Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics

Heavy flavour production in *pp* collisions at LHCb

Jibo HE (UCAS)

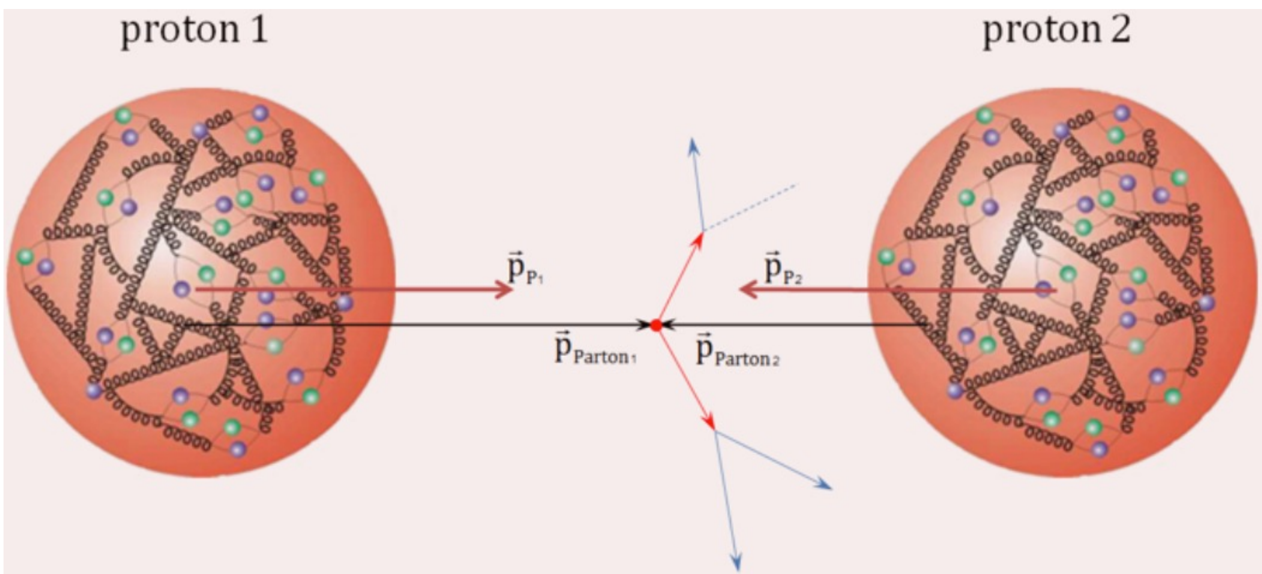
October 21, 2024

Outline

- Introduction
- Heavy flavour production
  - Charomonium(like)
  - Beauty
  - B_c^+
  - Doubly charmed baryon
- Status of Run-3 & prospects
- Summary

Introduction

- Heavy flavour production
  - Test QCD: PDF, hard scattering, fragmentation
  - New physics search: Background; f_s
  - *pp* collisions, reference for *p*Pb, PbPb



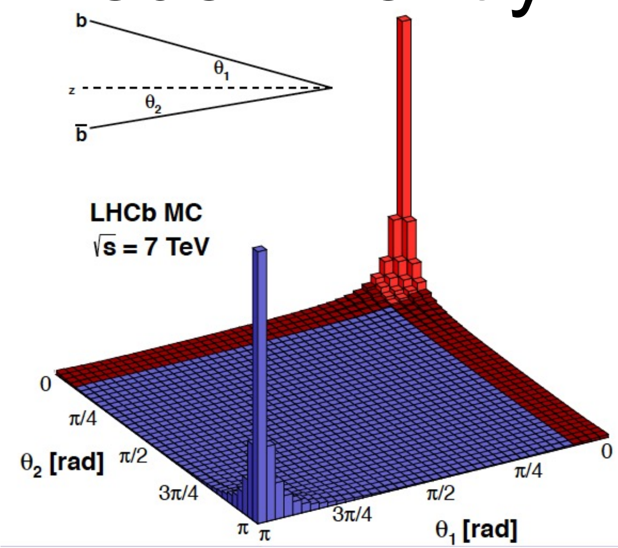
Large Hadron Collider

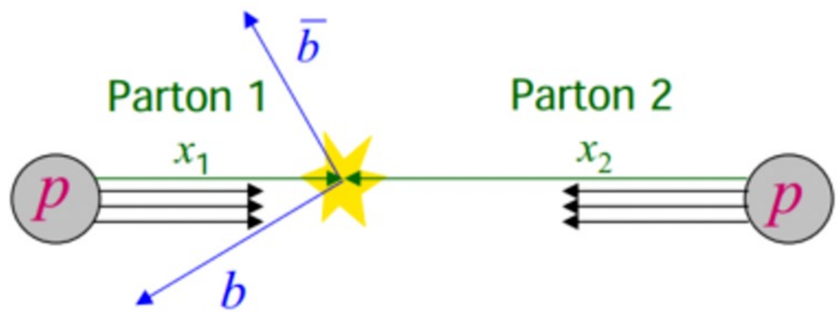
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb c.f. 1nb @$\Upsilon(4S)$

  } Flavour factory!
- Predominantly in forward/backward cones

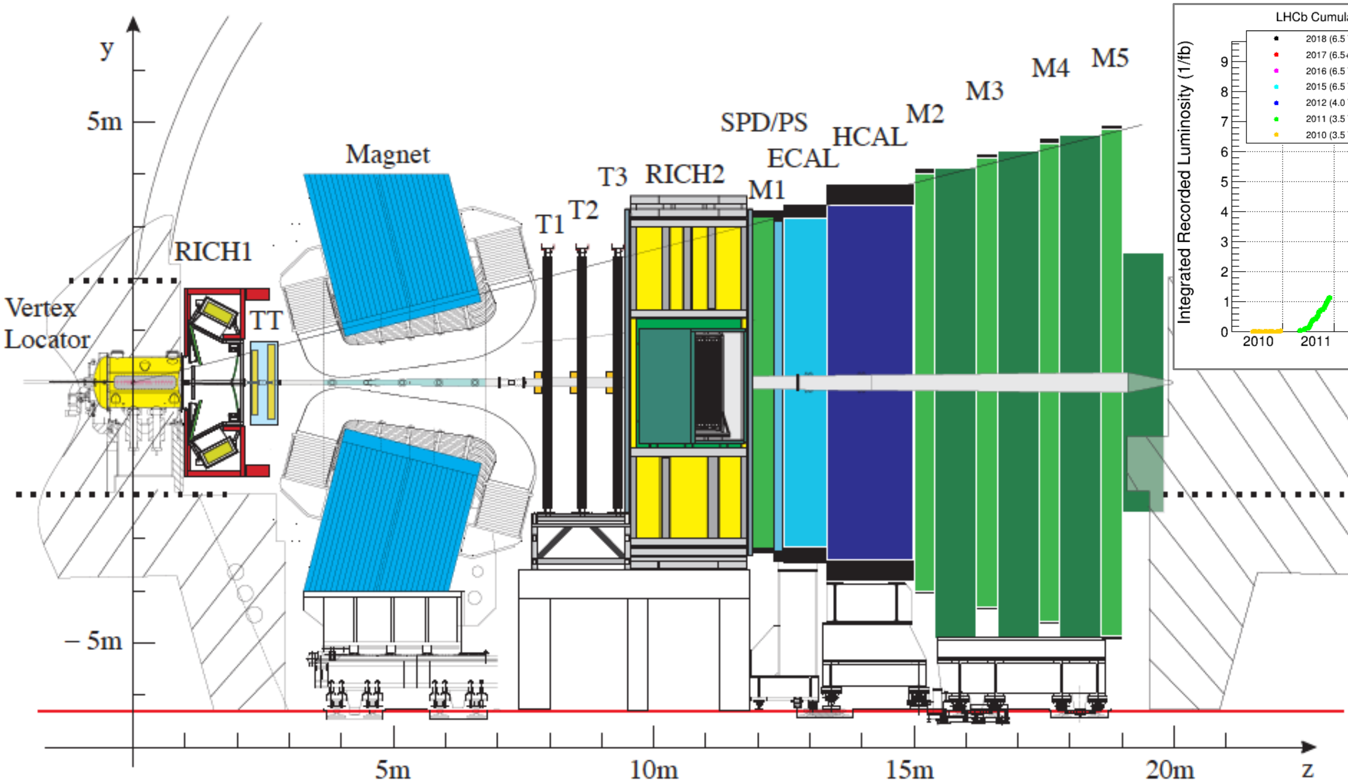


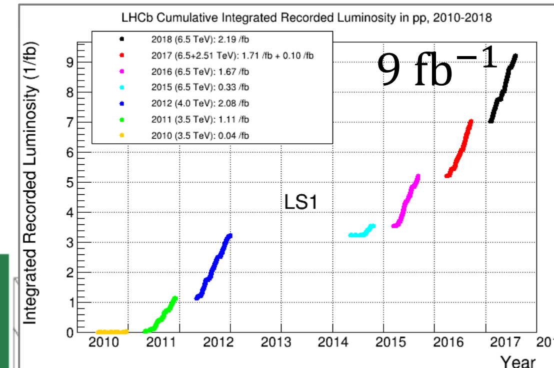


Initial energy of $b\bar{b}$ not known

The LHCb experiment

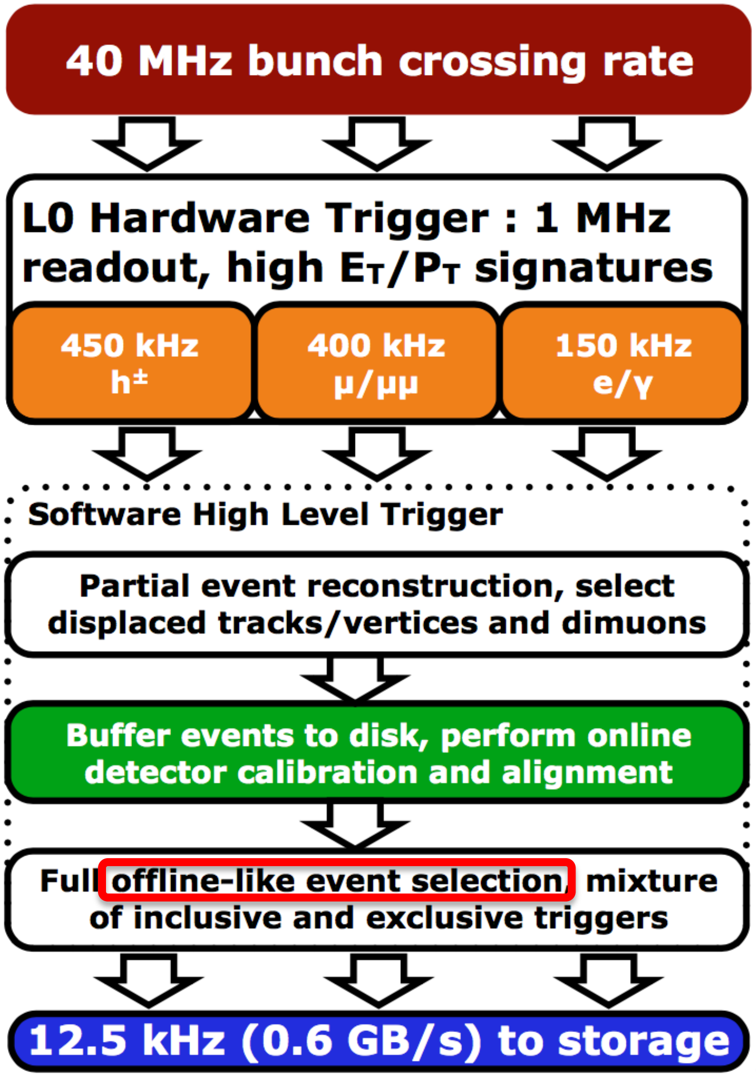
[JINST 3 (2008) S08005]





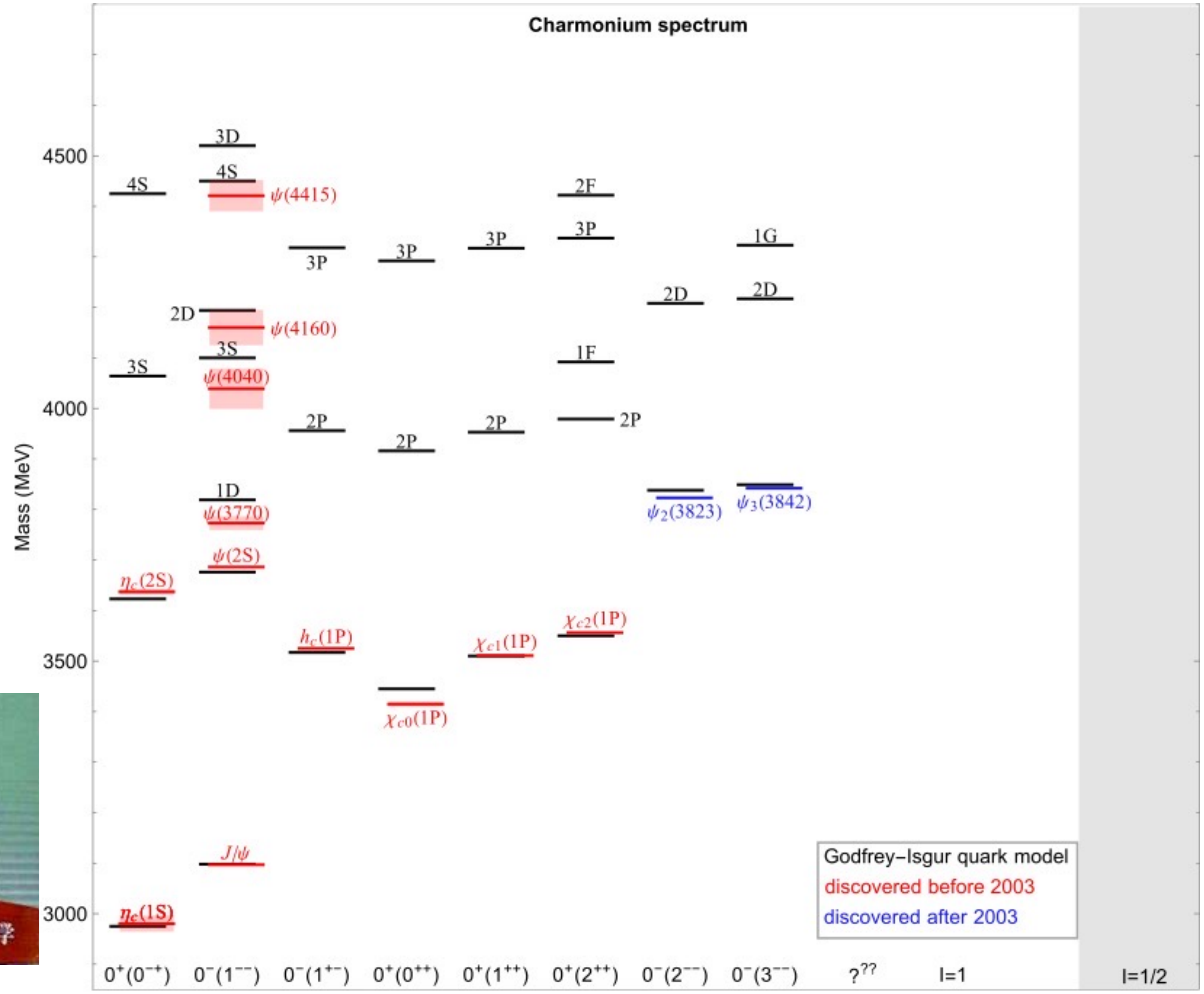
Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1-3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) >$ (1.5 GeV)^2
  - $p_{\mathrm{T}}(\mu) >$ 1.8 GeV
  - $E_{\mathrm{T}}(e) >$ 2.4 GeV
  - $E_{\mathrm{T}}(\gamma) >$ 3.0 GeV
  - $E_{\mathrm{T}}(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

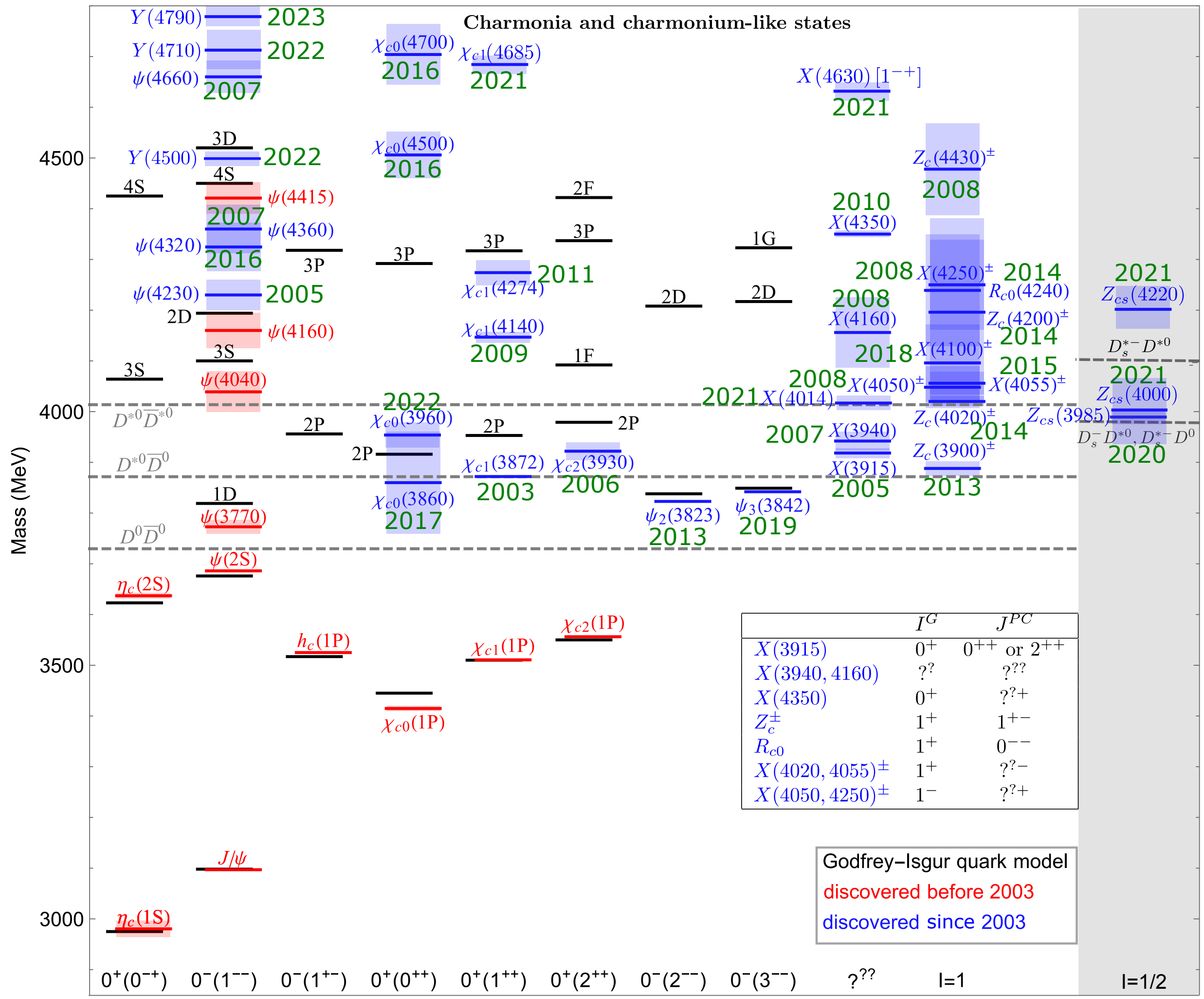
Charmonium states



[F.-K. Guo (郭奉坤), PoS LATTICE 2022 (2023) 232]

Samuel C.C.Ting

Charmonium(like) states



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^\pm$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^\pm$	1^+	$?^{?-}$
$X(4050, 4250)^\pm$	1^-	$?^{?+}$

[F.-K. Guo (郭奉坤), PoS LATTICE 2022 (2023) 232]

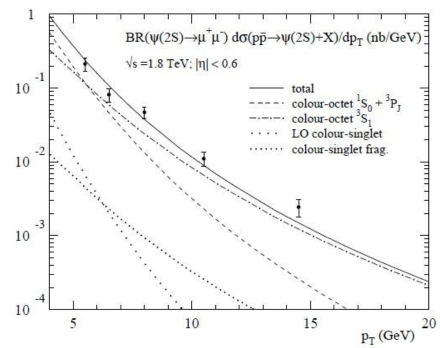
$X(3872)$?
- Tetraquark
- $\chi_{c1}(2P)$
- Molecule
- Mixture

J/ψ hadroproduction

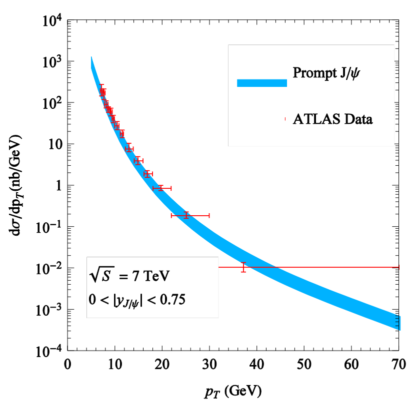
CO mechanism

- **Nicely explain ψ' surplus by CO contributions**

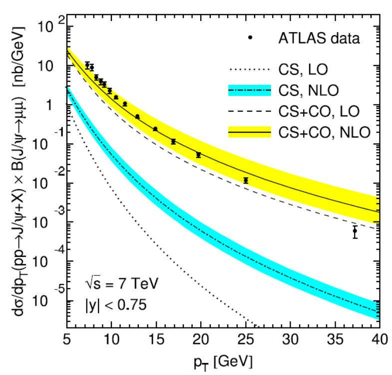
States	p_T behavior at LO
${}^3S_1^{[1]}$	p_T^{-8}
${}^3S_1^{[8]}$	p_T^{-4}
${}^1S_0^{[8]}$	p_T^{-6}
${}^3P_J^{[8]}$	p_T^{-6}



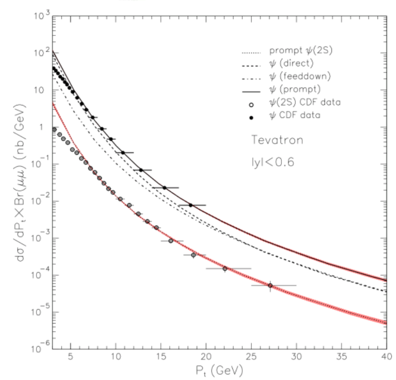
Kramer, 0106120



YQM, Wang, Chao, 1012.1030



Butenschoen, Kniehl, 1105.0820



Gong, Wan, Wang, Zhang, 1205.6682

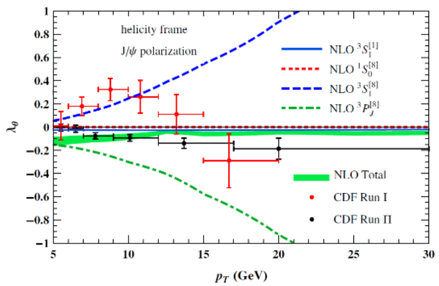
马滟青

Credit: Y.-Q. Ma

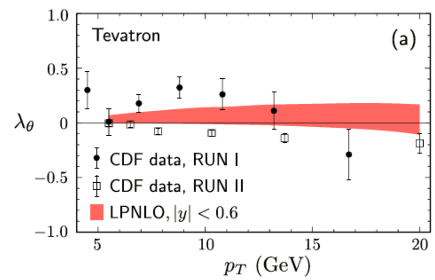
Polarisation?

Polarization puzzle at NLO

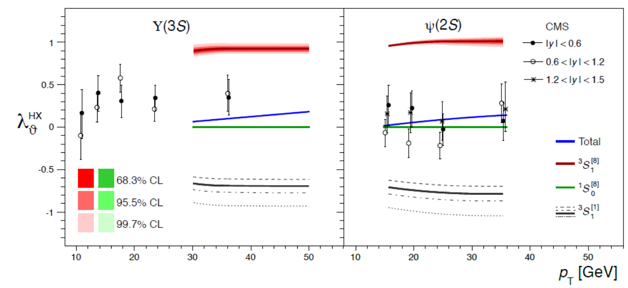
- J/ψ: transverse polarization canceled (*why?*) in $^3S_1^{[8]}$ and $^3P_J^{[8]}$



Chao,YQM,Shao,Wang, Zhang,1201.2675

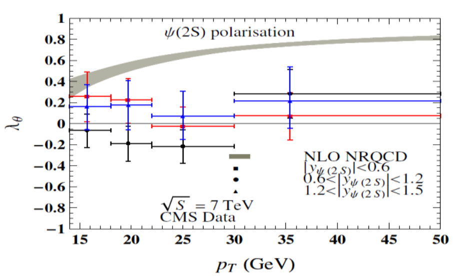


Bodwin, Chung, Kim, Lee, 1403.3612

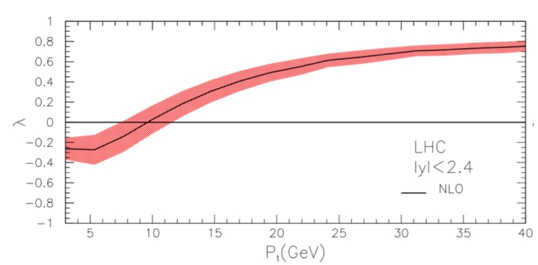


Faccioli,Knunz,Lourenco, Seixas,Wohri,1403.3970

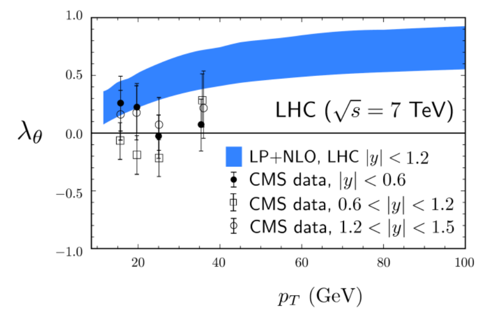
- $\psi(2S)$: cancelation weak, **hard to understand data**



Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



Gong, Wan, Wang, Zhang, 1205.6682



Bodwin et al., 1509.07904

Credit: Y.-Q. Ma

Hadronic decays

- Sizable branching fractions

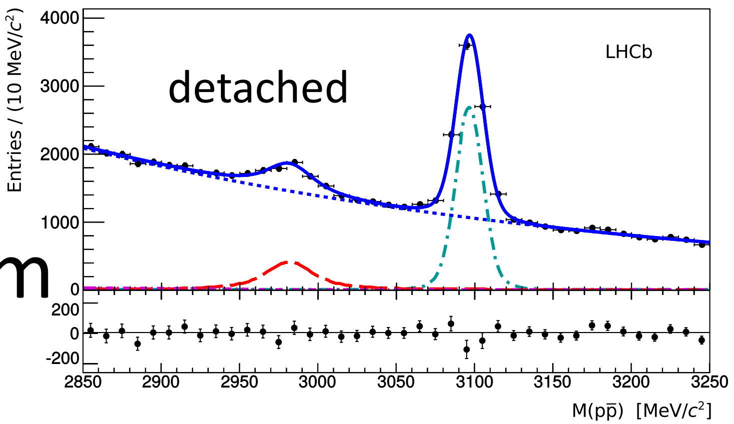
	$p\bar{p}$	$\phi\phi$	ϕK^+K^-	$\phi\pi^+\pi^-$	$\mathcal{B}\times 10^3$ $\Lambda\bar{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\bar{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.35 ± 0.13	1.58 ± 0.19	2.9 ± 1.4	unknown	1.02 ± 0.23	0.90 ± 0.26	-	-	5.5 ± 1.9
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.11	0.94 ± 0.15	1.89 ± 0.09	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.36 ± 0.02	0.45 ± 0.02	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.17	forbidden	unknown	unknown	unknown	unknown	unknown	570 ± 50	3.3 ± 0.6
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.13 ± 0.01	0.06 ± 0.01	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.01	0.46 ± 0.15	forbidden	1.32 ± 0.34
η_c'	< 2.0	< 1.0	unknown	unknown	unknown	unknown	unknown	forbidden	seen
ψ'	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

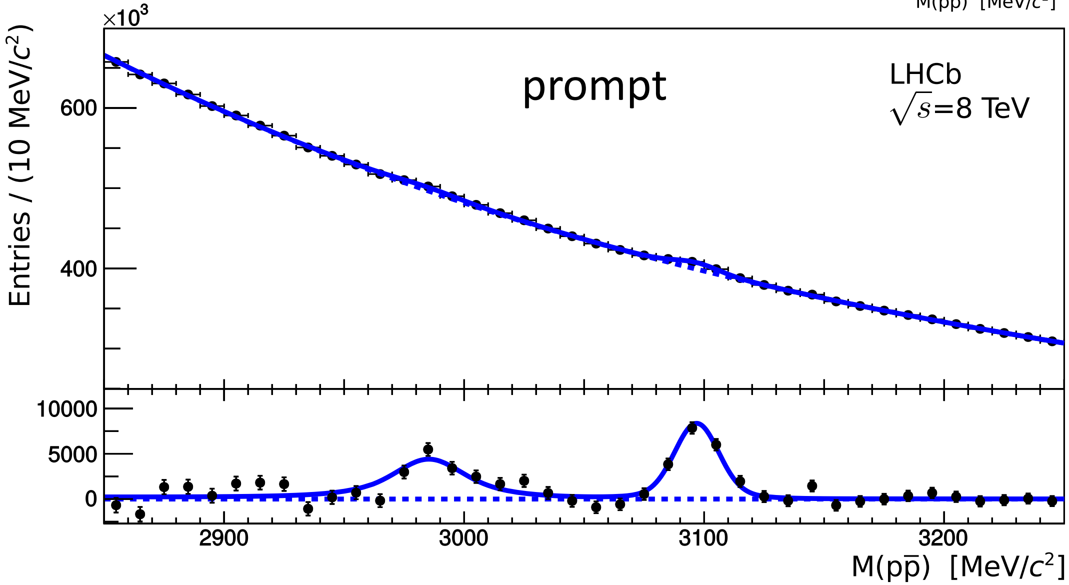
- High multiplicity in *pp* collisions, high level of background due to too many combinations, chanllenging even for LHCb that has excellent hadron particle-identification

$\eta_c(1S)$ production at 7/8 TeV

[LHCb, EJPC 75 (2015) 311]

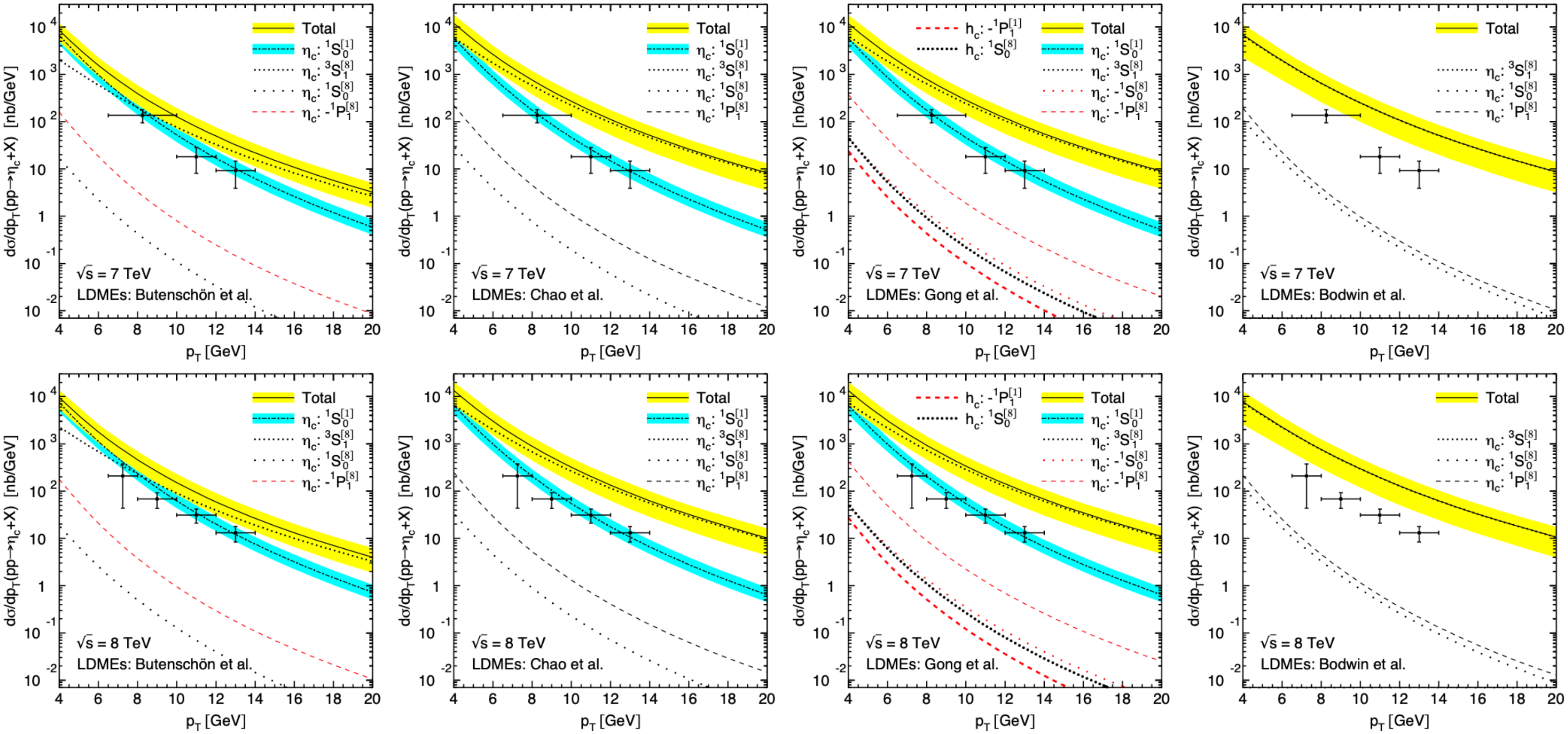
- $\eta_c(1S)$ hadroproduction firstly measured by LHCb
- Prompt signal suffers from high background





$\eta_c(1S)$ production at 7/8 TeV

- Results described by NLO CS?

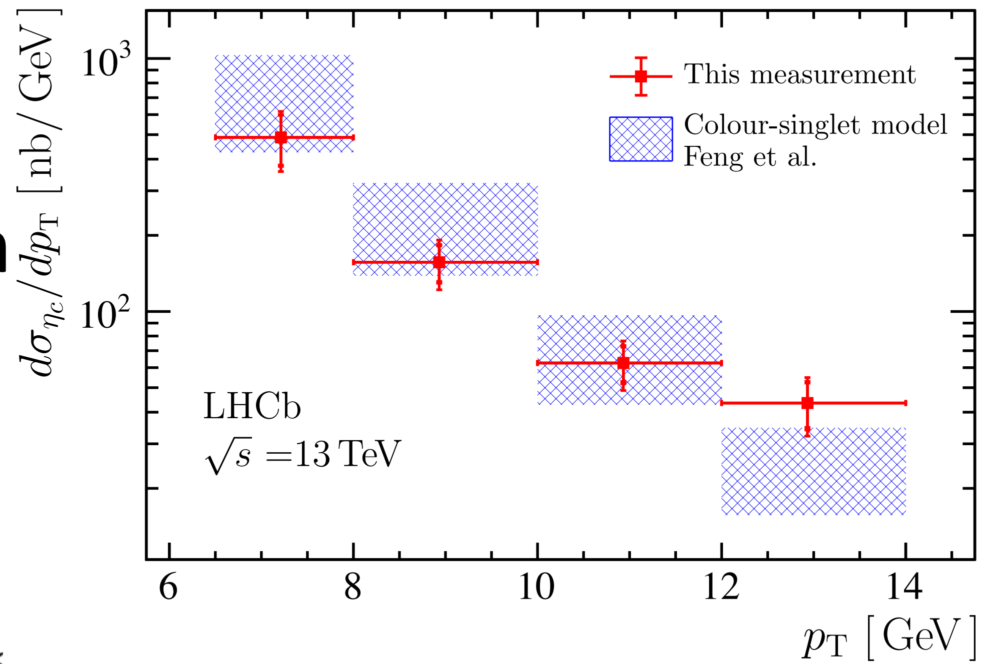


[M. Butenschoen, et al., PRL 114 (2015) 092004]

$\eta_c(1S)$ production at 13 TeV

[LHCb, EPJC 80 (2020) 191]

- Comparison w/ CS, good agreement
- Theoretical precision limited by scale uncertainty



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

Prediction: $1.56^{+0.83}_{-0.49}$ (scale)$^{+0.38}_{-0.17}$ (CT14NLO) μb

[Y. Feng, et al., NPB 945 (2019) 114662]

Impact of $\eta_c(1S)$ production

- **LHCb data + HQSS helps to constrain $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$**

$$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle = \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle$$

- **A conservative upper limit was set via**

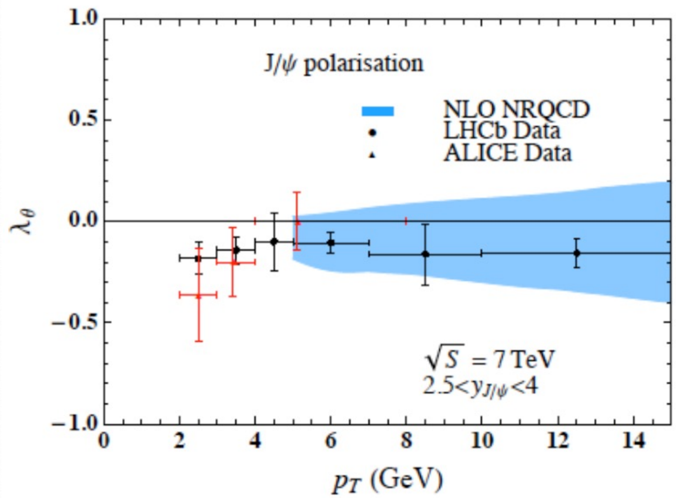
$$\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle \hat{\sigma}(c\bar{c}\left[{}^3S_1^{[8]}\right]) = \sigma_{\mathrm{LHCb\ data}}$$

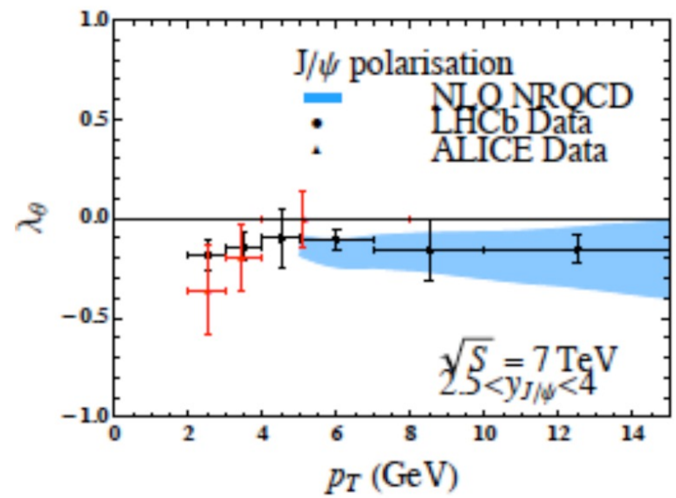
Before

After

Han et al. (2014)

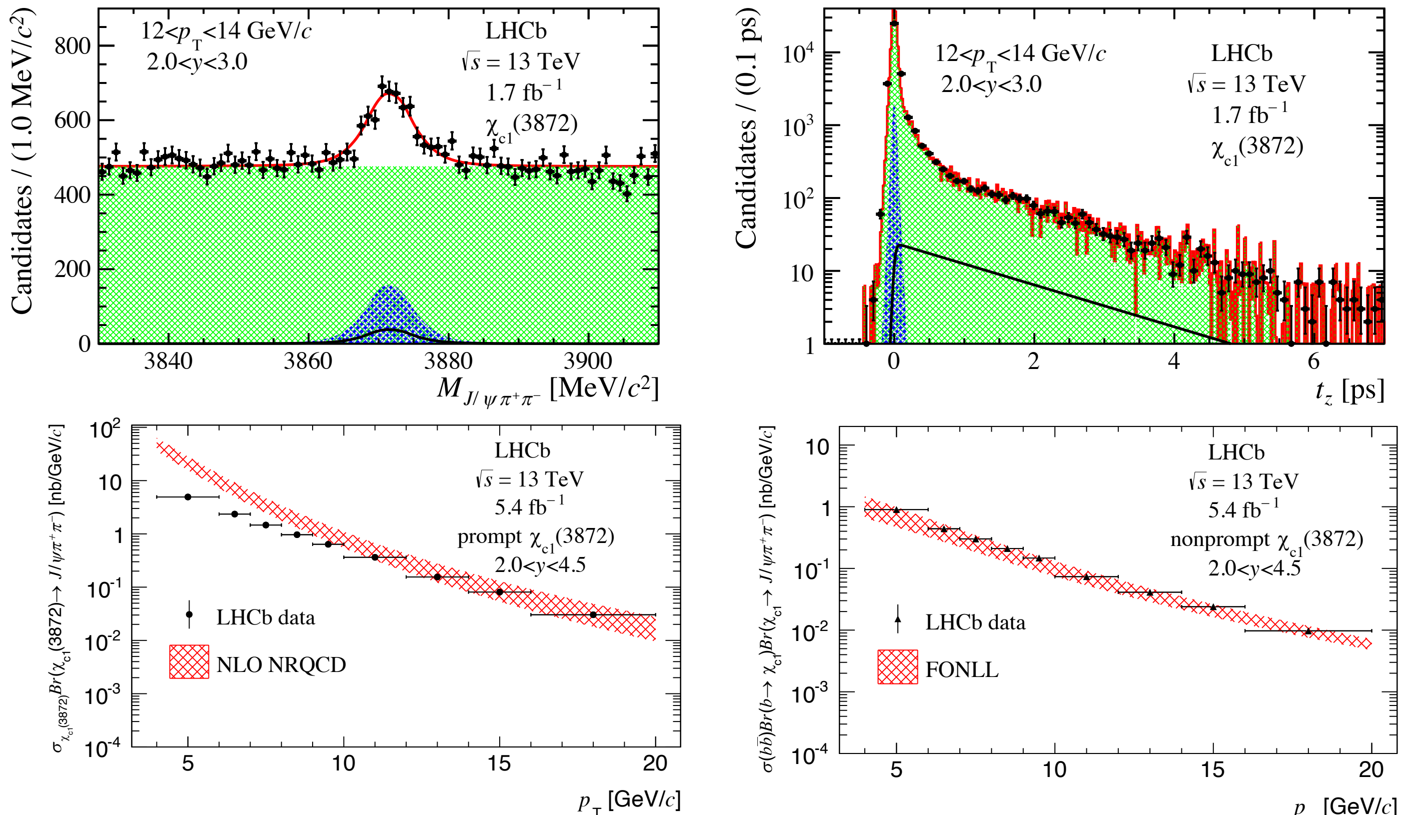
$$0 < \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$$





$X(3872)$ production

- First double-differential cross-section
- Consistent with $\chi_{c1}(2P) + D^0\overline{D}^{*0}$ mixture



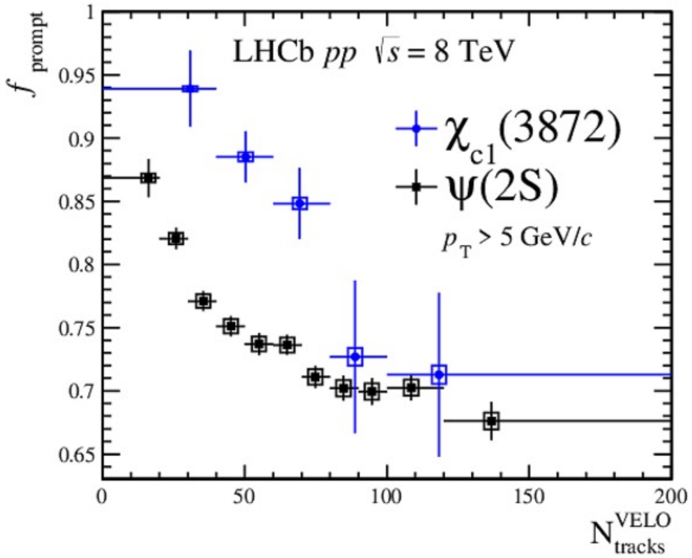
[JHEP 01 (2022) 131]

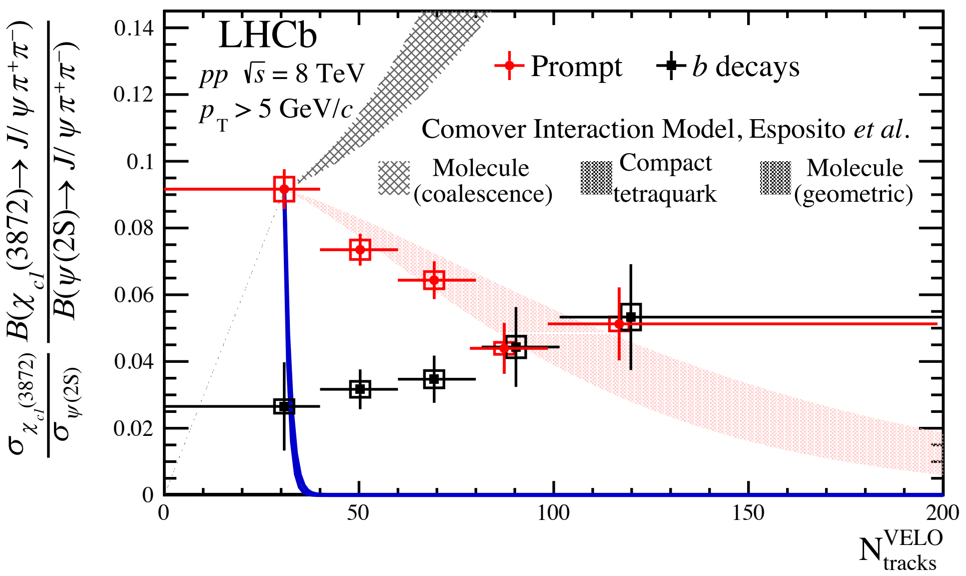
In pipeline: $J/\psi p, J/\psi \Lambda, J/\psi \phi, J/\psi \pi^+$...

$\sigma_{X(3872)}/\sigma_{\psi(2S)}$ Vs. Multiplicity

- Clear dependence, interpretation on debate

[PRL 126 (2021) 092001]



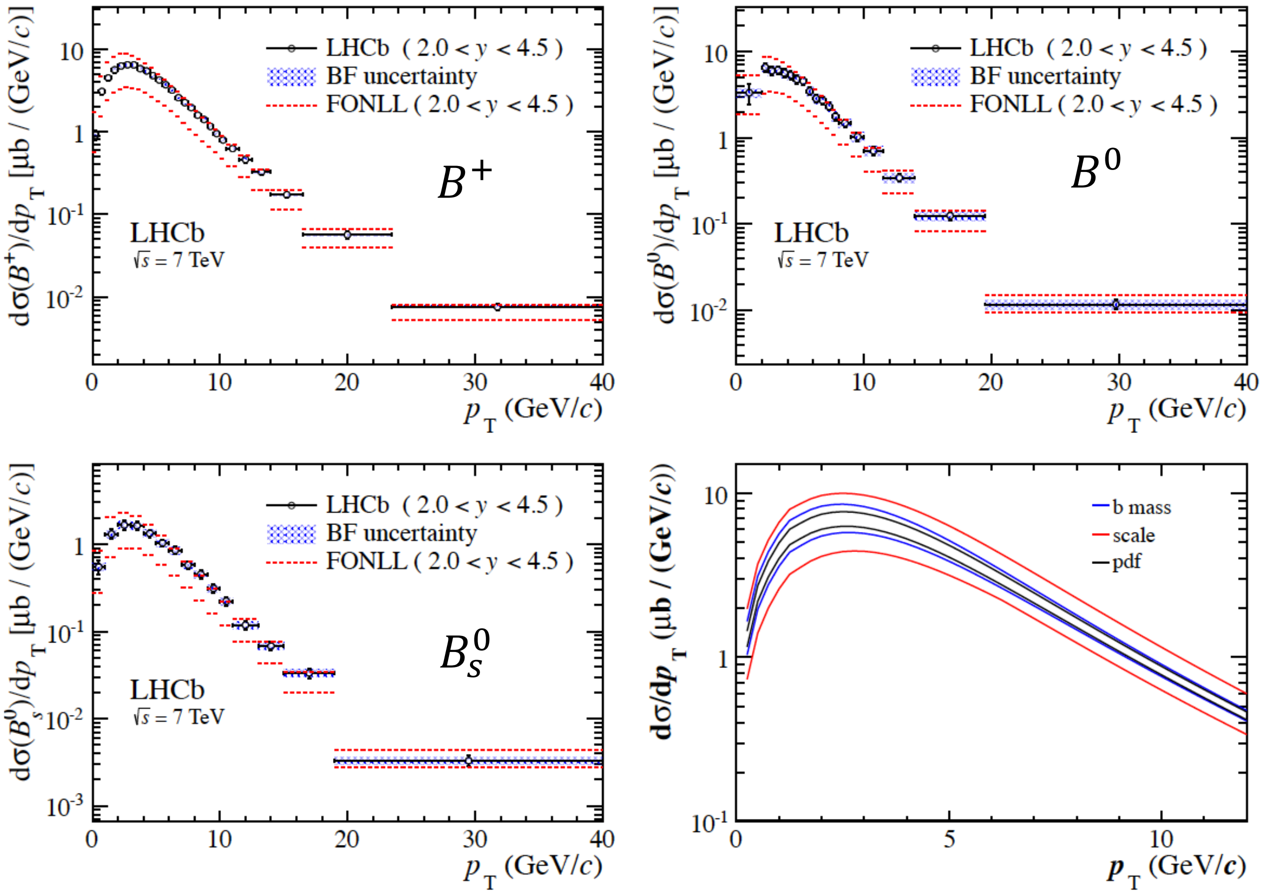


B mesons' production

- Measured B mesons' production at 7 TeV, agree with FONLL (Fixed Order+Next-to-Leading Log)

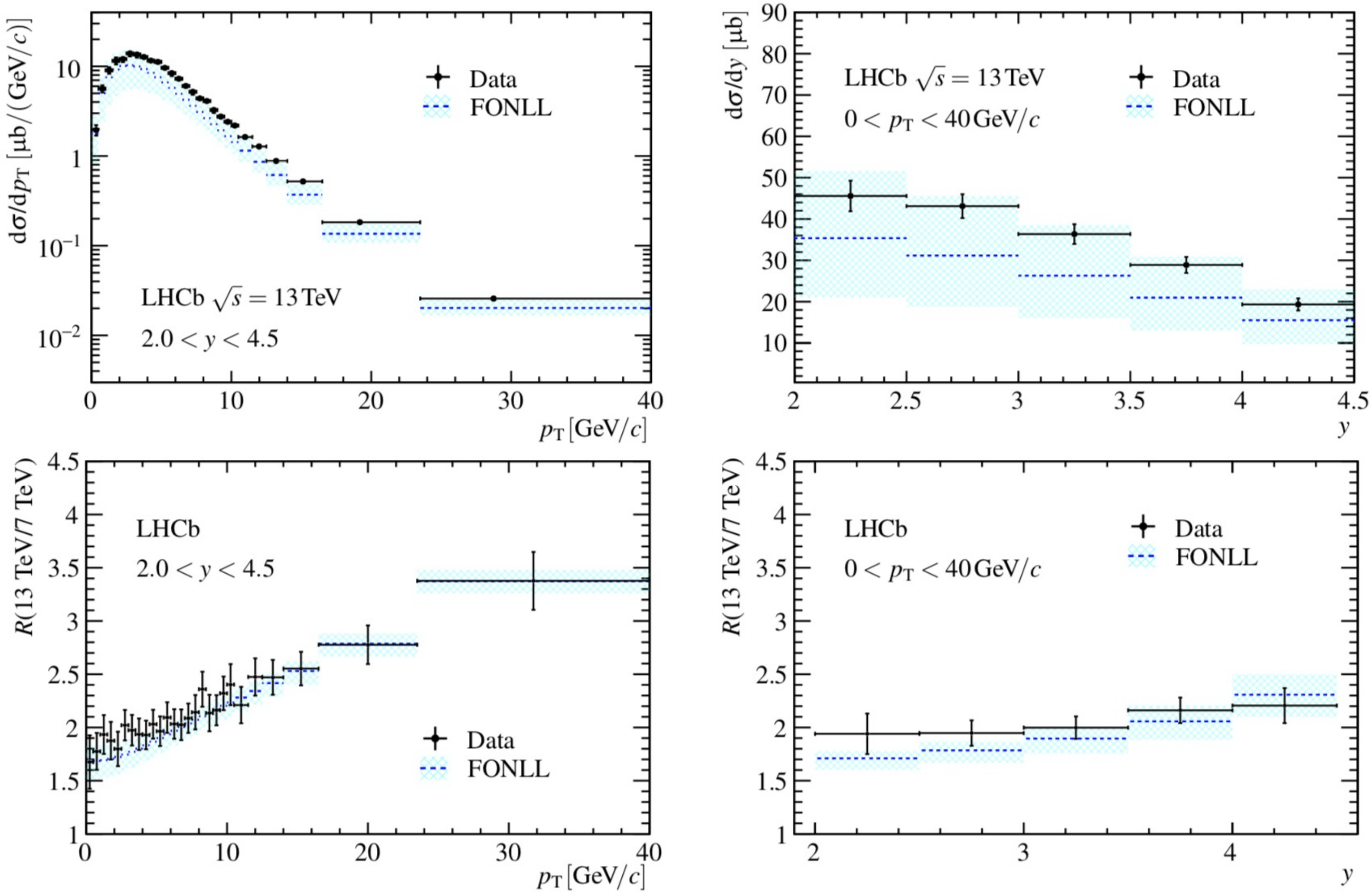
[M. Cacciari *et al.*, JHEP 10 (2012) 137]

[JHEP 08 (2013) 117]



B^+ production at 13 TeV

- New energy, ratio 13/7 TeV

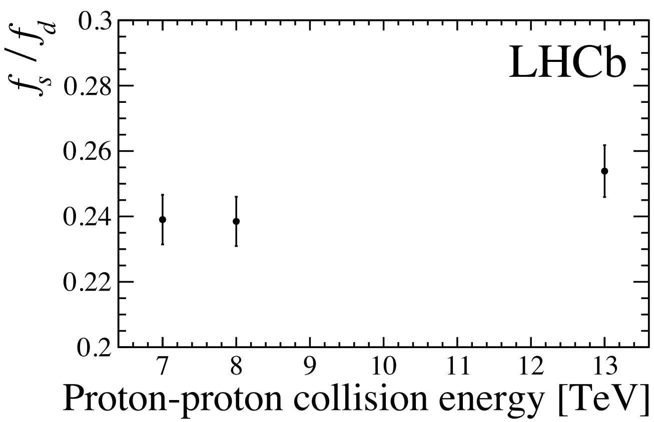


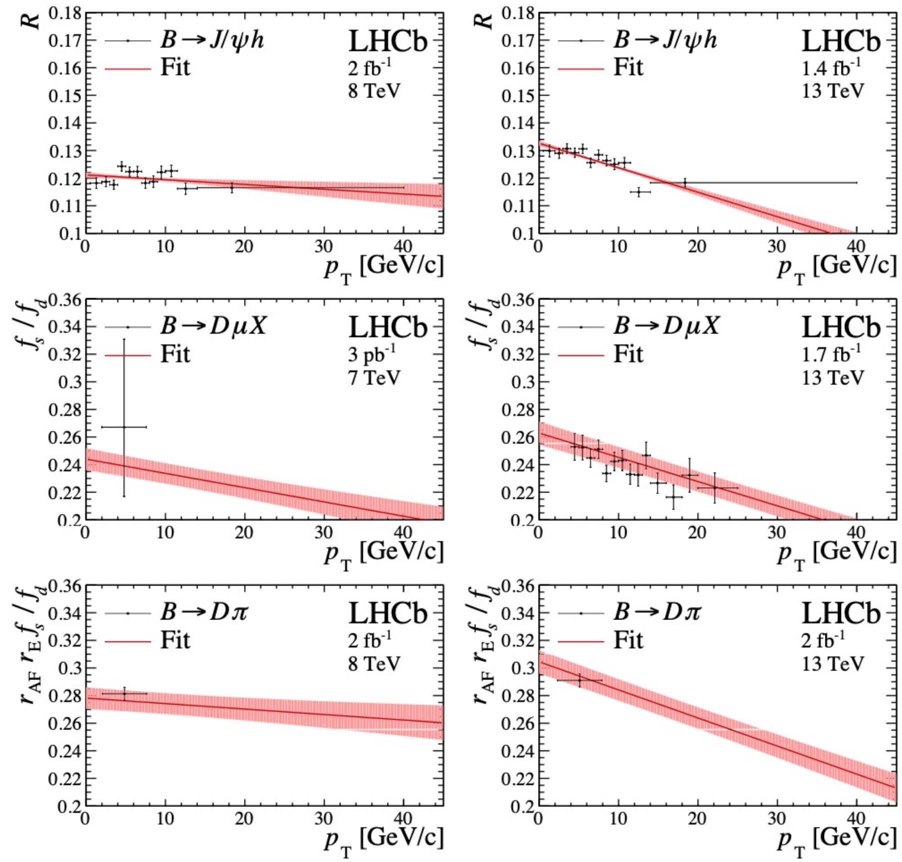
[JHEP 12 (2017) 026]

f_s/f_d in beauty system

[PRD 104 (2021) 032005]

- Combined analysis of different decay modes. BR of B_s^0 updated
  - $\mathcal{B}(B_s^0 \to J/\psi\phi)$ and $\mathcal{B}(B_s^0 \to D_s^-\pi^+)$ improved by a factor of 2

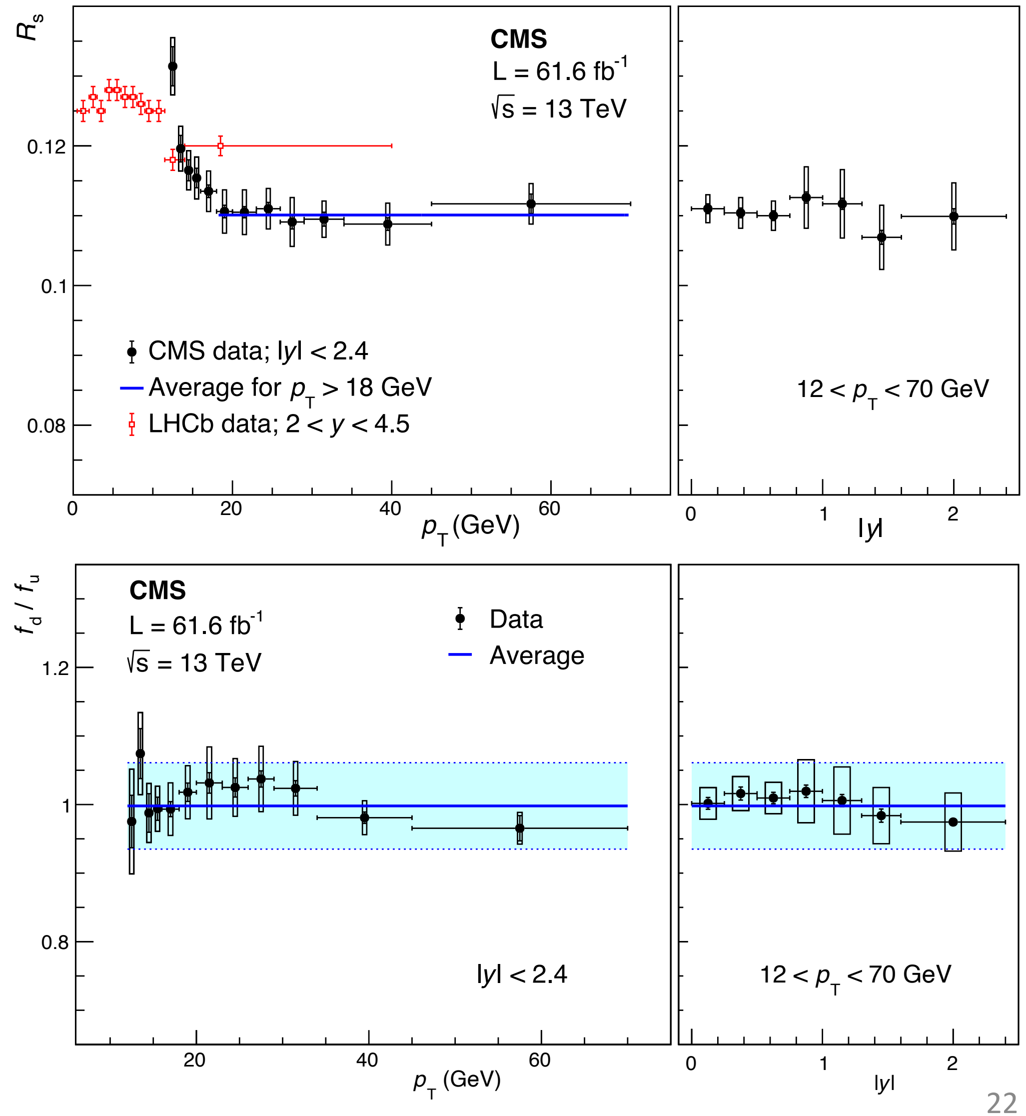




$$f_s/f_d \quad (p_T, 7\,\text{TeV}) = (0.244 \pm 0.008) + ((-10.3 \pm 2.7) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 8\,\text{TeV}) = (0.240 \pm 0.008) + ((-\ 3.4 \pm 2.3) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 13\,\text{TeV}) = (0.263 \pm 0.008) + ((-17.6 \pm 2.1) \times 10^{-4}) \cdot p_T$$

f_s/f_d in beauty system

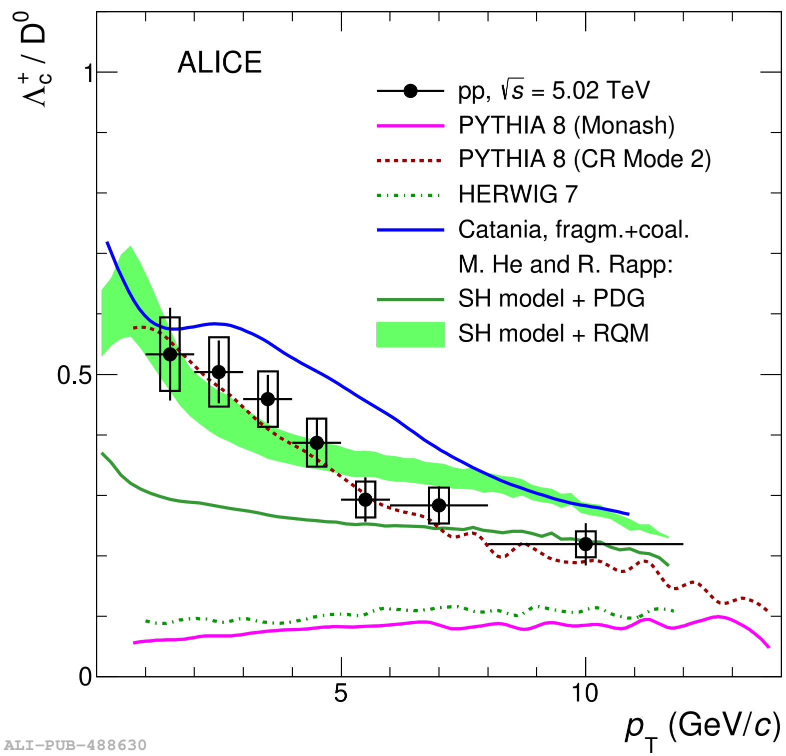
- Confirming p_T dependence seen by LHCb
- No dependence for f_d/f_u

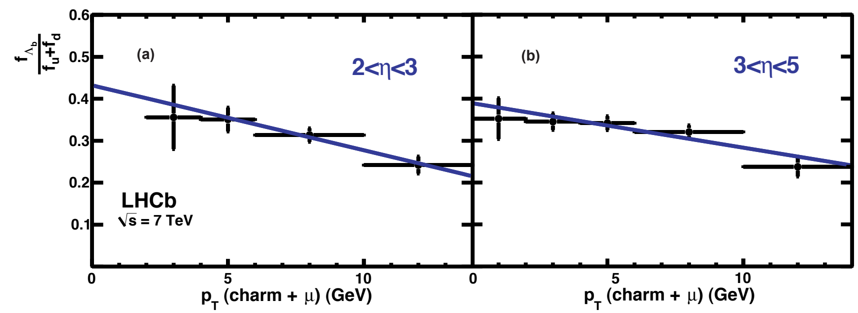


[CMS, PRL 131 (2023) 121901]

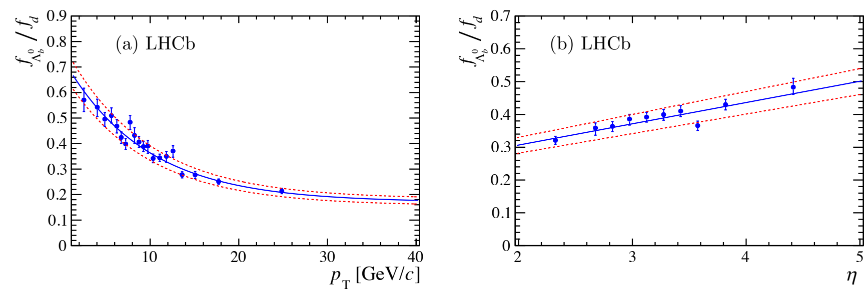
Baryon-to-meson ratio

[ALICE, PRL 127 (2021) 202301]





[PRD 85 (2012) 032008]

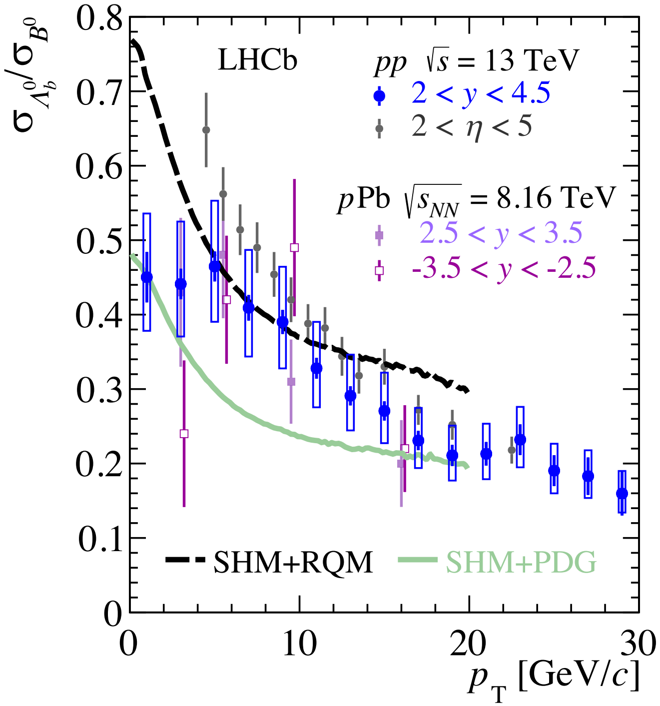


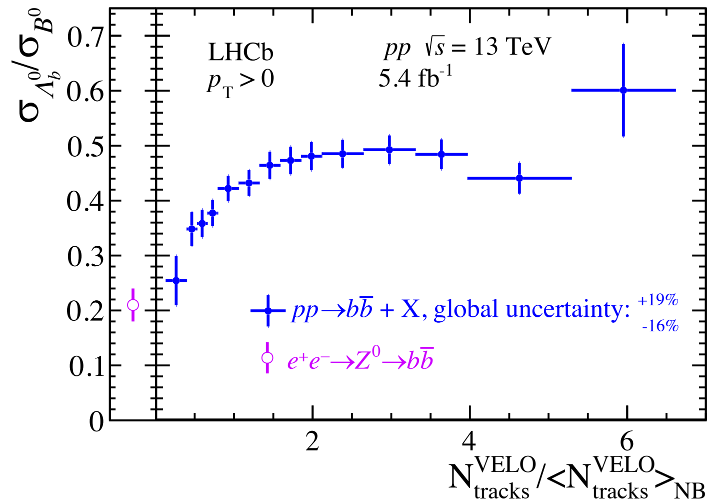
[JHEP 08 (2014) 143]

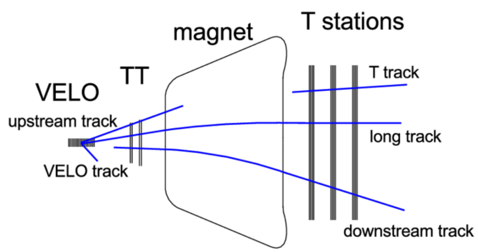
- Clear trend as function of p_T, well decribed by, e.g.,
  - Pythia8 + New Colour-Reconnection (CR) mode
  - Statistical Hadronisation (SH) including additional excited charm baryons predicted by Relativistic Quark Model (RQM)
  - Catania, hadronisation via coalescence + fragmentation

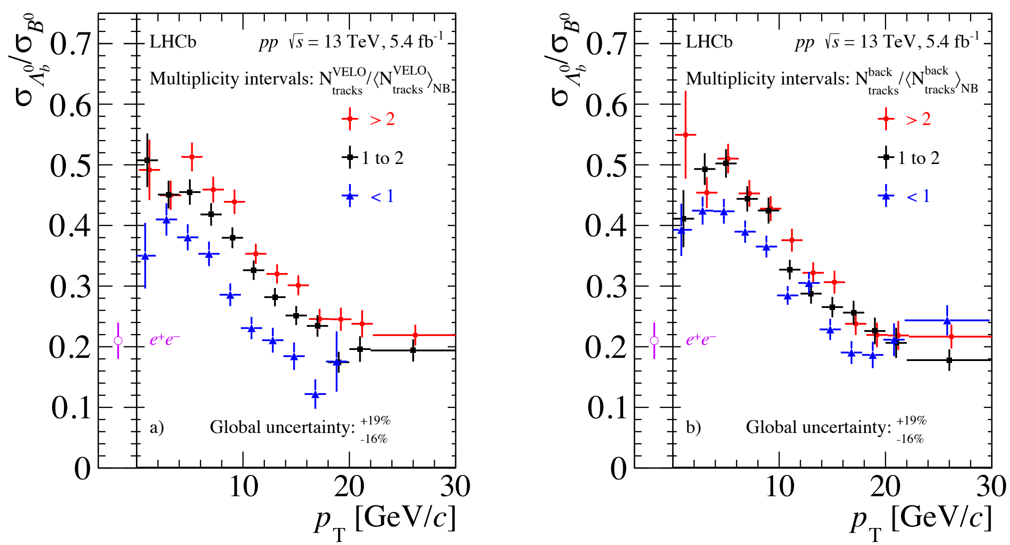
$\sigma(\Lambda_b^0)/\sigma(B^0)$ Vs. Multiplicity

[PRL 132 (2024) 081901]





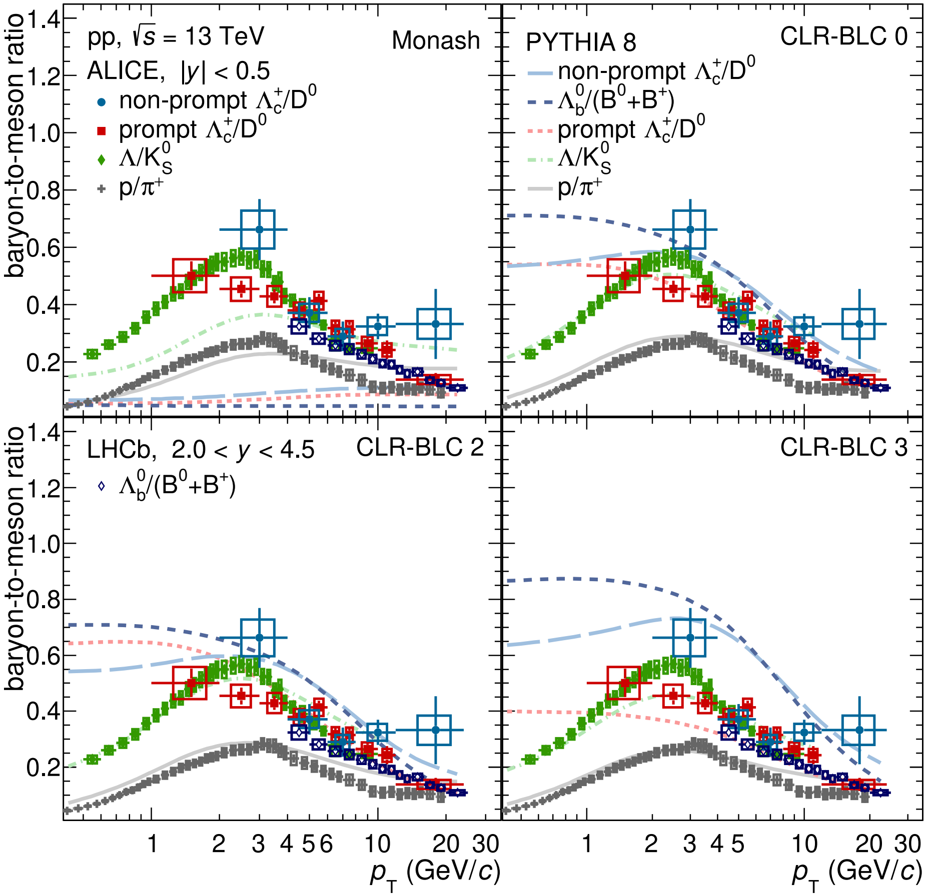


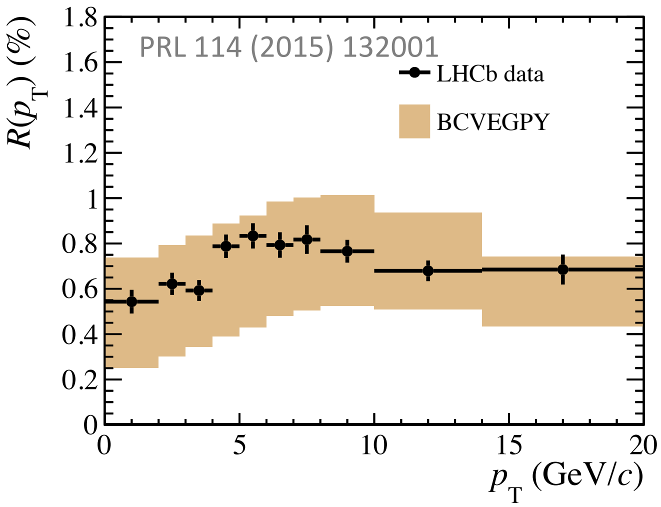


Flavour dep. of Baryon/meson

- Similar baryon-formation mechanism among light, strange, charm, and beauty hadrons?

[PRD 108 (2023) 112003]

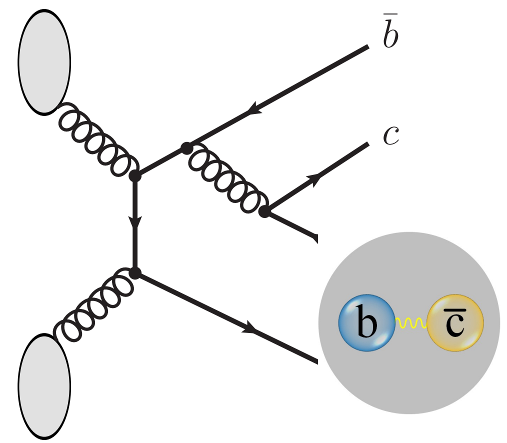




Meson-to-meson ratio?

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

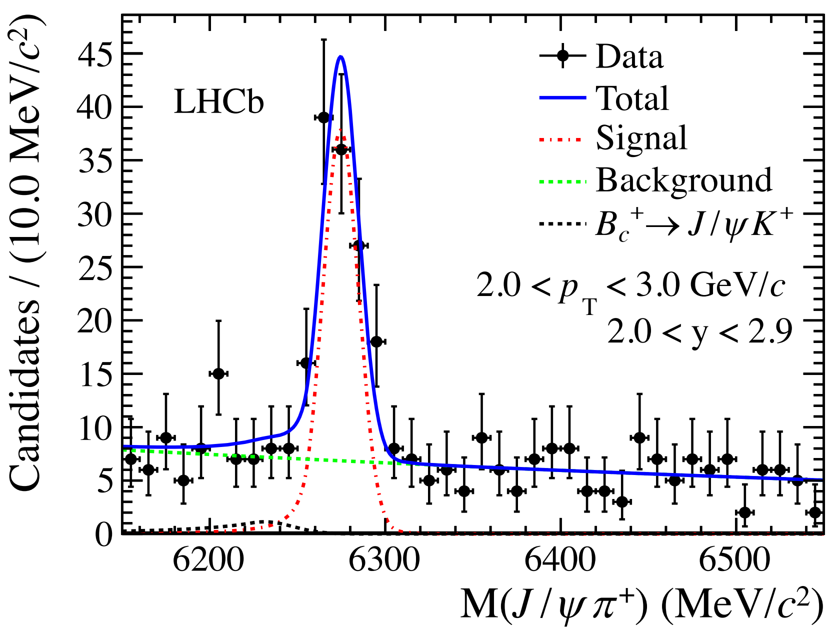
  – $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)| \approx 0.6$

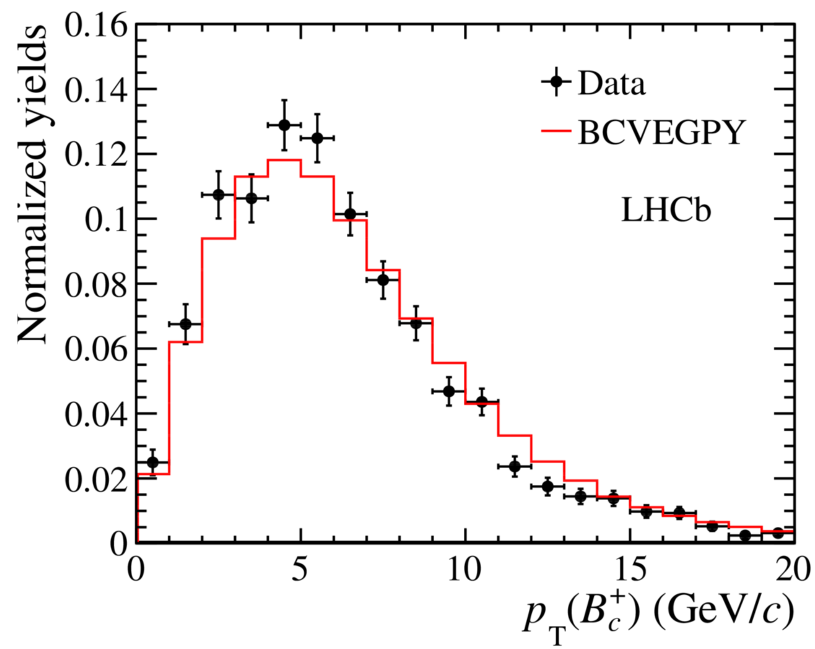
  – $\sigma(B_c^+) \sim 0.9\ \mu\text{b}$ for $\sqrt{s} = 14$ TeV

B_c^+ 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]

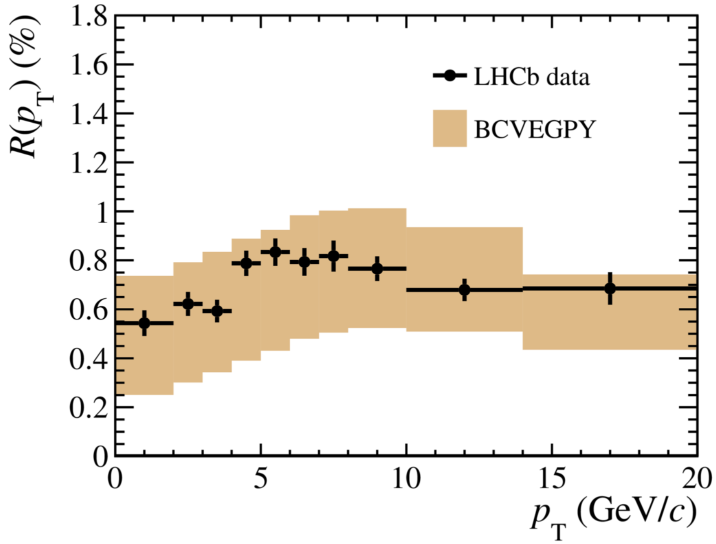


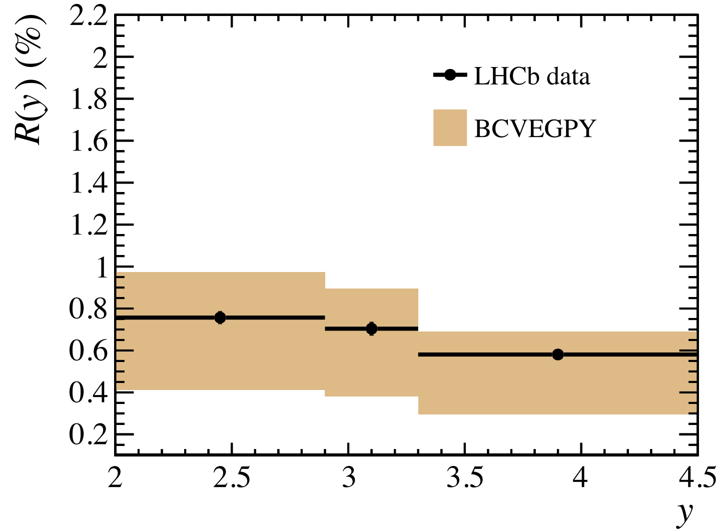


B_c^+ diff. production by LHCb

[PRL 114 (2015) 132001]

- $\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$ for $p_{\mathrm{T}} < 20\ \mathrm{GeV}, y \in [2, 4.5]$
- Using
  - $\sigma(B_c^+) = 0.47\ \mu\mathrm{b}$, theoretical prediction by BcVegPy
  - $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
  - $\sigma(B^+, p_{\mathrm{T}}(B) < 40\ \mathrm{GeV}/c, 2.0 < y < 4.5) = 38.9\ \mu\mathrm{b}$ 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





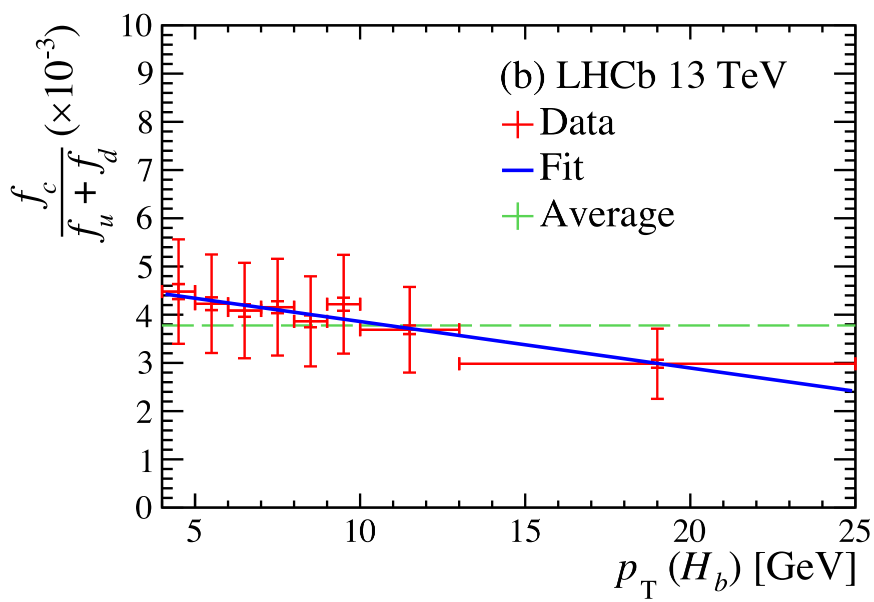
B_c^+ production w/ $J/\psi\mu^+X$

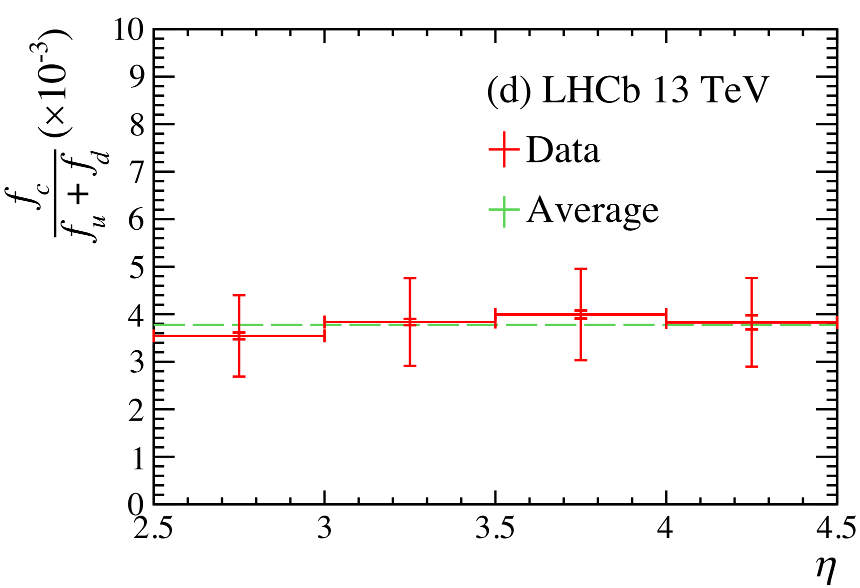
- Similar trend seen in $p_{\mathrm{T}} > 5\ \mathrm{GeV}$ region

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

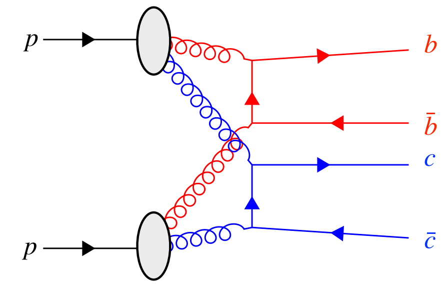
$$\frac{f_c}{f_u+f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89)\times 10^{-3} \text{ at 13 TeV}$$

[PRD 100 (2019) 112006]

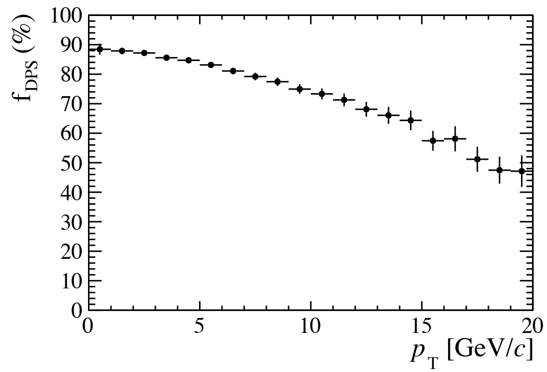


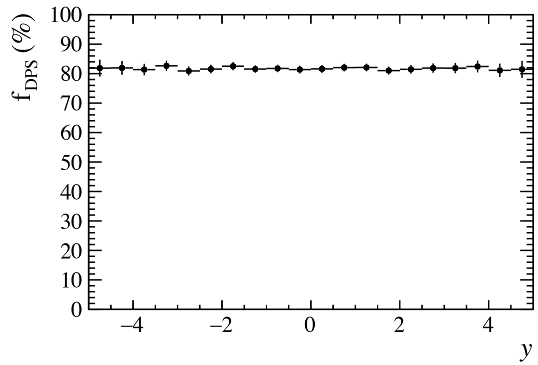


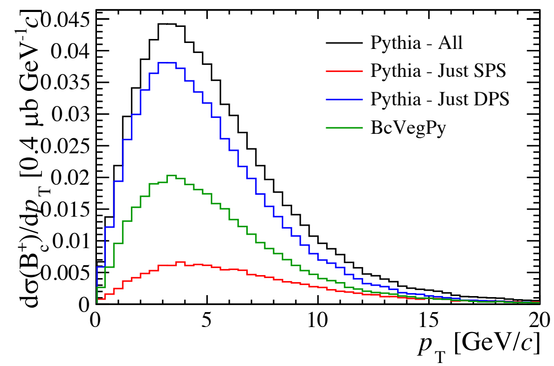
DPS contribution?

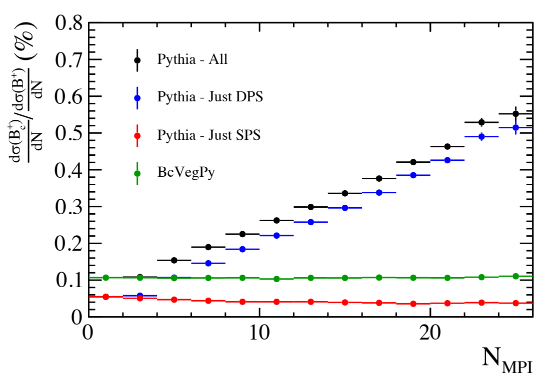


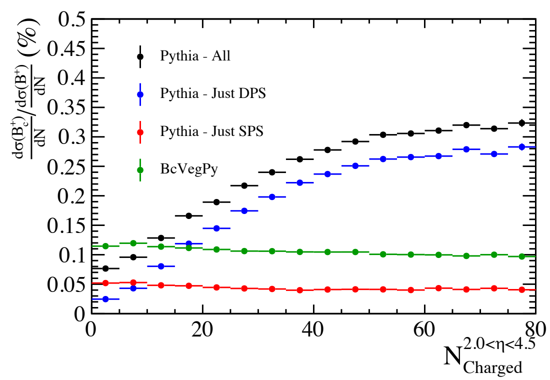
- Very big as predicted by Pythia
- Different p_{T} spectrum? However…

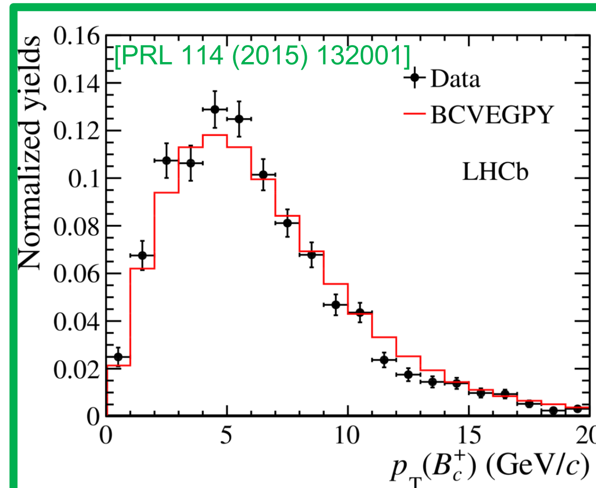








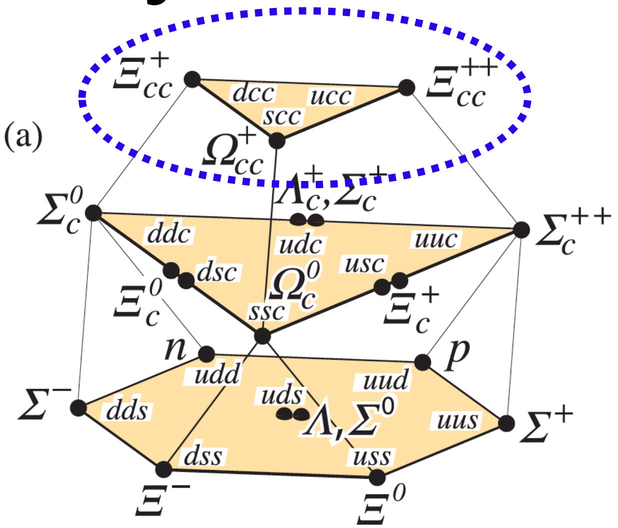




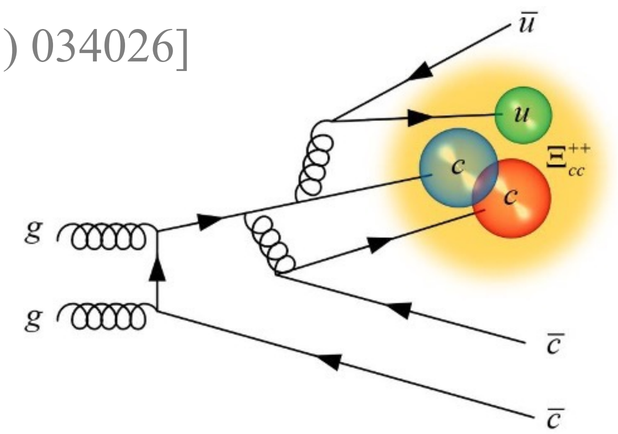
[U. Egede *et al.*, EPJC 82 (2022) 773]

Doubly charmed baryon

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



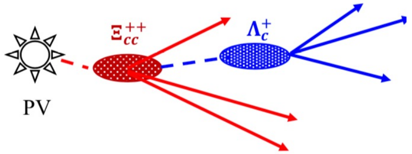
- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027$ ps
- Production [J.-W. Zhang *et al.*, PRD 83 (2011) 034026]
  - $\sigma(cc) = 90$ nb @ 13 TeV in LHCb
  - $f_{\text{frag}}\ u{:}\,d{:}\,s \sim 1{:}\,1{:}\,0.3$
    $\sigma(\Xi_{cc}^{++})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

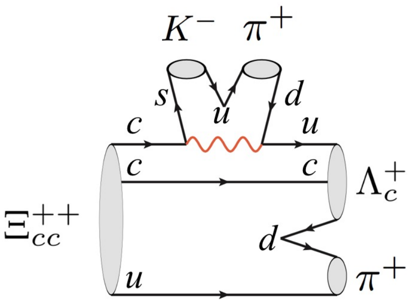


Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

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

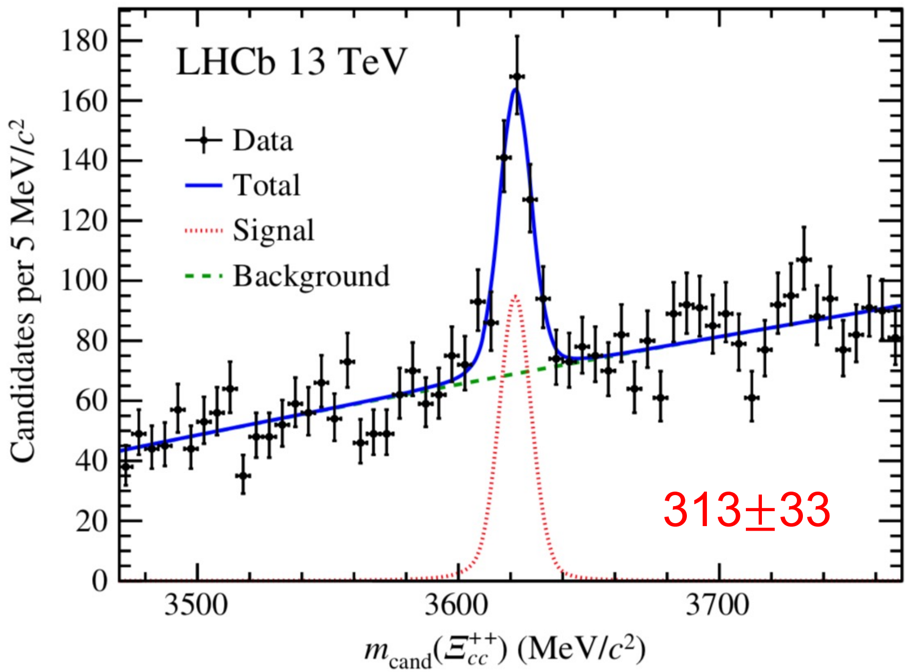
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]

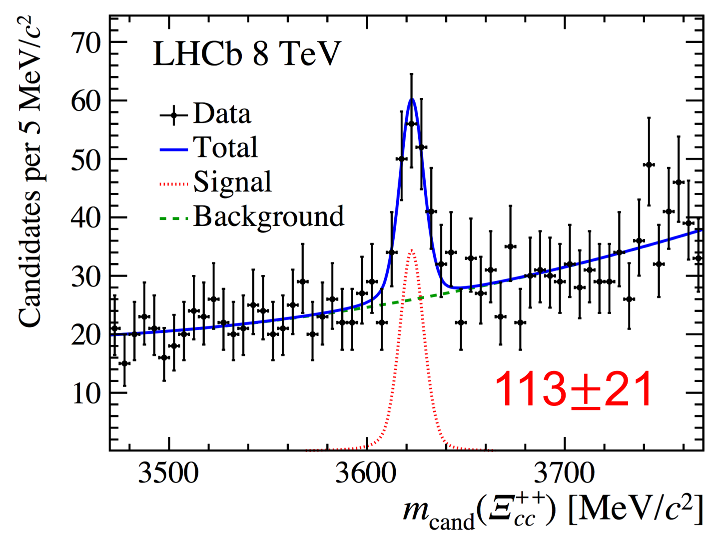




- First observation, in 2016 (>12σ) & Run-I (>7σ)

[PRL 119 (2017) 112001]



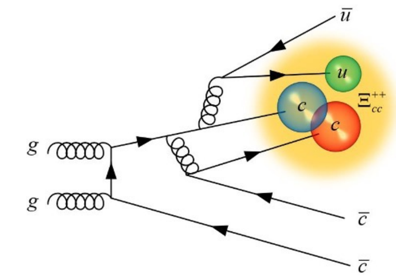


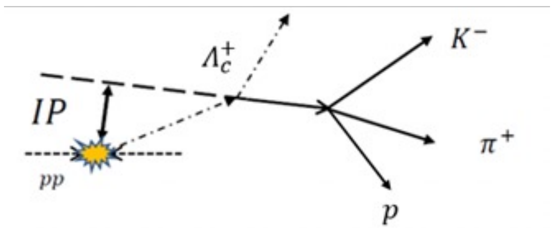
Measurement of Ξ_{cc}^{++} production

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

  $4 < p_{\mathrm{T}} < 15$ GeV,

  $2 < y < 4.5$



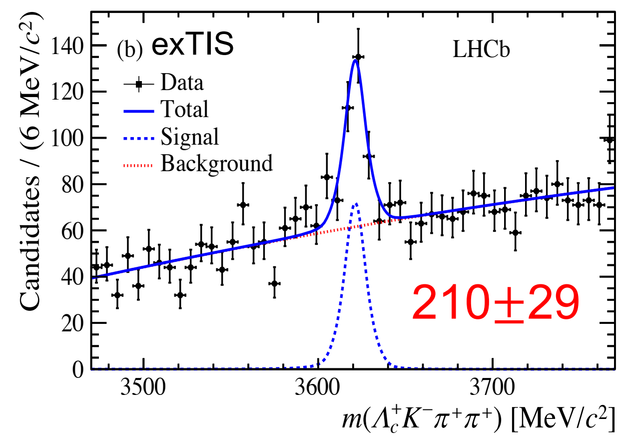


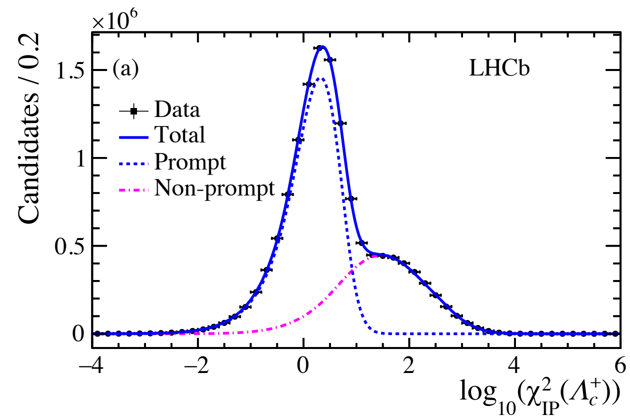
[CPC 44 (2020) 022001]

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

SELEX, 20% Λ_c^+ from Ξ_{cc}^+

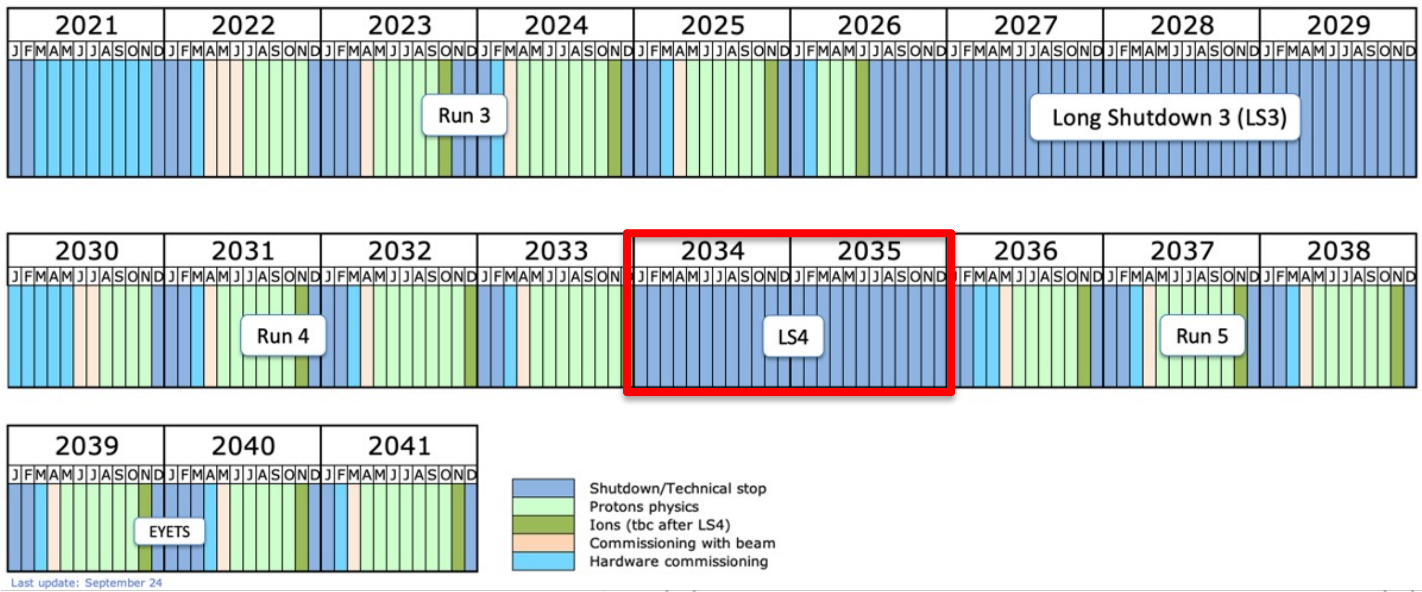
[SELEX, PRL 89 (2002) 112001]

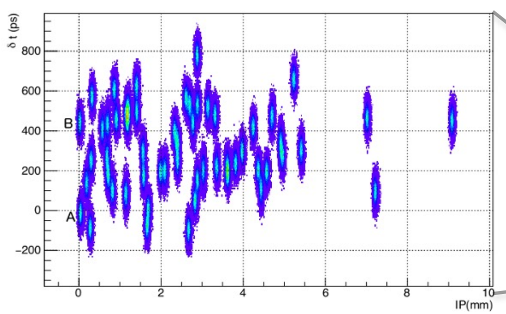


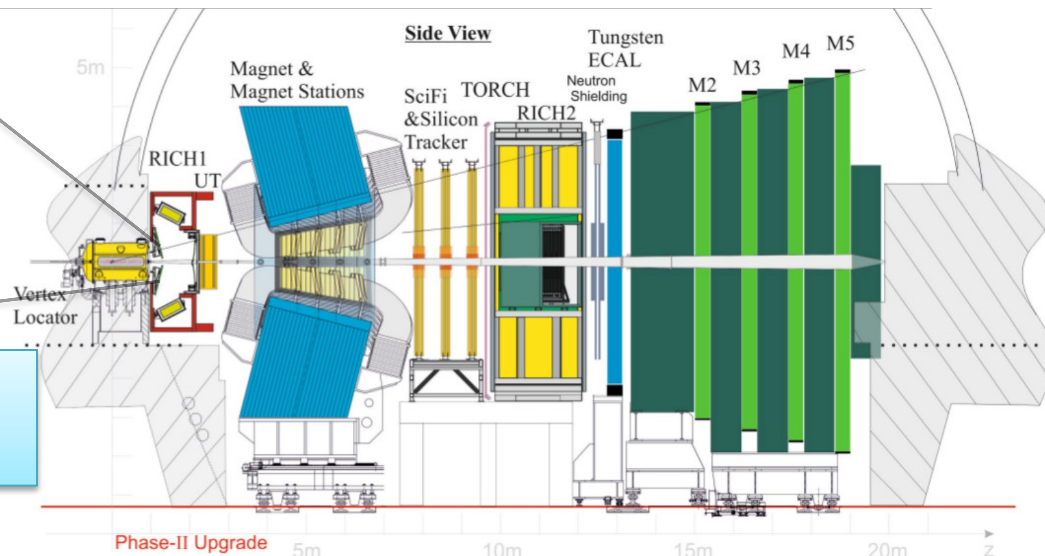


The LHCb upgrades

[CERN-LHCC-2018-027, 2021-012]

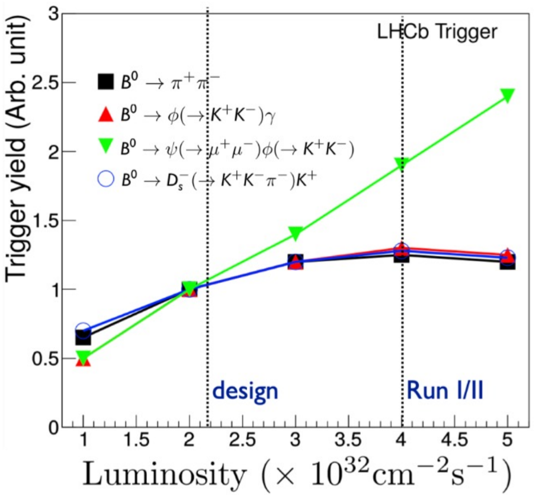






Upgrade II, 4D detector
Timing, $\mathcal{O}(10\text{ ps})$, is essential

The LHCb trigger (Run3)



Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

⇩

Buffer events to disk, perform online detector calibration and alignment

⇩

Full offline-like event selection, mixture of inclusive and exclusive triggers

⇩ ⇩ ⇩

12.5 kHz (0.6 GB/s) to storage

→

30 MHz inelastic event rate (full rate event building)

⇩ ⇩ ⇩

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

⇩

Buffer events to disk, perform online detector calibration and alignment

⇩

Add offline precision particle identification and track quality information to selections

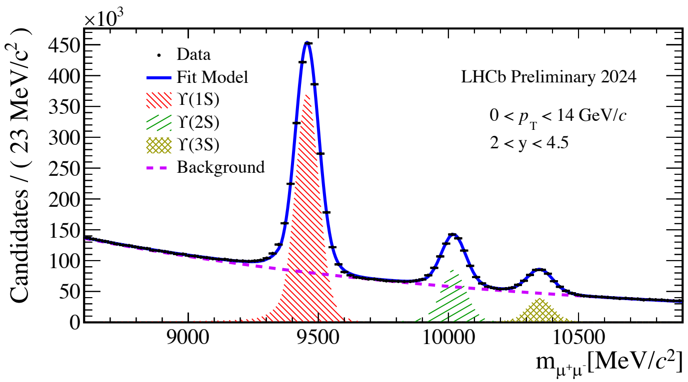
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

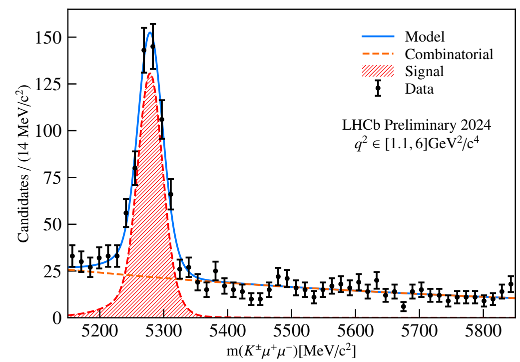
⇩ ⇩ ⇩

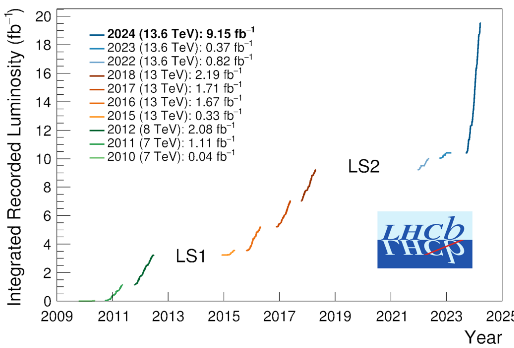
2-5 GB/s to storage

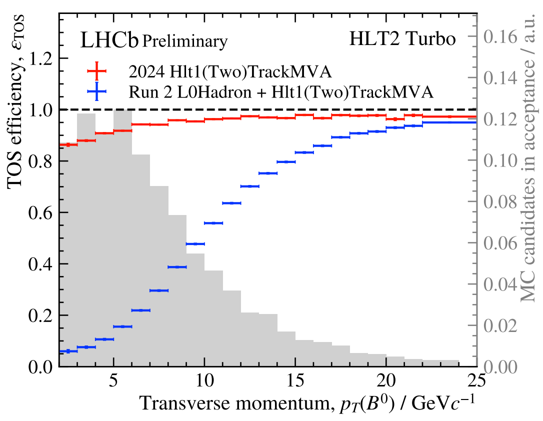
Data-taking in 2024

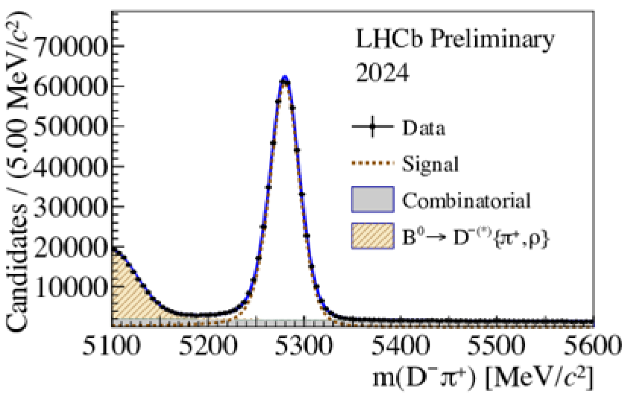
- Calibration / alignments much improved







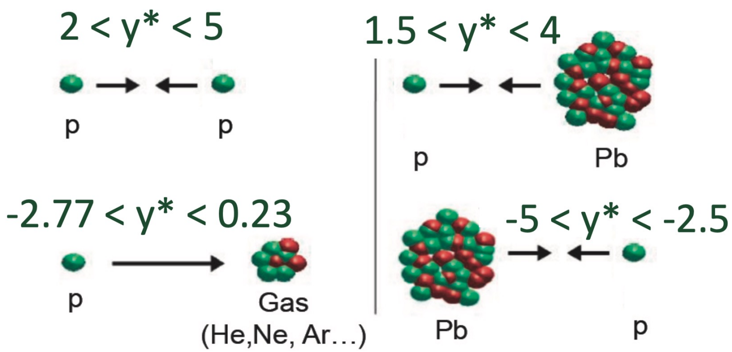


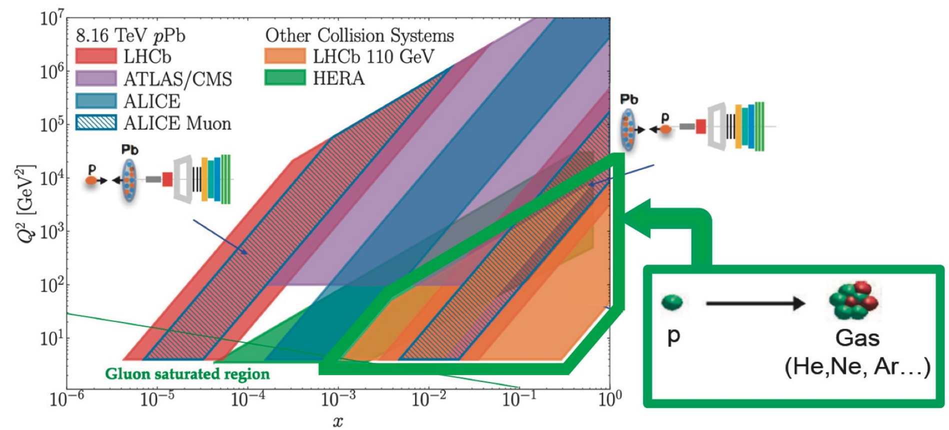


Trigger efficiency for hadronic modes improved by a factor of ~2

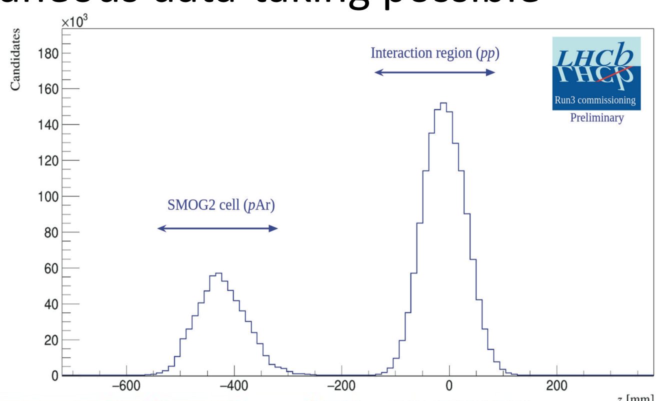
SMOG (System for Measuring Overlap with Gas)

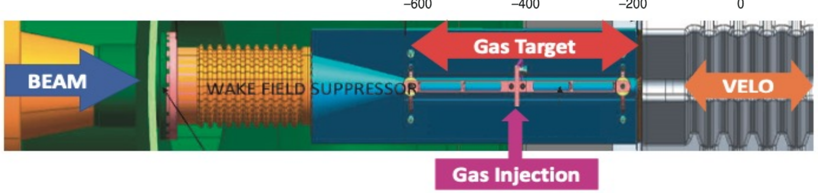
[LHCb-Figure-2023-008]

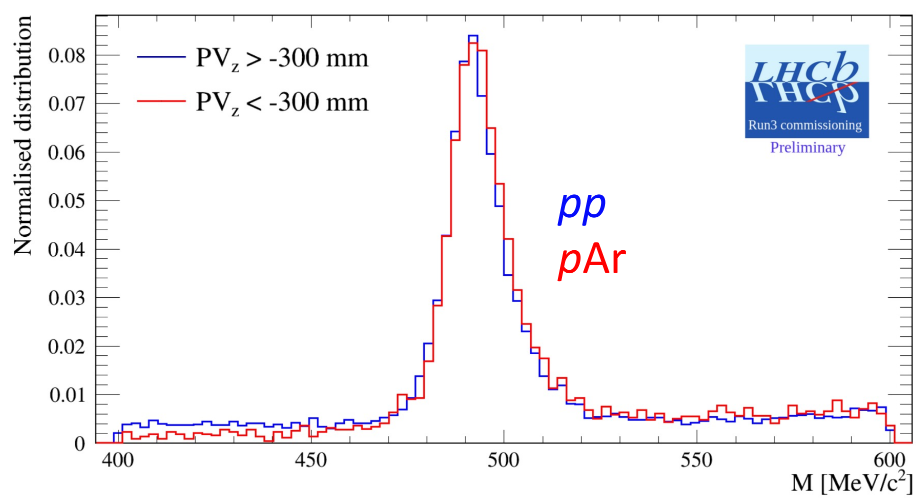




Simultaneous data-taking possible

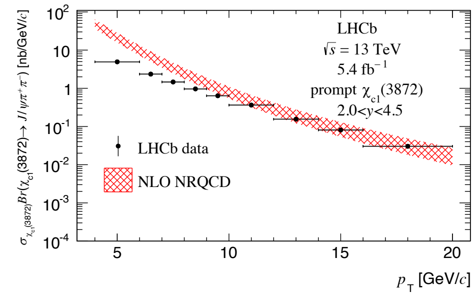


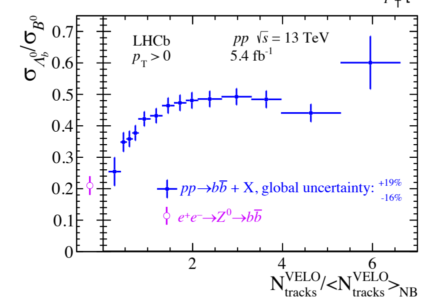




Summary

- Heavy flavour production in *pp* at LHCb
  - – Charomonium(like)
  - – Beauty
  - – B_c^+
  - – Doubly charmed baryon





- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always appreciated!