b and c hadron production and spectroscopy at LHCb

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On behalf of the LHCb collaboration

The 19th PASCOS @ Taipei, 20~27 Nov 2013

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  - B meson production
  - Observation of $B_c^+ \to B_s \pi^+$ decay
  - Observation of $B_c^+ \to J/\psi K^+ K^- \pi^+$ decay
  - D_J meson spectroscopy
  - Search for Ξ_{cc}^+ baryon
- Summary

b hadron

c hadron

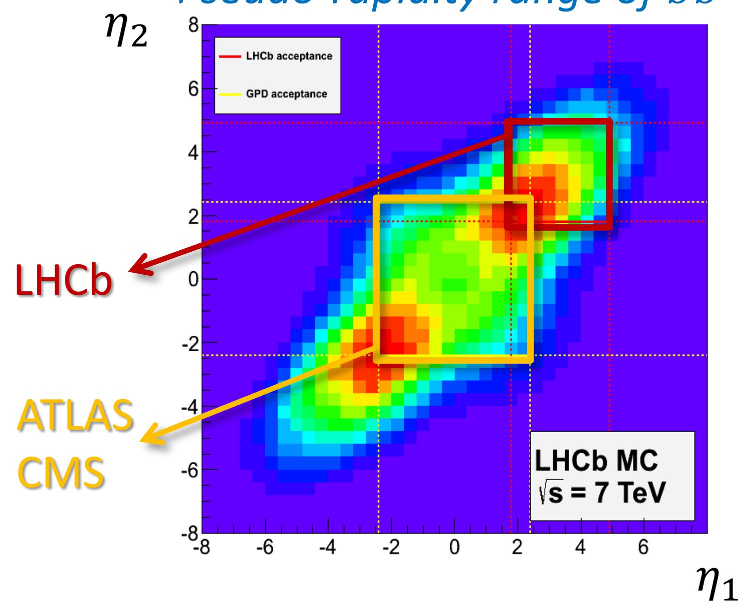
b,c hadron production & spectroscopy

- Various QCD models give different predictions
  - $\sigma_{\text{production}}$, M, τ, Br, …
- Experimental measurements test these predictions
- New states/decay modes provide inputs to theorists

Why at LHCb?

- Large production yields
  - $\sim 10^{11}$ $b\bar{b}$ pairs/yr,
  - 20 times for $c\bar{c}$
  - Plenty of B_c, b-baryons, …
- Unique kinematic range
  - $2 < \eta < 5$, access to low p_{T}
  - Complementary to ATLAS/CMS
- State-of-art detector designed for heavy flavour studies

Pseudo-rapidity range of $b\bar{b}$



→ E. Rodrigues' talk "Summary of flavour physics results" on 21 Nov.

$B_{u,d,s}$ meson production

b hadron

- Tests for pQCD calculations
- Status:
  - Studied by ATLAS (B^+) and CMS (B^+, B^0, B_s^0)
    - ATLAS: $9 < p_{\mathrm{T}} < 120$ GeV, $|y| < 2.25$
    - CMS: $p_{\mathrm{T}} > 5$ GeV, $|y| < 2.4$ (for B^+)

    JHEP10(2013) 042
    PRL 106(2011) 112001
    PRL 106(2011) 252001
    PRD 84 (2011) 052008

  - B^+ production was previously measured at LHCb using 35 pb^{-1} data

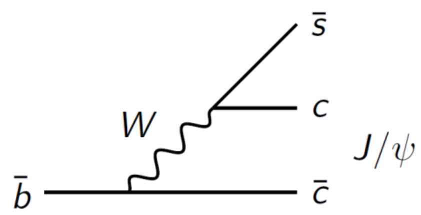
    JHEP04(2012) 093

- The latest analysis uses 0.36 fb^{-1} @ 7 TeV *JHEP08(2013) 117*
  - not only for B^+ but also for B^0 and B_s^0
  - $0 < p_{\mathrm{T}} < 40$ GeV, $2.0 < y < 4.5$

B selection with dimuon

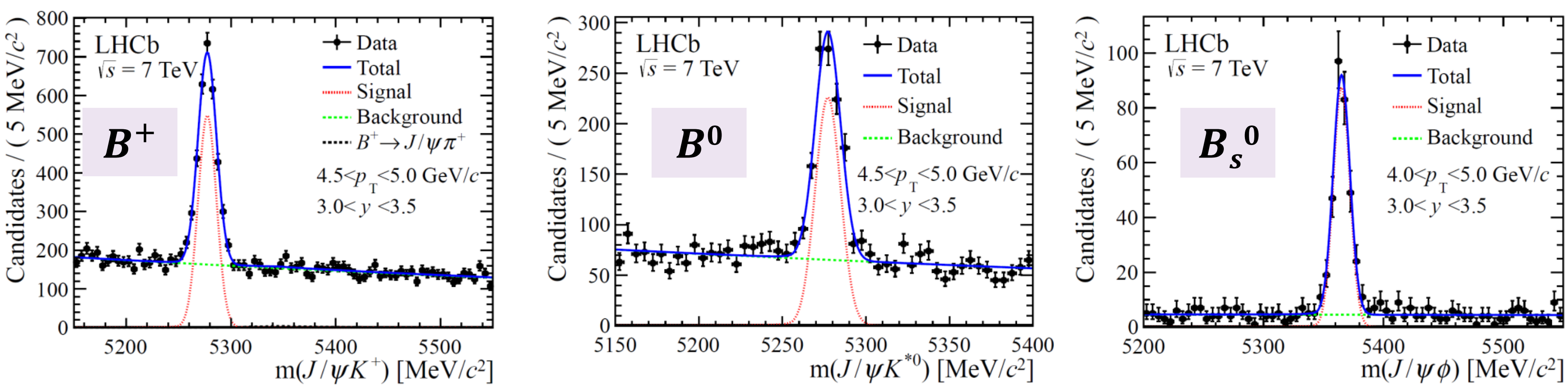
JHEP08(2013) 117

$0 < p_{\mathrm{T}} < 40$ GeV, $2.0 < y < 4.5$



$$B^+ \to J/\psi\, K^+;$$
$$B^0 \to J/\psi\, K^{*0},\ K^{*0} \to K^+\pi^-;$$
$$B^0_s \to J/\psi\, \phi,\quad \phi \to K^+K^-.$$
$$J/\psi \to \mu^+\mu^-$$

Trigger efficiency : ~ 90 % for dimuon channels



Integrated B production x-section

b hadron

JHEP08(2013) 117

- B^+ production updated with higher statistics, consistent with previous results
- New results for B^0 and B_s^0 in LHCb kinematic range

$0 < p_{\mathrm{T}} < 40$ GeV, $2.0 < y < 4.5$

Uncertainty on branching fractions

$$\sigma(pp \to B^+X) = 38.9 \pm 0.3(\text{stat}) \pm 2.5(\text{syst}) \pm 1.3(\text{norm})\ \mu\text{b}$$

$$\sigma(pp \to B^0X) = 38.1 \pm 0.6(\text{stat}) \pm 3.7(\text{syst}) \pm 4.7(\text{norm})\ \mu\text{b}$$

$$\sigma(pp \to B_s^0X) = 10.5 \pm 0.2(\text{stat}) \pm 0.8(\text{syst}) \pm 1.0(\text{norm})\ \mu\text{b}$$

Result with 35 pb^{-1} data: 41.4 ± 1.4 (stat) ± 3.2 (syst) μb

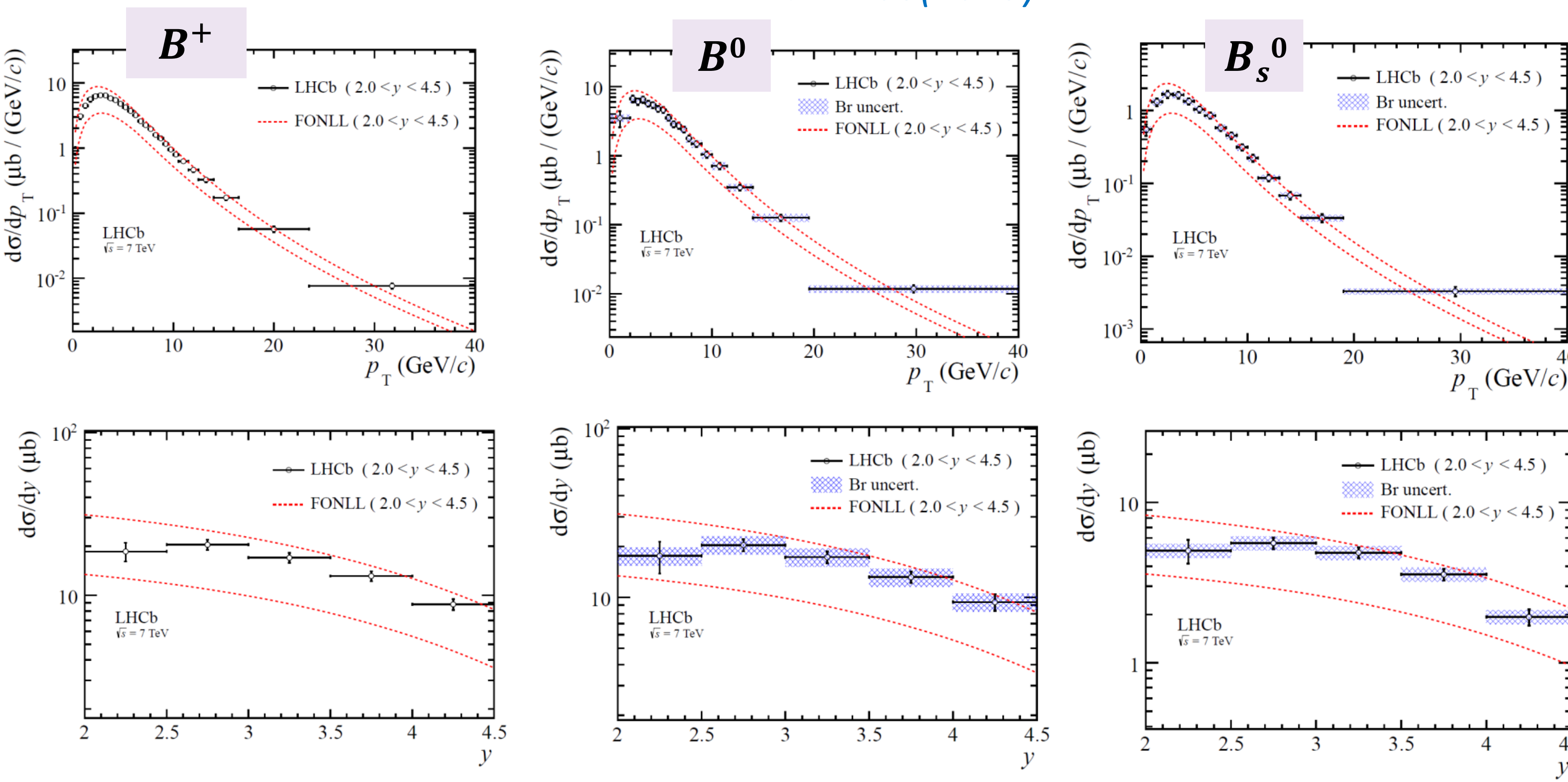
Differential production x-section

b hadron

JHEP08(2013) 117

In bins of p_T

In bins of y

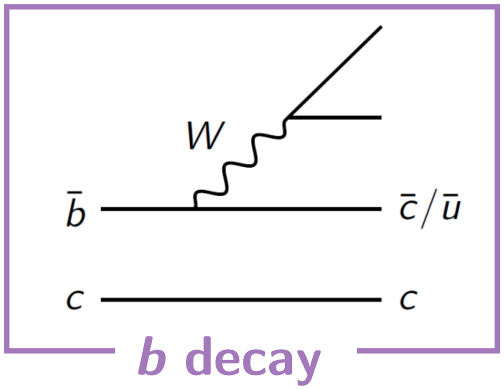


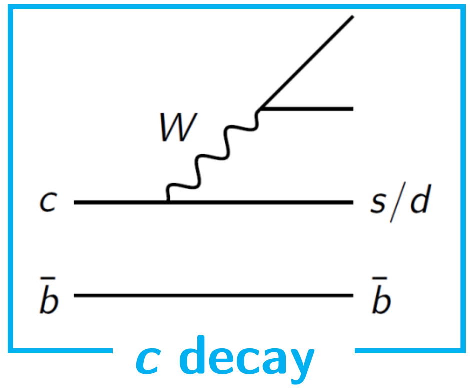
- Overall scale fixed using hadronisation fractions $f_{b\to B_{u,d}}, f_{b\to B_s}$ measured by LHCb
  PRD85(2012) 032008
- Consistent with Fixed-order plus next-to-leading logarithm (FONLL) calculations
  JHEP10(2012) 137

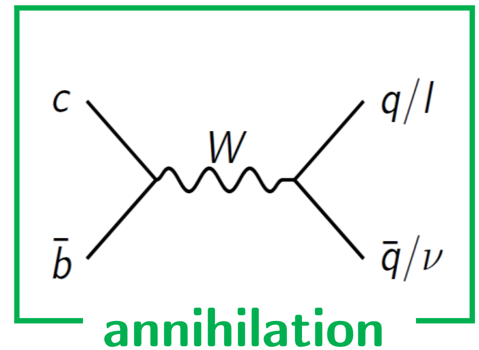
B_c decay

- A family of unique mesons consists of different heavy quarks
- Ground state only decays weakly

  ⇒ a large variety of decay modes expected







Experimentally confirmed channels: $B_c^+ \to \ldots$

$J/\psi\, l\nu\, l\upsilon$	*observed at Tevatron*	$J/\psi\, D_s^{(*)+}$	*PRD 87 (2013)112012*
$J/\psi\, \pi^+$	*PRL 109 (2012)232001* (also observed at Tevatron)	$J/\psi\, K^+$	*JHEP 09(2013) 075*
$J/\psi\, \pi^+\pi^-\pi^+$	*PRL 108 (2012)251802*	$\boldsymbol{J/\psi\, K^+K^-\pi^+}$	***arXiv:1309.0587***
$\psi(2S)\, \pi^+$	*PRD 87 (2013)071103*	$\boldsymbol{B_s\pi^+}$	***PRL 111(2013)181801***

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

b hadron

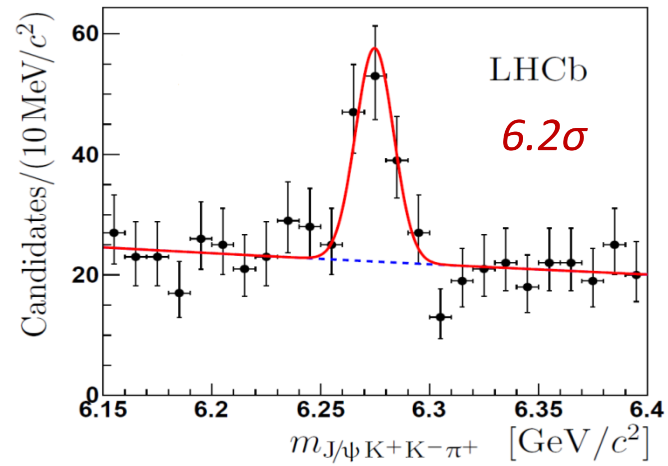
- 1 fb^{-1} (7 TeV) + 2 fb^{-1} (8 TeV)
- $m_{KK\pi}$ and $m_{J/\psi KK}$ from D_s and B_s sidebands to avoid contributions from $B_c \to J/\psi D_s$ or $B_s \pi$
- Largest contribution: $B_c^+ \to J/\psi \overline{K}^{*0} K^+$

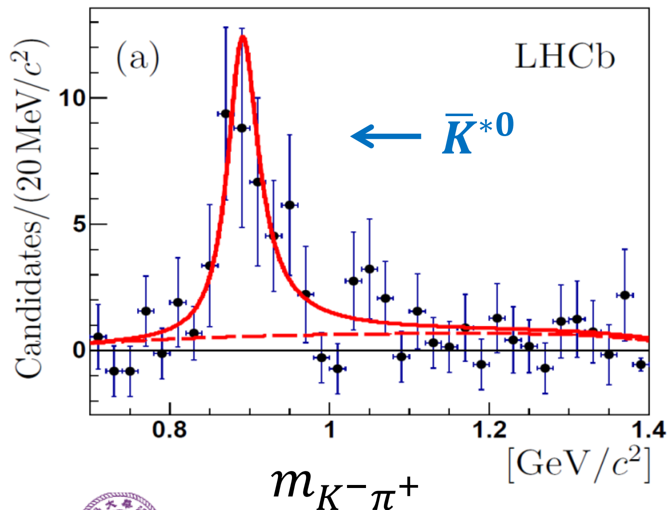
$$\frac{Br(B_c \to J/\psi K^+ K^- \pi^+)}{Br(B_c \to J/\psi \pi^+)} = 0.53 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$$

- In good agreement with theoretical predictions 0.49 and 0.47

arXiv: 1307.0953, Nucl.Phys.B585(2000)353, PRD 68(2003) 094020

arXiv:1309.0587



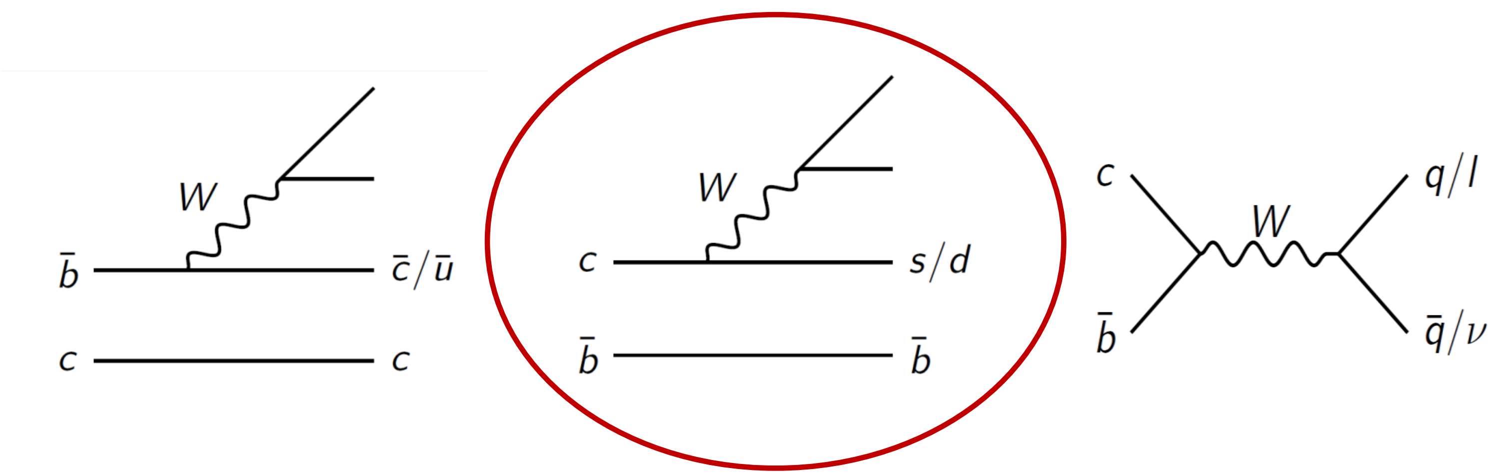


Observation of $B_c^+ \to B_s^0 \pi^+$

b hadron

PRL 111(2013)181801

- First observation of c decay in B_c^+
- First decay of $B \to B$ decay
- $\mathcal{L} = 3$ fb^{-1}
- B_s^0 decaying to two final states: $D_s^- \pi^+$ and $J/\psi\phi$
- Two-stage BDT for successive B_s and B_c selection

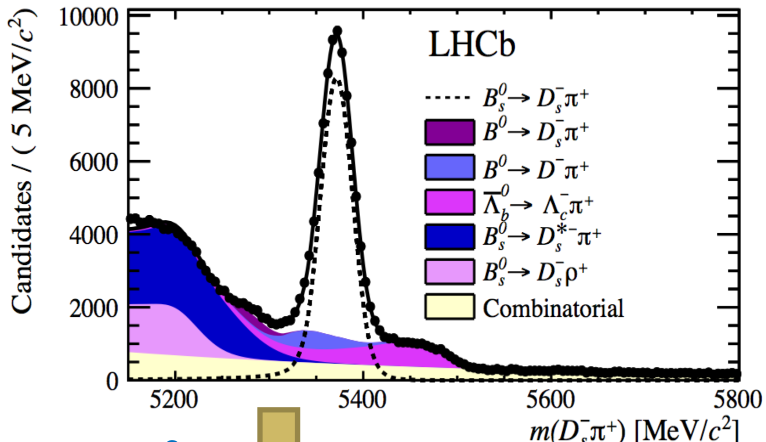


b hadron

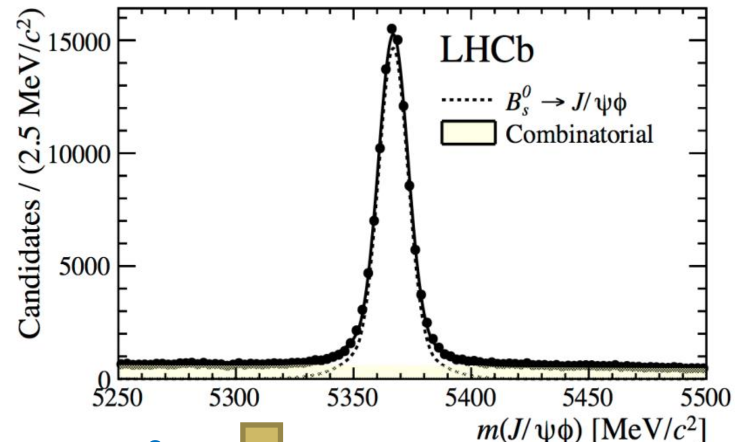
$B_c^+ \to B_s^0 \pi^+$

PRL 111(2013)181801

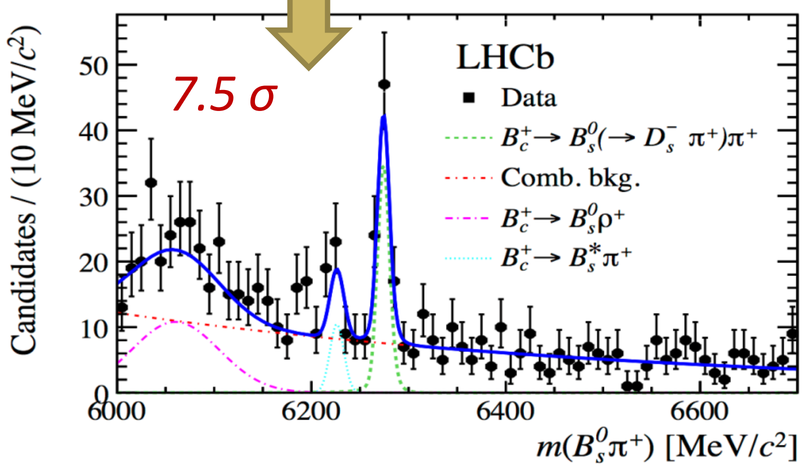
$D_s^- \pi^+$ ($D_s^- \to K^+ K^- \pi^-$)



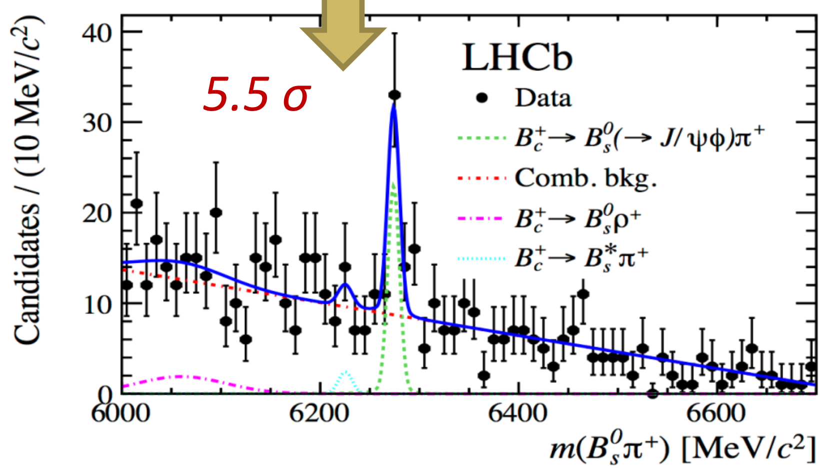
$J/\psi\, \phi$ ($J/\psi \to \mu^+ \mu^-, \phi \to K^+ K^-$)



$B_s^0 \pi^+$



$B_s^0 \pi^+$



$B_c^+ \to B_s^0 \pi^+$ branching fraction

b hadron

PRL 111(2013)181801

- Combining $(D_s^- \pi^+)_{B_s} \pi^+$ and $(J/\psi \phi)_{B_s} \pi^+$:

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$$
$$= \left(2.37 \pm 0.31(\text{stat}) \pm 0.11(\text{syst})^{+0.17}_{-0.13}(\tau_{B_c^+})\right) \times 10^{-3}$$

- Theory predicts $\mathcal{B}(B_c^+ \to J/\psi \pi^+) \sim 0.15\%$

PRD 73(2006) 054024

- $\frac{\sigma(B_c^+)}{\sigma(B^+)} \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$, f_s/f_d measured at LHCb

PRL 109(2012) 232001

JHEP 04(2013) 1

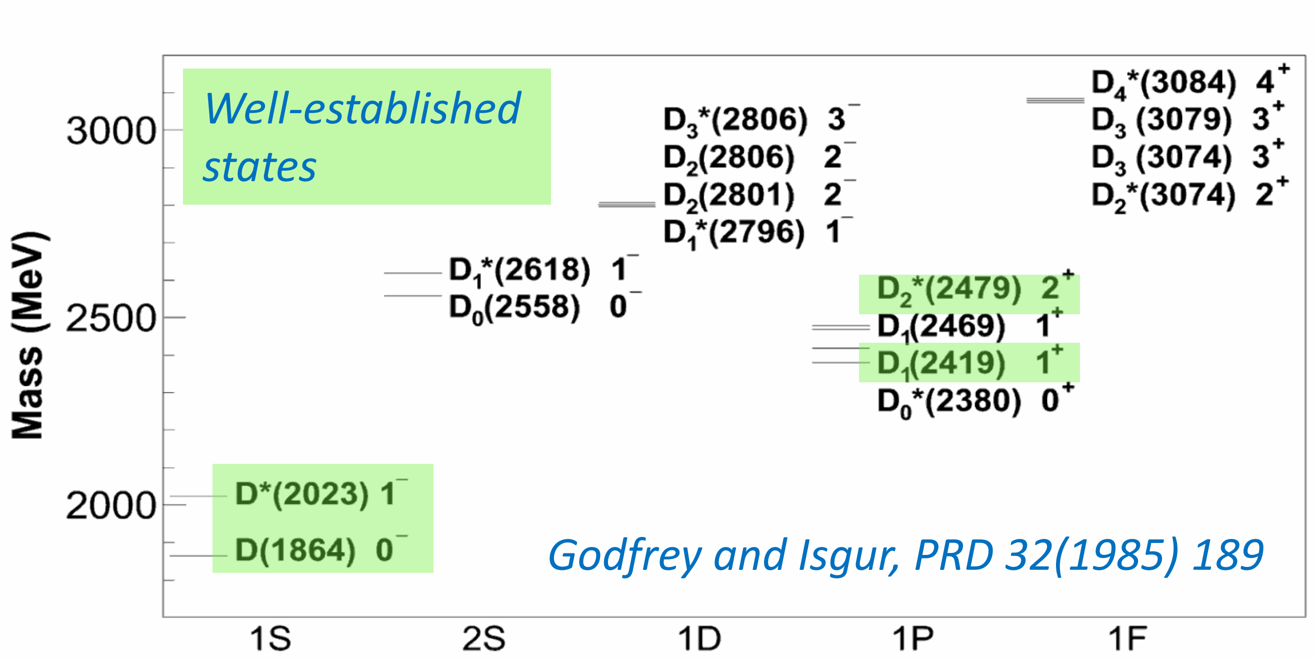
$\Rightarrow \frac{\sigma(B_c^+)}{\sigma(B_s^0)} \sim 0.02$

$\Rightarrow \mathcal{B}(B_c \to B_s \pi) \sim 10\%$, largest for any known B meson weak decay

Excited D mesons

c hadron

- Quark model predicts many excited D_J states
- Only a few are well established
- Search for new states using 1.0 fb^{-1} data @ 7 TeV
  - $D_J \to D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ $(D^{*+} \to D^0\pi^+)$ *JHEP 09(2013) 145*



Natural vs. unnatural parity

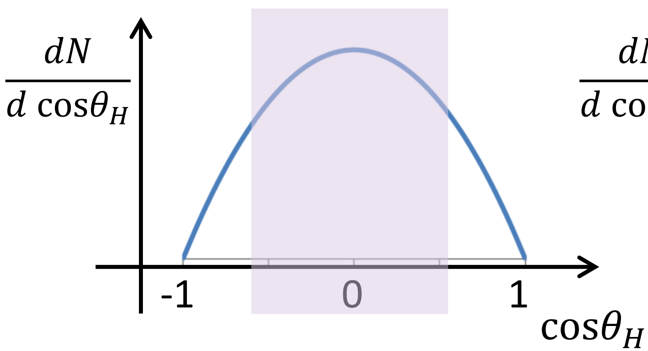
- Resonances decaying to $D^{*+}\pi^-$ ($D^{*+} \to D^0\pi^+$) are divided by helicity angle distribution

natural parity

$P = (-1)^J$

$J^P = 0^+, 1^-, 2^+ \dots$

$d\sigma \propto \sin^2\theta_H$



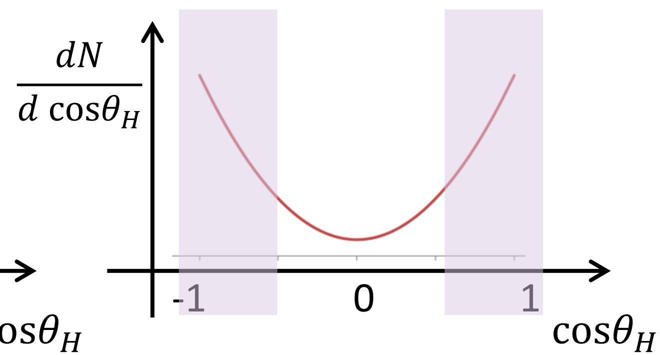
$|\cos\theta_H| < 0.5$:
Natural parity states are more prominent

unnatural parity

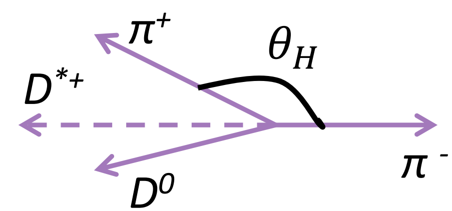
$P = (-1)^{J+1}$

$J^P = 0^-, 1^+, 2^- \dots$

$d\sigma \propto 1 + h\cos^2\theta_H \ (h > 0)$



$|\cos\theta_H| > 0.5$:
Unnatural parity states are more prominent



In $D^{*+}\pi^-$ c.m.s

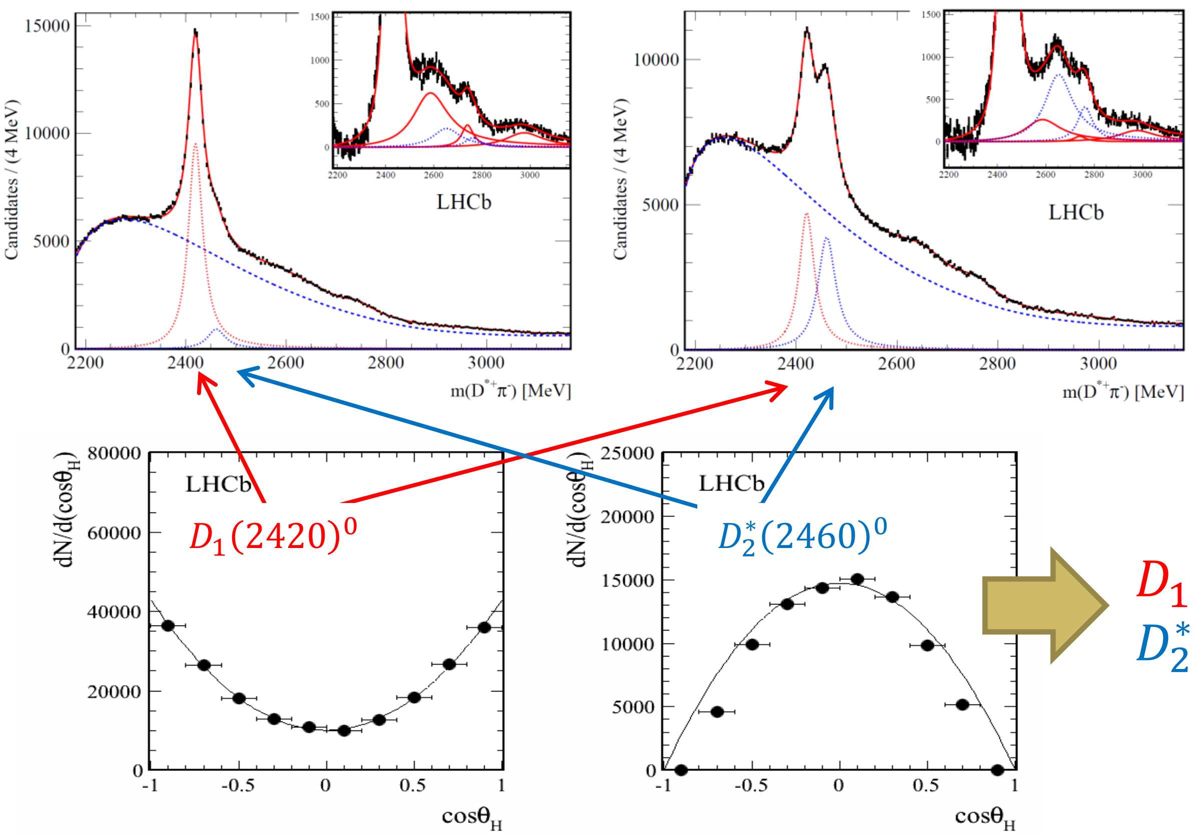
$D_1(2420)^0$, $D_2^*(2460)^0$

c hadron

JHEP 09(2013) 145

$D^{*+}\pi^-$ invariant mass spectrum, 1 fb^{-1} @ 7 TeV

$|\cos\theta_H| > 0.5$ | $|\cos\theta_H| < 0.5$



$D_1(2420)^0$, $D_2^*(2460)^0$: well-established states, with $J^P = 1^+$ and 2^+ respectively

Both confirmed in $D^{*+}\pi^-$, angular analyis results consistent with known J^P

$D_1(2420)^0$: unnatural parity
$D_2^*(2460)^0$: natural parity

New D_J resonances in $D^{*+}\pi^-$

c hadron

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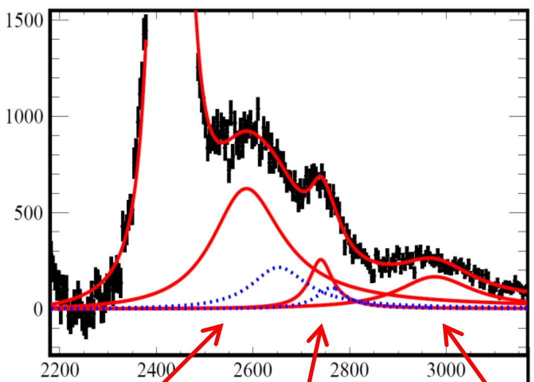
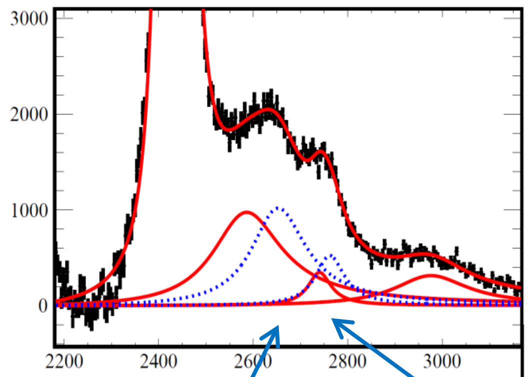
$|\cos\theta_H| > 0.5$



$|\cos\theta_H| < 0.5$



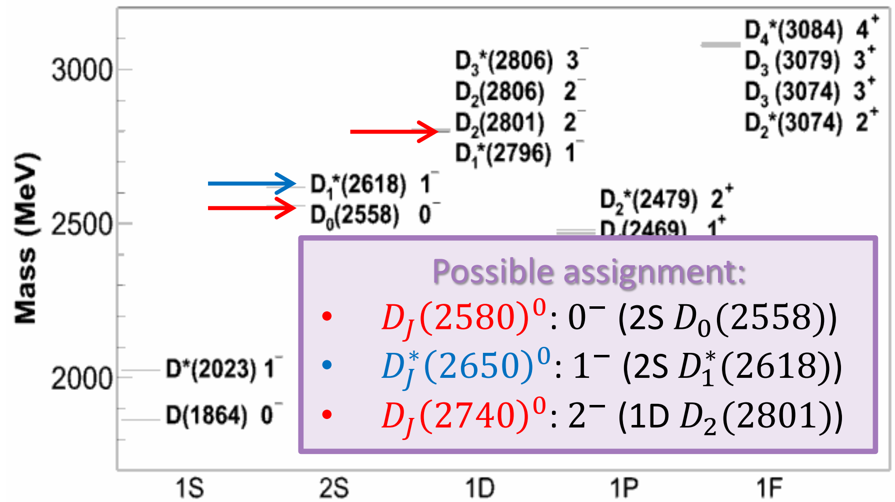
$D_J(2580)^0$, $D_J(2740)^0$, $D_J(3000)^0$ $D_J^*(2650)^0$, $D_J^*(2760)^0$

More resonances in $D^{*+}\pi^-$

- Two natural parity states:
  $D_J^*(2650)^0$, $D_J^*(2760)^0$
- Three unnatural parity states:
  $D_J(2580)^0$, $D_J(2740)^0$, $D_J(3000)^0$

Consistent with BaBar
PRD 82 (2010) 111101

- All observed with significance >5σ
- Properties for all states are uncertain
- To determine J^P, studies needed in decay from B



Possible assignment:
- $D_J(2580)^0$: 0^- (2S $D_0(2558)$)
- $D_J^*(2650)^0$: 1^- (2S $D_1^*(2618)$)
- $D_J(2740)^0$: 2^- (1D $D_2(2801)$)

D_J in $D^+\pi^-$ and $D^0\pi^+$

c hadron

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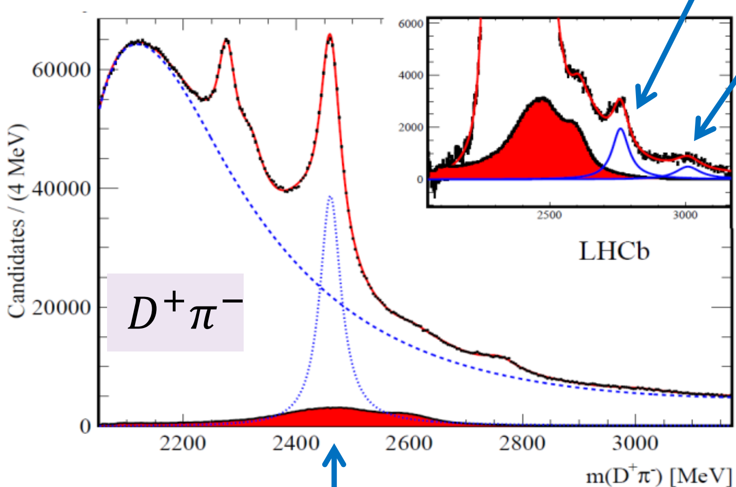
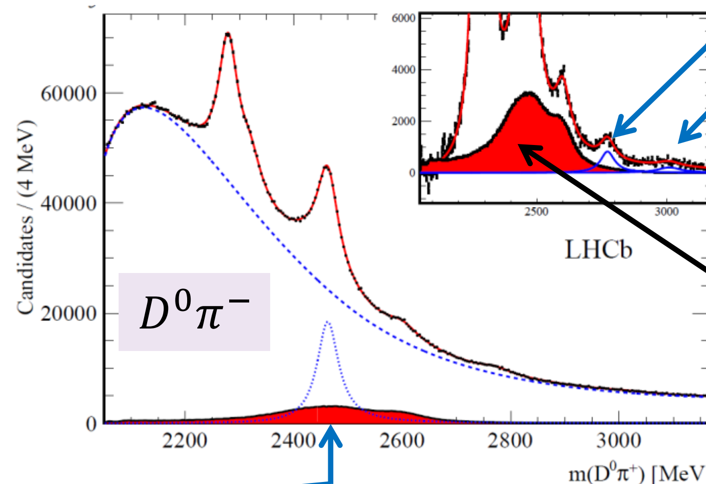
$D_J^*(2760)$, $D_J^*(3000)$



$D^+\pi^-$



$D^0\pi^-$

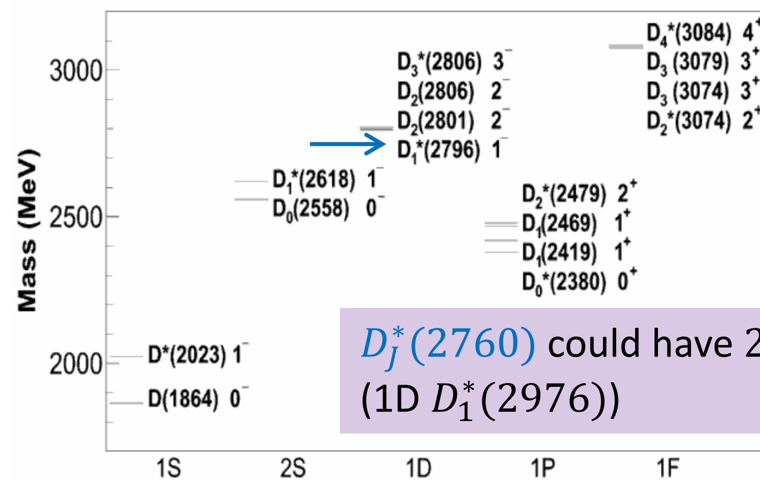
$D_J^*(2760)$

$D_J^*(3000)$

Cross-feed from $D^{*+}\pi^+$

$D_2^*(2460)$

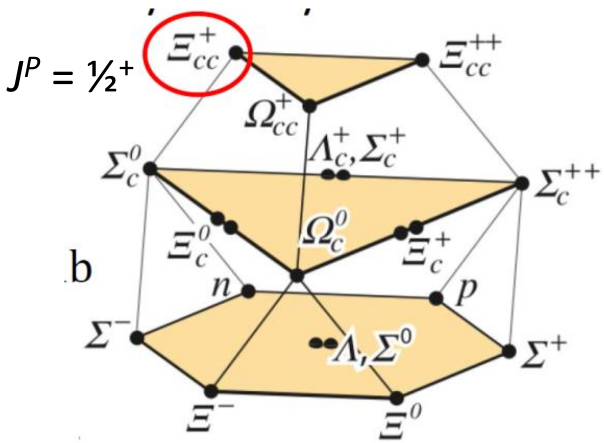
- $D^+\pi^-$ and $D^0\pi^+$ spectra affected by cross-feeds from $D^{*+}\pi^-$. In both final states:
  - $D_2^*(2460)$ are confirmed, and found to have natural parity, consistent with $J^P = 2^+$
  - $D_J^*(2760)$, $D_J^*(3000)$ observed ($> 5\sigma$)
- Precise quantum numbers cannot be determined



$D_J^*(2760)$ could have 2^- (1D $D_1^*(2976)$)

Ξ_{cc}^{+} baryon

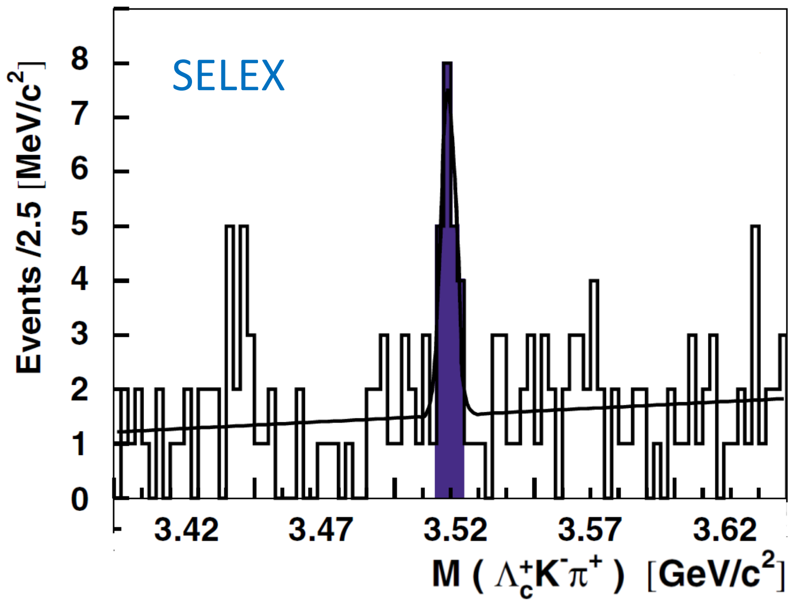
c hadron



- Predicted by quark model
  - $m \sim [3500, 3700]$ MeV/c²
  - $\tau \sim [100, 250]$ fs
- Expected cross-section at LHCb: $\mathcal{O}(10^2)$ nb

- SELEX claimed observation of Ξ_{cc}^{+} in $\Lambda_c^+ K^- \pi^+$ and pD^+K^-
  - $m = 3519$ MeV/c²
  - $\tau < 30$ fs @ 90% CL

  PRL 89(2002) 112001, PLB 628(2005) 18
- Not confirmed by FOCUS, BaBar or Belle



Search for Ξ_{cc}^{+}

c hadron

arXiv: 1310.2538

- Search for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$, $(\Lambda_c^+ \to p K^- \pi^+)$

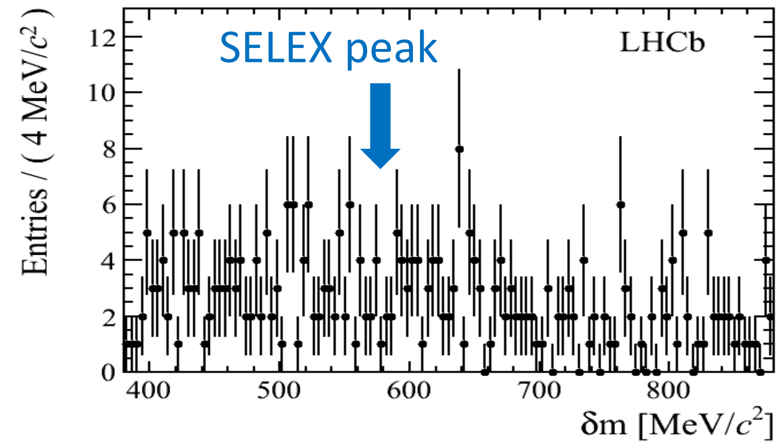
  with 0.65 fb^{-1} data @ 7 TeV

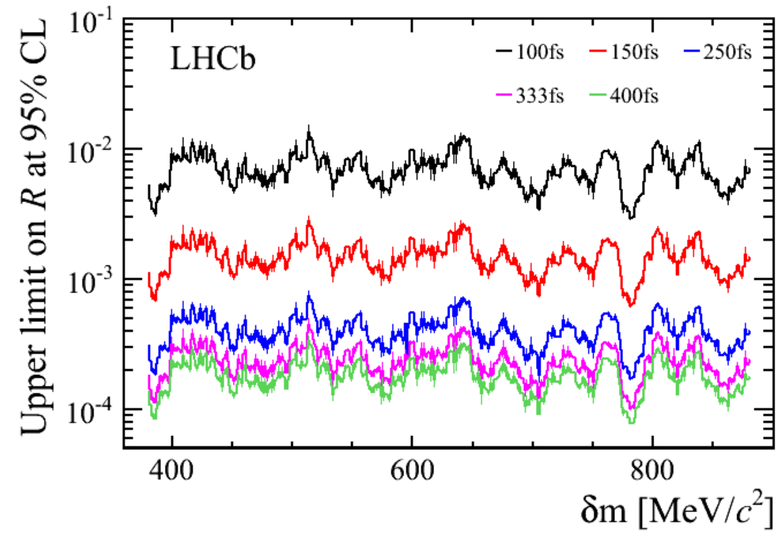
- No significant signal

- Upper limits for production cross-section as a function of δm for various lifetime assumptions

$$R = \frac{\sigma(\Xi_{cc}^{+})}{\sigma(\Lambda_c^{+})} \times \mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})$$

$$\delta m = m_{\Lambda_c^+ K^- \pi^+} - m_{\Lambda_c^+} - m_{K^-} - m_{\pi^+}$$





Summary

- LHCb has been fruitful in b and c hadron production and spectroscopy with the data collected in the first stage of LHC operation
  - B production studied in unique kinematic range
  - Many new B_c^+ decay channels observed, incl. first c decay
  - New D_J mesons observed
  - Upper limits given for Ξ_{cc}^+ production
- Many more results are not covered due to time constraint
- Analyses on 3 fb^{-1} data still onging, more excitement to come!

BACKUP

Inclusive $b\bar{b}$ and $c\bar{c}$ production

7 TeV, in LHCb acceptance:

$\sigma_{b\bar{b}} = 75.5 \pm 14.1\ \mu b$ *Phys. Lett. B694, 209*

$\sigma_{c\bar{c}} = 1419 \pm 134\ \mu b$ *Nucl. Phys. B871, 1*

Trigger efficiencies of B^+ mesons

Table 55: Trigger efficiencies (in %) for $B^+ \to J/\psi K^+$ in bins of B p_T and y.

p_T (GeV/c)	$2.0 < y < 2.5$	$2.5 < y < 3.0$	$3.0 < y < 3.5$	$3.5 < y < 4.0$	$4.0 < y < 4.5$
(0.0, 0.5]	29.9 ± 0.2	53.9 ± 0.4	63.0 ± 0.4	64.7 ± 0.4	69.2 ± 0.4
(0.5, 1.0]	35.3 ± 0.2	52.6 ± 0.2	63.0 ± 0.3	65.7 ± 0.3	69.3 ± 0.3
(1.0, 1.5]	36.0 ± 0.1	52.7 ± 0.2	62.6 ± 0.2	66.5 ± 0.2	69.8 ± 0.2
(1.5, 2.0]	37.3 ± 0.1	52.4 ± 0.2	62.5 ± 0.2	66.6 ± 0.2	70.1 ± 0.2
(2.0, 2.5]	38.8 ± 0.1	53.4 ± 0.2	63.6 ± 0.2	67.3 ± 0.2	71.0 ± 0.2
(2.5, 3.0]	42.2 ± 0.1	55.5 ± 0.2	64.7 ± 0.2	68.6 ± 0.2	70.8 ± 0.2
(3.0, 3.5]	42.7 ± 0.1	57.1 ± 0.2	65.4 ± 0.2	69.6 ± 0.2	71.7 ± 0.2
(3.5, 4.0]	46.5 ± 0.1	58.0 ± 0.1	67.0 ± 0.2	70.9 ± 0.2	73.0 ± 0.2
(4.0, 4.5]	47.8 ± 0.1	60.3 ± 0.1	68.4 ± 0.1	72.5 ± 0.2	73.8 ± 0.2
(4.5, 5.0]	49.4 ± 0.1	62.1 ± 0.1	70.2 ± 0.2	73.5 ± 0.2	74.7 ± 0.2
(5.0, 5.5]	50.7 ± 0.1	64.0 ± 0.1	71.4 ± 0.2	74.8 ± 0.2	75.9 ± 0.2
(5.5, 6.0]	52.5 ± 0.1	64.8 ± 0.1	72.6 ± 0.1	76.3 ± 0.1	76.9 ± 0.1
(6.0, 6.5]	55.5 ± 0.1	66.7 ± 0.1	73.8 ± 0.1	77.1 ± 0.1	77.7 ± 0.1
(6.5, 7.0]	56.7 ± 0.1	68.2 ± 0.1	74.7 ± 0.1	77.9 ± 0.2	78.8 ± 0.2
(7.0, 7.5]	58.7 ± 0.1	69.9 ± 0.1	75.7 ± 0.1	78.6 ± 0.2	79.5 ± 0.2
(7.5, 8.0]	59.8 ± 0.1	71.0 ± 0.1	76.0 ± 0.2	79.3 ± 0.2	80.6 ± 0.2
(8.0, 8.5]	62.0 ± 0.1	72.4 ± 0.1	77.1 ± 0.1	79.7 ± 0.2	80.7 ± 0.2
(8.5, 9.0]	61.7 ± 0.1	73.8 ± 0.1	77.7 ± 0.2	80.1 ± 0.2	82.0 ± 0.2
(9.0, 9.5]	63.0 ± 0.1	74.4 ± 0.1	78.4 ± 0.1	80.8 ± 0.2	81.9 ± 0.2
(9.5, 10.0]	64.5 ± 0.1	74.7 ± 0.1	79.0 ± 0.2	81.2 ± 0.2	83.0 ± 0.2
(10.0, 10.5]	66.4 ± 0.1	75.3 ± 0.1	79.1 ± 0.2	80.9 ± 0.2	82.8 ± 0.2
(10.5, 11.5]	67.3 ± 0.2	76.3 ± 0.2	79.6 ± 0.2	81.2 ± 0.2	83.1 ± 0.2
(11.5, 12.5]	67.6 ± 0.2	76.7 ± 0.2	79.4 ± 0.2	81.0 ± 0.2	83.3 ± 0.2
(12.5, 14.0]	69.2 ± 0.2	77.4 ± 0.2	79.8 ± 0.2	80.7 ± 0.2	82.9 ± 0.2
(14.0, 16.5]	70.1 ± 0.2	78.6 ± 0.2	80.0 ± 0.2	80.0 ± 0.2	82.3 ± 0.2
(16.5, 23.5]	71.1 ± 0.3	80.1 ± 0.3	80.3 ± 0.3	79.1 ± 0.3	74.8 ± 0.3
(23.5, 40.0]	71.7 ± 0.4	81.5 ± 0.4	80.5 ± 0.4	77.5 ± 0.4	68.7 ± 0.4

Excited D_J : resonance parameters, yields and sigfinicance

Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Significance (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	7.6 ± 1.2	6.6