LHCb Results on Exotic Mesons

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on behalf of LHCb collaboration

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Outline

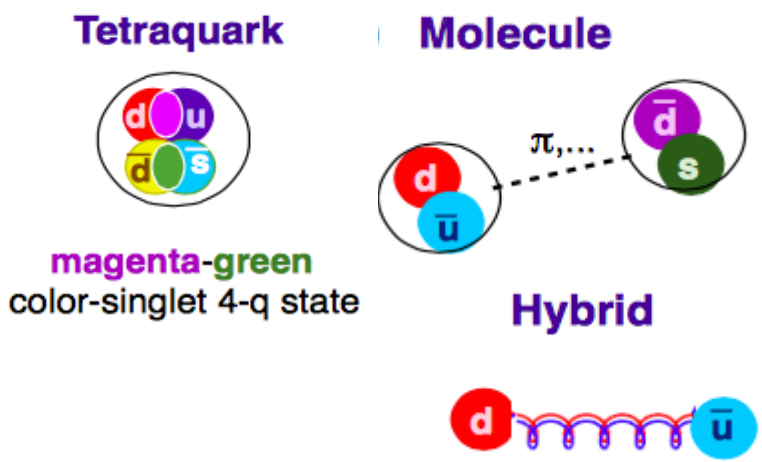
- Introduction
- $X(3872)$
  - J^{PC} determination
  - Radiative decays
- $Z(4430)^{\pm}$ confirmation
- Conclusion

Exotic states

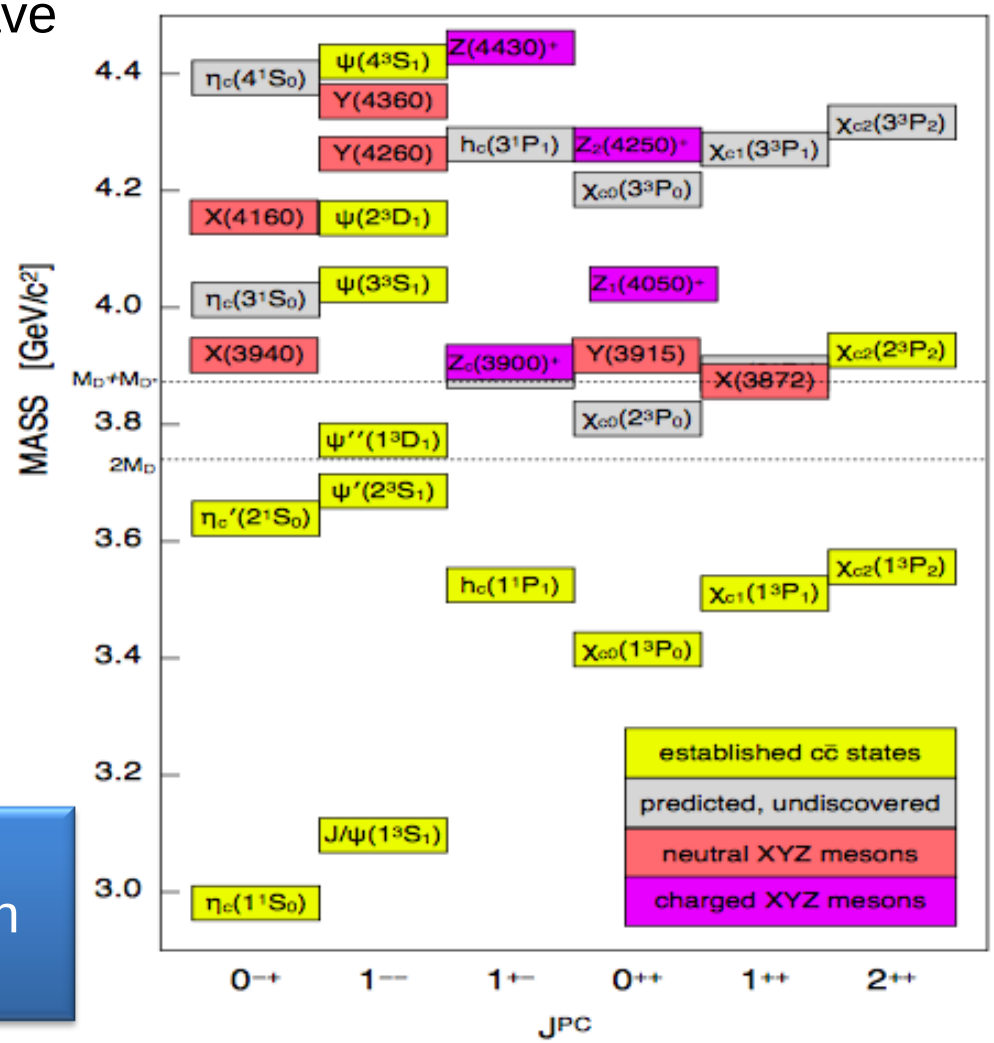
Many different exotic (XYZ) states have been seen

- BES III, Belle/BaBar, CDF/D0
- Mass/width, decay, J^{PC}

Possible structure



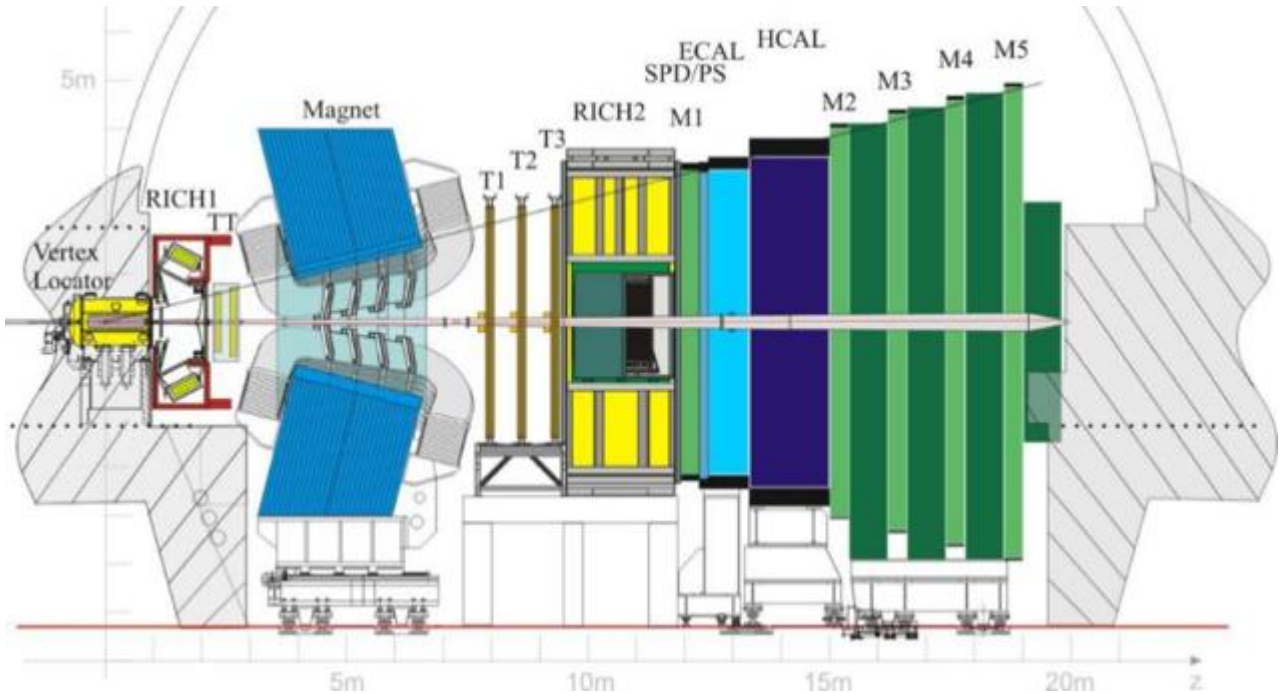
Hyperfine Interact. 229 (2014) 1-3, 7-20



Experimental & theoretical studies needed to understand the production and structure

LHCb detector

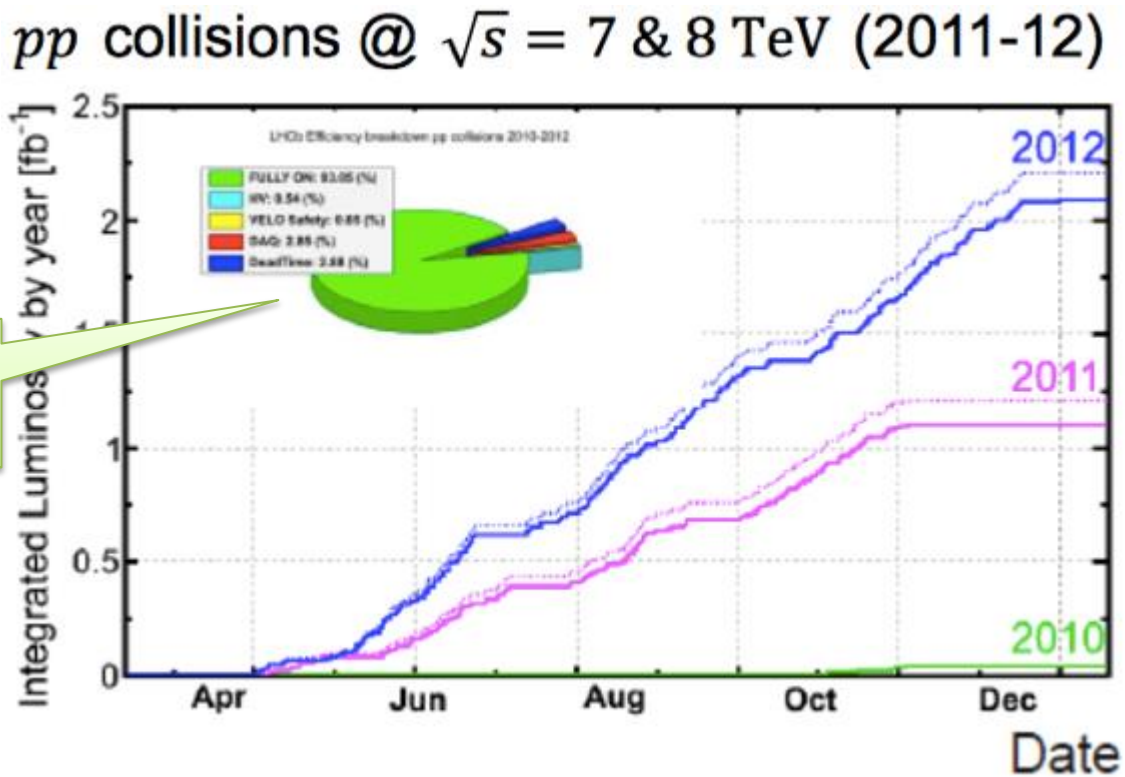
A signal-arm forward spectrometer covering $2 < \eta < 5$



Vertex Locator:	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3):	$\Delta p/p$: 0.4 % @ 5 GeV/c, 0.6 % @ 100 GeV/c
RICHs:	$\epsilon(K \to K) \sim 95$ %, misID rate $(\pi \to K) \sim 5$ %
Muon system (M1-M5):	$\epsilon(\mu \to \mu) \sim 97$ %, misID rate $(\pi \to \mu) \sim 1 - 3$ %
ECAL/HCAL:	$\sigma_E/E \sim 10$ % (ECAL) 70 % (HCAL)/$\sqrt{E} \otimes 1$ % (E in GeV)

Data taking

- Efficient data taking @ LHCb
  - Efficiency ~ 90 %



LHCb run-I data
- 1 fb^{-1} for 2011
- 2 fb^{-1} for 2012

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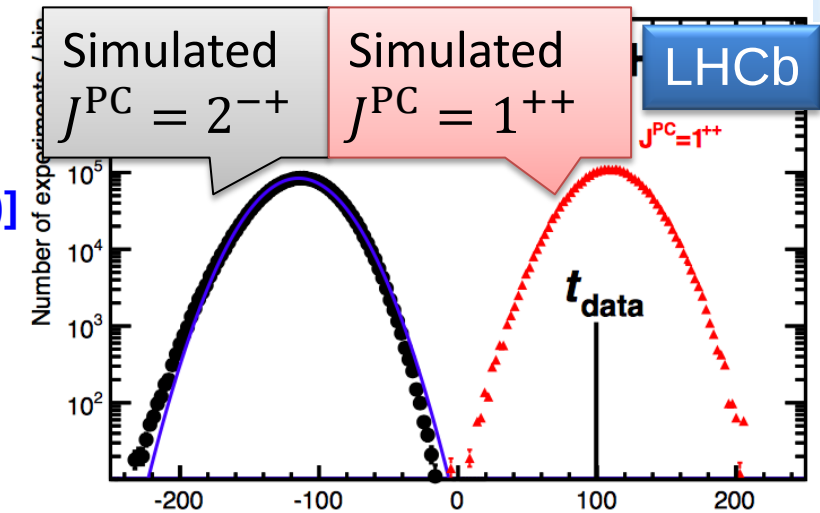
Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decay

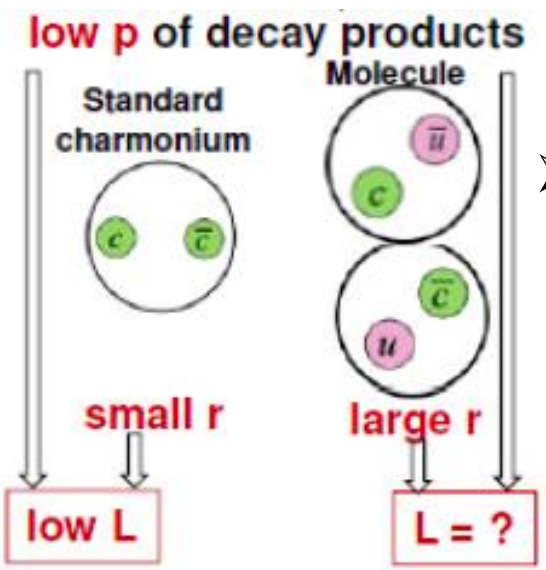
arXiv: 1504.06339

J^{PC} of $X(3872)$

- $C = +$ since $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi(2S)\gamma$
- LHCb determined 1^{++} **[PRL110,222001 (2013)]**
  - 5D angular analysis with 1 fb^{-1} data
  - 2^{-+} rejected @ 8.5σ
  - $X(3872)$ as $\eta_{c2}(1^1D_2)$ excluded
  - Assuming: Lowest possible orbital angular momentum (L_{min})



$$t = -2\ln\frac{\mathcal{L}(2^{-+})}{\mathcal{L}(1^{++})}$$



- Large $L(> L_{min})$ hint molecular structure of $X(3872)$
  - Exotic state (D^*D molecule) ➡ large size (r)
  - Large size ➡ $L > L_{min}$ happen
    - ✓ $L = r \times p$

The analysis without L assumption needed

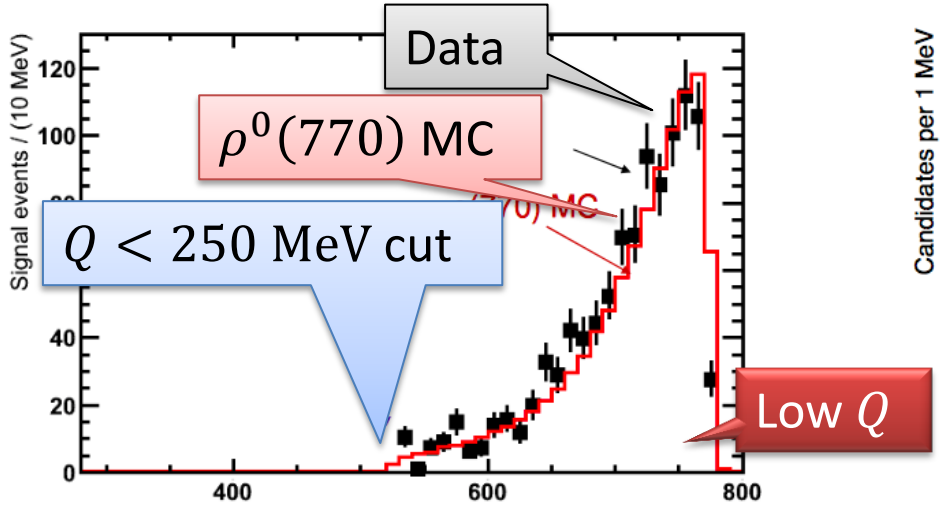
Signals of $B^+ \to X(3872)K^+$

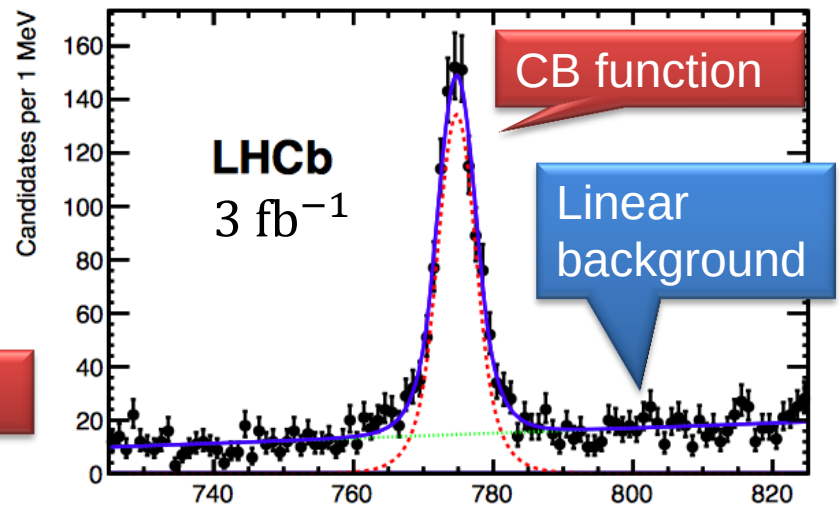
Event selection optimized in low Q region

- Energy release: $Q = m_{X(3872)} - m_{J/\psi} - m_{\pi^+\pi^-}$
- Background suppressed with $Q < 0.25\ \mathrm{GeV}/c$

Signal yields for $X(3872)$: 1011 ± 38 with $80\ \%$ purity

- 3 times more than LHCb previous analysis **[PRL110,222001 (2013)]**
  - $1\ \mathrm{fb}^{-1}$ ➡ $3\ \mathrm{fb}^{-1}$
  - Efficiency increased: lower p_T requirement for $\mu^\pm$ & $\pi^\pm$

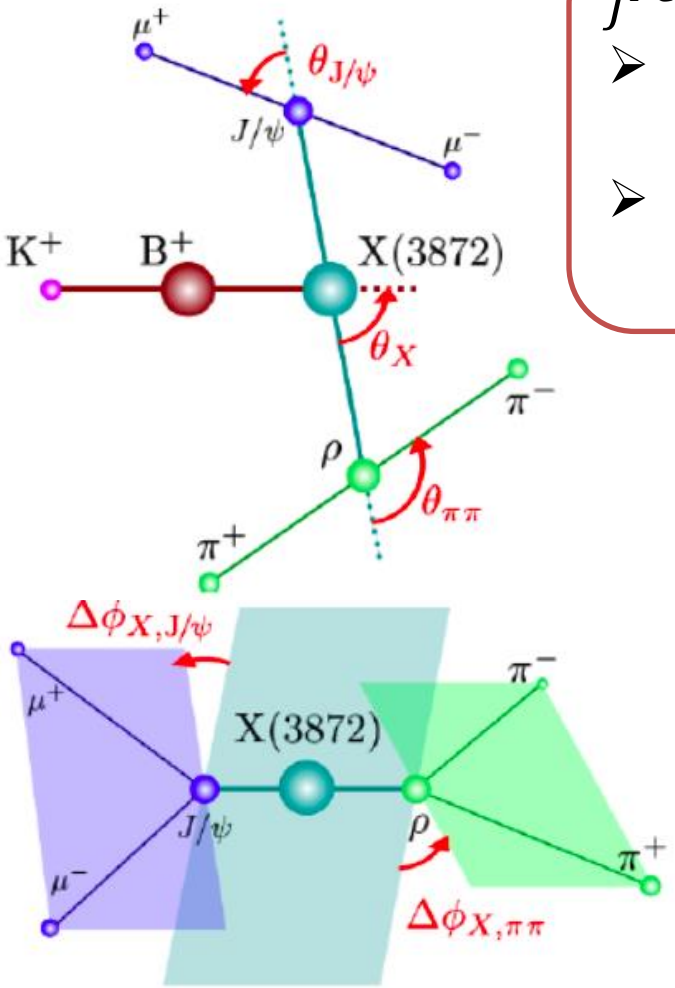




Angular distribution

J^{PC} & L determined by the fit to 5 angles distributions

- θ_X, $\theta\rho$ and $\theta_{J/\psi}$: helicity angles in $X(3872)$, ρ^0 and J/ψ decays
- $\Delta\phi_{X,J/\psi}$, $\Delta\phi_{X,\rho}$: angle between decay planes of $X(3872)$ and of its decay products



The probability density function:

$$\mathcal{P}(\Omega|J_X) \propto |\mathcal{M}(\Omega|J_X)|^2$$

- $\Omega \equiv \left(\cos\theta_X, \cos\theta_\rho, \Delta\phi_{X,\rho}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi}\right)$
- J_X: assumed value of J for $X(3872)$
  - each J^{PC} hypothesis tested
- $\mathcal{M}$: decay matrix element
- efficiency correction ➡ small and neglected

Helicity formalism

Wigner functions

Matrix element

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

Helicities: $\Delta\lambda_\mu = \lambda_{\mu^+} - \lambda_{\mu^-}$

Helicity coupling

$$A_{\lambda_{J/\psi},\lambda_\rho} = \sum_L \sum_S B_{LS} \left(\begin{array}{cc|c} J_{J/\psi} & J_\rho & S \\ \lambda_{J/\psi} & -\lambda_\rho & \lambda_{J/\psi}-\lambda_\rho \end{array} \right) \left(\begin{array}{cc|c} L & S & J_X \\ 0 & \lambda_{J/\psi}-\lambda_\rho & \lambda_{J/\psi}-\lambda_\rho \end{array} \right)$$

$L - S$ coupling amplitude

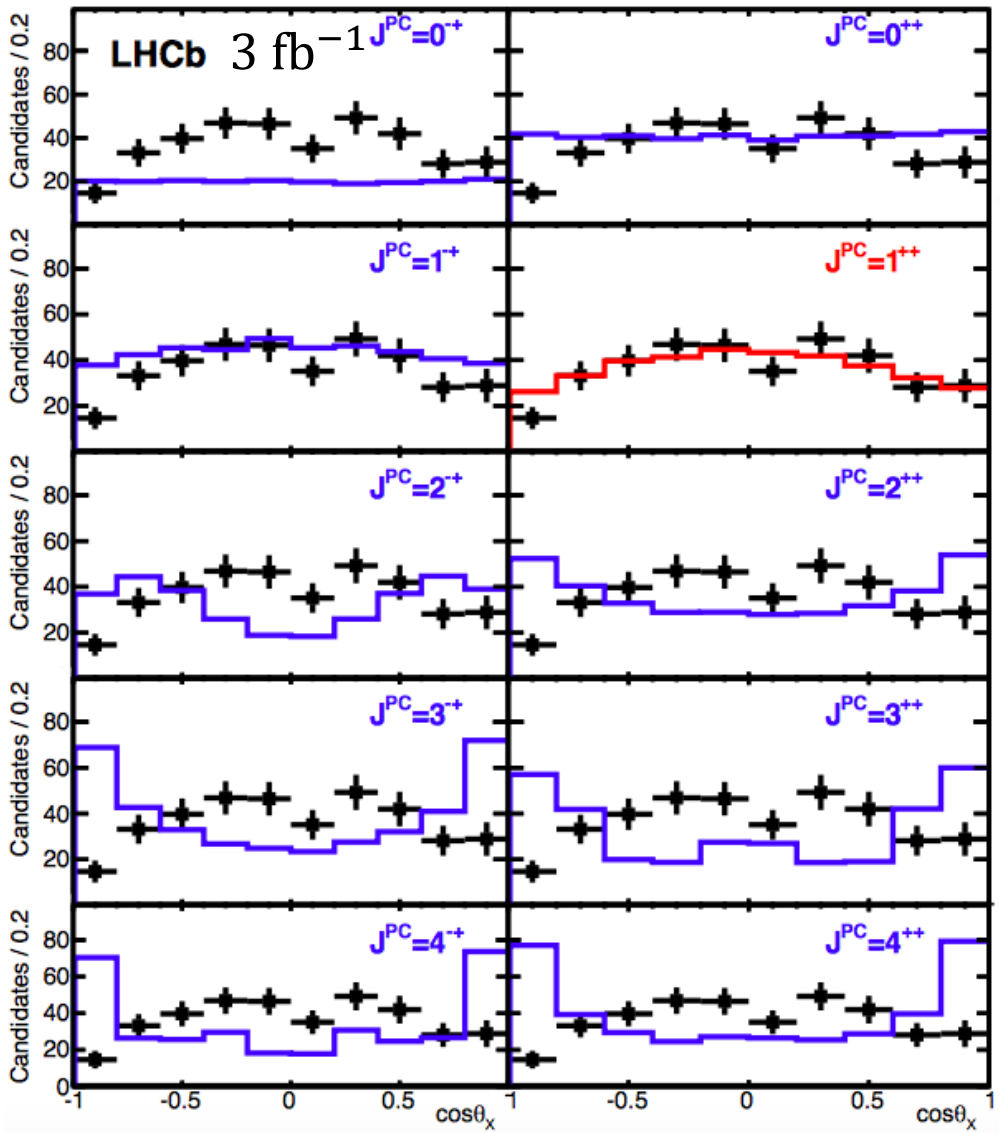
- L: angular momentum between J/ψ & ρ
- Constrained by $P_X = P_{J/\psi} P_\rho (-1)^L = (-1)^L$

All considered in this analysis

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

LHCb 2013 **[PRL110,222001 (2013)]**

Angular distribution

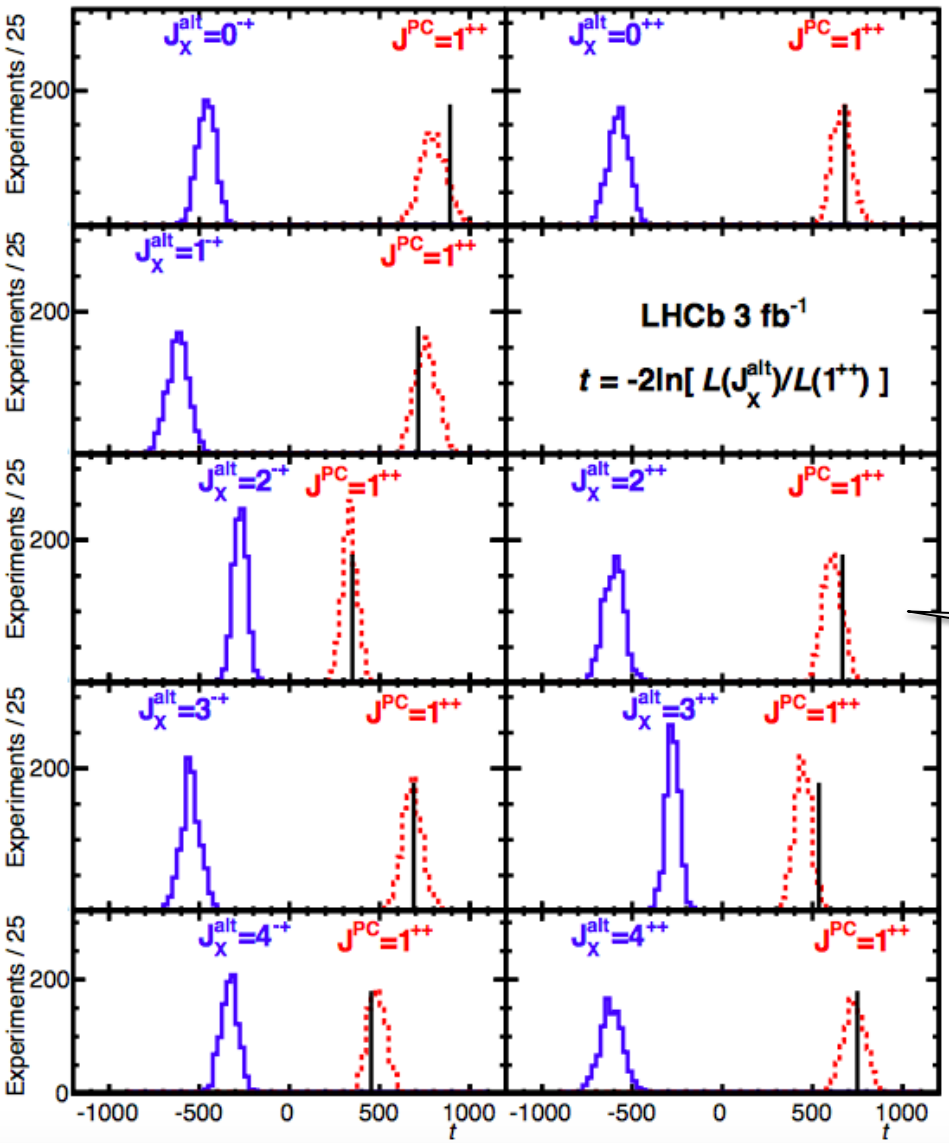


Distributions of $\cos\theta_X$ for signals after background subtraction

- All J^{PC} hypotheses used for fits
- 1^{++} favored to data

arXiv: 1504.06339

Determination of J^{PC}



Likelihood test

- $t \equiv -2\ln\mathcal{L}(J_X^{\mathrm{alt}})/\mathcal{L}(1^{++})$
- Data vs simulation (J_X^{alt} & 1^{++})
- Data prefers 1^{++} hypothesis
  - All J_X^{alt} ruled out
  - No assumptions about L

Value for data

arXiv: 1504.06339

Determination of D-wave fraction

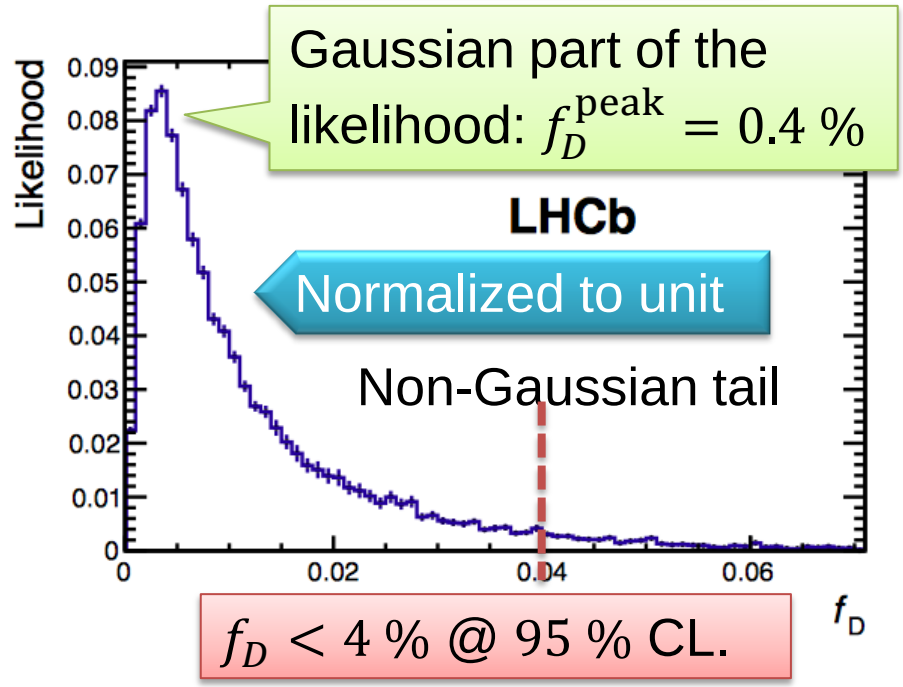
D-wave fraction

$$f_D = \frac{\int |\mathcal{M}(\Omega)_D|^2 d\Omega}{\int |\mathcal{M}(\Omega)_{S+D}|^2 d\Omega}$$

- $\mathcal{M}_{D,S+D}$: Only D or S+D decay matrix
- 1^{++} hypothesis ➡ $L = 0, 2$
  - S-wave: $S = 1$ ➡ Only B_{01}
  - D-wave: $S = 1$ or 2 ➡ B_{21} & B_{22}

Never considered before

Likelihood vs f_D



- No hints for a large size of $X(3872)$ from the studies of the orbital angular momentum in $X(3872) \to \rho^0 J/\psi$ decay
- Typical charmonium size

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Evidence for the decay $X(3872) \to \psi(2S)\gamma$

NPB 886, 665 (2014)

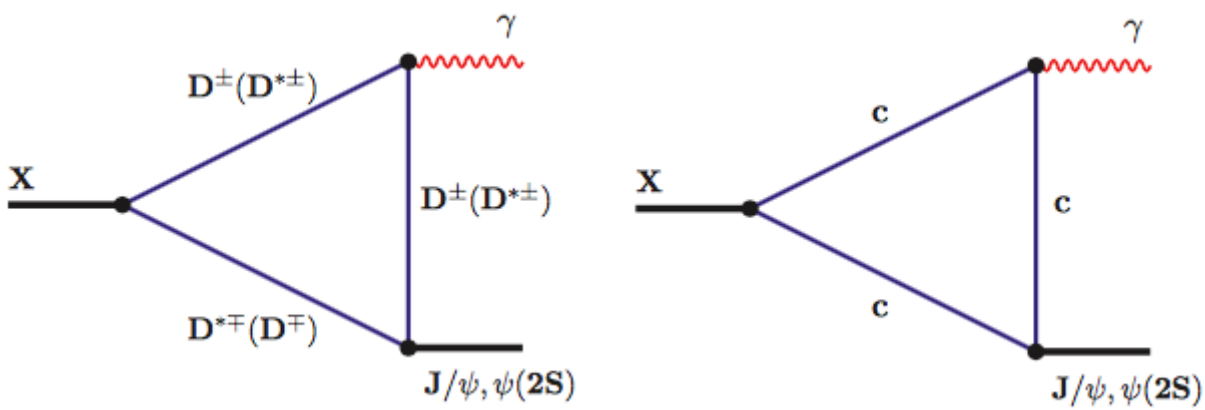
$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)(\mu^+\mu^-)\gamma)}{\mathcal{B}(X(3872) \to J/\psi(\mu^+\mu^-)\gamma)}$$

Structure of $X(3872)$ sensitive to ratio $R_{\psi\gamma}$

- D^*D molecular model: $(3-4)\times 10^{-3}$
  - PLB588, 189 (2004); JPG38, 015001 (2011)
- Pure charmonium state: 1.2 – 15
  - PRD72, 054026 (2005); PRD69, 054008 (2004); PRD79, 094004 (2009); NPA714,183 (2003); …

$\mathcal{B}(\chi_{c1}(2P) \to \psi(2S)\gamma) \sim \mathcal{O}(10) \times \mathcal{B}(\chi_{c1}(2P) \to J/\psi\gamma)$ enhance for $R_{\psi\gamma}$

- Mixing: 0.5 – 5
  - PRD73, 014014 (2006); PRD85, 114004(2012) …

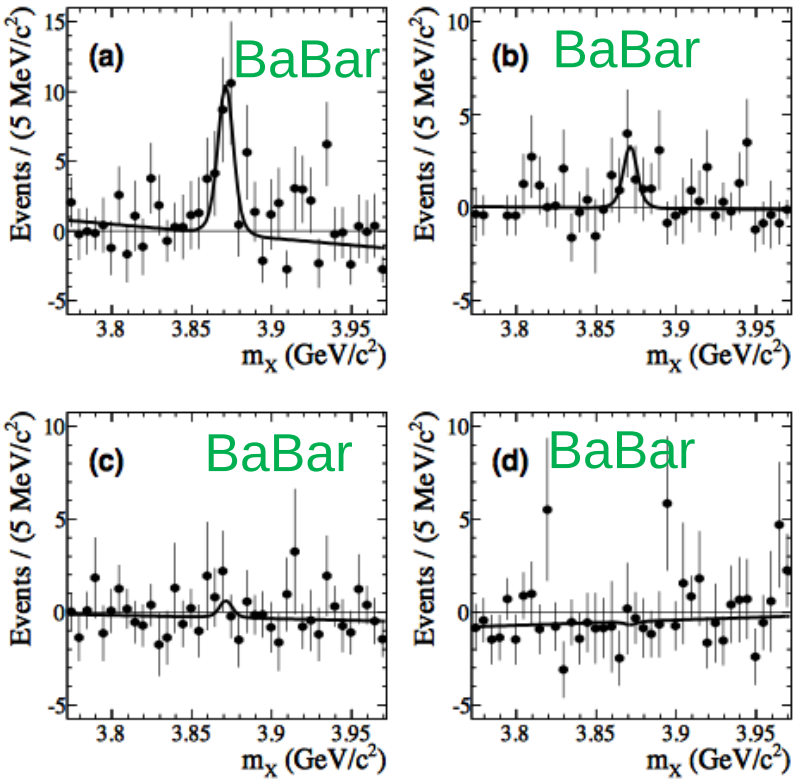


Decay of $X(3872) \to \psi(2S)\gamma$

First evidence reported by BaBar: $R_{\psi\gamma} = 3.4 \pm 1.4$

- Significance: 3.5 σ with $B^{+,0} \to X\, K_{(S)}^{(*)+,0}$
- Pure D^*D state ruled out

PRL 102, 132001 (2009)



Belle results

- UL: < 2.1 @ 90 %
- Not large $c\bar{c}$ admixture with D^*D molecular components as BaBar expected

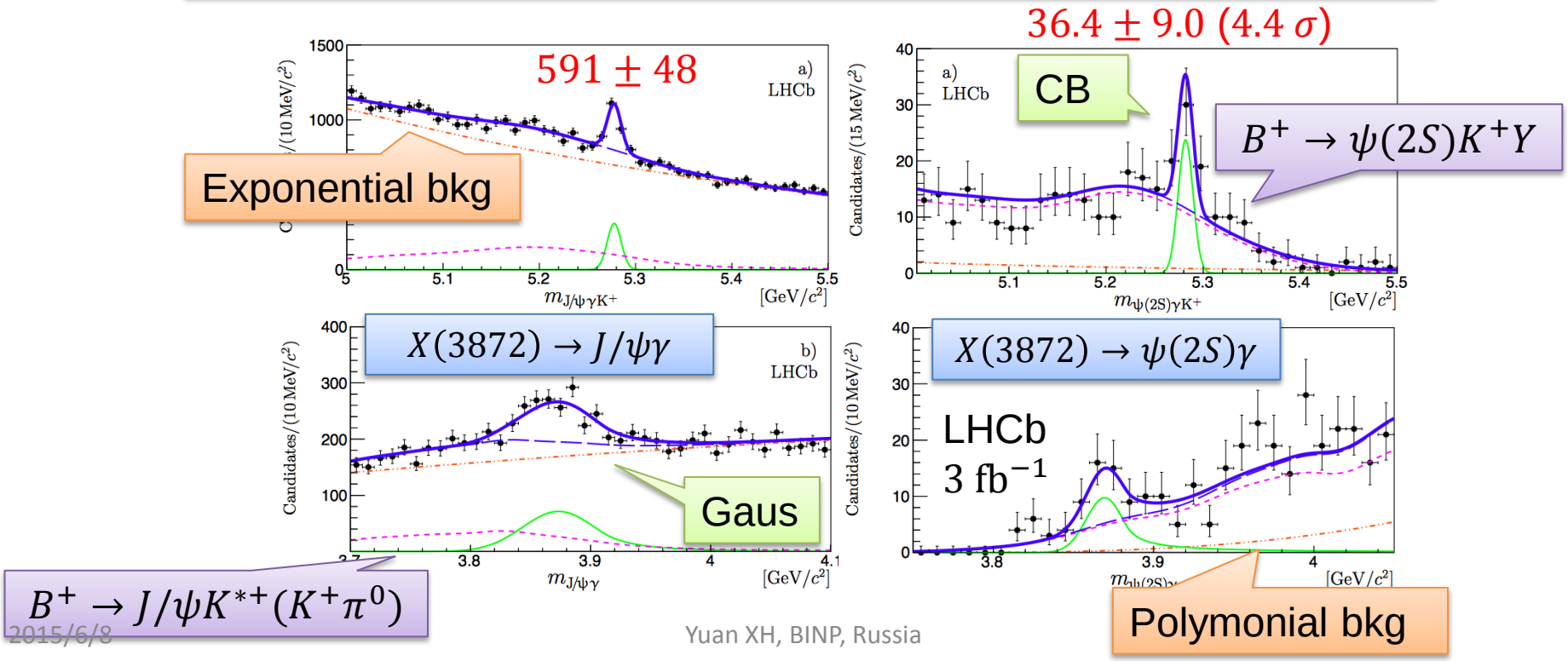
PRL 107, 091803 (2011)

More precision of $R_{\psi\gamma}$ needed to measure

Signals of $X(3872) \to \psi(2S)\gamma$

- 3 fb^{-1} data used
- $X(3872)$ from $B^+ \to X(3872)K^+$; $\psi(2S)(J/\psi) \to \mu^+\mu^-$
- $p_T(\gamma) > 1.0\ (0.6)\ \mathrm{GeV}/c$ for $J/\psi\gamma$ ($\psi(2S)\gamma$) ➡ Different energy release
- Mass veto for $\pi^0 \to \gamma\gamma$
  - Photons that can form part of π^0 candidate within 25 MeV/c^2 not used

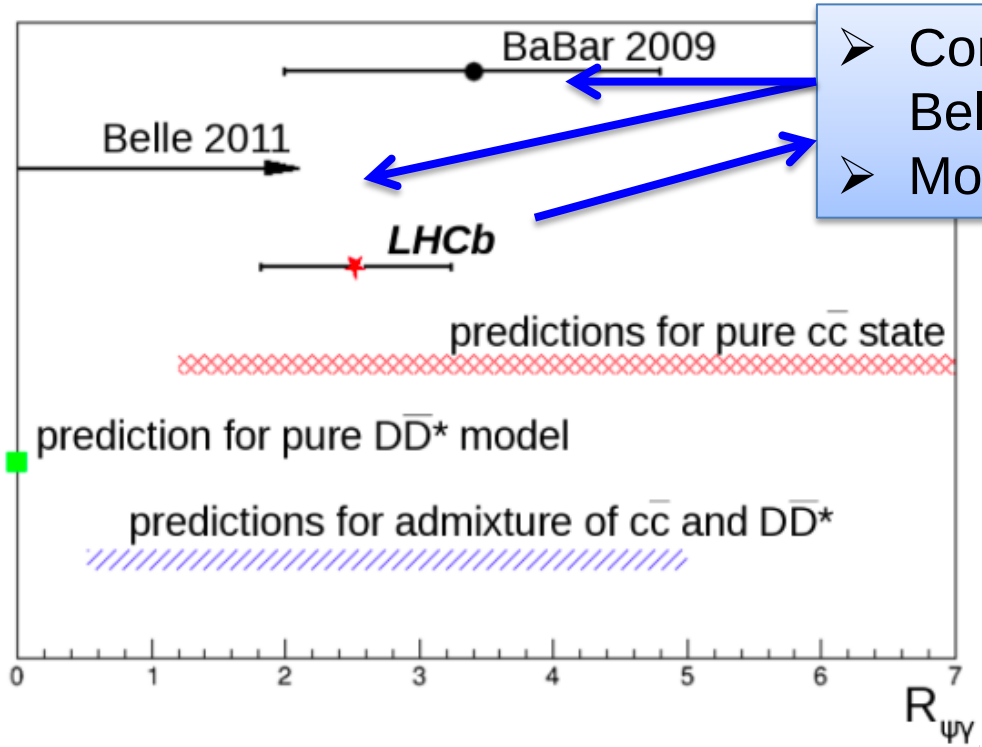
Signal yields determined by 2D fits to $m(B^+)$ vs $m(X(3872))$



Branching fraction ratio

Branching fraction measured as

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\psi(2S)}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$
$$= 2.46 \pm 0.64 \pm 0.29$$



- Compatible with BaBar and Belle measurements
- More precise

- Measured $R_{\psi\gamma}$ agrees with
  - A pure charmonium state
  - Molecular-$c\bar{c}$ mixture state
- Does not support a pure D^*D molecular state

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Observation of the resonant character of $Z(4430)^{\pm}$

PRL 112 (2014) 22, 222002

$Z(4430)^{\pm}$

Observed by Belle but not confirmed by BaBar

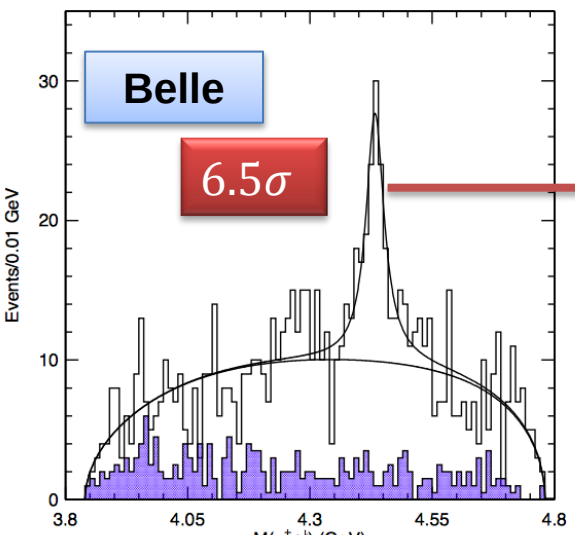
- Observed in $B^{0(+)} \to Z(4430)(\to \psi(2S)\pi^+)K^{-(0)}$ **PRL100, 142001 (2008)**

$$m = 4433 \pm 4 \pm 2\ \mathrm{MeV}/c^2;\ \Gamma = 45^{+18+30}_{-13-13}\ \mathrm{MeV}/c^2$$

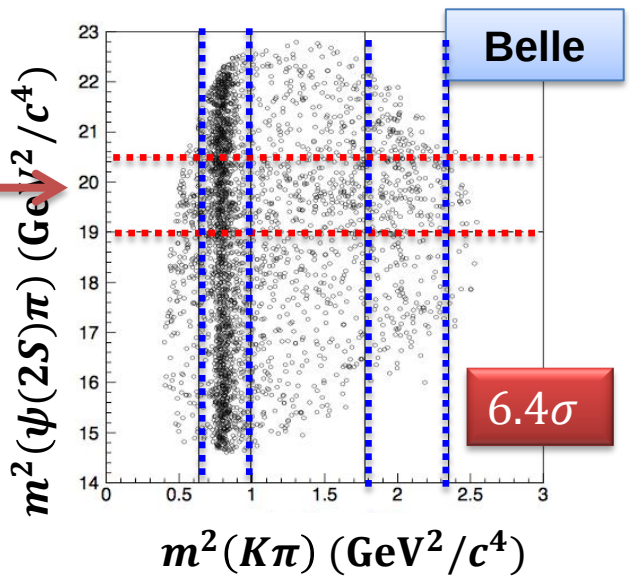
- 2D "Dalitz" analysis: $M^2(\psi(2S)\pi^+)$ vs $M^2(K^-\pi^+)$ **PRD80, 031104 (R) (2009)**

$$m = 4443^{+15+19}_{-43-56}\ \mathrm{MeV}/c^2;\ \Gamma = 107^{+86+74}_{-43-56}\ \mathrm{MeV}/c^2$$

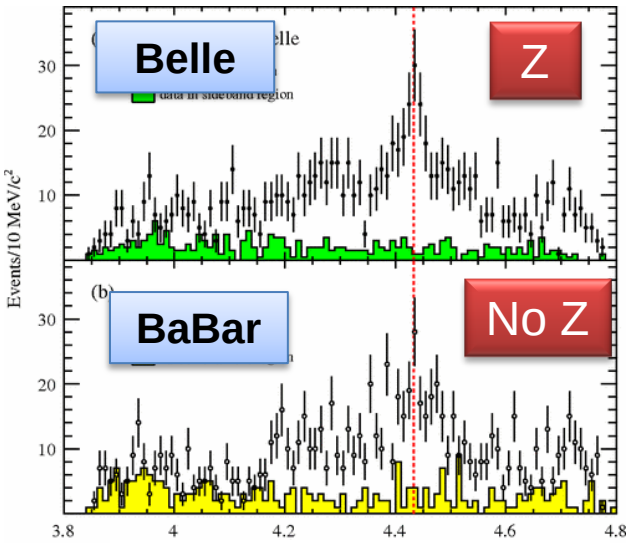
- No signals at BaBar **PRD79, 112001 (2009)**
  - Not confirmed; not excluded
  - The extent from reflection of $K\pi$ mass and angular structures



PRL100, 142001 (2008)



PRD80, 031104 (R) (2009)



PRD79, 112001 (2009)

Exotic state

Clear signature of exotic:

- Decay to charmonium: $B^{0(+)} \to Z(4430)(\to \psi(2S)\pi^+)K^{-(0)}$
  - $c\bar{c}$ pair content
- Electric charged: distinguished from all charmonia
  - At least 2 more light quarks $N_{\text{quark}} \geq 4$
- Tetraquark, D^*D_1 molecule?

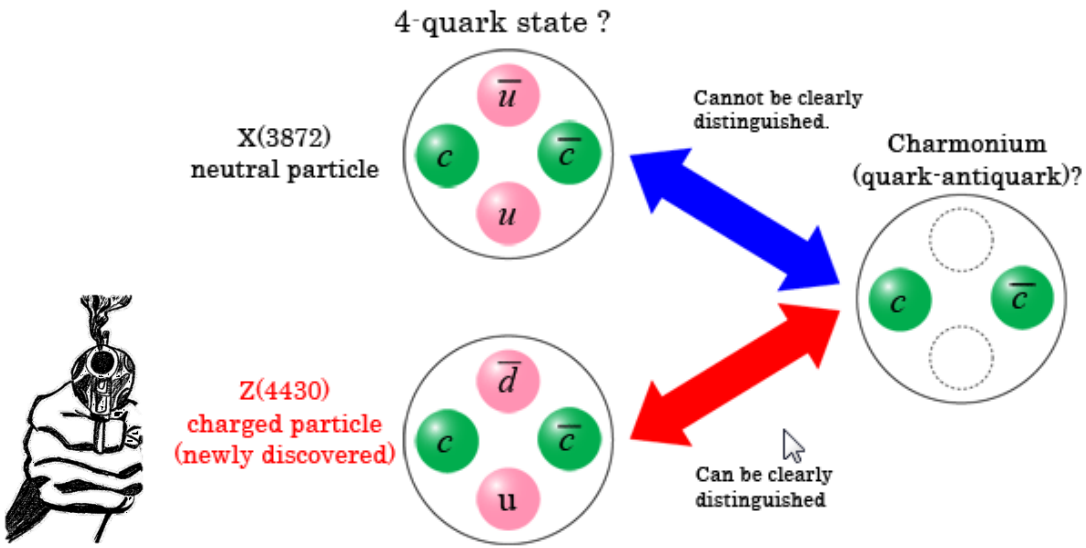


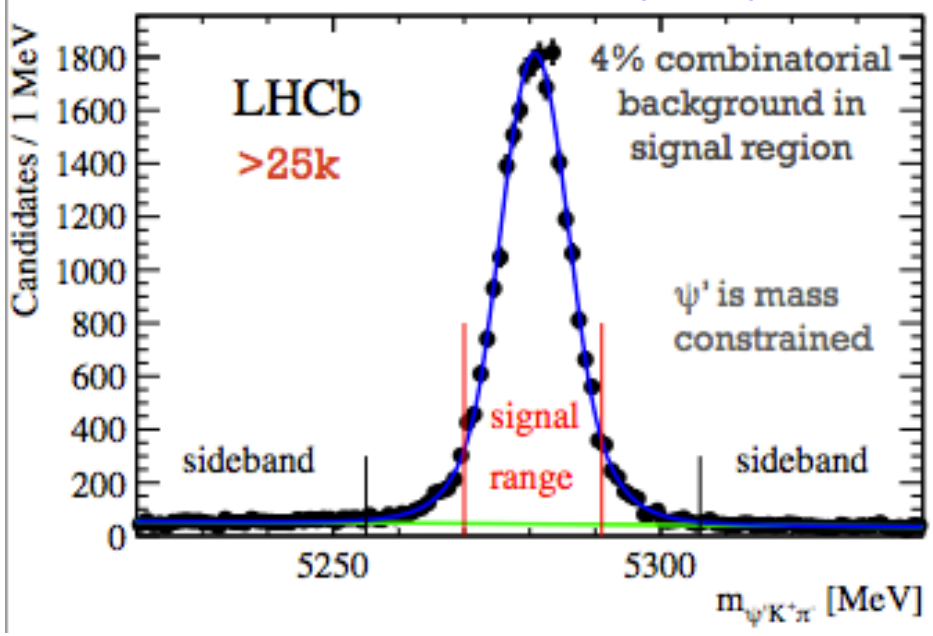
Figure 3 : The X(3872) particle, which is electrically neutral, cannot be clearly distinguished from an unusual charmonium meson. On the other hand, the newly found Z(4430), which is electrically charged, can be clearly distinguished from all charmonium mesons.

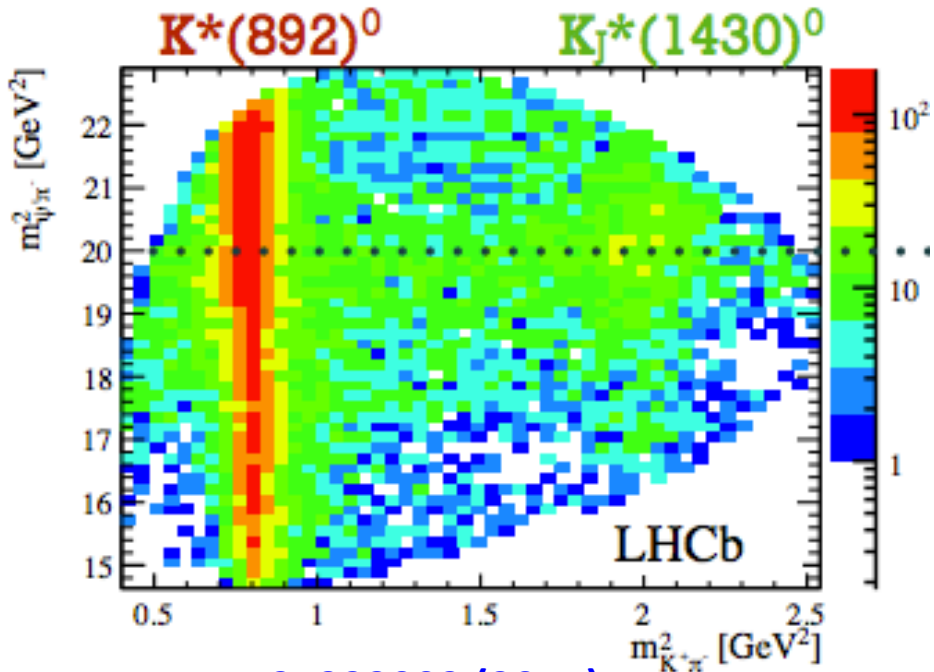
Further confirmation at LHCb needed

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

- Integrated Luminosity of 3.0 fb^{-1}
- Sample of >25K $B^0 \to \psi(2S)K^+\pi^-$ candidates ($\times$ 10 Belle/BaBar)
- Backgrounds from misID physics decay is small
- Sidebands are used to build 4D model of the combinatorial background

PRL 112, 222002 (2014)



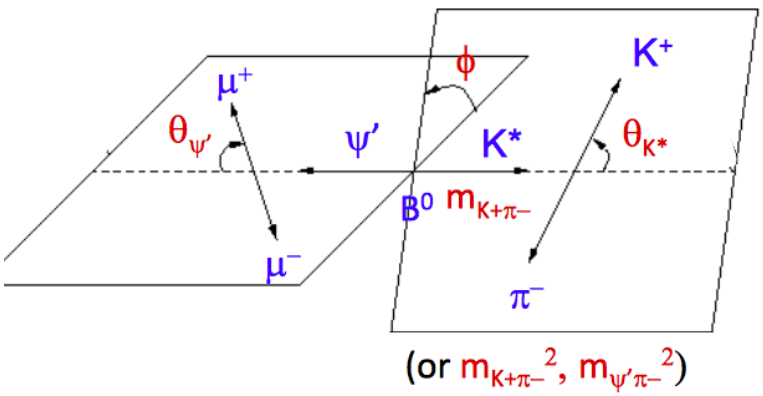


PRL 112, 222002 (2014)

Amplitude analysis

Amplitude calculated in 4D parameter space

$$\Phi = \left(m^2_{K\pi}, m^2_{\psi(2S)\pi}, \cos\theta_{\psi(2S)}, \phi\right)$$

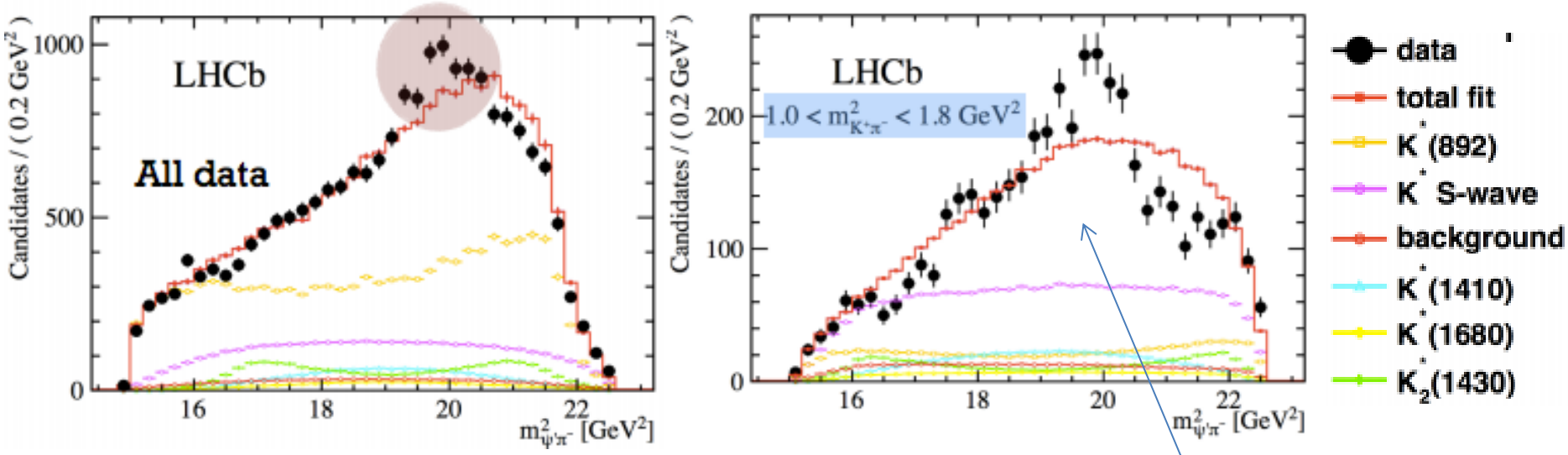


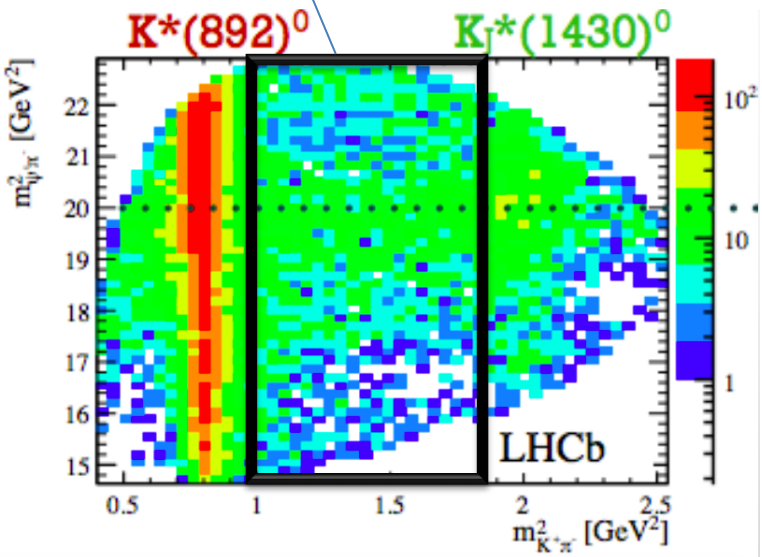
Resonance	J^P	Likely $n^{2S+1}L_J$	Mass (MeV)	Width (MeV)
$K_0^*(800)^0$ (κ)	0^+	—	682 ± 29	547 ± 24
$K^*(892)^0$	1^-	1^3S_1	895.94 ± 0.262	48.7 ± 0.7
$K_0^*(1430)^0$	0^+	1^3P_0	1425 ± 50	270 ± 80
$K_1^*(1410)^0$	1^-	2^3S_1	1414 ± 15	232 ± 21
$K_2^*(1430)^0$	2^+	1^3P_2	1432.4 ± 1.3	109 ± 5
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit			1593	
$K_1^*(1680)^0$	1^-	1^3D_1	1717 ± 27	322 ± 110
$K_3^*(1780)^0$	3^-	1^3D_3	1776 ± 7	159 ± 21
$K_0^*(1950)^0$	0^+	2^3P_0	1945 ± 22	201 ± 78
$K_4^*(2045)^0$	4^+	1^3F_4	2045 ± 9	198 ± 30
$B^0 \to J/\psi K^+\pi^-$ phase space limit			2183	
$K_5^*(2380)^0$	5^-	1^3G_5	2382 ± 9	178 ± 32

Amplitude

- Decay matrix element is sum of several two-body decays: $B^0 \to Z^-K^+$ & $B^0 \to \psi(2S)K^*$
- All K^* resonances with $J \leq 3$ consided
  - Even $K^*(1680)$: slightly above kinematic limit

Projections without $Z(4430)^-$

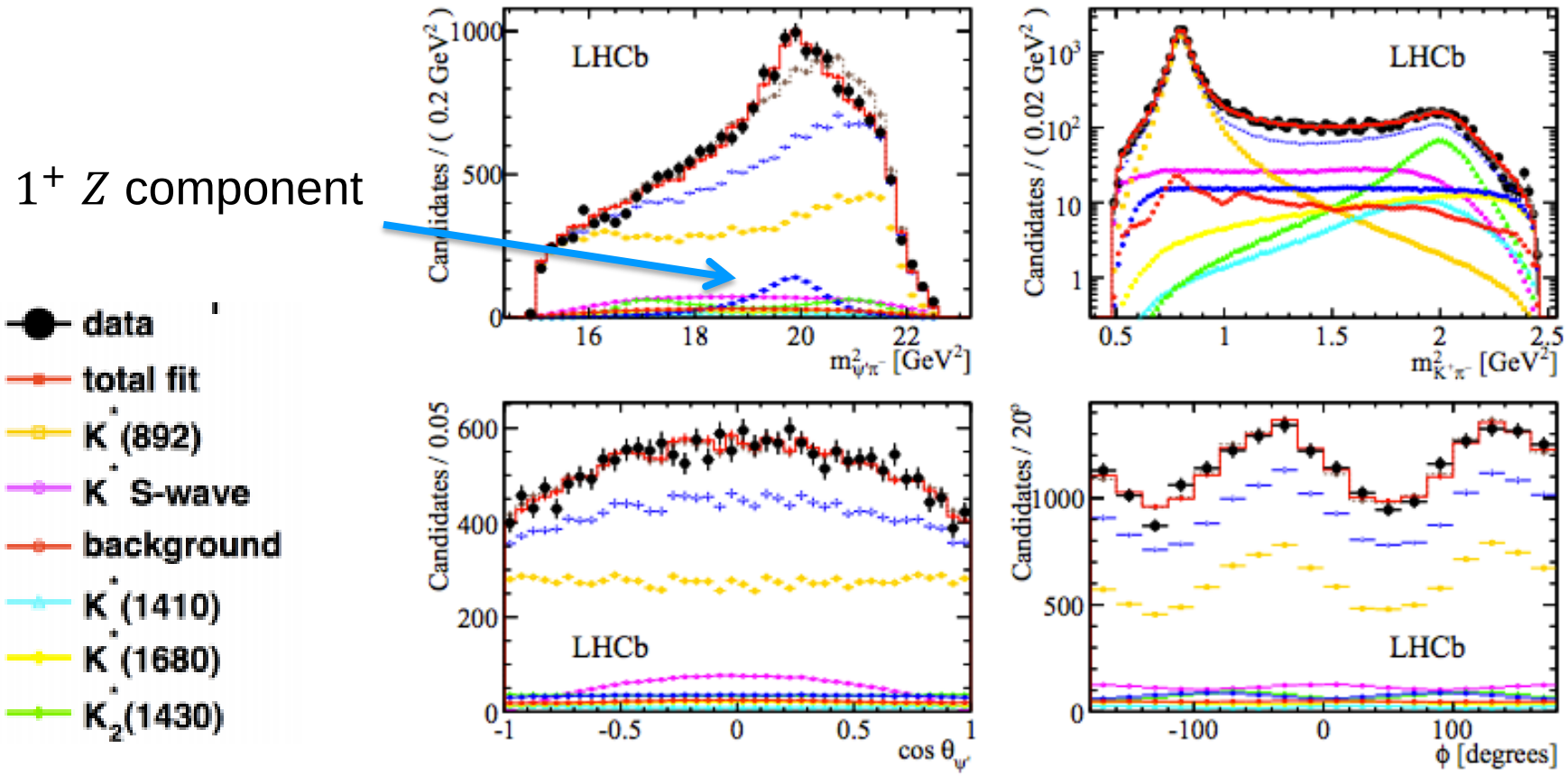




- Determine goodness-of-fit from 4D χ^2
- p-value $<2 \times 10^{-6}$ without $Z(4430)^-$
- The data cannot be adequately described only using $J \leq 3$ K^* contributions

Projections with $Z(4430)^-$

$J^P = 1^+$ Z component



- The 4D χ^2 p-value $= 12\%$
- The data are well described when including a $J^P = 1^+$ $Z(4430)$ in the fit

$Z(4430)^-$ parameters from amplitude fit

- Very good agreement between LHCb/Belle results
- Errors substantially improved

	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interference)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+
	New (large) systematic included	

Amplitude fractions [%]

Contribution	LHCb	Belle
S-wave total	10.8 ± 1.3	
NR	0.3 ± 0.8	
$K_0^*(800)$	3.2 ± 2.2	5.8 ± 2.1
$K_0^*(1430)$	3.6 ± 1.1	1.1 ± 1.4
$K^*(892)$	59.1 ± 0.9	63.8 ± 2.6
$K_2^*(1430)$	7.0 ± 0.4	4.5 ± 1.0
$K_1^*(1410)$	1.7 ± 0.8	4.3 ± 2.3
$K_1^*(1680)$	4.0 ± 1.5	4.4 ± 1.9
$Z(4430)^-$	5.9 ± 0.9	$10.3^{+3.0}_{-3.5}$

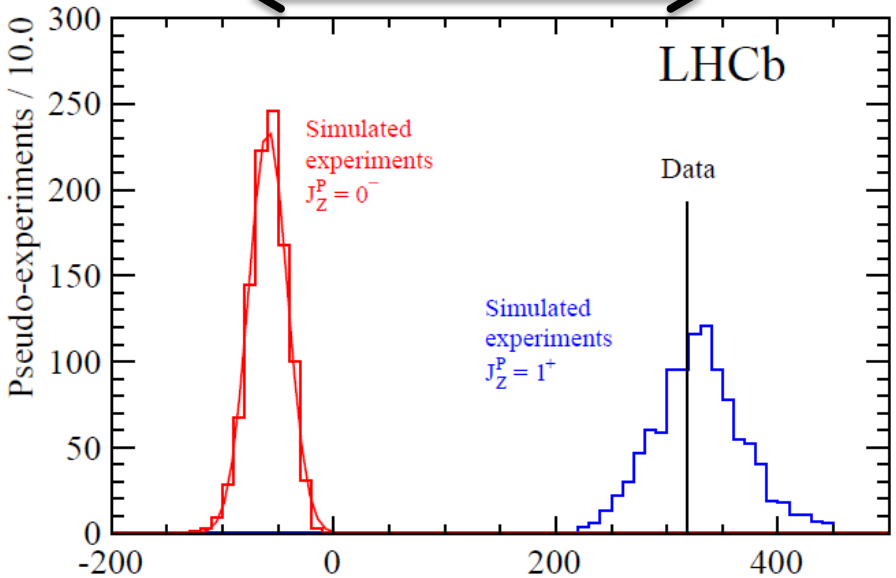
Phase-space integral

$$f_Z = \frac{\int |\mathcal{M}(Z)|^2 d\mathrm{PS}}{\int |\mathcal{M}(K^* + Z)|^2 d\mathrm{PS}} \qquad f_Z^I = 1 - \frac{\int |\mathcal{M}(Z)|^2 d\mathrm{PS}}{\int |\mathcal{M}(K^* + Z)|^2 d\mathrm{PS}}$$

Interferences included

Spin-parity analysis

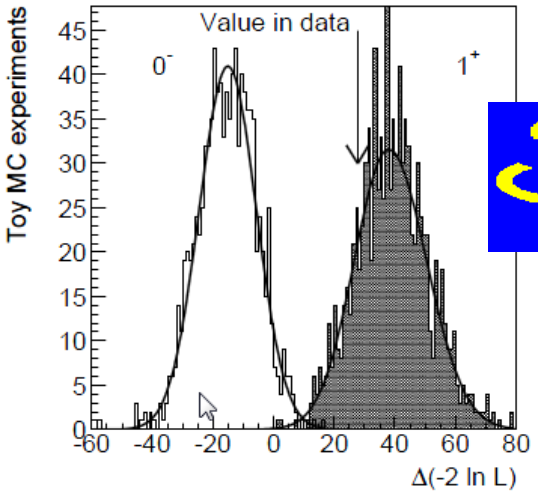
26 σ (18 σ using a conservative approach)



PRL 112, 222002 (2014)

$$t = -2\ln\frac{\mathcal{L}(0^-)}{\mathcal{L}(1^+)}$$

PRD 88, 074026 (2013)

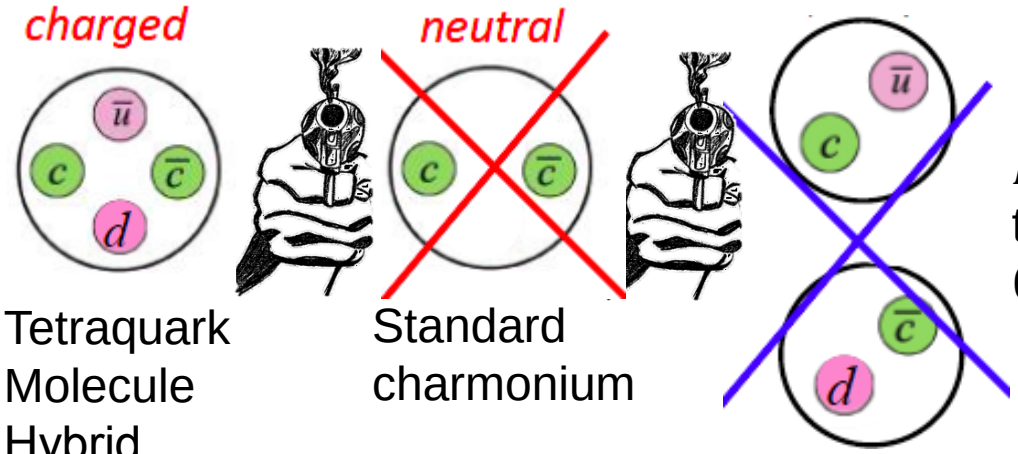


$J^P = 1^+$ now established beyond any doubt
Including systematic variations

	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

Implications

LHCb determined
$J^P = 1^+$



Tetraquark
Molecule
Hybrid …

Standard
charmonium

$D^* - \bar{D}^*$
threshold:
$0^-, 1^-, 2^-$

- $P = +$ rules out interpretation in terms of $\bar{D}^*(2010)D_1^*(2420)$ molecule or threshold effect **PRD 76 114002 (2007); JPG 35, 075005 (2008)**
- Four-quark bound state is a remaining explanation **PRD89, 114010 (2014)**
- 2013: Observation of another exotic charged state: $Z_c(3900)^\pm$
  - Is $Z(4430)^\pm$ a radial excitation of $Z_c(3900)^\pm$

PRL 110, 252001; PRL,110,252002

Resonance behavior

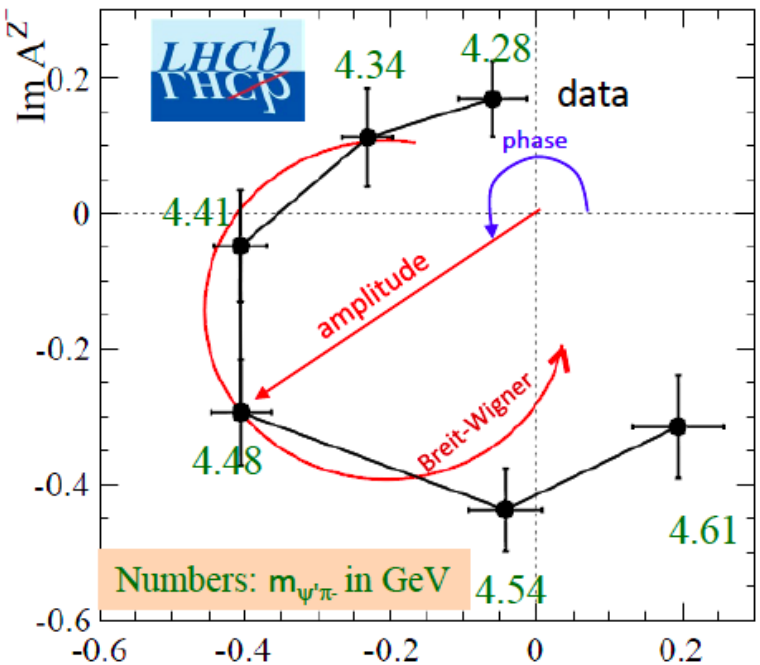
Does it follow resonant behavior if not forced to it by the amplitude model?

- BW function for amplitude fits

$$BW(m|m_0,\Gamma_0) = \frac{1}{m_0^2 - m^2 - im_0\Gamma(m)}$$

Magnitude $|A^{Z^-}|$ ⬆ : 0 → peak value → 0
➡ Phase goes: 0 → $\pi/2$ → π

Quick change of the phase ➡ signature of the resonant behavior



Argand Diagram

Additional fit performed with
$A^{Z^-} = \mathrm{Re}A^{Z^-} + i\mathrm{Im}A^{Z^-}$

- 6 bins in $m^2(\psi(2S)\pi)$ range: $(18.0 - 21.5)\mathrm{GeV}^2/c^4$

First time the resonant character demonstrated in Argand diagram

- Phase rapidly changed with A^{Z^-}
- An approximately circular trajectory

➡ Trajectory satisfies as what we expected as a resonance

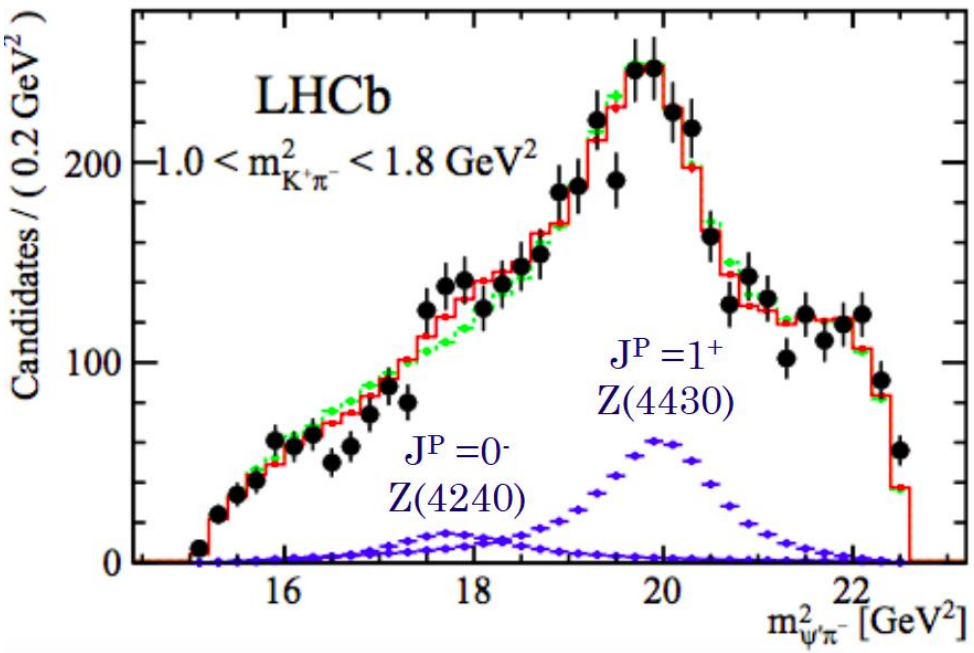
Second exotic Z^+

Fit confidence level increases with a second exotic ($J^P = 0^-$) component

- P value: 12 % → 26 %
- 0^- preferred over 1^-, 2^-, 2^+ @ 8 σ

Mass and width consistent with other Z observed by Belle:

- $Z^- \to \chi_{c1}\pi^-$ **[PRD78, 072004 (2008)]**
- $Z^- \to J/\psi\pi^-$ **[PRD90, 112009 (2014)]**



$$M(Z_0) = 4239 \pm 18^{+45}_{-10}\ \mathrm{MeV}/c^2$$
$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}\ \mathrm{MeV}/c^2$$

$$f(Z_0) = (1.6 \pm 0.5^{+1.9}_{-0.4})\ \%$$
$$f^I(Z_0) = (2.4 \pm 1.1^{+1.7}_{-0.2})\ \%$$

- No evidence for Z^0 in model independent approach
  - × $Z^-(0^-) \to \chi_{c1}\pi^-$
- Argand diagram for Z^0 is inconclusive
- More data needed to characterize this state

Outline

- Introduction
- $X(3872)$
  - J^{CP} determination
  - Radiative decays
- $Z(4430)^{\pm}$ confirmation
- Conclusion

Conclusion

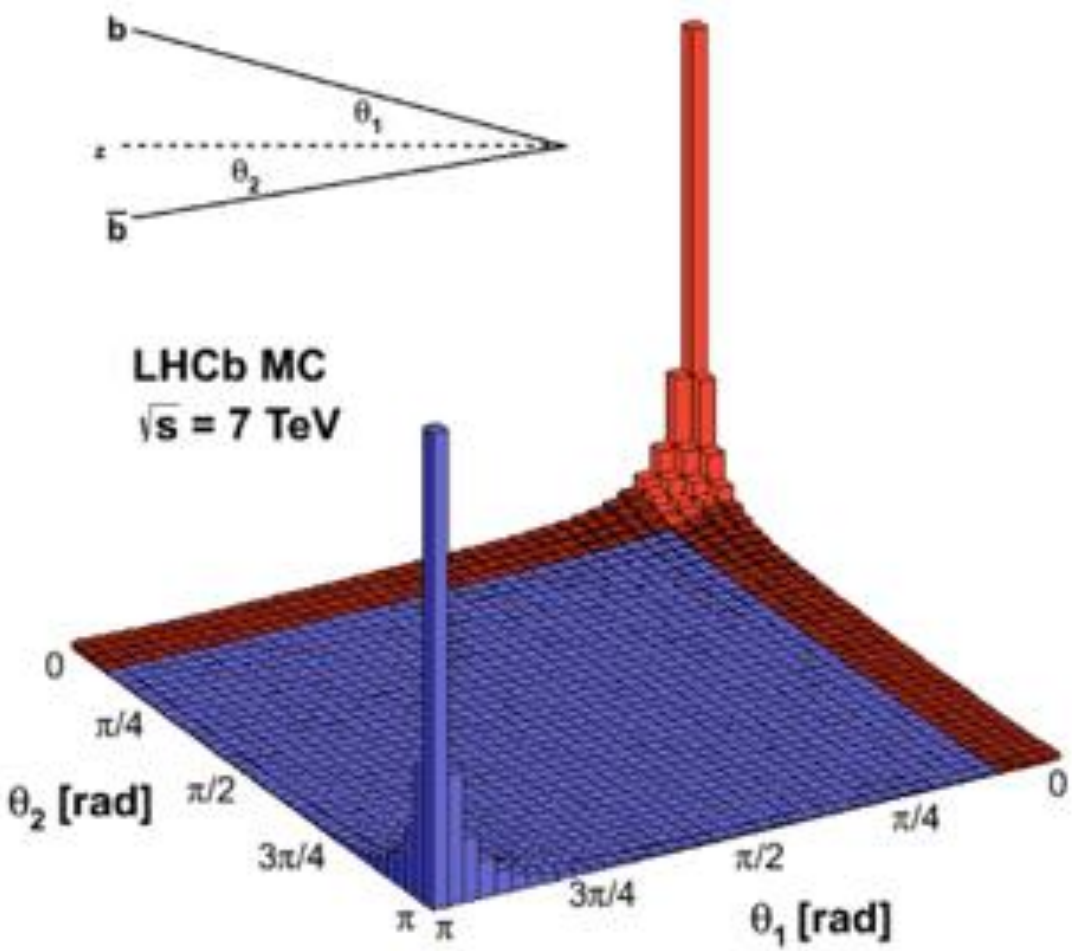
- $X(3872)$
  - Quantum number determined, $J^{PC} = 1^{++}$, with no L hypothesis
  - D-wave fraction $f_D < 4\ \%$ @ $95\ \%$ ➡ typical charmonia behaviors
  - $R_{\psi\gamma} = \mathcal{B}(X(3872) \to \psi(2S)\gamma)/\mathcal{B}(X(3872) \to J/\psi\gamma) = 2.46 \pm 0.64 \pm 0.29$
    - ➡ Ruling out the interpretation of a pure DD^* melcule
- $Z(4430)^+$
  - Confirmation of $Z(4430)^+$ @ $13.9\ \sigma$
  - Resonant behavior shown in Argand diagram
  - $J^P = 1^+$ established
    - ➡ Disfavor the interpretation as a D^*D_1 molecule state or threshold
    - ➡ Tetraquark scenario still standing
- More results are expected with Run-II data

Thank you for your attention

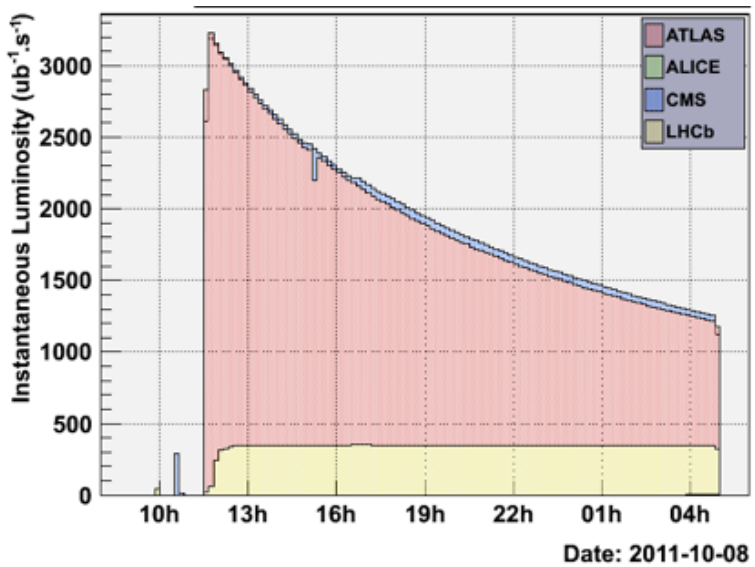
Backup

LHCb detector

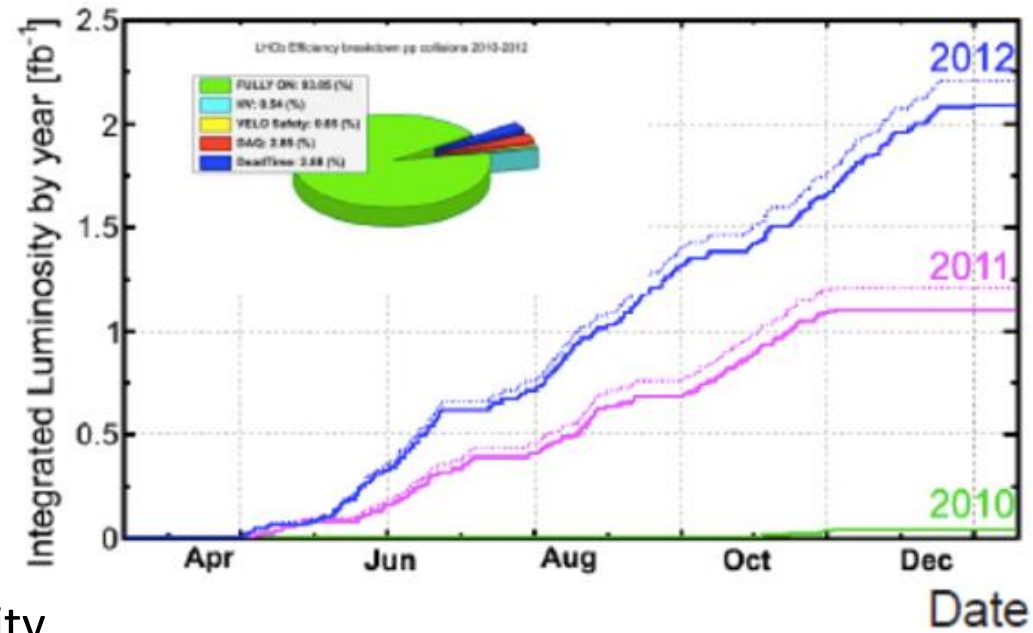
A signal-arm forward region spectrometer covering $2 < \eta < 5$



Data taking



pp collisions @ $\sqrt{s} = 7$ & 8 TeV (2011-12)



Low and stable instantaneous luminosity

- $\mathcal{L} \sim 4 \times 10^{32}\ \mathrm{cm}^2\mathrm{s}^{-1}$
- Factor 2 larger than design luminosity
- Average pile-up rate ~ 2
- pp primary vertex reconstructed well

- Efficient data taking @ LHCb
  - Efficiency $\sim 90\ \%$
- Results based on 2 magnet configurations

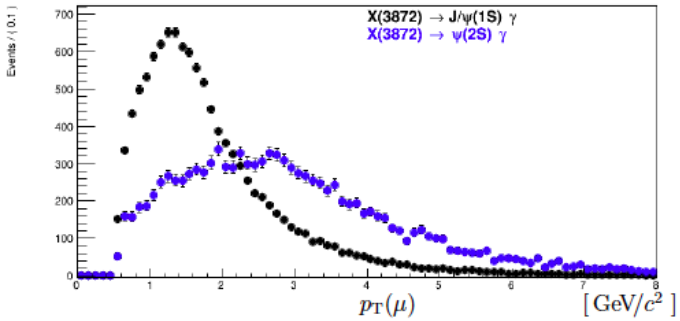
LHCb run-I data

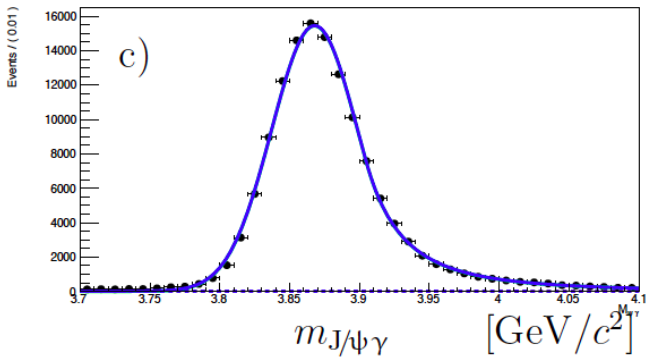
- $1\ \mathrm{fb}^{-1}$ for 2011
- $2\ \mathrm{fb}^{-1}$ for 2012

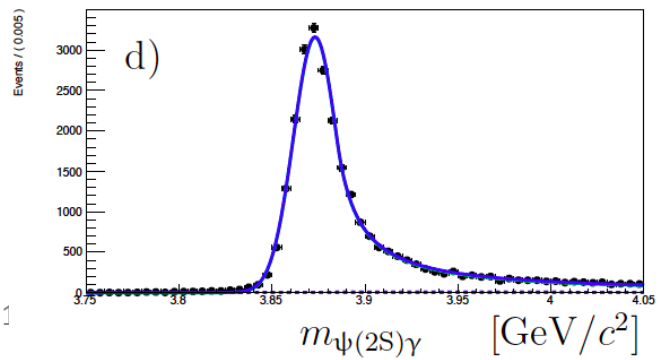
Signals of $X(3872) \to \psi(2S)\gamma$

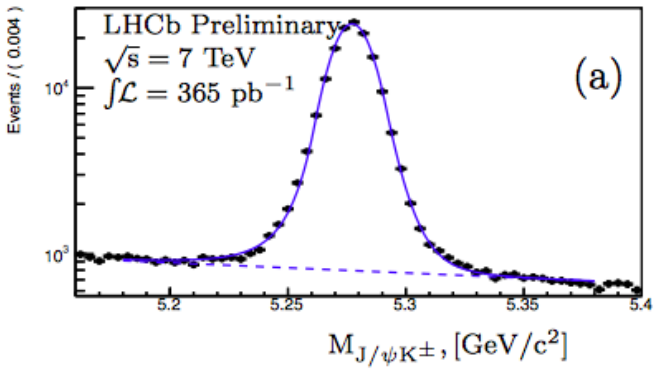
Very different kinematics in $X(3872) \to \psi(2S)\gamma$ and $J/\psi\gamma$:

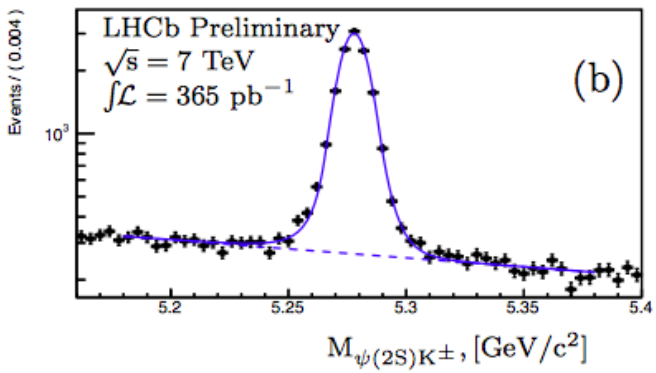
- $M\big(X(3872)\big) - M(J/\psi) \approx 4 * \big(M\big(X(3872)\big) - M(\psi(2S))\big)$











Measurement of $X(3872)$ mass & production in $X(3872) \to J/\psi\pi^+\pi^-$

EPJC72, 1972 (2012)

$X(3872)$ mass & production

Lights on nature of $X(3872)$

For mass:

PR429, 243 (2006)

- $\eta_{c2}(1D)$ meson: mass predicted far below the observed one
- $D^{*0}\overline{D}^{0}$ molecule: $m(X(3872))$ less than $m(D^{*0}) + m(D^{0})$

For production

- Tests needed for the prediction of $\sigma(X(3872))$ as the molecular nature

PRL103, 162001 (2006); PRD81, 114018 (2010)

LHCb can provide the measurements of mass and production of $X(3872)$ in $X(3872) \to J/\psi\pi^{+}\pi^{-}$

Signals of $X(3872) \to J/\psi\pi^+\pi^-$

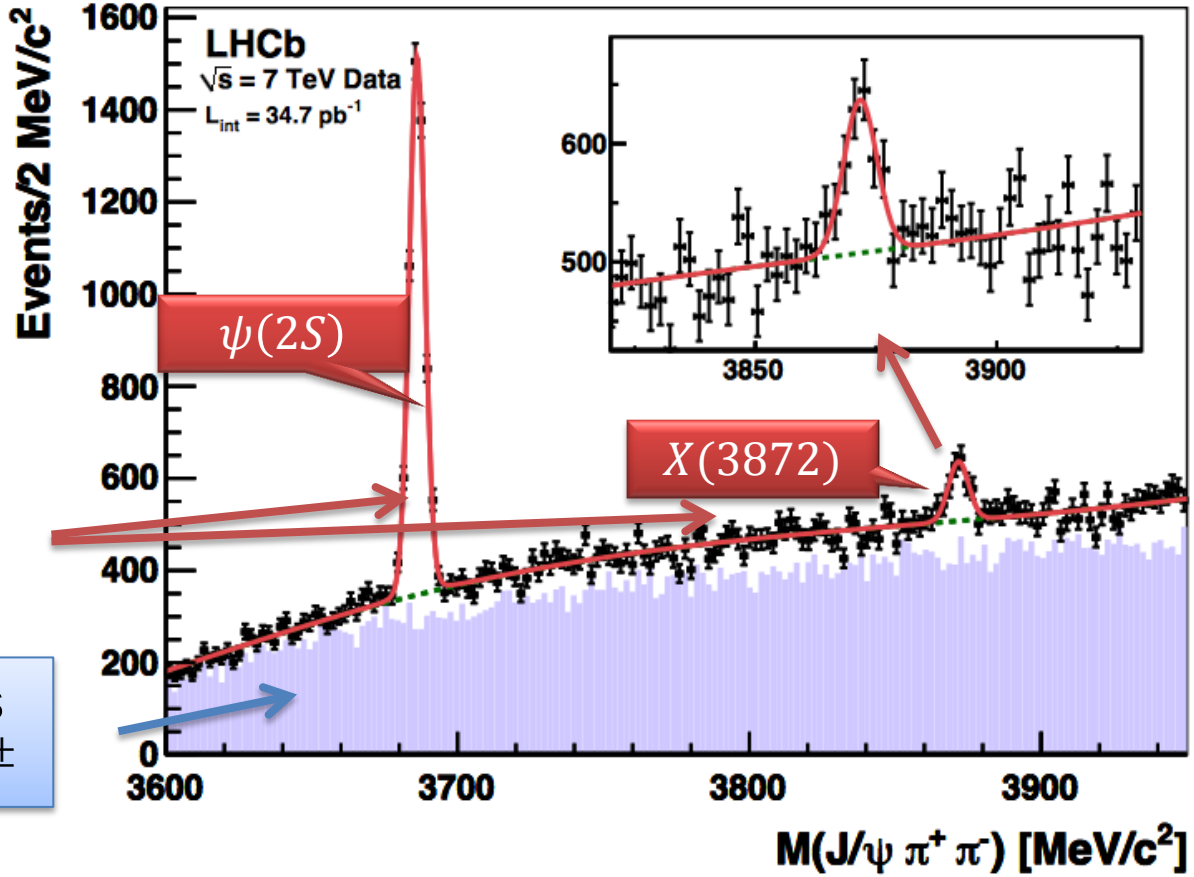
Mass & signal yields of $X(3872)$ determined by fit to $m(X)$ distributions

- Data sample: $35\ \mathrm{pb}^{-1}$
- Momentum scale: estimated from $J/\psi \to \mu^+\mu^-$

	$X(3872)$
Nsig	565 ± 62
σ	3.33 ± 0.08
Mass	3871.88 ± 0.48

NR BW function convolved with Gaus

Same-sign pion candidates from data sample: $J/\psi\pi^\pm\pi^\pm$



$X(3872)$ mass

$X(3872)$ fitted mass

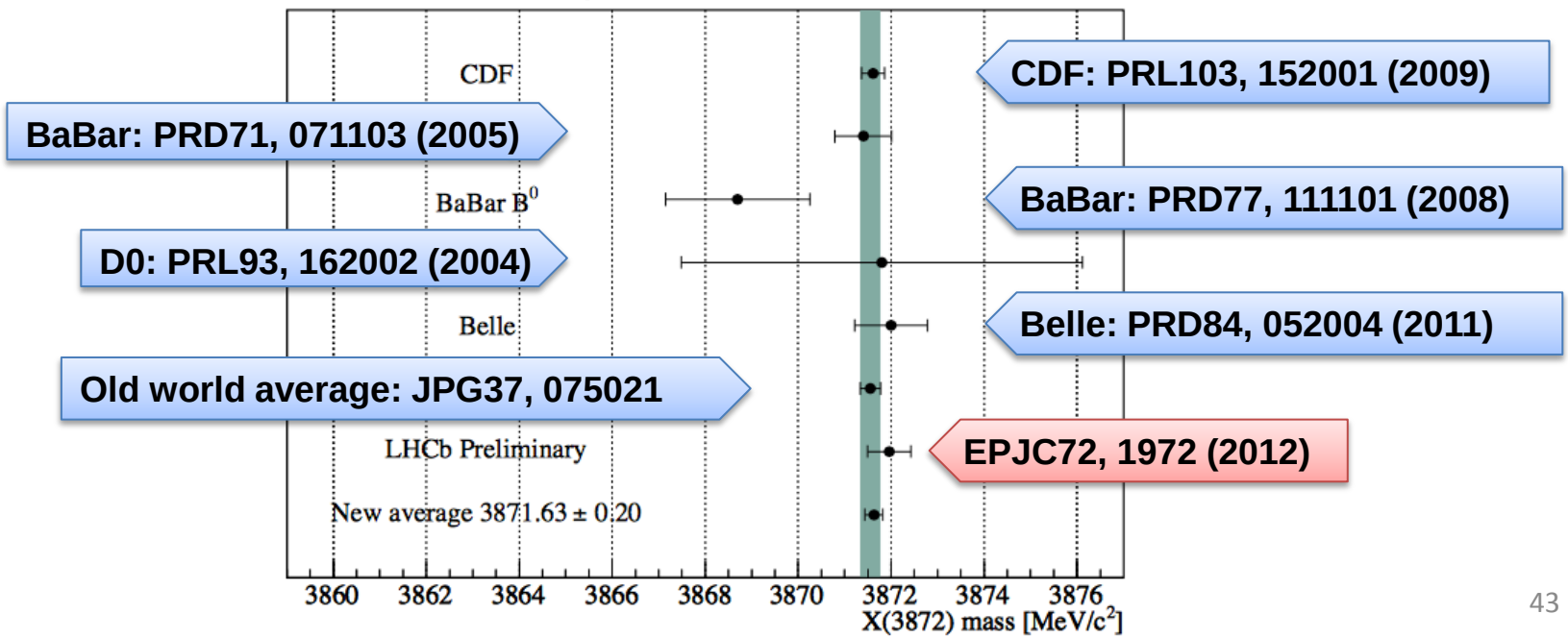
$$m\big(X(3872)\big) = 3871.88 \pm 0.48\ \mathrm{MeV}/c^2$$

Correction due to Final state radiation
$-0.07 \pm 0.02\mathrm{MeV}/c^2$

Measured mass

$$m(X(3872)) = 3871.95 \pm 0.48(\mathrm{stat}) \pm 0.12(\mathrm{syst})\ \mathrm{MeV}/c^2$$

- In agreement with previous measurements
- Consistent with the sum of the D^0 and D^{*0} masses
  $3871.79 \pm 0.29\ \mathrm{MeV}/c^2$



Production of $X(3872)$

Production cross-sections of $X(3872)$

$$\sigma(pp \to X(3872) + \cdots) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{N^{\mathrm{cor}}(X(3872))}{\mathcal{B}(J/\psi \to \mu^+\mu^-) \times \mathcal{L}_{\mathrm{int}}}$$

$$= 5.4 \pm 1.3(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{nb}$$

$2.5 < y < 4.5;\ 5 < p_{\mathrm{T}} < 20\ \mathrm{GeV}/c$

Prediction: $13.0 \pm 2.7\ \mathrm{nb}^{-1}$

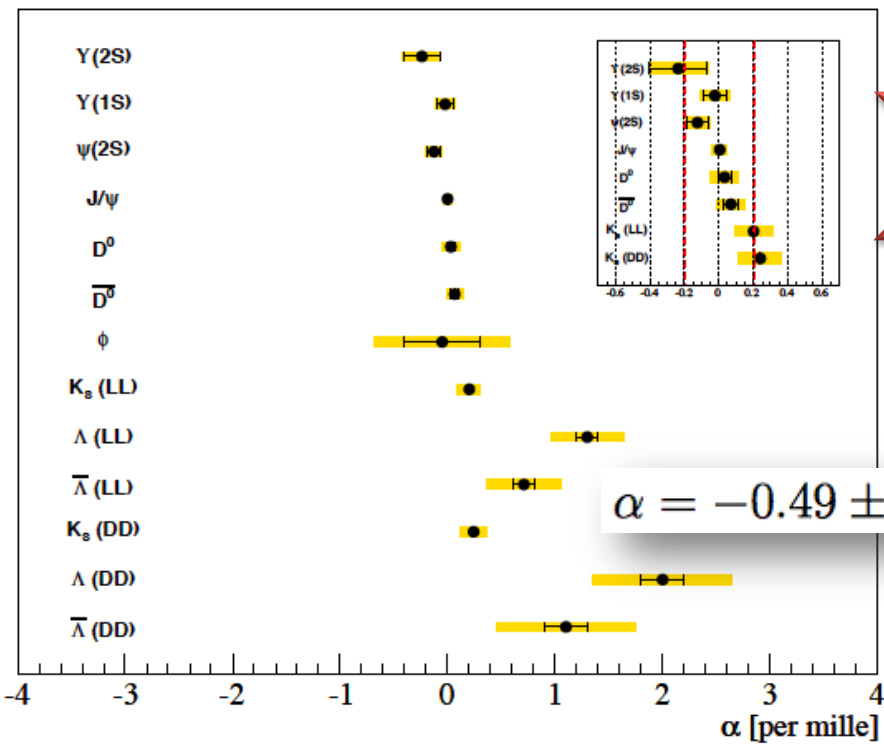
- NRQCD model
- Assuming $\sigma(X(3872))$ dominated by charm quark pairs
- Prompt production and from b decays taking into account
- $2.8\ \sigma$ deviation between LHCb measurement and prediction

PRD81, 114018 (2010)

Momentum scale

Mass of $X(3872)$ determined by fit to $m(J/\psi\pi^+\pi^-)$ distributions

- Data sample: momentum scale taken into account
  - Tracks' momenta measured smaller than true one: interaction between daughter particles & material in detector
  - Factor $(1-\alpha)$ as factor multiplied with tracks' momenta



$$\alpha = -0.49 \pm 0.03$$

$$m_{12}^2 = (E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2}) \cdot (\vec{p_1} + \vec{p_2})$$

At first order of p/m

$$m_{12}^2 = \frac{m_P^2 - f}{(1-\alpha)^2} + f\,,$$

where, m_P: true mass

$$f = m_1^2 + m_2^2 + \frac{p_2}{p_1} m_1^2 + \frac{p_1}{p_2} m_2^2$$

If $\alpha \ll 1$: $\Delta m = \alpha \times (f - m_P^2)/m_P$
$\approx -\alpha m_P$

Discovery of $X(4140)$ & $X(4274)$

CDF observed a $(J/\psi\phi)$ structure in $B^+ \to J/\psi\phi K^+$

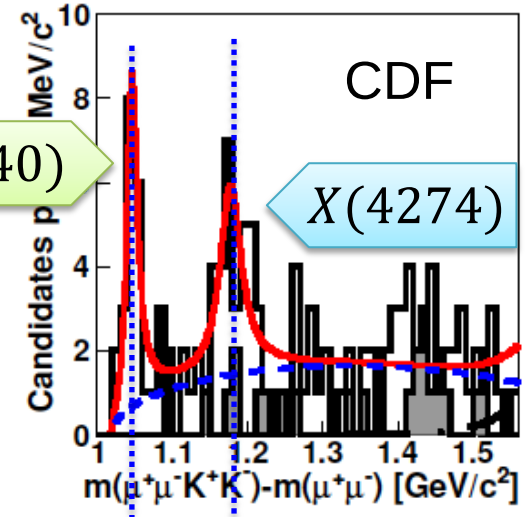
PRL 102, 242002 (2009), arXiv: 1101.6058

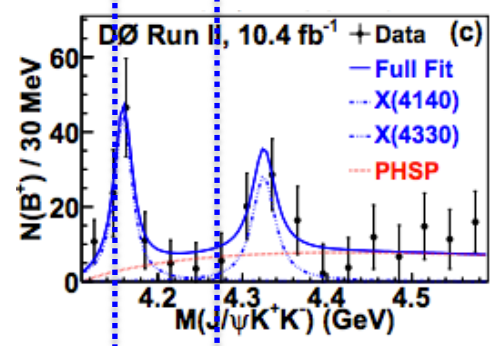
$X(4140)$

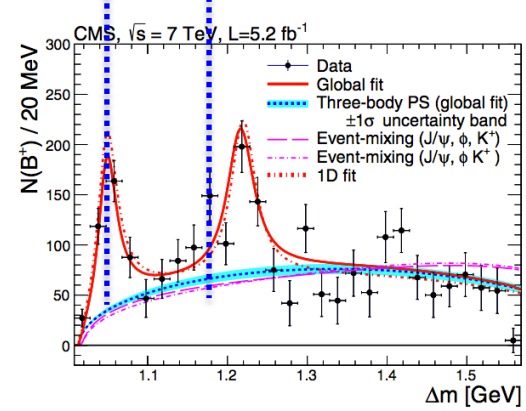
$$M = 4143.0^{+2.9}_{-3.0} \pm 0.6\ \mathrm{MeV}/c^2$$
$$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5\ \mathrm{MeV}/c^2$$

$X(4274)$

$$M = 4274.4^{+8.4}_{-6.7} \pm 1.9\ \mathrm{MeV}/c^2$$
$$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6\ \mathrm{MeV}/c^2$$







- Belle: No evidence of $X(4140)$ in $\gamma\gamma \to J/\psi\phi$; Observation of a new state $X(4350)$
  PRL 104,112004 (2010)
- D0: Threshold enhancement consistent with $X(4140)$ (3.1σ) and $X(4350)$
  PRD 89, 012004
- CMS: Peak in $J/\psi\phi$ consistent with $X(4140)$, Evidence of a 2nd peak affected by reflection **PLB 734, 261 (2014)**
- BaBar: No evidence of $X(4140)/X(4274)$

More confirmation needed

Search for $X(4140)$ & $X(4270)$

$0.37\ \mathrm{fb}^{-1}$ data used

- 35 ± 11 $X(4140)$ and 53 ± 19 $X(4274)$ expected according to CDF results
- No narrow structure is observed near the threshold
- The LHCb results disagree at $2.4\ \sigma$ level with the CDF measurement

LHCb (90%) C.L.

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

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

An amplitude analysis needed to investigate the resonance nature of these peaks