XYZ spectroscopy at LHCb

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On behalf of the LHCb collaboration

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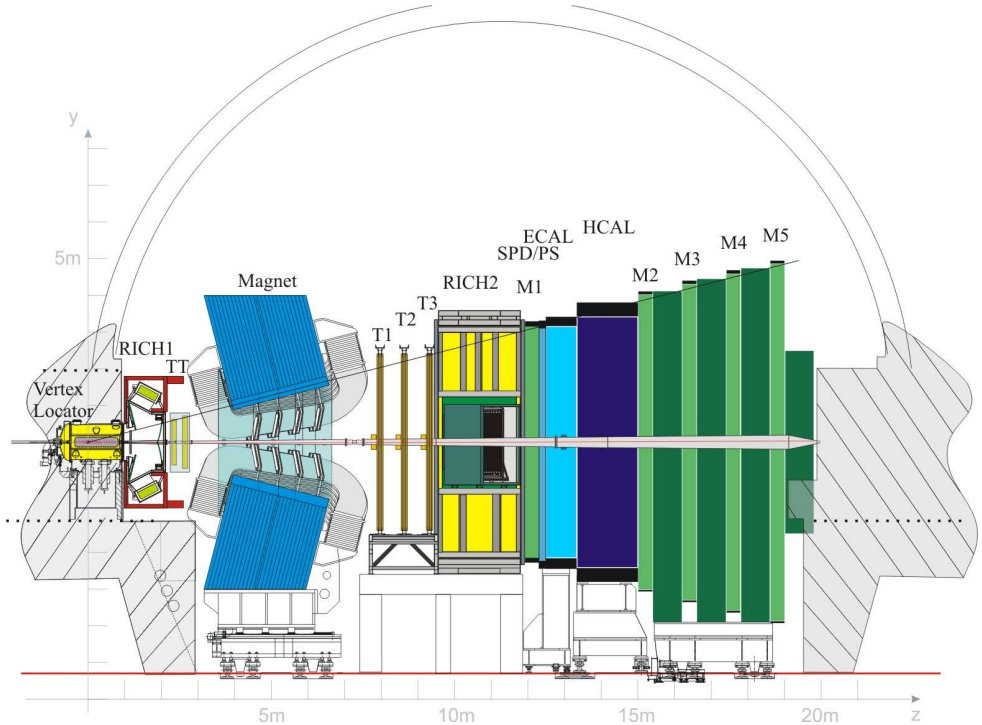
Outline

- The LHCb experiment
- $X(3872)$ studies
  - mass
  - production cross-section
  - search for $X(3872) \to p\bar{p}$
  - quantum numbers
- Search for the $X(4140)$ and $X(4274)$
- Conclusion

The LHCb experiment

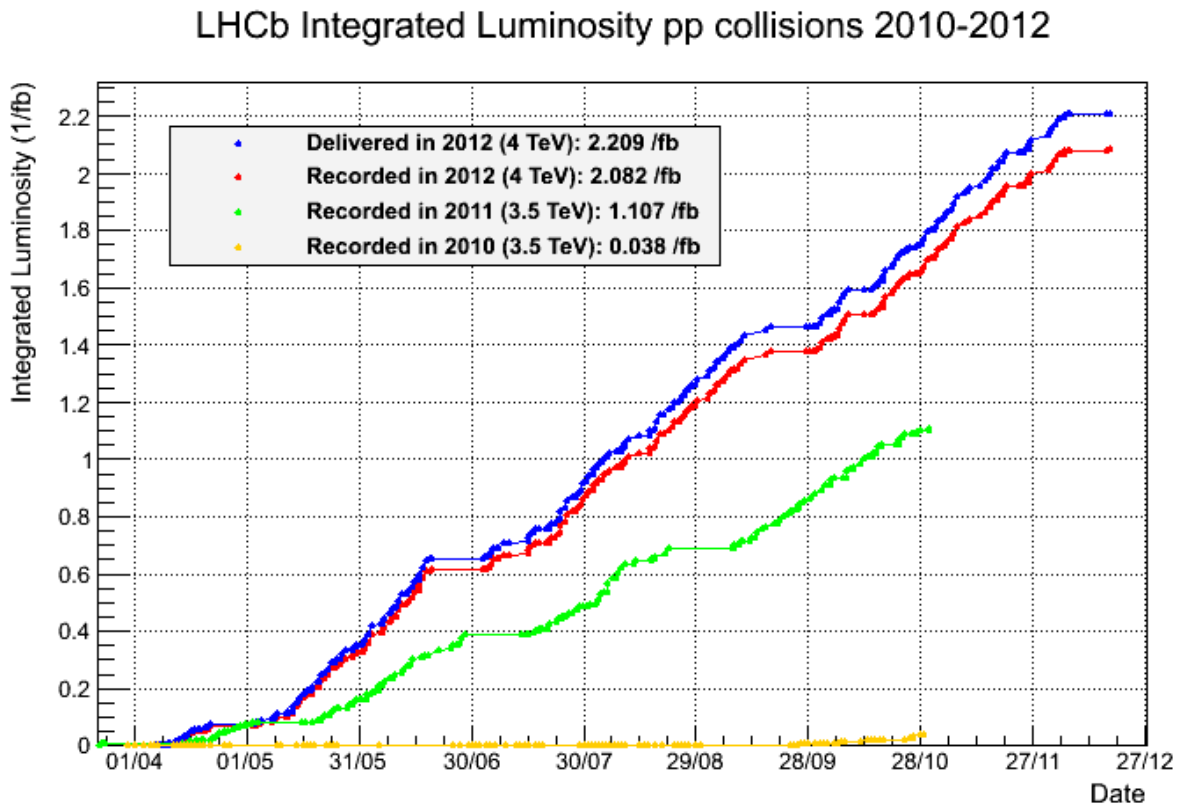
- Forward single arm spectrometer: large and correlated $b\bar{b}$ quark production in the forward region
- Coverage from the beam line: 15-300 mrad



- Mainly dedicated to heavy quark physics:
  - **CP violation** studies, measurement of the CKM parameters
  - **Rare decays**: e.g. $B_s \to \mu\mu$ decay channel studies
  - **Production and spectroscopy**: J/ψ, $\psi(2S)$ production and polarization studies, exotic mesons and baryons searches...

Status

- LHCb is in very good shape:
  - 37 pb^{-1} at $\sqrt{s} = 7$ TeV recorded in 2010
  - 1.1 fb^{-1} at $\sqrt{s} = 7$ TeV in 2011
  - 2 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012



Exotic mesons

In recent years, new exotic mesons have been observed by different experiments:

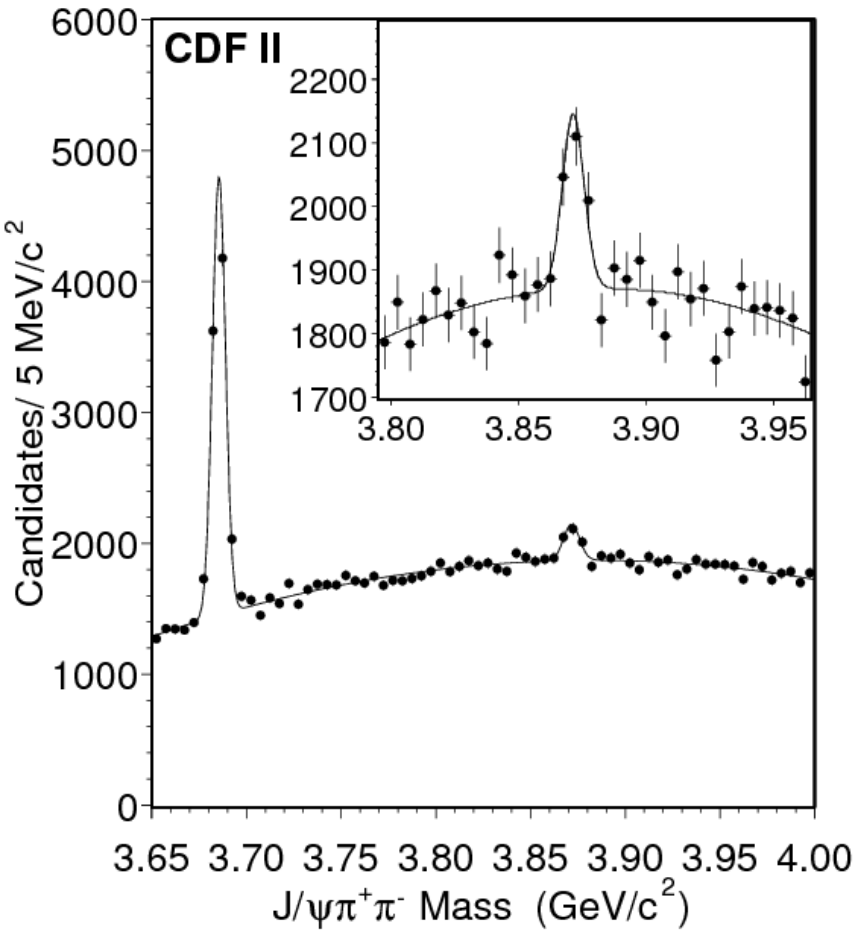
- $X(3872)$, $X(4140)$, $Z^{\pm}(4430)$...
- First assigned to $c\bar{c}$ charmonium states but they don't fit diquark model.
- Many models exists, all with limited success.
  - **Tetraquark:** Tightly bound four quark.
  - **Molecular state:** Loosely bound mesons with a quark/color exchange (short distance) or pion exchange (large distance).
  - **Charmonium hybrids:** States with excited gluonic degrees of freedom.
  - **Threshold effects:** Virtual states at thresholds.

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (<2.2)	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle , *BABAR*	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF, DØ		
				$B \to K(\omega J/\psi)$	Belle *BABAR*		
				$B \to K(D^{*0}\bar{D}^0)$	Belle, *BABAR*		
				$B \to K(\gamma J/\psi)$	Belle, *BABAR*		
				$B \to K(\gamma\psi(2S))$	*BABAR*, Belle		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle, *BABAR*	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle		
$X(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF	2009	NC!
$X(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF	2010	NC!
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle	2010	NC!

Taken from "Heavy quarkonium: progress, puzzles, and opportunities", arXiv:1010.5827

$X(3872)$ discovery and properties

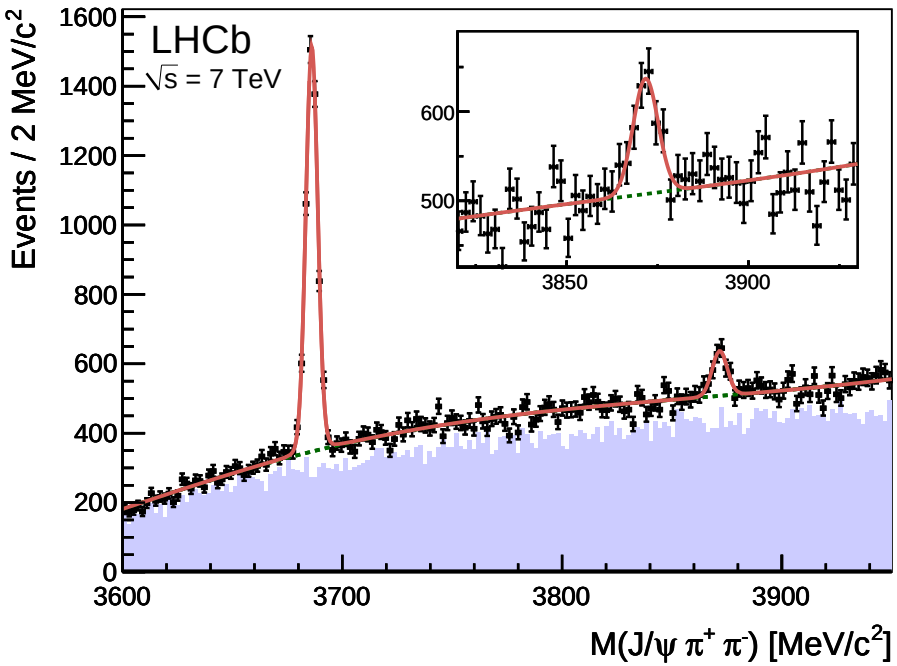
- First exotic meson observed.
  - Discovered in $B^{\pm} \to K^{\pm} X(3872)(\to J/\psi\pi^+\pi^-)$ by Belle in 2003 (*PRL 91:262001 2003*)
  - Confirmed by CDF in 2004
  - Confirmed by Babar in 2008
- Most abundant exotic state:
  - Already well studied:
    - ★ Di-pion mass spectrum studied by CDF
    - ★ Quantum numbers constrainted to be $J^{PC} = 1^{++}$ or 2^{-+}
- Nature still uncertain, possible models (arXiv:1010.5827):
  - tetraquark, $D^0 D^{0*}$ molecular state with $J^{PC} = 1^{++}$
  - conventional charmonium with $J^{PC} = 2^{-+}$



PRL 93:072001, 2004 (CDF)

$X(3872)$ mass measurement EPJC 72 (2012) 1972

- With the 2010 data sample only (34.7 pb^{-1})
- In the $X(3872) \to J/\psi\pi^+\pi^-$ channel, using $\psi(2S) \to J/\psi\pi^+\pi^-$ as a control
- Inclusively reconstructed $X(3872)$ (from pp collisions and B hadron decay)



Fit parameter or derived quantity	$\psi(2S)$	$X(3872)$
Number of signal events	3998 ± 83	565 ± 62
Mass m [MeV/c^2]	3686.10 ± 0.06	3871.88 ± 0.48
Resolution σ [MeV/c^2]	2.54 ± 0.06	3.33 ± 0.08
Signal-to-noise ratio in $\pm 3\sigma$ window	1.5	0.15
Number of background events	73094 ± 282	

- May gives some hint on the nature of $X(3872)$: in the molecular state hypothesis, the mass should be below the $D^{*0}\bar{D}^0$ threshold (3871.94 ± 0.32 MeV$/c^2$)
- Systematics are dominated by momentum calibration and energy-loss corrections

Category	Source of uncertainty	Δm [MeV$/c^2$]	
		$\psi(2S)$	$X(3872)$
Mass fitting	Natural width	–	0.01
	Radiative tail	0.02	0.02
	Resolution	–	0.01
	Background model	0.02	0.02
Momentum calibration	Average momentum scale	0.08	0.10
	η dependence of momentum scale	0.02	0.03
Detector description	Energy loss correction	0.05	0.05
Detector alignment	Track slopes	0.01	0.01
Total		0.10	0.12

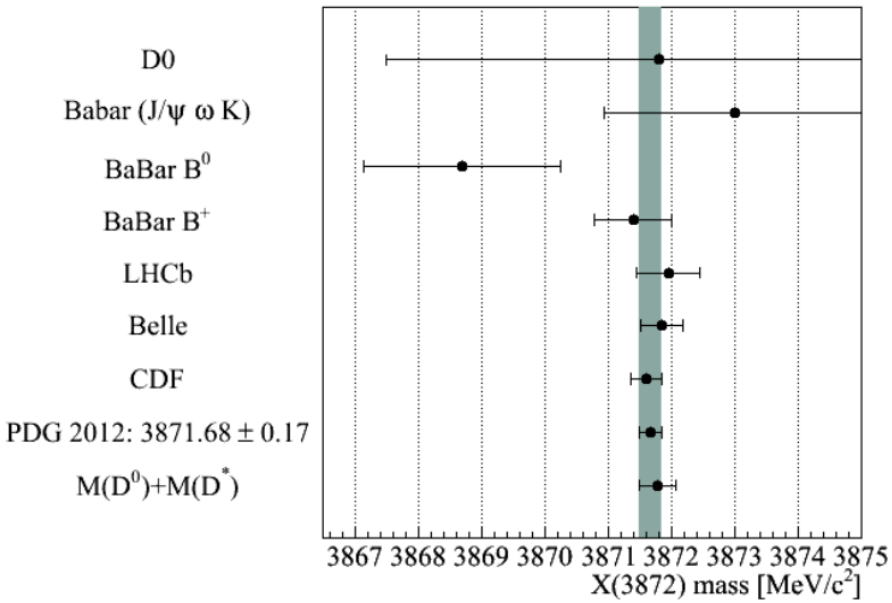
- Results (using 34.7 pb^{-1}):

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

The measurement is dominated by the statistical uncertainty. Good prospects for improvement!

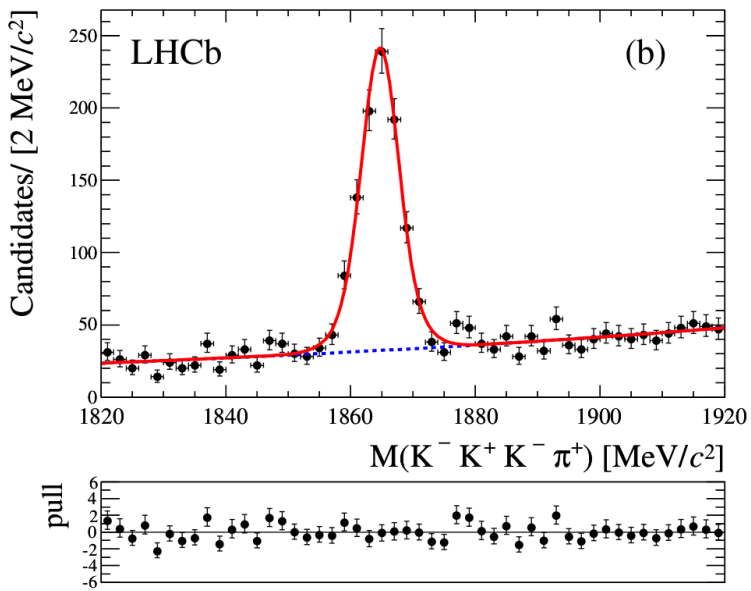
$X(3872)$ mass measurement EPJC 72 (2012) 1972

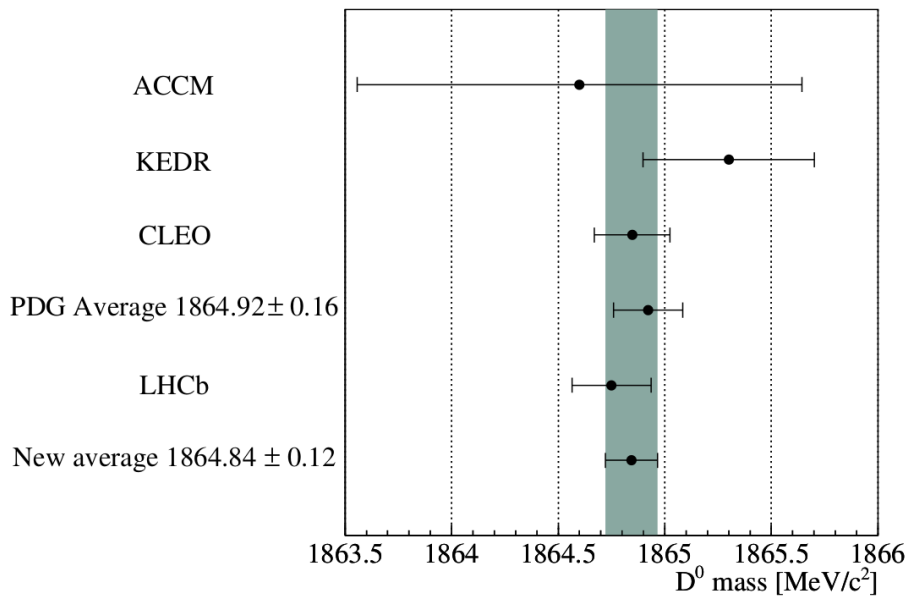
- The world average mass ($m_{X(3872)} = 3871.68 \pm 0.17$ MeV/c^2) is indistinguishable from the $D^{*0}\bar{D}^0$ threshold
- remains open if really is bound particle



- In case of a bound particle, the binding energy of the the $X(3872)$ meson is small: $E_B = 0.16 \pm 0.26$ MeV/c^2
- More precise knowledge of the D masses are needed

- Done with 1 fb^{-1} of data
- Using $D^0 \to K^-K^+K^-\pi^+$
- Result: $m_{D^0} = 1864.75 \pm 0.15$ (stat) ± 0.11 (syst) MeV/c^2





- Measurement of the $X(3872)$ cross-section $\times \mathcal{BR}(X(3872) \to J/\psi\pi^+\pi^-)$
- With the same data sample as for the mass measurement
- In the fiducial region $p_T \in [5; 20]$ GeV/c and $y \in [2.5; 4.5]$
- Inclusive cross-section, assuming a 1^{++} state
- The measured cross-section is measured through the formula:

$$\sigma_{X(3872)} \times \mathcal{BR}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{N_{X(3872)}}{\epsilon_{\rm tot} \times \mathcal{L}_{\rm int} \times \mathcal{BR}(J/\psi \to \mu^+\mu^-)}$$

  - $N_X/\epsilon_{\rm tot}$ is the efficiency corrected yield, taken from a fit
  - $\epsilon_{\rm tot}$ is the detection efficiency, taken from Monte Carlo
  - $\mathcal{L}_{\rm int} = 34.70$ pb^{-1} the integrated luminosity of the 2010 data sample used

$X(3872)$ production cross-section EPJC 72 (2012) 1972

- The systematics are dominated by the tracking efficiency and background modeling

Source of uncertainty	$\Delta\sigma/\sigma$ [%]
$X(3872)$ polarization	2.1
$X(3872)$ decay model	1.0
$X(3872)$ decay width	5.0
Mass resolution	5.8
Background model	6.4
Tracking efficiency	7.4
Track χ^2 cut	2.0
Vertex χ^2 cut	3.0
Muon trigger efficiency	2.9
Global event cuts	3.0
Muon identification	1.1
Integrated luminosity	3.5
$J/\psi \to \mu^+\mu^-$ branching fraction	1.0
Total	14.3

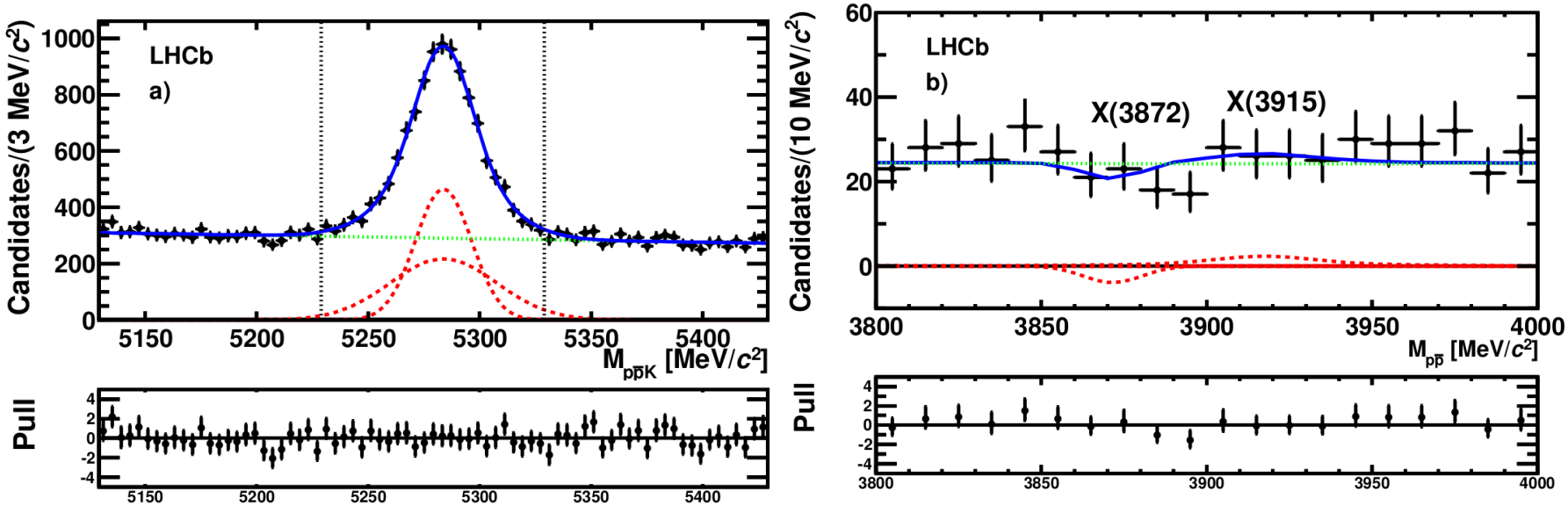
- The production cross-section:

$$\sigma_{X(3872)} \times \mathcal{BR}(X(3872) \to J/\psi\pi^+\pi^-) = 5.4 \pm 1.3\ (\text{stat}) \pm 0.8\ (\text{syst})\ \text{nb}$$

- NRQCD theory prediction is 2.4σ higher: 13.0 ± 2.7 nb (*PRD 81 (2010) 114018)*

Search for $X(3872) \to p\bar{p}$ arXiv:1303.7133

- Search for $B^+ \to X(3872)K^+$ In the $B^+ \to p\bar{p}K^+$ decay channel with 1 fb^{-1}
- $B^+ \to p\bar{p}K^+$ signal yield: 6951 ± 176
- $X(3872) \to p\bar{p}$ signal yield: -9 ± 8



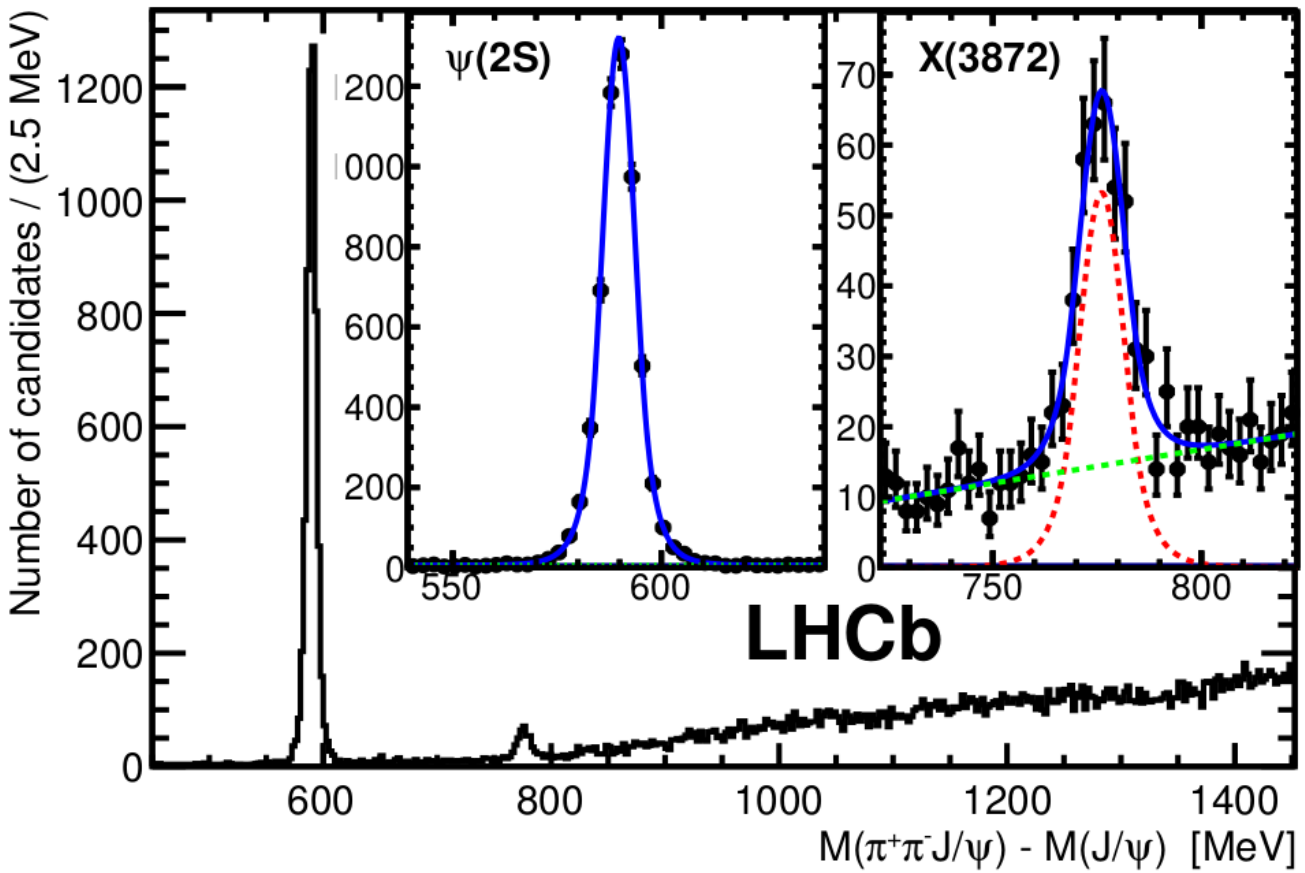
- No signal, but upper limit on the ratios:

$$\frac{BR(B^+ \to X(3872)K^+, X(3872) \to p\bar{p})}{BR(B^+ \to p\bar{p}K^+)} < 0.017$$

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

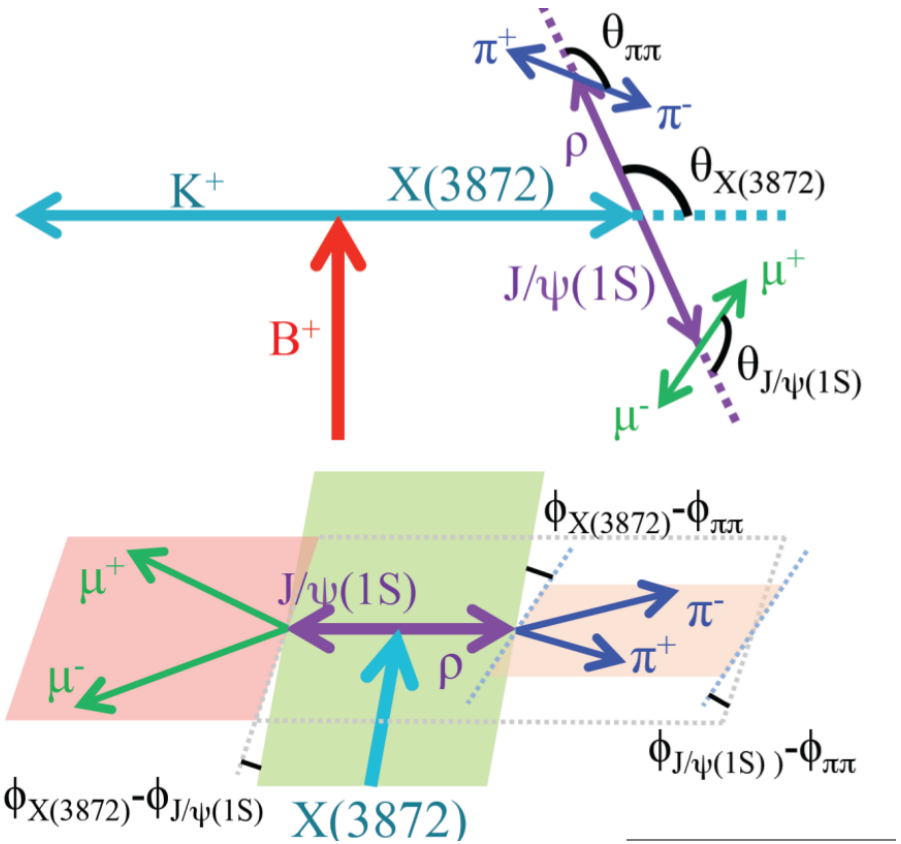
Determination of the $X(3872)$ quantum numbers arXiv 1302.6269

- The $X(3872)$ J^{PC} are determined using 1 fb^{-1} of data collected in 2011
- 313 ± 26 $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$ (568 ± 31 background)
- 5642 ± 76 $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$



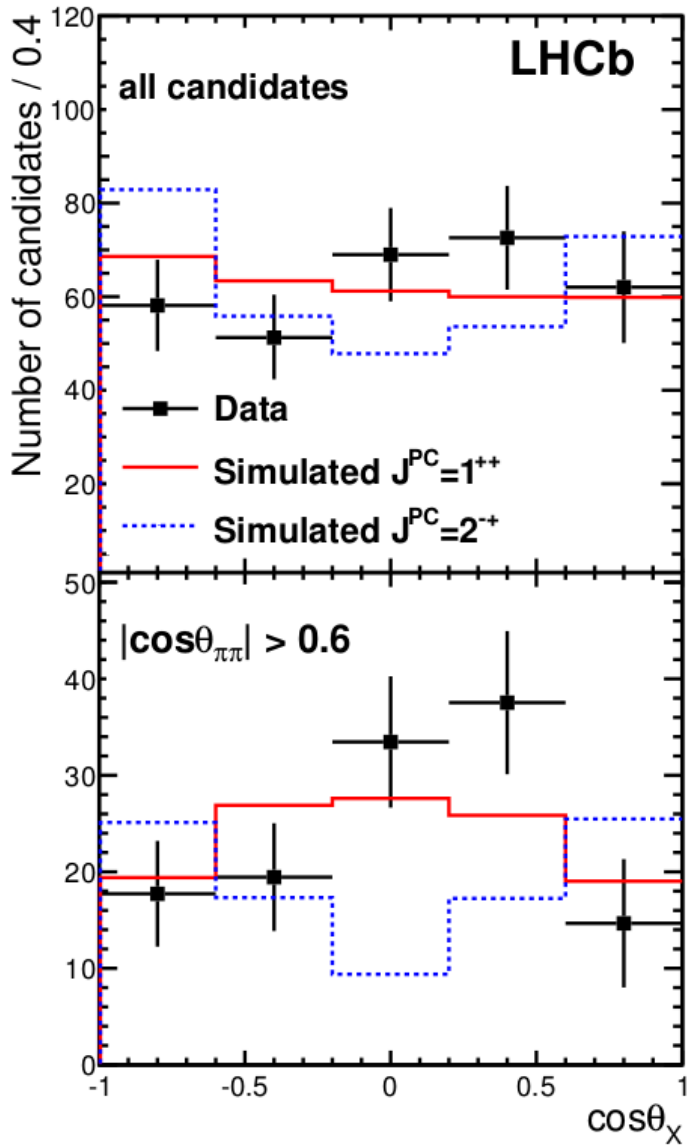
Determination of the $X(3872)$ quantum numbers arXiv 1302.6269

- Angular analysis of $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$
- The angular correlations in the B^+ decay carry information about the J^{PC} of the $X(3872)$.
- The analysis is performed in 5D considering all angular correlations



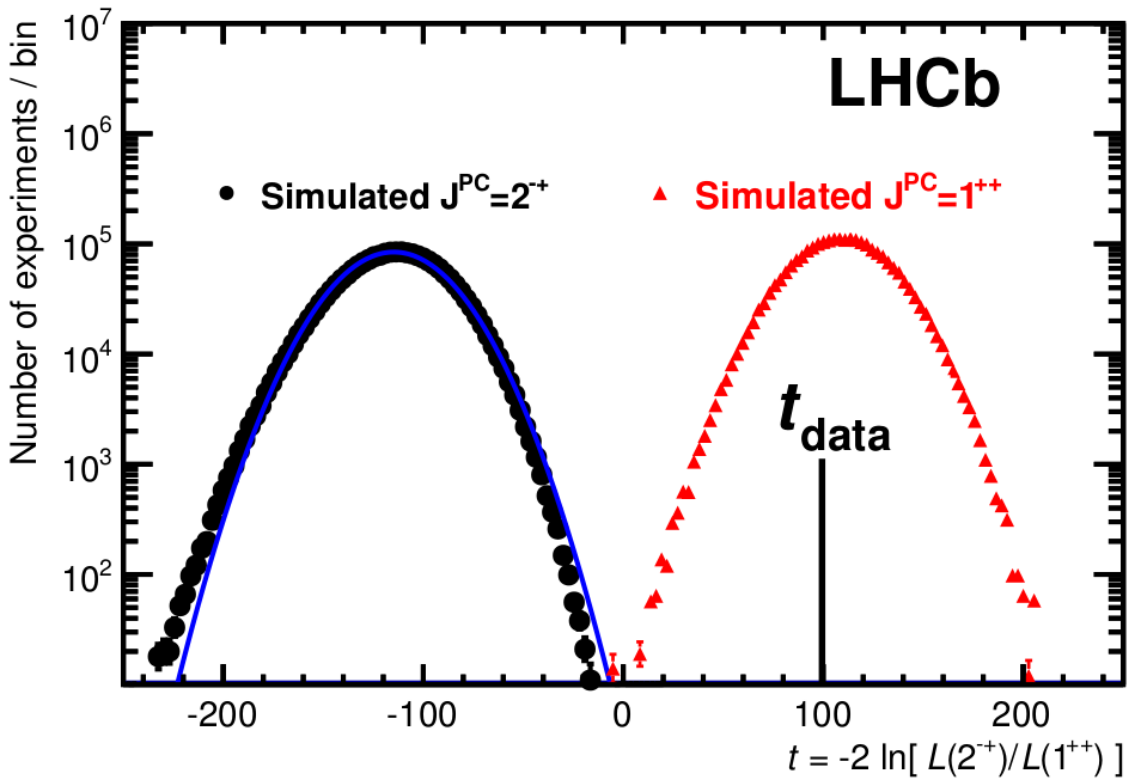
Determination of the $X(3872)$ quantum numbers arXiv 1302.6269

- Two $X(3872)$ spin configurations are considered:
- 1^{++} hypothesis: no free parameters
- 2^{-+} hypothesis: one complex parameter α accounting for the different LS combinations (L is the orbital angular momentum between the $\pi\pi$ and the J/ψ, S is the sum of their spins.)



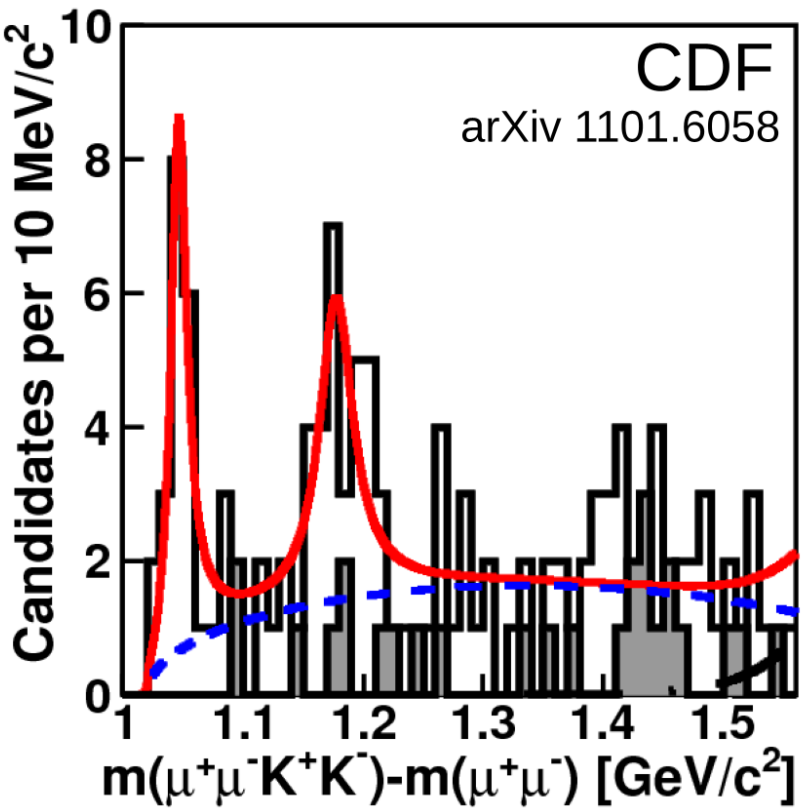
Determination of the $X(3872)$ quantum numbers arXiv 1302.6269

- Likelihood-ratio test, to discriminate between the 1^{++} and 2^{-+} assignments
  - $t > 0$ implies 1^{++} favoured
  - $t < 0$ implies 2^{-+} favoured
- Compare the results to simulated experiments, for both hypotheses
- Data favour the 1^{++} over the 2^{-+} hypothesis at 8.4σ
- This result rules out the conventional charmonium interpretations of the $X(3872)$ and favour the exotic interpretations.



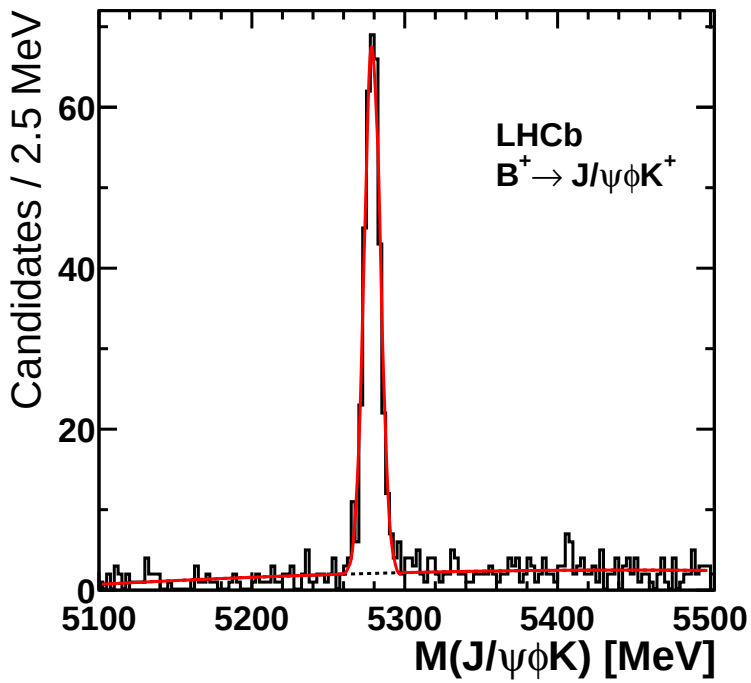
$X(4140)$ and $X(4274)$ observation

- $X(4140)$ observed by the CDF collaboration in $B^+ \to J/\psi\phi K^+$ decays (*PRL 102 (2009) 242002*)
  - $m_{X(4140)} = 4143.2^{+2-9}_{-3.0} \pm 0.6$ MeV/c^2
  - $\Gamma_{X(4140)} = 15.3^{+10.4}_{6.1} \pm 2.5$ MeV/c^2
- 3.8 σ evidence for a narrow $J/\psi\phi$ resonance
- Candidate for exotic bounds state
- Second state suggested by Tevatron data, at a mass of 4274.4±8.4±1.9 MeV/c^2 and a width of 32.3±21.9±7.6 MeV/c^2 (*arXiv 1101.6058*)



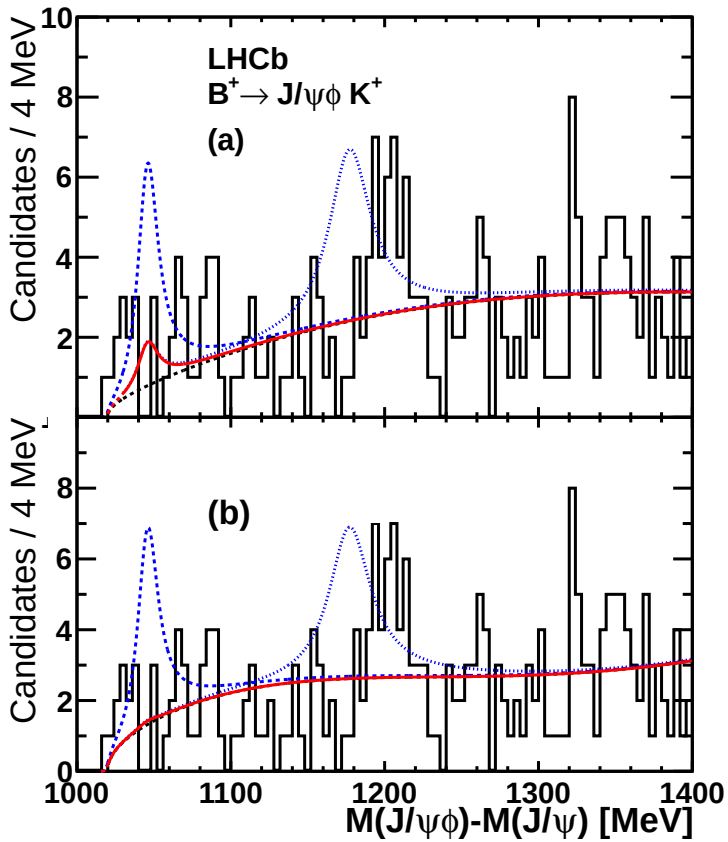
Search for $X(4140)$ and $X(4274)$ at LHCb PRD 85 (2012) 091103(R)

- The search is performed at LHCb using 0.37 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV
- 382 ± 22 $B^+ \to J/\psi\phi K^+$ reconstructed (6.2 times more than at CDF in 6 fb^{-1})
- The expected yields using CDF results:
  - $35\pm9\pm6$ for the $X(4140)$
  - 53 ± 19 for the $X(4274)$



Search for $X(4140)$ and $X(4274)$ at LHCb PRD 85 (2012) 091103(R)

- Signal: spin-zero relativistic Breit-Wigner shape
- Two background parametrizations are used:
  - (a) Three-body background phase-space function (as used by CDF):
    - ★ $N_{X(4140)} = 6.9 \pm 4.9$
    - ★ $N_{X(4274)} = 3.4^{+6.5}_{-3.4}$
  - (b) Efficiency corrected quadratic function that gives zero signal event for both states.



Search for $X(4140)$ and $X(4274)$ at LHCb PRD 85 (2012) 091103(R)

- Since no evidence for the $X(4140)$ and $X(4274)$ states are found, 90% C.L upper limits are set on their production:

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

and

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

- CMS performed a similar analysis and obtained different results (see next talk for more details)
- A 5D amplitude analysis is needed to understand what is in the Dalitz plot (*e.g.* reflections from excited K* states)

Conclusion

- The LHCb exotic mesons measurements are rich and promising
- Study of the $X(3872)$:
  - mass
  - production cross-section
  - determination of the quantum numbers
- No confirmation of the $X(4140)$ and $X(4274)$ existence
- Studies are in progress:
  - Search of the $Z(4430)^{\pm}$
  - More studies on the $X(3872)$: updated mass and production cross section, natural width, decay modes...
  - $B^+ \to J/\psi\phi K^+$ amplitude analysis
  - Search for other states