Heavy flavour production at LHCb

[LHC Heavy Flavour (production) WG]

Niels Tuning, 10 Nov 2015

Outline

1) Recent highlights
   - Open charm production at $\sqrt{s}$=13 TeV
   - Y production ratio (8 TeV / 7 TeV)
   - Y + D production
2) B production
   - Cross section
   - Production asymmetries
3) Relative production of b-hadron species
   - f_Λ/f_d
   - f_s/f_d
   - p_T, η dependence
4) B_c production

Motivation

1) Recent highlights
   - Open charm production at $\sqrt{s}$=13 TeV
   - Y production ratio (8 TeV / 7 TeV)

   Understanding QCD
   - Y + D production

   Double parton scattering

2) B production
   - Cross section

   Understanding QCD
   - Production asymmetries

   Crucial for CPV measurements

3) Relative production of b-hadron species
   - f_Λ/f_d
   - f_s/f_d

   Indispensable for all BR measurements

   notably $B_s \to \mu^+\mu^-$
   - p_T, η dependence

   LHCb vs GPD

4) B_c production

   Two heavy quarks

Non-exhaustive list of LHCb production papers

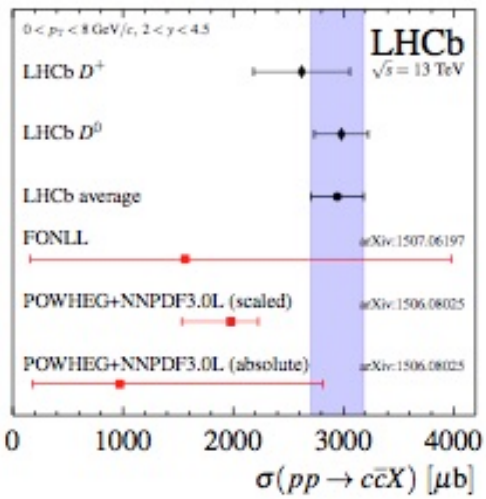
- No time for: *production of excited heavy hadrons (χ_c, Ξ_b, …), central exclusive J/Ψ production, cold nuclear effects in p-Pb, polarization, …*

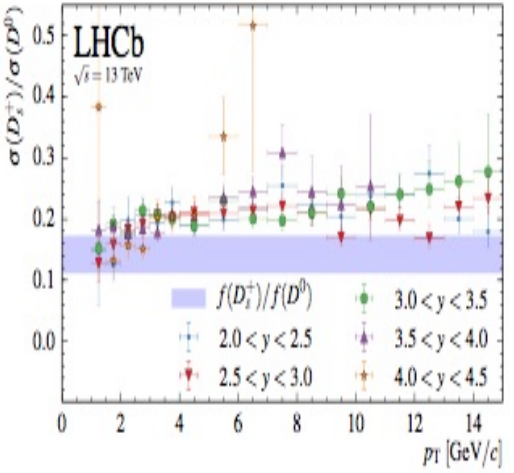
ID	Title
PAPER-2015-032	Study of the production of Λb and $B^{-}0$ hadrons in pp collisions and first measurement of the $\Lambda b \to J/\psi p K^-$ branching fraction
PAPER-2015-045	Forward production of Y mesons in pp collisions at $s\sqrt{}=7$ and 8 TeV
PAPER-2015-037	Measurement of forward J/ψ production cross-sections in pp collisions at $s\sqrt{}=13$ TeV
PAPER-2014-050	Measurement of $B+c$ production in proton-proton collisions at $s\sqrt{}=8$ TeV
PAPER-2014-042	Measurement of the $B^{-}0-B0$ and $B^{-}0s-B0s$ production asymmetries in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2014-040	Measurement of the $\chi b(3P)$ mass and of the relative rate of $\chi b1(1P)$ and $\chi b2(1P)$ production
PAPER-2014-031	Study of χb meson production in pp collisions at $s\sqrt{}$ =7 and 8 TeV and observation of the decay $\chi b \to \Upsilon(3S)\gamma$
PAPER-2014-029	Measurement of the $\eta c(1S)$ production cross-section in proton-proton collisions via the decay $\eta c(1S) \to pp^{-}$
PAPER-2014-015	Study of Y production and cold nuclear matter effects in p Pb collisions at $sNN\sqrt{}=5$ \,TeV.
PAPER-2013-066	Measurement of Y production in pp collisions at $s\sqrt{}=2.76$ ~TeV
PAPER-2013-052	Study of J/ψ production and cold nuclear matter effects in p Pb collisions at s\tiny{NN} $\sqrt{}=5$ \tev
PAPER-2013-028	Measurement of the relative rate of prompt $\chi c0$, $\chi c1$ and $\chi c2$ production at $s\sqrt{}=7$ \,TeV
PAPER-2013-004	Measurements of B meson production cross-sections in proton-proton collisions at $s\sqrt{}=7$ \,TeV
PAPER-2012-057	Measurements of the $\Lambda b \to \Lambda J/\psi$ decay amplitudes and the Λb baryon production polarisation in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2012-039	Measurement of J/ψ production in pp collisions at $s\sqrt{}=2.76$ TeV
PAPER-2012-028	Measurements of $B\pm c$ production and mass with the $B+c \to J/\psi\pi+$ decay
PAPER-2012-003	Observation of double charm production involving open charm in pp collisions at sqrt(s) = 7 TeV
PAPER-2011-045	Measurement of $\psi(2S)$ meson production in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2011-043	Measurement of the $B\pm$ production cross-section in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2011-036	Measurement of Y production in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2011-034	Observation of $X(3872)$ production in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2011-030	Measurement of the ratio of prompt χc to J/ψ production in pp collisions at $s\sqrt{}=7$ TeV
PAPER-2011-019	Measurement of the cross-section ratio $\sigma(\chi c2)/\sigma(\chi c1)$ for prompt χc production at $sqrts=7$ TeV
PAPER-2011-013	Observation of double J/ψ production in proton-proton collisions at a centre-of-mass energy of $s\sqrt{}=7$ TeV
PAPER-2011-003	Measurement of J/ψ production in pp collisions at $(\sqrt{}s)=7$ TeV

Recent highlights

- σ(pp→cc̄) at 13 TeV
  - $\sigma_{\text{LHCb acc}}$ = 2.94±0.24 mb
  - $d\sigma/dp_T$ agreement worsens with higher √s
  - f(c→$D_{(s)}$) fragmentation independent of c production

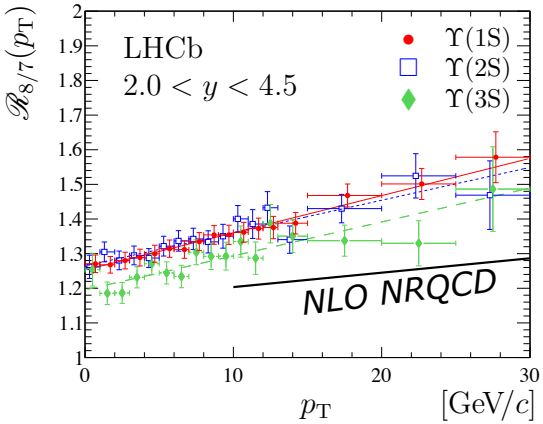
LHCb-2015-041, arXiv:1510.01707

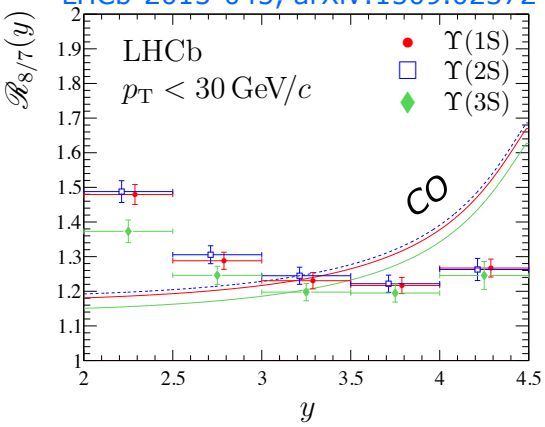




- σ(pp→Υ)$_{8TeV}$/σ(pp→Υ)$_{7TeV}$
  - Increase with √s larger than predicted
  - Colour-Octet model does not describe ratio vs η

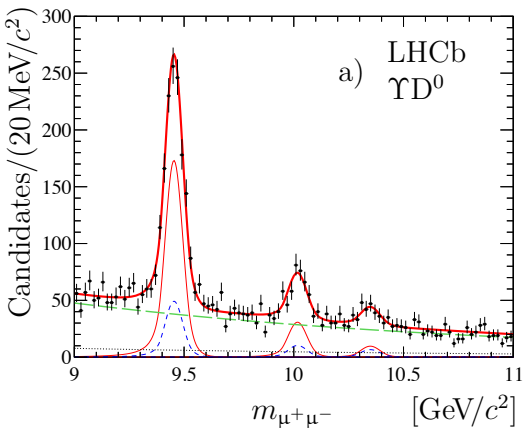
LHCb-2015-045, arXiv:1509.02372

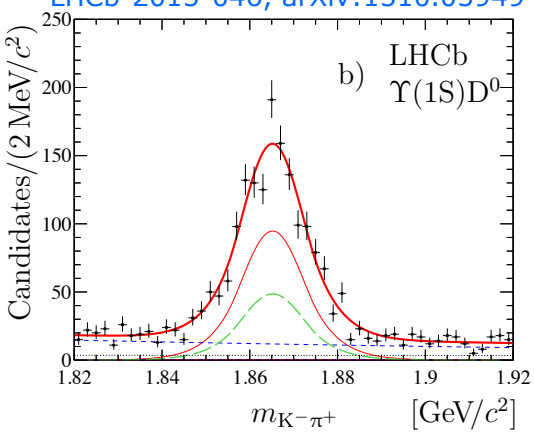




- σ(pp→YD)
  - b and c production
  - Good agreement with Double Parton Scattering

LHCb-2015-046, arXiv:1510.05949





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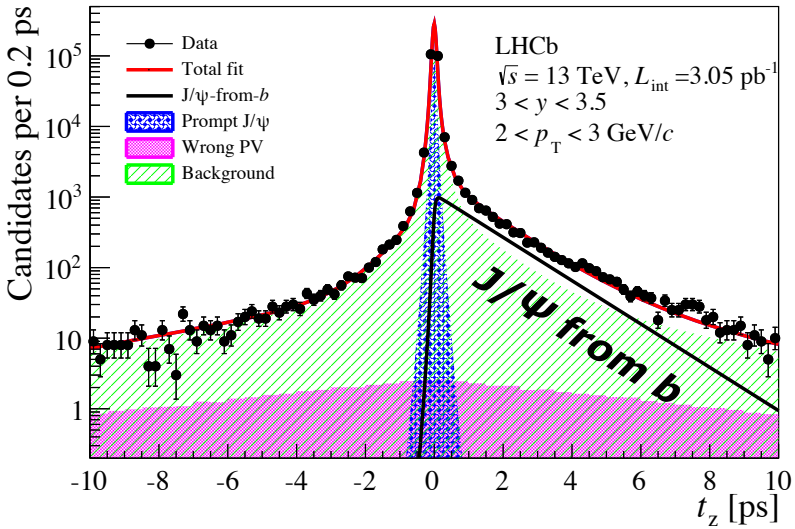
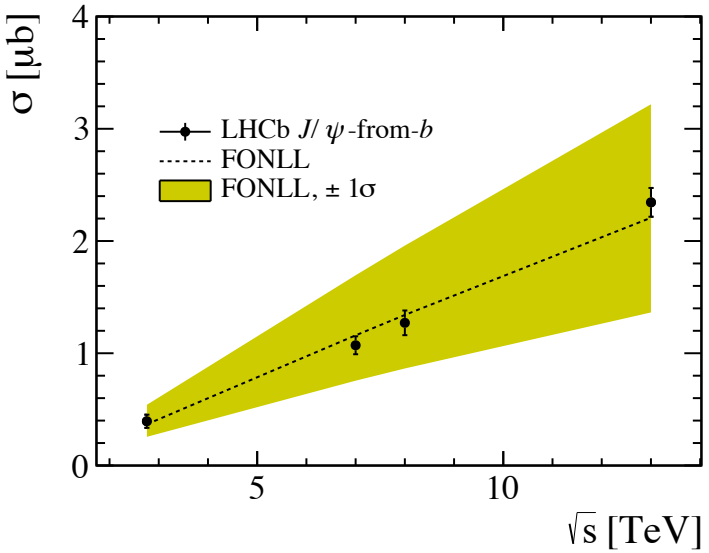
B production

- Production cross section from detached J/ψ: *B→J/ψX*





➢ σ(J/ψ(-from-b)) at √s=13 TeV:

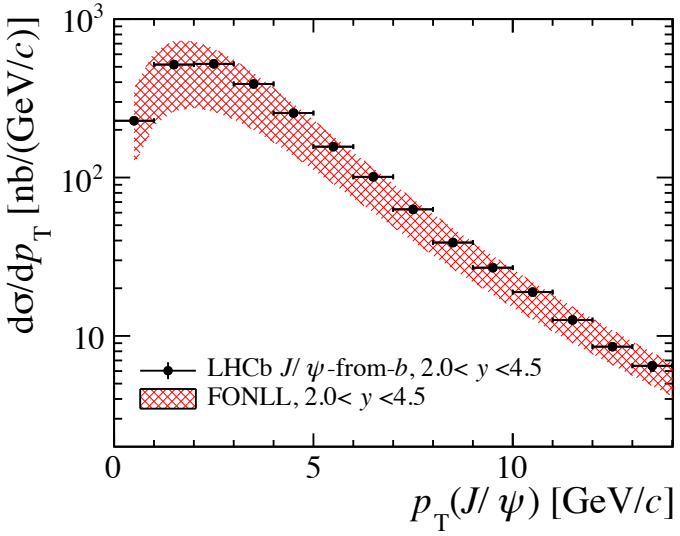
$$\sigma(\text{prompt } J/\psi, p_{\mathrm{T}} < 14\,\mathrm{GeV}/c, 2.0 < y < 4.5) = 15.30 \pm 0.03 \pm 0.86\,\mu\mathrm{b},$$
$$\sigma(J/\psi\text{-from-}b, p_{\mathrm{T}} < 14\,\mathrm{GeV}/c, 2.0 < y < 4.5) = 2.34 \pm 0.01 \pm 0.13\,\mu\mathrm{b},$$

➢ σ(bb) at √s=13 TeV: $\sigma(pp \to b\bar{b}X) = 515 \pm 2 \pm 53\,\mu\mathrm{b}$

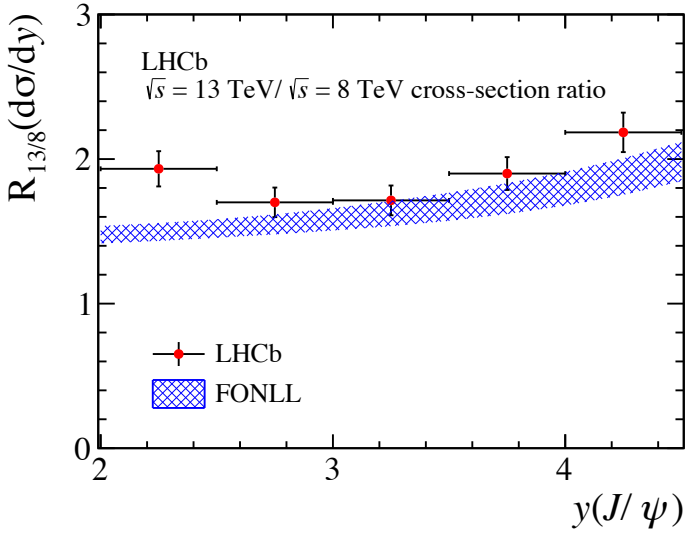
- No uncertainty from extrapolation to 4π
- Agreement with GPD ?

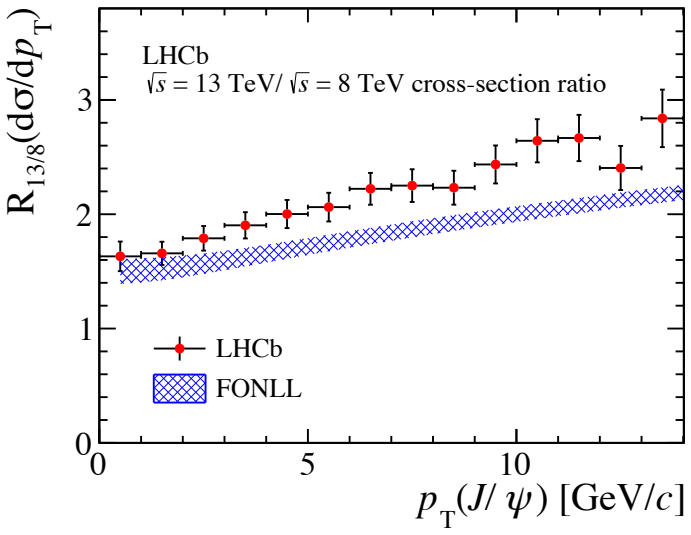
B production

- Single differential cross section well described by FONLL:



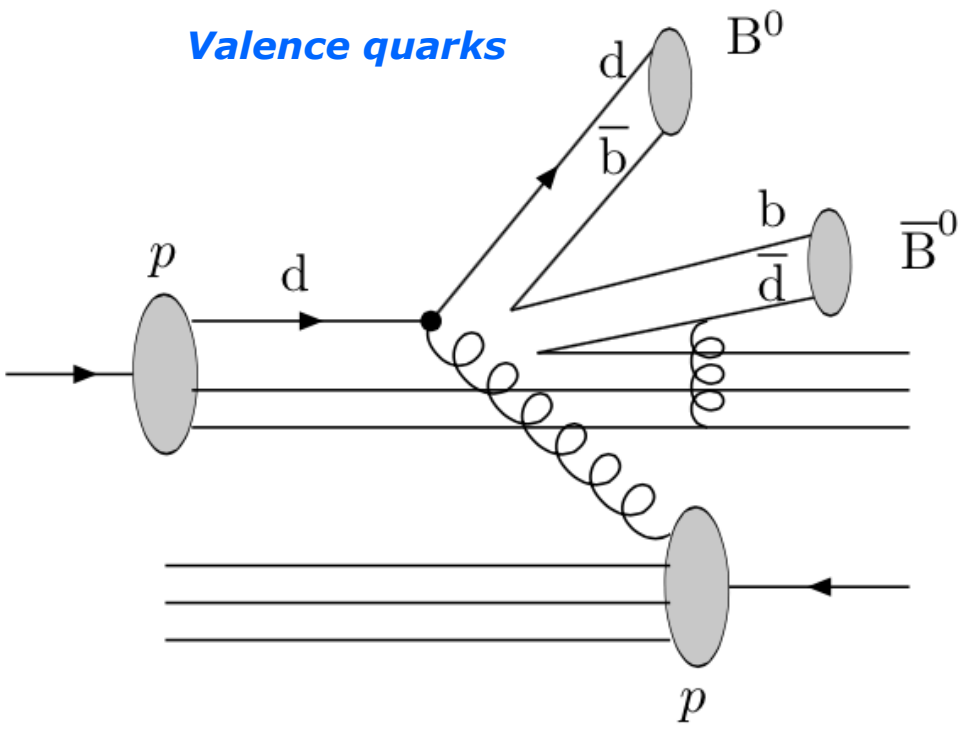
- Accurate measurement, and prediction of ratio
  - ➢ $R_{13/8} = \sigma_{\sqrt{s}=13TeV} / \sigma_{\sqrt{s}=8TeV}$





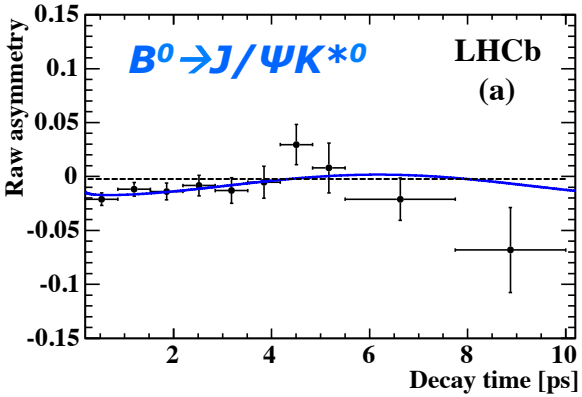
Production asymmetry?

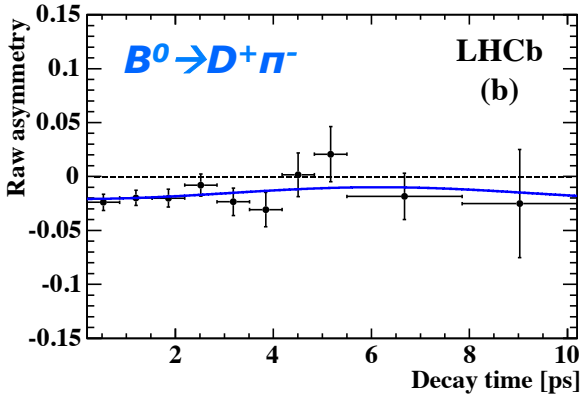
- Crucial ingredient for CP violation measurements
- Reasons to believe it's non-vanishing
  - Valence quarks in pp scattering
  - "drag effect" from proton remnant



B production asymmetry

$$A_{\mathrm{P}}\left(B^0_{(s)}\right) \equiv \frac{\sigma\left(\overline{B}^0_{(s)}\right) - \sigma\left(B^0_{(s)}\right)}{\sigma\left(\overline{B}^0_{(s)}\right) + \sigma\left(B^0_{(s)}\right)}$$

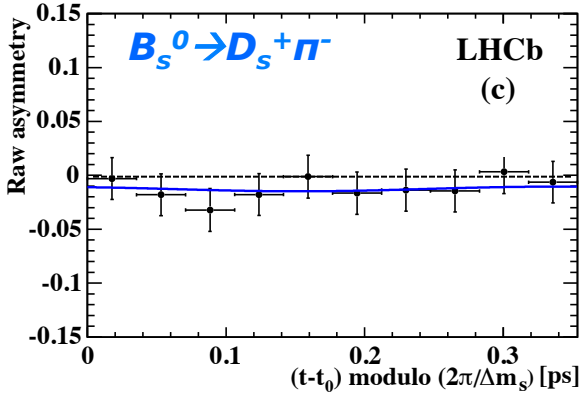




- Time-dependent fit, with 3 fb^{-1}:

$$A_{\mathrm{P}}(B^0) = -0.0035 \pm 0.0076\,(\mathrm{stat}) \pm 0.0028\,(\mathrm{syst})$$

$$A_{\mathrm{P}}(B^0_s) = \quad 0.0109 \pm 0.0261\,(\mathrm{stat}) \pm 0.0066\,(\mathrm{syst})$$



- Using B→hh, with 1 fb^{-1}:

$$A_{\mathrm{P}}\left(B^0\right) = (0.6 \pm 0.9)\% \text{ and } A_{\mathrm{P}}\left(B^0_s\right) = (7 \pm 5)\%$$

LHCb-2013-040, arXiv:1308.1428
LHCb-2014-042, arXiv:1408.0275

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B production: different species

- B meson production measured, using BR from B factories:

$$\frac{\mathrm{d}^2\sigma(B)}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y} = \frac{N_B(p_{\mathrm{T}},y)}{\epsilon_{\mathrm{tot}}(p_{\mathrm{T}},y)\,\mathcal{L}_{\mathrm{int}}\,\mathcal{B}(B\to J/\psi\,X)\,\Delta p_{\mathrm{T}}\,\Delta y}$$

- Integrated cross section $0<p_T<40$ GeV, $2<y<4.5$:

$$\begin{aligned}
\sigma(pp\to B^+\,X) &= 38.9\pm0.3\,(\mathrm{stat.})\pm2.5\,(\mathrm{syst.})\pm1.3\,(\mathrm{norm.})\ \mu\mathrm{b},\\
\sigma(pp\to B^0\,X) &= 38.1\pm0.6\,(\mathrm{stat.})\pm3.7\,(\mathrm{syst.})\pm4.7\,(\mathrm{norm.})\ \mu\mathrm{b},\\
\sigma(pp\to B_s^0\,X) &= 10.5\pm0.2\,(\mathrm{stat.})\pm0.8\,(\mathrm{syst.})\pm1.0\,(\mathrm{norm.})\ \mu\mathrm{b}.
\end{aligned}$$

- ➢ Need the branching fraction of $B_s^0 \to J/\Psi X$ …
- ➢ but for the branching fraction one needs the production rate

Relative production of different species

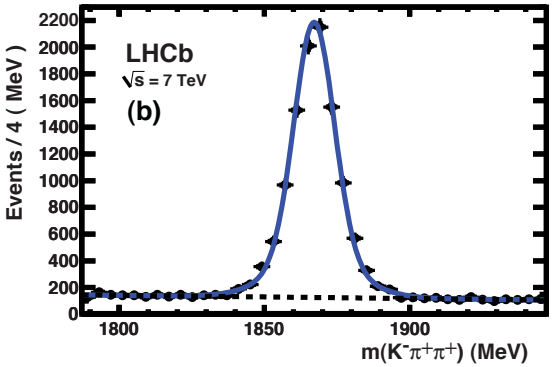
- Semileptonic
  - Assume equal inclusive decay width

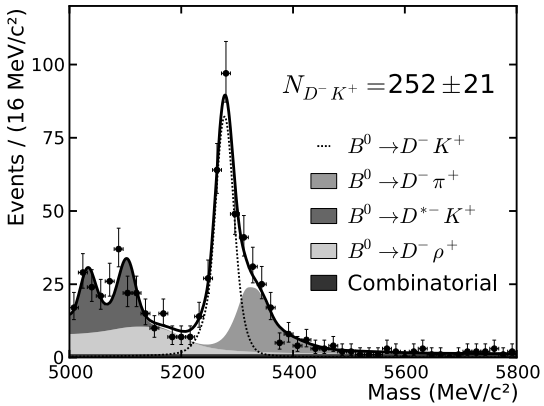
$$\frac{f_s}{f_u+f_d}=\frac{n_{\rm corr}(\overline{B}^0_s\to D\mu)}{n_{\rm corr}(B\to D^0\mu)+n_{\rm corr}(B\to D^+\mu)}\frac{\tau_{B^-}+\tau_{\overline{B}^0}}{2\tau_{\overline{B}^0_s}}$$

- Hadronic
  - Assume SU(3) symmetry

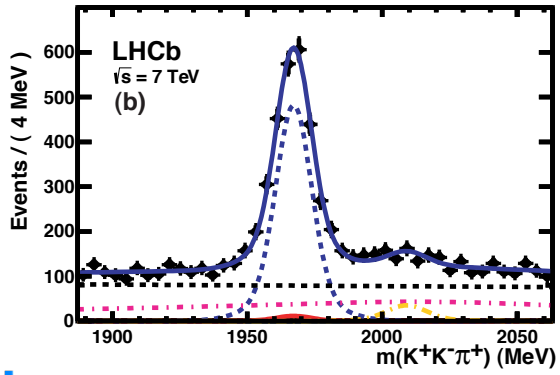
$$\frac{f_s}{f_d}=0.971\cdot\left|\frac{V_{us}}{V_{ud}}\right|^2\left(\frac{f_K}{f_\pi}\right)^2\frac{\tau_{B_d}}{\tau_{B_s}}\frac{1}{\mathcal{N}_a\mathcal{N}_F}\frac{\epsilon_{D^-K^+}}{\epsilon_{D_s^-\pi^+}}\frac{N_{D_s^-\pi^+}}{N_{D^-K^+}}$$

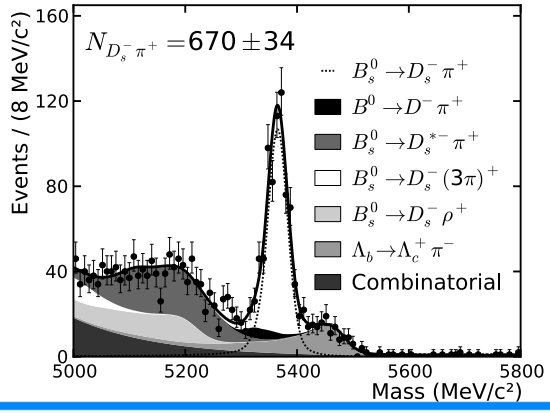
$N(B^0)$





$N(B_s^0)$



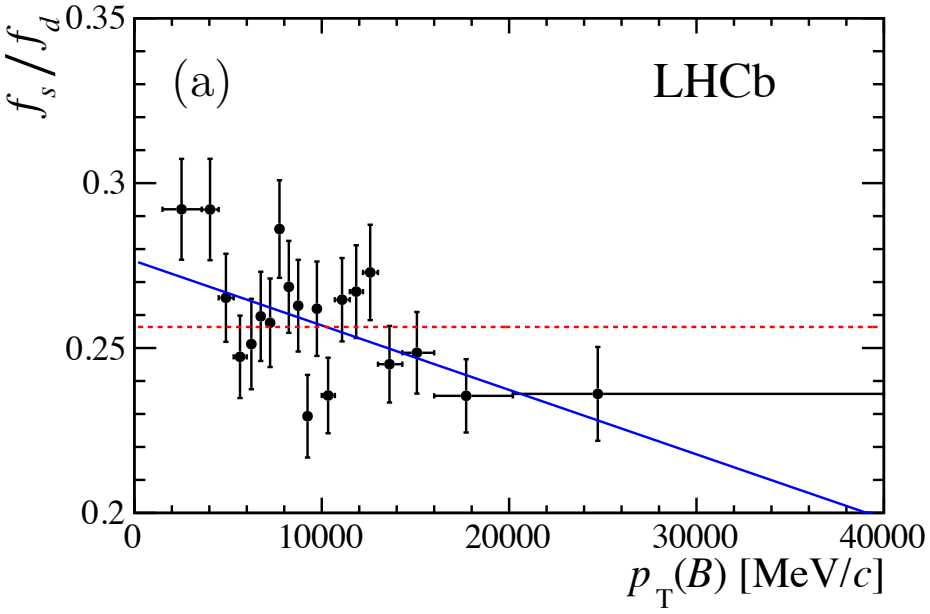


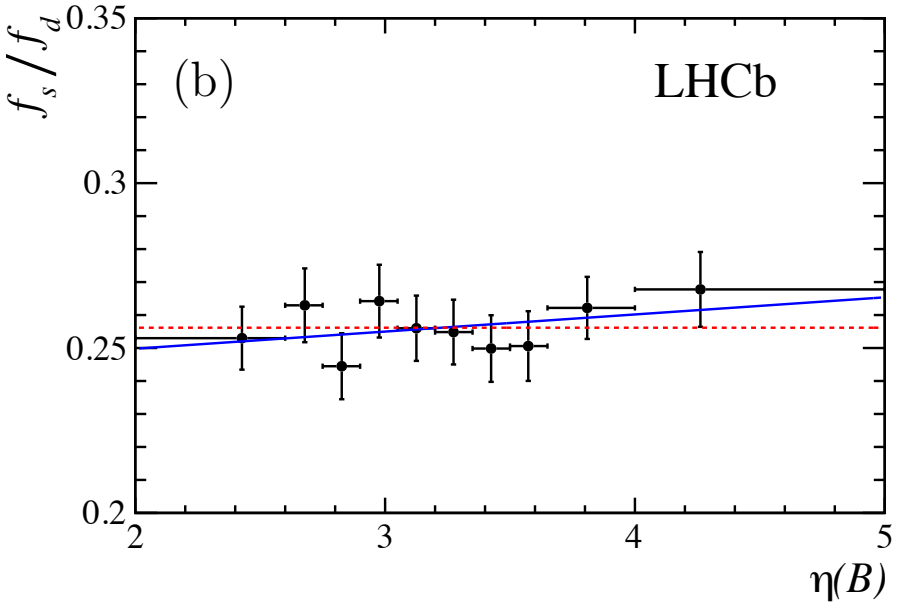
$$f_s/f_d = 0.259\pm0.015$$

LHCb-2011-018, arXiv:1111.2357
LHCb-CONF-2013-011
LHCb-2011-006, arXiv:1106.4435

Is f_s/f_d constant?

- Measured dependence of f_s/f_d vs p_T, η:





➢ Almost constant

- Important for BR($B_s^0 \to \mu^+\mu^-$)
- Extrapolation to full η-range necessary

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{\text{norm.}}} \times \frac{f_d}{f_s} \times \frac{\varepsilon_{\text{norm.}}}{\varepsilon_{B_s^0\to\mu^+\mu^-}} \times \mathcal{B}_{\text{norm.}} = \alpha_{\text{norm.}} \times N_{B_s^0\to\mu^+\mu^-}$$

LHCb-2012-037, arXiv:1301.5286

Is f_s/f_d constant?

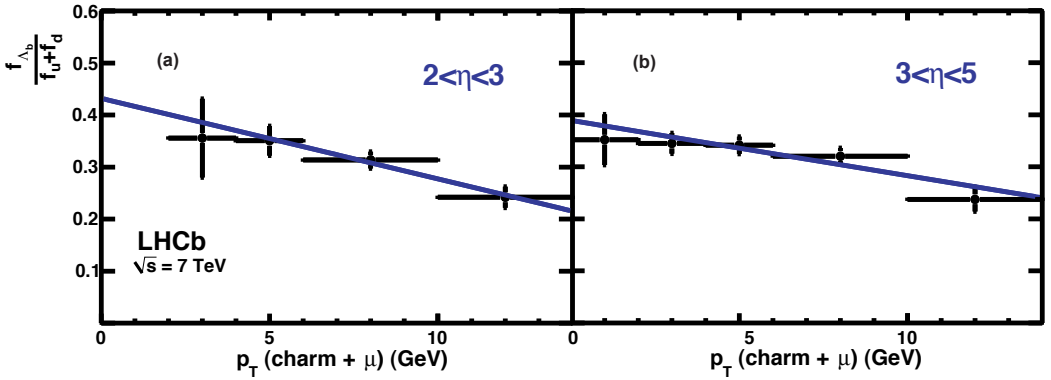
- Dependence of f_s/f_d vs centre-of-mass energy?
- No hint in Run-I; $(f_s/f_d)_{8\ \mathrm{TeV}}/(f_s/f_d)_{7\ \mathrm{TeV}} = 1.00 \pm 0.05$

(PhD thesis R.Koopman)

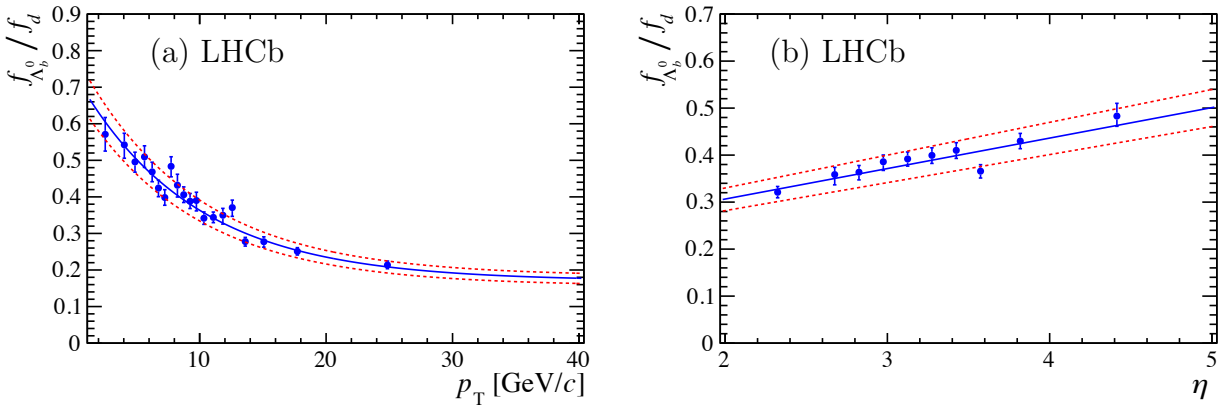
- **Absolute** measurement of f_s/f_d planned at $\sqrt{s}$=13 TeV, with semileptonic B decays
- **Relative** measurements with $B^+ \to J/\Psi K^+$ and $B_s^0 \to J/\Psi \phi$ also pursued

Relative production fraction of Λ_b^0 vs B^0

- Crucial for all BR(Λ_b^0) measurements
- **Absolute** determination of f_Λ/f_d with semileptonic decays



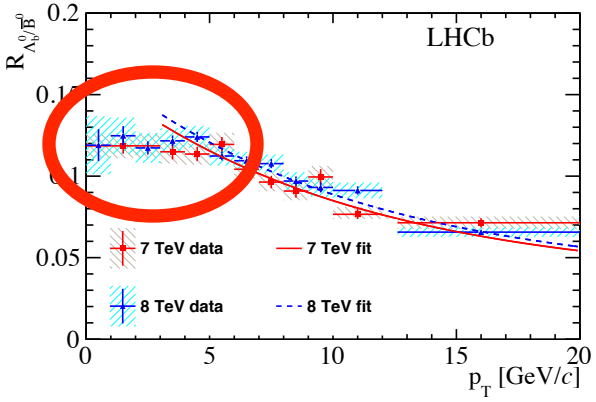
- **Relative** determination of f_Λ/f_d with hadronic decays:

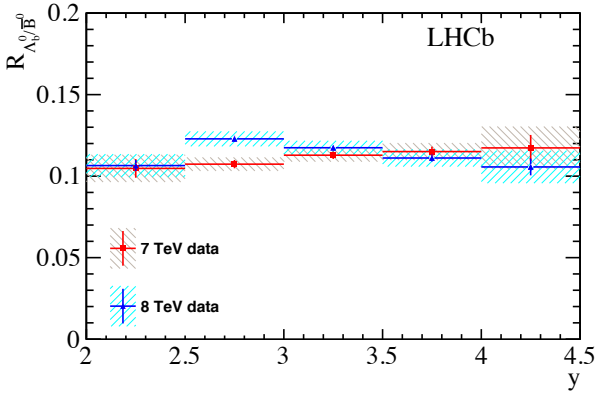


LHCb-2011-018, arXiv:1111.2357
LHCb-2014-004, arXiv:1405.6842

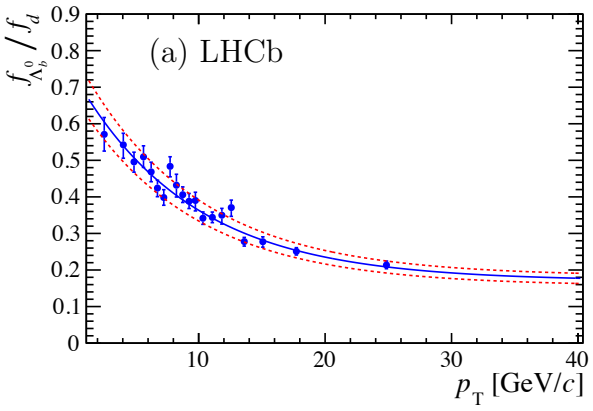
Relative production fraction of Λ_b^0 vs B^0

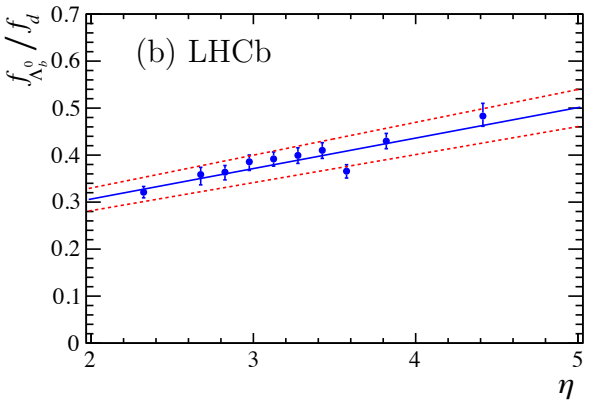
- It flattens of at low p_T:





- **Relative** determination of f_Λ/f_d with hadronic decays:





LHCb-2015-032, arXiv:1509.00292
LHCb-2014-004, arXiv:1405.6842

Intermezzo: Absolute branching fractions

- The relative production rates lead to accurate BRs

- Examples:

$$BR(B_s^0 \to D_s^+ \pi^-) = (2.95 \pm 0.27) \times 10^{-3}$$

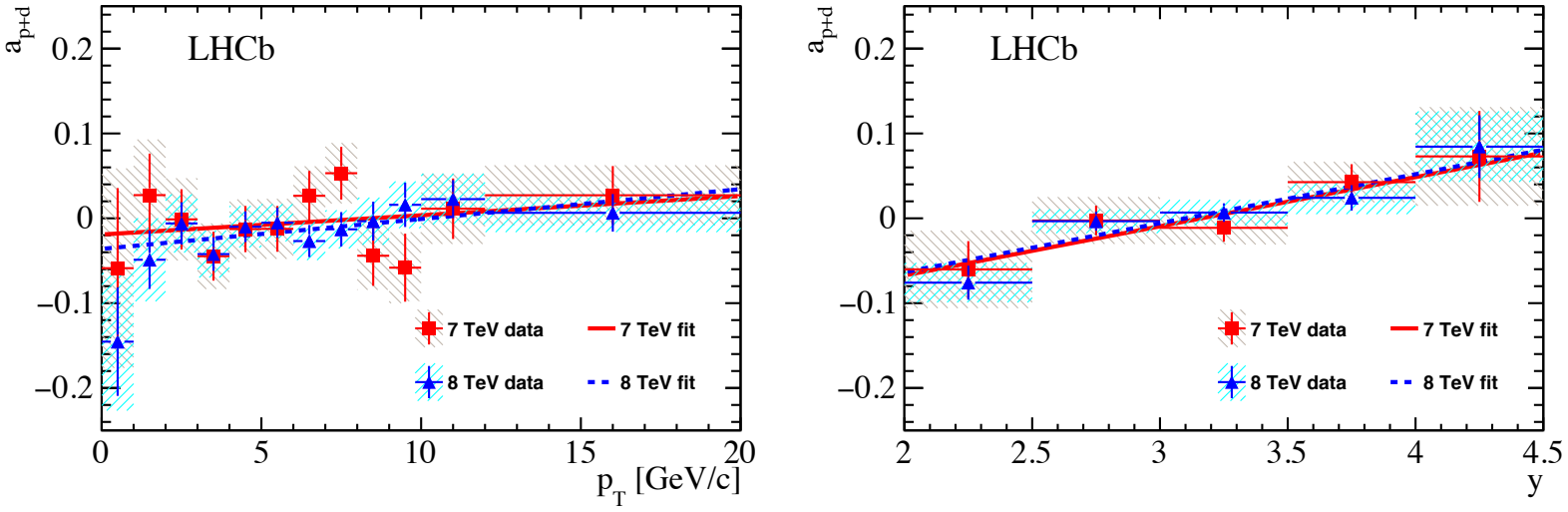
$$BR(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (4.30 \pm 0.36) \times 10^{-3}$$

- (Useful as normalisation modes)

LHCb-2012-037, arXiv:1301.5286
LHCb-2014-004, arXiv:1405.6842

Production asymmetry of Λ_b^0 baryons

- Small production(+decay) asymmetry (surprising?)



- Increase of production cross sections of 20% at √s=8TeV:

$$\frac{\sigma(\sqrt{s}=8\,\text{TeV})}{\sigma(\sqrt{s}=7\,\text{TeV})} = \begin{cases} 1.23 \pm 0.02 \pm 0.07 & \text{for } \Lambda_b^0, \\ 1.19 \pm 0.01 \pm 0.02 & \text{for } \overline{B}^0 \end{cases}$$

LHCb-2015-032, arXiv:1509.00292

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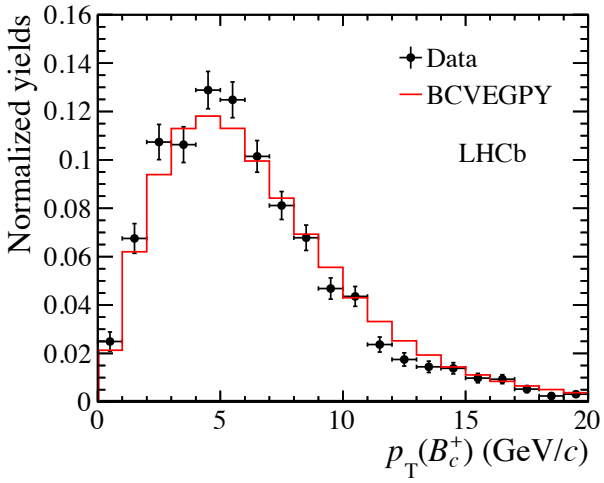
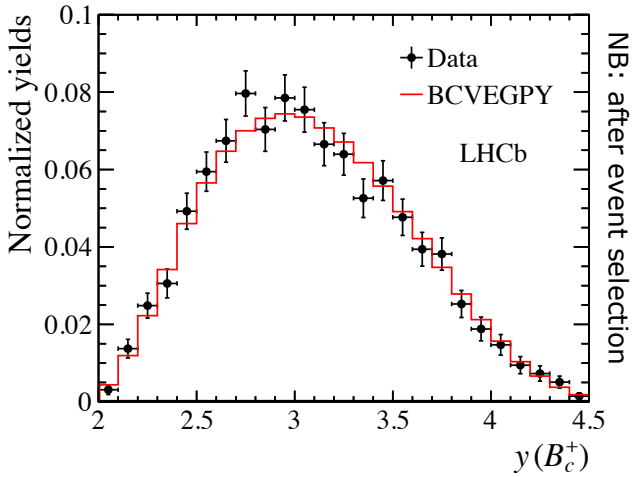
B_c^+ production

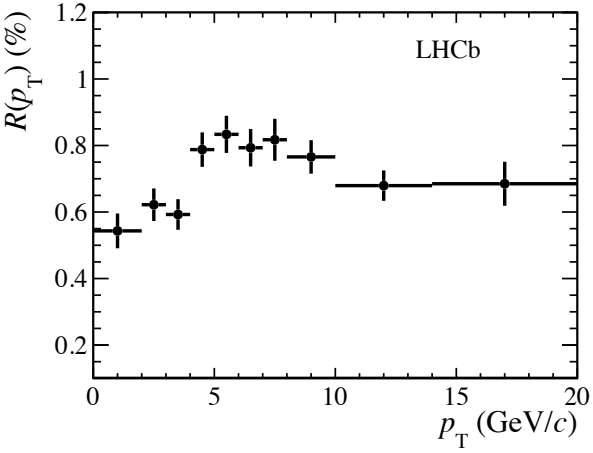
- B_c^+ is a fascinating system, consisting of 2 heavy quarks
- Study B_c^+ with $B_c^+ \rightarrow J/\Psi K^+$ decays. BCVEGPY is accurate:

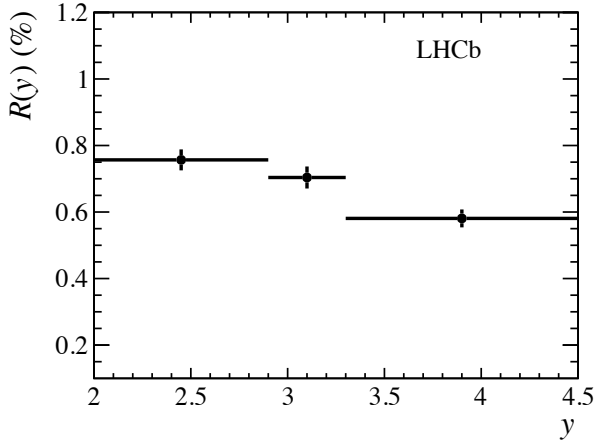




- More B_c^+ at higher p_T:

$N(B_c)/N(B^+)$





LHCb-2014-050, arXiv:1411.294

Conclusions

1) Recent highlights
   - Open charm production at $\sqrt{s}$=13 TeV — Larger than predicted
   - Y production ratio (8 TeV / 7 TeV) — Larger than NRQCD, CO poor
   - Y + D production — Double parton scattering
2) B production
   - Cross section — Ratio 13/8 TeV provides stringent test
   - Production asymmetries — Accurate to 1(3)% for $B^0_{(s)}$
3) Relative production of b-hadron species
   - f_Λ/f_d
   - f_s/f_d — Accurate input available (for eg. $B_s \to \mu^+\mu^-$)
   - p_T, η dependence
4) B_c production — Two heavy quarks