Heavy flavour spectroscopy at LHCb Experiment

X, Y, B_c, B^{**}...

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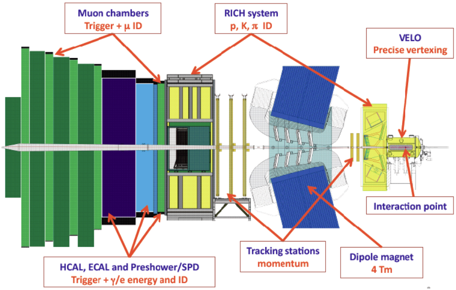
Outline

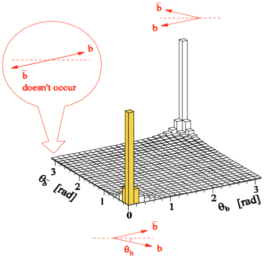
1. The LHCb detector, its trigger and dataset
2. Double J/ψ and χ_c production
3. Exotic charmonium-like candidates $X(3872)$, $X(4140)$and $X(4274)$
4. B, B_c^+, $B_{(s)}^{**}$, Υ, Ω_b and Ξ_b production and spectroscopy
5. Conclusions

The LHCb detector

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



- **Single-arm design.** The $b\bar{b}$ pairs are produced predominantly in the forward/backward region.
- **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.



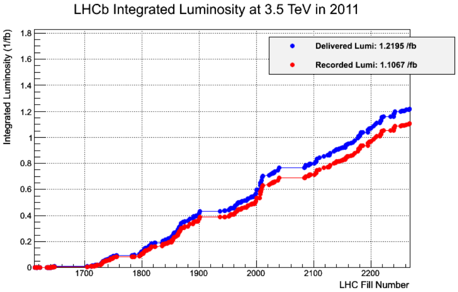
Copious statistics of B-hadrons:

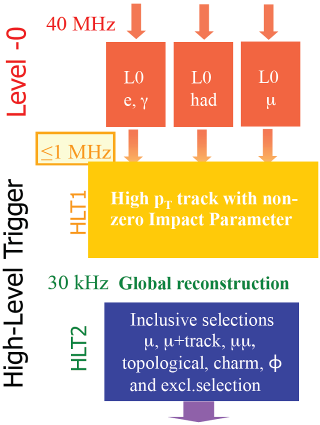
$\sigma(pp \to b\bar{b}X) = (284 \pm 53)\mu b$ @ 7TeV [PLB 694 209]

$\Rightarrow$ (100, 000 $b\bar{b}$ pairs/s)

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 pb^{-1} **acquired in 2010**

1.1 fb^{-1} **acquired in 2011**

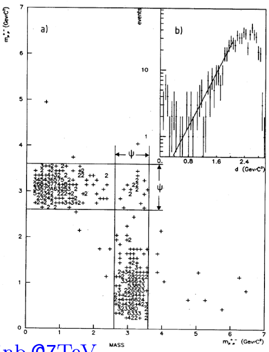
Flavor physics in LHCb

The high-performance, efficiency and flexibility of the trigger associated to the high quality of the event reconstruction, puts the LHCb experiment in very advantageous position to analyse the copious statistics provided by the LHC and perform competitive measurements in heavy flavor physics.

Double J/ψ production

- QCD predicts the production of charmonium pairs in the same reaction is to be a very rare effect.
- The NA3 collaboration measured J/ψ J/ψ-pair production in multi-muon events in pion-platinum interactions at 150 and 280 GeV and in 400 GeV proton-platinum interactions.
- The relative rate to inclusive J/ψ was measured at NA3 for pion-induced production: $\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (3 \pm 1) \times 10^{-4}$
- At NA3 energies the main contribution to the cross-section comes from the quark-antiquark annihilation channel.
- In the case of proton-proton collisions and at LHC energy the main contribution is predicted to come from gluon-gluon fusion process[Z. Phys. C 20,83(1983).]

[Phys. Lett. B 158 (1985)]



- QCD perturbation theory predicts: $\sigma(\mathrm{pp} \to J/\psi J/\psi + X) \sim 24.5\mathrm{nb}$ @7TeV

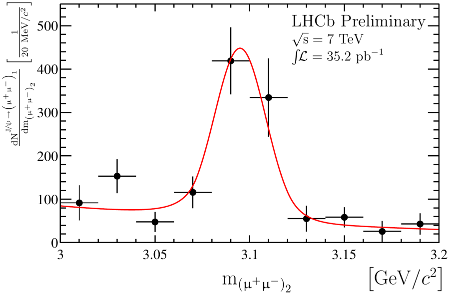
In the rapidity interval of $2.0 < y^{J/\psi} < 4.5$, relevant to the LHCb experiment, the cross-section is predicted to be:

- 4.34 nb, in the case initial state gluon radiation (ISR) is neglected
- 4.15 nb, if ISR is taken into account

For details and references in [arXiv:1109.0963]

Double J/ψ production at LHCb

Cristal Ball + exponential function



- The selected $\mu^+\mu^-$ pairs with invariant mass in the interval [3.0, 3.2] GeV/c2 have been paired to form $(\mu^+\mu^-)_1(\mu^+\mu^-)_2$ combinations.
- The four muon combinations are required to come from common vertex compatible with one of the reconstructed primary vertices from pp-collisions.
- The raw and efficiency corrected yields of $(J/\psi, J/\psi)$ events has been found to be 139 ± 18 and 672 ± 129 respectively, inside the signal window $y^{J/\psi} \in [2, 4.5]$ and $p_T^{J/\psi} < 10\, GeV/c$.
- The feedown from pileup events with the single- J/ψ production has been estimated from MC studies to be 1.5 events.

The cross-section of double J/ψ production in signal window

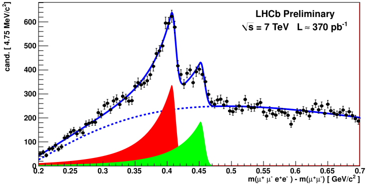
$$\sigma^{J/\psi, J/\psi} = \frac{1}{\mathcal{L} \times \mathcal{B}^2_{J/\psi \to \mu\mu}} \times N^{\text{corr}}_{J/\psi, J/\psi} = 5.6 \pm 1.0(\text{stat.}) \pm 1.1(\text{syst.})$$

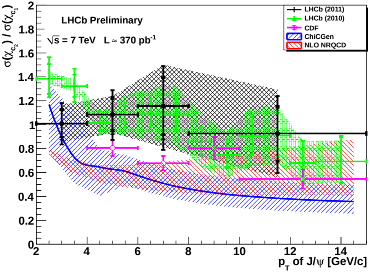
Where $\mathcal{L} = 37.5\text{pb}^{-1}$ and $\mathcal{B}_{J/\psi \to \mu\mu} = (5.93 \pm 0.06)\%$ [PDG].

Ref: [arXiv:1109.0963]

χ_{c1} and χ_{c2} production

- P-wave charmonia χ_c production gives substantial feed-down contributions to the prompt J/ψ production through $\chi_c \to$ J/$\psi\gamma$
- χ_{c1} and χ_{c2} cross-sections are important in the measurement of the J/ψ polarisation.
- The production rate ratio of χ_{c1} to χ_{c2} is sensitive to colour-singlet and color-octet production mechanisms.



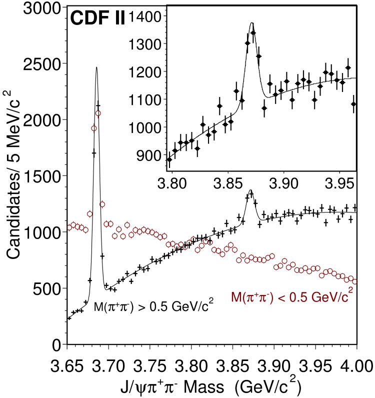


- 370pb^{-1} from the 2011 dataset (converted photons) and 36pb^{-1} from the 2010 dataset (unconverted photons).
- The χ_c states are identified through their radiative decay $\chi_c \to J/\psi\gamma$ with $J/\psi \to \mu^+\mu^-$ and $\gamma \to e^+e^-$
- The candidates are selected using the NeuroBayes neural network techniques.
- Combinatorial background estimated using "wrong-sign" photons $\gamma \to e^+e^+$, e^-e^-.
- Signal is fitted by a Cristall Ball shape.
- Yields calculated for four bins of $p_T^{J/\psi}$.
- The χ_c candidates are assumed to be unpolarised.
- The results are showed on the left.
- Ref: LHCb-CONF-2011-062, LHCb-CONF-2011-020

Two predictions from theoretical calculations are superimposed on the data. One prediction has been obtained using the ChiCGen generator and the other has been obtained using NLO NRQCD calculations.

$X(3872)$

- The X(3872) exotic-meson was discovered in 2003 by the Belle collaboration in the B decays doing $X(3872) \to J/\psi\pi^+\pi^-$.
- Its existence was confirmed by the CDF, DØ and BaBar collaborations.
- Quantum numbers are constrained to 1^{++} e 2^{-+}
- The $\pi^+\pi^-$ mass spectrum well studied
- The nature of the X(3872) remains uncertain:
  - Conventional charmonium $\eta_{c2}(1D)$.
  - Mesonic molecular state: $D^{*0}\bar{D}^0$ bound state.
  - A tetraquark (diquark-anti-diquark).



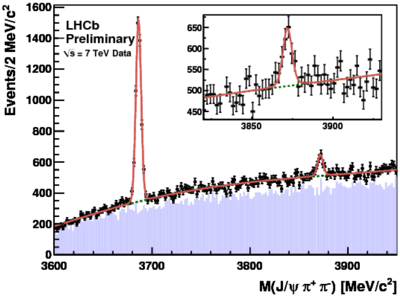
The mass value of the X(3872) is a critical input on the theoretical interpretation of this state.

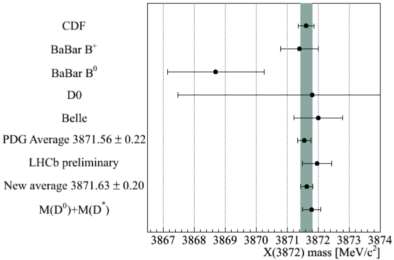
$X(3872)$ mass and cross-section at LHCb

- Inclusive selection of $X(3872) \to J/\psi\pi^+\pi^-$ final state
- Momentum scale calibration using $J/\psi \to \mu^+\mu^-$
- X(3872) peak fitted using a BW function with fixed width.
- Background studied from wrong-sign pions combinations.
- $34.7pb^{-1}$ from 2010 dataset. 585 ± 74 X(3872) signal candidates.
- Refs: LHCb-CONF-2011-021, LHCb-CONF-2011-043

$$\mathrm{M}(X(3872)) = 3871.96 \pm 0.46(\mathrm{stat}) \pm 0.10(\mathrm{syst})\mathrm{MeV/c^2}$$

$$\sigma(\mathrm{pp} \to X(3872) + \cdots) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 4.74 \pm 1.10(\mathrm{stat}) \pm 1.01(\mathrm{syst})\,\mathrm{nb}$$

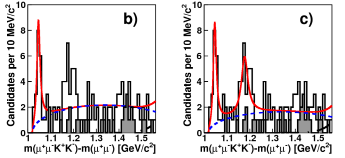




With the data collected in 2011, we will be able to study the X(3872) quantum-numbers !

CDF

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

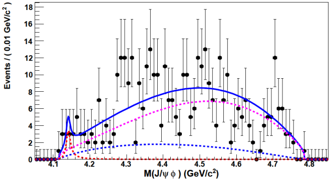


- Reported 115 ± 12 $B^+ \rightarrow J/\psi K^+ K^- K^+$ events;
- $X(4140)$ state: $M_1 = 4143.4^{+2.9}_{-3.0} \pm 0.6\mathrm{MeV}$ and $\Gamma_1 = 15.3^{+10.4}_{-6.1} \pm 2.5\mathrm{MeV}$ with yield 19 ± 6
- Maybe a second state: $M_2 = 4274.4^{+8.4}_{-6.4} \pm 1.9\mathrm{MeV}$, $\Gamma_2 = 32.3^{+21.9}_{-15.3} \pm 7.6\mathrm{MeV}$, and yield 22 ± 8

CDF results implies: $\mathcal{B}(B^+ \rightarrow X(4140)K^+) \times \mathcal{B}(X(4140) \rightarrow J/\psi\phi) = (5.2 \pm 1.7) \times 10^{-5}$

Belle search

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



- Belle accumulated more events on $B^+ \rightarrow J/\psi\phi K^+$ 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.
- $\mathcal{B}(B^+ \rightarrow X(4140)K^+) \times \mathcal{B}(X(4140) \rightarrow J/\psi\phi) < 6 \times 10^{-6}$

Search for X(4140) at LHCb

- LHCb searched for $X(4140)$ and $X(4274)$ in the $0.376\,\mathrm{fb}^{-1}$.
- The LHCb sensitivity to $X(4140)$ signal a factor of two better than in CDF.
- Selected $B^+ \to J/\psi\phi K^+$ 382 ± 22 events.
- According the CDF results, we should observe 35 ± 11 $X(4140)$ signal candidates and 49 ± 18 $X(4274)$ signal candidates.
- $\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)}$ @90% CL

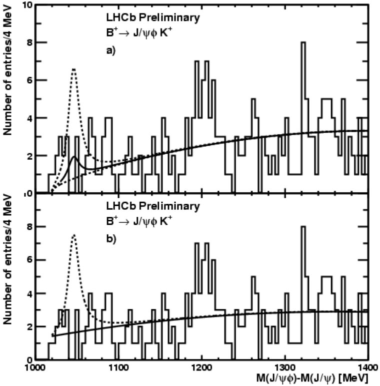
LHCb(a)	LHCb(b)	CDF
< 0.07	< 0.04	$0.149 \pm 0.039 \pm 0.024$

- $\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)}$ @90% CL

LHCb	CDF (our estimative)
< 0.08	0.17 ± 0.06

In conclusion:

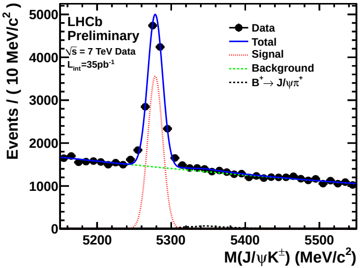
- We do not confirm the $X(4140)$ state previously reported by the CDF
- No evidence of the $X(4274)$
- Ref: LHCb-CONF-2011-045



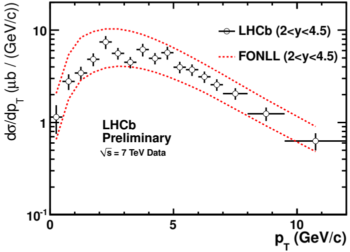
- The solid line represents the result of the fit to our data.
- The dashed line represents the the expected signal amplitude from the CDF results.
- The top and bottom plots background functions are: a) efficiency-corrected three-body phase-space; b) quadratic polynominal.

B^+ production cross-section at LHCb

The study of B^+ production cross-section provides a important test for the QCD predictions at NLO



- Measurement of $\sigma(pp \to B^+ + X)$ and $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{B}$ in the rapidity range $y \in [2; 4:5]$.
- using 35 pb^{-1} from the 2010 dataset.
- Reconstructing the B decay mode $B^+ \to J/\psi K^+$, with $J/\psi \to \mu^+\mu^-$.
- Selection procedure require: well identified tracks and good vertices.
- Just B candidates with $\tau > 0.3\mathrm{ps}$ are kept in order to reduce combinatorial background



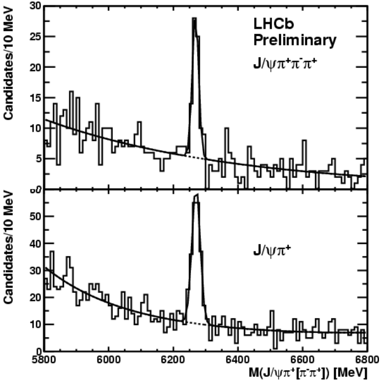
The total cross-section is measured to be

$$\sigma(B^{\pm}, y \in [2, 4.5]) = 37.1 \pm 1.9\,(\mathrm{stat.}) \pm 5.3\,(\mathrm{syst.})\,\mu\mathrm{b}$$

On the left, the differential cross-section measured is compared to a FONLL prediction. A good agreement is observed between the two distributions.
Ref:LHCb-CONF-2011-033

First obsevation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

- The B_c^+ meson was discovered by CDF in the decay mode $B_c^+ \to J/\psi\ell^+ \nu_\ell X$
- The only decay mode observed so far was $B_c^+ \to J/\psi\pi^+$
- The B_c^+ production rates are about tree orders of magnitude smaller compared to the heavy-light B mesons.
- Hard to observe due the high track multiplicity in the final state



The LHCb analysis and results:

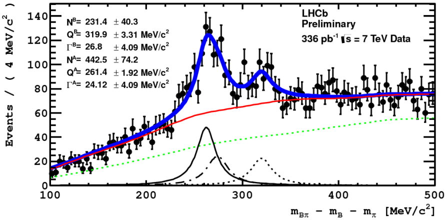
- Dataset $303pb^{-1}$
- Selected 163.1 ± 15.7 and 58.2 ± 9.6 candidates of $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, respectively.
- $\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 3.0 \pm 0.6(\mathrm{stat}) \pm 0.4(\mathrm{syst.})$
- Consistent with theoretical prediction within 1-σ. [Phys. Rev. D81 (2010) 014015]
- Ref:LHCb-CONF-2011-040

Search for orbitally excited $B_{(s)}^{**}$ mesons at LHCb

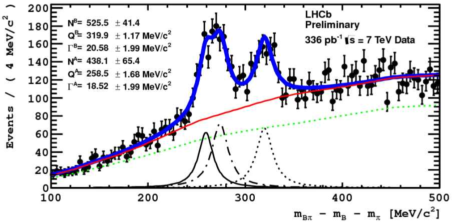
- The properties of the excited $B_{(s)}^{**}$ mesons predicted by Heavy Quark Effective Theory.
- Some of the predicted states was already observed (CDF and D0): $B_1(5721)^0$, $B_2^*(5747)^0$, $B_{s1}(5830)^0$ and $B_{s1}(5840)^0$,
- LHCb searched for $B_{(s)}^{**}$ states analysing the invariant mass distributions of $B^+ K^-$, $B^+ \pi^-$ and $B^0 \pi^-$
- The signals of excited B states are expected to appear as peaks in the $Q = M(B, h) - M(B) - M(h)$ distribution above a combinatorial background.

solid	$B_1 \rightarrow B^*\pi$
dash-dot	$B_2^* \rightarrow B^*\pi$
dotted	$B_2^* \rightarrow B\pi$

$$Q = M(\mathrm{B}^0, \pi) - M(\mathrm{B}^0) - M(\pi)$$

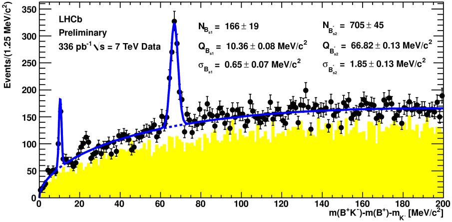


$$Q = M(\mathrm{B}^+, \pi) - M(\mathrm{B}^+) - M(\pi)$$



- The LHCb search performed with $0.336 fb^{-1}$ from the 2011 dataset

$$Q = M(\mathrm{B}^0, K) - M(\mathrm{B}^0) - M(K)$$



From the left to the right: B_{s1}^0 and B_{s2}^{*0} peaks in Q distribution.

B** mass measurements

- The measured Q values were translated into masses by adding the the PDG massses of the product mesons. in the case
- For the $B^0_{(s)1}$ states, was used the B* - B PDG mass difference:

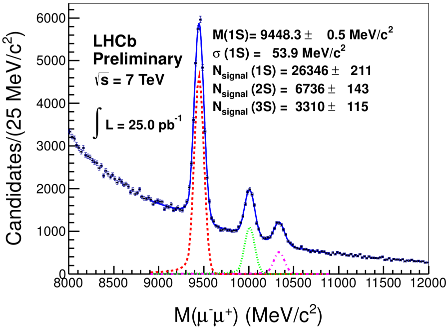
$$
\begin{aligned}
M_{B^0_{s1}} &= (5828.99 \pm 0.08_{\mathrm{stat}} \pm 0.13_{\mathrm{syst}} \pm 0.45^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 , \\
M_{B^{*0}_{s2}} &= (5839.67 \pm 0.13_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}} \pm 0.29^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 , \\
M_{B^0_1} &= (5724.1 \pm 1.7_{\mathrm{stat}} \pm 2.0_{\mathrm{syst}} \pm 0.5^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 , \\
M_{B^+_1} &= (5726.3 \pm 1.9_{\mathrm{stat}} \pm 3.0_{\mathrm{syst}} \pm 0.5^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 , \\
M_{B^{*0}_2} &= (5738.6 \pm 1.2_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}} \pm 0.3^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 , \\
M_{B^{*+}_2} &= (5739.0 \pm 3.3_{\mathrm{stat}} \pm 1.6_{\mathrm{syst}} \pm 0.3^{\mathrm{B\ mass}}_{\mathrm{syst}})\ \mathrm{MeV}/c^2 ,
\end{aligned}
$$

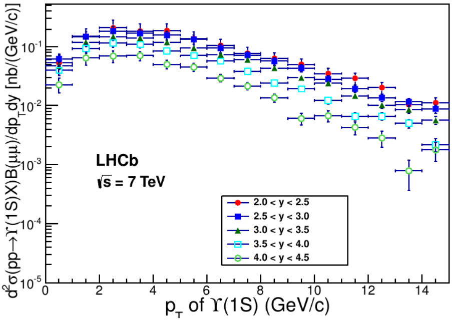
- Good agreement with the theoretical predictions;
- **First measurement of the B_1^+ and B_2^{*+} masses**
- Ref: Ref:LHCb-CONF-2011-053

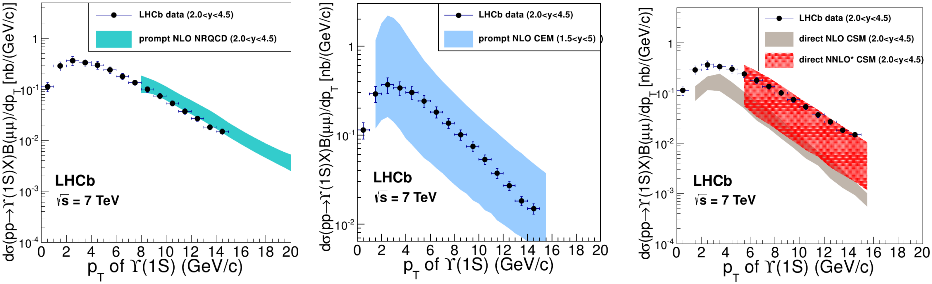
Υ production I

- The main sources of Υ production are:
  - Direct production;
  - Feed-down from the decay of heavier prompt bottomonium or excited Υ states
- Analysis was performed using $25pb^{-1}$ from 2010 run.
- $M(\mu^+, \mu^-)$ fit was repeated for 15×5 bins in $p_T \in [0; 15] GeV/c$ and $\eta \in [2.0; 4.5]$ respectively [LHCb-PAPER-2011-036, to appear]

$$\sigma(\mathrm{pp} \to \Upsilon(1S)X) \times \mathcal{B}(\mu^+\mu^-) = 2.290 \pm 0.015(\mathrm{stat}) \pm 0.095^{+0.371}_{-0.194}(\mathrm{sys})\mathrm{nb}$$
$$\sigma(\mathrm{pp} \to \Upsilon(2S)X) \times \mathcal{B}(\mu^+\mu^-) = 0.562 \pm 0.007(\mathrm{stat}) \pm 0.023^{+0.092}_{-0.048}(\mathrm{sys})\mathrm{nb}$$
$$\sigma(\mathrm{pp} \to \Upsilon(3S)X) \times \mathcal{B}(\mu^+\mu^-) = 0.283 \pm 0.005(\mathrm{stat}) \pm 0.012^{+0.048}_{-0.025}(\mathrm{sys})\mathrm{nb}$$

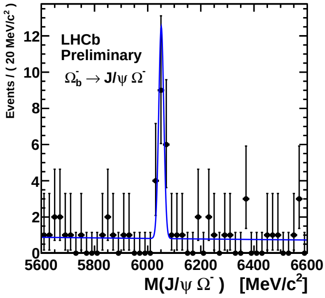


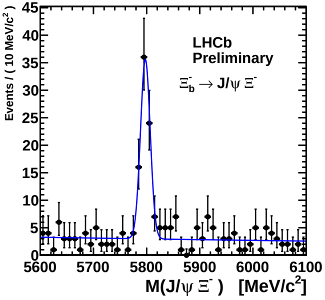




Differential $\Upsilon(1S)$ production cross-section $\times\mathcal{B}(\mu^+\mu^-)$ as a function of p_T integrated over y, compared with the predictions from the NNLO* CSM for direct production, NLO NRQCD and CEM for prompt production. Good agreement with theory predictions!

Ω_b and Ξ_b mass measurements at LHCb





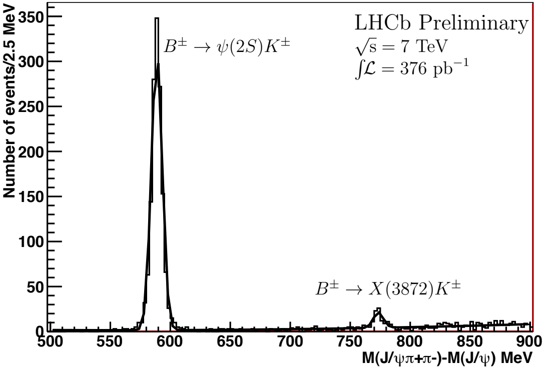
- The reconstructed modes are:
- $\Xi_b^- \to (J/\psi \to \mu^+\mu^-)(\Xi^- \to (\Lambda^0 \to p\pi^-)\pi^-)$;
- $\Omega_b^- \to (J/\psi \to \mu^+\mu^-)(\Omega^- \to (\Lambda^0 \to p\pi^-)K^-)$;
- Just kept candidates with $\tau > 0.3ps$
- Momentum scale calibration using the J/ψ

Performed with $0.62 fb^{-1}$ from the 2011 dataset.

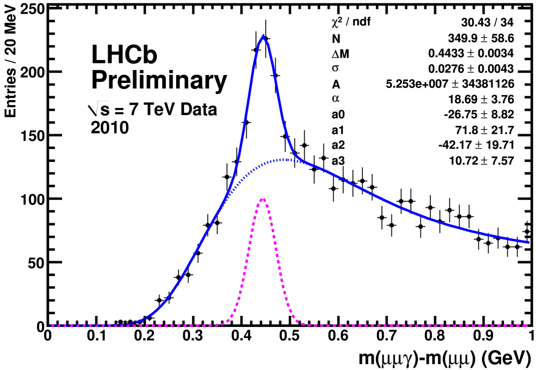
Decay mode	Yield	Mass (MeV/c^2)
$\Xi_b^- \to J/\psi\Xi^-$	72.2 ± 9.4	5796.5 ± 1.2
$\Omega_b^- \to J/\psi\Omega^-$	$13.9^{+4.5}_{-3.8}$	6050.3 ± 4.5

Ref: LHCb-CONF-2011-060

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



Observation of the decay $B^+ \to K^+ X(3872)$, with $X(3872) \to J/\psi \pi^+\pi^-$ in the channel $B^+ \to K^+ J/\psi \pi^+\pi^-$ (used as control channel in the $B_c^+ \to J/\psi \pi^+\pi^-\pi^+$ studies).



The plot represents $\chi_b \to \Upsilon(1S)\gamma$. Clean signal of χ_b production can be seen.

Conclusions

- We presented some of the results of LHCb in Heavy Flavor Physics in 2011.
- Very productive year:
  - First observation and mass measurement of the B_1^+ and B_2^{*+} states.
  - First obsevation of $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+\pi^-\pi^+$
  - Search and exclusion of two previously reported exotic candidates: $X(4140)$ and $X(4274)$
  - Competitive cross-section and mass measurements in a variety of states and channels: Υ, $(\mathrm{J}/\psi, \mathrm{J}/\psi)$, Ω_b, Ξ_b, $X(3872)$, χ_c , B^+, $\mathrm{B}_{(s)}^{**}$ and others...
- The Collaboration is working hard to update the analysis in order to provide results using the full $1.1\,fb^{-1}$ dataset recorded in 2011.
- New analysis and results are coming in 2012: exotic charmonium-like candidates, quarkonia production and polarisation and more.

Thanks!

Backup slides

Ω_b and Ξ_b mass world average