Phenomenology 2012 Symposium
Pittsburgh, May 7-9, 2012

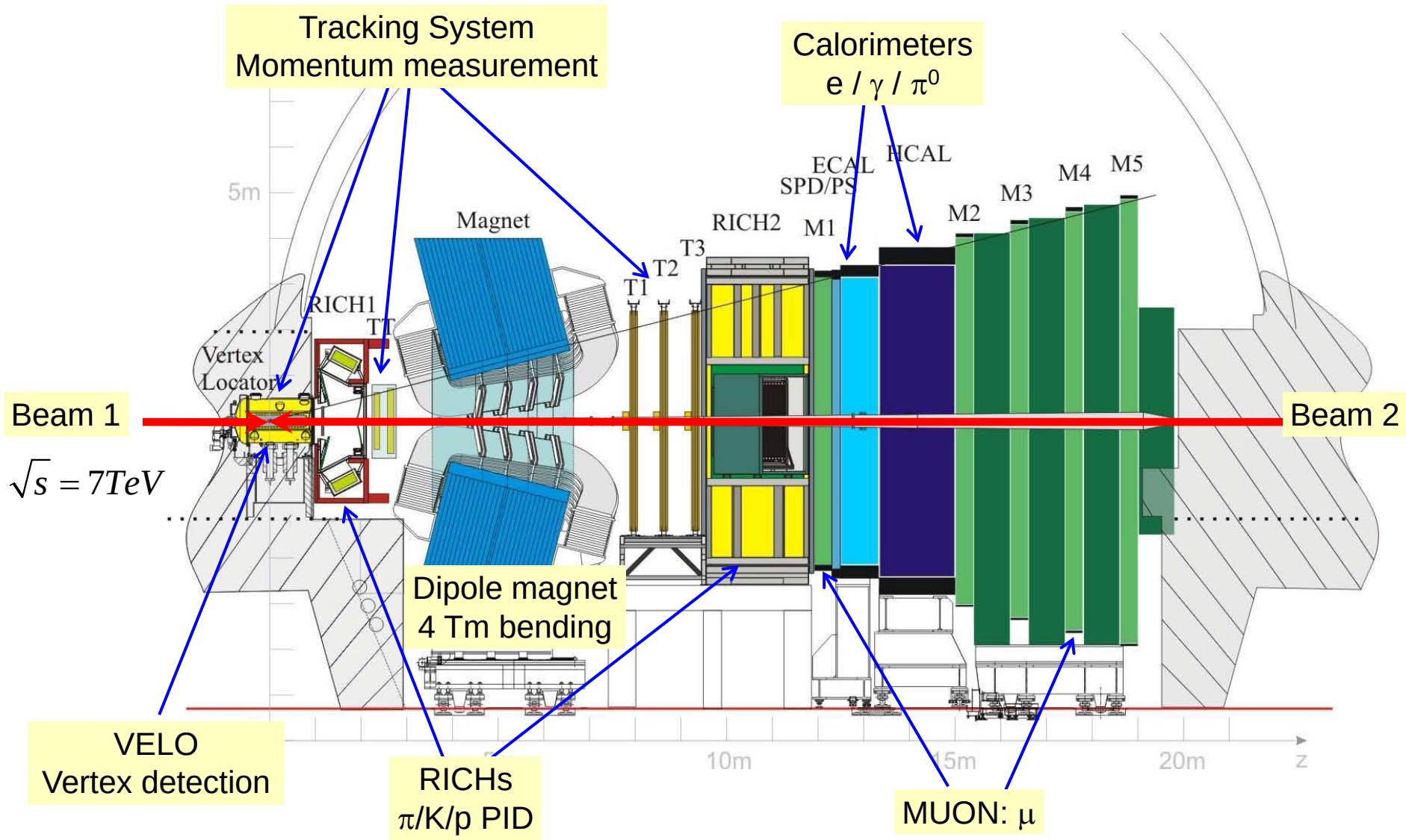
Heavy Flavor Production and Spectroscopy

(For The LHCb Collaboration)

Jianchun Wang

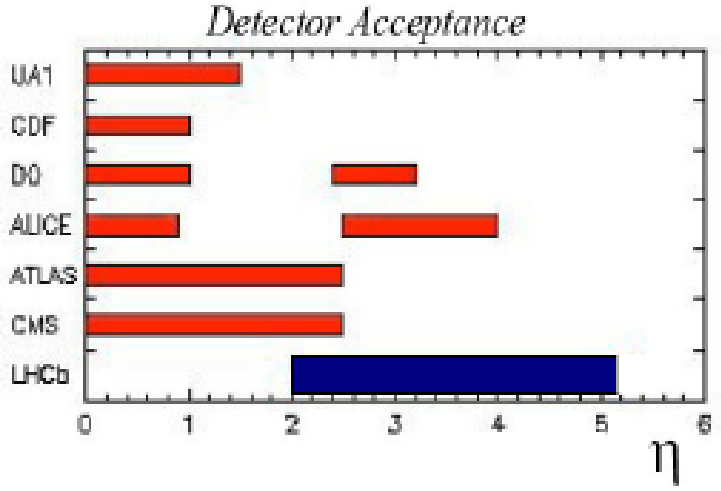
Syracuse University

The LHCb Forward Spectrometer



Heavy Flavor Physics at LHCb

- The LHCb detector is a forward spectrometer designed for CP violation and rare decays of b- or c- hadrons.
- Large heavy flavor production cross section in forward region ($2<\eta<5$).
  - $\sigma(c\bar{c})_{LHCb} = 1742 \pm 267\ \mu b$ (LHCb-CONF-2010-013)
  - $\sigma(b\bar{b})_{LHCb} = 75.3 \pm 5.4 \pm 13.0\ \mu b$ (Phys.Lett.B 694 (2010), 209)
- LHCb experiment accumulated ~1 fb^{-1} of data in pp collisions at 7 TeV, collected a sample rich in b- and c- hadrons.
- Measurements of heavy quark hadron production probe the dynamics of the colliding partons, and provide tests to different perturbative or non-perturbative QCD models.
- Copious heavy flavor hadron sample, large boost and forward coverage make LHCb unique in these studies.



ψ(2S) Production

- Reconstructed in ψ(2S) → $\mu^+\mu^-$, J/ψ($\mu^+\mu^-$)$\pi^+\pi^-$, two modes averaged.
- Pseudo decay time to separate prompt ψ(2S) from b-decayed products.

$$\sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01\ (\text{stat}) \pm 0.12\ (\text{syst})^{+0.20}_{-0.40}\ (\text{pol})\ \mu\text{b}$$

- Prompt ψ(2S) has negligible feed down from higher mass charmonia. Thus the production cross section can be directly compared with QCD prediction of direct production.
- The spectrum agrees with NRQCD predictions (*arXiv:hep-ph/1012.1030, PRL 106 (2011) 022003, PRL 101 (2008) 152001, EPJ C61 (2009) 693*).

$$\sigma_b(\psi(2S)) = 0.25 \pm 0.01\ (\text{stat}) \pm 0.02\ (\text{syst})\ \mu\text{b}.$$

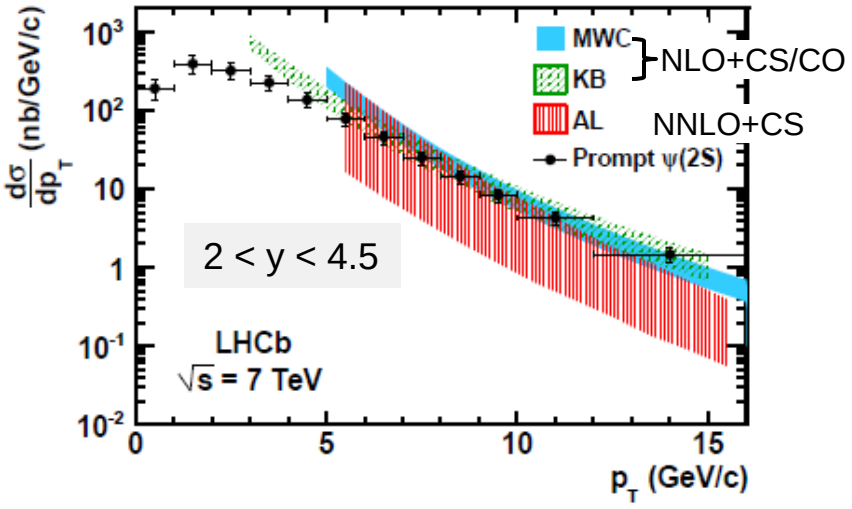
- QCD prediction is based on FONLL approximation that was for $b\bar{b}$ production (*JHEP 9805 (1998) 007, JHEP 0407 (2004) 033*) , consistent with the measurements.
- Combining with LHCb J/ψ measurement,

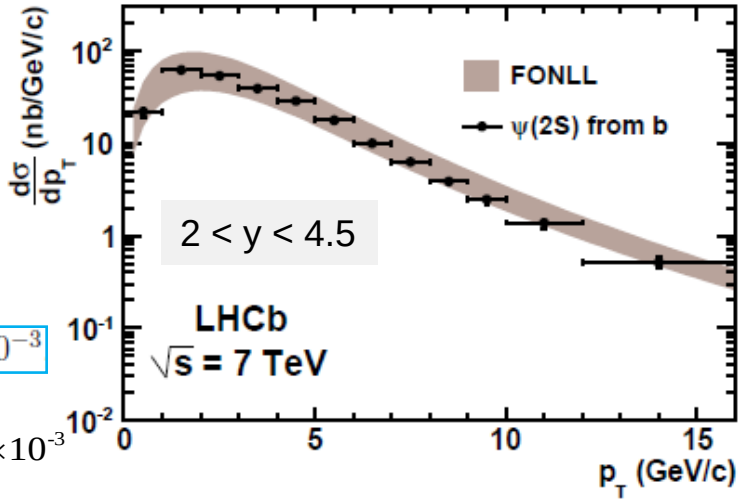
$$\mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06\ (\text{stat}) \pm 0.16\ (\text{syst}) \pm 0.24\ (\text{BF})) \times 10^{-3}$$

$$\mathcal{B}(b \to \psi(2S)X) = (3.08 \pm 0.12(stat \oplus sys) \pm 0.13(the) \pm 0.42(BF)) \times 10^{-3}$$

CMS, JHEP 02 (2011) 11

36 pb^{-1} LHCB-PAPER-2011-045



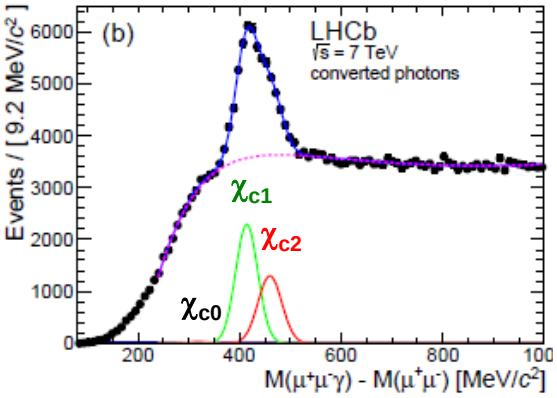


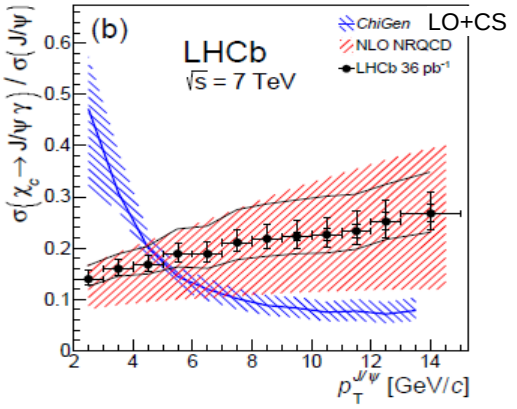
Direct χ_c Production

- Reconstructed in $\chi_{c0,1,2} \rightarrow J/\psi(\mu^+\mu^-)\,\gamma$. Psudo decay time $t_z < 0.1$ ps to suppress b-decay products.

36 pb^{-1} [LHCB-PAPER-2011-030]

- Converted or non-converted photon reconstructed at calorimeter.
- The combined χ_c differential cross section ratio over J/ψ is measured.
- Agree with CDF (*PRL 79 (1997) 578*), but different trend.
- Described well by NLO NRQCD (*PRD 83 (2011) 111503*), not by ChiGen (*projects.hepforge.org/superchic/chigen.html*).

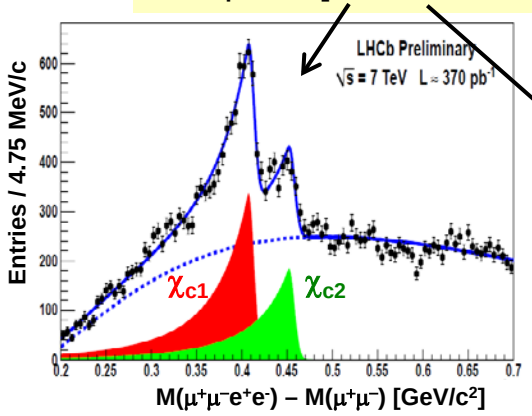


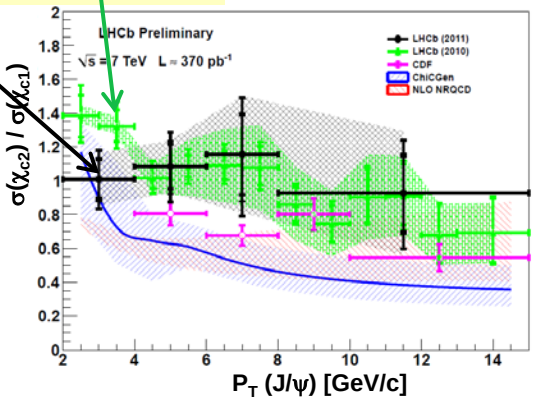


36 pb^{-1} [LHCB-PAPER-2011-019]

370 pb^{-1}, [LHCB-CONF-2011-062]

- Converted photon is reconstructed from two e tracks.
- Lower efficiency but better separation between χ_{c1} and χ_{c2} to measure the ratio of two production cross section.
- The measurements are consistent, and agree with both predictions with large uncertainty.





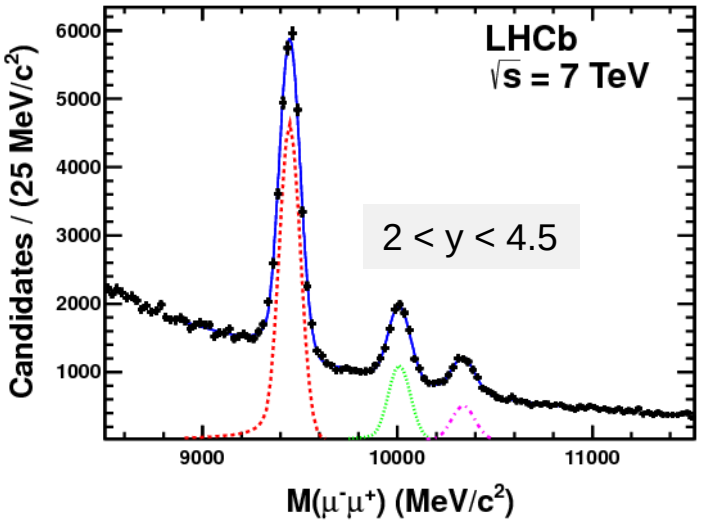
Upsilons Production

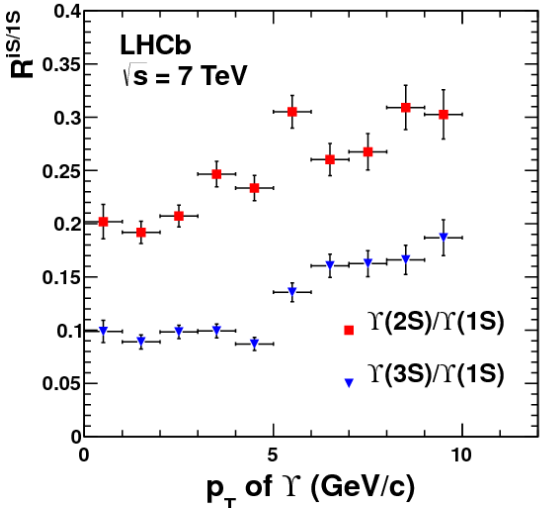
- Reconstruct $\Upsilon(nS) \to \mu^+\mu^-$ modes for n=1,2,3.

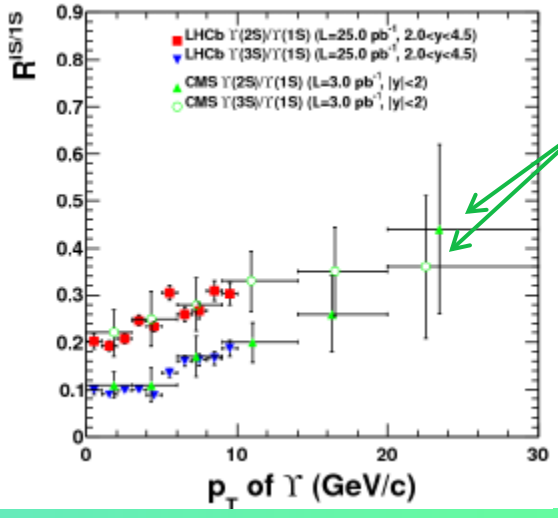
$$\sigma(pp \to \Upsilon(1S)\,X) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 2.29 \pm 0.01 \pm 0.10\ ^{+0.19}_{-0.37}\ \text{nb}$$
$$\sigma(pp \to \Upsilon(2S)\,X) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.562 \pm 0.007 \pm 0.023\ ^{+0.048}_{-0.092}\ \text{nb}$$
$$\sigma(pp \to \Upsilon(3S)\,X) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.283 \pm 0.005 \pm 0.012\ ^{+0.025}_{-0.048}\ \text{nb}$$

- QCD calculations are more robust due to heavier bottom quark mass.
- P_T spectra agree with theoretical predictions (*arXiv:0806.1013, EPJ C61 (2009) 693, PRL 106 (2011) 042002*)
- The differential production ratio of Υ(2S) and Υ(3S) over Υ(1S) agree with recent CMS measurements.
- The measurement is in pipeline for the 2012 data.

25 pb $^{-1}$ [LHCB-PAPER-2011-036]







CMS
PRD 83,112004 (2011)

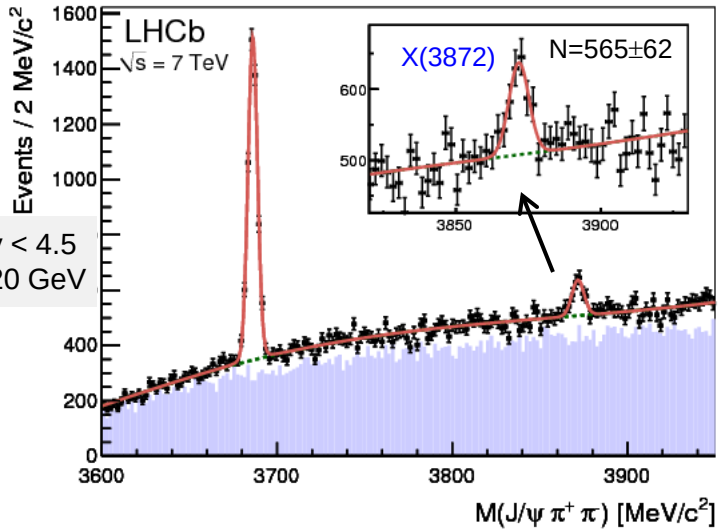
X(3872) & X(4140)

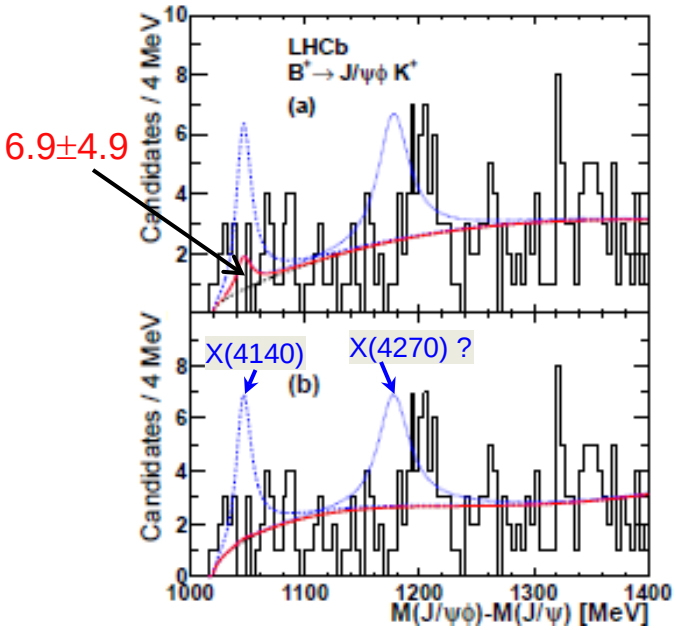
35 pb $^{-1}$ [LHCB-PAPER-2011-034]

- X(3872) was first observed by Belle (*PRL 91 (2003) 262001*).
- Its quantum numbers are constrained to $J^{pc} = 2^{-+}, 1^{++}$ by CDF (*PRL 98 (2007) 13202*). The nature is unclear: $c\bar{c}$, $D^{*0}\bar{D}^{0}$ molecule, tetraquark state.
- Measured mass agree with current world average

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

  $\sigma_{X(3872)}\,\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-) = 4.7 \pm 1.1 \pm 0.7$ nb
- NRQCD model predicts13.0 $\pm$ 2.7 nb for $c\bar{c}$ production, 2.8σ higher (*PRD 81 (2010) 114018*).





370 pb $^{-1}$ [LHCB-PAPER-2011-033]

- CDF (arXiv:1101.6058) reported a 5σ narrow J/$\psi\phi$ structure at ~4143 MeV/c^2, in 115$\pm$12 $B^+\to J/\psi\phi K^+$ samples: N=19$\pm$6.
- LHCb reconstructed 346$\pm$12 $B^+\to J/\psi\phi K^+$ signals with little bkg. No X(4140) signal found, 2.4σ disagreement with CDF.

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07$$ at 90% C.L.

Double Charm Production

- Measure production rate of $J/\psi C$, CC, $C\bar{C}$ ($C = D^0, D^+, D_s^+, \Lambda_c^+$) from pp collisions.
- Production mechanisms:
  - Gluon fusion ($gg \to J/\psi J/\psi$, $J/\psi c\bar{c}$, $c\bar{c}c\bar{c}$), agree with the LHCb J/ψ pair production measurement (*PLB 707 (2012) 52*).
  - Intrinsic charm (IC) content of proton (*PLB 93 (1980) 451*). Prediction has large uncertainty.
  - Double parton scattering (DPS): two independent scattering processes. Effective cross section from Tevatron ~14.5 mb. (*PRL 107 082002, PLB 705 116, arXiv:1106.2184, arXiv:1111.3255*)
- Observe no significant azimuthal or rapidity correlation within each pair.

355 pb $^{-1}$
[LHCb-paper-2012-003]

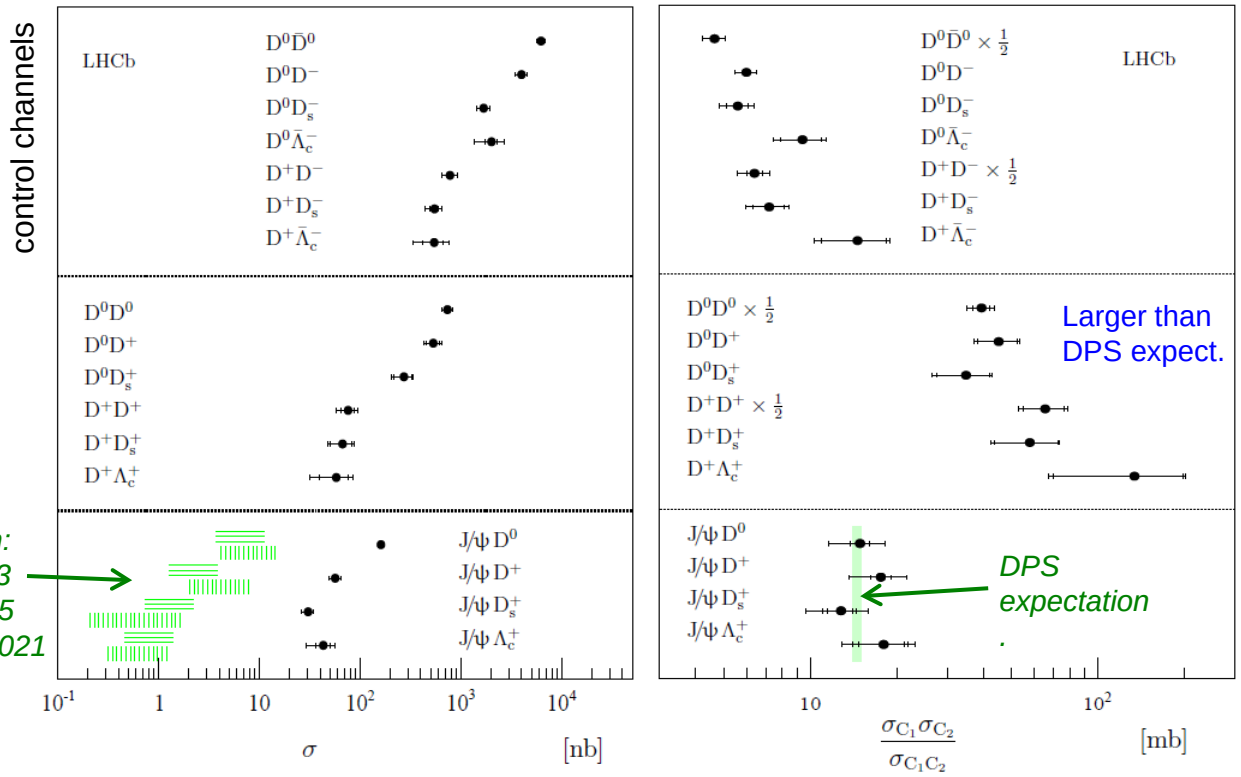
Modes

$J/\psi \to \mu^+\mu^+$
$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+$
$D_s^+ \to K^-K^+\pi^+$
$\Lambda_c^+ \to pK^-\pi^+$

$P_T^{J/\psi} < 12$ GeV/c
$3 < P_T^C < 12$ GeV/c
$2 < y < 4$

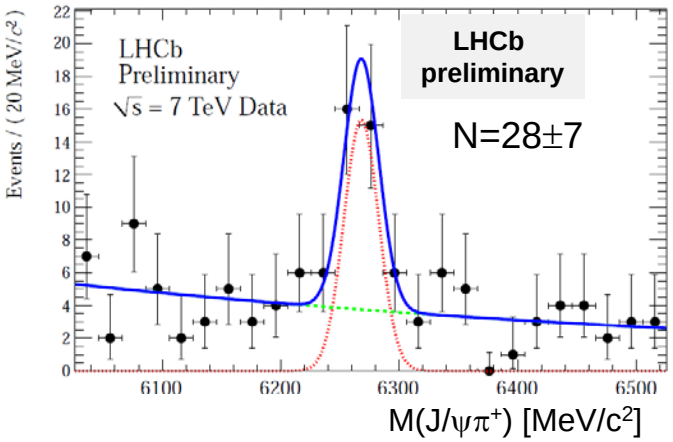
Both from the same PV.
Signal significance > 5σ.

Gluon fusion:
EPJ C61 693
PRD 57 4385
PRD 73 074021



B_c Meson Measurements

35 pb^{-1} [LHCB-CONF-2011-027]



- B_c^+ was discovered in $B_c^+ \to J/\psi l\nu$ X mode by CDF.
- The only exclusive mode observed before: $B_c^+ \to J/\psi\,\pi^+$.
- LHCb measures its mass in $J/\psi\,\pi^+$ mode

$$M(B_c^+) = 6268.0 \pm 4.0 \pm 0.6\ MeV/c^2$$ preliminary

(compare to world average 6277±6 MeV/c^2).

- For $P_T(B)>4$GeV, $2.5<\eta<4.5$, the production cross section rate is measured (33 pb^{-1}, preliminary, LHCB-CONF-2011-017)

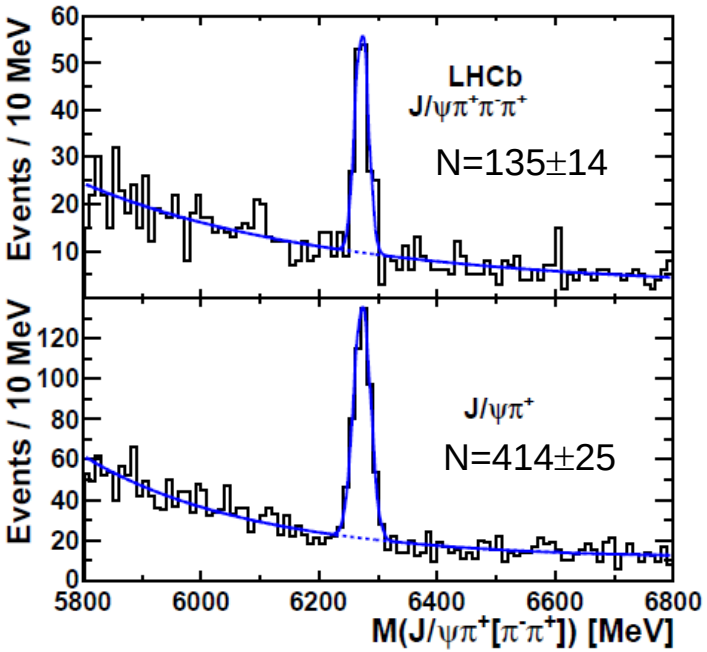
$$R_{c+} = \frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+ \to J/\psi K^+)} = (2.2 \pm 0.8 \pm 0.2)\%,$$

- LHCb has first observation of $B_c^+ \to J/\psi\,\pi^+\pi^+\pi^-$ mode.
- The relative BR is measured

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

consistent with theoretical predictions (*PRD81 (2010) 014015*)

0.8 fb^{-1} [LHCB-PAPER-2011-044]



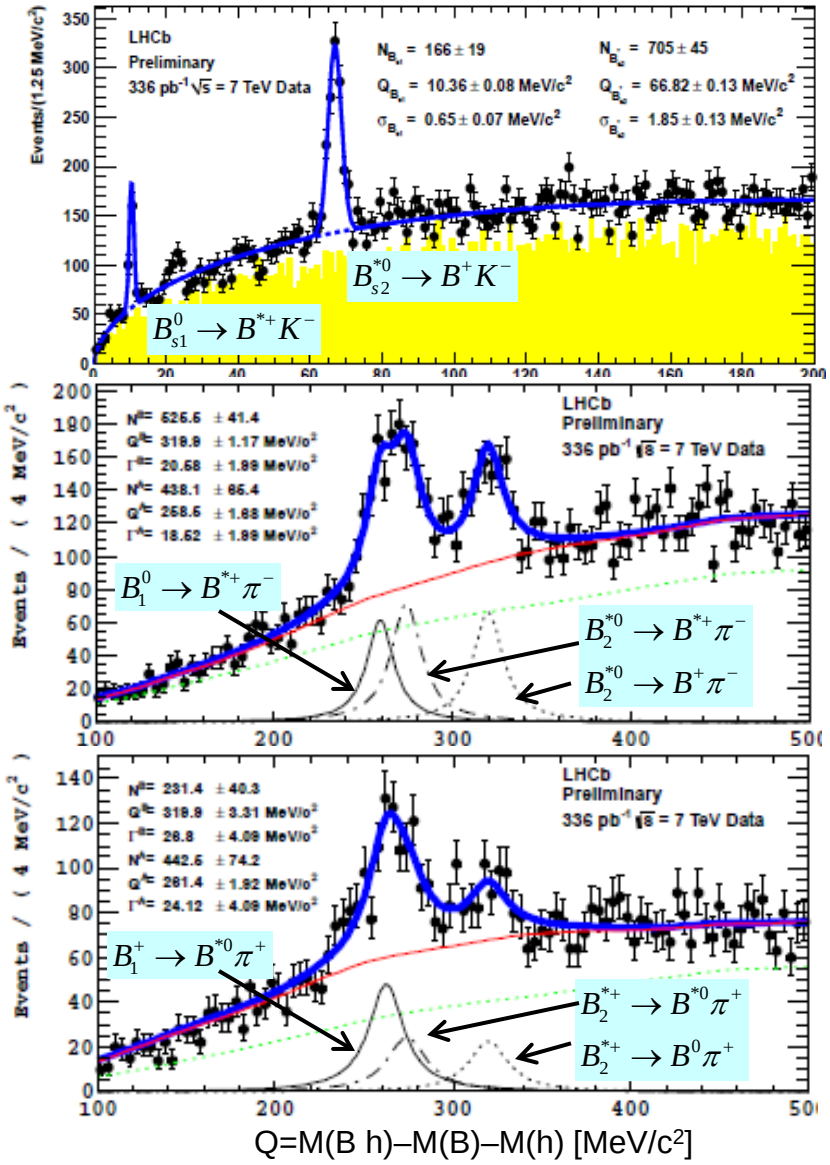
Observations of $B_{(s)}^{**}$ Mesons

336 pb^{-1} [LHCB-CONF-2011-053]

- The properties of the excited $B_{(s)}^{**}$ Mesons predicted by HQET.
- Some of these states were found at Tevatron.
- LHCb searches in $B^{+/0}h^-$ channels: B^+K^-, $B^+\pi^-$, $B^0\pi^-$.
- Photon from $B^* \to B\gamma$ is not reconstructed, resulting in shifted peak in Q distribution.
- No direct determination of quantum numbers, matching to expected states from HQET.
- First observation of the orbitally excited B_1^+ and B_2^{*+}

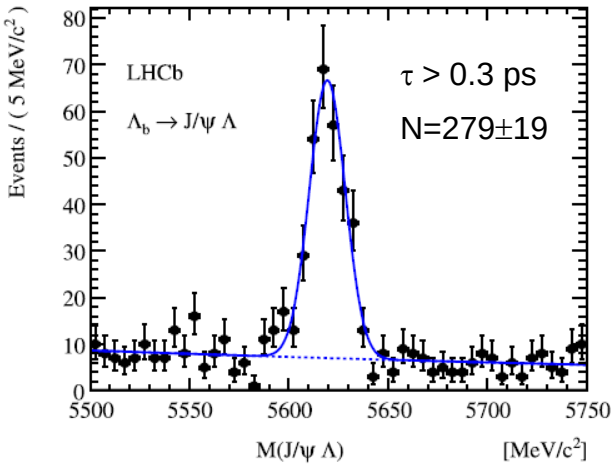
$$
\begin{aligned}
M_{B_{s1}^0} &= (5828.99 \pm 0.08_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,, \\
M_{B_{s2}^{*0}} &= (5839.67 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,, \\
M_{B_1^0} &= (5724.1 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,, \\
M_{B_1^+} &= (5726.3 \pm 1.9_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,, \\
M_{B_2^{*0}} &= (5738.6 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,, \\
M_{B_2^{*+}} &= (5739.0 \pm 3.3_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3^{B\,\text{mass}}_{\text{syst}})\ \text{MeV}/c^2\,,
\end{aligned}
$$

preliminary



Bottom Baryons (I)

35 pb^{-1} [PLB 708 (2012) 241]

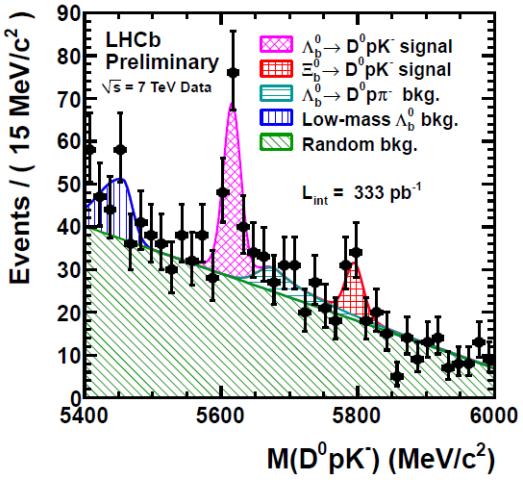


- LHCb observed 4 of the seven ground state b-Baryons.
- Λ is observed in several channels. It is mass is measured in J/ψ Λ mode:

$$M(\Lambda_b^0) = 5619.19 \pm 0.70 \pm 0.30 MeV$$

consistent with the current world average value 5620.2±1.6 MeV with better precision.

0.33 fb^{-1} [LHCB-CONF-2011-036]

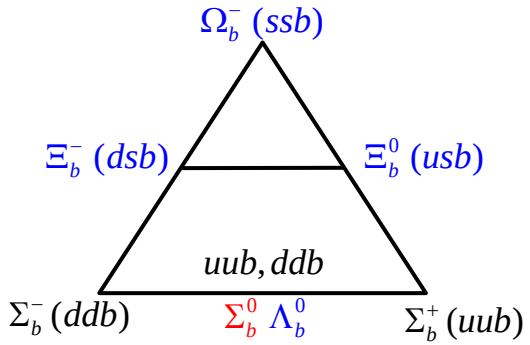


- Ξ_b^0 is observed in D^0pK^- mode with 2.6σ significance:

$$M(\Xi_b^0) = 5802.0 \pm 5.5 \pm 1.7 MeV$$ preliminary

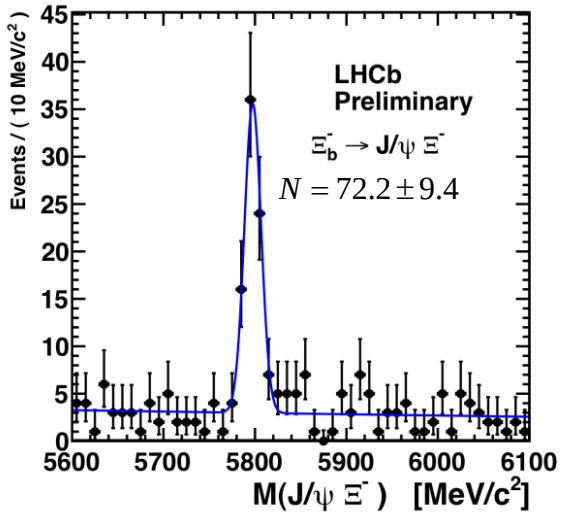
- The value is consistent with CDF measurement: 5785.8±5.0±1.3 MeV (*PRL 107, 102001 (2011)*)

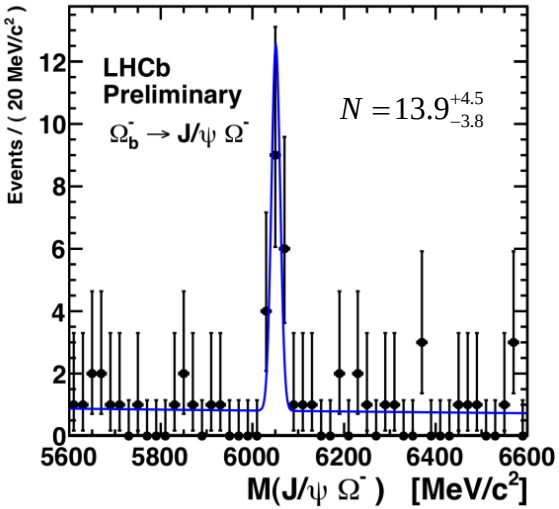
$$\Xi_b^0 \to D^0 pK^-$$
$$N = 26.9 \pm 10.0$$



Bottom Baryons (II)

0.62 fb^{-1} [LHCB-CONF-2011-060]





- LHCb observed Ξ_b^- and Ω_b^- in modes

$$\Xi_b^- \to J/\psi\,\Xi^-,\ \Xi^- \to \Lambda^0\pi^-$$
$$\Omega_b^- \to J/\psi\,\Omega^-,\ \Omega^- \to \Lambda^0 K^-$$

  where $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$.

- Their masses are measured

$$M(\Xi_b^-) = 5796.5 \pm 1.2 \pm 1.2 MeV$$
$$M(\Omega_b^-) = 6050.3 \pm 4.5 \pm 2.2 MeV$$

preliminary

- LHCb Ξ_b^- mass measurement is consistent with CDF & D0 with better precision.
- LHCb Ω_b^- mass has better precision.
- Ω_b^- mass values measured by CDF & D0 differ by ~110 MeV. The LHCb measured mass agrees with the CDF value.

	$M(\Xi_b^-)$	$M(\Omega_b^-)$	
DØ	5774 ± 19	6165 ± 16	← *PRL 101, 232002 (2008)*
CDF	5790.9 ± 2.7	6054.4 ± 6.9	← *PRD 80, 072003 (2009)*
PDG	5790.5 ± 2.7	6071 ± 40	
LHCb	5796.5 ± 1.7	6050.3 ± 5.0	

Summary

- The LHCb detector is in good shape and performs well.
- LHCb have collected ~1 fb^{-1} data at 7 TeV.
- In year 2012, ~1.5fb^{-1} data at 8 TeV is expected.
- Many interesting heavy flavor hadron results are produced including
  - Prompt $\psi(2S)$ production and production from b-decays.
  - Prompt χ_{cj} production.
  - $\Upsilon(nS)$ production.
  - Double charm production.
  - Search for X(3872) & X(4140) from b-decays.
  - B_c^+ mass and production, first observation of $B_c^+ \to J/\psi\, \pi^+\pi^+\pi^-$ mode.
  - First observation of B_1^+ and B_2^{*+} states, mass measurements of $B_{(s)}^{**}$ states.
  - Best or compatible mass measurements: Λ_b^0 , Ξ_b^0, Ξ_b^-, Ω_b^-.
- More new measurements or updates with more data are coming.