Quarkonium Physics and the $X(3872)$ Discovery

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Flavor Physics Lectures
VIII / XII

Karlsruhe Institute of Technology

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Reading material and references

Lecture material based on several textbooks and online lectures/notes.
Credits for material and figures include:

Literature

- Perkins, Donald H. (2000), *Introduction to High Energy Physics*.
- Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.
- Stone, Sheldon (2nd edition), B *decays*.

Online Resources

- Belle/BaBar Collaborations, *The Phyiscs of the* B*-Factories*.
  http://arxiv.org/abs/1406.6311
- Bona, Marcella (University of London), CP *Violation Lecture Notes*,
  http://pprc.qmul.ac.uk/ bona/ulpg/cpv/
- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and* CP *Violation*.
  http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf
- Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
  http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html
- Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
  http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf
- Kooijman, P. & Tuning, N., CP *Violation*,
  https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

In previous lectures, we:

- Learned how to perform a full analysis on Belle MC and data.

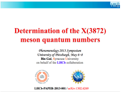
  This included various “Toy” MC studies, and the verification of signal yields by performing *background-subtracted fits* to the invariant mass spectrum(s).

- Introduced the Dalitz plot method and studied the $D \to K_S^0 \pi^+ \pi^-$ dalitz spectrum in $B^- \to D K^- \to K_S^0 \pi^+ \pi^- K^-$ decays.

Today, we'll:

- Introduce Quarkonium physics and the discovery/history of the $X(3872)$.
- See how we can use the tools we've developed to search for and confirm the existence of new resonances.

Credits for additional material and figures:
Physics of B Factories book, A. Garmash, K. Miyabayashi, S. Olsen, H. Guler, C. Shen, B. Gui

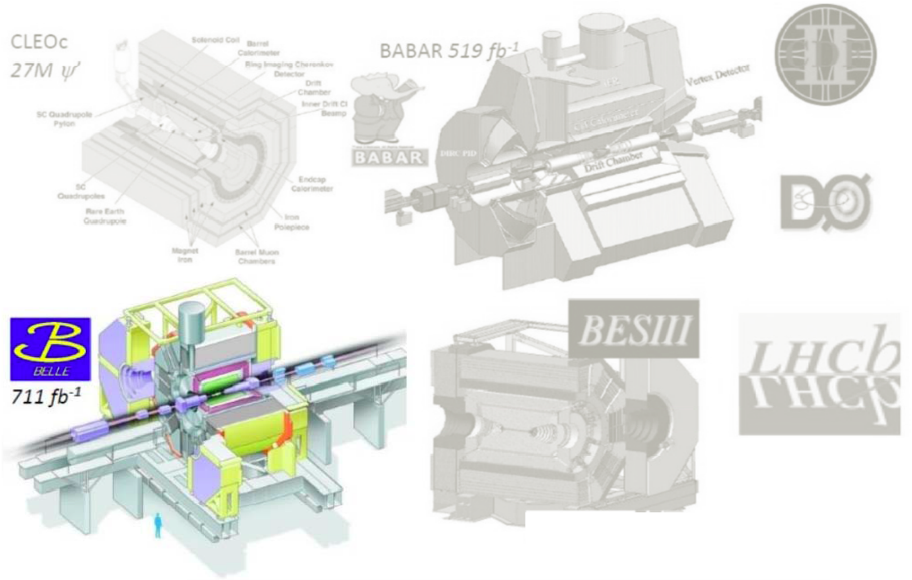


What is “quarkonium”?

Systems composed of a quark and antiquark of the same flavor.

The term “quarkonium” was coined because of the similarity of heavy quark-antiquark bound states to those of positronium: the bound state of an e^+ and an e^-.

Main suppliers of quarkonium *focus on Belle's $X(3872)$ analysis today*



Heavy quarkonia at B factories

- Heavy quarkonia are systems composed of a heavy quark and antiquark of the same flavor (charm or bottom).
- The large mass and the clean and known decay modes make quarkonia an ideal probe of NP in some well defined window of beyond Standard Model (BSM) parameters, in particular for some searches for dark matter candidates.
- Belle and BaBar have collected a wide range of quarkonium data, including:
  - Clean samples of charmonia produced in B decays.
  - Two-photon fusion.
  - Initial state radiation (ISR) e^+e^- annihilation, including the unexpected observation of large associated $(c\bar{c})(c\bar{c})$ production.
  - $b\bar{b}$ states.
- New states, new production mechanisms, and unexpected states of an exotic nature have been observed.

Quantum numbers & spectroscopy

Quantum numbers

- The spectroscopic notation $\boldsymbol{n^{2s+1}l_J}$ is conventionally used for quarkonium levels, where:
  - n = the radial quantum number (equal to the number of nodes in the wavefunction) plus 1;
  - l = the orbital angular momentum quantum number (S, P, D, etc.);
  - s = 0,1 is the total spin of the quarks;
  - J is the quarkonium spin ($|l-s| \leq J \leq l+s$).
- Only the spin of the state can be measured; the others are assigned based on the measured parity P and charge-conjugation C.

$\Rightarrow$ *As we'll see today, this is not trivial! In the case of the $X(3872)$ meson, it took over 10 years of analysis from Belle, BaBar, D0, CDF, and LHCb to nail down the numbers. Additionally, many new states have (as yet) undetermined C and/or P values.*

Parity and charge-conjugation

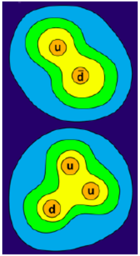
- The behavior of a state under parity is dictated by:
  - The symmetry of the angular momentum eigenfunctions (the spherical harmonics Y_l^m), for which $P = (-1)^l$ [ref];
  - The opposite parity of the antifermion w.r.t. the fermion;

  $\Rightarrow$ *Quarkonium parity:* $P = (-1)^{l+1}$
- Charge conjugation exchanges the two constituents;
  - Due to Fermi-Dirac statistics, the exchange of two identical fermions gives a minus sign.
  - But this exchange is also performed by:
    (1) Applying the charge conjugation operator (factor C);
    (2) Exchanging the coordinates (gives a factor of $(-1)^l$);
    (3) Exchanging the spin (gives $(-1)^{s+1}$).
  - All together this gives $C(-1)^l(-1)^{s+1} = -1$

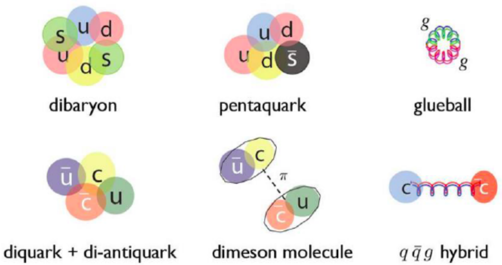
  $\Rightarrow$ *Quarkonium charge conjugation:* $C = (-1)^{l+s}$

Hadrons: normal and exotic

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks



Normal vs. Exotic



- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : N_{quarks} = 0 (gg, ggg, …)
  - Hybrid : N_{quarks} = 2 (or more) + excited gluon
  - Multiquark state : N_{quarks} > 3
  - Molecule : bound state of more than 2 hadrons
  - …

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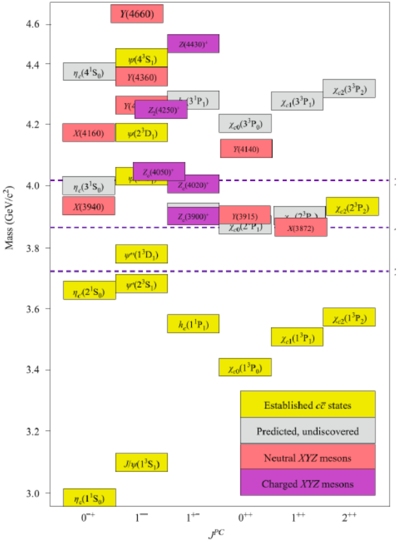
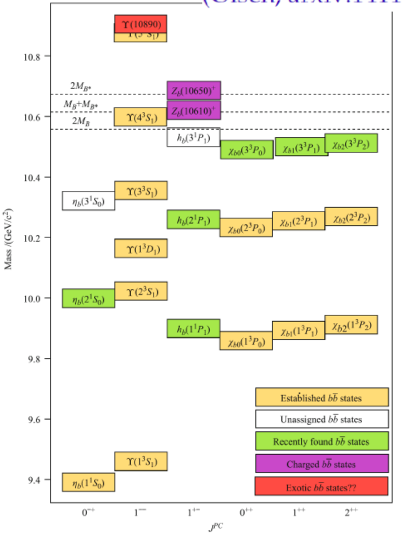
Quarkonium(like) systems

(Olsen, arxiv:1411.7738)



Charmonium(like) states



Bottomonium(like) states

Established and new states

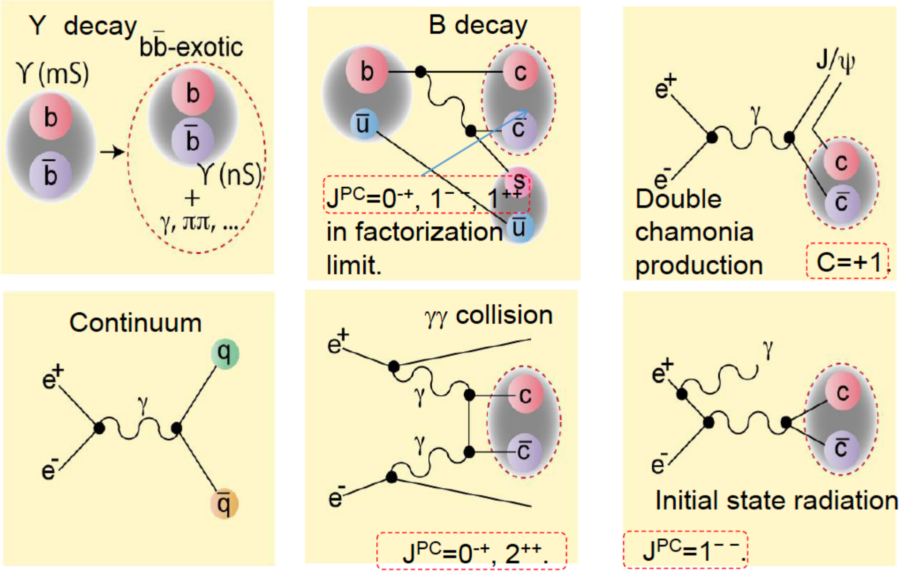
Established states are those predicted in theory and whose measured properties are in agreement with predictions.

New states are unpredicted and/or their measured properties are difficult to accommodate in the theory. Some have (so far) unknown quantum numbers.

$\Rightarrow$ More than 20 resonances observed with the last decade.
Most of them in the charm sector, and a few in the bottom sector.

- The most notable of them are: $X(3872)$, $Y(4260)$, $Zc(3900)/Zc(4200)$, and $Zb(10610)/Zb(10650)$.
- Not predicted by potential models; do not fit into quarkonia scheme.
- Poses a challenge for both theory and experiment
- Define extotic as: any multi-quark meson, or meson with $J^{PC} = 0^{--}, 0^{-+}, 1^{-+}, 2^{+-}, ...$

Variety of recorded reactions



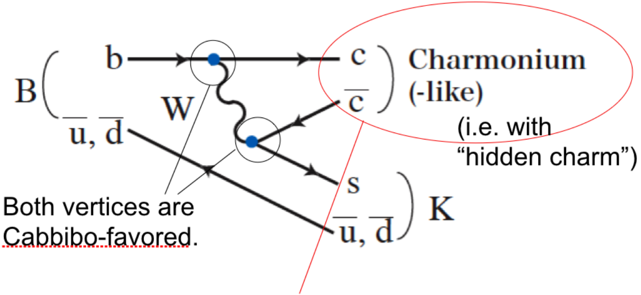
Analysis of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

(Starting with Belle's discovery in 2003[1])

[1] Most cited Belle paper: 1749 citations as of today [https://arxiv.org/abs/hep-ex/0309032]

Motivation

A B-factory serves as a Charmonium(-like) factory via B meson decay.

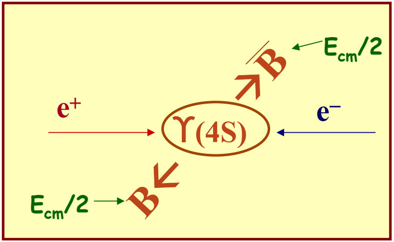


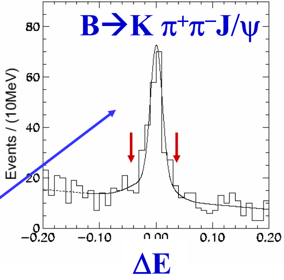
Interesting place to carry out spectroscopy studies!

Strategies for finding the remaining missing states motivated by theoretical work suggesting that a narrow $^3D_{c2}$ should have substantial decay branching fractions for $\pi^+\pi^- J/\psi$ final states

$\Rightarrow$ ***Search in*** $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ ***decays***

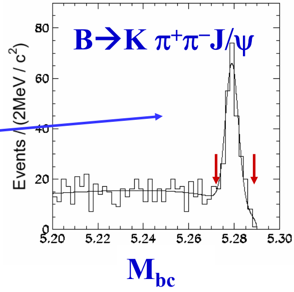
Kinematic variables for the $\Upsilon(4S)$





CM energy difference:

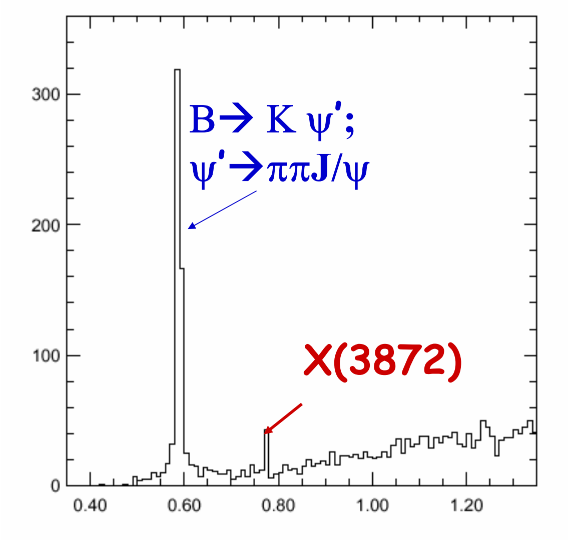
$$\Delta E = E_K + E_{\pi^+\pi^- J/\psi} - E_{cm}/2$$



Beam-constrained mass:

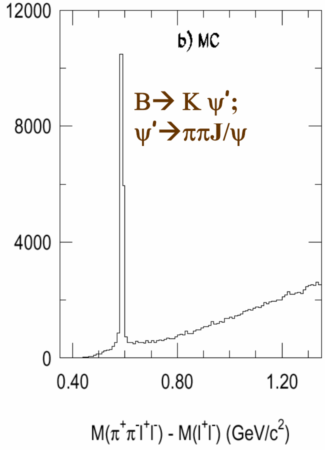
$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_K + \vec{p}_{\pi^+\pi^- J/\psi})^2}$$

$M(\pi^+\pi^- J/\psi) - M(J/\psi)$

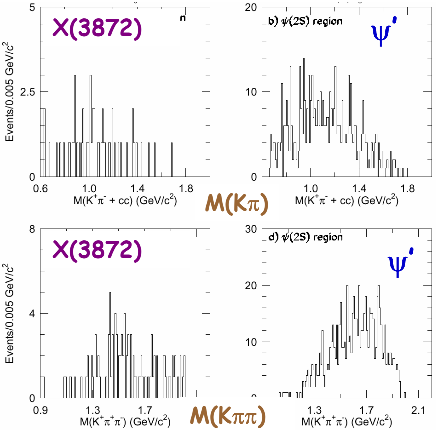


Not a reflection

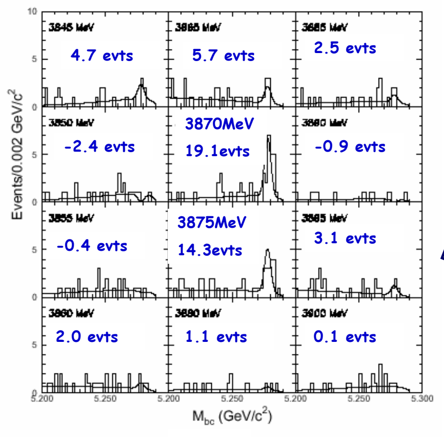
Doesn't show up in "generic" MC



Nothing peculiar in M(Kπ)& M(Kππ)

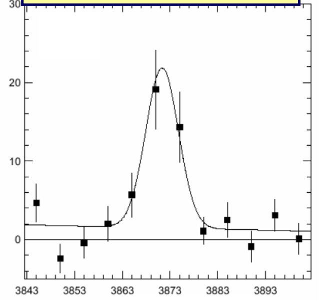


Magnify signal region



$\mathbf{M_{bc}}$

35±7 events
M=3872.0±0.8 MeV
Γ<2.3MeV (90%)



$\mathbf{M_{\pi\pi J/\psi}}$

Branching fraction

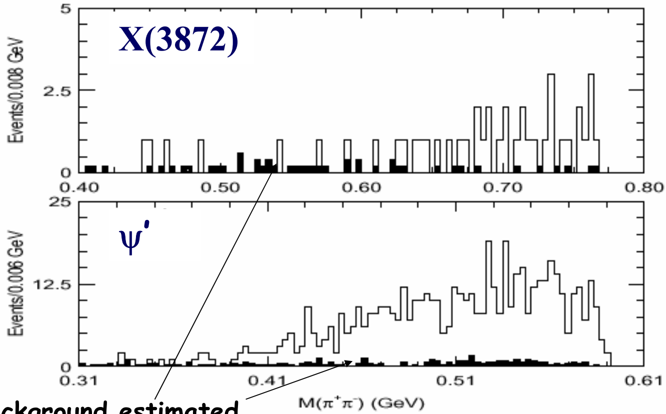
$$\frac{Br(B^- \rightarrow K^- X_{3872})\; Br(X_{3872} \rightarrow \pi^+\pi^- J/\psi)}{Br(B^- \rightarrow K^- \psi')\; Br(\psi' \rightarrow \pi^+\pi^- J/\psi)}$$

$$= 0.063 \pm 0.012 \pm 0.007$$

$$Br(B^- \rightarrow K^- X_{3872})\; Br(X_{3872} \rightarrow \pi^+\pi^- J/\psi) = 1.3 \pm 0.3 \times 10^{-5}$$

$$Br(B^- \rightarrow K^- X_{3872}) > 1 \times 10^{-5}$$

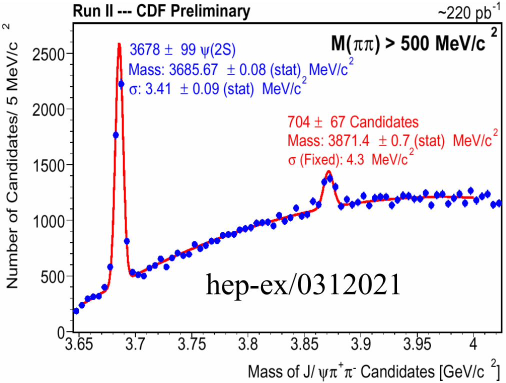
M $_{\pi+\pi-}$ crowds the upper limit

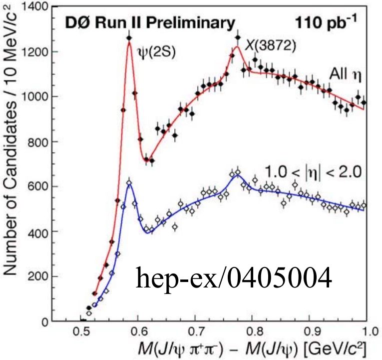


background estimated from M_{bc}-ΔE sidebands

if ρ(770), C = +1
if not, C = –1

Confirmed by CDF & D0

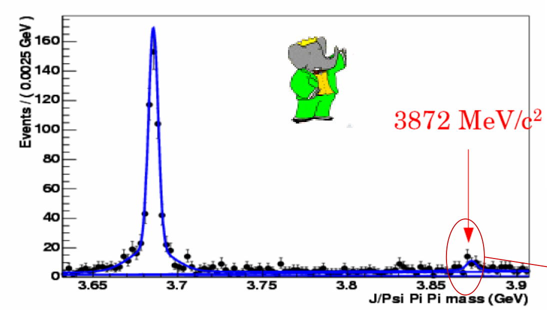


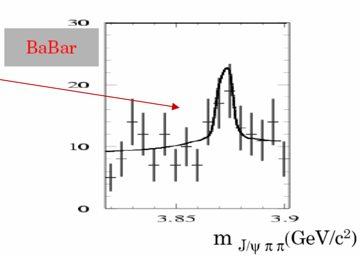


They also see a preference for high $M_{\pi\pi}$ values

also seen by BaBar

A. D'Orazio
APS mtg
Denver 5/04

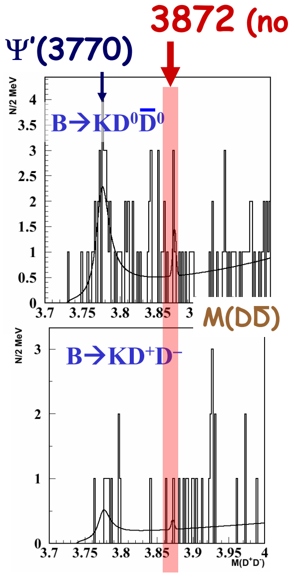




M=3873.4 ± 1.4 MeV

B(B→KX)B(X→$\pi^+\pi^-$J/ψ) = (1.28± 0.24) x 10^{-5}

$X(3872) \rightarrow D\bar{D}$ not seen



$$\frac{Br(X_{3872} \rightarrow D\bar{D})}{Br(X_{3872} \rightarrow \pi^+\pi^- J/\psi)} < 7$$

Note that: $$\frac{Br(\psi''_{3770} \rightarrow D\bar{D})}{Br(\psi''_{3770} \rightarrow \pi^+\pi^- J/\psi)} > 180$$

lots less phase space

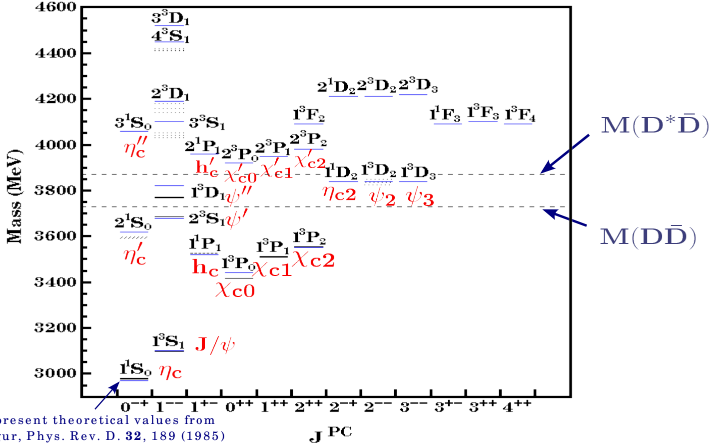
This (probably) rules out "natural" quantum numbers states like $J^{PC} = 0^{++}, 1^{--}, 2^{++}$

What is it?

- **Decays to a J/ψ**
  - **Charmonium?**
- **Narrow** **(Γ_{tot}<2.3 MeV) & X→D$\bar{D}$ suppressed**
  - **Natural qn's (0^+, 1^-, 2^+, …) ruled out?**
- **M ($\pi^+\pi^-$) peaks at large values (near m_ρ)**
  - **(X→ρ J/ψ implies C=+1 for the X)**
- **Produced in exclusive B→KX decays**
  - **Spin of the X can not be too large**

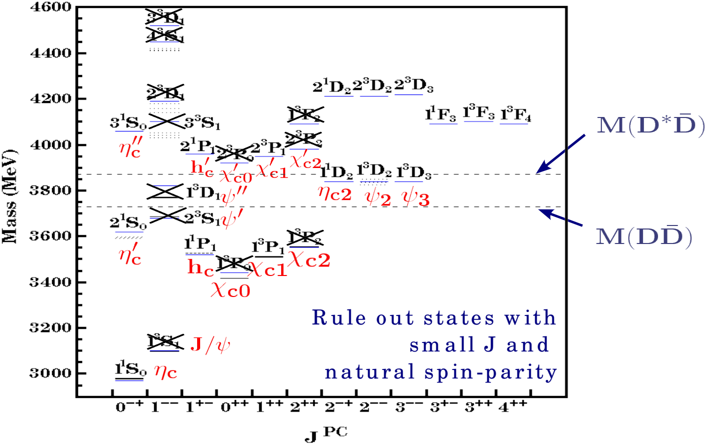
Can the X(3872) be identified with a charmonium state?

Charmonium Spectrum

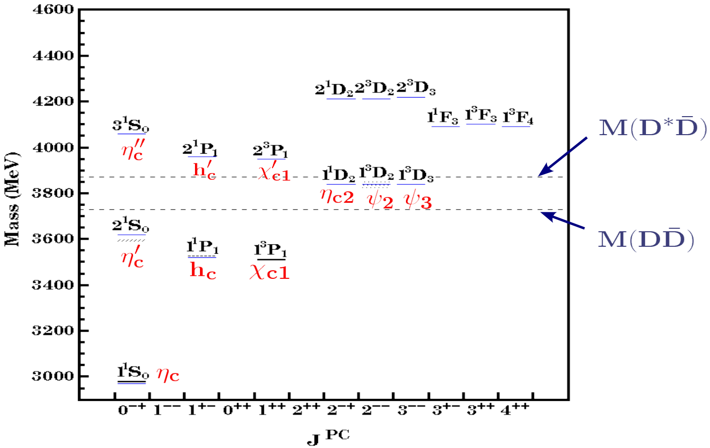


Blue lines represent theoretical values from
Godfrey & Isgur, Phys. Rev. D. **32**, 189 (1985)

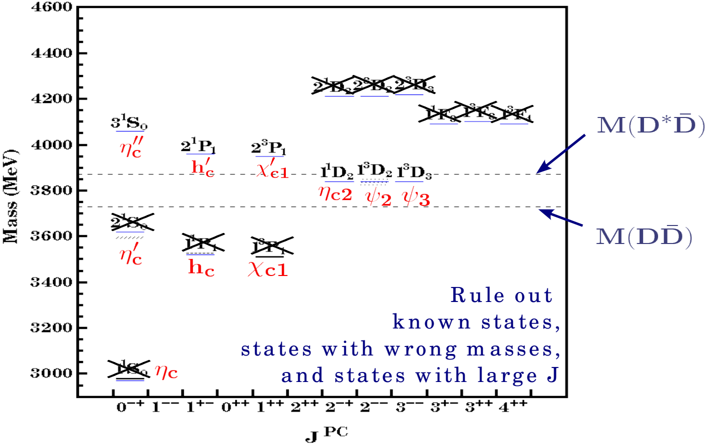
Charmonium Spectrum



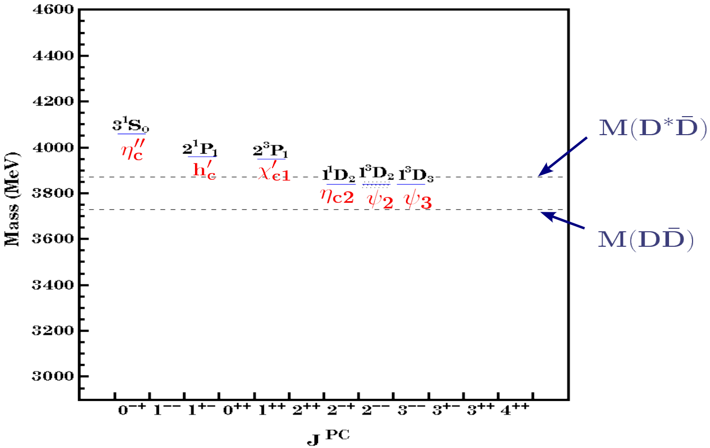
Charmonium Spectrum



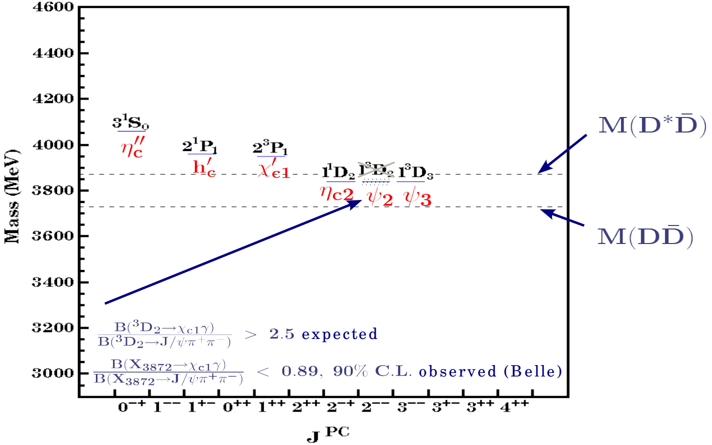
Charmonium Spectrum



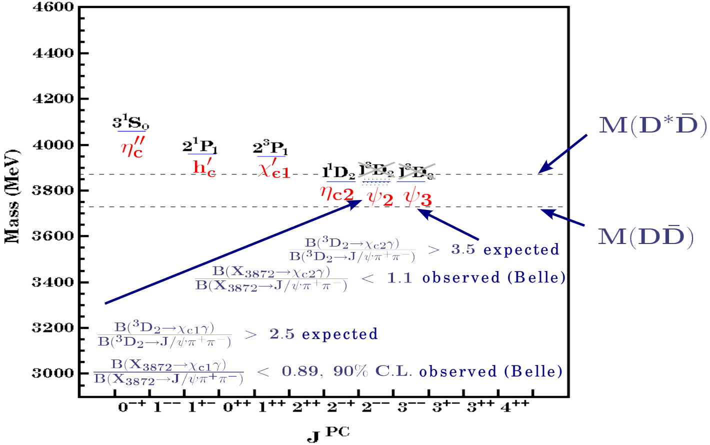
Charmonium Spectrum



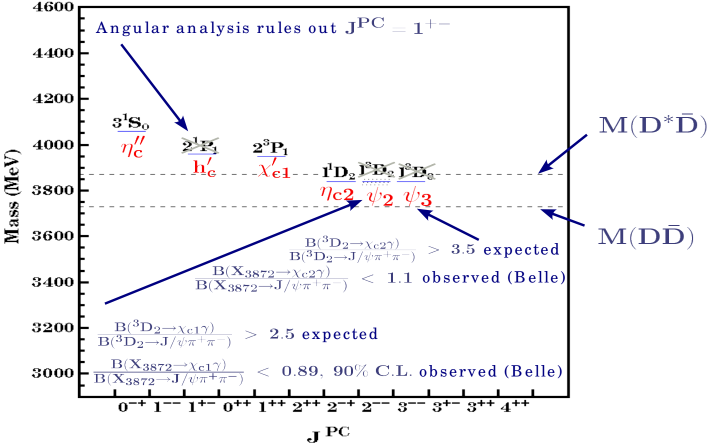
Charmonium Spectrum



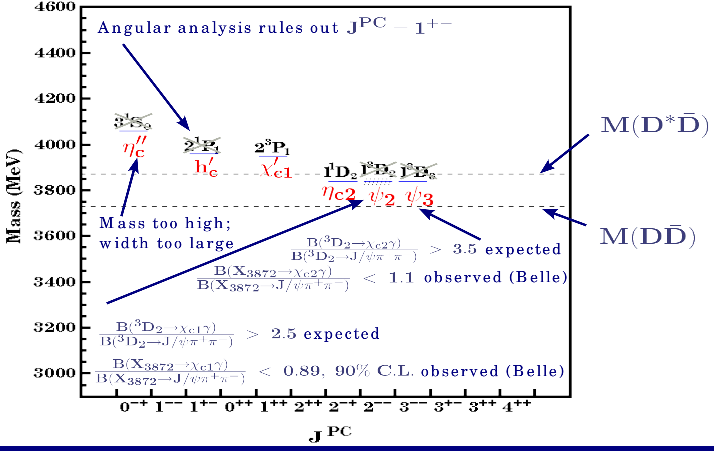
Charmonium Spectrum



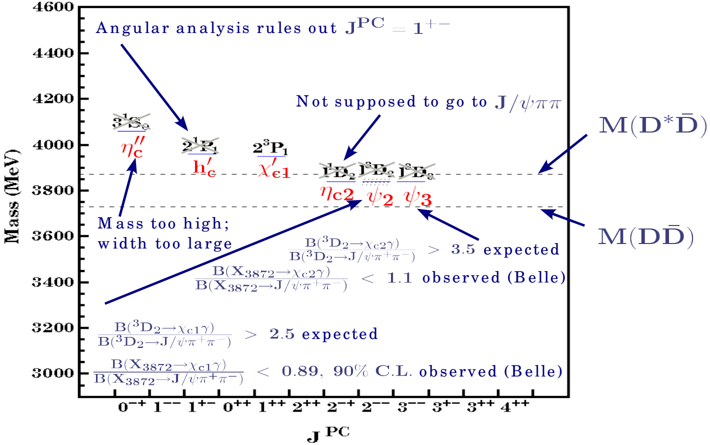
Charmonium Spectrum



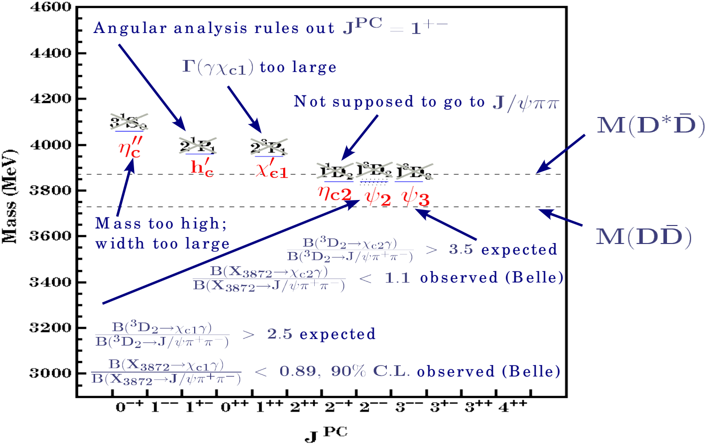
Charmonium Spectrum



Charmonium Spectrum



Charmonium Spectrum



No good $c\bar{c}$ candidates... Now what?!?

Curious fact

$$M_X = 3872 \pm 0.6 \pm 0.5 \text{ MeV}$$

$$M_{D0} + M_{D0*} = 3871.2 \pm 1.0 \text{ MeV}$$

lowest mass charmed meson (M_{D0})

lowest mass spin=1 charmed meson (M_{D0*})

X(3872) is very near DD* threshold.
Is it somehow related to that?

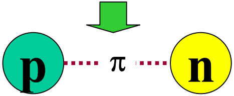
$h\bar{h}$ bound states (hadronium)??

There is lots of literature about this possibility

N. Tornqvist
hep-ph/0308277

deuteron:

attractive nuclear force

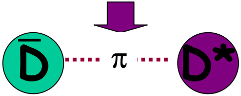


loosely bound
3-q color
singlets with

$M_d = m_p + m_n - \varepsilon$

Hadronium (dueson):

attractive force??



loosely bound
q-$\bar{q}$ color singlets
with

$M = m_D + m_{D^*} - \delta$

Fast-forward to status in 2012

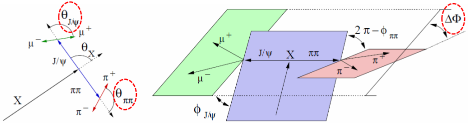
(much work on various $X(3872)$ decays done during this time)

Some important results emerged:

- A detailed angular anlysis (CDF 2007) showed that the $X(3872) \to J/\psi\rho$ decay is dominant.
- Evidence for $X(3872) \to \gamma J/\psi$ (Belle 2005, BaBar 2006) and an upper limit on $X(3872) \to \chi_{c1}\gamma$ (Belle 2003) establishes $C = +1$.

Previous experiments I

- **CDF (2007)** Phys. Rev. Lett. 98, 132002 (2007)
  - **Inclusive** production in pp at Tevatron, **unpolarized** $X(3872)\to\pi^+\pi^-(J/\psi\to\mu^+\mu^-)$, analyzed **3** decay angles ($\theta_{J/\psi}$, $\theta_{\pi\pi}$, $\Delta\Phi$).



  - **Cannot distinguish between 1^{++} and 2^{-+}, all other ruled out.**

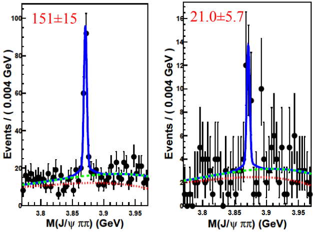
1^{++}: Only one LS amplitude, no free parameter in this fit

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	104	3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11	129	$\leq1\times10^{-20}$
0^{++}	$J/\psi\rho^0$	00	163	$\leq1\times10^{-20}$

2^{-+}: Two LS amplitudes, fit the ratio (complex parameter α)

Previous experiments II

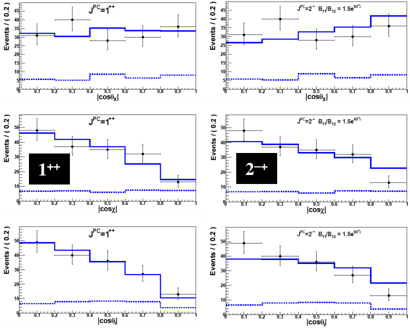
- **BaBar (2010)** Phys. Rev. D 82, 011101(R) (2010)
  - Observed 34 $X(3872)\to\omega J/\psi$, $\omega\to\pi^+\pi^-\pi^0$.
  - Not angular analysis.
  - **Prefer 2^{-+}** (C.L. = 62%) by the shape of M($\pi^+\pi^-\pi^0$) distribution, **1^{++} not ruled out** (C.L. = 7%).
- **Belle (2011)** Phys. Rev. D 84, 052004 (2011)
  - Polarized $X(3872)$ from $B\to X(3872)K$ ($K = K^\pm$ or K_S^0), $X(3872)\to\pi^+\pi^-(J/\psi\to l^+l^-)$.
  - **Cannot distinguish between 1^{++} and 2^{-+}**.



$B^+\to X(3872)K^+$ $\quad$ $B^0\to X(3872)K_S$

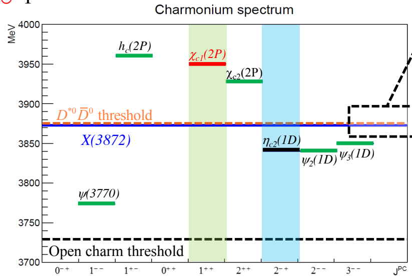
173±16 in total

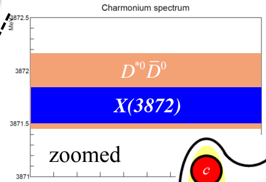
$\alpha_{Belle} = (0.64, 0.27)$

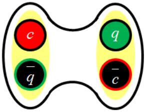


Motivation – nature of X(3872)

- $D^{*0}\bar{D}^0$ molecule, i.e. a $\left((u\bar{c})(c\bar{u})\right)$ system?
  - 1^{++}



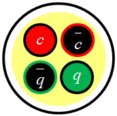




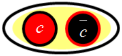
$$
\begin{aligned}
E_B &= M(D^0D^{*0}) - M(X(3872)) \\
&= 2M(D^0) + \Delta M(D^{*0} - D^0) - M(X(3872)) \\
&= 0.16 \pm 0.26\,\mathrm{MeV}/c^2.
\end{aligned}
$$

LHCb arXiv:1304.6865

- Tetraquark?
  - 1^{++}



- Conventional charmonium states?
  - $\chi_{c1}(2^3P_1)$ (1^{++})
  - $\eta_{c2}(1^1D_2)$ (2^{-+})

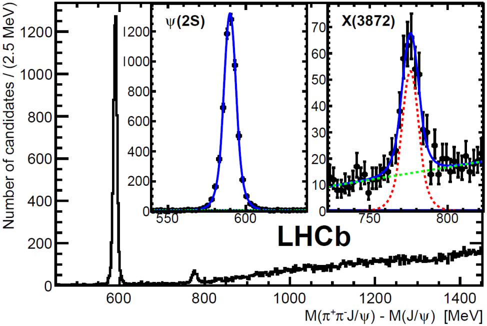


Measurement of *X(3872)* quantum numbers will help to better understand this intriguing narrow state.

Enter LHCb to finalize the quantum numbers

Data sample

- **Decay chain**: $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$.
- **Data**: 1 fb^{-1} collected in 2011 by the ***LHCb*** experiment.



$B^+ \rightarrow X(3872)K^+$
313±26 events
$B^+ \rightarrow \psi(2S)K^+$ control signal
5642±76 events

arXiv:1302.6269

Compare to Belle experiment, not a big increase in statistics:
313/173 ~ 1.8 times

Angular analysis

- To get maximal information, we do unbinned fit to data in full angular space (5D) for each hypothesis:

$$\Omega = \left(\cos\theta_X, \cos\theta_{\pi\pi}, \cos\theta_{J/\psi}, \phi_{J/\psi} - \phi_{\pi\pi}, \phi_{J/\psi} - \phi_X\right)$$

- Follow the same theoretical approach to predict the matrix elements as in the CDF and Belle analyses, the **angular correlations** are obtained using the helicity formalism,

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

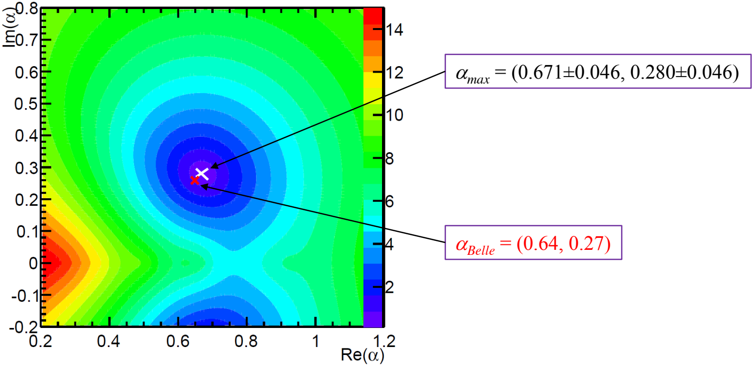
Helicity couplings, $A_{\lambda_{J/\psi},\lambda_{\pi\pi}}\left(J_X,(\alpha)\right)$, are expressed in terms of the LS amplitudes (B_{LS}).

- 1^{++} angular correlations predicted without free parameters (no α)
- 2^{-+} angular correlations depend on complex parameter $\alpha = B_{11}/(B_{12}+B_{11})$

  (ratio of B_{LS} amplitudes for $L_{\pi\pi,J/\psi}$=1, $S_{\pi\pi}+S_{J/\psi}$=1,2)

Fit data for 2^{-+} hypothesis

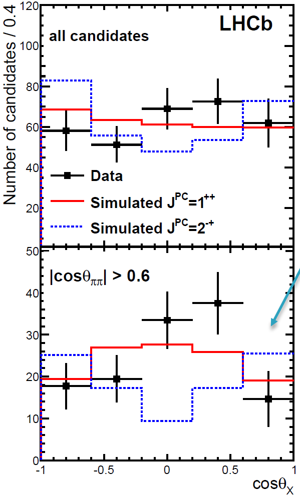
- Value of α maximizing the unbinned likelihood for 2^{-+} hypothesis
  - $\alpha_{max} = (0.671 \pm 0.046, 0.280 \pm 0.046)$
  - Within the errors consistent with the value deduced by Belle $\alpha_{Belle} = (0.64, 0.27)$



Contours of $\sqrt{\chi_L^2(2^{-+},\alpha) - \chi_L^2(2^{-+},\alpha_{max})}$

Illustration of importance of angular correlations

Projection of 5D fit



arXiv:1302.6269

Data: subtract background using sWeights.

2^{-+} with $\alpha = (0.671, 0.280)$.

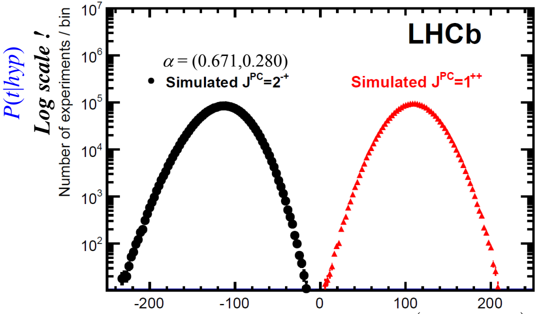
The separation between the two hypotheses in the helicity angle of *X(3872)* **increases** when **correlation** with $cos\theta_{\pi\pi}$ is taken into account.

Preference of the data for 1^{++} now clearly visible.

By constructing the likelihood ratio in full angular phase-space (5D), we extract maximal information from the angular correlations

Likelihood ratio – toy experiments

- Ensemble of simulated experiments ("toy experiments"), each with the number of signal and background events as in the real experiment.

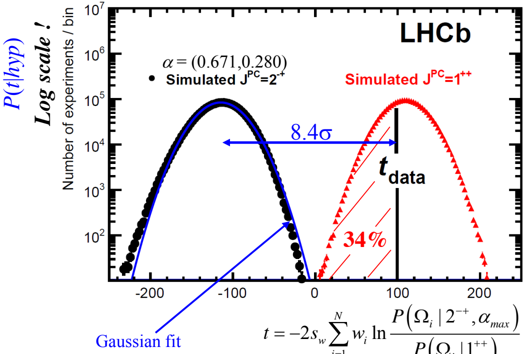


$$t = -2 s_w \sum_{i=1}^{N} w_i \ln \frac{P\left(\Omega_i \,|\, 2^{-+}, \alpha_{max}\right)}{P\left(\Omega_i \,|\, 1^{++}\right)}$$

arXiv:1302.6269

- Good separation between two hypotheses.

Likelihood ratio – results for real data



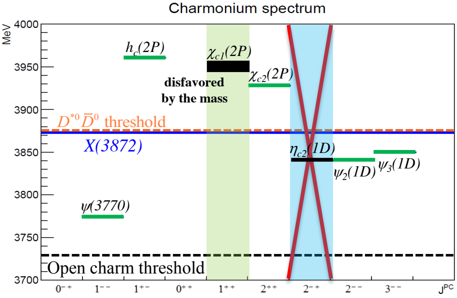
$$t = -2 s_w \sum_{i=1}^{N} w_i \ln \frac{P(\Omega_i \mid 2^{-+}, \alpha_{max})}{P(\Omega_i \mid 1^{++})}$$

arXiv:1302.6269

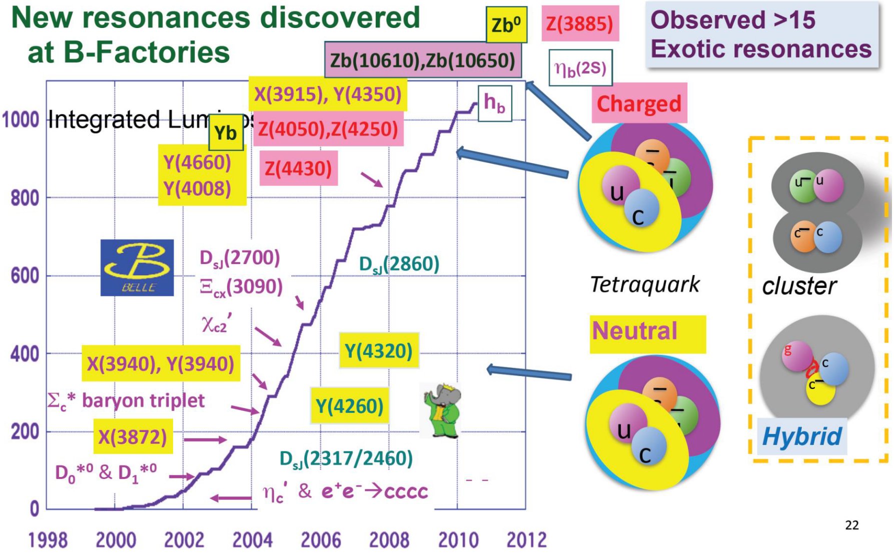
- The Gaussian approximation conservative since the actual distribution to the left of the Gaussian fit. **The 2^{-+} hypothesis is ruled out at 8.4σ.**
- 1^{++} C.L. is high (34%).

Conclusions

- Correlations between angles carry important spin information.
- **2^{-+} rejected with significance of more than 8σ.**
  - The significant rejection preserved under all variations of cuts and efficiency corrections.
- **Our data are fully consistent with the *X(3872)* having $J^{PC}=1^{++}$.**
- **This determination favors the exotic models of *X(3872)*:**
  - **$\eta_{c2}(1^1D_2)$ is ruled out.**
  - **$\chi_{c1}(2^3P_1)$ is possible but disfavored by the mass.**
  - $D^{*0}\bar{D}^0$ molecule and **tetraquark** are the two models favored by *X(3872)*.

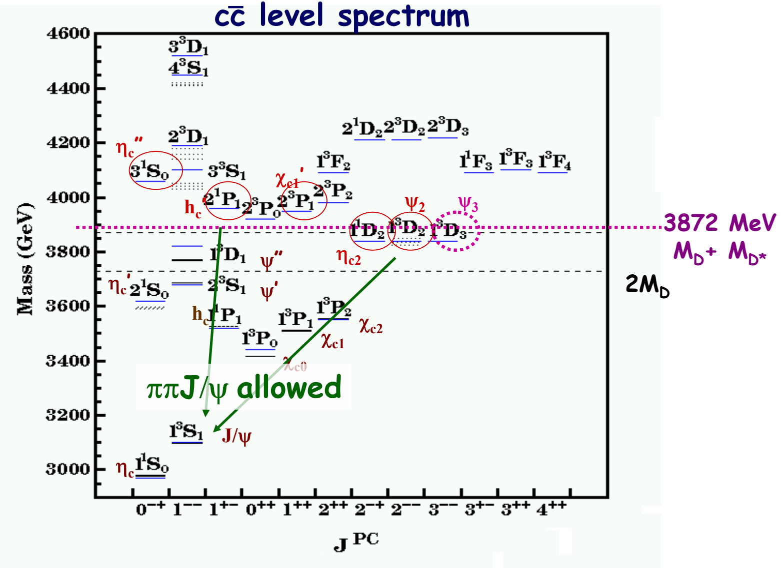


Much more than the $X(3872)$!



Extra material - Excluding Charmonium possibilities

Charmonium possibilities



Summary of charmonium possibilities

$\pi\pi$ is 0^{++}

Best bets!

1^{+-} h_c'

2^{--} ψ_2

3^{--} ψ_3

$\Psi_3 \rightarrow D\bar{D}$ allowed, but suppressed

$\pi\pi$ is 1^{--} (ρ)

1^{++} χ_{c1}'

0^{-+} η_c''

2^{-+} η_{c2}

For these, $X \rightarrow \pi\pi J/\psi$ violates isospin (unlikely for charmonium)

$X \rightarrow \pi^0\pi^0 J/\psi \approx ½\, X \rightarrow \pi^+\pi^- J/\psi$

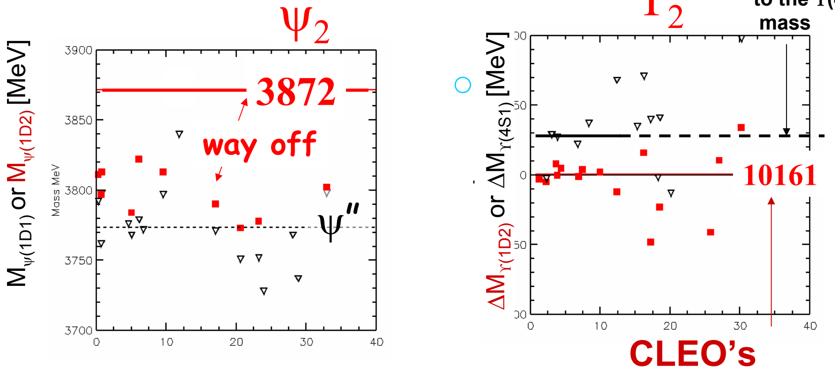
$X \rightarrow \pi^0\pi^0 J/\psi = 0$

Is it the $\psi_{2(or3)}$?

i.e. $^3D_{2(or3)}$

Mass predictions

T. Skwarnicki

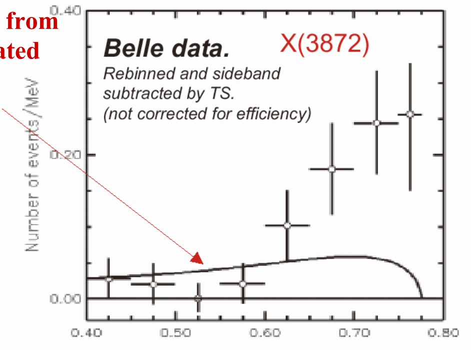


~30 MeV correction needed to the Υ(4S) mass

CLEO's Υ_2 mass is ~right on

M $_{\pi^+\pi^-}$ different from expectations

D-wave Mππ distribution from T.M.Yan's QCD-motivated model

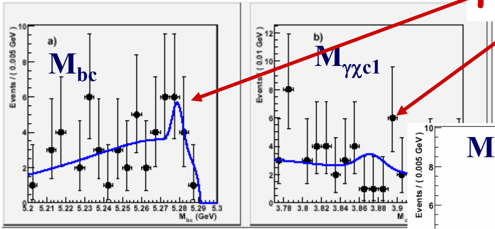


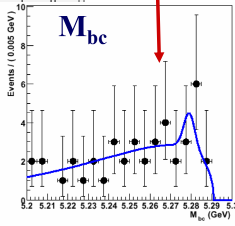
$^3D_{2,3}$ ($\psi_{2,3}$) decay-width expectations

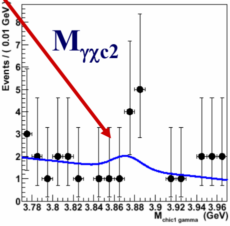
		Eichten, Lane & Quigg hep-ph/0401210 (keV)	Barnes & Godfrey PRD **69,** 054008 (keV)
ψ_2:	$\frac{\Gamma(\psi_2 \to \gamma\chi_{c1})}{\Gamma(\psi_2 \to \pi^+\pi^- J/\psi)}$	~2.5	~4
ψ_3:	$\frac{\Gamma(\psi_3 \to \gamma\chi_{c2})}{\Gamma(\psi_3 \to \pi^+\pi^- J/\psi)}$	~3.5	~4
	$\frac{\Gamma(\psi_3 \to D\bar{D})}{\Gamma(\psi_3 \to \pi^+\pi^- J/\psi)}$	~11	~50

Look for $X(3872) \rightarrow \gamma\chi_{c1}$ ($\gamma\chi_{c2}$)

No significant signals







$$\frac{\Gamma(X \rightarrow \gamma\chi_{c1})}{\Gamma(X \rightarrow \pi^+\pi^- J/\psi)} < 0.9$$

ψ_2: expect > 2.5

$$\frac{\Gamma(X \rightarrow \gamma\chi_{c2})}{\Gamma(X \rightarrow \pi^+\pi^- J/\psi)} < 1.1$$

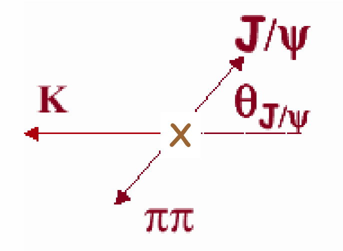
ψ_3: expect > 3.5

The ψ_2 or ψ_3 are poor matches:

- **Mass too high**
  - **3872MeV *vs* 3810 MeV**
- **$\Gamma(\gamma\, \chi_{c1,2})$ too small**
  - **$\Gamma(\gamma\, \chi_{c1,2}) < \Gamma(\pi\pi J/\psi)$ *vs* $\sim 3 \times \Gamma(\pi\pi J/\psi)$ expt'd**
- **M($\pi^+\pi^-$) too peaked**
  - **looks like $\rho \rightarrow \pi\pi$; $\psi_2 \rightarrow \rho\, J/\psi$ is forbidden**

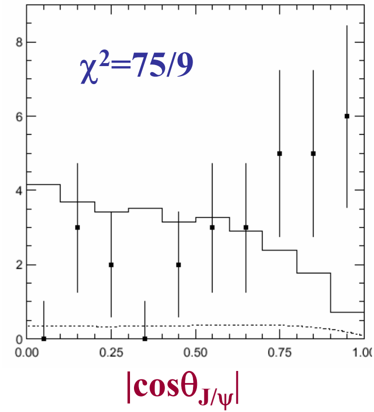
What about $(1^{+-})\ h_c'$

Look at J/ψ angular distribution:



For 1^{+-} expect: $dN/d\cos\theta_{J/\psi} \propto \sin^2\theta$

Fit to 1^{+-}



h_c' is ruled out

What about C=+1 charmonium?

- $\pi^+\pi^-$ **system would be a** ρ
  - consistent with $M(\pi^+\pi^-)$ dist

- $X \rightarrow \pi^+\pi^- J/\psi$ **would violate isospin**
  - should be strongly suppressed

- **Candidates:** $0^{-+}(\eta_c'')$; $1^{++}(\chi_{c1}')$; $2^{-+}(\eta_{c2})$
  - $\Gamma(\eta_c'')$ should be wide: $\sim\Gamma(\eta_c) \approx 20$ MeV; $M(\eta_c'') \approx \psi(3S)$ - ~40 MeV: (4040-40 = 4000 MeV)
  - $Br(\chi_{c1}' \rightarrow \gamma J/\psi) >> Br(\chi_{c1}' \rightarrow \pi\pi J/\psi)$
  - $Br(\eta_{c2} \rightarrow \pi\pi\, \eta_c) >> Br(\eta_{c2} \rightarrow \pi\pi J/\psi)$

Look for B→K X(3872); X(3872)→γ J/ψ

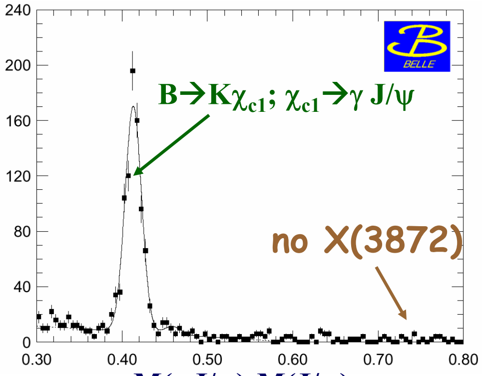
Expectation:

Barnes, Godfrey hep-ph/0311162

$$\frac{\Gamma(2^3P_1 \rightarrow \gamma\, J/\psi) \sim 11\ \mathrm{keV}}{\Gamma(2^3P_1 \rightarrow \pi\pi J/\psi) \sim \Gamma(\psi' \rightarrow \pi^o\, J/\psi) \sim \mathcal{O}\ (0.3\ \mathrm{keV})} \quad \sim 30$$

isospin violating

$B \to K \gamma J/\psi$



M(γ J/ψ)-M(J/ψ)

90% CL upper limit:

$$\frac{Br(X \to \gamma\, J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} < 0.4$$

Probably not the χ_{c1}'

no good $c\bar{c}$ candidates)

$\pi^+\pi^-$J/ψ decays violate isospin

- η_c'' ← M too low and Γ too small
- h_c' ← angular dist'n rules out 1^{+-}
- χ_{c1}' ← $\Gamma(\gamma J/\psi)$ way too small
- ψ_2 ← $\Gamma(\gamma\chi_{c1})$ too small; $M(\pi^+\pi^-)$ wrong
- η_{c2} ← $\pi\pi\,\eta_c$ should dominate $\pi\pi J/\psi$
- ψ_3 ← $\Gamma(\gamma\chi_{c2}$ & $D\bar{D})$ too small; $M(\pi^+\pi^-)$ wrong