Exotic Spectroscopy at LHCb

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On behalf of the LHCb collaboration

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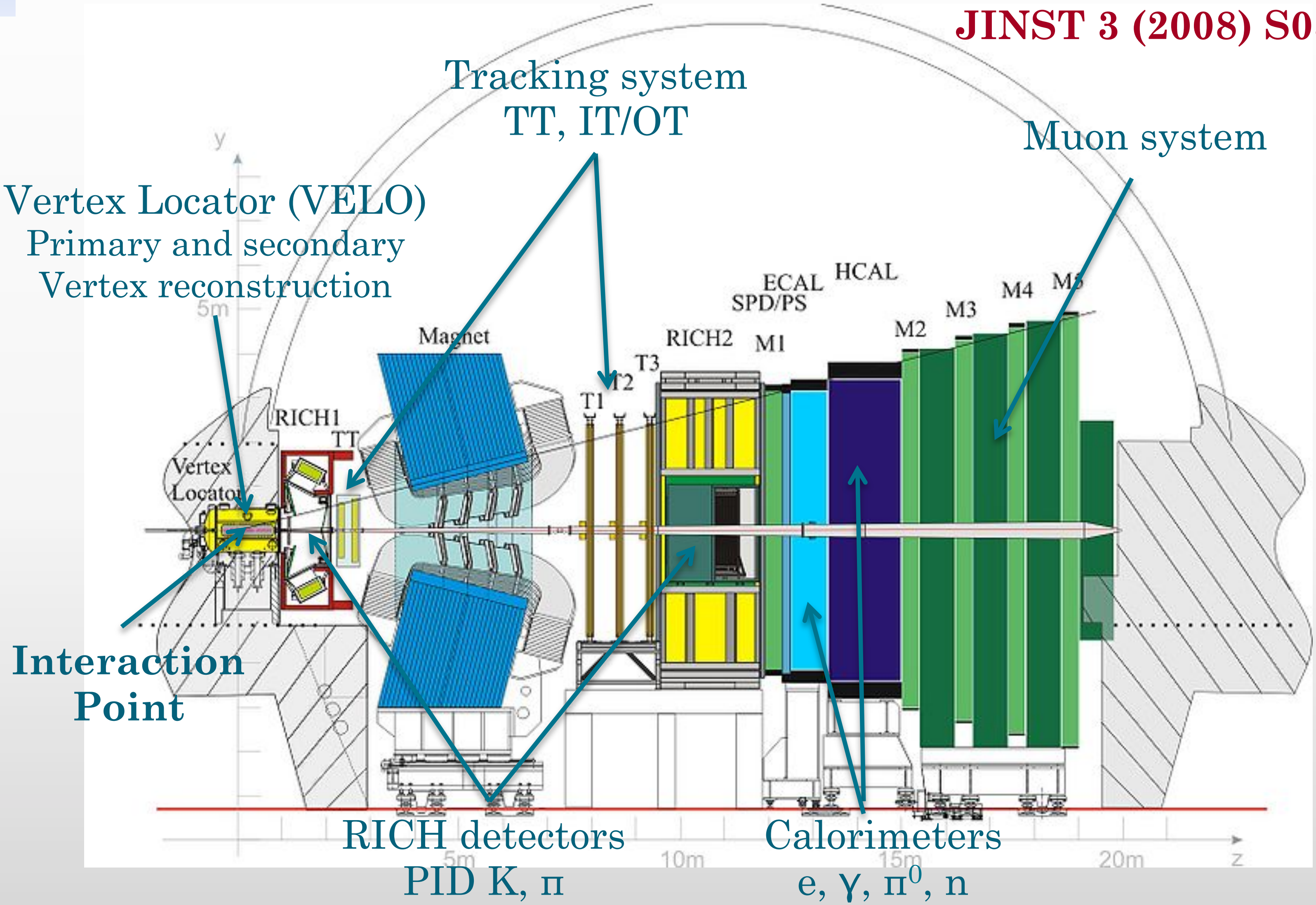
Outline

- *LHCb detector*
- *X(3872)*
  - ✓ Spin-Parity
  - ✓ Radiative decays
- *X(4140)*
- *$Z(4430)^+$*
  - ✓ Model independent analysis
  - ✓ Amplitude analysis

The LHCb detector

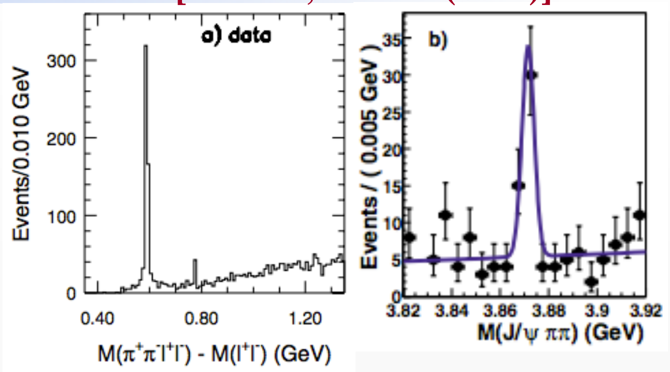
JINST 3 (2008) S08005



X(3872)

The X(3872) Meson

[PRL 91, 262001 (2003)]



Discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ decay where $X(3872) \to J/\psi\pi^+\pi^-$

- Mass is roughly equal to $m(D^0) + m(D^{*0})$
- Width is surprisingly narrow (< 1.2 MeV)
- Large production rate in $p\bar{p}$ collisions

LHCb is largely contributing to shed light on the nature of the X(3872) state:

- Determination of the quantum numbers **[PRL 110, 222001 (2013)]**
- Measurement of *B*(X(3872)→ψ(2S) γ)/*B*(X(3872)→J/ψ γ) **[Nucl.Phys.B886 (2014) 665]**
- Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0\bar{D}^{*0}) - m(X(3872)) = 0.09 \pm 0.28\,\mathrm{MeV}/c^2$$ ➡ *Loosely bound in the molecule scenario*

- Production cross-section in *pp* collisions at √s = 7 TeV **[EPJC 72 (2012) 1972]**

$$\sigma_{X(3872)} \times BR(X(3972) \to J/\psi\pi^+\pi^-)^{[2.5<y<4.5, p_T>5\mathrm{GeV}]} = 5.4 \pm 1.3 \pm 0.8\,\mathrm{nb}$$

- Search for X(3872)→ $p\bar{p}$ **[EPJC 73 (2013) 2462]**

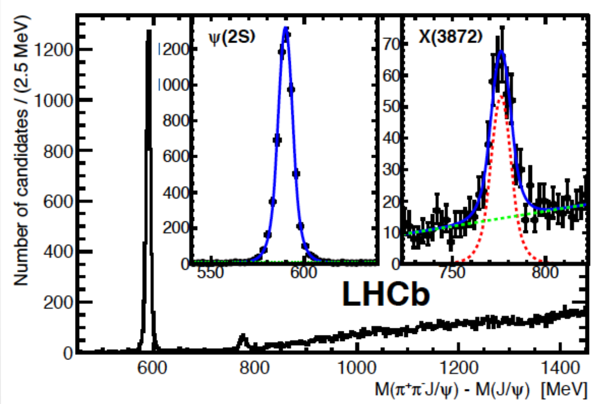
$$\frac{BR(X(3872) \to p\bar{p})}{BR(X(3872) \to J/\psi\pi^+\pi^-)} < 2.0 \times 10^{-3}$$

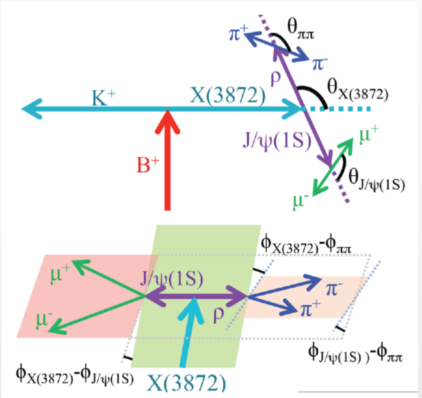
X(3872) Quantum Numbers

[PRL 110, 222001 (2013)]

Previously:

- B factories: Observation of the $X(3872) \to J/\psi\gamma$ decay $\Rightarrow$ **C=+**. [PRL 102 132001] [PRL 107 091803]
- CDF: 2292±113 $p\bar{p} \to X(3872)+anything$ events. Unknown X(3872) polarization (only 3 angles). Quantum numbers constrained to 1^{++} or 2^{-+}. [PRL 98, 132002 (2007)]
- Belle: 173±16 $B \to K X(3872)$ events. 1D analysis carried out (Not enough events to bin in 5D). 1^{++} or 2^{-+} could not be distinguished. [hep-ex/0505038]



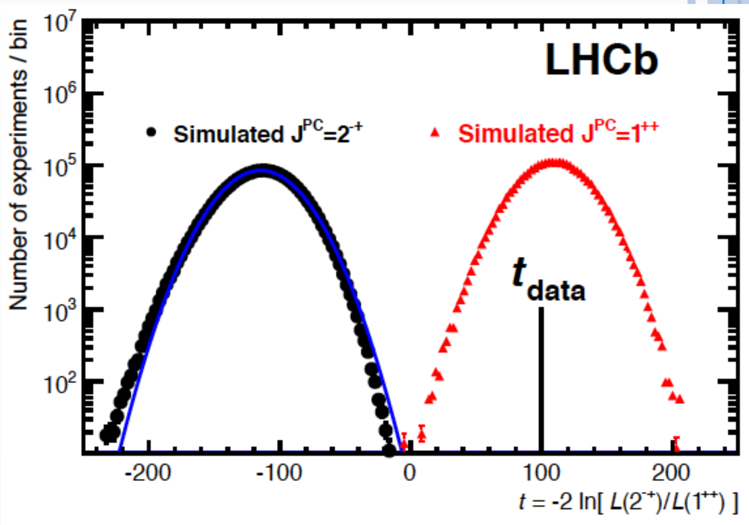


- $1.0\ \text{fb}^{-1}$ dataset collected by LHCb in 2011
- $313 \pm 26\ B^+ \to K^+ X(3872)$ with $X(3872) \to J/\psi\pi^+\pi^-$
- LHCb performs a 5D analysis which benefits of the angular correlations to disentangle the quantum number of the X(3872)

X(3872) Quantum Numbers: $J^P = 1^{++}$!

[PRL 110, 222001 (2013)]

- Likelihood-ratio test to discriminate between the 1^{++} and the 2^{-+} assignments
- Simulated experiments, each with the number of signals and background events as in the real experiment
- The two spin hypotheses are completely separated
  - $t > 0$ implies 1^{++} favoured
  - $t < 0$ implies 2^{-+} favoured
- Data favour the 1^{++} over the 2^{-+} hypothesis at 8.4σ



- $\eta_{c2}(1^1D_2)$ $(J^{PC} = 2^{-+})$ ruled out
- $\chi_{c1}(2^3P_1)$ disfavoured by the measured mass
- Conventional charmonium interpretation of the X(3872) seems fading in favour of an exotic scenario!

EVIDENCE FOR X(3872)→ ψ (2S) γ

[Nucl.Phys.B886 (2014) 665]

- ⊛ Observation of the $X(3872) \to J/\psi\gamma$ decay ⇒ C=+ [PRL 102 132001] [PRL 107 091803]
- ⊛ Measurement of $R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J\psi\gamma)}$ to disentangle the nature of $X(3872)$
- ⊛ Predicitions of $R_{\psi\gamma}$ vary widely across different models:
  - → $\chi_{c1}(2^3P_1)$ interpretation: $R_{\psi\gamma} \sim 1.2 - 15$
  - → $D\bar{D}^*$ molecular picture: $R_{\psi\gamma} \sim (3-4) \times 10^{-3}$
  - → Mixture of $c\bar{c}$ and $D\bar{D}^*$: $R_{\psi\gamma} \sim 0.5 - 5$

Controversial experimental status:

- ➢ In 2009 BaBar: Evidence of X(3872)→ψ(2S)γ in $B^\pm$→X(3872)$K^\pm$ decays:

  $R_{\psi\gamma} = 3.4 \pm 1.4$ [PRL102 (2009) 132001]

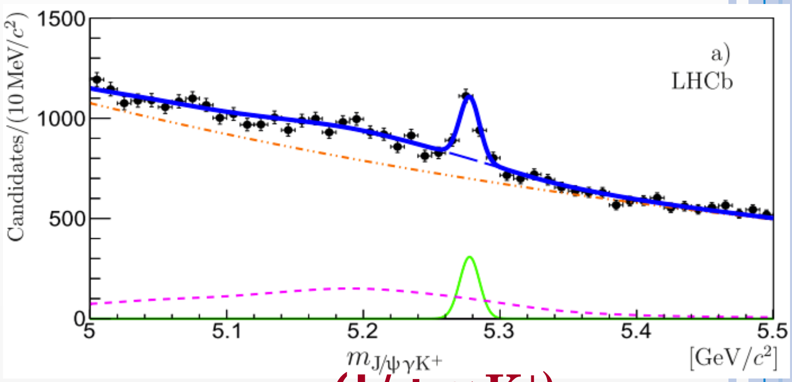
- ➢ In 2011 Belle: No evidence for X(3872)→ψ(2S)γ:

  $R_{\psi\gamma} < 1.2$ @ 90 C.L. [PRL107 (2011) 091803]

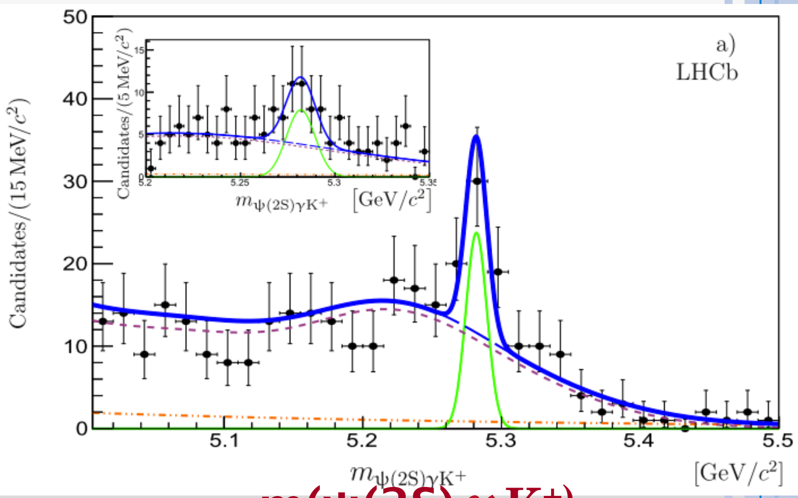
EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

- Integrated luminosity 3.0 fb^{-1}
- Reconstruction of $B^+ \rightarrow \psi(\rightarrow \mu\mu)\gamma K^+$, where $\psi = J/\psi$ or $\psi(2S)$
- π^0 veto
- $m(\psi\gamma) \in [3.7\text{-}4]\ GeV/c^2$
- ψ mass and PV constrained to improve mass resolution



$m(J/\psi\gamma K^+)$

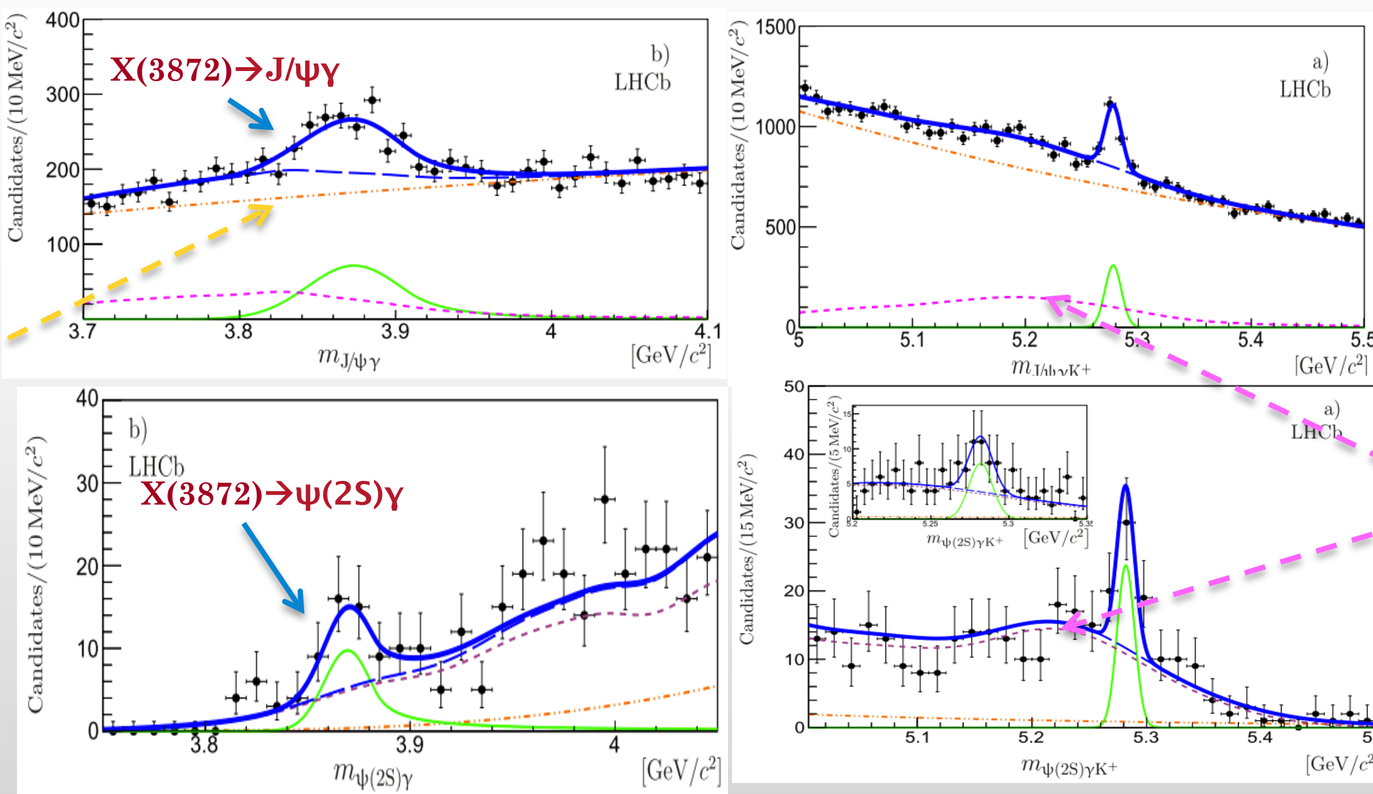


$m(\psi(2S)\gamma K^+)$

EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

- 2D Fit: m(ψγK) vs m(ψγ)
- Peaking backgrounds:
  - J/ψ mode: $B^+ \rightarrow J/\psi\, K^{*+}$, $K^{*+} \rightarrow K^+ \pi^0 (\rightarrow \gamma\gamma)$
  - ψ(2S) mode: b →J/ψ K⁺ h + random γ



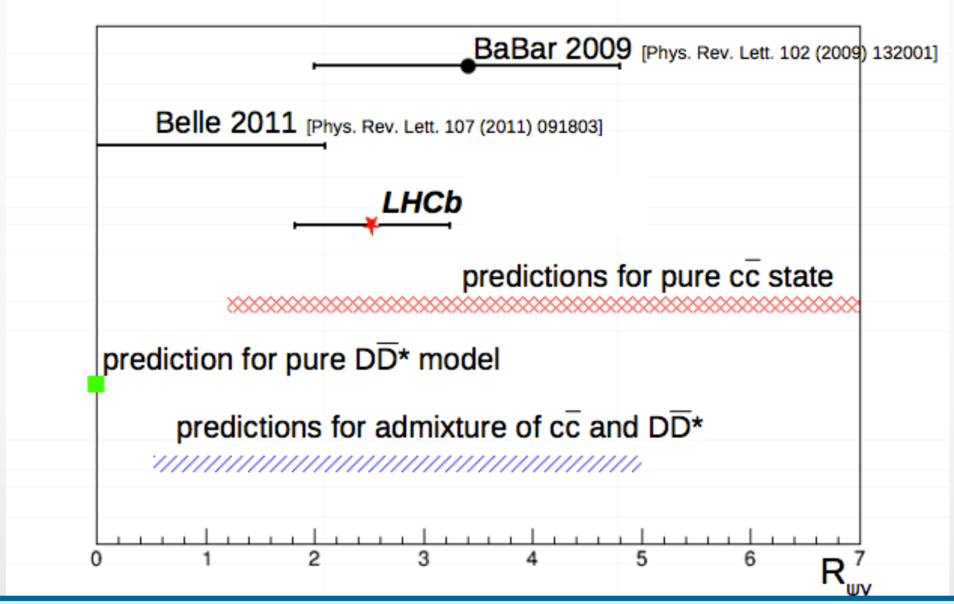
Comb. Bkg.

Peaking Bkg.

EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

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



Does not support a <u>pure</u> DD* molecular interpretation.
Standard charmonium and other scenarios still compatible

Can the radiative decays tell us more?
[F.Guo, C. Hanhart et al., arXiv:1410.6712]

X(4140) & X(4270)

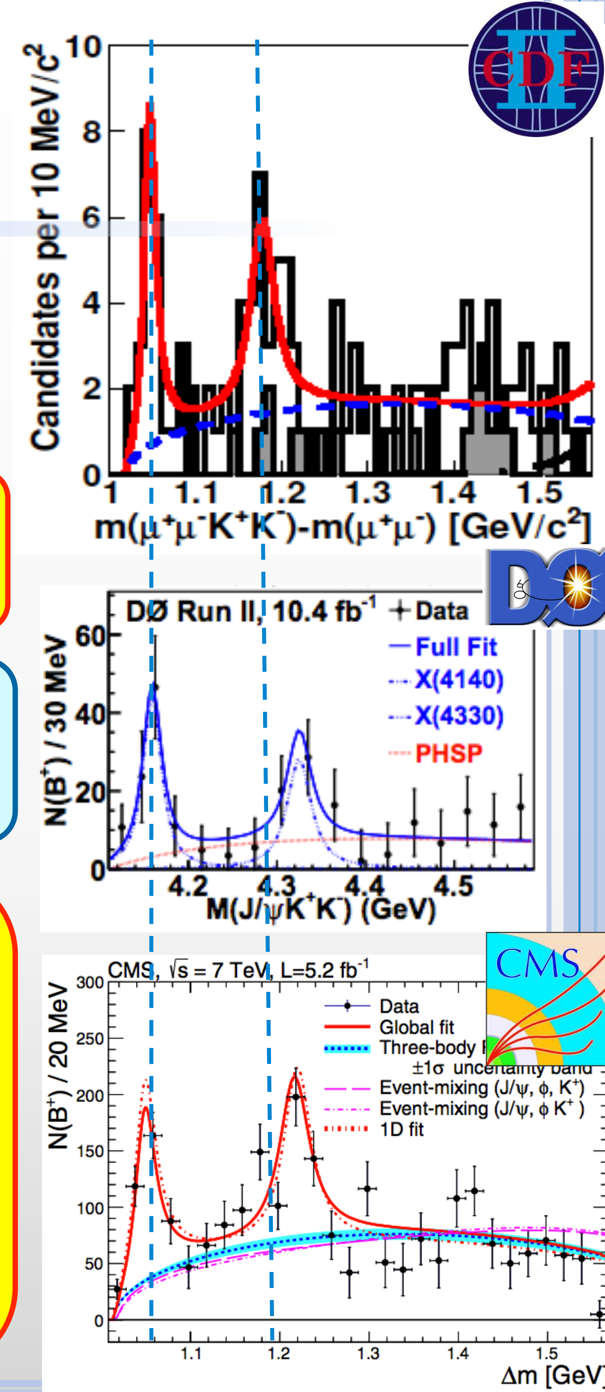
A BIT OF HISTORY

CDF: Evidence/"Observation" in $B^+ \rightarrow J/\psi\ \phi\ K^+$
[PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)	X(4274)
$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV	$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

Charmonium states with $m_X >> D_{(s)}^{(*)} D_{(s)}^{(*)}$ should decay easily into D mesons. The narrow widths hint that their nature is different: meson-meson, hybrid, tetraquark …

- Belle: No evidence of X(4140) in $\gamma\gamma \rightarrow J/\psi\ \phi$. Observation of a new state X(4350) **[PRL 104, 112004 (2010)]**
- D0: "Threshold enhancement consistent with the X(4140) (3.1σ) …Second structure consistent with X(4350)" **[PRD89 012004 (2014)]**
- CMS: Peak in $J\psi\ \phi$ consistent with X(4140). Evidence of a 2^{nd} peak affected by reflections **[PLB 734 (2014) 261]**
- BaBar: No evidence of X(4140)/X(4274) **[arXiv: 1407.7244]**



Search for X(4140)/X(4270) at LHCb

- According to the CDF results, 35 ± 11 X(4140) signal candidates and 53 ± 19 X(4274) signal candidates expected
- No narrow structure is observed near the threshold
- The LHCb results disagree at 2.4σ level with the CDF measurement

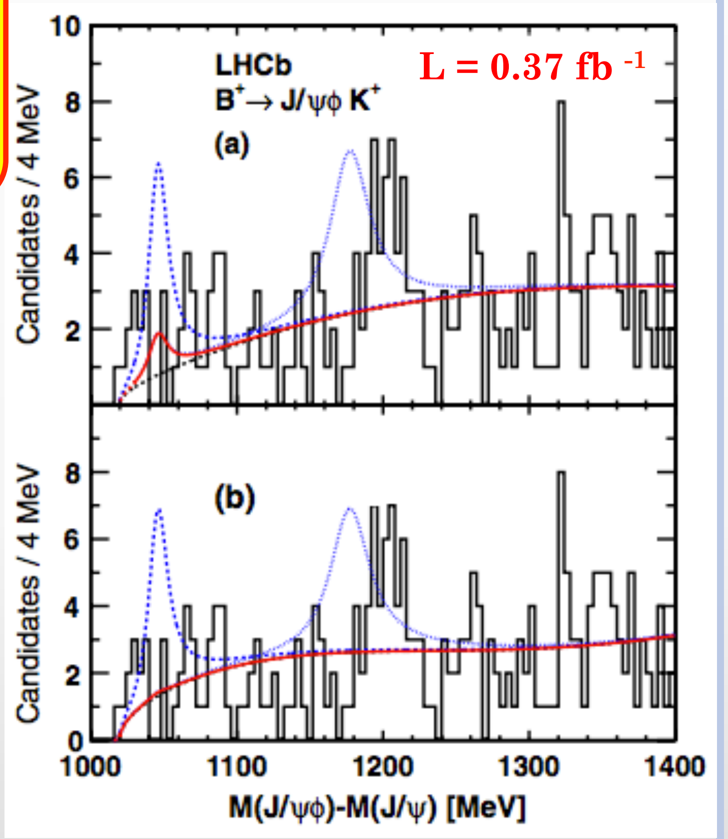
LHCb(90%) C.L.

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

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

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

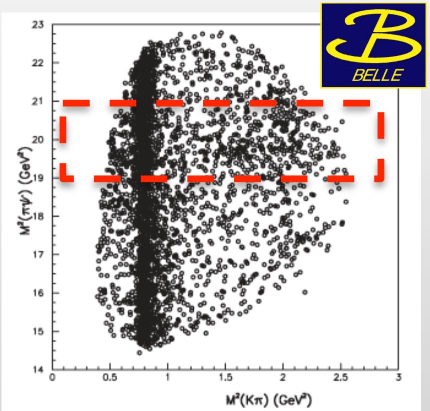
[LHCb, PRD 85, 091103(R) (2012)]

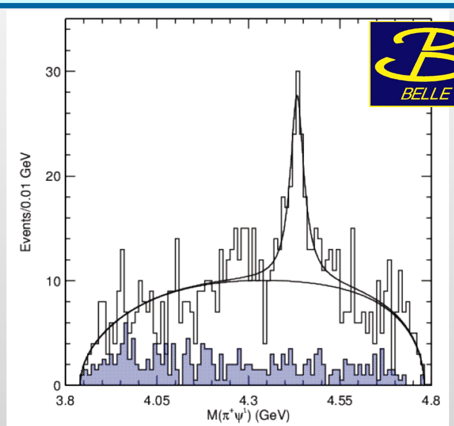


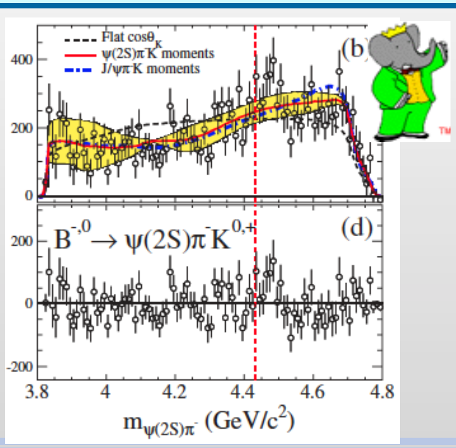
$Z(4430)^{+}$

$Z(4430)^+$

- Observed in the $\psi(2S)\pi^+$ in $B^{0(+)} \to \psi(2S)\pi^+ K^{-(0)}$ decays by Belle **[Belle, PRL100, 142001 (2008)]**
- Clear signature of exotic:
  - Decay to charmonium $\to c\bar{c}$ pair content
  - Electric charged $\to$ at least 2 more light quarks $N_{quarks} >= 4$!
  - Tetraquark, $D^* D_1$ molecule?
- Later 2D "Dalitz" technique: $M^2(\psi(2S)\pi^+)$ vs $M^2(K^-\pi^+)$ **[Belle, PRD 80, 031104 (R) (2009)]**
- $Z(4430)^+$ not confirmed (nor excluded) by BaBar: Investigation the extent to which reflection of the $K\pi$ mass and angular structures are able to reproduce the $\psi(2S)\pi$ mass distributions **[BaBar, PRD 79, 112001 (2009)]**
- Belle presented results of a full 4D amplitude analysis. $J^P = 1^+$ favoured but $J^P = 0^-$ not excluded **[Belle, PRD 88 (2013) 074026]**



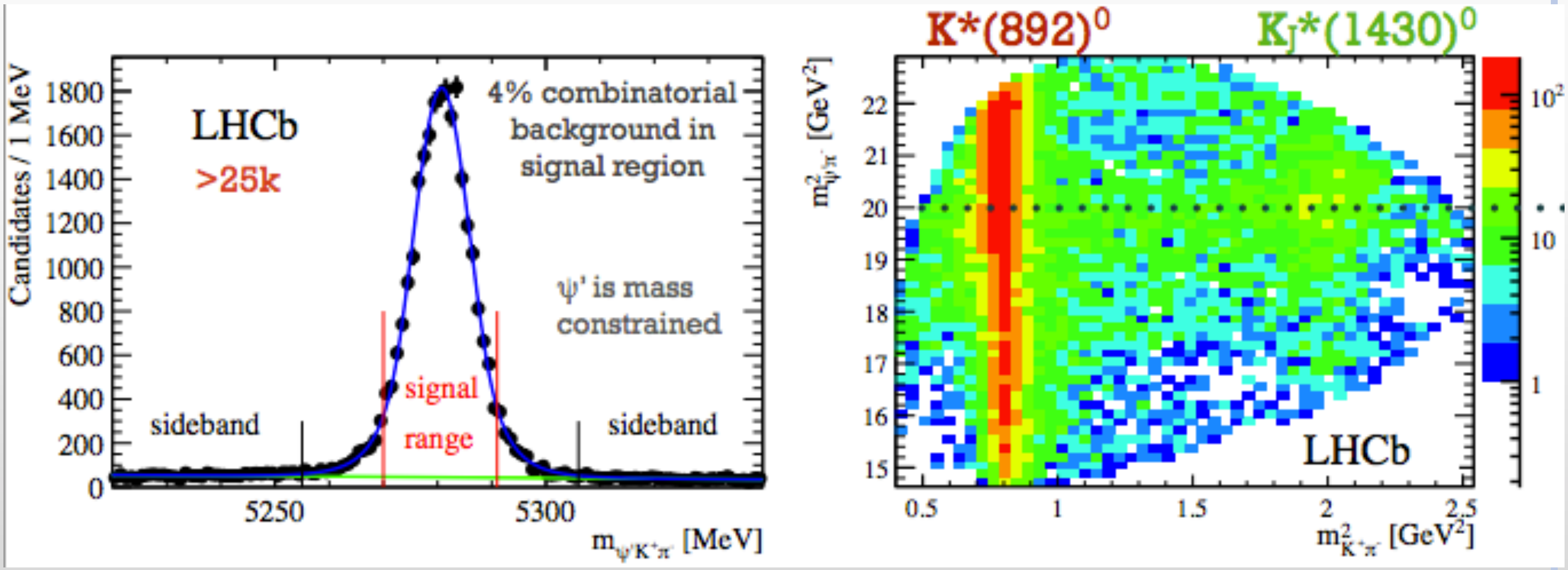




CONFIRMATION OF Z(4430)$^+$

[PRL 112, 222002 (2014)]

- Integrated luminosity of 3.0 fb^{-1}
- Sample of > 25k $B^0 \rightarrow \psi(2S) K^+ \pi^-$ candidates (x10 Belle/BaBar)
- Backgrounds from mis-ID physics decay is small
- Sidebands are used to build 4D model of the combinatorial background



Model Independent Analysis

[PRL 112, 222002 (2014)]

Can reflection of the structures in m(Kπ) and cos θ reproduce the m(ψ'π) distribution?

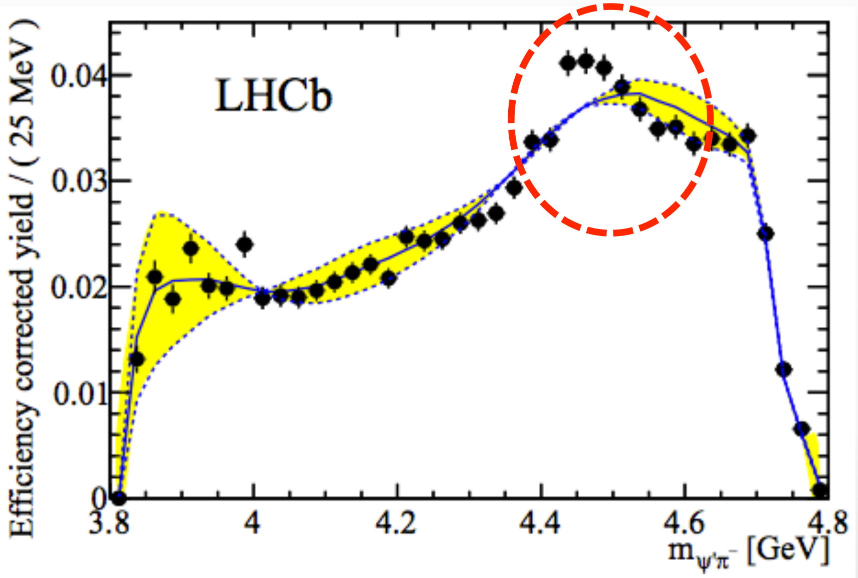
[S.U.Chung, Phys. Rev. D56, 7299(1997)]

$$I(\theta) = \sum_L \langle Y_L^0 \rangle Y_L^0 = \frac{1}{\sqrt{4\pi}}\langle Y_0^0\rangle + \sqrt{\frac{3}{4\pi}}\langle Y_1^0\rangle \cos\theta + \sqrt{\frac{5}{4\pi}}\langle Y_2^0\rangle\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$M(\theta) = \sum_L A_L Y_L^0 \overset{Hp:\,L_{max}=1}{=} \frac{1}{\sqrt{4\pi}} S + \sqrt{\frac{3}{4\pi}} P \cos\theta$$

$$I(\theta) = |M(\theta)|^2 = \left|\frac{1}{\sqrt{4\pi}} S + \sqrt{\frac{3}{4\pi}} P \cos\theta\right|^2$$

$$\begin{cases} \sqrt{4\pi}\langle Y_0^0\rangle = S^2 + P^2 \\ \sqrt{4\pi}\langle Y_1^0\rangle = 2|S||P|\cos\phi_{SP} \\ \sqrt{4\pi}\langle Y_2^0\rangle = \frac{2}{\sqrt{5}} P^2 \end{cases}$$



- Does not make any assumption on the underlying K* resonances in the system, only restricts their maximal spin (J ≤ 2).
- Weight phase space simulated $B^0 \to \psi' K^+ \pi^-$ events with the spherical harmonic moments of cos θ_K .
- Moments of K* resonances are unable to explain observed distribution

AMPLITUDE MODEL

[PRL 112, 222002 (2014)]

Use the Isobar approach:

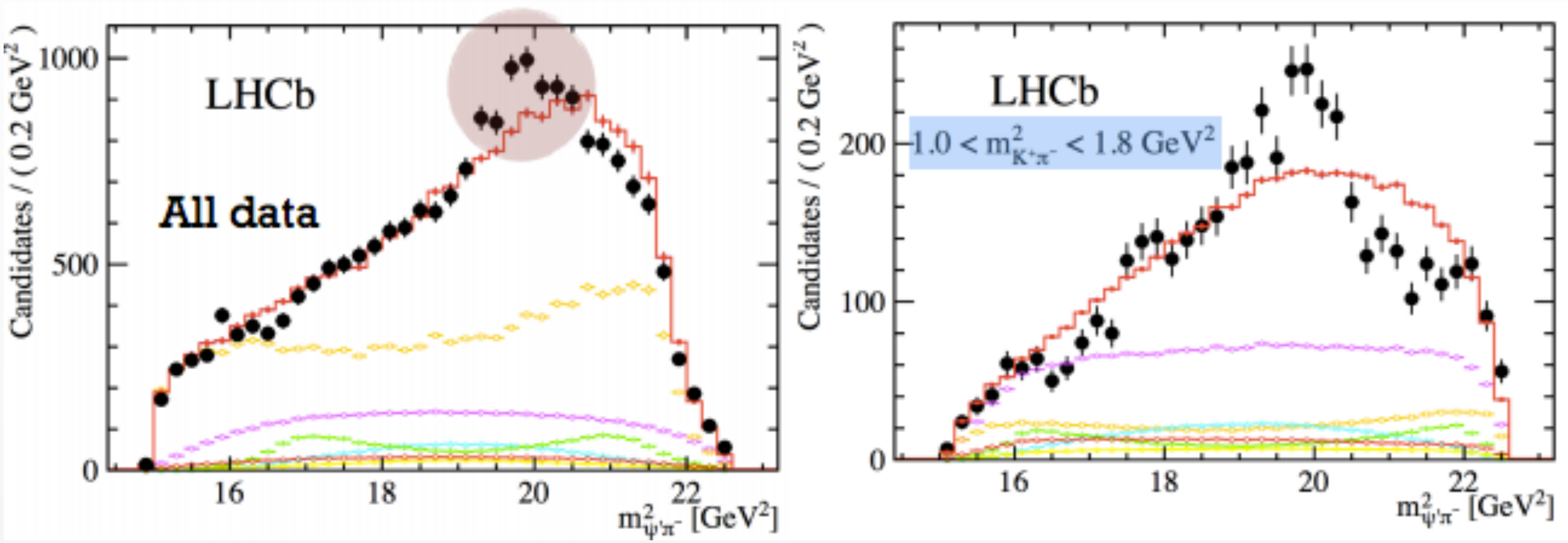
- Build amplitude from sum of two-body decays:

  $B^0 \longrightarrow \psi(2S)\ K^*(\rightarrow \pi^- K^+)$ and $B^0 \longrightarrow Z(4430)^- (\rightarrow \psi(2S)\ \pi^-) K^+$
- Overlapping and interfering Breit-Wigner resonances.
- Kπ sector:
  - Default result includes all resonances up to $K^*_1(1680)$ ($J \leq 2$).
  - Kπ S-wave: K*(800) + K*(1430) + NR (LASS as cross-check)
  - K* with J>2 for systematics

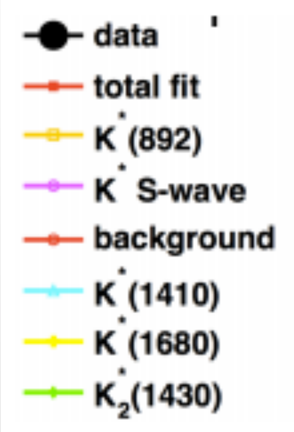
Resonance	J^P	Likely $n^{2S+1}L_J$	Mass (MeV)	Width (MeV)
$K_0^*(800)^0$ (κ)	0^+	—	682 ± 29	547 ± 24
$K^*(892)^0$	1^-	1^3S_1	895.94 ± 0.262	48.7 ± 0.7
$K_0^*(1430)^0$	0^+	1^3P_0	1425 ± 50	270 ± 80
$K_1^*(1410)^0$	1^-	2^3S_1	1414 ± 15	232 ± 21
$K_2^*(1430)^0$	2^+	1^3P_2	1432.4 ± 1.3	109 ± 5
$B^0 \to \psi(2S)K^+\pi^-$ 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

PROJECTIONS OF 4D AMPLITUDE FIT WITHOUT Z(4430)$^+$

[PRL 112, 222002 (2014)]



- Determine goodness-of-fit from 4D χ^2.
- The χ^2 p-value $< 2 \times 10^{-6}$.
- The data cannot be adequately described only using $J \leq 3$ K* contributions.

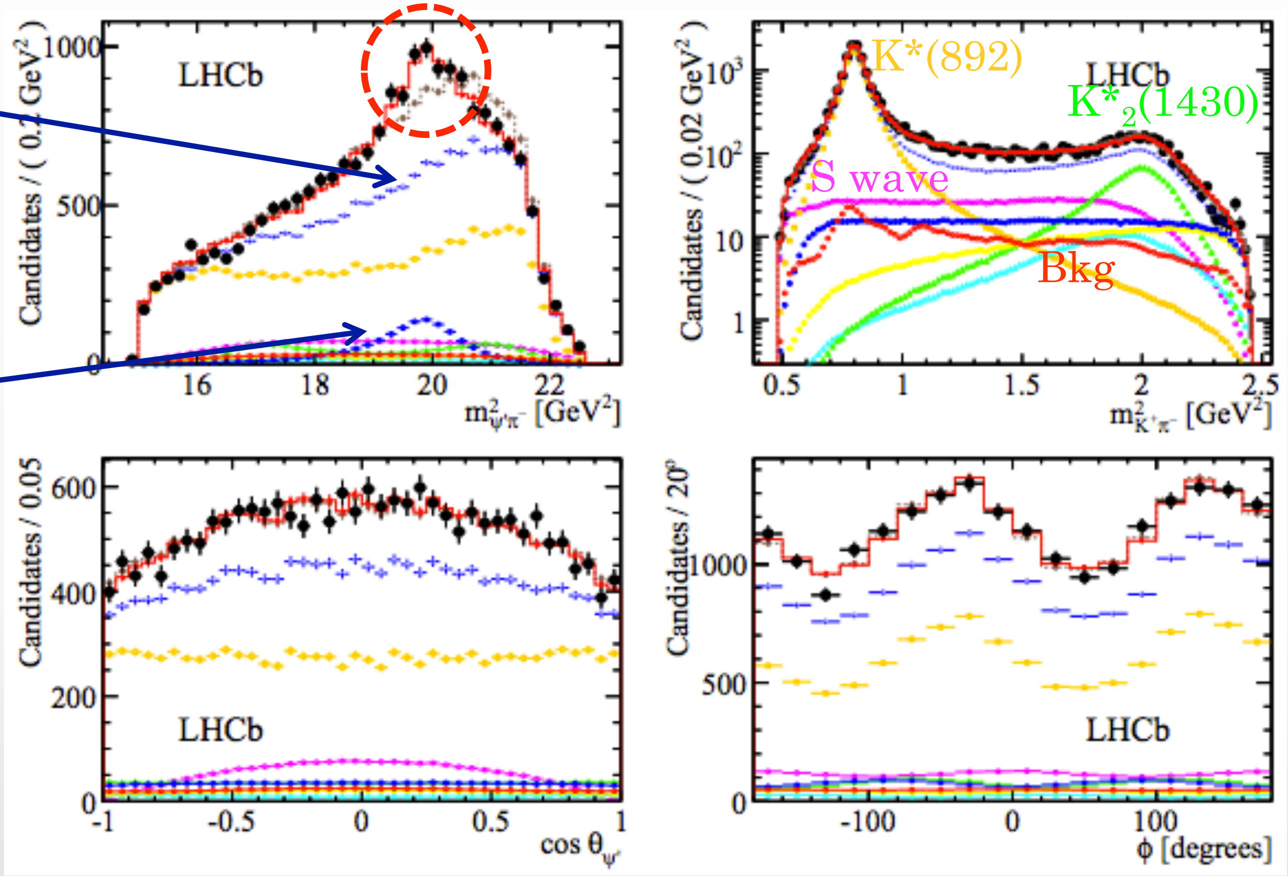


Projections of 4D Amplitude Fit with Z(4430)$^+$

[PRL 112, 222002 (2014)]

Everything except the Z →large interference between Z and Kπ sector

$J^P = 1^+$ 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

[PRL 112, 222002 (2014)]

	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	$10.3^{+3.0}_{-3.5}$

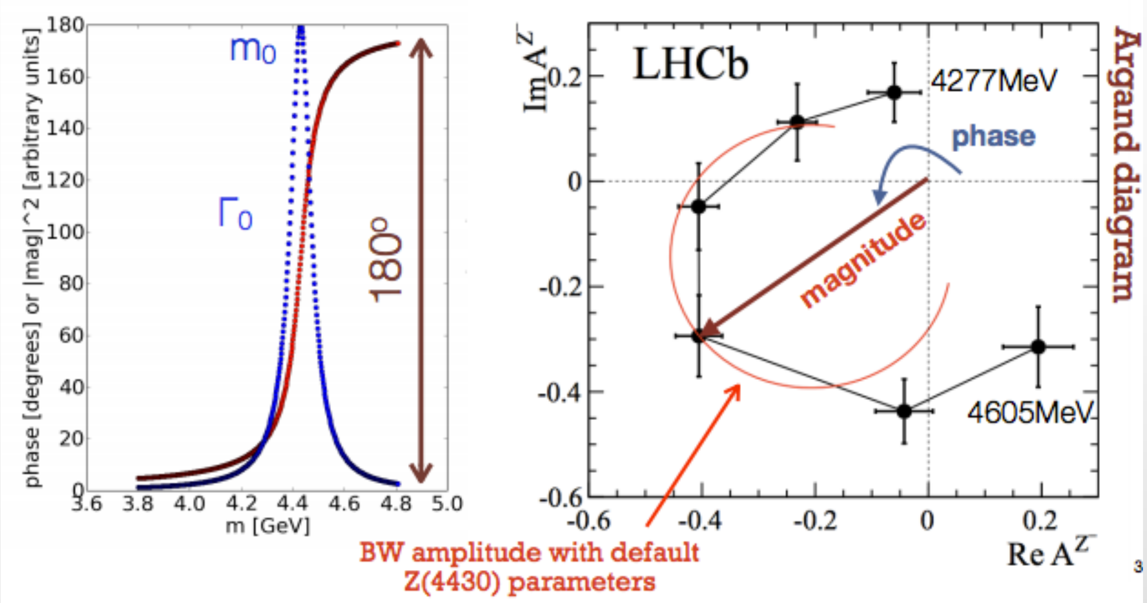
Very good agreement between LHCb/Belle results

Resonant Behaviour – a bound state?

[PRL 112, 222002 (2014)]

Replace BW amplitude with 6 independent complex numbers in 6 bins of m(ψ'π) in region of Z(4430) mass peak.

- Allows Z(4430) shape to be constrained only by amplitudes in Kπ sector.
- Observe rapid change of phase near maximum of magnitude ⇒ resonance!



Still room for non-resonant interpretation?

[P.Pakhlov, T.Uglov, arXiv: 1408.5295]

Second Exotic Z^+?

[PRL 112, 222002 (2014)]

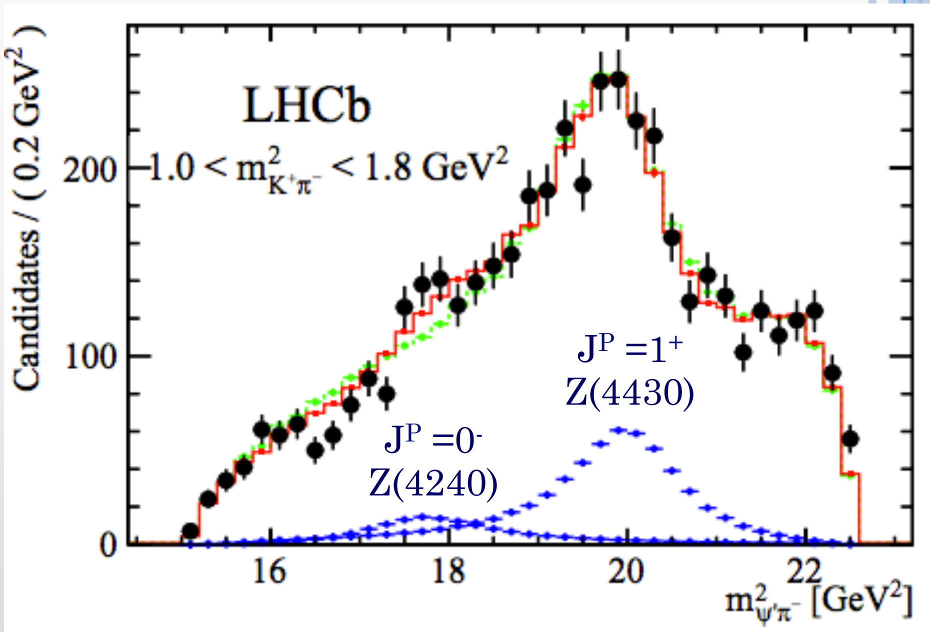
Fit confidence level increases with a second exotic ($J^P=0^-$) component, but…

- No evidence for Z_0 in model independent approach.
- Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterize this state.

$$M_{Z_0} = 4239 \pm 18^{+45}_{-10}\,\mathrm{MeV}$$

$$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}\,\mathrm{MeV}$$

$$f_{Z_0} = (1.6 \pm 0.5^{+1.9}_{-0.4})\%$$



Mass and width consistent with other Z's observed by Belle:

- $Z^- \rightarrow \chi_{c1}\pi^-$ ($J^P \neq 0^-$) [PRD 78 (2008) 072004]
- $Z^- \rightarrow J/\psi\pi^-$ [arXiv: 1408.6457]

Conclusion

- *X(3872)*
  - ✓ Elusive nature despite the world wide efforts
  - ✓ Radiative decays ruled out the interpretation of a pure DD* molecule
- *X(4140)/X(4274)*
  - ✓ No evidence of such states/structures in L=0.36 fb^{-1}
  - ✓ But much larger dataset on tape
- *Z(4430)*$^{+}$
  - Confirmation of $Z(4430)^{+}$
  - Resonant behaviour shown
  - $J^{P} = 1^{+}$ established → Disfavor the interpretation as a $D^{*}D_{1}$ molecule or cusp. Tetraquark scenario still standing

    [Maiani et al, arXiv:1405.1551]
  - Amplitude fit model accommodates a 2nd Z but more studies are required

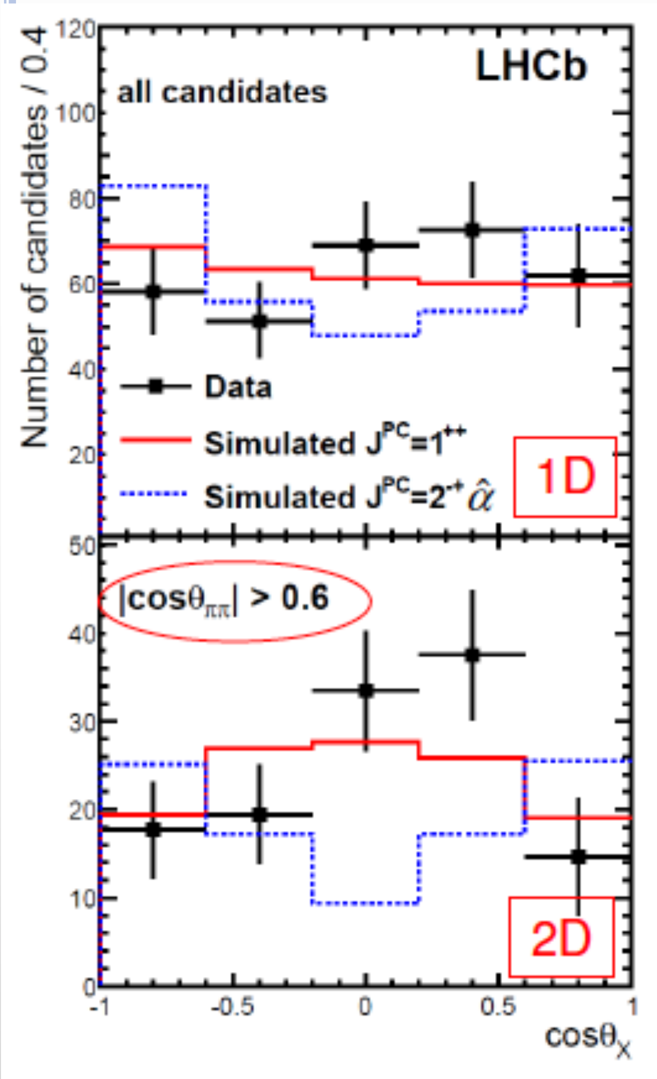
Conclusion (2)

- ***List of charmonium-like states is getting longer and longer***
- ***Plan to study them in b-hadron decays because of their broad widths or because they have been observed in such decays***
- ***Amplitude analyses are time consuming due to presence of vectors in the decays products but needed to establish the resonant character/quantum numbers***
- ***Excited prospects ahead due to the upcoming data taking!*** *(RUN I + RUN II ~ 10 fb^{-1})*

Back Up

X(3872) QUANTUM NUMBERS: $J^P = 1^{++}$!

[PRL 110, 222001 (2013)]



- How important are the angular correlations?
- Projections in $\cos\theta_X$ for all background-subtracted signal candidates (top) and background-subtracted signal candidates with $|\cos\theta_{\pi\pi}| > 0.6$ (bottom)
- Little discrimination between $J^{PC} = 1^{++}$ (red), $J^{PC} = 2^{-+}$ (blue) without using correlations.