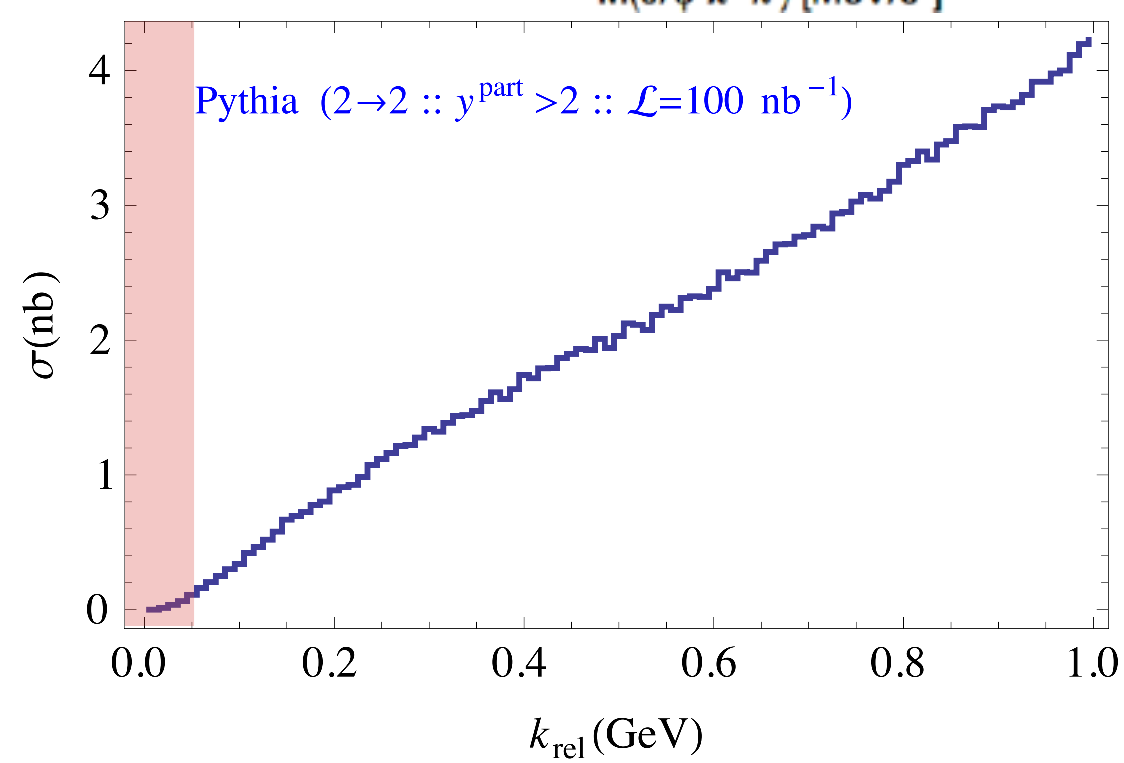


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. Th lines represent the signal-plus-background fits (solid), the background-only (dashed), and th signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region

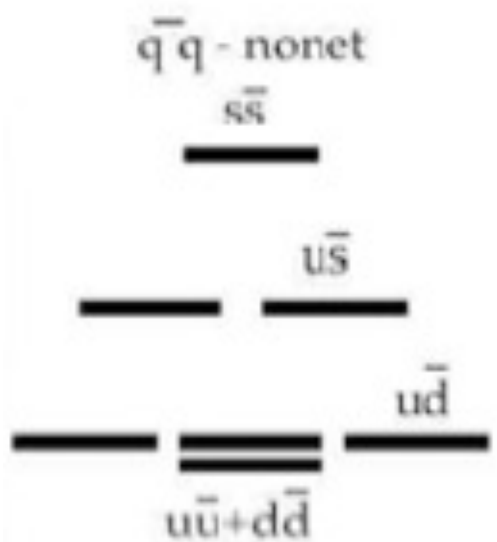


- Production at Colliders speaks against extended objects;
- using Pythia to estimate the probability to find a D-Dbar pair in the relevant phase space, factors of 10^{-2} are found with respect to the X(3872) cross section measured by CDF (~ 30 nb).

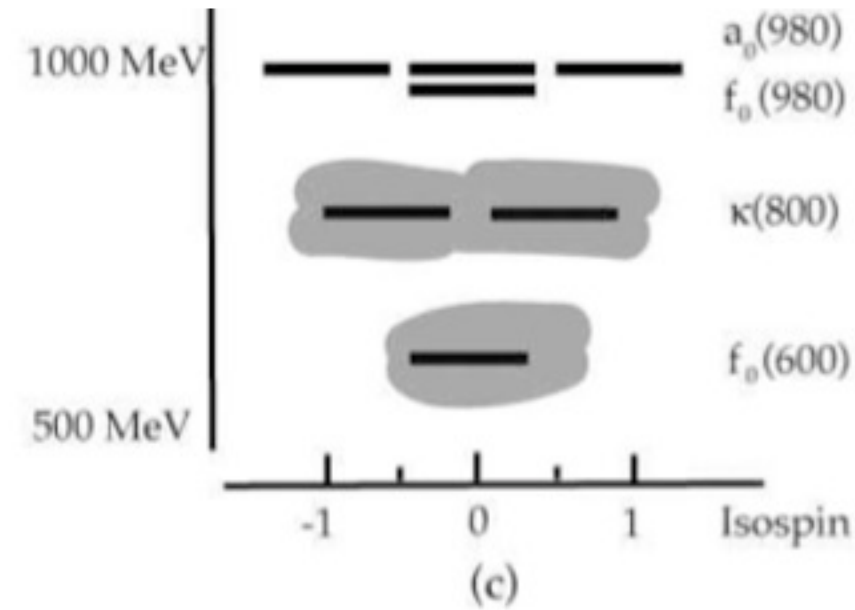


C. Bignamini, B. Grinstein, F. Piccinini, A. Polosa, C. Sabelli, *Phys Rev Lett*, ***103***, *162001 (2009)*

2.The octet of light scalar mesons and diquarks

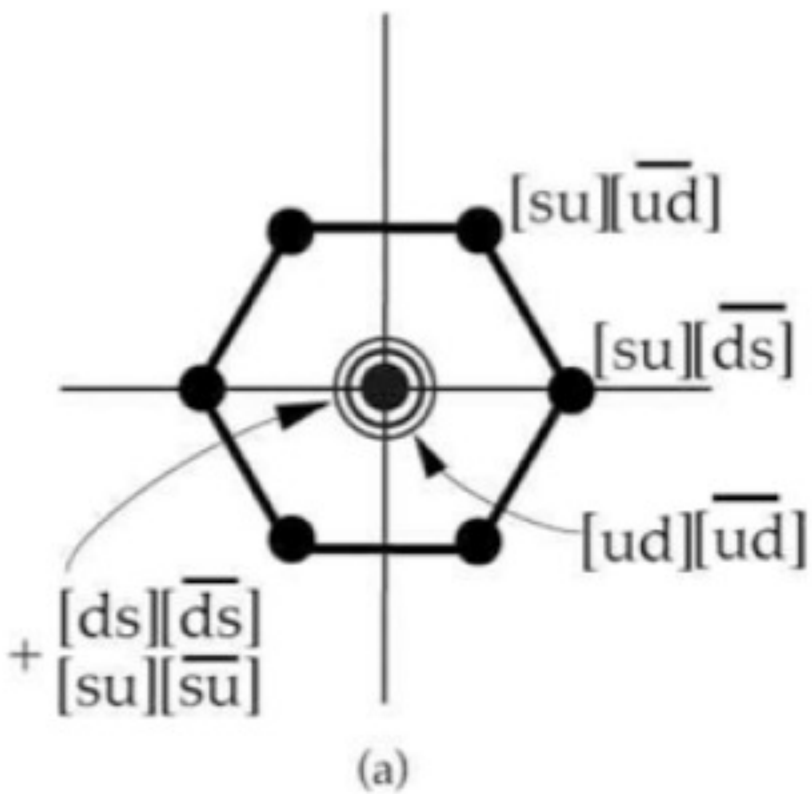


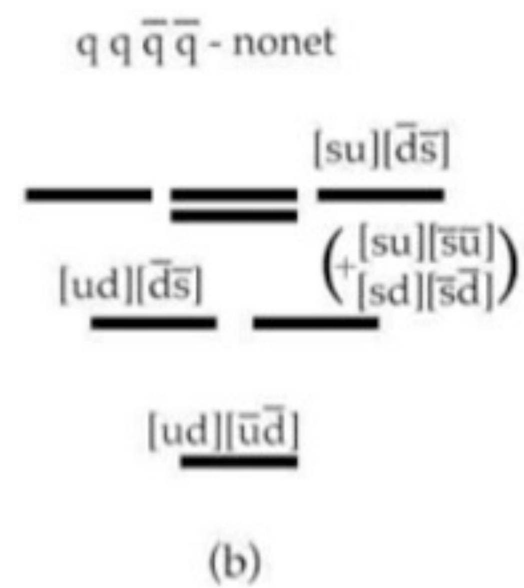
???????



$= \sigma$

Antisymmetric tetraquarks work better



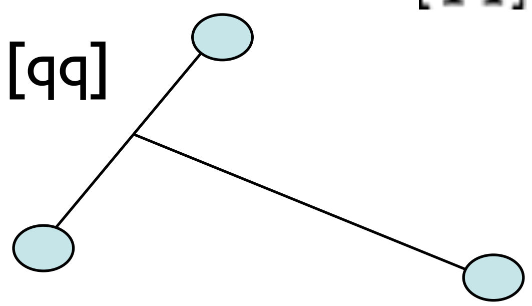


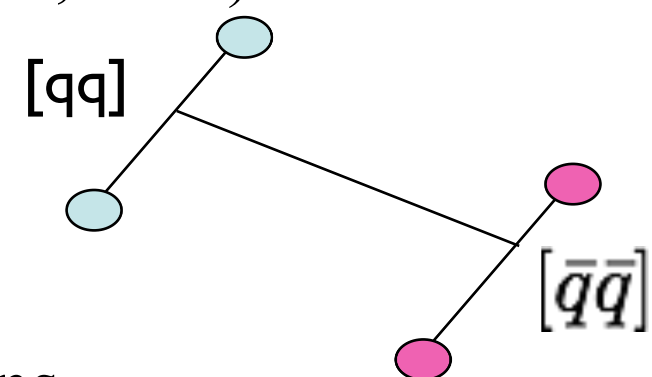
Diquarks vs molecules

QCD forces are attractive (in 1 gluon approx.) for diquark [qq’]: color = 3bar, SU(3) flavour = 3bar, spin=0, spin-spin force also attractive: *good diquark* (Jaffe, 1977)
-makes a simple unit to form color singlets (Jaffe & Wilcezck, 2003)
- [cq] may make a stable configuration even for spin 1, *bad diquark,* since spin-spin interactions, repulsive in spin 1, decrease with mass)

Diquark needs to combine with other colored objects:

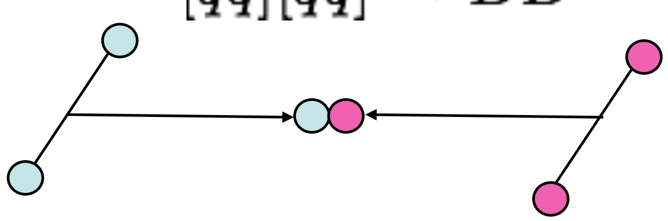
with q → baryon (e.g. Λ), Y-shape
with $[\bar{q}\bar{q}]$→ scalar meson, H-shape (Rossi &Veneziano, 1980)



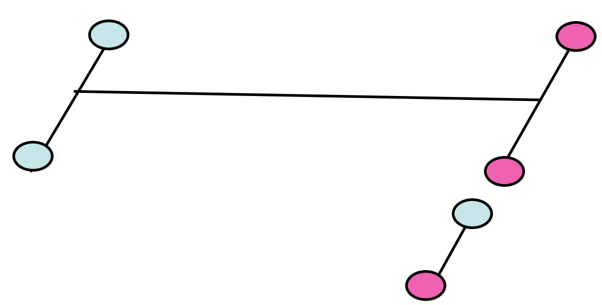


Many states: tetraquarks may have radial and orbital excitations
string topology is more related to Baryon-antiBaryon:
if you break the string,

$[qq][\bar{q}\bar{q}] \rightarrow B\bar{B}$

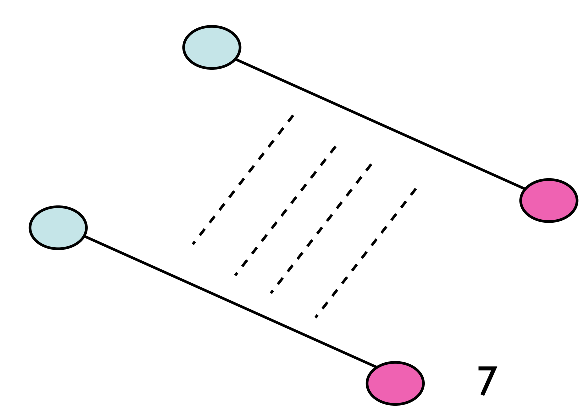


$[qq][\bar{q}\bar{q}] \rightarrow [qq][\bar{q}\bar{q}] + \text{meson}$



A. De Rujula, H. Georgi and S. L. Glashow, Phys. Rev. Lett. 38 (1977) 317.

Meson-meson molecules have a different string topology:
- are they bound?
- very few states



3. Conventional and less conventional Quarkonia

- The accuracy with which the spectra of Q Qbar states (Q=c, b) are predicted and measured makes it possible to discover new states "by difference"
- Terminology of Q-Qbar states in S and P wave:

$$\text{spin} = S,\ \text{orb. ang. mom.} = L,\ \text{tot. ang. mom.} = J:\ {}^{2S+1}L_J$$

$$\text{radial excitation} = n$$

$$\eta_c(1S) = {}^1S_0;\ J/\Psi(1S) = {}^3S_1$$

$$h_c(1P) = {}^1P_1,\ \chi_c(1P) = {}^3P_J$$

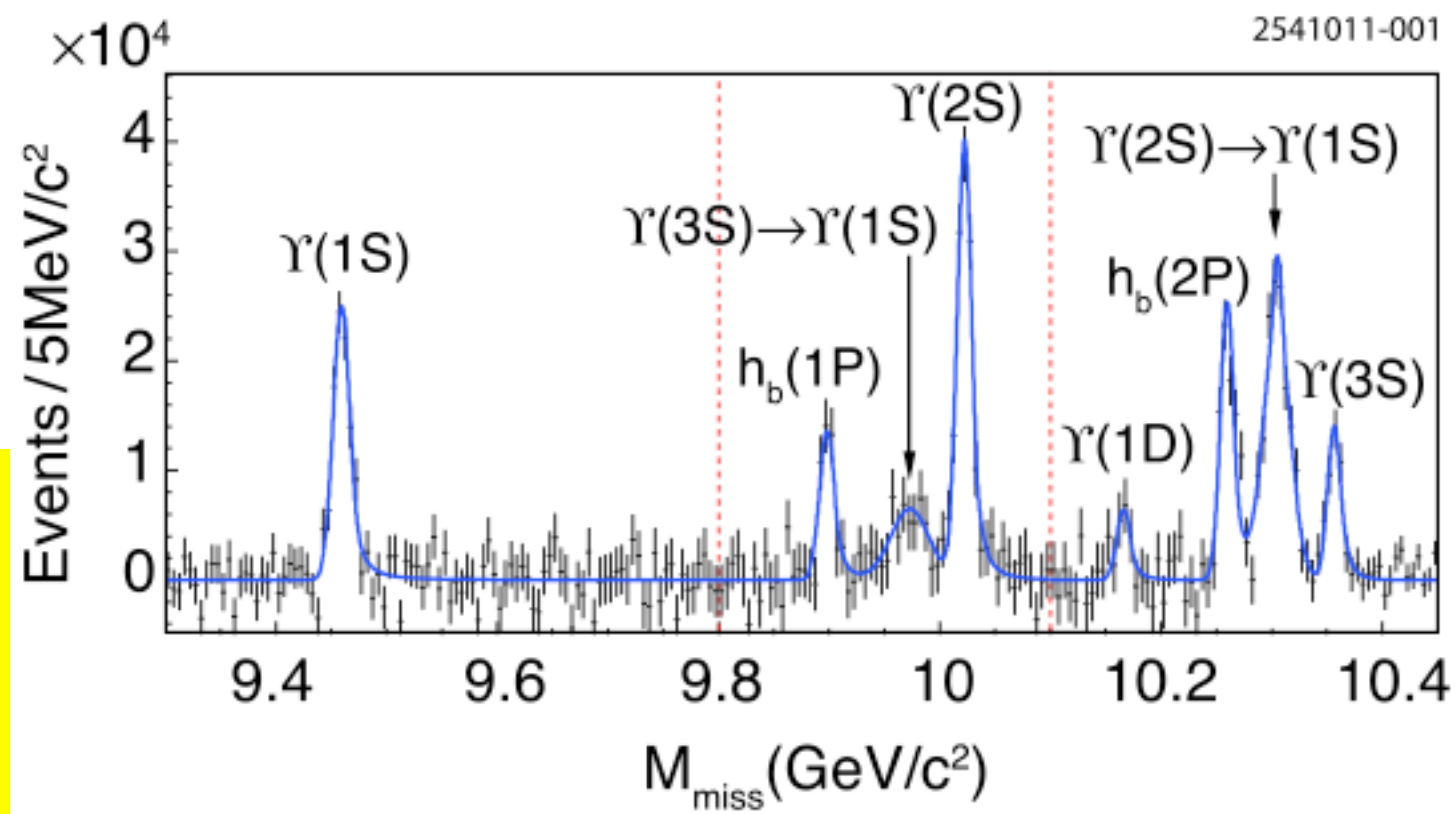
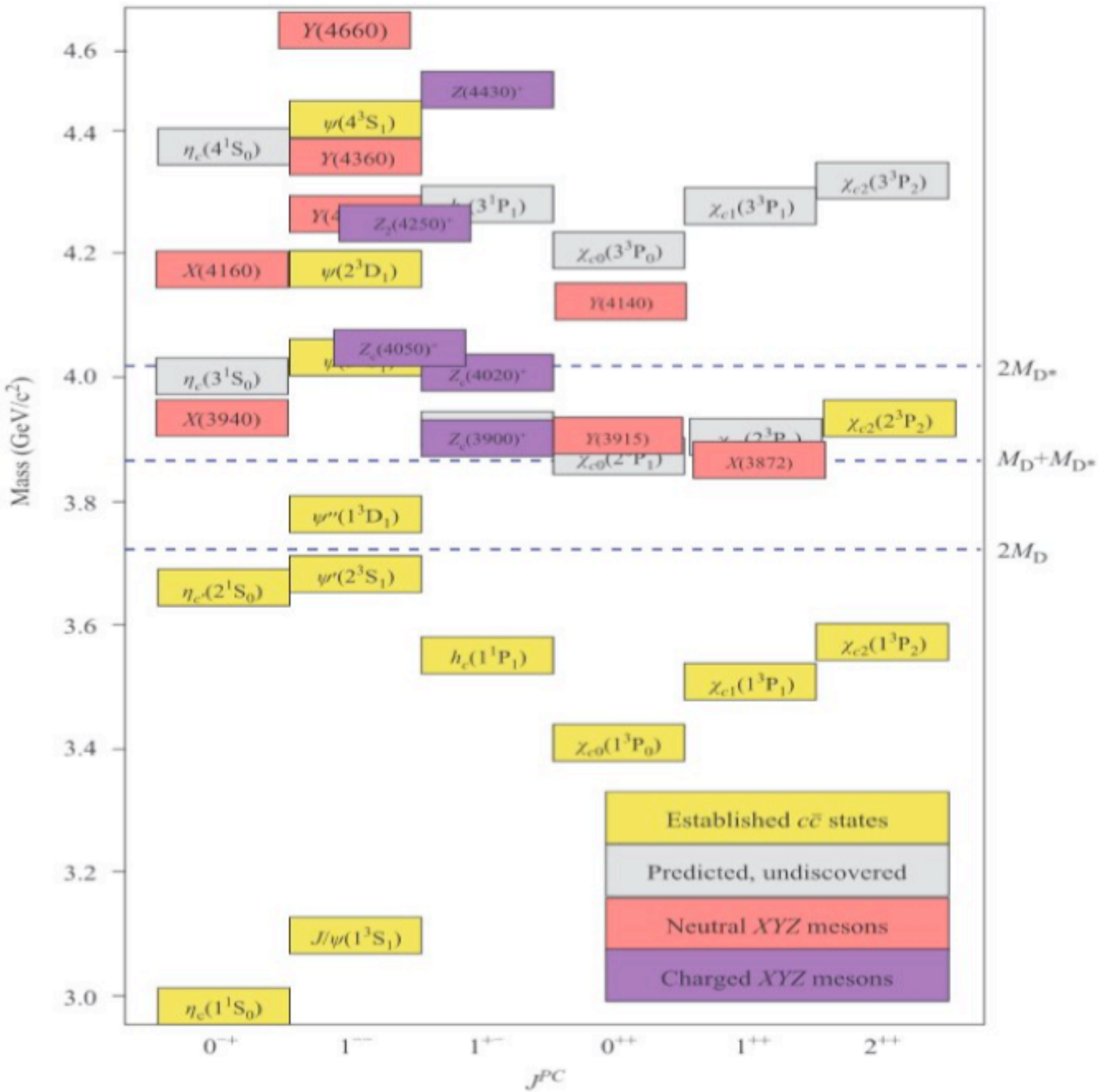


Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision

Particle Data Group:
S. Eidelman et al., DEVELOPMENTS IN HEAVY QUARKONIUM SPECTROSCOPY Updated March 2014;

Quarkonium Working Group:
N. Brambilla et al., arXiv:1404.3723v1 [hep-ph] 14 Apr 2014

Charmonia and Charmonium-like Hadrons (Olsen, arxiv:1411.7738)



terminology of unanticipated charmonia

- X, e.g. X(3872): neutral, typically seen in J/Psi+pions, positive parity, $J^{PC}=0^{++}, 1^{++}, 2^{++}$
- Y, e.g. Y(4260): neutral, seen in e^+e^- annihilation with Initial State Radiation, therefore $J^{PC}=1^{--}$
- Z, eg. Z(4430): charged/neutral, typically positive parity, mostly seen in J/Psi+pion and some in $h_c(1P)$ +pion

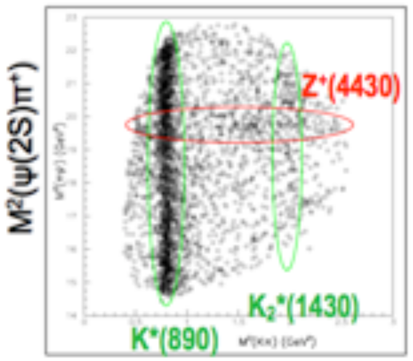
4. The $Z^{\pm}(4430)$ saga

Belle observed $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$

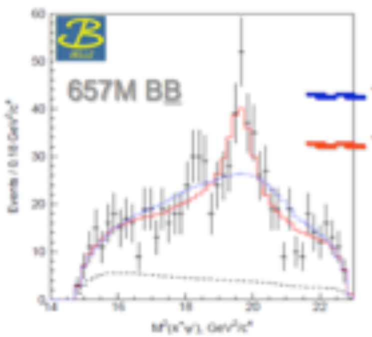
PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B \to \psi(2S)\pi^+K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B \to \psi(2S)\pi^+K$
- $B \to \psi(2S)\pi^+K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^* \to K\pi^+$ resonances only

  all known $K^* \to K\pi^+$ and $Z^+ \to \psi(2S)\pi^+$ ⇨ favored by data



$M^2(K\pi^+)$



$M^2(\psi(2S)\pi^+)$ after K^* veto

Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433\,^{+15\,+19}_{-12\,-13}\ \mathrm{MeV}$$

$$\Gamma = 107\,^{+86\,+74}_{-43\,-53}\ \mathrm{MeV}$$

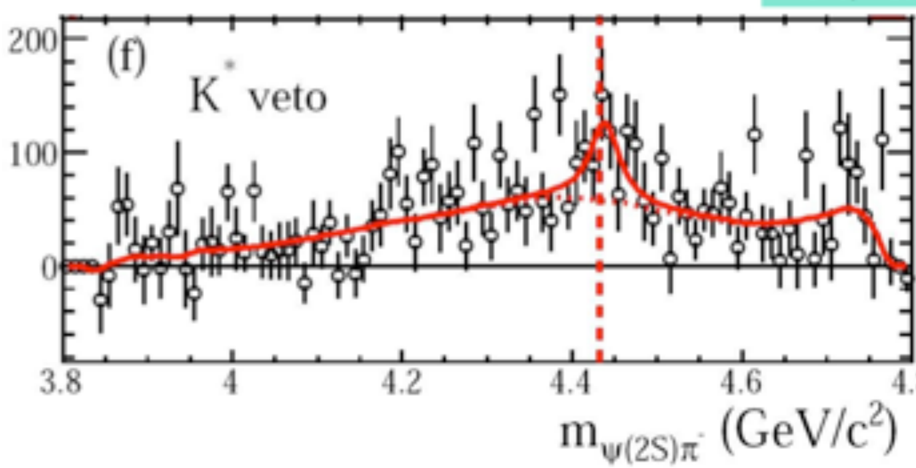
PRD80, 031104 (2009)

- [cu][cd] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\pi$

42

BaBar doesn't see a significant $Z(4430)^+$

PRD79, 112001 (2009)



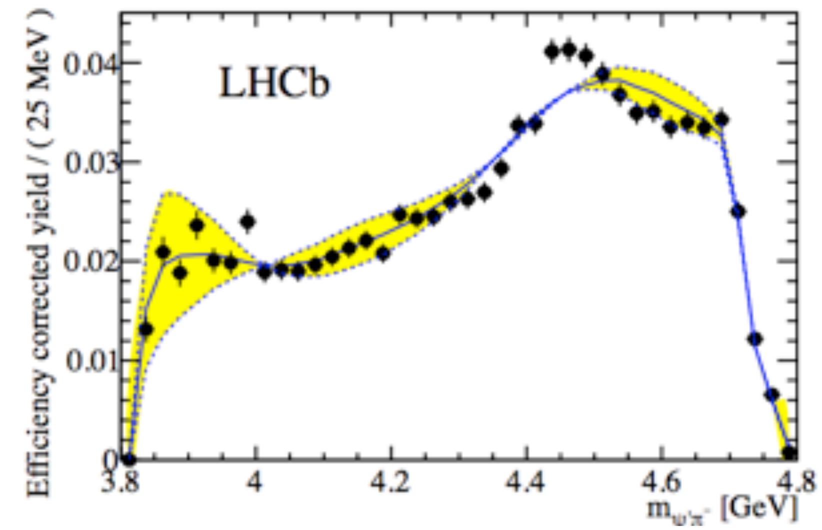
"For the fit ... equivalent to the Belle analysis...we obtain mass & width values that are consistent with theirs,... but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

$BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

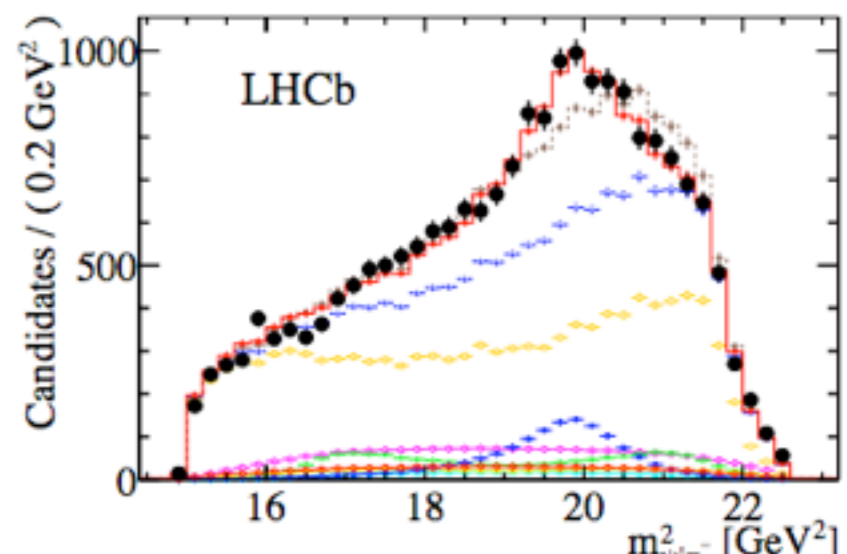
Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

44

- Babar inserts in the fit all K* resonances
- is Belle effect due to K* reflections ???



no Z



with Z

- D^*D_1= in S-Wave: may have J=1 but has negative parity
- Argand Plot shows 90^0 phase: Z is a genuine resonance

Z(4430) as a radially excited tetraquark

- There ***are*** 4 quarks in Z(4430)
- in 2007 we classified the Z(4430) as a tetraquark, the radial excitation of the S-wave companion of X(3872)
- this was because of its decay into ψ(2S)+ π and its mass ~550 MeV larger than the X
- We noted then: *A crucial consequence of a Z(4430) charged particle is that a charged state decaying into $\psi(1S)\ \pi^{\pm}$ or $\eta_c\ \rho^{\pm}$ should be found around 3880 MeV* (i.e. almost degenerate with X(3872))
- The Z_c(3900) has been seen later by BES III and Belle with the anticipated decay:
  - Z^+ (3900)$\rightarrow$ $\psi(1S)\ \pi^+$
- a neutral partner was suggested by CLEO,
- The further observation of Z(4020) by the BES III Collaboration reinforces the tetraquark picture, which looks more attractive and constrained as compared to some years ago
- The Z(4430) decay into ψ(2S) as indication of a radially excited tetraquark has been confirmed by S. Brodski *et al*. (arXiv:1406.7281 [hep-ph])

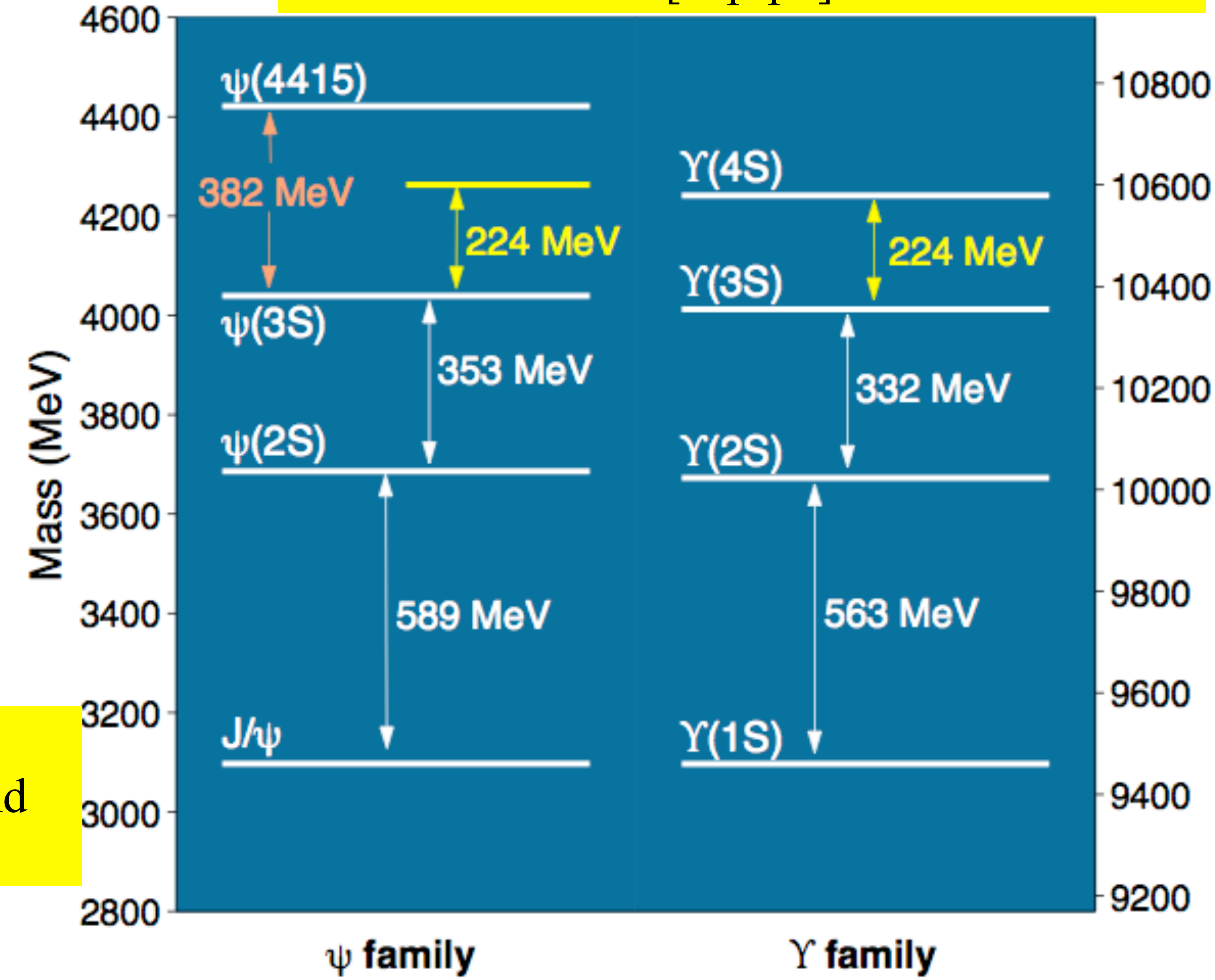
Radial excitations

L.-P. He, D.-Y. Chen, X. Liu and T. Matsuki arXiv:1405.3831 [hep-ph].

Spacing of radial excitations are the same in Charmonia and Bottomonia;

- gap between 1P-2P states is smaller :

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



Is a diquark-antidiquark pair similar to a quark-antiquark pair? a very tightly bound diquark?

5. Tetraquarks in the large N expansion

- Reputation of tetraquarks was somehow tarnished by a theorem of S. Coleman: *tetraquarks correlators for $N \to \infty$ reduce to disconnected meson-meson propagators*

S. Coleman, Aspects of Symmetry (Cambridge University Press, Cambridge, England, (1985), pp. 377–378

- The argument was reexamined by S. Weinberg who argued that if the connected tetraquark correlator develops a pole, it will be irrelevant that it is of order $1/N$ with respect to the disconnected part: *at the pole the connected part will dominate anyhow*;

S. Weinberg, PRL 110, 261601 (2013)

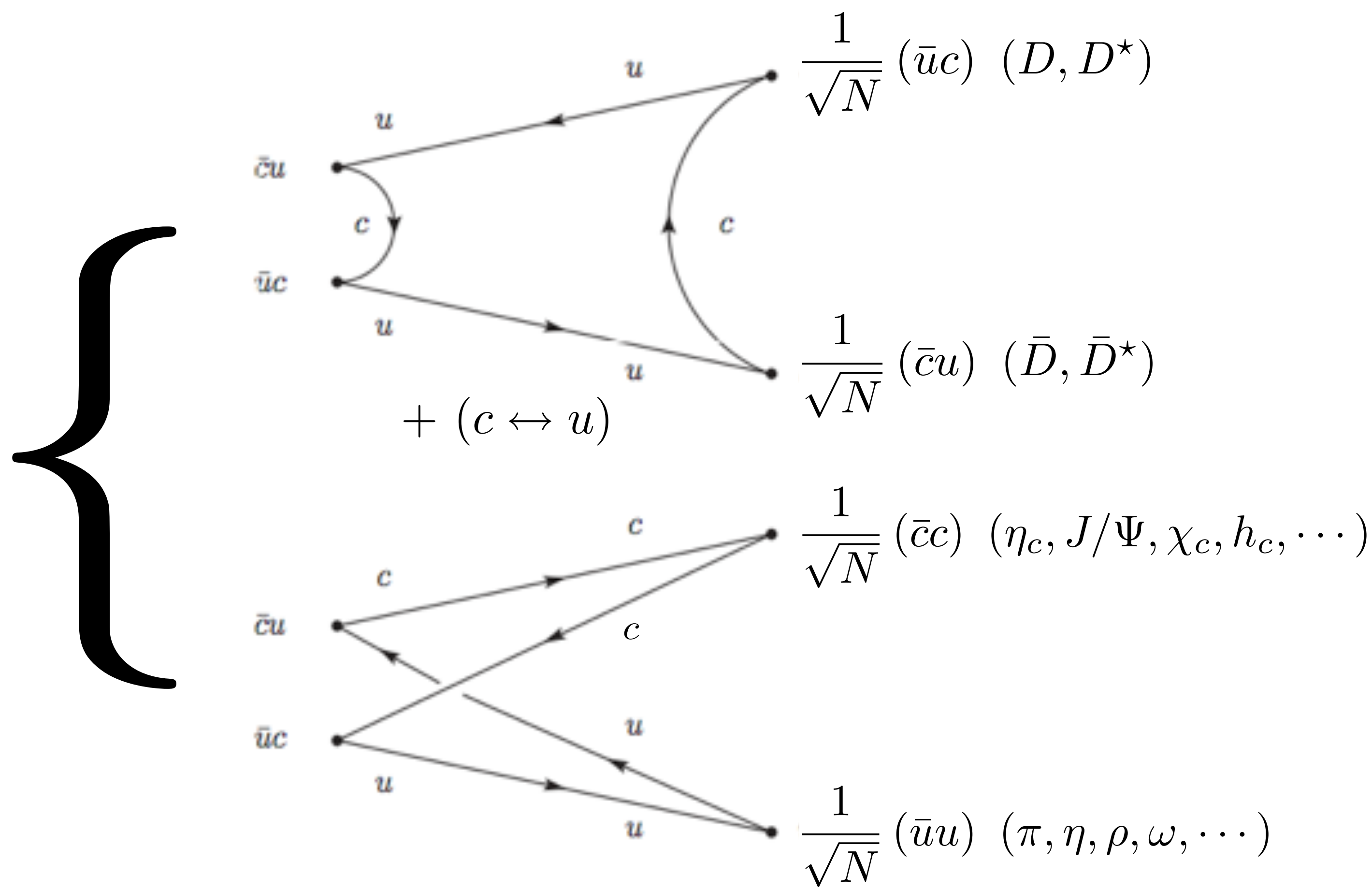
- the real issue is the width of the tetraquark pole: it may increases for large N, to the point of making the state undetectable;
- Weinberg's conclusions is the the decay rate goes like $1/N$, making tetraquarks a respectable possibility.
- Weinberg's discussion has been enlarged by M. Knecht and S. Peris (arXiv:1307.1273) and further considered by T. Cohen and R. Lebed et al. (arXiv: 1401.1815, arXiv: 1403.8090).

What is not forbidden is NECESSARY

Decay amplitudes in 1/N expansion

- By Fierz rearrangements, tetraquark operators can be reduced to products of color singlet bilinears;
- interpolating field operators have to be multiplied by powers of N, such as to make the connected two-point correlators to be normalized to unity;
- one loop amplitude with insertions of quark color singlet operators gives a factor N.

$$\mathcal{Q} = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$



- two independent amplitudes

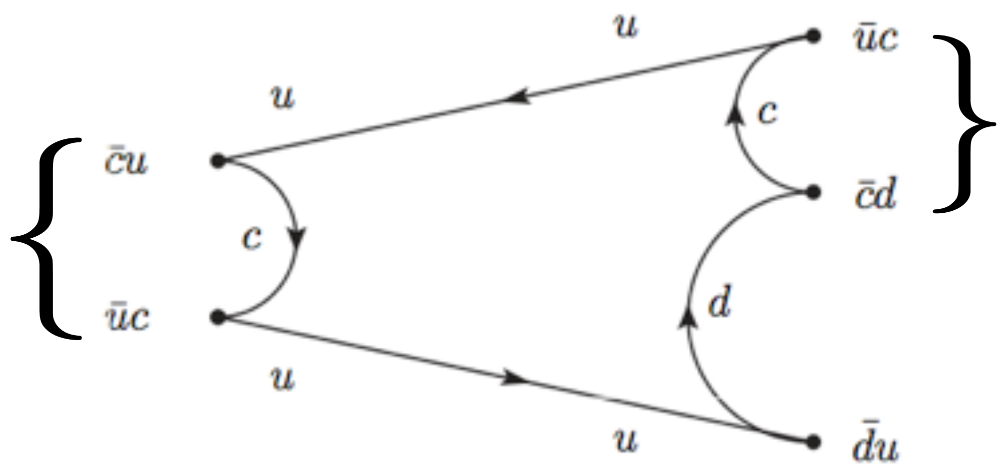
- The result is that *decay amplitudes into two mesons are of order*: $\frac{1}{N^{3/2}}N = \frac{1}{\sqrt{N}}$
- These two amplitudes were introduced long ago for tetraquark light scalar decay: reassuringly, they turn out both to be leading in 1/N.

L. Maiani, F.Piccinini, A. D. Polosa, V. Riquer, PRL **B93**, 212002 (2004)

further decay amplitudes

- tetraquark de-excitation amplitudes by meson emission, e.g. $Y(4260) \to Z_c(3900) + \pi$, are also of order $1/\sqrt{N}$

$$Y(4260) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$

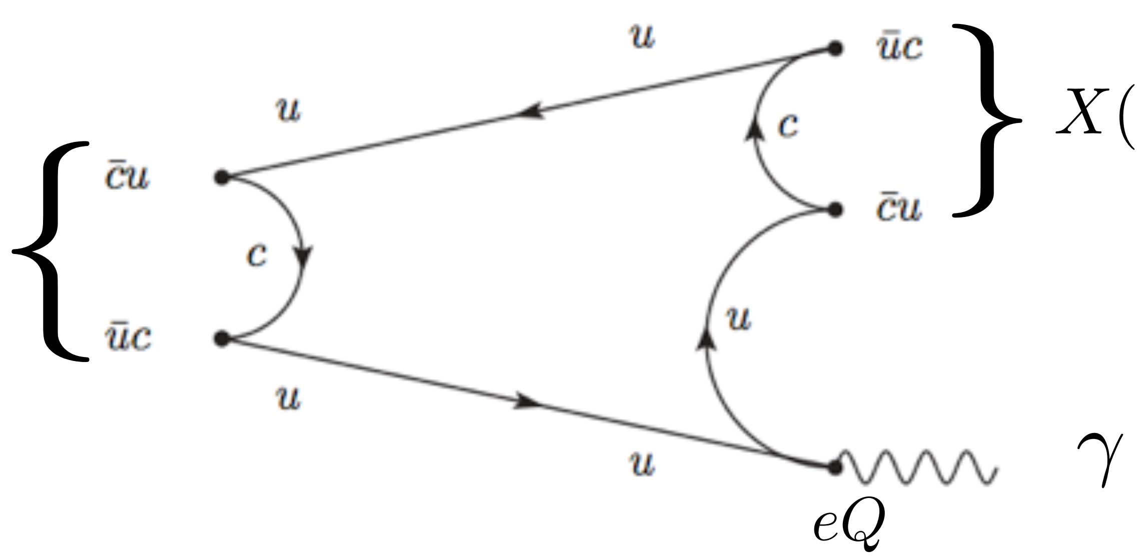


$$Z_c^-(3900) = \frac{1}{\sqrt{N}}[cd][\bar{c}\bar{u}]$$

$$\pi^+ = \frac{1}{\sqrt{N}}(u\bar{d})$$

- however, e.m. currents need no normalization factor, so that the de-excitation amplitudes via photon emission are of order $eQ \times 1$.

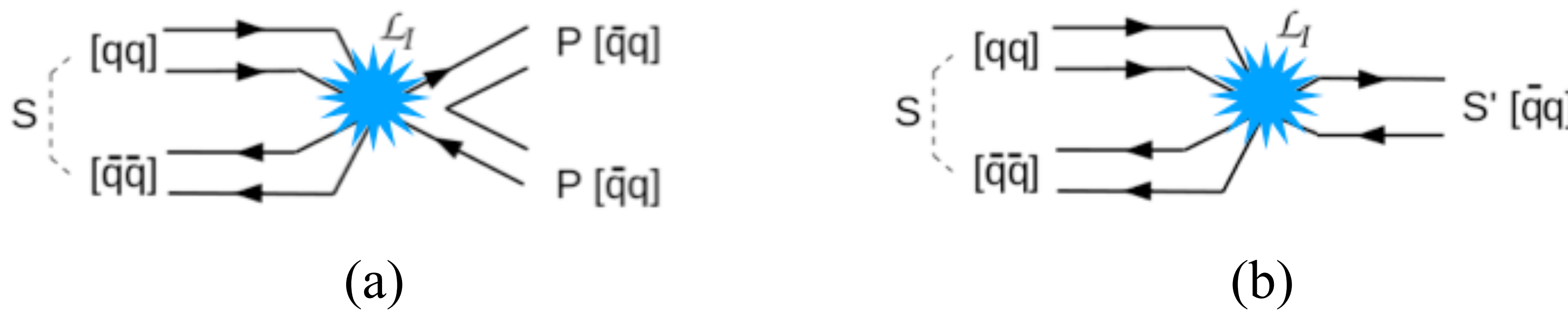
$$Y(4260) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$



$$X(3872) = \frac{1}{\sqrt{N}}[cu][\bar{c}\bar{u}]$$

Non-perturbative instantons: may explain two or three further puzzles

G. 't Hooft, G. Isidori, L. Maiani, A. D. Polosa and V. Riquer, PL **B662** (2008) 424.
A. H. Fariborz, R. Jora and J. Schechter, PR **D77** (2008) 094004.



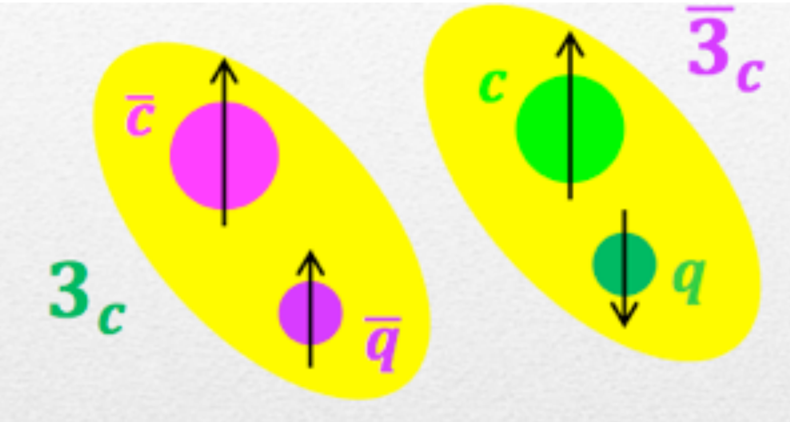
- (a) the decay $f_0(980) \to 2\pi$ ($f_0 = \frac{([su][\bar{s}\bar{u}] + u \to d)}{\sqrt{2}}$)
- (b) the mixing of light (tetraquark) scalar mesons with q-qbar mesons, the latter being made by $a_0(1474)$ (I=1), $K_0(1412)$, (I=1/2), and three isosinglets: $f_0(1370)$, $f_0(1507)$ and $f_0(1714)$ (one could be a glueball);
- (c)= (b) in the reverse:
  - with: $Y(4260) = \frac{([cu][\bar{c}\bar{u}] + u \to d)}{\sqrt{2}}$, the u-ubar or d-dbar pair in Y may give rise to the observed decay:

$$Y(4260) \to J/\Psi + f_0(q\bar{q})_{off-shell} \to J/\Psi + f_0([qq][\bar{q}\bar{q}])$$

6. Tetraquark picture of unexpected quarkonia

L.Maiani, F.Piccinini, A.D.Polosa and V.Riquer, Phys. Rev. D 71 (2005) 014028

$$[\mathrm{cq}]_{s=0,1}[\bar{c}\bar{q}']_{\bar{s}=0,1}$$



- I=1, 0
- S-wave: positive parity
- total spin of each diquark, S=1, 0
- neutral states may be mixtures of isotriplet and isosinglet
- mass splitting due to spin-spin interactions (e.g. the non-relativistic costituent quark model)

$$H = 2M_{diquark} - 2\sum_{i<j} \kappa_{ij}(\vec{s}_i \cdot \vec{s}_j)\ \frac{\lambda_i^A}{2}\frac{\lambda_j^A}{2}$$

The S-wave, J^P=1 $^+$ charmonium tetraquarks

- use the basis $|s, \bar{s}\rangle_J$

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

$$\mathrm{J^P} = 1^+ \quad C = + \quad X_1 = \frac{1}{\sqrt{2}}\left(|1,0\rangle_1 + |0,1\rangle_1\right)$$

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

$$\mathrm{J^P} = 2^+ \quad C = + \quad X_2 = |1,1\rangle_2$$

X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H
X(3940)=X_2 ??

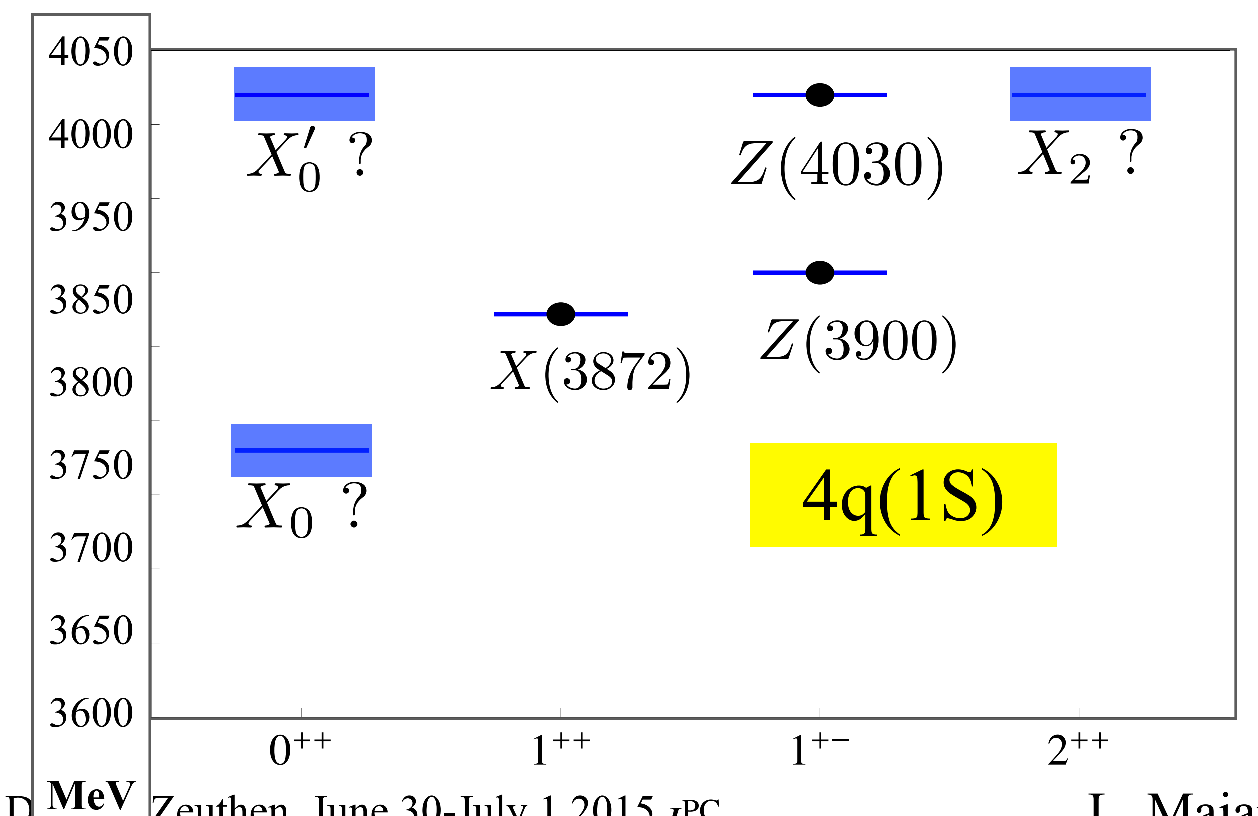
Mass spectrum: the new paradigm

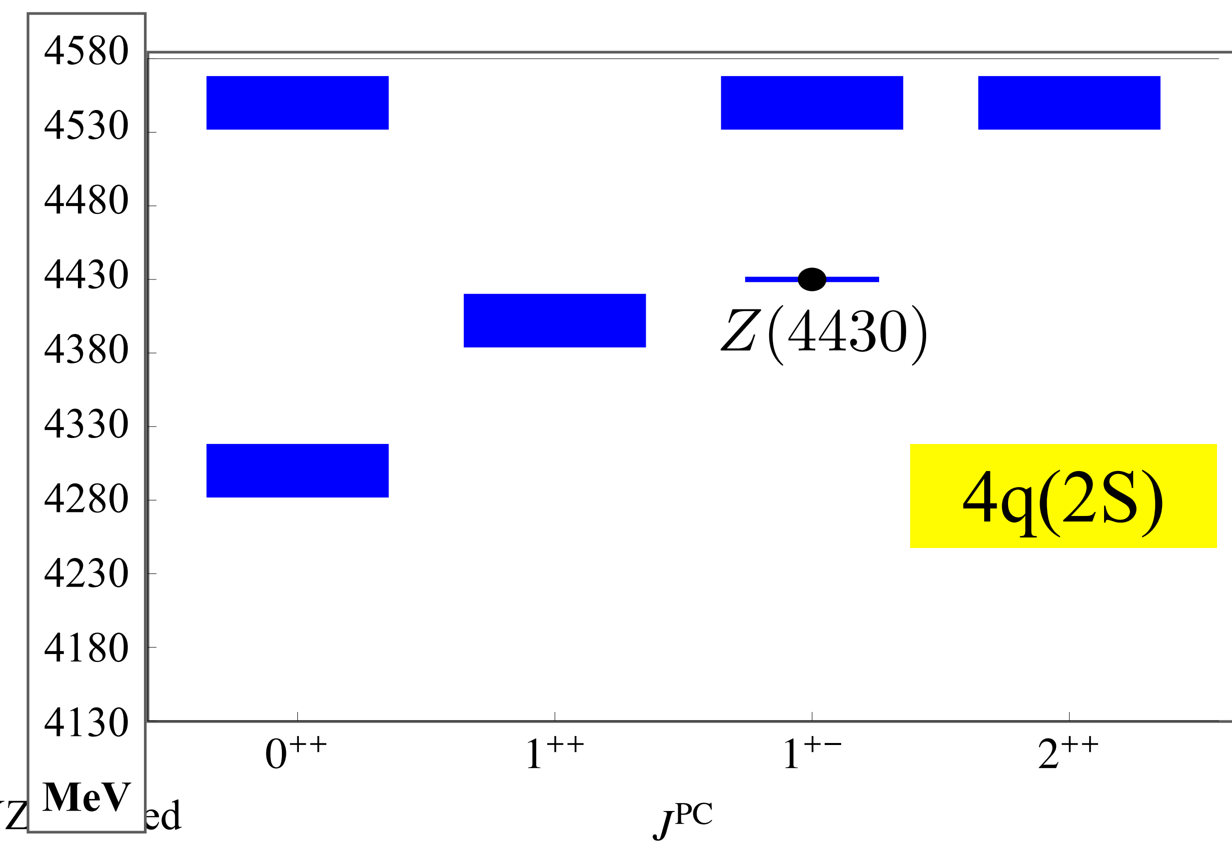
A. Polosa, V. Riquer, F, Piccinini, PRD **89**, 114010 (2014)

- A tentative mass spectrum for the S-wave tetraquarks was derived in the 2005 paper, based on an extrapolation of the spin-spin interactions in conventional S-wave mesons and baryons.
- Does NOT agree with the observed level ordering of X(3872), Z(3900) and Z(4020)
- A new, simple paradigm accounts for the observed pattern: dominant interactions are those ***between quarks in the same (tightly bound?) diquark*** (or antiquarks in the same antidiquark):

$$H \approx 2\kappa_{qc} \ (s_q \cdot s_c + s_{\bar{q}} \cdot s_{\bar{c}}) = \kappa_{qc} \left[s(s+1) + \bar{s}(\bar{s}+1) - 3\right]$$

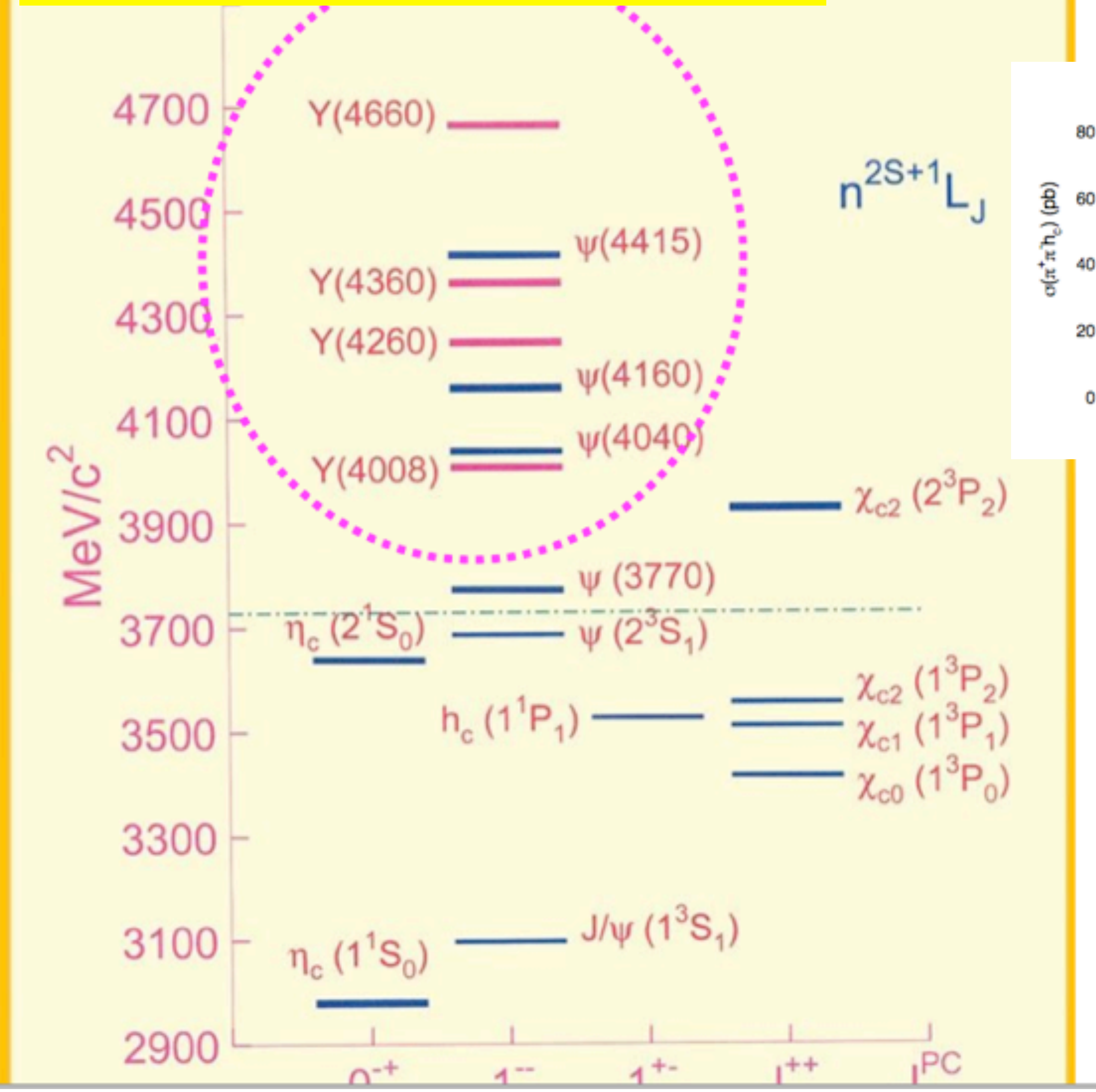
- H is diagonal in the basis of diquark total spin and counts the number of spin=1 diquarks
- one Z is degenerate with X(3872), the other is heavier;
- κ_{qc}~60 MeV from fit (larger than κ_{qc} in baryons).



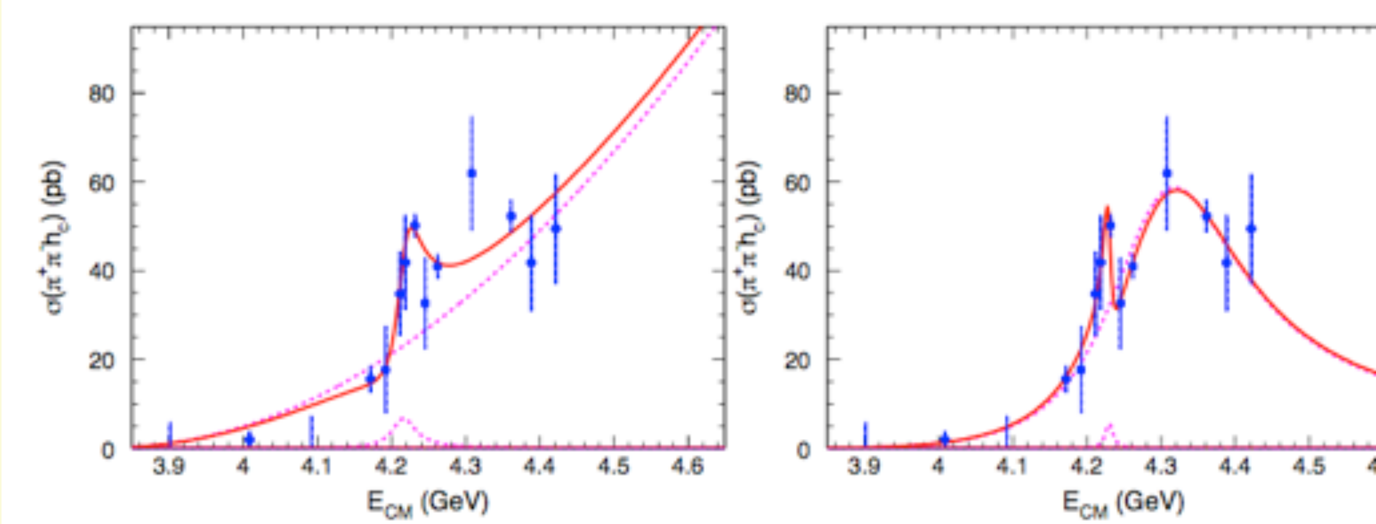


7. What are the Y states?

Changzheng YUAN, IHEP Beijing, 2014



later BES III has observed another one: Y(4230) which decays in $h_c\,\pi\,\pi$



or maybe two? (narrow and wide)

Our survey:

- $Y(4660)$ and $Y(4360)$, decaying into $\psi(2S)\pi$
- $Y(4630)$ decaying into $\Lambda_c\bar{\Lambda}_c$
- $Y(4220)$, narrow (and $Y(4290)$, wide ???) in $h_c(1P)+\pi$, BES III
- $Y(4260)$ and $Y(4008)$ decaying into $J/\psi+\pi$,

Y- tetraquarks

- Tetraquark states with $J^{PC}=1^{--}$ can be obtained with odd values of the orbital angular momentum L=1, 3 and diquark and antidiquark spins s, s bar=0,1.

- use the notation: |s,s bar; S,L$>_{J=1}$, and charge conjugation invariance we get four states with L=1:

	spin composition:$\|s, \bar{s}, S, L>_J$	$P(s_{c\bar{c}}=1)$	$P(s_{c\bar{c}}=0)$	assign.
Y_1	$\|0,0;0,1\rangle_1$	0.75	0.25	$Y(4008)$
Y_2	$\frac{1}{\sqrt{2}}(\|1,0;1,1\rangle_1 + \|0,1;1,1\rangle_1)$	1	0	$Y(4260)$
Y_3	$\|1,1;0,1\rangle_1$	0.25	0.75	$Y(4230)$
Y_4	$\|1,1;2,1\rangle_1$	1	0	$Y(4630)$

Interpretation of Y states:

- leave aside the $L=3$ state (too heavy);
- $Y(4360)$ and $Y(4660)$ = radial excitations of $Y(4008)$ and $Y(4260)$ (decay into $\psi(2S)$, $\Delta M \sim 350, 400$ MeV in the range of ΔM of $L=1$ charmonia and bottomonia);
- the 4 states Y_{1-4} identified with $Y(4008)$, $Y(4260)$, $Y(4220)$ (the narrow structure in the h_c channel) and $Y(4630)$.

Selection rules

- Conservation of the heavy quark spin is well established in QCD: decays indicate the value of c-cbar spin in the initial wave function:
  - X(3872): S(c-cbar)=1$\rightarrow$ J/Ψ yes, but no η_c
  - Y(4230): both χ_c (S (c-cbar) =1) and h_c (S (c-cbar) =0)
- conservation of light quark spin is not reliable:
  - initial spin composition not necessarily reflected in K K* vs K*K* decay modes
- observed X, Y, Z in the new paradigm of spin-spin coupling respect these rules, as far as we can see !
- more precise measurements of different decay channel will be of the outmost importance.

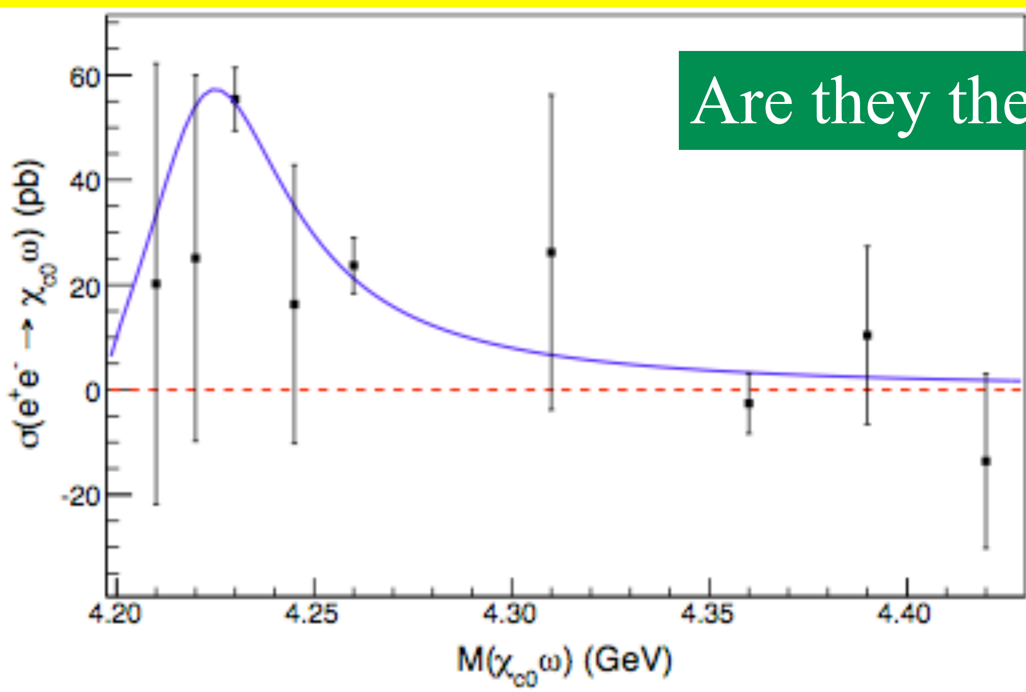
Y states, decay patterns and very tentative assignements

	$J/\Psi+\pi\pi$	$\psi(2S)+\pi\pi$	$h_c+\pi\pi$	$\chi_{c0}+\omega$	$\Lambda_c+\bar{\Lambda}_c$		$P(S_{c\bar{c}}=1)$	$P(S_{c\bar{c}}=0)$
$S_{c\bar{c}}$	1	1	0	1	1			
Y(4008)	seen	-	-	-		Y_1	0.75	0.25
Y(4230)	-	-	seen	seen		Y_3	0.25	0.75
Y (4260)	seen	-	-	-	-	Y_2	1	0
Y(4360)	-	seen				Y_1'	1	0
Y(4630)	-	-	-	-	seen	Y_4	1	0
Y(4660)	-	seen	-	-	-	Y_2'	1	0

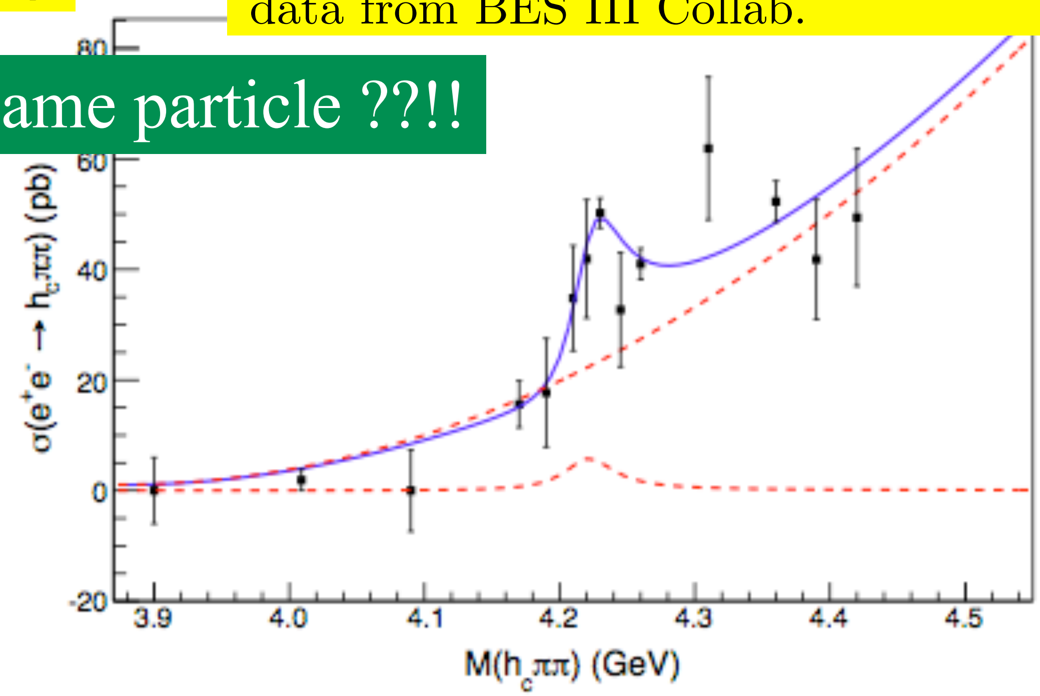
M. Ablikim *et al.* [BESIII Collaboration], arXiv:1410.6538 [hep-ex].

C. Z. Yuan, Chin. Phys. C **38** (2014) 043001
data from BES III Collab.

Are they the same particle ??!!



$$Y(4230) \to \chi_c + \omega$$



$$Y(4230) \to h_c + \pi^+ + \pi^-$$

Y(4230) has $S_{c\,\mathrm{cbar}}=1$ and $S_{c\,\mathrm{cbar}}=0$ decays, as required by Y_3

Radiative decays

- The identical spin structure implied in the model for Y(4260) and X(3872) suggests the decay

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

M.Ablikim et al. [BESIII Collaboration], arXiv:1310.4101 [hep-ex]

to be an ***unsuppressed E_1 transition***, with ΔL=1 and ΔSpin =0, similar to the observed transitions of charmonium χ states.

- The decay rate could provide a first estimate of the radius of the tetraquark.
- A comparison of the spin structures in Y and X states provides selection rules for E_1 transitions that should provide a better identification of the levels.
- The assignments we have made produce the table:

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

Basic formulae

Hua-Xing Chen, Luciano Maiani, Antonio Polosa

PRELIMINARY, NOT TO BE QUOTED

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

ED1 transition from a Ytetraquark, P-wave, to a X tetraquark, S-wave, with the same spin structure.
can be computed in the approximation where diquarks are treated as pointlike objects of electric charge Q:

$$Q = \left\{ \begin{array}{c} +\frac{4}{3}, \text{for } [cu] \\ \\ +\frac{1}{3}, \text{for } [cd] \end{array} \right\}$$

$$\Gamma = \alpha \, \frac{\omega^3}{9\pi} \sum_{mki} |\langle X, m| Q x^i | Y, k\rangle|^2$$

pointlike approx. introduced by: A. Ali, C. Hambrock and S. Mishima, Phys. Rev. Lett. **106** (2011) 092002

- First estimate (not to be quoted): $\Gamma(Y4260 \to \gamma + X3872) \sim 40$ keV
  $B(Y4260 \to \gamma + X3872) \sim 3 \cdot 10^{-4}$

- Basic formula: $\sigma_{peak}(e^+ + e^- \to V \to f) = \frac{12\pi}{M^2} B(V \to e^+e^-) B(V \to f)$

- BES III measures: $5 \cdot 10^{-3} = \frac{\sigma(e^+e^- \to \gamma + [J/\Psi\ \pi\pi]_X)}{\sigma(e^+e^- \to J/\Psi\ \pi\pi)} \approx \frac{B(Y \to \gamma X) B(X \to J/\Psi\ \pi\pi)}{B(Y \to J/\Psi\ \pi\pi)}$

- our result implies: $B(Y \to J/\Psi \pi\pi) \sim 0.06\ B(X \to J/\Psi \pi\pi)$

  that is: B(Y → J/Ψ ππ) ~ 3 10^{-3}, assuming B(X → J/Ψ ππ) ~ 5 10^{-2}

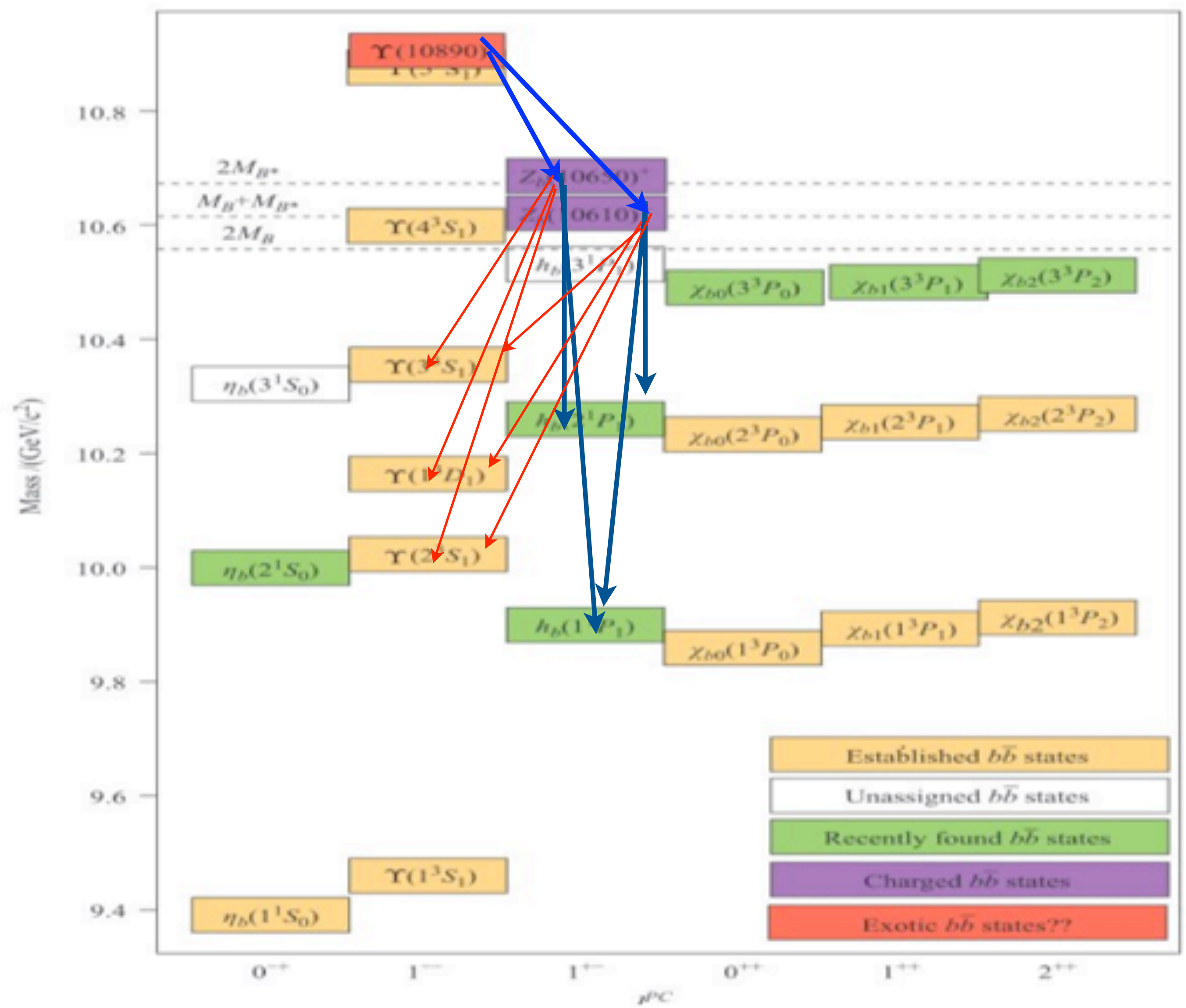
  or Γ (Y → J/Ψ ππ) ~ 7 Γ(X → J/Ψ ππ) for Γ (X) ~1 MeV....can be tested ???

8. Hidden beauty tetraquarks

A. Ali, C. Hambrock, I. Ahmed and M. J. Aslam, Phys. Lett. B 684, 28 (2010);
A. Ali, C. Hambrock and M. J. Aslam, Phys. Rev. Lett. 104, 162001 (2010) [Erratum-ibid. 107, 049903 (2011)];
A. Ali, BELLE II ITIP, Krakow, 2015

Bottomonia and Bottomonium-like Hadrons (Olsen, arxiv:1411.7738)

- note: $\Delta M(Z_b)/\Delta M(Z_c) \sim m_c/m_b$, as expected
- Y(10850) usually identified with Y(5S)
- however Ali et al suggest Y(5S) is superimposed to the b-analog of Y(4260) with the decays:
  - $Y_b \to Z_b/Z_b' \, \pi \to h_b(nP) \, \pi \, \pi$
  - $Y_b \to Z_b/Z_b' \, \pi \to Y(nS) \, \pi \, \pi$
- simultaneous decay in h_b and Y ***is compatible*** with heavy quark spin conservation, since Z_b are not degenerate and each has both $S_{(b\, b\, bar)} = 0,1$ components



Ahmed Ali (DESY, Hamburg)

$$|Z_b\rangle = \frac{|1_{bq}, 0_{\bar b \bar q}\rangle - |0_{bq}, 1_{\bar b \bar q}\rangle}{\sqrt{2}} = \frac{\alpha|1_{q\bar q}, 0_{b\bar b}\rangle - \beta|0_{q\bar q}, 1_{b\bar b}\rangle}{\sqrt{2}}$$

$$|Z_b'\rangle = |1_{bq}, 1_{\bar b \bar q}\rangle_{J=1} = \frac{\beta|1_{q\bar q}, 0_{b\bar b}\rangle + \alpha|0_{q\bar q}, 1_{b\bar b}\rangle}{\sqrt{2}}$$

$\alpha \approx \beta \approx 1$

A. Ali, L. Maiani, A.D. Polosa, and V. Riquer, Phys. Rev. D **91**, 017502 (2015)

- heavy quark spin conservation implies:
  - Y -> h_b (nP) $S=1 \to S=0:$

$$g_Z = g(\Upsilon \to Z_b\pi)g(Z_b \to h_b\pi) \propto -\alpha\beta\langle h_b|1_{q\bar q}, 0_{b\bar b}\rangle\langle 0_{q\bar q}, 1_{b\bar b}|\Upsilon\rangle$$
$$g_{Z'} = g(\Upsilon \to Z'_b\pi)g(Z'_b \to h_b\pi) \propto \alpha\beta\langle h_b|1_{q\bar q}, 0_{b\bar b}\rangle\langle 0_{q\bar q}, 1_{b\bar b}|\Upsilon\rangle = -g_Z$$

  - Y-> Y(nS)

$$f_Z = f(\Upsilon \to Z_b\pi)f(Z_b \to \Upsilon(nS)\pi) \propto |\beta|^2\langle \Upsilon(nS)|0_{q\bar q}, 1_{b\bar b}\rangle\langle 0_{q\bar q}, 1_{b\bar b}|\Upsilon\rangle$$
$$f_{Z'} = f(\Upsilon \to Z'_b\pi)f(Z'_b \to \Upsilon(nS)\pi) \propto |\alpha|^2\langle \Upsilon(nS)|0_{q\bar q}, 1_{b\bar b}\rangle\langle 0_{q\bar q}, 1_{b\bar b}|\Upsilon\rangle = \frac{\alpha^2}{\beta^2}f_Z$$

- in agreement, within still large errors, with Belle data:

Final State	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
Rel. Norm.	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. Phase	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Table 1: Relative normalizations and relative phases (in degrees), for $s_{b\bar b} : 1 \to 1$ and $1 \to 0$ transitions, as reported by Belle.

$s_{b\bar b} : 1 \to 1$ transition :

$\underline{\text{Rel.Norm.}} = 0.85 \pm 0.08 = |\alpha|^2/|\beta|^2$

$\underline{\text{Rel.Phase}} = (-8 \pm 10)^\circ$

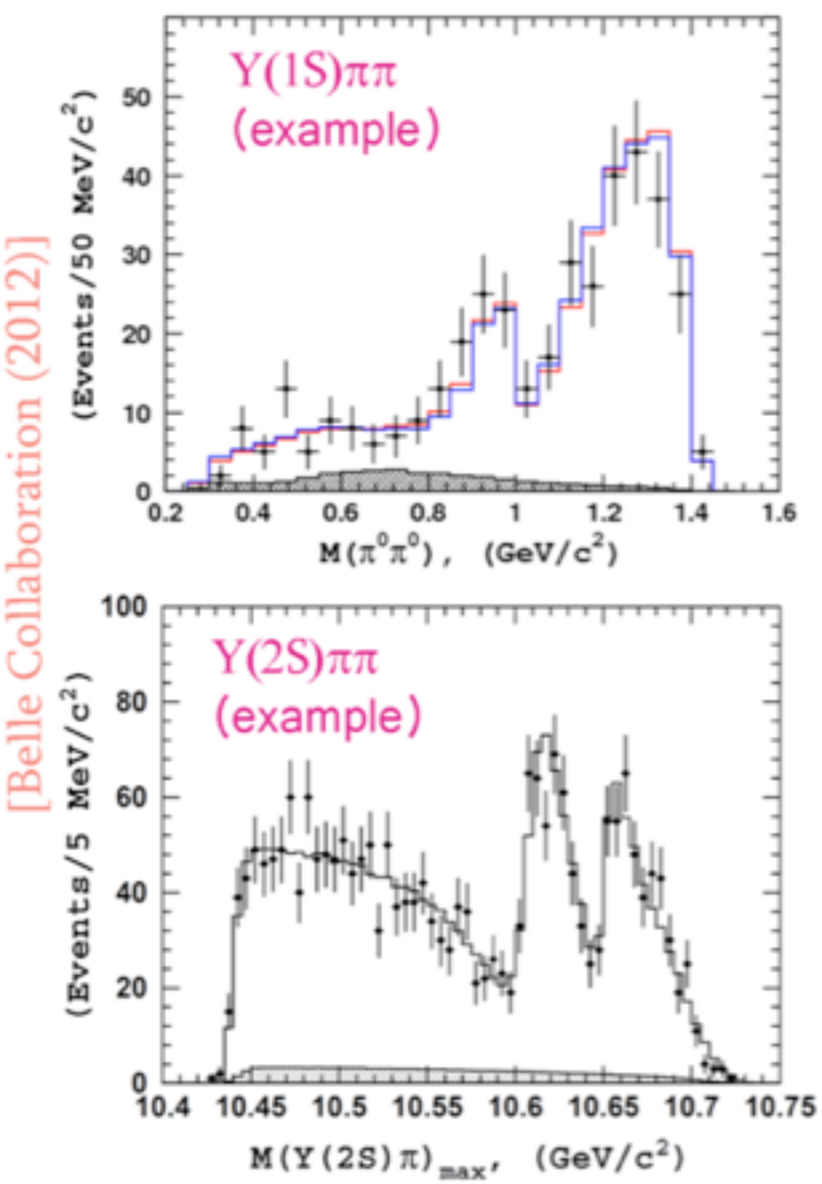
$s_{b\bar b} : 1 \to 0$ transition :

$\underline{\text{Rel.Norm.}} = 1.4 \pm 0.3$

$\underline{\text{Rel.Phase}} = (185 \pm 42)^\circ$

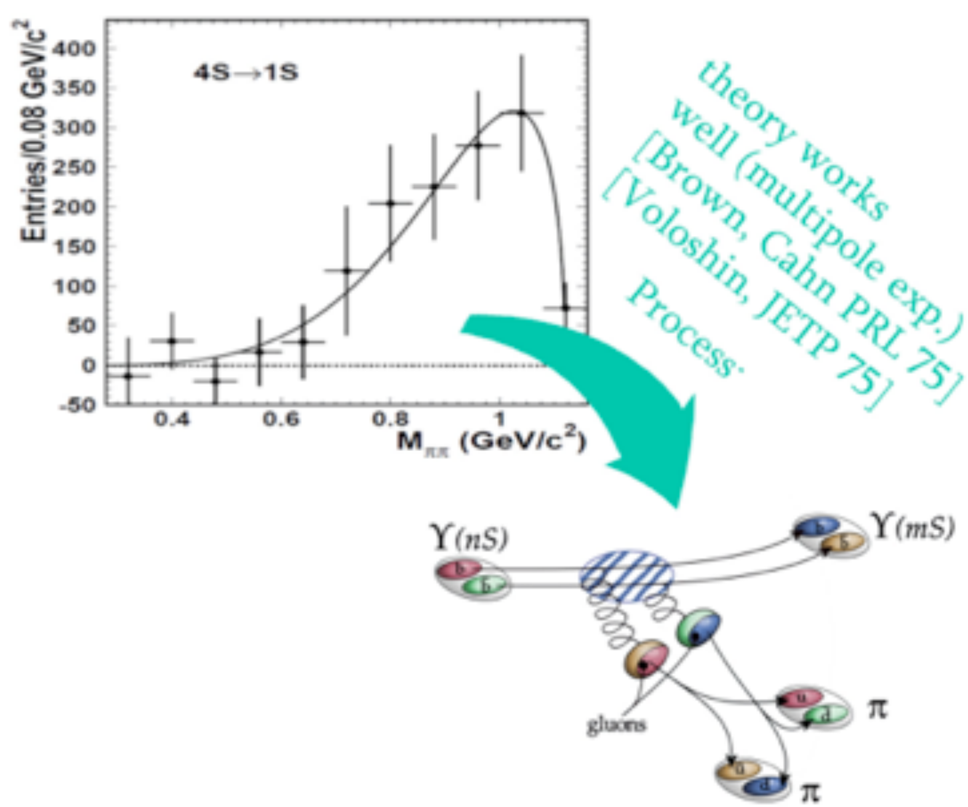
has the $\Upsilon_b(10850)$ bump a 4quark component, besides the $\Upsilon(5S)$ one, as proposed by Ali and coworkers?

Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

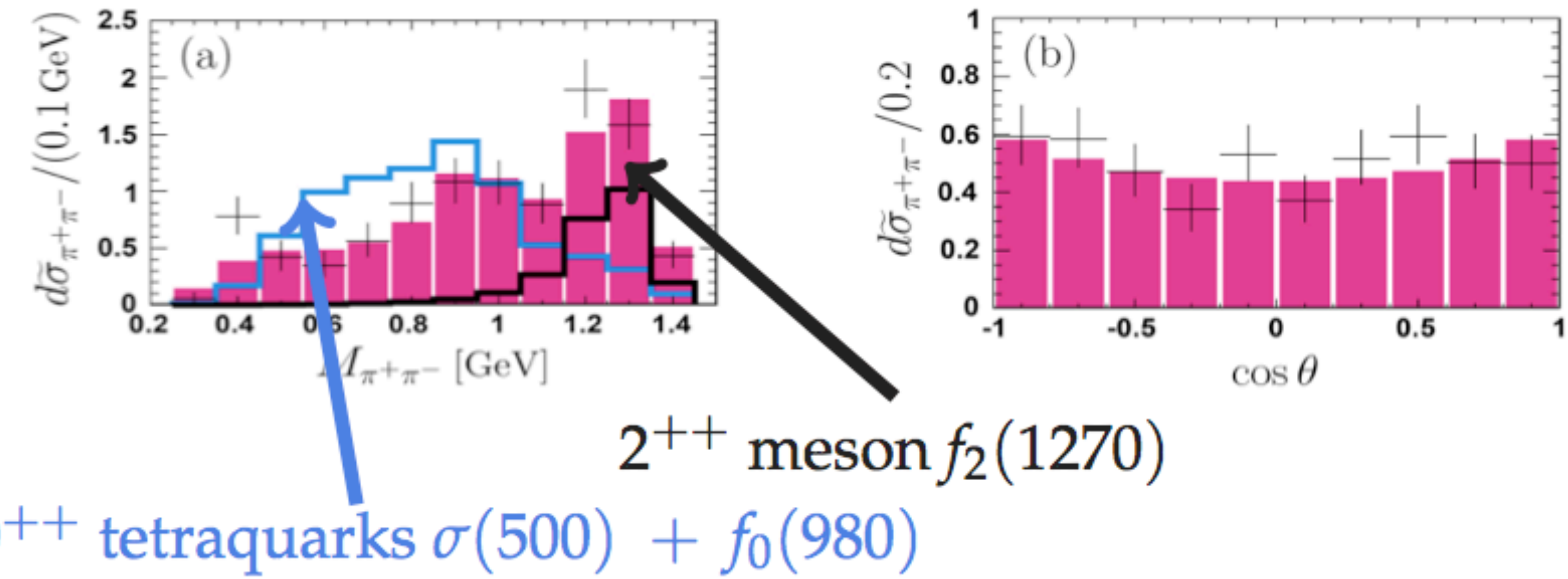


Ahmed Ali (DESY, Hamburg)

- the dipion spectrum strongly suggestive of the characteristic processes:
  - 4quark decay in $\Upsilon(1S)$+q qbar -> $f_2(1270)$
  - same with $f_0(1370)$-> $f_0(990)$ by instanton mixing [$f_0(1370)$ goes essentially in 4pi only]
  - hint of de-excitation in Υ_b(b b bar)+4quark $f_0(500)$
  - note the difference w.r.t. the 2 pion spectrum in the decay of $\Upsilon_b(4S)$!!



Fit to $\sigma(e^+e^- \to Y_b \to Y(1S)\pi^+\pi^-)$



- Fit results, data from [Belle, PRL 08]
- $\chi^2/\mathrm{d.o.f.} = 21.5/15$ → Good agreement with data
- Clear resonance dominance!

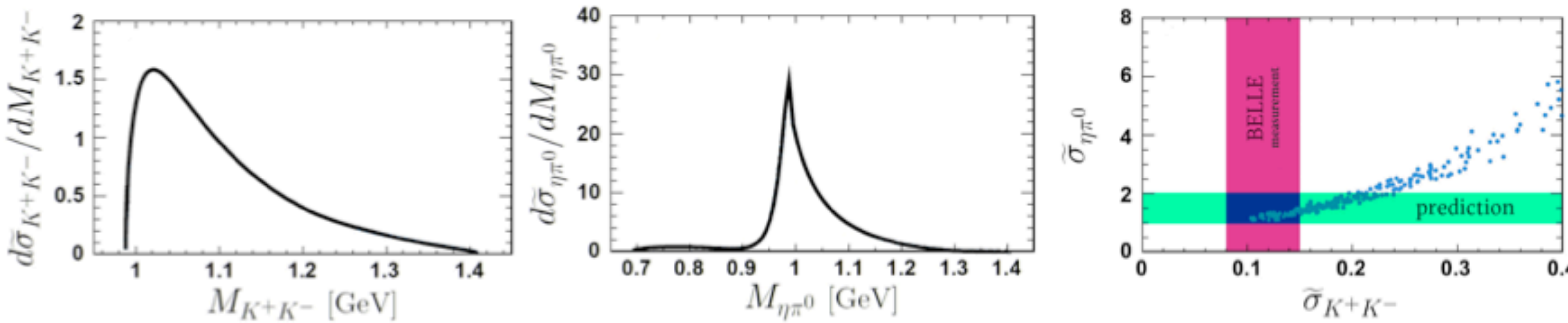
($\tilde{\sigma}$: normalized to measurement)

Ahmed Ali (DESY, Hamburg)

Predictions for : $Y(10850) \to Y(1S) + K^+K^-$, or $\eta\,\pi^0$

Fit determines couplings (assume $SU(3)$ flavor symmetry for couplings $(\sigma(500), f_0(980), a_0(980)) \to PP'$, ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08])

- predictions for spectra:



- Agreement with $\tilde{\sigma}_{K^+K^-} = 0.11^{+0.04}_{-0.03}$ (BELLE)
  - $1.0 \lesssim \tilde{\sigma}_{\eta\pi^0} \lesssim 2.0$ predicted
- Resonance dominance
  - Characteristic shape
    - **Good tests (relying on Y_b has 2 flavor states)**

Ahmed Ali (DESY, Hamburg) 31 / 33

9. To be convinced that we *do see* a new spectroscopy....

- $Z\_c(3900)^0$ has been found: BES III, arXiv:1506.06018
- Is there the I=1 (i.e. charged) companion of X(3872)? is it very wide? are there more neutral Z ?
- Complete the 1S tetraquark multiplet (masses estimated with ± 40 MeV ?):
  - X_0: 3780, X_0, X_2: 4020, decay: $J/\Psi\ \pi\pi$
- Fill the 2S multiplet
  - Z'(2S): 4550, decay $\psi(2S)\ \pi$, $h_c(2S)\ \pi$
  - X(2S): 4430
  - $X_0(2S)$: 4310, $X'_0(2S)$, $X_2(2S)$: 4550 decay $\psi(2S)\ \pi$
- $Y(4660) \to \psi(2S)\ \pi\pi$ decay:
  - does it go via $Z(4430)+\pi$? and there is a trace of $Z'(2S)+\pi$?
- $Y(4660) \to \gamma +$... to discover X(2S) ??
- are there $Y_b(10850) \to Y(1S)\ \eta\ \pi^0$ decays?
- Can LHCb see the X, Y, Z states seen by Belle and BES?
- ....

Many Thanks !!