BEAUTY 2019

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Heavy flavour production at LHCb

Marcello Rotondo

Laboratori Nazionali di Frascati

On behalf of the LHCb collaboration

Heavy flavour production

- Cross-section of heavy-flavour hadrons measurements in various environments and experimental setup

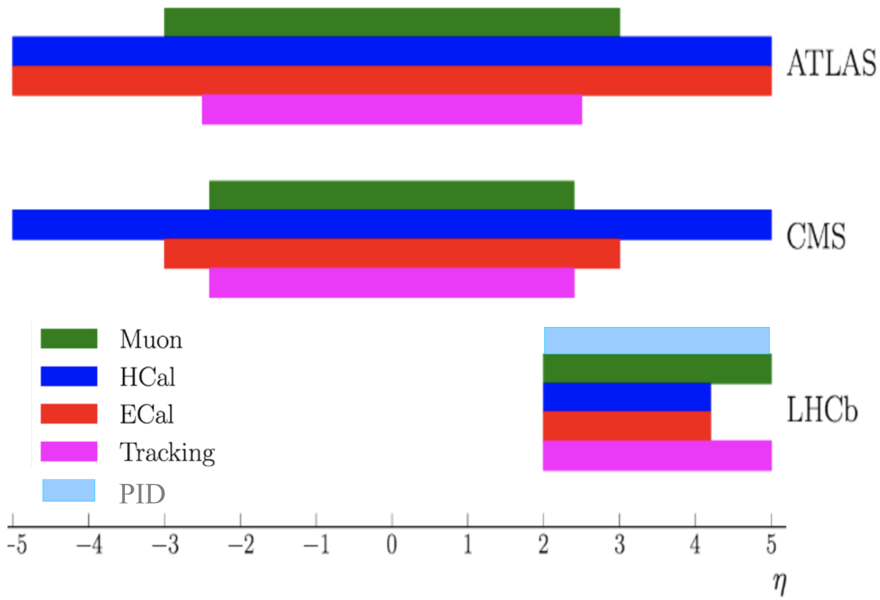
- Provide powerful QCD test
- Needed for tuning of event generators
  - Crucial ingredients for searches and measurements of rare or new processes
  - Crucial for precise measurements of b-hadron decay properties

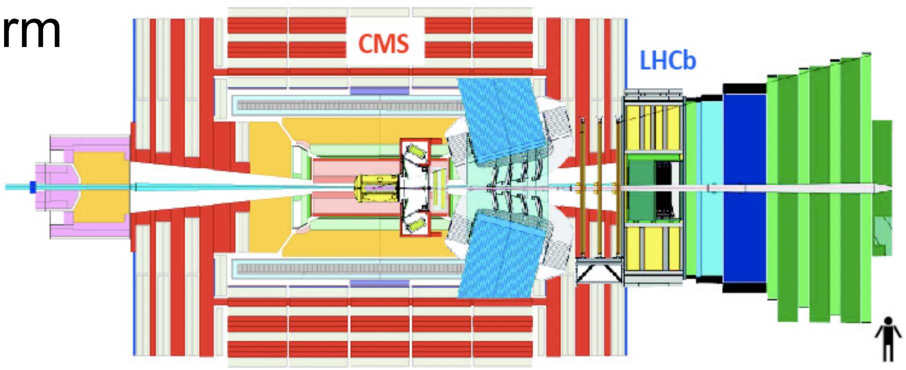
- Studies of heavy hadron properties at production
  - Particle-antiparticle asymmetry
  - Hadron polarization
  - Fragmentation fractions

- Measurement of CP violation observables
- Amplitude analysis of heavy hadron decays
- Branching fractions often measured as ratio with decay modes of $B^{+/0}$ mesons accurately known from B-Factory measurements

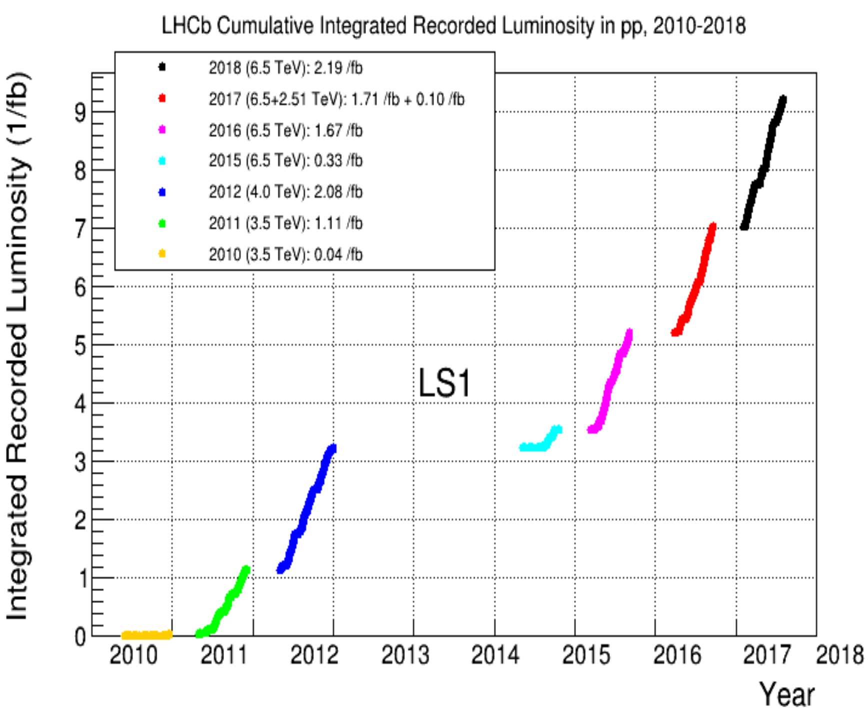
Heavy flavor production with LHCb

- LHCb geometrical acceptance allows to perform unique measurements in the forward region
  - Complementary to ATLAS/CMS and Alice





- Key detector systems: Vertex reconstruction, dedicated particle identification systems (μ and charged hadrons)



- Complementary collision data at LHC: pPb, and PpPb at different $\sqrt{s_{NN}}$
- Fixed-target mode with data taken with SMOG: injecting He, Ne, Ar in the interaction point

Many results on charm and beauty production in heavy ion is not covered here

Outline

- Heavy Quarkonium in pp
  - Production of $\psi(2S)$ at 7 and 13 TeV NEW
  - Production of $\eta_c(1S)$ NEW
- Open charm and beauty in pp
  - Λ_b and B_s production fractions at 13 TeV
  - B_c production fraction at 7 and 13 TeV NEW
  - Ξ_b production fraction and asymmetry at 7, 8 and 13 TeV
  - Ξ_{cc} production rate at 13 TeV NEW
- Conclusions

Heavy Quarkonium production

- Two scales of production
  - Hard process for $Q\overline{Q}$ formation
  - Hadronisation of $Q\overline{Q}$ at softer scale

- Several models proposed to describe the underlying dynamics
  - Color-Singlet Model (CS)
  - Non-relativistic QCD (NRQCD)

$$d\sigma(pp \to H + X) = \sum_n d\sigma(pp \to Q\overline{Q}_n + X) \times \langle \mathcal{O}_n^H \rangle$$

$Q\overline{Q}$ production: short distance, perturbative cross sections and PDFs

Hadron production: long distance matrix elements, non-perturbative part

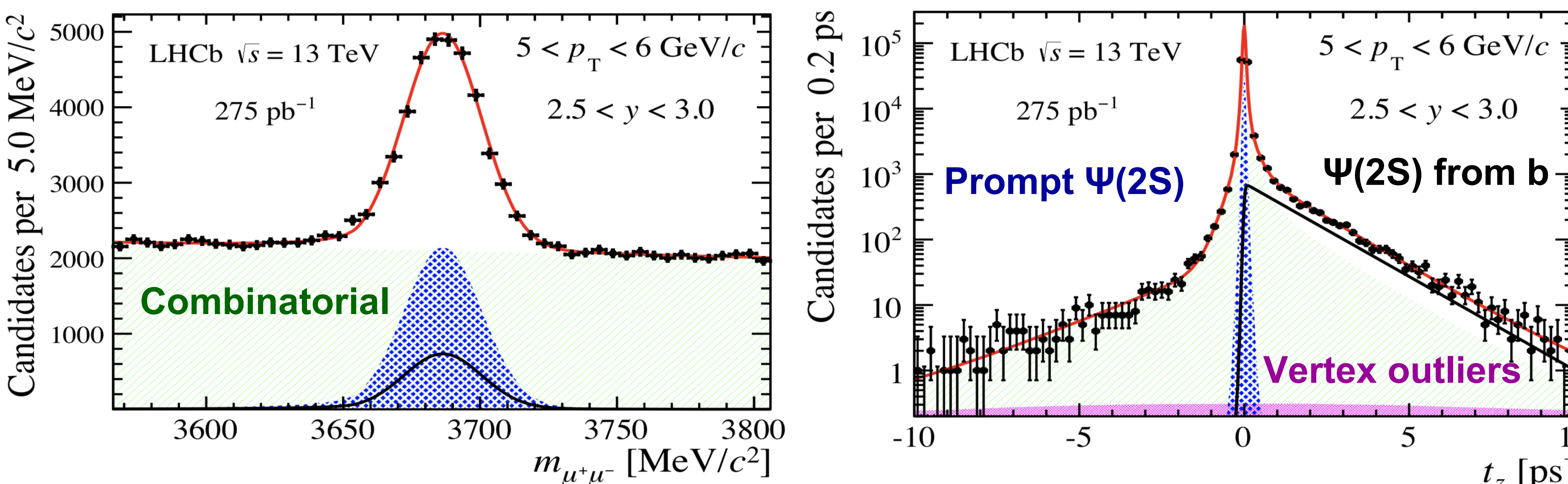
Production of ψ(2S) at 7 and 13 TeV

arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV
∫Ldt ~ 614, 275 pb^{-1}

- Study separately prompt production (pp collision vertex) and production in b-decays
  - From simultaneous fit to m(μ$^+$μ$^-$) and pseudo-lifetime distribution

$$t_z = \frac{\left(z_{\psi(2S)} - z_{\rm PV}\right) \times M_{\psi(2S)}}{p_z}$$



Integrated cross sections

Assuming zero polarization
No large polarization observed at 7 TeV **LHCb EPJC74(2014) 2872**

$$\sigma(\text{prompt }\psi(2S), 7\,\text{TeV}) = 0.471 \pm 0.001\,(\text{stat}) \pm 0.025\,(\text{syst})\,\mu\text{b}$$
$$\sigma(\psi(2S)\text{-from-}b, 7\,\text{TeV}) = 0.126 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst})\,\mu\text{b}$$

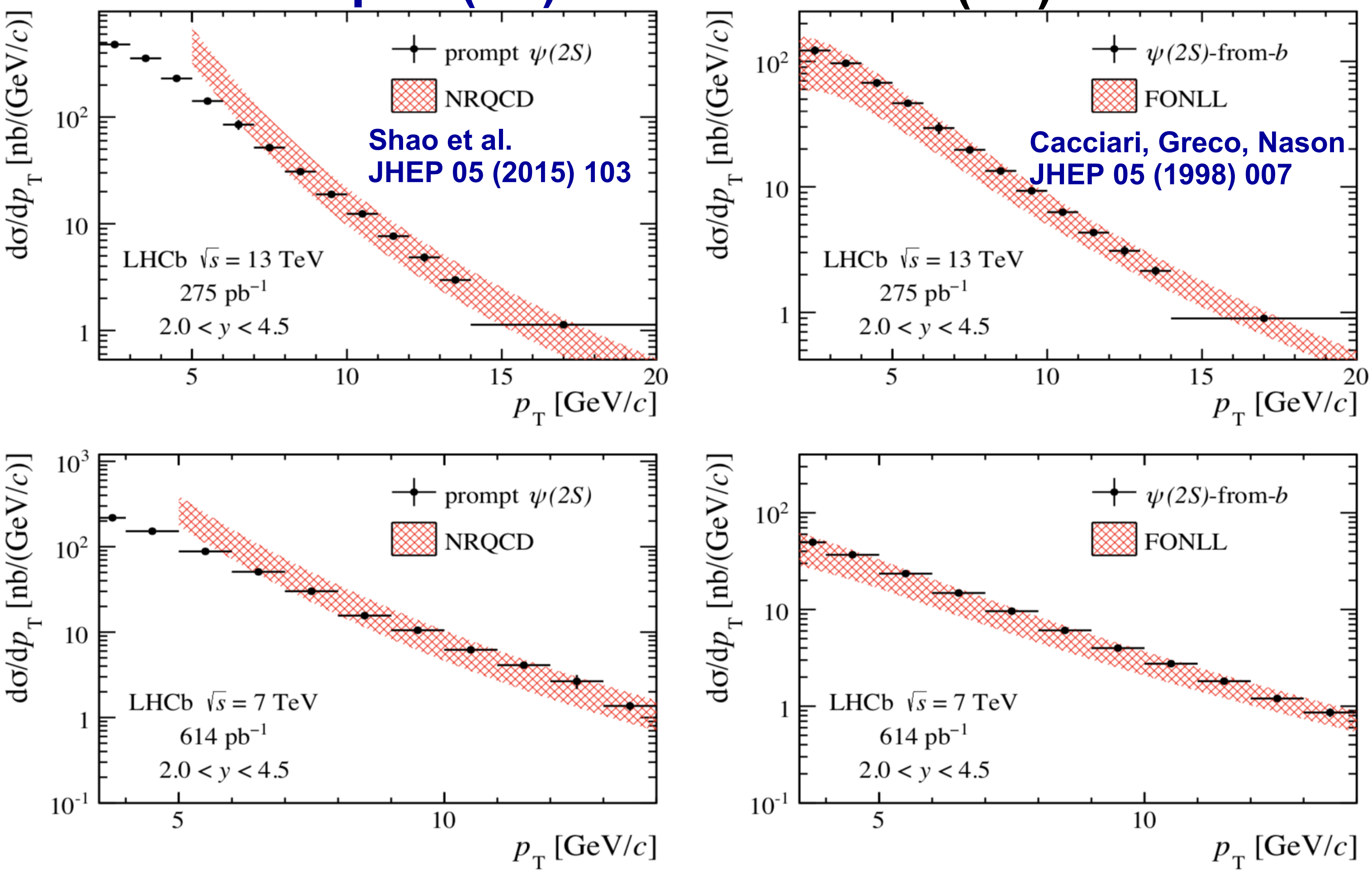
$$\sigma(\text{prompt }\psi(2S), 13\,\text{TeV}) = 1.430 \pm 0.005\,(\text{stat}) \pm 0.099\,(\text{syst})\,\mu\text{b}$$
$$\sigma(\psi(2S)\text{-from-}b, 13\,\text{TeV}) = 0.426 \pm 0.002\,(\text{stat}) \pm 0.030\,(\text{syst})\,\mu\text{b}$$

Production of ψ(2S) at 7 and 13 TeV

arXiv:1908.03099

- Differential cross section

Prompt Ψ(2S) | **Ψ(2S) from b**



- New measurement at 7 TeV supersedes earlier result based on smaller event sample
- Studied also ratios of cross-sections
- Ratio between ψ(2S) and J/ψ production cross-sections
- Ratio between the ψ(2S) productions at 13 and 7 TeV
  - Overall good description of both ratios

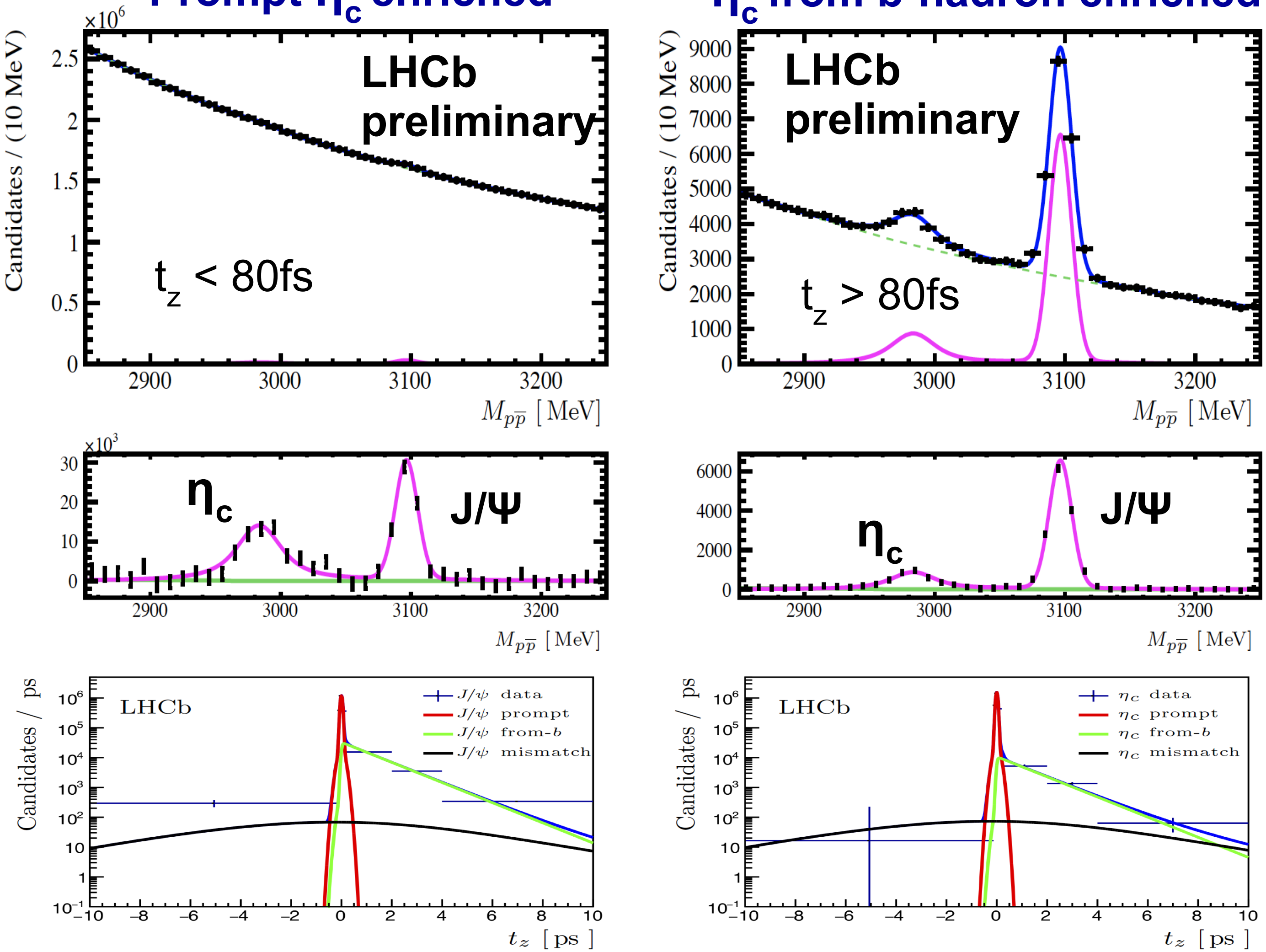
- Overall good agreement with predictions
- Deviation at low $\mathbf{p_T}$ for prompt ψ(2S): important to extend theory predictions to low $\mathbf{p_T}$

Production of $\eta_c(1S)$

PAPER-2019-024
$\sqrt{s}$ = 13 TeV
$\int L dt \sim 2\ fb^{-1}$

- Update of the analysis of the first prompt $\eta_c(1S) \to p\bar{p}$ production measurement at 7 and 8 TeV: **LHCb EPJC75(2015) 311**
- Measurement relative to $J/\psi \to p\bar{p}$ to cancel uncertainties

Prompt η_c enriched | **η_c from b-hadron enriched**



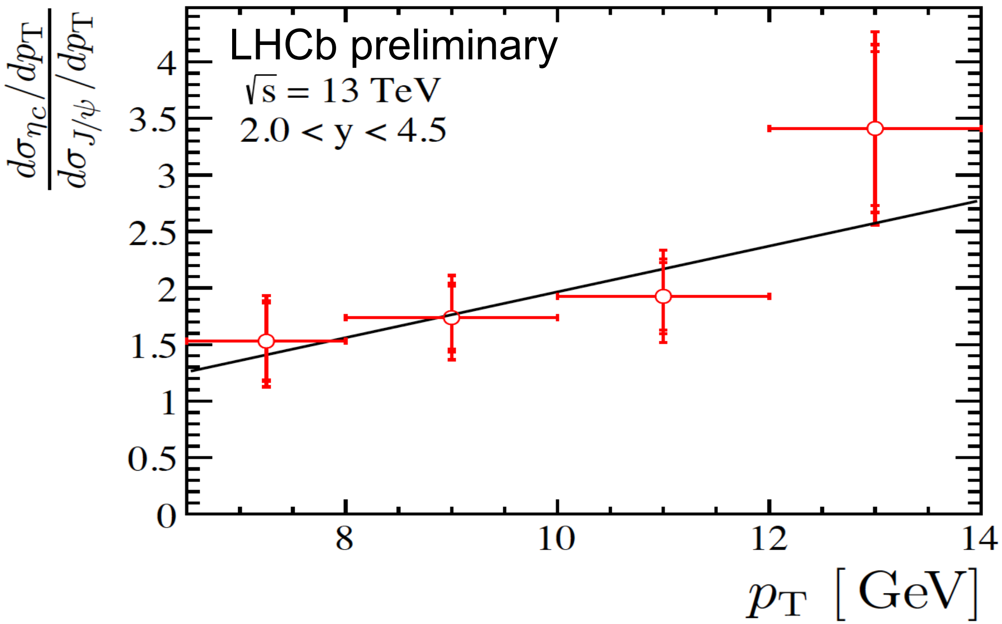
- Prompt and from b-hadron decays are separated cutting on t_z
- Strategy used also at 7 and 8 TeV

Both techniques yield consistent results

- Yields extracted directly from a fit to t_z

Production of $\eta_c(1S)$

- First measurement of $\eta_c(1S)$ production measurement at 13 TeV



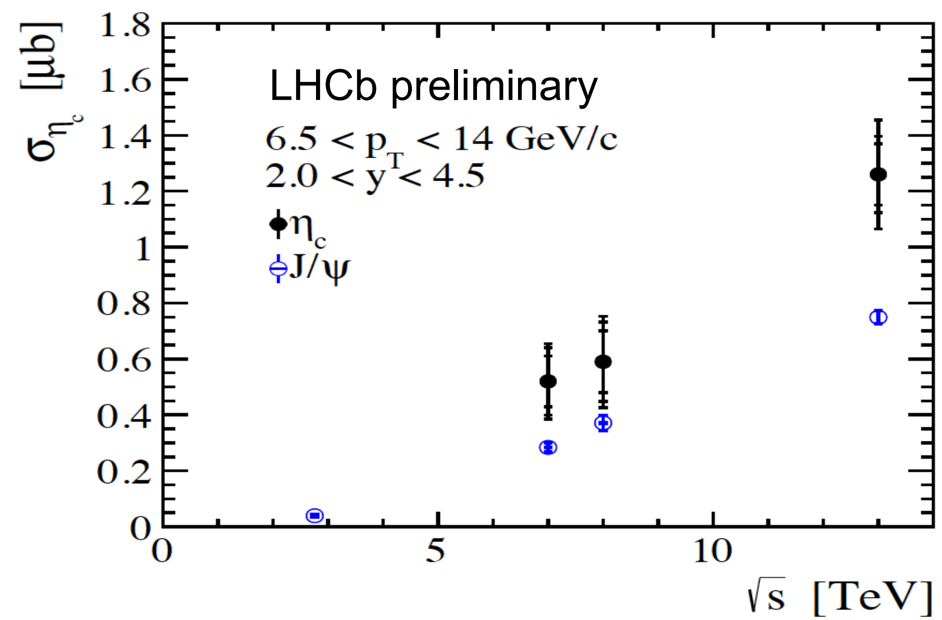
$$\left(\sigma_{\eta_c}\right)^{6.5\,\text{GeV}<p_T<14.0\,\text{GeV},\,2.0<y<4.5}_{13\,\text{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\text{b}$$

- Result consistent with CS model prediction (**Feng et al. NPB 945 (2019) 114662**)

$$\sigma_{\eta_c} = 1.56^{+0.83+0.38}_{-0.49-0.17}$$

- With present statistics no energy dependence on $\sigma(\eta_c)/\sigma(J/\psi)$ has been observed
- Inclusive production in b-decays consistent with previous results

$$\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32 \pm 0.29 \pm 0.77) \times 10^{-3}$$



Production of open beauty & charm

- The b-hadron production cross section can be expressed as a convolution of **dσ(pp→b$\bar{b}$)** and the b hadron fragmentation function $D_{b\to B}(x)$

$$\frac{d\sigma^B}{dp_T^B} = \int dp_T^b \, dx \, \frac{d\sigma^{pp\to b\bar{b}}}{dp_T^b} \mathcal{D}_{b\to B}(x) \, \delta(p_T - x p_T^b)$$

Perturbative:
Can be computed

Non-perturbative:
not known from first principles

- The relative b-hadron production in bins of B meson kinematics allows us to experimentally probe the shape of the b quark fragmentation functions

The probabilities for a b quark to hadronise in a specific hadron H_b are essential to determine absolute branching fractions of H_b

$$f_{H_b} = Prob(b \to H_b)$$

Relative Λ_b and B_s production at 13 TeV

PRD 100 (2019) 031102
$\sqrt{s}$ = 13 TeV
$\int L dt \sim 1.67\ fb^{-1}$

- Measure $f_s/(f_u + f_d)$ and $f_{\Lambda b}/(f_u + f_d)$ with semileptonic decays
- All b hadron species have almost the same semileptonic widths Γ_{SL}

$$\Gamma_{SL}(B_s) = \Gamma_{SL}(B)[1 - (1.0 \pm 0.5)\%]$$
$$\Gamma_{SL}(\Lambda_b) = \Gamma_{SL}(B)[1 + (3.0 \pm 1.5)\%]$$

Bigi, Mannel, Uraltsev JHEP09(2011)012

- Better control of the theoretical uncertainties than using hadronic decays: $B_s \rightarrow J/\psi\phi$ / $B \rightarrow J/\psi K^{(*)}$
- Analysis in bins of b-hadron p_T and η, restricted to the region
  - $4 < p_T < 25$ GeV
  - $2 < \eta < 5$

Update of the previous measurement at 7TeV
LHCb PRD 85(2012)032008
(different $0 < p_T < 25$ GeV)

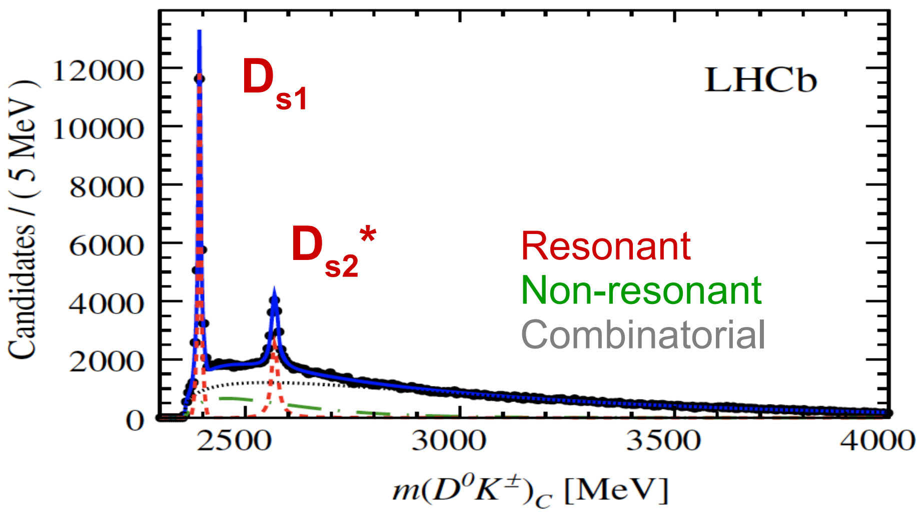
  - η computed from the flight direction
  - Neutrino missing: hadron $p_T(H_b)$ obtained applying a correction to the reconstructed $p_T(H_c\mu)$ as a function of $m(H_c\mu)$ determined from simulation

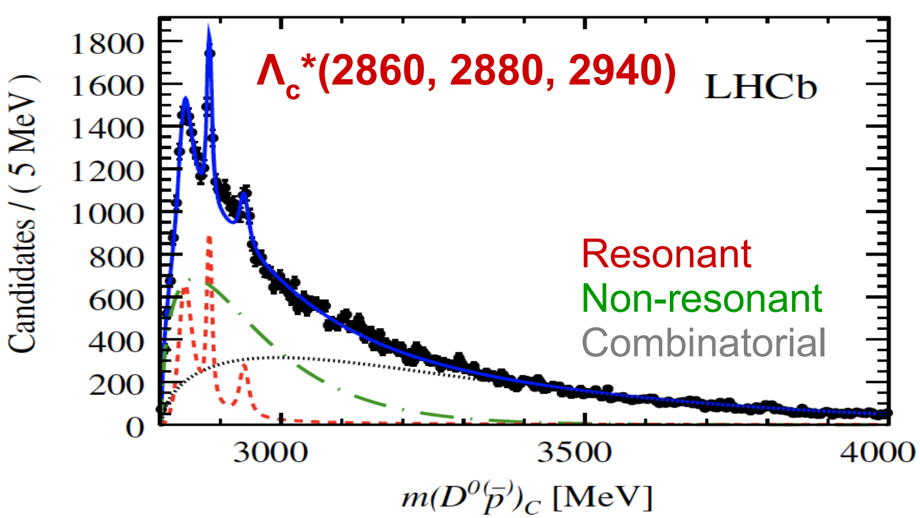
Relative Λ_b and B_s production at 13 TeV

PRD 100 (2019) 031102

- Reconstructed charm hadrons ($D^0 \to K\pi$, $D^+ \to K\pi\pi$, $D_s \to KK\pi$, $\Lambda_c \to pK\pi$) are combined with muons
  - B_s decay mainly in D_sX but can also give D^0K, D^+K
  - Λ_b decay mainly in Λ_cX but can also give D^0p, D^+n

$H_b \to H_c \mu \nu_\mu X$	Yields (10^6)
D^0	13.775
D^+	4.283
D_s^+	0.845
Λ_c^+	1.753





- Resonant and non-resonant $B_s \to (D^0K)\,\mu\nu$ and $\Lambda_b \to (D^0p)\,\mu\nu$ from simultaneous fit to mass distributions and vertex likelihood difference $\chi^2(D^0\mu h) - \chi^2(D^0\mu)$
- Clearly peaks due to D_{s1} and D_{s1}^* and Λ_c excited states
- Large component of non-resonant contribution

Relative Λ_b and B_s production at 13 TeV

$$\frac{f_s}{f_u+f_d} = \frac{n_{\rm corr}(\overline{B}{}^0_s \to D\mu^-)}{n_{\rm corr}(B\to D^0\mu^-)+n_{\rm corr}(B\to D^+\mu^-)}\frac{\tau_{B^-}+\tau_{\overline{B}{}^0}}{2\tau_{\overline{B}{}^0_s}}(1-\xi_s)$$ **+** { Correction on f_u+f_d ($B\to D\mu$) due to cross feed from $B\to D_sK\mu\nu X$ }

Theory corrections

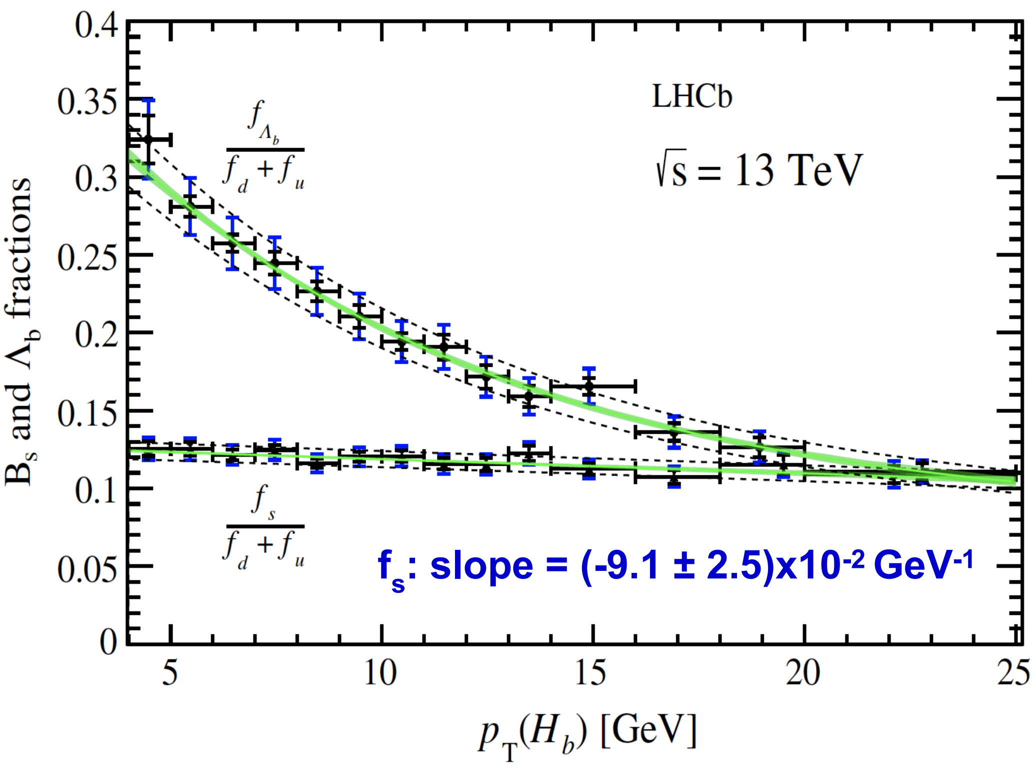
$$\frac{f_{\Lambda_b^0}}{f_u+f_d} = \frac{n_{\rm corr}(\Lambda_b^0 \to H_c\mu^-)}{n_{\rm corr}(B\to D^0\mu^-)+n_{\rm corr}(B\to D^+\mu^-)}\frac{\tau_{B^-}+\tau_{\overline{B}{}^0}}{2\tau_{\Lambda_b^0}}(1-\xi_{\Lambda_b^0})$$

f_s: efficiency and BF corrected yields of D_sX and DK

$f_{\Lambda b}$: efficiency and BF corrected yields of Λ_cX and Dp,n

- Summing over p_T and η

$$\frac{f_s}{f_u+f_d} = 0.122(6) \quad \sigma_{tot} = 4.9\% \qquad \frac{f_{\Lambda_b^0}}{f_u+f_d} = 0.259(18) \quad \sigma_{tot} = 6.9\%$$



- Largest uncertainties are BFs for
  - $D_s \to KK\pi$: 3.3%
  - $\Lambda_c \to pK\pi$: 5.3%
- Production rate for both B_s and Λ_b
  - $p_T(H_b)$ dependence
  - No η dependence

PRD 100 (2019) 031102

B_c production fraction

NEW

PAPER-2019-033
$\sqrt{s}$ = 7, 13 TeV
$\int Ldt \sim$ 1, 1.6 fb-1

- With a similar approach used to extract $f_{s,\Lambda b}/(f_d + f_u)$
- Using semileptonic $B_c \to J/\psi \mu \nu$ decays

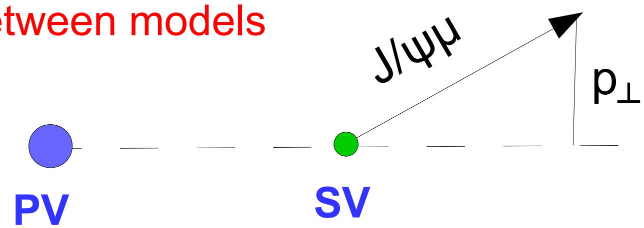
Two heavy quarks: $\Gamma_{SL}(B_c) \neq \Gamma_{SL}(B)$

$$\frac{f_c}{f_u + f_d} \equiv \frac{n_{\rm cor}(B_c^- \to J/\psi\, \mu^- \overline{\nu})}{n_{\rm cor}(B \to D^0 X \mu^- \overline{\nu}) + n_{\rm cor}(B \to D^+ X \mu^- \overline{\nu})} \cdot \frac{\langle \mathcal{B}_{\rm sl} \rangle}{\mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu})}$$

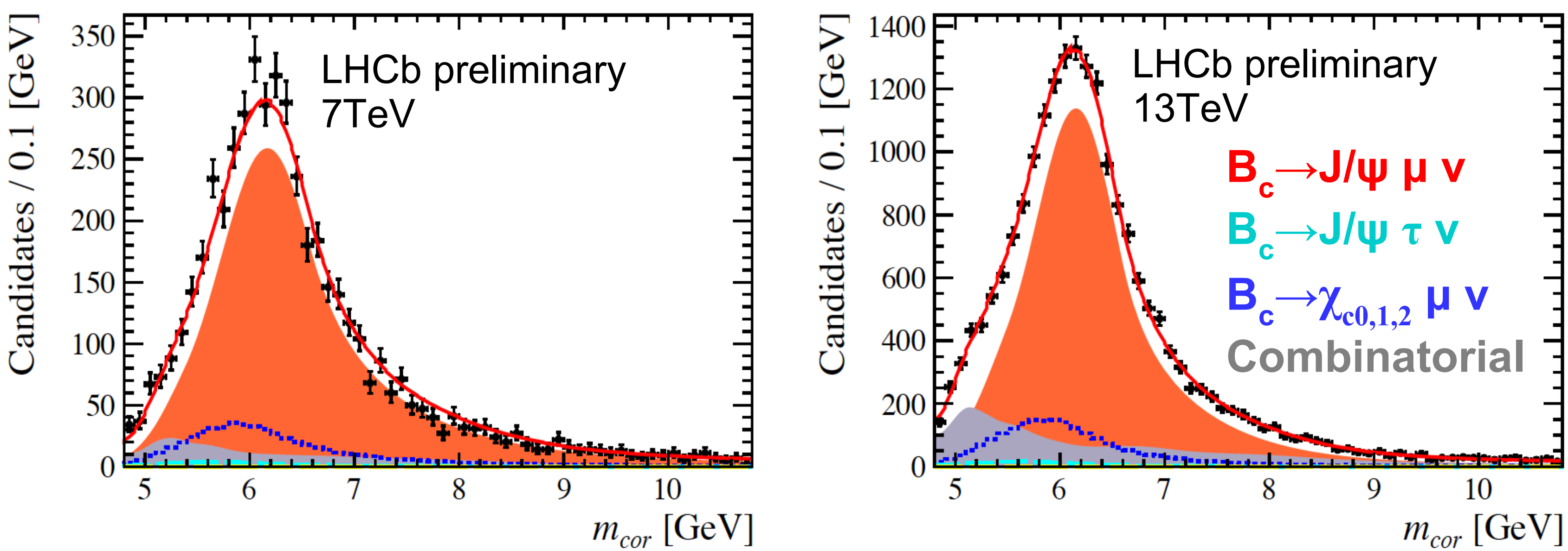
  - $4.5 < p_T < 25$ GeV
  - $2.5 < \eta < 4.5$

Need inputs from theory:
large discrepancies between models

- Signal yields extracted fitting $m_{\rm cor} \equiv \sqrt{m^2_{H_c\mu} + p_\perp^2} + p_\perp$



Potential background from $B_c \to \psi(2S)\, \mu\, \nu$ found to be negligible



B_c production fraction

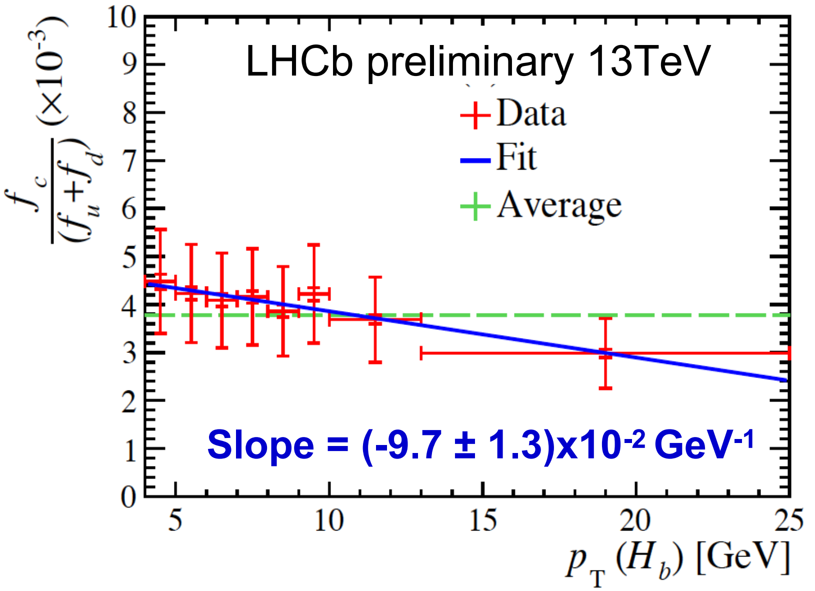
PAPER-2019-033

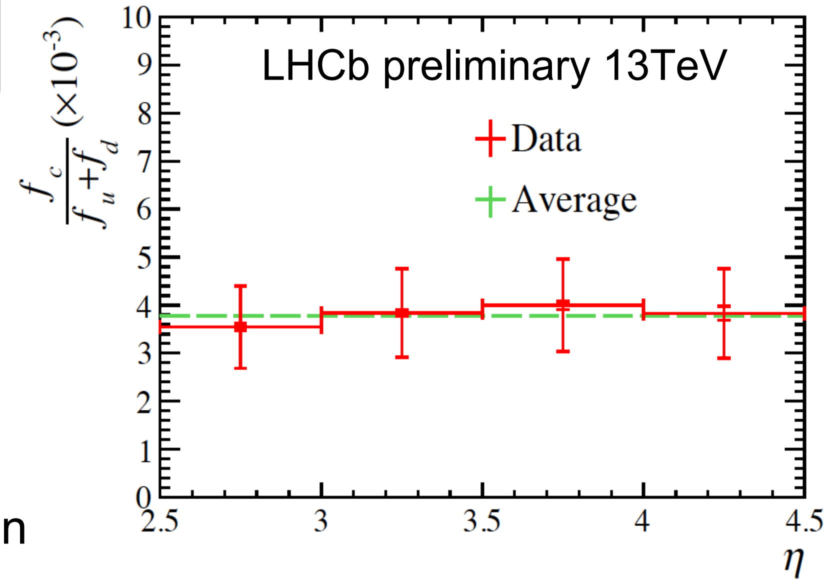
$$\frac{f_c}{f_u+f_d}\cdot\mathcal{B}(B_c^-\to J/\psi\,\mu^-\overline{\nu}) = (7.07\pm0.15\pm0.24)\cdot10^{-5}\ \text{for 7 TeV},$$
$$\frac{f_c}{f_u+f_d}\cdot\mathcal{B}(B_c^-\to J/\psi\,\mu^-\overline{\nu}) = (7.36\pm0.08\pm0.30)\cdot10^{-5}\ \text{for 13 TeV}.$$

- Assuming BF($B_c\to J/\psi\mu\nu$)=(1.95 ± 0.46)%, where the uncertainty reflects the spread in the calculations

$$\frac{f_c}{f_u+f_d} = (3.63\pm0.08\pm0.12\pm0.86)\cdot10^{-3}\ \text{for 7 TeV},$$
$$\frac{f_c}{f_u+f_d} = (3.78\pm0.04\pm0.15\pm0.89)\cdot10^{-3}\ \text{for 13 TeV},$$

- Measurement of the form factors and precise lattice calculations would pin down the error on $f_c/(f_d+f_u)$
- The slope of the p_T dependence is similar to the one measured for the B_s
- $f_c(13)/f_c(7)$=1.02 ± 0.02 ± 0.04: no increase of B_c fraction with √s

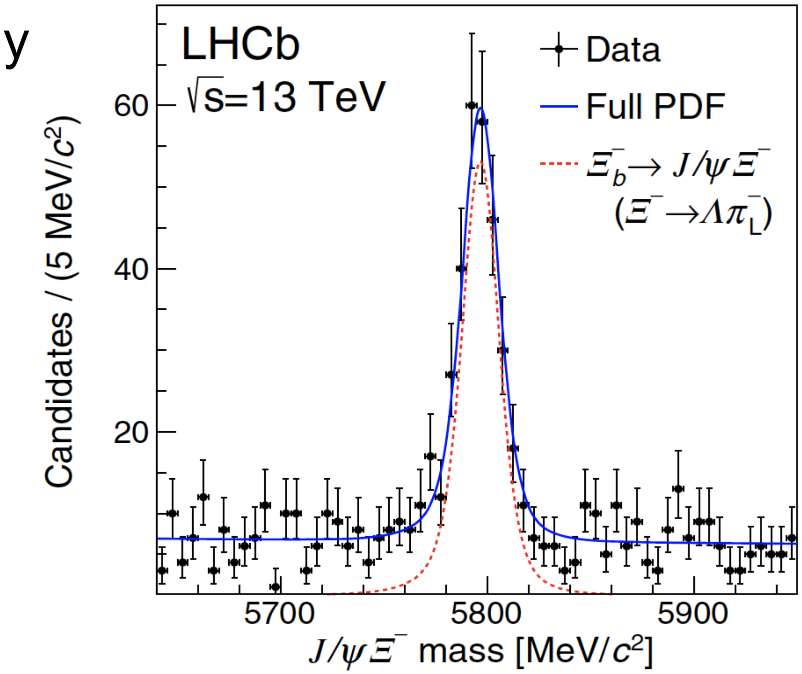




Ξ_b production fraction

PRD 99, (2019) 052006
$\sqrt{s}$ = 7, 8,13 TeV
$\int L dt \sim$ 1, 2, 1.6 fb^{-1}

- Decay chain: $\Xi_b^- \rightarrow J/\psi\Xi^-$, $\Xi^- \rightarrow \Lambda\pi^-$
- Production rate measured as ratio to kinematically similar decay $\Lambda_b \rightarrow J/\psi\Lambda$



Measured Ratio of the yields Corrected for the efficiencies

3/2 in SU(3) flavour symmetry

PDG

$$R \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\Gamma(\Xi_b^- \to J/\psi\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda)} \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm \underline{2.0}) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}]$$

SU(3) flavor symmetry (30%)

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm \underline{2.5}) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}].$$

- p_T < 20 GeV
- 2 < η < 6

Predictions:

$f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.065 \pm 0.020$ Wang, EPJC 79 5 (2019) 429

$f_{\Xi_b^0}/f_{\Lambda_b^0} = 0.050 \pm 0.020$ Jiang, Yu EPJC 78, (2018) 224

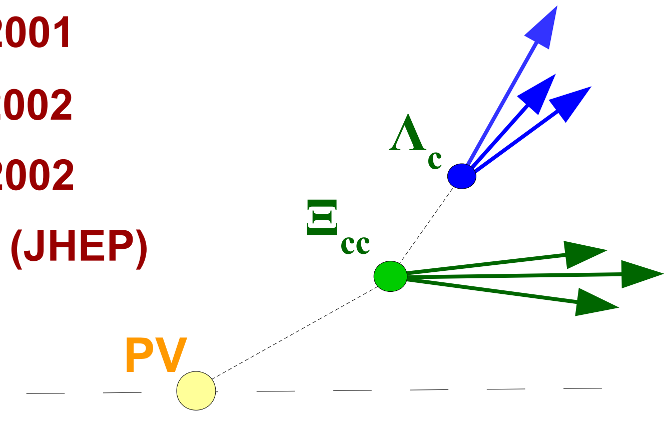
- First measurement of Ξ_b production
- Also first measured of the Ξ_b production asymmetry
- Precise determination of the Ξ_b mass

Ξ_{cc}^{++} production at 13 TeV

NEW

PAPER-2019-035
$\sqrt{s}$ = 13 TeV
$\int L dt \sim$ 1.65 fb-1

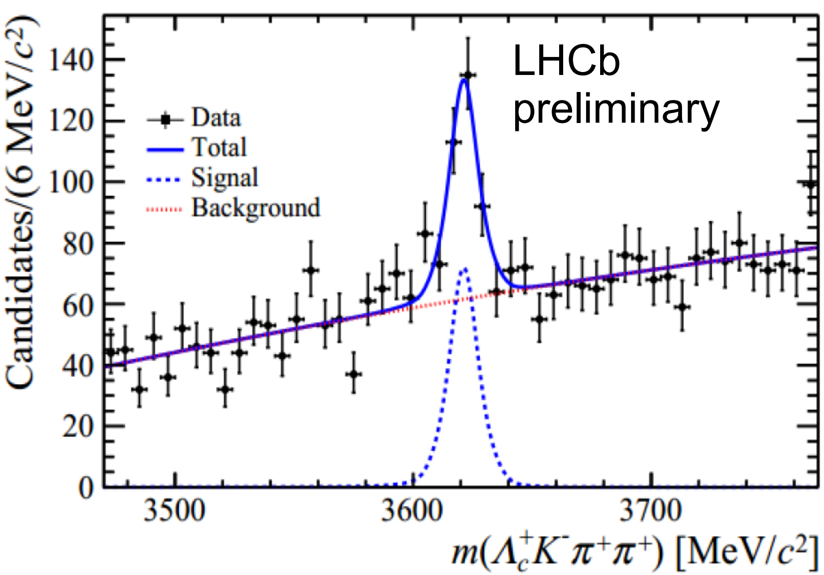
- Ξ_{cc}^{++} observed by LHCb: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - $M(\Xi_{cc}^{++})$ = 3621.40 ± 0.78 MeV — **LHCb PRL119(2017)112001**
  - Lifetime: τ = 0.256 ± 0.028 ps — **LHCb PRL121(2018)052002**
  - Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ — **LHCb PRL121(2018)162002**
  - Non-observation of $\Xi_{cc}^{++} \to D p K \pi$ — **LHCb arXiv:1905.02421 (JHEP)**



- Ξ_{cc}^{++} production ratio with respect to prompt Λ_c

$$R \equiv \frac{\sigma(\Xi_{cc}^{++})\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\text{sig}}}{N_{\text{con}}} \frac{\varepsilon_{\text{con}}}{\varepsilon_{\text{sig}}}$$

- $4 < p_T < 15$ GeV
- $2.0 < y < 4.5$



- Trigger acceptance (and systematics) depends on the assumed Ξ_{cc}^{++} lifetime
- First measurement of Ξ_{cc}^{++} production rate

$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)} \cdot \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

(@ mean lifetime)

Summary

- Many results in Heavy Flavour production from LHCb
  - Only most recent reported here
- Great progress in the theory/experiment agreements, but still many inconsistencies remain
  - Efforts needed in both theory and experiment to establish a consistent model for Heavy Flavour production
- These measurements provide crucial inputs for tuning of MC needed for precise measurements in LHC
- Many other results in the pipeline: stay tuned!

Thanks !

BACKUP

Heavy flavour production at LHC

- Huge $b\bar{b}$ cross section from pp collisions

$$\sigma(b\bar{b})(7\ TeV) = 295\mu b$$

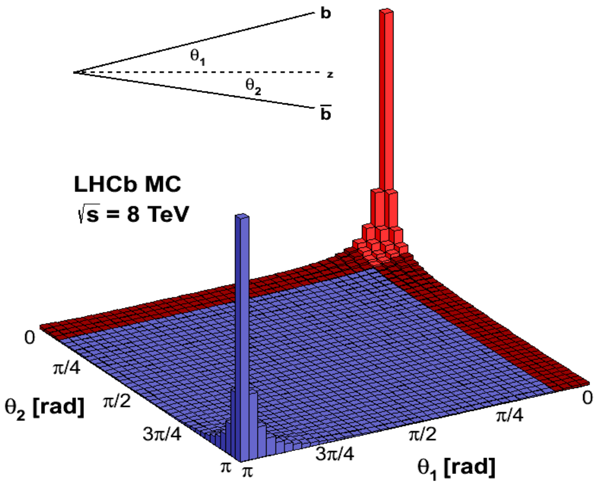
$$\sigma(b\bar{b})(13\ TeV) = 560\mu b$$

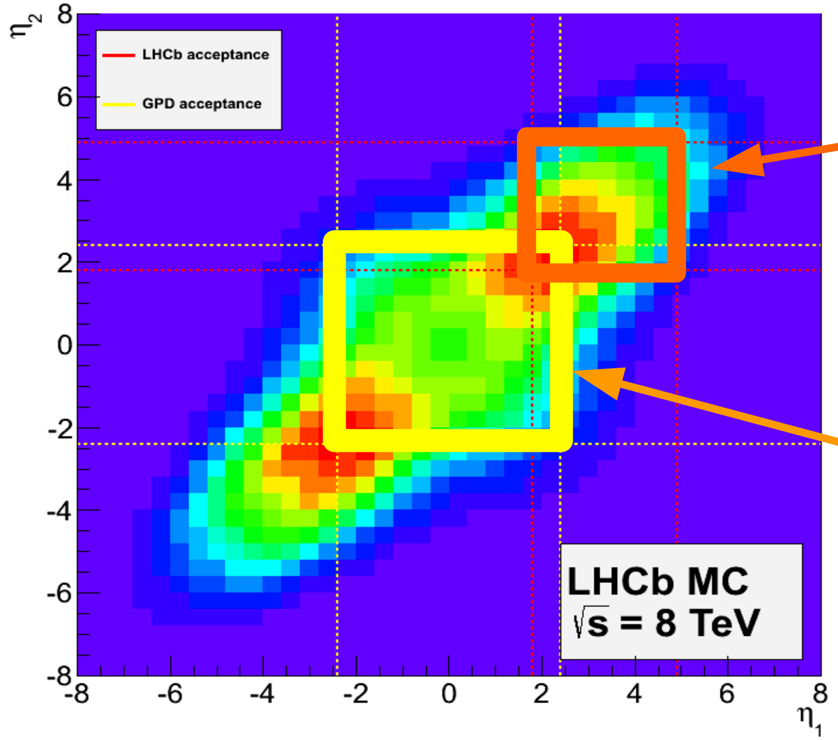
PLB 118, 052992(2017)

- Charm ~ 20 x beauty

JHEP 03(2016)159

gluon-gluon fusion





LHCb acceptance: 2 < η < 5

4% of solid angle

7 TeV 25% of $b\bar{b}$
14 TeV 24% of $b\bar{b}$

$N(b\bar{b}) = 70\cdot10^9/fb^{-1}$
$N(b\bar{b}) = 134\cdot10^9/fb^{-1}$

ATLAS/CMS acceptance: -2.4 < η < 2.4

7 TeV 44% of $b\bar{b}$
14 TeV 41% of $b\bar{b}$

$B_c \to J/\psi\mu\nu$ branching fraction predictions

Ref.\Mode	$J/\psi\,\mu^-\overline{\nu}$	$\eta_c\mu^-\overline{\nu}$	$\psi(2S)\mu^-\overline{\nu}$	$\left(\sum_{i=1}^{3}\chi_{c_i}\right)\mu^-\overline{\nu}$	$h_c\mu^-\nu$	$\mathcal{B}_{S\mathcal{L}}$ of B_c^-
Rui et al. EPJC76(2016) 564	6.4	5.0	1.3			13.6
Ebert et al. PRD82(2010) 034019				0.5		
Ebert et al. PRD68(2003) 094020	1.4	0.5				2.9
Qiao et al. PRD87(2013) 014009	7.5	2.4				10.9
Chang et al. CPMA58(2015) 071001	1.9	0.6	0.1			3.5
Ivanov et al. PRD73(2006) 054024	2.3	0.9		0.8		4.2
Huang, Zao, EPJC51(2007) 833	2.7	1.8				5.5
Wang et al. PRD79(2009) 054012	1.6	0.8				3.4
Hernandez et al. PRD74(2006) 074008	1.7	0.5		0.6		3.3
Colangelo et al. PRD61(2000)034012	1.7	0.2				2.9
Gouz et al. PAN67(2004) 1559	1.9	0.8	0.1			3.7
Abd El-Hady et al. PRD62(2000)014019	2.3	0.9				4.2
Kiselev, hep-ph/0211021	2.2	0.8	0.1			4.0
Chang, Chen PRD49(1994)3399	2.6		0.1	1.1		4.2
Ivaniv et al PRD63(2001)074010	2.5	1.1				4.6
Scora, Isgur PRD52(1995)2783	1.3	0.8	0.2			3.1
Yu. Anisimov et al. PAN62(1999)1739	1.4	0.7				3.1
Wang, Zhu, ArXiv: 1808.10830	1.5	0.7		0.5	0.3	3.2
Geng et al. ArXiv: 1809.02968	1.9	0.6	0.1	0.3	0.31	3.5
Leljak et al. Arxiv: 1901.08368	2.2	0.8				4.0

Heavy flavour in pN collisions

- Beauty production in pPb collision **PRD 99 (2019) 052011**
  - Differential cross section B^0, B^+. Λ_b hadrons in p_T and y
  - Small nuclear effects, in agreement with predictions
- Prompt Λ_c in pPb **JHEP 02 (2019) 102**
  - Forward-backward: in agreement with predictions
  - Λ_c/D^0 ratio: lower than predicted in the forward direction and pT> 7 GeV
- Υ(nS) production in pPb collisions **JHEP 11 (2018) 194**
  - Suppression of n>1 states, in agreement with predictions and previous measurements
  - Stronger suppression at low p_T
- J/Ψ and D^0 in pAr and pHe (gas) **PRL 122 (2019) 132002**
  - First measurement of charm in fixed-target mode
  - Data agree with predictions without intrinsic valence-like charm contribution