XYZ states at LHC

Results and prospects

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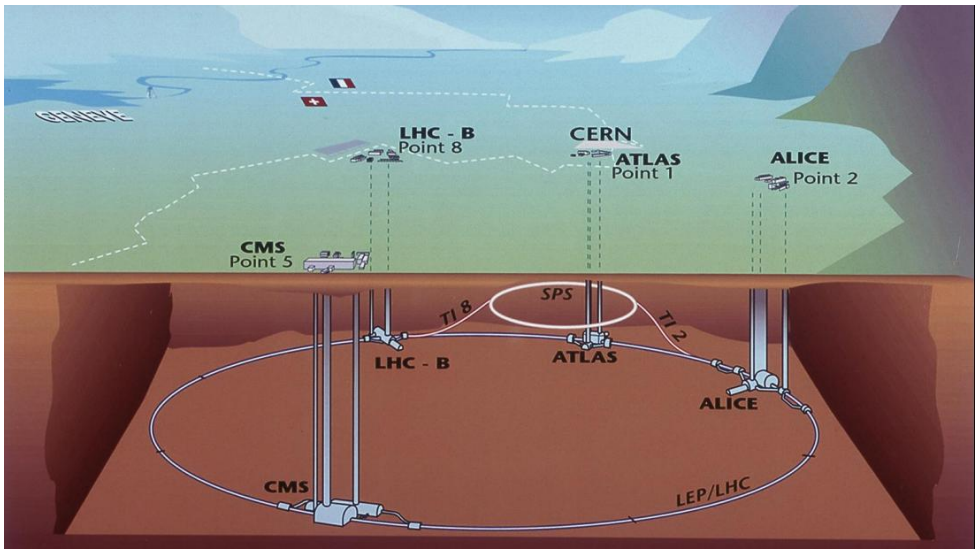
Outline

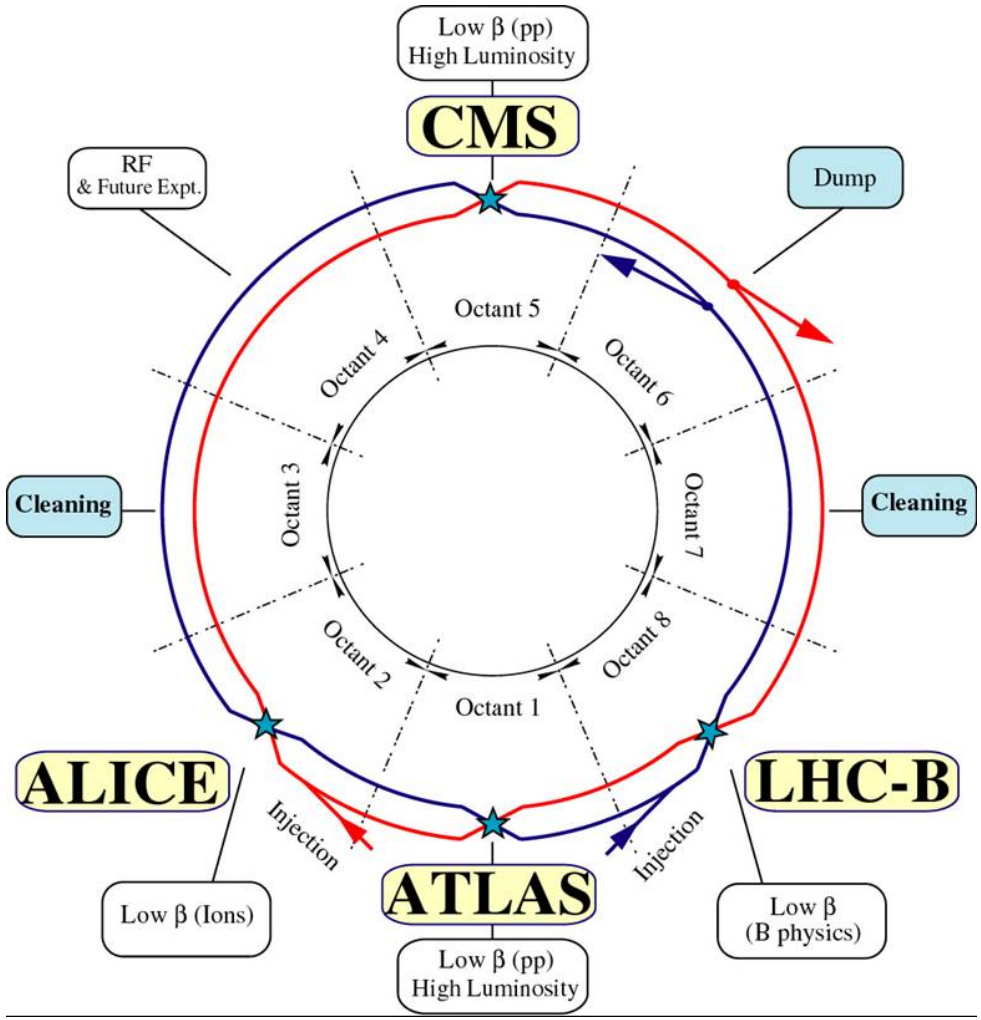
1. The LHC accelerator and its detectors
2. The LHCb detector, its trigger and dataset
3. Exotic charmonium-like candidates at LHC
4. Results on $\mathrm{X}(3872)$ at LHCb and CMS
5. Results on $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$
6. Prospects for $Z(4430)^{+}$
7. Conclusions

The LHC accelerator and its detector

The LHC is designed to collide two high luminosity and energy counter rotating beams of protons or heavy ions.

- Two general proposal high luminosity experiments: CMS and ATLAS
- One low luminosity experiment, dedicated to flavour physics experiment: LHCb
- Heavy-ion experiment: ALICE



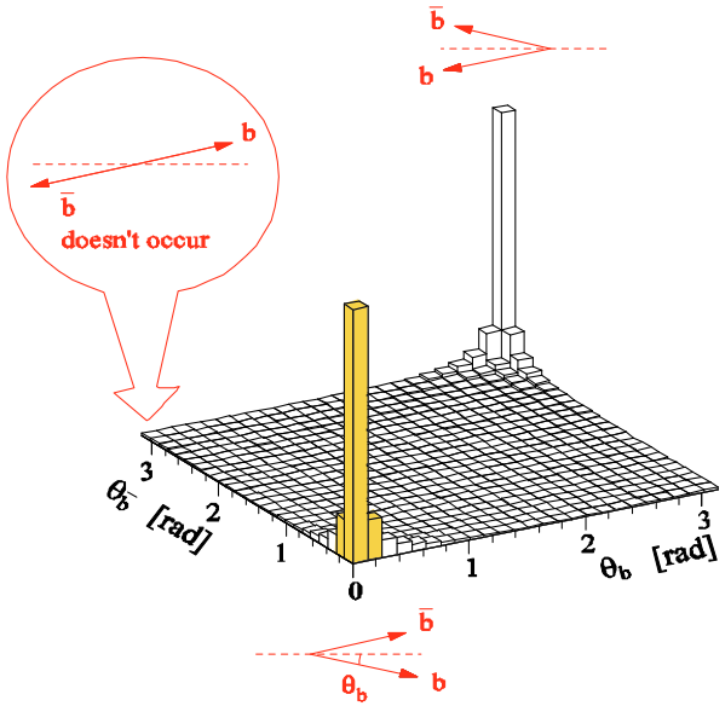


The LHC environment

During most of 2011, LHC collided protons at 7 TeV with instantaneous luminosity up to $2 \times 10^{35} cm^{-2} s^{-1}$ and 20 MHz of bunch crossing.

At these conditions:

- Inelastic cross section $\sim 60\,\mathrm{mb}$
- $\sigma(\mathrm{pp} \to \mathrm{b\bar{b}}X) =$
  $(288 \pm 4(\mathrm{stat}) \pm 48(\mathrm{syst}))\ \mu\mathrm{b}$
  [Eur.Phys.J.C (2011)71:1645]
- $\Longrightarrow$ $\sim 10^6$ $\mathrm{B\bar{B}}$ pairs per second

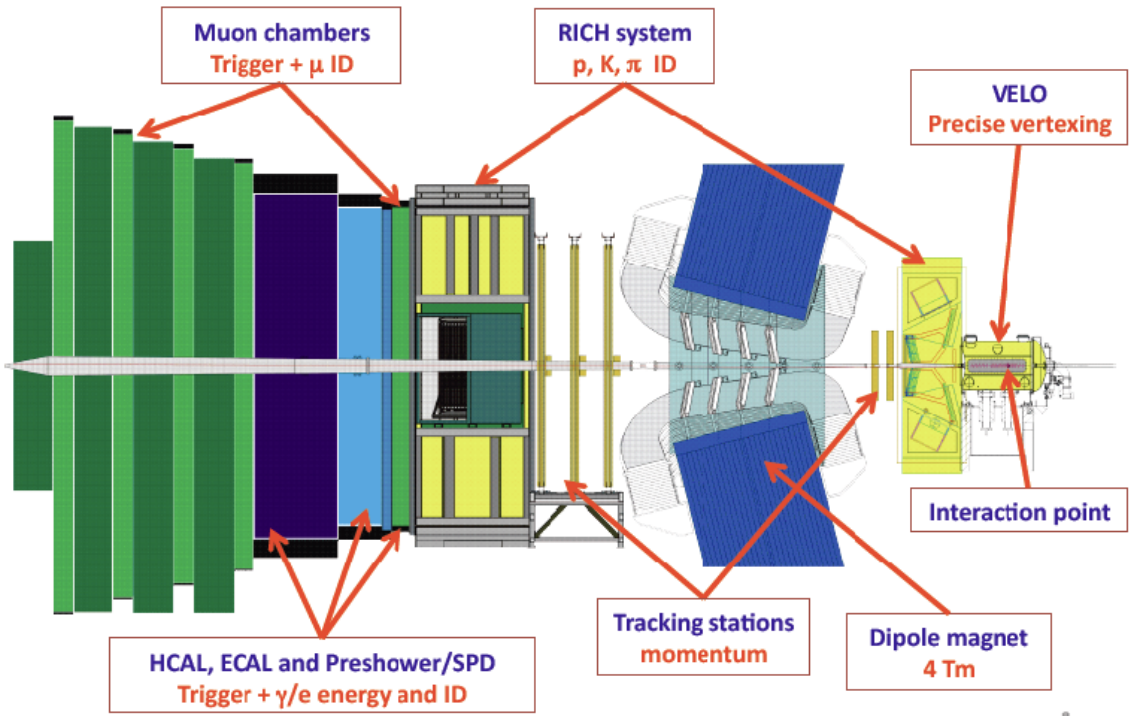


At the LHC energy, the $\mathrm{b\bar{b}}$ pairs are produced preferentially at forward (backward) directions.

- 4π acceptance design is not optimal
- Optimal solution is a forward detector: LHCb

The LHCb detector

LHCb experiment was designed to perform high precision flavor physics measurements in the LHC.



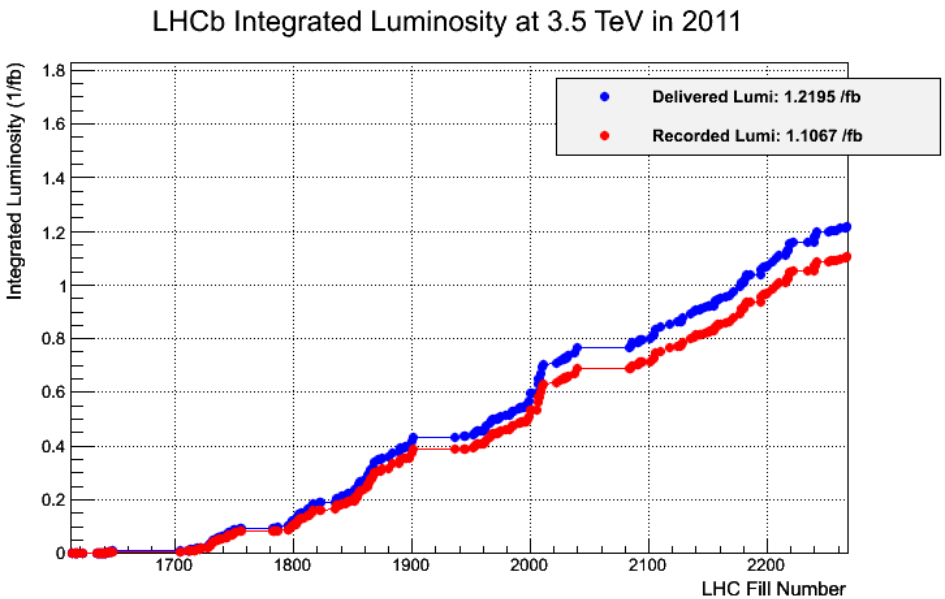
- **Single-arm design.** Covering the range $2 < \eta < 5$, LHCb can exploit the dominant heavy flavour production mechanism at the LHC and detects $\sim$ 40% of the differential $\mathrm{b\bar{b}}$ cross-section.
- **Good particle identification.** Excellent muon identification and good separation of π, K and p over (2 - 100) GeV.

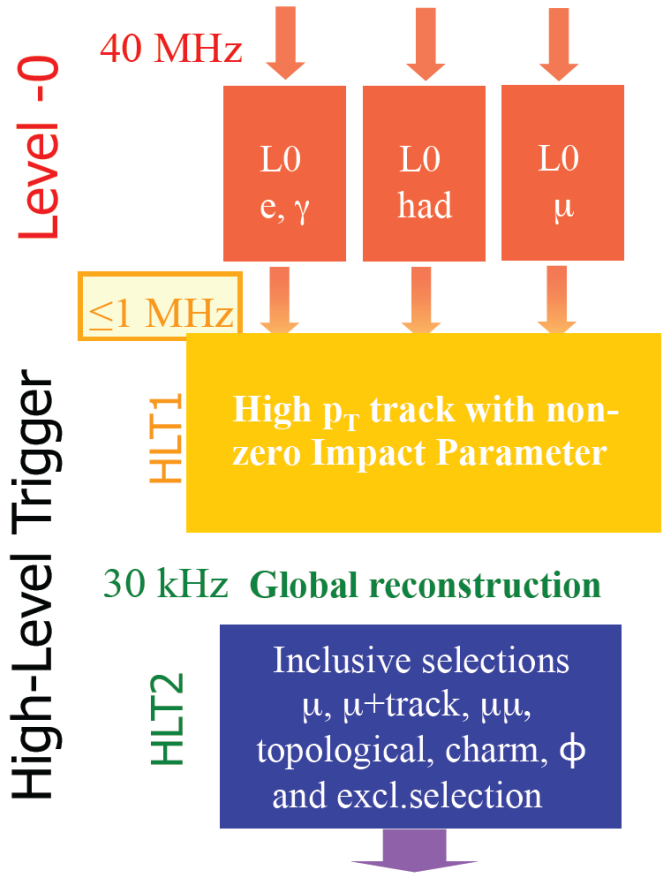
- **Good vertexing and tracking.** Precise primary and secondary vertex reconstruction. Excellent momentum, IP and proper time resolution.

The LHCb trigger and dataset

Running conditions in the second half of 2011

- LHC: 1092 - 1380 bunches/beam with 50 ns of separation
- Luminosity: $3.8 \times 10^{32} cm^{-2} s^{-1}$
- Visible interactions rate: 12.0 MHz
- L0 output rate: 860 kHz
- HLT output rate: 3.6 kHz





$37.5\,\mathrm{pb}^{-1}$ acquired in 2010

$1.0\,\mathrm{fb}^{-1}$ acquired in 2011

Charmonia status

In QCD models, charmonia states are described as $c\bar{c}$ pairs bound by a short-distance potential approximately Coulombic (single-gluon exchange) plus a linearly increasing confining potential at large separations.

- All charmonium states below the $D\bar{D}$ mass threshold have been observed.
- Charmonium states above the $D\bar{D}$ or $D\bar{D}^*$ mass threshold can decay into $D\bar{D}$ and $D\bar{D}^*$ final states.
- Many predicted states still not observed.

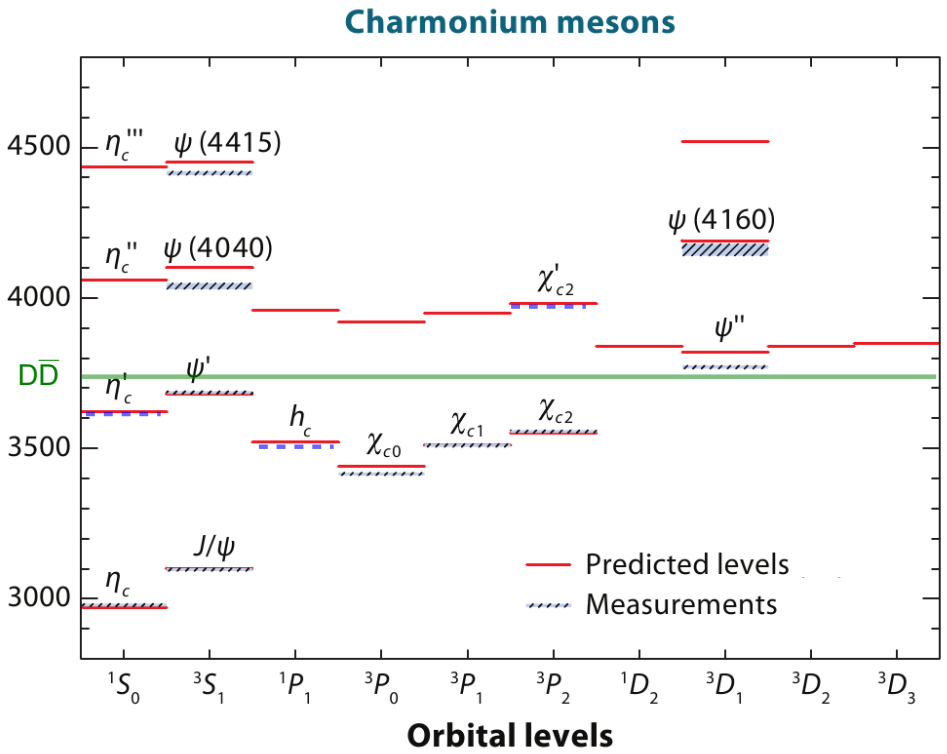


Figure from [Annu.Rev.Nucl. Part. Sci. 2008. 58:51–73]

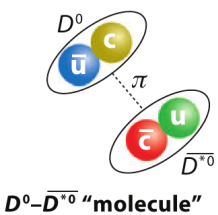
XYZ states

Many new states have been observed at B-factories and Tevatron

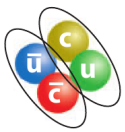
- Masses lying on the limits of the charmonia spectrum
- Observed many different production mechanisms: ISR, e^+e^-, $\gamma\gamma$ and B decays.
- The measured masses do not correspond to the predicted values for conventional charmonia.
- Properties does not fit very well to the charmonium picture.

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	Production modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR), J/ψ decay
$X(3872)$	3871.4 ± 0.6	<2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$	$B \to KX(3872)$, $p\bar{p}$
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$		$D^0\bar{D}^0\pi^0$	$B \to KX(3875)$
$Z(3940)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma$
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^-\psi'$	e^+e^- (ISR)
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm\psi'$	$B \to KZ^\pm(4430)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\psi'$	e^+e^- (ISR)
Y_b	$\sim 10,870$	?	1^{--}	$\pi^+\pi^-\Upsilon(nS)$	e^+e^-

Table from [Annu.Rev.Nucl. Part. Sci. 2008. 58:51–73]



D^0–$\overline{D^{*0}}$ "molecule"


Diquark–diantiquark


$q\bar{q}$–gluon hybrid

Many theoretical interpretations in discussion: conventional charmonium, tetra-quarks states, meson-molecules, hybrid mesons, threshold effects...

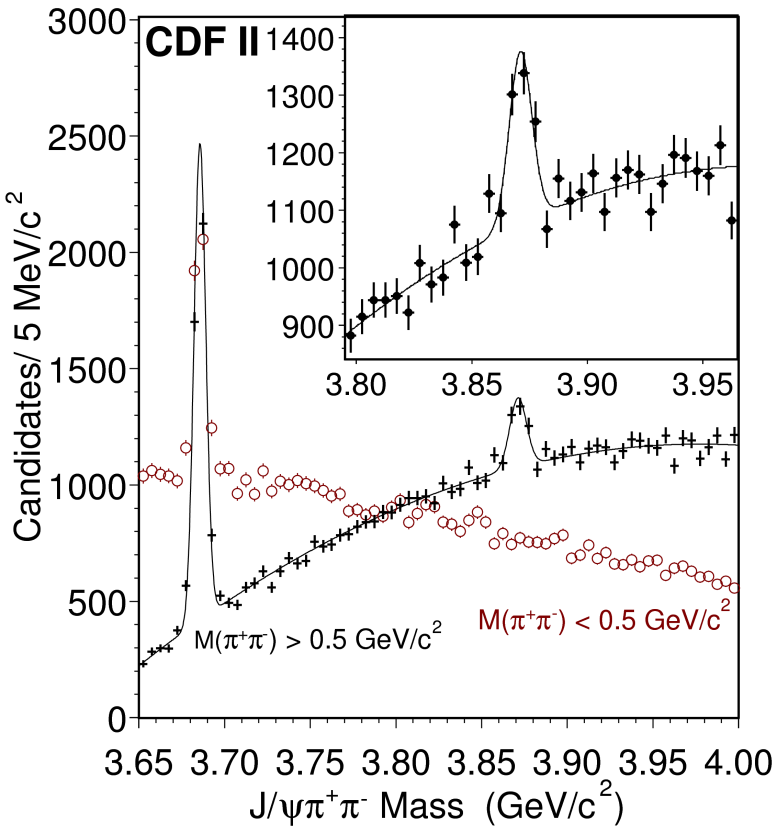
See the theoretical talks

X(3872)

The X(3872) exotic-meson was discovered in 2003 by the Belle collaboration in decays $\mathrm{B} \to \mathrm{KX(3872)}$ with $\mathrm{X(3872)} \to \mathrm{J}/\psi\pi^+\pi^-$.

[Phys. Rev. Lett. 93, 072001 (2004)]

- Its existence was confirmed by BaBar, CDF, DØ collaborations.
- Quantum numbers are constrained to 1^{++} or 2^{-+}
- Clear signature on the $\mathrm{X(3872)} \to \mathrm{J}/\psi\pi^+\pi^-$ mode. $\pi^+\pi^-$ mass spectrum well studied.
- Mass known to 0.2 MeV and width < 1.2 MeV.



The nature of the X(3872) remains uncertain:

- Conventional charmonium $\eta_{c2}(1\mathrm{D})$.
- Mesonic molecular state: $D^{*0}\bar{D}^0$ bound state.
- A tetraquark (diquark-anti-diquark).

The mass value of the X(3872) is a critical input on the theoretical interpretation of this state.

$\mathrm{X}(3872)$ production studies at LHCb

At LHCb, the $\mathrm{X}(3872)$ can be studied using:

- Prompt candidates: higher statistics but large combinatorial background.
- Candidates from B decays: lower statistics but more clear samples
- Both kinds of candidates (inclusive selection)

$\mathrm{X}(3872)$ production studies at LHCb were performed:

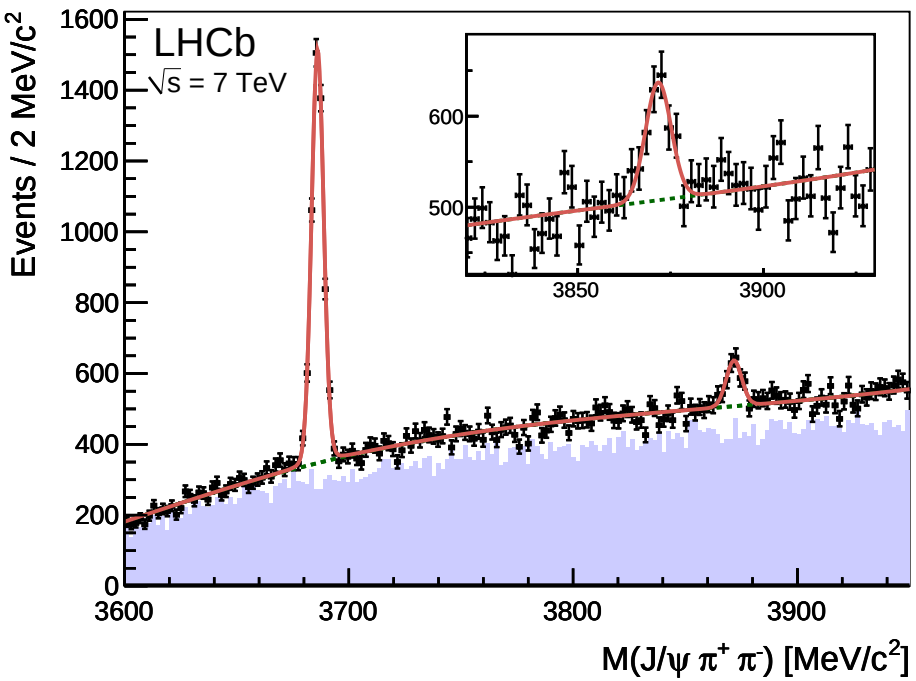
- Measure the product of production cross-section multiplied by branching ratio to $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-$
- Assuming $\mathrm{X}(3872)$ as a 1^{++} state
- Inclusive selection of $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-$ final state
- Fiducial range: $5 < p_{\mathrm{T}} < 20\ \mathrm{GeV}$ and $2.5 < \mathrm{y} < 4.5$
- Efficiency estimated from Monte Carlo

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

X(3872) production studies at LHCb

Analysis performed on data sample with integrated luminosity of 34.7 pb^{-1} collected by the LHCb experiment in pp collisions at $\sqrt{s} = 7$ TeV in 2010. [ref. arXiv:1112.5310]

$$\sigma(\text{pp} \to \text{X}(3872) + \cdots) \times \mathcal{B}(\text{X}(3872) \to \text{J}/\psi\,\pi^+\pi^-) = 4.7 \pm 1.1(\text{stat}) \pm 0.7(\text{syst})\,\text{nb}$$

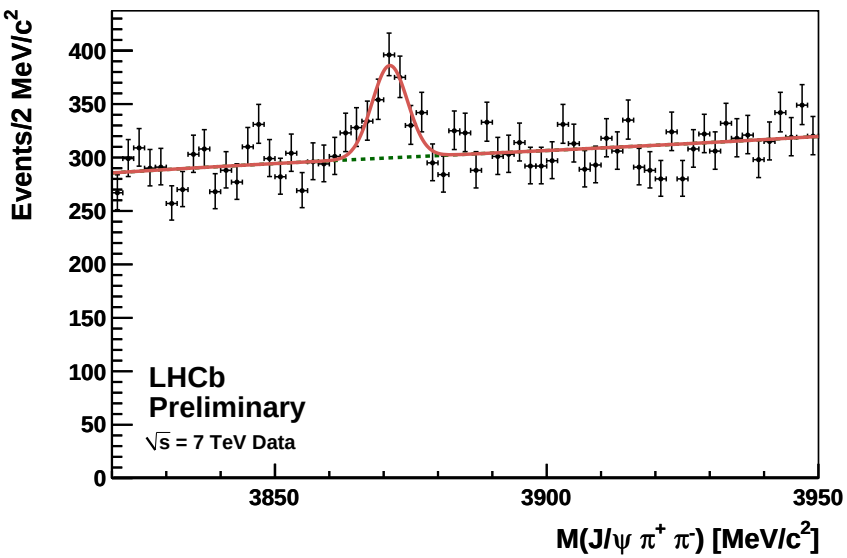


Source of uncertainty	$\Delta\sigma/\sigma$ [%]
$X(3872)$ polarization	2.1
$X(3872)$ decay model	1.0
$X(3872)$ decay width	5.0
Mass resolution	5.8
Background model	6.4
Tracking efficiency	7.4
Track χ^2 cut	2.0
Vertex χ^2 cut	3.0
Muon trigger efficiency	2.9
Global event cuts	3.0
Muon identification	1.1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

X(3872) mass measurement at LHCb

Using 585 ± 74 X(3872) signal candidates from data sample with integrated luminosity of 34.7 pb^{-1} collected by the LHCb experiment in pp collisions at $\sqrt{s} = 7$ TeV in 2010. [ref. arXiv:1112.5310]

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



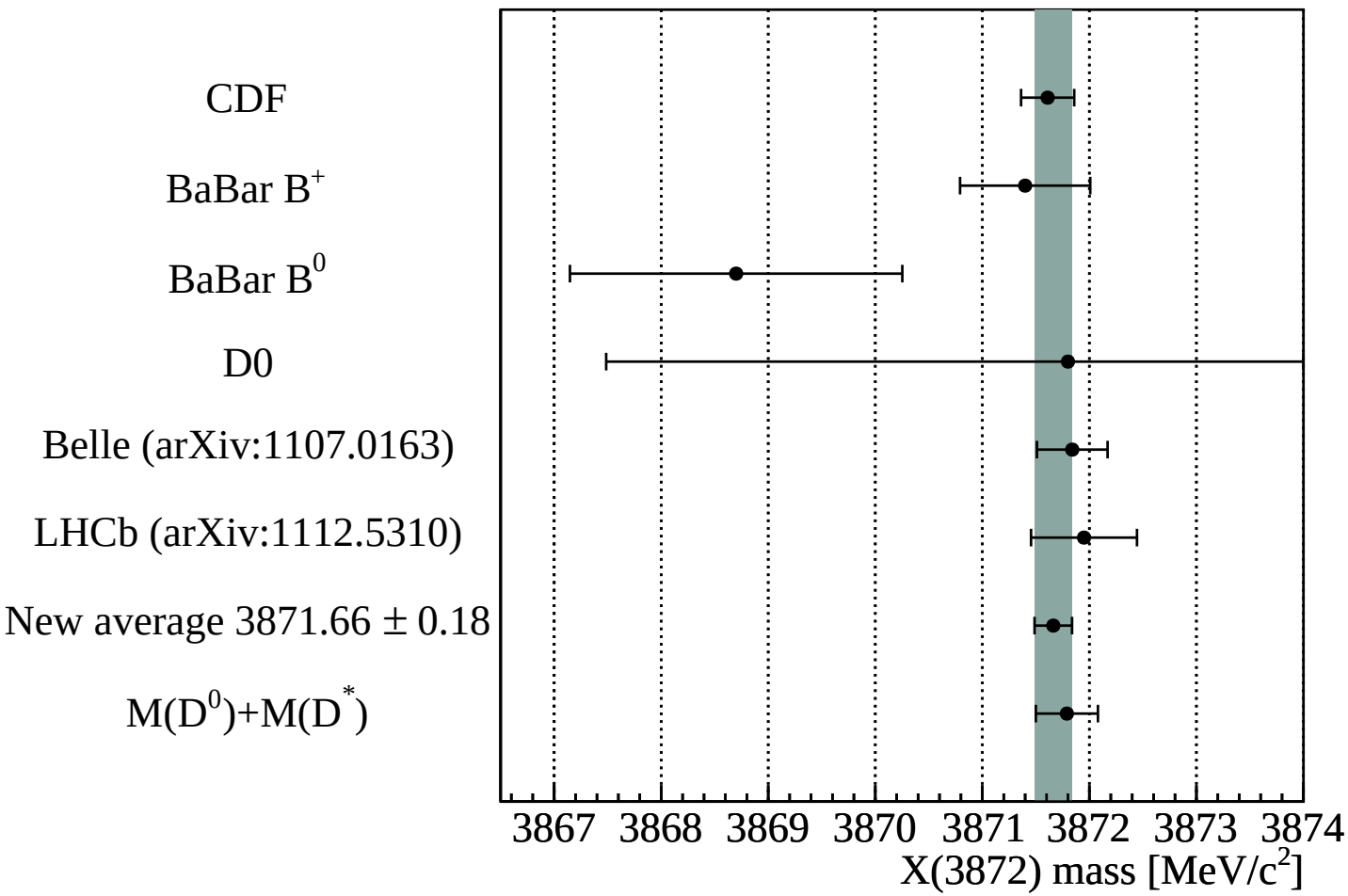
- Uncertainty dominated by statistics
- Improve with 2011 dataset

- Momentum scale calibration using $J/\psi \to \mu^+\mu^-$.
- X(3872) peak fitted using a Voigt function with fixed width.
- Background studied from wrong-sign pions combinations and modeled by exponential function.

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

X(3872) mass

Current PDG value : $\mathrm{M(X(3872))} = 3871.57 \pm 0.25\ \mathrm{MeV}/c^2$
(without LHCb and Belle's lastest results)



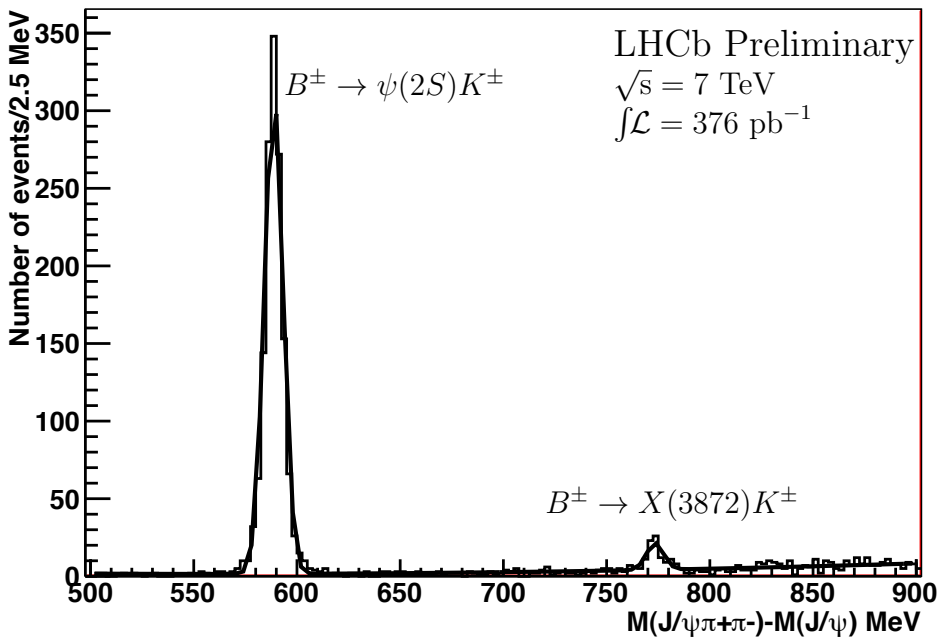
Prospects for X(3872) at LHCb

Using the 1.0 fb^{-1} dataset recorded by LHCb in 2011:

- About 30 times more luminosity
- Expected about 16,000 prompt candidates.
- Expected about 200 candidates $B^{\pm} \to X(3872)\ K^{\pm}$

Will have enough statistics to:

- Perform precision production studies (in bins of p_T).
- Study the X(3872) quantum numbers
- Improve the X(3872) mass measurement
- Study the $\pi^+\pi^-$ spectrum



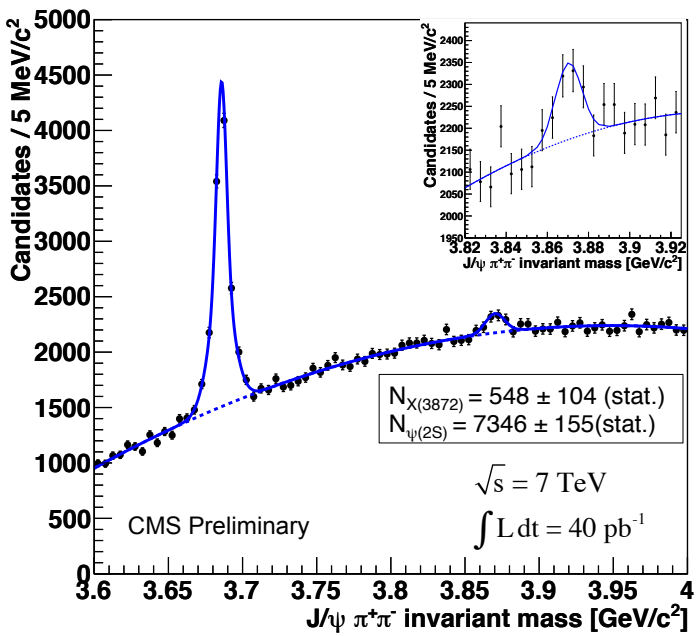
In the figure: 70 ± 12 $B^{\pm} \to X(3872)\ K^{\pm}$ candidates

X(3872) production studies at CMS

CMS collaboration measured the ratio of the cross sections times the branching fractions for $\psi(2S) \to J/\psi\ \pi^+\pi^-$ and $X(3872) \to J/\psi\,\pi^+\pi^-$

$$R = \frac{\sigma(pp \to X(3872) + \cdots) \times \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)}{\sigma(pp \to X(3872) + \cdots) \times \mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)}$$

- Dataset with 40 pb^{-1} @ 7 TeV recorded by CMS in 2010.
- $p_T > 8\ \mathrm{GeV}/c$ and $|y| < 2.2$
- $N_{X(3872)} = 548 \pm 104(\mathrm{stat})$
- $N_{\psi(2S)} = 7346 \pm 155(\mathrm{stat})$,



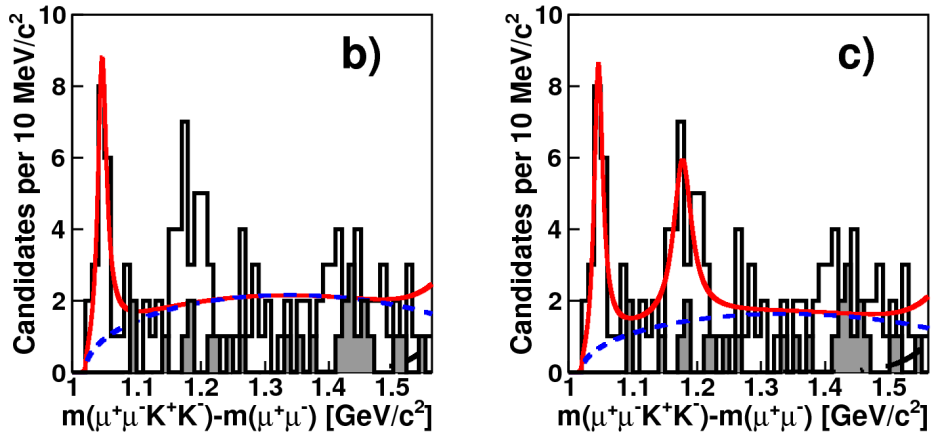
$R = 0.087 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst})$

[Ref. CMS PAS BPH-10-018]

The X(4140) and X(4274) candidates

Two exotic resonance candidates observed by CDF in $B^{\pm} \to J/\psi\,\phi K^{\pm}$ decays and decaying into $J/\psi\,\phi$.

[Ref. Phys.Rev.Lett. 102.242002, arXiv:1101.6058].



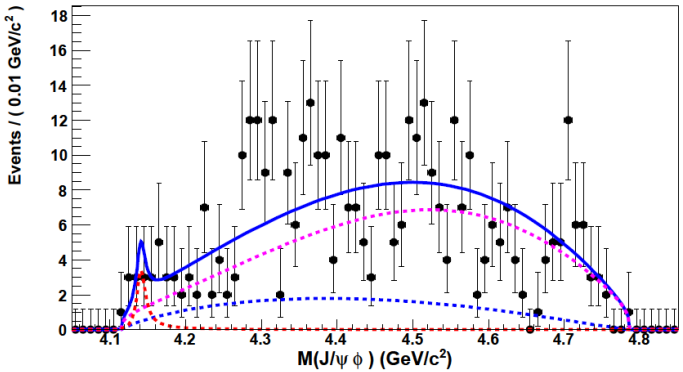
- 115 ± 12 candidates of $B^{\pm} \to J/\psi\,\phi K^{\pm}$
- $X(4140)$ candidate with $M_{X(4140)} = 4143.4^{+2.9}_{-3.0} \pm 0.6\ \mathrm{MeV}/c^2$, $\Gamma_{X(4140)} = 15.3^{+10.4}_{-6.1} \pm 2.5\ \mathrm{MeV}/c^2$, with yield of 19 ± 6 and statistical significance of 5.0σ.
- Maybe a second state: $M_{X(4274)} = 4274.4^{+8.4}_{-6.4} \pm 1.9\,\mathrm{MeV}/c^2$, $\Gamma_{X(4274)} = 32.3^{+21.9}_{-15.3} \pm 7.6\,\mathrm{MeV}/c^2$, with yield of 22 ± 8 and statistical significance of 3.1σ.
- CDF results implies:

$$\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi) = (5.2 \pm 1.7) \times 10^{-5}$$

The X(4140) and X(4274) candidates

Belle experiment also have searched for X(4140) and X(4274)

[see J. Brodzicka, Heavy flavour spectroscopy (LP09)]



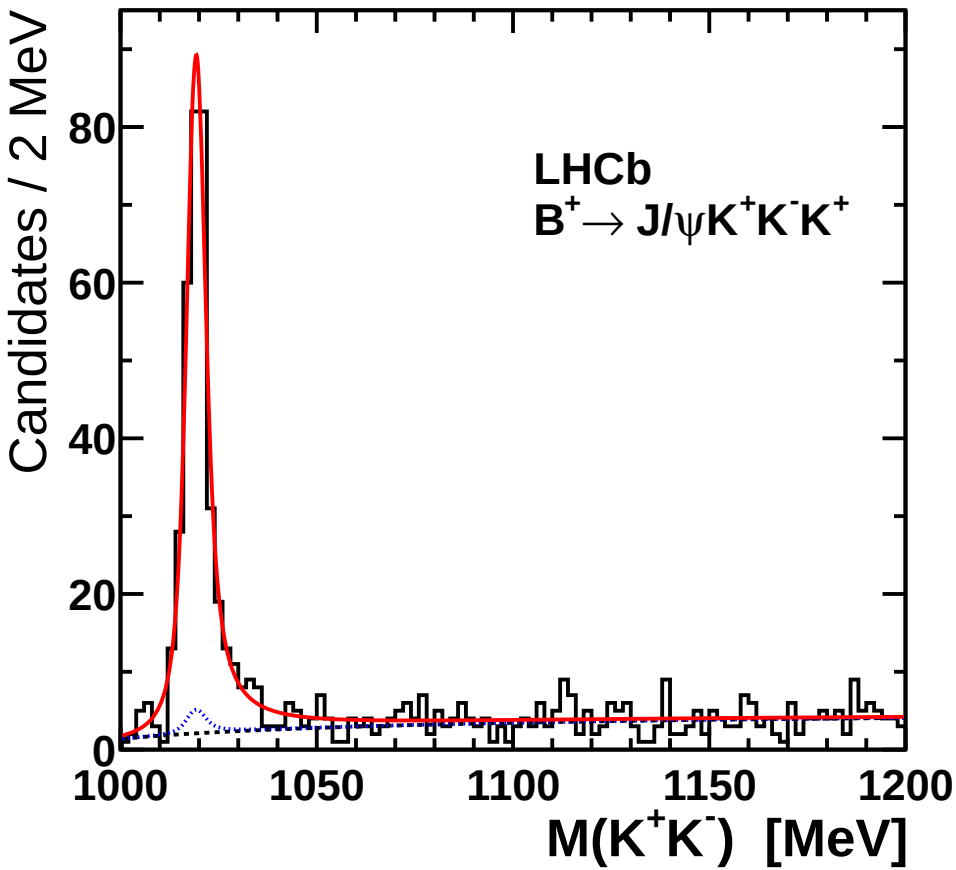
- Belle accumulated more events on $B^+ \to J/\psi\phi K^+$ than CDF but could not confirm or exclude the X(4140).
- Loss of efficiency near the threshold resulted in a lower sensitivity to X(4140) at Belle.
- $\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi) < 6 \times 10^{-6}$

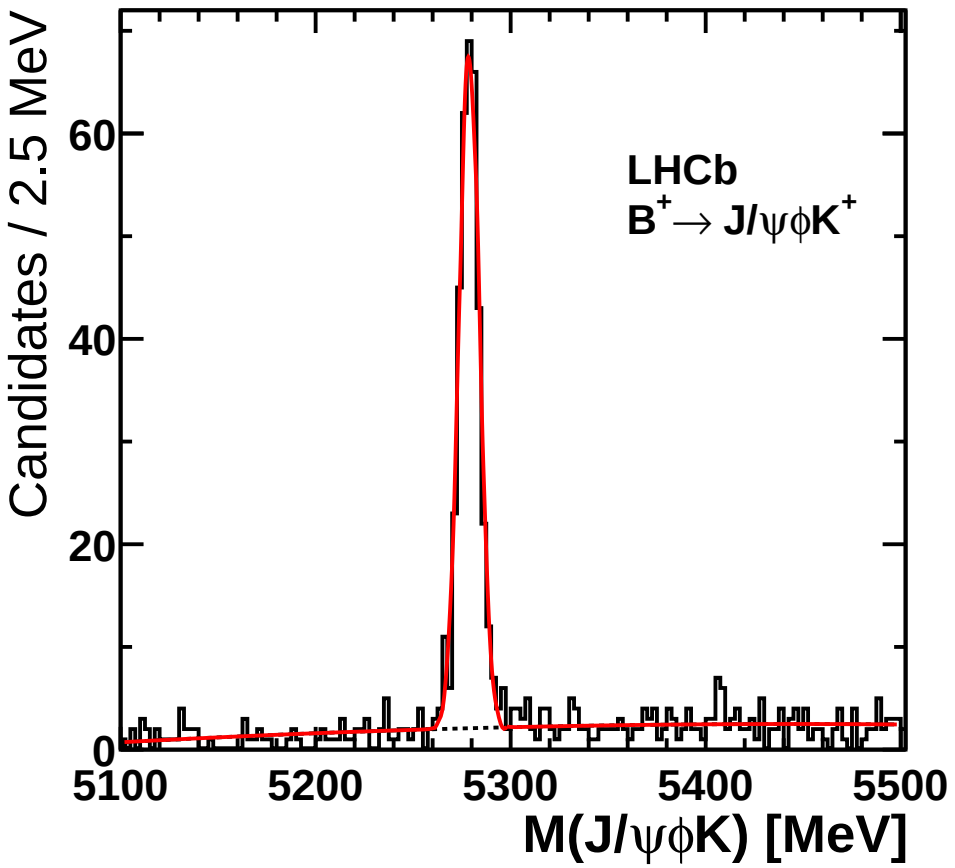
In summary:

- Charmonium states at this mass are expected to have much larger widths because of open flavour decay channels.
- Their decay rate into the $J/\psi\,\phi$ mode (so near the kinematic threshold) should be small and unobservable.
- Then, the observation by CDF has triggered much theoretical interest about the nature of this candidates.
- The existence of X(4140) and X(4274) candidates remains unconfirmed.

Search for $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$ at LHCb

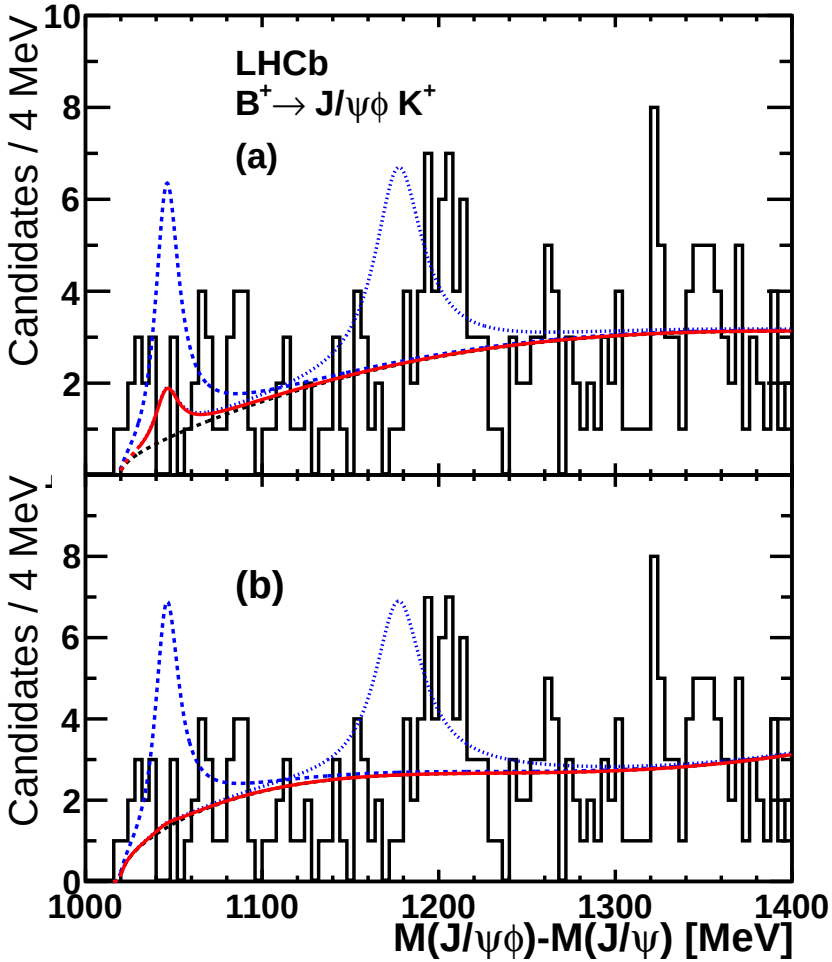
- LHCb searched for $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$ in a sample with 0.376 fb^{-1} of 2011 dataset [Ref. arXiv:1202.5087v1].
- Background subtracted sample with 382 ± 22 $\mathrm{B}^{\pm} \to \mathrm{J}/\psi\,\phi\mathrm{K}^{\pm}$ events





Search for X(4140) and X(4274) at LHCb

- The LHCb sensitivity to X(4140) signal a factor two better than in CDF.
- According the CDF results, we should observe 35 ± 11 X(4140) signal candidates and 53 ± 19 X(4274) signal candidates.
- Signal modelled by a spin-zero relativistic Breit-Wigner shape. Two models of background have been tested:
  - (a) A three-body background phase-space function (used by CDF)
  - (b) A quadratic function
- No narrow structure is observed near the threshold.
- The fit shown in (a) gives a X(4140) yield of 6.9 ± 4.9 events and a X(4274) yield of $3.4^{+6.5}_{-3.4}$ events.
- The fit shown in (b) gives a X(4140) yield of 0.6 events with a positive error of 7.1 events and zero signal X(4274) events with a positive error of 10.



- The solid red line represents the result of the fit to our data.
- The dashed blue line represents the the expected signal amplitude from the CDF results.
- The top and bottom plots background functions are: a) efficiency-corrected three-body phase-space; b) quadratic polynominal.

Results on $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$ at LHCb

The results of the search for $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$ at LHCb are the two following limits calculated at 90%CL:

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

LHCb(a)	LHCb(b)	CDF
< 0.07	< 0.04	$0.149 \pm 0.039 \pm 0.024$

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

LHCb	CDF (our estimate)
< 0.08	0.17 ± 0.06

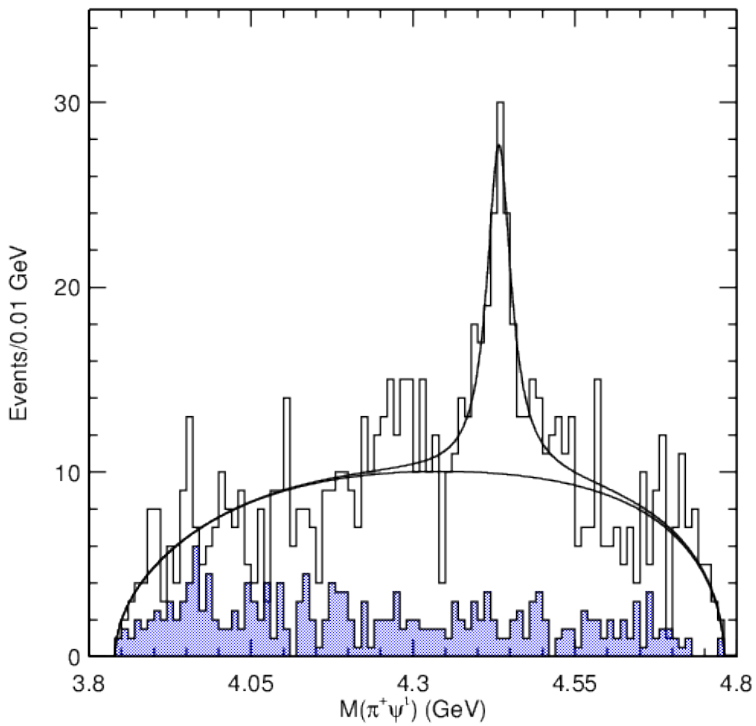
In conclusion, LHCb performed the most sensitive search for the narrow $\mathrm{X}(4140)$ and $\mathrm{X}(4274)$ structures and:

- Does not confirm the $\mathrm{X}(4140)$ state previously reported by the CDF
- Does not observe any evidence of the $\mathrm{X}(4274)$
- The LHCb results disagree at the 2.4σ level with the CDF measurement.
- Ref: arXiv:1202.5087v1, just appeared in Phys. Rev. D 85,091103(R)(2012)

Prospects for $Z(4430)^+$ at LHCb

- Charged charmonium like state reported by Belle in $B^+ \to \psi(2S)K^+\pi^-$ decays
  [Phys.Rev.Lett.100:142001,2008, Phys.Rev.D80:031104,2009]
- Searched and not confirmed by BaBar[Phys.Rev.D79:112001,2009]
- If confirmed it will be the strongest tetraquark candidate.
- No structure reported in the $B^+ \to J/\psi K^+\pi^-$

$Z(4430)^+$ signal from Belle with $6.5\,\sigma$



Studies in progress at LHCb using the full 2011 dataset

- Analysing both $B^+ \to J/\psi K^+\pi^-$ and $B^+ \to \psi(2S) \to K^+\pi^-$ modes.
- High statistics: expected more candidates of $B^+ \to J/\psi K^+\pi^-$ and $B^+ \to \psi(2S)K^+\pi^-$ than Belle and BaBar together.

If the $Z(4430)^+$ is there, we should be able to see it.

Summary and perspectives

X(3872)[ref. arXiv:1112.5310]

- LHCb has measured the production cross section in the range: $5 < p_{\mathrm{T}} < 20$ GeV and $2.5 < y < 4.5$
- CMS has measured the ratio of the cross sections in the range: $p_{\mathrm{T}} > 8$ GeV/c and $|y| < 2.2$
- Both used 2010 data and the measurements are complementary.
- Using the 2011 dataset: precision production studies, measurement of the quantum numbers and improved mass determination.

X(4140)[Phys. Rev. D 85, 091103(R) (2012)]

- Not confirmed by LHCb.
- Use the 2011 dataset to search for the other exotic candidates.

$Z(4430)^{+}$

- Work in progress at LHCb.

We hope to double data set in 2012

Thanks!