Bottomonia and B_c^+ Production at LHCb

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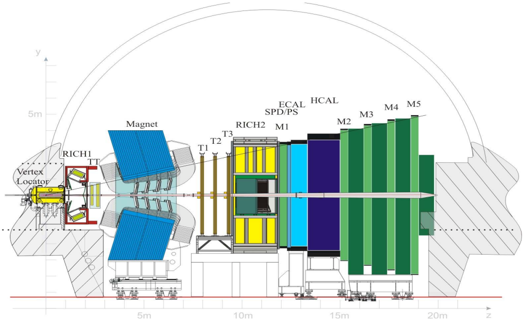
Outline

- LHCb detector
- Bottomonia studies
    - $\Upsilon(nS)$ production
    - χ_b production
- B_c^+ studies
    - B_c^+ mass and production using $B_c^+ \to J/\psi\pi^+$
    - Observation of $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$

LHCb Detector



Daria Savrina's talk this morning: *LHCb status and overview*.

Smooth running so far:

- ✓ 2010: 37 pb^{-1}
- ✓ 2011: 1 fb^{-1}
- ✓ 2012: 2 fb^{-1} delivered by last Thursday!

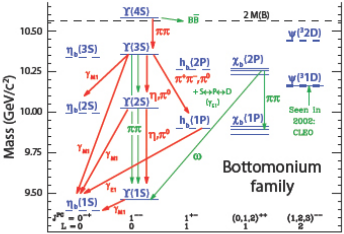
- Unique rapidity range: $2 < \eta < 5$;
- Precision vertexing and tracking;
- Excellent particle identification;
- Precise and efficient muon reconstruction: $\sim 90\%$ trigger rate for dimuon channels!

Bottomonia Productions

Bottomonia production mechanism is not yet well understood, several models exist:

- Colour Singlet Model (CSM, NLO CSM)
- Nonrelativistic QCD expansion (NRQCD) with contributions from Colour Octet Mechanism
- Colour Evaporation Model

Experimental inputs from LHC are needed.



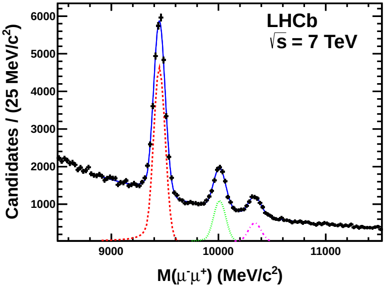
✓ $\Upsilon(nS)$ inclusive production $(n = 1, 2, 3)$

✓ Υ from χ_b feed-down

$\Upsilon(nS)$ Production

Eur.Phys.J.C(2012)72:2025

- 25 pb^{-1} of 2010 data, $\sqrt{s} = 7$ TeV
- $\Upsilon(nS)$ reconstructed from di-muon final states:
  - 1 μ $p_{\mathrm{T}} > 1.4$ GeV/c; or 2 μ $p_{\mathrm{T}}(\mu_1) > 0.56$ GeV/c, $p_{\mathrm{T}}(\mu_2) > 0.48$ GeV/c *typical trigger requirement*
  - $M(\mu^+\mu^-) > 2.9$ GeV/c
  - good fit quality of track & vertex
- The fitting is repeated for each p_T and y bin to obtain differential cross-section.



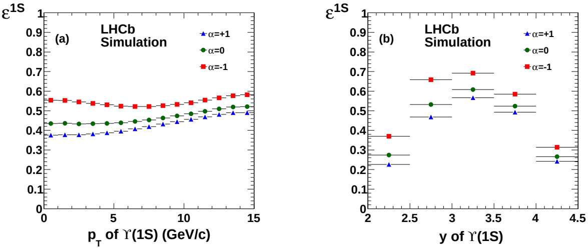
Fitting functions:
Crystal Ball for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$;
Exponential background.

$$\begin{aligned} N(1S) &= 26410 \pm 212 \\ N(2S) &= 6726 \pm 142 \\ N(3S) &= 3260 \pm 112 \end{aligned}$$

Integrated Cross-sections

$$\boxed{\begin{aligned}\sigma(pp\to\Upsilon(1S)X)\times\mathcal{B}^{1S} &= 2.29\pm0.01\pm0.10^{+0.19}_{-0.37}\ \text{nb},\\ \sigma(pp\to\Upsilon(2S)X)\times\mathcal{B}^{2S} &= 0.562\pm0.007\pm0.023^{+0.048}_{-0.092}\ \text{nb},\\ \sigma(pp\to\Upsilon(3S)X)\times\mathcal{B}^{3S} &= 0.283\pm0.005\pm0.012^{+0.025}_{-0.048}\ \text{nb}\end{aligned}}$$

- Uncertainties: statistical, systematics and from the unknown Υ polarisation.



α: polarisation parameter
$+1$ fully transverse
-1 fully longitudinal
0 unpolarised

- A factor of 3 smaller than the ATLAS and CMS results, though different rapidity ranges are covered (ATLAS: $|y| < 2.4$; CMS: $|y| < 2.0$; LHCb: $2.0 < y < 4.5$).

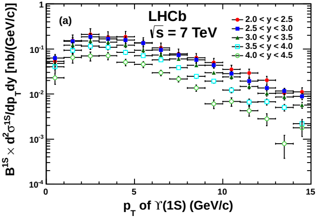
ATLAS: Phys.Lett.B 705,9(2011) CMS: Phys.Rev.D 83,112004(2011)

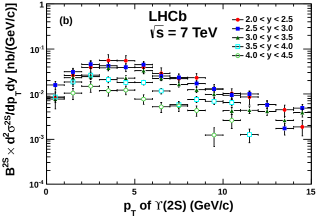
Determination of Differential Cross-section

$$\frac{\mathrm{d}^2\sigma^{nS}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} \times \mathcal{B}^{nS} = \frac{N^{nS}}{\mathcal{L} \times \varepsilon^{nS} \times \Delta y \times \Delta p_\mathrm{T}}, n = 1, 2, 3.$$

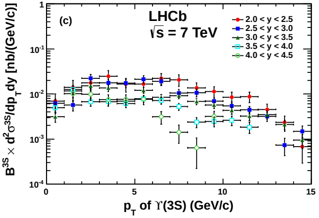
- N^{nS}: signal yield from fits
- $\mathcal{L}$: luminosity with uncertainty of 3.5%
- ε^{nS}: efficiencies estimated from Monte Carlo
- Δy, Δp_T: $\Delta y = 0.5$, $\Delta p_\mathrm{T} = 1\ \mathrm{GeV}/c$ for $2.0 < y < 4.5$, $p_\mathrm{T} < 15\ \mathrm{GeV}/c$

Results - Differential Cross-sections



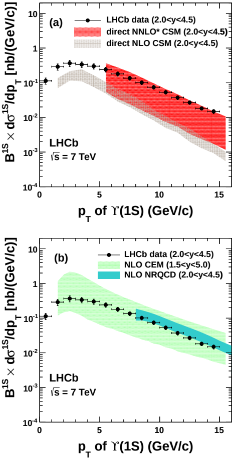


The first measurement of Υ production in the forward region at $\sqrt{s} = 7$ TeV!

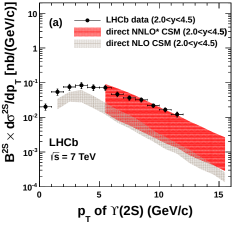


Comparison with Theory

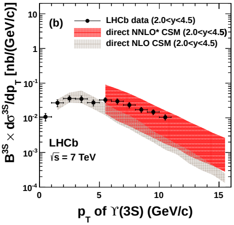
$\Upsilon(1S)$



$\Upsilon(2S)$



$\Upsilon(3S)$

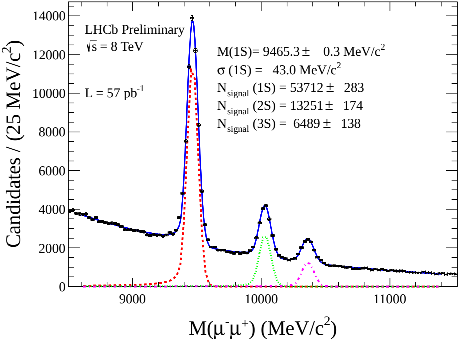


- General agreement with NNLO CSM, NLO NRQCD and NLO CEM
- NNLO CSM only calculate the direct production - feed-down information is important

NNLO CSM: Artoisenet et al, Phys.Rev.Lett.101,152001(2008)
NRQCD: Ma et al, Phys.Rev.Lett.106,042002(2011)
NLO CEM: Frawley et al, Phys.Rep.462,125(2008)

$\Upsilon(nS)$ with 8 TeV Data

LHCb-CONF-2012-025



- 57 pb^{-1} of early 2012, $\sqrt{s} = 8$ TeV
- Fitted resolution: 43 MeV/c^2 (47 MeV/c^2 in 2011)

Study on $\Upsilon(nS)$ polarisation is ongoing with the full 2011+2012 datasets.

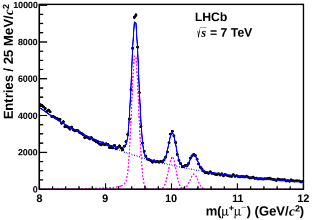
$\chi_b(1P)$ Production

JHEP 11(2012),31

In order to interpretate the cross-section and polarisation of bottomonia data, we need to better understand the Υ feed-down from higher states.

- $\chi_b(1P) \rightarrow \Upsilon(1S)\gamma \rightarrow \mu^+\mu^-\gamma$
- 32 pb^{-1} data from 2010, $\sqrt{s} = 7$ TeV
- $2.0 < y^{1S} < 4.5$, $6 < p_{\mathrm{T}} < 15$ GeV/c

$\Upsilon(1S)$ candidates:

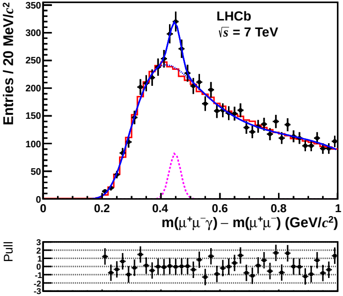


$$N_{\Upsilon(1S)} = 39635 \pm 252$$
$$M_{\Upsilon(1S)} = 9449.2 \pm 0.4\ \text{MeV}/c^2$$
$$\sigma_{\Upsilon(1S)} = 51.7 \pm 0.4\ \text{MeV}/c^2$$

Reconstruction of χ_b from $\Upsilon(1S)$:

- $p_{\mathrm{T}}^{\Upsilon(1S)} > 6$ GeV/c
- $9.36 < M(\mu\mu) < 9.56$ GeV/c^2
- $p_{\mathrm{T}}^{\gamma} > 0.6$ GeV/c^2
- $\cos\theta_\gamma^* > 0$, θ_γ^* is polar angle of γ in χ_b rest frame

Reconstructed $\chi_b(1P)$ Signal



$$\frac{dN}{dx} = A_1 \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\Delta M)^2}{2\sigma^2}}$$
$$+A_2(x-x_0)^{\alpha} e^{-(c_1 x + c_2 x^2 + c_3 x^3)},$$

Gaussian signal + background

$$N_{\chi_b(1P)} = 201 \pm 55$$

$$\Delta M = 447 \pm 4 \text{ MeV}/c^2$$

$$\sigma = 19.0 \pm 4.2 \text{ MeV}/c^2$$

- Clear $\chi_b(1P)$ signal
- Yet no hint for higher state ($\Delta M(\chi_b(2P)) \sim 800$ MeV$/c^2$)
- $\chi_{bJ}(J = 0, 1, 2)$ mass difference is comparible with resolution, so the observed signal is a mixture ($\Delta M_{2-1} \sim 20$ MeV$/c^2$, $\Delta M_{1-0} \sim 33$ MeV$/c^2$).

Determination of $\chi_b(1P)$ Yield

The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$:

$$f_{\chi_b \to \Upsilon} = \frac{N_{\text{rec}}(\chi_b)}{N_{\text{rec}}(\Upsilon)} \cdot \varepsilon_{\text{cond}}(\chi_b)$$

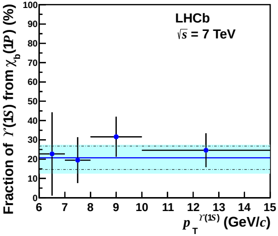
where $\varepsilon_{\text{cond}}(\chi_b)$ is the reconstruction efficiency after $\Upsilon(1S)$ is selected
$\Rightarrow \varepsilon_{\text{cond}}(\chi_b) = (9.4 \pm 0.1)\%$

$$\boxed{f_{\chi_b \to \Upsilon} = (20.7 \pm 5.7(\text{stat.}) \pm 2.1(\text{syst.})^{+2.7}_{-5.4}(\text{pol.}))\%}$$

Comparing with CDF result
($\sqrt{s} = 1.8$ TeV, $p_{\text{T}} > 8$ GeV$/c$):

$$f_{\chi_b \to \Upsilon} = (27.1 \pm 6.9 \pm 4.4)\%$$

CDF, Phys.Rev.Lett.84(2000)2094

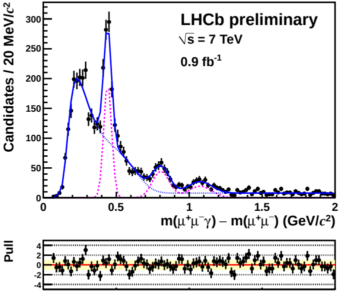


The ratio shows no dependence on p_{T}.

Observation of $\chi_b(3P)$

LHCb-CONF-2012-020

$\chi_b(nP) \to \Upsilon(1S)\gamma$, 0.9 fb^{-1} of 2011 data; $\sqrt{s} = 7$ TeV



- Signal yield: $N_{\chi_b(3P)} = 196 \pm 19$, significance $> 12\sigma$ First observed at LHCb!
- Fitted masses:

  ** Satistical uncertainties only*

  $$M_{\chi_b(1P)} = 9901 \pm 2 \text{ MeV}/c^2$$
  $$M_{\chi_b(2P)} = 10266 \pm 6 \text{ MeV}/c^2$$
  $$M_{\chi_b(3P)} = 10535 \pm 10 \text{ MeV}/c^2$$

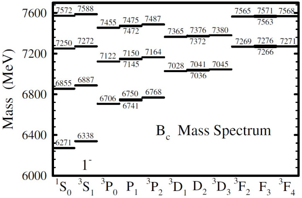
  consistent with ATLAS and D0 results.

ATLAS,arXiv:1112.5154

D0,arXiv:1203.6034

B_c^+ Studies

- B_c : unique meson family formed by two different heavy flavoured quarks
- Mass prediction: $6.2 - 6.4\ \mathrm{GeV}/c^2$ by potential models and Lattice QCD
- Produced mainly via gluon-gluon fusion at LHC, $\sigma \sim 0.4\mu\mathrm{b}$, one order of magnitude higher than Tevatron ($\sqrt{s} = 1.96$ TeV)
- Decay modes: $\bar{b}$ or c decay, annihilation; yet only a few channels observed experimentally.



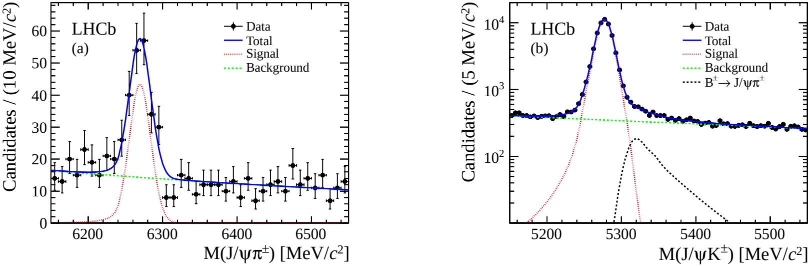
Godfrey,Phys.Rev.D 70,054017(2004)

- ✓ B_c^+ Production and Mass Measurement with $B_c^+ \to J/\psi\pi^+$
- ✓ Observation of $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$ decay

B_c^+ Production and Mass Measurement

arXiv:1209.5634

- $B_c^+ \to J/\psi\pi^+, J/\psi \to \mu^+\mu^-$, control channel $B^+ \to J/\psi K^+$
- Based on 0.37 fb^{-1} 2011 data ($\sqrt{s} = 7$ TeV), $p_\mathrm{T} > 4$ GeV$/c$, $2.5 < \eta < 4.5$



$N = 162 \pm 18$ $N = 56243 \pm 256$

- Signal fitted with double-sided Crystal Ball function
- Cabbibo suppressed background $B^+ \to J/\psi\pi^+$ for $B^+ \to J/\psi K^+$ is considered

B_c Production Cross-section

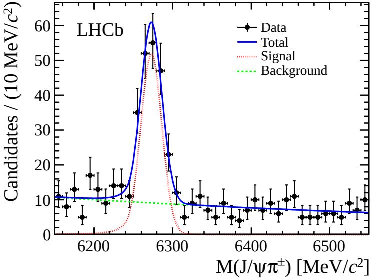
$$\boxed{\begin{aligned}&\frac{\sigma(pp \to B_c^+X)\cdot\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(pp \to B^+X)\cdot\mathcal{B}(B^+ \to J/\psi K^+)}\\ &= (0.68 \pm 0.10(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.05(\text{lifetime}))\%\end{aligned}}$$

- Efficiencies are calculated in individual (p_T, η) bin to avoid bias
- Systematics uncertainty is dominated by the contribution from B_c^+ lifetime (0.453 ± 0.041) ps, reducible with a better lifetime measurement

B_c Mass Measurement

To measure $M(B_c^+) - M(B^+)$, invariant masses of $J/\psi\pi^+$ and $J/\psi K^+$ are fitted simultaneously

$\Rightarrow$ systematic uncertainty is reduced.



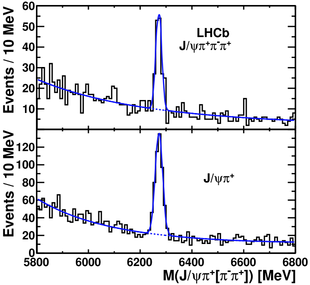
$$M(B_c^+) = 6273.7 \pm 1.3(\text{stat.}) \pm 1.6(\text{syst.})\ \text{MeV}/c^2$$

$$M(B_c^+) - M(B^+) = 994.6 \pm 1.3(\text{stat.}) \pm 0.6(\text{syst.})\ \text{MeV}/c^2$$

World best measurement!

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

Phys.Rev.Lett.108,251802(2012)



- 0.8 fb^{-1} data from 2011
- $N(B_c^+ \to J/\psi\pi^+\pi^+\pi^-) = 135 \pm 14$

  First observation!
- $N(B_c^+ \to J/\psi\pi^+) = 414 \pm 25$

$$\boxed{\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.41 \pm 0.30(\text{stat.}) \pm 0.33(\text{syst.})}$$

The main systematic uncertainty: model dependence of efficiency
Consistent with theoretical predictions 1.9 – 2.3 Likhoded and Luchinsky, Phys.Rev.D 81,014015(2010)

Onging Studies on B_c^+

- Lifetime measurement
  - $B_c^+ \to J/\psi(\mu\mu)\mu^+\nu$ and $B_c^+ \to J/\psi\pi^+$
- Search for new decay channels:
  - $B_c^+ \to B_s\pi^+, J/\psi K^+, \psi(2S)\pi^+, J/\psi D_s^+, \ldots$
- Search for excited states:
  - $B_c^{*+} \to B_c^+\gamma$, $B_c(2S) \to B_c^{*+}\pi^+\pi^-$

...

Summary

- LHCb brings great opportunities for bottomonia and B_c studies
  - Inclusive $\Upsilon(nS)$ differential cross-section measured, and updated with $\sqrt{s} = 8$ TeV data;
  - $\Upsilon(1S)$ feed-down from $\chi_b(1P)$ measured; New state of $\chi_b(3P)$ observed;

  - B_c^+ mass measured to the world best precision using $B_c^+ \to J/\psi\pi^+$, and its production measured w.r.t $B^+ \to J/\psi K^+$;
  - $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$ first observed;
- ... and many more going on!