ALICE

Hadronisation studies at the LHC with ALICE

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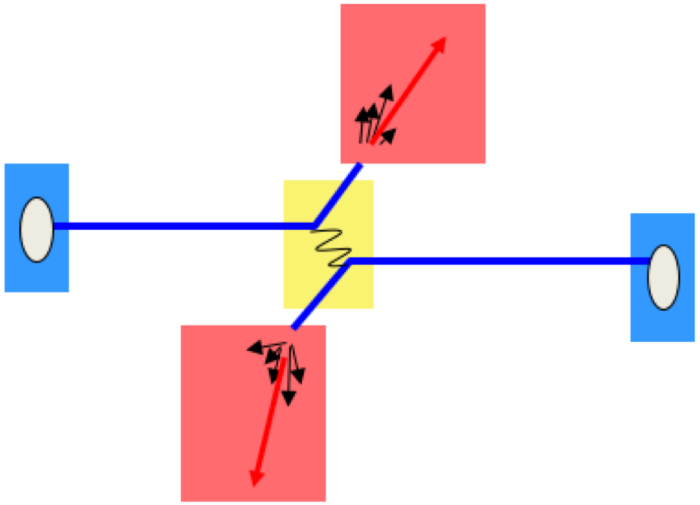
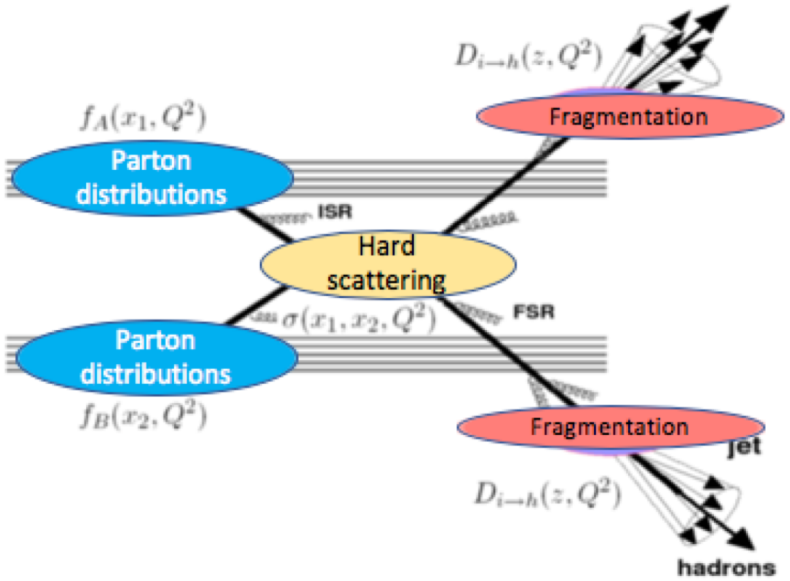
The boring "physics motivations slide"

The heavy-flavour production is a test of pQCD

- large quark mass provides hard scale
- pQCD can calculate cross sections down to low p_T



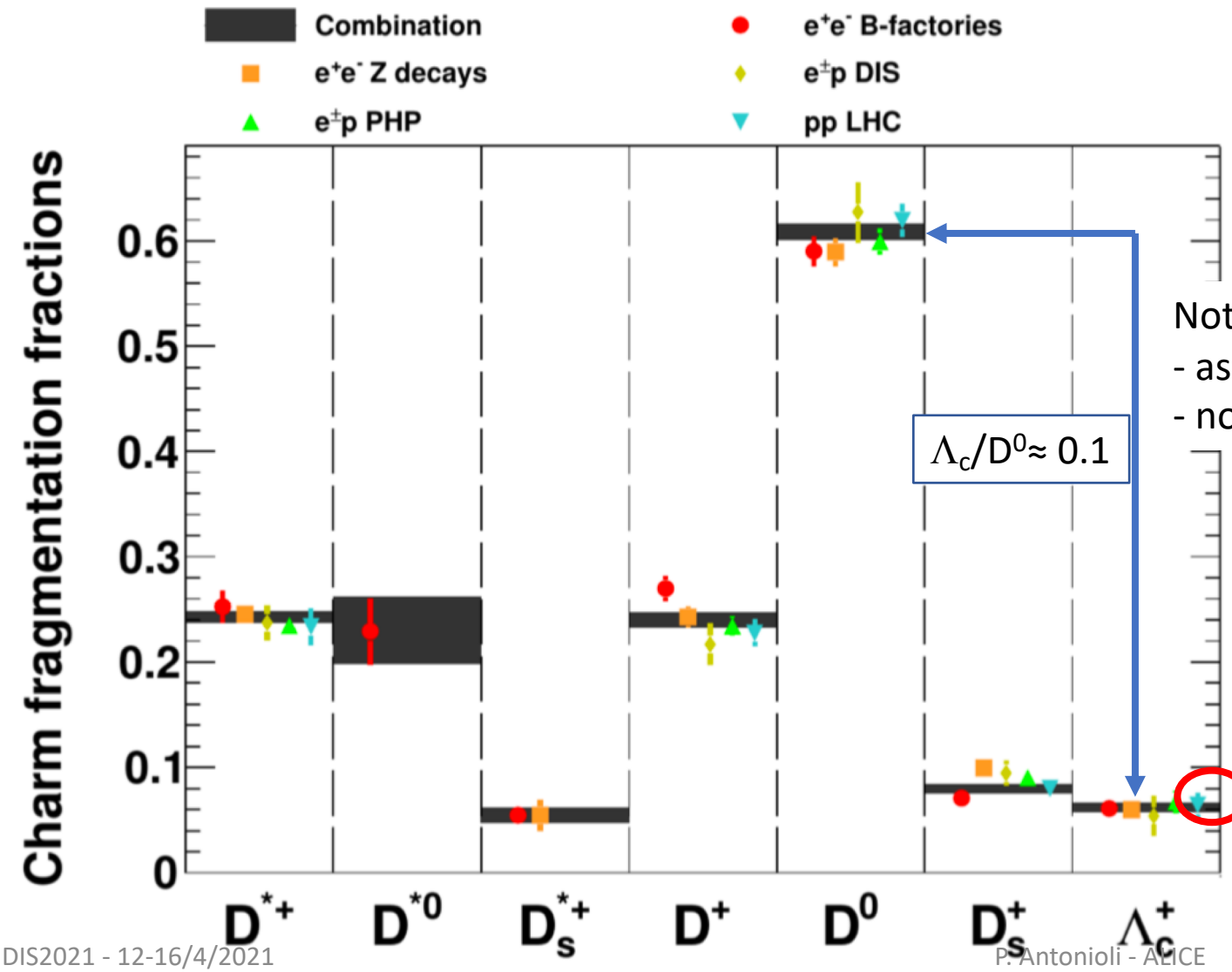


$$\frac{d\sigma^{h}_{pp}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd) \frac{D^{0}_{h/c}}{\pi z_c}$$

factorization of the QCD problem holds if the non-perturbative part can be “captured” in universal PDF and FF

Fragmentation functions and fractions: state of the art 2016

Lisovyii M. et al, EPJ C 76 (**2016**) no.7, 397



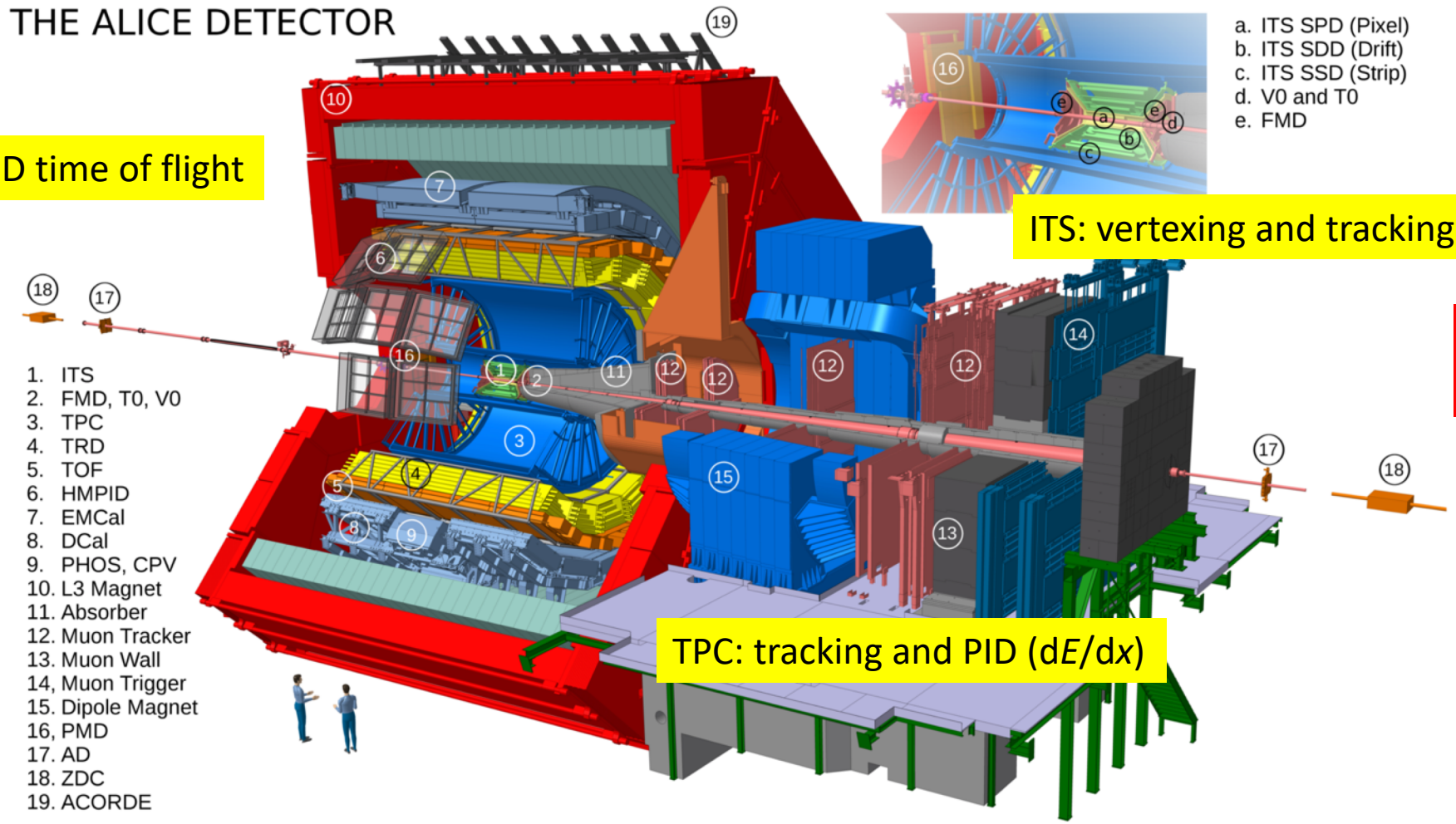
- global analysis that include e^+e^- (B factories and LEP), $e^{\pm}p$ (HERA)and pp (LHC) data
- very nice agreement across collision systems

Notes:
- assumptions on Ω_c and Ξ_c (based on light flavour sector)
- no p-A /π-A measurements included

2015 analysis, only LHCb Λ_c measurement available at LHC for baryons
Nucl. Phys. B871 (2013) 1

So... fragmentation is well understood....

ALICE detector can help for hadronization studies!



TOF: PID time of flight

ITS: vertexing and tracking

PID capabilities
low p_T reach

TPC: tracking and PID (dE/dx)

- charmed baryons studied in the central barrel $|y|<0.5$ in pp
- complementary to LHCb

Data samples and c-baryons @ALICE [RUN 2]

System	Year(s)	$\sqrt{s_{NN}}$(TeV)	L_{int}
Pb—Pb	2010,2011	2.76	~75 μb^{-1}
	2015	5.02	~0.25 nb^{-1}
	2018	5.02	~0.55 nb^{-1}
Xe—Xe	2017	5.44	~0.3 μb^{-1}
p—Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}; ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}; ~100 nb^{-1}; ~1.5 pb^{-1}; ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2018	13	~36 pb^{-1}

$D^0 \to K^-\pi^+$; $D^+ \to K^-\pi^+\pi^+$; $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$;
$D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$
(fully reconstructed hadronic decays)

$\Lambda_c^+ \to pK^-\pi^+$; $\Lambda_c^+ \to pK^0_s$
$\Sigma_c^{0,++} \to \Lambda_c^+ + \pi^{-,+}$
$\Xi_c^0 \to \Xi^-\pi^+$, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$
(fully reconstructed hadronic decays)

RUN 1 & 2

RUN 2

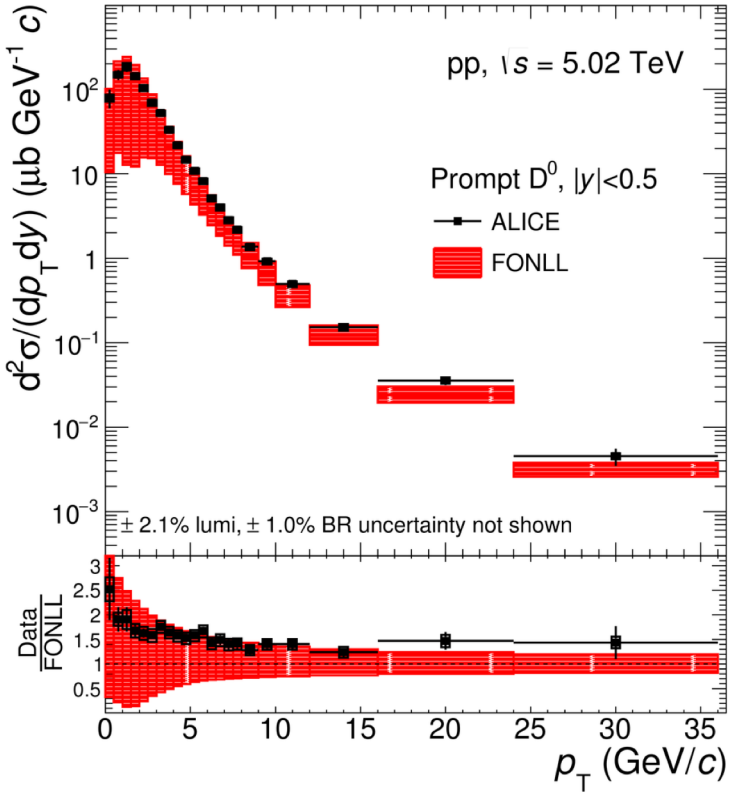
$\Lambda_c^+ \to e^+\Lambda\nu_e$; $\Xi_c^0 \to e^+\Xi^-\nu_e$
(partially reconstructed semi-leptonic decays)

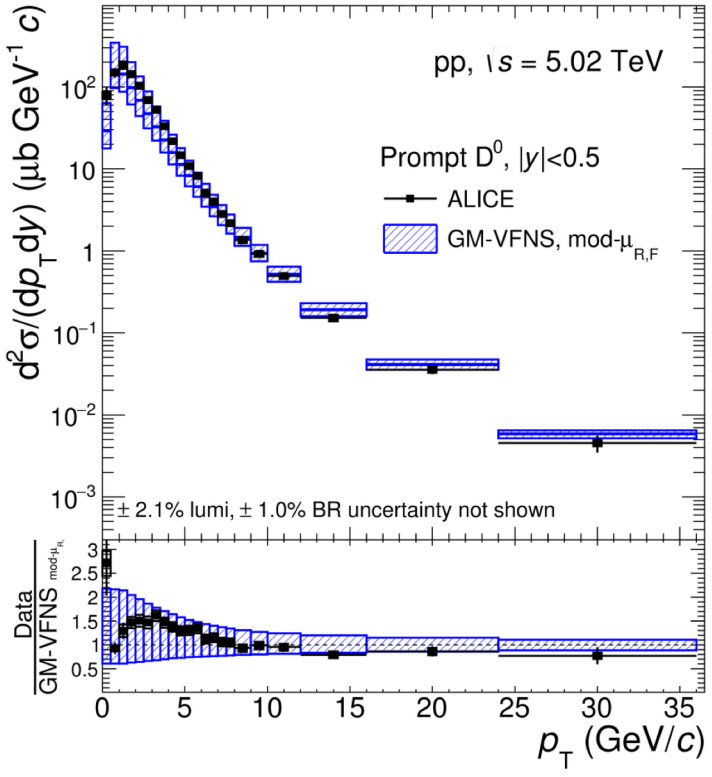
- charmed mesons
- charmed baryons

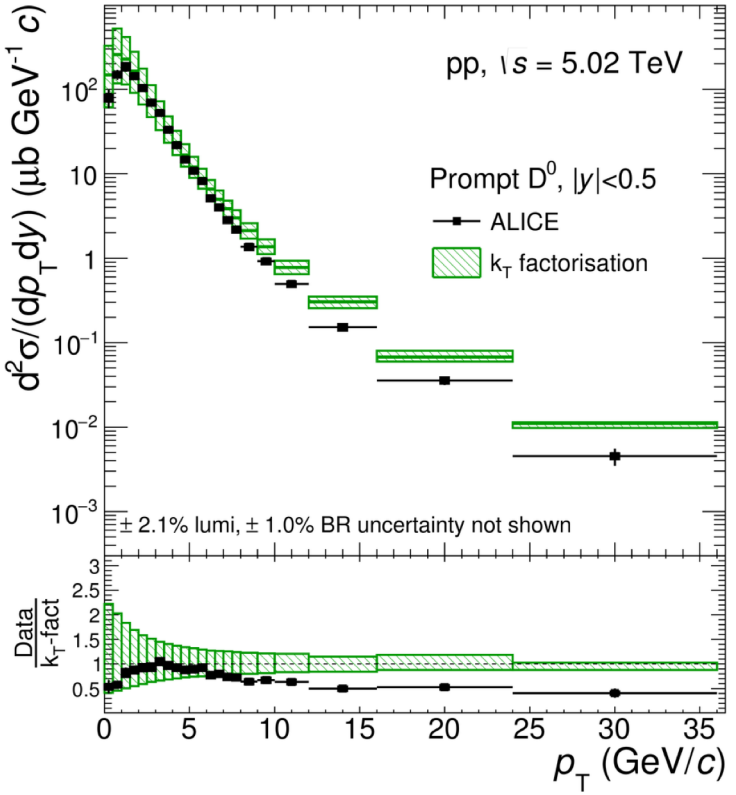
→baryon-to-meson ratio sensitive to hadronization
→Λ/K^0 ratio gives "a LF reference"

D mesons are candles here

EPJ C79 5 (2019) 388 (previous measurements at 7 TeV in backup)



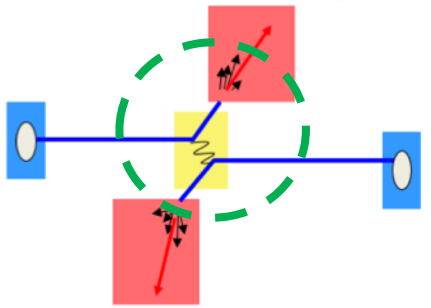




wide p_T range / cross section measured down to p_T = 0 for D^0 meson. Comparison with:

- FONLL (Fixed Order with Next to Leading Log resummation): Cacciari et al., JHEP 1210 (2012) 137
- GM-VFNS (General Mass Variable Flavour Number Scheme): Kniehl et al., EPJ C72 (2012) 2082
- k_T-factorization (LO accuracy + unintegrated gluon distribution function): Maciula, Szczurek, PRD 87 (2013) 094022)

FONLL: describes data within uncertainties, central value *below* data
GM-VNFS: the same, (updated calculations: central value *below* data)
k_T: data overstimated above p_T>10 GeV/c

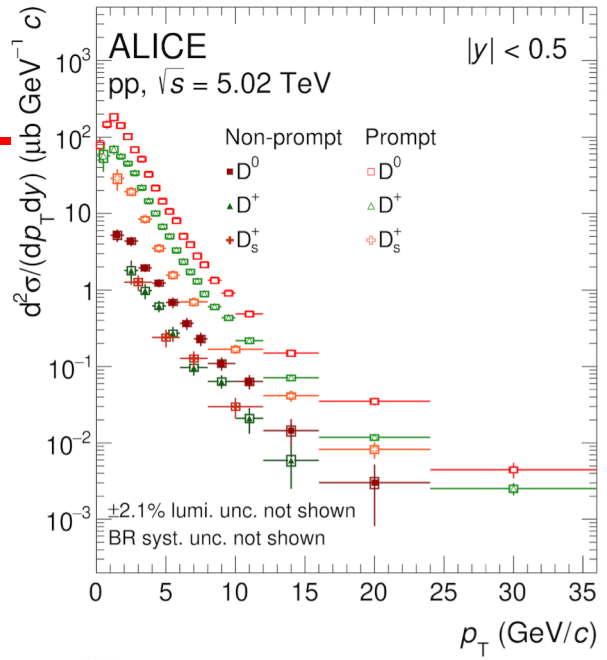


non-prompt component: pp at $\sqrt{s_{NN}}$ =5.02 TeV

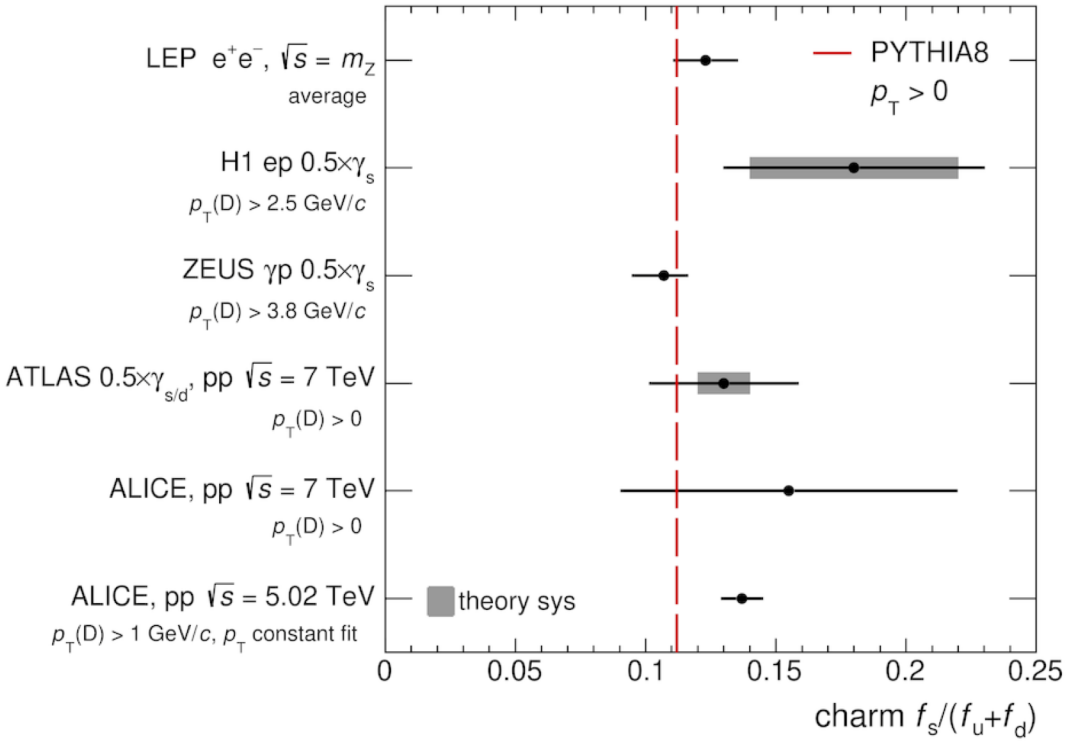
arXiv:2102.13601 (submitted to JHEP)

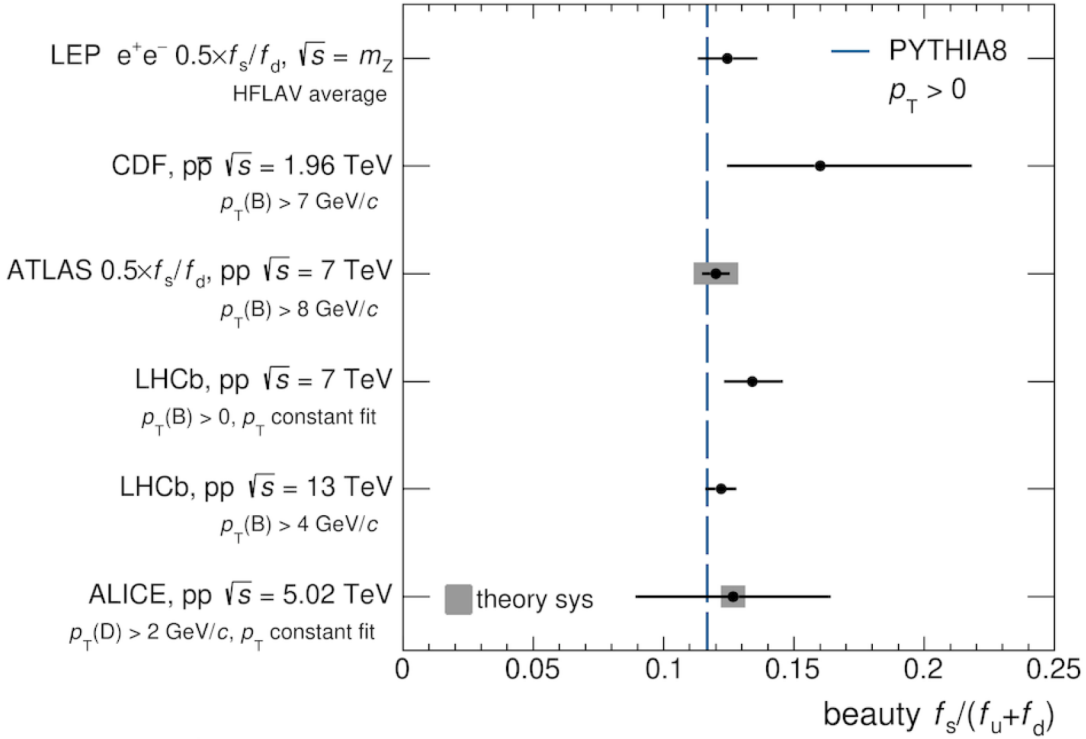
Recently on arXiv

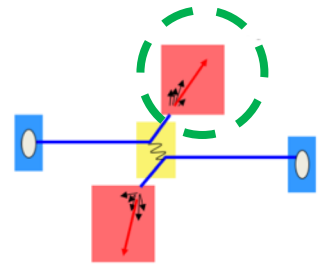
- Measurement of non-prompt component using ML and data-driven techniques
- f_s / (f_u+f_d) fragmentation fractions of HQ to strange/non-strange mesons compatible with previous measurements (different s and collision system)
- General agreement with pQCD calculations (FONLL/GM-VFNS)



More → F. Grosa talk this morning





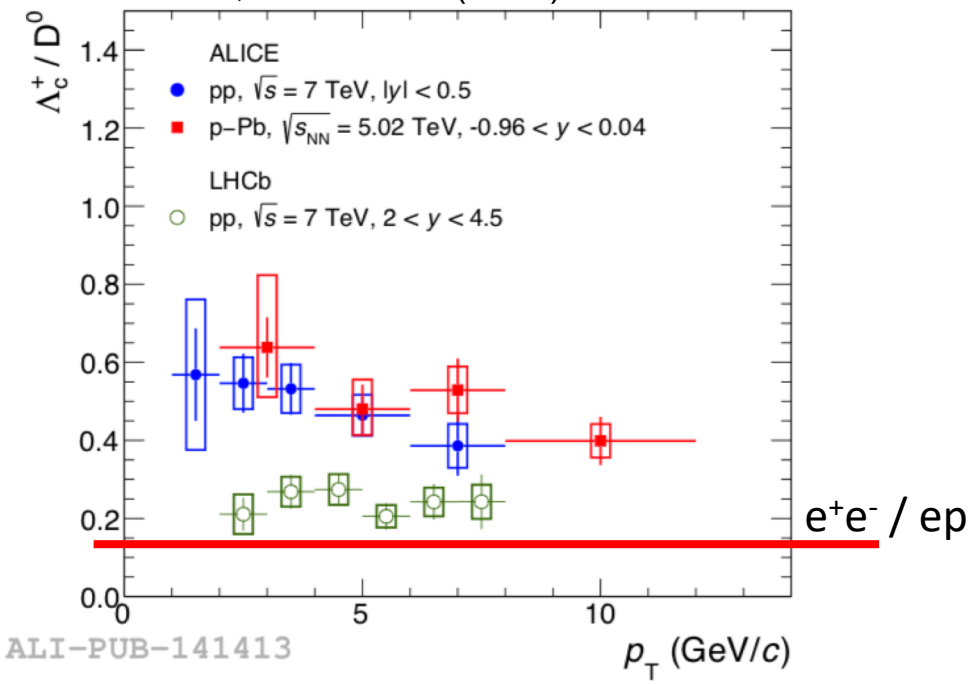


ALI-PUB-482597

ALI-PUB-482601

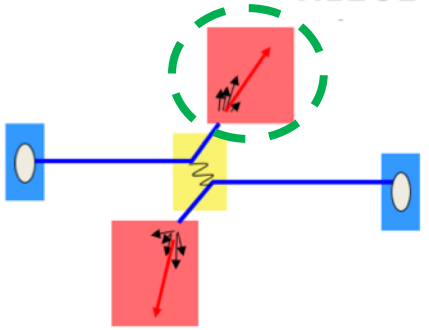
Baryon-to-meson ratio as a probe of our understanding of hadronization, but...

ALICE, JHEP 1804 (2018) 108



e^+e^- / ep

	$\Lambda_c^+/D^0 \pm$ 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



"fragmentation to heavy-flavour baryons is **not** well understood"

- no drastic change between pp and p—Pb
- "tension" with LHCb but at different rapidity + we have now CMS result + LHCb p—Pb result
- "supertension" with e^+e^- and ep results (that are p_T integrated though)

Do the **√*s*** and/or **the collision system** play a role here?
Remember f(b→Λ_b) at Tevatron/LHC vs LEP

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].

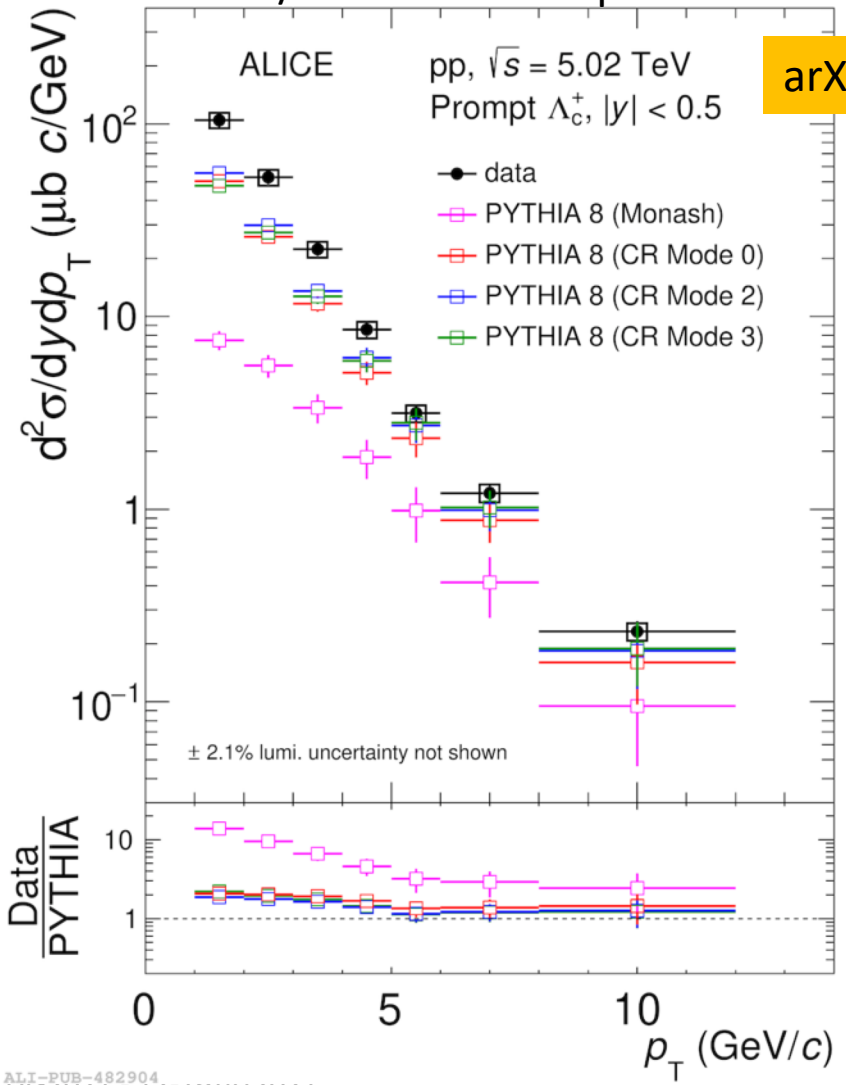
b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7

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

Baryon-to-meson ratio with RUN2 data: Λ_c/D^0 pp at $\sqrt{s}$ =5.02 TeV

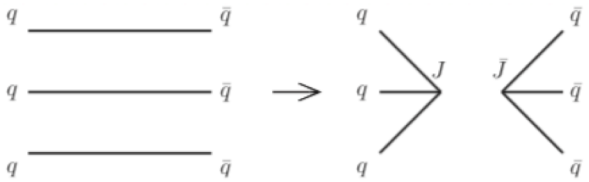
- "anomalous" Λ_c/D^0 ratio seen in RUN1 fully confirmed
- Models with enhanced CR mechanisms closer to data
- POWHEG/GM-VFNS undepredict data (see backup)

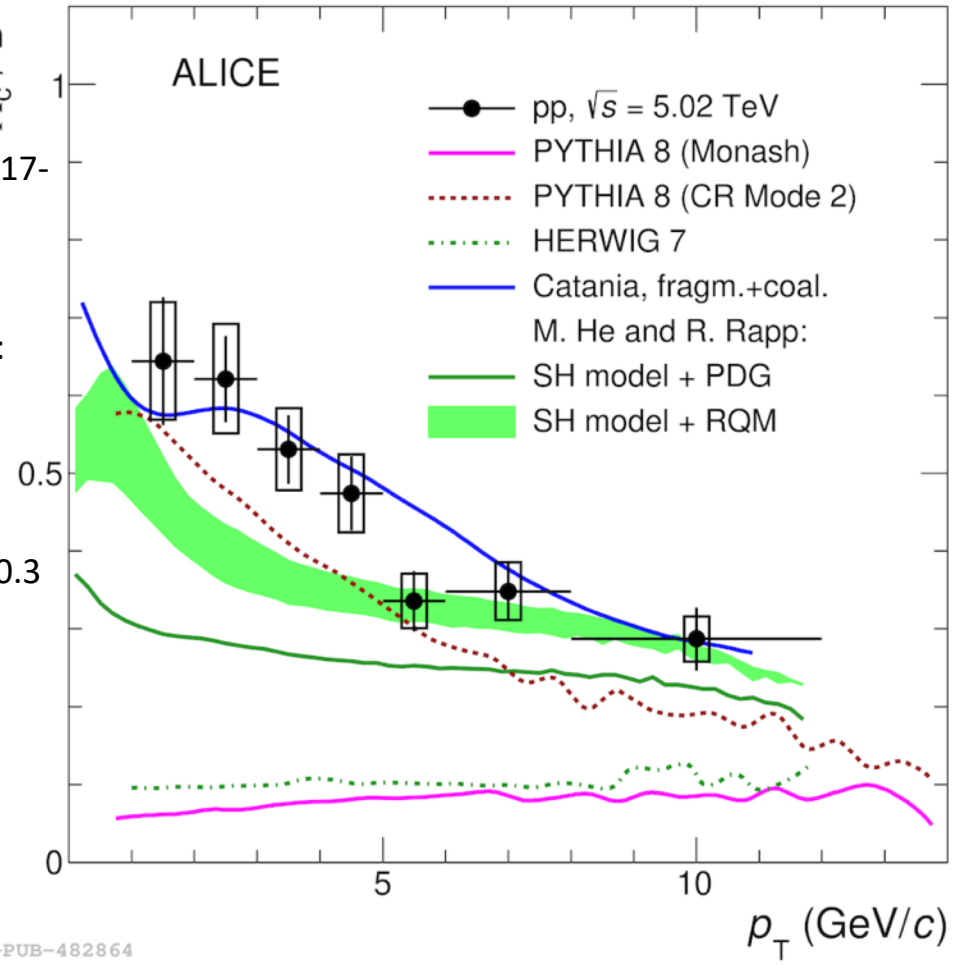
arXiv:2011.06078 (submitted to PRL)



arXiv:2011.06078 (submitted to PRC)

- M. He and R. Rapp, Phys.Lett. B795 (2019) 117-121: SHM + feed down from standard states (PDG) or unobserved higher mass resonant states (RQM)
- Catania: S. Plumari et al. EPJ C78 (2018) 348: fragmentation + coalescence
- CR Mode 2 → J. Christiansen and P. Skands, JHEP 08 (2015) 003: enhanced CR mechanisms with 3-leg junctions
- CMS result on Λ_c/D^0: PLB (2020) 135328 ≅ 0.3





and some common pattern emerges between light-flavour and heavy-flavour hadronisation

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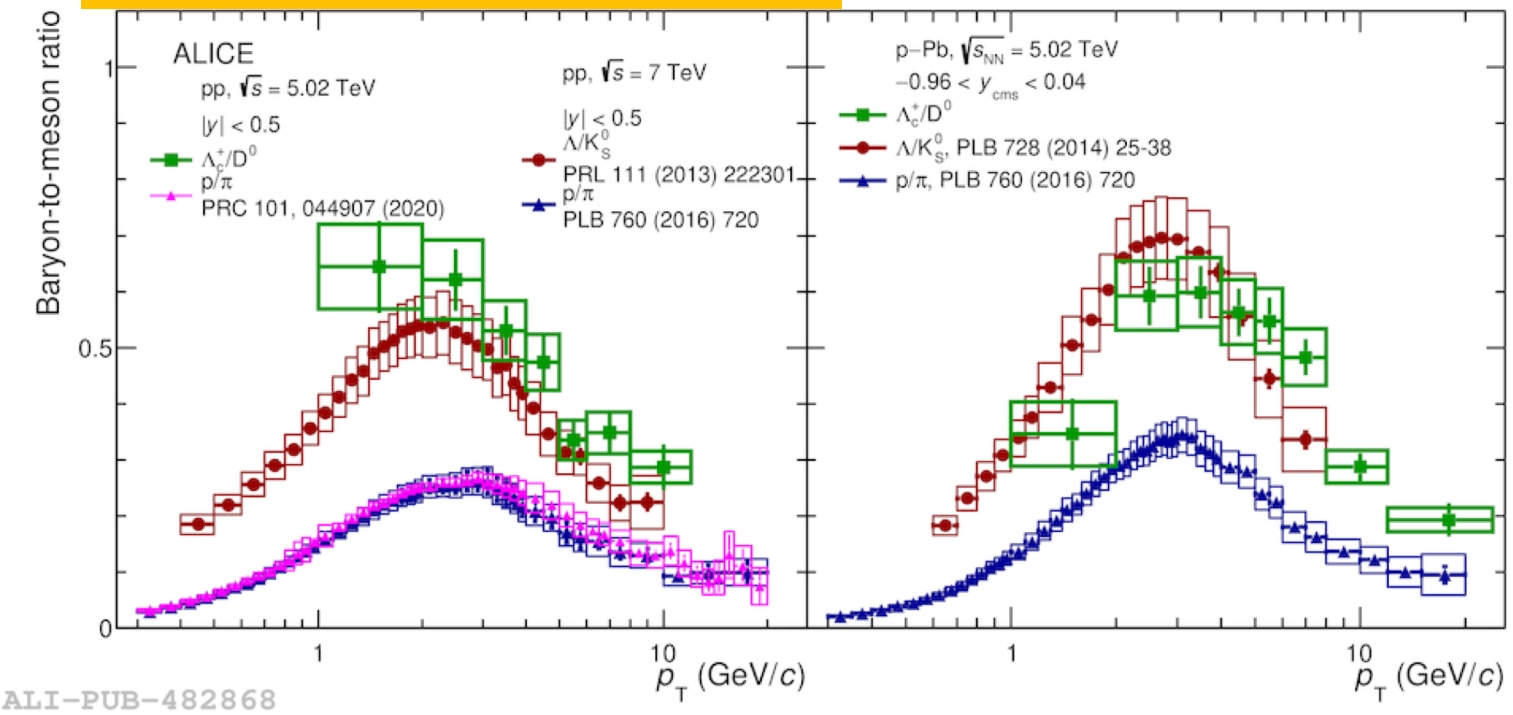

baryon production increases at intermediate p_T

note in HF sector hadronisation is quite different due to the hard scale (the c/b quark produced in the hard scattering not in the fragmentation)

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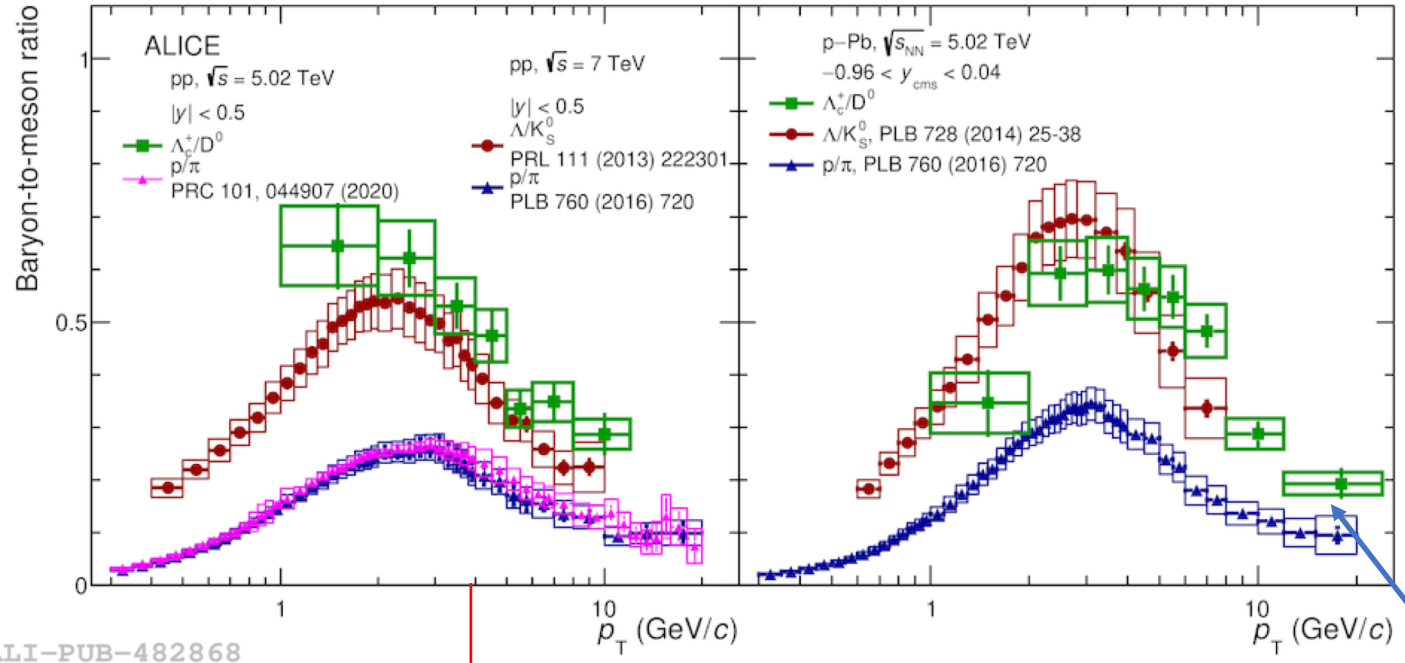
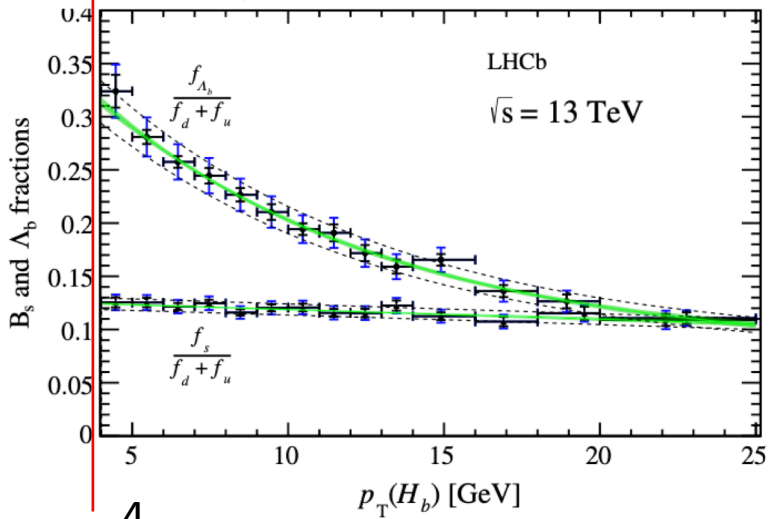
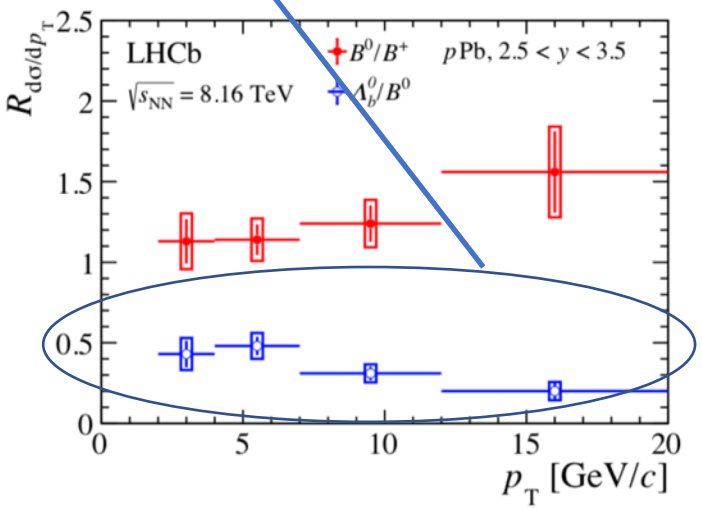






baryon production increases at intermediate p_T

note in HF sector hadronisation is quite different due to the hard scale (the c/b quark produced in the hard scattering not in the fragmentation)

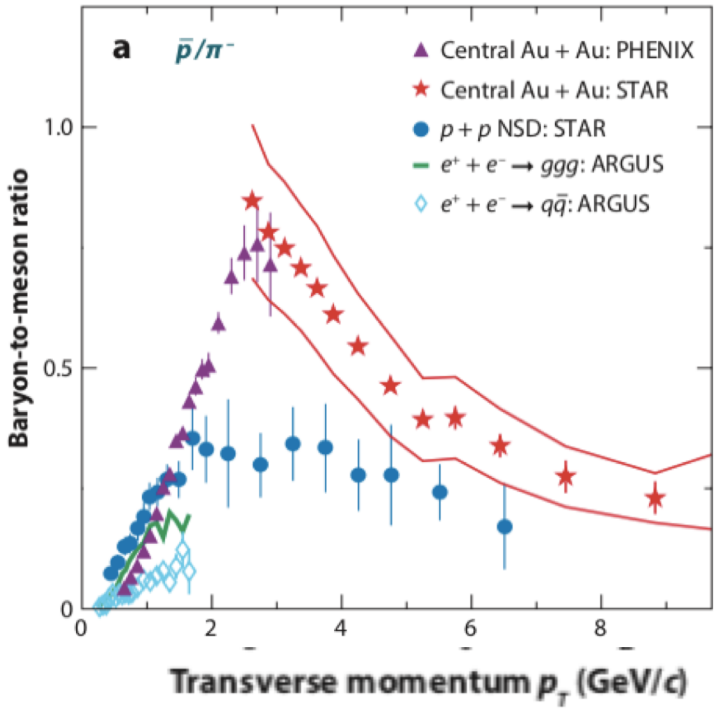
- note also LHCb results with Λ_b over B mesons

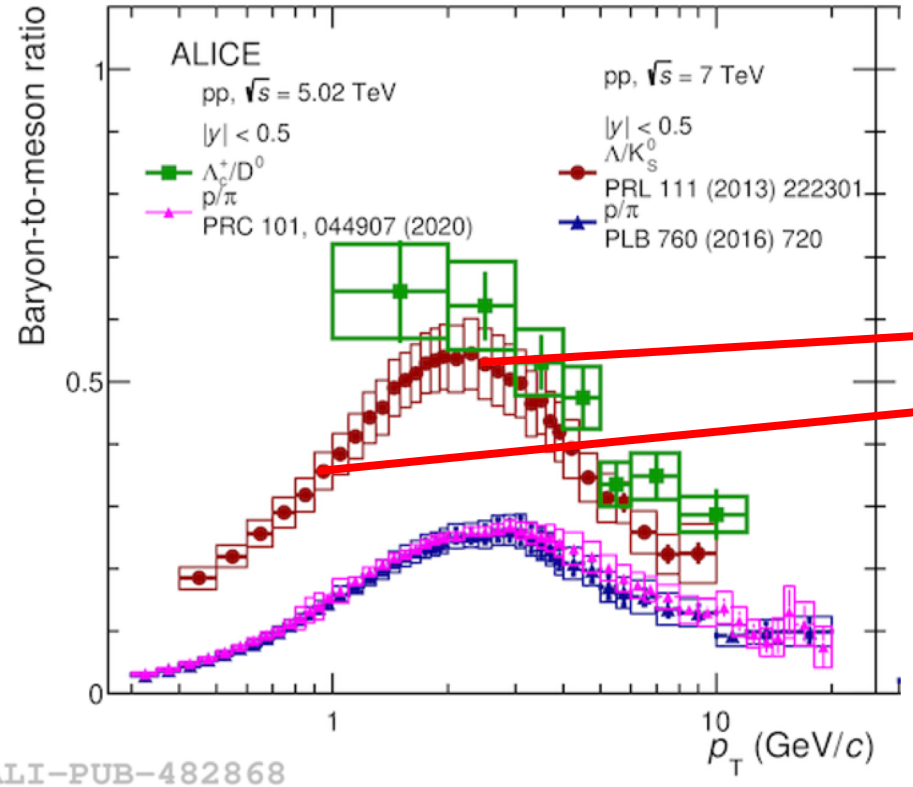
LHCb, Phys.Rev. D100 (2019) 031102 (pp)
LHCb, Phys. Rev. D99, (2019) 052011 (p—Pb)

CAVEAT:
For completeness don't forget LHCb in pp ($\Lambda_c/D^0 \approx 0.25 \pm 0.05$)
and p—Pb ($\Lambda_c/D^0 \approx 0.35 \pm 0.05$)!

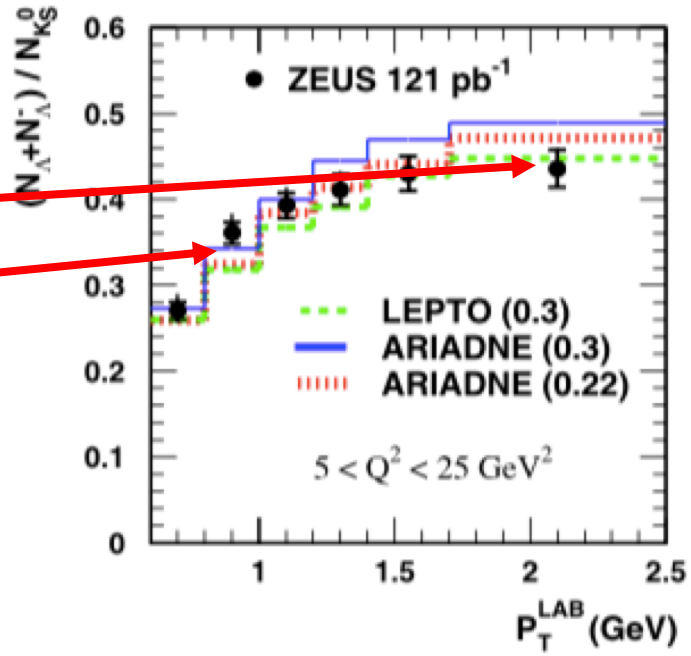
Note in e^+e^- and ep (DIS!) for the LF sector this was already there...

R. Fries et al. Ann.Rev.Nucl.Part.Sci 58 (2008) 177



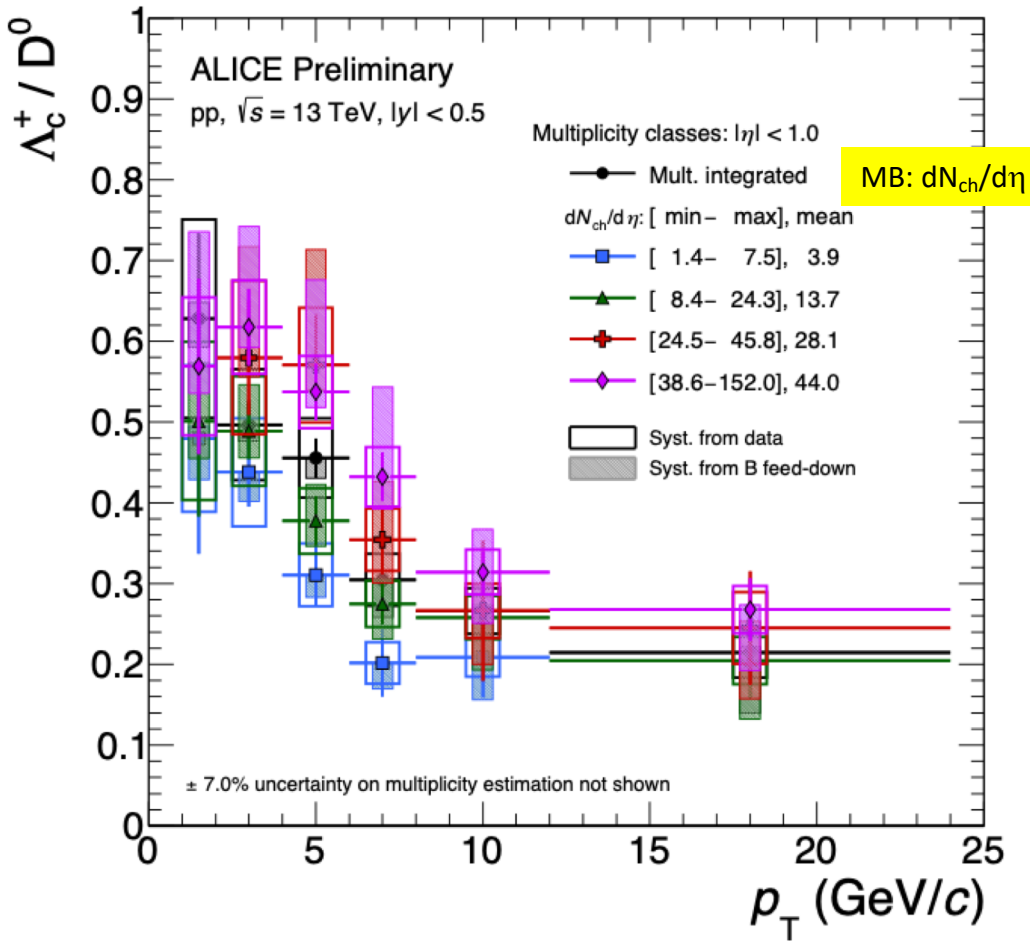


ZEUS, Eur. Phys. J. C 51, 1–23 (2007)



- in e^+e^- (ep) baryon-to-meson measurements limited to p_T <2 (2.5) GeV/c
- in vacuum, fragmentation function (Albino et al., NPB 803 (2008)) predicts < 0.25 for baryon-to-meson ratio
- larger values seen already at HERA in strange sector

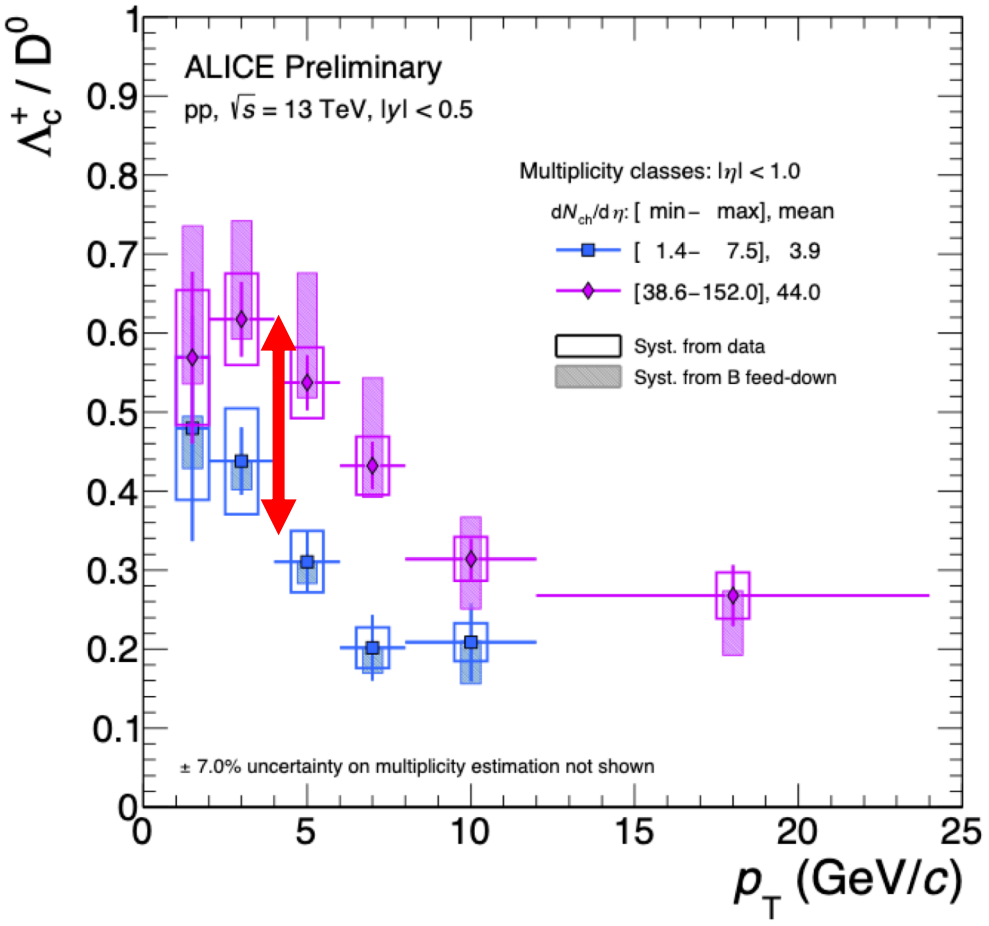
pp at $\sqrt{s} = 13$ TeV: a more differential study on final state (multiplicity)



MB: $dN_{ch}/d\eta \sim 7$

- number of "tracklets" reconstructed in the Silicon Pixel as multiplicity estimator

pp at $\sqrt{s} = 13$ TeV: a more differential study on final state (multiplicity)



- number of "tracklets" reconstructed in the Silicon Pixel as multiplicity estimator
- indications that the "enhancement" depends on multiplicity

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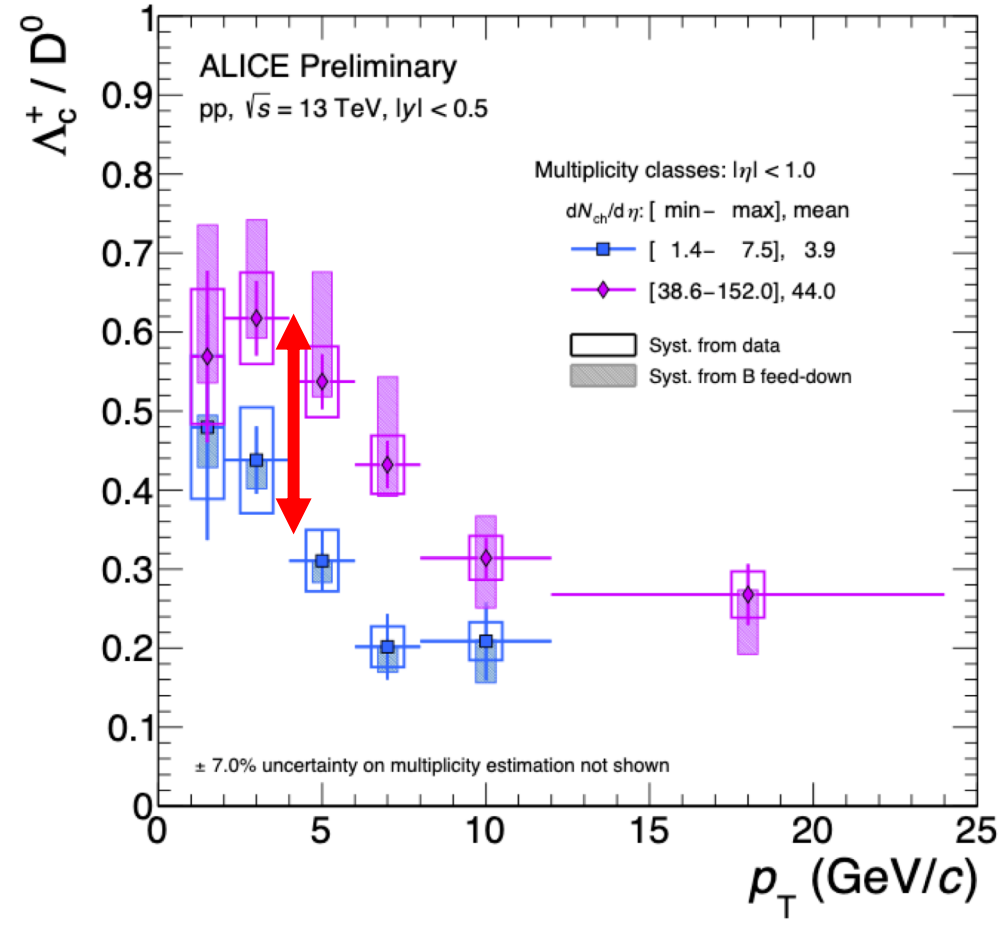
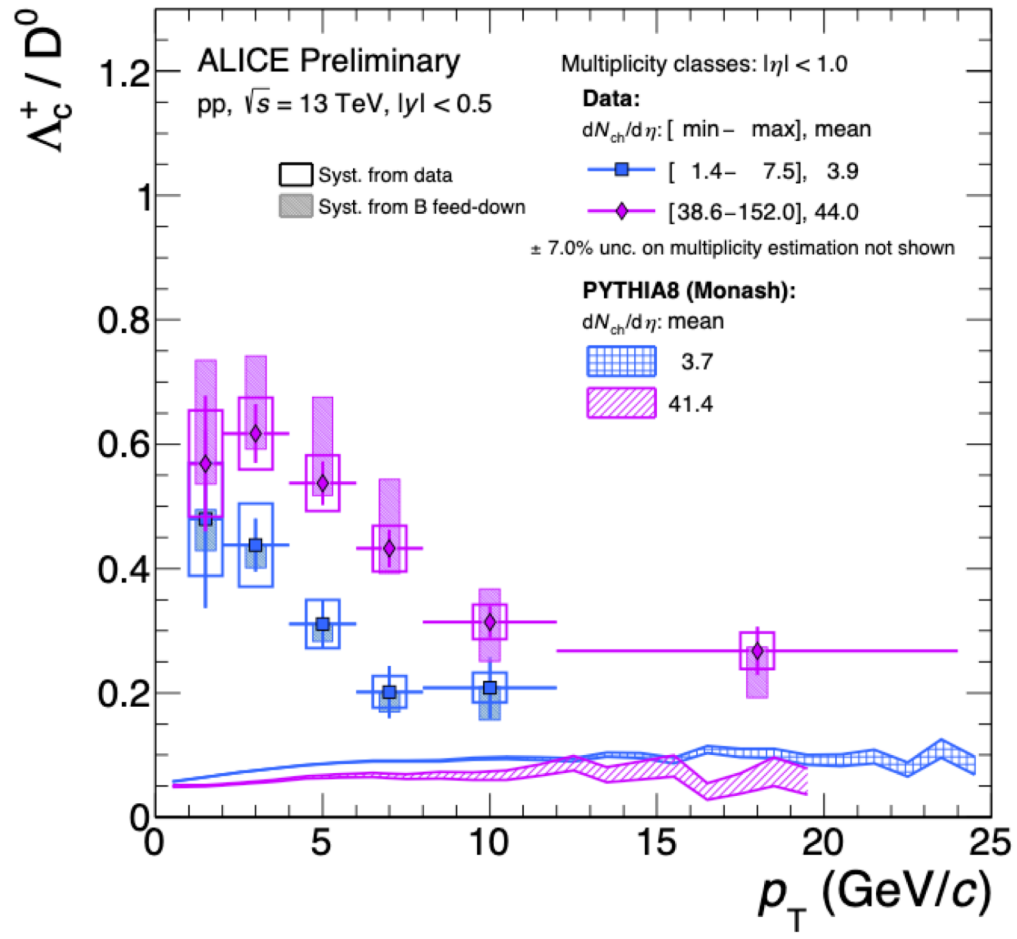


ALI-PREL-336418

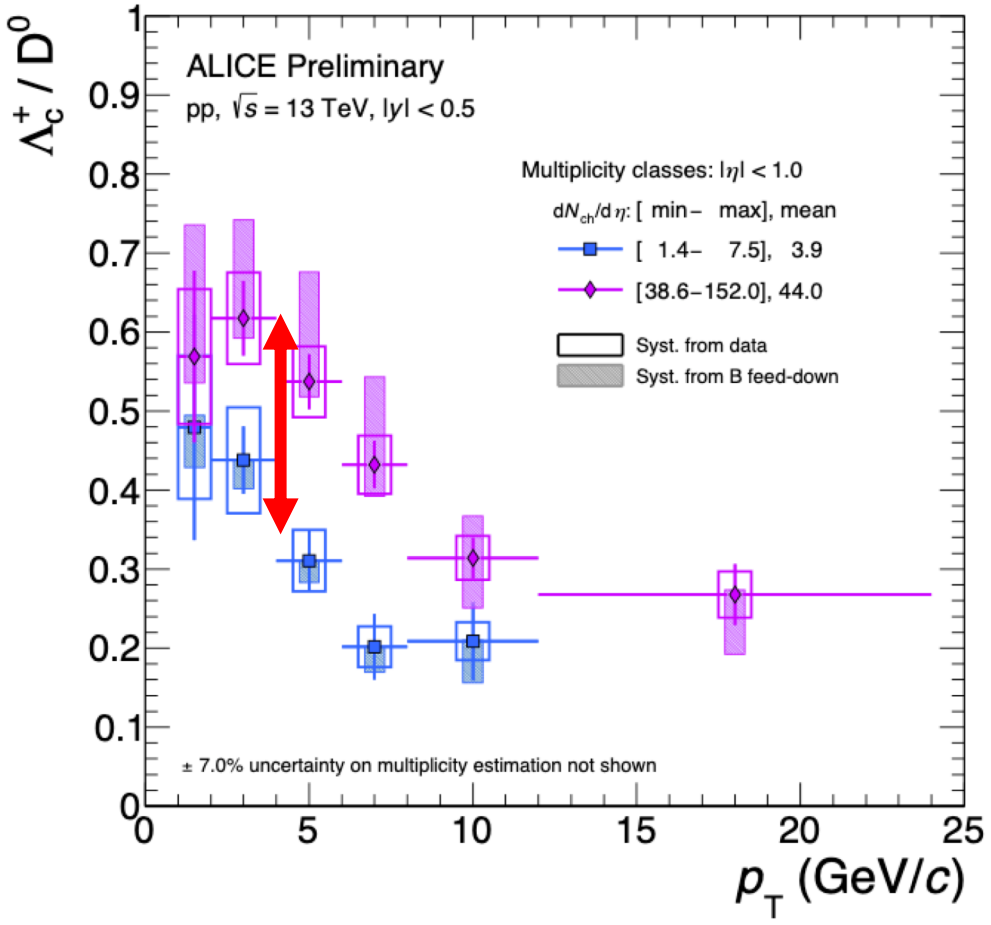


ALI-PREL-336426

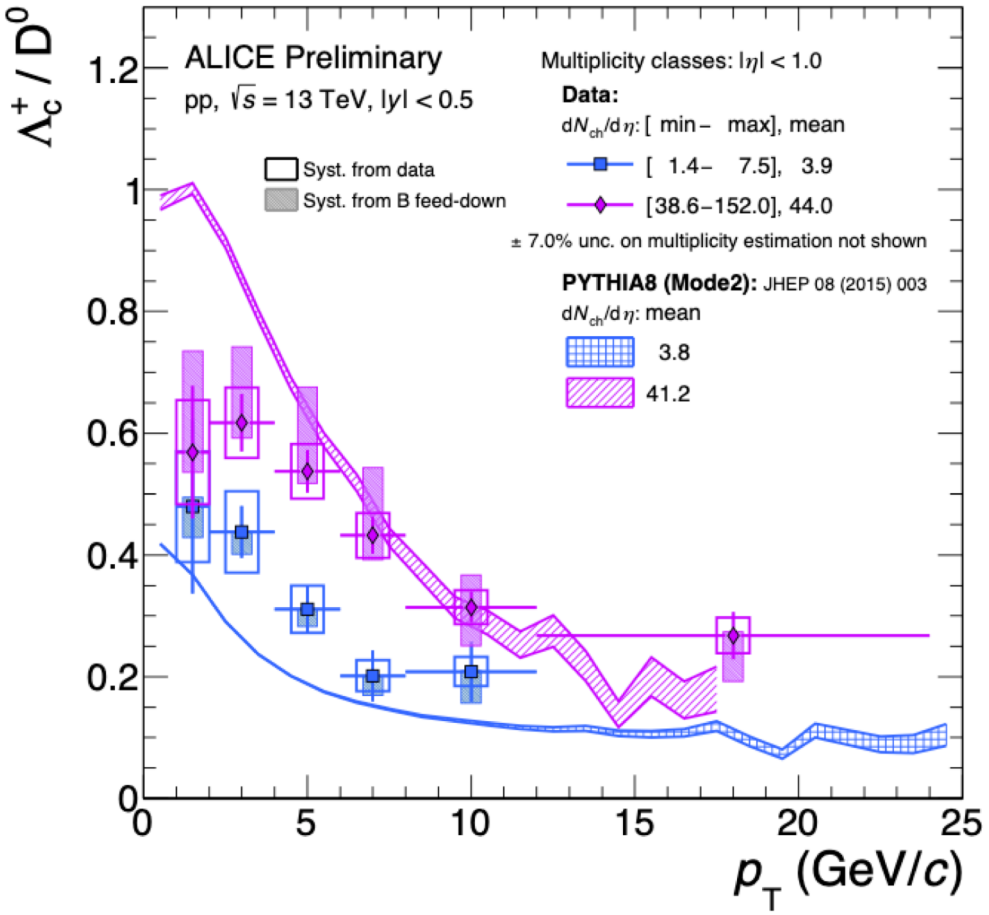
- number of "tracklets" reconstructed in the Silicon Pixel as multiplicity estimator
- indications that the "enhancement" depends on multiplicity

- Monash tune doesn't reproduce the pattern

pp at $\sqrt{s} = 13$ TeV: a more differential study on final state (multiplicity)



ALI-PREL-336418

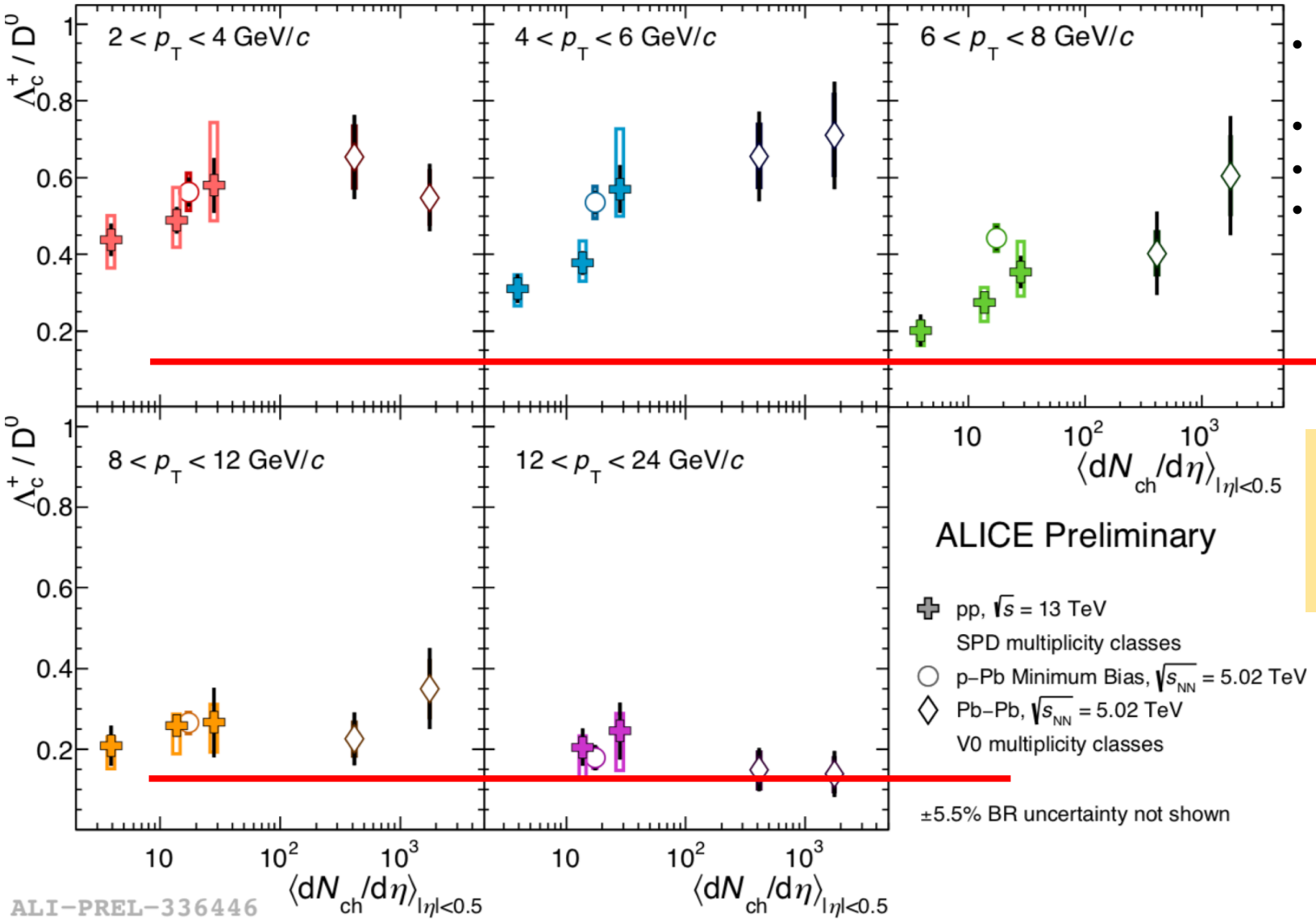


ALI-PREL-336434

- number of "tracklets" reconstructed in the Silicon Pixel as multiplicity estimator
- indications that the "enhancement" depends on multiplicity

- Monash tune doesn't reproduce the pattern
- enhanced CR mechanisms shows much better agreement

Λ_c/D^0 vs multiplicity across colliding systems

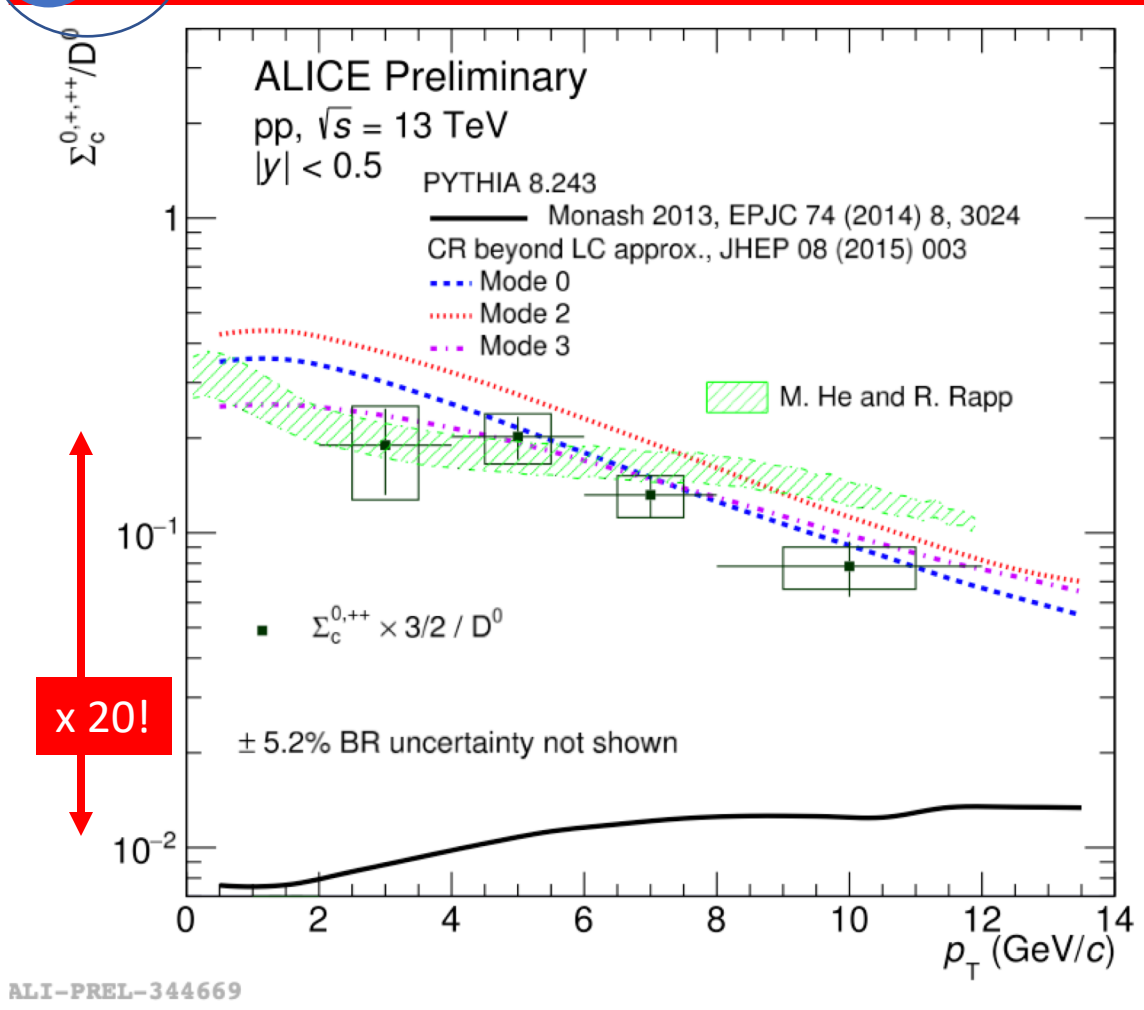


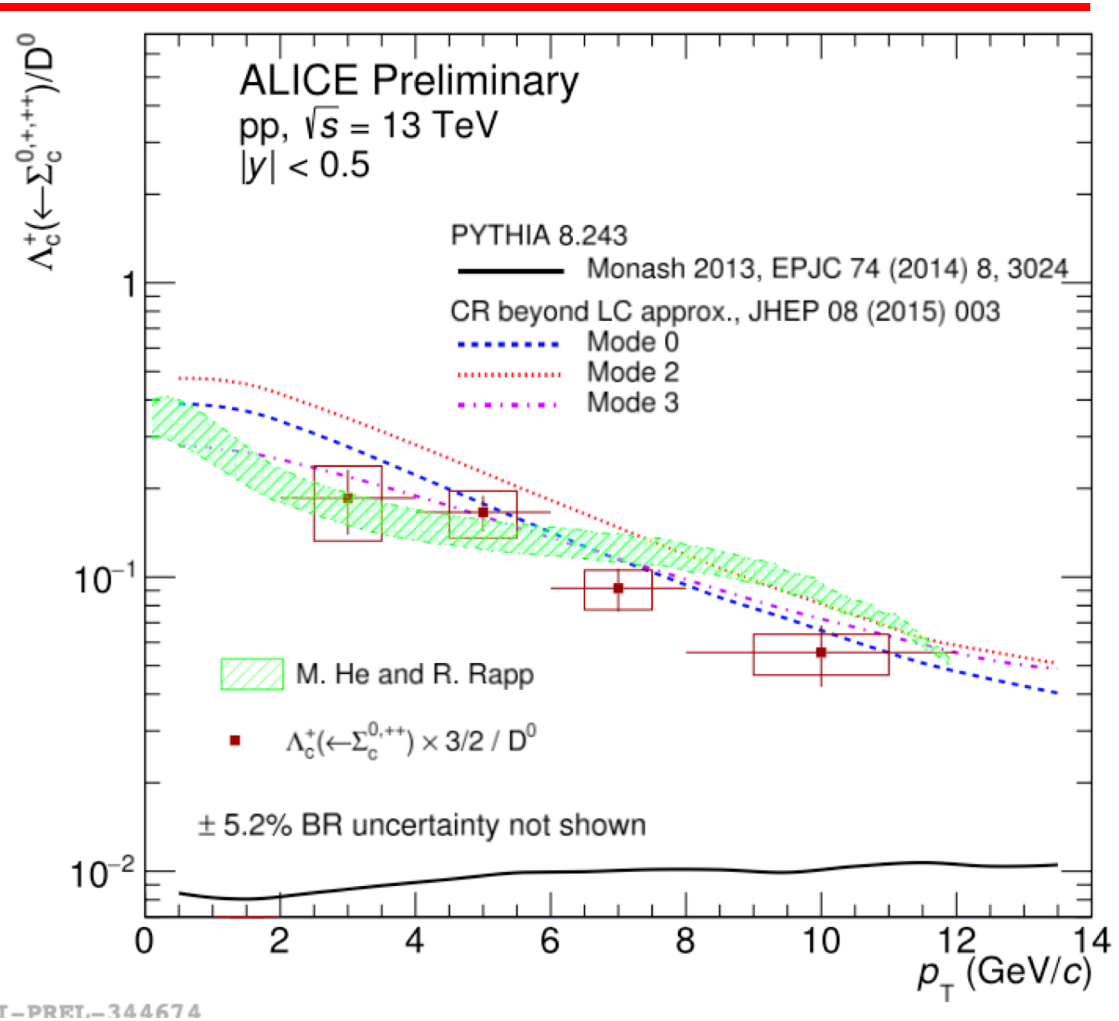
- increase at intermediate p_T from pp to Pb—Pb multiplicities
- ratio at highest pp multiplicities similar to Pb—Pb
- "distance" from e^+e^- dependent on p_T
- at high p_T ratio closer to e^+e^- data

CAVEAT:
- other p_T-dependent effects might be present here (e.g. radial flow)
- CNM effects

$\Sigma_c^{0,++}$ at $\sqrt{s} = 13$ TeV : a big increase

Baryon-to-meson ratios

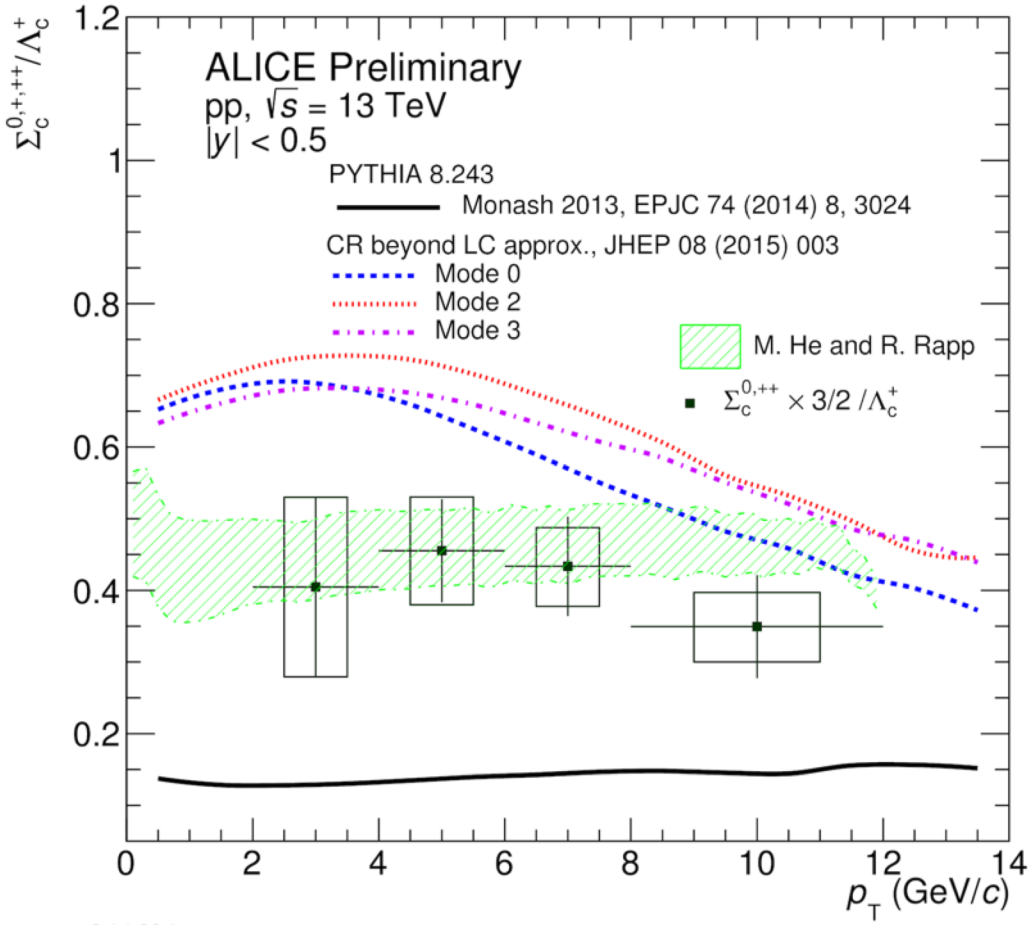




PYTHIA (enhanced CR) and RQM models describe baryon-to-meson ratios

$\Sigma_c^{0,++}$ at $\sqrt{s} = 13$ TeV - pp

Baryon-to-baryon ratios



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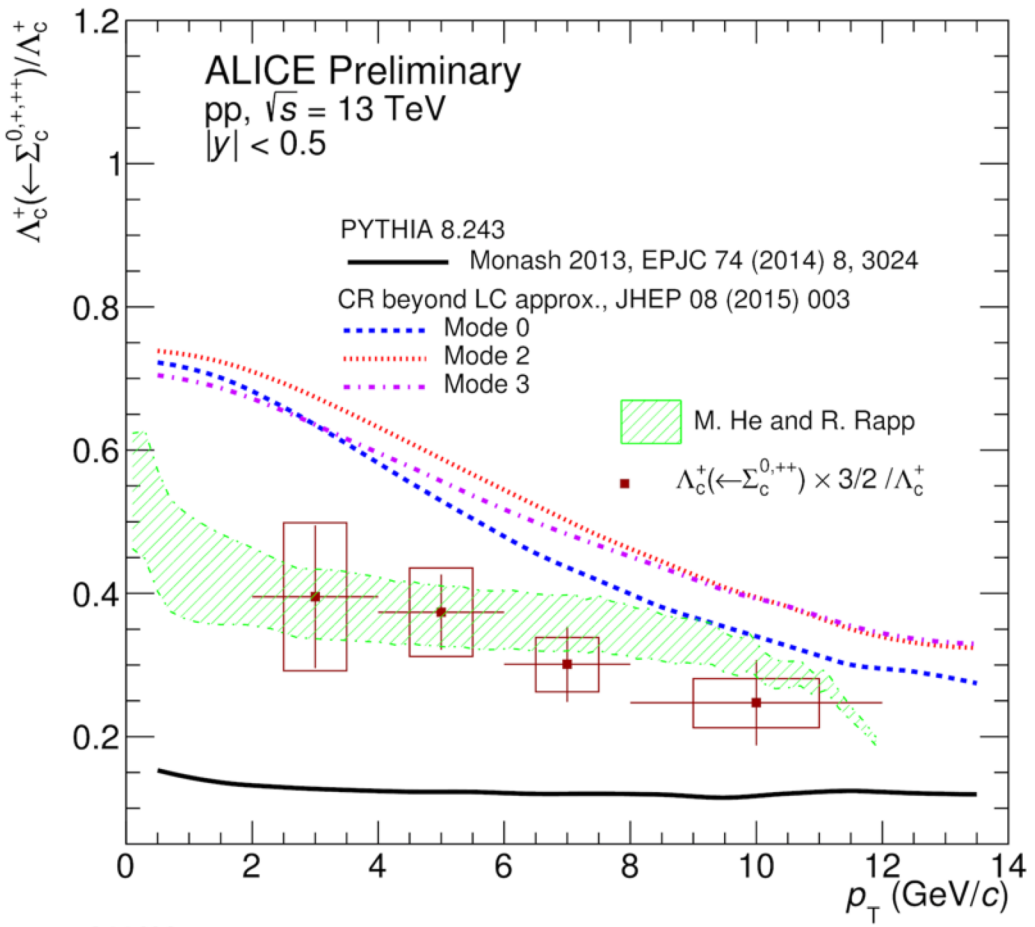
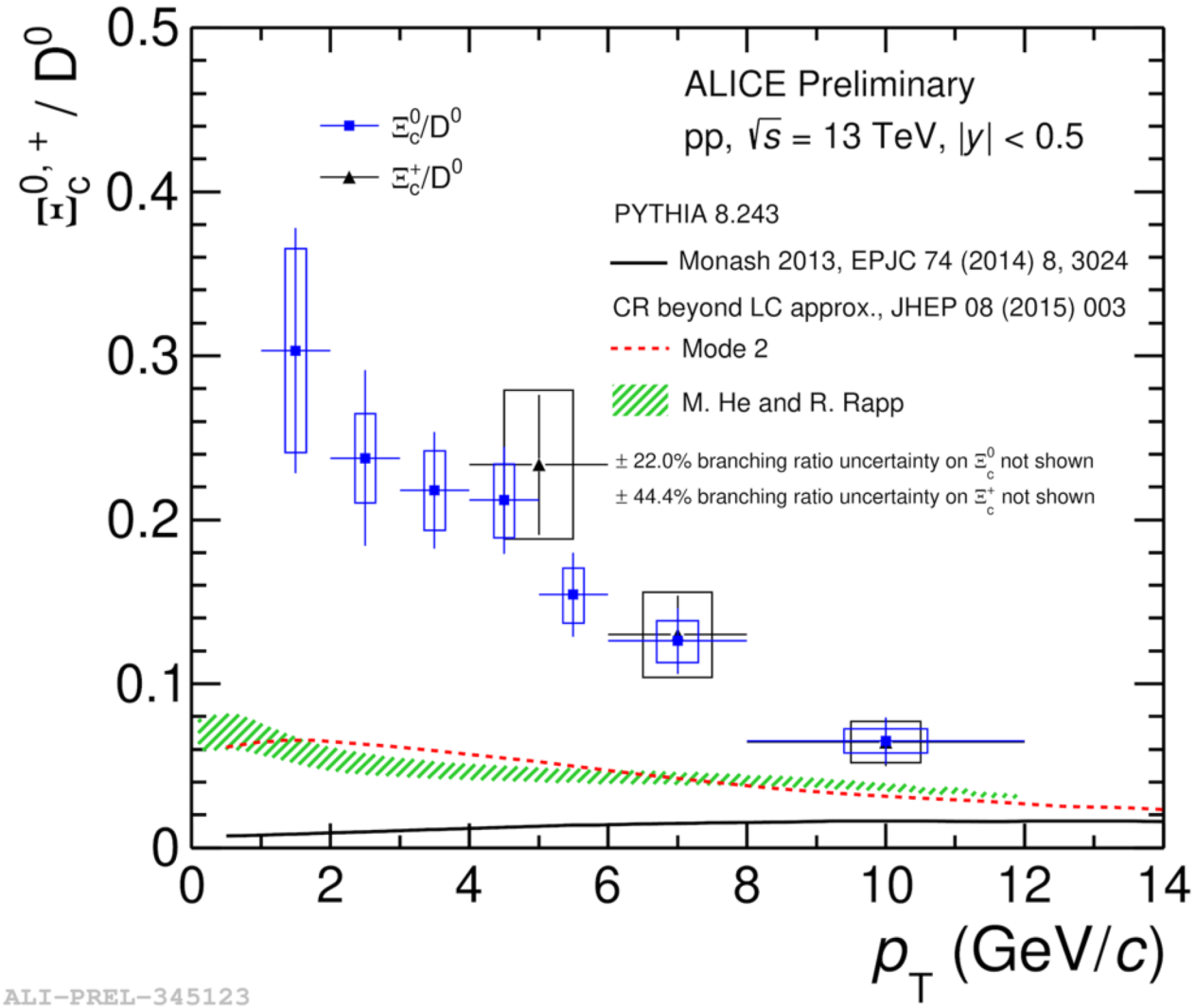


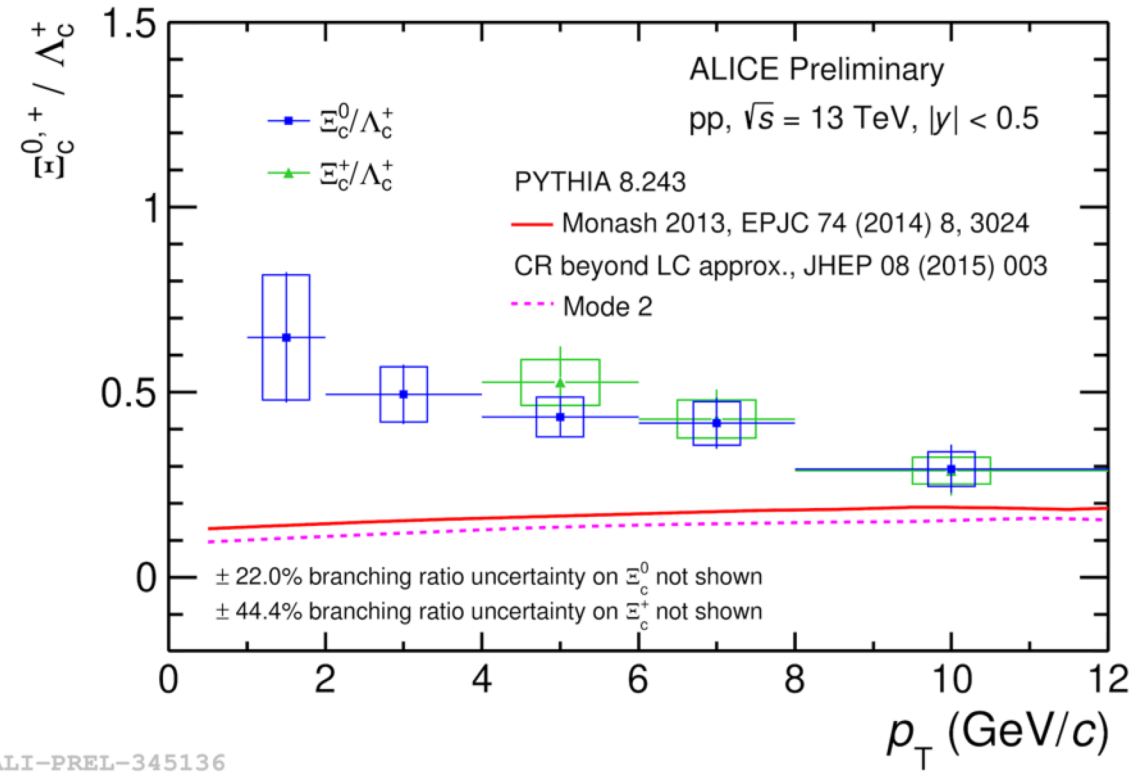
ALI-PREL-344689

- PYTHIA (with enhanced CR or not) doesn't describe baryon-to-baryon ratios
- ≈ 40% Λ_c is feeddown from Σ_c, not all "additional" Λ_c production comes from Σ_c

$\Xi_c^{0,+}$ at $\sqrt{s} = 13$ TeV - pp



ALI-PREL-345123



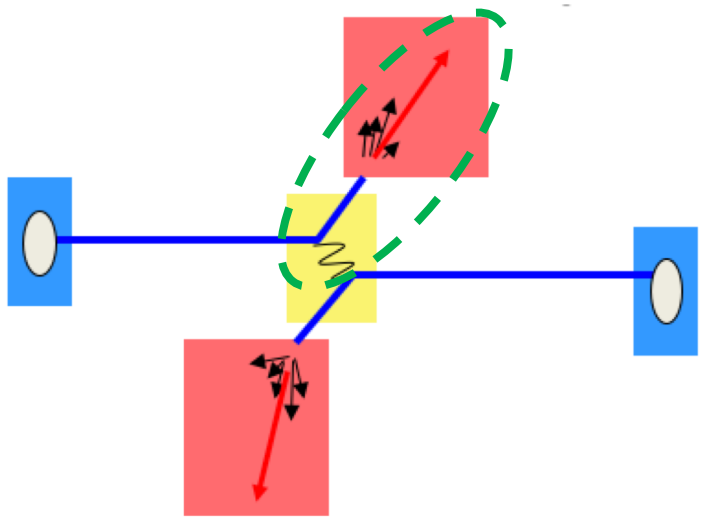
ALI-PREL-345136

- Models don't describe Ξ_c production
- stronger p_T dependence of baryon-to-meson ratio seen on data

Conclusion(s) # 1: quick summary and outlook

- charmed **baryons** @LHC are **a surprise:** from a pp baseline to search an enhancement in Pb--Pb, we found something quite different between pp and e^+e^- /ep. Collision system or collision energy makes the difference?
- **dependence of the fragmentation fractions from p_T** now firmly established, clear evidence in pp and p--Pb collisions, by different LHC Collaborations
- intriguing **similarities among LF and HF families** on the baryon-to-meson ratio
- **ALICE results with three different c-baryons** and the access to low p_T region allow us to test and set constraints on different hadronization ("baryonization"?) models in the LHC "**parton rich environment**"
- Additional measurements and channels/baryons will provide soon further additional key pieces of information (including cc cross section).
  Upcoming results at Summer conferences!

Conclusion # 2: the revisited surprising "physics motivations slide"?



$$\frac{d\sigma^{h}_{pp}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd) \frac{D^{0}_{h/c}}{\pi z_c}(\rho(q,g))$$

The LHC is a perfect laboratory to study the dependence of the fragmentaton functions from the surrounding parton rich environment

BACKUP

Λ_c and Ξ_c^0 baryons (RUN1 results)

- Λ_c **hadronic decays**
- Two channels → Cross check
- No vertex selection ($c\tau$=60 μm)

pp √s=7 TeV

- **Semileptonic decays** for Λ_c^+ e Ξ_c^0
- Candidates identified working on $e^+\Lambda$ and $e^+\Xi^-$ pairs
- Background subtracted using wrong-sign pairs
- Electrons identified via TPC+TOF

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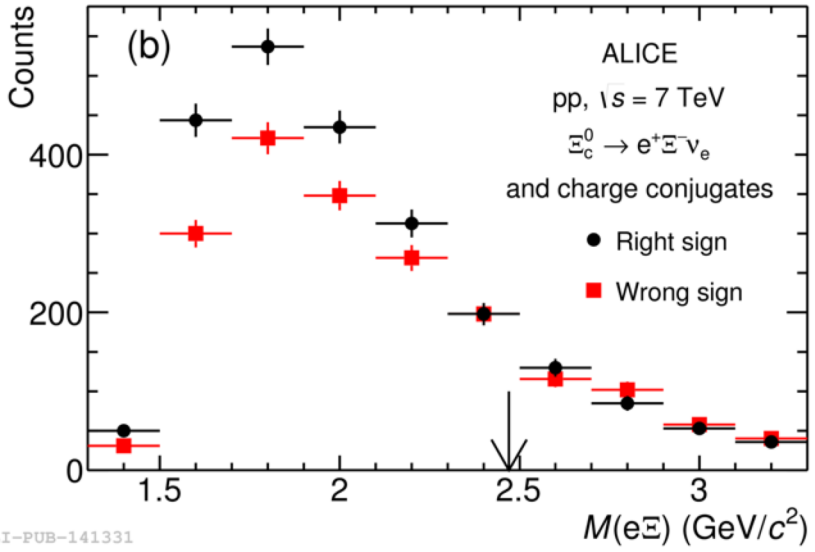

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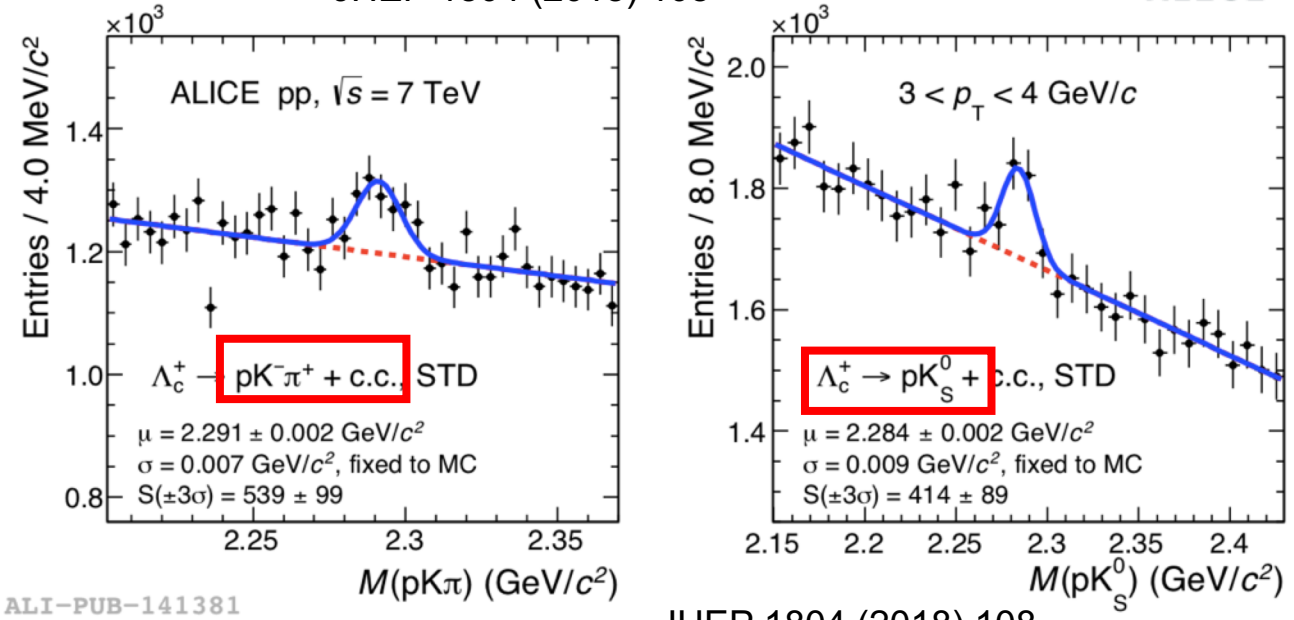

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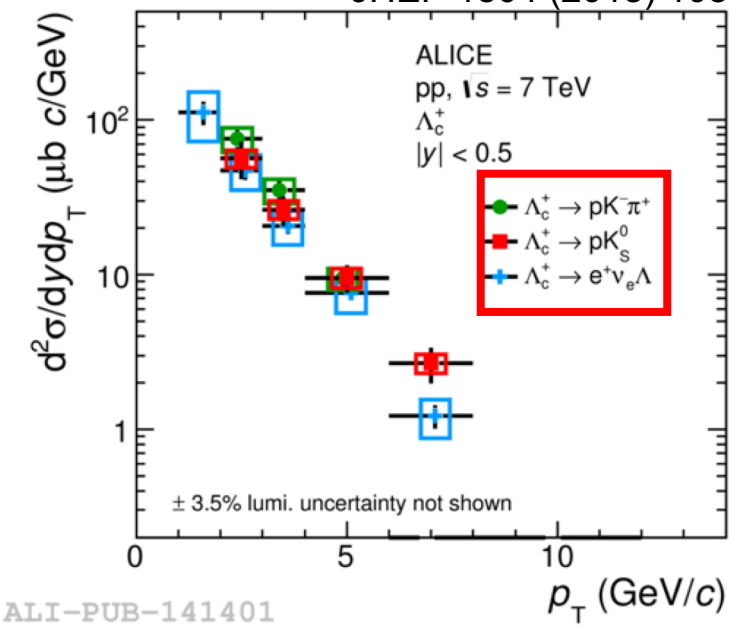
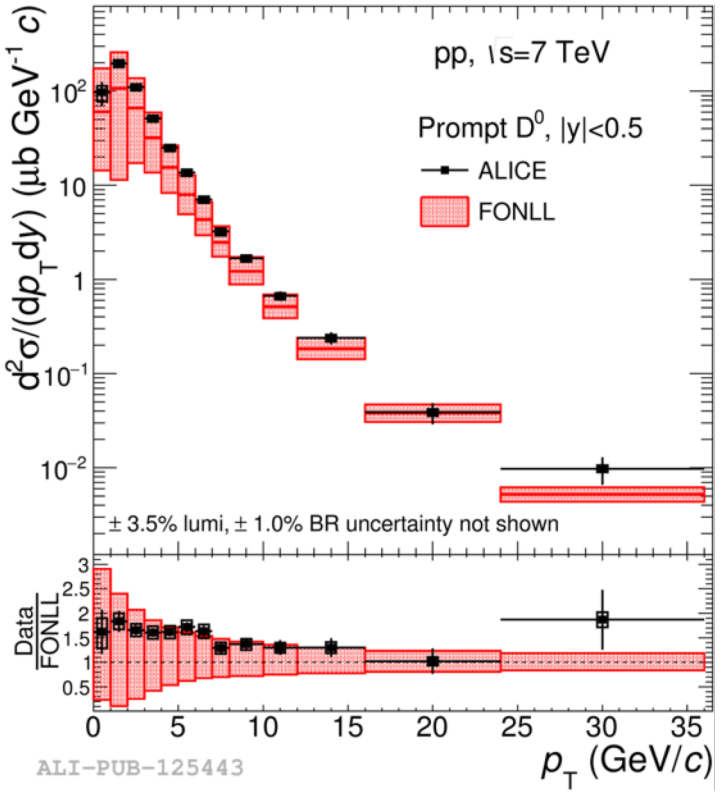
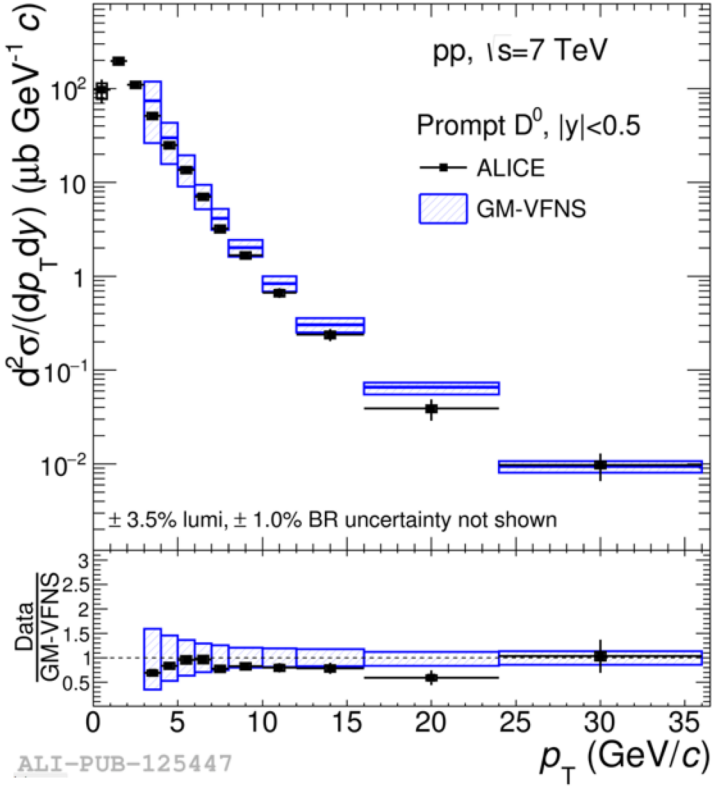
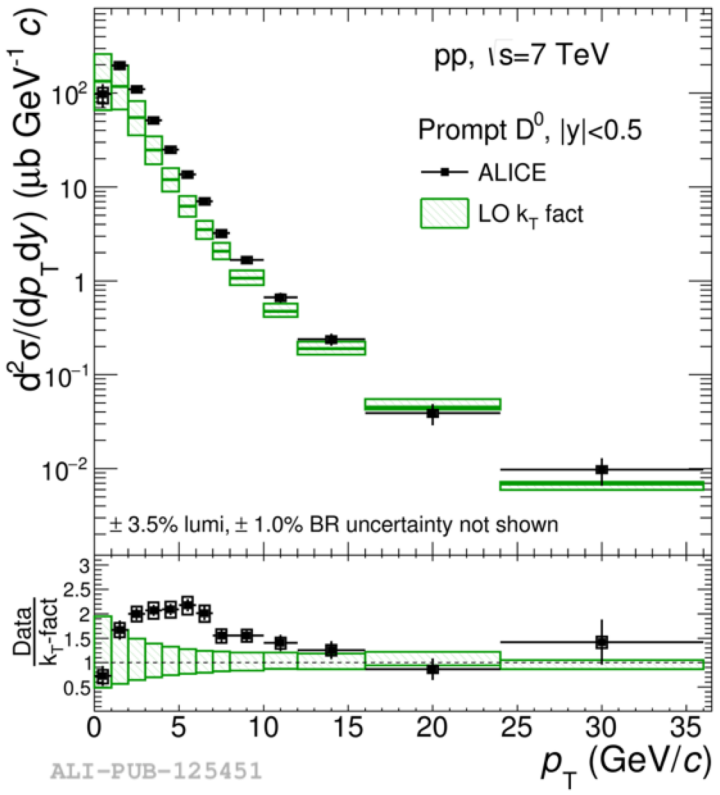


D mesons are candles here

EPJ C77 (2017) 550)



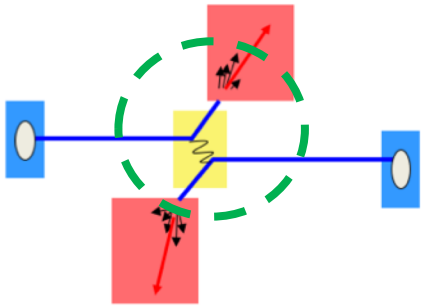




wide p_T range / cross section measured down to p_T = 0 for D^0 meson. Comparison with:

- FONLL (Fixed Order with Next to Leading Log resummation): Cacciari et al., JHEP 1210 (2012) 137
- GM-VFNS (General Mass Variable Flavour Number Scheme): Kniehl et al., EPJ C72 (2012) 2082
- k_T-factorization (LO accuracy + unintegrated gluon distribution function): Maciula, Szczurek, PRD 87 (2013) 094022)

FONLL: describes data within uncertainties, central value *below* data
GM-VNFS: the same, but central value above data
k_T: data underestimated in $2<p_T<10$ GeV/c interval



pp and p—Pb at $\sqrt{s_{NN}}$ =5.02 TeV

EPJ C79 5 (2019) 388
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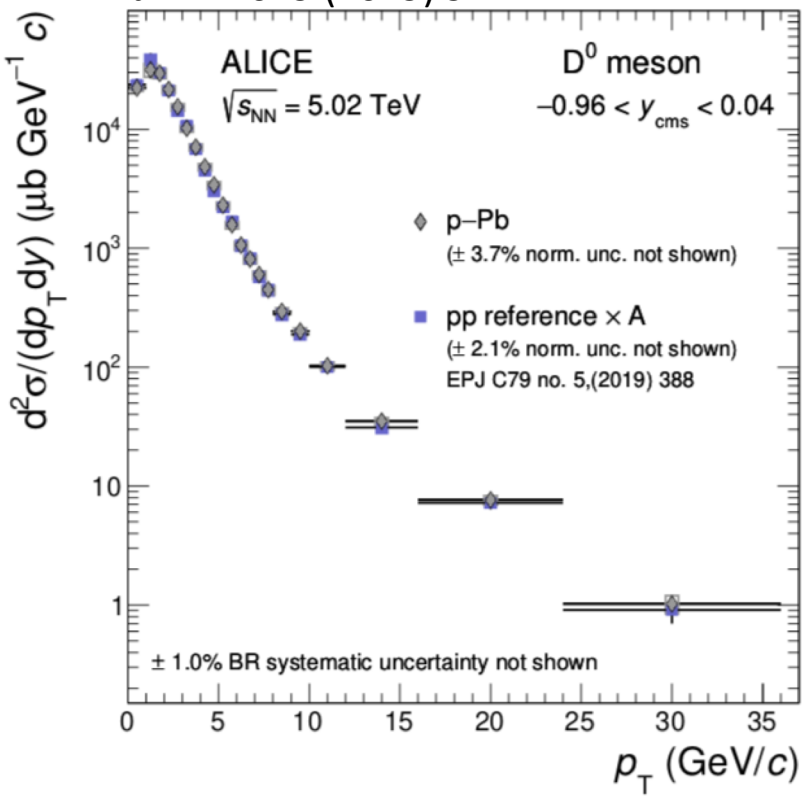

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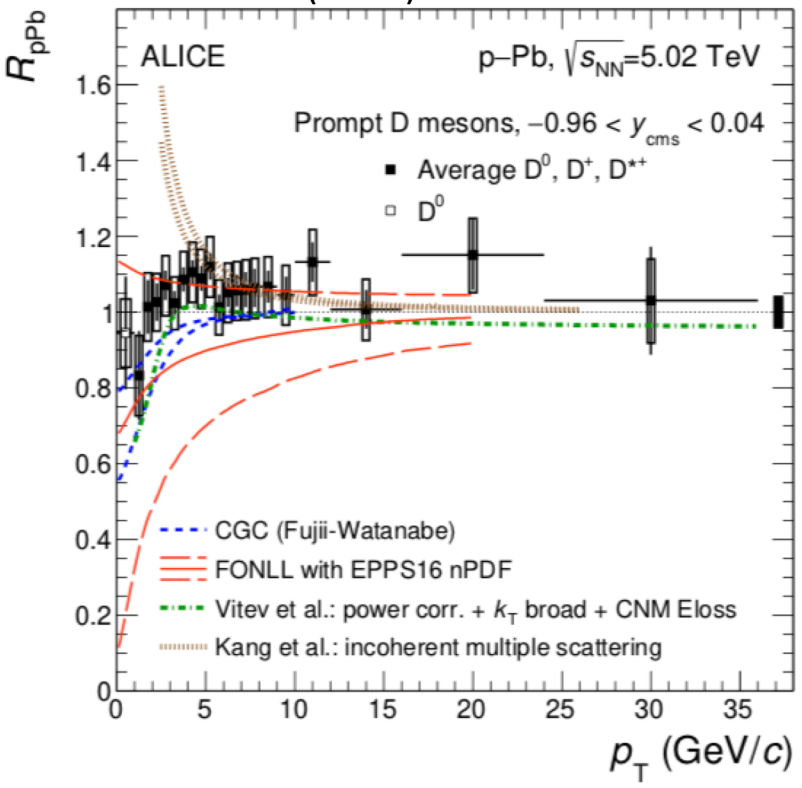
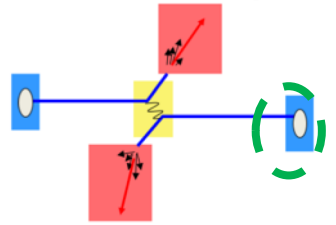


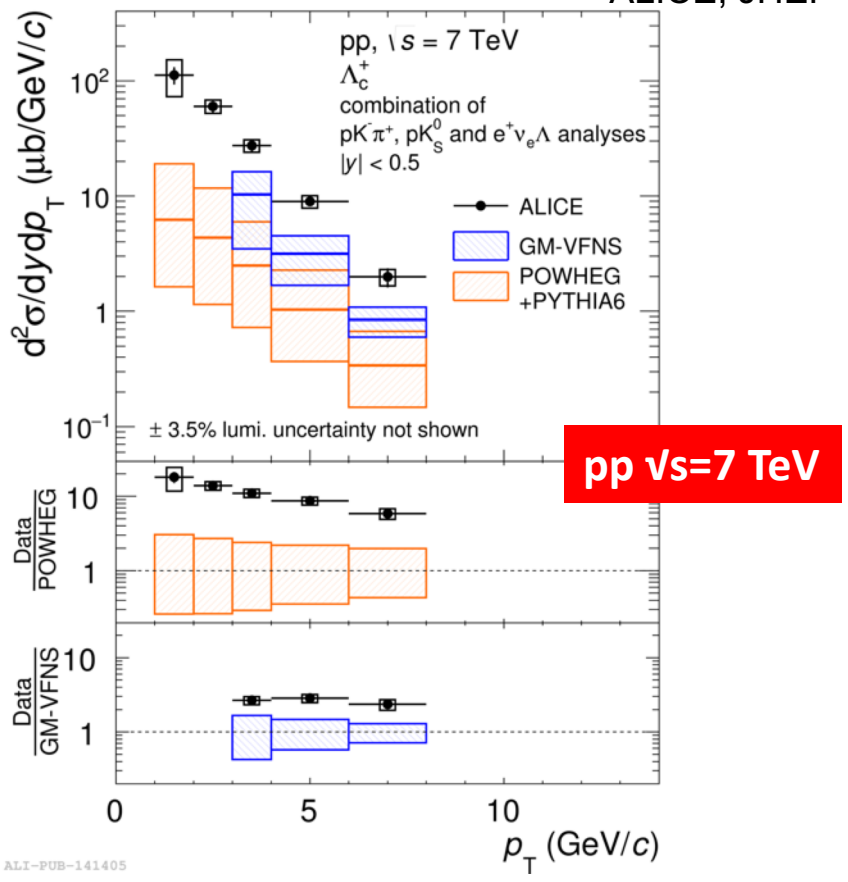
$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{p-Pb}}^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



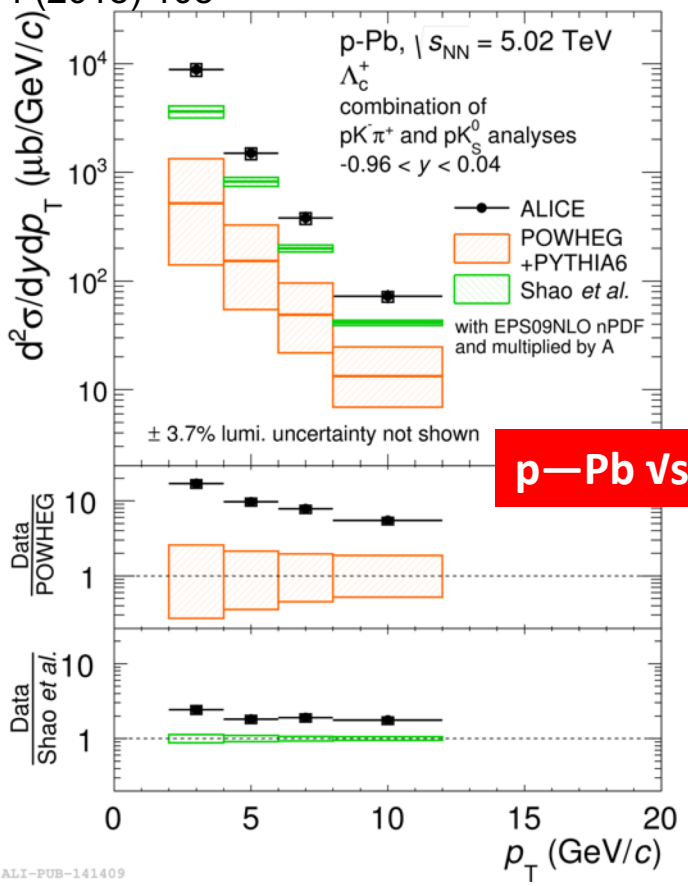
- R_{pPb} (nuclear modification factor) consistent with unity
- data set constraints to models that include CNM effects (note: "QGP in p—Pb" predicted trends not shown here)

First ALICE Λ_c measurements (RUN 1)

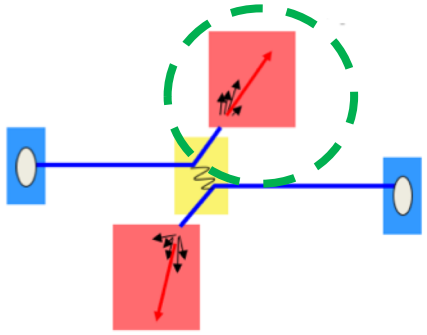
ALICE, JHEP 1804 (2018) 108



pp $\sqrt{s}$=7 TeV



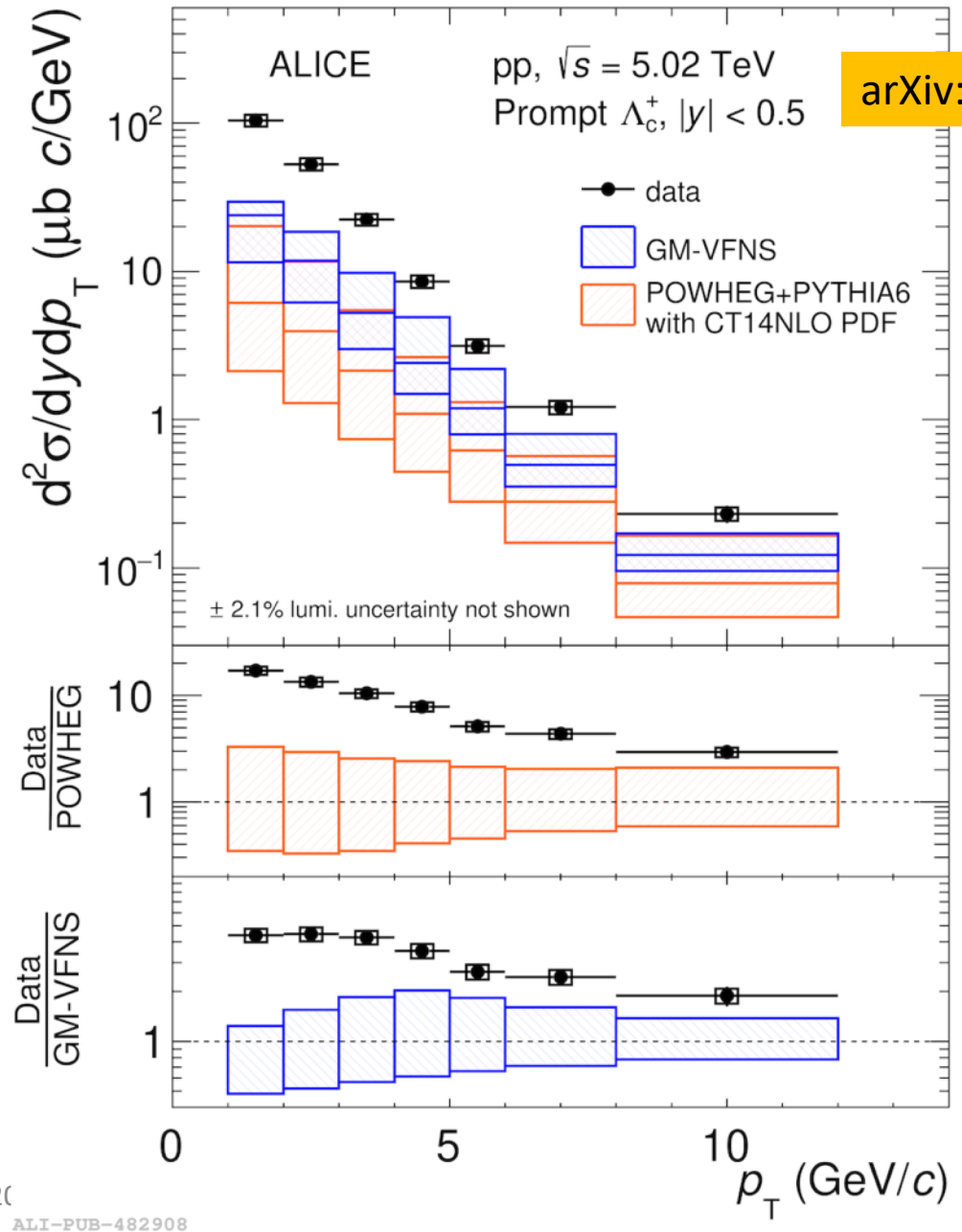
p—Pb $\sqrt{s_{NN}}$=5.02TeV



- 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

"fragmentation to heavy-flavour baryons is **not** well understood"

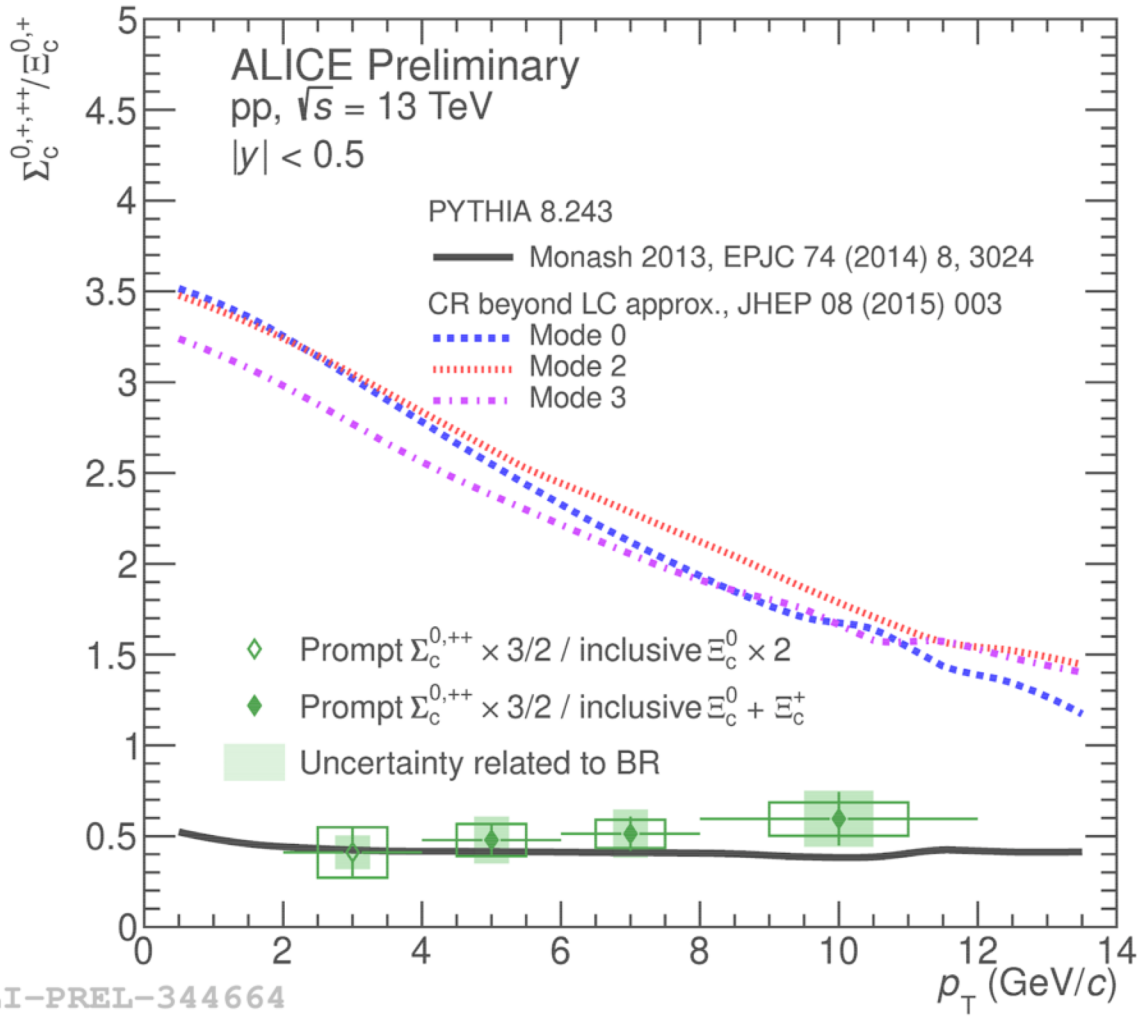
Λ_c (RUN2 results): pp at $\sqrt{s}$ =5.02 TeV



arXiv:2011.06078 (submitted to PRC)

- pQCD calculations underestimate data especially at low p_T
- results at 7 TeV confirmed with larger statistics and extened p_T range
- FF used by GM-VFNS includes new input from Belle measurements

$\Sigma_c^{0,++}/\Xi_c^{0,+}$ at $\sqrt{s} = 13$ TeV - pp



- given PYTHIA8 Monash fails to predict both baryons, by "chance" (?), ratio consistent with data
- PYTHIA8 with enhanced CR predicts Σ_c not Ξ_c so fails to describe this ratio
- similar mass but different quark content: different process?