Heavy flavour hadron production and spectroscopy

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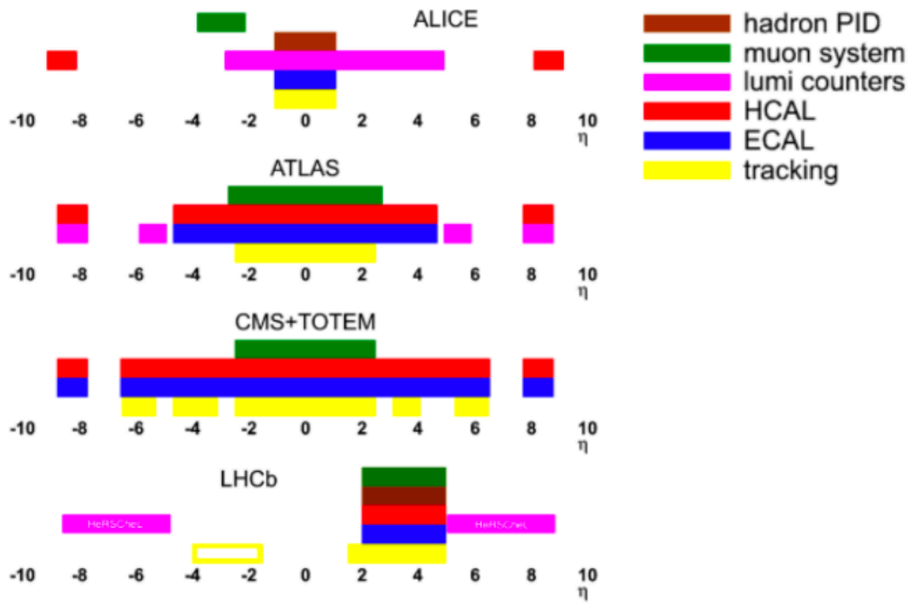
for the **ALICE**, **ATLAS**, **CMS**, **LHCb** Collaborations

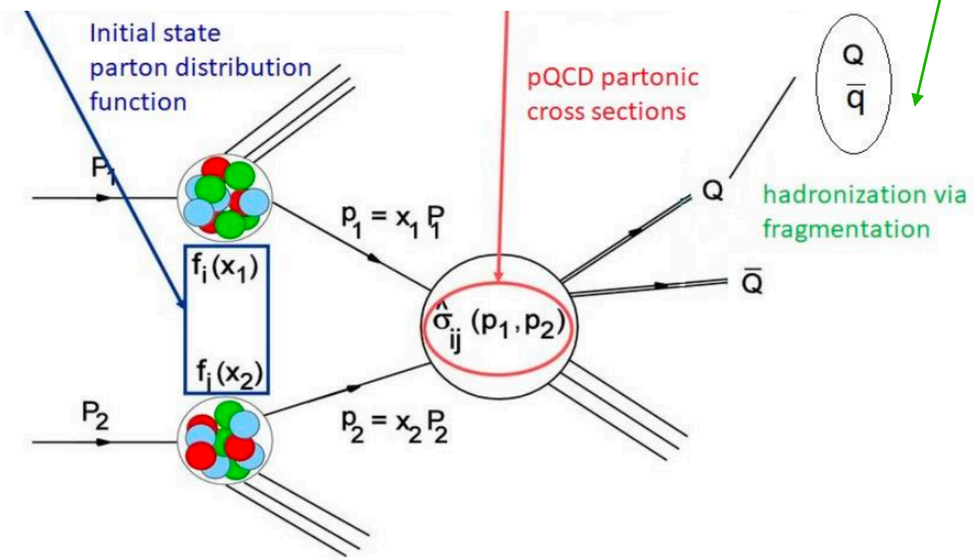
Heavy flavour hadron physics

Heavy flavour measurements as important test of perturbative QCD calculation in pp collisions

- **Charmed and beauty hadron production** precisely measured by all the experiments:
  - complementary features: p_T and rapidity coverage, Particle Identification (PID), dedicated triggers
- Charmed and beauty meson production cross section well described by factorisation theorem:



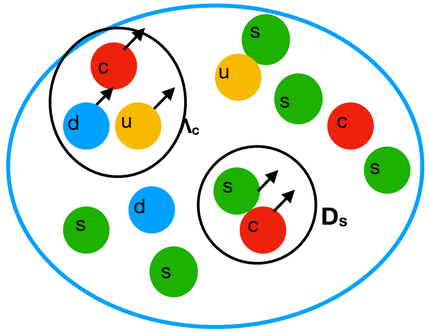
$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$



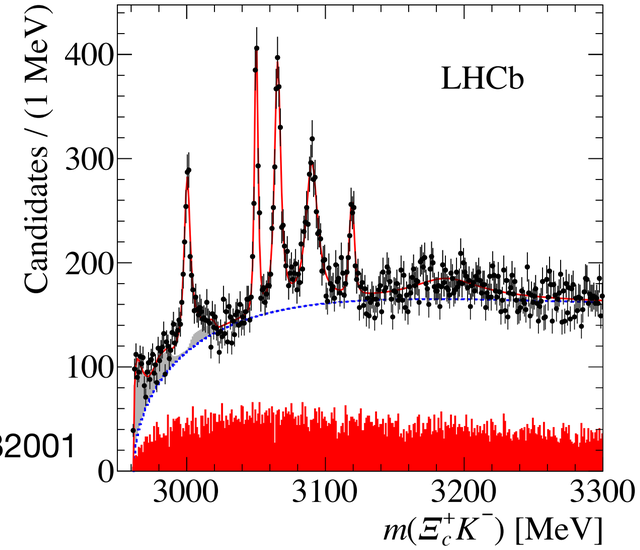
Heavy flavour hadron physics

Heavy flavour measurements as important test of perturbative QCD calculation in pp collisions

- **Ratios of baryon-to-meson spectra in different collision systems**
  - Sensitive to hadronisation mechanism at low p_T



- **Spectroscopy studies**
  - Provide further test of theoretical models probing QCD
  - Increase understanding of the nature of exotic hadrons
  - Measure the masses and widths of excited baryons



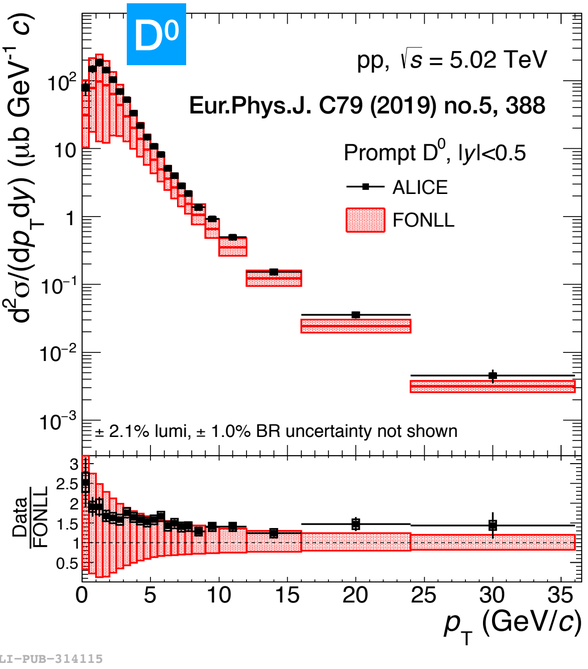
PRL118(2017) 182001

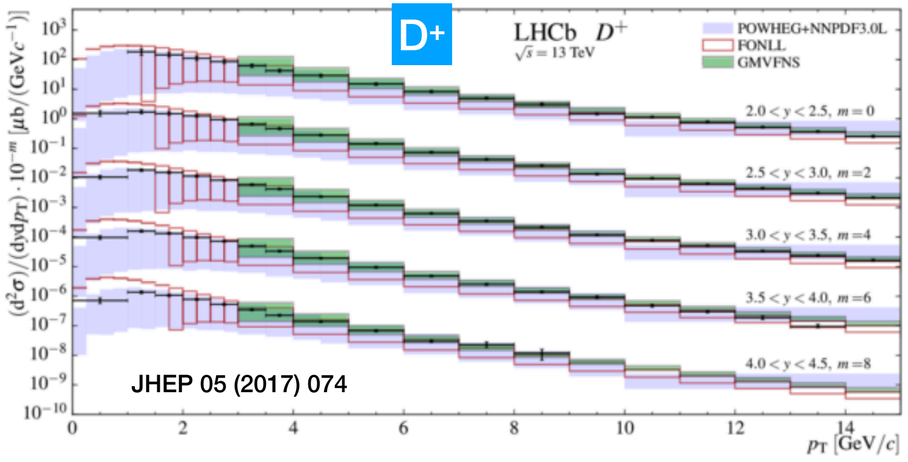
Selection of the most recent measurements

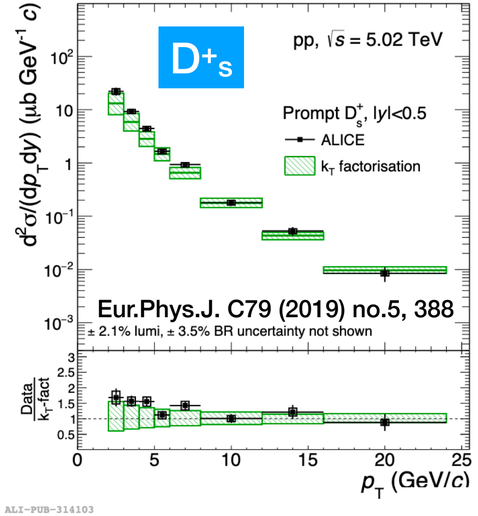
Overview of charm and beauty meson productions

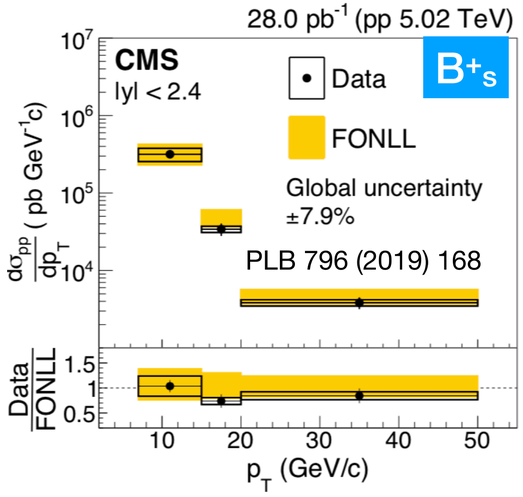
D and B meson production measured at different energies and in different systems at LHC

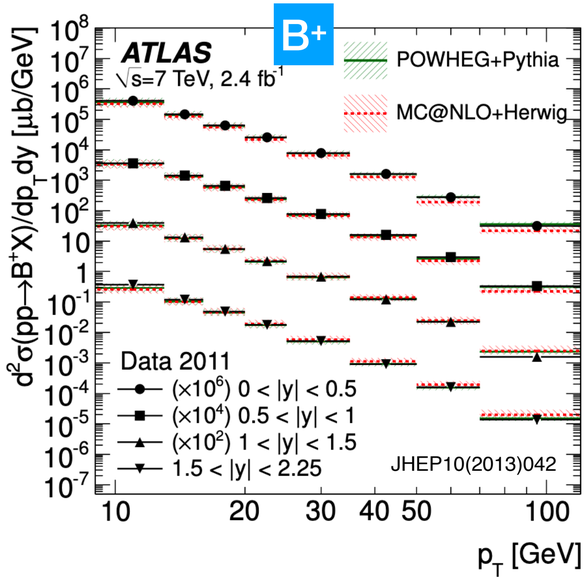
- Precise charm/beauty meson production cross-section measurements











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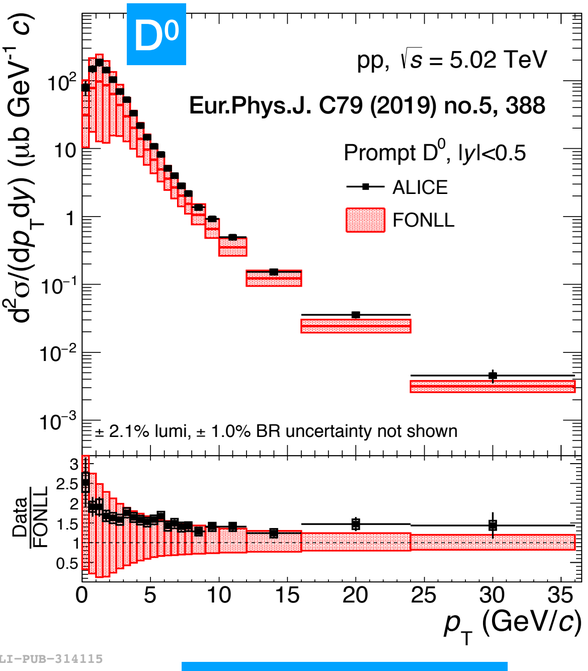
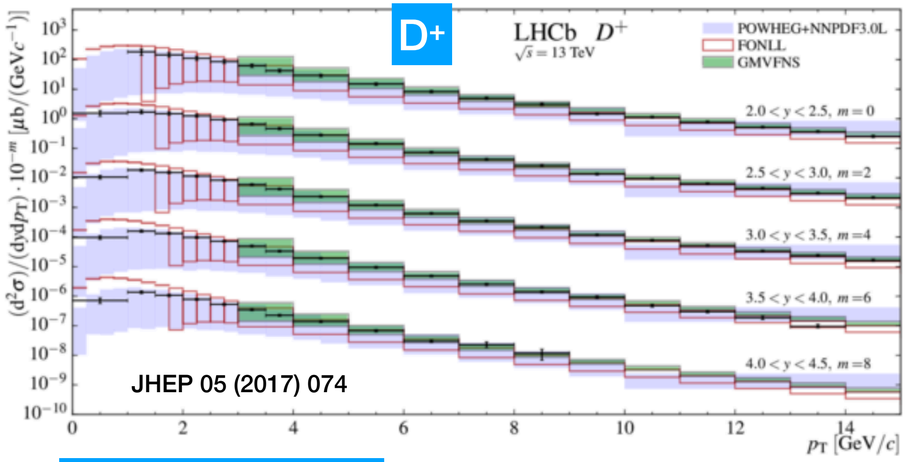
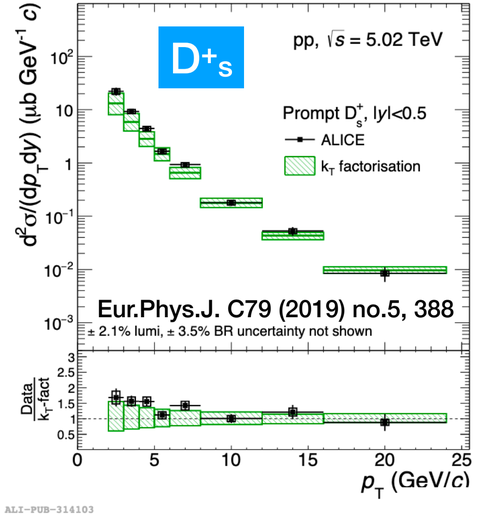
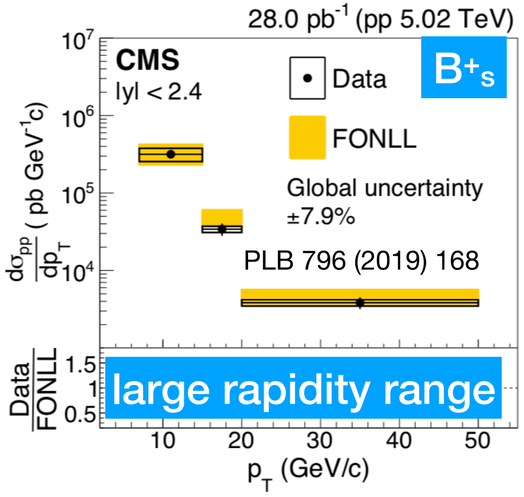


down to zero p_T



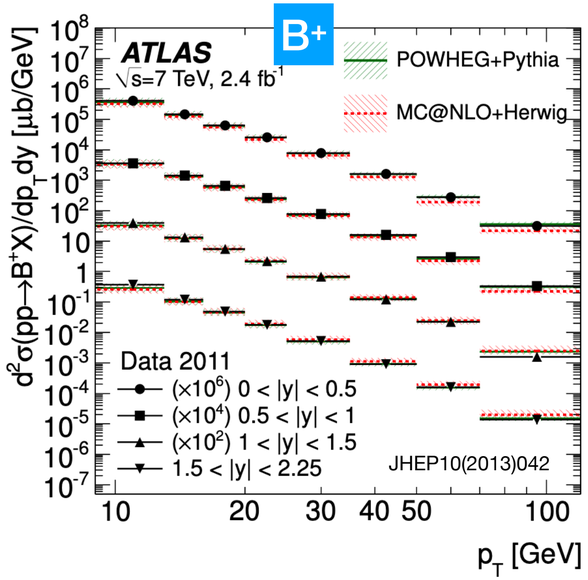
forward rapidity





large rapidity range

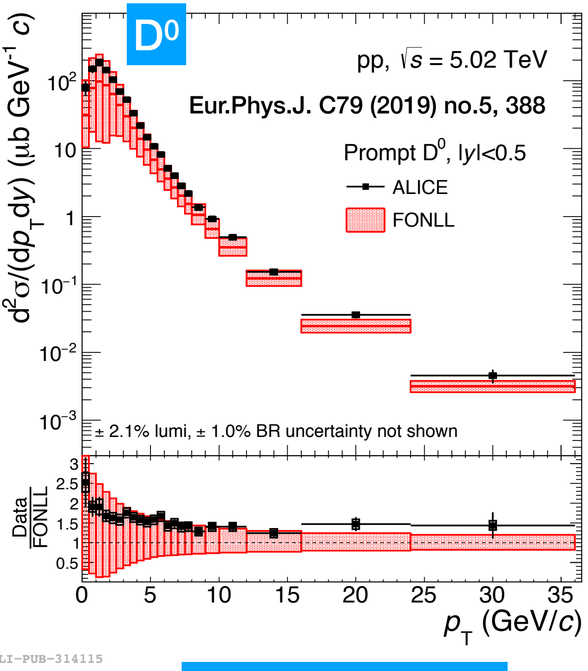
wide p_T range



Overview of charm and beauty meson productions

Theory predictions based on factorisation approach describe data within uncertainties

- models include NLO calculations and fragmentation fractions from production constrained at e^+e^- and ep colliders



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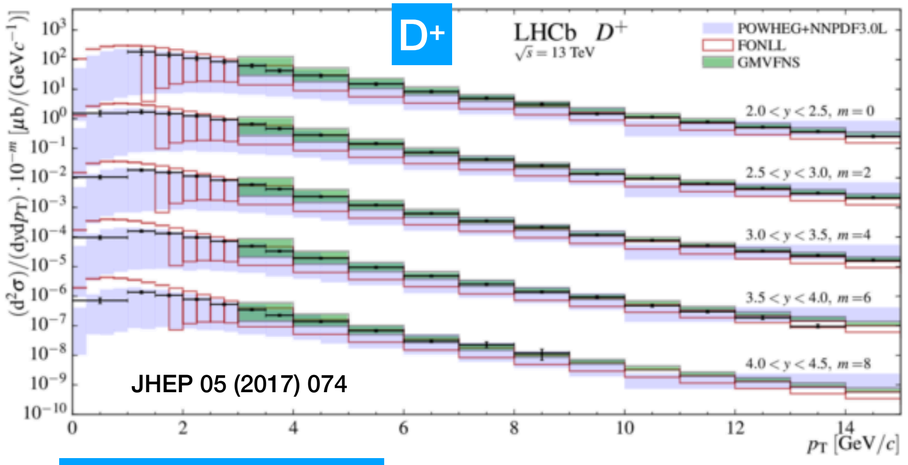

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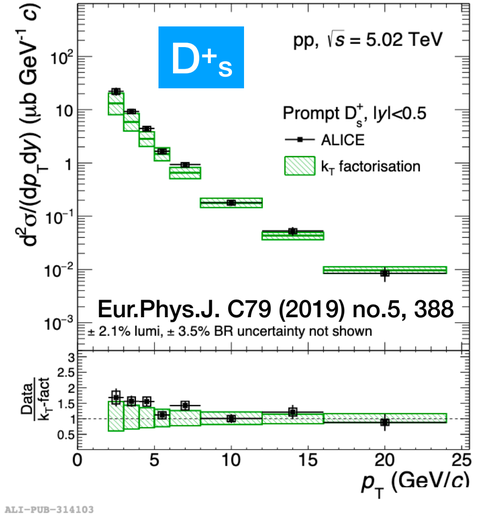
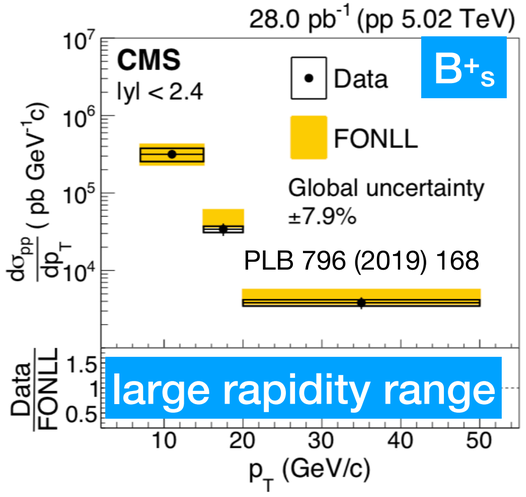
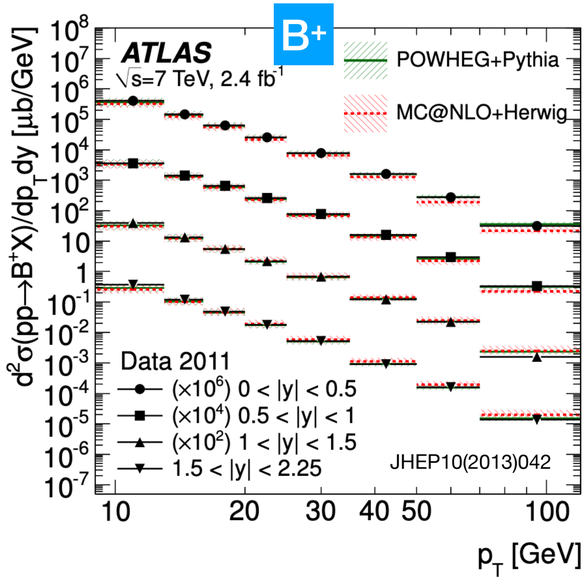




large rapidity range

wide p_T range



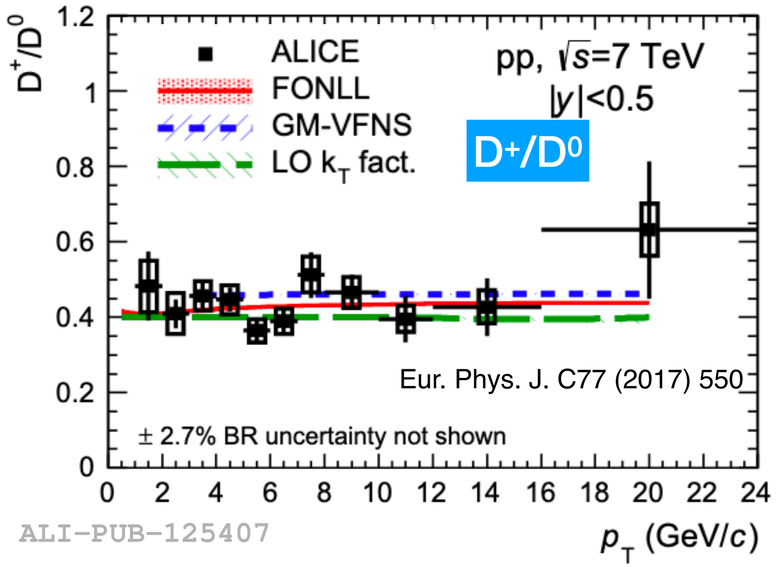
Success of factorisation theorem

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

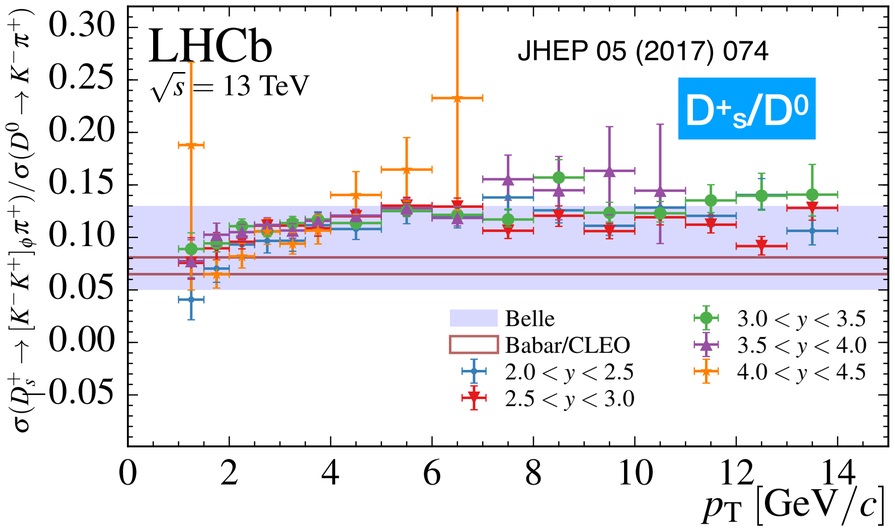
Charmed meson production ratios

$$\frac{d\sigma^{D}}{dp_T^{D}}(p_T;\mu_F,\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_T^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

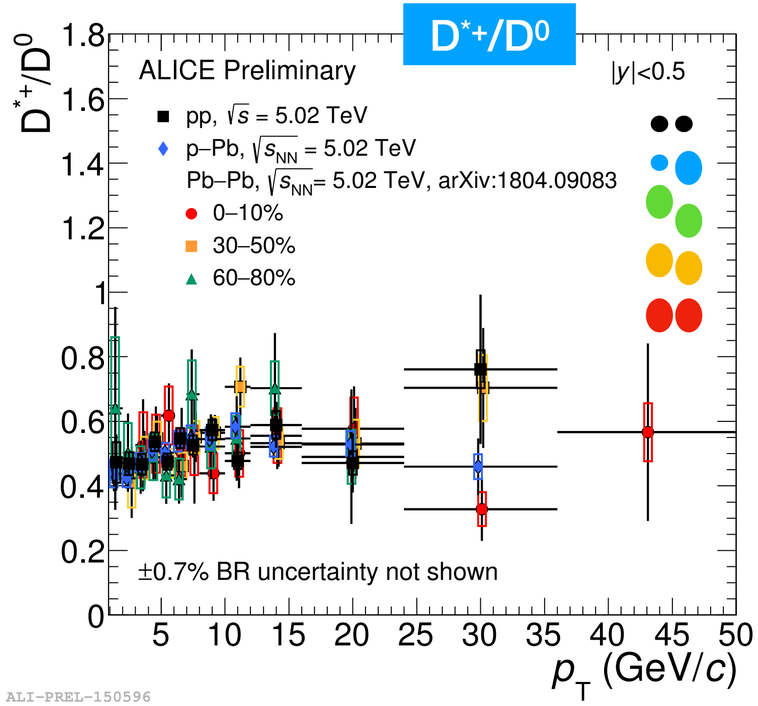
Charm meson species relative abundances sensitive to fragmentation functions



- ~ flat trend vs p_T
- agreement with models



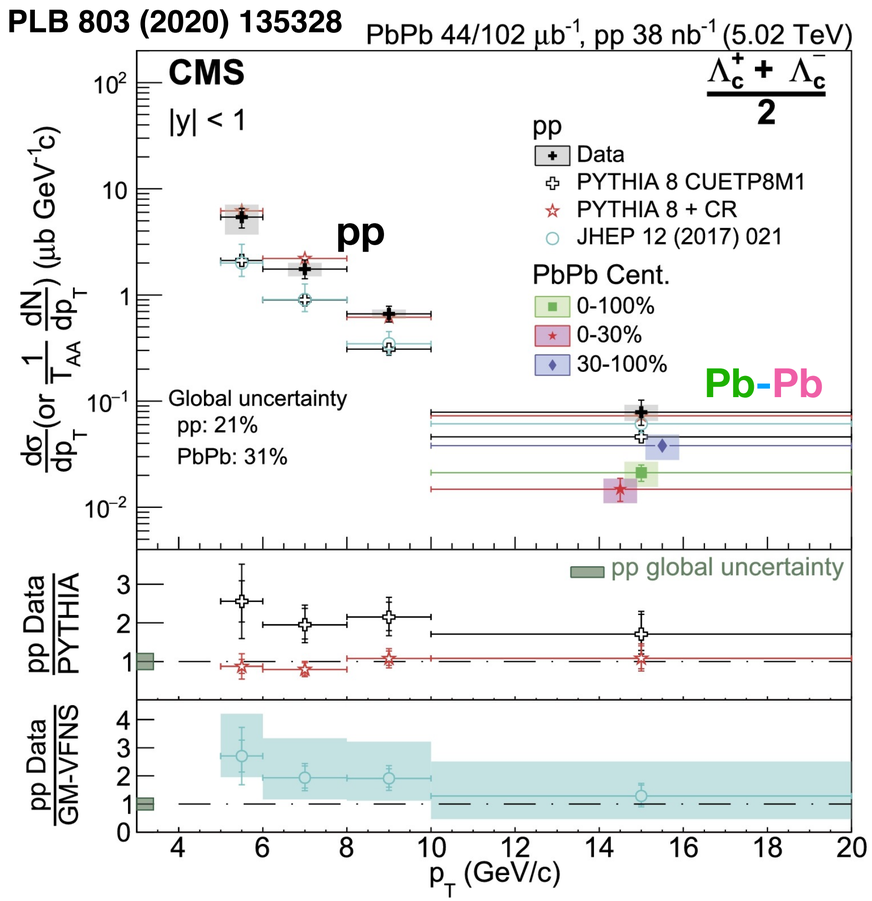
agreement with measurements at e+e- colliders

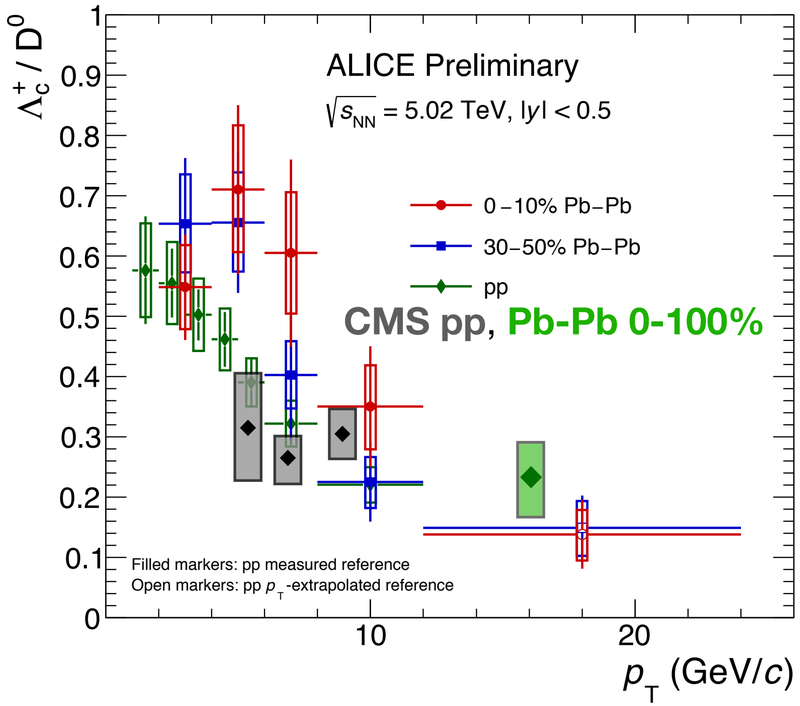


compatible in different systems (pp, p-Pb, Pb-Pb)

Universality of fragmentation functions in the meson sector

Charm and beauty baryon productions

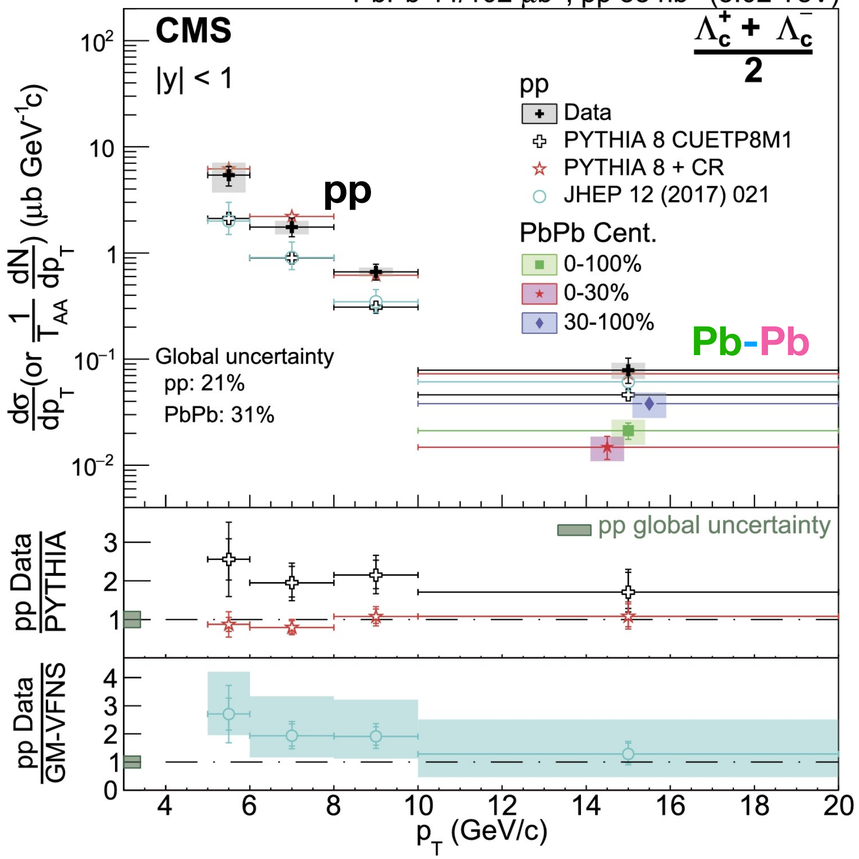


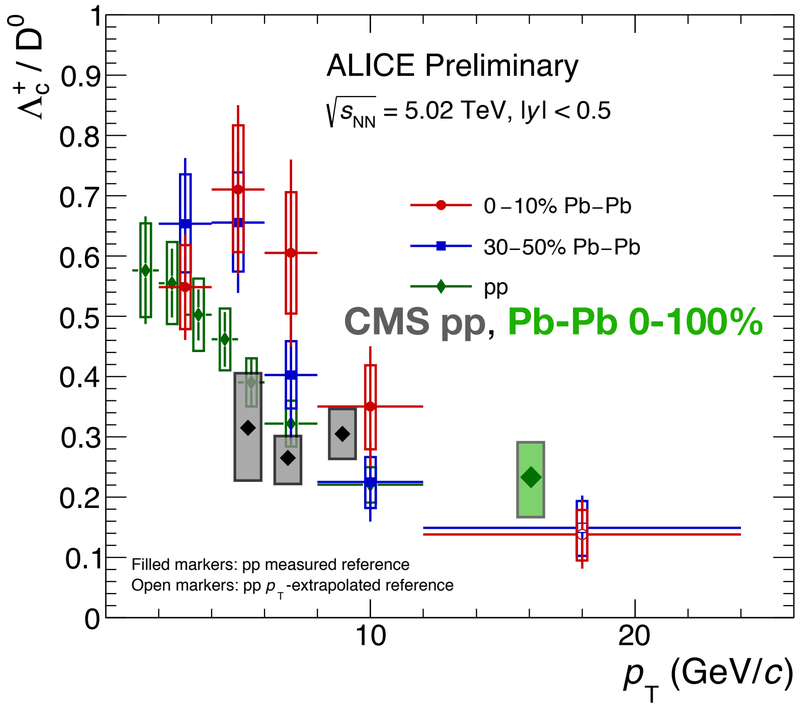


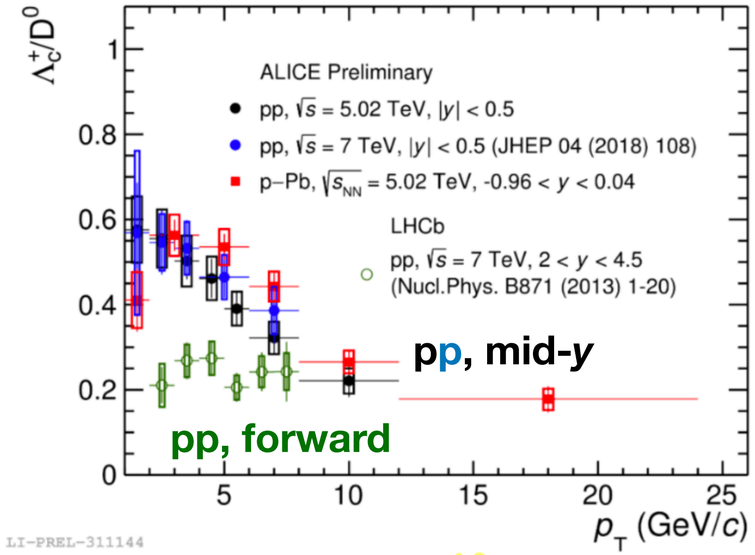
- Λ_c/D^0 measurements: nice agreement at mid-rapidity among experiments

Charm and beauty baryon productions

PLB 803 (2020) 135328



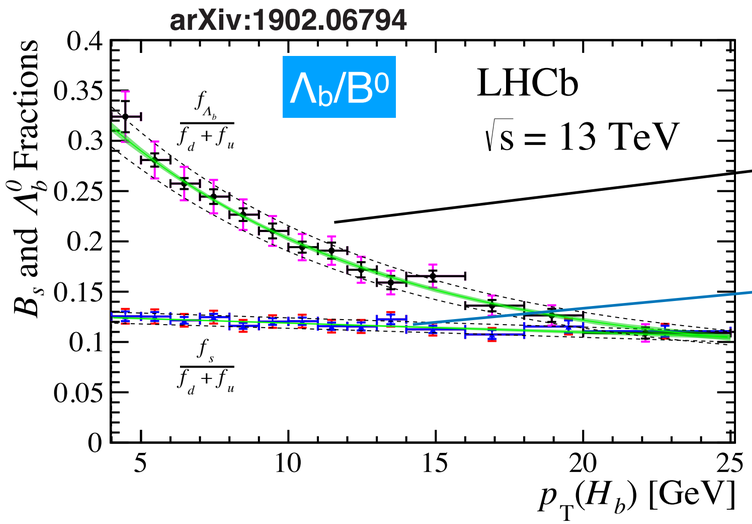




Open questions on baryon productions

- Λ_c/D^0 measurements: nice agreement at mid-rapidity among experiments, tension **mid-forward** rapidity?

Charm and beauty baryon-over-meson ratios



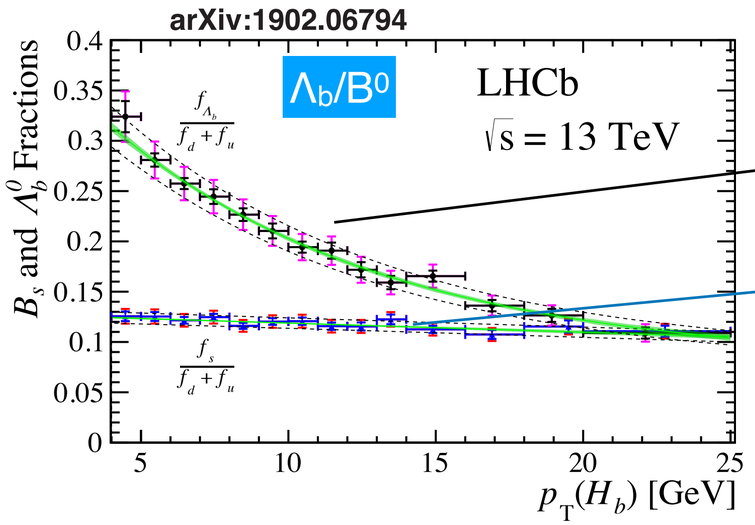
$$\frac{f_{\Lambda_b}}{f_u+f_d} \propto \frac{n_{corr}(\Lambda_b^0)}{n_{corr}(\bar{B}_0)+n_{corr}(B^-)}$$

$$\frac{f_s}{f_u+f_d} \propto \frac{n_{corr}(\bar{B}_s^0)}{n_{corr}(\bar{B}_0)+n_{corr}(B^-)}$$

Fragmentation fractions for $f(\Lambda_b)/f_d+f_u$ (Λ_b/B^0) at low p_T significantly higher than f_s/f_d+f_u (B_s/B^0)

decreasing trend of Baryon-over-meson is a baryon/meson effect of large/small mass?

Charm and beauty baryon-over-meson ratios



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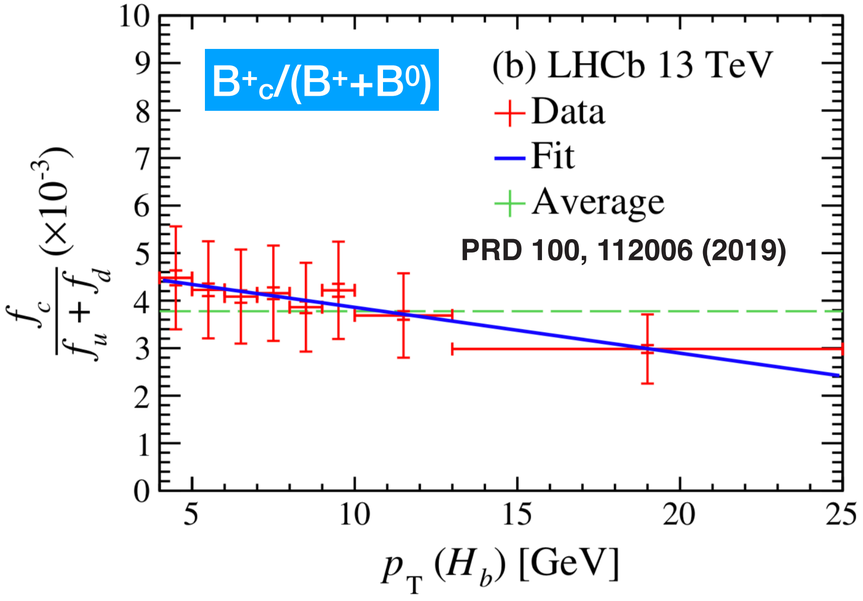
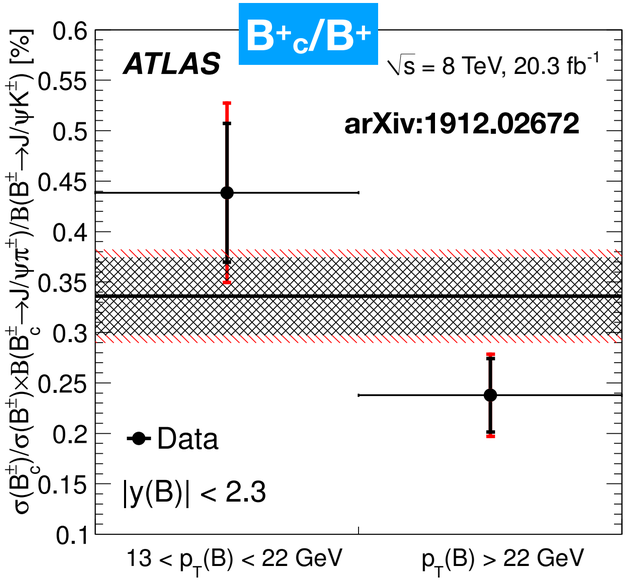
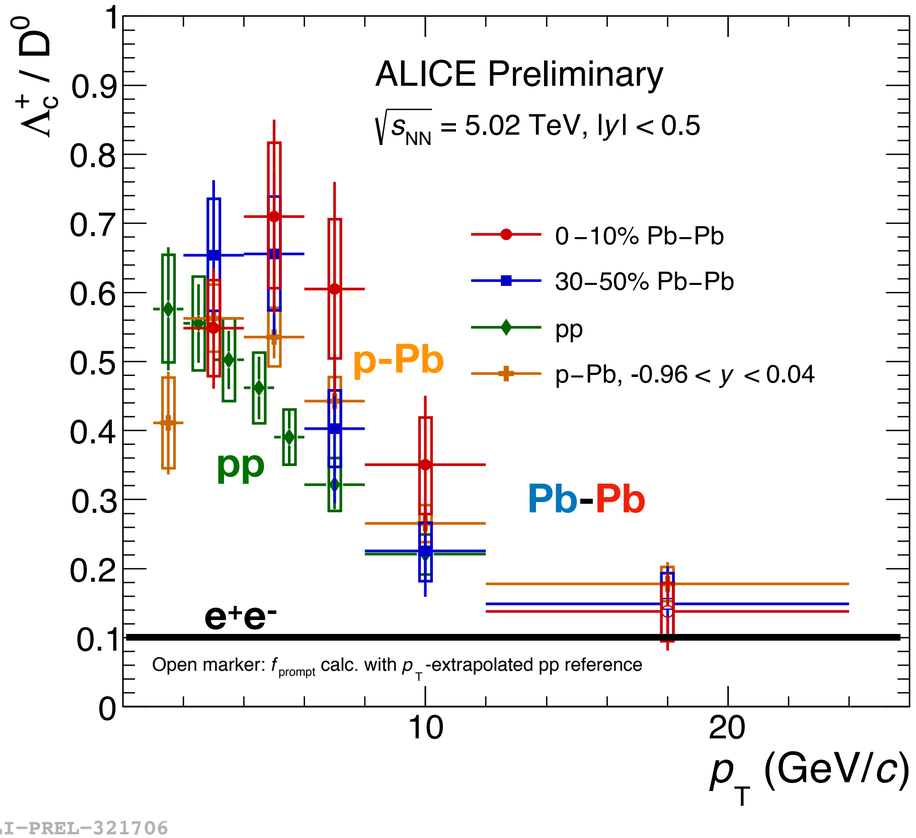




- **Recent measurements of B^+_c/B^+** ($B^+_c/(B^++B^0)$):
  - c+b state, largest mass for ground state meson with two different flavoured quarks (mass B_c >> mass Λ_b)
  - **hint of not-flat p_T trend**, but not as pronounced as Λ_b/B^0:
    ➡ p_T trend for Baryon/Meson not related to particle masses?

Charm and beauty baryon-over-meson ratios

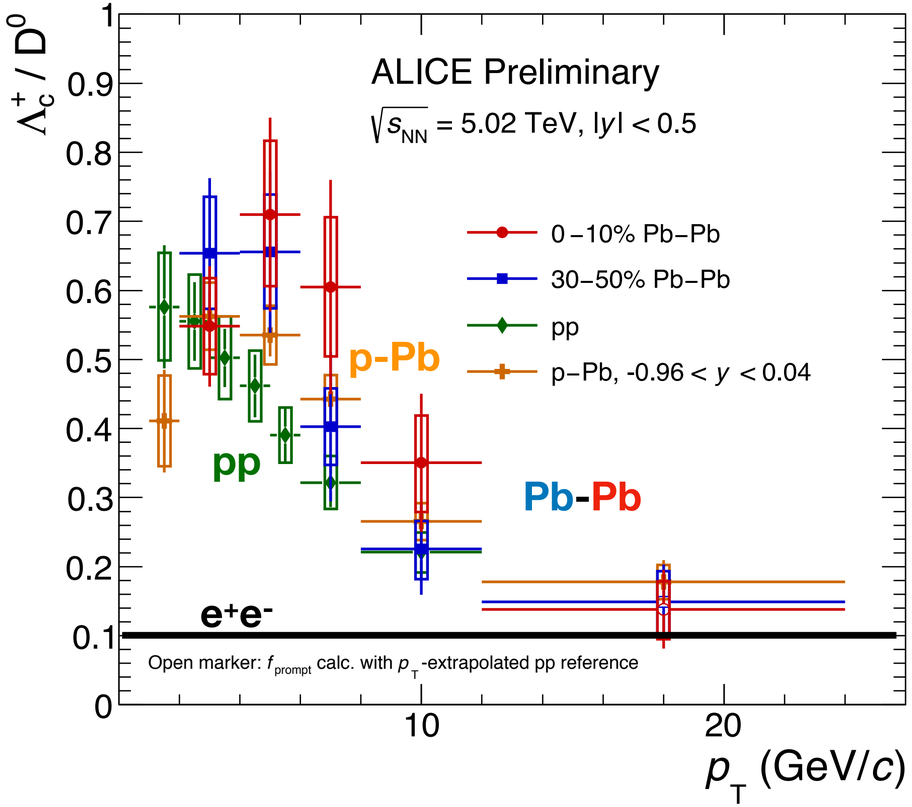


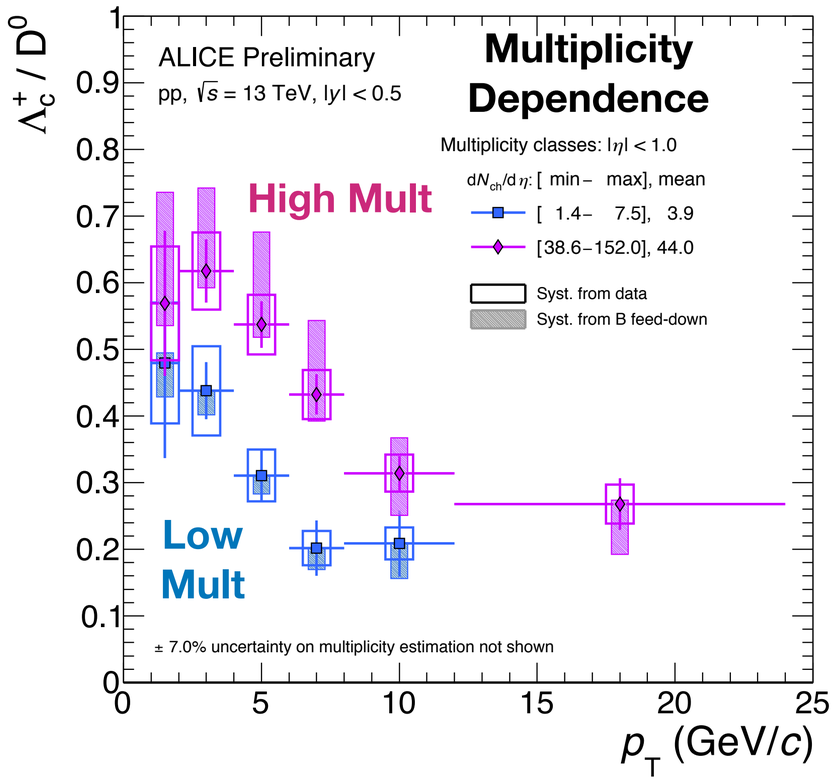
Open questions on baryon productions

Λ_c/D^0 strongly differs wrt to e^+e^- measurements: **loss of fragmentation functions universality for baryon production?**

- **strong p_T dependence** shown in hadronic collision systems
  - similar p_T trend going from **pp** to **p-Pb** and **Pb-Pb**

Charm and beauty baryon-over-meson ratios





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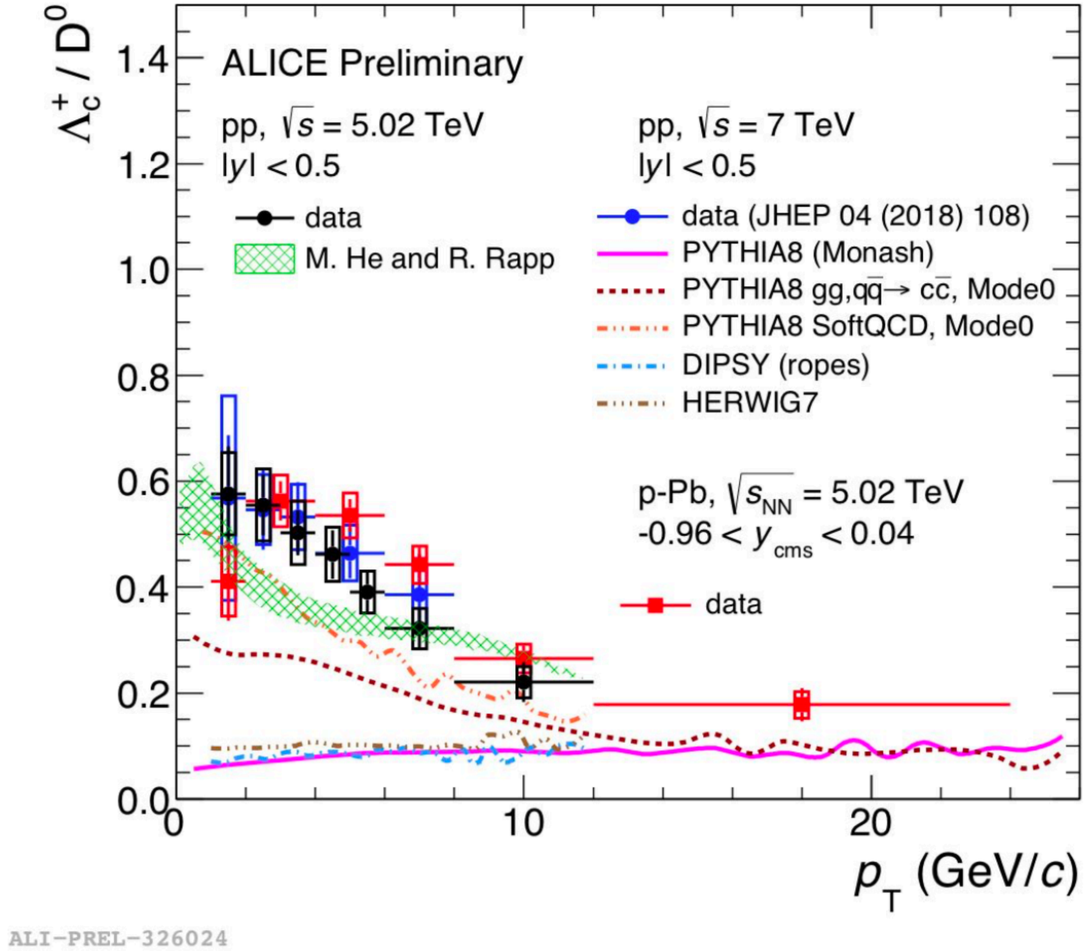
- **strong p_T dependence** shown in hadronic collision systems
  - similar p_T trend going from **pp** to **p-Pb** and **Pb-Pb**
  - **Λ_c/D^0 is multiplicity dependent:** ratio in low multiplicity pp collisions still much larger than e^+e^- measurements
  - **hint of large Λ_c/D^0 ratio in Pb-Pb collisions at intermediate p_T:** hadronisation mechanism? Different p_T shape? Radial-flow push in Pb-Pb?

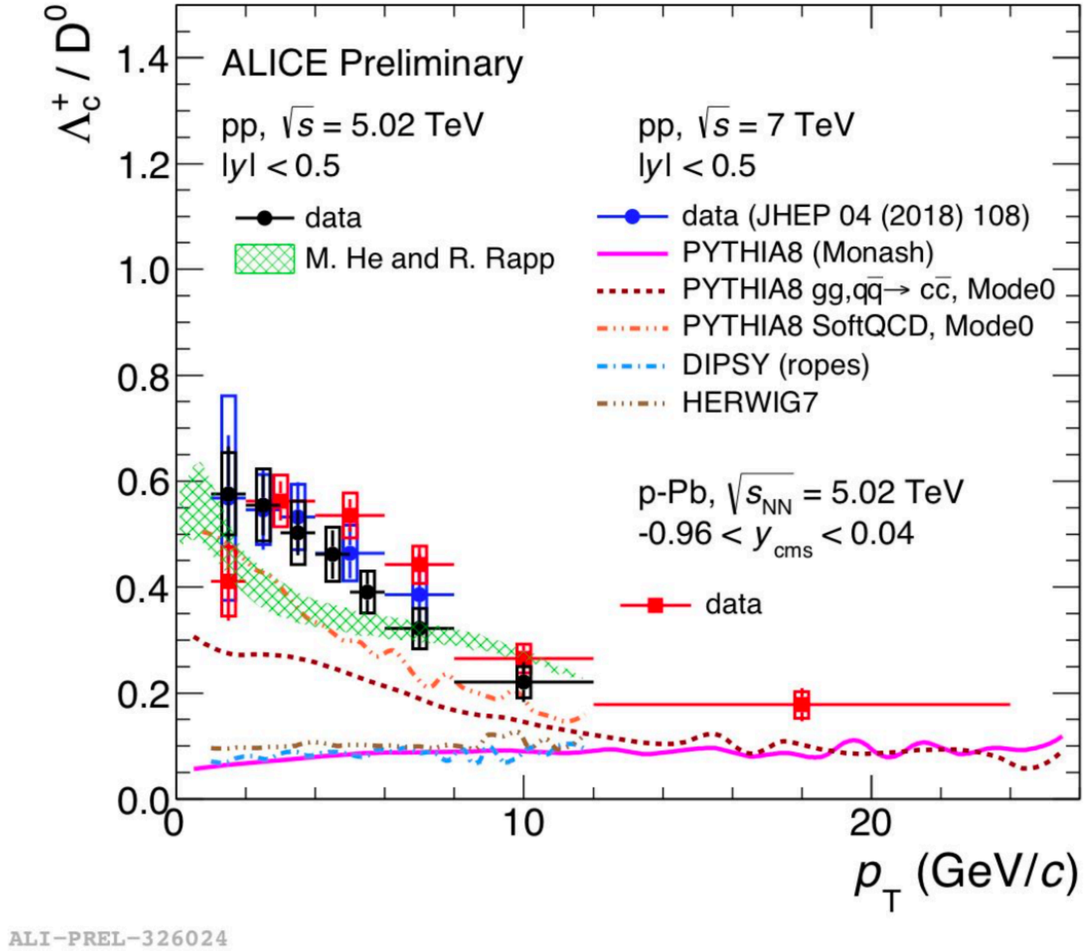
Baryon-over-meson: theoretical model comparisons



- **Λ_c/D^0: models tend to underestimate data**

"**Standard PYTHIA** (Monash, standard Lund string-fragm), **DIPSY** (rope hadronization), **HERWIG** (cluster hadronisation) underestimate data by factor of ~5, and do not catch p_T shape

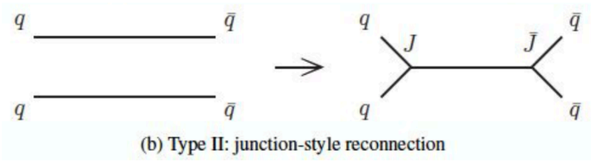
Baryon-over-meson: theoretical model comparisons



- **Λ_c/D^0: models tend to underestimate data**

Colour reconnection [1] with string formation beyond leading colour (LC) approximation (enhanced CR mechanisms with 3-leg junction→ enhance baryons)
Statistical Hadronization Model (SHM) with **increased number of higher-mass baryon states** [2]
among possible explanations for the enhancement

[1]



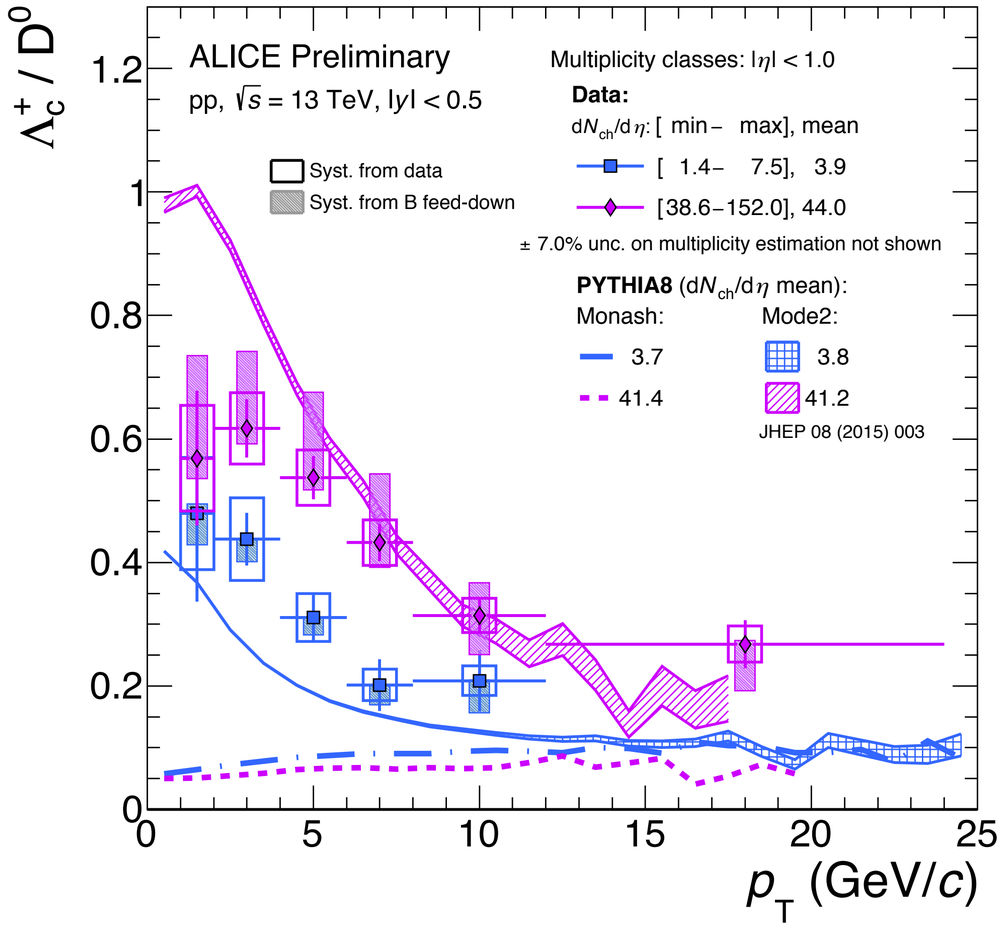
(b) Type II: junction-style reconnection

J.R. Christiansen, P. Skands: JHEP 1508 (2015) 003

[2] **RQM (Relativistic Quark Model) more baryon states wrt to PDG: extra**18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

[2] M.He, R. Rapp: Phys.Lett. B795 (2019) 117-121

Baryon-over-meson: theoretical model comparisons



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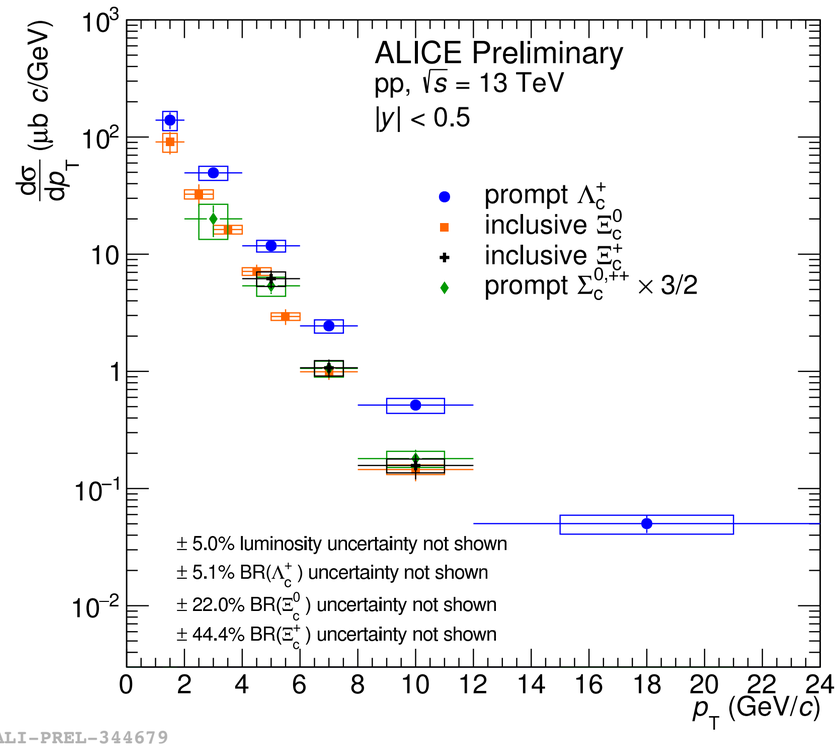
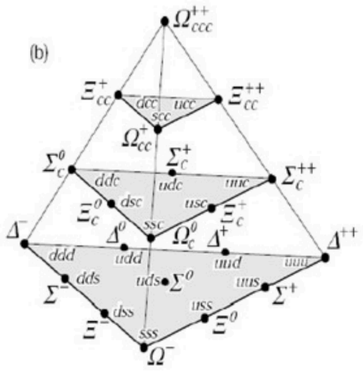
Multiplicity dependence well described by CR beyond LC approximation
No multiplicity dependence for "standard" Pythia Monash

Measure more massive baryon states

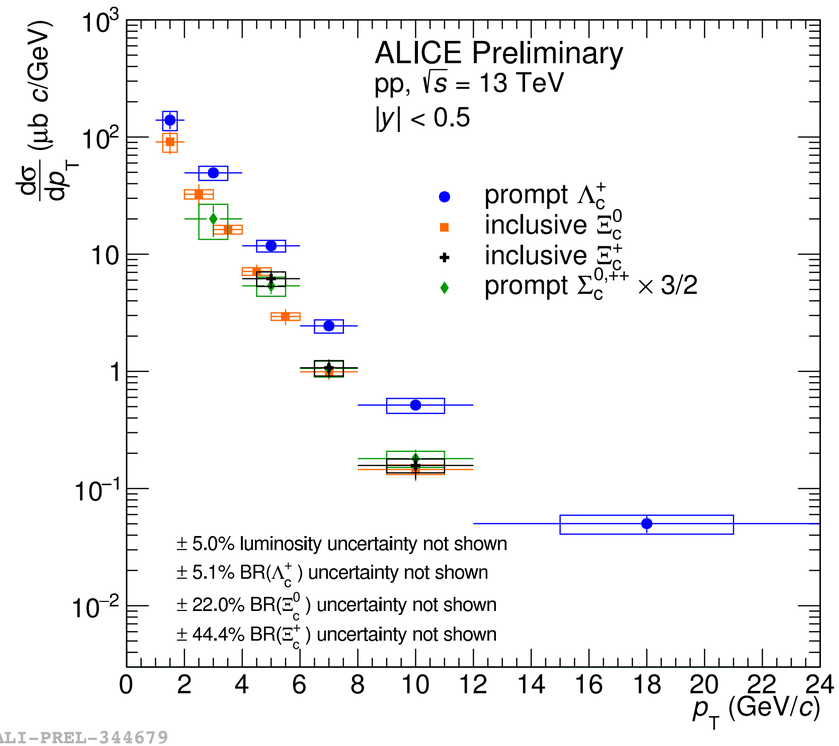


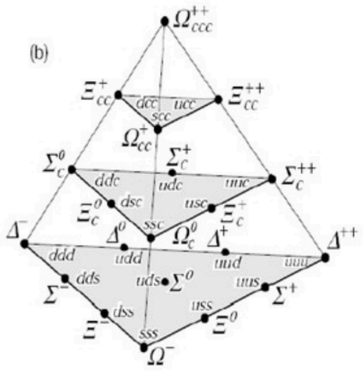


	mass (MeV/c²)	Quark content
Λ_c^+	2286	udc
Ξ_c^+	2467	usc
Ξ_c^0	2471	dsc
Σ_c^{++}, Σ_c^0	2455	uuc, ddc

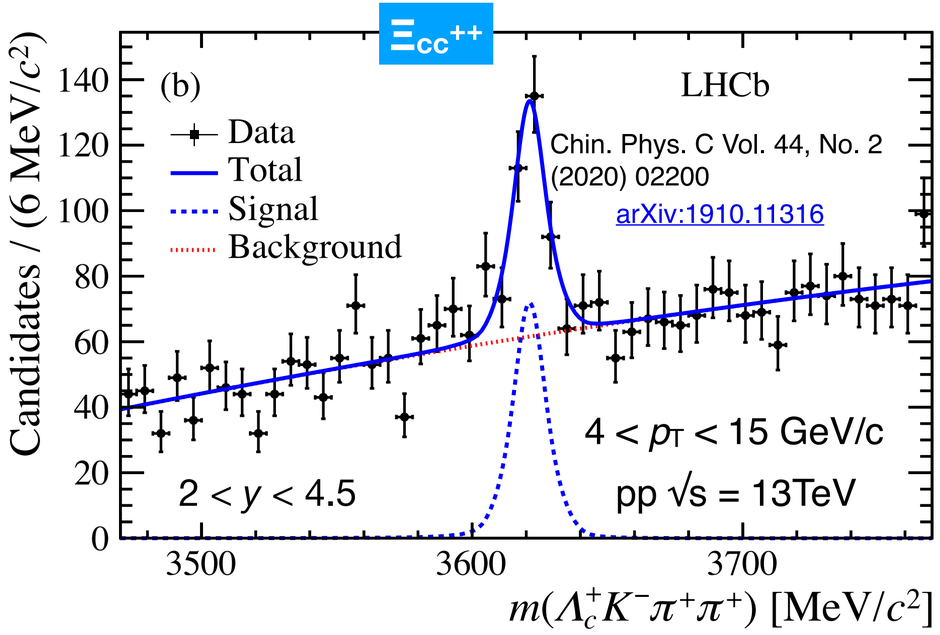
Λ_c, Ξ_c, Ω_c measurements also needed to compute the total charm cross section

Measure more massive baryon states





Doubly charmed baryon production measurement



	mass (MeV/c²)	Quark content
Λ_c^+	2286	udc
Ξ_c^+	2467	usc
Ξ_c^0	2471	dsc
Σ_c^{++}, Σ_c^0	2455	uuc, ddc

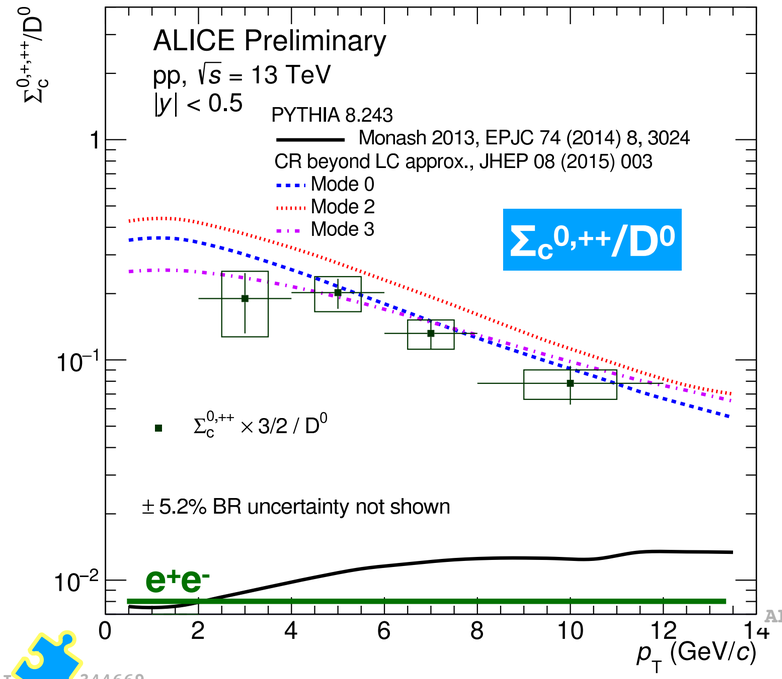
Λ_c, Ξ_c, Ω_c measurements also needed to compute the total charm cross section

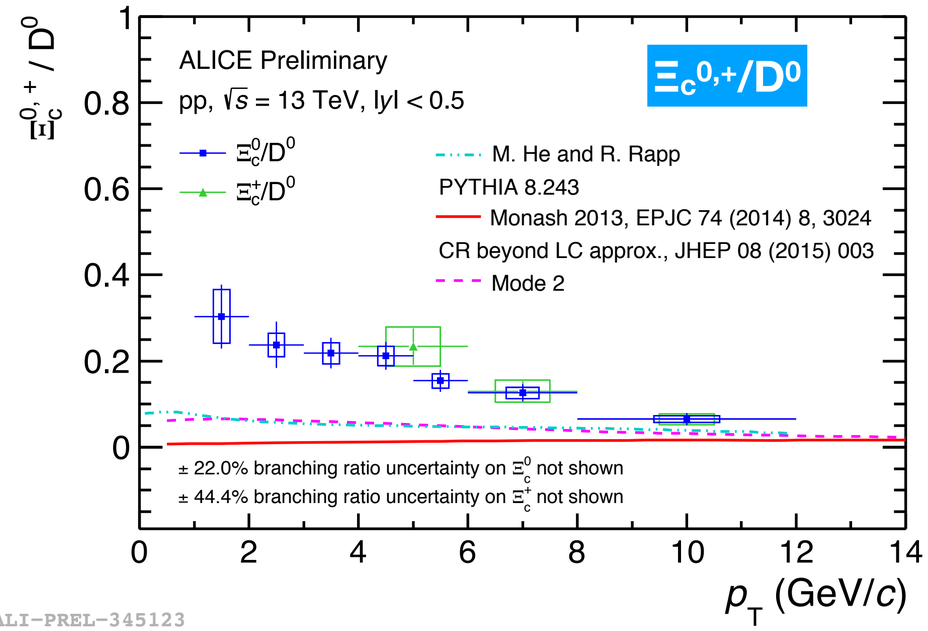
Ratio of production cross section times BR of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
relative to prompt Λ_c production cross-section

$$R \equiv \frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} = (2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$$

	mass (MeV/c²)	Quark content
Ξ_{cc}^{++}	3621	ucc

Massive baryon states: theoretical calculation comparisons





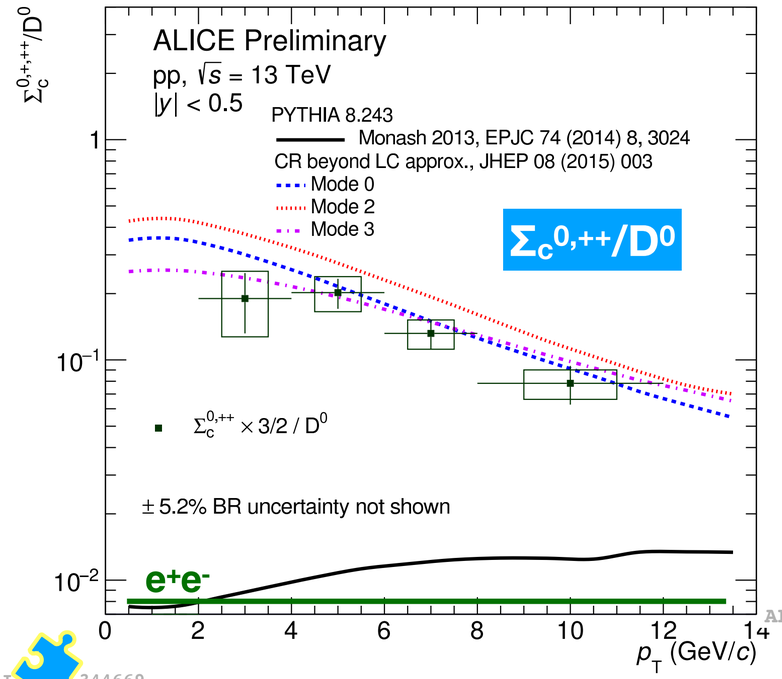
ALI-PREL-345123

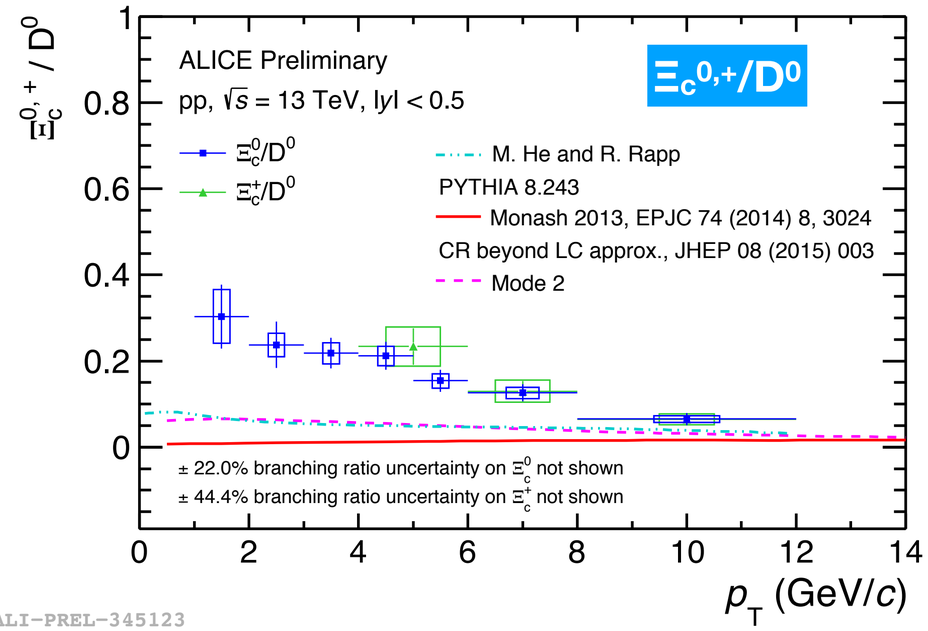
$\Sigma_c^{0,++}/D^0$: data catch by CR beyond LC and underestimated by "standard" Pythia

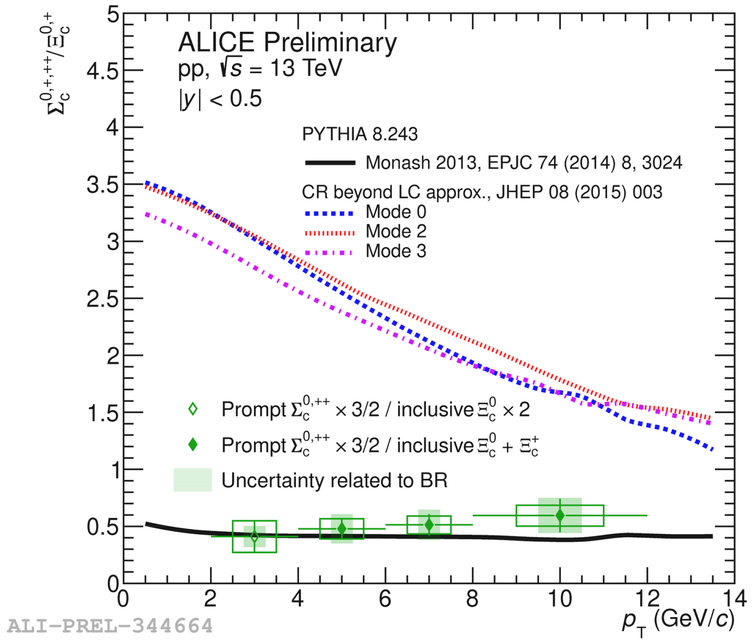
- Σ_c contributes to the larger Λ_c/D^0 ratio in pp than in e^+e^-

Ξ_c^0/D^0 and Ξ_c^+/D^0 not reproduced by any model

Massive baryon states: theoretical calculation comparisons







$\Sigma_c^{0,++}/D^0$: data catch by CR beyond LC and underestimated by "standard" Pythia

- Σ_c contributes to the larger Λ_c/D^0 ratio in pp than in e^+e^-

Ξ_c^0/D^0 and Ξ_c^+/D^0 not reproduced by any model

$\Sigma_c^{0,++}/\Xi_c^{0,+}$ reproduced by "standard" Pythia: due to the identical mass?

Σ_c and Ξ_c have almost identical masses and different quark content: uuc vs usc

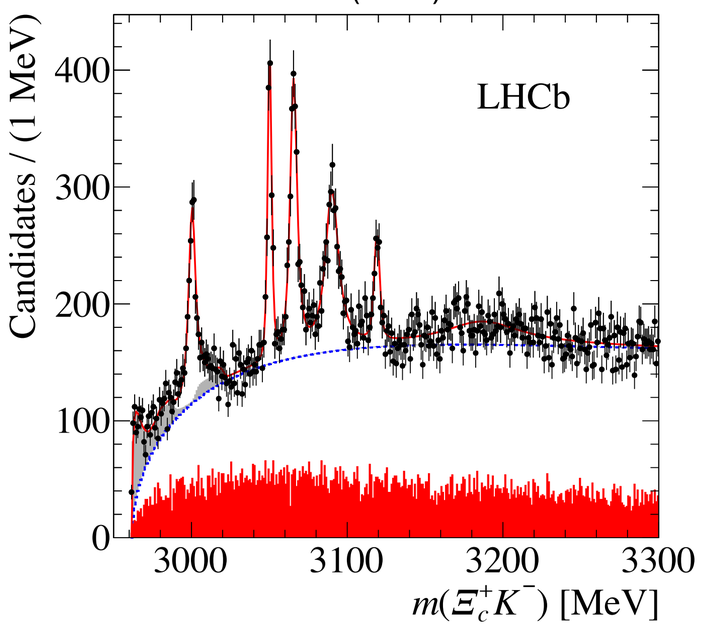
role of diquark production for charm "baryonisation"?

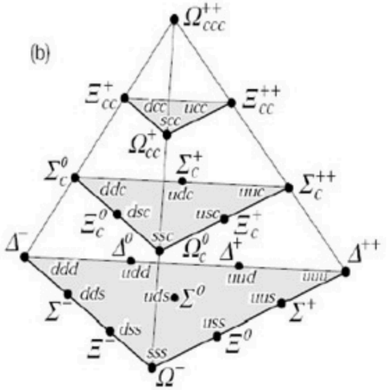
- **String fragmentation scenario:** suppression in e^+e^- due to high spin-1 diquark mass dynamics?
- **Junctions:** no difference in having two legs end on same-flavour quarks, same ud and dd(uu) production

Spectroscopy: new states for charm baryons

further test of theoretical models probing QCD
increase understanding of the nature of exotic hadrons

PRL118(2017) 182001





Beginning of discoveries by LHCb

Five very narrow excited Ω^0_c states in the $\Xi^0_c K^-$ spectrum

$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$

Spectroscopy: new states for charm baryons

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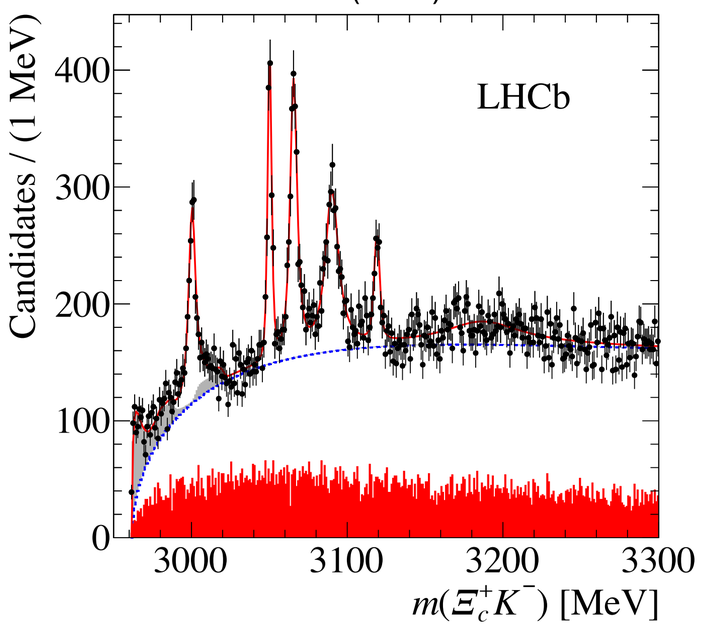
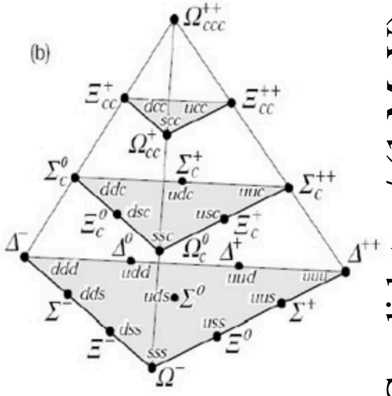
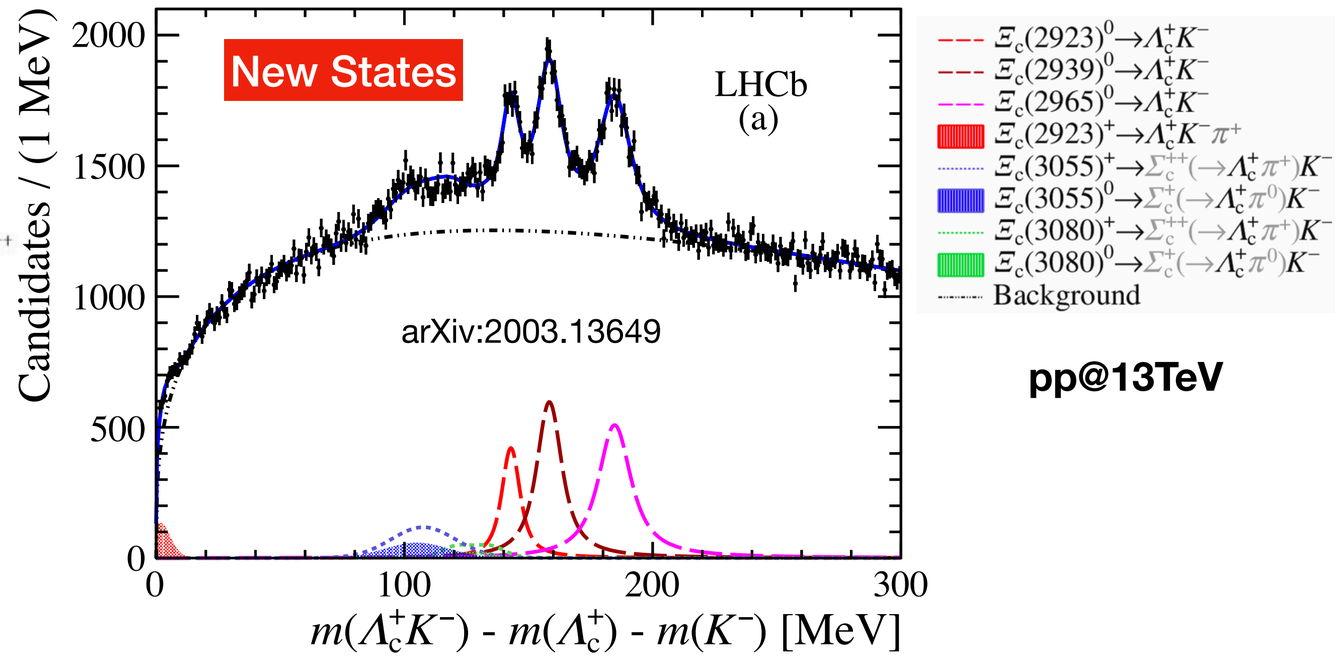




Search for **Ξ^0_c resonances**: three Ξ^0_c baryon states observed in the $\Lambda_c K^-$ spectrum

$$\Xi_c^0 \to \Lambda_c^+ K^-$$
$$\hookrightarrow pK^-\pi^+$$



pp@13TeV

Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

Beginning of discoveries by LHCb

Five very narrow excited Ω^0_c states in the $\Xi^0_c K^-$ spectrum

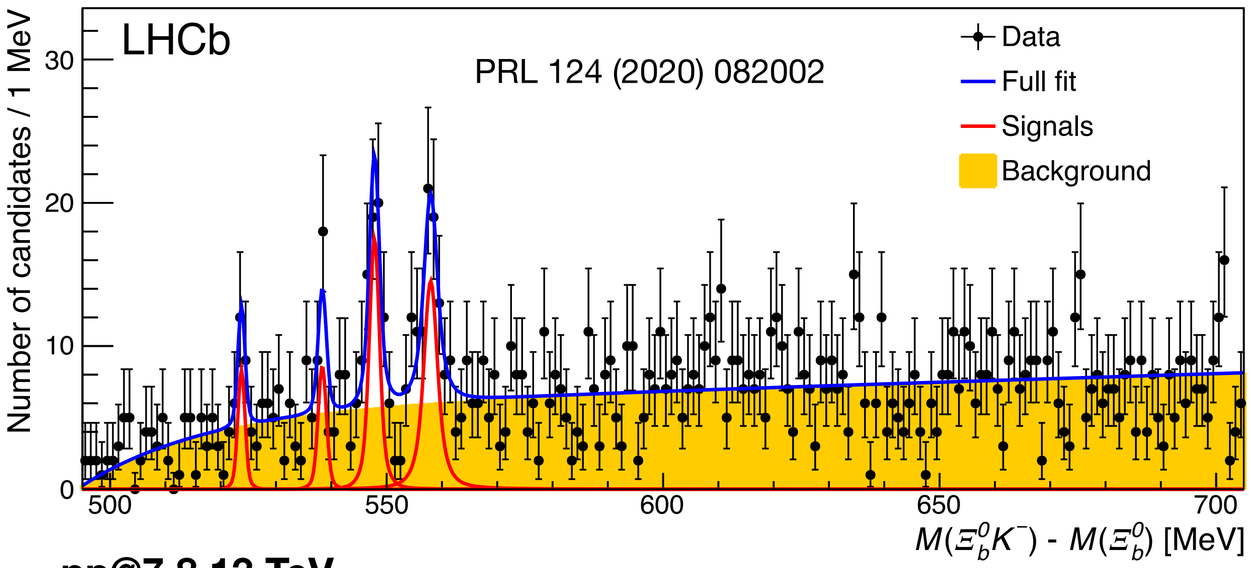
$$\Omega_c(3000)^0,\ \Omega_c(3050)^0,\ \Omega_c(3066)^0,\ \Omega_c(3090)^0,\ \Omega_c(3119)^0$$

$\Xi^0_c(2965)$ in vicinity of $\Xi^0_c(2970)$ (already observed, but not seen in $\Lambda_c K^-$)

- different mass and very different width: different status? More studies required

Spectroscopy: new states for beauty baryons

Four peaks consistent with **excited Ω^-_b baryons resonances** in the $\Xi^0_b K^-$ spectrum



pp@7,8,13 TeV

	δM_{peak} [MeV]	Mass [MeV]	Width [MeV] (90% upper limit)
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$< 2.8\ (4.2)$
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$< 3.1\ (4.7)$
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$< 1.5\ (1.8)$
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$< 2.8\ (3.2)$
			$1.4^{+1.0}_{-0.8} \pm 0.1$

Similar spectra as for Ω_c in $\Xi^0_c K^-$ observed in the beauty sector, in $\Xi^0_b K^-$ spectra, as expected from heavy quark symmetry

$$\Omega_b^- \to \Xi_b^0\ K^-$$
$$\hookrightarrow \Xi_c^+\ \pi^-$$
$$\hookrightarrow pK^-\pi^+$$

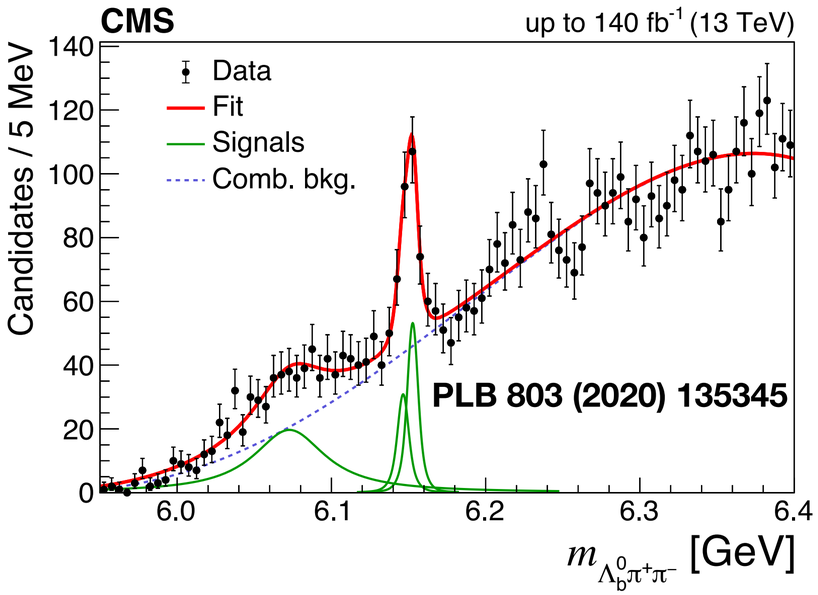
Possible interpretations:

- Excited Ω^-_b states
- Decay of higher mass excited Ω^-_b state:

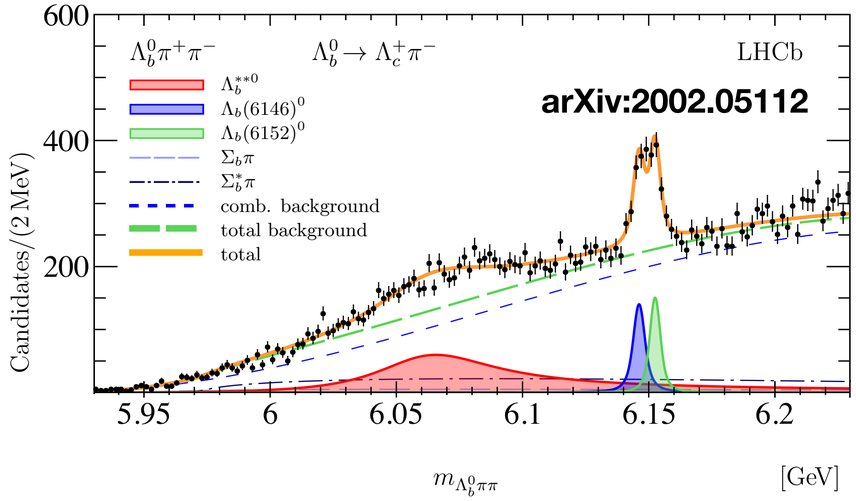
$$\Omega_b^{**-} \to \Xi_b'^0(\to \Xi_b^0\pi^0)K^-$$

Excited baryon production: Λ_b

A number of excited Λ^0_b states predicted in 5.9-6.4 GeV, widths and production cross section unknown: challenging search



Ground state $\Lambda^0_b \rightarrow \Psi(2S)\Lambda$ or $\Lambda^0_b \rightarrow J/\Psi\Lambda$



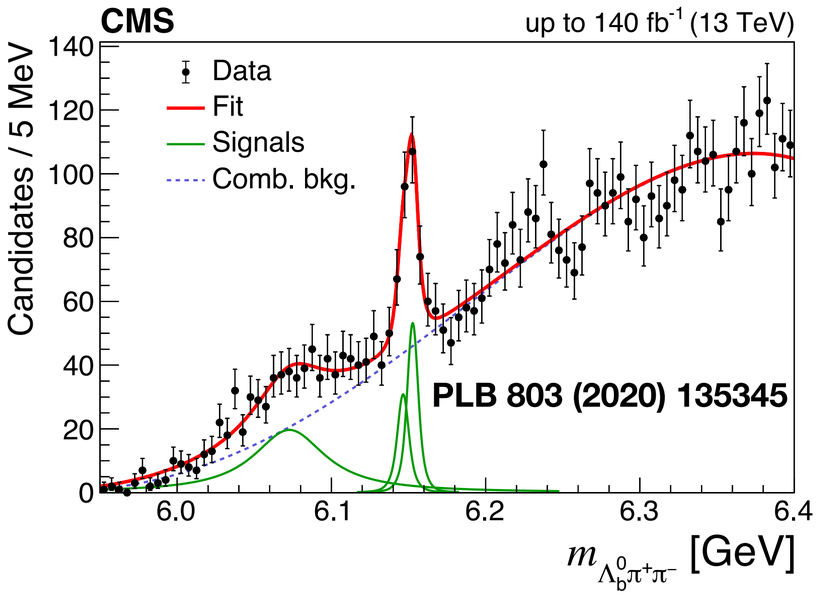
Ground state $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ or $\Lambda^0_b \rightarrow J/\Psi pK^-$

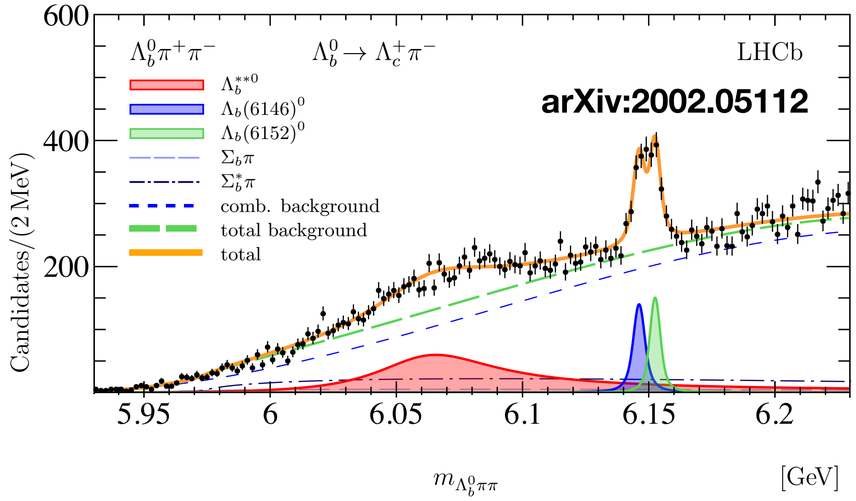
New excited Λ^0_b states decaying to $\Lambda_b^0\pi^+\pi^-$ in pp collisions

- Λ^0_b states **(5912), (5920):** doublet of first orbital excitations in the Λ^0_b system $\Lambda^0_b(1P)^0$
- Recent measurements **(6146), (6152)** consistent with expectations for $\Lambda^0_b(1D)^0$ doublet
- **Broad excess around 6040-6100 GeV**

Excited baryon production: Λ_b

A number of excited Λ^0_b states predicted in 5.9-6.4 GeV, widths and production cross section unknown: challenging search





CMS

$$m(\Lambda_b^{**0}) = 6073 \pm 5 \text{ MeV}$$
$$\Gamma(\Lambda_b^{**0}) = 55 \pm 11 \text{ MeV}$$

LHCb

$$m(\Lambda_b^{**0}) = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV}$$
$$\Gamma(\Lambda_b^{**0}) = 72 \pm 11 \pm 2 \text{ MeV}$$

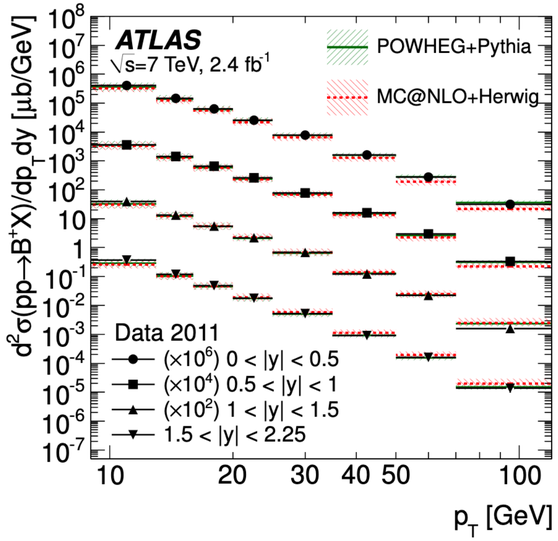
new broad resonance-like state $\Lambda^0_b(2S)^0$?

New excited Λ^0_b states decaying to $\Lambda_b^0\pi^+\pi^-$ in pp collisions

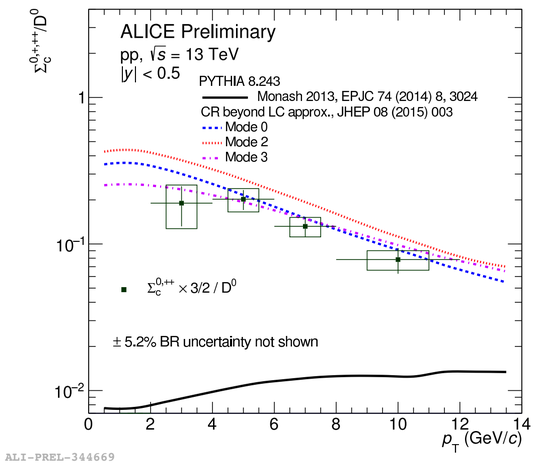
- Λ^0_b states **(5912), (5920):** doublet of first orbital excitations in the Λ^0_b system $\Lambda^0_b(1P)^0$
- Recent measurements **(6146), (6152)** consistent with expectations for $\Lambda^0_b(1D)^0$ doublet
- **Broad excess around 6040-6100 GeV**

Conclusions

- **Charm and beauty meson production precisely measured by the four experiments at LHC:**
  - success of the factorisation theorem and universality of fragmentation fractions

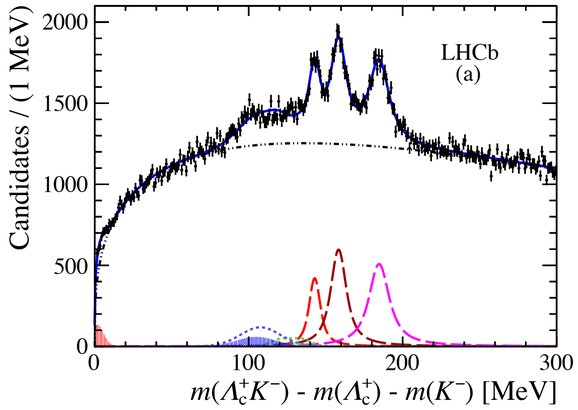


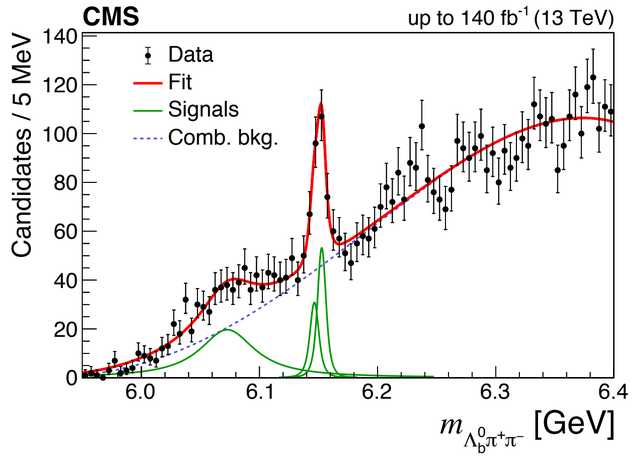
- **Baryon production measurements well performed, some open questions to be addressed:**
  - rapidity dependence?
  - baryon production fully understood?
  - **validity of the universality of the fragmentation fractions for baryons?**



- **More baryon states to be measured to further investigate the baryon production mechanisms:**
  - **new results** about massive charmed baryon
  - **wide spectroscopy studies of beauty baryons**
    - **excited charmed and beauty baryon states**
  - give further hints to pQCD calculations

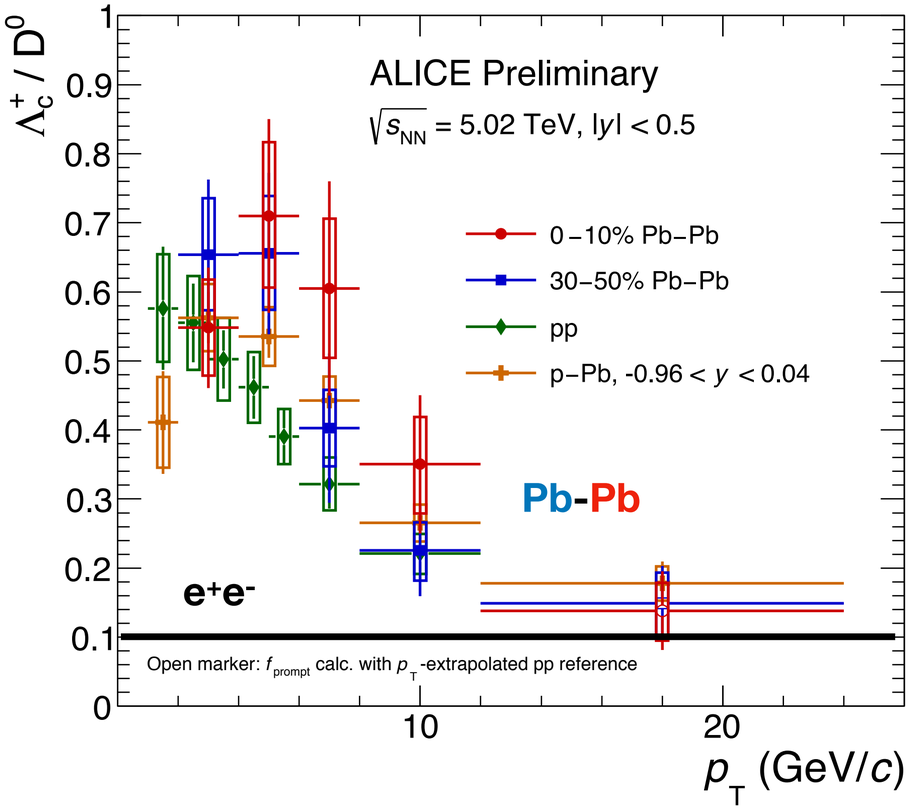
➡ **Heavy-flavor measurements are ideal tools to investigate into the hadronisation dynamics and baryon formation**





Thanks!

baryon/meson ratios and colliding systems



f(b → Λ_b) at Tevatron/LHC vs LEP

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-b-meson-prod-decay.pdf

ALICE, JHEP 1804 (2018) 108

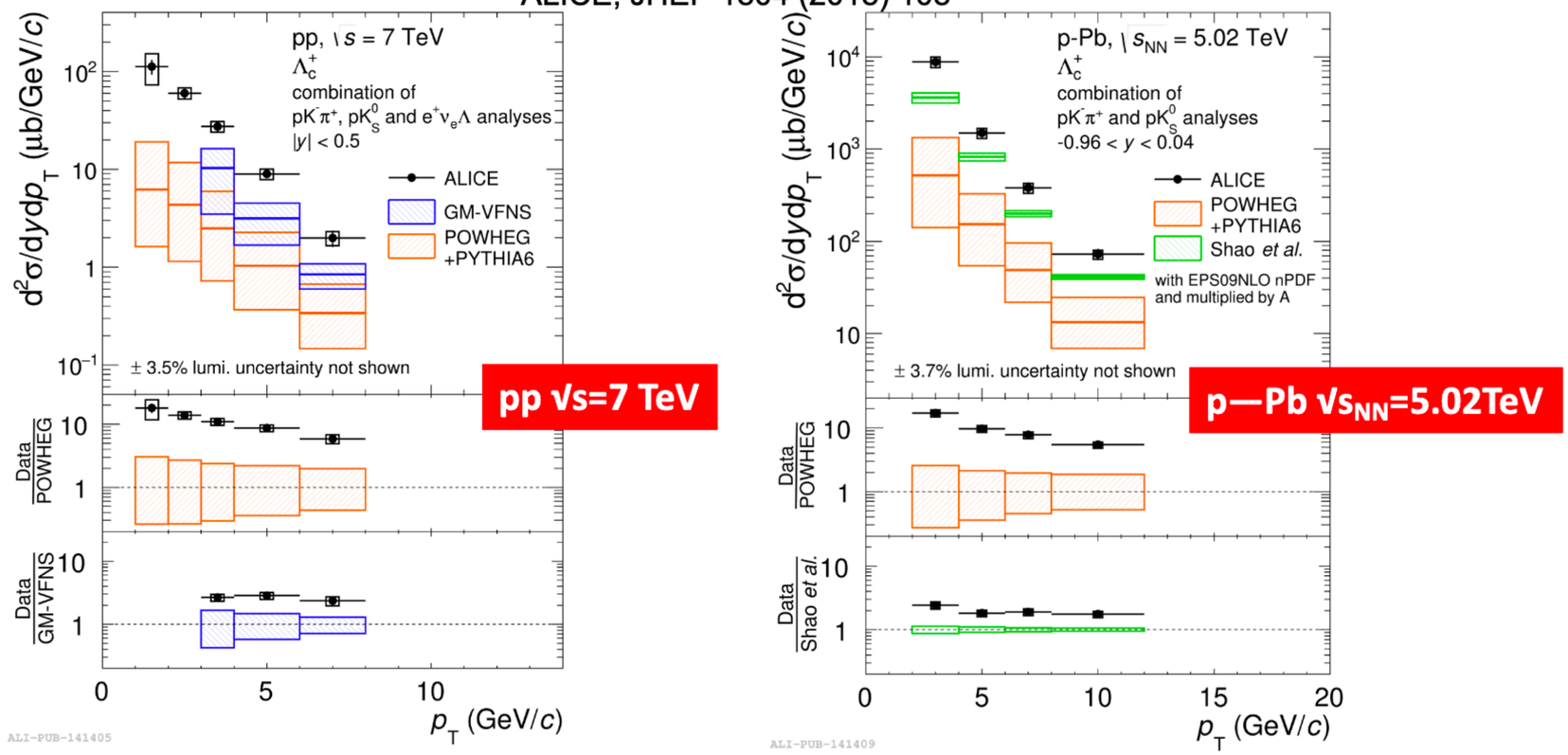
	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320

Table 85.1: Fragmentation fractions of b quarks into weakly-decaying b-hadron species in $Z \to b\bar{b}$ decay, and in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [26].

b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7

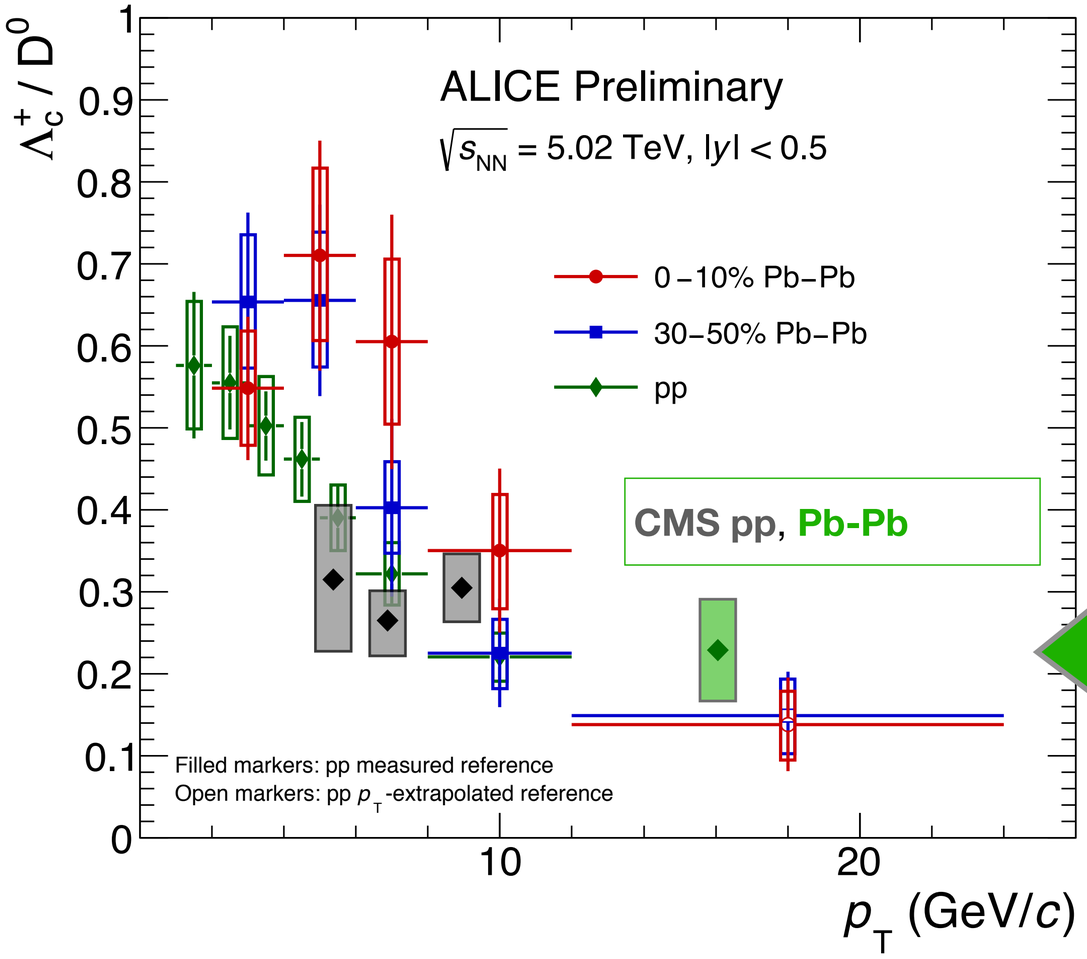
Charmed baryons and models

ALICE, JHEP 1804 (2018) 108



- pQCD based calculations underestimate baryon production (but they do good job on D mesons!)
- note: for GM-VFNS FF derived from e^+e^- data (Knihel et al., PRD 74 (2006) 037502)
- *same* considerations of comparisons with models hold in p-Pb collisions
- Shao et al. (EPJC 77 (2017) 1) model based on pp LHC data (LHCb) + nPDF

baryon/meson ratios: ALICE and CMS



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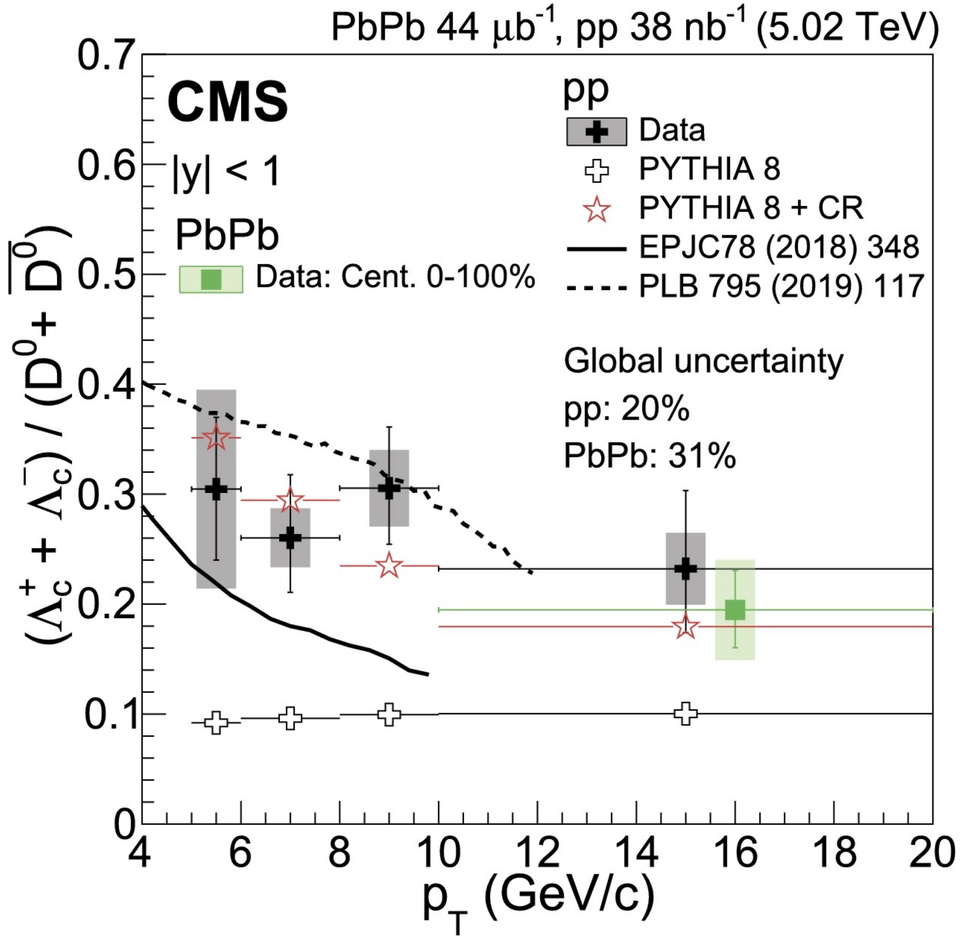
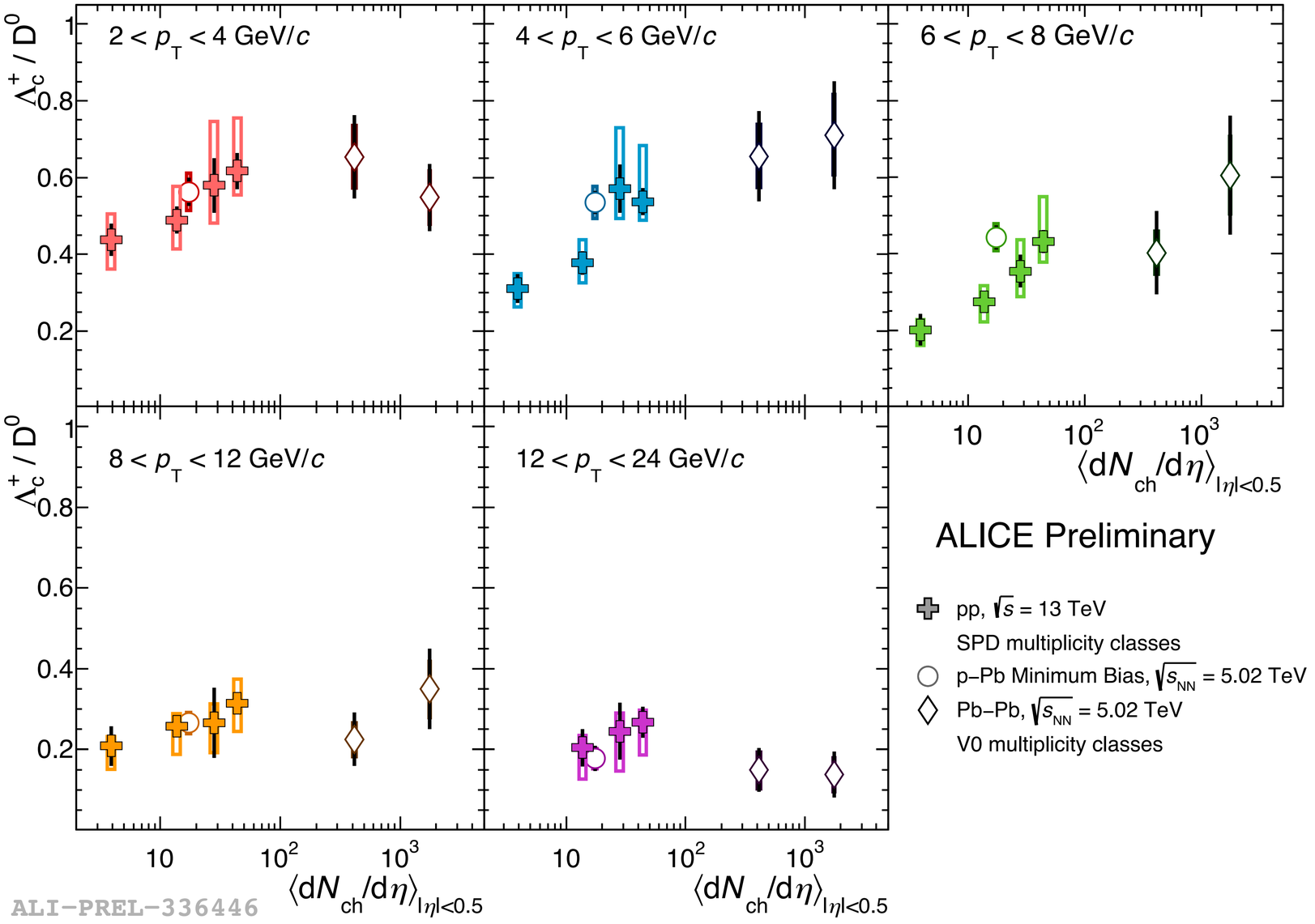
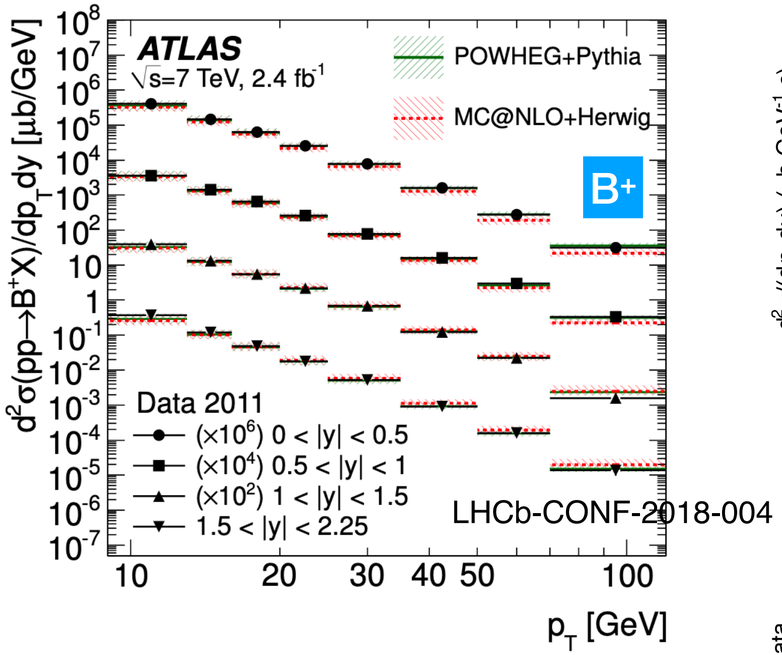
PLB 803 (2020) 135328

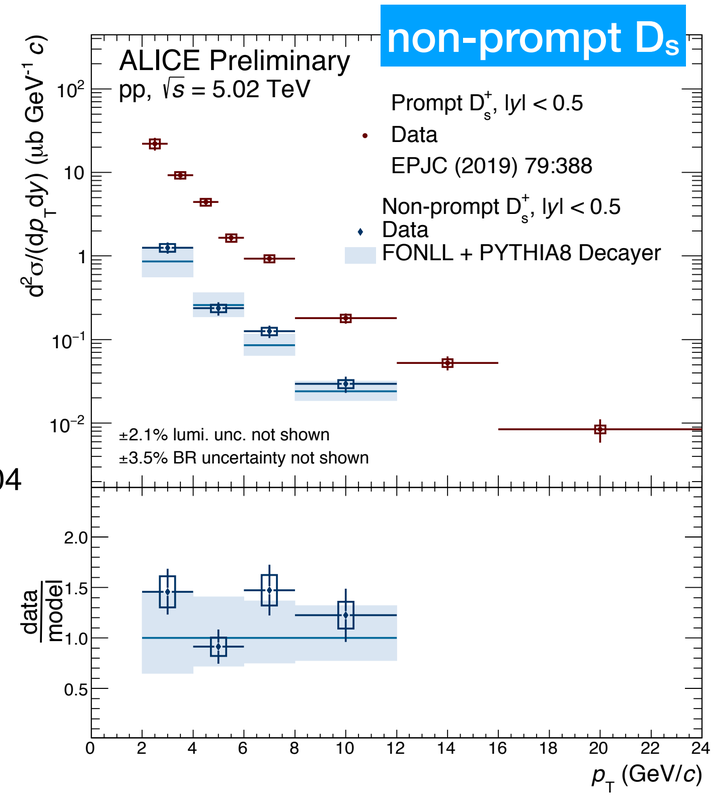


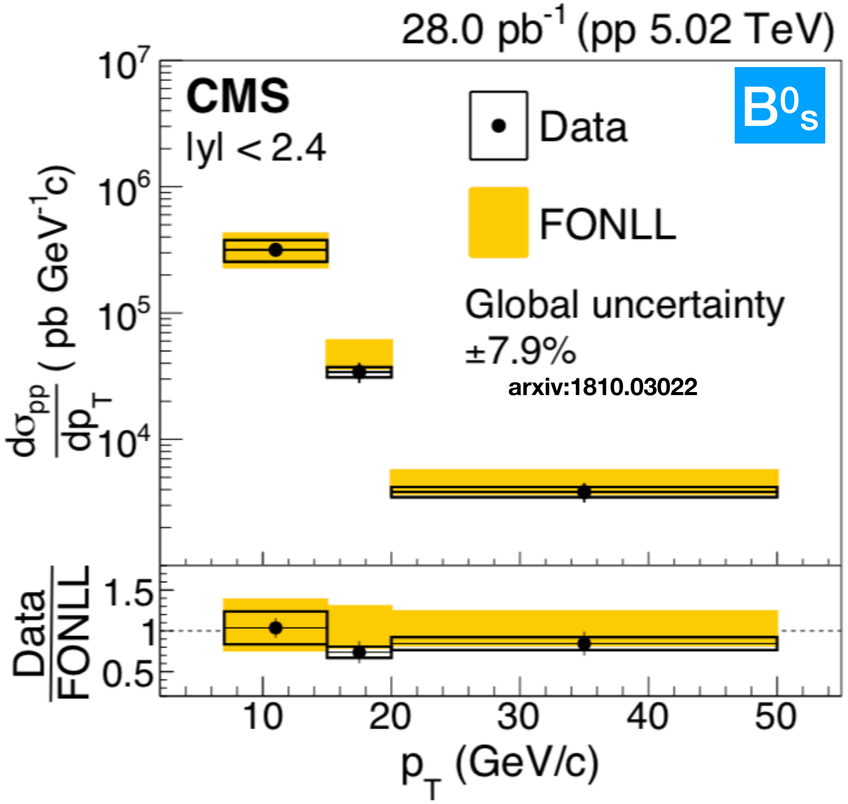
baryon/meson ratios vs mult across systems

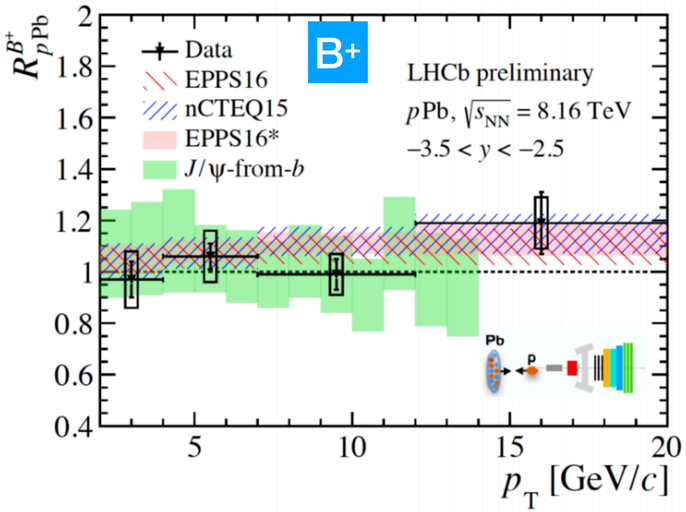


Beauty meson productions





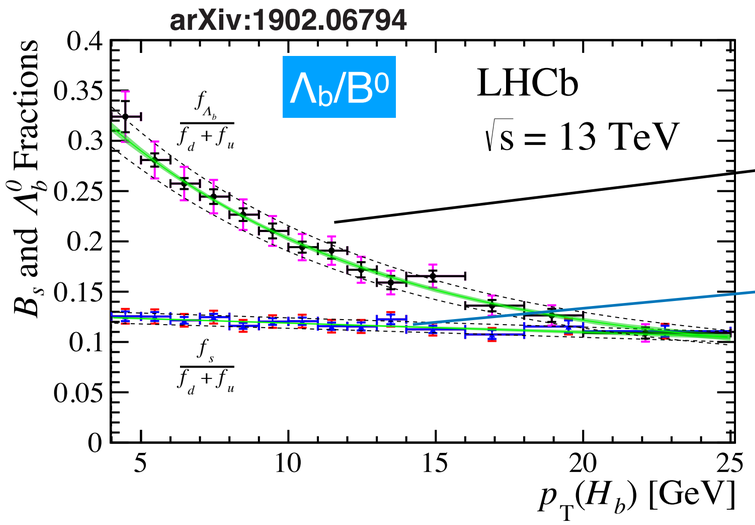




B meson measurements addressed in different collision systems, from pp to Pb-Pb:

- production well described by pQCD calculations
- Still challenging measurements of bottom strange baryons in Pb-Pb: will profit of large statistics in Run3

Charm and beauty baryon-over-meson ratios

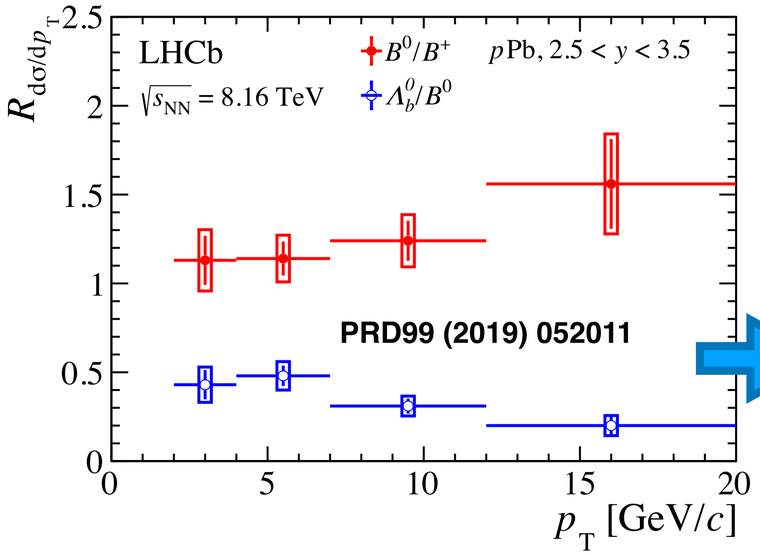


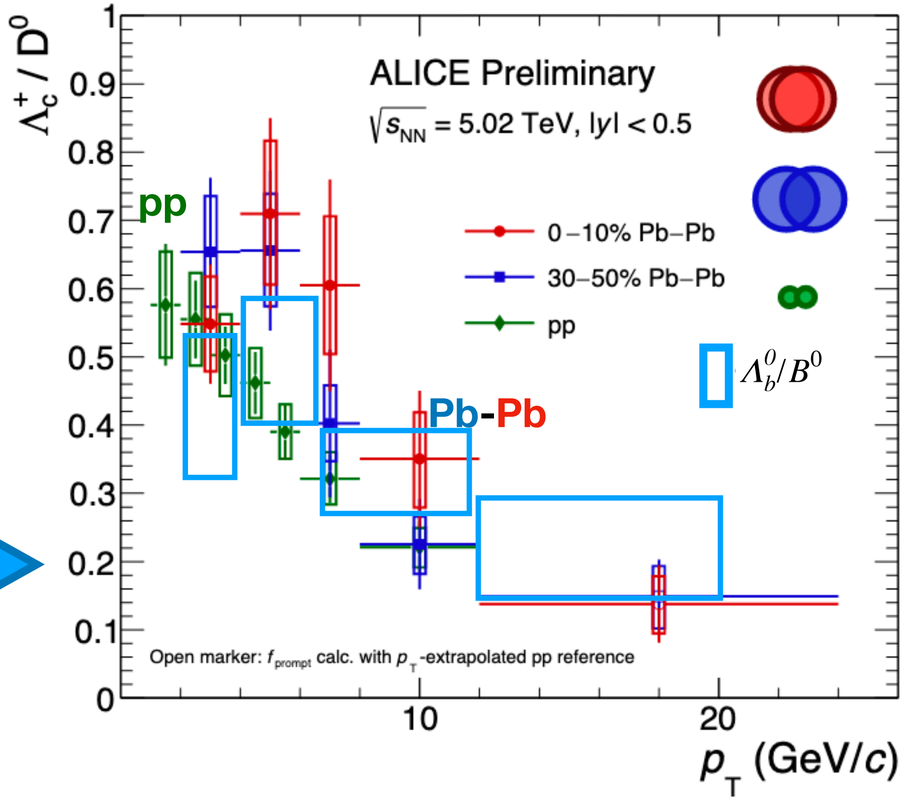
$$\frac{f_{\Lambda_b}}{f_u+f_d} \propto \frac{n_{corr}(\Lambda_b^0)}{n_{corr}(\bar{B}_0)+n_{corr}(B^-)}$$

$$\frac{f_s}{f_u+f_d} \propto \frac{n_{corr}(\bar{B}_s^0)}{n_{corr}(\bar{B}_0)+n_{corr}(B^-)}$$

Fragmentation fractions for $f(\Lambda_b)/f_d+f_u$ (Λ_b/B^0) at low p_T significantly higher than f_s/f_d+f_u (B_s/B^0)

- **~flat trend of beauty-meson ratios** vs p_T, hint of a decreasing trend of baryon-over-meson **Λ_b/B ratio**
- **Λ_b/B** p_T trend **similar to what observed for Λ_c/D^0** (caveat: different rapidity range, and smaller Λ_c/D^0 at forward wrt to mid-rapidity)





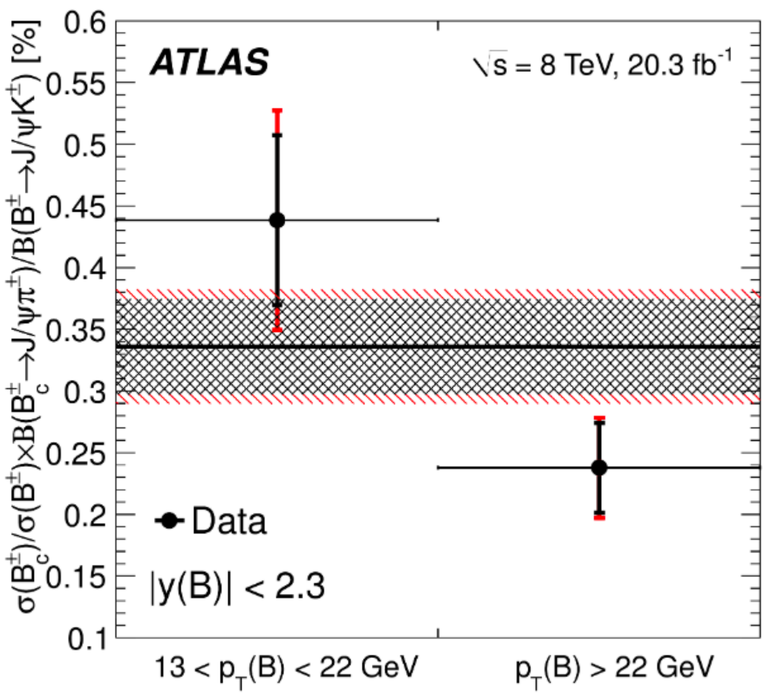
B^+_c relative cross section to B^+

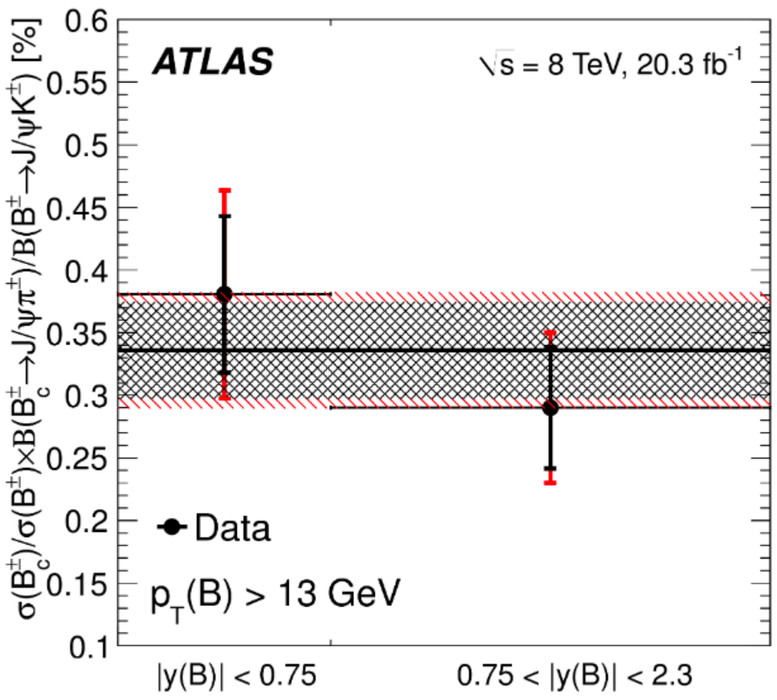
$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm\to J/\psi K^\pm)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}=\frac{N^{\text{reco}}(B_c^\pm)}{N^{\text{reco}}(B^\pm)}\cdot\frac{\epsilon(B^\pm)}{\epsilon(B_c^\pm)}$$

ATLAS has studied the $B_c^\pm/B^\pm$ production cross section at 8 TeV.

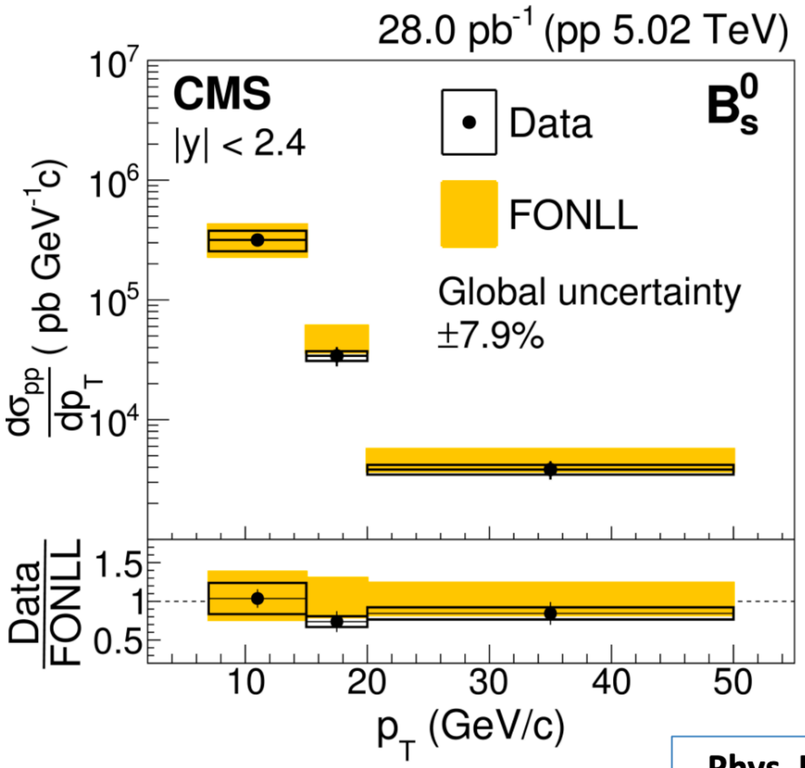
Differential (p_{T}, y) study in the central rapidity region.

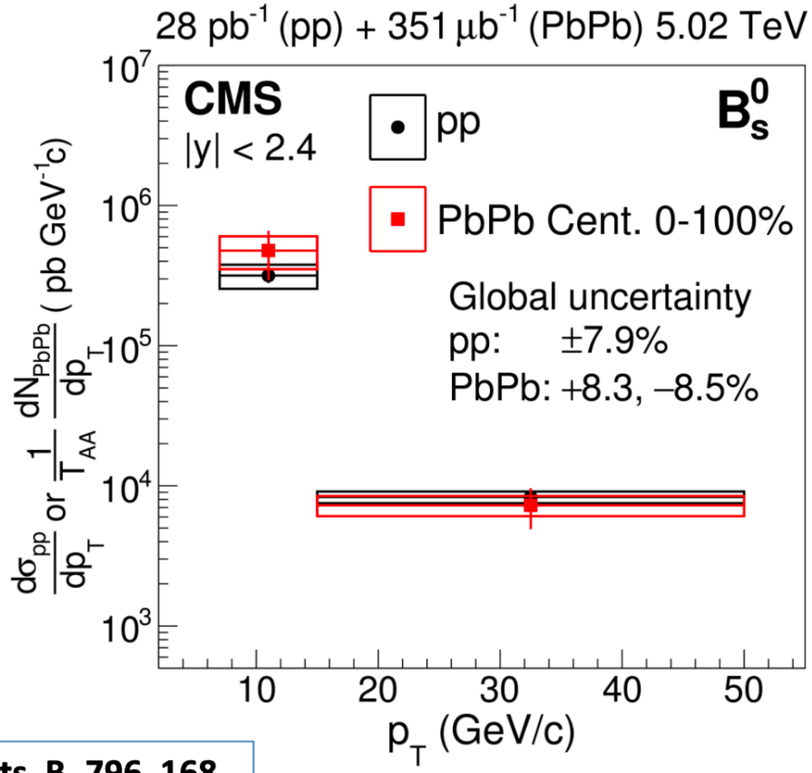
The measurement suggests some p_{T} dependence.

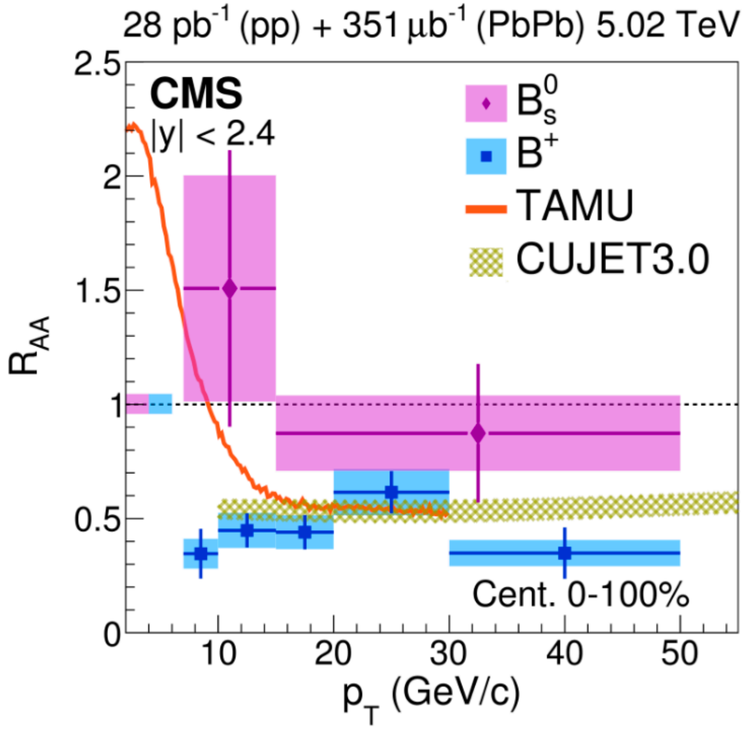




B^0_s measurements







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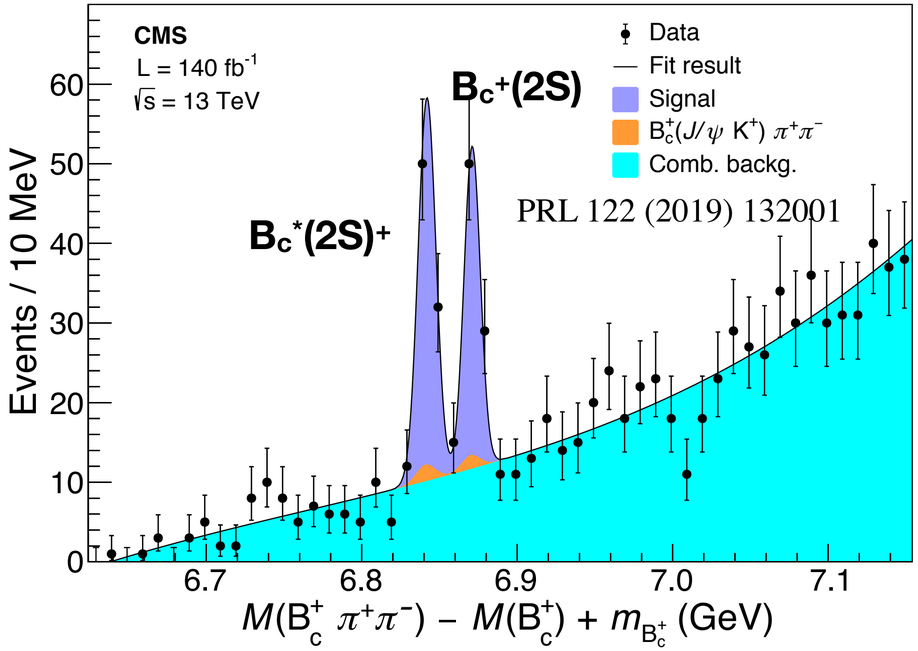
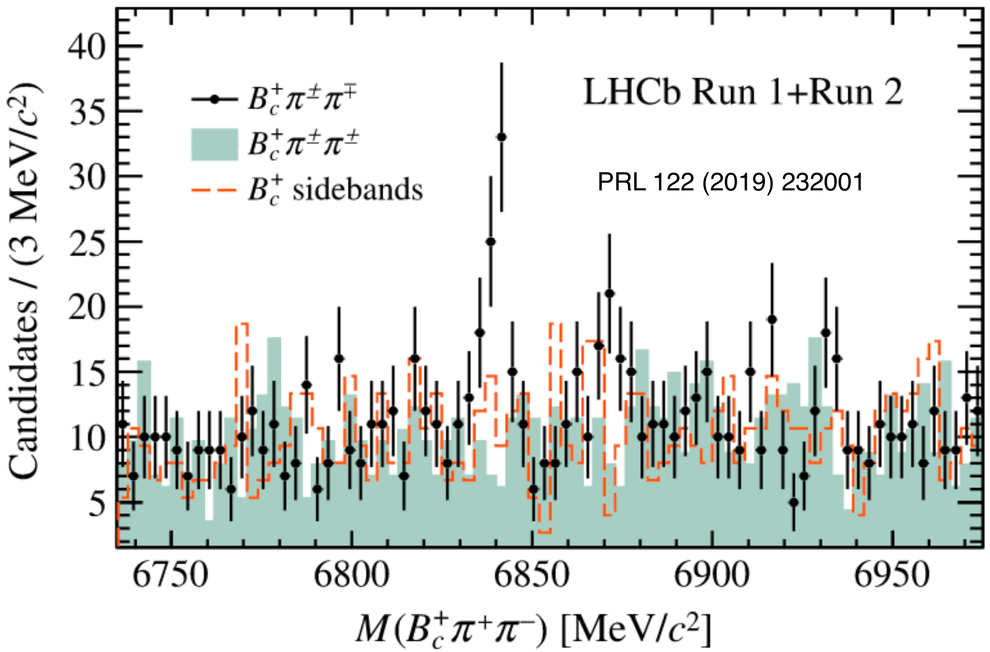
Excited beauty meson production: B_c



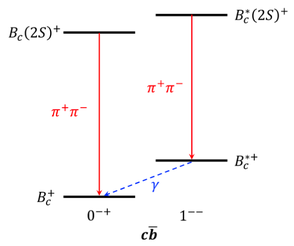
$N(B_c^*(2S)^+) = 67 \pm 10$

$N(B_c^+(2S)) = 51 \pm 10$



$N(B_c^*(2S)^+) = 51 \pm 10$

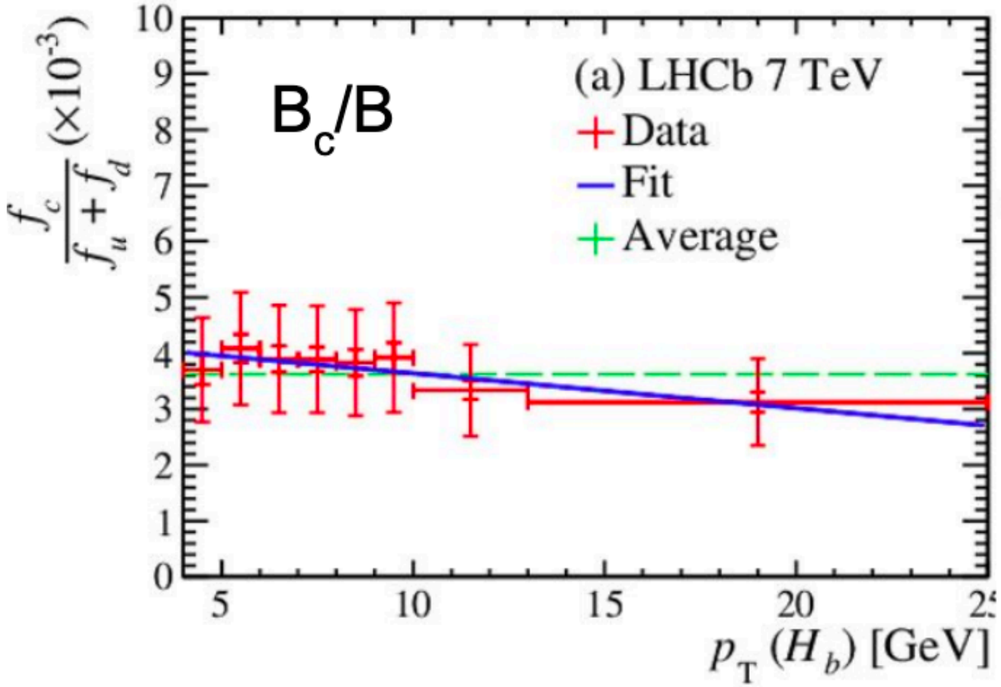
$N(B_c^+(2S)) = 24 \pm 9$

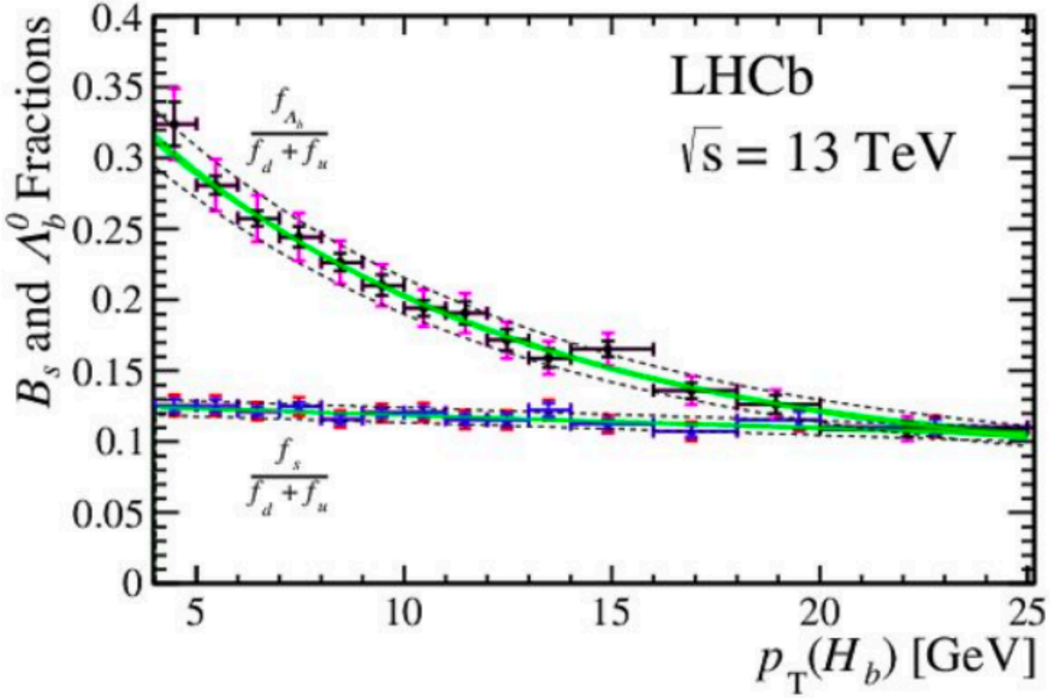


Particle	Predicted mass [MeV]
B_c^+	6247-6286
B_c^{+*}	6308-6341
$B_c^+(2S)$	6835-6882
$B_c^{*+}(2S)$	6881-6914

Mass and hyperfine splitting in agreement in the two experiments

Beauty meson and baryon fragmentation fractions

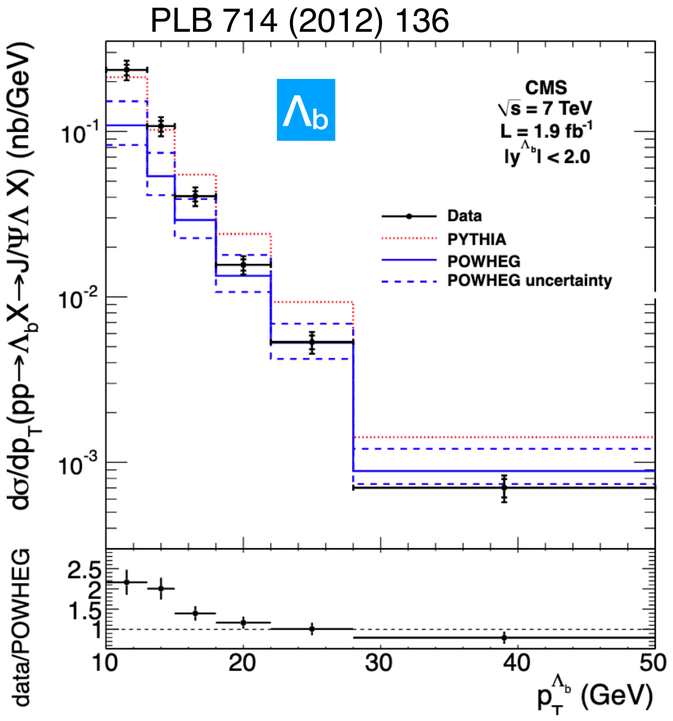


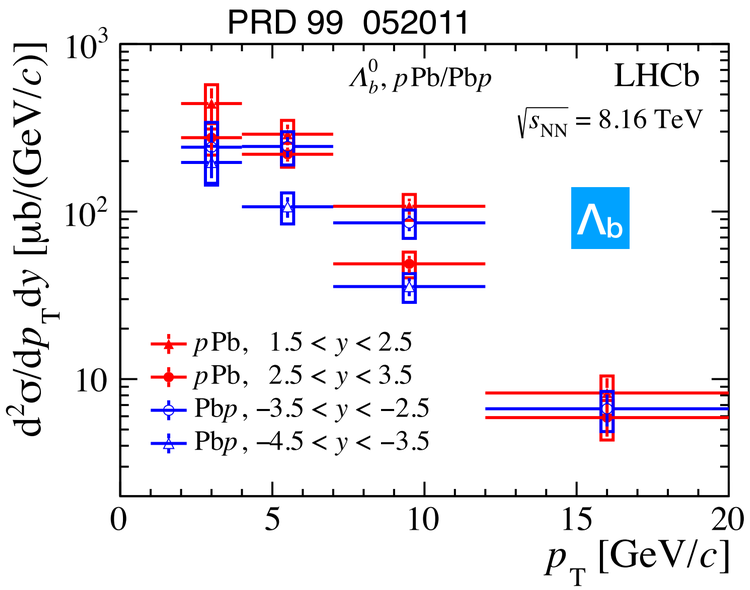


B_c mass >> Λ_b mass + requires another charm meson in the event (D mass >> p mass) → even stronger constraints to phase space from B_c than Λ_b

But **B_c/B shows a much milder p_T trend (if any)** → p_T trend not related to particle mass: does this support a baryon-related effect?

Charm and beauty baryon productions





Beauty baryons: **Λ_b measurements** performed by ATLAS, CMS and LHCb in pp and p-Pb collisions

baryon productions in CR beyond LC

J.R. Christiansen, P. Skands: JHEP 1508 (2015) 003

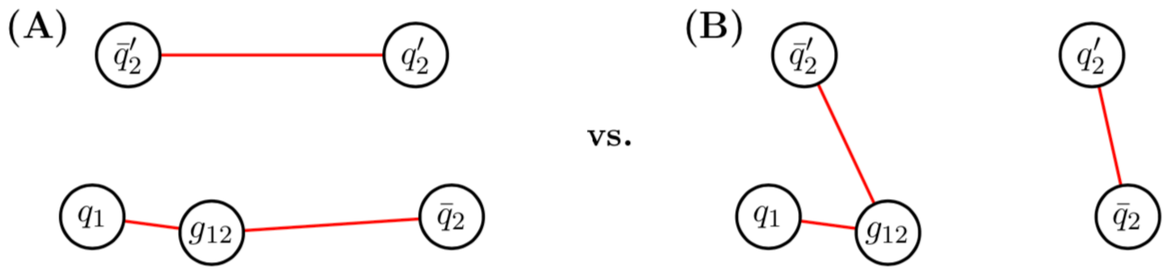


Figure 4. Illustration of a multi-parton state with a rather simple colour-space ambiguity. Subscripts indicate colour-space indices. *(A):* the "original" (LC) string topology. *(B):* an alternative string topology, allowed by the accidentally matching "2" indices.

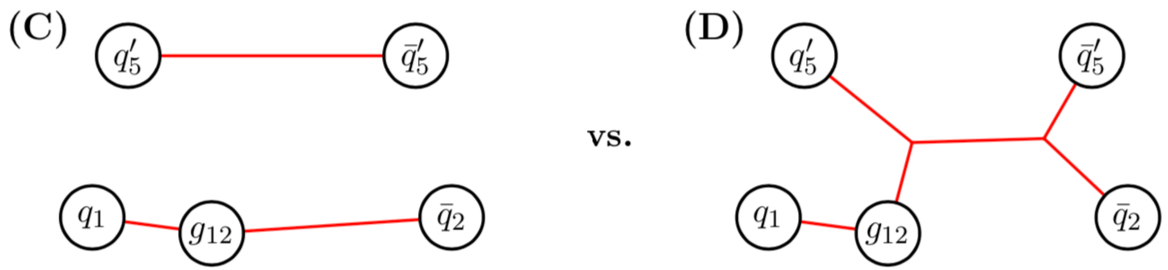
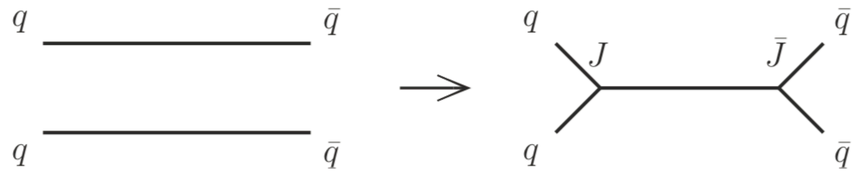
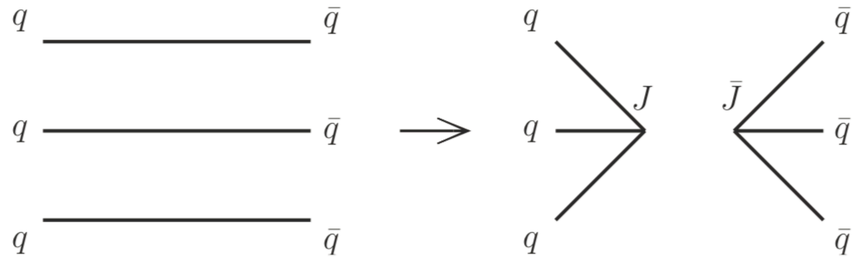


Figure 5. Illustration of a similar multi-parton state as in figure 4, but now with index assignments resulting in a junction-type colour-space ambiguity. The orientation of the top $q_5' - \bar{q}_5'$ dipole has also been reversed relative to figure 4. *(C):* the original (LC) string topology. *(D):* an alternative string topology with a junction and an antijunction, allowed by the cyclically matching "2" and "5" indices.

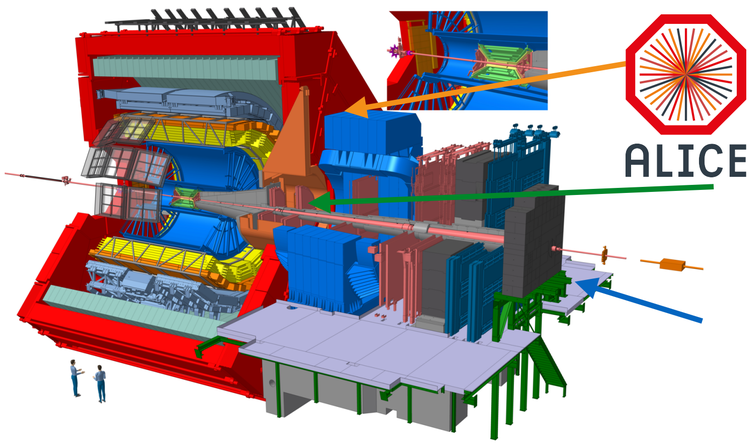


(b) Type II: junction-style reconnection

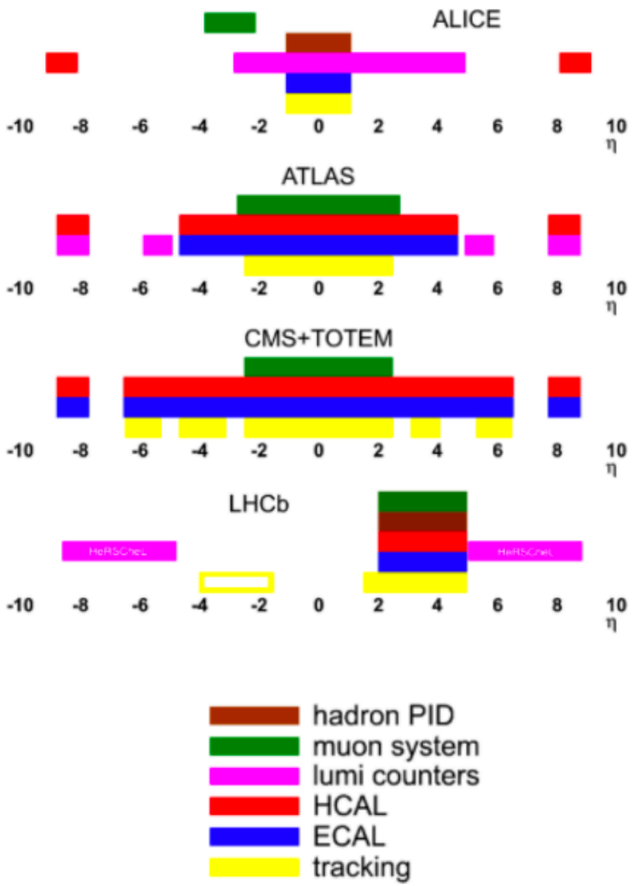


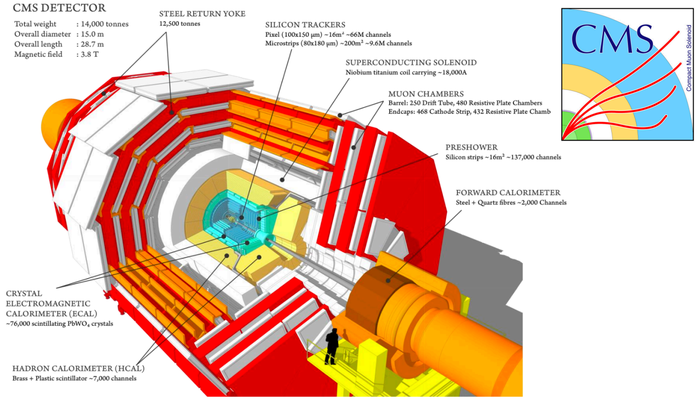
(c) Type III: baryon-style junction reconnection

Experiment uniqueness: complementarity of momentum and rapidity coverage

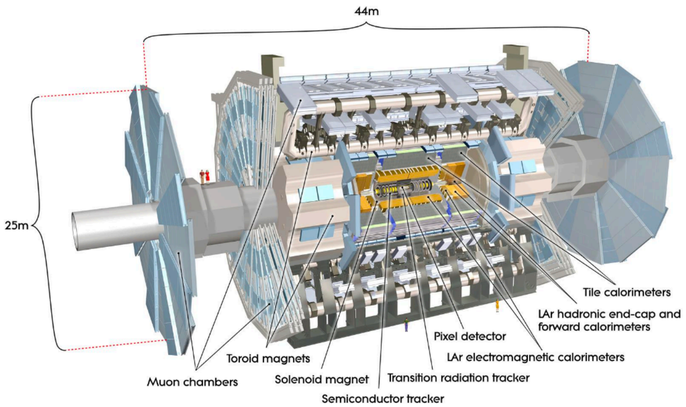


- Vertexing, tracking and PID at mid rapidity
- HF reconstruction down to $p_T = 0$



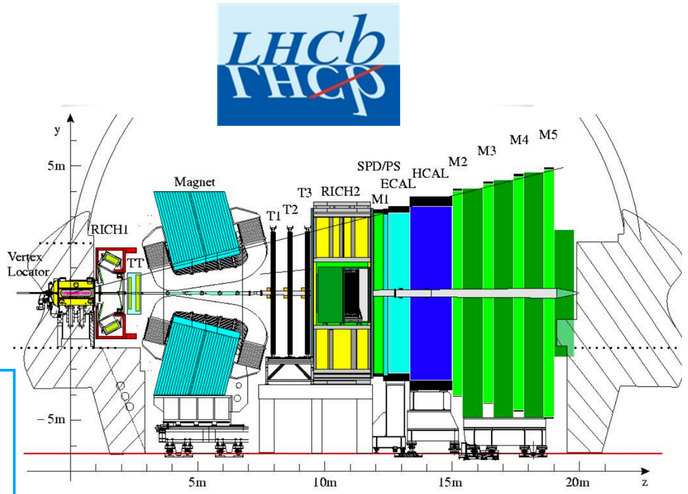


- Vertexing and tracking in a wide p_T range
- Dedicated triggers for open heavy flavor physics



ATLAS EXPERIMENT

- tracking, momentum and vertexing in a wide p_T range, in $|\eta| < 2.5$



- High p_T, mass resolution, vertexing reconstruction and PID at forward rapidity
- HF reconstruction down to $p_T = 0$