OPEN CHARM AND BEAUTY AT LHCb

Patrick Spradlin
on behalf of the LHCb collaboration

University of Glasgow Particle Physics

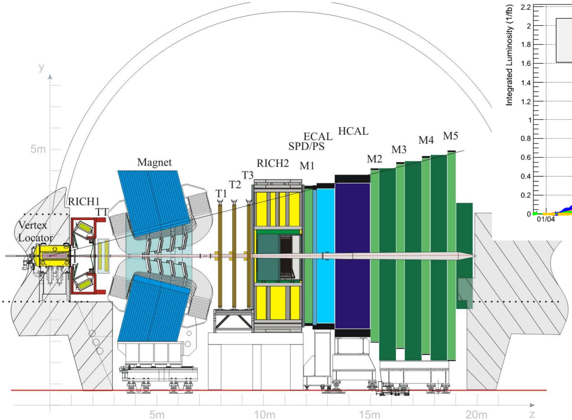
LHCb workshop on quantum interference effects, QCD measurements and generator tuning
20-22 October 2014, CERN, Geneva, Switzerland

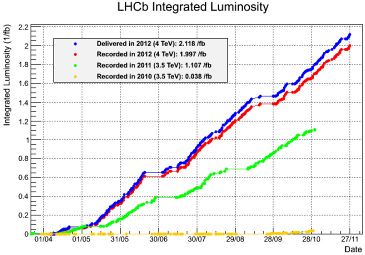
OUTLINE

LHCb

LHCb: a forward-arm spectrometer at the LHC

Optimized for heavy flavor physics in *pp* collisions.





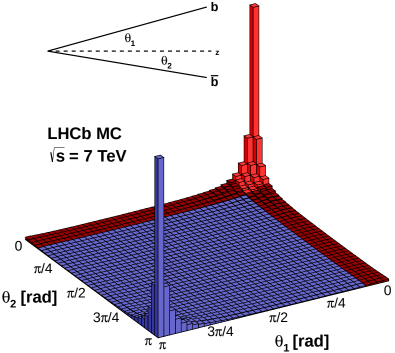
Data collection:

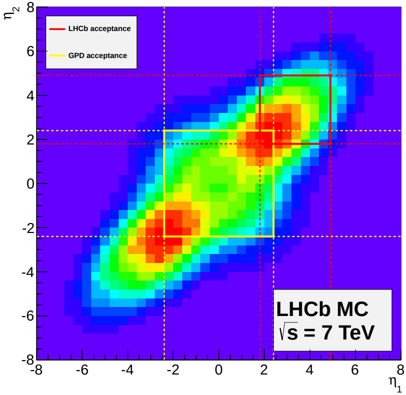
2010 $38\,\mathrm{pb}^{-1}$ $\sqrt{s} = 7\,\mathrm{TeV}$,
2011 $1.1\,\mathrm{fb}^{-1}$ $\sqrt{s} = 7\,\mathrm{TeV}$,
2012 $2.0\,\mathrm{fb}^{-1}$ $\sqrt{s} = 8\,\mathrm{TeV}$.

FORWARD ACCEPTANCE

Forward acceptance $2 < \eta < 5$.

Takes advantage of the predominant forward production of heavy flavored hadrons.

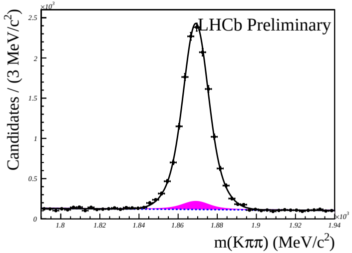


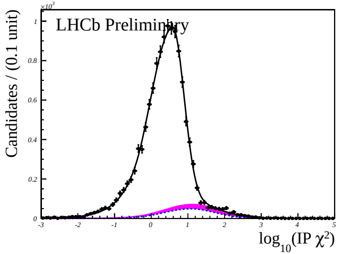


Pseudorapidity range unique among the LHC detectors.

Complementary to the GPDs.

OPEN CHARM PRODUCTION CROSS-SECTIONS
NUCL.PHYS. B871 (2013) 1-20





Supercedes LHCb-CONF-2010-013.

Suite of open charm cross-sections

- $D^0 \to K^-\pi^+$
- $D^{*+} \to D^0\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D_s^+ \to \phi(K^-K^+)\pi^+$
- $\Lambda_c^+ \to p^+K^-\pi^+$

Binned in p_{T} and y, differential $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$

- $p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$, $2 < y < 4.5$,
- $15\,\mathrm{nb}^{-1}$ of 2010 data

Measure prompt production

- Production from b-hadron decays isolated with $IP\chi^2$ distribution.

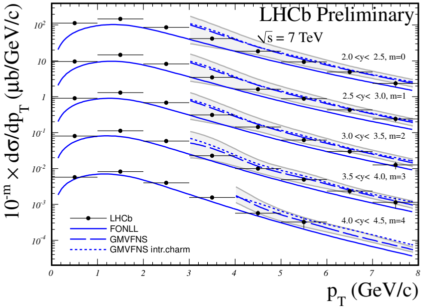
Includes measurements of

- Differential cross-sections,
- Charm species production ratios,
- Total $c\bar{c}$ cross-section.

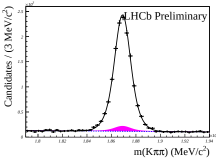
DIFFERENTIAL CROSS-SECTIONS: D^0 AND D^+

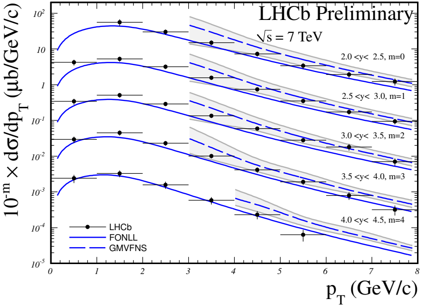
NUCL.PHYS. B871 (2013) 1-20

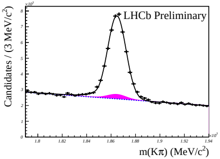
$d\sigma/dp_T$ compared to predictions from FONLL and GMVFNS



D^+ from
$D^+ \to K^-\pi^+\pi^+$







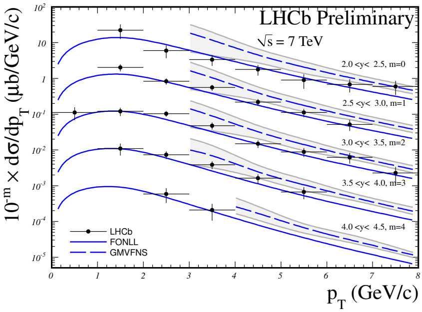
D^0 from
$D^0 \to K^-\pi^+$

FONLL: Fixed-Order-Next-to-Leading-Logarithm, JHEP 1210 (2012) 137
GMVFNS: Generalized Mass Variable Flavour Number Scheme, Eur.Phys.J.C72 (2012) 2082

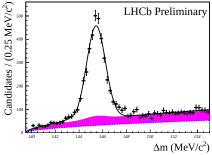
DIFFERENTIAL CROSS-SECTIONS: D_s^+ AND D^{*+}

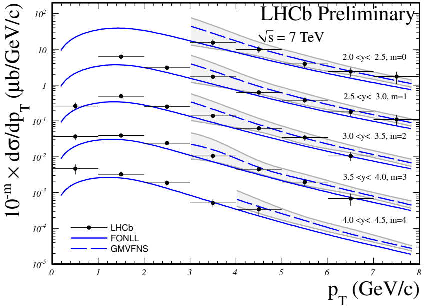
NUCL.PHYS. B871 (2013) 1-20

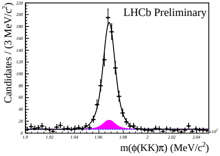
$d\sigma/dp_T$ compared to predictions from FONLL and GMVFNS



D^{*+} from $D^{*+} \to D^0\pi^+$



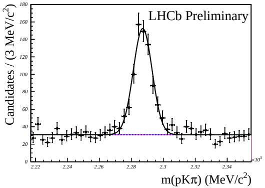


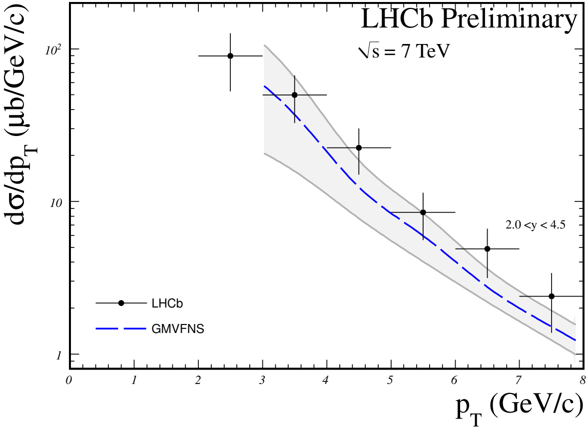


D_s^+ from $D_s^+ \to \phi(K^-K^+)\pi^+$

DIFFERENTIAL CROSS-SECTIONS: $\Lambda_c^+ \to p^+ K^- \pi^+$
NUCL.PHYS. B871 (2013) 1-20

$d\sigma/dp_T$ compared to predictions from GMVFNS





D_s^+-D_s^- PRODUCTION ASYMMETRY

PHYS.LETT. B713 (2012) 186-195

Measured with decays $D_s^\pm \to \phi\pi^\pm$

- $\sim$0.8 million signal decays in 1 fb^{-1} at $\sqrt{s} = 7\,\mathrm{TeV}$.

Production asymmetry in bins of $D_s^\pm$ (p_T, y)

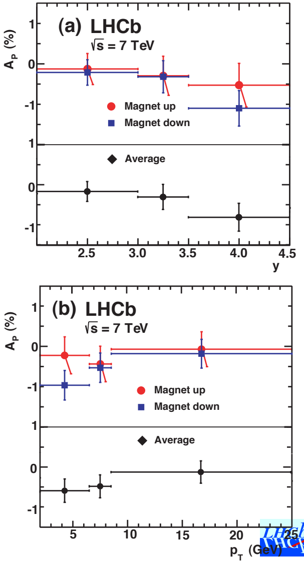
$$A_\mathrm{P} = \frac{\sigma D_s^+ - \sigma D_s^-}{\sigma D_s^+ + \sigma D_s^-}$$

Includes a precise measurement of the $\pi^\pm$ detection asymmetry

- With $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$ decays,
- Incorporated into A_P determination.

3 bins in p_T range $[2, 25]\,\mathrm{GeV}$,
3 bins in y range $[2.0, 4.5]$.

Average asymmetry integrated over full range
$A_\mathrm{P} = (-0.33 \pm 0.22 \pm 0.10)\%$



D^+-D^- PRODUCTION ASYMMETRY

PHYS.LETT. B718 (2013) 902-909

Measured with decays $D^\pm \to K_S^0 \pi^\pm$

- $\sim$1 million signal decays in 1 fb^{-1} at $\sqrt{s} = 7\,\text{TeV}$.

Production asymmetry in bins of $D^\pm$ (p_T, η)

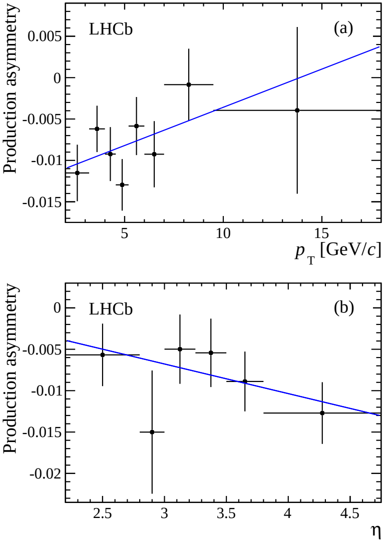
$$A_P = \frac{\sigma D^+ - \sigma D^-}{\sigma D^+ + \sigma D^-}$$

Corrected for *CP* violation in the neutral kaons and $\pi^\pm$ detection asymmetry.

8 bins in p_T range $[2, 18]\,\text{GeV}$,
6 bins in η range $[2.20, 4.75]$.

Average asymmetry integrated over full range
$A_P = (-0.96 \pm 0.26 \pm 0.18)\%$

No significant trend in p_T or η.



From inclusive $b\bar{b}$ to hadron cross-sections

Two LHCb measurements of the inclusive $b\bar{b}$ production cross-section for pp $\sqrt{s} = 7\,\text{TeV}$ (extrapolated to 4π)

- Using $b \to D\mu\nu X$ with $14.9\,\text{nb}^{-1}$ (Phys. Lett. B694 (2010) 209-216)
  $\sigma(pp \to b\bar{b}X) = 284 \pm 20 \pm 49\,\mu\text{b}$
- Using detached J/ψ with $5.2\,\text{pb}^{-1}$ (Eur. Phys. J. C 71 (2011) 1645)
  $\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\,\mu\text{b}$

Related to production cross-sections of specific b-hadron species by fragmentation functions

- Here we use $f_q \equiv \mathcal{B}(b \to B_q)$, $f_{\Lambda_b^0} \equiv \mathcal{B}(b \to \Lambda_b^0)$,
- In principle, can depend on $\sqrt{s}$ and location in b phase space.

Necessary for normalization of B_s^0 and Λ_b^0 branching ratio measurements at LHC

- Also useful for sensitivity and background studies.

Two measurements of fragmentation function ratios at LHCb.

$\sigma pp \to b\bar{b}X$ WITH $b \to D^0 \mu\nu X$

PHYS.LETT. B694 (2010) 209-216

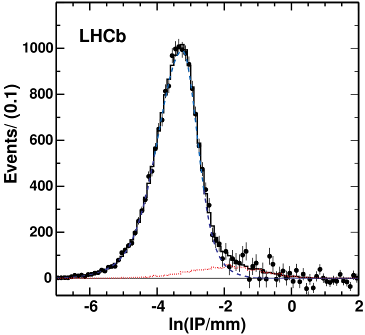
Analysis of $D^0(K^-\pi^+)\mu$ combinations in $14\,\text{nb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$.

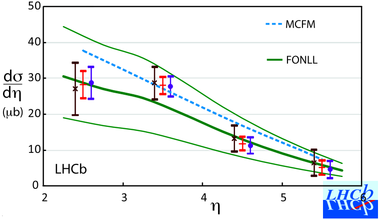
Separation of prompt D^0 and D^0 from b with log of impact parameter of D^0 with respect to PV.

Differential cross-sections in 4 bins of η, where η is determined by the displacement from the PV to the $D^0\ \mu^-$ vertex.

Converted to $\sigma(pp \to b\bar{b}X)$ with inclusive $\mathcal{B}(b \to D^0\mu^-\nu_\mu X)$.

Integrated over fiducial region
$\sigma(pp \to H_b X, 2 < \eta < 6) = 75.3 \pm 5.4 \pm 13.0\,\mu\text{b}$.





$\sigma\, pp \to b\bar{b}X$ WITH $b \to J/\psi\, X$

EUR.PHYS.J. C71 (2011) 1645

Analysis of 565,000 $J/\psi \to \mu^+\mu^-$ in $5.2\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$.

Separation of prompt J/ψ and J/ψ from b with pseudo-proper time

$$t_z = \frac{(z_{J/\psi} - z_V)M_{J/\psi}}{p_z}$$

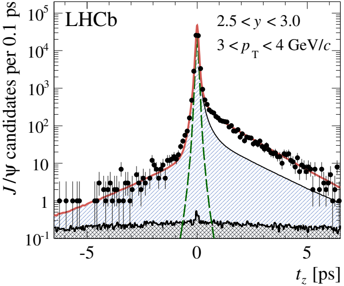
Double differential cross-sections in 14 bins of p_T and 5 bins of y

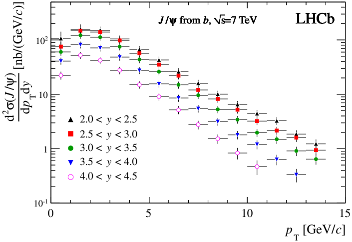
$$\mathrm{d}^2\sigma(J/\psi \text{ from } b)/\mathrm{d}p_\mathrm{T}\mathrm{d}y$$

Integrated over fiducial region

$$\sigma(J/\psi \text{ from } b, p_\mathrm{T} < 14\,\mathrm{GeV}, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16\,\mu\mathrm{b}.$$

Converted to $\sigma(pp \to b\bar{b}X)$ with inclusive $\mathcal{B}(b \to J/\psi\, X)$.





f_s/f_d WITH $B \to Dh$

PHYS. REV. LETT. 107 (2011) 211801

Three decay modes for two determinations of f_s/f_d:

$$B^0 \to D^- K^+, \qquad B^0 \to D^- \pi^+, \qquad B^0_s \to D^-_s \pi^+.$$

Using theoretical expressions for the branching fractions, the ratio from $B^0_s \to D^-_s \pi^+$ and $B^0 \to D^- K^+$ is

$$\frac{f_s}{f_d} = 0.971 \left| \frac{V_{us}}{V_{ud}} \right|^2 \left(\frac{f_K}{f_\pi} \right)^2 \frac{\tau_{B^0}}{\tau_{B^0_s}} \frac{1}{\mathcal{N}_a \mathcal{N}_F} \left(\frac{\epsilon(D^- K^+)}{\epsilon(D^-_s \pi^+)} \frac{N(D^-_s \pi^+)}{N(D^- K^+)} \right)$$

and that from $B^0_s \to D^-_s \pi^+$ and $B^0 \to D^- \pi^+$ is

$$\frac{f_s}{f_d} = 0.982 \frac{\tau_{B^0}}{\tau_{B^0_s}} \frac{1}{\mathcal{N}_a \mathcal{N}_F \mathcal{N}_E} \left(\frac{\epsilon(D^- \pi^+)}{\epsilon(D^-_s \pi^+)} \frac{N(D^-_s \pi^+)}{N(D^- \pi^+)} \right)$$

$N(X)$ and $\epsilon(X)$ are the experimental yields and efficiencies, $\mathcal{N}_a$ parameterizes nonfactorizable SU(3)-breaking, $\mathcal{N}_F$ is the ratio of form factors, and $\mathcal{N}_E$ accounts for the W-exchange diagram in $B^0 \to D^- \pi^+$.

f_s/f_d WITH $B \to Dh$

PHYS. REV. LETT. 107 (2011) 211801

Result from $B_s^0 \to D_s^- \pi^+$ and $B^0 \to D^- K^+$

$$\frac{f_s}{f_d} = (0.310 \pm 0.030(\text{stat}) \pm 0.021(\text{syst}))\frac{1}{\mathcal{N}_a \mathcal{N}_F}$$

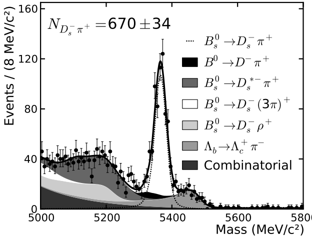
and that from $B_s^0 \to D_s^- \pi^+$ and $B^0 \to D^- \pi^+$ is

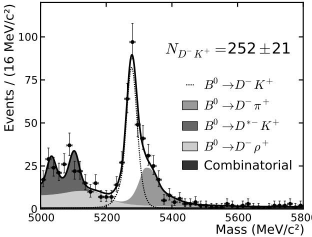
$$\frac{f_s}{f_d} = (0.307 \pm 0.017(\text{stat}) \pm 0.023(\text{syst}))\frac{1}{\mathcal{N}_a \mathcal{N}_F \mathcal{N}_E}$$

Combining the two with substituted theory parameters

$$\frac{f_s}{f_d} = 0.253 \pm 0.017(\text{stat}) \pm 0.017(\text{syst}) \pm 0.020(\text{theor})$$

$B_s^0 \to D_s^- \pi^+$





$B^0 \to D^- K^+$

$f_{s(\Lambda_b^0)}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

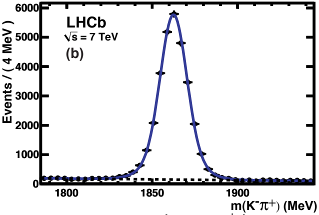
PHYS. REV. D 85 (2012) 032008

Attempt to reduce theoretical input by analyzing the abundances of the products of semileptonic *b*-hadron decays.

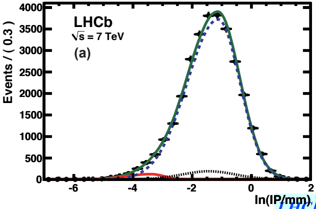
Six inclusive final states

- $\Lambda_c^+\mu^+\nu X$ and $D^0 p\mu^+\nu X$ to determine abundance of Λ_b^0, $n_{\mathrm{corr}}(\Lambda_b^0 \to D\mu)$,
- $D_s^-\mu^+\nu X$ and $\bar{D}^0 K^-\mu^+\nu X$ to determine abundance of B_s^0, $n_{\mathrm{corr}}(B_s^0 \to D\mu)$,
- $\bar{D}^0\mu^+\nu X$ and $D^-\mu^+\nu X$ with corrections from the other final states to determine the combined abundance of B^0 and B^+, $n_{\mathrm{corr}}(B^0 \to D\mu) + n_{\mathrm{corr}}(B^+ \to D\mu)$.

b-hadron semileptonic decays separated from prompt *D* production with characteristic distribution of *D* impact parameter.



Mass $m(K^-\pi^+)$



$\log(IP/\,\mathrm{mm})$

$f_{s(\Lambda_b^0)}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

PHYS. REV. D 85 (2012) 032008

From these,

$$\frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(B_s^0 \to D\mu)}{n_{\text{corr}}(B^0 \to D\mu) + n_{\text{corr}}(B^+ \to D\mu)} \frac{\tau_{B^+} + \tau_{B^0}}{2\tau_{B_s^0}}$$

and

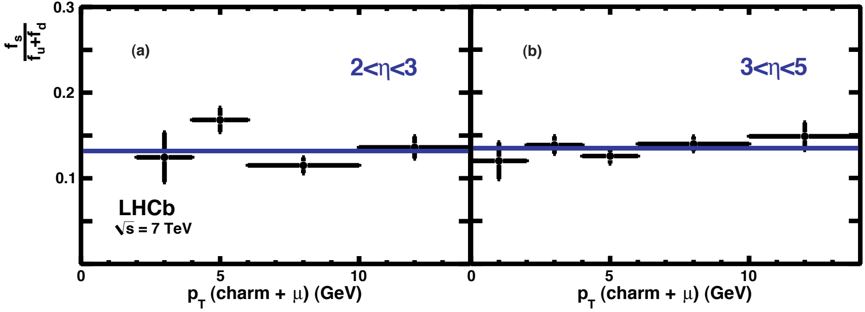
$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = \frac{n_{\text{corr}}(\Lambda_b^0 \to D\mu)}{n_{\text{corr}}(B^0 \to D\mu) + n_{\text{corr}}(B^+ \to D\mu)} \frac{\tau_{B^+} + \tau_{B^0}}{2\tau_{\Lambda_b^0}}(1 - \xi)$$

where the factor ξ accounts for the chromomagnetic correction that affects b mesons but not b baryons.

Analyzed as a function of $D\mu$ p_{T} in two bins of $D\mu$ η to investigate variations in phase space.

$f_s/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

PHYS. REV. D 85 (2012) 032008



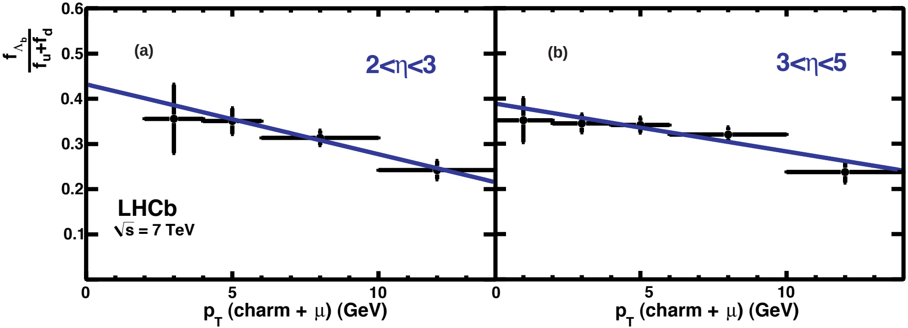
No sign of p_{T} dependence for $f_s/f_u + f_d$

Constant fit to all data gives

$$\frac{f_s}{f_u + f_d} = 0.134 \pm 0.004^{+0.011}_{-0.010}$$

$f_{\Lambda_b^0}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

PHYS. REV. D 85 (2012) 032008



Apparent p_{T} dependence for $f_{\Lambda_b^0}/f_u + f_d$.

Expressing the result as a best-fit linear function of p_{T}:

$$\left[f_{\Lambda_b^0}/(f_u + f_d)\right](p_{\mathrm{T}}) = a \times [1 - b \times p_{\mathrm{T}}],$$

$$a = 0.404 \pm 0.017(\mathrm{stat}) \pm 0.027(\mathrm{syst}) \pm 0.105(\mathrm{BF}) \quad (1)$$

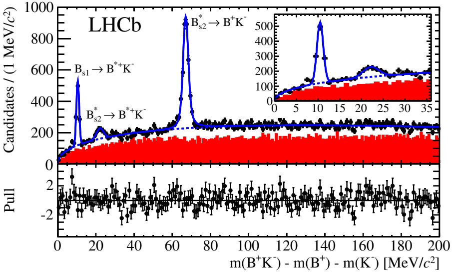
$$b = 0.031 \pm 0.004 \pm 0.003\,\mathrm{GeV}^{-1}$$

RELATIVE PRODUCTION OF B_s^{**} STATES

PHYS.REV.LETT. 110 (2013) 15, 151803

Analysis of excited B_s^0 statues in the $B^+ K^-$ mass spectrum,

- Total $\sim$1 million B^+ in four decay modes in 1 fb^{-1} at $\sqrt{s} = 7$ TeV.



Three mass peaks identified as

- $B_{s1} \to B^{*+}K^-$
- $B^*_{s2} \to B^{*+}K^-$
- $B^*_{s2} \to B^+K^-$

where the γ in $B^{*+} \to B^+\gamma$ is not observed.

Includes the first observation of $B^*_{s2} \to B^{*+}K^-$.

Analysis includes several properties of the observed states, and the relative production of B_{s1} and B^*_{s2}

$$\frac{\sigma(pp \to B_{s1}X)\mathcal{B}(B_{s1} \to B^{*+}K^-)}{\sigma(pp \to B^*_{s2}X)\mathcal{B}(B^*_{s2} \to B^+K^-)} = 0.232 \pm 0.014 \pm 0.013.$$

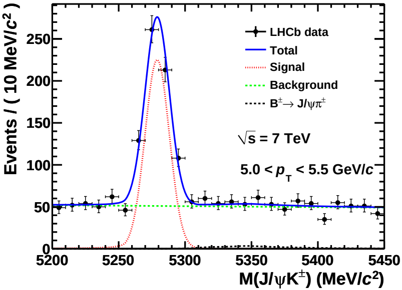
$B^{\pm}$ PRODUCTION CROSS-SECTION

JHEP 04 (2012) 039

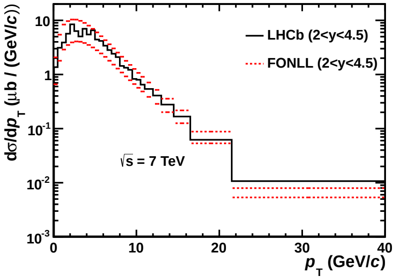
Measured in the mode $B^{\pm} \to J/\psi\, K^{\pm}$

- $\sim$9100 signal events in $35\,\mathrm{pb}^{-1}$ $\sqrt{s} = 7\,\mathrm{TeV}$ data,

Total cross-section and $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$



Mass distribution for bin $5 < p_{\mathrm{T}} < 5.5\,\mathrm{GeV}/c$



Differential $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ compared to FONLL predictions (JHEP 03 (2001) 006),

- $f_{\bar{b} \to B^{+}} = (40.1 \pm 1.3)\%$.

$\sigma(pp \to B^{\pm}X) = 41.4 \pm 1.5(\mathrm{stat}) \pm 3.1(\mathrm{syst})\,\mu\mathrm{b}$ for $0 < p_{\mathrm{T}} < 40\,\mathrm{GeV}/c$, $2 < y < 4.5$.

$B_c^{\pm}$ PRODUCTION CROSS-SECTION

PHYS.REV.LETT. 109 (2012) 232001

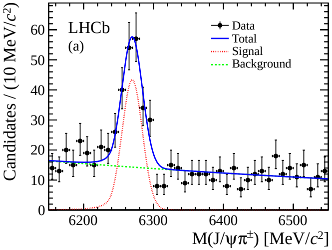
$B_c^{\pm} \to J/\psi\,\pi^{\pm}$ production at $\sqrt{s} = 7\,\text{TeV}$,

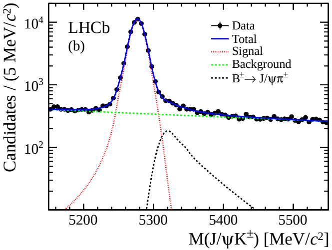
- 162 ± 18 signal in $370\,\text{pb}^{-1}$,
- Measurement range: $p_{\text{T}} > 4\,\text{GeV}/c$, $2.5 < \eta < 4.5$

$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi\,K^+)}$$
$$= (0.68 \pm 0.10(\text{stat}) \pm 0.03(\text{syst}) \pm 0.05(\text{lifetime}))\%$$

Measurement includes the most precise measurement of $M(B_c^+)$

$$M(B_c^+) = 6273.7 \pm 1.3(\text{stat}) \pm 1.6(\text{syst})\,\text{MeV}/c^2$$
$$M(B_c^+) - M(B^+) = 994.6 \pm 1.3(\text{stat}) \pm 0.06(\text{syst})\,\text{MeV}/c^2$$





Λ_b^0 PRODUCTION CROSS-SECTION
LHCb-CONF-2012-031

$\Lambda_b^0 \to J/\psi\,\Lambda$ production at $\sqrt{s} = 7\,\text{TeV}$,

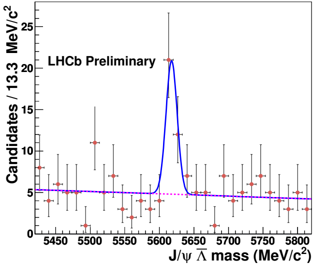
- Measurement range: $p_{\text{T}} > 13\,\text{GeV}/c$, $2.2 < \eta < 4.5$,
- 2010 data, $36\,\text{pb}^{-1}$

Analyzed in eight subsets divided by

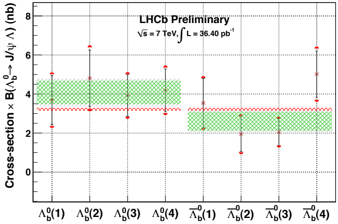
- Λ_b^0 and $\overline{\Lambda}_b^0$
- Magnet polarity,
- Whether the Λ decays in the VELO,

Cross-section of conjugates measured separately

$$\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda) = 4.19 \pm 0.61(\text{stat}) \pm 0.37(\text{syst})\,\text{nb}$$
$$\sigma(\overline{\Lambda}_b^0)\mathcal{B}(\overline{\Lambda}_b^0 \to J/\psi\,\overline{\Lambda}) = 2.63 \pm 0.48(\text{stat}) \pm 0.27(\text{syst})\,\text{nb}$$



One of eight subsamples



Summary

LHCb has made precise measurements of forward production of heavy flavored hadrons at $\sqrt{s} = 7\,\mathrm{TeV}$, including

- Production cross-sections of ground state b and c hadrons.
- Inclusive $b\bar{b}$ cross-section and form factor ratios,
- Production asymmetries of charmed mesons.

Results of several of these measurements with the $\sqrt{s} = 8\,\mathrm{TeV}$ data collected in 2012 are in preparation.

LHCb has created an Early 2015 Measurements Task Force with the goal of rapid publication of production measurements at $\sqrt{s} = 13\,\mathrm{TeV}$.