# Heavy flavor production in the forward acceptance at the LHC

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(on behalf of the LHCb collaboration)

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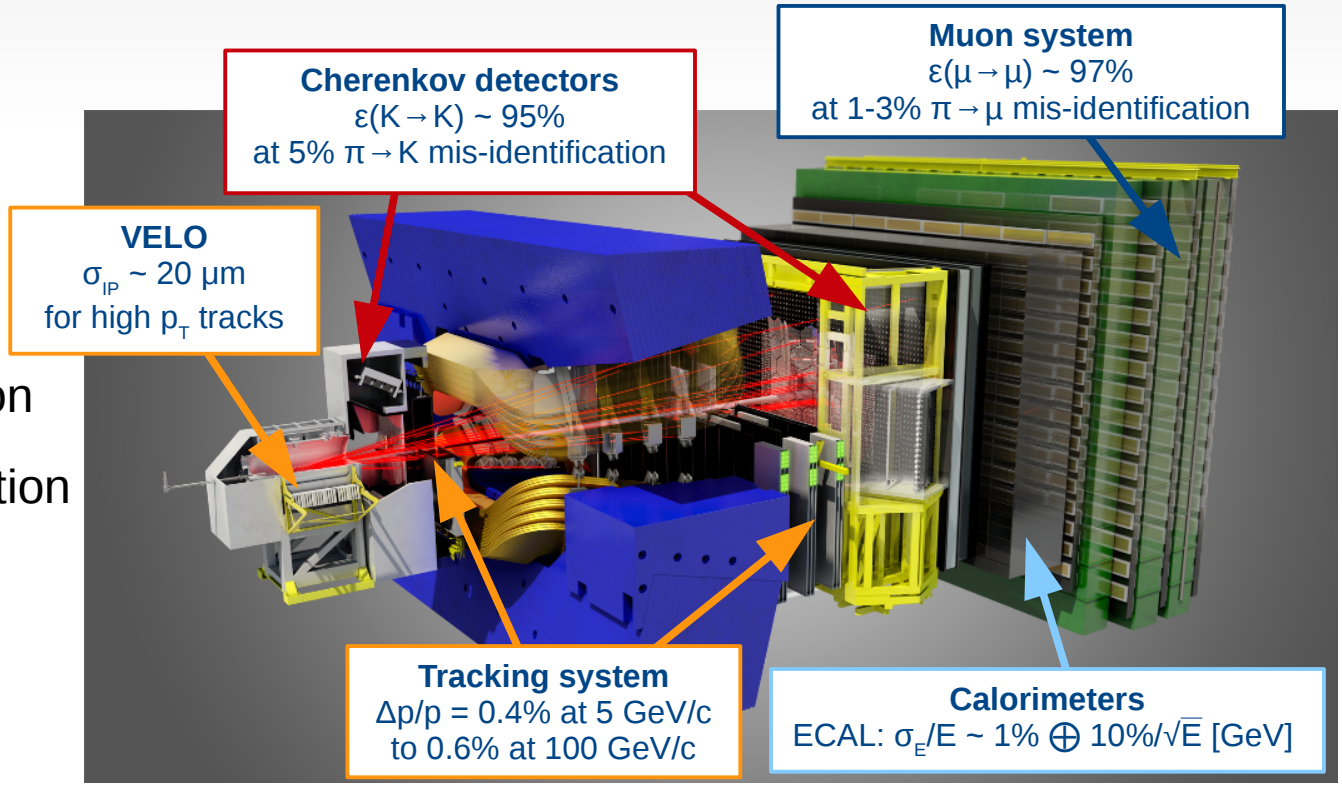
# Introduction

- Heavy flavor and quarkonia production is a puzzle of QCD
- Relative role of competing production mechanisms is poorly understood
- LHCb provides unique possibility to probe forward region of 2<y<5 and to imply a stronger tests on theory

- LHCb detector

JINST 3 (2008) S08005

talk by **Sheldon Stone**




- High $b\bar{b}$-/$c\bar{c}$-pair cross-section
- Good B-decay vertex resolution
- Good particle identification
- Good momentum resolution

# Overview

- List of analyses on heavy flavor production during last year

  - $\chi_b(nP) \rightarrow \Upsilon(n'S)\gamma$ at $\sqrt{s}$=7&8 TeV
  - $\eta_c(1S)$ at $\sqrt{s}$=7&8 TeV
  - $B_c^+$ differential at $\sqrt{s}$=8 TeV

  - $\Upsilon$ in pPb at $\sqrt{s_{NN}}$=5 TeV — talk by **Marco Meissner** (HIP, right now)

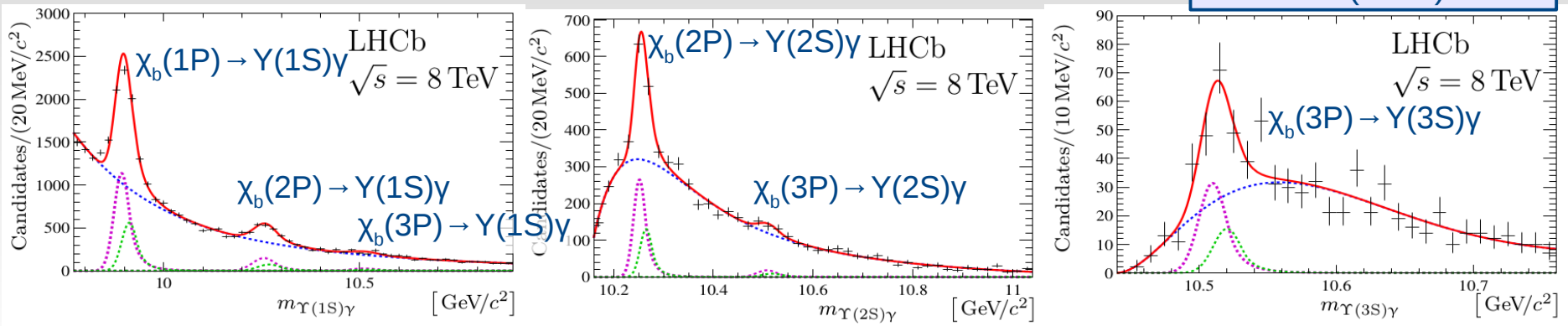
**!New!** - Exclusive $\Upsilon$ at $\sqrt{s}$=7&8 TeV — talk by **Paolo Gandini** (QCD&HP, today)

**!New!** - $J/\psi$ at $\sqrt{s}$=13 TeV — talk by **Ilya Komarov** (QCD&HP, 24 July)

# $\chi_{bJ}$(nP) production

- $\chi_b$(1,2,3P)→Υ(1,2,3S)γ with unconverted photons at 7&8 TeV

EPJC 74 (2014) 3092

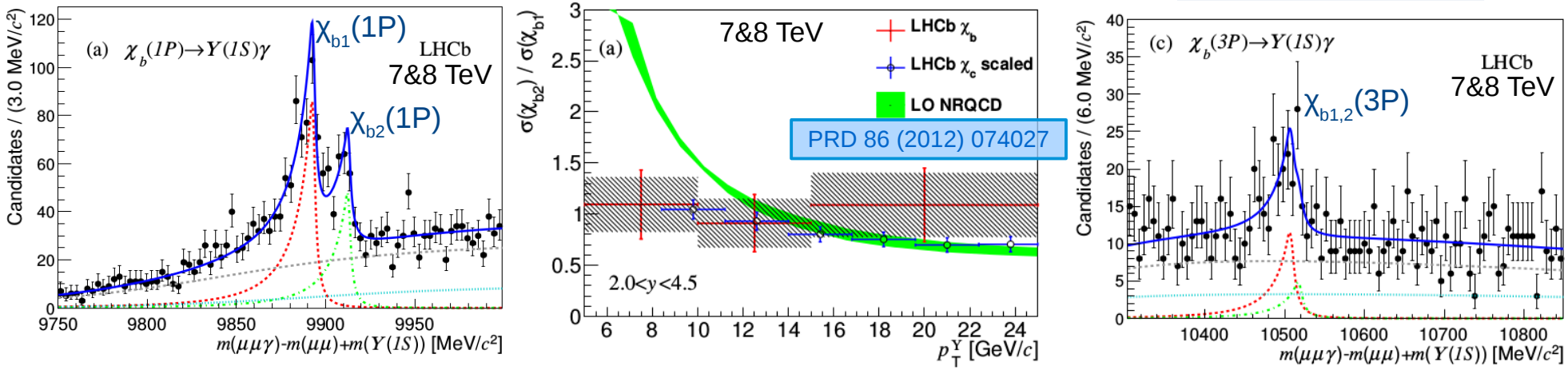



~30% of Υ(nS) are from feed-down

$$m_{\chi_{b1}(3P)} = 10\,511.3 \pm 1.7 \pm 2.5\,\text{MeV}/c^2$$

- Ratio of $\chi_{b2}$(1P) and $\chi_{b1}$(1P) cross-sections with converted photons

JHEP 10 (2014) 088




$$m(\chi_{b1}(3P)) = 10515.7^{+2.2}_{-3.9}(\text{stat})^{+1.5}_{-2.1}(\text{syst})\,\text{MeV}/c^2$$

# $\eta_c(1S)$ production

EPJC 75 (2015) 311

- Complementary to studies of J/ψ, ψ(2S) and $\chi_{c0,1,2}$ production
- NLO NRQCD predicts different $p_T$-dependence for $\eta_c$ and J/ψ and $\chi_{cJ}$

PRD 70 (2004) 054014
NPB 514 (1998) 245
PRD 48 (1993) 179

- Probe inclusive $b \to \eta_c X$ decays

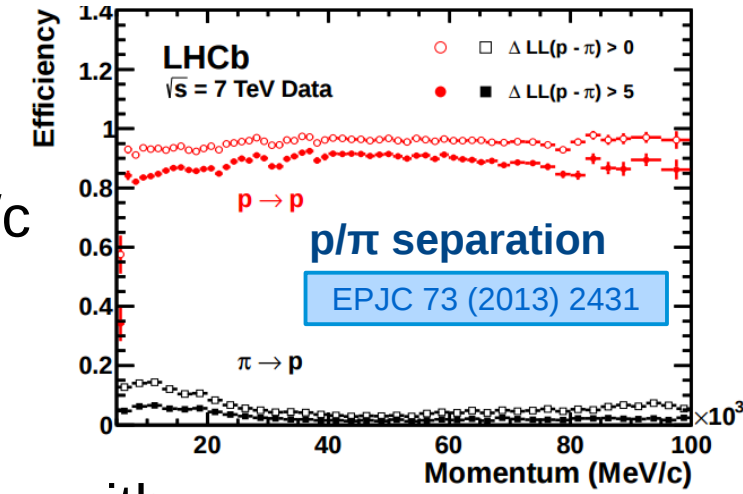
  CLEO limit: $\mathcal{B}(B^-, \bar{B}^0 \to \eta_c(1S)X) < 9 \times 10^{-3}$ at 90%

PRD 52 (1995) 2661

- **$\eta_c \to p\bar{p}$** and **J/ψ $\to p\bar{p}$** decay modes are used

  $\mathcal{B}(\eta_c \to p\bar{p}) = (1.52 \pm 0.16) \times 10^{-3}$

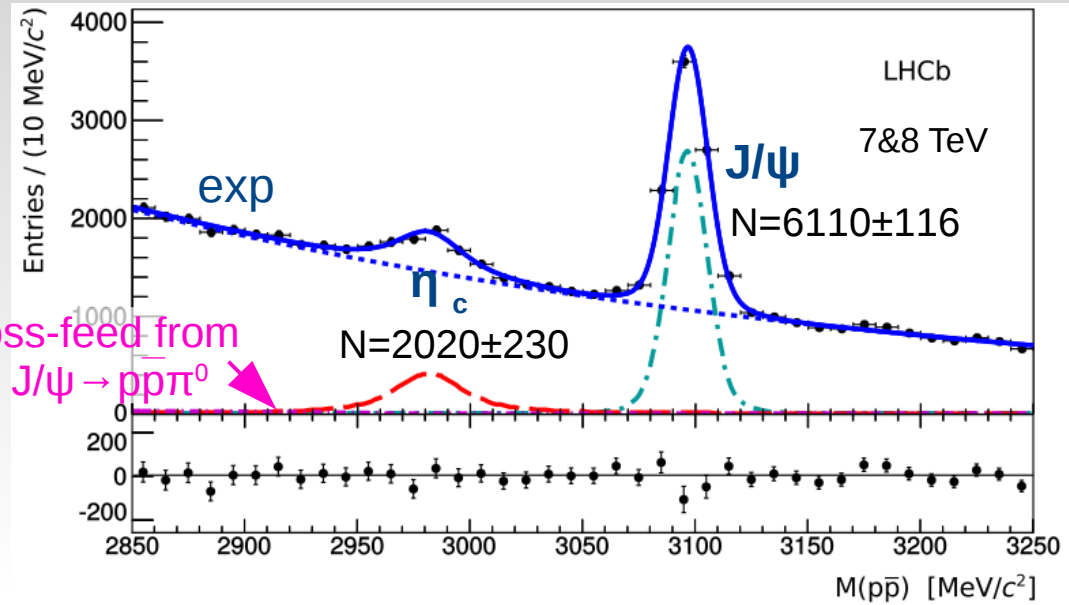
- Selection:
  - trigger by hadron calorimeter
  - $p_T(p,\bar{p}) > 2$ GeV/c
  - PID requirements
  - $p_T(p\bar{p}) > 6.5$ GeV/c
  - $2 < y(p\bar{p}) < 4.5$




- Separate prompt production and b-decays with
  - pseudo-decay time ( $t_z = \Delta z \, M / p_z$ )
  - impact parameters of protons with respect to primary vertex

# $\eta_c(1S)$, from b-decays

EPJC 75 (2015) 311




- Since efficiencies are the same for $\eta_c$ and J/ψ within 0.5%

$$\frac{N^b_{\eta_c(1S)}}{N^b_{J/\psi}} = \frac{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to p\bar{p})}{\mathcal{B}(b \to J/\psi X) \times \mathcal{B}(J/\psi \to p\bar{p})}$$

- Neglecting the $p_T(p\bar{p})$>6.5 GeV/c bias derive:

**First measurement**

$$\mathcal{B}(b \to \eta_c(1S)X)/\mathcal{B}(b \to J/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045_{\mathcal{B}}$$

in agreement with CLEO upper limit

dominant systematics:
background model, J/ψ polarization, cross-feed from prompt

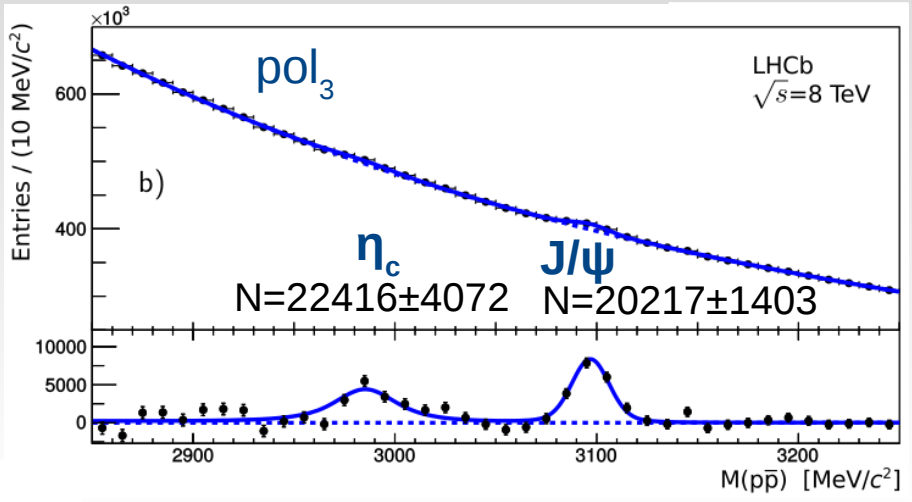
- Mass difference: $\Delta M_{J/\psi,\,\eta_c(1S)} = 114.7 \pm 1.5 \pm 0.1\,\mathrm{MeV}/c^2$

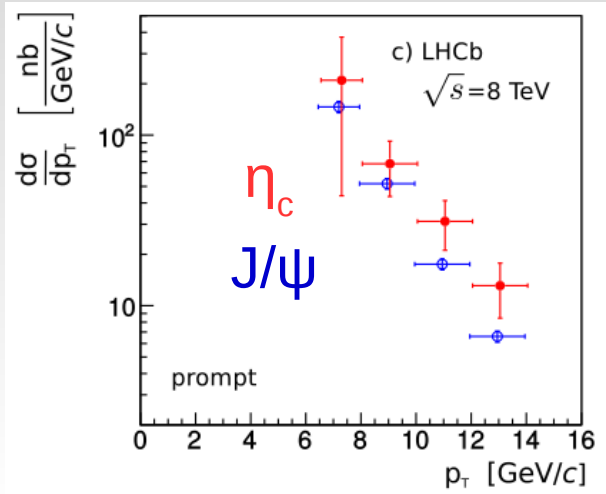
in agrement with world average (PDG 2014)

# $\eta_c(1S)$, prompt

EPJC 75 (2015) 311

- Constraint signal shape from fit of "from b-decays" sample




- Similar $p_T$ dependence for $\eta_c$ and J/ψ (in contrast to NRQCD expectations)

$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=8\,\mathrm{TeV}} = 1.60 \pm 0.29 \pm 0.25 \pm 0.17_{\mathcal{B}},$$
$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=7\,\mathrm{TeV}} = 1.74 \pm 0.29 \pm 0.28 \pm 0.18_{\mathcal{B}},$$

dominant systematics: $\Gamma(\eta_c)$, background model

- Use previously measured J/ψ cross-section as reference

EPJC 73 (2013) 2631
JHEP 06 (2013) 064

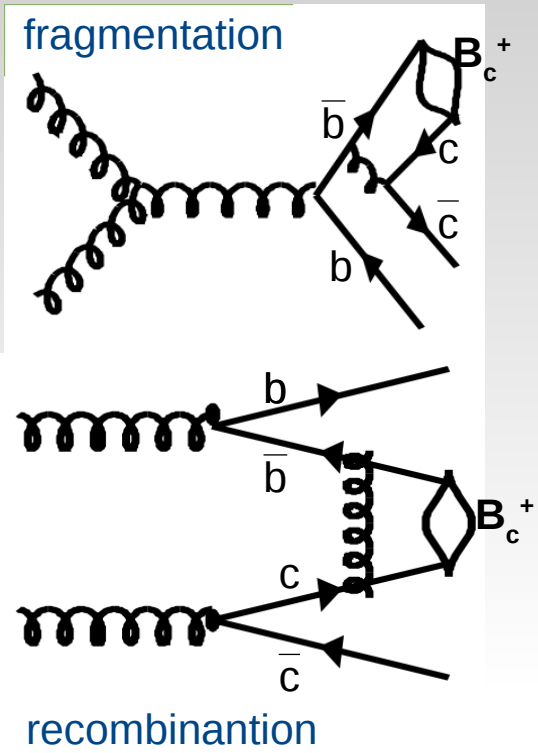
$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=7\,\mathrm{TeV}} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$
$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=8\,\mathrm{TeV}} = 0.59 \pm 0.11 \pm 0.09 \pm 0.08_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$

**First measurements**

consistent with color-singlet NLO predictions

JPG 39 (2012) 015008

# $B_c^+$ production




- Similarities of $B_c^+$ with both B mesons and quarkonium

- Main process: $gg \to (b\bar{b})(c\bar{c}) \to B_c^+ + b + \bar{c}$ (order of $\alpha_s^4$)

suppression $\sigma(B_c^+)/\sigma(B^{+/0}) \sim 10^{-3}$ arXiv:hep-ph/9408284

Phys. Atom. Nucl. 67 (2004) 1559

- Competitive role of fragmentation and recombination

→ different impact on $p_T$ spectra

+ difference with $B^{+/0}$ spectra

- Measure cross-section with respect to $B^+$:

using decays $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ with similar kinematics

$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N(B_c^+ \to J/\psi\,\pi^+)}{\epsilon_{\rm tot}^c} \frac{\epsilon_{\rm tot}^u}{N(B^+ \to J/\psi K^+)}$$

- Previously only average ratios of $\sigma(B_c^+)$ to $\sigma(B^+, B_s^0)$ were measured at LHCb and CMS PRL 109 (2012) 232001 PRL 111 (2013) 118801 JHEP 01 (2015) 063

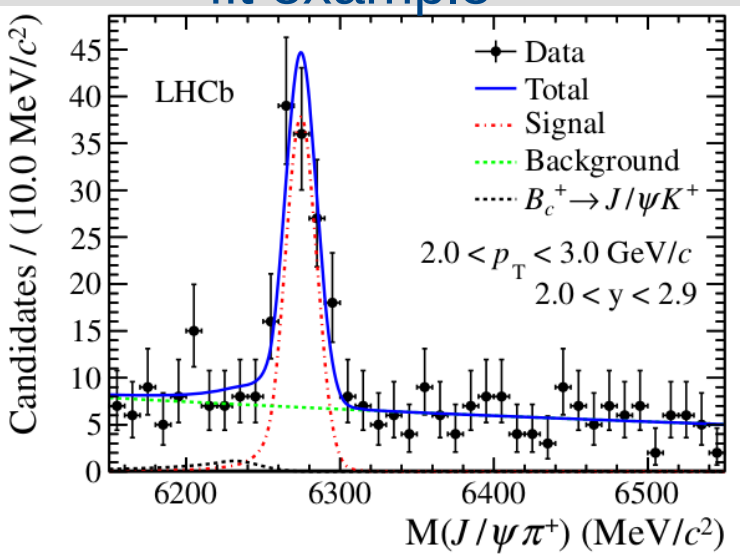
→ measure the kinematics dependence for the first time

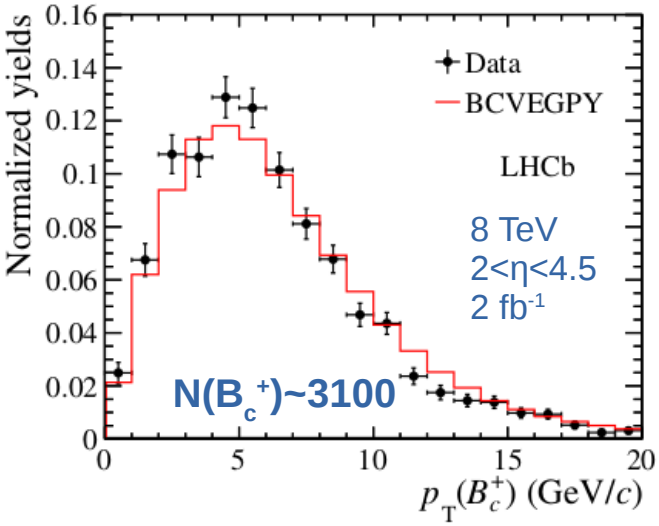
# $B_c^+$ production, 8 TeV

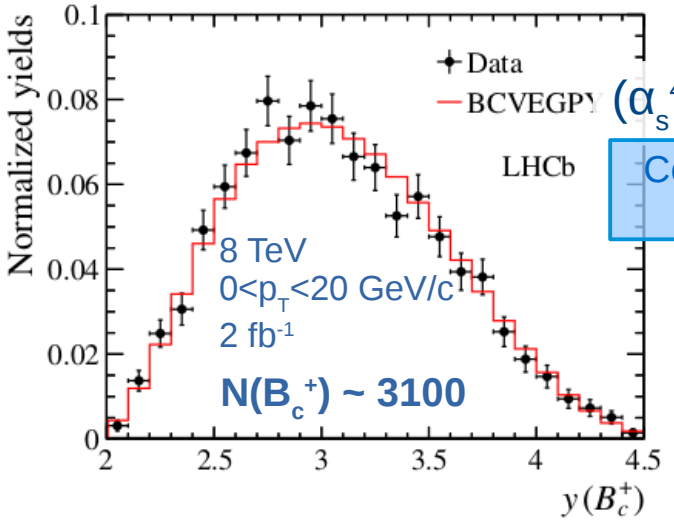
PRL 114 (2015) 132001

- Study $R_{c/u}$ kinematic dependency in range $0<p_T<20$ GeV/c and $2<y<4.5$
- BDT-based selection
- Excellent description of $B_c^+$ spectra by BCVEGPY

fit example




($\alpha_s^4$ approach)

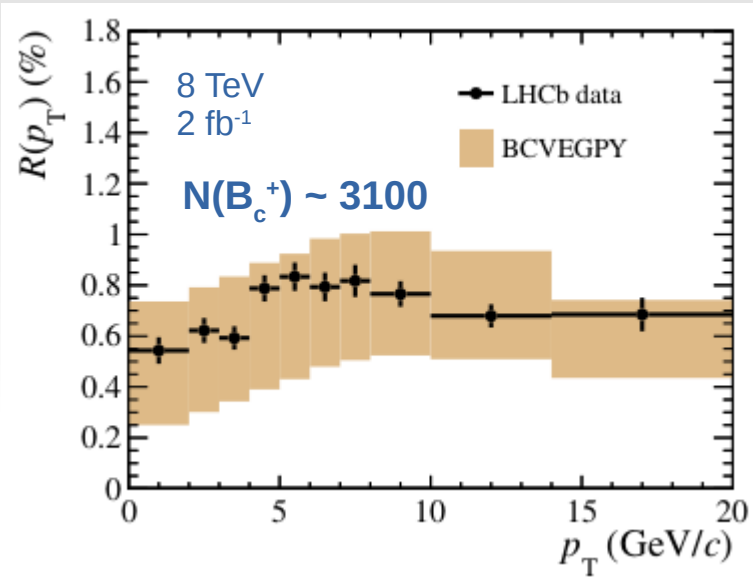
Comput. Phys. Commun. 174 (2006) 241

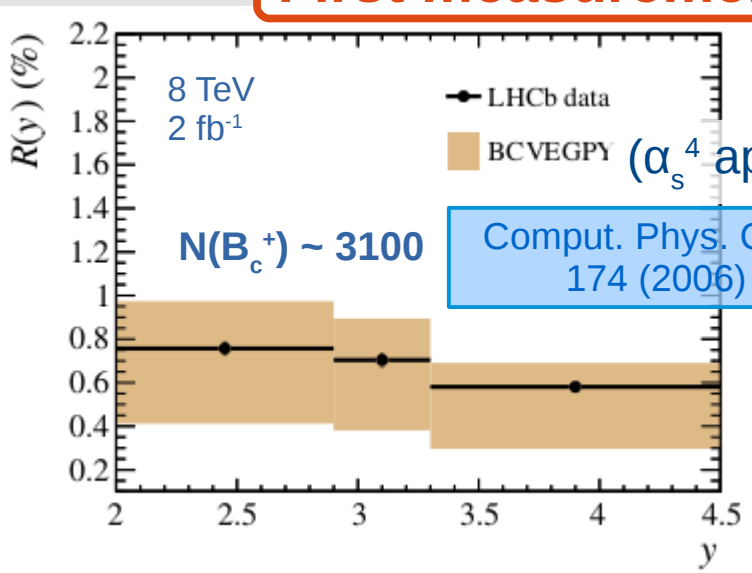
# $B_c^+$ production, 8 TeV

PRL 114 (2015) 132001

- Dependence on $p_T$ and y is observed:

**First measurement**




($\alpha_s^4$ approach)

Comput. Phys. Commun. 174 (2006) 241

in $p_T$<20 GeV/c and 2<y<4.5: $R = (0.683 \pm 0.018 \pm 0.009)\%$

dominant systematics: fit model

in 4<$p_T$<20 GeV/c and 2.5<y<4.5: $R = (0.698 \pm 0.023)\%$

(to compare with previous measurement)

consistent with measurements at 7 TeV (0.61±0.12)%

!New!

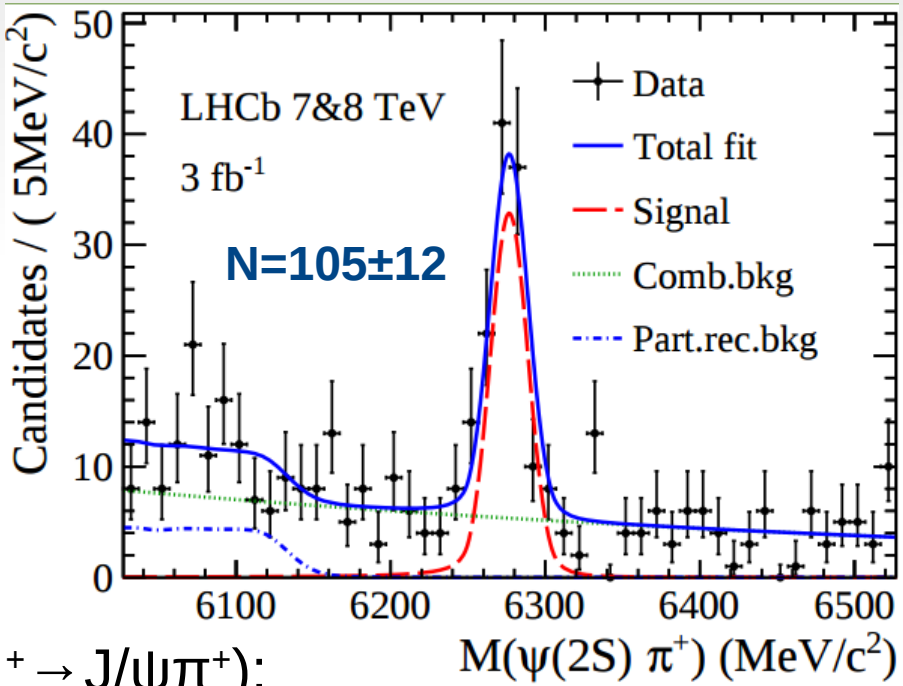
# $B_c^+ \to \psi(2S)\pi^+$

arXiv:1507.03516

- Update measurement on relative $\mathcal{B}$ of $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to J/\psi\pi^+$ based on only 7 TeV data: $0.250 \pm 0.068\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.006\,(\text{BF})$

PRD 87 (2013) 071103

- BDT-based selection




- $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$:

$$R_{\mathcal{B}} = 0.268 \pm 0.032\,(\text{stat}) \pm 0.007\,(\text{syst}) \pm 0.006\,(\text{BF})$$

consistent with the previous measurement

# Summary

- LHCb provides unique input for QCD
  with exploiting HF production in forward region

- $\chi_b(nP) \to \Upsilon(n'S)\gamma$ with unconverted and converted photons
- $\eta_c(1S)$ production (first time measured in pp collisions)
- $B_c^+$ differential cross-section + update on $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)$

- We are looking forward for run at 13 TeV