B_c^+ production

Jibo HE (UCAS)

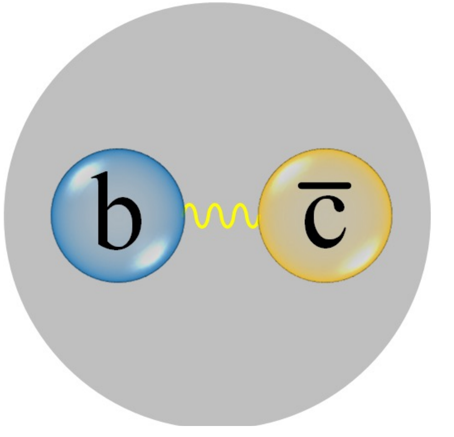
Quarkonia As Tools 2024

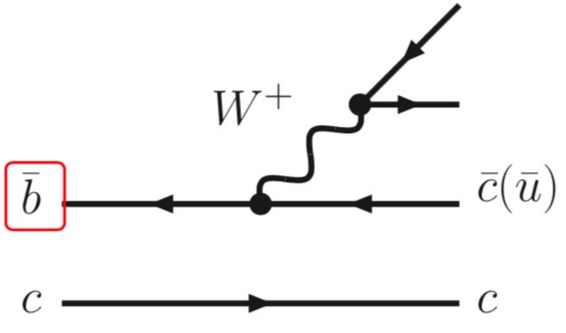
Centre Paul Langevin, Aussois (France)

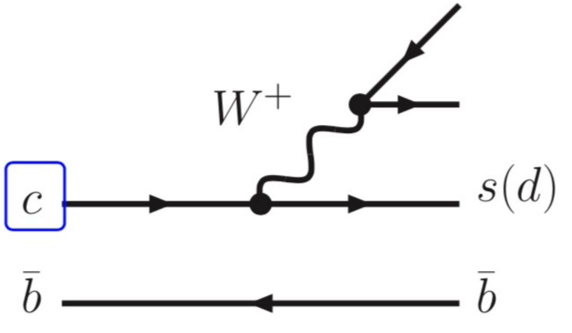
7-13 Jan 2024

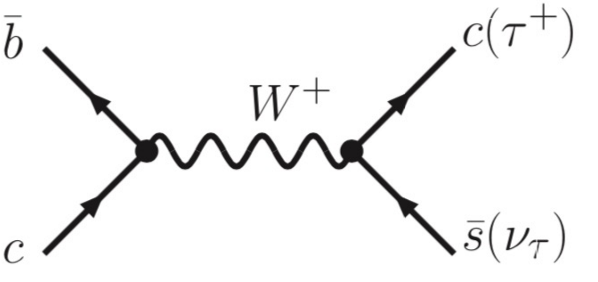
B_c meson

- Formed by two different heavy quarks, unique in the Standard Model. Both *b*- & *c*-quark can decay, or annihilate
  - $\bar{b} \to \bar{c}W^+$, e.g., $J/\psi\ell^+\nu_\ell$
  - $c \to sW^+$, e.g., $B_s^0\pi^+$
  - $c\bar{b} \to W^+$, e.g., $\tau^+\nu_\tau$

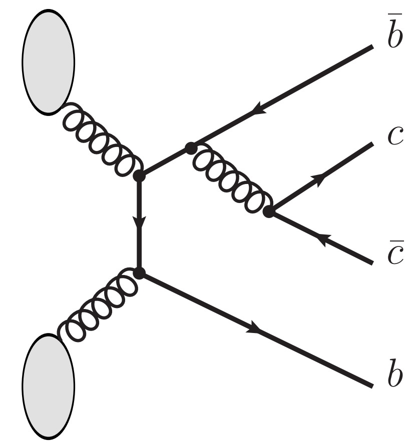








B_c production



- Difficult to produce at e^+e^- machine. Mainly through $gg \to B_c + b + \bar{c}$ at LHC
- Production rate
  - Theoretical prediction (in nb)

[C.-H. Chang, *et al.*, PRD 71 (2005) 074012]

-	$\|({}^1S_0)_{\mathbf{1}}\rangle$	$\|({}^3S_1)_{\mathbf{1}}\rangle$	$\|({}^1S_0)_{\mathbf{8}}g\rangle$	$\|({}^3S_1)_{\mathbf{8}}g\rangle$	$\|({}^1P_1)_{\mathbf{1}}\rangle$	$\|({}^3P_0)_{\mathbf{1}}\rangle$	$\|({}^3P_1)_{\mathbf{1}}\rangle$	$\|({}^3P_2)_{\mathbf{1}}\rangle$
LHC†	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

- Color octet contribution is small

  - $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)| \approx 0.6$
  - $\sigma(B_c^+)\sim 0.9\ \mu\text{b}$ for $\sqrt{s} = 14$ TeV

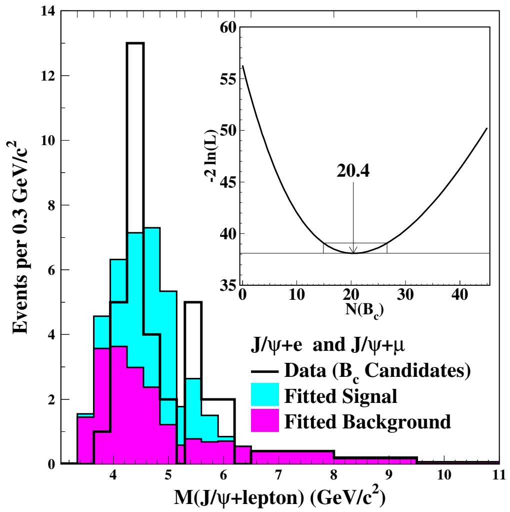
B_c^+ production at Tevatron

- B_c^+ observed by CDF in 1998, production rate at $\sqrt{s} = 1.8$ TeV in $p\bar{p}$, measured w/ 0.11 fb^{-1}

$$\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\ell^+\nu)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = 0.132^{+0.041}_{-0.037} \pm 0.031^{+0.032}_{-0.020}\,(\tau_{B_c})$$

for $p_{\mathrm{T}} > 6$ GeV, $|y| < 1$

[CDF, PRL 81 (1998) 2432]



- R at $\sqrt{s} = 1.96$ TeV in $p\bar{p}$, w/ 8.7 fb^{-1} [CDF, PRD 93 (2016) 052001]

$$\mathcal{R} = 0.211 \pm 0.012^{+0.021}_{-0.020}$$ for $p_{\mathrm{T}} > 6$ GeV, $|y| < 0.6$

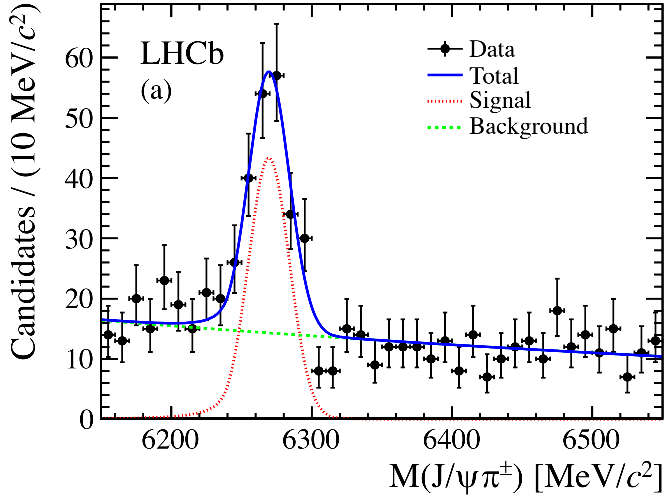
B_c^+ production at LHC

- Measured firstly by LHCb in 2012, production rate at $\sqrt{s} = 7$ TeV in pp, w/ 0.37 fb^{-1}

$$\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = \left(0.68 \pm 0.10 \pm 0.03 \pm 0.05\,(\tau_{B_c})\right)\%$$

for $p_\mathrm{T} > 4\ \mathrm{GeV}, \eta \in [2.5, 4.5]$

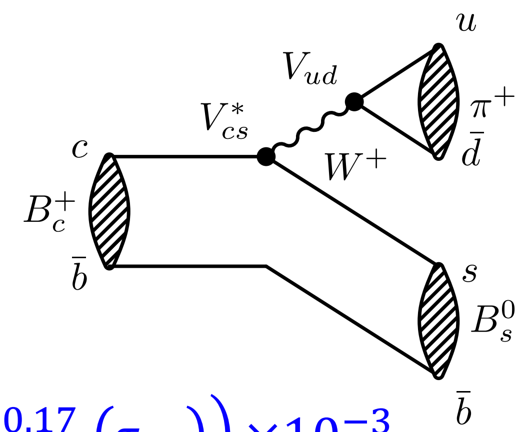
[LHCb, PRL 109 (2012) 232001]



- R by CMS at $\sqrt{s} = 7$ TeV, w/ 5.1 fb^{-1} [CMS, JHEP 01 (2015) 063]

$$\mathcal{R} = \left(0.48 \pm 0.05 \pm 0.03 \pm 0.05\,(\tau_{B_c})\right)\% \text{ for } p_\mathrm{T} > 15\ \mathrm{GeV}, |y| < 1.6$$

- LHCb also measured B_c^+ production with $B_c^+ \to B_s^0\pi^+$ when observing this decay



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

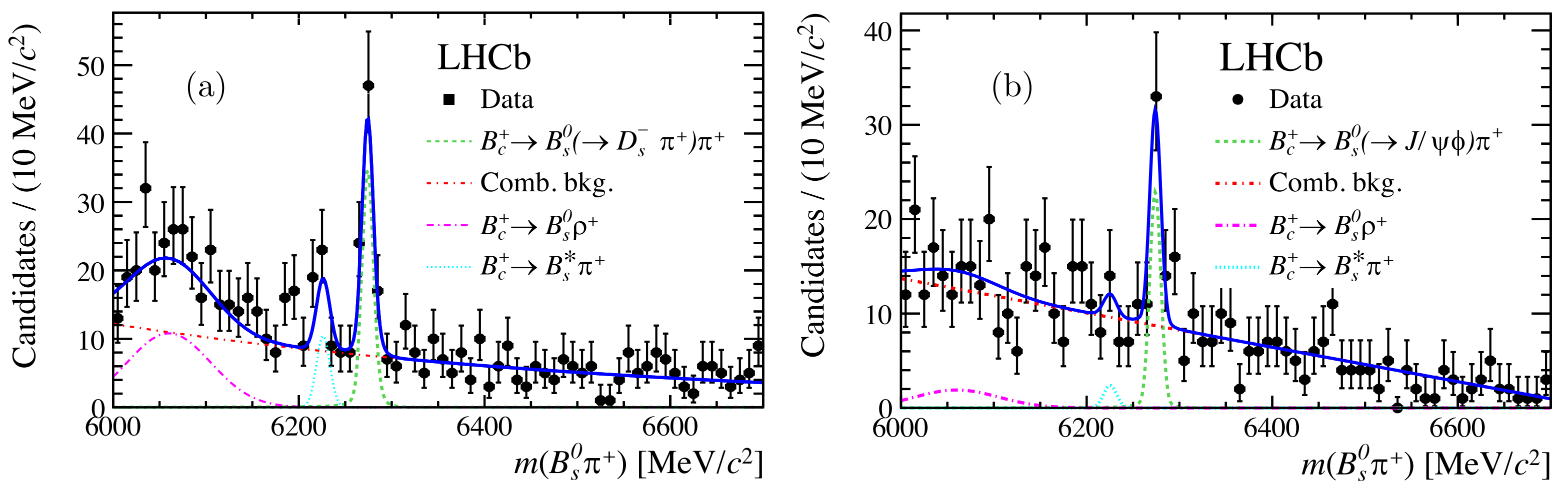
for $\eta \in [2, 5]$

[LHCb, PRL 111 (2013) 181801]

- $\frac{\mathcal{B}(B_c^+ \to B_s^0\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 91 \pm 13$

[LHCb, JHEP 07 (2023) 066]

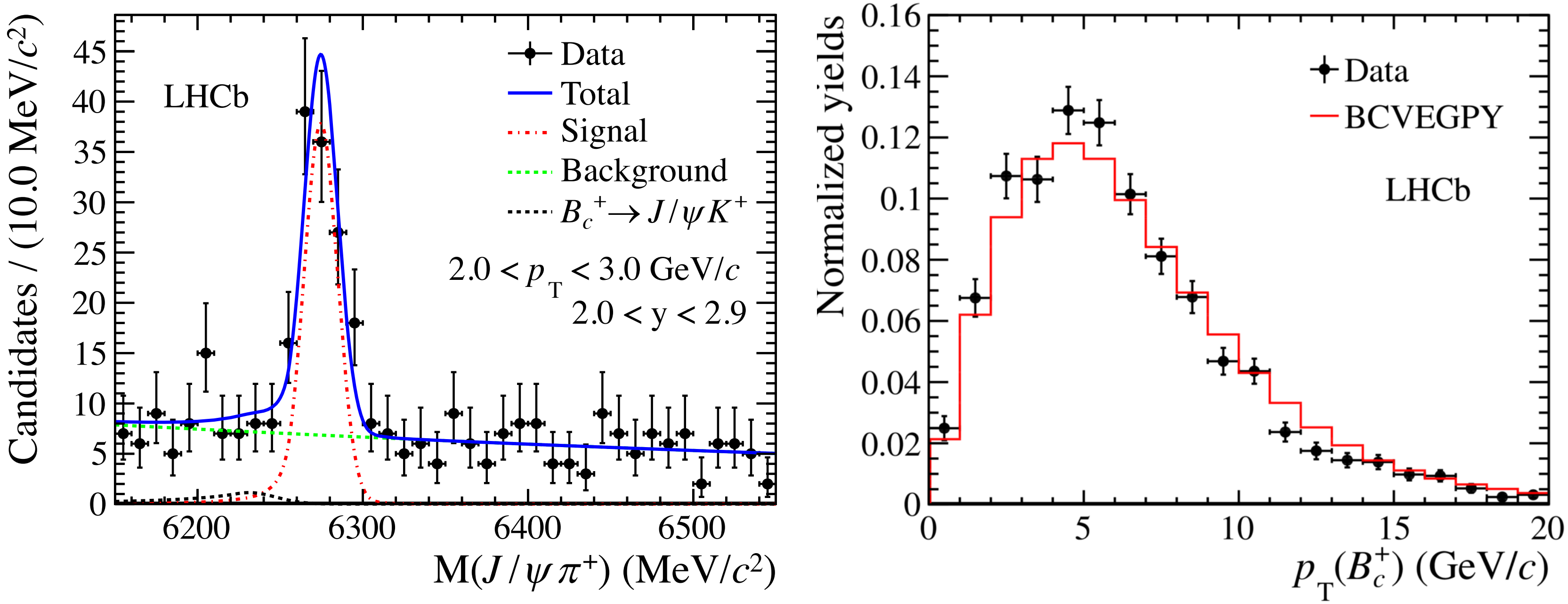
$\Longrightarrow \mathcal{B}(B_c^+ \to B_s^0\pi^+)$ is 8% - 30% depending on $\mathcal{B}(B_c^+ \to J/\psi\pi^+)$



B_c^+ diff. production by LHCb

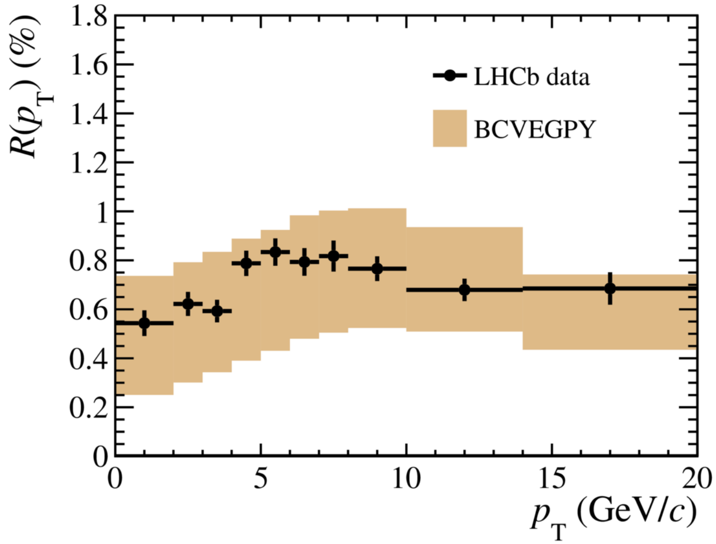
- Double-differential production as (p_T, y), w/ 2 fb^{-1} data at 8 TeV
- p_T distribution well described by BcVegPy

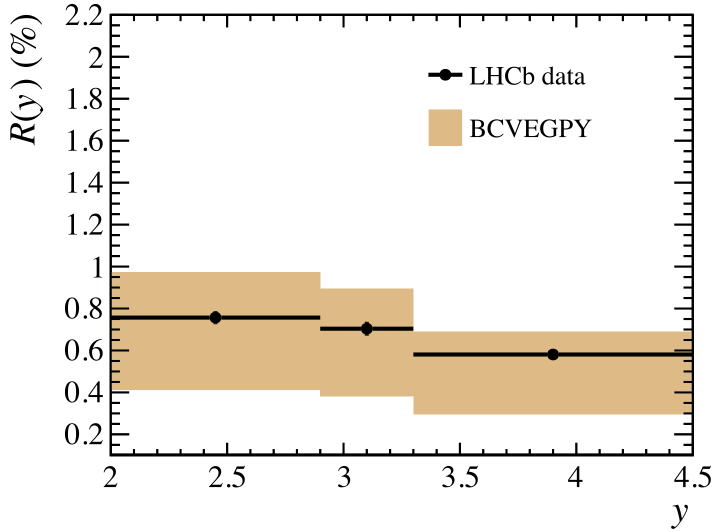
[PRL 114 (2015) 132001]



B_c^+ diff. production by LHCb

- $\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$
for $p_T < 20\ \text{GeV}, y \in [2, 4.5]$
- Using
$\sigma(B_c^+) = 0.47\ \mu\text{b}$, theoretical prediction by BcVegPy
$\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
$\sigma(B^+, p_T(B) < 40\ \text{GeV}/c, 2.0 < y < 4.5) = 38.9\ \mu\text{b}$ at $\sqrt{s} = 7$ TeV, measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
$\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12



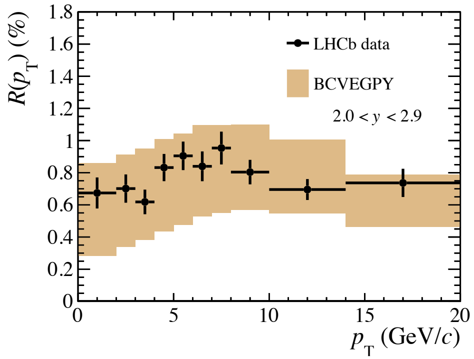


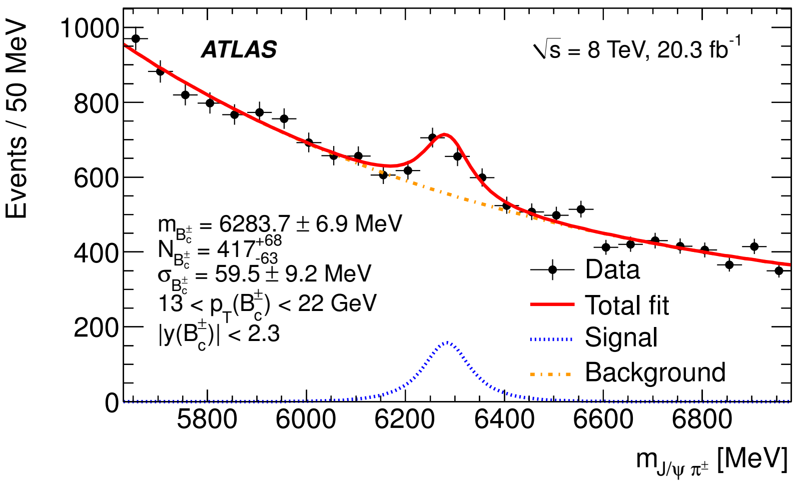
[PRL 114 (2015) 132001]

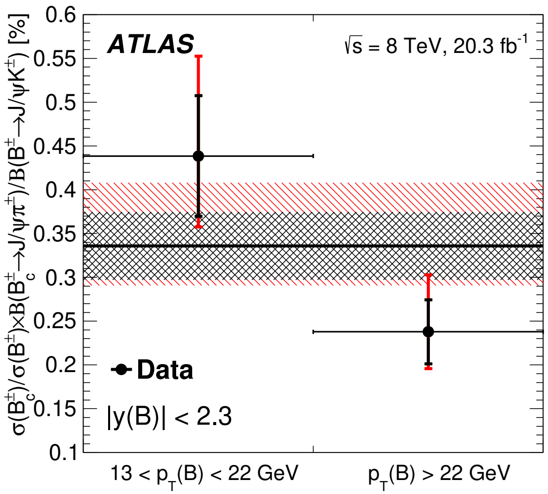
B_c^+ diff. production by ATLAS

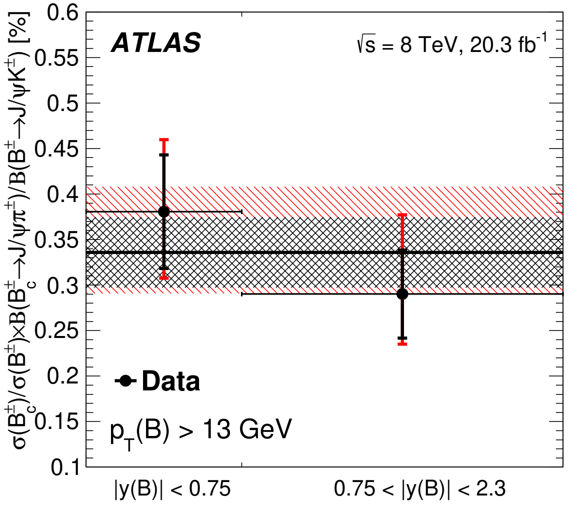
[ATLAS, PRD 104 (2021) 012010]

- As a function of p_T / y, consistent w/ LHCb





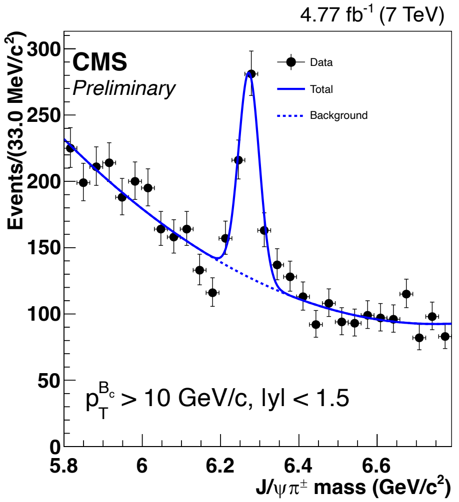




Band: average

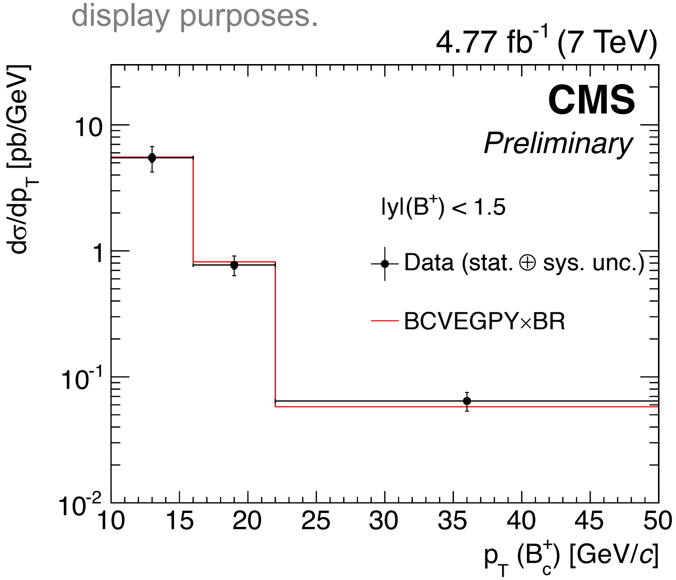
B_c^+ diff. production by CMS

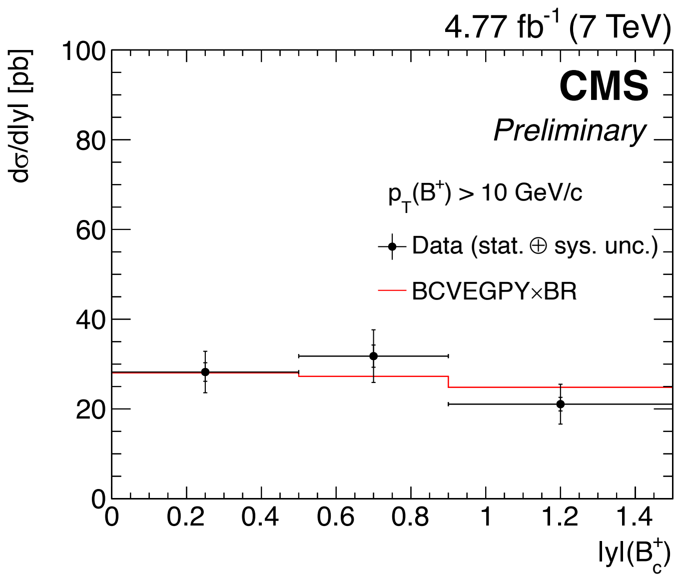
- Measured trends agree w/ BcVegPy



[CMS-PAS-BPH-13-002]

The prediction of the B_c^+ production cross section by BcVegPy times the branching fraction $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ is scaled by 2.75 for display purposes.

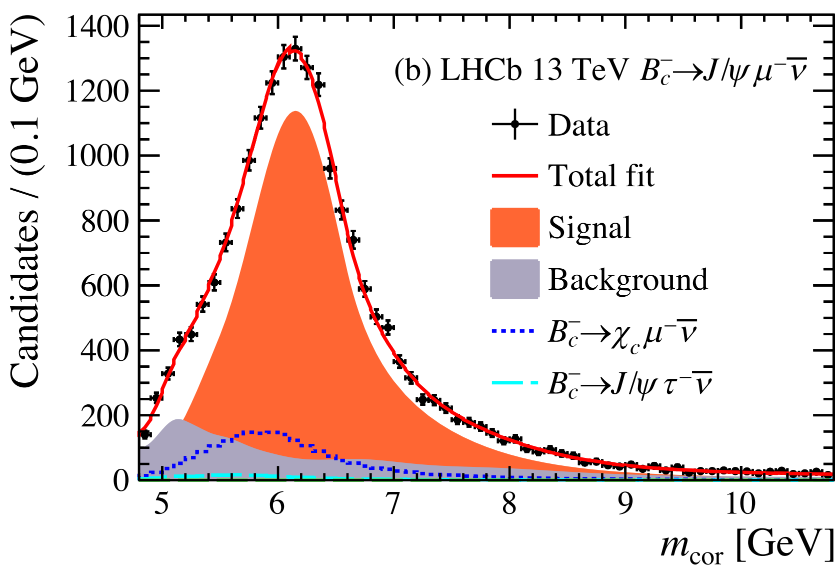


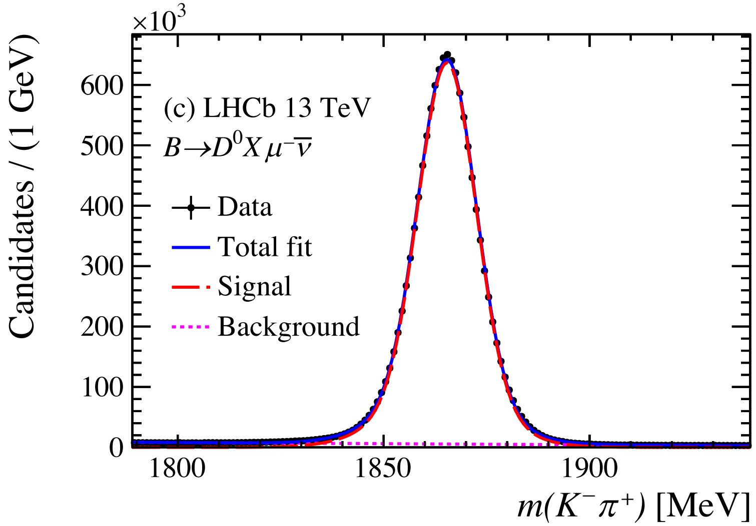


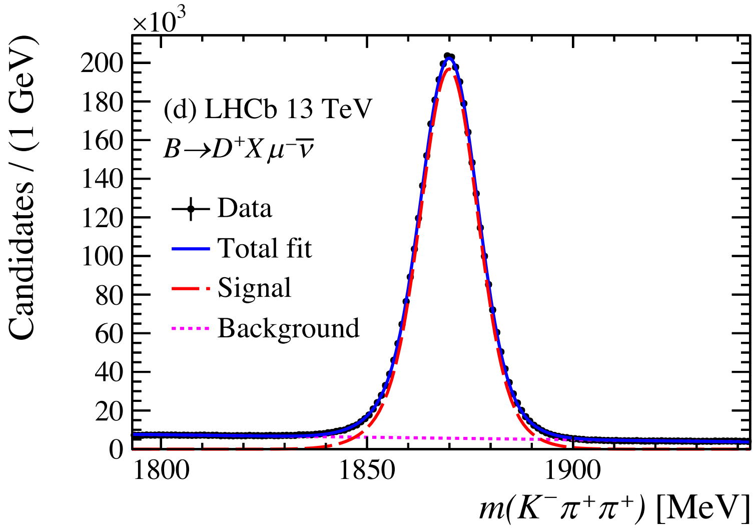
B_c^+ production w/ $J/\psi\mu^+X$

[PRD 100 (2019) 112006]

- Normalized to $B \to D^{0/+}\mu^- X$, w/ 7 and 13 TeV data
- 15170 ± 710 signal







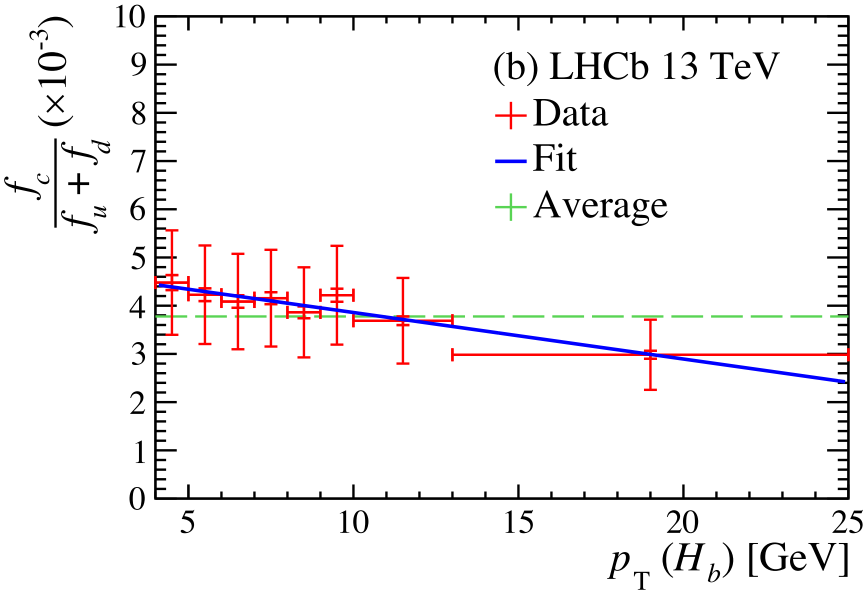
B_c^+ production w/ $J/\psi\mu^+X$

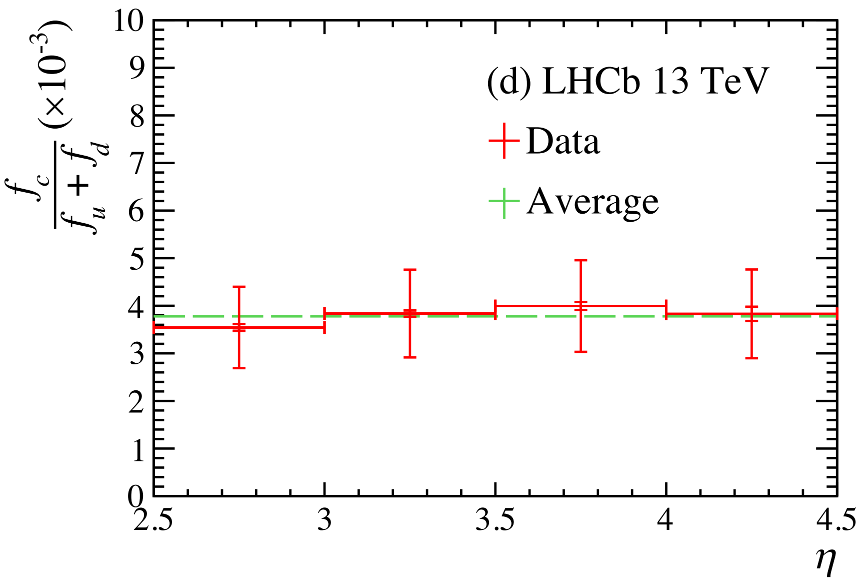
- Similar trend seen in $p_{\mathrm{T}} > 5$ GeV region

Use $\langle\mathcal{B}_{sl}\rangle = (10.70 \pm 0.19)\%, \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu) = (1.95 \pm 0.46)\%$

$$\frac{f_c}{f_u+f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89)\times10^{-3} \text{ at 13 TeV}$$

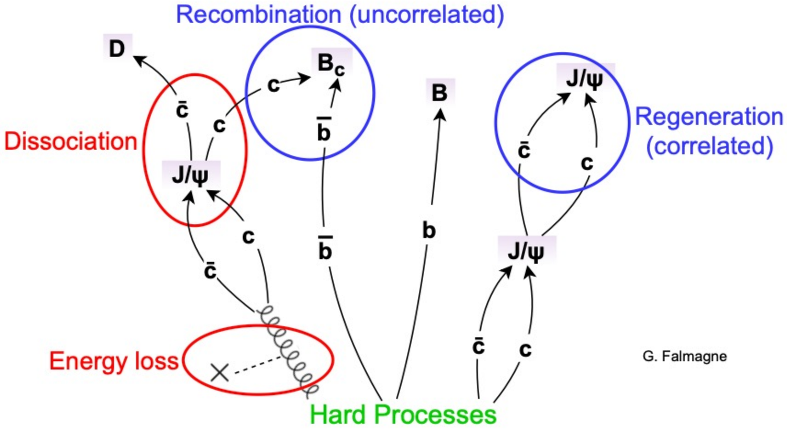
[PRD 100 (2019) 112006]





B_c^+ production in PbPb

- B_c^+, bridge between $c\bar{c}$ & $b\bar{b}$, & b/c-hadron
  - Dissociation, binding energy
  - Recombination, $\sigma_{pp}(B_c^+)$ small $\Longrightarrow$ enhancement at $p_{\mathrm{T}} \lesssim m(B_c^+)$ could be big
  - Partonic energy loss, mass and color-charge dependence?



- First $R_{\mathrm{PbPb}}(B_c^+)$ measured by CMS

[G. Falmagne, CERN Seminar, 07/2021]

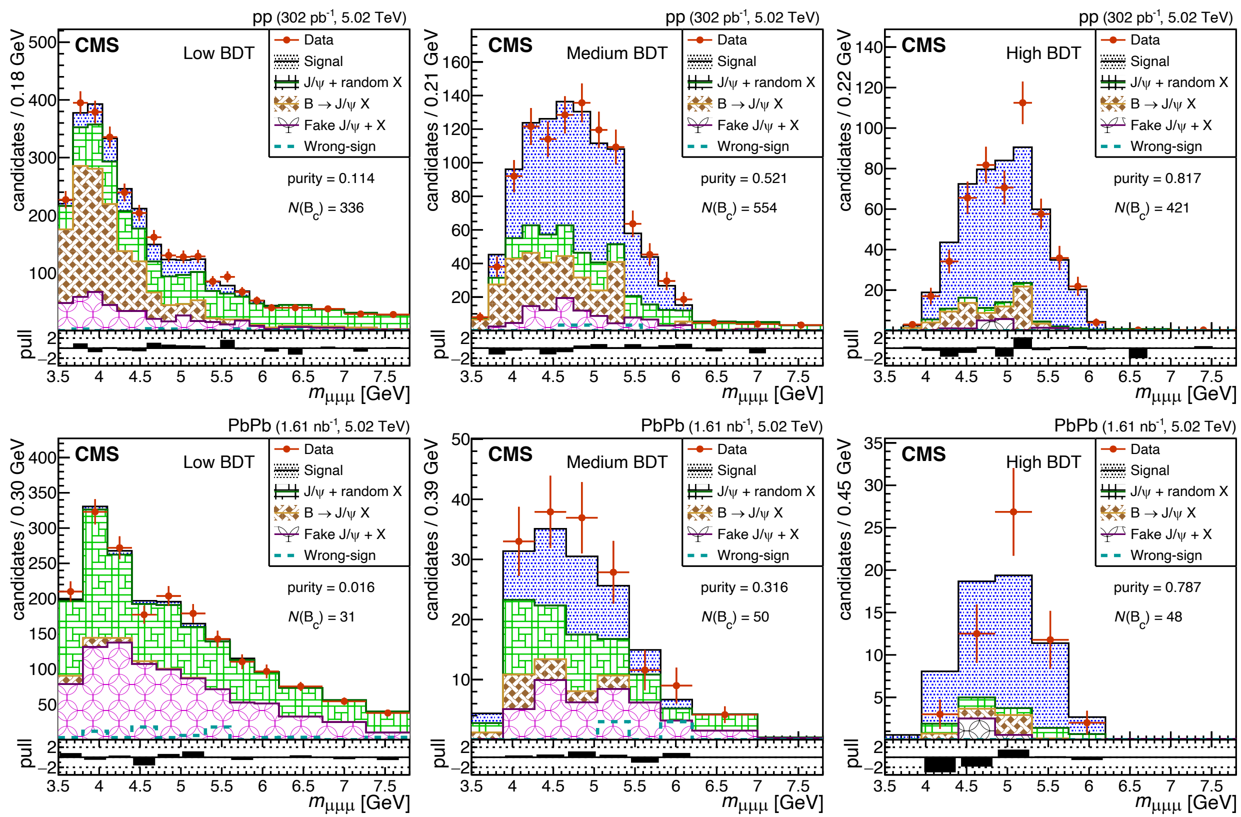
B_c^+ production in PbPb

- Measured by CMS, w/ $B_c^+ \to J/\psi \mu^+ X$, using $\sqrt{s_{NN}} = 5.02$ TeV, 302 pb^{-1} (pp), 1.61 nb^{-1} (PbPb)

[PRL 128 (2022) 252301]

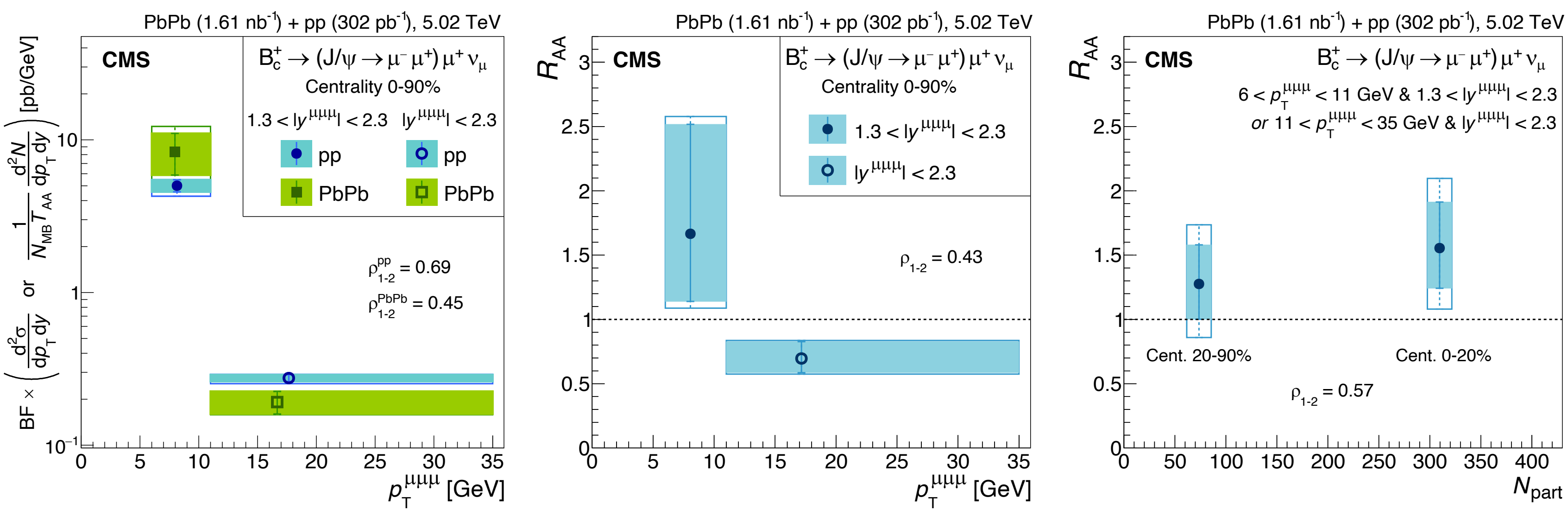
pp

PbPb



First $R_{\mathrm{PbPb}}(B_c^+)$ by CMS

- Moderate suppression in the high $p_{\mathrm{T}}^{\mu\mu\mu}$ bin, difference between two $p_{\mathrm{T}}^{\mu\mu\mu}$ bins, $1.8\sigma \Longrightarrow$ a softening of p_{T} spectrum in the QGP
- No significant variation as centrality

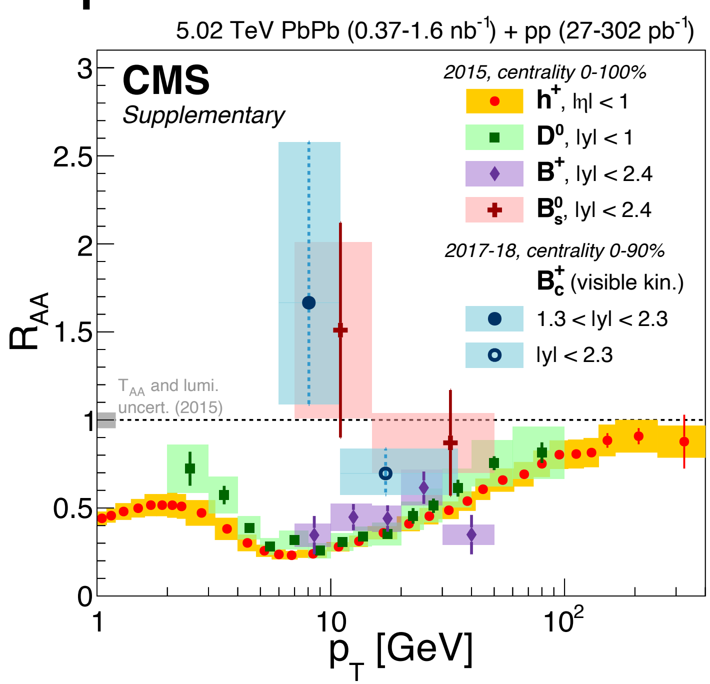


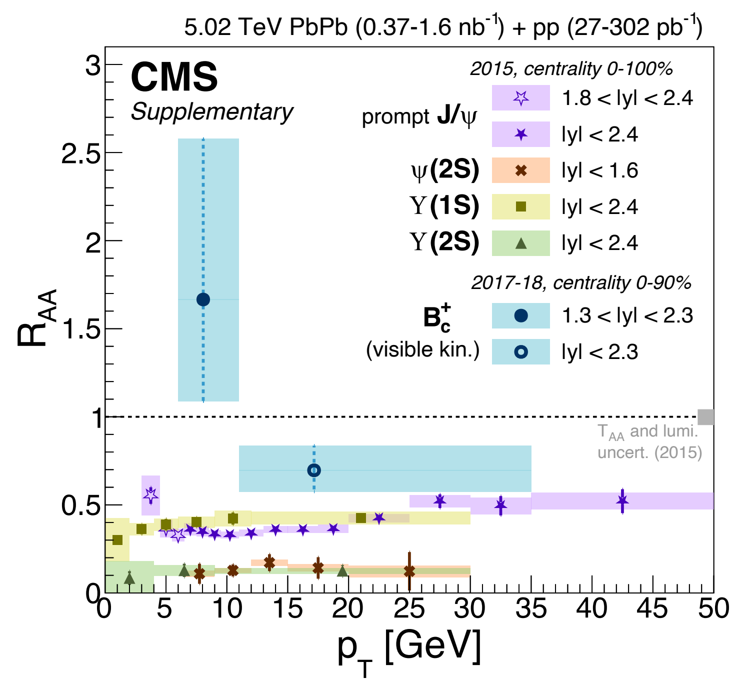
[PRL 128 (2022) 252301]

First $R_{\mathrm{PbPb}}(B_c^+)$ by CMS

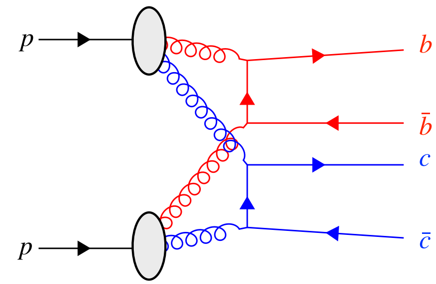
- B_c^+ modification similar to B_s^0, less than light hadrons, *B/D*, and quarkonium
  - Heavy quark recombination is a significant B_c^+ production mechanism in QGP?

[PRL 128 (2022) 252301]

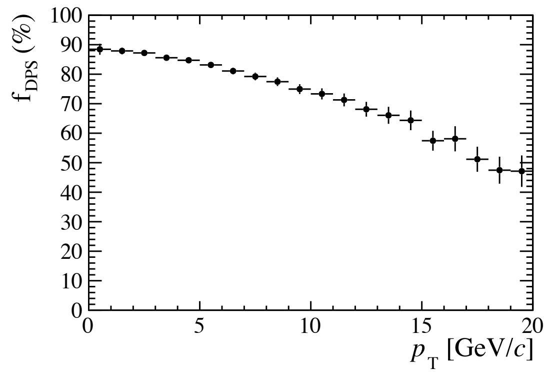


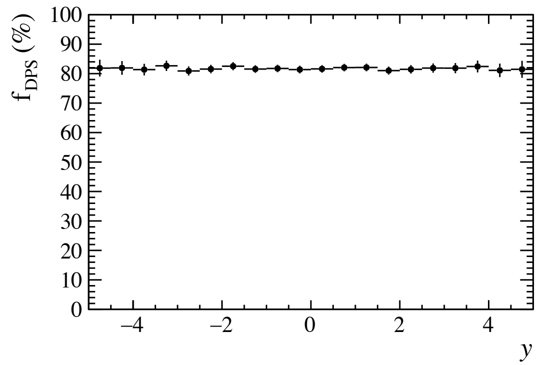


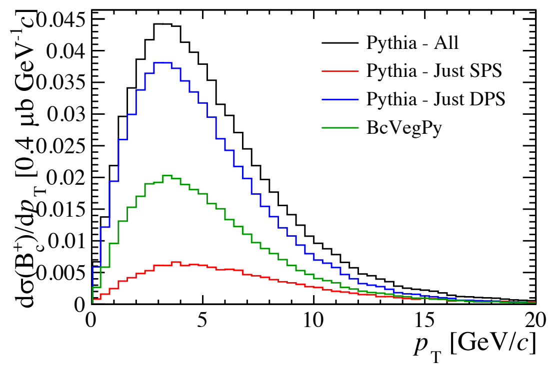
DPS contribution?

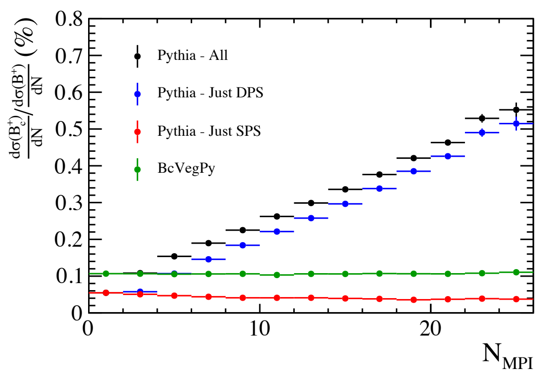


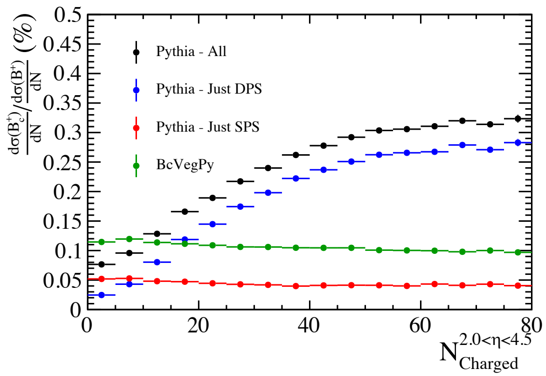
- Very big as predicted by Pythia
- Different p_{T} spectrum? However…

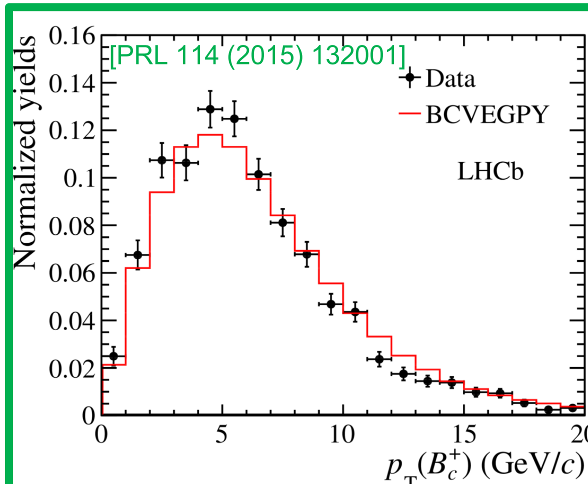








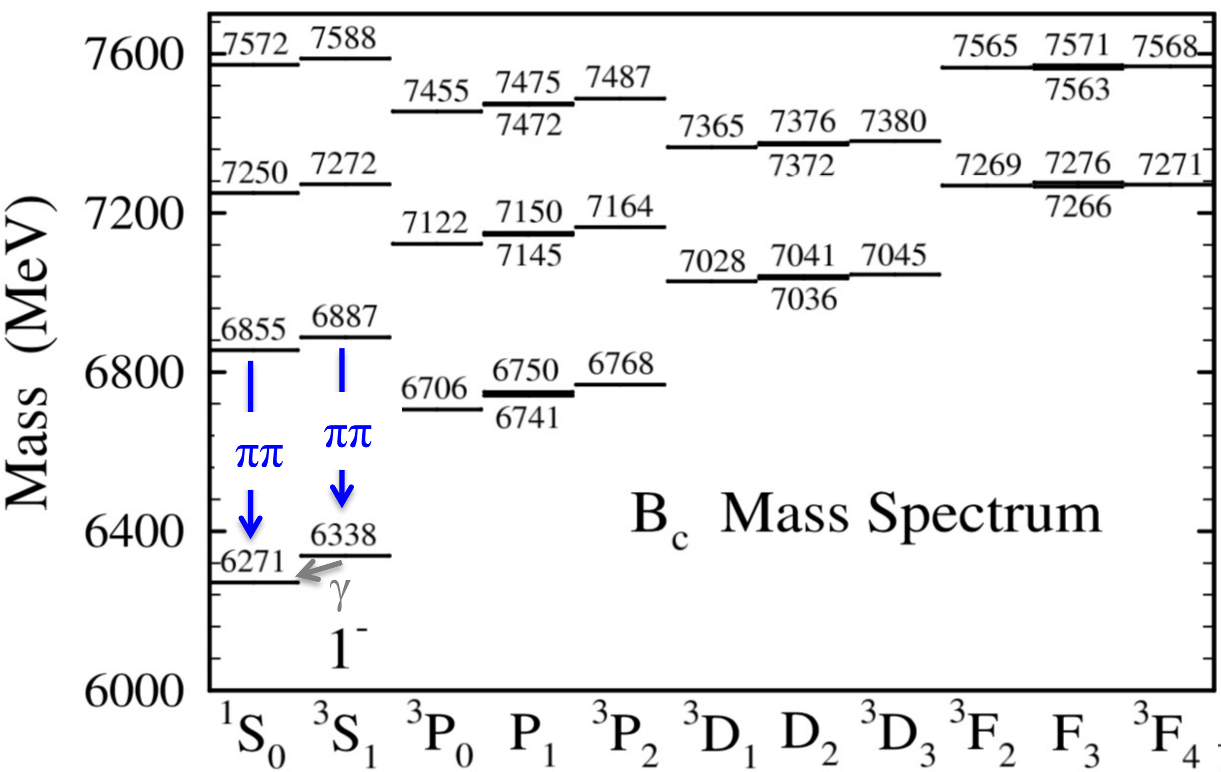




[U. Egede *et al.*, EPJC 82 (2022) 773]

Excited B_c^+ states

- B_c has a rich spectrum



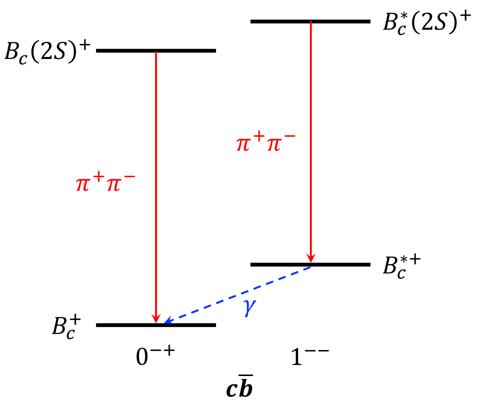
[S.Godfrey, PRD 70 (2004) 054017]

State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P_1'+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8

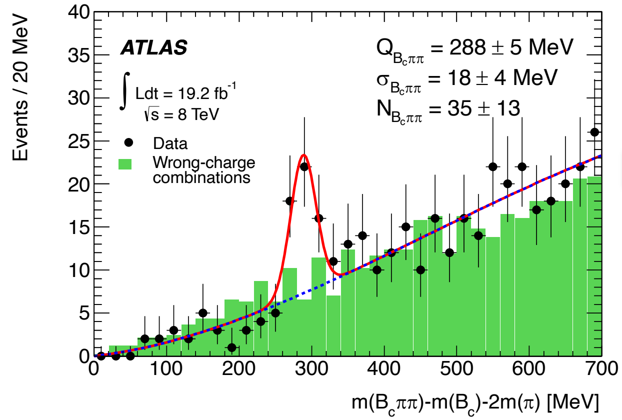
* [I. P. Gouz, *et al.*, Phys. Atom. Nucl. 67 (2004) 1559]
† [S.Godfrey, PRD 70 (2004) 054017]

Observation of $B_c^{(*)}(2S)^+$

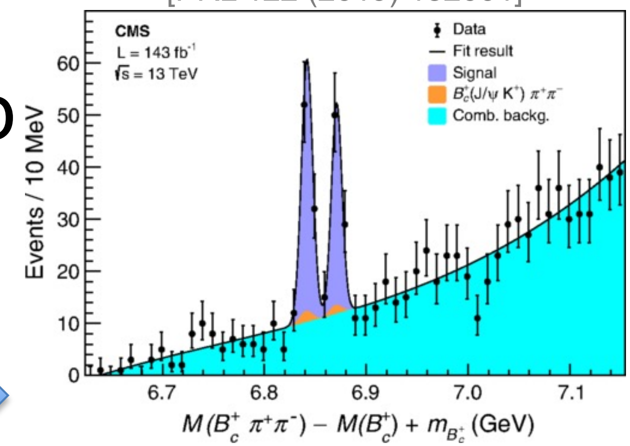
- Mixture (?) by ATLAS, then both states by CMS and LHCb

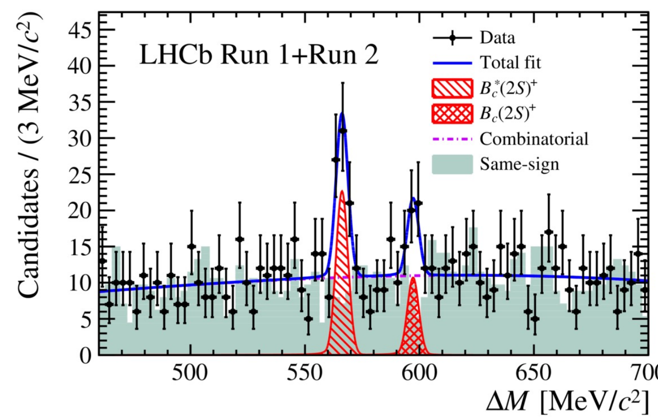


[PRL 113 (2014) 212004]



[PRL 122 (2019) 132001]





[PRL 122 (2019) 232001]

LHCb

$$M(B_c(2^3S_1)^+)_{\text{rec}} = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\text{rec}} = 31.0 \pm 1.4(\text{stat}) \pm 0.0(\text{syst})\ \text{MeV}/c^2$$

CMS

$$M(B_c(2^3S_1)^+)_{\text{rec}} = 6842.0 \pm 1.0(\text{stat}) \pm 0.0(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)\ \text{MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\text{rec}} = 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}/c^2$$

$B_c^{(*)}(2S)^+$ production

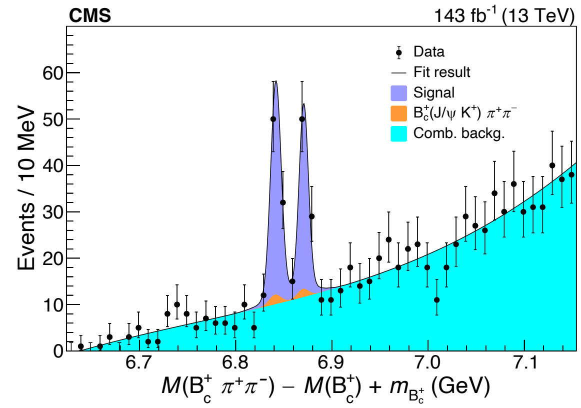
- Measured relative to B_c^+

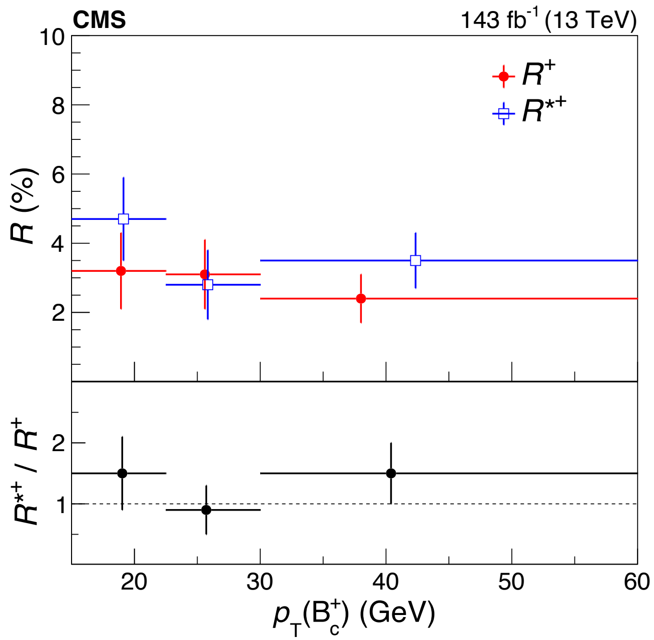
$$R^{(*)+} \equiv \frac{\sigma\left(B_c^{(*)}(2S)^+\right)}{\sigma(B_c^+)} \mathcal{B}\left(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-\right)$$

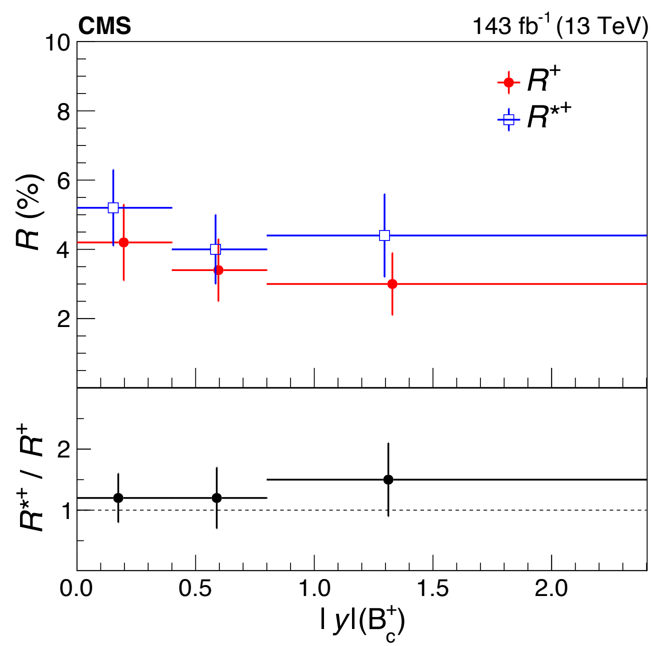
$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$

$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$

$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$



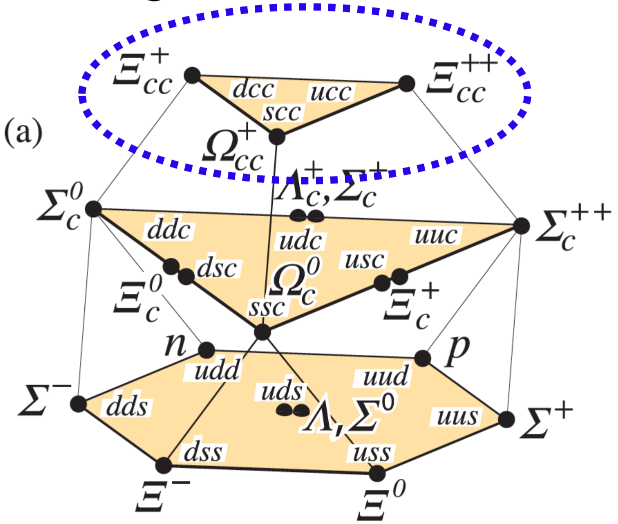




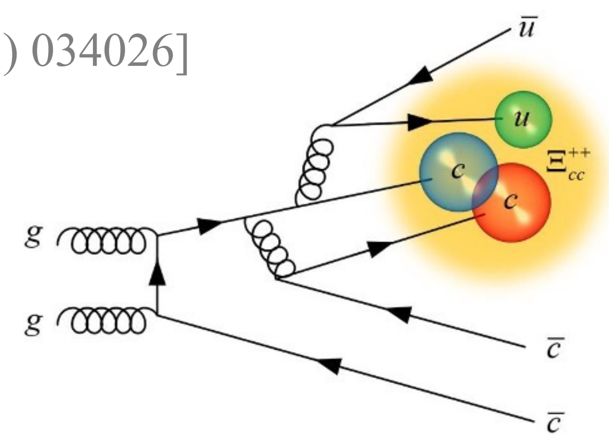
[PRD 102 (2020) 092007]

Doubly charmed baryon

- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$
    $= 3621.55 \pm 0.38\ \text{MeV}$
  - $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}^{++}) + 100\ \text{MeV}$

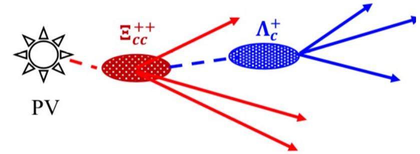


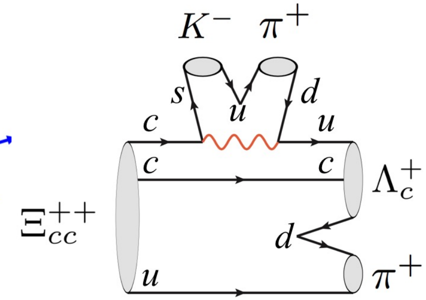
- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027\ \text{ps}$
- Production [J.-W. Zhang *et al.*, PRD 83 (2011) 034026]
  - $\sigma(cc) = 90\ \text{nb @ } 13\ \text{TeV in LHCb}$
  - $f_{\text{frag}}\ u : d : s \sim 1 : 1 : 0.3$
    $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40\ \text{nb}$
    $\sigma(\Omega_{cc}^{+}) \sim 13\ \text{nb}$



Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel

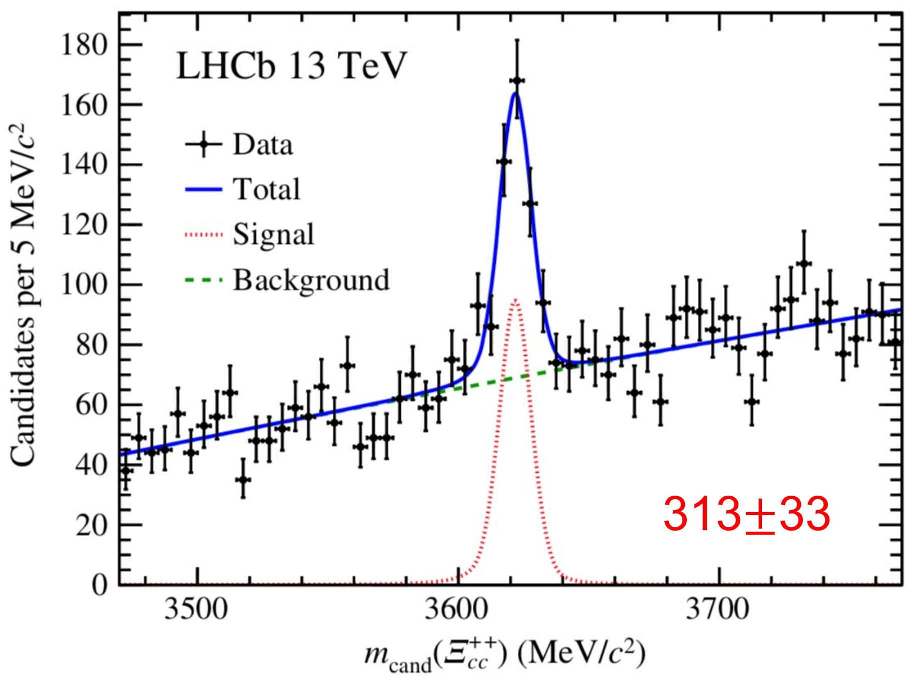


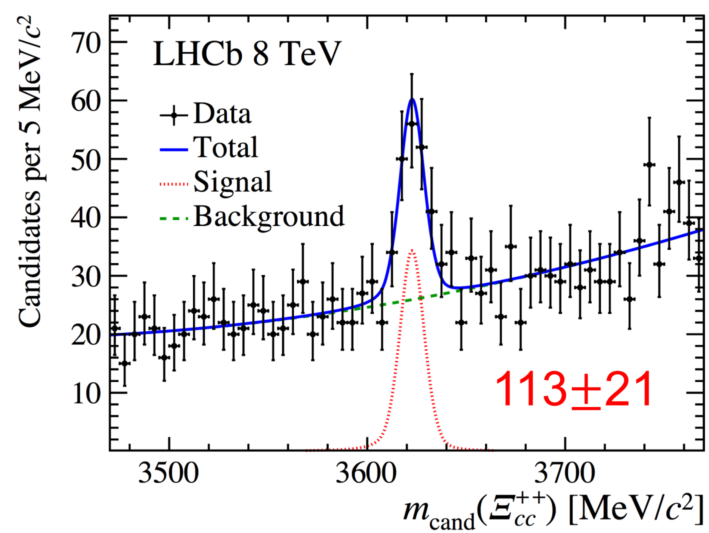


[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

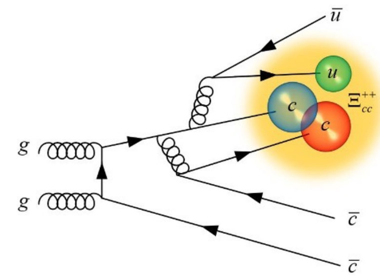
- First observation, in 2016 (>12σ) & Run-I (>7σ)

[PRL 119 (2017) 112001]





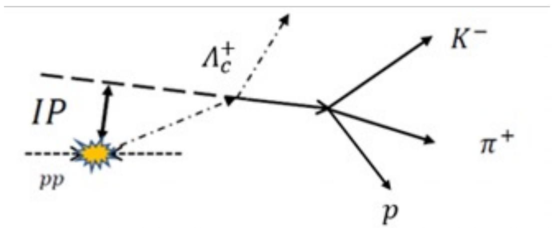
Measurement of Ξ_{cc}^{++} production



- Measured by LHCb w/ 2016 data
- Relative to Λ_c^+, in

  $4 < p_T < 15$ GeV,

  $2 < y < 4.5$

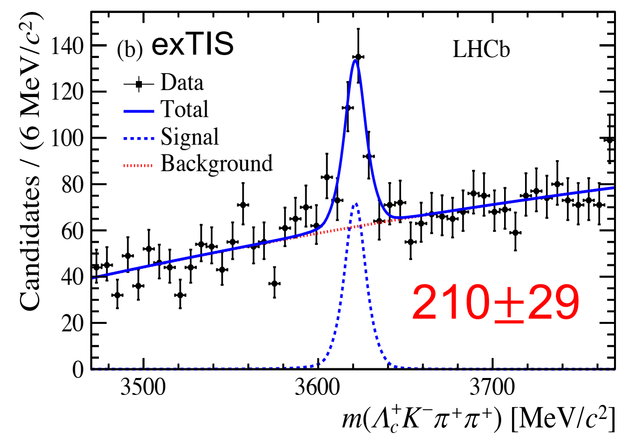


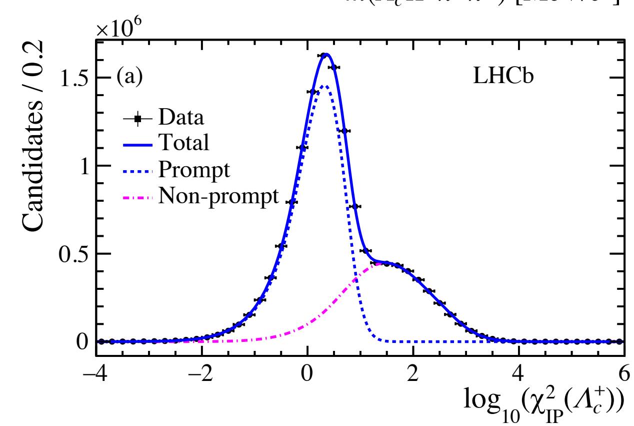
$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)$$
$$= (2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$$

SELEX, 20% Λ_c^+ from Ξ_{cc}^+

[SELEX, PRL 89 (2002) 112001]

[CPC 44 (2020) 022001]





Summary

- Many measurements of B_c^+ production with both $J/\psi\pi^+$, $J/\psi\mu^+X$
  - Integrated cross-section in $p\bar{p}, pp$
  - (Double) differential cross-section at LHC, p_T spectrum well described by BcVegPy. However, more accurate BR needed to conclude on the absolute cross-section
  - First $R_\mathrm{PbPb}(B_c^+)$
- Ξ_{cc}^{++} production also measured
- Your suggestions are always welcome！