Exotic states discovered
or not
at the B-factories and LHC

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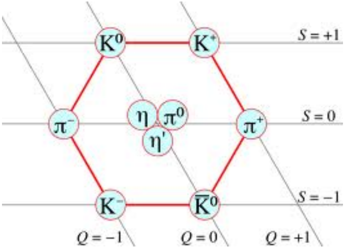
Conventional mesons

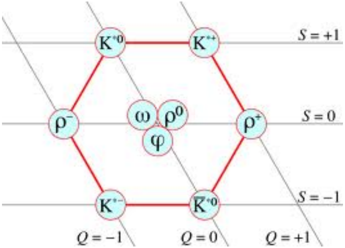
The simplest colorless configuration with zero baryon number is $q\bar{q}$:

- SU(3):

$$q \bigotimes \bar{q}' = 3 \bigotimes \bar{3} = 8 \bigoplus 1$$

quark and antiquark in color singlet configuration $(q\bar{q})_0$

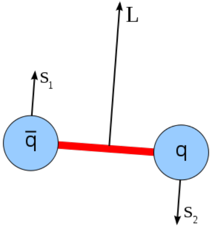




the good-old light quark nonets

Meson quantum numbers

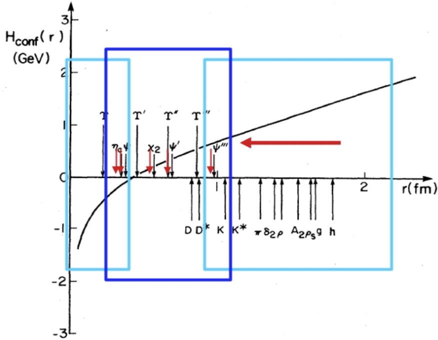
The quantum numbers are determined from the relative angular momentum L and the quark spin relative orientation $\vec{s}_1$ and $\vec{s}_2$:



- $P = (-1)^{L+1}$
- $|L - S| \leqslant J \leqslant |L + S|$
- C only defined for flavor-less mesons

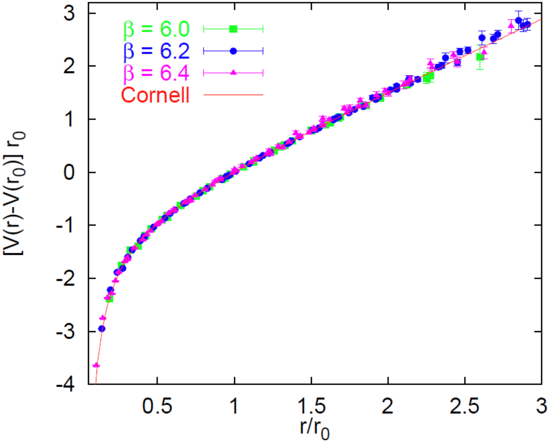
Naïve picture of quark binding force

No free quarks found
binding force should become large at large distances
"perturbative regime"
Linear term
At small distance:
one-gluon exchange+ asymptotic freedom
Coulomb-like term



The "meat" is in-between!

Naïve potential vs QCD



Quarkonium: charmonium and bottomonium

Heavy quarks $\longrightarrow$ non relativistic
relativistic corrections in $b\bar{b}$ smaller than in $c\bar{c}$ (?)

- Potential models: Cornell (Coulomb +linear term)
  but also
- Lattice NRQCD, pNRQCD: α_s, m_b/m_c, lattice spacing, ...

$c\bar{c}$ or $b\bar{b}$ bound states: spectroscopic notation: $n^{2S+1}L_J$

fermion-antifermion: $P = (-1)^{L+1}$ $\quad C = (-1)^{L+S}$

$$\psi(nS), \Upsilon(nS) = n^3S_1 \qquad \eta_Q(nS) = n^1S_0$$
$$\chi_{QJ}(nP) = n^3P_J \qquad h_Q(nP) = n^1P_1$$

Quarkonium physics

Decay widths:

above open $D\bar{D}$ or $B\bar{B}$ threshold dominant decay to heavy mesons unless forbidden by quantum numbers broad states

below open $D\bar{D}$ or $B\bar{B}$ threshold, $Q\bar{Q}$ annihilate to gluons (or virtual photon) OZI-rule $\longrightarrow$ narrow states:

- $\psi(nS)$,$\Upsilon(nS) \to ggg,\ \gamma gg$ [$\approx$ %] or $\gamma*$ [$\ell^+\ell^- \approx$ %]
- other states decay to ggg or gg depending on J odd/even
  $\eta_Q(nS), \chi_{Q0}(nP), \chi_{Q2}(nP) \to gg$
  $h_Q(nP), \chi_{Q1}(nP) \to ggg$ or $gq\bar{q}$
- very few exclusive hadronic modes observed especially in $b\bar{b}$

Radiative and hadronic transitions:

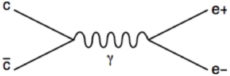
- photon or gluons radiation from $Q\bar{Q}$ state

  multipole expansion if radius $\ll$ wavelength

Spectroscopy:

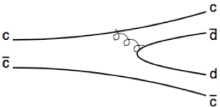
- fine and hyperfine splitting (spin-dependent terms)
  mass splitting between n^3S_1 and n^1S_0 depend strongly on α_s

Charmonium and Bottomonium decays

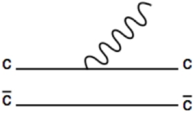


only $J^{PC}=1$

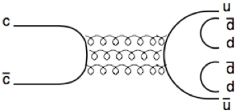
Experimentally clean



Dominant above $D\bar{D}$



Radiative transitions



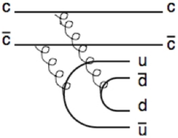
2 [3] gluons   J odd[even]

α_{ss}suppressed

For bottomonium just replace

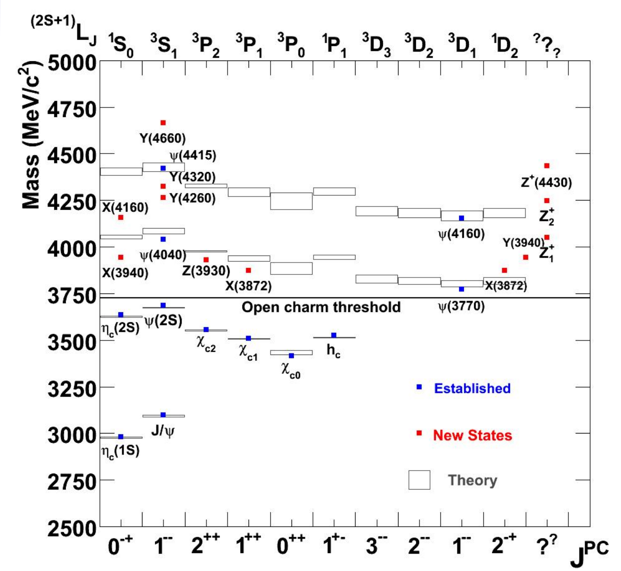
$$b \leftrightarrow c$$

$$B \leftrightarrow D$$

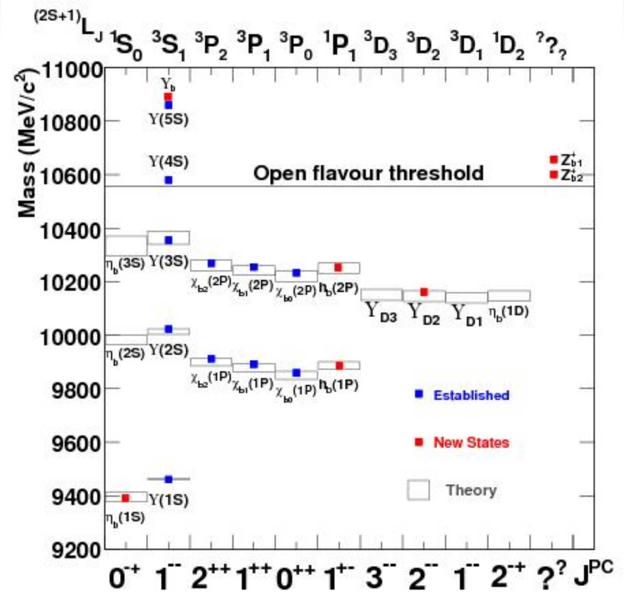


Hadronic transitions

Charmonium spectrum



Bottomonium spectrum



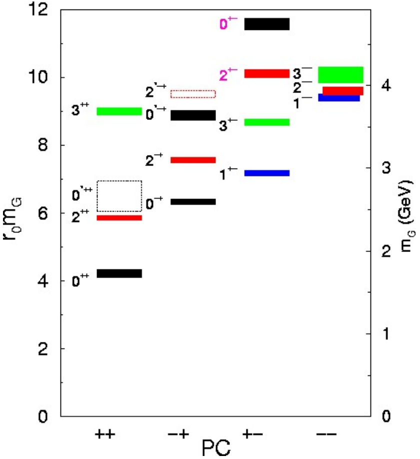
Exotic mesons

QCD can allow other color-less states with 0 baryon number:

- glueballs
- $q\bar{q} - g$ hybrids
- a variety of 4-quark states:
  - molecules
  - diquark-anti-diquark
  - hadro-quarkonium

Glueballs

Glueballs are bound states of gluons without valence quarks



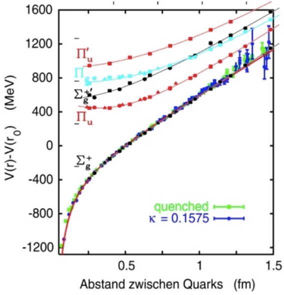
Morningstar and Peardon, PRD 60, 034509 (1999)

- masses can be calculated in LQCD
- difficult to identify glueballs with same J^{PC} as conventional mesons
- can mix with $q\bar{q}$ states with same J^{PC}
- states with exotic $J^{PC} = 0^{+-}, 1^{-+}, 3^{-+}$ expected above 4 GeV
- Signatures:
  - flavor democracy in decay
  - no radiative or $\gamma\gamma$ decay

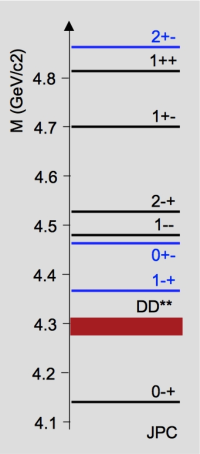
Hybrids

Normal mesons have radial and orbital excitations
Hybrids: excitation of gluonic degrees of freedom (or angular momentum in flux-tube model)

Potential and spectrum also from lattice

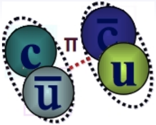


Juge, Kuti, Morningstar hep/lat 9709131



Lightest $c\bar{c}g$ predicted at $\approx 4200\ \mathrm{MeV}/c^2$
Natural preference to decay to $J/\psi +$ pions

Hadronic molecules



Weakly bound states of mesons (or baryons)

Difficult to make predictions

- short range interactions between mesons
  $L = 0$ states
- small binding energy $100\,\mathrm{keV} \div 10\,\mathrm{MeV}$ for heavy mesons

$$R \approx 1\,\mathrm{fm} \qquad E = \frac{1}{2\mu R^2}$$

$\bar{D}^{(*)}_{(s)} D^{(*)}_{(s)}$ and $\bar{B}^{(*)}_{(s)} B^{(*)}_{(s)}$ molecules should have masses close to corresponding thresholds

- large $\mathcal{B}$'s to final states with constituent mesons

Not all pairs of mesons will be bound $\rightarrow$ no need to find a new state at each threshold

Diquark-antidiquark (tetraquark)

qq behave as a color $\bar{3}$ and bind tightly to a q (color 3) to form baryons

$\bar{q}\bar{q}$ behave as a color 3
qq' and $\bar{q}''\bar{q}'''$ can bind tightly to form color singlets

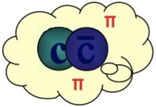
- masses not necessarily close to threshold
- many states, charged and neutral, a nonet for each spin-parity
- neutral states expected to appear in doublets
- decays include both open and hidden charm channels and (if kinematically allowed) baryonium

Hadroquarkonium

Compact $Q\bar{Q}$ bound state or heavy hadron "embedded" into an extended light $q\bar{q}'$ meson

Decay by "undressing" to constituent heavy hadron + light hadrons Naturally explain

- why some states decay to J/ψ and not to $\psi(2S)$
- why decays to open charm/bottom are suppressed



How to identify exotic mesons?

Smoking guns:
quark content and/or quantum numbers not allowed for $(q\bar{q})_0$

- manifestly exotic quantum numbers: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
- charged charmonium or bottomonium states

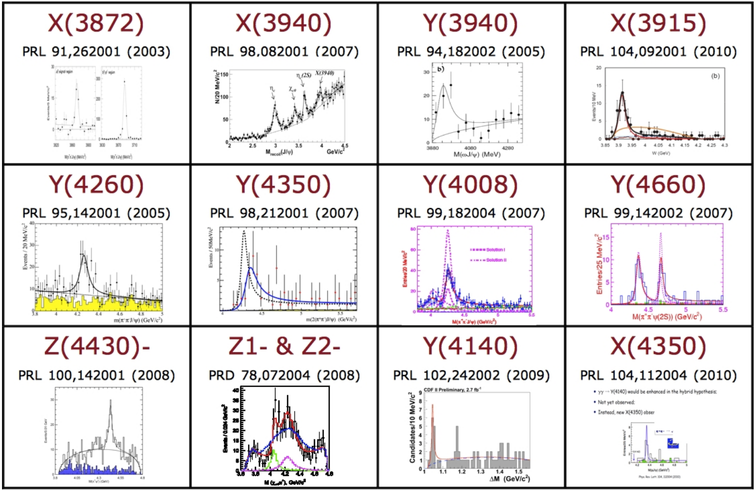
not-so-smoking guns:

- over-population of the spectrum
- anomalous decay or production properties

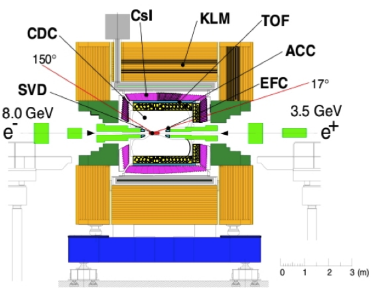
But

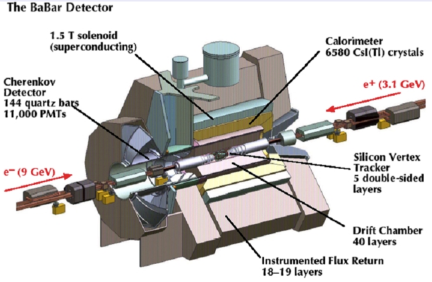
- threshold effects, mixing and coupled channels can significantly affect masses and decay widths of conventional quarkonia
- Artifacts (cusps, virtual states, **reflections**) can be mistaken as resonances

Puzzling charmonium-like states



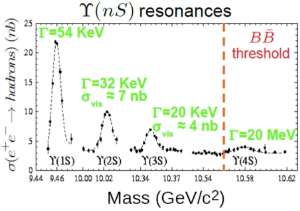
BaBar and Belle





Samples	Υ(1S)	Υ(2S)	Υ(3S)	Υ(4S)	Υ(5S)
BaBar		14 fb^{-1}	30 fb^{-1}	433 fb^{-1}	3.2 fb^{-1} (scan)
Belle	6 fb^{-1}	24 fb^{-1}	3 fb^{-1}	711 fb^{-1}	121 fb^{-1}

running at $\Upsilon(nS)$ formation energy



Large samples of Υ(nS) and B mesons

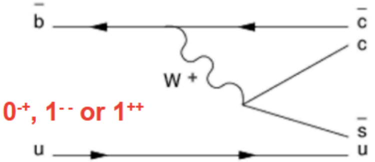
also very large samples of charm mesons and charmonium:

- $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb
- Charm meson and charmonium in b→c decays
- charmonium in ISR and γγ processes

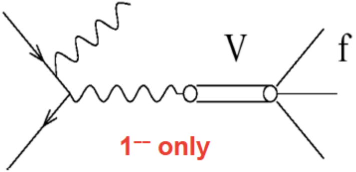
Low multiplicity, can reconstruct complete events

Charmonium at B-factories

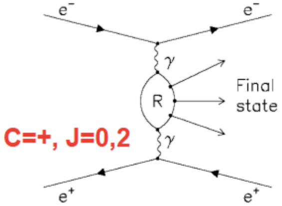
B→c$\bar{c}$ K$^{(*)}$



ISR production

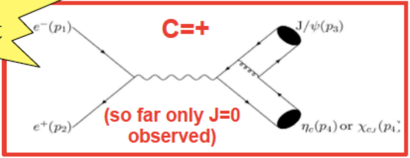


two-photon fusion



first observed at B-factories

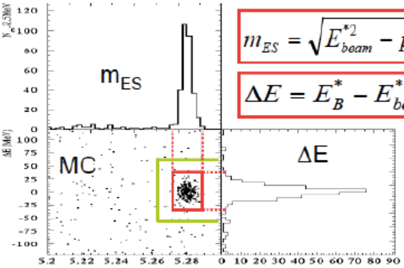
double c$\bar{c}$



Experimentally clean environment
+
large cross section

Common selection variables for charmonia in B decays

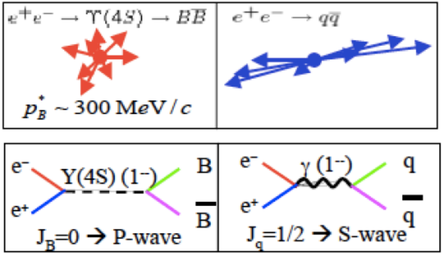
The B mesons are produced in pairs from $\Upsilon(4S)$:



$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^*_B - E^*_{beam}$$

E^*_B should be equal to $E^*_{beam}(= E_{CM}/2)$



- m_{es}: beam energy substituted mass (also named m_{bc} beam constrained mass)
- ΔE: difference between expected and reconstructed energy

- more spherical $B\bar{B}$ vs jet-like $c\bar{c}$ or light quark pairs
- different angular distribution of the "thrust" axis

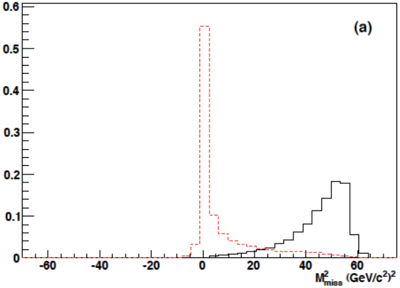
Common selection variables for charmonia in ISR or $\gamma\gamma$

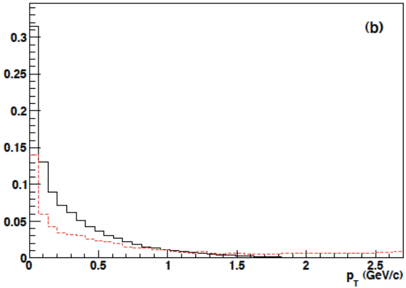
ISR: energetic photon radiated by incoming $e^{\pm}$ lowers the CM energy
ISR cross section strongly forward peaked, photon often undetected along the beam pipe

- low p_t of reconstructed final state
- missing mass M^2_{miss} of reconstructed final state compatible with 0

$\gamma\gamma$ reactions: virtual photons emitted by beam particles, the outgoing $e^{\pm}$ scattering angle depends on the momentum tranfer
For quasi-real photons the scattering angle is small and the scattered e^+e^- escape along the beam pipe

- low p_t of reconstructed final state
- large missing mass M^2_{miss} of reconstructed final state



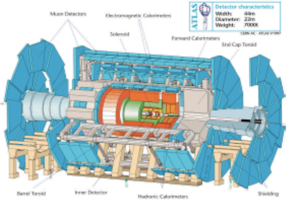


LHC experiments

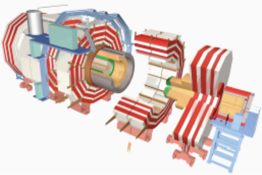
General purpose detectors
High p_T regime

High luminosity and pile-up

pp collisions at 7 TeV
(in 10-11)



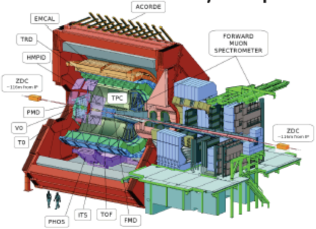
ATLAS



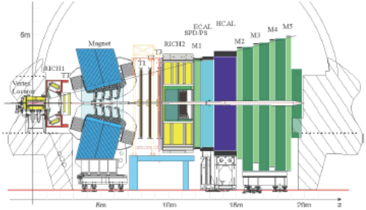
CMS

Dedicated detectors
Low p_T regime

Low or moderate luminosity and pile-up



ALICE

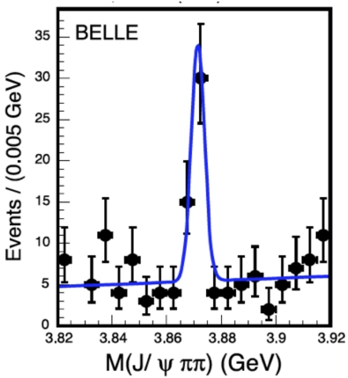


LHCb

Exclusive final states in high multiplicity environment

The discovery of the $X(3872)$

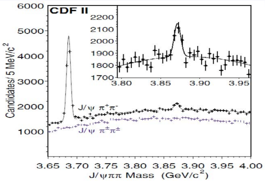
Narrow peak in $J/\psi\pi^+\pi^-$ invariant mass observed by Belle in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays



PRL 91 (2003) 262001

Confirmation of $X(3872)$

Soon confirmed by CDF, D0 in inclusive $p\bar{p}$ production



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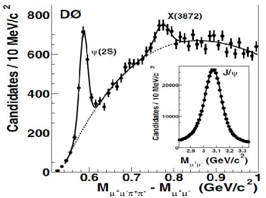
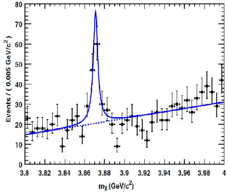
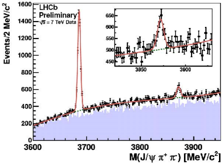


BABAR in B decays



and later also seen by LHCb and CMS in inclusive pp production



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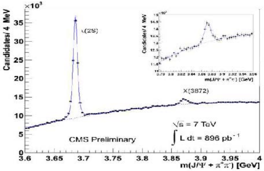
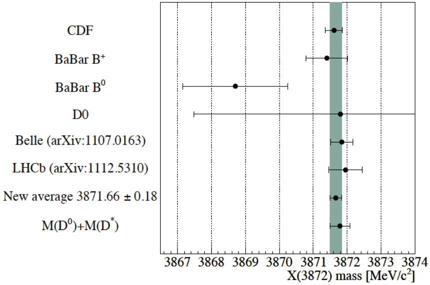


Mass and width of $X(3872)$

The mass difference between the $X(3872)$ and the opening of the $D\bar{D}^*$ is crucial for the molecular interpretation

But also for other models since vicinity to the threshold affects predictions for $\mathcal{B}$'s



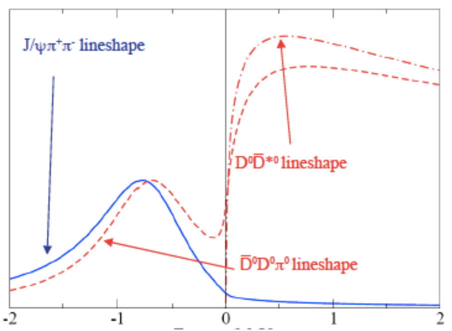
$$\text{Mass (average)} = 3871.66 \pm 0.18\ \mathrm{MeV}/c^2$$

$$M(D^0) + M(D^{0*}) = 3871.79 \pm 0.29\ \mathrm{MeV}/c^2$$

The $X(3872)$ lineshape

Proximity to the $D\bar{D}^*$ threshold affects lineshape differently in different final states if

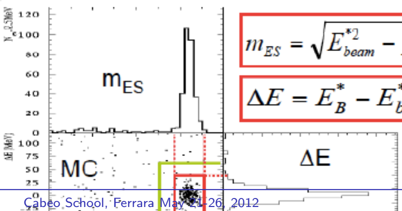
- cusp (no resonance)
- molecule
- hadrocharmonium
- di-quark/anti-diquark
- Narrow $\longrightarrow$ peak position shift for J=2



Braaten, Stapleton arXiv:0907.3167 (2009)

Dunwoodie, Ziegler PRL 100, 062006 (2008)

Hanhart, Kalashikova, Nefediev PRD 81, 094028 (2010)

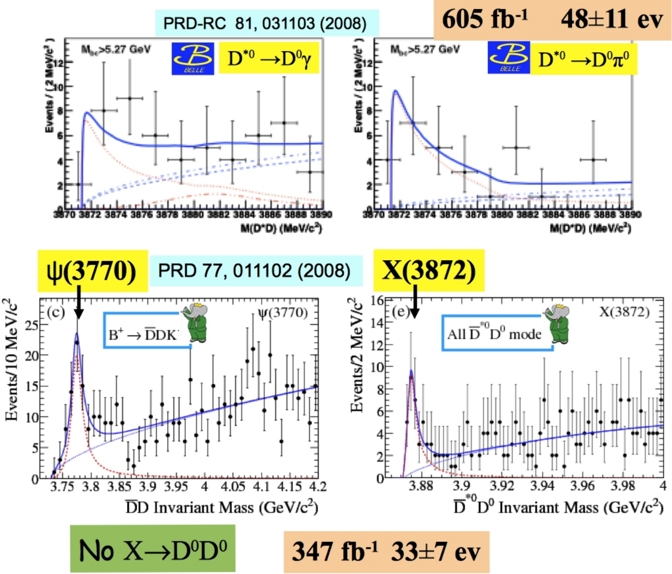


$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

$$\Delta E = E^*_B - E^*_{beam}$$

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

- Belle updated it's first measurement and find mass compatible to $J/\psi\pi\pi$
- Babar studies also $D\bar{D}$ (finds no signal) and finds a mass ~3MeV higher
- resolution
- background modeling
- lineshape at threshold

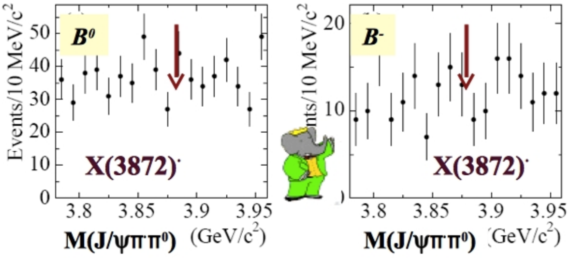


Search for I-spin partner or neutral doublet

If the $X(3872)$ is a tetraquark, it could be a member of a multiplet

$$(cq)(\bar{c}\bar{q}')$$

$\longrightarrow$ search for states decaying to $J/\psi\pi^+\pi^0$
$\longrightarrow$ search for mass difference between $J/\psi\pi^+\pi^-$ from B^+ and B^0

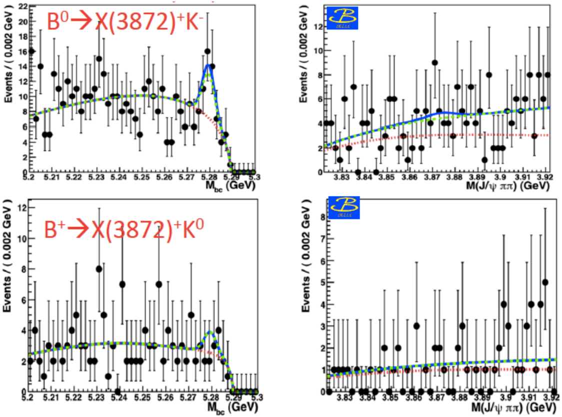


PRD 71, 031501 (2005)

No evidence, exclude I-vector hypotesis where

$$\frac{\mathcal{B}(B^0 \to X^- K^+) \cdot \mathcal{B}(X^- \to J/\psi\pi^-\pi^0)}{\mathcal{B}(B^- \to X^0 K^-) \cdot \mathcal{B}(X^0 \to J/\psi\pi^+\pi^-)} \approx 2$$

Belle: search for I-spin partner



PRD 85, 052003 (2012)

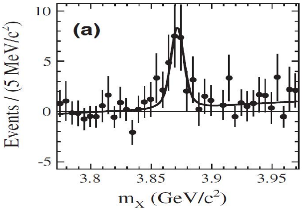
more stringent limits

Rule out I-spin triplet models?

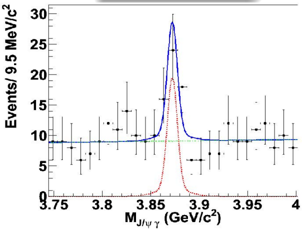
Radiative $X(3872)$ decays: $X(3872) \to J/\psi\gamma$

Establish C=+ for the $X(3872)$

BABAR: PRL 102, 132001 (2009)



Belle: PRL 107, 091803 (2011)



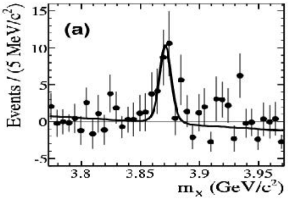
$$\frac{\mathcal{B}(X \to \gamma J/\psi)}{\mathcal{B}(X \to J\psi\pi^+\pi^-)} = 0.33 \pm 12$$

$$\frac{\mathcal{B}(X \to \gamma J/\psi)}{\mathcal{B}(X \to J\psi\pi^+\pi^-)} = 0.22 \pm 0.05$$

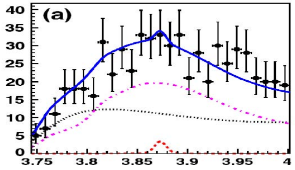
Too large for charmonium?

Radiative $X(3872)$ decays: $X(3872) \to \psi(2S)\gamma$

BABAR: PRL 102, 132001 (2009)



Belle: PRL 107, 091803 (2011)



$$\frac{\mathcal{B}(X \to \gamma\psi(2S))}{\mathcal{B}(X \to J\psi\pi^+\pi^-)} = 3.4 \pm 12$$

$$\frac{\mathcal{B}(X \to \gamma\psi(2S))}{\mathcal{B}(X \to J\psi\pi^+\pi^-)} < 2.1(90\% CL)$$

BABAR result too large for molecular interpretation

Quantum numbers: angular distribution

CDF: angular distribution of $X(3872) \to J\psi\pi^+\pi^-$

PRL 98 (2007) 132002

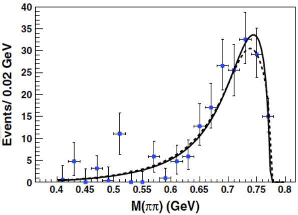
- Allow for $(\pi^+\pi^-)_{S-wave}$ and ρ contributions, with lowest P-conserving L
- Subthreshold $\pi^+\pi^- = \rho$ favored
- $J^P = 2^-$ or 1^+ similar χ^2 prob.

J^{PC}	decay	LS	χ^2 (11 d.o.f.)	χ^2 prob.
1^{++}	$J/\psi\rho^0$	01	13.2	0.28
2^{-+}	$J/\psi\rho^0$	11,12	13.6	0.26
1^{--}	$J/\psi(\pi\pi)_S$	01	35.1	2.4×10^{-4}
2^{+-}	$J/\psi(\pi\pi)_S$	11	38.9	5.5×10^{-5}
1^{+-}	$J/\psi(\pi\pi)_S$	11	39.8	3.8×10^{-5}
2^{--}	$J/\psi(\pi\pi)_S$	21	39.8	3.8×10^{-5}
3^{+-}	$J/\psi(\pi\pi)_S$	31	39.8	3.8×10^{-5}
3^{--}	$J/\psi(\pi\pi)_S$	21	41.0	2.4×10^{-5}
2^{++}	$J/\psi\rho^0$	02	43.0	1.1×10^{-5}
1^{-+}	$J/\psi\rho^0$	10,11,12	45.4	4.1×10^{-6}
0^{-+}	$J/\psi\rho^0$	11		3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11		$\leq1\times10^{-20}$
0^{++}	$J/\psi\rho^0$	00		$\leq1\times10^{-20}$

Belle's update: angular distribution of $X(3872) \to J\psi\pi^+\pi^-$ from B decays Possible assignment:

PRD 85, 052003 (2012)

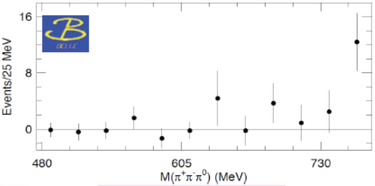
- 1^+
- $J^P = 2^-$ for a definite value of a complex parameter



The $X(3872) \to \omega J/\psi$ decay

$J/\psi\pi^+\pi^-\pi^0$ decay first reported by Belle (unpublished)

hep-ex/0505037

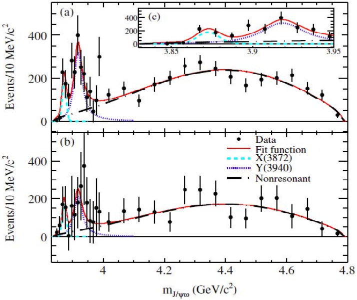


possibly sub-threshold $\omega \to$ large I-spin violation

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

confirmed by BABAR in both B^0 and $B^{\pm}$

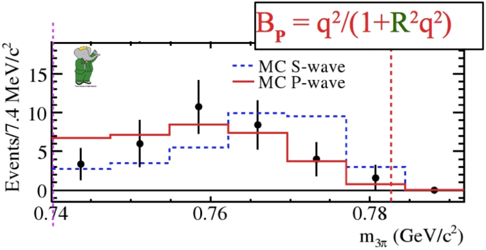
PRD-RC 82,011101(2010)



$$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$$

Impact of angular momentum on ω lineshape

- S-wave: $P(\chi^2) = 7\%$ vs P-wave: $P(\chi^2) = 62\%$
- Negative parity favored: 2^- favored over 1^+
- consistent with $\eta_{c2}(1D)$??



$R = 3\ GeV^{-1}$ Blatt-Weisskopf radius

$0 < R < 5\ GeV^{-1}$ give similar results

$X(3872)$ interpretation

- Conventional charmonium
  - $\chi_{c1}(2P)$ ($J^{PC} = 1^{++}$)
    radiative decay should be two orders of magnitude larger
    mass off by 100 MeV/c^2 higher
  - $\eta_{c1}(1D)$ ($J^{PC} = 2^{-+}$)
    should have large partial width to gg and small partial width to $J/\psi\pi^+\pi^-$
    mass off by 50 MeV/c^2
- Tetraquark:
  No I-spin partners, no neutral doublet

Mixture of $D^0\bar{D}^{*0}$ and $\chi_{c1}(2P)$??

- $D^0\bar{D}^{*0}$ molecule
  natural explanation for mass almost coincident with threshold
  $D^0\bar{D}^{*0}$ decay
  $J^{PC} = 1^{++}$ ($D^0\bar{D}^{*0}$ in S-wave)
  small $J/\psi\gamma$ can be accomodated
  but
  - too large $\psi(2S)\gamma$ (if confirmed)
  - small binding energy $\rightarrow$ large radius, difficult to explain production in high energy pp or $p\bar{p}$ collisions

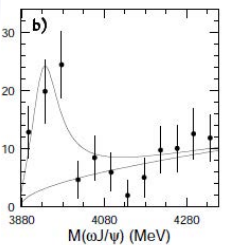
The $Y(3940) \to J/\psi\omega$ observed in B decays

Observed by Belle PRL 94,180002 (2005)

$$M = 3943 \pm 11 \pm 13\,\mathrm{MeV}/c^2$$

$$\Gamma = 87 \pm 22 \pm 26$$

$$\mathcal{B}(B \to YK)\cdot\mathcal{B}(Y \to \omega J/\psi) = (7.3 \pm 1.3 \pm 3.1)\cdot 10^{-5}$$



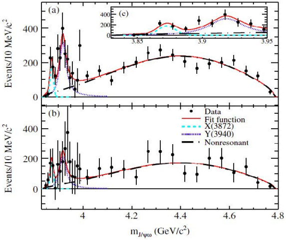
confirmed by *BABAR* PRD-RC 82,011101(2010)

$$M = 39.19^{+3.8}_{-3.5} \pm 2.0\ \mathrm{MeV}/c^2$$

$$\Gamma = 31^{+10}_{-8} \pm 5,\ \mathrm{MeV}$$

$$\mathcal{B}(B^+ \to YK^+)\cdot\mathcal{B}(Y \to \omega J/\psi) = (3.0^{+0.7}_{-0.6}{}^{+0.5}_{-0.3})\cdot 10^{-5}$$

$$\mathcal{B}(B^0 \to YK^0)\cdot\mathcal{B}(Y \to \omega J/\psi) = (2.1 \pm 0.9 \pm 0.3)\cdot 10^{-5}$$



Not seen in $B \to D\bar{D}^* K$ (expected dominant for 1^{++})

$\mathcal{B}(B \to YK)$ large for 2^{++} in B decays. $0^{++}, 0^{-+}$???

The $X(3915) \to J/\psi\omega$ observed in $\gamma\gamma$ reactions

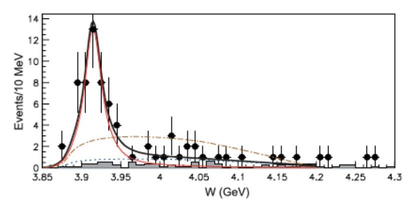
Observed by Belle PRL 104, 092001 (2010)

$$M = 3915 \pm 3 \pm 2 \text{ MeV}/c^2$$

$$\Gamma = 17 \pm 10 \pm 3 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 61 \pm 17 \pm 8 \text{ eV} \quad (J = 0)$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 18 \pm 5 \pm 2 \text{ eV} \quad (J = 2)$$



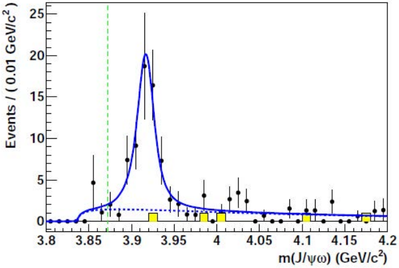
Confirmed by *BABAR* Guttmann –MoriondQCD12

$$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 52 \pm 10 \pm 3 \text{ eV} \quad (J = 0)$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) = 10.5 \pm 1.9 \pm 0.6 \text{ eV} \quad (J = 2)$$

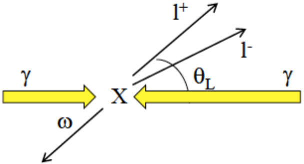


If $\Gamma_{\gamma\gamma} = \mathcal{O}(1 \text{ keV})$ (typical $c\bar{c}$), then $\mathcal{B}(J/\psi\omega) > (1-6)\%$
Limit for $J = 2$ hypothesis of $X(3872)$: $\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J\psi\omega) < 1.7$ eV

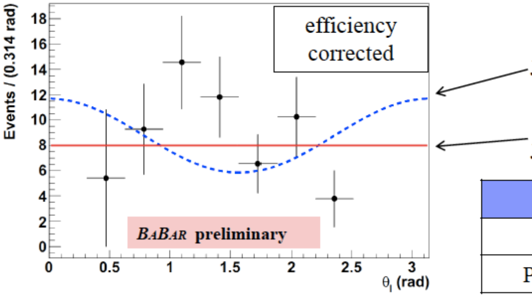
$X(3915)$ spin determination

- Define θ_L: the angle between the two-photon collision axis and the positive charged lepton in the two-photon rest frame.

Guttmann –MoriondQCD12



$3890 < m(J/\psi\omega) < 3950$ MeV/c^2



J=2 $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_L} = \frac{3}{8}(1+\cos^2\theta_L) \quad [1]$$

J=0

	J=0	J=2
χ^2	9.48	14.56
$P(\chi^2)$	14.8%	2.4%

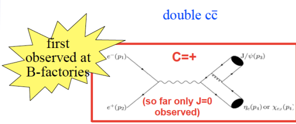
[1] J. L. Rosner, PRD 70, 094023 (2004)

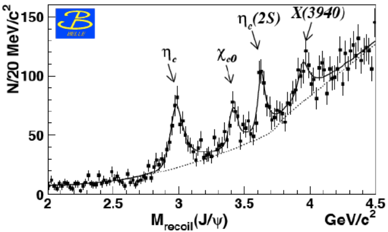
The $X(3940) \to D\bar{D}^*$ observed in double $c\bar{c}$ production

Unexpectedly large cross section for
$\sigma(e^+e^- \to J/\psi(c\bar{c}))$ measured by Belle

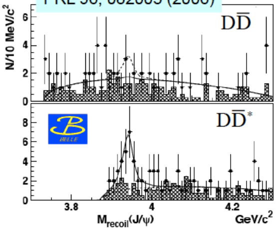
Observe known $0^{\pm+}$ states recoiling againts a J/ψ

+ another one





PRL 96, 082003 (2006)



PRL 100:202001,2008

$M = 3942^{+7}_{-6} \pm 6\ \mathrm{MeV/c^2}$

$\Gamma = 37^{+26}_{-15} \pm 8\ \mathrm{MeV}$

- observed in the recoil of the J/ψ (double $c\bar{c}$) ...
- The only other states clearly visible have J=0 C=+
  - → that suggest either $\chi_{c0}(2P)$ or $\eta_c(3S)$
- decay to $D\bar{D}^*$ but not to $D\bar{D}$ suggest P=-1 thus hypothesis of $\eta_c(3S)$
- the 3^1S_0 mass is predicted at ~4050 or above

not seen in $B \to DD^*K$

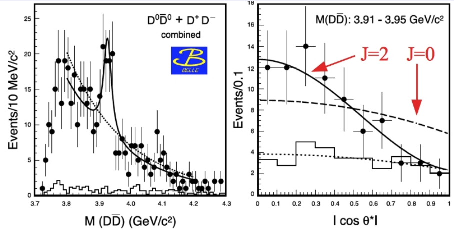
The $Z(3930) \to D\bar{D}$ observed in $\gamma\gamma$: $\chi_{c2}(2P)$ candidate

Observed by Belle in $\gamma\gamma \to D\bar{D}$
NOT in $D\bar{D}^*$

$$M = 3929 \pm 5 \pm 2\,\mathrm{MeV}/c^2$$

$$\Gamma = 29 \pm 10 \pm 2\,\mathrm{MeV}$$

$$\Gamma_{\gamma\gamma} \times \mathcal{B}(D\bar{D}) = 0.18 \pm 0.05 \pm 0.03\,\mathrm{keV}$$

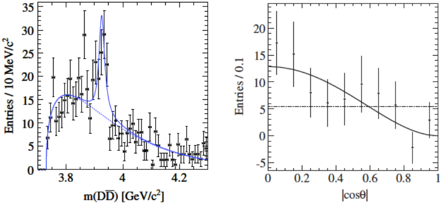


Confirmed by *BABAR*

$$M = 3926.7 \pm 2.7 \pm 1.1\,\mathrm{MeV}/c^2$$

$$\Gamma = 21.3 \pm 6.8 \pm 3.6\,\mathrm{MeV}$$

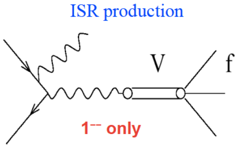
$$\Gamma_{\gamma\gamma} \times \mathcal{B}(D\bar{D}) = 0.241 \pm 0.054 \pm 0.043\,\mathrm{keV}$$



Angular distribution strongly favors $J = 2$: generally identified as $\chi_{c2}(2P)$ candidate
Mass lower by $\approx 50\,\mathrm{MeV}/c^2$ but Γ, $\Gamma_{\gamma\gamma}$ and $\mathcal{B}(D\bar{D})$ consistent with expectations
Could be interesting to search for $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_c\pi^+\pi^-$ or $J/\psi\omega$

$Y(4260) \to J/\psi\pi\pi$

BABAR searched for states decaying to $J/\psi\pi^+\pi^-$ in ISR process

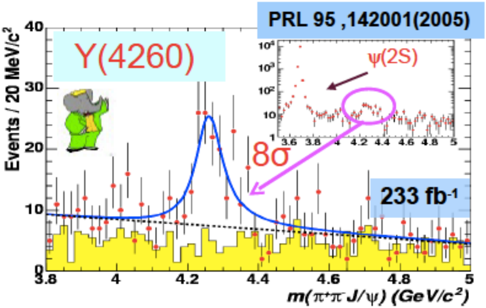


did not find the $X(3872)$ nor one of its predicted partners but found an unexpected broad state

$$M = 4259 \pm 8^{+2}_{-6}\ \mathrm{MeV}/c^2$$

$$\Gamma = 88 \pm 23^{+6}_{-4}\ \mathrm{MeV}$$

$$\Gamma_{ee} \cdot \mathcal{B}(J\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7}\ \mathrm{eV}$$



The hadronic cross section has a dip at this mass

From the total cross section estimate

$\mathcal{B}(Y \to J/\psi\pi^+\pi^-) > 8\%$

$\Gamma(Y \to J/\psi\pi^+\pi^-) > 8\ \mathrm{MeV}$

Search for $Y(4260)$ decay modes

The $Y(4260)$ is not seen in the inclusive hadronic cross section measurements

It has been searched (and not found) in

- many exclusive $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$ modes
- many exclusive light hadron modes
- $p\bar{p}$

CLEO: $Y(4260) \to J/\psi\pi^+\pi^-$ and $Y(4260) \to J/\psi\pi^0\pi^0$

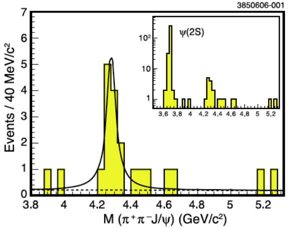
Confirmed $Y(4260)$ in ISR

PRD-RC 74, 091104 (2006)

$$M = 4284^{+17}_{-16} \pm 4 \text{ MeV}/c^2$$

$$\Gamma = 73^{+39}_{-25} \pm 5 \text{ MeV}$$

$$\Gamma_{ee} \cdot \mathcal{B}(J\psi\pi^+\pi^-) = 8.9^{+3.9}_{-3.1} \pm 1.8 \text{ eV}$$

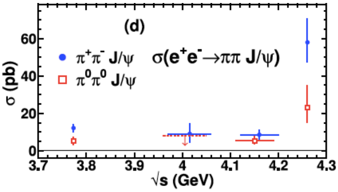


Observed it also in the energy scan in both $J/\psi\pi^+\pi^-$ and $J/\psi\pi^0\pi^0$

$$\frac{\mathcal{B}(J/\psi\pi^0\pi^0)}{\mathcal{B}(J/\psi\pi^+\pi^-)} \approx 1/2$$

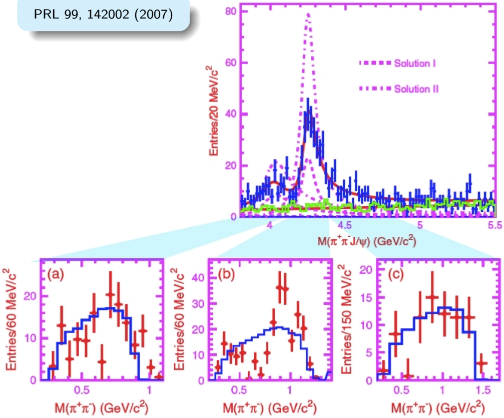
as expected by I-spin 0

PRL 96, 162003 (2006)



Belle: $Y(4260)$ confirmed, plus new state at $Y(4008)$?

PRL 99, 142002 (2007)



Belle studied the $J\psi\pi^+\pi^-$ final state in ISR

The Y(4260 is prominent

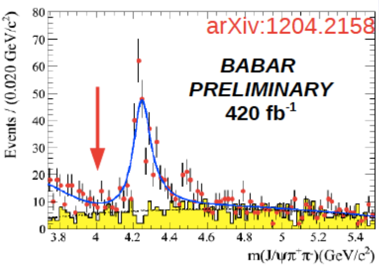
width and $\Gamma_{ee} \cdot \mathcal{B}(J/\psi\pi^+\pi^-)$ depend on possible interference with a new state at 4008 MeV/c^2

The $\pi^+\pi^-$ invariant mass spectrum in the $Y(4260)$ region has a peak around $f_0(980)$

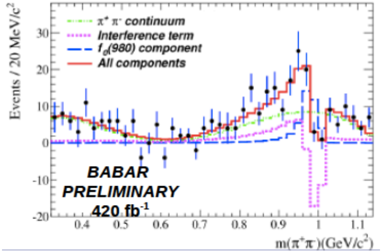
BABAR update: $Y(4260)$ and study of $\pi^+\pi^-$ spectrum

BABAR update with the full dataset

Mass (Y(4260)) = $4244 \pm 5 \pm 4$ MeV/c^2
$\Gamma(Y(4260)) = 114^{+16}_{-15} \pm 7$ MeV
$\Gamma_{e^+e^-} \times B(J/\psi\pi^+\pi^-) = 9.2 \pm 0.8 \pm 0.7$ eV



No evidence for $Y(4008)$



Non dominant $f_0(980)$ contribution

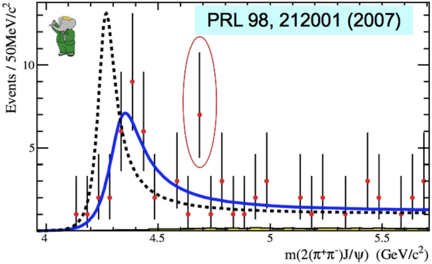
$$\frac{B(Y_{4260} \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-)}{B(Y_{4260} \to J/\psi\pi^+\pi^-)} = (17 \pm 13)\%$$

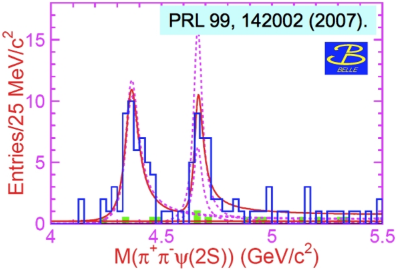
The π^+ angle with respect to the J/ψ direction in the $\pi^+\pi^-$ rest frame is consistent with S-wave $\longrightarrow \pi^+\pi^-$ system has I=0

fit the $\pi^+\pi^-$ invariant mass distribution as a coherent sum of NR + $f_0(980)$

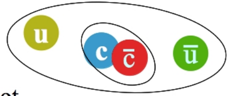
mass dependence of $f_0(980)$ amplitude and phase from $D_s^+ \to \pi^+\pi^-\pi^+$ DP analysis

$Y(4350)$ and $Y(4660) \to \psi(2S)\pi\pi$





- observed by BaBar in ISR $\psi(2S)\pi^+\pi^-$
- confirmed by Belle, which finds a significant excess also at 4660 MeV
- no evidence for Y(4260)...
- why are there states decaying to 2^3S_1 and not to 1^3S_1



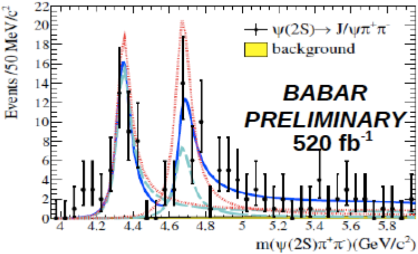
hadro-charmonium?

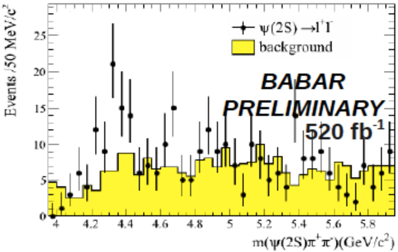
- MB Voloshin arXiv:0711.4556
- Dubynsky, & Voloshin PLB 671 (2009) 82

BaBar update on $Y(4350)$ and $Y(4660) \to \psi(2S)\pi\pi$

BaBar update using the full dataset, including $\Upsilon(2S)$ and $\Upsilon(3S$ Use both $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\psi(2S) \to \ell^+\ell^-$

Principe – CHARM2012

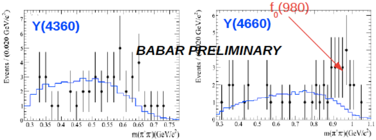




Confirm Belle's $Y(4660)$

Mass(Y(4350)) = 4340±16±9 *MeV/c²*
Γ(Y(4350)) = 94±32±13 *MeV*

Mass(Y(4660)) = 4669±21±3 *MeV/c²*
Γ(Y(4660)) = 104±48±10 *MeV*



statistics too low to draw conclusions on $\pi^+\pi^-$ invariant mass distribution

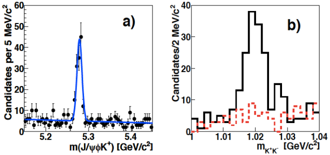
$Y(4140) \to \phi J/\psi$ decay?

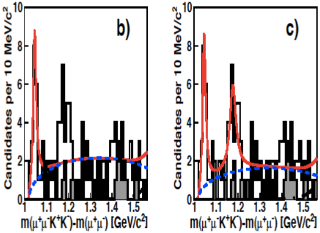
CDF studied $B^+ \to J/\psi \phi K^+$ decays and found an excess of events in the $J\psi\phi$ invariant mass at threshold PRL 102, 242002 (2009)

Allowed $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$

Updated in arXiv:1101.6058

115 ± 12 B^+ events





$Y(4140)$: $19 \pm 6 \pm 3\,\mathrm{evts}$ $(5\,\sigma)$

$$M = 4143^{+2.9}_{-3.0} \pm 0.6\,\mathrm{MeV}/c^2$$

$$\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7\,\mathrm{MeV}$$

$$\frac{\mathcal{B}(B^+ \to YK^+) \times \mathcal{B}(Y \to J\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} = 0.149 \pm 0.039 \pm 0.024$$

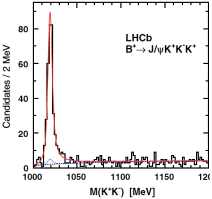
$X(4274)$: $22 \pm 8\,\mathrm{evts}$ $(3.1\,\sigma)$

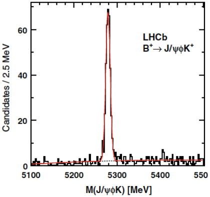
$$M = 4274.4^{+8.4}_{-6.7} \pm 1.9\,\mathrm{MeV}/c^2$$

$$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6\,\mathrm{MeV}$$

LHCb study of $B^+ \to \phi J/\psi K^+$ decays

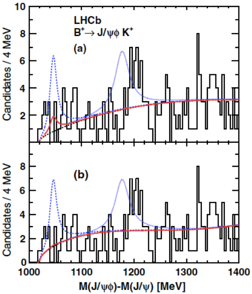
LHCb searched for $J/\psi\phi$ resonances in $B^+ \to J/\psi\phi K^+$ PRD-RC 85, 091103 (2012)





$\mathcal{L} = 0.37\,\text{fb}^{-1}$

382 ± 22 B^+ *events*



Y(4140) : Expect: $35 \pm 9 \pm 6$ evts

< 16evts (a)

< 13evts (b)

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

X(4274) : Expect: 53 ± 19 evts

< 24evts (a)

< 20evts (b)

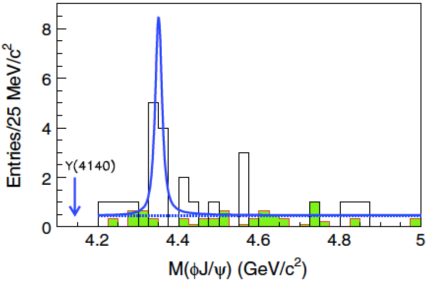
$$\frac{\mathcal{B}(B^+ \to YK^+) \times \mathcal{B}(X \to J\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.08$$

Search for $\gamma\gamma \to Y(4140) \to \phi J/\psi$

Belle searched for $\gamma\gamma \to Y(4140) \to \phi J/\psi$ PRL 104, 112004 (2010)

No evidence for $Y(4140)$
set upper limits
$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\omega) < 41 \text{ eV} \quad (J=0)$
$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\omega) < 6 \text{ eV} \quad (J=2)$

Find 3.1 σ evidence for a new structure...

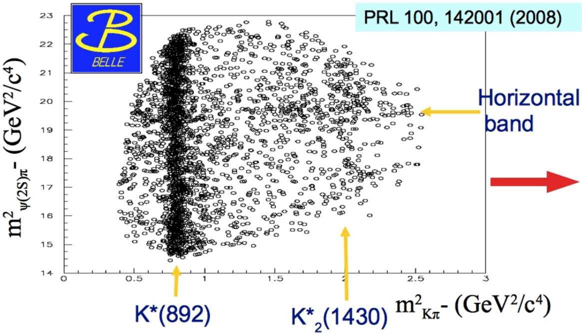


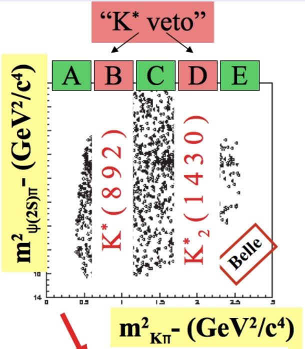
$$M = 4350.6^{+4.6}_{-5.1} \pm 0.7 \text{ MeV}/c^2$$

$$\Gamma = 13^{+18}_{-9} \pm 4 \text{ MeV}$$

$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\omega) = 6.7^{+3.2}_{-2.4} \pm 1.1 \text{ eV} \quad (J=0)$$
$$\Gamma_{\gamma\gamma} \cdot \mathcal{B}(J/\psi\omega) = 1.5^{+0.7}_{-0.6} \pm 0.3 \text{ eV} \quad (J=2)$$

Charged charmonium? $Z(4430)^{\pm}$ from Belle



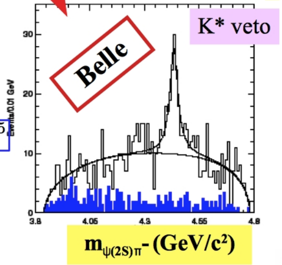


121 ± 30 ev 6.5σ

$$M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2$$

$$\Gamma = 43^{+18}_{-13}{}^{+30}_{-13} \text{ MeV}$$

$$\mathcal{B}(B^0 \to Z^- K^+)\mathcal{B}(Z^- \to \psi(2S)\pi^-) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$



first genuine $c\bar{c}d\bar{u}$ "tetraquark" candidate:
charged and carries hidden charm

Search for $Z(4430)^-$ in *BABAR*

Search in four B decay modes:

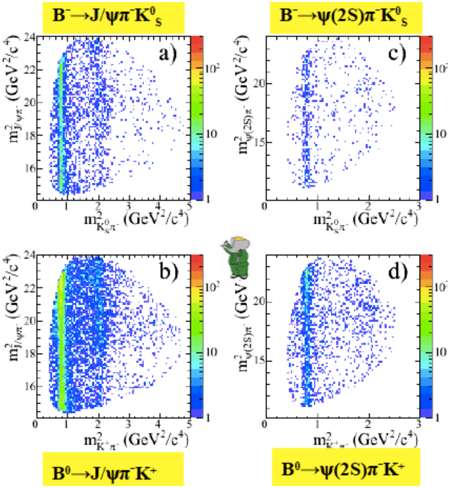
$B^{-/0} \rightarrow J/\psi\ \pi^- K^{0/+}$

$B^{-/0} \rightarrow \psi(2S)\ \pi^- K^{0/+}$

[in the following ψ denotes J/ψ and ψ(2S)]

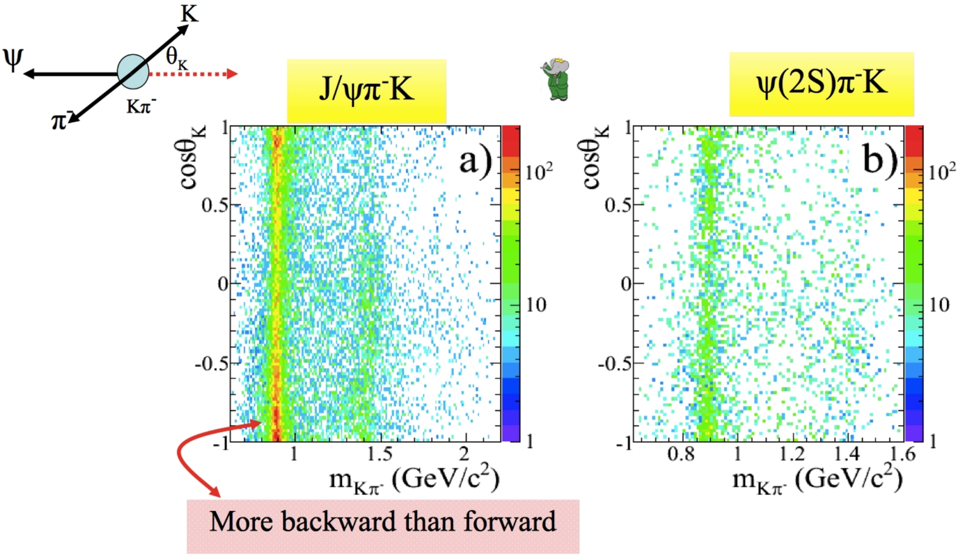
- subtract background (sidebands)
- correct for efficiency event by even
- describe in detail the $K\pi^-$ system
  - → structures in the $K\pi^-$ mass and angular distributions dominate each Dalitz plot

Project each $K\pi^-$ description onto the relevant $\psi\pi^-$ mass distribution to investigate the need for $Z(4430)^-$ signal above this “ $K\pi^-$ background”

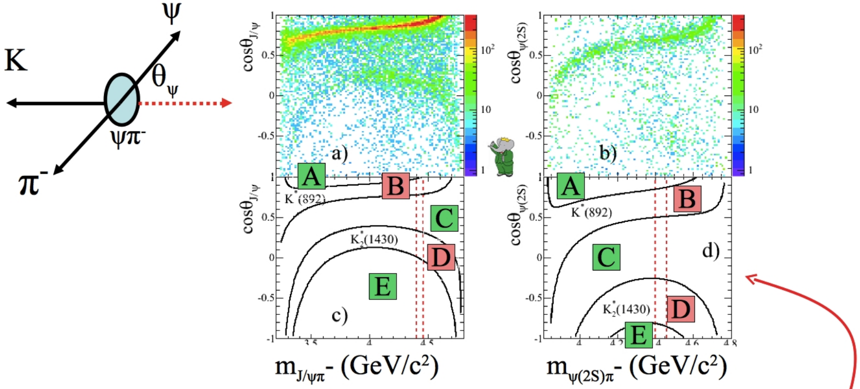


PRD 79, 112001 (2009)

"Square" Dalitz plot



$K\pi$ reflections and the $Z(4430)^-$



- $m_{\psi\pi}$ peaks at high values because of the asymmetry in the $\cos\theta_K$ distributions
- The K^* regions dominate, and affect different regions of $\cos\theta_\psi$ for J/ψ and $\psi(2S)$
- The K^* veto removes approximately half of the angular distribution at the $Z(4430)^-$

$K\pi$ description: S, P and D wave intensities

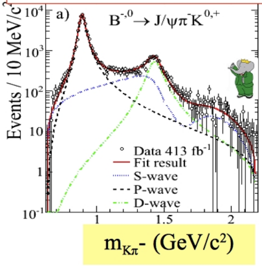
Fit with S- (LASS), P-, and D-wave intensity

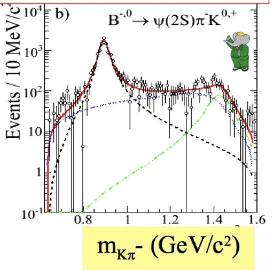
Mode	Events	m(K*(892)) (MeV/c2)	Γ(K*(892)) (MeV)	S-wave (%)	P-wave (%)	D-wave (%)
$B^0 \to J/\psi \pi^- K^+$	57231±561	895.5±0.4	48.9±1.0	15.7±0.8	73.5±0.7	10.8±0.5
$B^- \to J/\psi \pi^- K^0_S$	20985±393	892.9±0.8	49.0±1.9	17.0±1.6	72.5±1.3	10.5±1.0
$B^0 \to \psi(2S) \pi^- K^+$	13237±377	895.8±1.0	43.8±3.0	25.4±2.2	68.2±2.0	6.4±1.2
$B^- \to \psi(2S) \pi^- K^0_S$	5016±292	891.6±2.1	44.8±6.0	23.4±4.5	71.3±4.4	5.3±2.7

compatible with being equal (first two rows)

compatible with being equal (last two rows)

It is justified to combine the K^0_S and K^+ modes





PRD 79, 112001 (2009)

$B \to \psi(K\pi)$ S, P and D wave moments

The expression of the angular distribution for B→ψπK is complicated
(see e.g. S. T'Jampens, Ph.D. Thesis, Universite Paris XI (2002), SLAC-R-838)

Integrating over the ψ decay angles: 5 observables, 7 amplitudes, 6 relative phases

$$N = S_0^2 + P_0^2 + D_0^2 + P_{+1}^2 + P_{-1}^2 + D_{+1}^2 + D_{-1}^2$$

$$\langle P_1^U \rangle = S_0 P_0 \cos(\delta_{S_0} - \delta_{P_0}) + 2\sqrt{\frac{2}{5}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0}) + \sqrt{\frac{6}{5}} \left[P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) + P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}}) \right]$$

$$\langle P_2^U \rangle = \sqrt{\frac{2}{5}} P_0^2 + \sqrt{\frac{10}{7}} D_0^2 + \sqrt{2} S_0 D_0 \cos(\delta_{S_0} - \delta_{D_0}) - \left[\frac{1}{\sqrt{10}} (P_{+1}^2 + P_{-1}^2) + \frac{5\sqrt{10}}{28} (D_{+1}^2 + D_{-1}^2) \right]$$

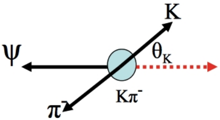
$$\langle P_3^U \rangle = 3\sqrt{\frac{6}{35}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0}) - 3\sqrt{\frac{2}{35}} \left[P_{+1} D_{+1} \cos(\delta_{P_{+1}} - \delta_{D_{+1}}) + P_{-1} D_{-1} \cos(\delta_{P_{-1}} - \delta_{D_{-1}}) \right]$$

$$\langle P_4^U \rangle = \frac{3\sqrt{2}}{7} D_0^2 - \frac{2\sqrt{2}}{7} (D_{+1}^2 + D_{-1}^2)$$

Complete Kπ amplitude analysis of DP not possible without making assumptions

For Kπ scattering

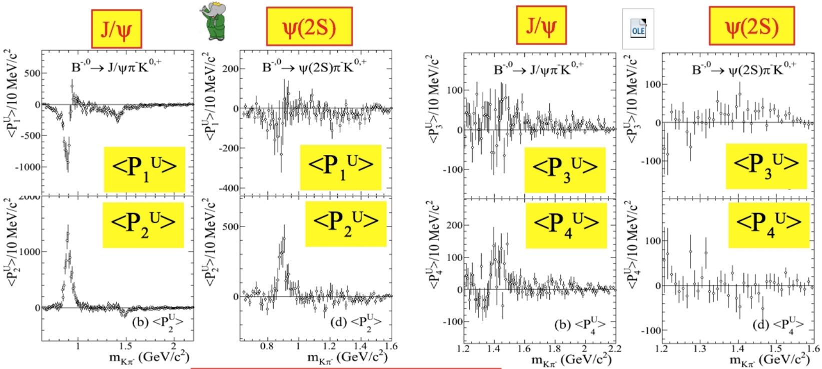
Legendre polynomial moments description of $K\pi^-$ angular structure



$$\frac{dN}{d\cos\theta_K} = N\sum_{i=0}^{4} <P_i> P_i(\cos\theta_K) = \frac{N}{2} + \sum_{i=1}^{4} (N<P_i>)\, P_i(\cos\theta_K)$$

assume only S,P and D wave

Unnormalized moment $<P_i^U>$



$<P_1^U>$ and $<P_2^U>$ dominant

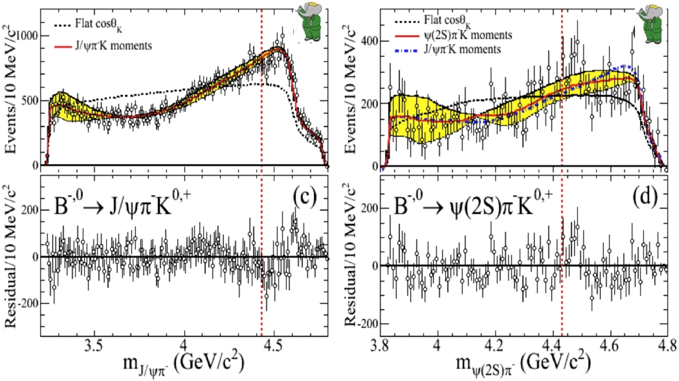
PRD 79, 112001 (2009)

$K\pi^-$ reflection onto the $\psi\pi^-$ projection

10M events generated flat in $\cos\theta_K$ according to the $m_{K\pi^-}$ fit function

- Weight each event using Legendre moments: $w_j = 1 + \sum_{i=1}^{4} < P_i^N > P_i(\cos\theta_{Kj})$

i^{th} **normalized** moment, obtained from data by linear interpolation → $< P_i^N > = \frac{2}{N} < P_i^U >$



Compare $\psi\pi^-$ distribution in data after background subtraction and efficiency correction to what expected from $K\pi^-$ reflections

$K\pi^-$ reflections reproduce data

PRD 79, 112001 (2009)

Belle update on the $Z(4430)^+$

Belle re-analyzed their dataperforming an isobar fit to the Dalitz plot

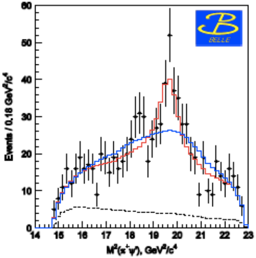
confirm large significance

PRD 80, 031104 (2009)

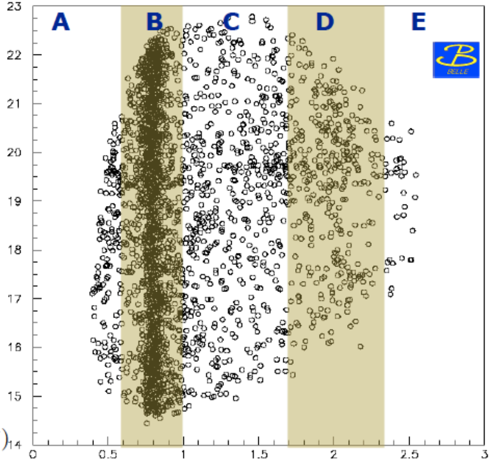
width somewhat different
but compatible(large errors)

$$M = (4443^{+15+17}_{-12-13})\ \mathrm{MeV}/c^2,$$

$$\Gamma = (109^{+86+57}_{-43-52})\ \mathrm{MeV},$$

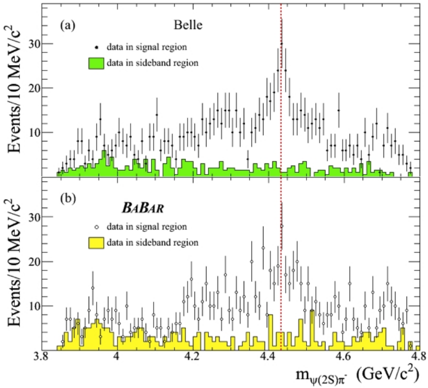


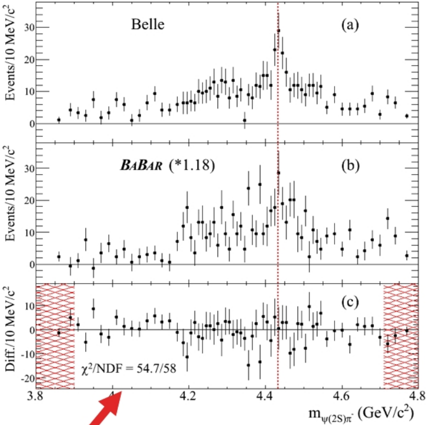
$$\mathcal{B}(B^0 \to Z^+K^+) \times \mathcal{B}(Z^+ \to \psi(2S)\pi^+)$$
$$= (3.2^{+1.8+5.3}_{-0.9-1.6})10^{-5}$$



Direct data comparison

Uncorrected data in the K* veto region



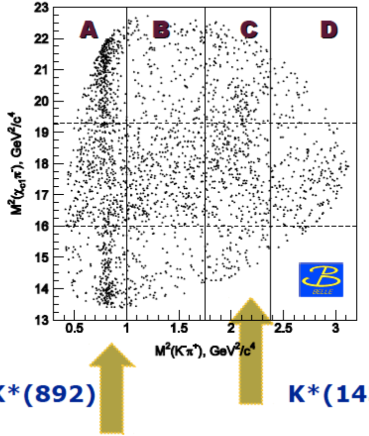


- Both Belle and *BABAR* data are re-binned (to calculate χ^2) and side-band subtracted
- The *BABAR* data are normalized (*1.18) to the Belle sample; Luminosity ratio is 1.46

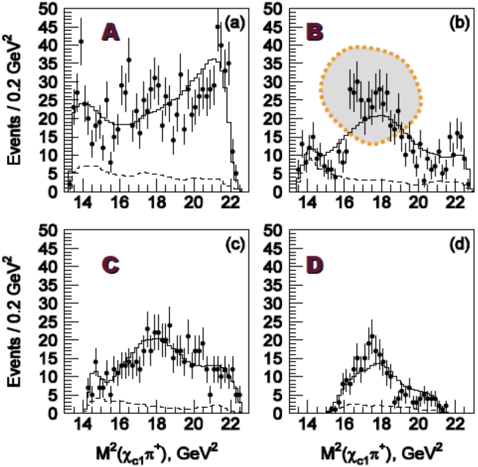
The data distributions are statistically consistent (χ^2=54.7/58)

More charged states in $B^0 \to \chi_{c1}\pi^+ K^-$

Dalitz plot fit including all known K*:
κ, K*(892), K*(1410), $K^*_0(1430)$, $K^*_2(1430)$, K*(1680), $K^*_3(1780)$

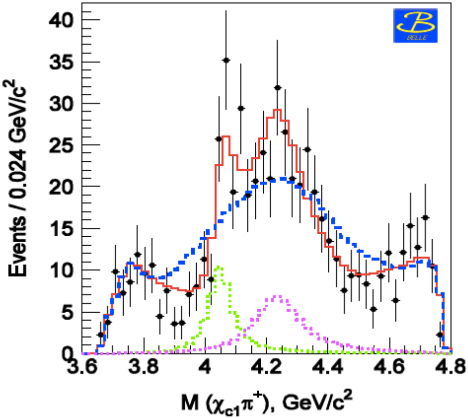


K*(892) K*(1430)



CL of the fit ~10^{-10}

$Z_1(4050)^+$ and $Z_2(4250)^+$



$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$

$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$

$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$

$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

with the product branching fractions of

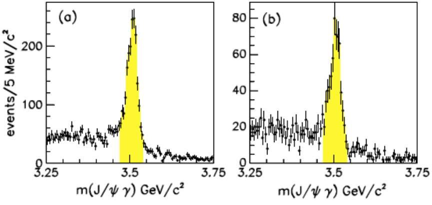
$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

PRD 78, 072004 (2008)

$B\!A\!B\!AR$ search for $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B^0 \to \chi_{c1}\pi^+K^-$ and $B^+ \to \chi_{c1}\pi^+K_S$

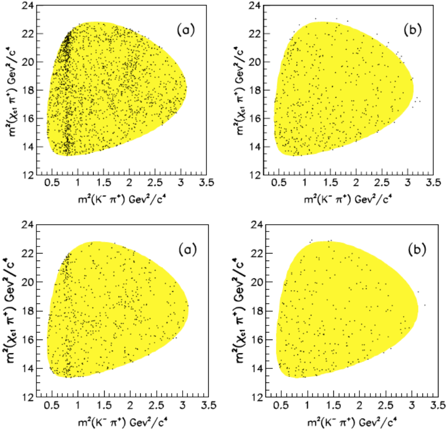
Select samples with relatively large purities



Channel	$\sigma_{\Delta E}$(MeV)	$\sigma_{m_{ES}}$(MeV/c^2)	Events	Purity %
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$ $(\mu^+\mu^-)$	6.96 ± 0.34	2.60 ± 0.10	980	79.3 ± 1.3
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$ (e^+e^-)	7.81 ± 0.43	2.77 ± 0.12	883	77.1 ± 1.4
$B^+ \to \chi_{c1}K^0_S\pi^+$ $(\mu^+\mu^-)$	6.65 ± 0.55	2.65 ± 0.27	299	81.7 ± 2.2
$B^+ \to \chi_{c1}K^0_S\pi^+$ (e^+e^-)	7.52 ± 0.70	2.65 ± 0.18	329	77.5 ± 2.3

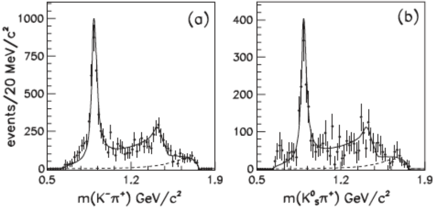
PRD 85, 052003 (2012)

and study DP for signal region and background sidebands



$K\pi$ description in $B^0 \to \chi_{c1}\pi^+K^-$ and $B^+ \to \chi_{c1}\pi^+K_S$

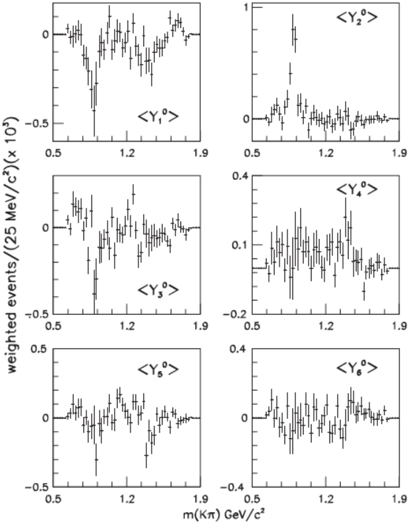
Fit the $K\pi$ invariant mass distribution to a sum of S-P-D wave



Channel	S wave	P wave	D wave	χ^2/NDF
$\bar{B}^0 \to \chi_{c1}K^-\pi^+$	40.4 ± 2.2	37.9 ± 1.3	11.4 ± 2.0	58/54
		10.3 ± 1.5		
$B^+ \to \chi_{c1}K_S^0\pi^+$	42.4 ± 3.5	37.1 ± 3.2	10.1 ± 3.1	55/54
		10.4 ± 2.5		

PRD 85, 052003 (2012)

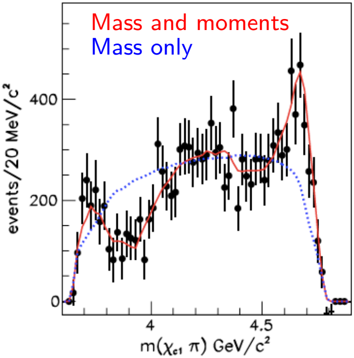
and weight each event by Legendre Y_L^0 polynomials



No evidence from *BABAR* for $Z_1(4050)^+$ and $Z_2(4250)^+$

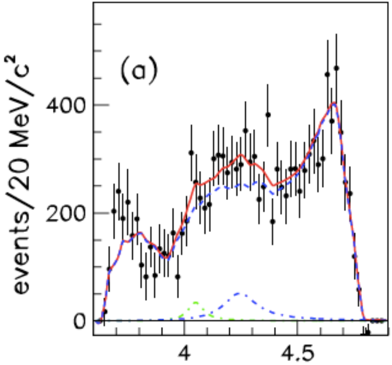
Use MC to predict reflections of $K\pi$ mass and angular structures in $\chi_{c1}\pi^+$

No Z's

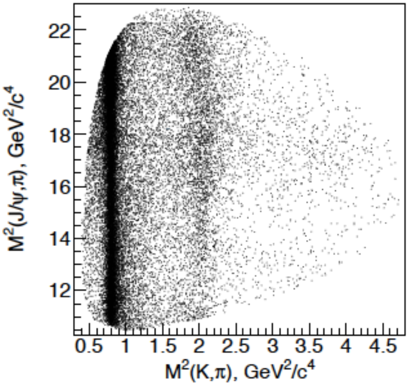


PRD 85, 052003 (2012)

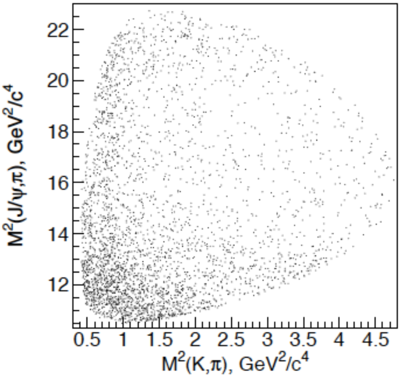
with Z's



New: Belle's search for $Z(4430)^+$ in $B \to J/\psi K\pi$



$K^*(892)$ $K^*(1430)$



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4-D fit: $M^2(\psi\pi), M^{(}K\pi), \theta_\psi, \phi_\psi$

Signal model for $B \to J/\psi K\pi$

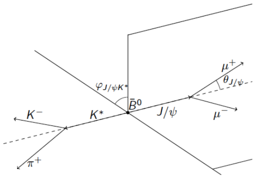
$$S(s_x, s_y, \varphi_{J/\psi K^*}, \theta_{J/\psi}) = \sum_{\xi=1,-1} \left| \sum_{\lambda=-1,0,1} A_\lambda d^1_{\lambda\ \xi}(\theta_{J/\psi}) \right|^2 ,$$

where

$s_x = M^2(K,\pi),\ s_y = M^2(J/\psi,\pi)$,

ξ - sum of lepton helicities, λ - helicity of J/ψ,

$A_\lambda = A_\lambda^{K^*} e^{-i\lambda\varphi_{J/\psi K^*}} + A_\lambda^{Z_c^+}$.



$\bar{K}^{*0} \to K^-\pi^+$ amplitude:

$$A_\lambda^{K^*} = \sum_{K^*} a_\lambda^{K^*} e^{i\phi_\lambda^{K^*}} A^{K^*}(s_x, s_y) d^{J(K^*)}_{\lambda\ 0}(\theta_{K^*}),$$

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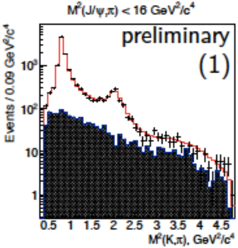
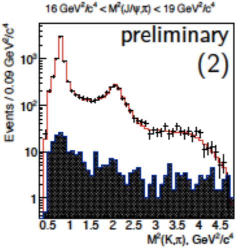
$Z_c^+ \to J/\psi\pi^+$ amplitude:

$$A_\lambda^{Z_c^+} = \sum_{\lambda'=-1,0,1} a_{\lambda'}^{Z_c^+} e^{i\phi_{\lambda'}^{Z_c^+}} A^{Z_c^+}(s_x, s_y) d_{0\ \lambda'}^{J(Z_c^+)}(\theta_{Z_c^+}) e^{-i\lambda'\tilde{\varphi}_{J/\psi K^*}} d^1_{\lambda'\ \lambda}(\theta_{K^*\pi^+}),$$

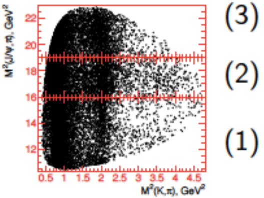
Search for $Z+$ with quantum numbers $J^P = 0^-, 1^\pm, 2^pm$

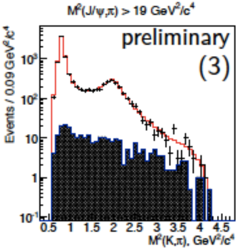
Fit result: $K\pi$ projections





Slices





good description of $K\pi$ projection

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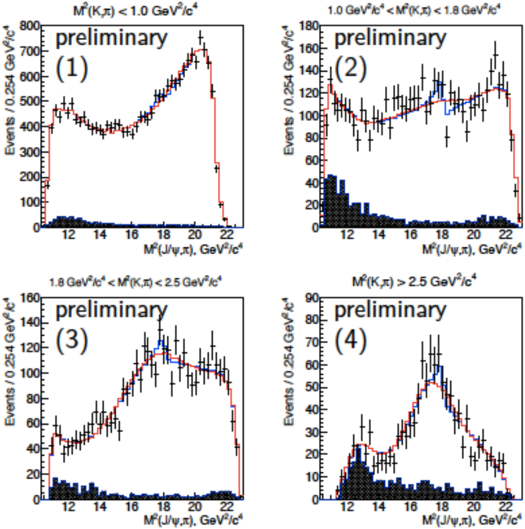
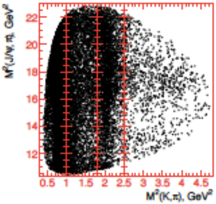
Fit result: $\psi\pi$ projections



Slices

(1)(2)(3) (4)



No evidence for $Z^{\pm}$

Belle: K.Chilikin – Charm 2012

$\mathcal{B}(B^0 \to Z^- K^+)\cdot\mathcal{B}(Z^- \to J/\psi\,\pi^+) < 8\cdot10^{-6}$

BABAR : PRD 79, 112001 (2009)

$\mathcal{B}(B^0 \to Z^- K^+)\cdot\mathcal{B}(Z^- \to J/\psi\,\pi^+) < 4\cdot10^{-6}$

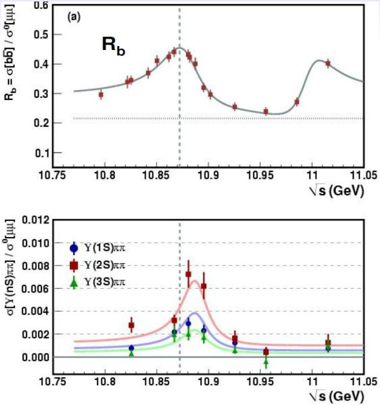
$\Upsilon(5S) \to \pi^+\pi^-\Upsilon(ns)$

Belle searched for non-$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ decays of the $\Upsilon(5S)$

The resonance parameters measured in $\Upsilon(nS)\pi^+\pi^-$ final state differ from the parameters measured in the ratio

$$R_b = \frac{\sigma(e^+e^- \to b - \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

interference with continuum? non trivial description of R_b



PRL 100, 112001 (2008)

PRD-RC 82, 091106 (2010)

Bottomonium partner of the $Y(4260)$?

- anomalously large partial widths $\Gamma(\Upsilon(nS)\pi^+\pi^-)$
  dipion transitions are large also at the $\Upsilon(4S)$
- $\Gamma(\Upsilon(1S)\pi^+\pi^-) \approx 2 \times \Gamma(\Upsilon(2,3S)\pi^+\pi^-)$

$\Upsilon(5S) \to \pi^+\pi^- X$

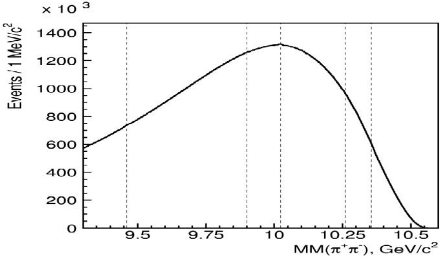
Belle studied the inclusive dipion transitions at the $\Upsilon(5S)$

study of the distribution of the invariant mass recoiling against $\pi^+\pi^-$

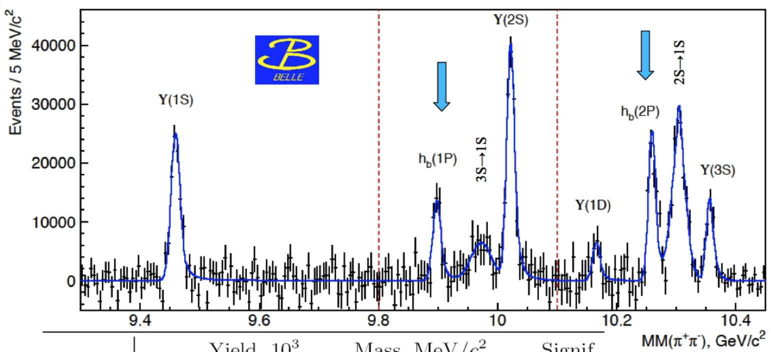
$$MM_{\pi^+\pi^-} = \sqrt{(E_{beam} - E_{\pi^+\pi^-})^2 - (\vec{p}_{beam} - \vec{p}_{\pi^+\pi^-})^2}$$

Fit the large smooth background and subtract

PRL 108, 032001, (2012)



$\Upsilon(5S) \to \pi^+\pi^- X$: observation of $h_b(1P)$ and $h_b(2P)$



	Yield, 10^3	Mass, MeV$/c^2$	Signif.
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	$6.2\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	$16.6\,\sigma$
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$
$2S \to 1S$	$151.6 \pm 9.7^{+9.0}_{-20.}$	$10304.57 \pm 0.61 \pm 1.03$	$15.7\,\sigma$
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	$8.5\,\sigma$

Significance w/ systematics

$h_b(1P)$ 5.5σ

$h_b(2P)$ 11.2σ

PRL 108, 032001, (2012)

$h_b(1P)$ and $h_b(2P)$

BELLE

Deviations from CoG of χ_{bJ} masses

$h_b(1P)$ 1.62 ± 1.52 MeV/c² }
$h_b(2P)$ $0.48\,^{+1.57}_{-1.22}$ MeV/c² } consistent with zero, as expected

PRL 108, 032001, (2012)

Ratio of production rates

spin-flip

no spin flip

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

$S(\Upsilon) = 1$ $S(h_b) = 0$

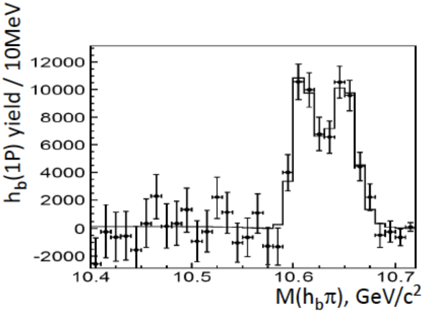
Process with spin-flip of heavy quark is not suppressed

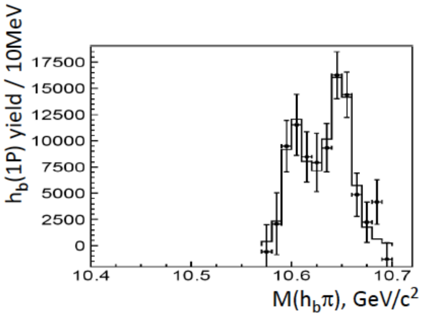
- exotic ?
- rescattering? Simonov JETP Lett 87,147(2008), D. Bugg, arXiv:1101.1659

No h_b signal at $\Upsilon(4S)$

Substructures in $\Upsilon(5S) \to \pi^+\pi^- h_b(nP)$?

Plot of invariant mass recoiling against $\pi^\pm$





	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_{Z_{b1}}$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma_{Z_{b1}}$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M_{Z_{b2}}$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma_{Z_{b2}}$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
a	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
ϕ	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Almost all of $h_b(nP)$ seem to be produced through intermediate states

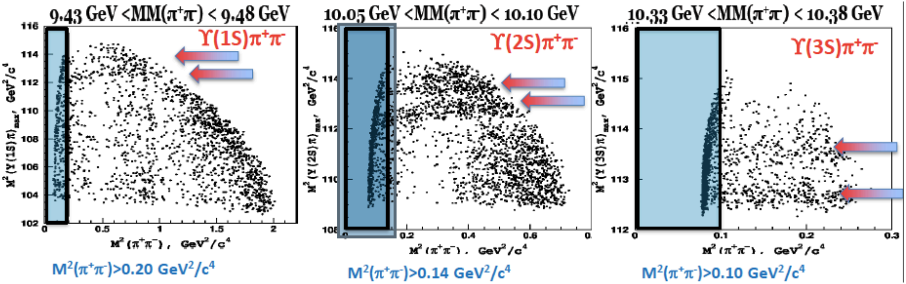
$$\Upsilon(5S) \to Z^-\pi^+ \to h_b(nP)\pi^+\pi^-$$

arXiv:1110.2251

More substructures in $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$?

Dalitz plot of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ show horizontal bands

Plot of invariant mass recoiling against $\pi^\pm$ (squared) vs invariant mass recoiling against $\pi^+\pi^-$ (squared)



Exclude regions contaminated by photon conversions and fit assuming contributions from

- Z_{b1}, Z_{b2} (BW)
- NR $\pi^+\pi^-$ (S-wave)
- $f_0(980)$ (Flatté)
- $f_2(1275)$ (BW)

arXiv:1110.2251

$Z_b(10610)$ and $Z_b(10660)$?

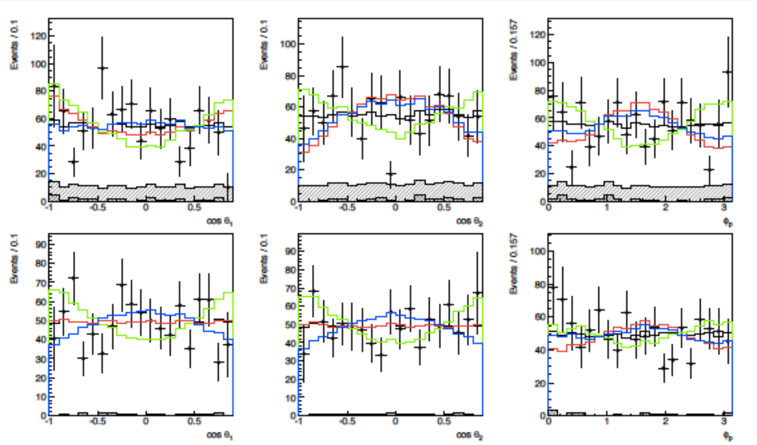
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

In all modes the two peaks have the same mass and width

Large decay to both h_b (P singlet) and Υ (S-vector)

arXiv:1110.2251

$Z_b(10610)$ and $Z_b(10660)$ quantum numbers?



$\pi^+\pi^-$ angular distribution favours $J^P = 1+$

arXiv:1105.4583

Since $\Upsilon(5S)$ has negative G-parity, the Z_b's would have positive G-parity

It's been fun to do spectroscopy in the past 10 years!

Every time people looked to an exclusive final state with quarkonia+light hadrons in a different process found a new state

... and sometime two!

Some of these states might "disappear", some will be recognized to be the same state, but most of them are there to stay

Interplay between experiment and theory to sort out what's going on

In the process we could learn how to handle QCD corrections a bit further away from the easy limits

XYZ samples at B-factories have size of at most hundreds

For some of these states in some of these modes LHC(b) will have $\times$ 10 or 100!