Production and Spectroscopy at LHCb

International Conference of New Frontiers in Physics

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INFN Cagliari

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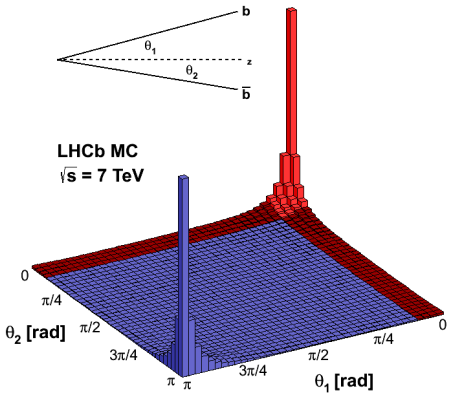
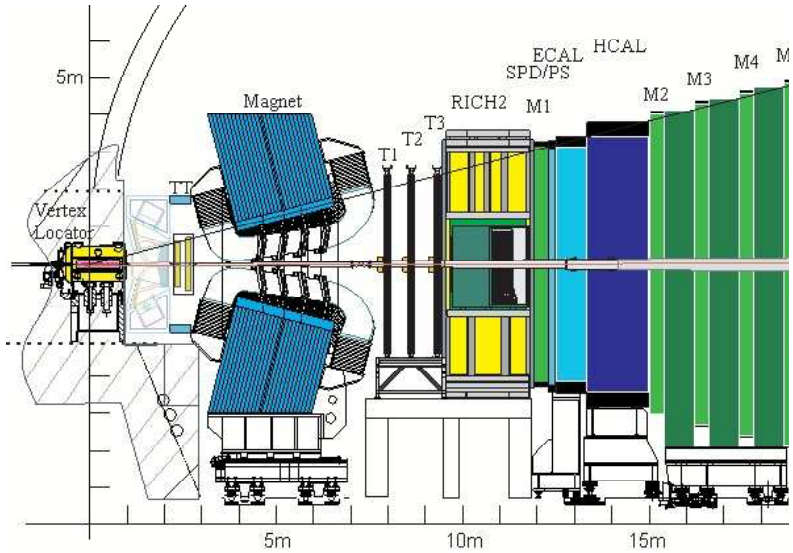
Outline

1. The LHCb detector
2. Overview of heavy flavour physics at LHCb
3. Results
   - b-hadrons
   - c-hadrons
   - Quarkonia
4. Conclusions

The LHCb detector





- Multi-stage trigger:
  - First level is hardware
  - Subsequent two levels are software
- Performances:
  - $\Delta p/p = 0.35\% - 0.55\%$
  - Mass resolution$= 10 - 25\,\mathrm{MeV/c^2}$
  - ECAL $\sigma(E)/E = 10\%(E/\mathrm{GeV})^{-1/2} \oplus 1\%$
  - Muon ID: $\epsilon(\mu \to \mu) = 97\%$, *mis*ID$(\pi \to \mu) = 1 - 3\%$
  - Proper time resolution: $30 - 50\,\mathrm{fs}$

Heavy Flavour Physics at LHCb

- Valuable tests of perturbative QCD, non-perturbative QCD and underlying event modelling in a kinematic region complementary to ATLAS and CMS
- Large production cross sections ($2 < y < 6$) at $\sqrt{s} = 7\,\mathrm{TeV}$:
  - $\sigma(c\bar{c}) = 1742 \pm 267\,\mu\mathrm{b}$ (LHCb-CONF-2010-013)
  - $\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\,\mu\mathrm{b}$ (Phys.Lett.B 694(2010), 209)
- Presenting results from:
  - 2010 run: $37\,\mathrm{pb}^{-1}$
  - 2011 run: $1\,\mathrm{fb}^{-1}$

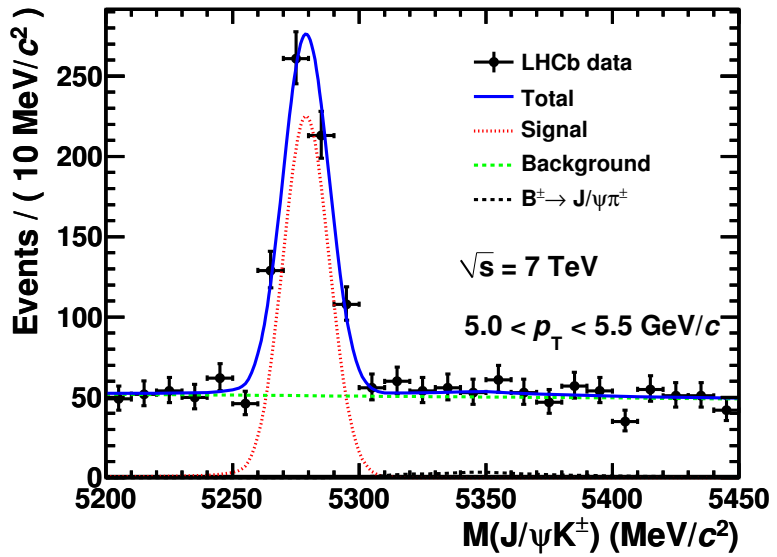
Uncertainty on integrated luminosity for all analyses is 3.5%
(J. Instrum. 7 (2012) P01010)

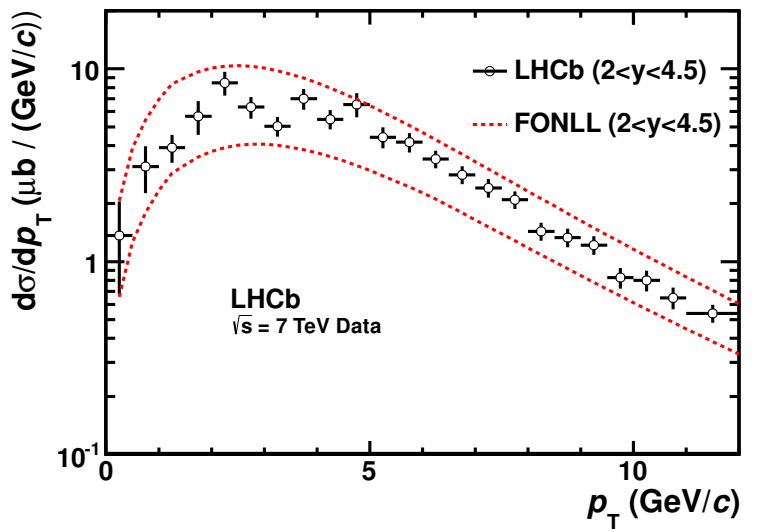
Now running at $8\,\mathrm{TeV}$, more than $500\,\mathrm{pb}^{-1}$ on tape

B^+ production

J. High Energy Phys. 04 (2012) 093

- Powerful test of QCD@NLO
- Cross section measurement:
  - $\sigma(pp \to B^{\pm}X)$ and $d\sigma/dp_T$
  - Data from 2010 run, $35\,\mathrm{pb}^{-1}$
  - $\sim 9K$ $B^{\pm} \to J/\psi(\mu\mu)K^{\pm}$ selected candidates within $2 < y < 4.5$ and $0 < p_T < 15\,\mathrm{GeV}/c$ fiducial region
  - Main systematics are $\epsilon_{tracking}$ (4%) and μ ID (2.5%)
- Comparison to FONLL prediction
  - JHEP 05(1998) 007
  - Assumes $f_{b\to B^{\pm}} = 40.1 \pm 1.3\%$
  - Uncertainties: b mass, CTEQ6.6 PDFs, scales
- $\sigma(pp \to B^{\pm}X) = 41.4 \pm 1.5_{stat} \pm 3.1_{syst}\ \mu\mathrm{b}$





First measurement of B production in the forward region
Currently being updated with more luminosity + B_s and B^0

B_c^+ to B^+ production ratio (preliminary)

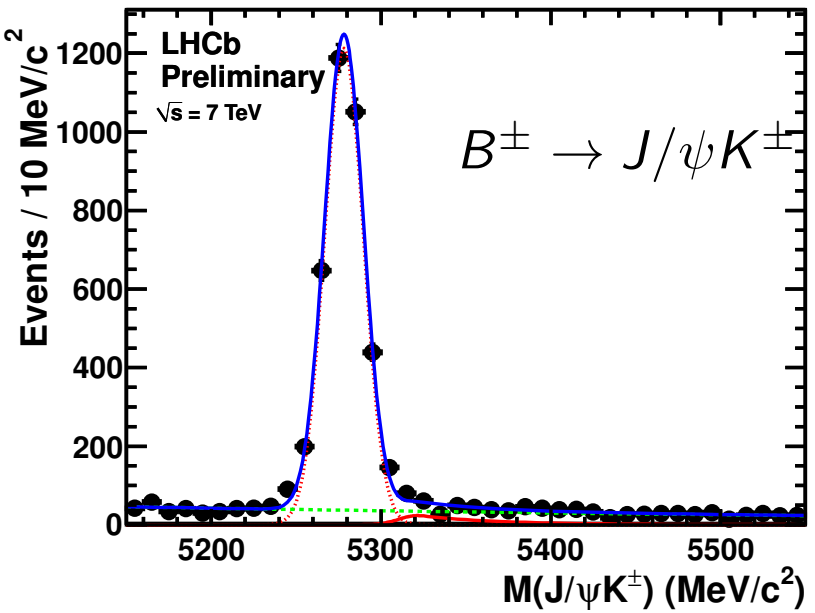
- Measurement of B_c^+ mass, lifetime and production constrains QCD calculations
- First B_c^+ observation by CDF (PRL: 81(1998)2432)
- Absolute $\mathcal{B}$ not measured yet

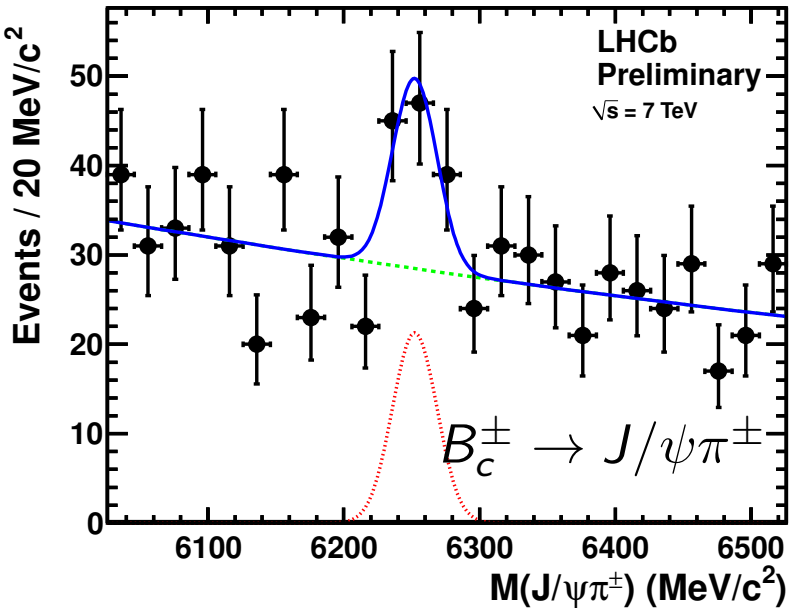
LHCb measurement performed with 2010 data, with $B_{(c)}^+ p_T > 4\,\mathrm{GeV}/c$ and $2.5 < \eta < 4.5$

$$R_c^+ = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi K^+)}$$

$$= (2.2 \pm 0.8_{stat} \pm 0.2_{syst})$$

LHCb-CONF-2011-017

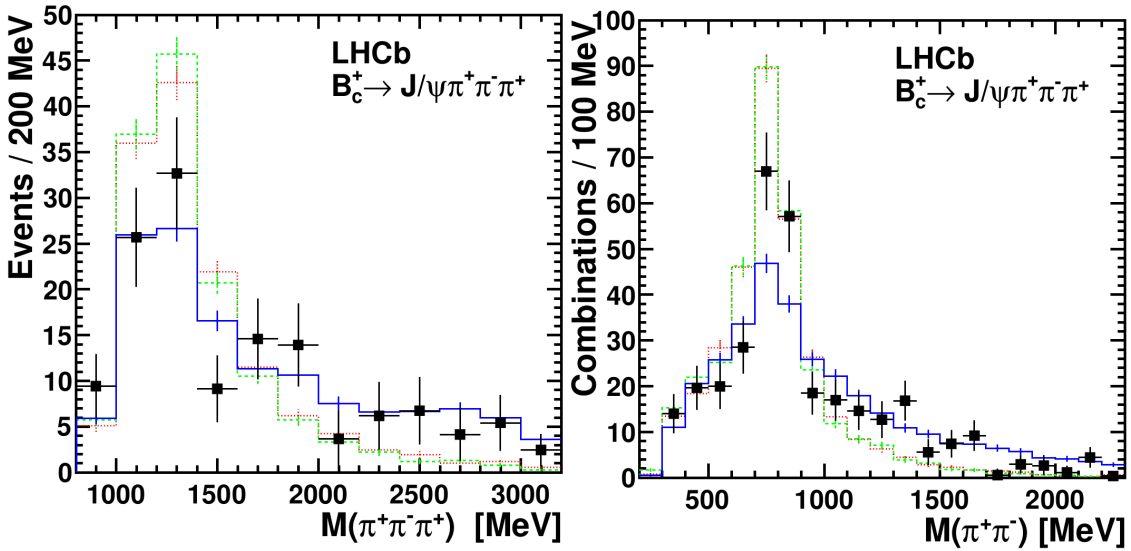


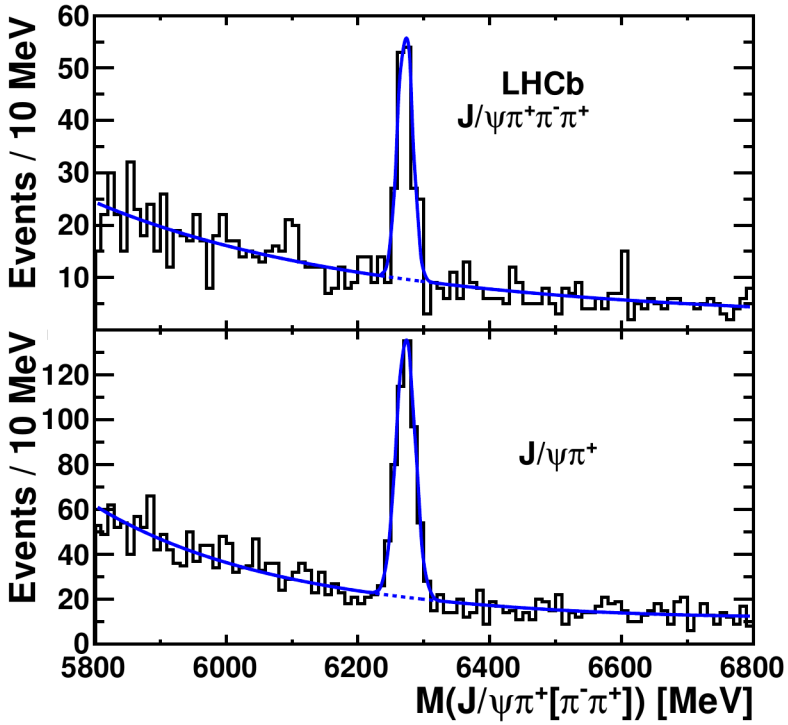


First observation of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

Resonant structure dominated by
$B_c \to J/\psi a_1^+,\ a_1^+ \to \rho^0\pi^+$

Phase space
Phase space with polarisation, Phys. Rev. D42 (1990) 3732
BLL, Phys. Rev. D81 (2010) 014015 and arXiv:1104.0808





$$\frac{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.41 \pm 0.30_{stat} \pm 0.33_{syst}$$

In agreement with theoretical predictions

LHCB-PAPER-2011-044, *accepted by PRL*

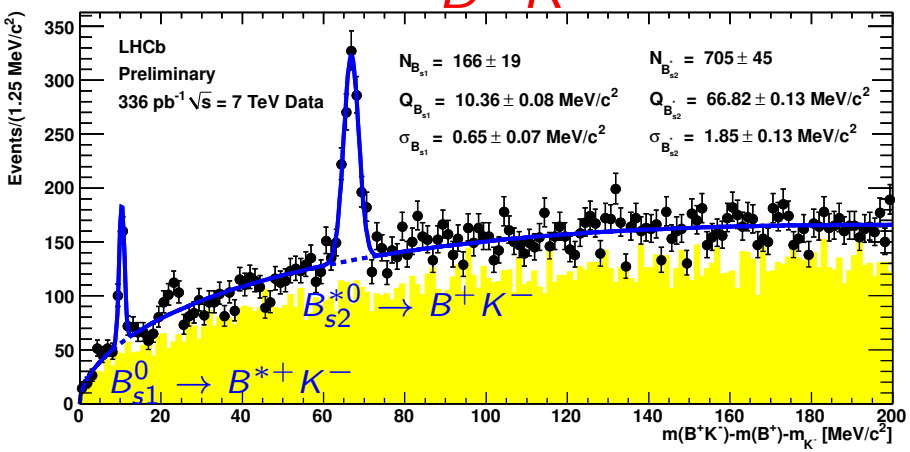
$B^{**}_{(s)}$ observation (preliminary)

LHCb-CONF-2011-053

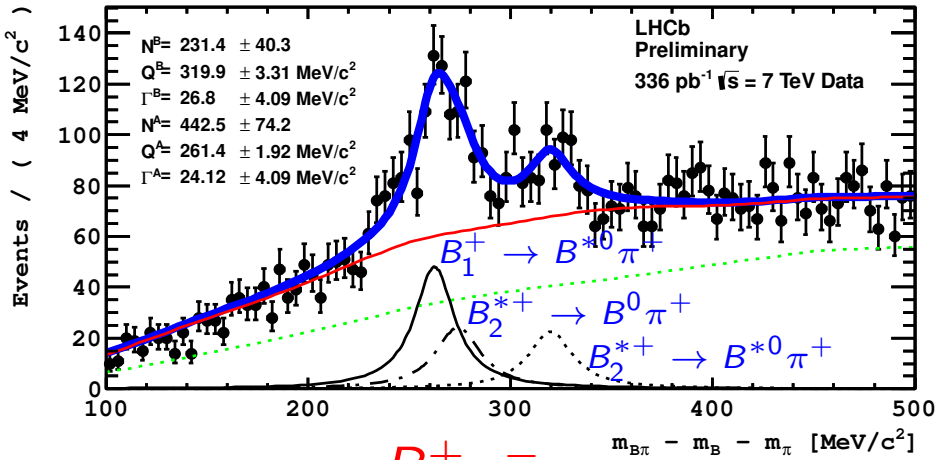
- Excited $B_{(s)}$ mesons ($L = 1$) are predicted by Heavy Quark Effective Theory
  (PRD: 64(2001)114004)
- $B_1(5721)^0, B_2^*(5830)^0, B_{s1}(5830)^0, B_{s2}(5840)^0$ observed by CDF and D0
  (PRL: 102(2009)102003, 99(2007)172001, 100(2008)082001/082002)

- Search for $B^{**} \to Bh$ and $B^{**} \to B^*(B\gamma)h$ with 336 pb^{-1} from 2011 run
- Signal peaks are expected in relative to threshold invariant mass $Q = M(Bh) - M(B) - M(h)$

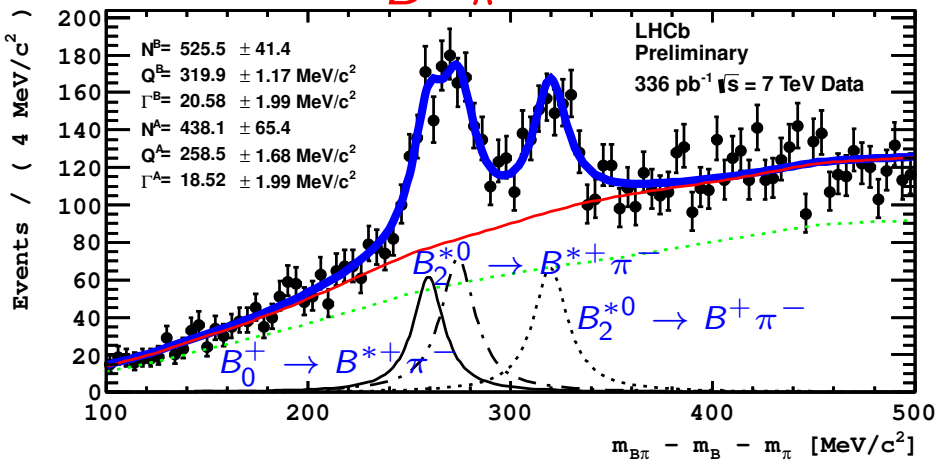
B^+K^-



$B^0\pi^-$



$B^+\pi^-$



$B^{**}_{(s)}$ observation (preliminary)

LHCb-CONF-2011-053

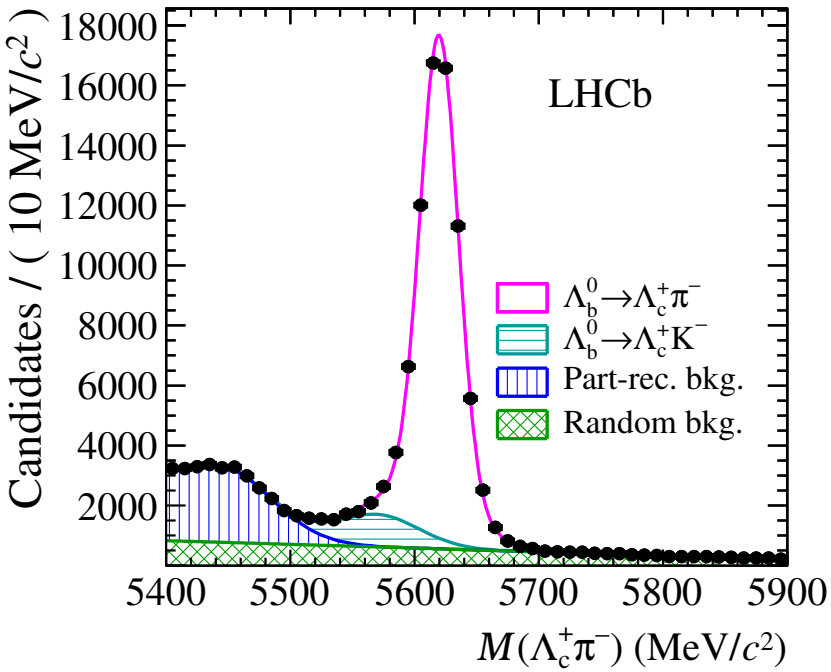
Measured Q values are translated into masses:

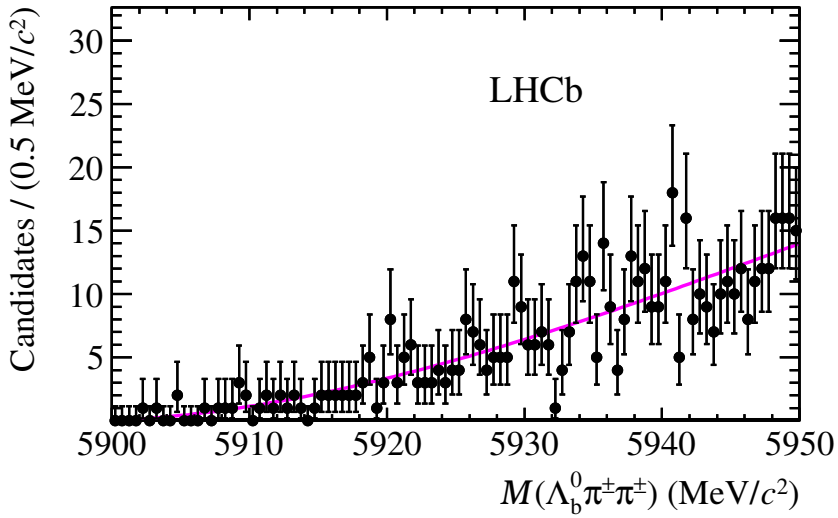
$$
\begin{aligned}
M_{B^0_{s1}} &= (5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2 \\
M_{B^{*0}_{s2}} &= (5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.29^{B\,\rm mass}_{\rm syst})\ \ {\rm MeV}/c^2 \\
M_{B^0_1} &= (5724.1 \pm 1.7_{\rm stat}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

- First measurement of the B^{*+}_2 and B^+_1 masses
- Masses of isospin partners are compatible
- Good agreement with HQET prediction
- Being updated with more luminosity

First observation of Λ_b^{0*}

- Quark model predict two orbitally excited Λ_b^0 states at $J^P = 1/2^-$ and $J^P = 3/2^-$
- Search for new states in the $\Lambda_b^0 \pi^+ \pi^-$ mass spectrum
- Data from 2011 run, $1\,\mathrm{fb}^{-1}$
  arxiv:1205.3452, *submitted to PRL*





First observation of Λ_b^{0*}

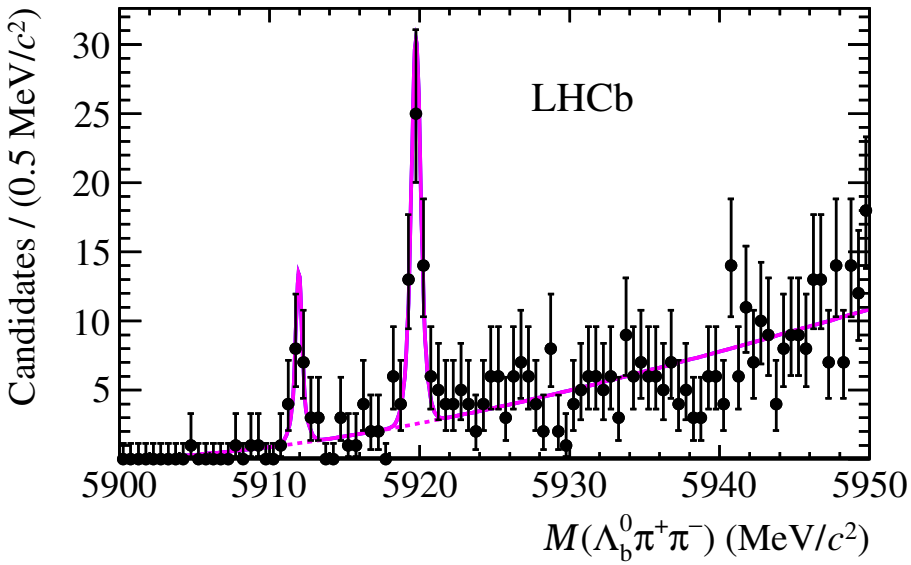
- Observation of two narrow states with masses:

$$5911.95 \pm 0.12_{stat} \pm 0.03_{syst} \pm 0.66_{\Lambda_b^0 \text{ mass}}$$

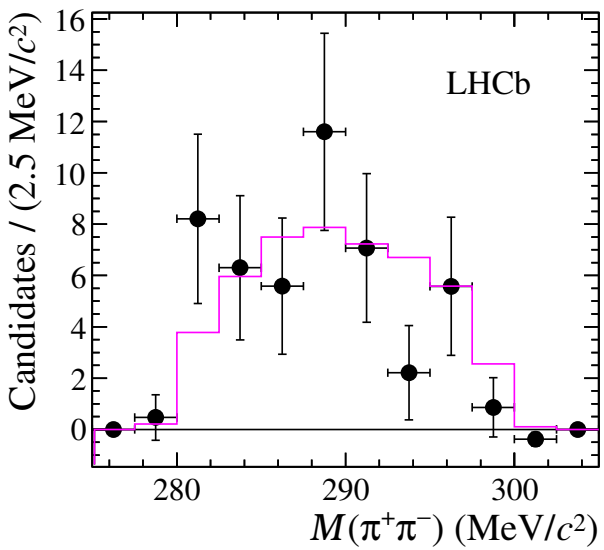
$$5919.76 \pm 0.07_{stat} \pm 0.02_{syst} \pm 0.66_{\Lambda_b^0 \text{ mass}}$$

- Interpreted as $\Lambda_b^{*0}(5912)$ and $\Lambda_b^{*0}(5920)$

arxiv:1205.3452, *submitted to PRL*



Background subtracted



$\Lambda_b^0, \Xi_b^0 \to D^0 p K^-, D^0 p \pi^-$ (preliminary)

- Measured ratio:

$$\frac{\mathcal{B}(\Lambda_b^0 \to D^0 p \pi^-) \times \mathcal{B}(D^0 \to K^- \pi^+)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)} = 0.119 \pm 0.006_{stat} \pm 0.013_{syst}$$

- First observation of $\Lambda_b^0 \to D^0 p K^-$: $\frac{\mathcal{B}(\Lambda_b^0 \to D^0 p K^-)}{\mathcal{B}(\Lambda_b^0 \to D^0 p \pi^-)} = 0.112 \pm 0.019_{stat}{}^{+0.011}_{-0.014}$

- Observation of Ξ_b^0: $\frac{f_{b\to\Xi_b^0} \times \mathcal{B}(\Xi_b^0 \to D^0 p K^-)}{f_{b\to\Lambda_b^0} \times \mathcal{B}(\Lambda_b^0 \to D^0 p K^-)} = 0.29 \pm 0.12_{stat} \pm 0.08_{syst}$

- $M(\Xi_b^0) = (5802.0 \pm 5.5 \pm 1.7)\,\mathrm{MeV}/c^2$
- Consistent with CDF result (PRL: 107, 102001 (2011))

  $M(\Xi_b^0) = (5787.8 \pm 5.5 \pm 0.5)\,\mathrm{MeV}/c^2$

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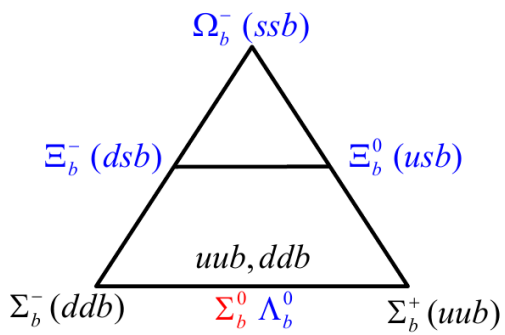
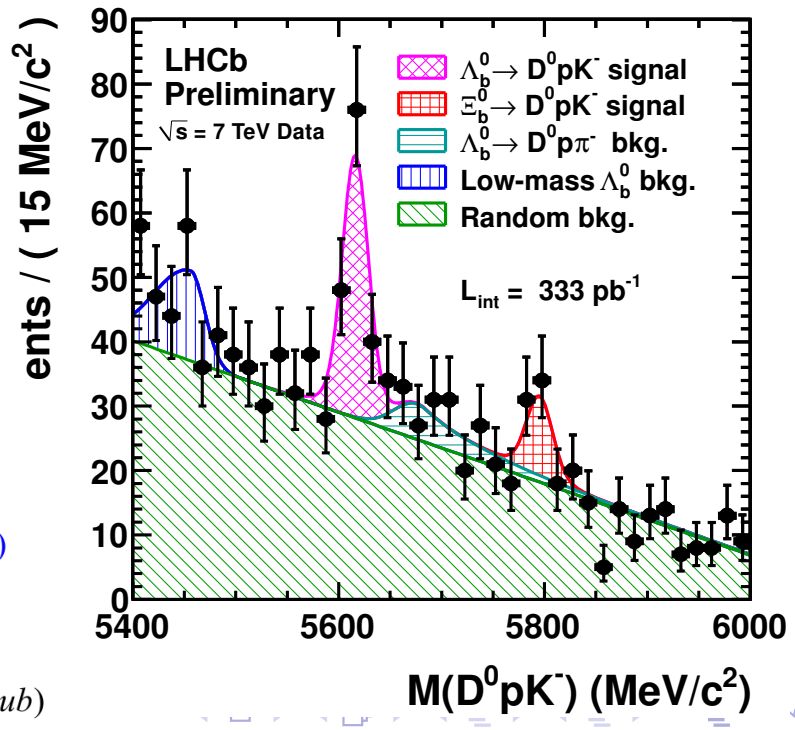




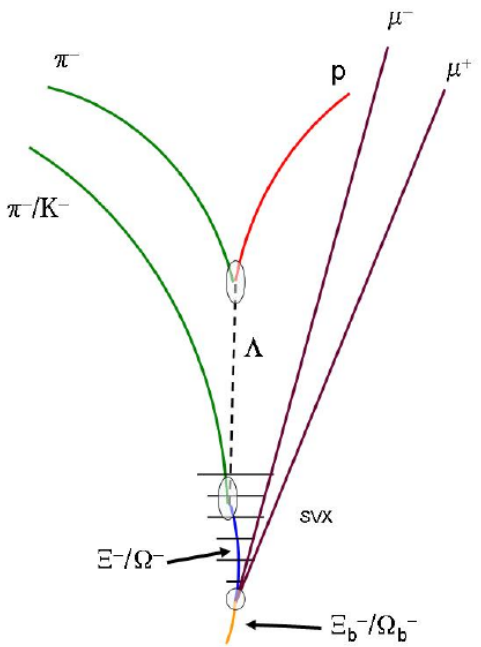
Measurement of Ξ_b^- and Ω_b^- masses (preliminary)

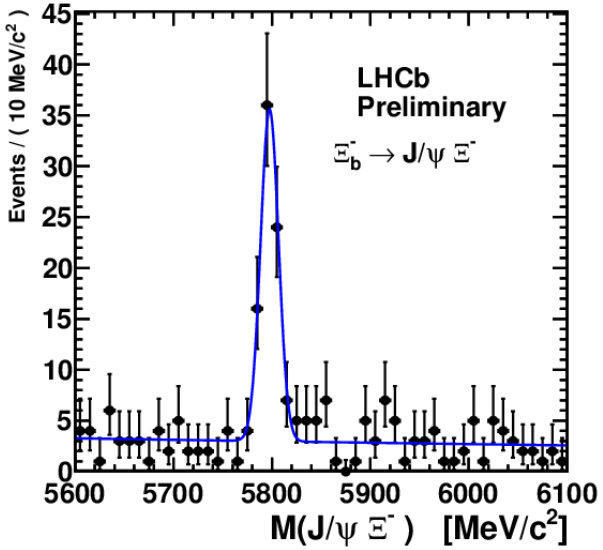
- Search $\Xi_b^-(\Omega_b^-) \to J/\psi\Xi^-(\Omega^-)$
- Rich topology, 3 displaced vertices
- $M(\Xi_b^-) = (5796.5 \pm 1.2 \pm 1.2)\,\mathrm{MeV}/c^2$
- $M(\Omega_b^-) = (6050.3 \pm 4.5 \pm 2.2)\,\mathrm{MeV}/c^2$

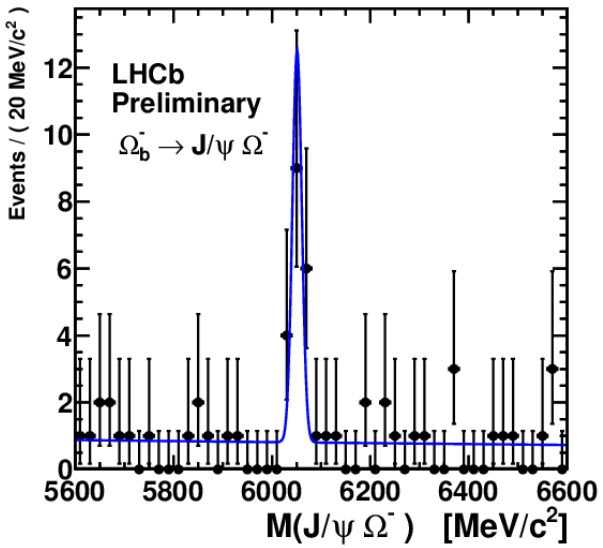
$M(\Xi_b^-)$ in good agreement with CDF (PRD: 80, 072003 (2009)) and D0 (PRL: 101 232002 (2008))
$M(\Omega_b^-)$ favours CDF

	$M(\Xi_b^-)$	$M(\Omega_b^-)$
DØ	5774 ± 19	6165 ± 16
CDF	5790.9 ± 2.7	6054.4 ± 6.9
PDG	5790.5 ± 2.7	6071 ± 40
LHCb	5796.5 ± 1.7	6050.3 ± 5.0

LHCb-CONF-2011-060



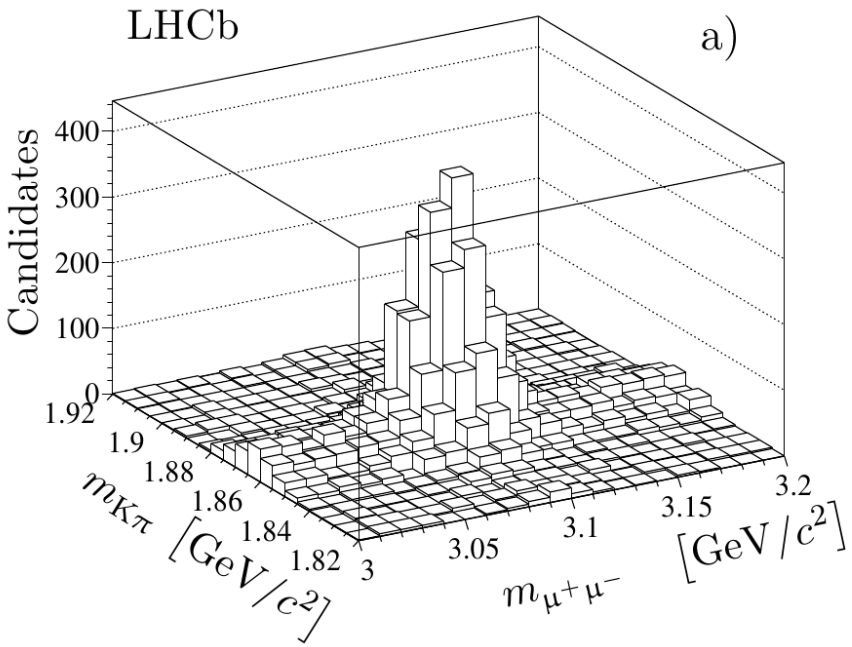




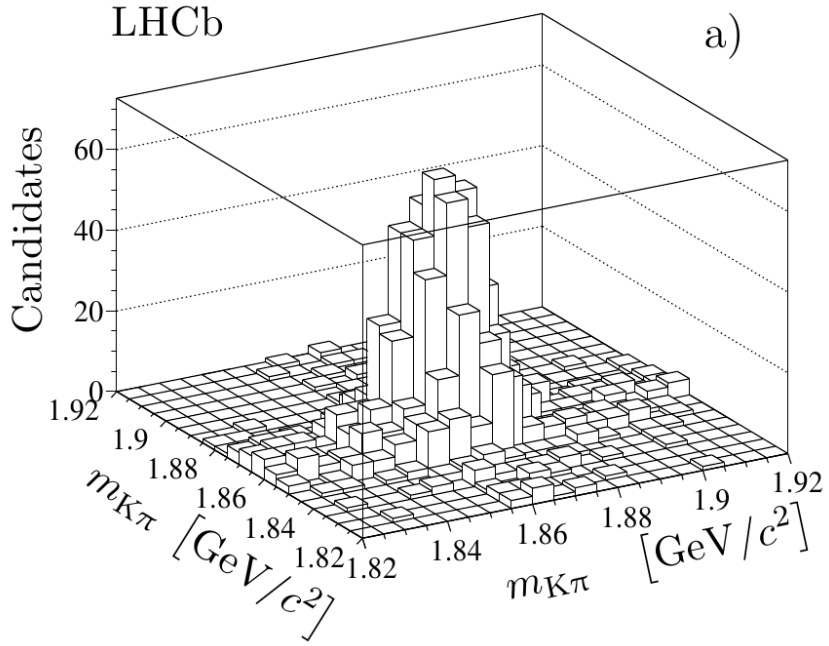
Double charm production

- Production of J/ψ + open charm hadron (D^0, D^+, D_s^+, Λ_c^+) and double open charm hadron
- Useful to probe quarkonium production mechanism
- Double J/ψ production already published (Phys. Lett. B 707 (2012) 5259)

$J/\psi D^0$



$D^0 D^0$



arXiv:1205.0975

Double charm production

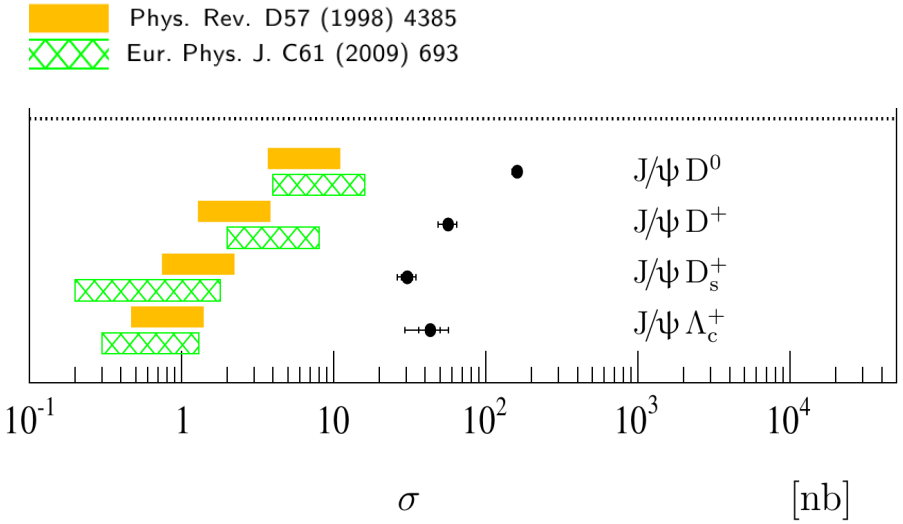
16 channels studied!

Mode	σ [nb]
$J/\psi D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_C$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_C/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

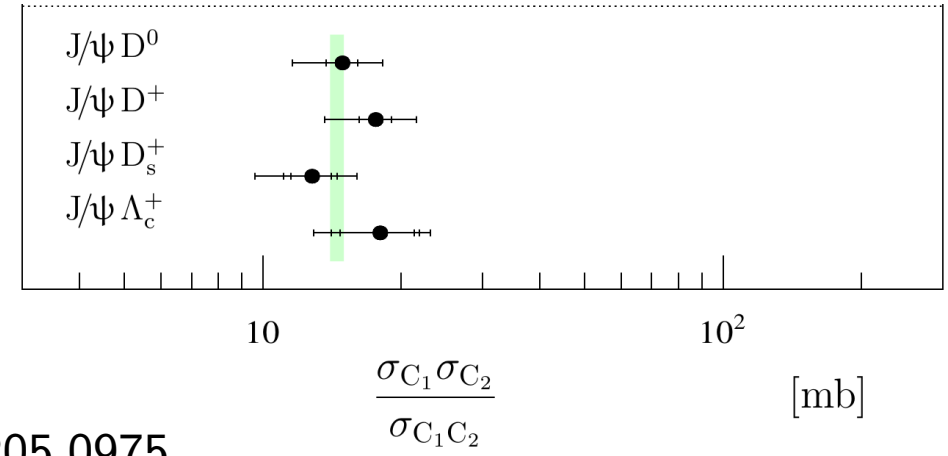
Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\bar{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1	$47 \pm 7 \pm 4$
D^0D^-	$3990 \pm 90 \pm 500$		$6.0 \pm 0.2 \pm 0.5$
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4	$36 \pm 8 \pm 4$
$D^0D_s^-$	$1680 \pm 110 \pm 240$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6	$2 \times (66 \pm 11 \pm 7)$
D^+D^-	$780 \pm 40 \pm 130$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3	$59 \pm 15 \pm 6$
$D^+D_s^-$	$550 \pm 60 \pm 90$		$7 \pm 1 \pm 1$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9	$140 \pm 70 \pm 20$
$D^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$		$15 \pm 4 \pm 2$

Compared to $gg \to J/\psi c\bar{c}$ calculations



Comparison with Double Parton Scattering

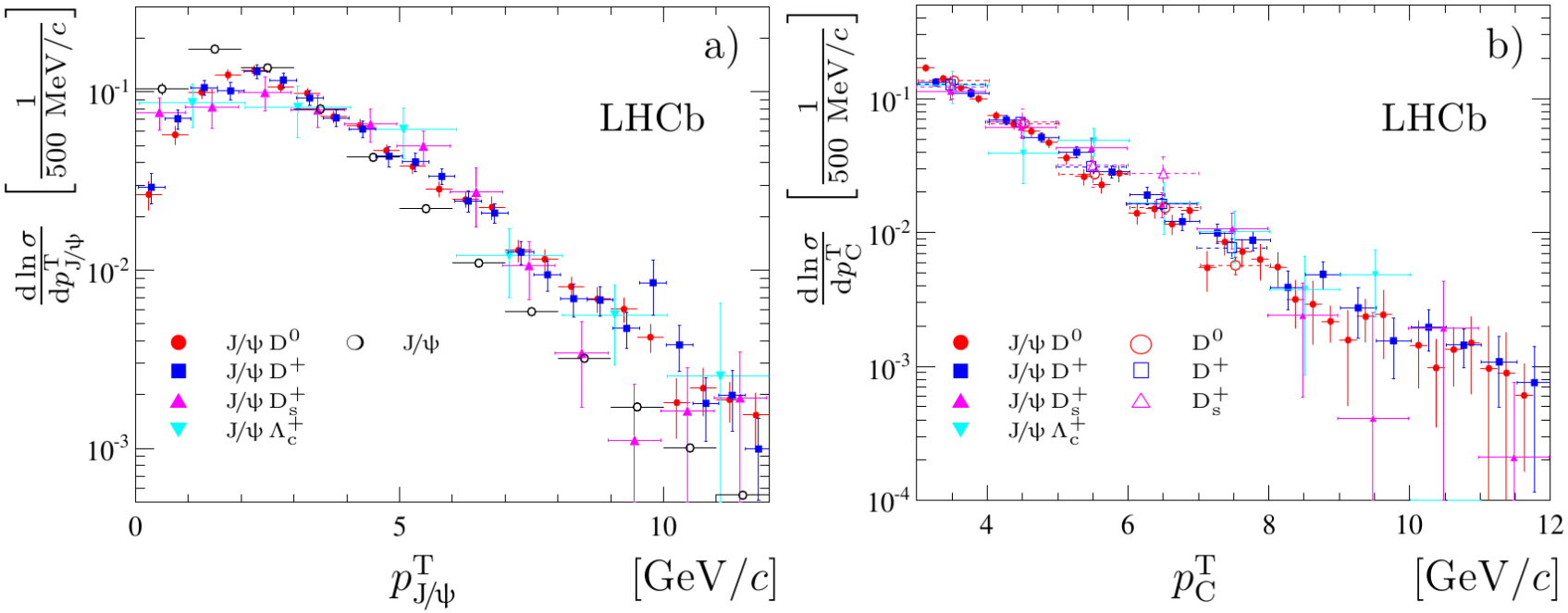
arXiv:1105.4186, arXiv:1106.2184



arXiv:1205.0975

Double charm production

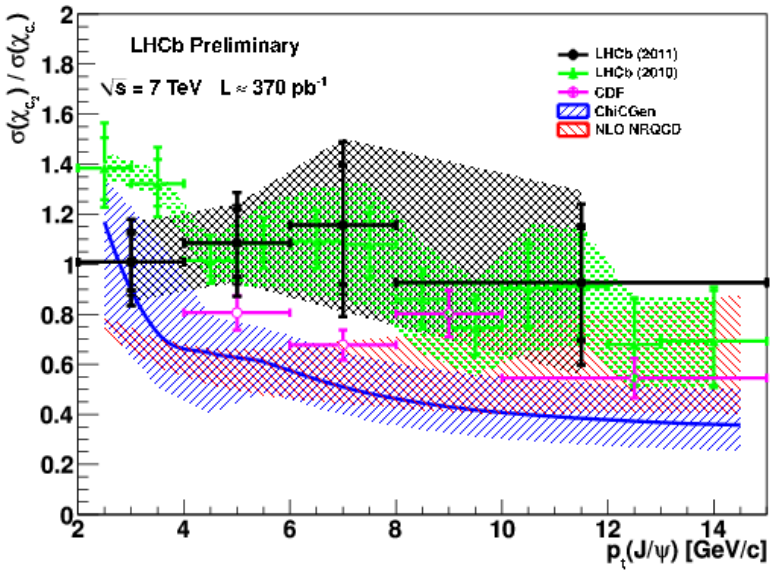
Kinematics are also investigated

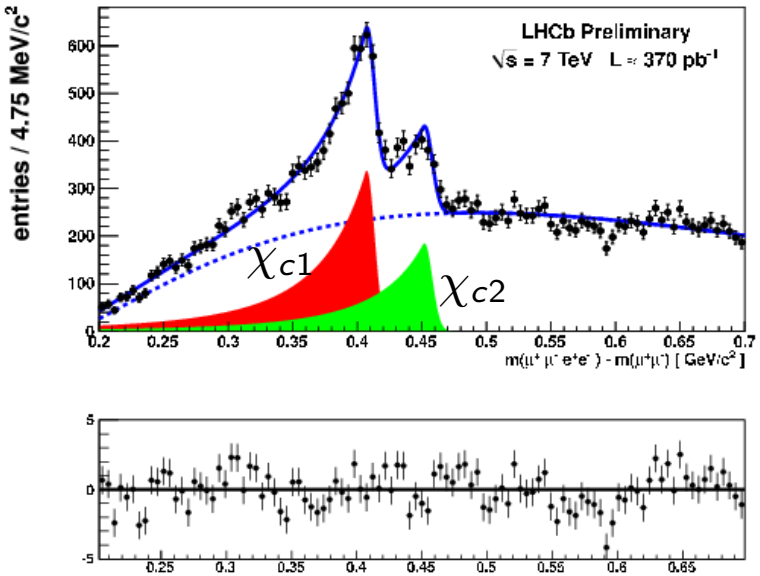


- More results at arXiv:1205.0975 (approved by JHEP)
- More channels to explore with increased statistics

χ_c production (preliminary)

- Measurement of the production cross section ratio of χ_{c2} to χ_{c1}
- Sensitive to colour-singlet and colour-octet production mechanisms
- Identification through radiative decay $\chi_c \to J/\psi\gamma$, only converted photons are used in 2011





CDF: PRL 98 (2007) 232001
ChiCGen: http://projects.hepforge.org/superchic/chigen.html
NRQCD: PR D83 (2011) 111503

LHCb-CONF-2011-062

Conclusions

- LHCb produced many interesting results with 2010 and 2011 data
- Some measurements are currently being updated with the full 2011 luminosity or will be re-performed at 8 TeV (expect $1.5\,\mathrm{fb}^{-1}$)
- LHCb will continue to provide precise and competitive measurements in the heavy flavour sector