Unconventional spectroscopy
experimental overview

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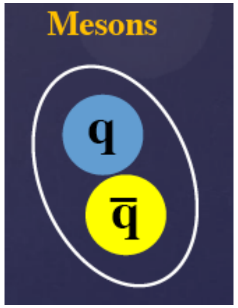
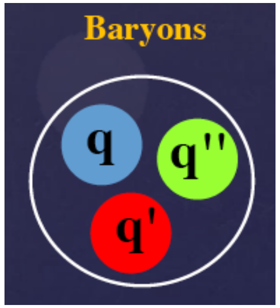
Introduction to charmonium spectroscopy

- **Costituent Quark Model & Quark-potential models**
- **Conventional charmonium**
- **Charmonium production processes**
- **Exotic charmonium**

- 1964: Gell-Mann & Zweig postulate Constituent Quark Model (CQM) –
  - Explained all known mesonic and baryonic states
  - Predicted others that were subsequently confirmed experimentally

CQM ⇒ Quarks form two types of bound states:





Only colorless combinations allowed

When the quark model was first postulated in the 1960s it was to organize the states then known to be in existence in a meaningful way.

- What about other combinations in bound states?

No theoretical reason to exclude other types of (colorless) bound quark state

As Quantum Chromodynamics (QCD) developed over the next decade, it became apparent that there was no fundamental reason why only 3-quark and quark-antiquark combinations should exist.
In addition it seemed that gluons, the force carrying particles of the strong interaction, should also form bound states by themselves (glueballs) and with quarks (hybrid hadrons).

Mesons, Barions and beyond ? - II

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

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Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

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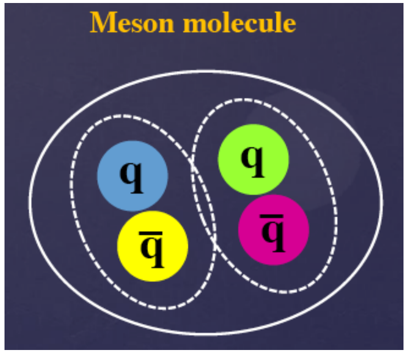
(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [ε(700), S^*, δ, κ] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L = 1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.

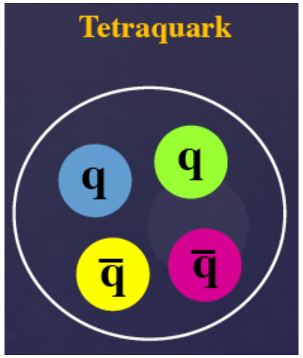
Mesons, Barions and beyond ? - III

- Exotic hadrons are subatomic particles made of quarks (and possibly gluons), but which do not fit into the usual scheme of hadrons; they were proposed initially by Jaffe.

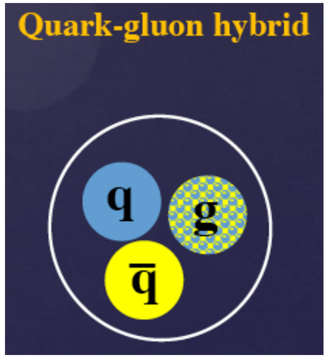
  Exotic hadrons do not have the same quark content as ordinary hadrons: exotic baryons have more than just the three quarks of ordinary baryons and exotic mesons do not have one quark and one antiquark like ordinary mesons.



- Loosely bound
- Pion exchange @ large distances
- Some color exchange @ short distances
- Predicted to decay like pair of free mesons



- Tightly bound
- Some models group into diquark-antidiquark pairs



- Extra gluonic degree-of-freedom

But… until recently, no experimental evidence for any such states

Charmonium - I

Exotic multi-quark states have been long predicted in the light quark sector

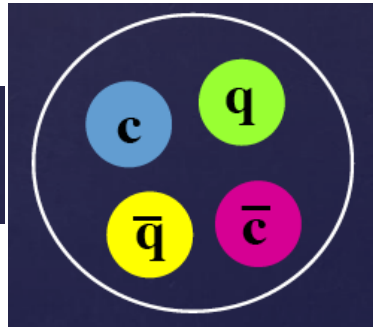
e.g. $f_0(980)$ and $a_0(980)$ candidates for $K\bar{K}$ molecules

But… Difficult to differentiate from conventional states – 3 light quarks, isospin symmetry, dense spectrum of predicted mesons.

Charmonium ($c\bar{c}$) states have well-predicted conventional spectrum, and distinct properties:

- Zero charge, zero strangeness
- Constrained decay channels
- Easier to differentiate from exotic states

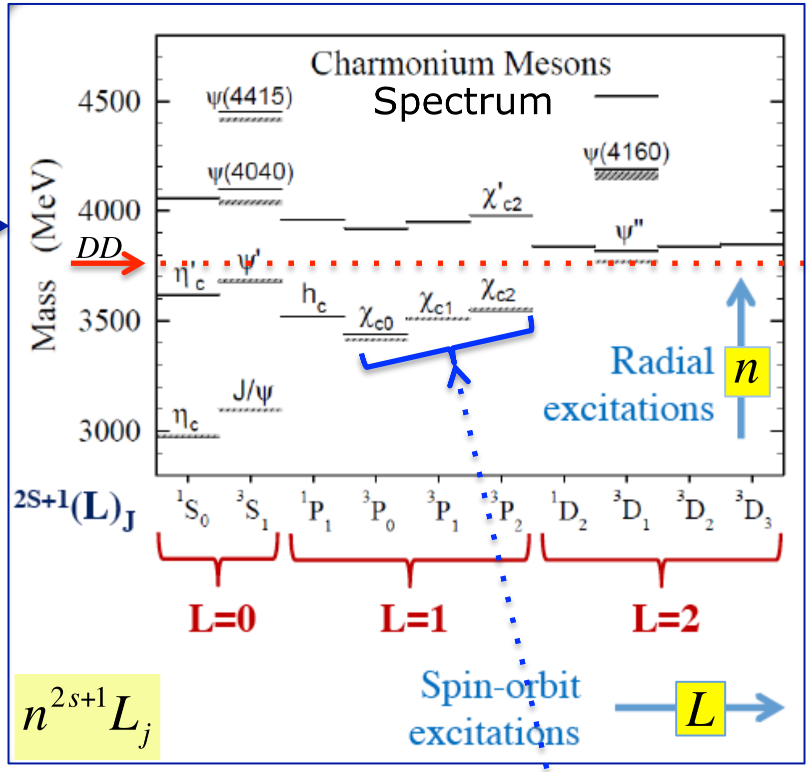
Exotic charmonium states can be charged ($c\bar{c}u\bar{d}$), strange ($c\bar{c}d\bar{s}$) or both ($c\bar{c}u\bar{s}$)



Charmonium - II

States defined by radial, spin, orbital, and total angular momentum quantum numbers

Spectrum well described by QCD quark-potential models



Potential model for $c\bar{c}$:

$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

[Colored flux tube Model]

Quark confinement
(at large r)

Not relativistic phenomenological bound potential
(at small r)

[Cornell Model]

This model can include relativistic corrections corresponding to spin-spin, spin-orbit interactions.
Spin-dependent interaction at work in the splitting into multiplets.

Natural spin-parity for *quarkonium*: $0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}$,...
[forbidden are: $0^{--}, 1^{-+}, 2^{+-}$,...]

Charmonium - III

Open charm thresholds ($D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$) are important for $c\bar{c}$ decays

Lowest threshold @ $m(D\bar{D}) \approx 3730 MeV$: charmonium states above this mass decay predominantly to $D\bar{D}$

Charmonium states above the open charm thresholds :

- should be large resonances rapidly decaying into charmed mesons pairs (through a mechanism that implies the creation of a light quark-antiquark pair)

Charmonium states below the open charm thresholds :

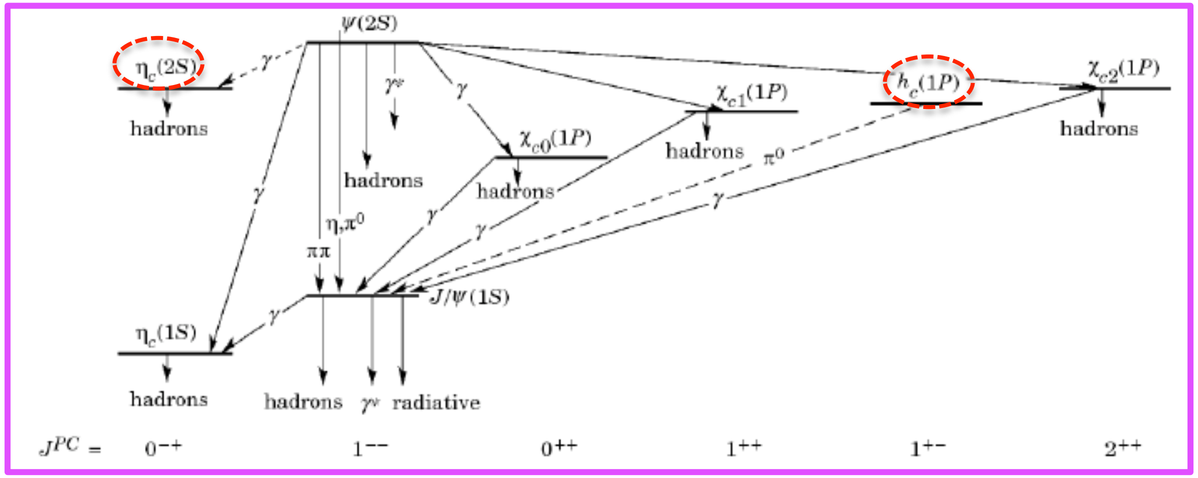
- should be narrow resonances slowly decaying into - non-charmed mesons or
  - lepton pairs

  (through a mechanism that implies the annihilation of a $c\bar{c}$ pair)

Charmonium spectrum and properties are well understood up to the $\psi(3770)$ (i.e. about the $D\bar{D}$ threshold)

Later discoveries [$\eta_c(2S)$, h_c, χ'_{c2}] agree with predictions of the quark-potential models

Conventional Charmonium - I



- The experimental **spectrum below the open-charm threshold**, consisting in the states $\eta_c,\ \eta_c' \equiv \eta_c(2S),\ J/\psi,\ \psi' \equiv \psi(2S),\ \psi'',\ h_c,\ \chi_{c0},\ \chi_{c1},\ \chi_{c2}$, can be **perfectly identified** with the spectroscopic levels predicted by the quark-potential models.

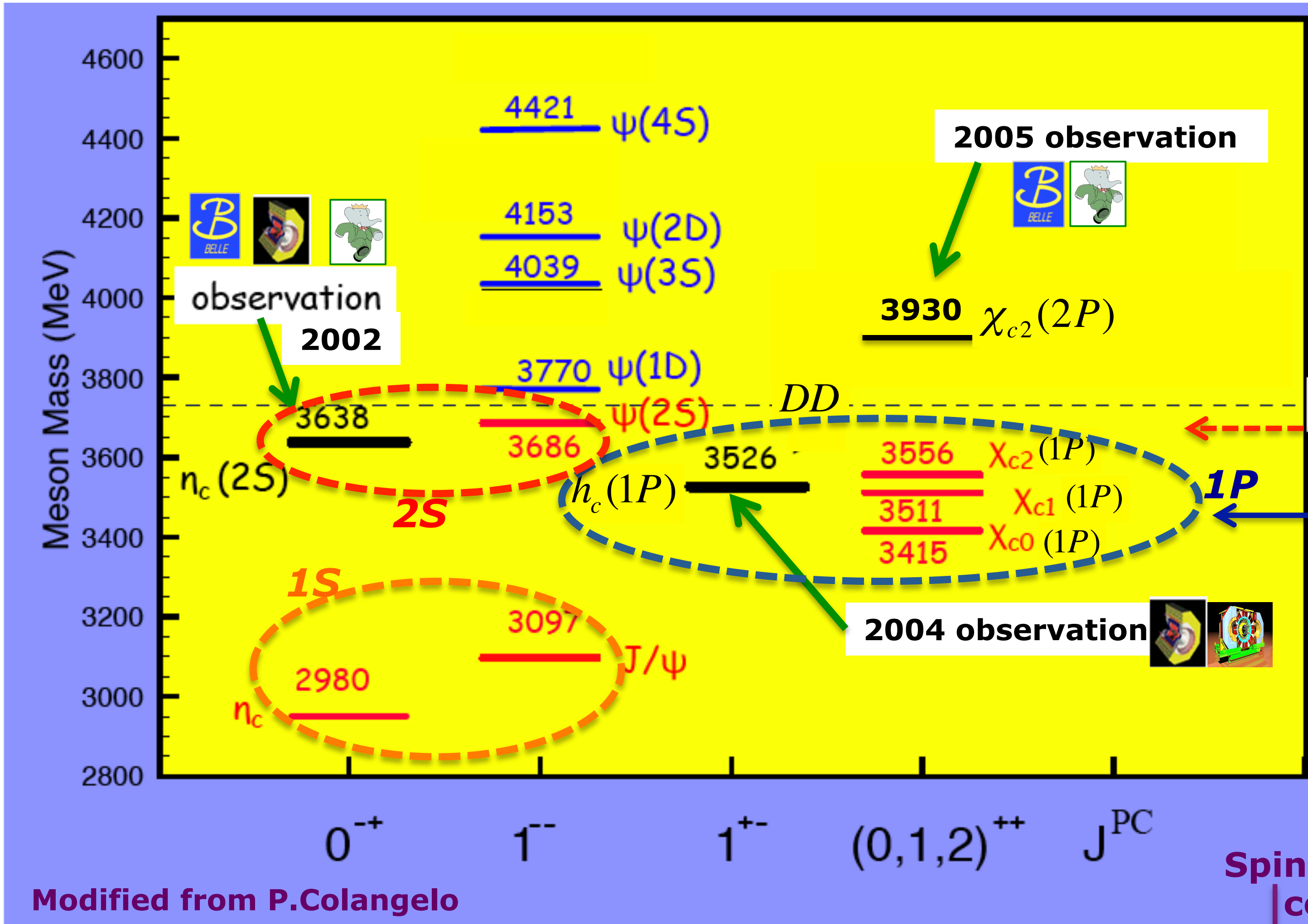
  The **completion of the *2S* and *1P* multiplets** has been reached quite recently:

  - $\eta_c(2S)$ by CLEO, Belle, BaBar in 2002

  - $h_c(1P)$ by CLEO, BES-II in 2004

  (see next slide)

Conventional Charmonium - II



2S & 1P multiplets completed

Hyperfine mass splitting calculation!

Spin-averaged centroid

Quark potential model successful below $D\bar{D}$ threshold: $\langle m(^3P_J)\rangle_{J=0,1,2} - m(h_c) \cong 1 MeV$

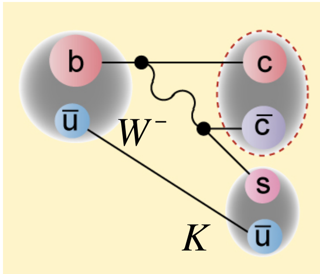
Charmonium production processes - I

Various processes to produce charmonium(-like) particles @ B-factories :

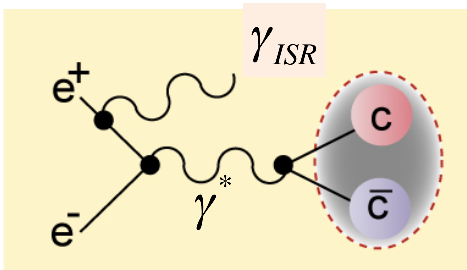
Two-body B decays : $B \rightarrow (c\bar{c})K$

In factorization limit:

$J^{PC} = 0^{-+}, 1^{--}, 1^{++}$



Initial State Radiation : $e^+e^- \rightarrow \gamma_{ISR}(c\bar{c})$



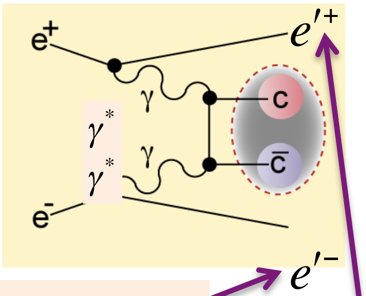
$J^{PC} = 1^{--}$

Two-photon fusion : $\gamma\gamma$ collisions

$C = +1$; J even $(= 0, 2)$

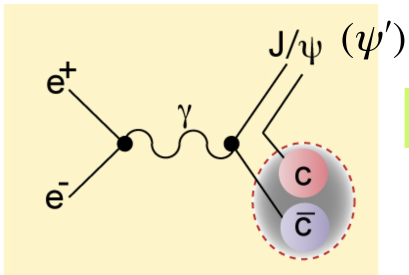
[Yang's theorem]

$J^{PC} = 0^{++}, 2^{++}$



[tipically undetected: *0-tag*, or *1-tag*]

Double charmonia : $e^+e^- \rightarrow J/\psi(c\bar{c})$



$C = +1$

$J = 0$ **only observed so far**

B-factories have run for most of their life on (and off) the Υ(4S) resonance; at the end of their life they took data @ Υ(3S), Υ(5S) and in scanning mode.

Charmonium production processes - II

- **BEPC is an easily tunable e^+e^- machine operating at lower energies than B-factories and running @ specific charmonium resonances and nearby. Initially started as Charmonium factory and lately has even become an *Y(4260)* factory (the first exotic resonance factory!)**
  [but also @ *Y(4360)*, ψ(3770)]

- **Two main production processes @ Hadron Machines (LHC, Tevatron) :**
  1) Prompt (inclusive): $pp(p\bar{p}) \to (c\bar{c}) + X$
  ***2) b-jets* (exclusive B-decays):** $B \to (c\bar{c}) + X$

Exotic Charmonium - I

- **In the last 12 years about 30 states have been observed while decaying to conventional charmonium in spite of being above the open-charm threshold.**

  They are inconsistent with expected charmonium spectrum:

  - **mass values do not fit the levels calculated by quark-potential models (even if threshold effect might deform the spectrum)**
  - **widths surprisingly narrow**
  - **many experimental decay rates do not agree with those expected**

- **After the *X(3872)* observation in 2003, many unexpected states observed either at B-factories and/or at Hadron-machines:**

  - 3 states of equal mass that differ for quantum numbers: *X(3940),Y(3940), Z(3940)*
  - 2 states with C-parity = +1 : *Y(4140)* and *X(4350)*
  - a family of vector states (*Y* states with $J^{PC}=1^{--}$): *Y(4260), Y(4350), Y(4660)/Y(4630)*
  - a set of charged states: $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$, and in 2013 the $Z(3900)^+$

  Few of these states subsequently adopted into exististing $c\bar{c}$ scheme,
  but the great majority of them still remain a mistery
  (for many of them … quantum numbers are not experimentally established).

XYZ charmonium-like mesons … at a glance - I

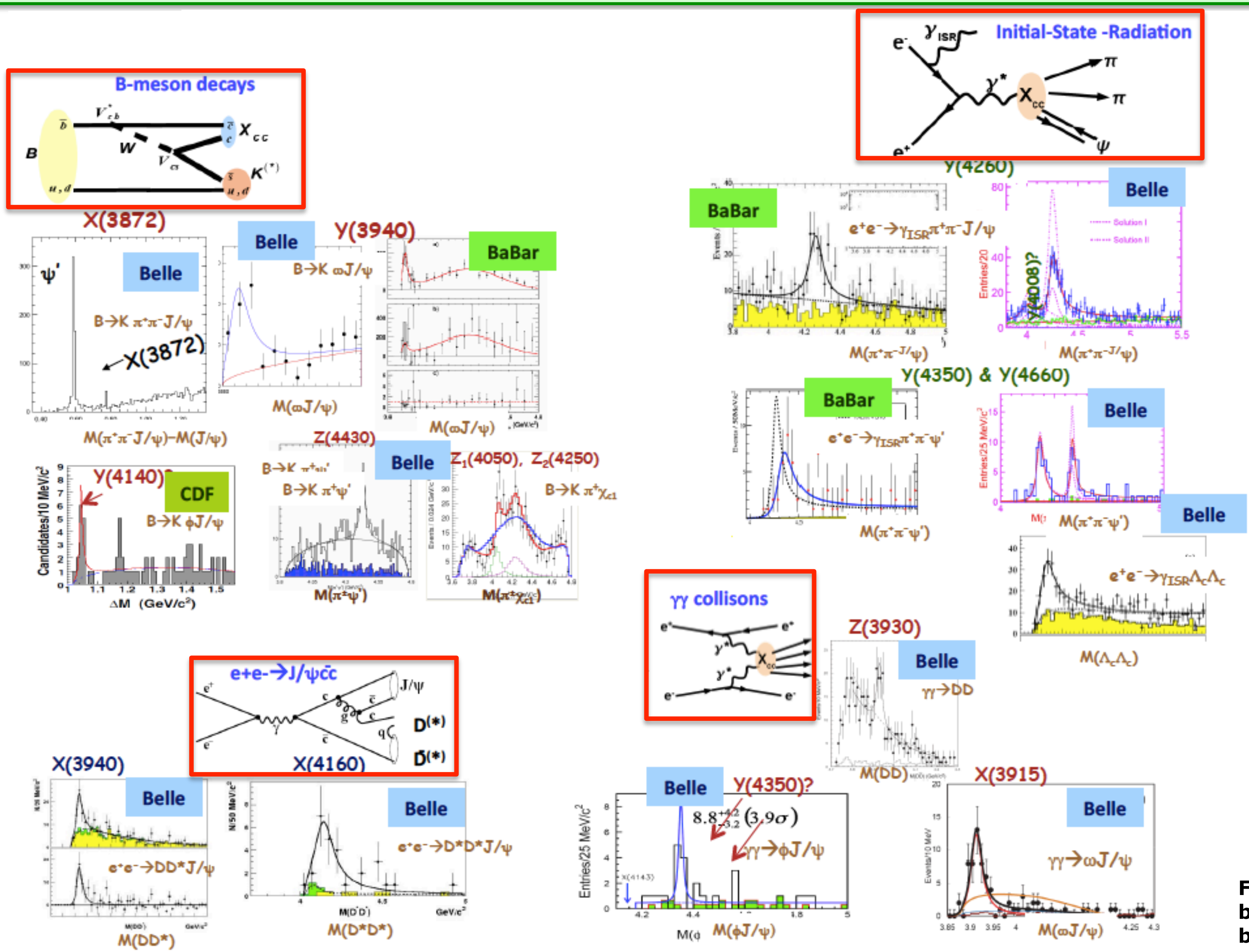
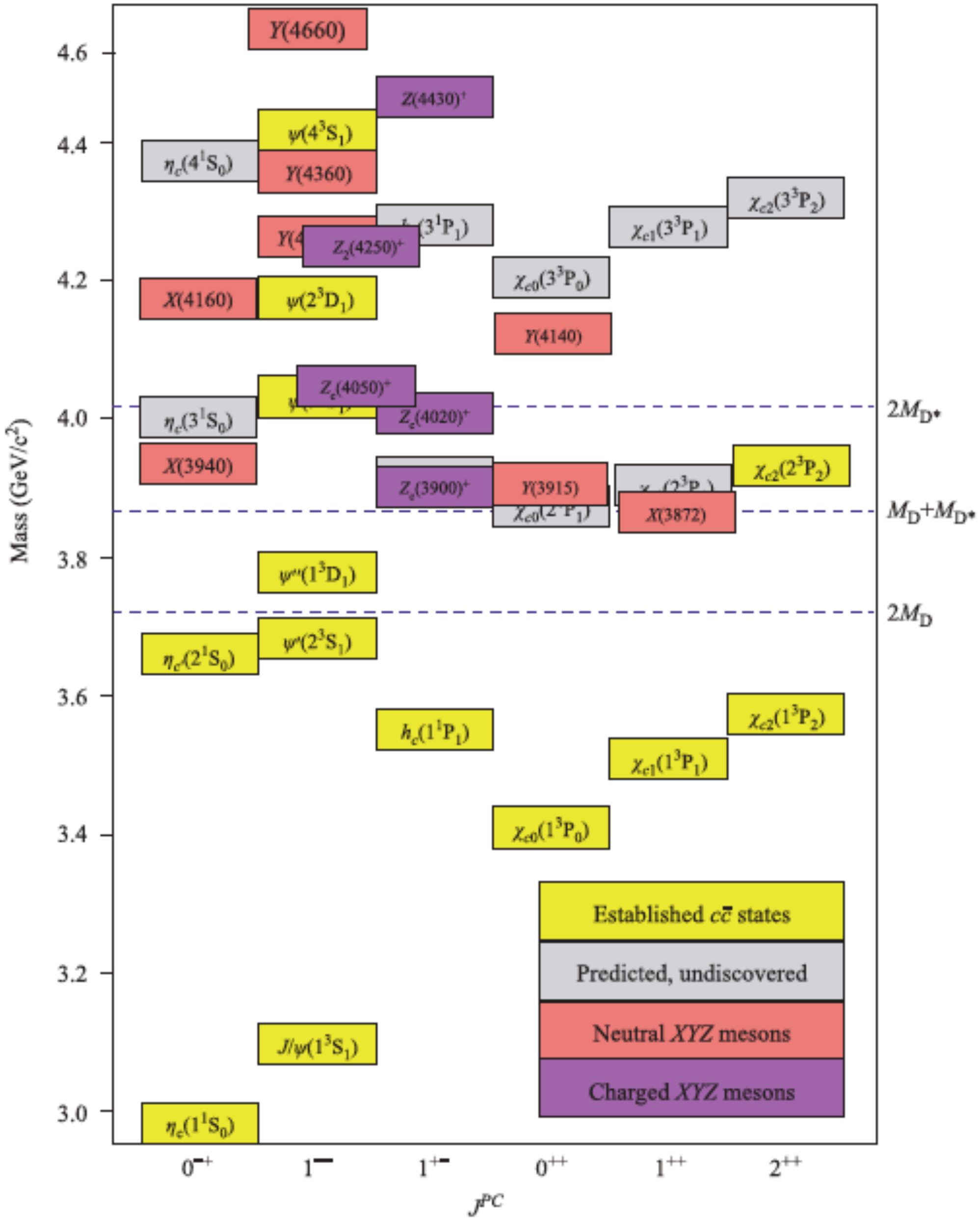


Figure borrowed by S.L.Olsen

XYZ charmonium-like mesons … at a glance - II

Charmonium spectrum & ***charmonium-like* states** :



XYZ charmonium-like mesons … at a glance - III

	State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
Neutral	$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
					$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	CDF [83, 91, 92, 125], D0 [84]
					$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
					$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
					$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
					$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
					$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	LHCb [86], CMS [87]
	$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
					$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
	$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
	$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
					$e^+e^- \to J/\psi + (\ldots)$	Belle [26]
	$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
	$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
	$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
	$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
	$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
					$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
					$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
	$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
	$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [81]
	$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
	$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
	$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
Charged	$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
					$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
	$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
					$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [42]
	$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
	$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
	$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
	$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
					$B \to K + (J\psi\,\pi^+)$	Belle [51]

Exotic Charmonium - II

The decay modes of the $c\bar{c}$ mesons listed in Tables I and II are of four kinds:

(i) a hadronic decay into a pair of charm mesons, such as $D\bar{D}$, or a pair of charm baryons, such as $\Lambda_c^+\Lambda_c^-$,

(ii) a hadronic transition to a lighter $c\bar{c}$ meson through the emission of light hadrons, such as a single vector meson ω or ϕ, a single pion, or a pair of pions,

(iii) an electromagnetic transition to a lighter $c\bar{c}$ meson through the emission of a photon,

(iv) an electromagnetic annihilation "decay mode" (e^+e^-) or $(\gamma\gamma)$, in which the parentheses indicate that it has actually been observed as a production channel. They provide strong constraints on the J^{PC} quantum numbers: (e^+e^-) requires 1^{--} and $(\gamma\gamma)$ requires either 0^{++} or 2^{++}.

from Brateen et al., PRD 90 (2014) 014044

Exotic Charmonium - III

Proliferation of 'charmonium-like' resonances presents challenges

- *Too many states for charmonium spectrum, & disagreement with predicted masses, widths, decay rates*
- *Can be threshold effects, interference (of known and as-yet-unknown states), experimental effects (reflections, acceptance effects…)*
- *Some states in experimental limbo – seen by some, not by others*
- *Multiple possible models for most states ($c\bar{c}$, molecule, tetraquark, hybrid)*

(see next slide)

Even the X(3872) is not understood, ten years after discovery, with quantum numbers confirmed, and with many thousand events seen by multiple experiments

To identify the exotics:
- **measure J^{PC} that is forbidden for charmonium**
- **observe a narrow width above $c\bar{c}$ threshold**
- **observe $c\bar{c}$ -like states with charged and/or strangeness**

To further explore them:
- **reconstruct as many decay modes as possible (radiative, …) for these states**
- **measure BF ratios**

➤ To explain their nature ... **alternative models** have been introduced:

(i) *conventional quarkonium*, which consists of a color-singlet heavy quark-antiquark pair: $(Q\bar{Q})_1$,

(ii) *quarkonium hybrid meson*, which consists of a color-octet $Q\bar{Q}$ pair to which a gluonic excitation is bound: $(Q\bar{Q})_8 + g$,

(iii) *compact tetraquark* [8], which consists of a $Q\bar{Q}$ pair and a light quark q and antiquark $\bar{q}$ bound by interquark potentials into a color singlet: $(Q\bar{Q}q\bar{q})_1$,

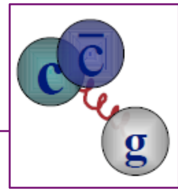
(iv) *meson molecule* [9], which consists of color-singlet $Q\bar{q}$ and $\bar{Q}q$ mesons bound by hadronic interactions: $(Q\bar{q})_1 + (\bar{Q}q)_1$,

(v) *diquarkonium* [10], which consists of a color-anti-triplet Qq diquark and a color-triplet $\bar{Q}\,\bar{q}$ diquark bound by the QCD color force: $(Qq)_{\bar{3}} + (\bar{Q}\,\bar{q})_3$,

(vi) *hadroquarkonium* [11], which consists of a color-singlet $Q\bar{Q}$ pair to which a color-singlet light-quark pair is bound by residual QCD forces: $(Q\bar{Q})_1 + (q\bar{q})_1$. An essentially equivalent model is a quarkonium and a light meson bound by hadronic interactions.

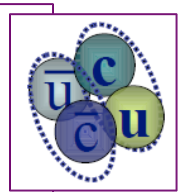
(vii) *quarkonium adjoint meson* [12], which consists of a color-octet $Q\bar{Q}$ pair to which a light quark-antiquark pair is bound: $(Q\bar{Q})_8 + (q\bar{q})_8$.

from Brateen et al., PRD 90 (2014) 014044

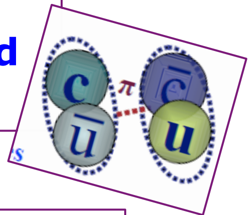


Hybrids :
bound states of quarks and gluons
(i.e. charmonium + excited gluons)

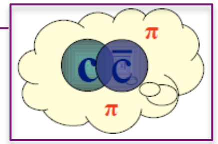
Tetraquarks :
bound states made of a diquark-antidiquark pair (charged and doubly charged states foreseen)



Hadron molecules :
weakly bound states formed by 2 (or more) hadrons



Hadro-charmonium :
binding a compact charmonium state inside an excited state of light hadronic matter (QCD analog of the Van der Waals force)



➤ **Non-resonant kinematic effect** (in proximity to thresholds) - CUSP

4-quarks systems

- **So far we have discussed how … many of these states have a minimal quark content of 4 quark, and regardless the way they are organized and interacting [compact system or molecular system? if compact: diquark-antidiquark or quark-antiquark pairs?] they can be considered 4-valence quarks bound systems. For istance:**

Y(3872) $c\bar{c}u\bar{u}$

Y(4140) $c\bar{c}s\bar{s}$

Z(4430)$^+$
Z(3900)$^+$ $c\bar{c}u\bar{d}$

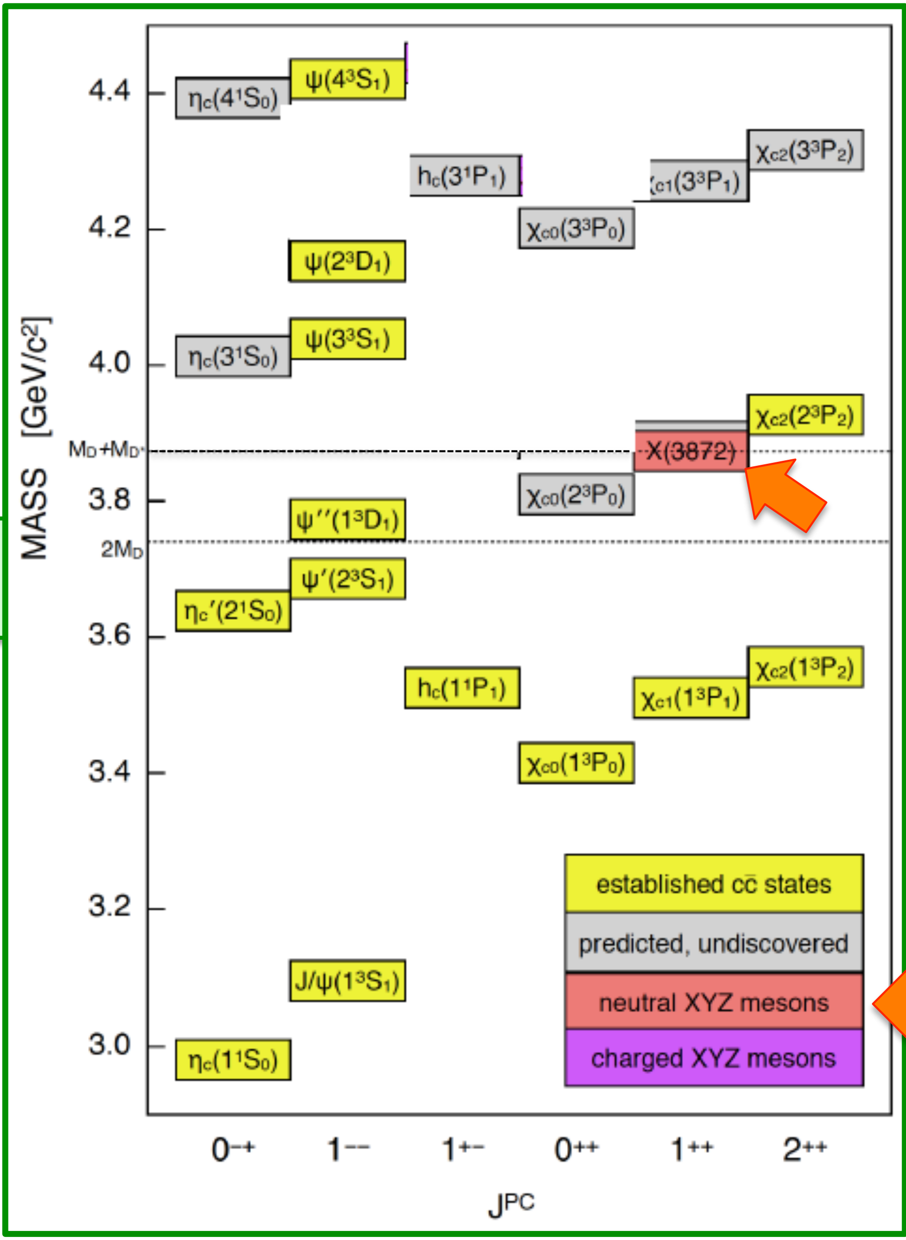
Z$_b$(10610)$^+$
Z$_b$(10650)$^+$ $b\bar{b}u\bar{d}$

Part – 1 : 4-quarks systems

- a) Charmonium-like exotics (1.neutral, 2. charged)
- b) Bottomonium-like exotics

Part – 1 / 4-quarks systems :
a1) Neutral charmonium-like exotics

X(3872)



MASS [GeV/c²]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
MD+MD*
2MD
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc0(3³P0)
χc1(3³P1)
χc2(3³P2)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
X(3872)
χc2(2³P2)
χc0(2³P0)
ψ''(1³D1)
ψ'(2³S1)
ηc'(2¹S0)
hc(1¹P1)
χc1(1³P1)
χc2(1³P2)
χc0(1³P0)
J/ψ(1³S1)
ηc(1¹S0)
established cc̄ states
predicted, undiscovered
neutral XYZ mesons
charged XYZ mesons
0−+
1−−
1+−
0++
1++
2++
JPC

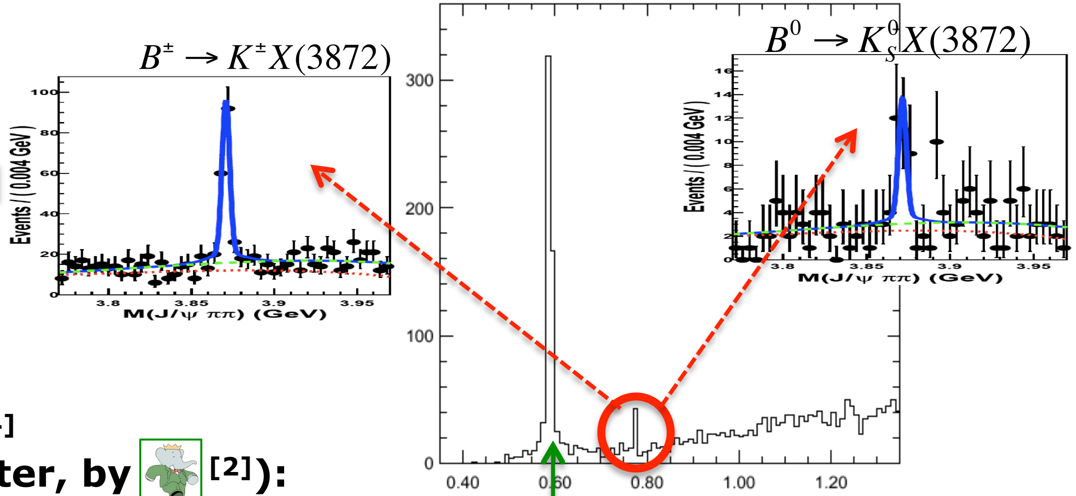
Discovery of X(3872)

- **First exotic state discovered (2003) by Belle [1] in $B \to KX(3872) \to K(J/\psi\ \pi^+\pi^-)$ decays:**

X(3872) sits on $\bar{D}^0 D^{*0}$ threshold and is narrow:

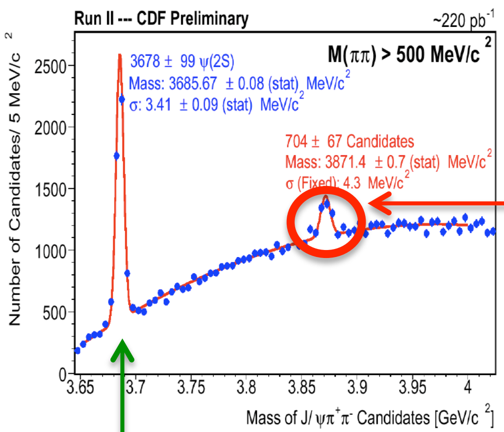
$$\Gamma_{J/\psi\pi\pi} < 2.3 MeV\ @\ 90\%\ C.L.$$

$$B\left(B^+ \to K^+X\right) \times B\left(X \to J/\psi\pi^+\pi^-\right) \approx 8.5 \cdot 10^{-6}$$



$B \to K\psi(2S) \to K(J/\psi\ \pi^+\pi^-)$ control signal

- **Quickly confirmed by CDF [3], D0 [4] with inclusive $p\bar{p}$ collisions (and, later, by BaBar [2]):**



$p\bar{p} \to X(3872) + \text{other}$

$p\bar{p} \to \psi(2S) + \text{other}$

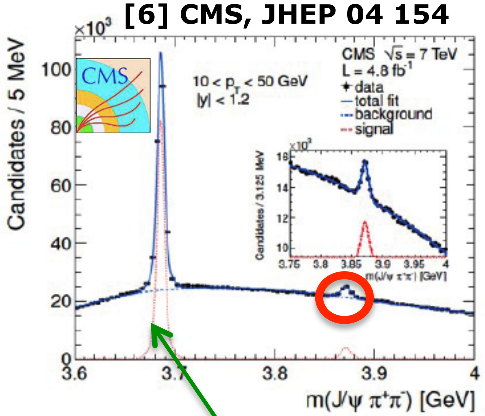
Mainly prompt production (only ~16% from B's)

[1] Belle, PRL 91, 262001 (2003)
[2] BaBar, PRD 71, 071103 (2005)
[3] CDF, PRL 93, 072001 (2004)
[4] D0, PRL 93, 162002 (2004)

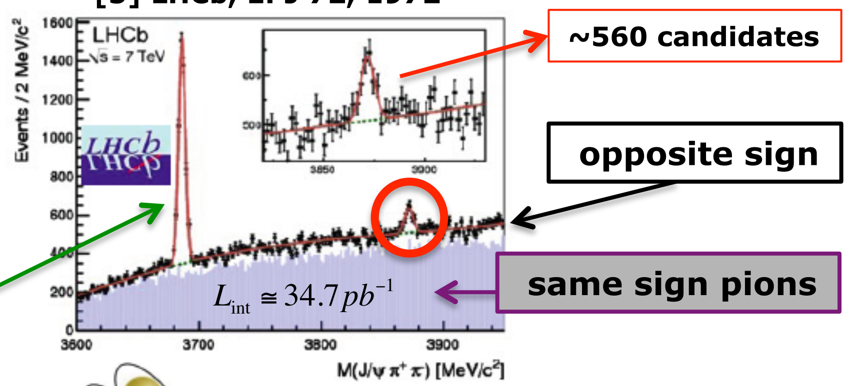
Rediscovery of *X(3872)*

And recently "rediscovered" @ LHC (LHCb (2012)[5], CMS (2013)[6]):

[6] CMS, JHEP 04 154

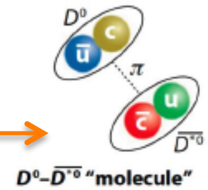


[5] LHCb, EPJ 72, 1972



ψ(2S) control signal

After 12 years …
…its nature still unkown : Tetraquark?
Conventional charmonium?
Molecule?



Anyway a lot of information has been derived experimentally in 12 years, with the most recent (2013) result being the LHCb determination of J^{PC}.

There are 3 main directions to undercover its nature:

1) **Mass measurement**
2) **Cross section measurement**
3) **Decays' analysis (J^{PC})**

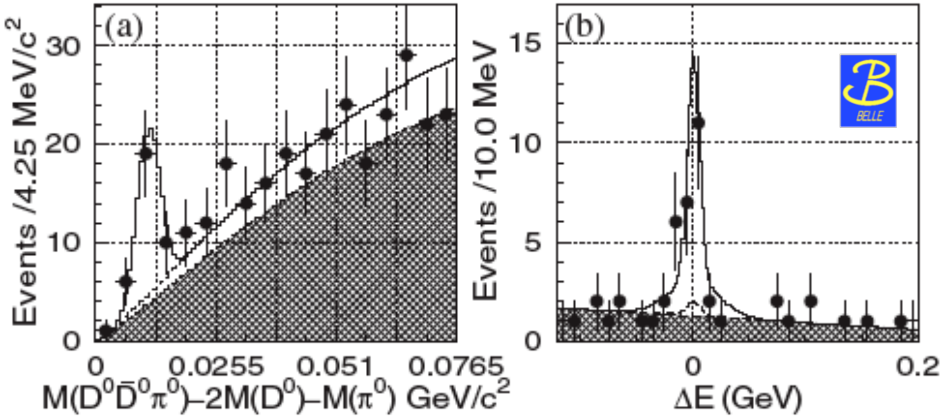
X(3872) mass measurement - I

(2006)[1] & (2008)[2] observed the decay

$$X(3872) \to \bar{D}^0 D^{*0} \to \bar{D}^0 (D^0 \pi^0)$$

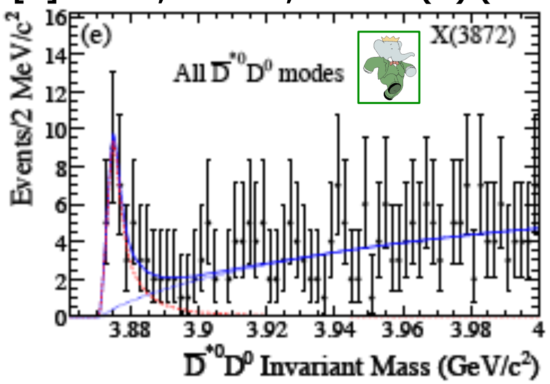
and their mass measurements are very consistent but $\sim 3 MeV/c^2$ above the mass measured in the $J/\psi \pi^+ \pi^-$ decay mode.

[1] Belle, PRL 97, 162002 (2006)



(2008): width $\Gamma_{D^0 \bar{D}^{0*}} = (3.0^{+1.9}_{-1.4} \pm 0.9) MeV$

[2] BaBar, PRD 77, 011102(R) (2008)



This shift faded out more recently with latest 's measurement (2010)[3], discarding the idea that there could be 2 different states with two different decay modes [X(3872) & X(3875)].

The $\bar{D}^0 D^{*0}$ is the favourite over $J/\psi \pi^+ \pi^-$ by almost 1 order of magnitude:

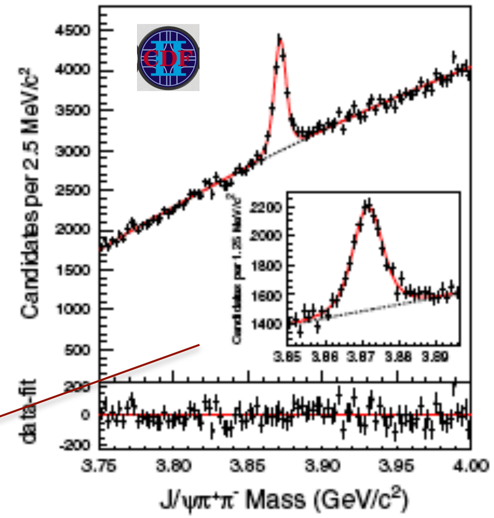
$$\left\langle \frac{B\left(X(3872) \to D^0 \bar{D}^{*0}\right)}{B\left(X(3872) \to J/\psi\ \pi^+ \pi^-\right)} \right\rangle_{Belle-BaBar} \approx 16.7 \pm 5.8$$

X(3872) mass measurement - II

In molecular state hypothesis (loosely bound $\bar{D}^0 D^{*0}$) the mass should be below the mass of the $\bar{D}^0 D^{*0}$ threshold.

Precise mass measurement would tell us what fraction of X lineshape (determined by $E_{binding}^{X(3872)}$) would lie below/above $\bar{D}^0 D^{*0}$ threshold;

$$E_{binding}^{X(3872)} \cong m(D^0 D^{*0}) - m(X) = 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X)$$

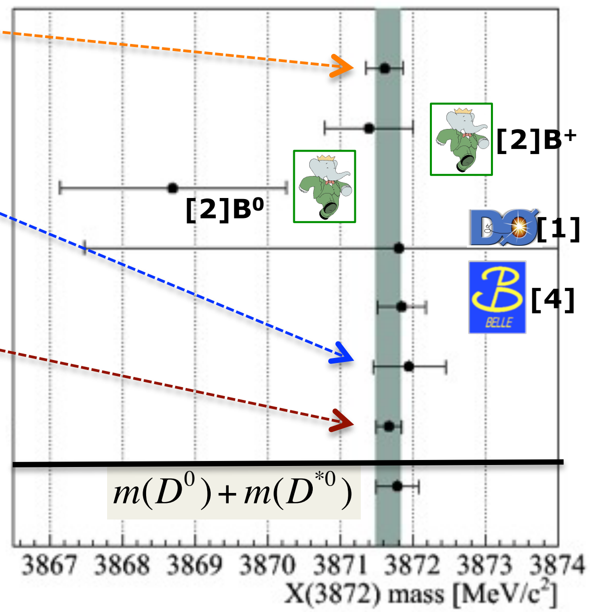


Mass average with inclusive $J/\psi \pi^+ \pi^-$ final state is dominated by the CDF [3] most precise single measurement :

$$3871.61 \pm 0.16 \pm 0.19 MeV$$

Recent LHCb result [5] is less precise: $3871.95 \pm 0.48 \pm 0.12 MeV$
(by 2010 data; the update should be better with 2011 data).

With this result new average is: $3871.66 \pm 0.18 MeV$



[1] D0, PRL 93, 162002 (2004)
[2] BaBar, PRD77,111101 (2008)
[3] CDF, PRL 103, 152001 (2009)
[4] Belle, PRD 84, 052004 (2011)
[5] LHCb, EPJ C72, 1972 (2012)

X(3872) mass measurement - III

$\langle m_{X\to J/\psi\pi\pi} \rangle = (3871.66 \pm 0.18) MeV$ **vs** $m(D^0) + m(D^{*0}) \cong 3871.94 \pm 0.33\, MeV/c^2$ **(PDG2008)**

$\Delta m_{thr} \cong (-0.42 \pm 0.18 \pm 0.33) MeV$ **[below threshold]**

± 0.39

Molecular model still possible
[but very loosely bound molecule !]

This limits the hypothetical binding energy to $E^{X(3872)}_{binding} < 1 MeV$ **.**
Using PDG2012 averages (and high precision on Δm exp. estimation):

$$E^{X(3872)}_{binding} \cong m(D^0 D^{*0}) - m(X) = 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X) = (0.16 \pm 0.32) MeV$$

This limit doesn't foreclose the possibility for the X(3872) to be above threshold: **relevant fraction of X lineshape will lie above.**

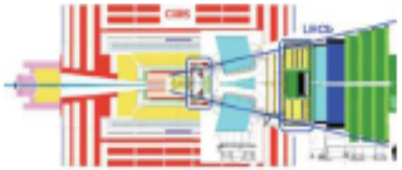
Precise mass measurement of X(3872) and *D^0* needed

[1] LHCb, JHEP 06, 065 (2013)

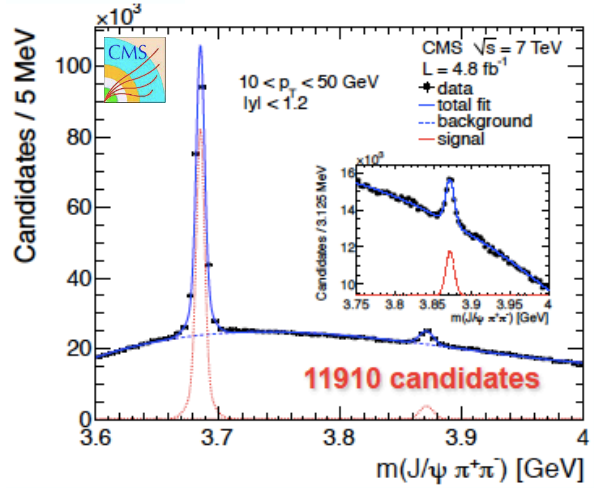
Recent LHCb *m(D^0)* result[1] provided new PDG average & $E^{X(3872)}_{binding} = (0.09 \pm 0.28) MeV$

This vanishingly small binding energy (~100keV) leads to a radius of *~14fm* (3 times as large as the deuteron)

- Measurements of the prompt production rate at the LHC as a function of p_T provides a test of the NRQCD factorization approach to X(3872) production;
  CMS does @ central rapidities, kinematic region complementary to that of LHCb



Differential xsection for prompt prod. measured using $J/\psi\ \pi^+\pi^-$ decays and assuming unpolarized *X(3872)* with $J^{PC}=1^{++}$ (later confirmed by LHCb)



X(3872) production @LHC

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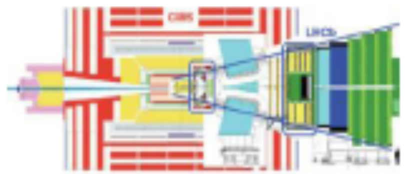
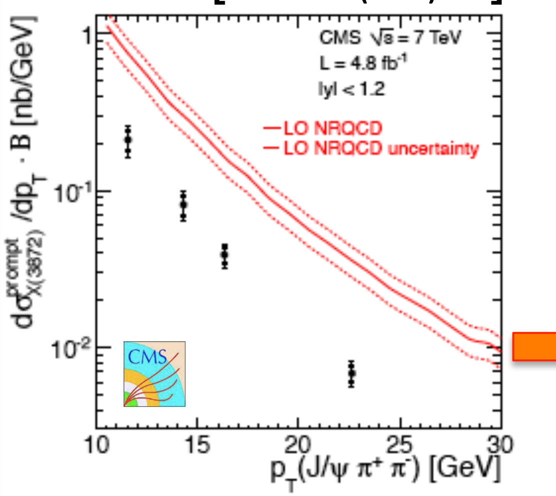


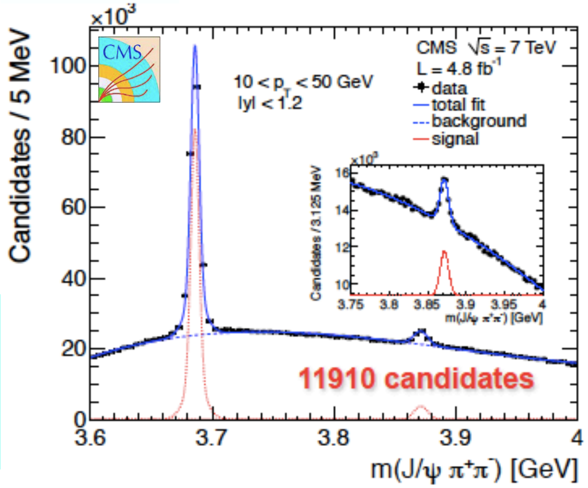
[**JHEP 1304 (2013) 154**]



Predictions by Artoisenet & Brateen [**PRD 81,(2010),114018**] with calculations normalized using Tevatron results, modified by the authors to match the phase-space of the CMS measurement

Differential xsection for prompt prod. measured using $J/\psi\ \pi^+\pi^-$ decays and assuming unpolarized *X(3872)* with $J^{PC}=1^{++}$ (later confirmed by LHCb)

NRQCD predictions rather exceed the measured value, while p_T dependence is reasonably described



- Integrating over p_T (10-30*GeV*) [and $|y|<1.2$] get the integrated cross section times the branching fraction:

$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872) \rightarrow J/\psi\ \pi^+\pi^-\right) \cong (1.06 \pm 0.11 \pm 0.15)nb$$

Comparing vs NRQCD prediction $\cong (4.01 \pm 0.88)nb$: **difference >3σ**
[LHCb gets a difference ~2.4σ in its kinematic region]

X(3872) production @LHC

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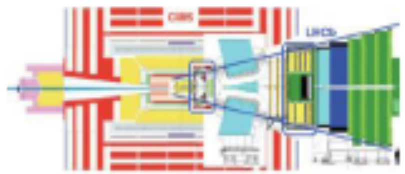
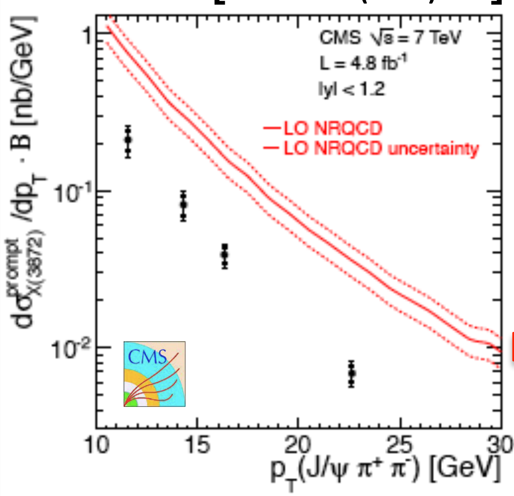


[JHEP 1304 (2013) 154]



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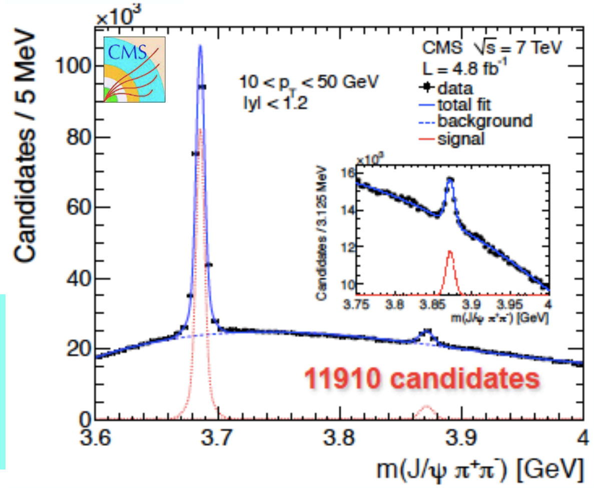

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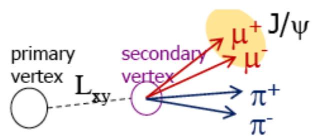
[LHCb gets a difference ~2.4σ in its kinematic region]

- Further results:
  - Dipion invariant mass consistent with intermediate ρ
  - Total xsection largely dominated by prompt production (~75%)
  - Non-prompt fraction ($\cong 0.263 \pm 0.028$) independent on p_T



X(3872) decays & J^{PC} - I

Possible hypotheses for the nature of X(3872):

- Close proximity to $D^0\bar{D}^{*0}$ threshold → **loosely bound molecular state**
  - mass value is crucial but not enough experimental sensitivity so far
  - molecular state is compatible with $J^{PC} = 0^{-+},\ 1^{++}$

$J^{PC} = 2^{-+}$ would make impossible a pure $\bar{D}^0 D^{*0}$ molecule that would have a P-wave between the $\bar{D}^0$ & D^{*0} mesons.

Experimental determination of quantum numbers is crucial !

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- **tetraquark**
  - (2005) searched, with no result, for a charged partner state $X^+ \to J/\psi\ \rho^+ \to J/\psi\ (\pi^+\pi^0)$ suggested by the 4-quark interpretation; no charged equivalent (D^+D^{*0}) observed!
  - favoured J^{PC} assignement would be $J^{PC}=1^{++}$

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- **conventional charmonium**: assignements would be $\chi_{c1}(2^3P_1)$ or $\eta_{c2}(1^1D_2)$
  - J^{PC} would be respectively $J^{PC} = 1^{++},\ 2^{-+}$
  - $c\bar{c} \to \rho J/\psi$ maximally violates isospin
  - somehow ruled out by the fact that should be a pure isoscalar state; X(3872) shows an equal amount of isospin components (I=0 & I=1):

taking into account kinematical suppression it is still strong ~25% [Suzuki], while usual sizes of isospin symmetry breaking is at most a few %

$$\frac{B(X \to J/\psi\,\pi^+\pi^-\pi^0)}{B(X \to J/\psi\,\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

$\pi^+\pi^-\pi^0$ → ω^0; $\pi^+\pi^-$ → ρ^0

Experimental determination of quantum numbers is crucial !

X(3872) decays & J^{PC} - II

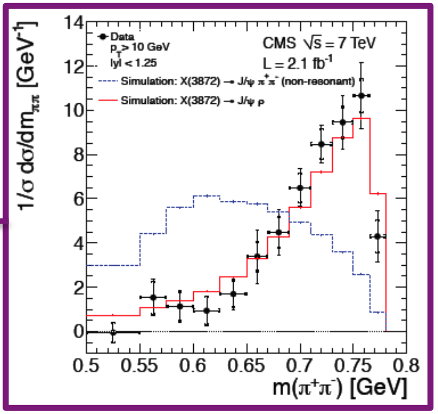
- $X(3872) \to J/\psi\ \gamma$ — BaBar 2009, Belle 2011
- $X(3872) \to \psi'\ \gamma$ seen — BaBar 2009
- $X(3872) \to \psi'\ \gamma$ not seen (U.L.) — Belle 2009

→ $C_X = +1$ → for $X \to J/\psi\ \pi\pi : C_{\pi\pi} = (-1)^{L+S} = -1$ → $[S = 0 \to \text{odd } L(=1,3,\ldots)]$

→ **consistent with a** $\rho^0(1^{--}) \to \pi^+\pi^-$

- Indeed... **di-pion mass spectrum consistent with an intermediate** $\rho^0 \to \pi^+\pi^-$

This has been observed by many experiments: Belle 2005, CDF 2007, CMS 2012



C-parity is positive !

- $\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.4 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})) \times 10^{-6}$ — BaBar 2008

$\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8(\text{stat}) \pm 0.1(\text{syst})) \times 10^{-6}$ — BaBar 2009

$$\frac{\mathcal{B}(X(3872) \to J/\psi\gamma)}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} = (0.3 \pm 0.1)$$

unexplainable assuming it is the conventional charmonium state *$1^1D_2(2^{-+})$*

- **Detailed angular analysis [CDF[1](2007); *method of helicity amplitudes*] definitely favours $J^P = 1^+,\ 2^-$ assignments both decaying via $J/\psi\,\rho^0$ (they favour the vector di-pion, in *S-wave* or *P-wave* with the J/ψ).**

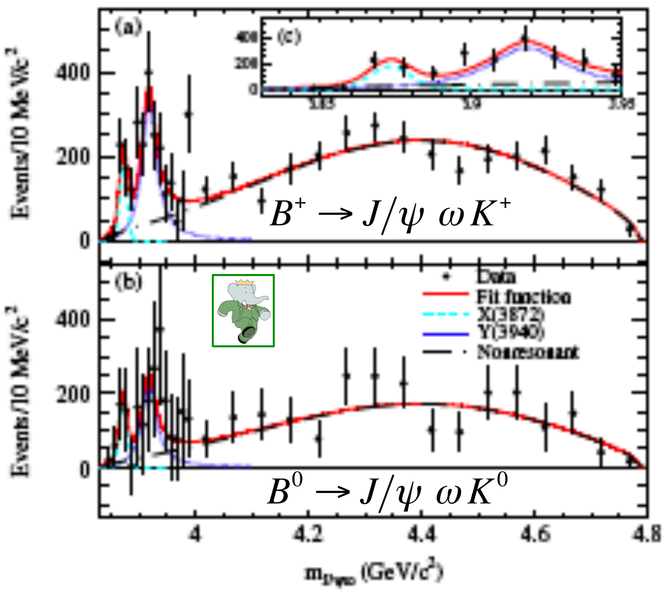
- Belle [3](2011) wasn't able to discriminate between *1*++ & *2*-+

- BaBar [2](2010) **suggested *2*-+** to explain the newly observed decay mode via $J/\psi\,\omega$(~equal rate with $J/\psi\,\rho^0$): $J/\psi(\pi\pi\pi^0)$ system in *P-wave* & $L=1 \rightarrow P=-1$

  ***2*-+ favoured** (CL~62%), ***1*++ not ruled out** (CL~7%)

  This was obtained extending the previous analysis of the observation of Y(3940) in $B^{0+} \rightarrow J/\psi\ \pi^+\pi^-\pi^0\ K^{0+}$ decays.

PHYSICAL REVIEW D 82, 011101(R) (2010)



- Belle **searched unsuccessfully for X(3872) in γγ fusion: it would have implied *J*=2 (because *J* even).**

[1] CDF, PRL 98, 132002 (2007)
[2] BaBar, PRD 82, 011101 (2010)
[3] Belle, PRD 84, 052004 (2011)

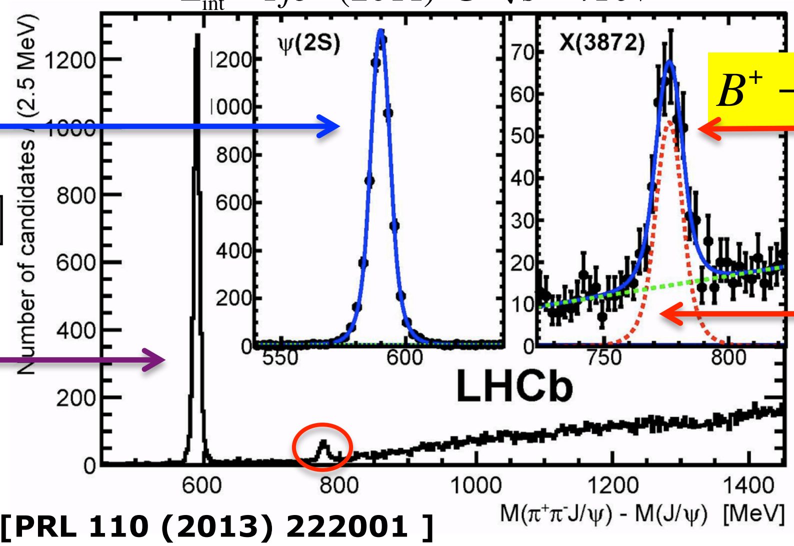
Unambiguous experimental discrimination between *1*++ & *2*-+ (being only *1*++ the "exotic" option) crucial; it has been provided by LHCb in 2013/5 !

X(3872) : J^{PC} by Full Amplitude Analysis - I

LHCb made a sophisticated angular analysis of the whole B^+ decay chain in order to unambiguously determine the quantum numbers to be $J^{PC}=1^{++}$

$$B^+ \to X(3872)\, K^+ \quad \hookrightarrow J/\psi\, \pi^+\pi^-$$

$L_{int} \cong 1 fb^{-1}(2011)$ @ $\sqrt{s} = 7TeV$



$B^+ \to \psi(2S)K^+$

$N_{sig} = 5642 \pm 76$

$[\sigma_{\Delta m} \cong (3.99 \pm 0.05) MeV]$

ψ(2S) control signal

$B^+ \to X(3872)K^+$

$N_{sig} = 313 \pm 26$

Linear Bkg

Sym.-CB Signal

68% signal purity in $\pm 2.5 \cdot \sigma_{\Delta m}$ region $[\sigma_{\Delta m} \cong (5.5 \pm 0.5) MeV]$

[PRL 110 (2013) 222001]

The full angular analysis of the whole B^+ decay chain is performed in 5D considering all angular correlations [see next slide for the definition of 6 angles]**.**
CDF analysis was 3D [X(3872) reconstructed inclusively]

The angular correlations carry information about the J^{PC} *of the X(3872)*.

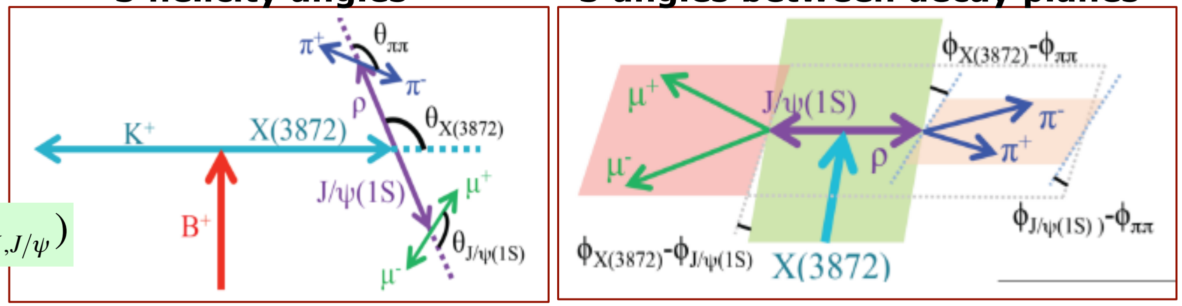
Compared with previous analysis, the measurement benefits from larger statistics.

Definition of 6 angular variables (5 independent):

5D angular space :

$$\Omega \equiv (\cos\vartheta_X, \cos\vartheta_{\pi\pi}, \cos\vartheta_{J/\psi}, \Delta\phi_{X,\pi\pi}, \Delta\phi_{X,J/\psi})$$

3 helicity angles / **3 angles between decay planes**



Define PDF in 5D angular space : $P(\Omega \,|\, J_X) \propto \left|\mathrm{M}(\Omega \,|\, J_X)\right|^2 \cdot \varepsilon(\Omega)$

5D angular efficiency

decay matrix element

Note: **CDF analysis was 3D** [X(3872) reco. inclusively: prompt prod. → unknown polarization] and the 3 angles were: $\vartheta_{J/\psi}, \vartheta_{\pi\pi}, \Delta\phi_{J/\psi,\pi\pi} = \phi_{J/\psi} - \phi_{\pi\pi}$

Angular correlations obtained [PRL 98, 132002 (2007)] using the *helicity formalism* :

$$\left|\mathrm{M}(\Omega \,|\, J_X)\right|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \left| \sum_{\lambda_{J/\psi},\lambda_{\pi\pi}=-1,0,+1} A_{\lambda_{J/\psi},\lambda_{\pi\pi}} \cdot D^{J_X}_{0,\lambda_{J/\psi}-\lambda_{\pi\pi}}(\phi_X, \vartheta_X, -\phi_X) \cdot D^1_{\lambda_{\pi\pi},0}(\phi_{\pi\pi}, \vartheta_{\pi\pi}, -\phi_{\pi\pi}) \cdot D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\phi_{J/\psi}, \vartheta_{J/\psi}, -\phi_{J/\psi}) \right|^2$$

with... $\lambda_\mu, \lambda_{J/\psi}, \lambda_{\pi\pi}$: particles' helicities ; $D^J_{\lambda_1,\lambda_2}$: Wigner functions ;

$A_{\lambda_{J/\psi},\lambda_{\pi\pi}}$: helicity couplings (in terms of LS couplings, B_{LS}); $L \equiv L(J/\psi, \pi\pi)$, $S = S_{J/\psi} + S_{\pi\pi}$

Energy release is small →
→ **lowest L dominates**:

- se $J = 1 : L_{\min} = 0 \Rightarrow S = 1$ → 0 free parameters
- se $J = 2 : L_{\min} = 1 \Rightarrow S = 1,2$ → 1 complex free parameter:

Discriminant construction (with background subtraction by *sPlot* technique) :

Likelihood ratio test : $$t = 2\ln\left[\frac{L(2^{-+})}{L(1^{++})}\right] = -2 s_w \sum_{i=1}^{N} w_i \frac{P(\Omega_i | 2^{-+}, \alpha_{max})}{P(\Omega_i | 1^{++})}$$

α_{max} maximizes $L(2^{-+})$

sWeights

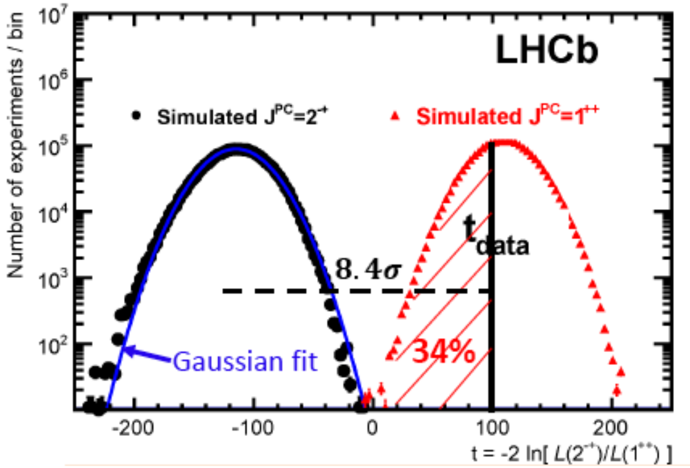
By definiton :
- *t>0* implies 1^{++} favoured
- *t<0* implies 2^{-+} favoured

Compare results to simulated experiments for both hypotheses :

$t_{data} \cong 99$ observed

1^{++} favoured over 2^{-+} @ 8.4σ

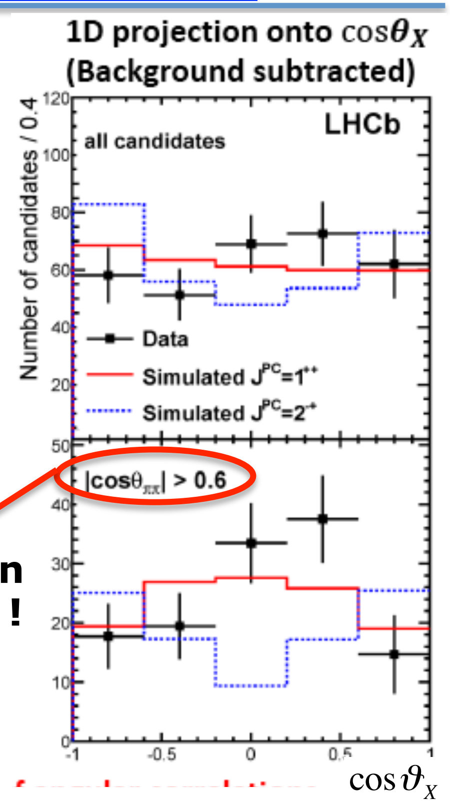
***1^{++} p-value* is high (34%)**



This favours an exotic interpretation

1^{++} consistent with molecule, 4-quark, mixture molecule- $\chi_{c1}(2^3P_1)$

Additional test



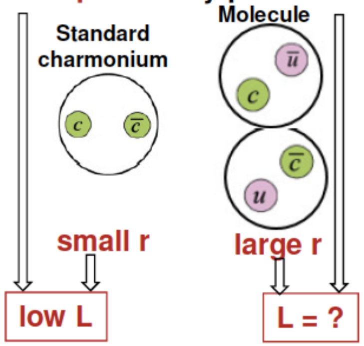
Separation increases !

Importance of angular correlations !

X(3872) : J^{PC} by Full Amplitude Analysis - IV

- **LHCb presented @ MoriondQCD-2015 [1] a re-analysis of the quantum numbers of X(3872)[2]. Previous analysis assumed the lowest possible orbital angular momentum (*L*) in the X(3872) sub-decay within $B^+ \to X(3872)K^+ \to (J/\psi\ \pi^+\pi^-)K^+$. Significant $L > L_{min}$ can a) invalidate the previous assignment, b) hint a molecular structure.**

low p of decay products [small Q-value]

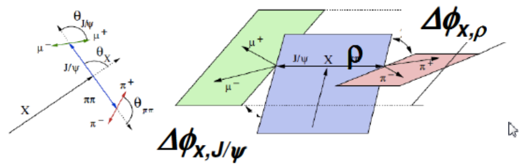


[1] LHCb-PAPER-2015-015
[2] PRL 110 (2013) 222001

Heavy Quark Spectroscopy at LHCb; Moriond QCD 2015 T.Skwarnicki 7

Determination of X(3872) J^{PC}: formalism

$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\ \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$



5 independent angles describing the decay in helicity formalism

Matrix element

$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho} \times D^{J_X}_{0,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \times D^1_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^* \times D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Big|^2$$

Relation of the helicity couplings to LS amplitudes

$$A_{\lambda_{J/\psi},\lambda_\rho} = \sum_L \sum_S B_{LS} \times \begin{pmatrix} J_{J/\psi} & J_\rho & \Big| & S \\ \lambda_{J/\psi} & -\lambda_\rho & \Big| & \lambda_{J/\psi}-\lambda_\rho \end{pmatrix} \times \begin{pmatrix} L & S & \Big| & J_X \\ 0 & \lambda_{J/\psi}-\lambda_\rho & \Big| & \lambda_{J/\psi}-\lambda_\rho \end{pmatrix}$$

Parity conservation

$$P_X = P_{J/\psi}\, P_\rho\, (-1)^L = (-1)^L$$

J^{PC}	B_{LS} all L	B_{LS} minimal L
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

LHCb 2015 — Many more amplitudes to fit

CDF 2007

LHCb 2013

LS amplitudes to be determined from the data

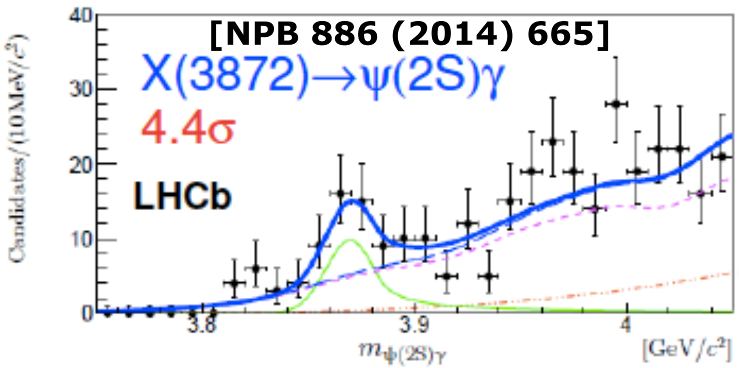
Data ($3fb^{-1}$) strongly prefer 1^{++} hypothesis (more than a confir-mation: here no assumption about *L*)!

***D*-wave fraction in the decay $X(3872) \to J/\psi\ \rho^0$ for $J^{PC}=1^{++}$ results to be consistent with zero.**

No hints for a large size of X(3872) from this *L*-study.

X(3872) from radiative decays

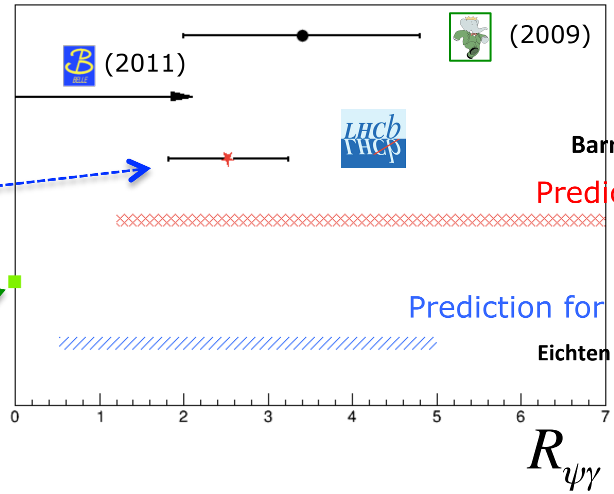
- **Pure molecular model (still possible with a positive $E_{binding}^{X(3872)} \cong m(D^0 D^{*0}) - m(X) \cong (0.09 \pm 0.28 MeV)$) is not supported by recent measurement by LHCb of $X(3872) \to \psi' \gamma$ in $B^+ \to X(3872)K^+ \to (\psi' \gamma)K^+$**



Peaking BKG (from $B^+ \to \psi' K^{*+}$)

Combinatorial BKG

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$



Barnes et al.(2005), Li et al.(2009)

Prediction for pure $c\bar{c}$ state

Prediction for admixture of $c\bar{c}$ + $\bar{D}^0 D^{*0}$

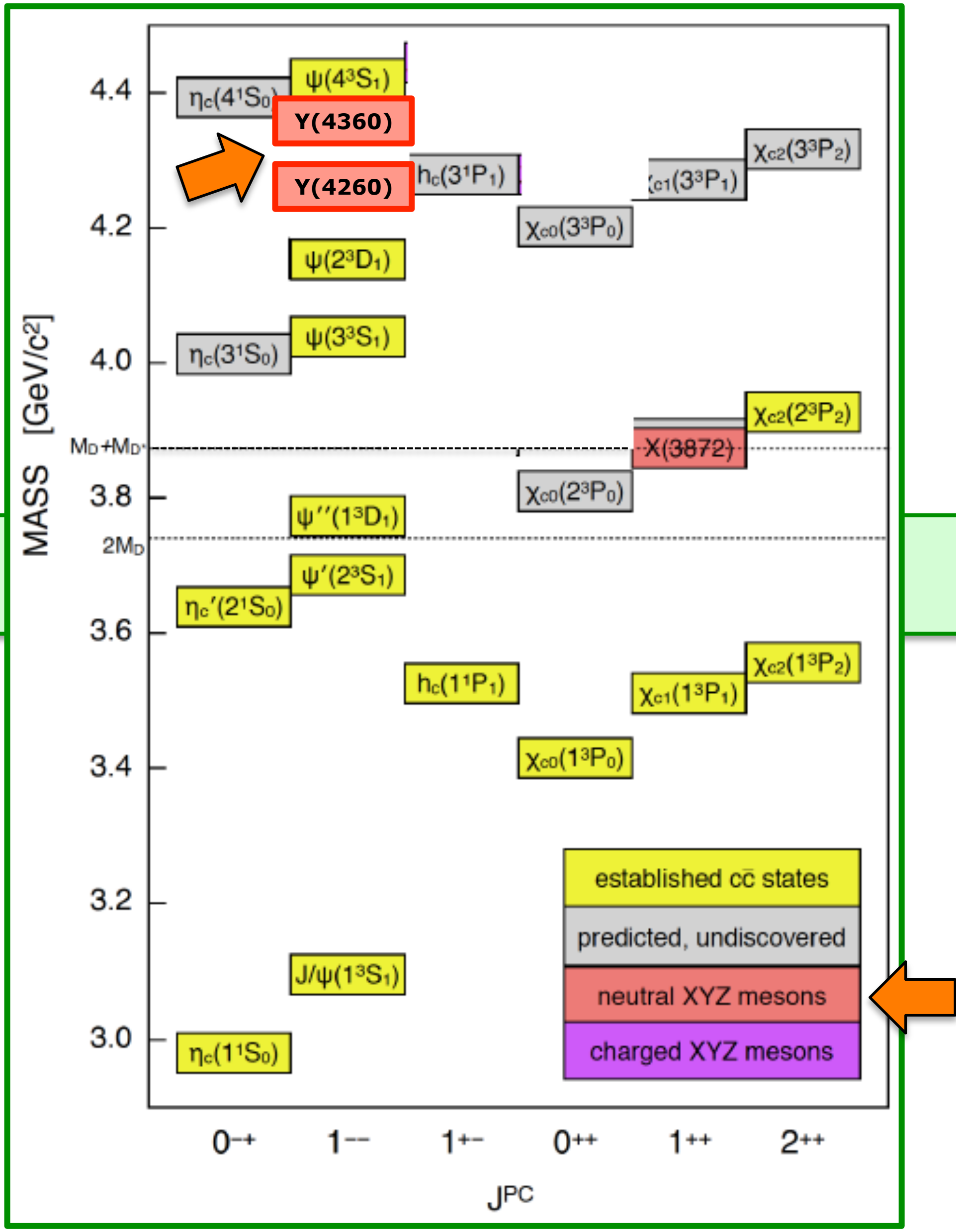
Eichten et al.(2006), Badalin et al.(2012)

Prediction for pure $\bar{D}^0 D^{*0}$ molecule

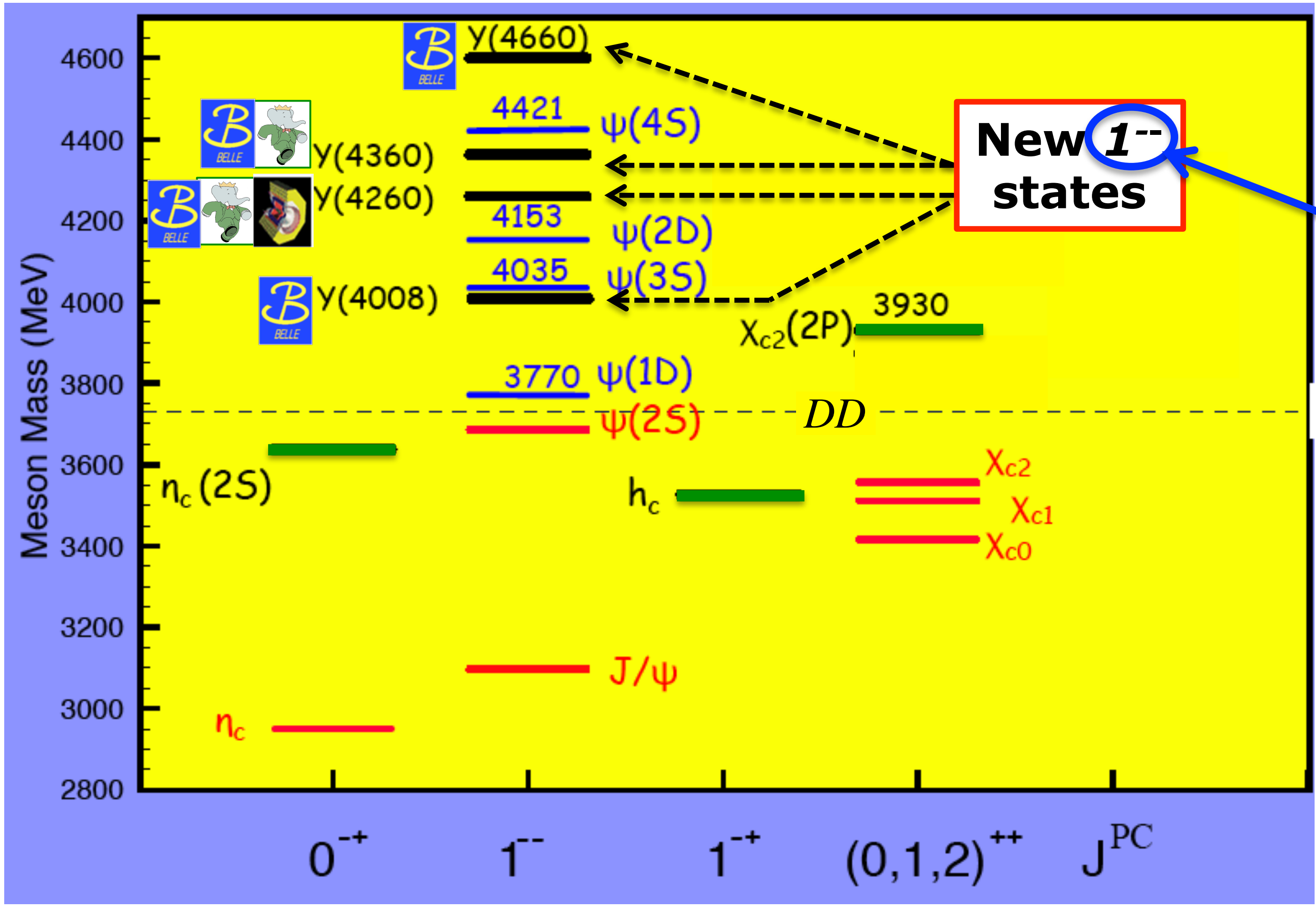
Swanson et al.(2004), Dong et al.(2011), Ferretti et al.(2014)

Alternatively to the tetraquark option ($c\bar{c}\ u\bar{u}$), the X(3872) may have a significative $\chi_{c1}(2^3P_{1^{++}})$ component [see Karliner&Rosner, PRD91 (2015) 014014]: $\bar{D}^0 D^{*0} + c\bar{c}\left[\chi_{c1}\left(2^3P_1\right)\right]$ (mixed wave-functions)

1⁻⁻ states & *Y(4260)*

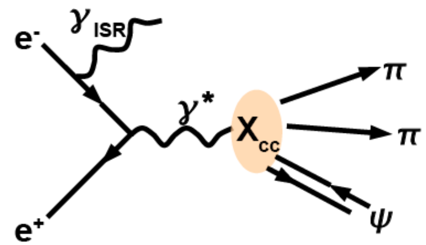


The 1^{--} family & *Y(4260)* - I



in ISR processes :

$$e^+e^- \to \gamma_{ISR} Y$$



Exotic since all the $1^{--}\ c\bar{c}$ states near their masses have already been assigned!

$$2005 : e^+e^- \to \gamma_{ISR} Y(4260) \to \gamma_{ISR}\left(J/\psi\ \pi^+\pi^-\right)$$

$$2007 : e^+e^- \to \gamma_{ISR} Y(4008) \to \gamma_{ISR}\left(J/\psi\ \pi^+\pi^-\right)$$

$$2007 : e^+e^- \to \gamma_{ISR} Y(4360) \to \gamma_{ISR}\left(\psi(2S)\pi^+\pi^-\right)$$

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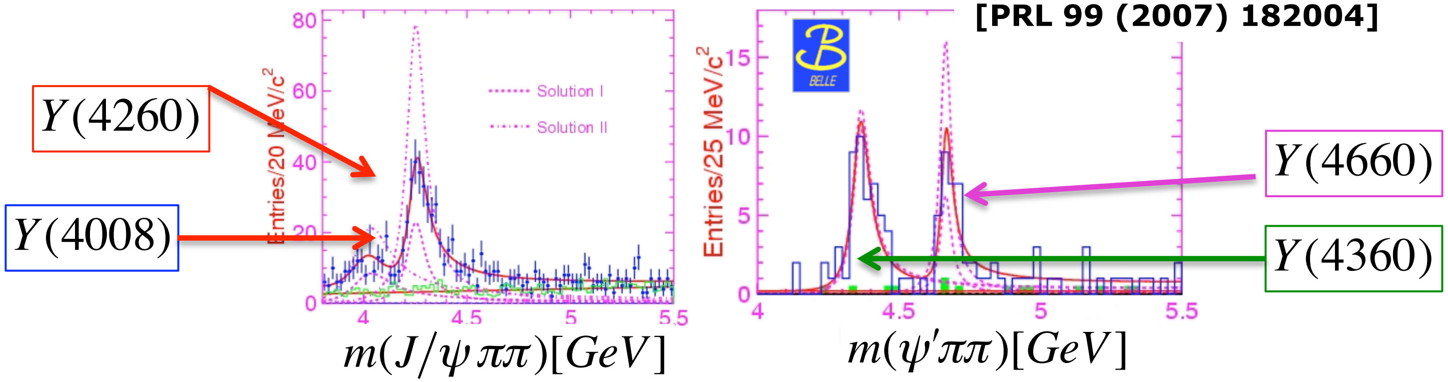
The 1^{--} family & *Y(4260)* - II

- **B-factories can investigate a large range of masses for 1^{--} particles produced in e^+e^- annihilation by looking ISR radiation bringing the center-of-mass energy to the particle's mass. The *Y(4260)* was discovered by in 2005, confirmed by :**



[PRL 99 (2007) 182004]

- **Discriminantion between conventional/exotic is related to relative rates between decays into charmonium and two open charm mesons! (2007) found no evidence of $Y \to D^{(*)}\bar{D}^{(*)}$ decays in ISR events.**

- **These states are hybrid <u>candidates</u>**
  (1^{--} at ~*4.2*GeV is expected by LatQCD), or molecules [$DD_1(2420)$, $\chi_c\rho$, $\chi_c\omega$] or 4quark.

The 1^{--} family & *Y(4260)* - II

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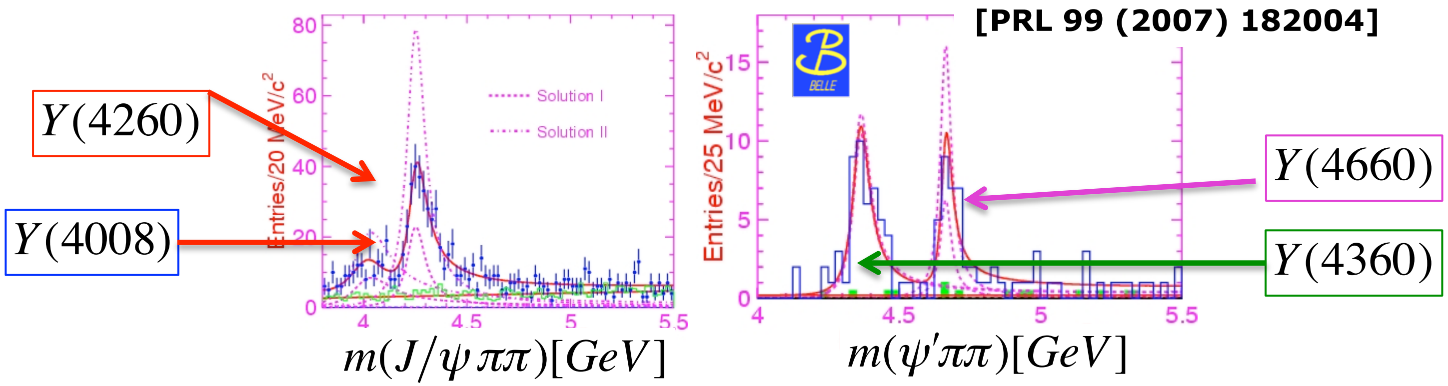
[PRL 99 (2007) 182004]



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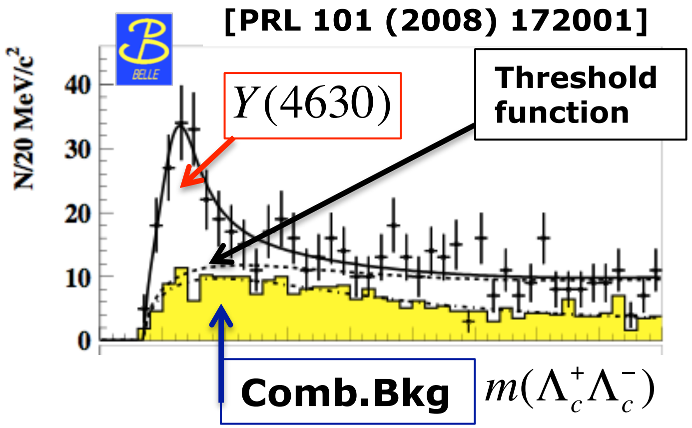
- **These states are hybrid candidates (1^{--} at ~4.2GeV is expected by LatQCD), or molecules [$DD_1(2420)$, $\chi_c\rho$, $\chi_c\omega$] or 4quark.**

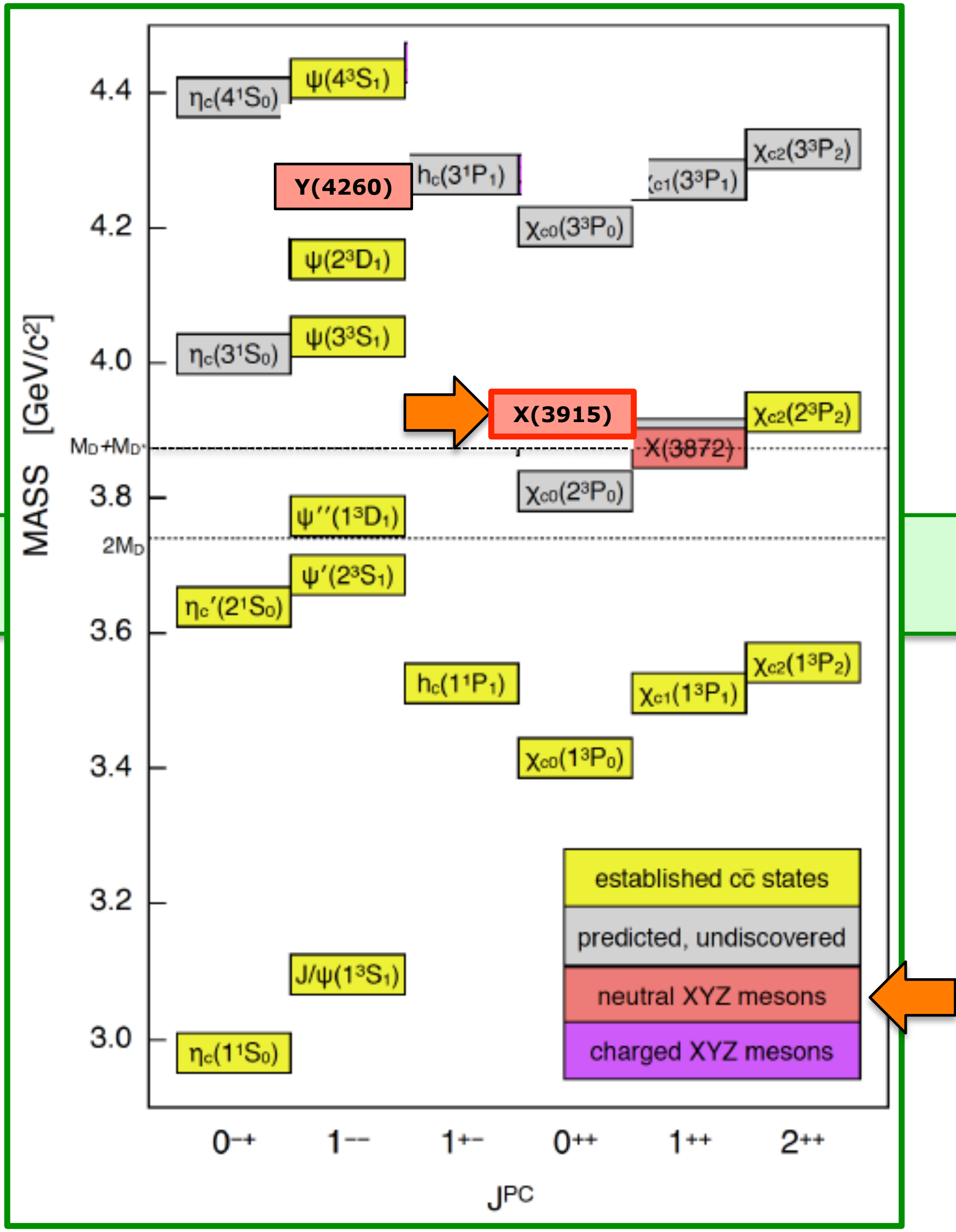
- **The *Y(4660)* may be the same state as X(4630) [consistent mass & width] found by (2008) in ISR events (eventually a baryonium state?)**

$$e^+e^- \to \gamma_{ISR} X(4630) \to \gamma_{ISR}(\Lambda_c \bar{\Lambda}_c)$$

[PRL 101 (2008) 172001]



The "3940 family"



Y(3940)/*X(3915)* - I

[PRL 101 (2008) 082001]

- **In 2008 the BaBar's first *Y(3940)* analysis of $B \to J/\psi\omega$ decays confirmed Belle's observation [but at lower mass: *X(3915)*]:**

$$B^{0+} \to Y(3940)K^{0+} \to (J/\psi\ \omega)K^{0+}$$

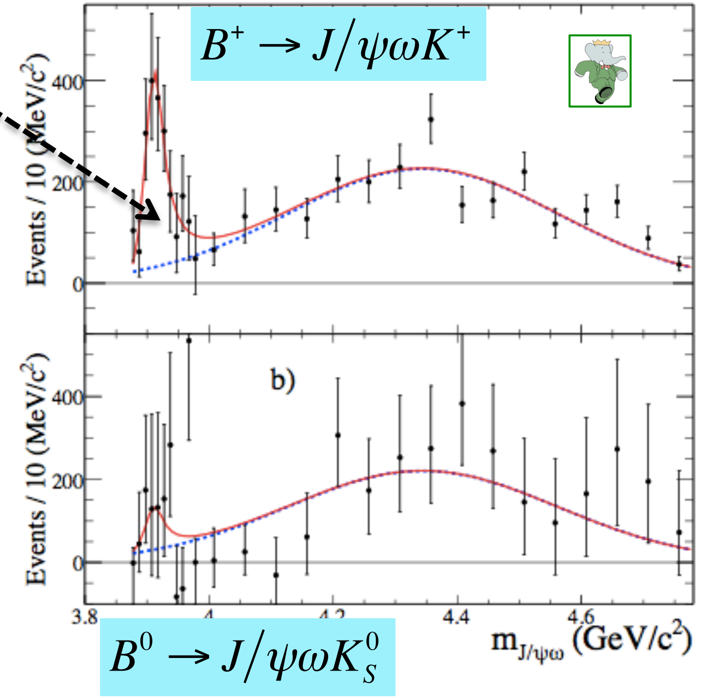
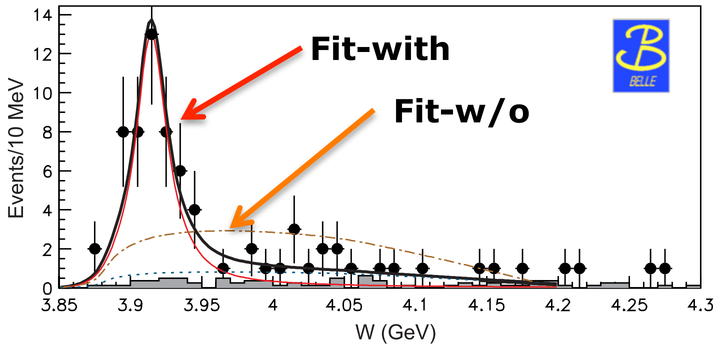


FIG. 3: The corrected $J/\psi\omega$ mass distribution for (a) B^+ and (b) B^0 decay. Each solid (dashed) curve represents the total fit function (the nonresonant contribution).

- **Later (2010) Belle [and BaBar] observed the state, called Y(3915), in γγ fusion (0^{++}, ~~2^{++}~~), consistent with the parameters of *X(3915)*:**

$$e^+e^- \to (e^+e^-)(\gamma\gamma) \to (e^+e^-)(J/\psi\ \omega)$$

PRL 104:092001 (2010)



$$[W = m(\mu\mu\pi\pi\pi^0) - m(\mu\mu) + m(J/\psi)]$$

Under the reasonable hypothesis that *Y(3940)* & *Y(3915)=X(3915)* are the same state, this would be the first case of an "exotic" observation with 2 different production mechanisms.

Why it must be exotic ? **For Belle (2010) the signal is absent in $B \to (D^0 \bar{D}^0)K$! Otherwise the conventional assignment would be $\chi_{c0}(2P)$ [but mass is also too high], i.e. another radial excitation of χ triplet [remember that *Z(3930)*, decaying in $D\bar{D}$ was identified as one of the $\chi_{c2}(2P)$].**

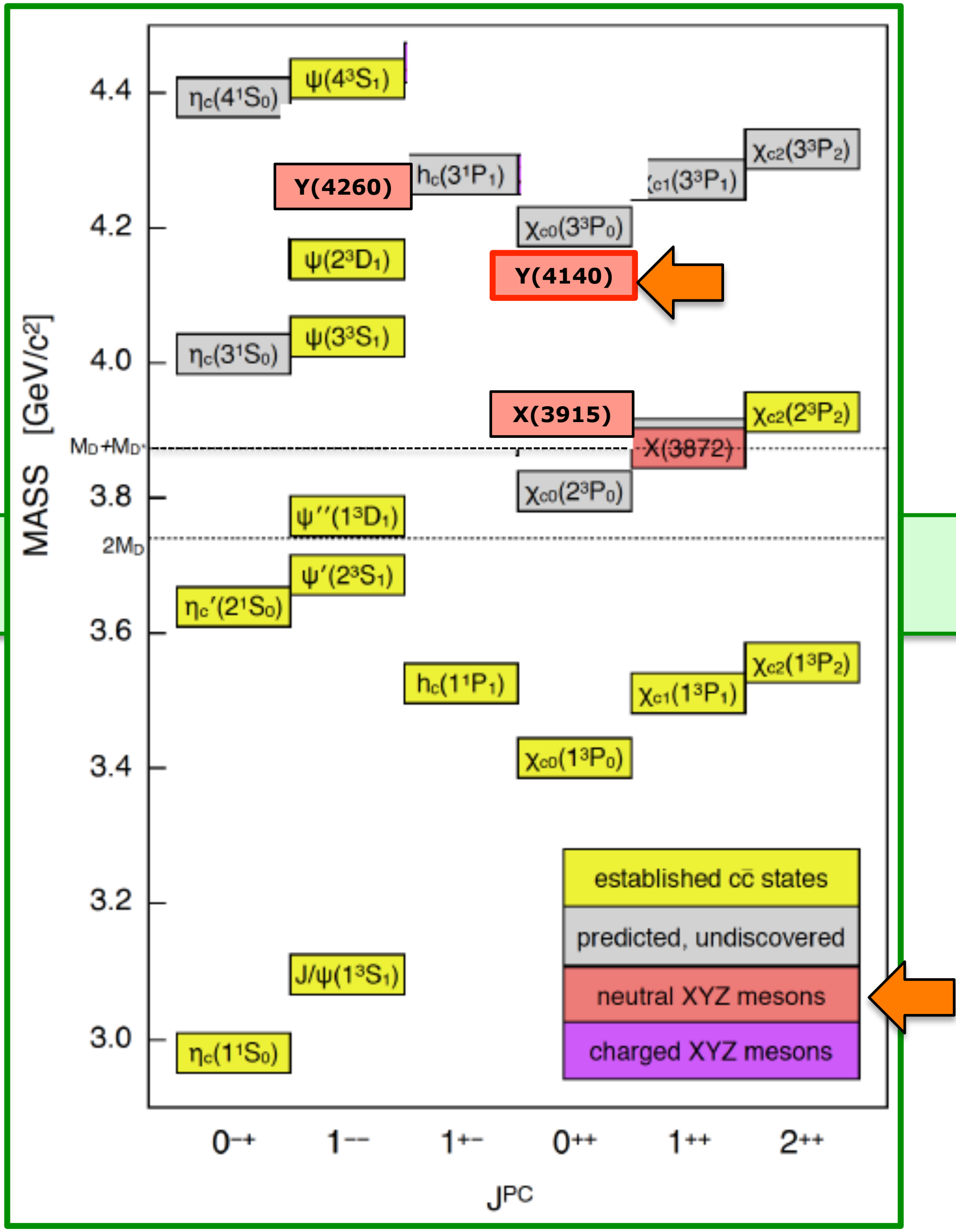
What kind of exotic ?

1) $D^* \bar{D}^*$ **molecule with $J^P = 0^{++}$ & with an hadronic wave function given by**

$$\frac{1}{\sqrt{2}}\left(\left|D^{*+}D^{*-}\right\rangle + \left|D^{*0}\bar{D}^{*0}\right\rangle\right)$$

2) a 0^{-+} hybrid charmonium (which cannot decay in $D\bar{D}$)
and, in this case, may be the lighter 0^{-+} partner (spin dependent splittings for hybrids) of the Y(4260) considered as the 1^{--} hybrid !

Y(4140)

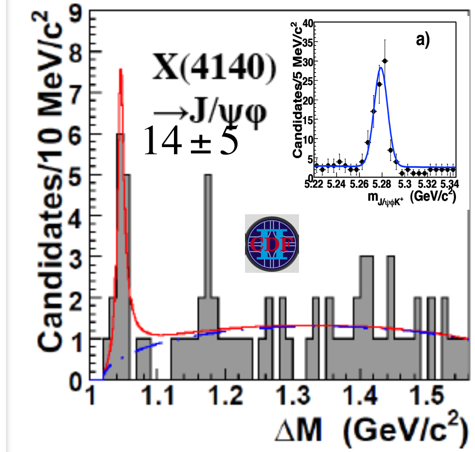


4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
MASS [GeV/c²]
MD+MD*
2MD
ηc(4¹S₀)
ψ(4³S₁)
Y(4260)
hc(3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
ψ(2³D₁)
Y(4140)
ηc(3¹S₀)
ψ(3³S₁)
X(3915)
χc2(2³P₂)
X(3872)
χc0(2³P₀)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
J/ψ(1³S₁)
ηc(1¹S₀)
established cc̄ states
predicted, undiscovered
neutral XYZ mesons
charged XYZ mesons
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

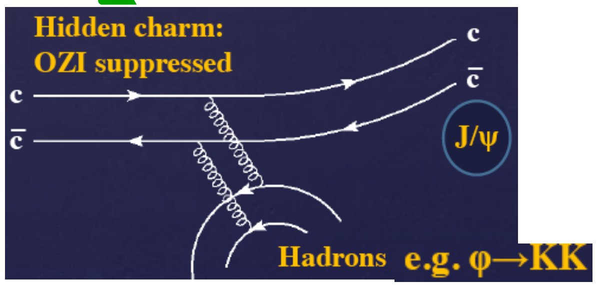
Y(4140) - I

[1] (2009) **reported evidence (@3.8σ) for …**
narrow peak in $J/\psi\varphi$ mass spectrum,
close to the kinematical threshold,
in decays $B^{\pm} \rightarrow J/\psi\ \phi\ K^{\pm}$

[PRL 102 (2009) 242002]



Mass is well above 3770MeV open charm threshold;
the conventional charmonium …
should decay into $D\bar{D}$ **, with tiny B.R. to** $J/\psi\varphi$ **.**



This OZI suppressed transition is rare [*B.R.* $\sim 10^{-5}$] can proceed either as a 3-body decay and/or as a quasi- 2-body decay, in which J/ψ and φ come from an intermediate state $Y(c\bar{c}s\bar{s})$ **.**
Constrained phase-space would favour forming of 2-body intermediate structures.

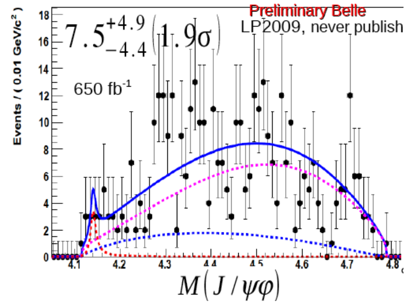
If this Y state exists and it decays into $J/\psi\varphi$, its inv. mass must be below the $D\bar{D}^*$ threshold (~4.3*GeV*) : above this threshold, the dominant decay would be $Y \rightarrow D\bar{D}^*$

Y(4140) - II

$Y(4140) \to J/\psi\phi$ ⇨ $C_{Y(4140)} = +1$ ⇨ **Possible states:** $J^{PC} = 0^{++},\ 1^{++},\ 2^{++},\ 0^{-+},\ 1^{-+},\ 2^{-+},\ 3^{-+}$

S-wave coupling ($0^{++}, 1^{++}, 2^{++}$) — P-wave coupling ($0^{-+}, 1^{-+}, 2^{-+}, 3^{-+}$)

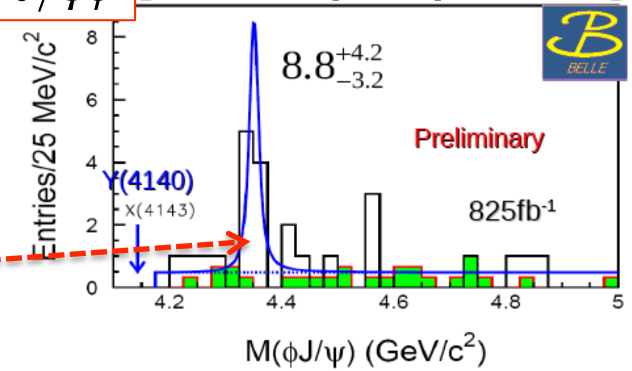
- (2009) **searched and did not find this state in the same decay: limit set on production rate, but cannot exclude CDF peak: upper limit value lower than CDF's central value!**
  [efficiency depletion at the threshold]



- ***(2010)* searched for direct production allowed if Y(4140) is a state 0^{++} or 2^{++}: no signal found.**
  This disfavors a $D_s^*\bar{D}_s^*$ molecule interpretation.

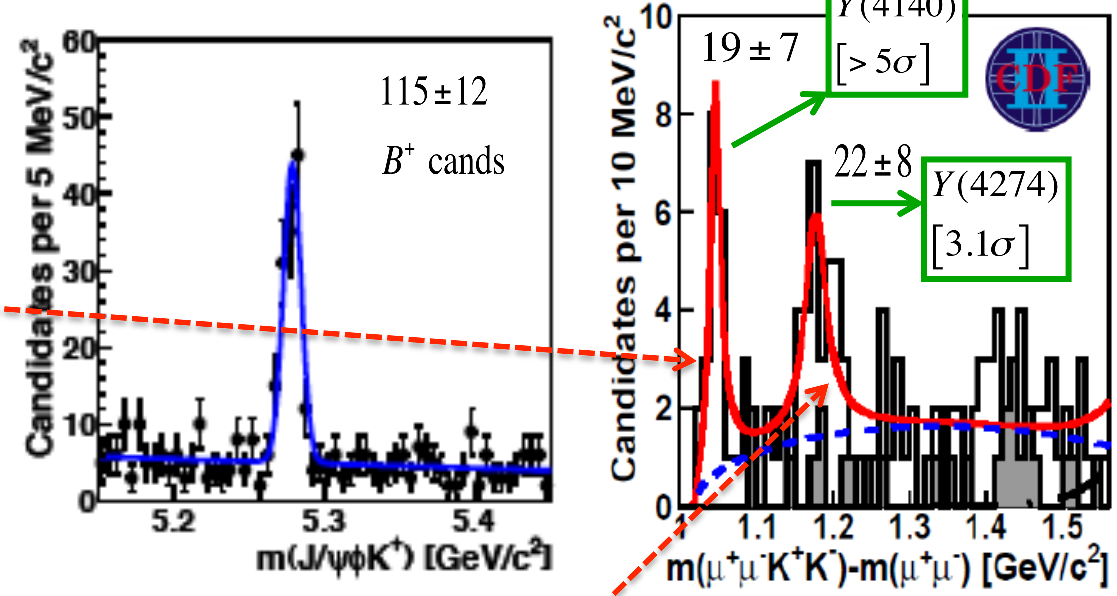
  However... they see a 3.2σ effect @ 4350*MeV* !
  This state was labelled *X(4350)*.

$\gamma\gamma \to J/\psi\phi$ **[PRL 104 (2010) 112004]**



Y(4140) - III

[arXiv:1101.6058 (2011), never published]

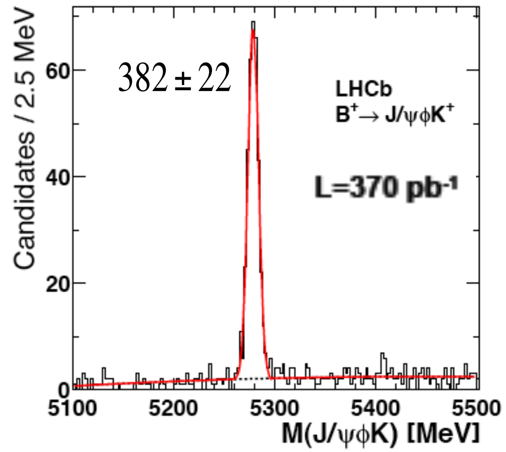


Fit assumes spin-0 relativistic B.-W.

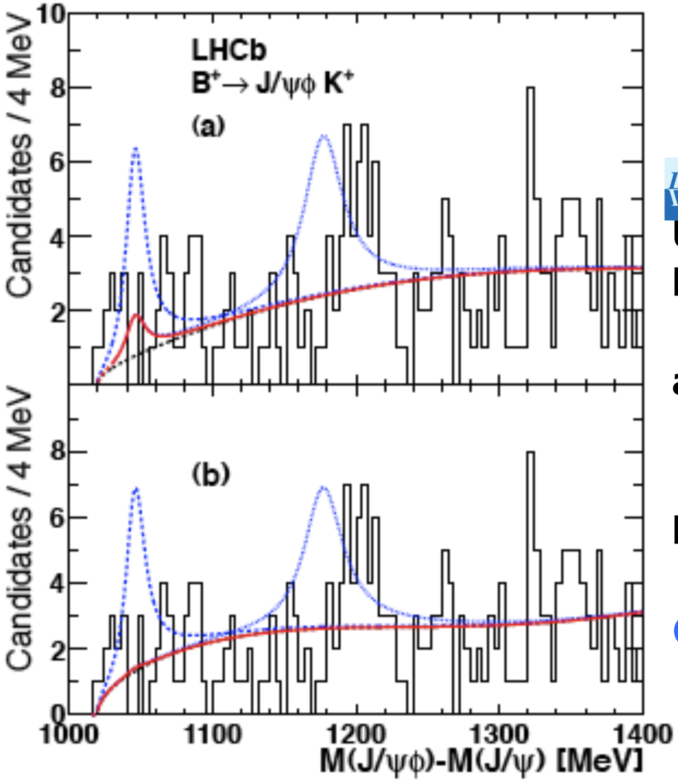
- CDF (2011) **presents update analysis with larger dataset (6.0fb^{-1} vs 2.7fb^{-1}) observing *Y(4140)* with a signif. >5σ**
  - M_1=4143.0$^{+2.9}_{-3.0}$(stat)±0.6(syst) MeV
  - Γ_1=15.3$^{+10.4}_{-6.1}$(stat)±2.5(syst) MeV

- CDF **also presents an evidence (@ a 3.1σ signif.) for higher mass peak [called *Y(4274)* state], but not consistent with Belle's signal in $\gamma\gamma \to J/\psi\phi$**
  - M_2=4274.4$^{+8.4}_{-6.7}$(stat)±1.9(syst) MeV
  - Γ_2=32.3+21.9(stat)±7.6(syst) MeV

- LHCb (2012) **has searched for these two states reconstructing** $382 \pm 22 \; B^{\pm} \rightarrow J/\psi \phi K^{\pm}$ **candidates.**



[PRD 85 (2012) 091103]



LHCb **observed no signals; this implies a 2.4σ tension with CDF. Using CDF's fit model for the signals and 2 options for bkg. parametrizations:**

a) phase-space function (as CDF) gives:

$$N_{Y(4140)} = 6.9 \pm 4.9$$
$$N_{Y(4274)} = 3.4^{+6.5}_{-3.4}$$

b) efficiency-corrected quadratic function gives **no signal.**

@90%CL upper limits on ratios of branching fractions :

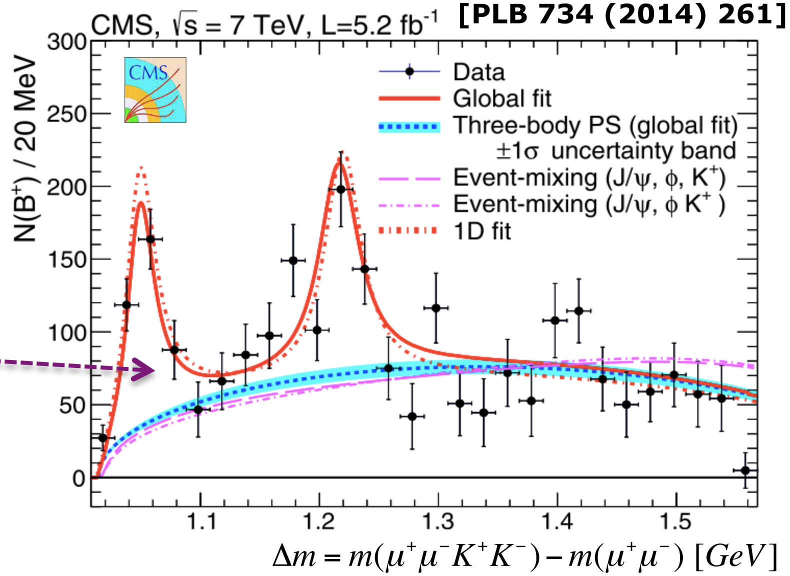
$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.08$$

Y(4140) - V

- CMS (2013) **observes two peaking structures** in the Δm mass difference spectrum by recostructing the $B^+ \to J/\psi\ \phi\ K^+$ decay (extracted B^+ signal is the largest sample collected so far).

[PLB 734 (2014) 261]



- **Peaking structure @ threshold with:**

$$m = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst}) MeV$$

$$\Gamma = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst}) MeV$$

  - **observed with >5σ stat. significance**
  - **consistent with the charmonium-like state, possibly exotic, Y(4140) from CDF [evidence also from D0 (2013)]**

- **Naïve yields' ratio estimate:** $\frac{Y_{Y(4140)}}{Y_{J/\psi\phi K}} \approx 0.11 \pm 0.03\%$ **consistent with CDF & LHCb UL**

Y(4140) - VI

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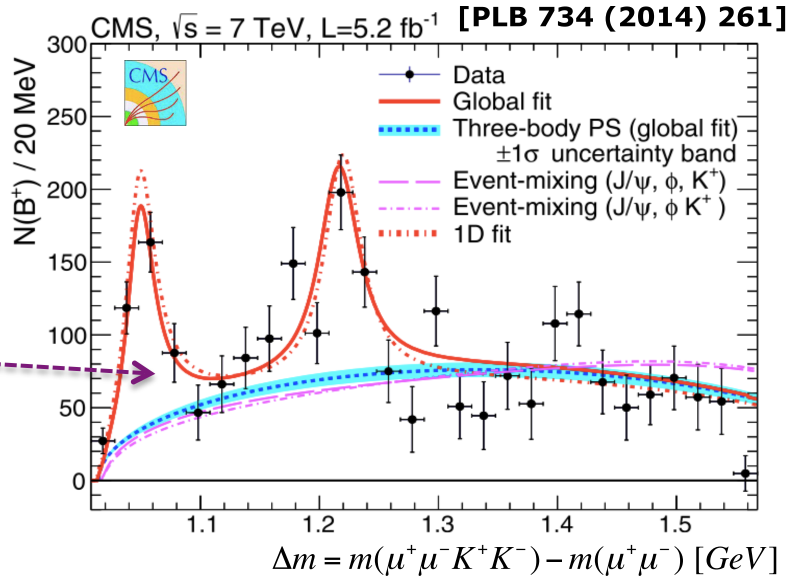
[PLB 734 (2014) 261]



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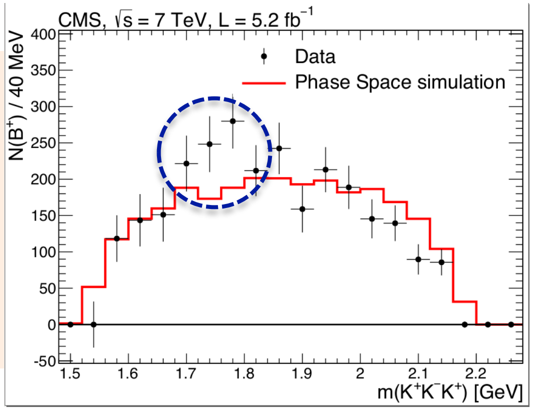
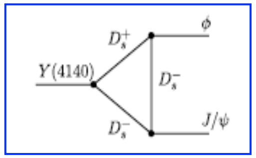
Naïve yields' ratio estimate: $\frac{Y_{Y(4140)}}{Y_{J/\psi\phi K}} \approx 0.11 \pm 0.03\%$ **consistent with CDF & LHCb UL**

Since ϕK^+ *mass* distrib. shows an excess w.r.t. PHSP profile in the region where large resonances [K_2(1770) & K_2(1820)], may appear, reflections studies are carried out and helicity configurations of the decay products are considered. Hence: Y(4140) appears to be fully uncorrelated to ϕK^+ resonances! Additional peak (*m*-shifted wrt CDF) maybe affected by them.



Y(4140) - VII

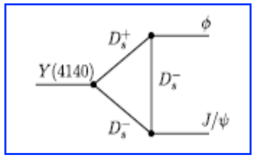
- For the *Y(4140)* decaying into $J/\psi\varphi$ several interpretations have been proposed:
  - $D_s^* \bar{D}_s^*$ **molecule**, that is the **molecular strange partner of the *Y(3940)***
  - $cs\bar{c}\,\bar{s}$ **tetraquark**,
  - **threshold kinematic effect,**
  - **hybrid charmonium,**
  - **weak transition with $D_s \bar{D}_s$ rescattering**



- **Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not easy task: 2 vectors in the final state!). It is suitable for LHCb [& CMS (adding RunII data to extract an enough pure B^+ sample with enough statistics)].**

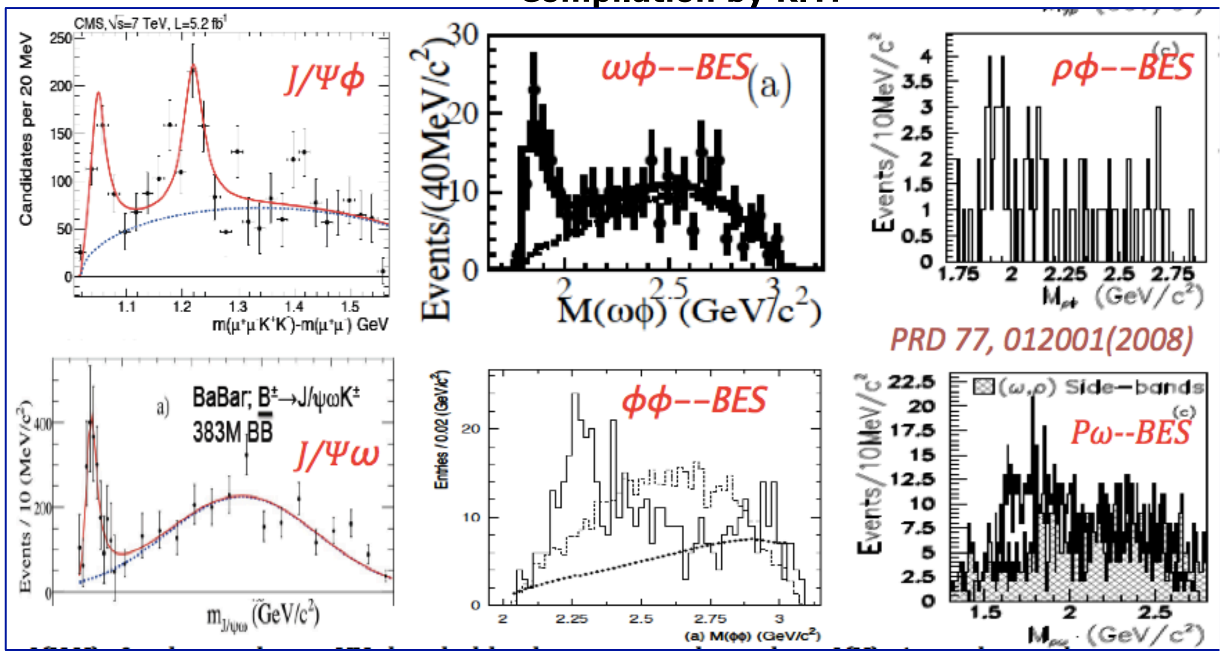
Y(4140) - VII

- For the ***Y(4140)*** **decaying into $J/\psi\varphi$ several interpretations have been proposed:**
  - $D_s^* \bar{D}_s^*$ **molecule, that is the molecular strange partner of the *Y(3940)***
  - $cs\bar{c}\,\bar{s}$ **tetraquark,**
  - **threshold kinematic effect,**
  - **hybrid charmonium,**
  - **weak transition with $D_s \bar{D}_s$ rescattering**



- **Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not easy task: 2 vectors in the final state!).**
  It is suitable for LHCb [& CMS (adding RunII data to extract an enough pure *B*⁺ sample with enough statistics)].

Compilation by K.Yi

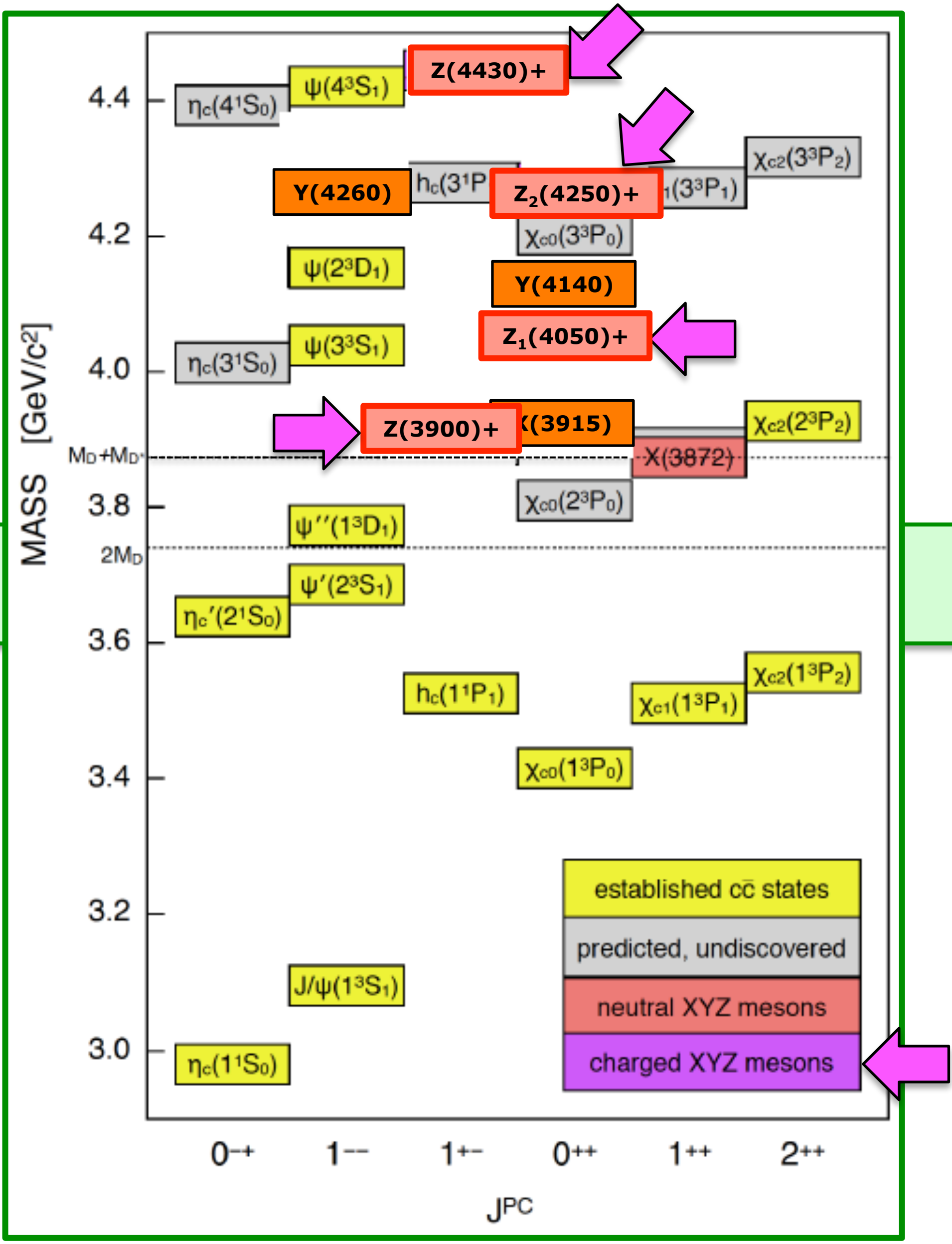


- **Maybe worthy to note that the Y(4140) state is the most recent of a series of vector-vector threshold enhancements from OZI suppressed strong processes:**

  Possibility to similar behaviour in pairs of heavy quarkonia?

Part – 1 / 4-quarks systems :
a2) Charged charmonium-like exotics

Exotic charges *Z* states

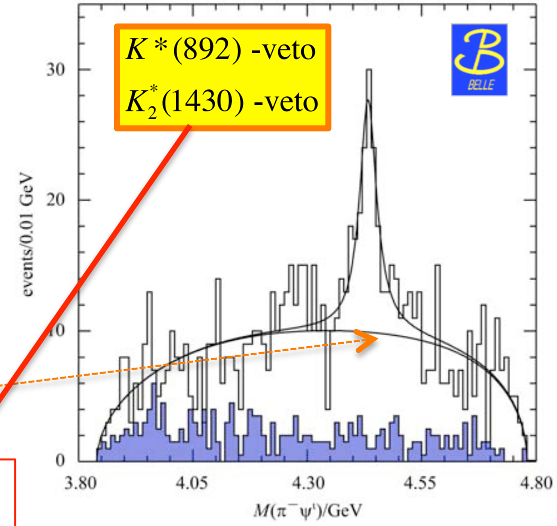


$Z(4430)^+$ - I

(2008) observes (signif.>6σ) a narrow structure in $\psi(2S)\pi^\pm$ inv. mass spectrum of the 3-body decay:

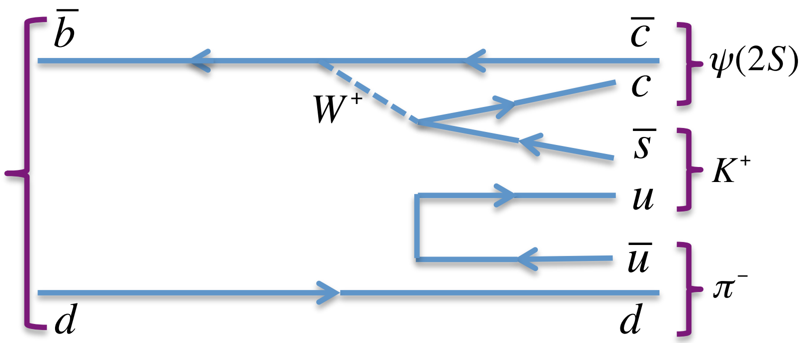
$$B^0 \to \psi(2S)\pi^- K^+ \qquad B^- \to \psi(2S)\pi^- K^0$$

with : $\psi(2S) \to \ell^+\ell^-,\ J/\psi\ \pi\pi$; $J/\psi \to \ell^+\ell^-$

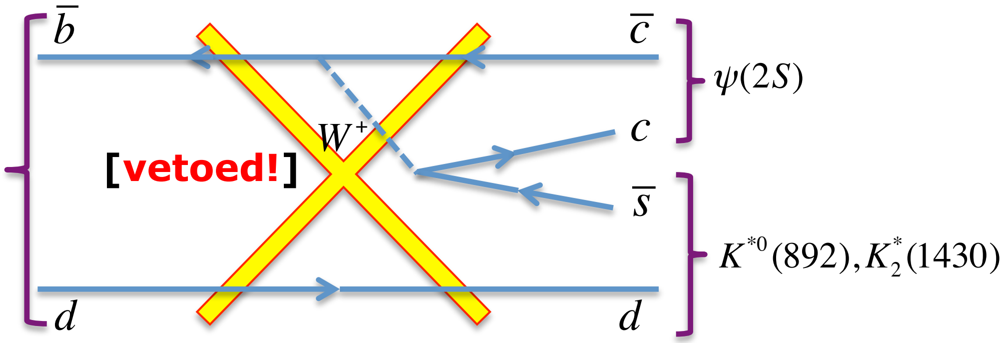


Quark diagrams with weak effective transition:

Incoherent 3-body



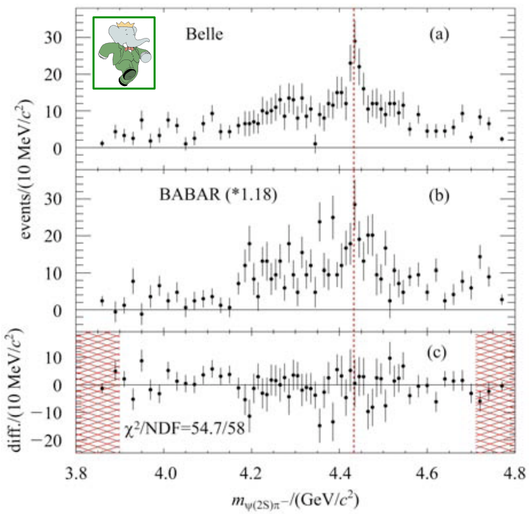
Quasi 2-body with kaons excitations



This structure would imply the quasi-two-body decay with the charged *Z* being an intermediate state:

$$B^{-,0} \to Z(4430)^- K^{0,+} \to \left[\psi(2S)\pi^-\right] K^{0,+}$$

(2009) argued that **dynamics in the Kπ system can reflect structures in $\psi'\pi$ inv. mass.**



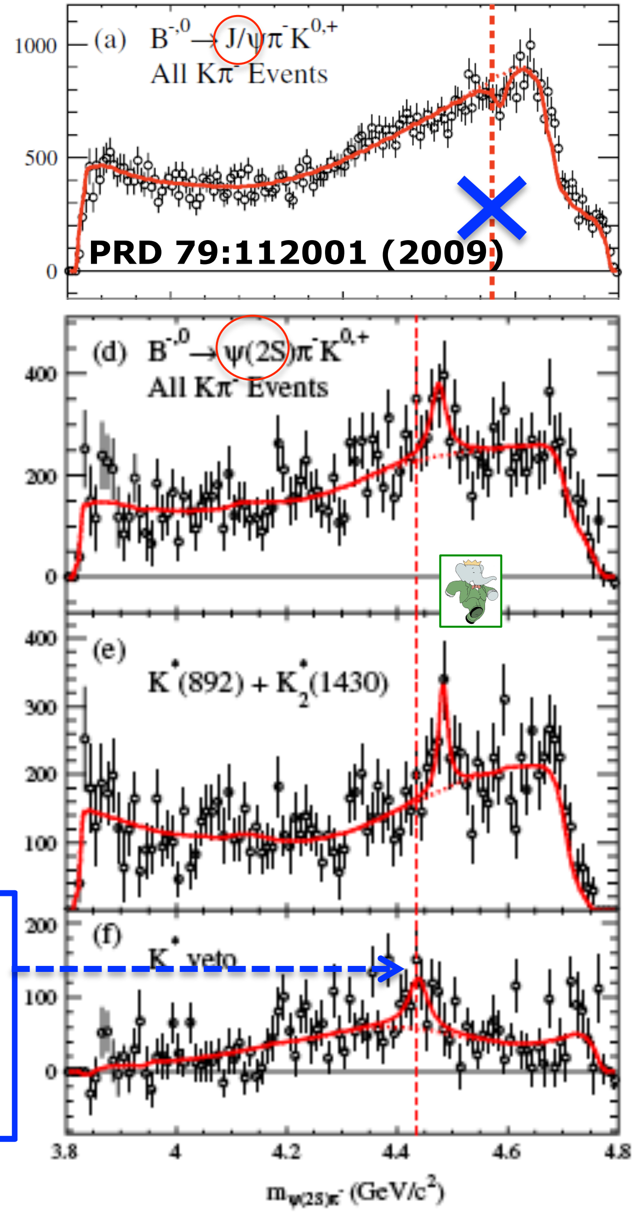
Comparing bkg-subtracted normalized distributions of the 2 experiments: the difference plot indicates that the 2 samples are statistically equivalent.

Performed a detailed study of Kπ mass and angular distributions to draw projections of the Kπ system onto $\psi'\pi$ inv. mass (used as background for a BW representing an eventual Z^+ signal):

(signif.~1.9σ @ shifted mass)

[~3.1σ forcing parameters]

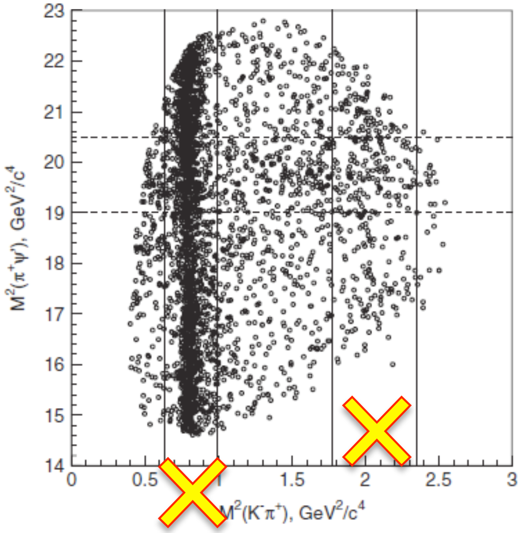
Kπ reflection well reproduces the $\psi'\pi$ inv. mass distribution

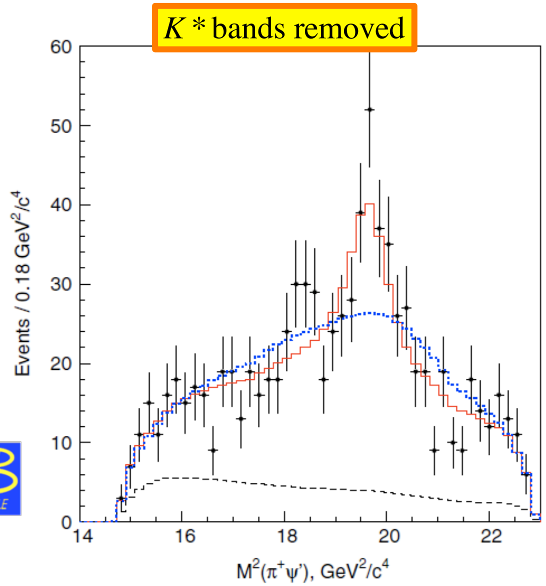


$Z(4430)^+$ - III

- This triggered [Belle logo] 's re-analysis(2009) performing a **dalitz-plot fit** including relativistic BW for $K\pi$ resonances (S,P,D waves)

PRD 80:031104 (2009)





Z^+ signal still there with:
- signif.=6.4σ
- width doubled (within syst.err)

Useful cross-check by [Belle logo] would be to do same with J/ψ mode: [BaBar logo] didn't find any signal.

- **This hidden-charm charged state has generated a great interest since it must have a minimum quark content $c\bar{c}d\bar{u}$ and thus it would represent an unequivocal manifestation of a 4-quark state meson.**

$Z_1(4050)^+$ & $Z_2(4250)^+$ - I

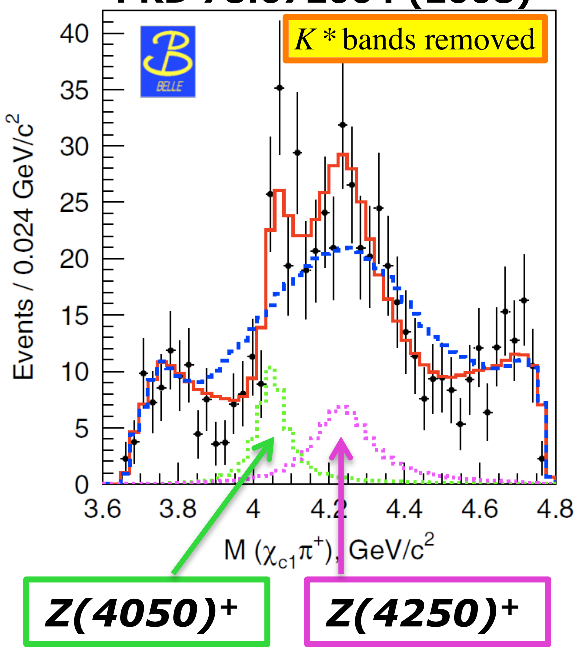
Belle (2008) looked for other **4-quark candidates** observing two more resonances (with same dalitz fit technique) in the decays:

$$\bar{B}^0 \to \chi_{c1}\pi^+K^- \ \ \& \ \ B^+ \to \chi_{c1}\pi^+K_s^0 \qquad \chi_{c1} \to J/\psi\,\gamma \ ; \ J/\psi \to \ell^+\ell^-$$

The 2 resonant structures observed in $\chi_{c1}\pi$ system are labelled: $Z_1(4050)^+$ & $Z_2(4250)^+$

The 2 states' fit is favoured (model syst. included):
- By >8.1σ signif. (over no states)
- by >5.1σ signif. (over 1 state)

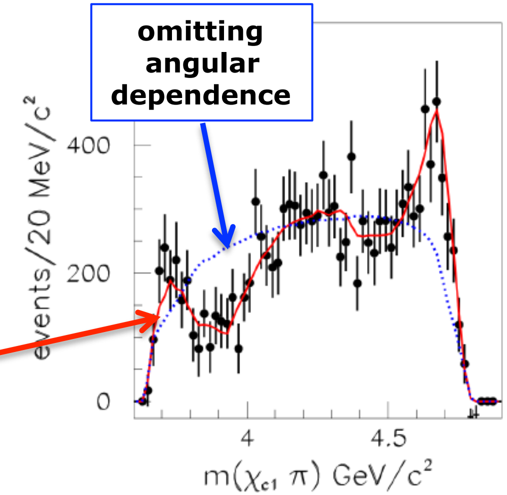
PRD 78:072004 (2008)



$Z_1(4050)^+$ & $Z_2(4250)^+$ - II

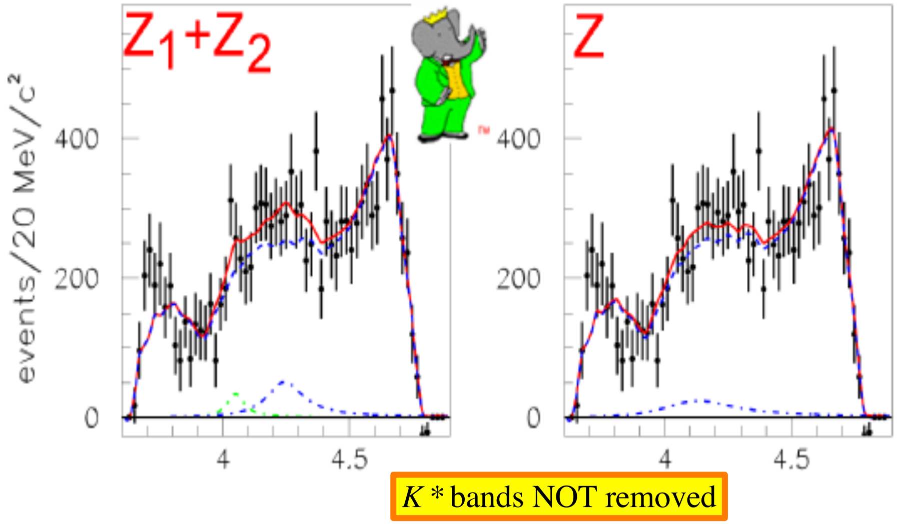
(2012) didn't find them **[by using similar method for the $Z(4430)^+$ search]**

After bkg-subtraction & efficiency-correction the $\chi_{c1}\pi$ inv. mass distrib. has been modelled using the angular information from $K\pi$ inv. mass distrib. as represented using only low--order (up to L=5) Legendre-polynomial moments (these are related to partial wave amplitudes).
The excellent description of $\chi_{c1}\pi$ mass obtained in this approach shows no need for any additional structure in order to describe the distribution.



PRD 85:052003 (2012)

In both cases fits give fractional contributions for 1 or 2 resonances consistent with zero;
in any case yield significance is <2σ (even when K*bands removed).



Z(4430)$^+$ - IV

- **There is a methodological difference between *Belle*/*BaBar* !**

Belle's Dalitz Plot analysis is over-simplified because they integrate over the ψ' & χ_{c1} decay angular distribution, thus ignoring the correlations. If there were any structure in the $\psi'\pi$ & $\chi_{c1}\pi$ systems … there would be the need to include higher partial waves in the K-π system since they would be built up from these "extra" K-π amplitudes contributions.

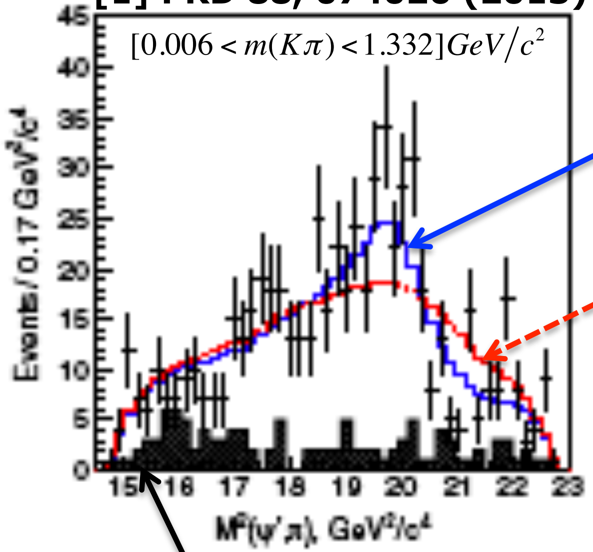
- **Amplitudes analyses are the "last frontier" to assess the existence of a state as intermediate resonance in 3-body decays. For the Z(4430), Belle took 5 years (and 3 papers) to come out with it. This is understandable since B-factories mainly have faced 3-body decays of charmed and beauty mesons into 3 pseudoscalars (a traditional Dalitz plot fit was enough) and not 3-body decays with vectors in the final states (like $J/\psi,\ \psi'$ and also $\chi_{c1},\ \phi,\ \ldots$).**

$Z(4430)^+$ - V

- This controversy triggered Belle 's re-analysis(2013) [1] performing a **full amplitude analysis** (**4D : 2 inv. masses + 2 angular variables**) including all known Kπ resonances within the kinematic boundary.

$$\left(m^2_{K^+\pi^-},\ m^2_{\psi'\pi^-},\ \theta_{\psi'},\ \varphi_{\psi' K^*}\right)$$

[1] PRD 88, 074026 (2013)



Fit with $Z^+(J^P=1^+)$

Fit without $Z^+(J^P=1^+)$

ψ' sidebands

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV$/c^2$	4479 ± 16	4477 ± 4	4485 ± 20	4478 ± 22	4384 ± 19
Width, MeV	110 ± 50	22 ± 14	200 ± 40	83 ± 25	52 ± 28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ

[0^+ forbidden]

$Z(4430)^+$ is now confirmed through the appropriate method;
$J^{PC}=1^{+-}$ is the favoured hypothesis
(favoured over others by >3.4σ)

However a confirmation from other experiments is needed to definitely establish it ! It came by LHCb (next slide).

Z(4430)+ - VI

[1] confirmed *Z(4430)*⁻ applying exactly Belle's method (and improving fit results). $J^P=1^{+-}$ **is the favoured hypothesis** (favoured over others by >9.7σ) .

[PRL 112 (2014) 222002]

However the story doesn't end here!

The 4D fit probability improves from 7% to 26% by adding a further $\psi' \pi^\pm$ resonance (for which $J^P=0^-$ is favoured over $J^P=1^+$ by 1σ) that has a significance of ~6σ .

Z(4430)-	$m \cong 4475 \pm 7^{+15}_{-25}\, MeV$	$\Gamma \cong 172 \pm 13^{+37}_{-34}\, MeV$
new Z-	$m \cong 4239 \pm 18^{+45}_{-10}\, MeV$	$\Gamma \cong 220 \pm 47^{+108}_{-74}\, MeV$

It has same mass and width of Z(4250) reported by [Belle] but a 0- state cannot decay strongly to $\chi_{c1}\pi^-$

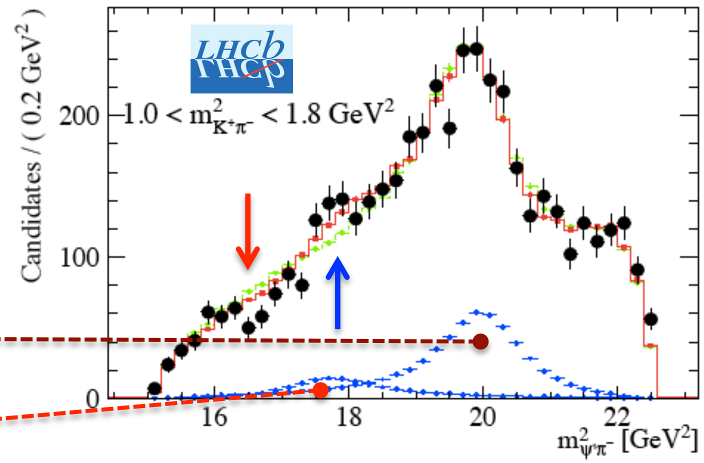


Figure 4: Distribution of $m^2_{\psi'\pi^-}$ in the data (black points) for $1.0 < m^2_{K^+\pi^-} < 1.8$ GeV² ($K^*(892)$, $K_2^*(1430)$ veto region) compared with the fit with two, 0^- and 1^+ (solid-line red histogram) and only one 1^+ (dashed-line green histogram) Z^- resonances. Individual Z^- terms (blue points) are shown for the fit with two Z^- resonances.

$Z(4430)^+$ - VI

[1] confirmed $Z(4430)^-$ applying exactly Belle's method (and improving fit results). $J^P=1^{+-}$ is the favoured hypothesis (favoured over others by >9.7σ) .

[PRL 112 (2014) 222002]

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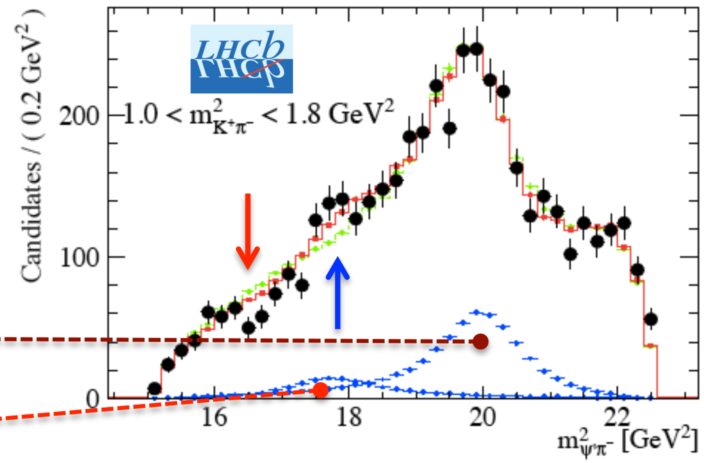

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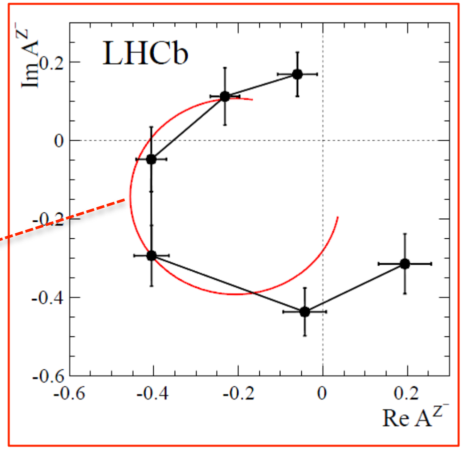
The **Argand diagram** (real vs imaginary parts of the 1^+ amplitude for difference mass spanning the 4430Mev region) is **consistent with a resonant amplitude**
[red curve shows expectations for a BW resonance amplitude]
The phase from **rescattering effect** [Pakhlov *et al.* model, arXiv:1408.5295] run in the opposite way (anti-clockwise)

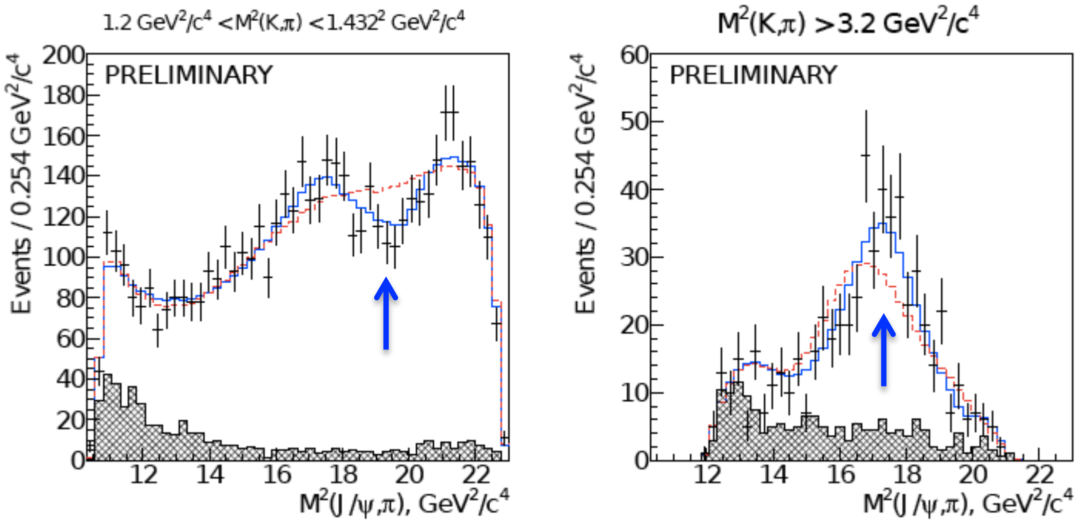


- **In 2014** Belle **presented the same full 4D amplitude analysis for** $B^0 \to J/\psi\ K^+\pi^-$

The *Z(4430)*$^-$ is significant : 4.0σ evidence for this new decay mode: $\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$

[PRD 90 (2014) 112009]

Comparison of the fit results with $Z_c(4430)^+$ and additional Z_c^+ (blue) and without any Z_c^+ (red).



New Z_c^+ is found ($J^P = 1^+$) [$Z_c(4200)^+$, 7.2σ with syst. error]

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}.$$

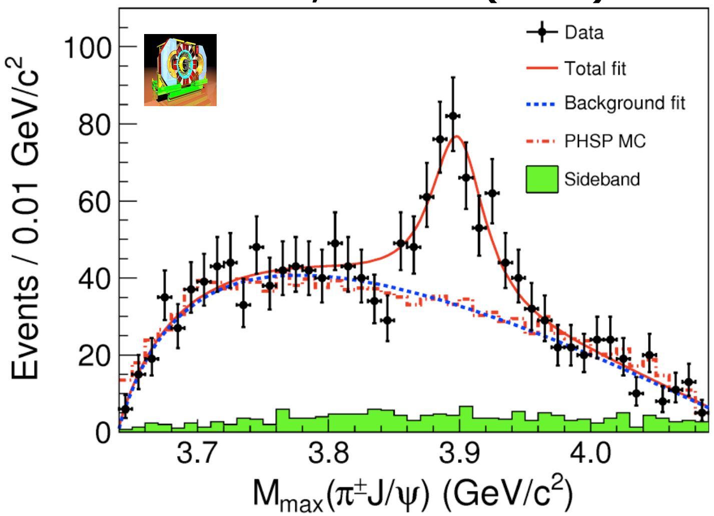
- **BESIII (2013) studies the process $e^+e^- \to J/\psi\,\pi^+\pi^-$ @ c.m. energy of $\sqrt{s} \cong (4260 \pm 1)MeV$ corresponding to the peak of the *Y(4260)* cross section.**

- **(2013) observe a charmonium-like charged structure (close to $D\bar{D}^*$ threshold reconstructed as intermediate state in the decay:**

$$Y(4260) \to [Z_c(3900)^{\pm}]\pi^{\pm} \to [J/\psi\ \pi^{\pm}]\pi^{\pm}$$

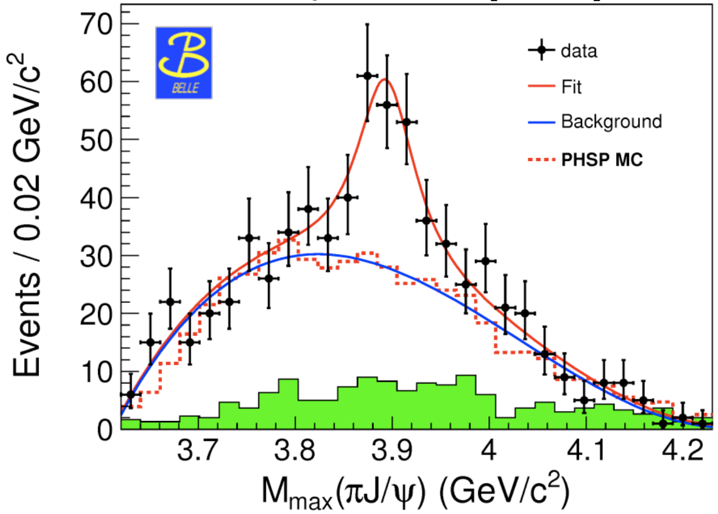
$M_{max}(J/\psi\pi^{\pm})$ larger one of the 2 combinations $M(J/\psi\pi^+)$, $M(J/\psi\pi^-)$

PRL 110, 252001 (2013)



$M = 3899.0 \pm 3.6 \pm 4.9$ MeV
$\Gamma = 46 \pm 10 \pm 20$ MeV

PRL 110, 252002 (2013)



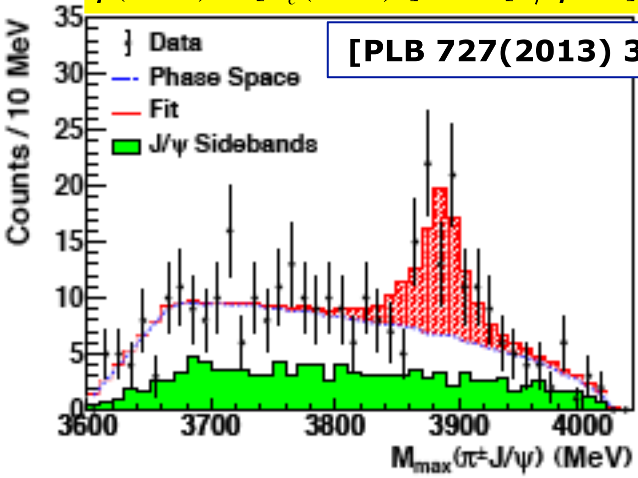
$M = 3894.5 \pm 6.6 \pm 4.5$ MeV
$\Gamma = 63 \pm 24 \pm 26$ MeV

They checked (by MC simulation) that effects of dynamics in the $\pi^+\pi^-$ inv. mass spectrum [associated to $f_0(980)$, $\sigma(500)$] do not project peaking structures onto the $J/\psi\ \pi$ mass spectrum.

$Z(3900)^{+}$ - II [& $Z(3900)^{0}$]

(2013) confirms this state studying the events $e^+e^- \rightarrow J/\psi\,\pi^+\pi^-$ @ c.m. energy of $\sqrt{s} \approx 4170 MeV$ corresponding to the peak of the $2^3D_1 \equiv \psi(4160)$ charmonium resonance.

$\psi(4160) \rightarrow [Z_c(3900)^{\pm}]\pi^{\pm} \rightarrow [J/\psi\ \pi^{\pm}]\pi^{\pm}$



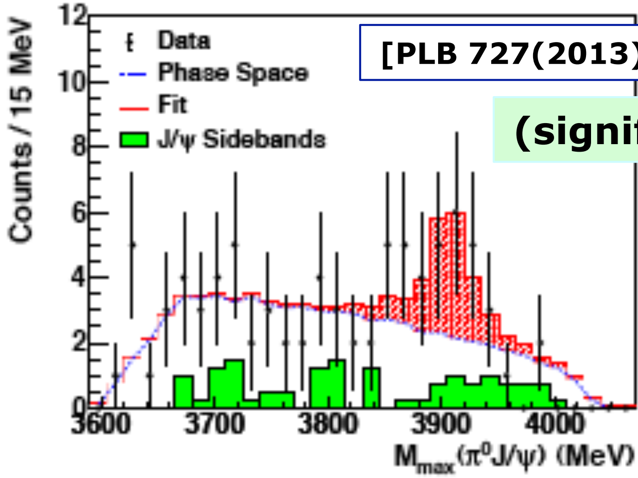
[PLB 727(2013) 366]

$M(Z_c(3900) = 3885 \pm 5 MeV/c^2$

$\Gamma(Z_c(3900) = 34 \pm 13$ MeV

In the same paper CLEO-c presents evidence of a neutral state:

$\psi(4160) \rightarrow [Z_c(3900)^{0}]\pi^{0} \rightarrow [J/\psi\ \pi^{0}]\pi^{0}$



[PLB 727(2013) 366]

(signif.~3.5σ)

$Z_c(3900)^{+/-}$ and $Z_c(3900)^{0}$ should form the isospin triplet with $J^P=1^+$

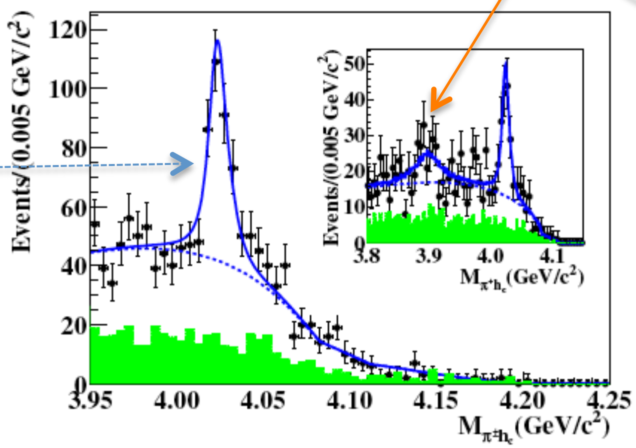
$Z_c(4020)^+$

- (2013) taking data @ 4.23*GeV*, 4.26*GeV* and 4.36*GeV* sees a structure in $h_c\pi^{\pm}$ mass spectrum, close to $D^*\bar{D}^*$ threshold, in the channel: $e^+e^- \rightarrow h_c\pi^+\pi^-$

$h_c(1P) \rightarrow J/\psi\pi^0$

[PRL 111 (2013) 242001]

$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7\,\mathrm{MeV}/c^2$
$\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6\,\mathrm{MeV}$

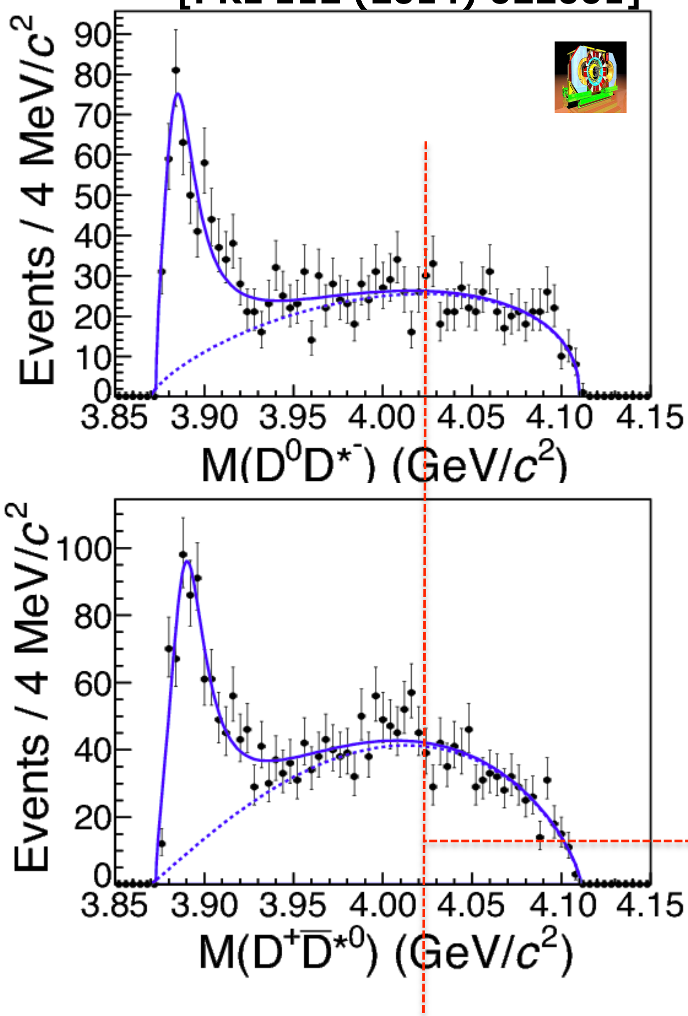


No significant $Z_c(3900)^{\pm} \rightarrow h_c\pi^{\pm}$ **signal seen.**

$Z(3900)^+$ - III

(2013), taking data @ 4.26*GeV*, observes (@ 18.0σ !) this decay mode :

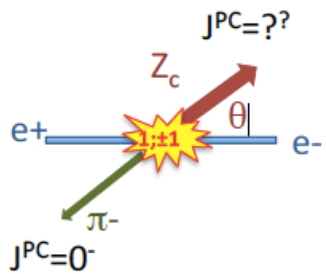
[PRL 112 (2014) 022001]

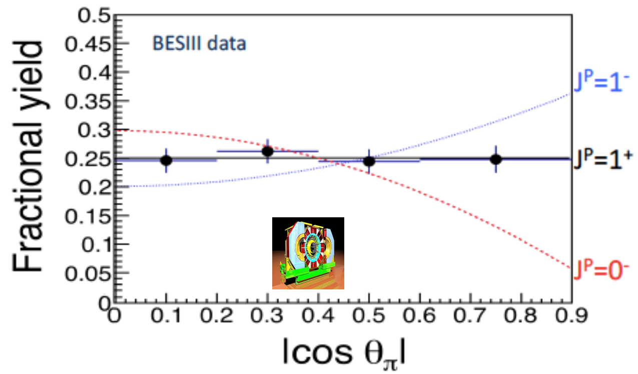


$$e^+e^- \to Y(4260) \to Z_c(3885)^+\pi^- \to [\bar{D}^0 D^{*+}, D^+\bar{D}^{*0}]\pi^-$$

Assume $Z_c(3885)^+$ & $Z(3900)^+$ are the same state!

Spin-parity is deduced by efficiency-corrected production angle distribution: $J^P = 1^+$ is preferred!





NO hint for $Z_c(4020)^+ \to (D\bar{D}^*)^+$;
instead it appears $Z_c(4025)^+ \to (D^*\bar{D}^*)$.
Assume they are the same state!

Z states' spectroscopy !

In 2013-2014 the number of Z states is "exploding" :

TABLE II. Positively charged $c\bar{c}$ mesons. The C in J^{PC} is that of a neutral isospin partner.

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
$Z_c^+(3885)$	3883.9 ± 4.5	24.8 ± 11.5	$1^{+?}$	$D^{*+}\bar{D}^0$, $D^+\bar{D}^{*0}$	BESIII 2013
$Z_c^+(3900)$	3898 ± 5	51 ± 19	$?^{?-}$	$J/\psi\pi^+$	BESIII 2013
$Z_c^+(4020)$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$h_c(1P)\pi^+$, $D^{*+}\bar{D}^{*0}$	BESIII 2013
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\chi_{c1}(1P)\pi^+$	Belle 2008
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\chi_{c1}(1P)\pi^+$	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	1^{+-}	$\psi(2S)\pi^+$ $[J/\psi\ \pi^+]$	Belle 2007

Belle 2014

Not to mention the two new states suggested by amplitudes analyses of $B^0 \to J/\psi\ K^+\pi^-$ & $B^0 \to \psi'\ K^+\pi^-$:

$$Z_c(4200)[J^P = 1^+] \qquad Z_c(4240)[J^P = 0^-, 1^+ ?]$$

As Maiani *et al*. has foreseen with the title of one [1] of their papers ...
... we are indeed beginning to face an hidden charm Z states' spectroscopy !

[1] Maiani et al., arXiv:0708.3997 (2007)

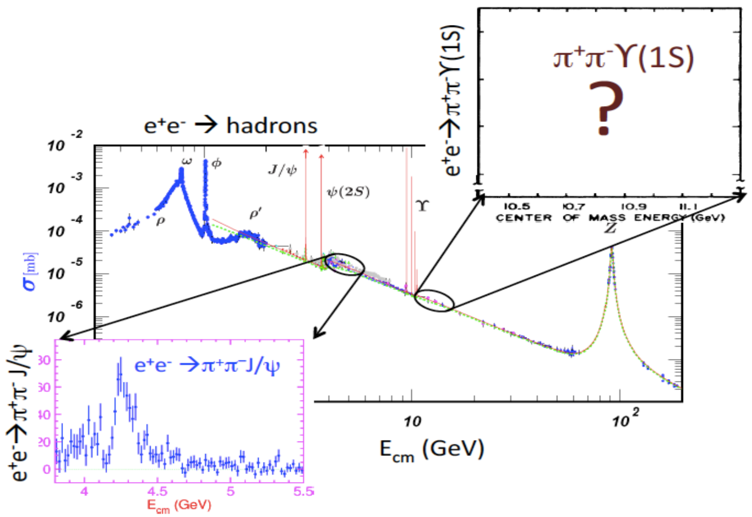
Part – 1 / 4-quarks systems :
b) Bottomonium-like exotics

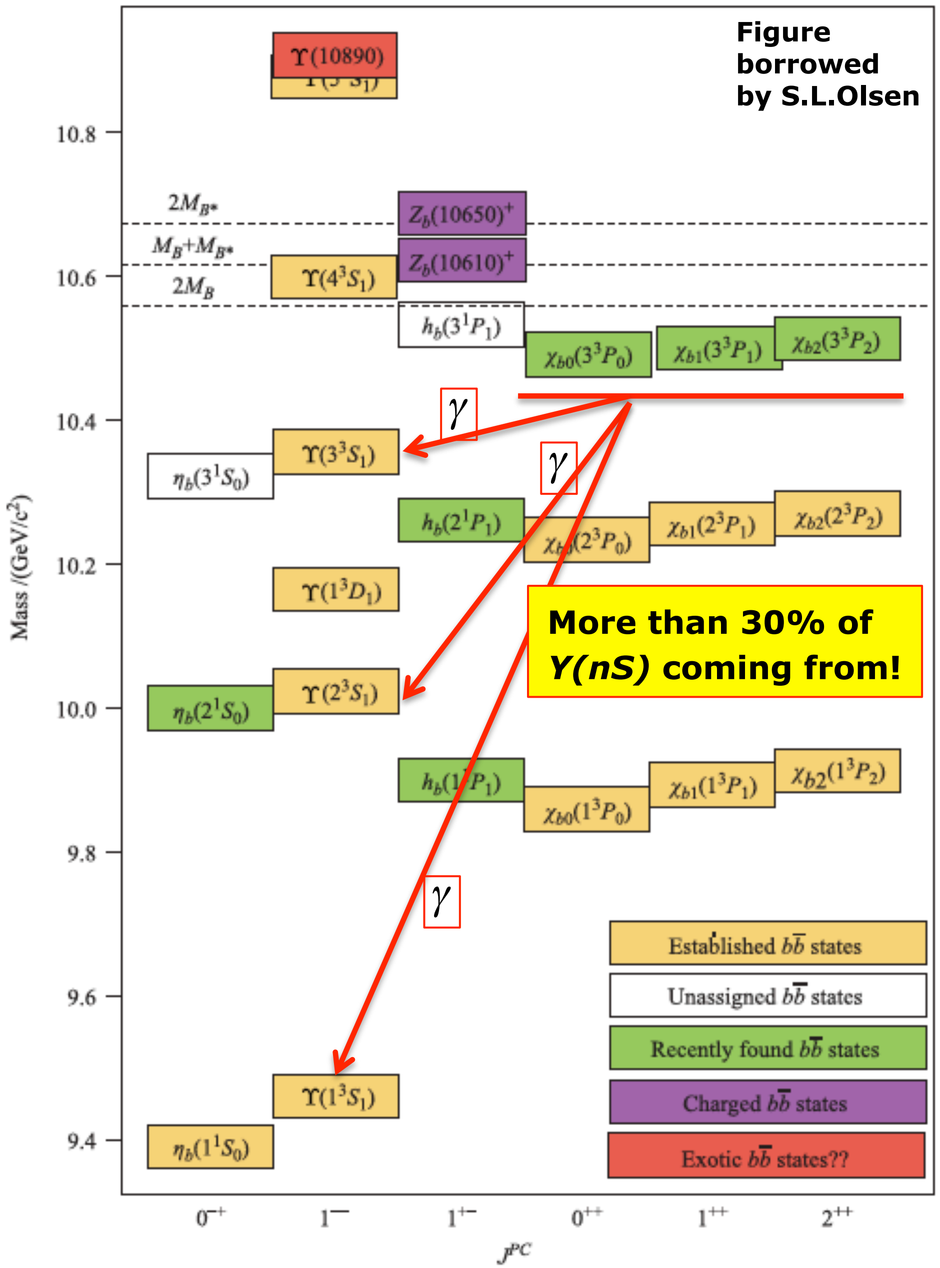
Bottomonium like mesons

- **Recent status of the $b\bar{b}$ bottomonium and bottomonium-like mesons :**

  Red/purple boxes indicate "anomalous" states that we are going to discuss :
  - $\Upsilon(10890)$
  - $Z_b(10610)^+$ **&** $Z_b(10650)^+$

- **The large $\Upsilon(4260) \to J/\psi\,\pi^+\pi^-$ signal discovered by [BaBar] triggered [Belle] to search for similar behaviour in $b\bar{b}$:**





Bottomonium like mesons : *Y(10890)*

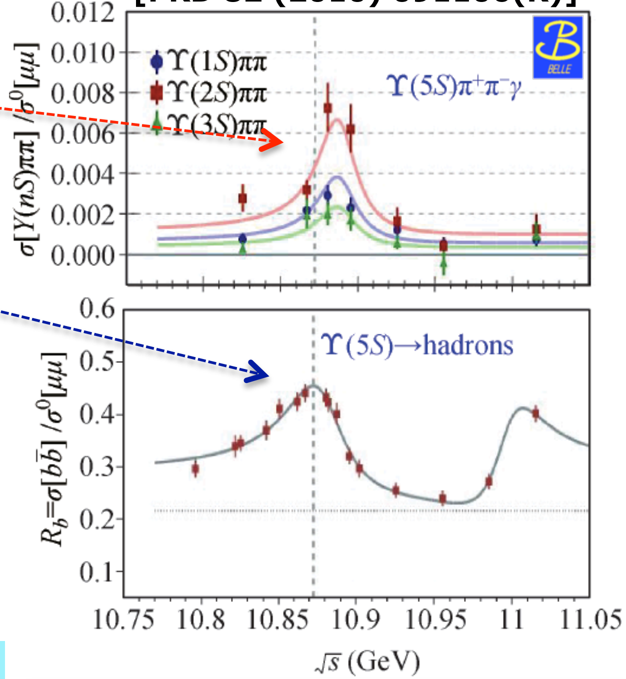
- **In 2010 Belle uncovers an anomalously large production rate of $\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$ peaking @ $\sqrt{s}\approx 10.89 GeV$:**

  This peak energy is $\approx 2\sigma$ higher than that of the peak in the $e^+e^- \to hadrons$ xsection @ $\sqrt{s}\cong 10.87 GeV$ that is usually associated with the conventional $\Upsilon(5^3S_1)$ meson:

  If the "shifted" peak were to be attributed to $\Upsilon(5S)$ decays it would imply partial widths for $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$ hundred of times larger than theoretical predictions ! It would also be incompatible with the production rates measured for the $\Upsilon(4S)$!

  This signal, called $\Upsilon(10890)$, should be a $\mathrm{non}-b\bar{b}$ state, equivalent of the $\Upsilon(4260)$ in the b-quark sector !

[PRD 82 (2010) 091106(R)]



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Bottomonium like mesons : *Y(10890)*

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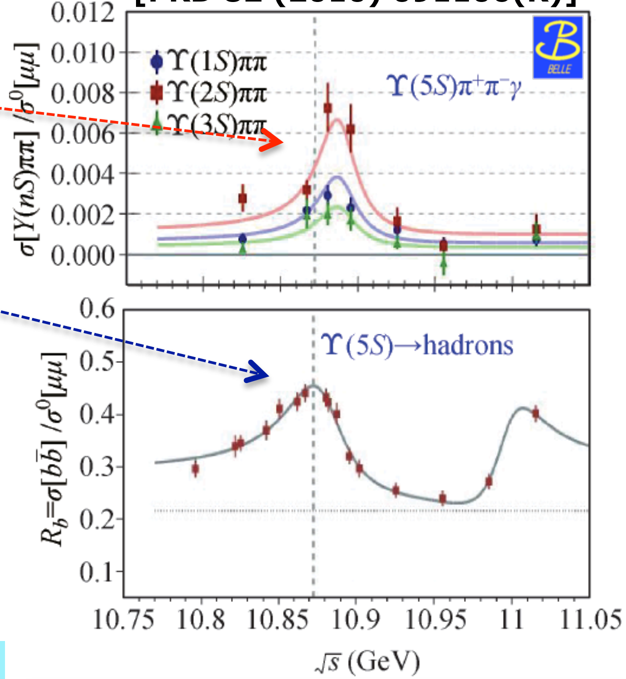
> **It would also be incompatible with the production rates measured for the $\Upsilon(4S)$!**

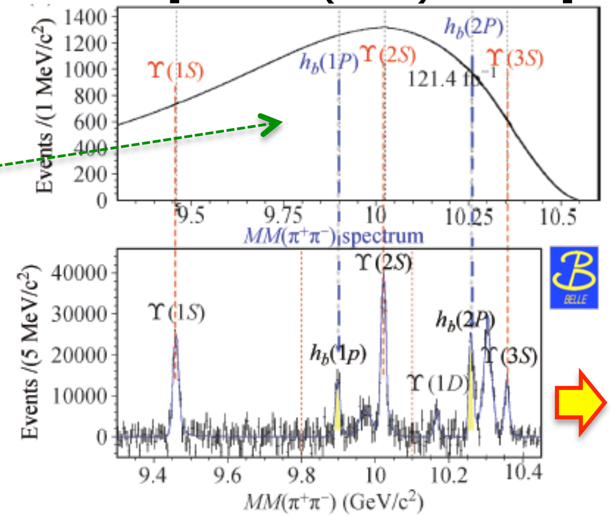
This signal, called $\Upsilon(10890)$, should be a $\mathrm{non}-b\bar{b}$ state, equivalent of the $\Upsilon(4260)$ in the b-quark sector !

[PRD 82 (2010) 091106(R)]



- **By purpose Belle integrated data near the peak of the $\Upsilon(5S)$ and studied the *inclusive missing-mass spectrum* recoiling from $\pi^+\pi^-$ pairs. Residuals from *piecewise fits* to the data with smooth polynomials show, in addition to the expected $\Upsilon(nS)\pi^+\pi^-[n=1,2,3]$ peaks, the unambiguous signal for the conventional bottomonium states $h_b(1P)$ & $h_b(2P)$, till then elusive (first observation !).**

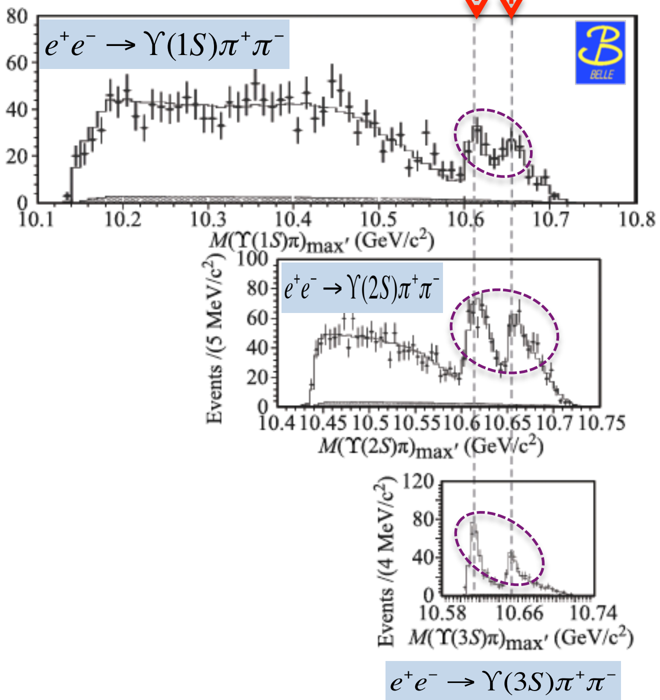
[PRL 108 (2012) 032001]



New puzzle : $h_b(mS)\pi^+\pi^-$ $[m=1,2]$ **final states are produced at rates not dissimilar from those for** $\Upsilon(nS)\pi^+\pi^-$ $[n=1,2,3]$ **(spin-conserving transitions) even though the transitions require an heavy quark spin-flip that should imply a strong suppression.**

A subsequent study with the same data (near the $\Upsilon(5S)$ **peak) and with fully reconstructed decays** $"\Upsilon(5S)" \to \Upsilon(nS)\pi^+\pi^-$ $[n=1,2,3]$ **finds peaks @ two mass values (**$m \approx 10.61,\ 10.65 GeV$**) of the *maximum* inv. mass** $\Upsilon(nS)\pi^\pm[n=1,2,3]$ **:**

[PRL 108 (2012) 122001]



Bottomonium like mesons : $Z_b(10610)^+$ & $Z_b(10650)^+$ - I

New puzzle : $h_b(mS)\pi^+\pi^-\ [m=1,2]$ **final states are produced at rates not dissimilar from those for** $\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$ **(spin-conserving transitions) even though the transitions require an heavy quark spin-flip that should imply a strong suppression.**

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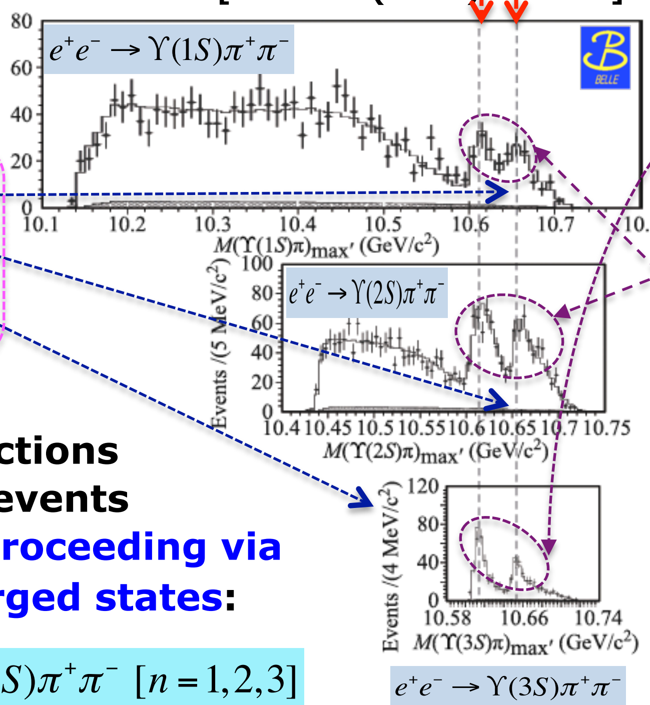
[PRL 108 (2012) 122001]



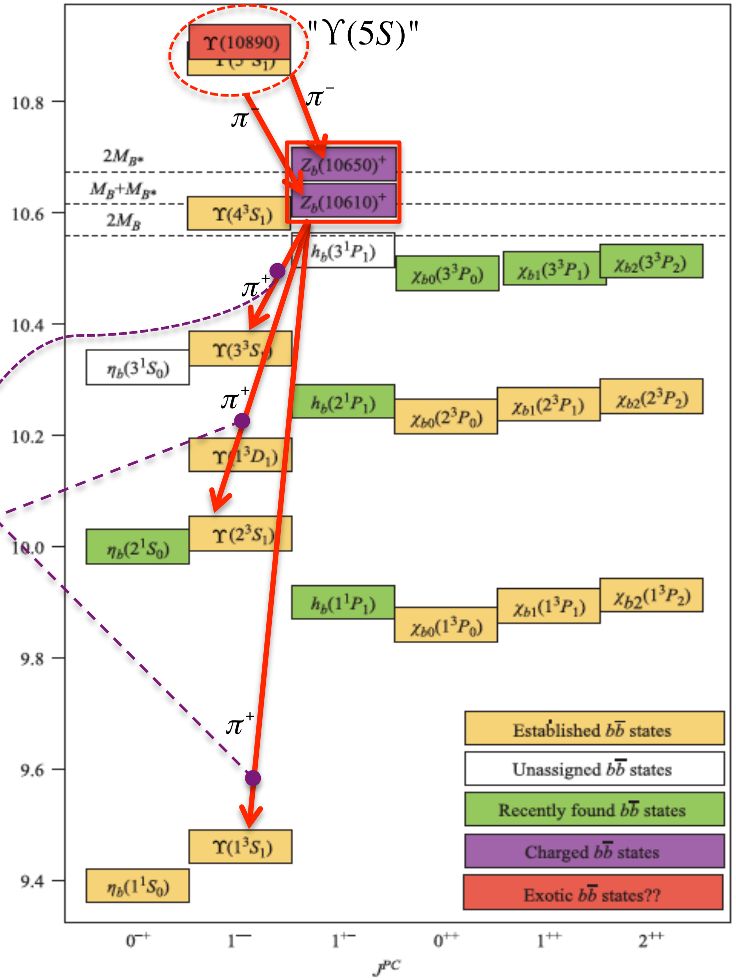
$yield: 6\%$ in the peaks

$yield: 22\%$ in the peaks

$yield: 43\%$ in the peaks

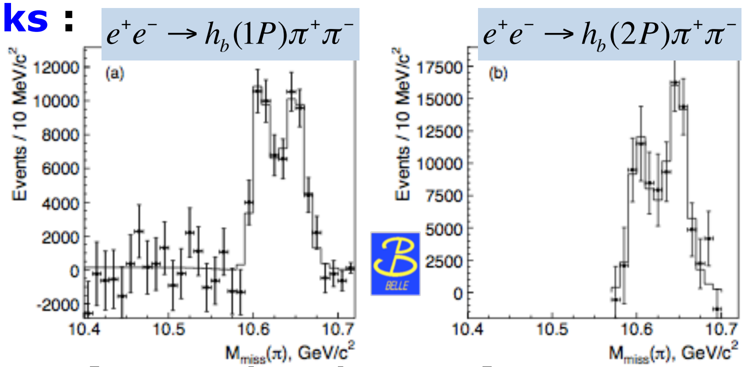
... these are the fractions of $\Upsilon(nS)\pi^+\pi^-[n=1,2,3]$ **events with the 3 decays proceeding via 2 intermediate charged states:**

$$"\Upsilon(5S)" \to Z_{b(1,2)}\pi^- \to \Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$$



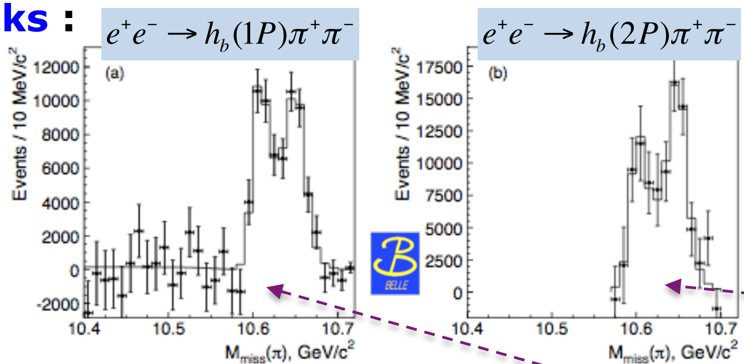
Bottomonium like mesons : $Z_b(10610)^+$ & $Z_b(10650)^+$ - II

- **Moreover Belle studies the resonant substructure of the $"\Upsilon(5S)" \rightarrow h_b(mP)\pi^+\pi^-[m=1,2]$ decays reconstructed inclusively by fitting the spectrum of the missing-mass of $\pi^+\pi^-$ pair in bins of $h_b(mP)\pi^\pm$ inv. mass, defined as missing mass of the opposite sign pion $M_{miss}(\pi^\mp)$.**
  All the events $h_b(mP)\pi^+\pi^-$ $[m=1,2]$ are fully concentrated in the two peaks :



[PRL 108 (2012) 122001]

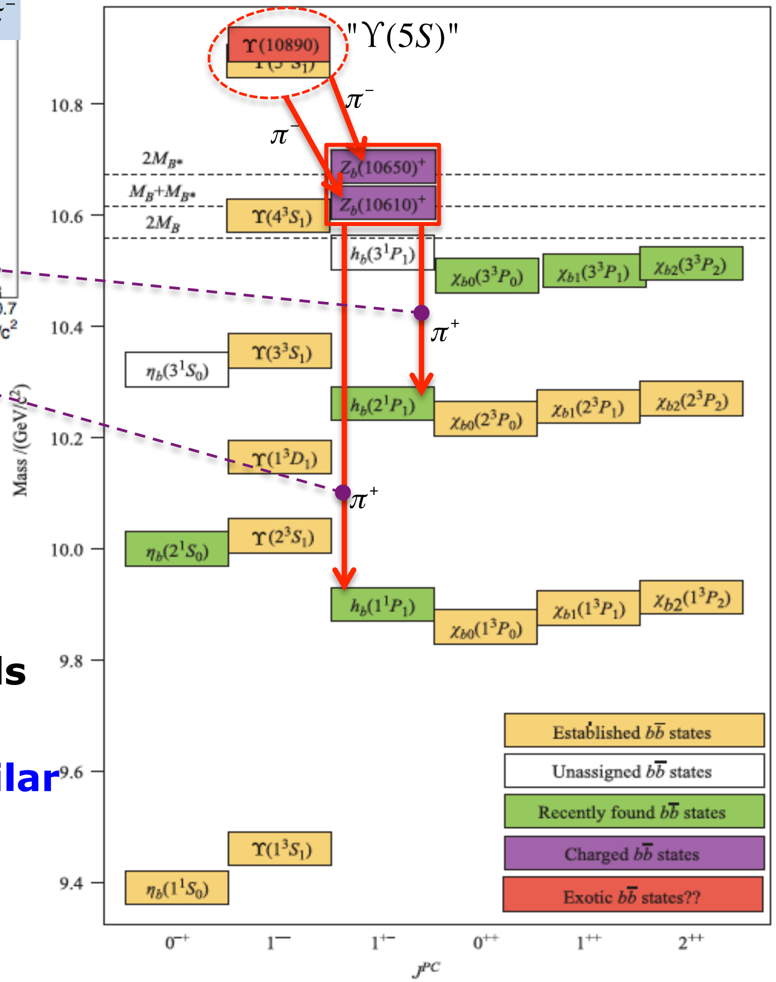
- Moreover Belle studies the resonant substructure of the $"\Upsilon(5S)" \rightarrow h_b(mP)\pi^+\pi^-[m=1,2]$ decays reconstructed inclusively by fitting the spectrum of the missing-mass of $\pi^+\pi^-$ pair in bins of $h_b(mP)\pi^\pm$ inv. mass, defined as missing mass of the opposite sign pion $M_{miss}(\pi^\mp)$.
All the events $h_b(mP)\pi^+\pi^-$ $[m=1,2]$ are **fully concentrated in the two peaks** :



[PRL 108 (2012) 122001]

The 2 **decays fully proceed via the same 2 intermediate charged states** :

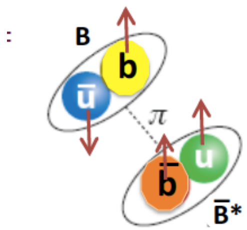
$$"\Upsilon(5S)" \rightarrow Z_{b(1,2)}\pi^- \rightarrow h_b(mP)\pi^+\pi^- \ [n=1,2,3]$$



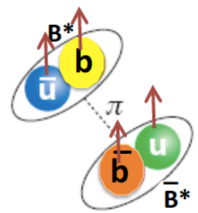
- Fitted values of the peak masses in all 5 channels are **consistent** with each other; $<\Gamma_{1(2)}> \cong 18(12)MeV$.
- Production rates of $Z_b(10610)^+$ and $Z_b(10650)^+$ are **similar**
- Analyses of charged pion angular distributions favour the $J^P=1^+$ assignment for **both** states [later confirmed by a Dalitz Plot analysis]

Bottomonium like mesons : $Z_b(10610)^+$ & $Z_b(10650)^+$ - III

- The close proximity of the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds [$(2.6 \pm 2.2)MeV$ above $m_B + m_{B*}$ & $(2.0 \pm 1.6)MeV$ above $2m_{B*}$] and the $J^P = 1^+$ assignement for both states would suggest **a virtual S-wave molecule-like states**.



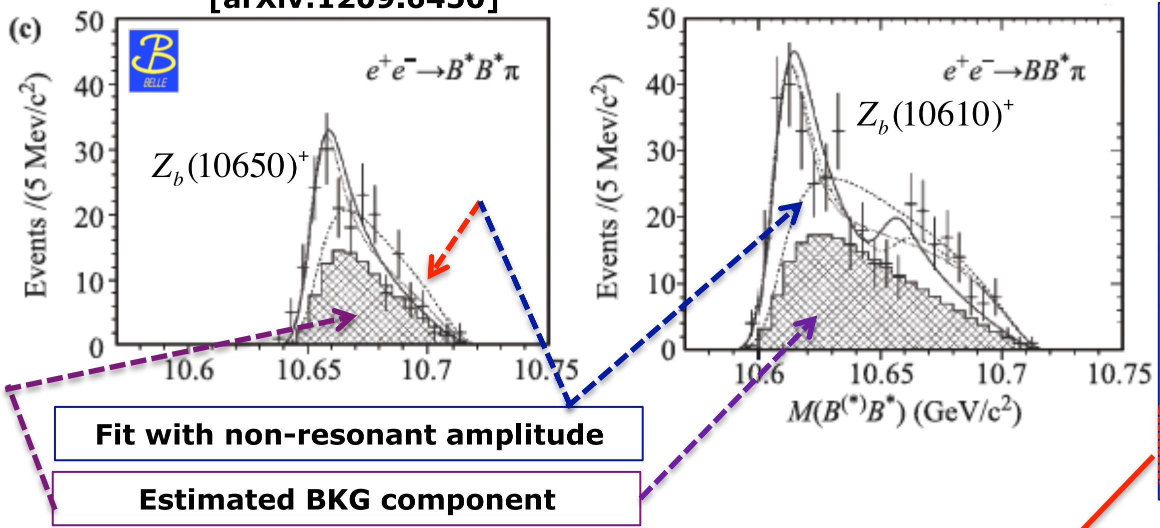
B-B̄* "molecule"



B*-B̄* "molecule"

- The $B^{(*)}\bar{B}^*$ molecule picture is supported by a  's study (2012) of $"\Upsilon(5S)" \to B^{(*)}\bar{B}^{(*)}\pi$ where peaks in the inv. masses $B\bar{B}^*$ & B^*B^* at the $Z_b(10610)^+$ & $Z_b(10650)^+$ are found!

[arXiv:1209.6450]



Channel	Fraction, % $Z_b(10610)$	Fraction, % $Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

This pattern where $B\bar{B}^*$, $B^*\bar{B}^*$ decays dominate for the $Z_b(10610)^+$ & $Z_b(10650)^+$ are consistent with expectations for molecule-like structures.

Bottomonium like mesons : $Z_b(10610)^+$ & $Z_b(10650)^+$ - IV

[PRD 88 (2013) 052016]

- **In 2013 Belle studies the $\Upsilon(nS)\pi^0\pi^0$ $[n=1,2,3]$ final states finding (6.5σ) the neutral $Z_b(10610)^0$ isospin partner of $Z_b(10610)^\pm$ and a production rate that is consisyent with isospin-based expectations.**

- **The actual compilation of anomalous/exotic bottomonium states looks like:**

$Y_b(10890)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [119, 122]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n=1,2$	Belle [123]
$Z_b^0(10610)$	10609± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n=1,2,3$	Belle [121]
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n=1,2$	Belle [123]

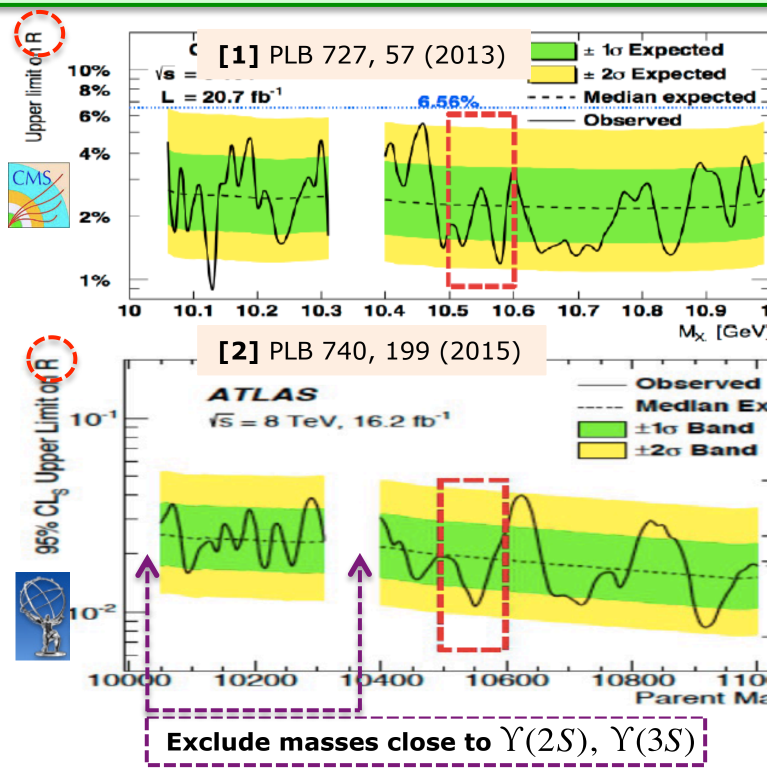
In search for the bottomonium partner of the *X(3872)* - I

- **HQ symmetry suggests the X_b analog of X_c. There are model-dependent mass predictions;** e.g. $m \cong 10.561 GeV$ for $B\bar{B}^*$ molecule (Swanson,2004).

  CMS [1] & ATLAS [2] looked for it in the decay $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ motivated by the seemingly analogous decay $X(3872) \to J/\psi\;\pi^+\pi^-$.

  Both experiments set upper limits for the $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ production, namely for

$$R = \frac{\sigma\left(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{\sigma\left(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$



- **According to Karliner&Rosner [PRD91 (2015) 014014],** **this analogy is misguided for this particular decay channel.** **In the bottom sector isospin should be well conserved, while in charm sector X(3872) maximally breaks isospin conservation:**

$$\frac{B(X \to J/\psi\,\pi^+\pi^-\pi^0)}{B(X \to J/\psi\,\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

$\pi^+\pi^-\pi^0 \to \omega^0$; $\pi^+\pi^- \to \rho^0$

  Thus for X_b, isoscalar with $J^{PC}=1^{++}$, this decay should be forbidden by G-parity conservation!

In search for the bottomonium partner of the *X(3872)* - II

The strategy for X_b observation should include search modes such as ...

$X_b \to \Upsilon(1S)\ \omega(\to \pi^+\pi^-\pi^0),\quad X_b \to \chi_{b1}(1P)\pi^+\pi^-,\quad X_b \to \Upsilon(3S)\gamma$ **; [not easy @ LHC: involve soft γ reco].**

No significant signal - for the 1st - found by Belle in *Υ(5S)* decays [PRD91, 014014 (2015)].

Moreover Karliner & Rosner suggest that the X_b may be close in mass to the $\chi_{b1}(3P)$, mixing with it and sharing its decay channels [just as X(3872) may be a mixture of a $D^0\bar{D}^{*0}$ molecule and $\chi_{c1}(2P)$].
Thus the experiments (ATLAS, D0, LHCb both with non-converted & converted photons) that reported observing $\chi_{b1}(3P) \to \Upsilon(1S,2S)\gamma$ might have actually discovered the X_b or a mixture of the two states!
It would be worthwhile to examine the $\Upsilon(1S,2S)\gamma$ mass spectra for any departure from single BW behaviour.

Few comments on molecules VS compact 4quarks - I

- **A partial picture of many XYZ states establishes:**
  1) a concentration of charmonium-like states crowding the $D\bar{D}^*, D^*\bar{D}^*$ threshold regions
  2) bottomonium isospin triplets near the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds
  These circumstances suggest molecule-like structures.

- **For istance for the charmonium states there can be introduced two isotriplets, while for isotopic triplet in the bottomonium sector the X(3872) counterpart is still missing.**

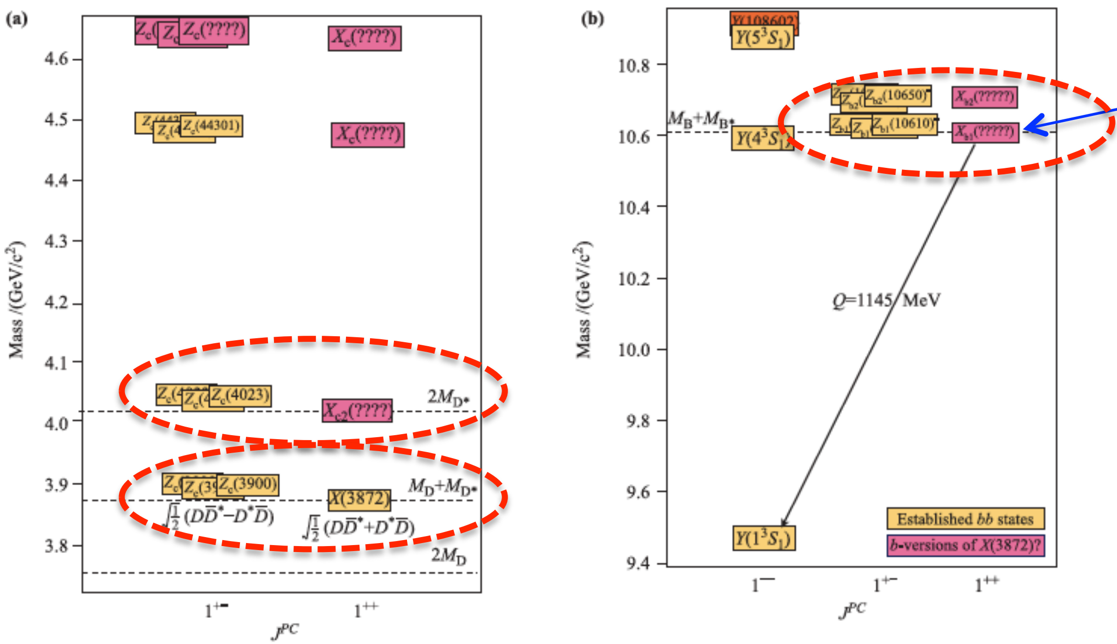


Fig. 22 (a) Level diagram for the $X(3872)$, the recently discovered $Z_c(3900)$ & $Z_c(4020)$ isotopic triplets, and the $Z(4430)$ isospin triplet. The salmon-colored boxes indicate other states that are suggested by the molecule picture. (b) Level diagram for the recently discovered Z_b states, a conjectured b-sector equivalent of the $X(3872)$ at the $m_B + m_{B^*}$ threshold and an additional isoscalar partner of the $Z_b(10650)$ at the $2m_{B^*}$ theshold. The transition between a $m_B + m_{B^*}$ threshold state to the $\Upsilon(1S)$ would have a Q-value of $\simeq 1145$ MeV, well above the mass of the ρ and ω mesons.

Few comments on molecules VS compact 4quarks - II

- **However there are states , for istance *Z(4430)*$^+$, Z_1 and Z_2 which are far from thresholds !**
  Other weak point of the molecular interpretation have been already mentioned [for istance the radiative decays of *X(3872)*].

- **Another strong argument against the molecular model is the following (see also talk by Piccinini this morning):**

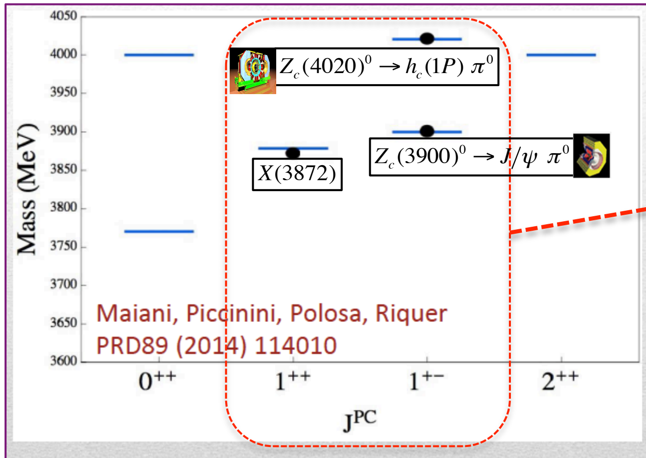
  The size of the X(3872) as a $D\bar{D}^*$ molecule is determined by its scattering length which in turn depends upon the binding energy; the size turns out to be ~ $10 \div 15 fm$.
  In other words X(3872) would be a large & fragile molecule with a miniscule binding energy.
  Therefore the question is : why would its production characteristics in high energy *pp* collisions match those of the nearly pointlike and tightly bound ψ' ?

Few comments on molecules VS compact 4quarks - III

- **On the countrary one attractive feature of the compact 4quark model is that it can explain in a natural way the large partial widths for transitions such as:**

$$Y(4260) \to J/\psi \pi^+ \pi^- \qquad Y(3940) \to J/\psi\, \omega \qquad Z(4430)^+ \to \psi' \pi^+$$

- **In the new diquark/anti-diquark paradigm [Maiani et al., PRD89 (2014) 114010] in which dominant interaction are between (anti)quarks in the same (anti)diquark :**



The pattern of $X(3872)$, $Z_c(3900)$, $Z_c'(4020)$, is understood

Prediction for radial excitation $Z(4430)$ ✓

A full nonet for each level is expected ✗

We need a mechanism that disfavors the formation of the unobserved states

Neutral isospin multiplet with $I^G = 1^+ \;\&\; J^P = 1^+$

$Z_c(3900)^0$ is the neutral isospin partner of X(3872);
$Z_c(3900)^+$ is its charged partner;
$Z(4430)^+$ is its first radial excitation.

Black disks represent the $X(3872)$, $Z(3900)$ and $Z(4020)$ masses. The C quantum number is the charge-conjugation eigenvalue of the neutral component of the multiplet.

Charge conjugation is given by[3]

$$C = (-1)^{s_{q\bar{q}} + s_{c\bar{c}}},$$

[3] The formula holds for states with $L = 0$, L being the relative orbital angular momentum of the diquark-antidiquark pair; for general L the formula is $C = (-1)^{L + s_{q\bar{q}} + s_{c\bar{c}}}$.

Inclusive searches for prompt production @ LHC ?

- **Reminder: X(3872) production - in $pp(p\bar{p})$ collisions - predominantly (~80%) prompt**

- **Considering the prompt hadroproduction of the charged hidden charm/beauty states (with a minimal 4-quark content, e.g. $cu\bar{c}\bar{d}$ / $bu\bar{b}\bar{d}$ for posit. charged) $Z_c^{\pm}(3900)$, $Z_c^{\pm}(4020)$, $Z_b^{\pm}(10610)$, $Z_b^{\pm}(10650)$ and *assuming them to be S-wave hadronic molecules* (as pairs of heavy mesons), …**
… *Guo et al.* [1] provide the following *integrated normalized production cross sections*:

Table 2 Integrated normalized cross sections (in units of nb) for the reactions $pp/\bar{p} \to Z_b(10610), Z_b(10650), Z_c(3900)$, and $Z_c(4020)$ at the LHC and the Tevatron. Results are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV, respectively, for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for LHCb.

	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26 (0.47)	0.06 (0.17)	11 (13)	1.7 (2.0)
LHC 7	4.8 (8.0)	1.2 (3.0)	187 (211)	29 (31)
LHCb 7	0.76 (1.3)	0.18 (0.47)	33 (39)	5.5 (5.8)
LHC 8	5.9 (9.5)	1.4 (3.5)	220 (240)	34 (36)
LHCb 8	0.9 (1.4)	0.22 (0.56)	40 (48)	6.3 (6.9)
LHC 14	11 (17)	2.6 (6.5)	382 (423)	61 (63)
LHCb 14	1.9 (3.0)	0.52 (1.2)	84 (88)	14 (14)

[1] Guo, Meissner, Wang, Commun.Theor.Phys, 61 (2014)

Signal event yield:
~220x20x10^6
~4.4x10^9
but then …
kinematical cuts &
high backgrounds !

CMS = 5 x LHCb

- **Inclusive analyses of ~broad states in high background environment are difficult !**

4-quarks bound systems : extentions?

- So far we have discussed how … many of these states have a minimal quark content of 4 quark, and regardless the way they are organized and interacting [compact system or molecular system? if compact: diquark-antidiquark or quark-antiquark pairs?] they can be considered 4-valence quarks bound systems. For istance:

Y(3872)	$c\bar{c}u\bar{u}$		
Y(4140)	$c\bar{c}s\bar{s}$		
$Z(4430)^+$ $Z(3900)^+$	$c\bar{c}u\bar{d}$	$Z_b(10610)^+$ $Z_b(10650)^+$	$b\bar{b}u\bar{d}$

- Note that these systems contain 2 heavy quarks + 2 light quarks. However nothing prevents from thinking about 4-quark systems composed by all 4 heavy quarks : $c\bar{c}c\bar{c}$ $c\bar{c}b\bar{b}$ $b\bar{b}b\bar{b}$

Reference: Berezhnoy *et al.*, PRD 84 (2011) 094023
PRD 86 (2012) 034004

Double-bottom baryons (bbq) & double bottom tetraquarks ?

Arguments in favour of their existence provided by Karliner *et al.* [arXiv:1401.4058; PRD 90 (2014) 094007] :

Hadrons containing two b quarks, such as double-bottom baryons bbq or $b\bar{b}q\bar{q}$ and $bb\bar{q}\bar{q}$ tetraquarks have a unique and a spectacular decay mode with two J/ψ-s in the final state. It is mediated by both b quarks decaying via $b \to \bar{c}cs \to J/\psi s$ and yields

$$(bbq) \to J/\psi\, J/\psi(ssq) \to J/\psi\, J/\psi\, \Xi \qquad (3)$$

and

$$(b\bar{b}q\bar{q}) \to J/\psi\, J/\psi(\bar{s}sq\bar{q}) \to J/\psi\, J/\psi\, K\, \bar{K}, \qquad (4)$$

as well as

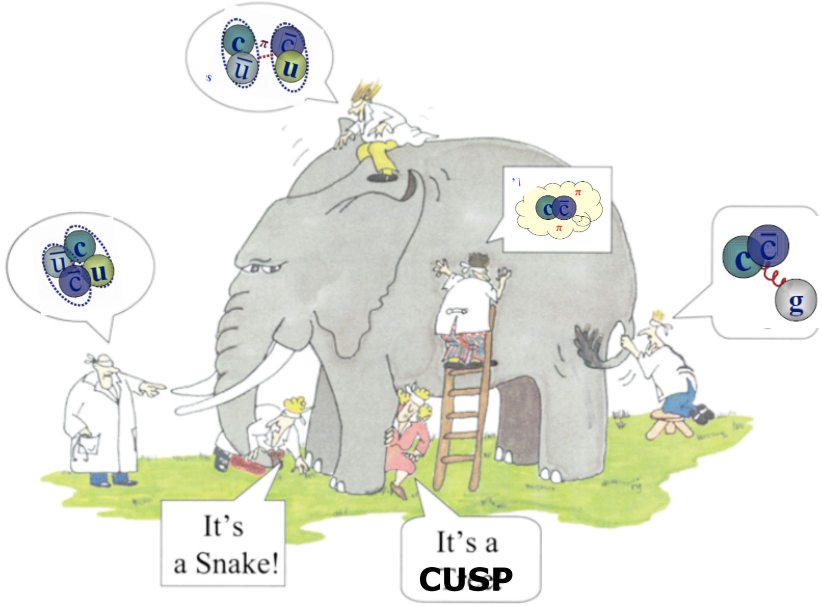
$$(bb\bar{q}\bar{q}) \to J/\psi\, J/\psi(ss\bar{q}\bar{q}) \to J/\psi\, J/\psi\, \bar{K}\, \bar{K}, \qquad (5)$$

etc., with all final state hadrons coming from the same vertex. This unique signature is however hampered by a very low rate, expected for such a process, especially if one uses dimuons to identify the J/ψ-s. It is both a challenge and an opportunity for LHCb [25].

Conclusion First Part (4-quark systems)

- The XYZ mesons are unexpected mesons discovered since 2003 that contain a heavy quark-antidiquark pair and are above the open-heavy-flavour threshold (open-charm/open-beauty). More than a decade has elapsed since the discovery of X(3872) and no compelling explanation for the pattern of the XYZ mesons has emerged.

Models for XYZ Mesons



- Models for the XYZ mesons can be classified according to their constituents and how they are clustered within the meson. None of these models has rroven to be very predictive for the pattern of XYZ mesons.

It's desirable to have a theoretical framework based on QCD that describes all or - realistically - the majority of the XYZ mesons.