Open heavy flavour baryon production results from e^+e^- to Pb-Pb (with some input for EIC)

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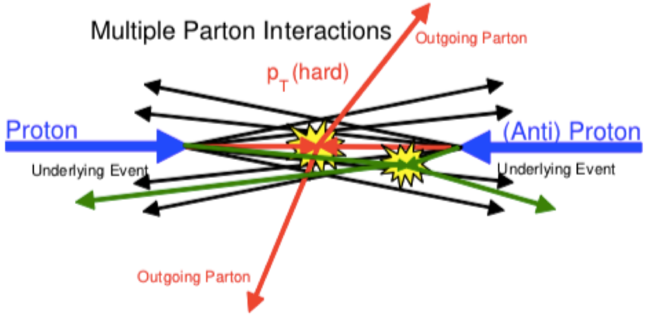
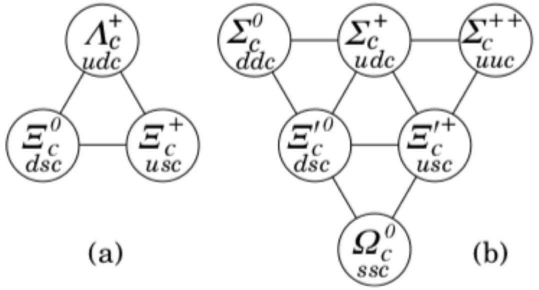
INFN - Bologna

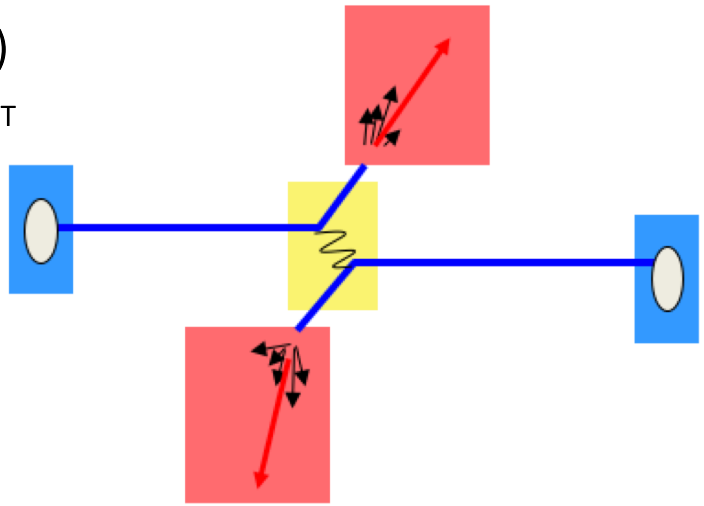
(emphasis on recent **LHC** results, mainly on **c**-baryons, and despite the title emphasis on **pp** collisions))

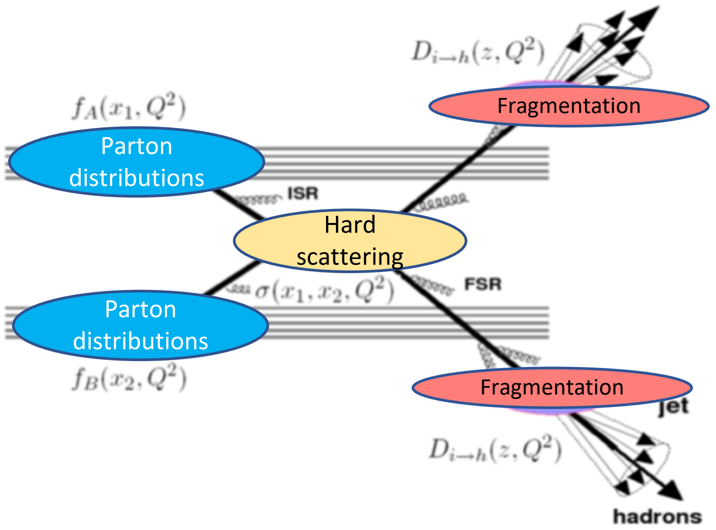




Open HF production in hadron-hadron environment

The heavy-flavour production is a test of pQCD
- large quark mass provides hard scale ($m_Q >> \Lambda_{QCD}$)
- pQCD can calculate cross sections down to low p_T





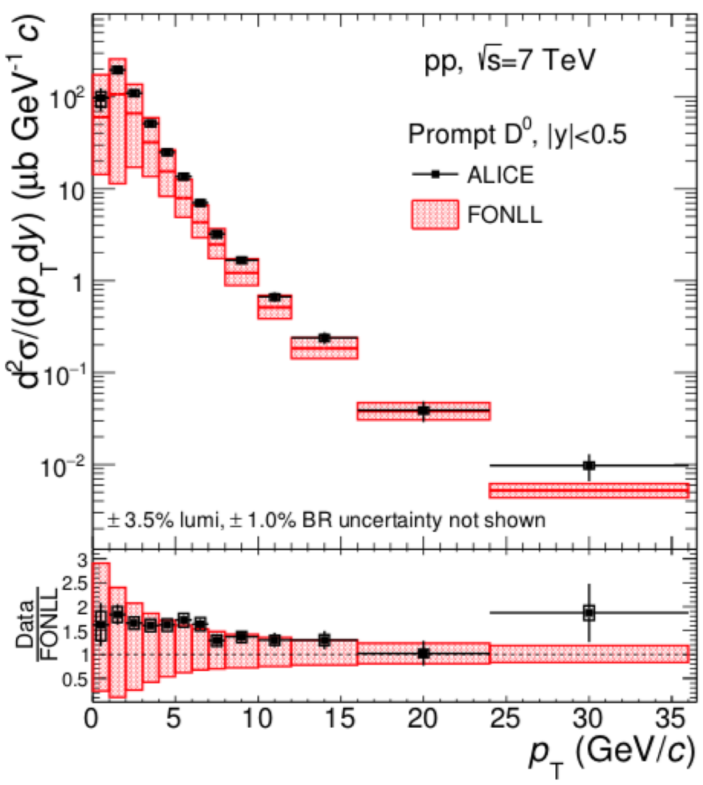
$$\frac{d\sigma^h_{pp}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2)\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\frac{D^0_{h/c}}{\pi z_c}$$

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

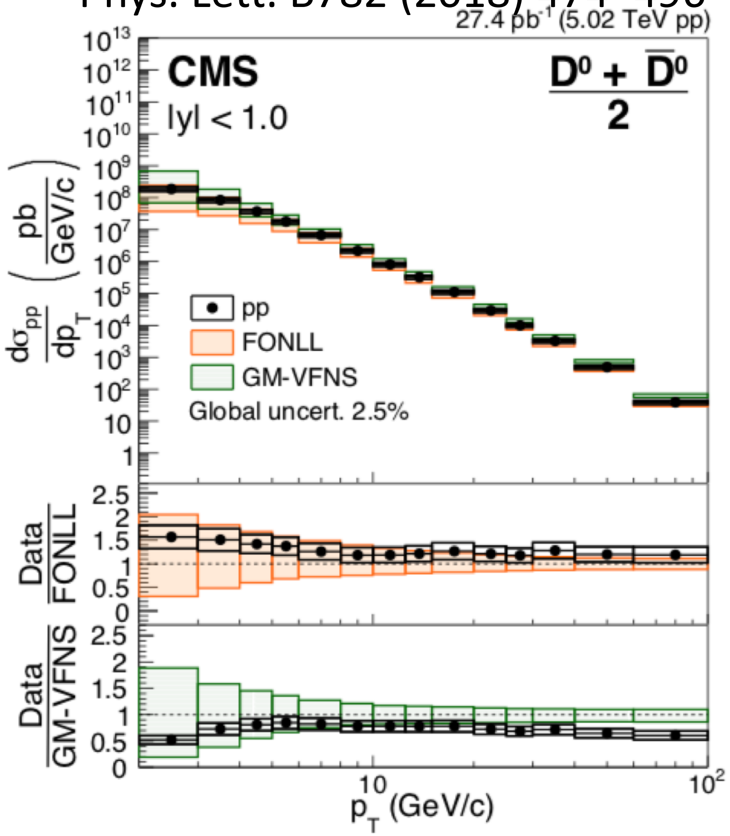
A wealth of LHC measurements at unprecedented center-of-mass energy collision in pp, p-Pb and Pb-Pb collision systems
- sensitive to fragmentation functions determined in e^+e^- collisions
- sensitive to low-x gluon PDF ($p_T \rightarrow 0$)

LHC is not so surprising about D and B mesons in pp

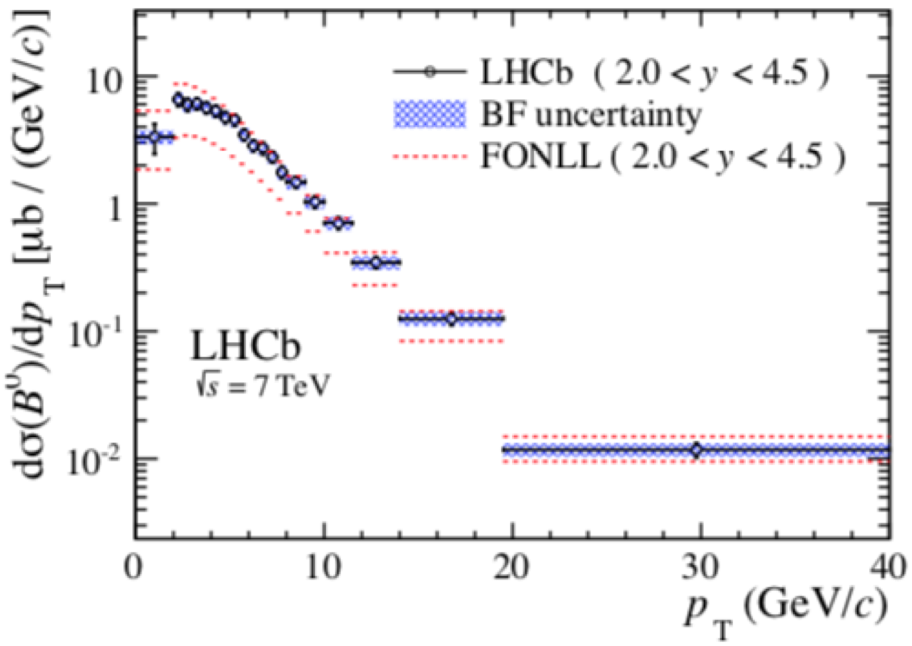
Eur. Phys. J. C77 (2017) 550



Phys. Lett. B782 (2018) 474–496



JHEP08(2013)117

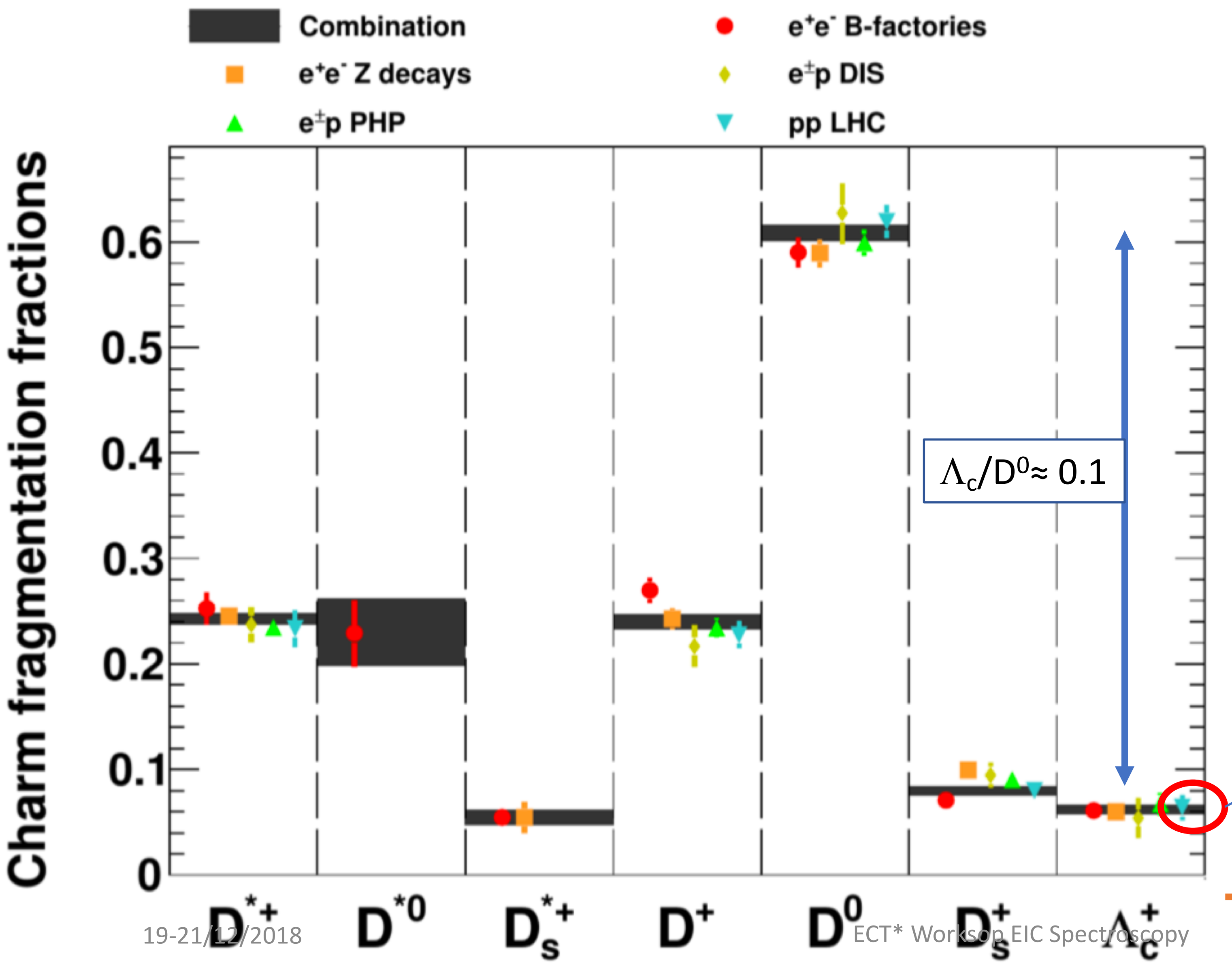


- open-HF meson production generally **well described** by pQCD calculations such as FONLL, GM-VFNS
- (tendency for data to stay in the upper part of the uncertainty band)
- many center-of-mass energies (LHC scale) now tested

see Rongrong Ma talk at this workshop

Universality of fragmentation fractions

Lisovyii M., Verbytskyi A and Zenaiev A, 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 (including ep)
- no Tevatron measurement of Λ_c

Note recent Belle results on HF baryons: PRD 97 (2018), 072005

2015 analysis, only LHCb Λ_c measurement available at LHC for baryons

So... everything ok and understood?

Some caveat about HF baryons and fragm. functions

$$f(c \to H) = \sigma(H)/\sigma(c).$$

$$f(c \to H) = \sigma(H)/\sum_{w.d.} \sigma(H)$$

To obtain the charm-quark fragmentation fractions according to Eq. (2), in addition to the production cross-sections of D mesons and Λ_c^+, it is necessary to know the cross-sections of the weakly decaying $\Xi_c^{+,0}$ and Ω_c^0 states. Those states are poorly studied, therefore as in Ref. [9] it is assumed that ratios of fragmentation fractions of charm and strange quarks into the corresponding baryons are similar, $f(c \to \Xi_c^+)/f(c \to \Lambda_c^+) = f(c \to \Xi_c^0)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda^0)$ and $f(c \to \Omega_c^0)/f(c \to \Lambda_c^+) = f(s \to \Omega^-)/f(s \to \Lambda^0)$. In this approach the sum of the production cross-sections of these states can be estimated as

OPAL (1996) approach

$$\sigma(\Xi_c^+) + \sigma(\Xi_c^0) + \sigma(\Omega_c^0) = \lambda\sigma(\Lambda_c^+), \quad (3)$$

where we define

$$\lambda = 2\frac{f(s \to \Xi^-)}{f(s \to \Lambda^0)} + \frac{f(s \to \Omega^-)}{f(s \to \Lambda^0)} = 0.136 \pm 0.006. \quad (4)$$

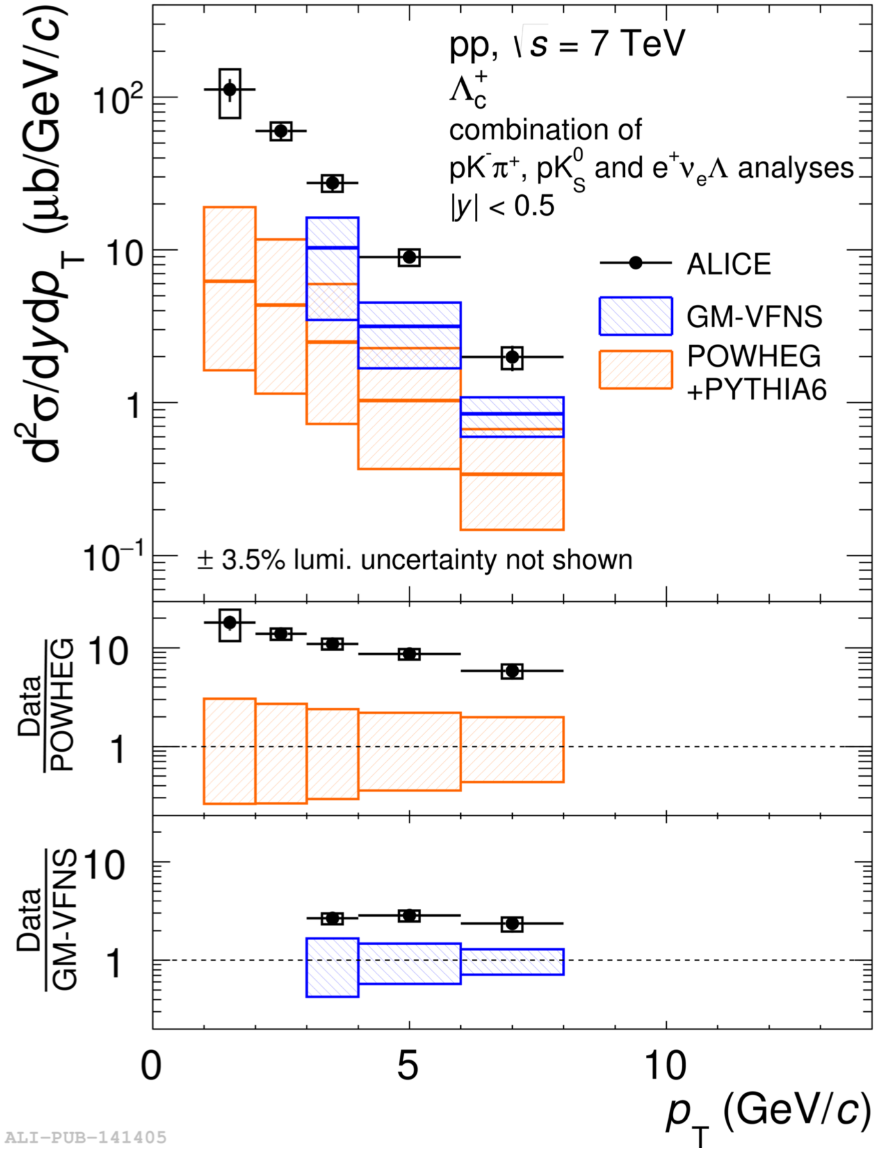
c- (and b-) baryon spectroscopy!

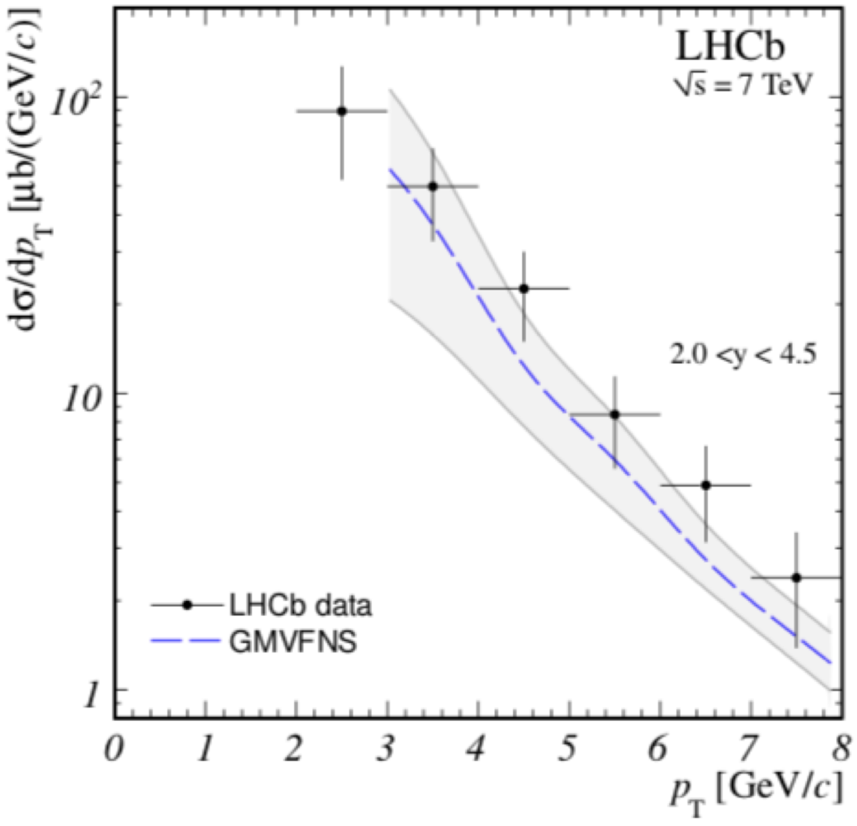
p-A (Fermilab, RHIC, LHC) and π-A measurements not included “as those provide results in very specific production environment and energy ranges which cannot be easily compared to the results in other experiment"

EIC as opportunity to explore in detail a “very specific production environment” (i.e. CNM)

Λ_c production at LHC shows some surprises

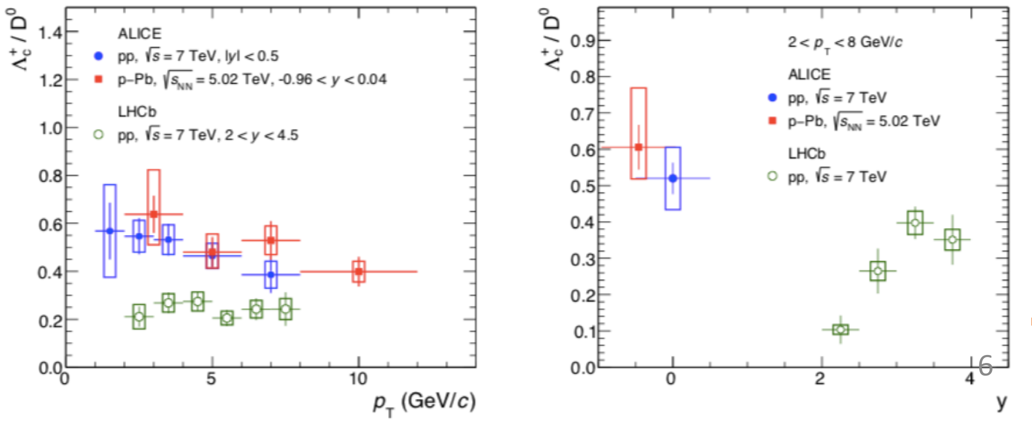
ALICE, JHEP 1804 (2018) 108





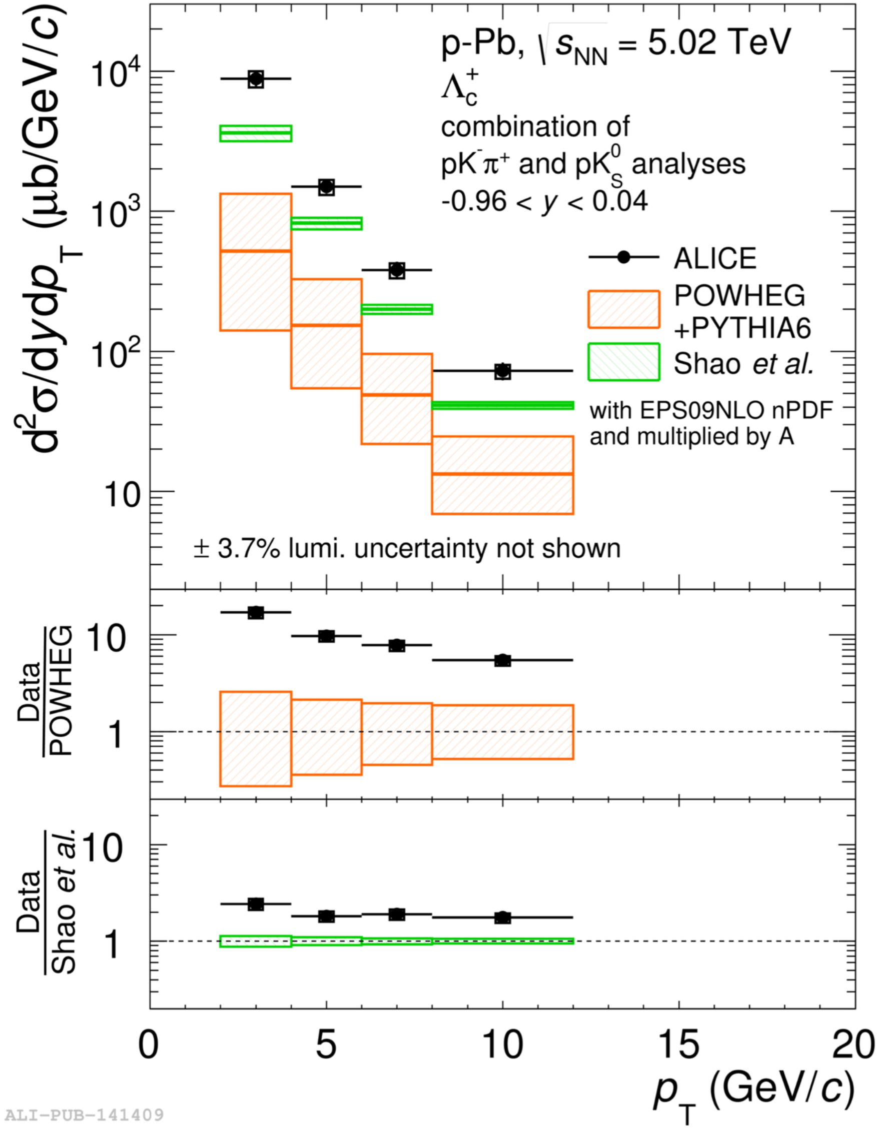
LHCb, Nucl. PhysB 871 (2013), `

- Λ_c production much higher than expected
- tension between ALICE and LHCb results
- different rapidity plays a role?
- study baryon-to-meson ratio to check differences

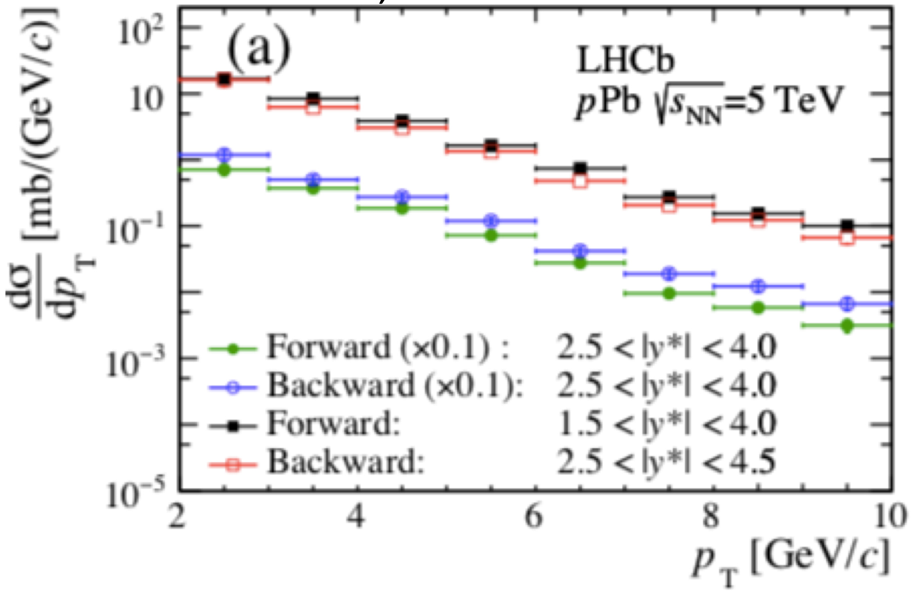


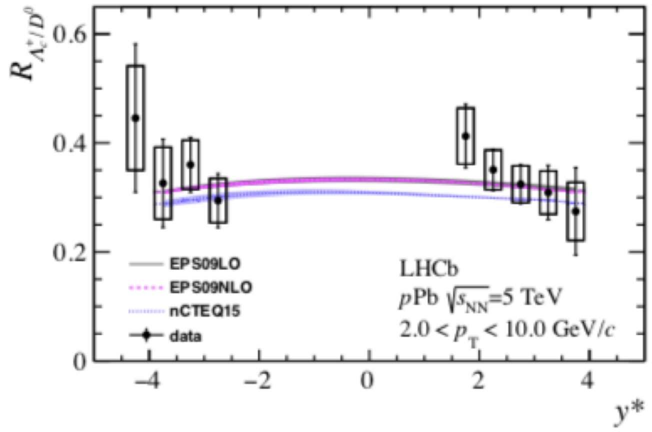
Λ_c production in p-Pb

ALICE, JHEP 1804 (2018) 108

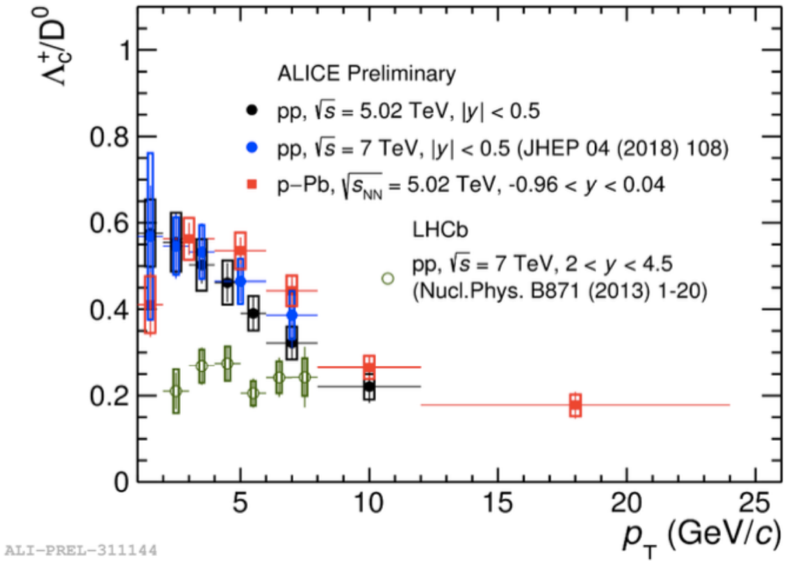


LHCb, arXiv:1809.1404





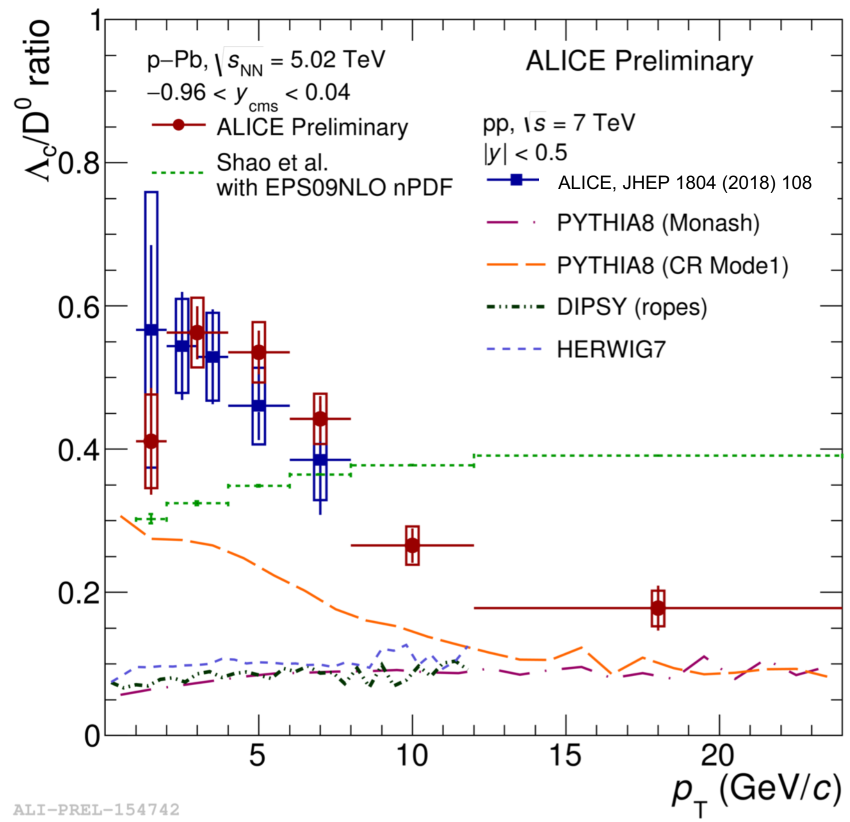
- LHCb and ALICE data closer in p-Pb
- Shao model (pp data driven + nPDF) still undepredicts ALICE data (but better than NLO) and describes LHCb
- p_T trend toward e+e+ values?



(ALICE + LHCb) pPb

MC generators are based on e^+e^- and ep data

baryon-to-meson ratio to study hadronization mechanisms

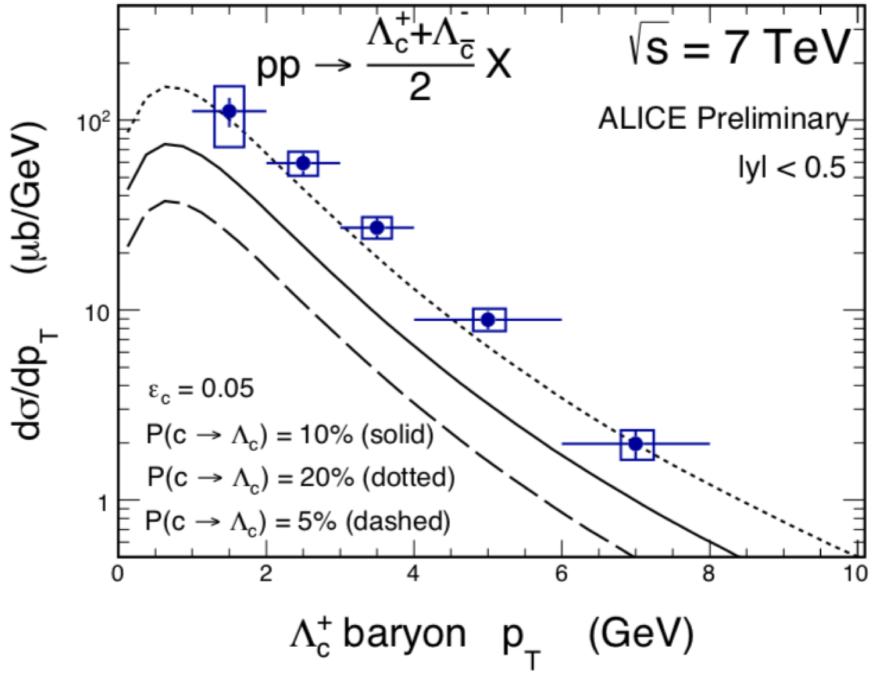


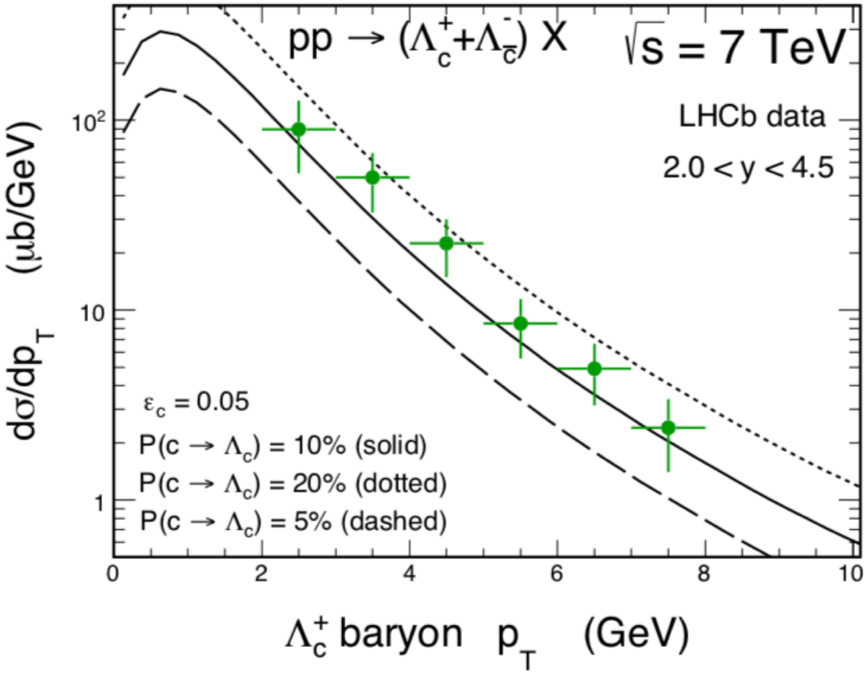
	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [42, 98]	0.127 ± 0.031	ee	10.55
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$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

- LO generators use fragmentation fractions and functions tuned on LEP data
- enhanced CR seems to add p_T dependency seen in data (but still undepredicts data)
- data-driven model (based on LHCb pp results) closer to p-Pb data

Independent fragmentation picture and LHC results

R. Maciula and A. Szczurek, Phys. Rev. D 98, 014016 (2018)





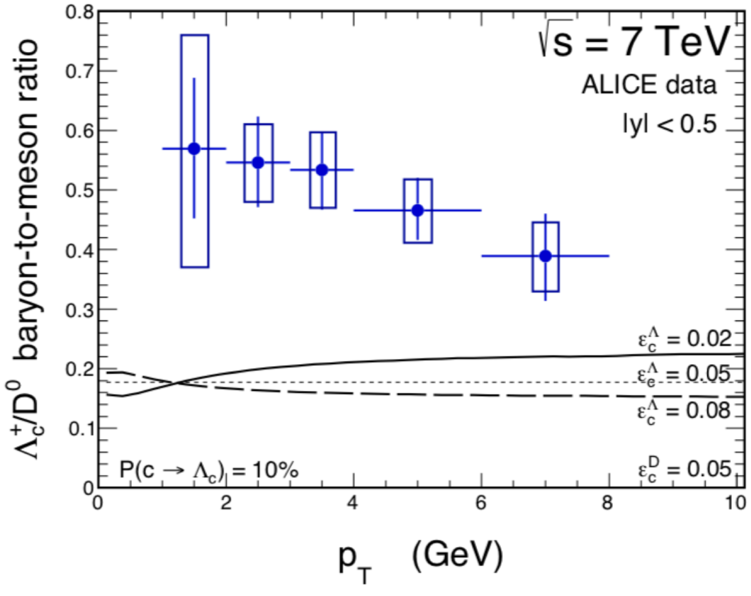
$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2}$$

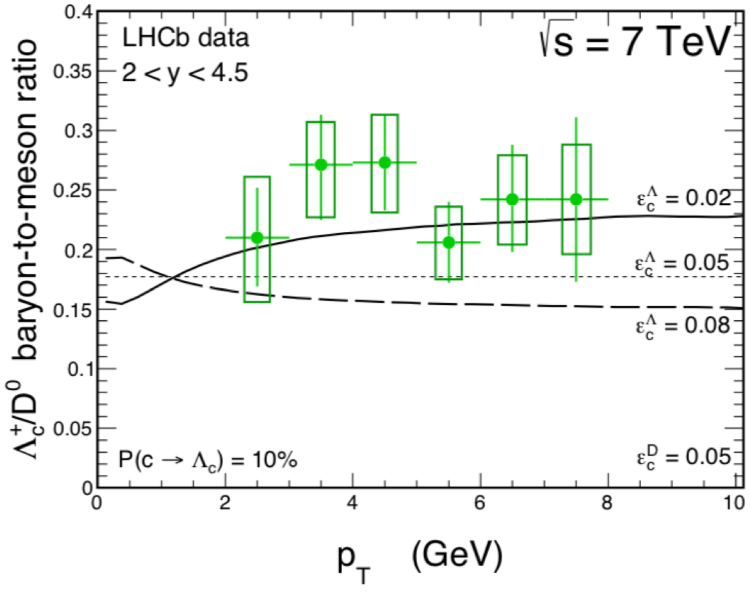
k_T-factorization approach
FF (Petersen) tuned on D-meson
much larger f(c→Λ_c) needed to expain data (LHCb 10%, ALICE 20%)

Petersen et. al, PRD 27 (1983) 105

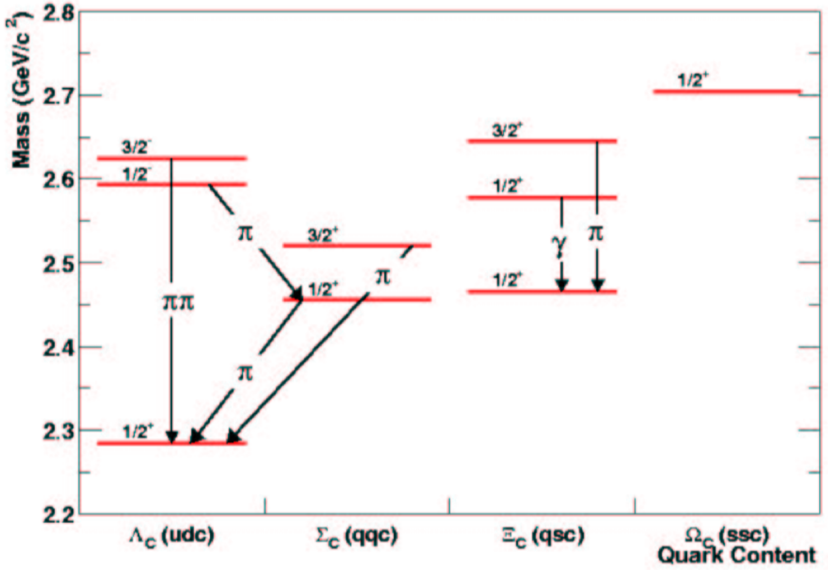
Possible explanations? Not for the moment...

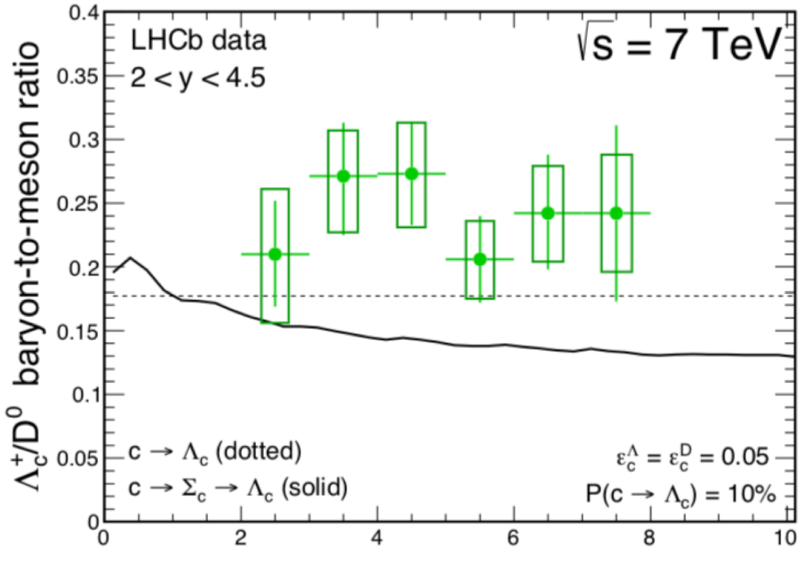
R. Maciula and A. Szczurek, Phys. Rev. D 98, 014016 (2018)





Tailored Peterson FF for Λ_c baryon doesn't change very much p_T shape





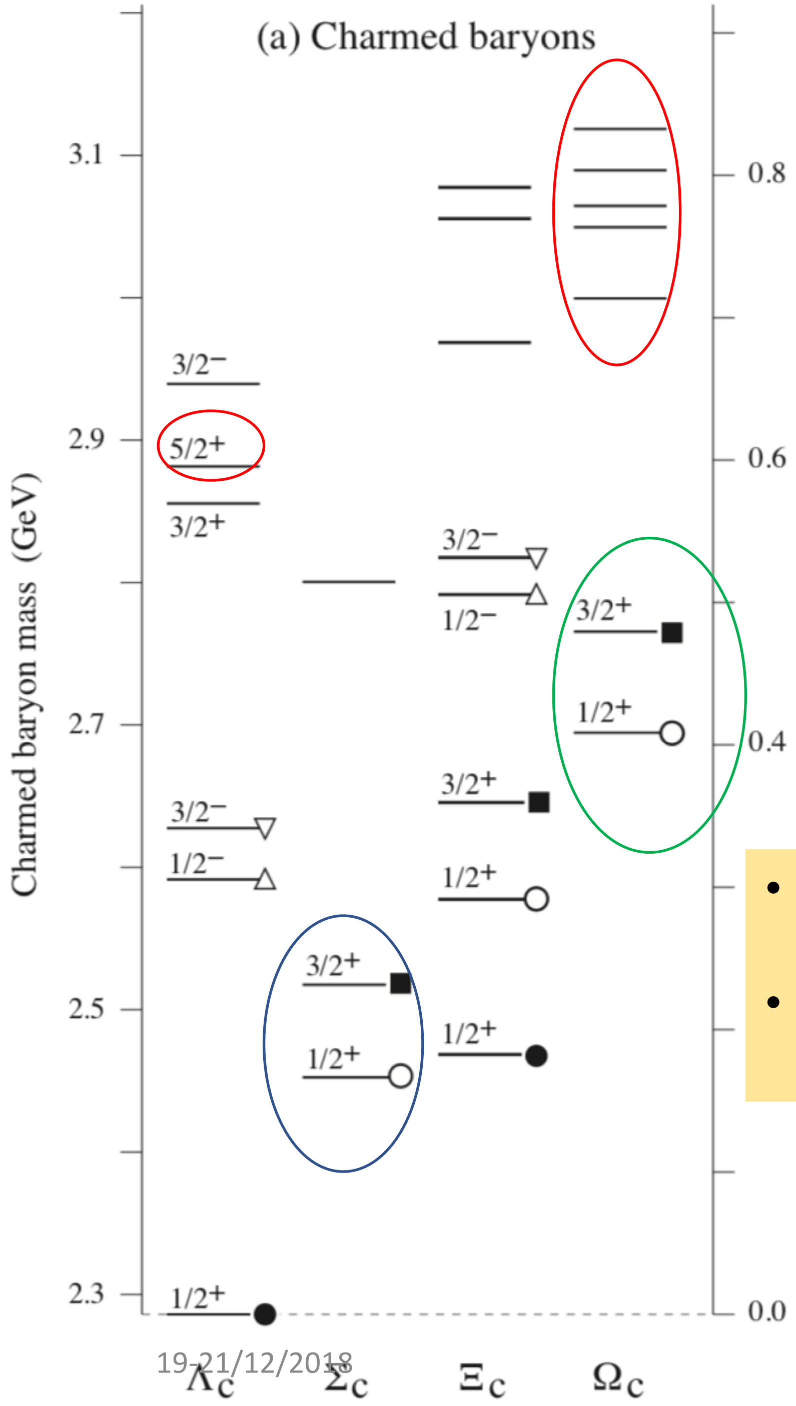
Feed-down from Σ_c (J=1/2 and J=3/2)

$\Sigma_c \rightarrow \Lambda_c\, \pi$

Σ_c production not firmly measured

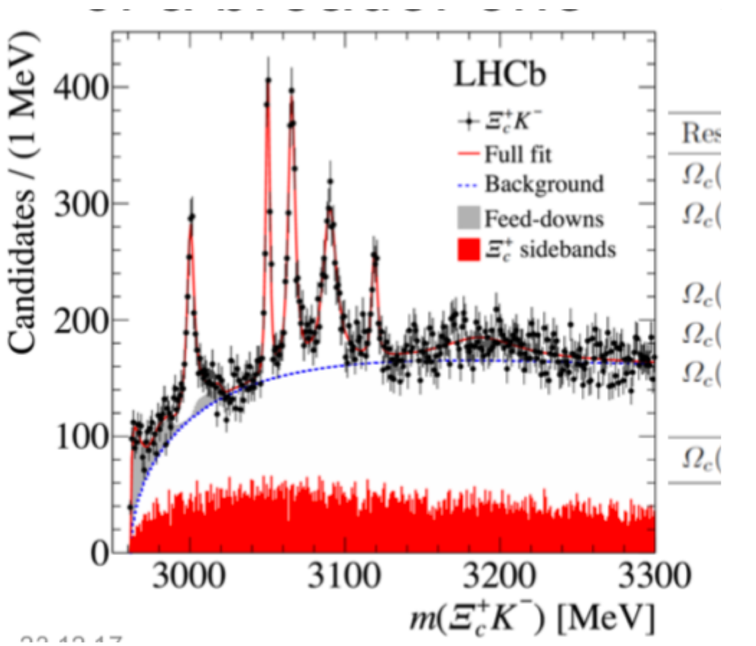
«Even in the "independent" parton picture the hadronization fractions $f_{c\to D_i}$ or $f_{c\to\Lambda_c}$ do not need to be universal and may depend on **partonic surrounding associated with the collision** which may be, in principle, reaction and energy dependent.»

A quick comment about spectroscopy



Σ_c **production** not firmly measured → contributing to feed-down?
Λ_c (2860) and top five Ω_c **new** in PDG2018 edition
LHCb JHEP 05 (2017) 030
LHCb PRL 118 (2017) 182001 (+ BELLE, PRD 97, 051102 (2018))
Ξ_c measured by LHCb and ALICE at **LHC**
Ω_c **part of assumptions** computing fragmentation fractions (note we have now more known states for Ω_c than for Ω!)

- At "EIC time" we will have a much more complete picture
- Relative abundances of HF baryon resonances may change given "production environment"?



And beauty baryon fragmentation?

We indeed have already (in the PDG!) some indications that fractions of b-baryons do depend on collision systems!

- LEP (e^+e^-) vs Tevatron (pp)
- "more partons around so more baryons"?
- Uncertainties large but...

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].

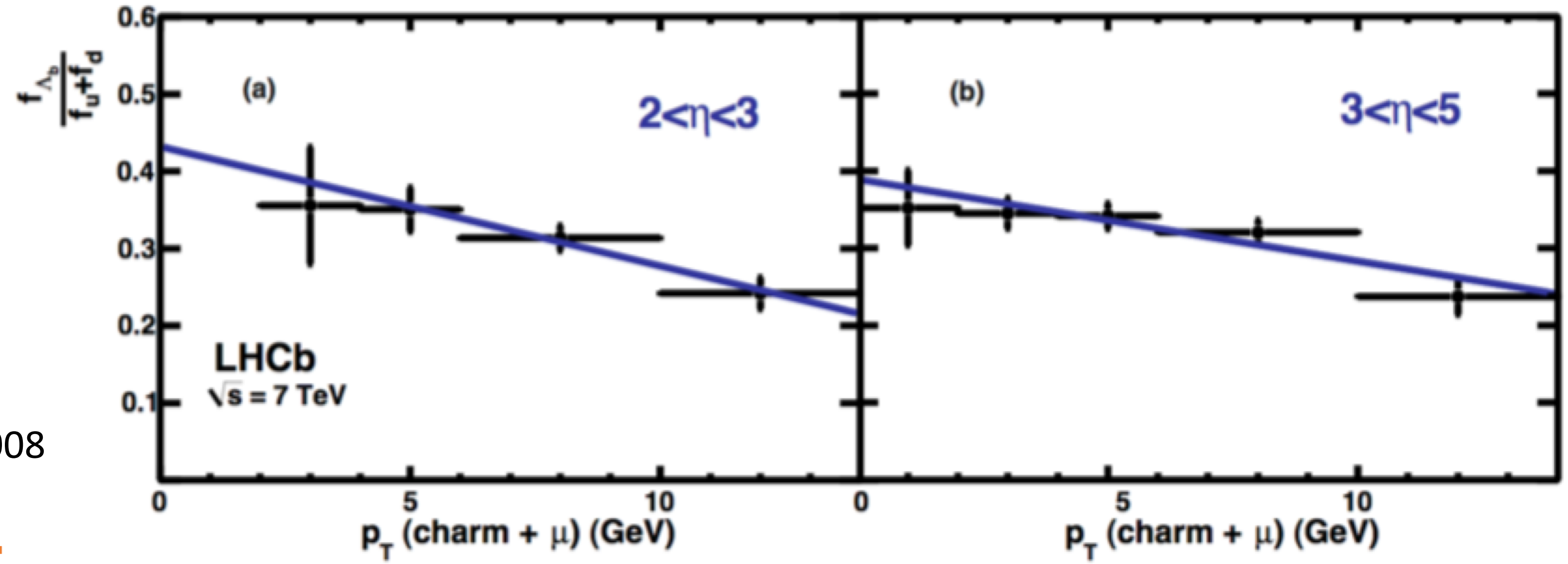
b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B^0_s	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7

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

- observation of ***p*$_T$ dependence** of

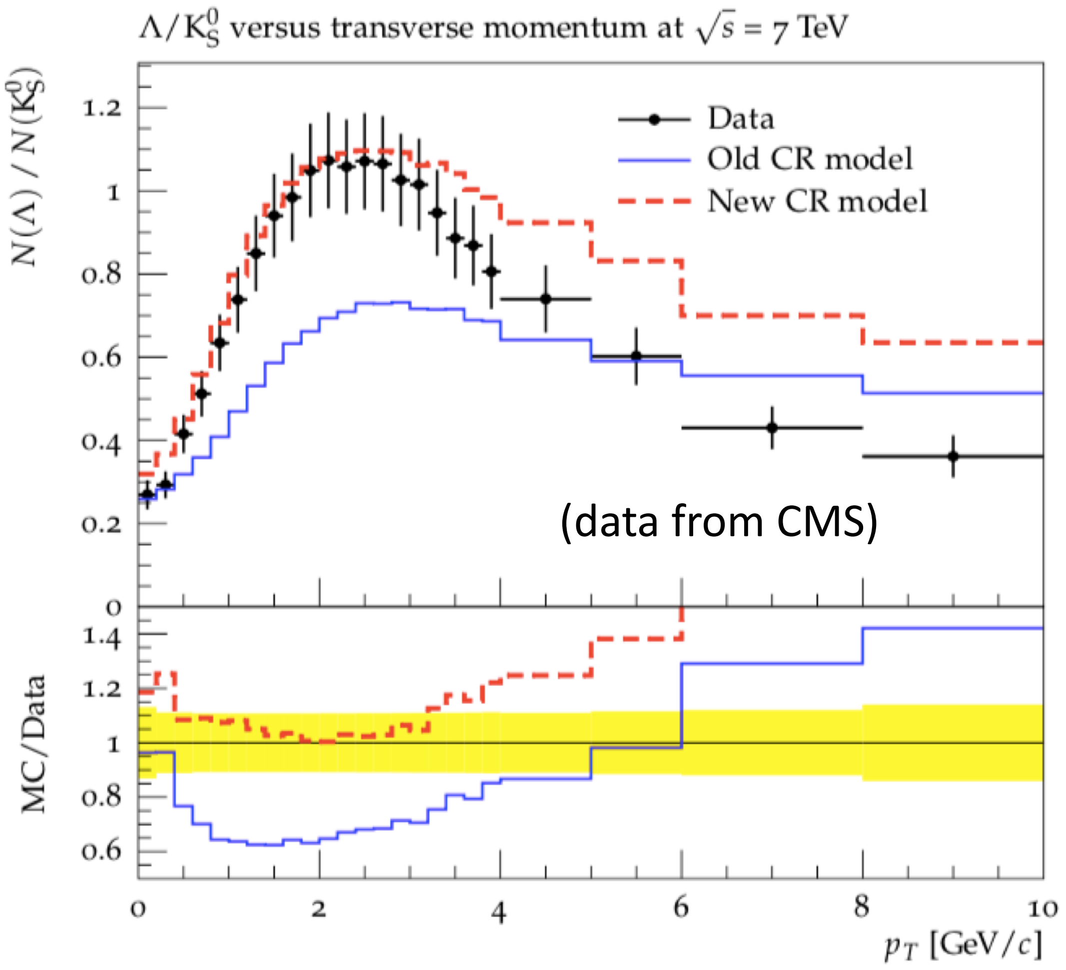
$$\frac{f_{\Lambda_b}}{f_u+f_d}$$

- Seen at LHC and Tevatron
  - CDF: Phys.Rev.D77 (2008)072003
  - LHCb: LHCb: Phys. Rev. D85 (2012) 032008



Color reconnection and HF-baryons

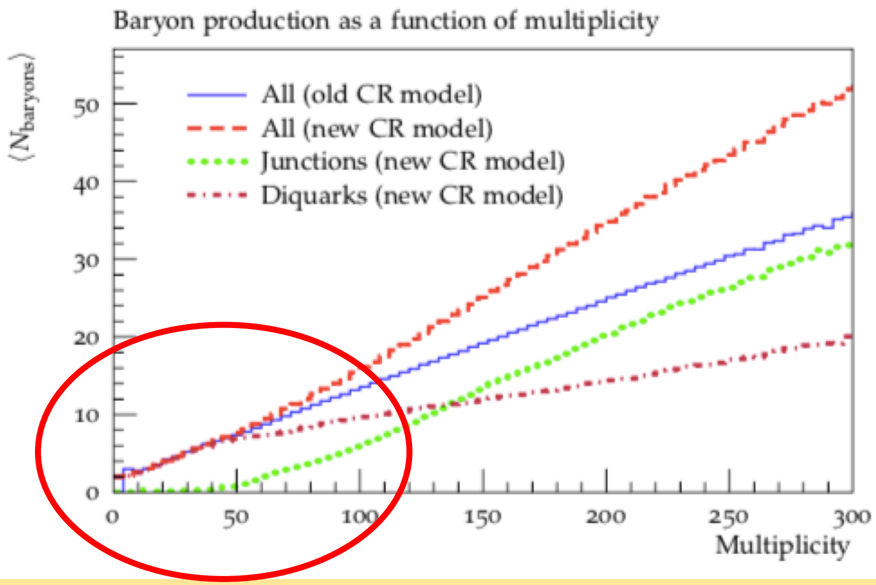
can hadronization be modified by "first principles" in a parton-rich environment



Multi-parton interactions may affect hadronisation

Enhanced CR gives better agreement on Λ/K^0_s ratio

Addtional string junctions allows for enhanced baryon formation

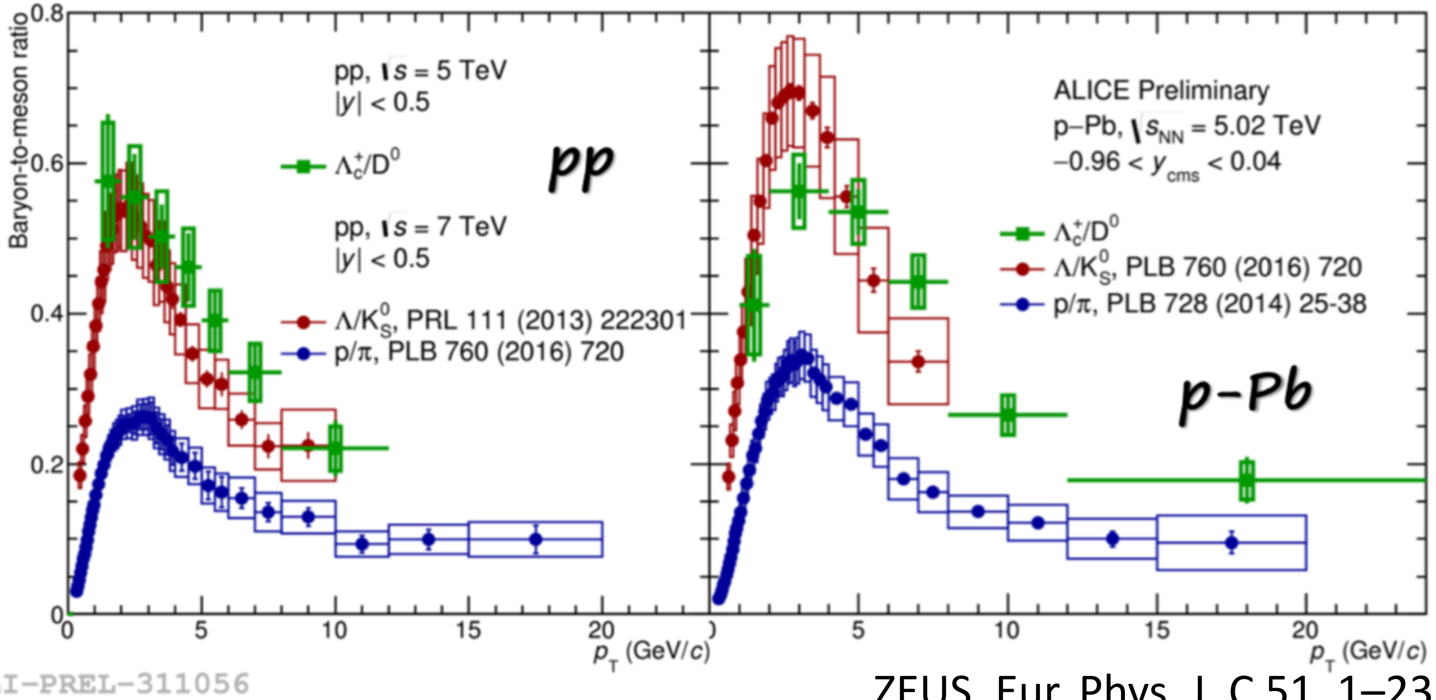


- Exclusive of hadron-hadron environment at LHC energies or it can play a role at EIC if hadronization is in the nuclei?
- (ep collisions not discussed in these works, but multiplicity plays big role)

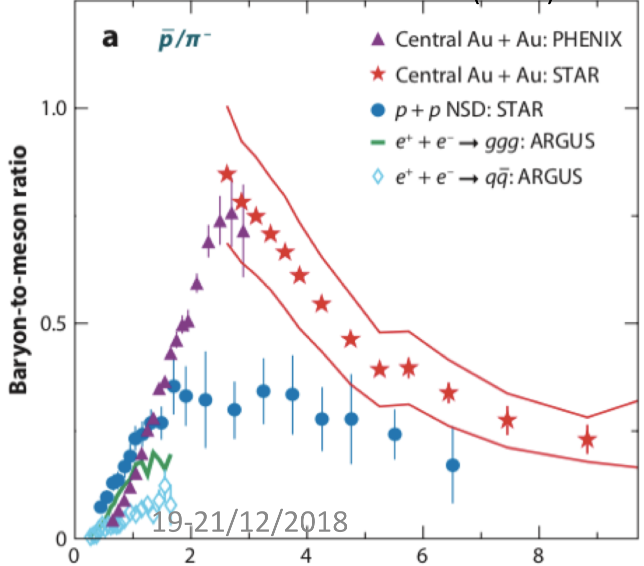
J. R. Christiansen and P. Skands, JHEP 08 (2015) 003

C. Bierlich and J. Christiansen, Phys. Rev. D 92 (2015) 094010

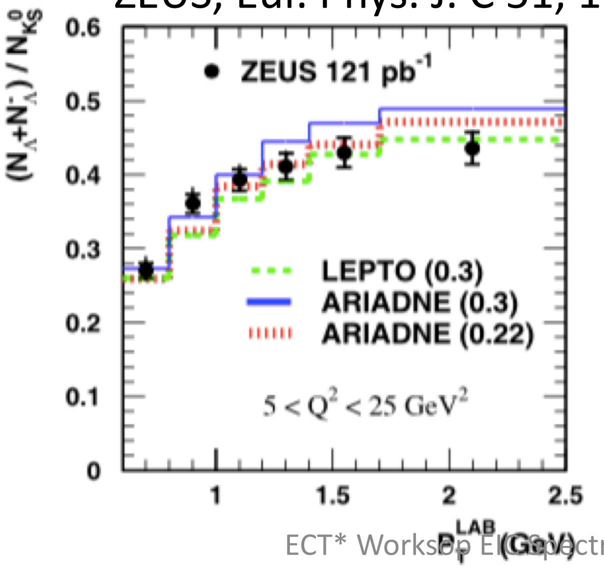
Baryon-meson ratio (at LHC and in e^+e^- / ep)



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



ZEUS, Eur. Phys. J. C 51, 1–23 (2007)



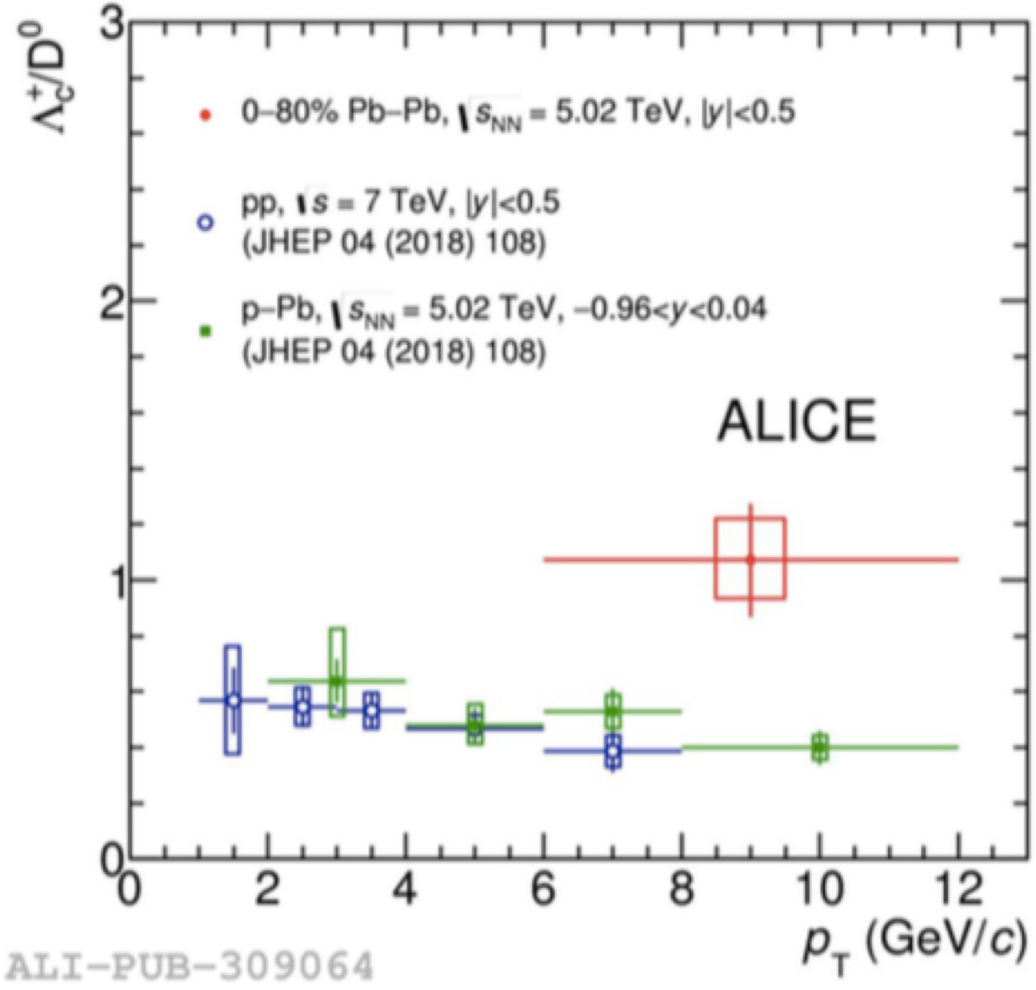
- Baryon-to-meson ratio to study hadronization
- p-Pb environment still expected «cold»
- p_T dependency of the ratio, affecting also heavy sector → fragmentation fractions p_T dependent?
- Similar trend to baryon-to-meson ratio in the light-flavour sector

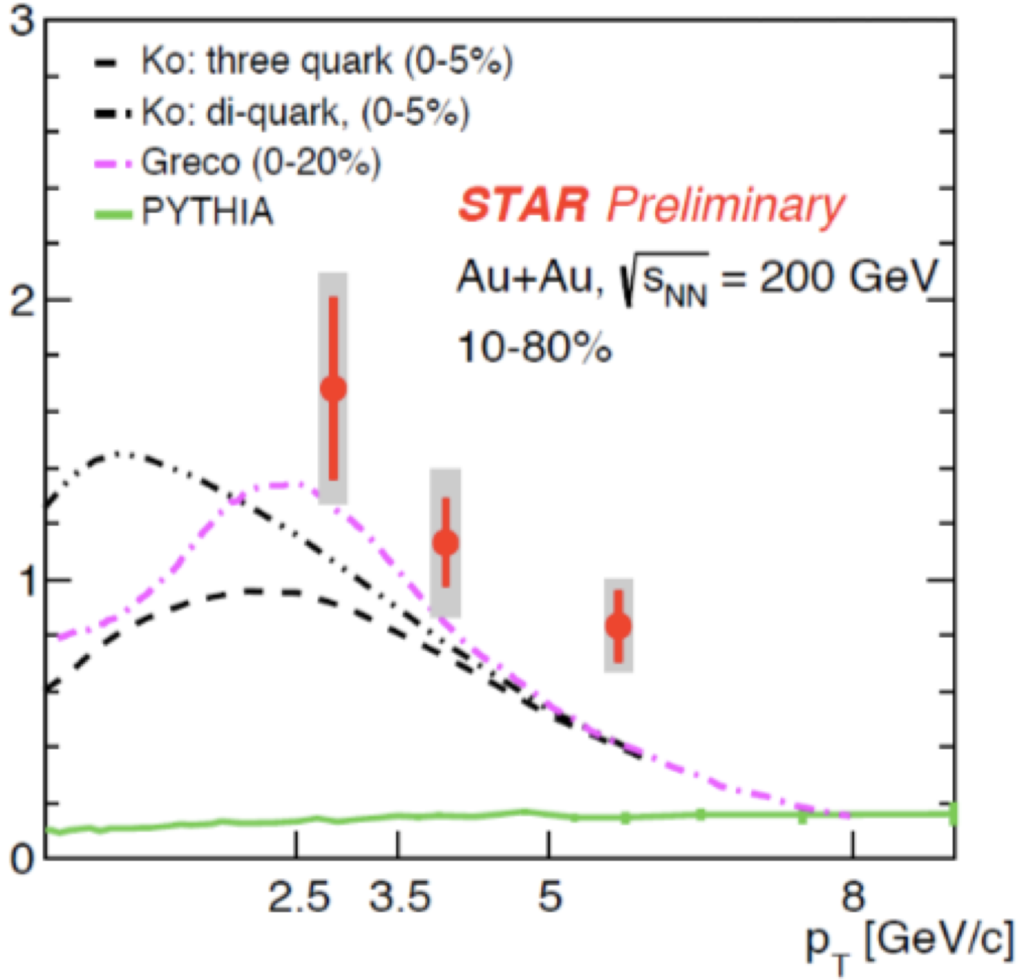
- in e+e- and ep data limited to p_T <2 .5 GeV/c
- in vacuum fragmentation function (Albino et al., NPB 803 (2008)) predicts < 0.25 for baryon-to-meson ratio
- larger values seen already at HERA in strange sector

Baryon-to-meson ratio at EIC (for ep and **eA**)

Nucleus-nucleus collisions: Au-Au (RHIC) and Pb-Pb (LHC)

arXiv:1809.10922

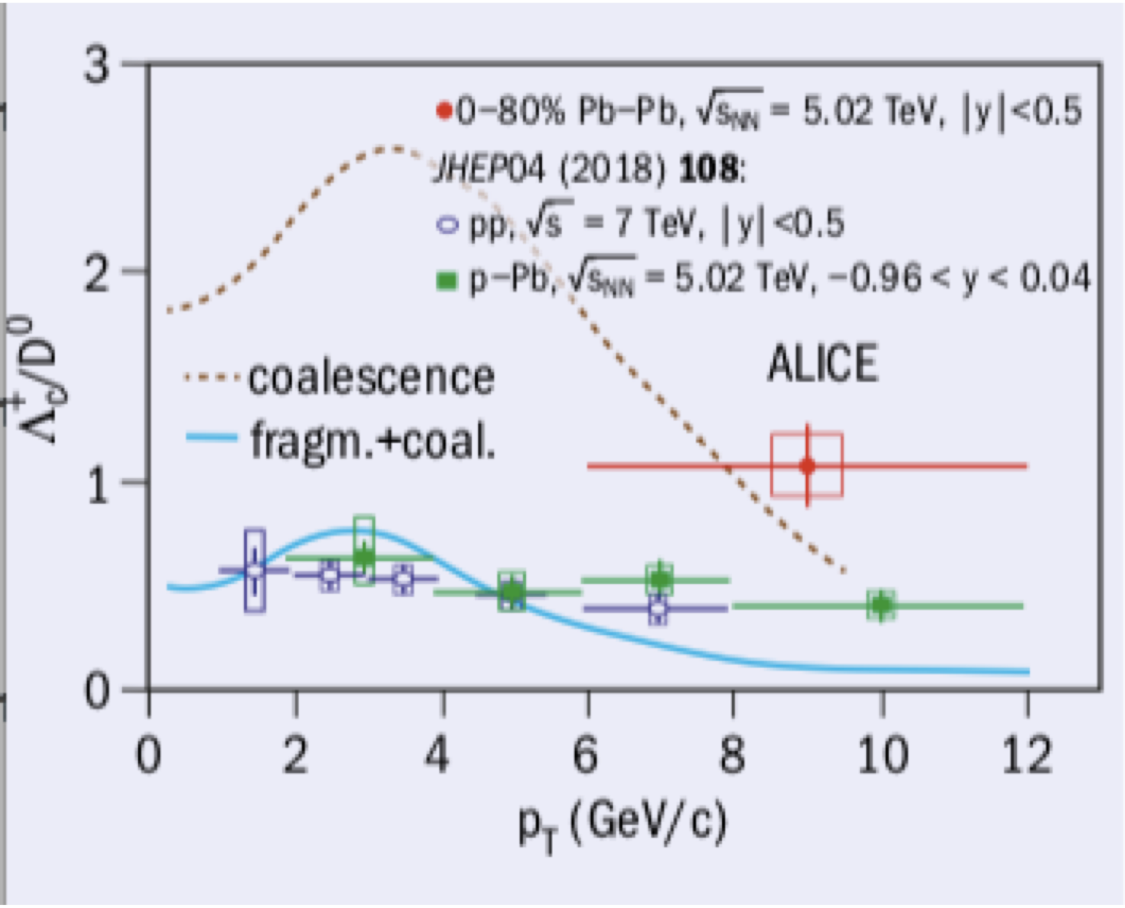




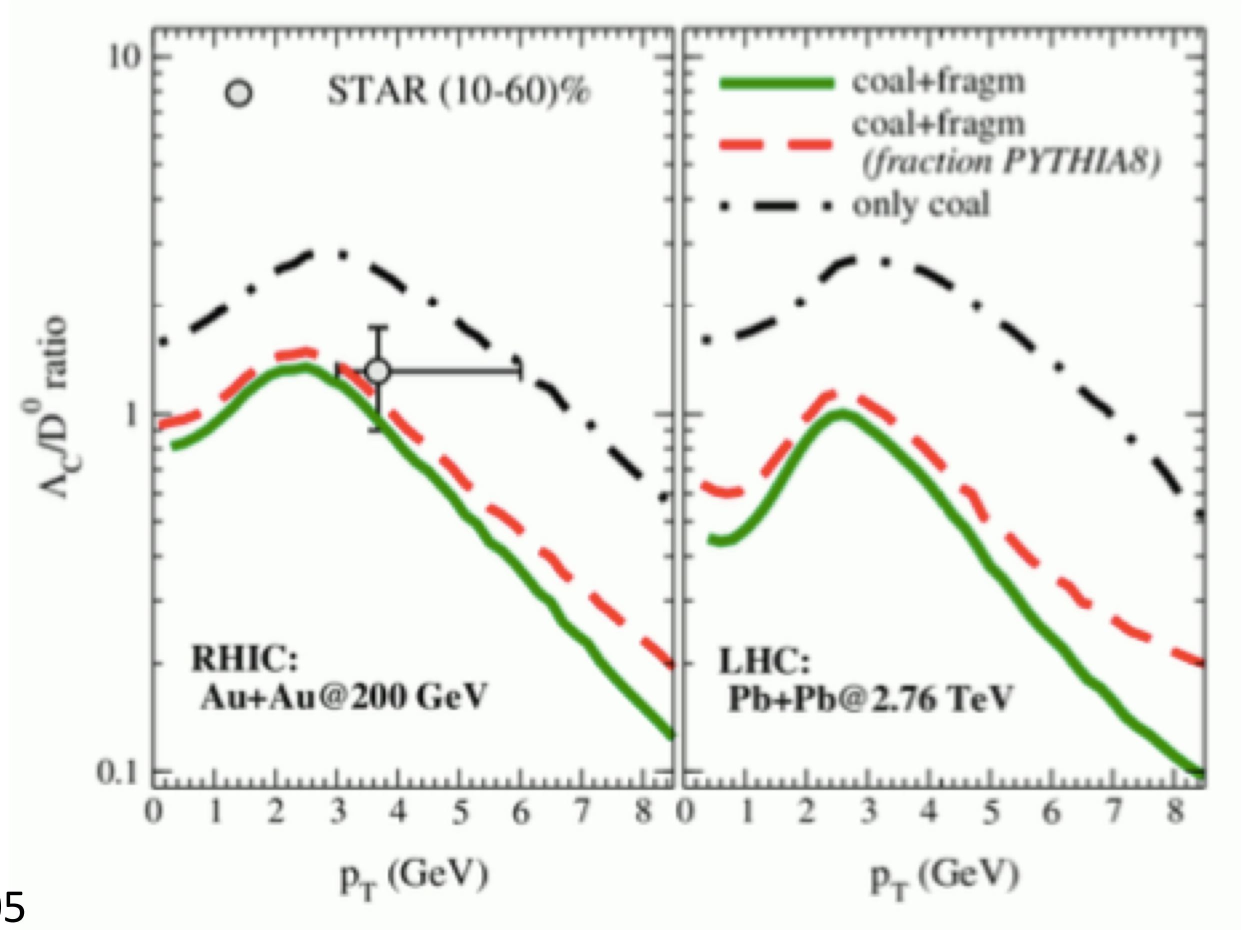
Λ_c enhancement predicted by coalescence models in the hot medium

The interplay between fragmentation and coalescence

ALICE, arXiv:1809.10922



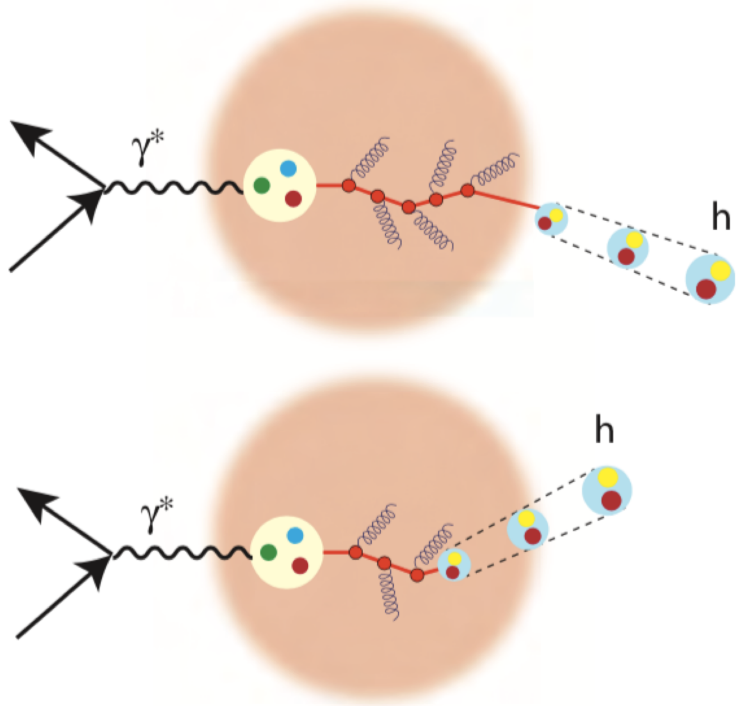
Model by S. Plumari et al, EPJ C78 (2018) 348
introduces coalescence also in pp and pPb to fit data



Review ref: Fries et al., Ann.Rev.Nucl.Part.Sci.58 (2008) 177-205

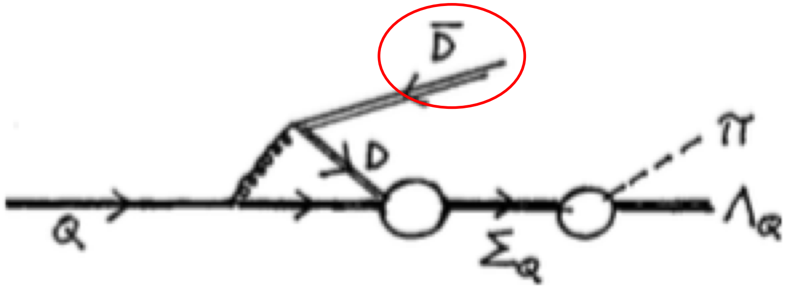
Could it be visibile such effect in eA?

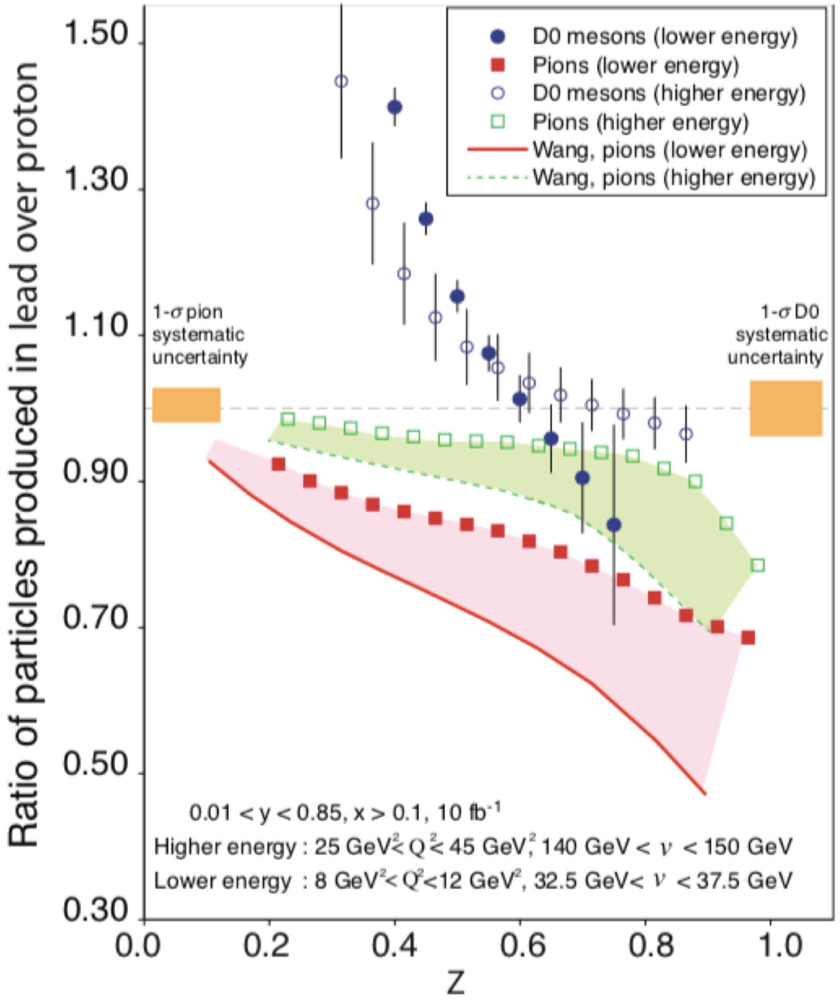
Some relevant ideas from EIC White Paper



Basic idea:
use Q^2 and $\nu = q{\cdot}p/M$ to control **where** hadronization happens

- effect foreseen for D^0/π (based on different FF) might be there also for HF baryons/hyperons (FF Belle: PRD 97 (2018), 072005: hyperons and HF-baryons)
- usually pre-hadron and absorption in CNM discussed for mesons (Kopeliovich et al., Nucl.Phys. A740 (2004) 211-245)
- role of **di-quark** for baryon hadronization (Adamov et al., Phys.Rev. D64 (2001) 014021





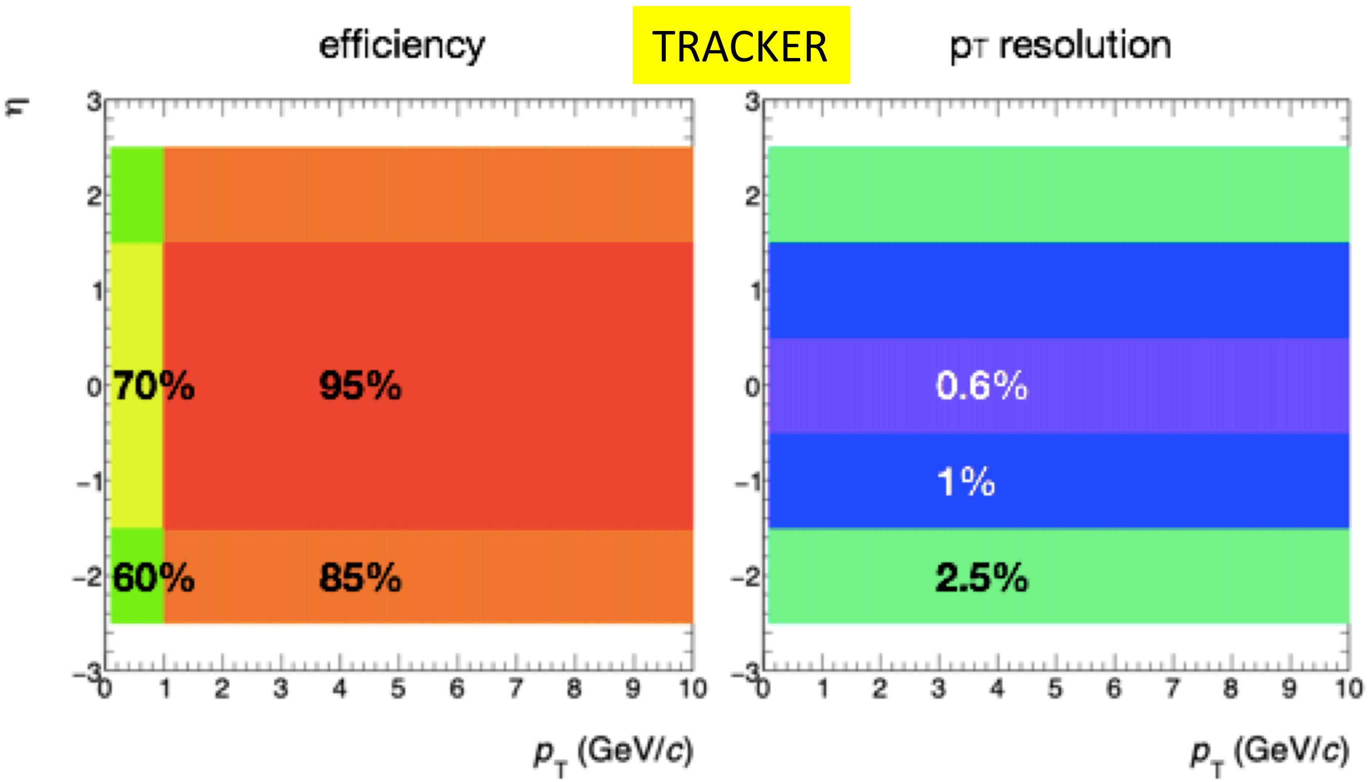
- Λ_c baryons: repeat ep HERA measurements, but differentially in ν → move to eA
- clean environment to study baryon/meson ratio: → hadronization?
- HF baryon spectroscopy to test CR models?
- could we see (and ideally turn on/off) the onset of coalescence in CNM? (in pp and p-Pb we don't expect a hot QGP but...)

Some very preliminary estimates/studies

- **ep collisions with Pythia 6.4.28**
  E_e = 15.9 GeV E_p = 250 GeV $\sqrt{s}$ = 126.1 GeV

- **fast detector simulation: DELPHES**

- **tracking in B = 2 T**
  p_T resolution from (ATLAS parameterisation)
  efficiency from (ATLAS parameterisation)
  with p_T and η dependence



barrel TOF detector $-1.2<\eta<1.2$

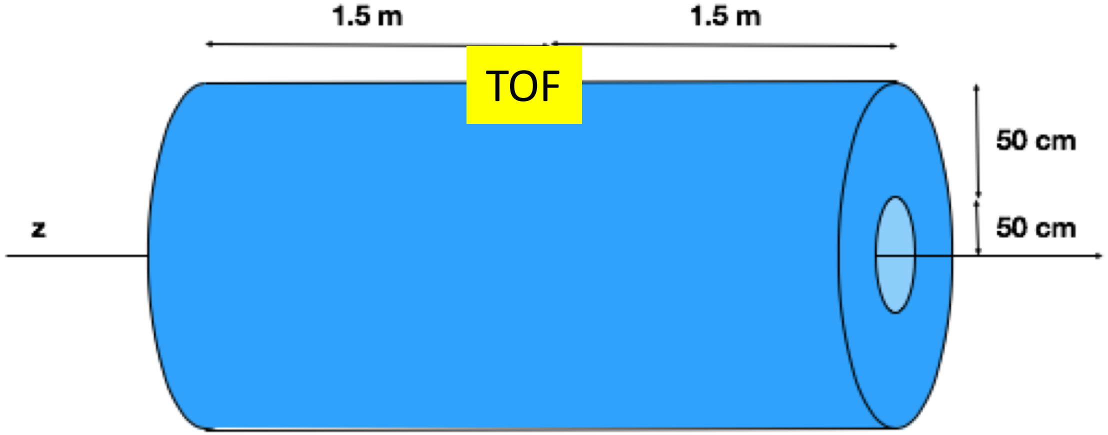
cylindrical surface centred at z = 0

r = 1 m L = 3 m σ_t = 30 ps

forward TOF detector $-1.2<\eta<-1.8$ and $1.2<\eta<1.8$

two discs located at z = ±1.5 m

r_{in} = 50 cm r_{out} = 1 m σ_t = 30 ps



Λ_c reconstruction and production rates

- **secondary vertices with 3 charged tracks**
  assume ideal position resolution
  vertexing from Monte Carlo truth

invariant mass reconstruction
$|y_{rapidity}| < 2$
as a function of p_T

particle identification strategies
1. no PID
2. inclusive 3σ TOF PID (veto)
3. ideal PID (from MC truth)

"eRHIC scenario: https://www.bnl.gov/cad/eRhic/mainAccParam.asp
E_e = 15.9 GeV
E_p = 250 GeV
√s = 126.1 GeV

0.01 < $|y_{inelasticity}|$ < 0.95

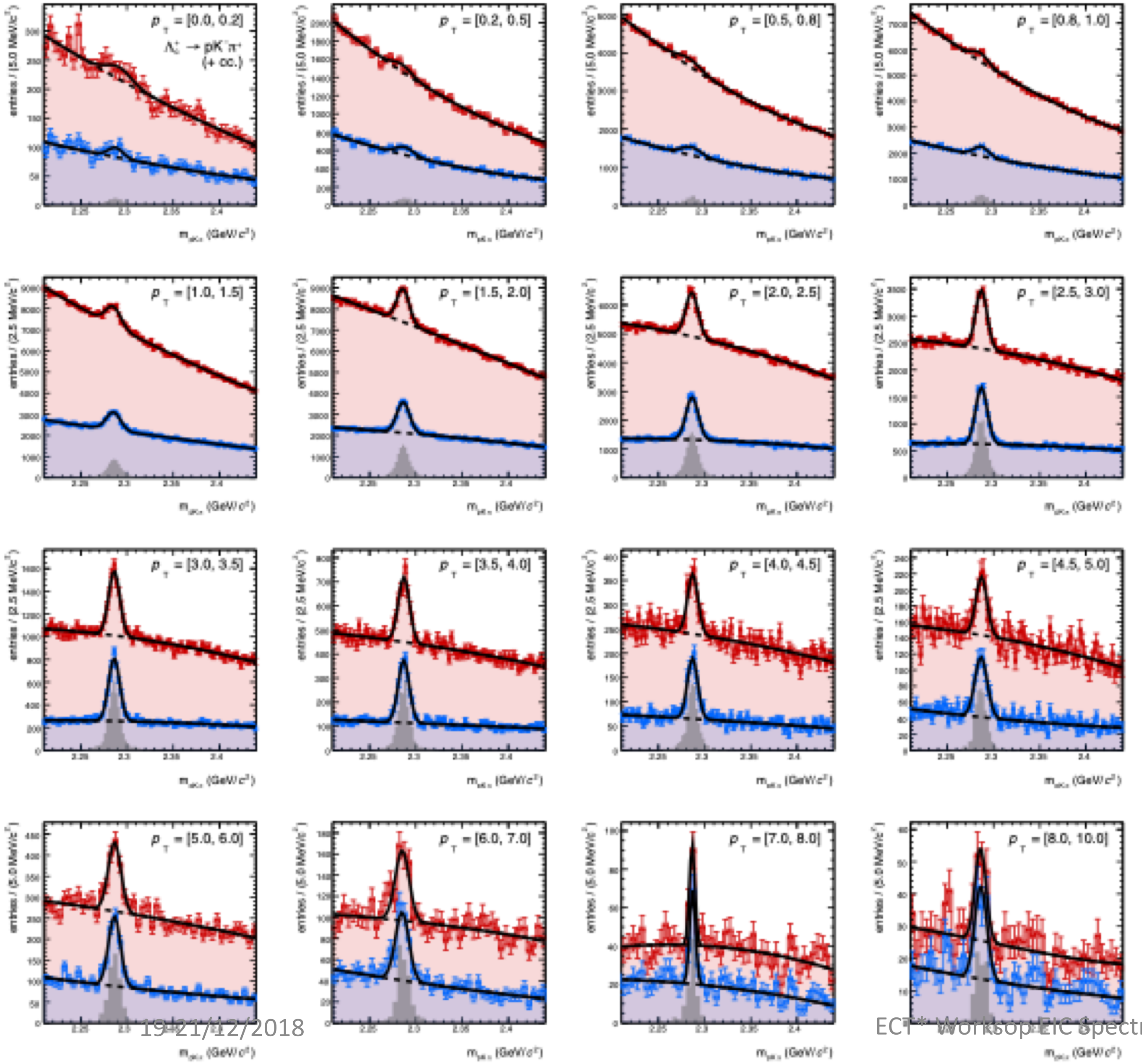
$|y_{rapidity}| < 2$
$\mathcal{L} = 10^{33}$ cm^{-2} s^{-1}

$\Lambda_c^+ \rightarrow p\, K^- \pi^+$ (BP 6.35%)

Λ_c^+ (+ cc.)

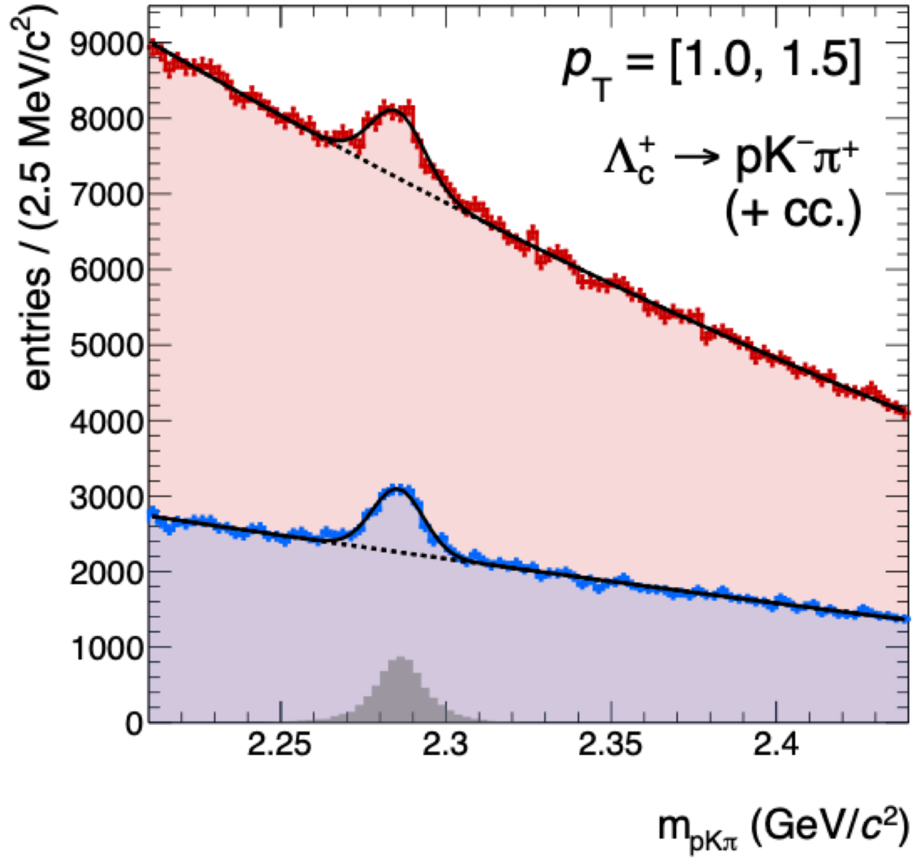
Q^2 (GeV)	< 1	> 1	[2, 4]	[8, 16]	[32, 64]
$\sigma_{process}$ (total)	28 μb	560 nb	150 nb	41 nb	8.4 nb
$\sigma_{particle}$ (Λ_c >= 1)	59 nb	4.8 nb	1.3 nb	490 pb	92 pb
rate	59 Hz	4.8 Hz	1.3 Hz	490 mHz	92 mHz

Λ_c reconstruction examples…



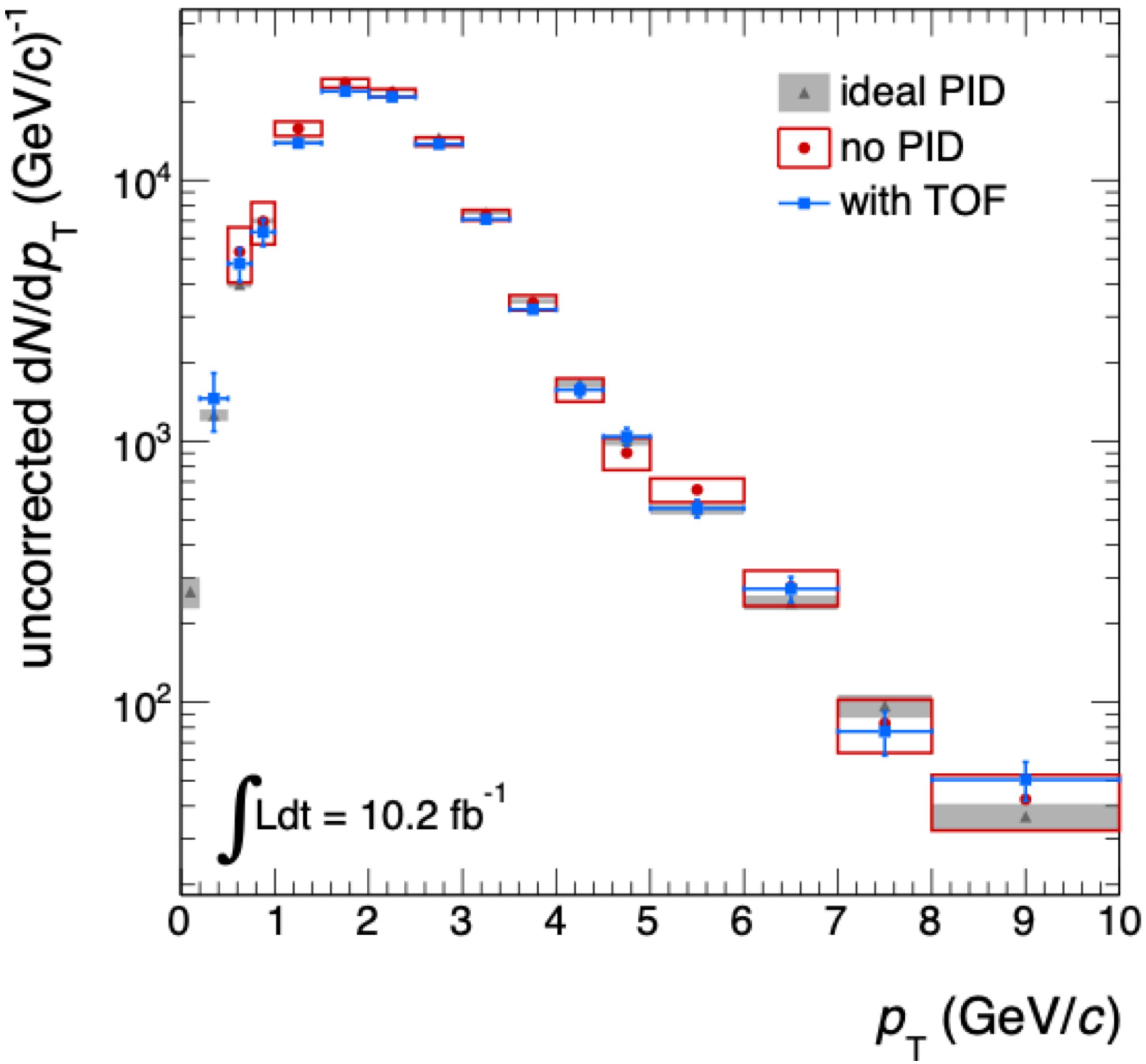
$8 < Q^2 < 16$ GeV^2/c^4

$0.01 < y_{inelasticity} < 0.95$

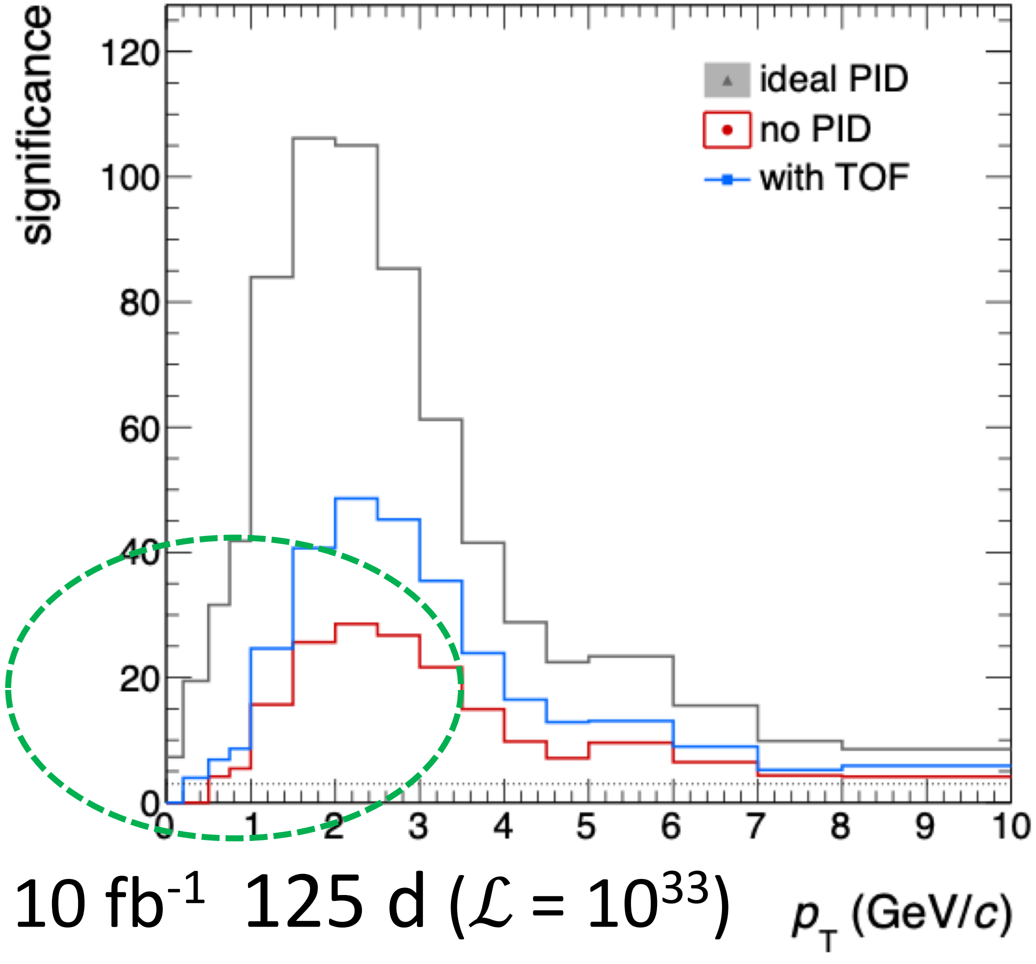


$\int\mathcal{L}$ = 10 fb^{-1} 125 d ($\mathcal{L} = 10^{33}$)

PID helps...

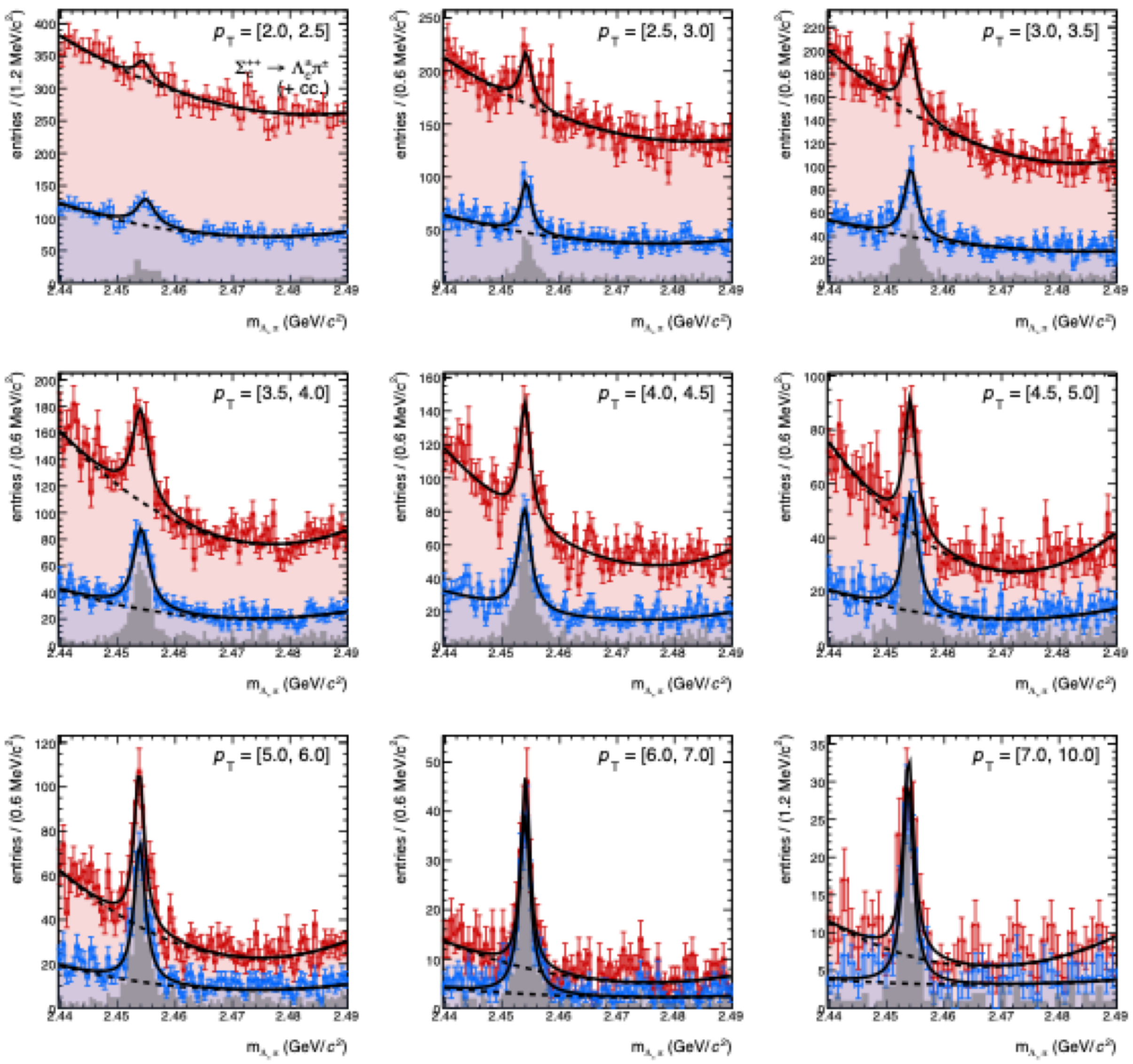


$8 < Q^2 < 16 \quad 0.01 < y_{inelasticity} < 0.95$

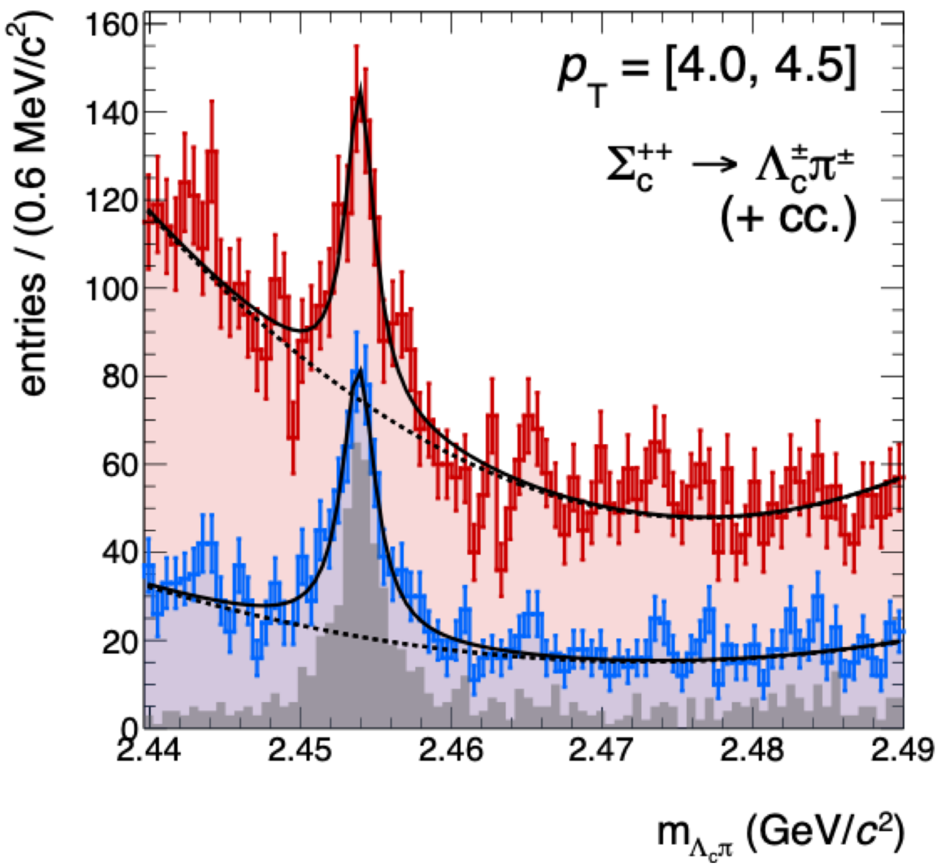


$\int \mathcal{L} = 10\ fb^{-1}$ 125 d ($\mathcal{L} = 10^{33}$)

A Σ_c study seems possible (soft pion combined with rec. Λ_c)



$32 < Q^2 < 64 \quad 0.01 < y_{inelasticity} < 0.95$



$\int\mathcal{L} = 100\ fb^{-1}$ 3.5 y ($\mathcal{L} = 10^{33}$)

Charmed baryon production rates at EIC

Q^2 (GeV)	< 1	> 1	[2, 4]	[8, 16]	[32, 64]
$\sigma_{process}$	28 μb	560 nb	150 nb	41 nb	8.4 nb
$\sigma_{particle}$	59 nb	4.8 nb	1.3 nb	490 pb	92 pb
rate	59 Hz	4.8 Hz	1.3 Hz	490 mHz	92 mHz

Λ_c^+ (+ cc.)

$\sigma_{process}$	28 μb	560 nb	150 nb	41 nb	8.4 nb
$\sigma_{particle}$	1.9 nb	160 pb	45 pb	17 nb	3.0 nb
rate	1.9 Hz	160 mHz	45 mHz	17 mHz	3.0 mHz

Σ_c^{++} (+ cc.)

$\sigma_{process}$	28 μb	560 nb	15 nb	41 nb	8.4 nb
$\sigma_{particle}$	1.9 nb	150 pb	45 pb	16 nb	3.0 nb
rate	1.9 Hz	150 mHz	45 mHz	16 mHz	3.0 mHz

Σ_c^0 (+ cc.)

E_e = 15.9 GeV E_p = 250 GeV $\sqrt{s}$ = 126.1 GeV

$0.01 < |y_{inelasticity}| < 0.95$

$|y_{rapidity}| < 2$ $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1}

Summary with some questions

some **unexpected** results at LHC from HF-baryon studies
→ do we understand hadronization? (and hadronization to baryons in particular...)
→ can HF-baryon spectroscopy be part of the solution?

relevance for **EIC**:
→ HF-baryons studies in CNM might clarify hadronization mechanisms ("sensitivity to surrounding environment")
→ (not limited to HF): baryon-to-meson ratio at low/intermediate p_T

Questions/Outlook:

- theoretical input needed (and need of MC tools for a eA proper simulation)
- constrain kinematics to constrain hadronization in(out) nuclear medium
- detector design should consider also these probes (vertexing + PID for low p_T reach)

Backup...

PID performance