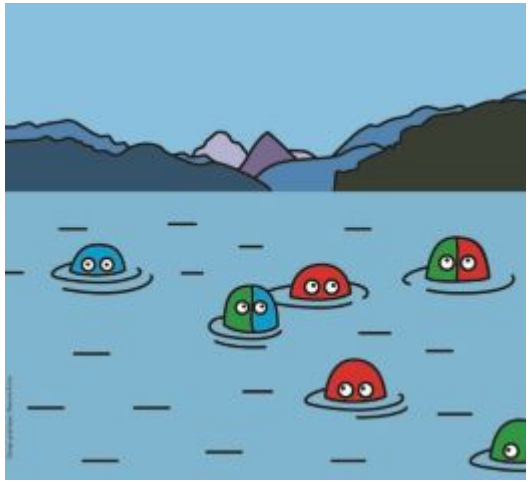
Open heavy-flavour results related to hadronisation



A. Rossi, INFN Padova

Introduction

Focus on selected results (among many) on open-HF hadronisation that in recent years indicated that

- HF hadronisation and in particular baryon formation is not well understood

- HQ, formed in initial hard scattering, can be exploited as “perturbative probes” of hadronisation
  - exploiting properties of different hadron species
  - collision systems and system properties as lever arm to investigate different mechanisms

In the spirit of the workshop, I tried to highlight what are the main open points and possible next steps

Disclaimer: not a comprehensive review. Not covered:
- HF jets and correlations
- Dependence of relative open-HF yields on multiplicity (dedicated talks in next days)
- “exotic” states (X(3879), pentaquarks)

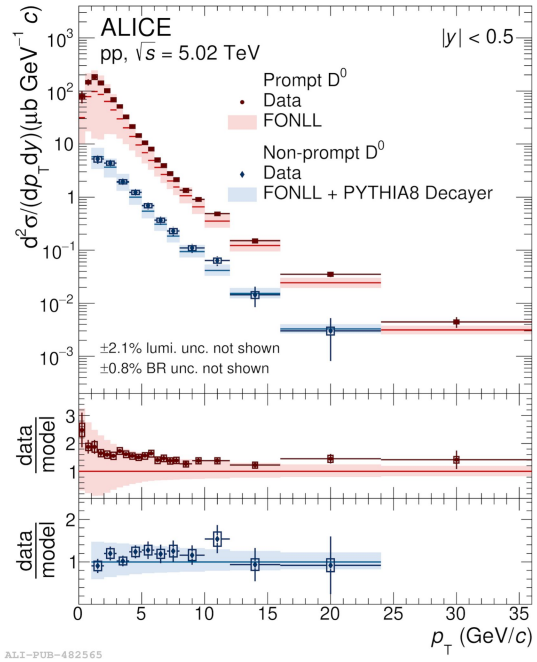
Add your questions, proposal for the afternoon discussion (even beyond what shown in this morning talks):

2:00 PM **Discussion: particle production in vacuum, data vs.model,...**
Speakers: Andrea Rossi, Sergey Barsuk (LAL)
Discussion propos...

(Discussion proposals collection)

Goal: discuss doubts, identify main “what’s next” steps

Factorisation: a very successful framework for HF mesons!



JHEP 05 (2021) 220 ; EPJC 79 (2019) 5, 388

FONLL: JHEP 10 (2012) 137

Prompt and non-prompt D meson production described within uncertainties by pQCD-based calculations based on factorisation approach.

Plethora of results at the LHC:

- wide p_T,y coverage
- for both charm and beauty mesons

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

Fragmentation functions ($D_{c\text{->}D}$) often **assumed** "**universal**": once constrained to e^+e^- and ep data they are used in different collision systems and energies.

Factorisation: a very successful framework for HF mesons!

JHEP 05 (2021) 220 ; EPJC 79 (2019) 5, 388

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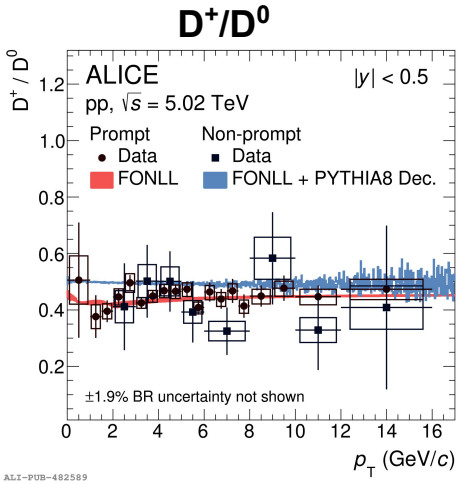
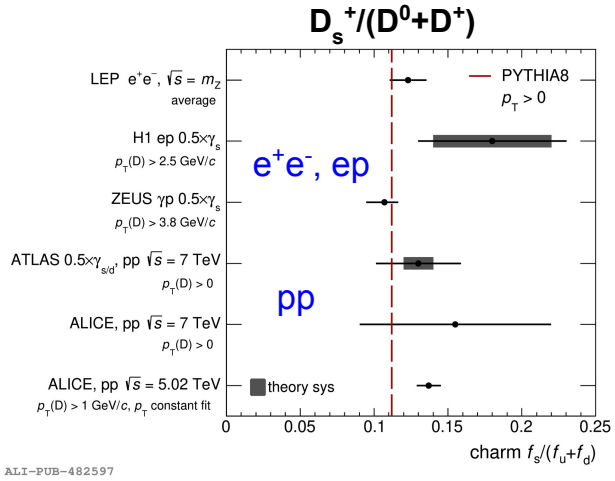




$$\frac{d\sigma^D}{dp_T}(p_T^D;\mu_F;\mu_R)=PDF(x_1,\mu_F)PDF(x_2,\mu_F)\otimes\frac{d\sigma^c}{dp_T^c}(x_1,x_2;\mu_F;\mu_R)\otimes D_{c\to D}(z=\frac{p_D}{p_c};\mu_F)$$

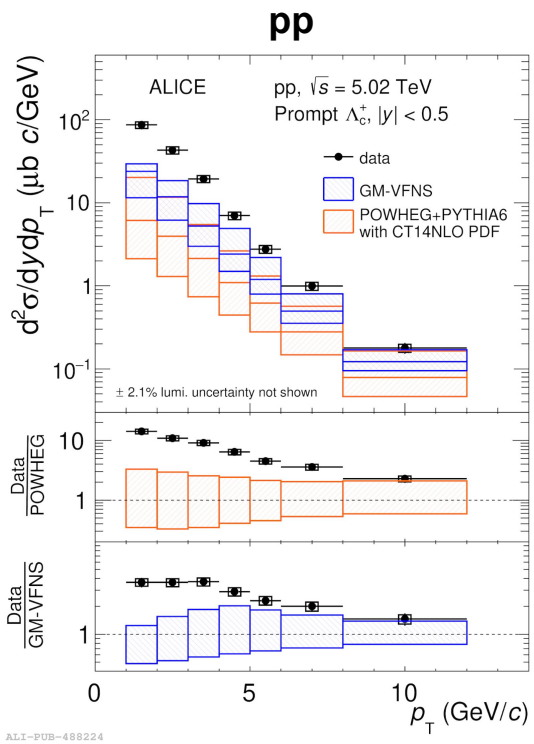
Fragmentation functions ($D_{c\text{->}D}$) often **assumed** "**universal**": once constrained to e^+e^- and ep data they are used in different collision systems and energies.

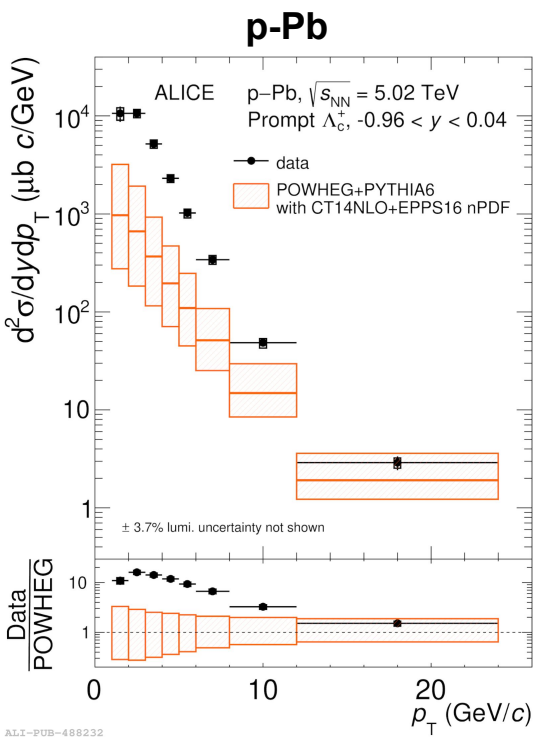
Naïve expectation: ratios of particle-species yields independent from collision system

→ **holds for mesons**

Λ_c^+ cross section in pp and p-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV

PRC 104 054905 (2021)
PRL 127 202301 (2021)

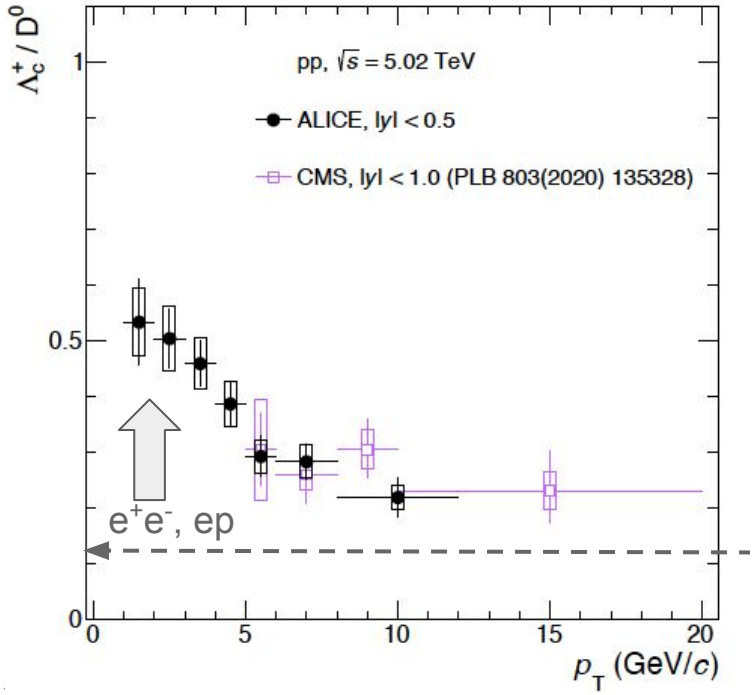




Λ_c^+ production significantly underestimated by pQCD-based models

GM-VFNS: PRD 101 (2020) 114021
POWHEG: JHEP 09 (2007) 126
PYTHIA6: JHEP 05 (2006) 026
CT14 NLO: Phys. Rev. D 93, 033006 (2016)

Λ_c^+/D^0 ratio in pp collisions at 5 TeV



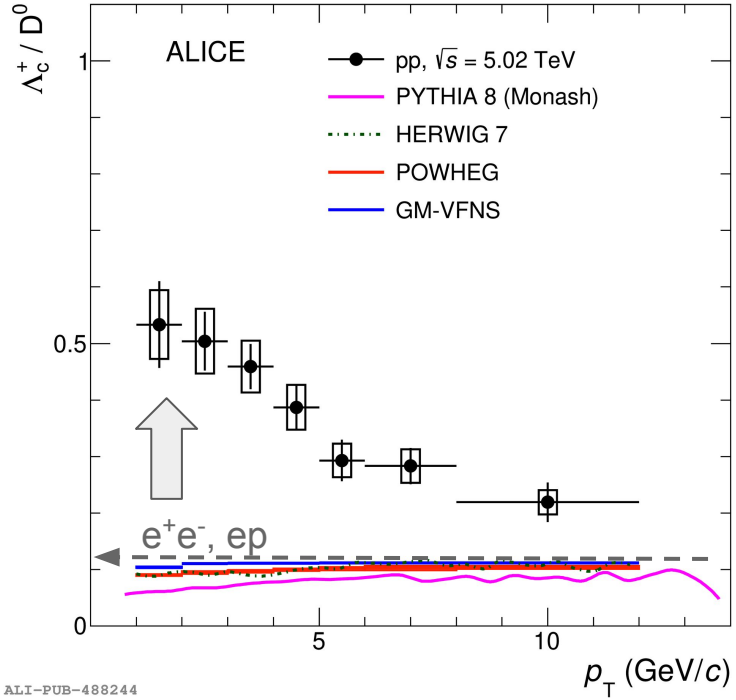
Λ_c^+/D^0 ratio higher (x4-5) values at low p_T than e^+e^-, ep

Significantly decreasing with p_T

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
ALICE	$0.51 \pm 0.04 \pm 0.04^{+0.01}_{-0.02}$	pp	5020	$p_T > 0, \lvert y \rvert < 0.5$
ALICE	$0.43 \pm 0.03 \pm 0.05^{+0.05}_{-0.03}$	p–Pb	5020	$p_T > 0, -0.96 < y < 0.04$
CLEO [16]	$0.119 \pm 0.021 \pm 0.019$	e^+e^-	10.55	
ARGUS [15, 17]	0.127 ± 0.031	e^+e^-	10.55	
LEP average [18]	$0.113 \pm 0.013 \pm 0.006$	e^+e^-	91.2	
ZEUS DIS [21]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	e^-p	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp, HERA I [19]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$
ZEUS γp, HERA II [20]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$

ALICE, PRC 104 054905 (2021), arXiv:2011.06079
ALICE, PRL 127 202301 (2021), arXiv:2011.06078
CMS, PLB 803 13428 (2020)

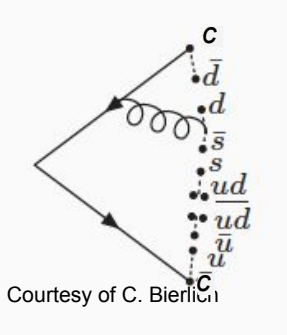
Λ_c^+/D^0 ratio in pp collisions vs. models (1)



PRC 104 054905 (2021), arXiv:2011.06079
PRL 127 202301 (2021), arXiv:2011.06078

Default PYTHIA8 (Monash, EPJC 74 (2014) 3024), standard Lund string fragmentation

- Light quark/diquark pairs popping out from QCD color-confinement potential (← strings)
  - **Diquarks ↔ baryons**
- Hadronisation of different MPI products largely independent
- Reproduces fragmentation functions used in pQCD-based calculations

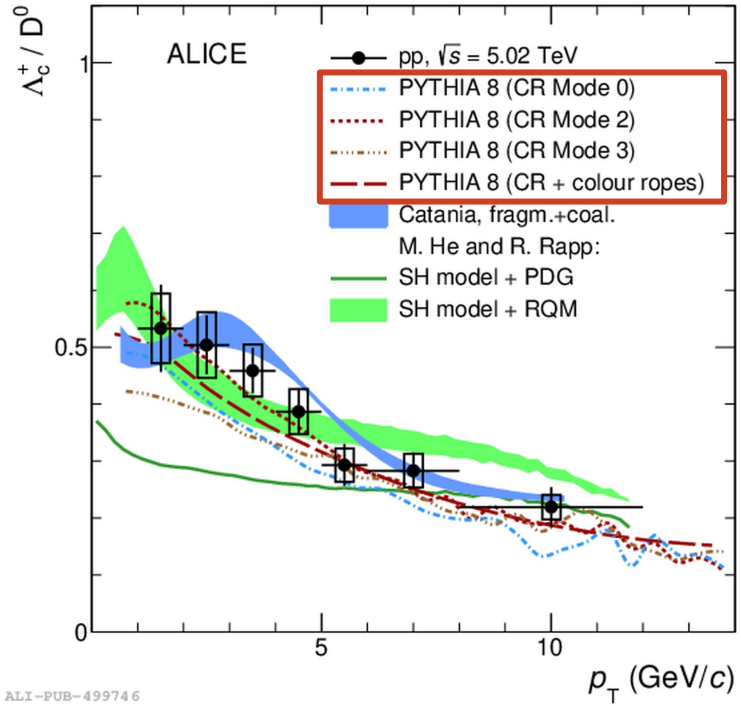


Courtesy of C. Bierlich

HERWIG7 (EPJC 58 (2008) 639-707), cluster hadronisation

Undershoot data by factor about 5 and do not catch p_T shape

Λ_c^+/D^0 ratio in pp collisions vs. models (2)



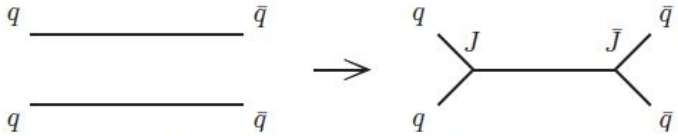
Data described by:

PYTHIA8 with String Formation beyond Leading Colour approximation (JHEP 1508 (2015) 003).

More complete and realistic (=closer to QCD) colour-reconnection (CR) scheme

- ***"...between which partons do confining potentials arise?"***

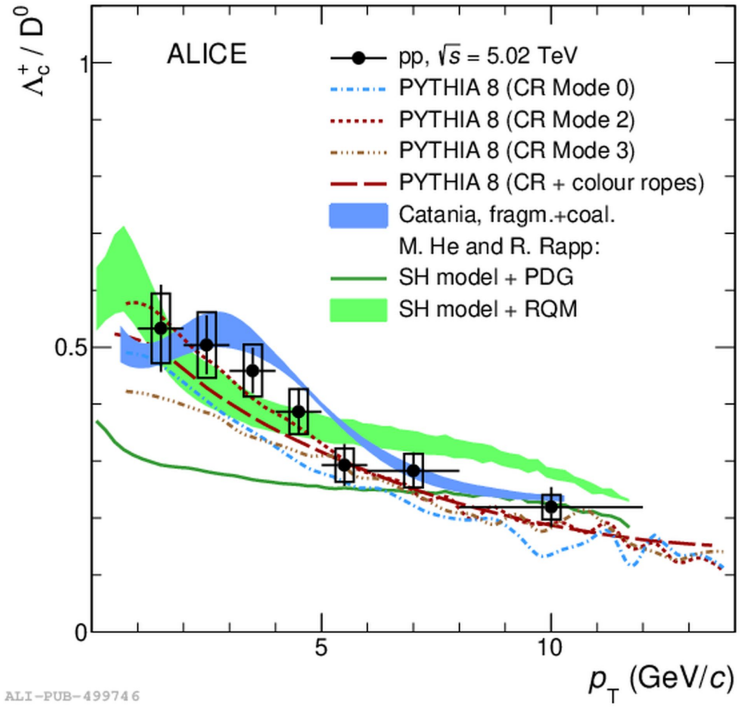
Junction reconnection topologies → enhance baryons.



(b) Type II: junction-style reconnection

PRC 104 054905 (2021), arXiv:2011.06079
PRL 127 202301 (2021), arXiv:2011.06078

Λ_c^+/D^0 ratio in pp collisions vs. models (3)



PRC 104 054905 (2021), arXiv:2011.06079
PRL 127 202301 (2021), arXiv:2011.06078

Data described by:

PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation (arxiv 2012.12001)

Expanding system of thermalised light quarks and gluons

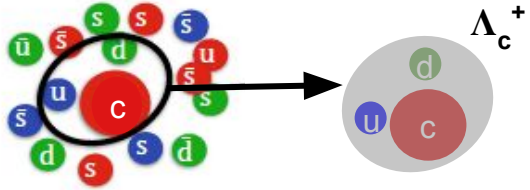
"Sudden" (fixed temperature) coalescence:

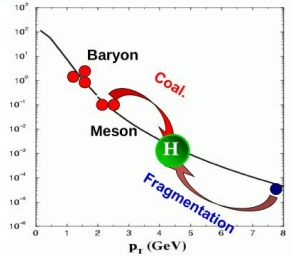
f_q = phase-space distributions of quarks in the system

$$\frac{dN_H}{dy d^2 P_T} = g_H \int \prod_{i=1}^{N_q} \frac{d^3 p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i \; f_{q_i}(x_i, p_i)$$

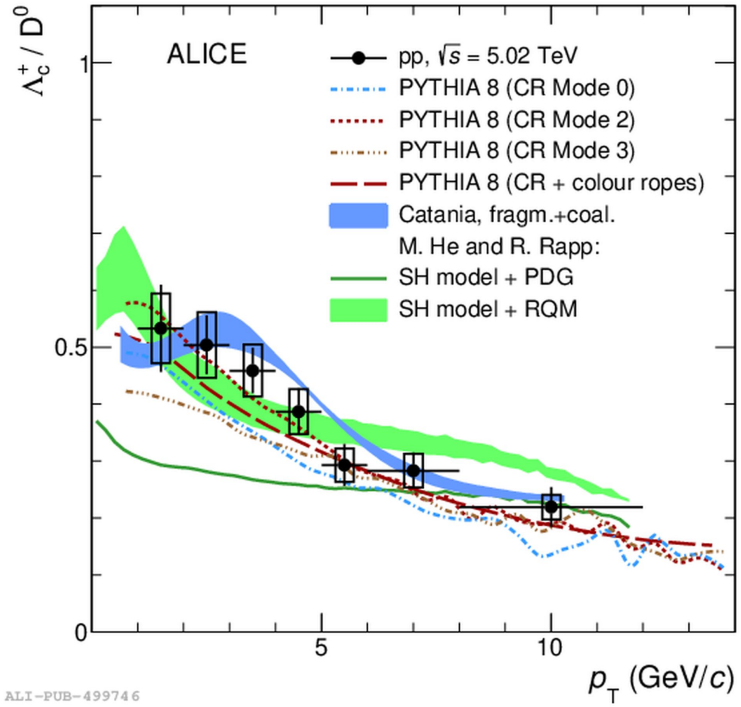
$$\times f_H(x_1 \ldots x_{N_q}, p_1 \ldots p_{N_q}) \, \delta^{(2)} \left(P_T - \sum_{i=1}^{n} p_{T,i} \right)$$

f_H= phase-space distributions of quarks within hadron





Λ_c^+/D^0 ratio in pp collisions vs. models (4)



PRC 104 054905 (2021), arXiv:2011.06079
PRL 127 202301 (2021), arXiv:2011.06078

Data described by:

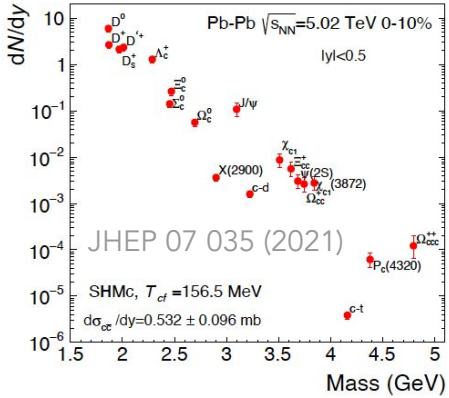
PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

SH+PDG/RQM, PLB 795 117-121 (2019):
Hadron abundances based on **statistical hadronisation model** + feed-down from **augmented set of charm-baryon states** (from RQM)

→ PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c

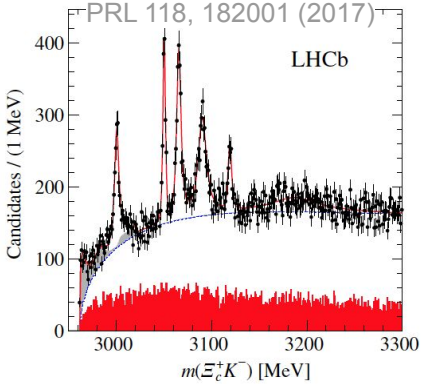
→ RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c



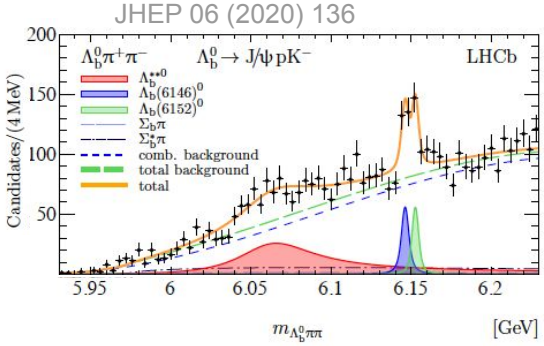
Why not discovered in e^+e^-?

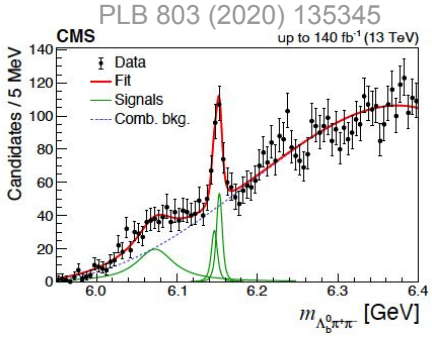
Higher-mass states: new states popping up

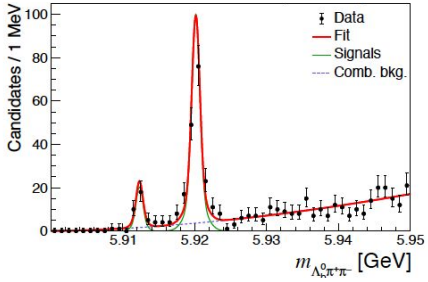
Ω_c excited states



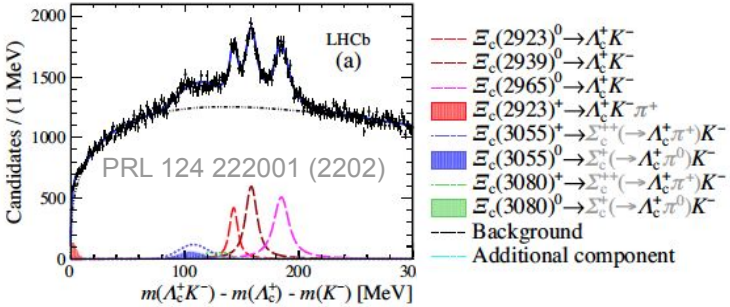
Λ_b excited states



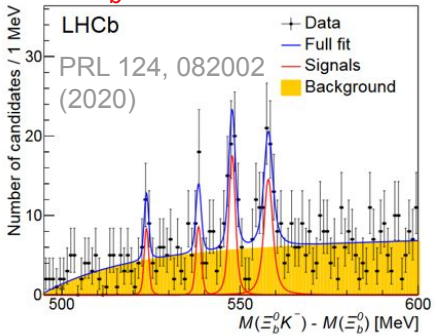


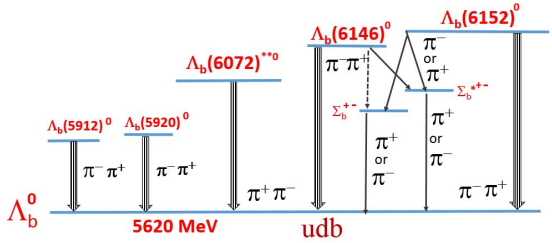


Ξ_c excited states



Ω_b excited states





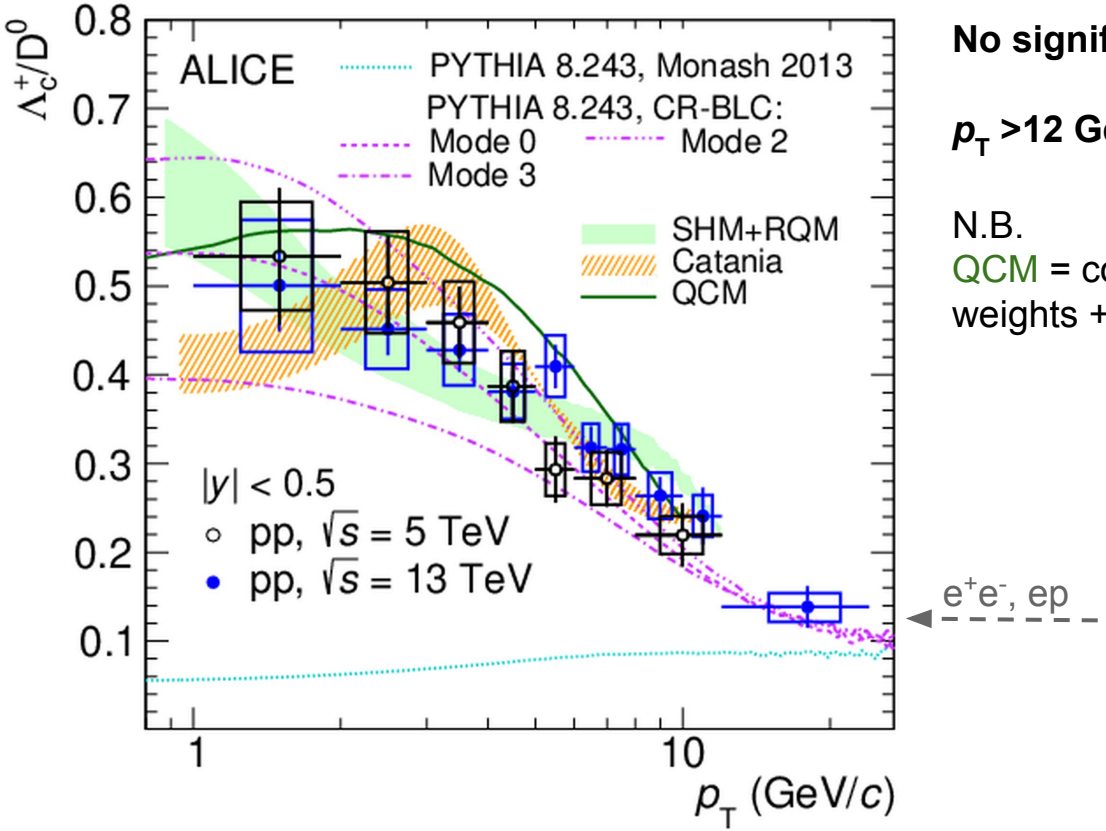
Many states with Γ~10 MeV

Also several lifetime measurements, very important spectroscopy results

Typically not measurements of (prompt) cross sections. Prospects?

Λ_c^+/D^0 ratio in pp collisions at 5 TeV and 13 TeV

PRL 128 (2022) 012001, arxiv 2106.08278



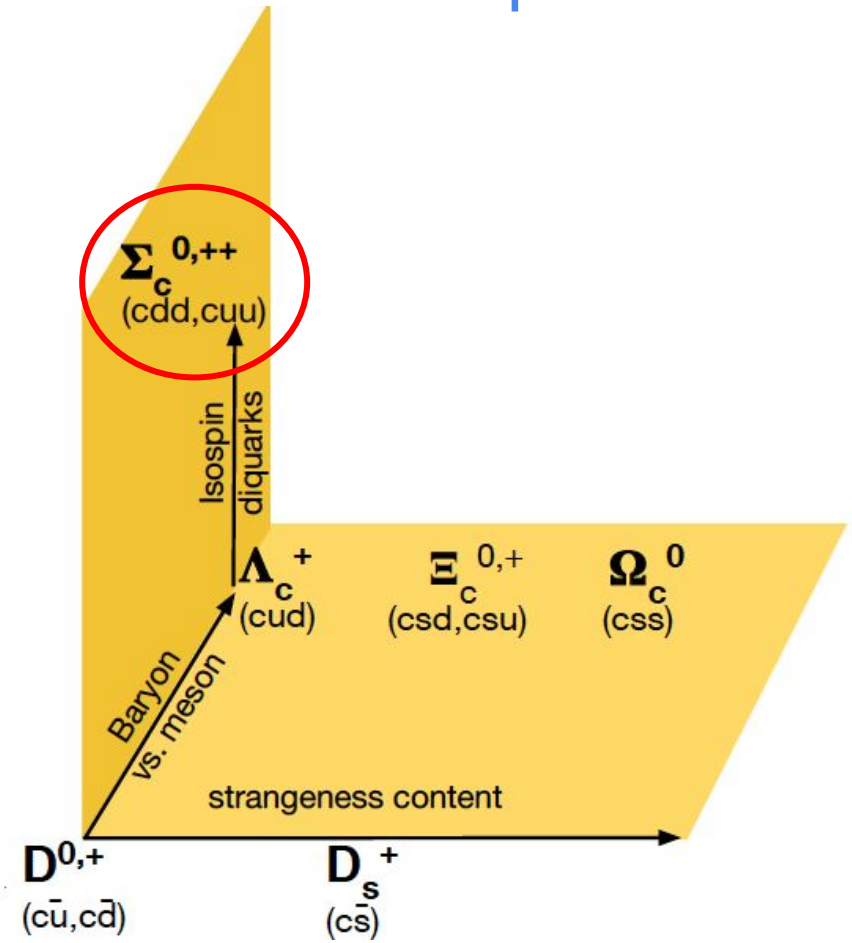
No significant dependence on collision energy

p_T >12 GeV/c: approaching e^+e^- values?

N.B.
QCM = coalescence model based on statistical weights + "equal quark-velocity" (EPJC 78, 2018 4, 344)

ALI-DER-493896

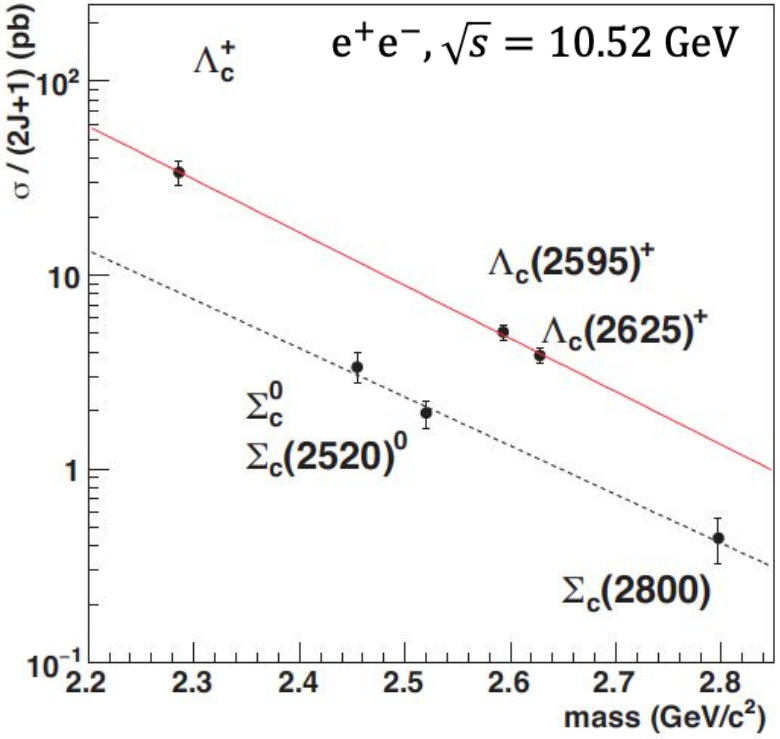
Several arrows in the quiver



Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

$\Sigma_c^{0,++}$ production and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ feedown

Belle, PRD 97, 072005 (2018)

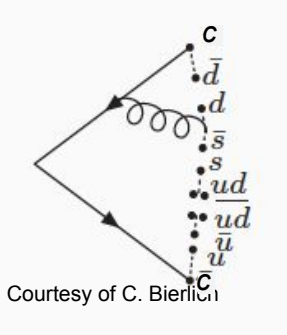


e^+e^- collisions: production of Σ_c states suppressed w.r.t. Λ_c states

In string fragmentation models charm baryons formed by combining initially produced c quarks with light-quark diquarks, produced in pair in string breaking

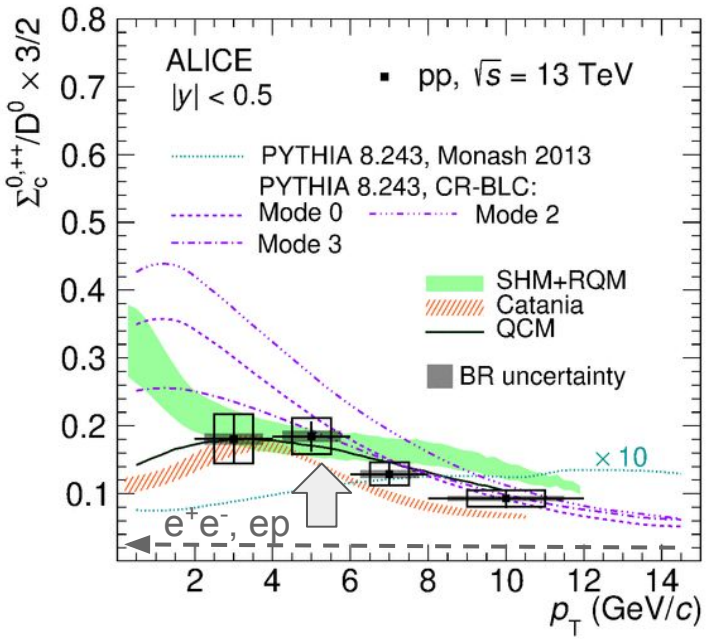
Λ_c (isospin = 0) needs diquark with spin = 0 $(ud)_0$
Σ_c (isospin = 1) needs diquark with spin = 1 $(ud,dd,uu)_1$

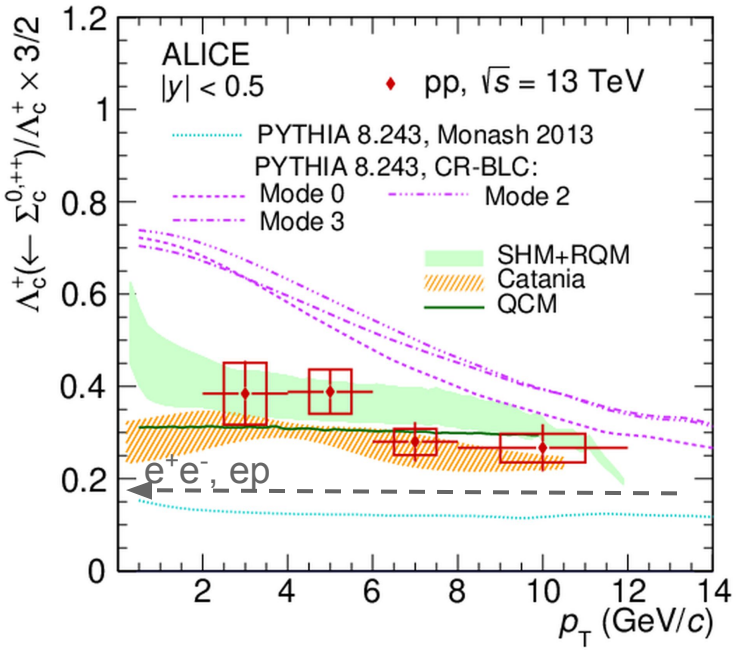
$(ud,dd,uu)_1$ larger mass than $(ud)_0$ mass → suppression



$\Sigma_c^{0,++}/D^0$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feedown

PRL 128 (2022) 012001, arxiv 2106.08278





$\Sigma_c^{0,+,++}/D^0$ ratio significantly larger than in e^+e^- collisions

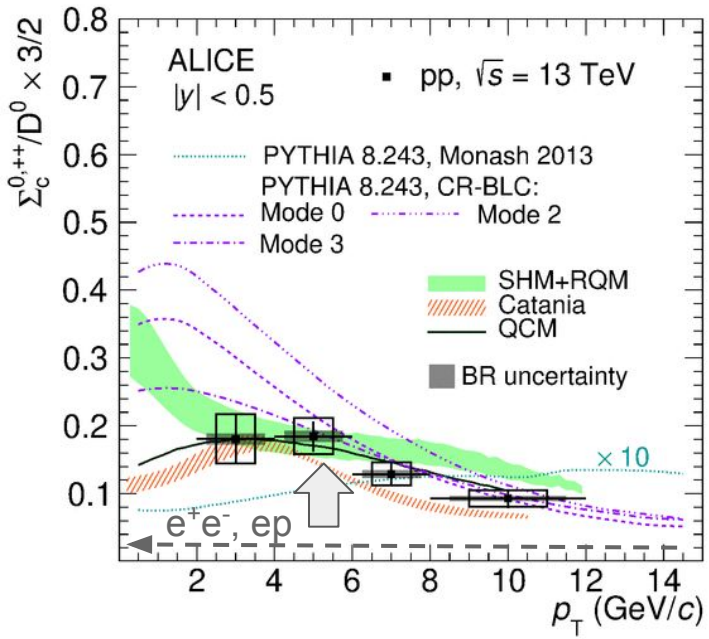
About x2 increase of $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feed-down → $\Sigma_c^{0,+,++}$ "enhancement" larger than Λ_c^+ one

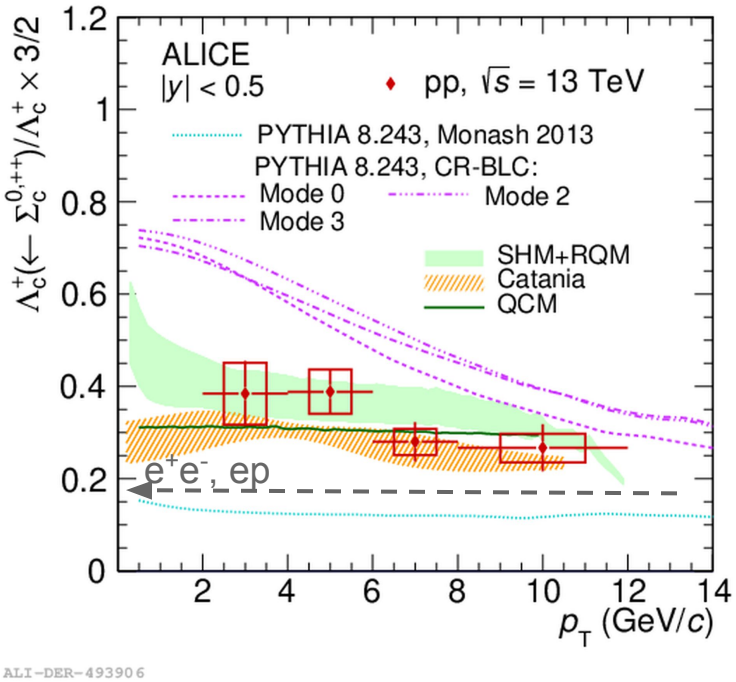
→ $\Sigma_c^{0,+,++}$ produced differently in pp than e^+e^- collisions

→ suppression from $(ud,dd,uu)_1$ diquark creation absent or reduced, as comparison to models suggests

$\Sigma_c^{0,++}/D^0$ and $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feedown

PRL 128 (2022) 012001, arxiv 2106.08278





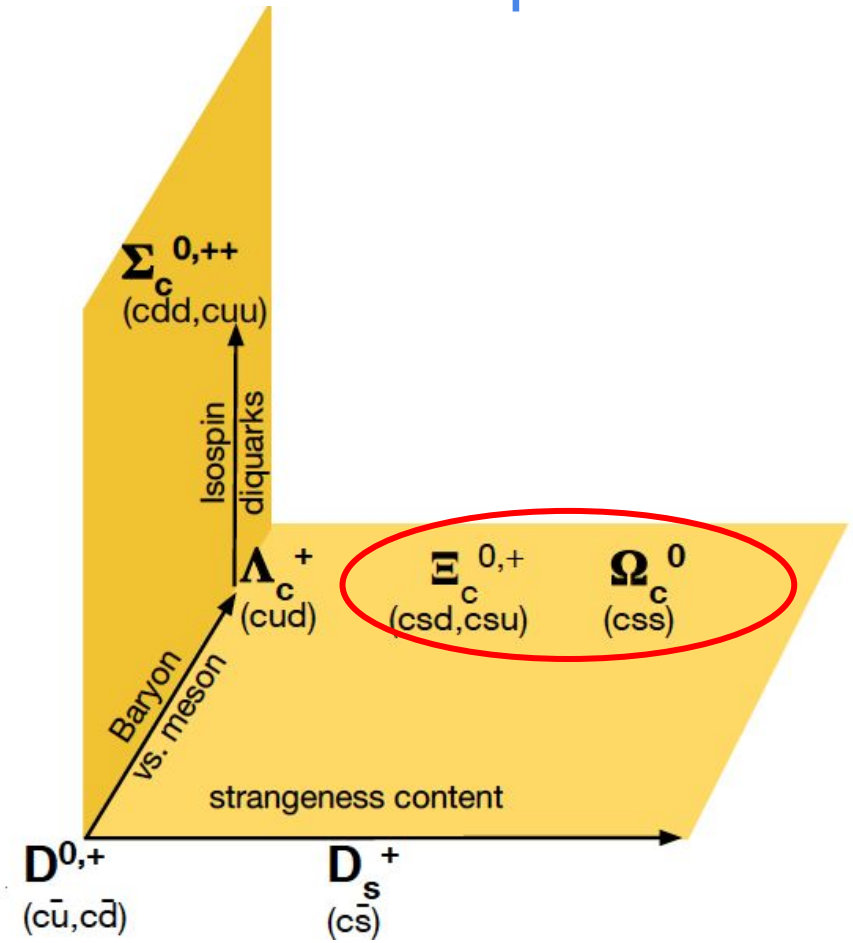
Default PYTHIA8 (Monash 2013): significantly underestimates data (worse than for Λ_c^+)

PYTHIA8 with CR Beyond Leading Colour: Σ_c enhanced by junction CR topologies (n.b. heavy cu, cd diquarks)

- describes $\Sigma_c^{0,+,++}/D^0$ but overestimates $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}/D^0$

Catania, QCM and SHM+RQM models describe both ratios

Several arrows in the quiver



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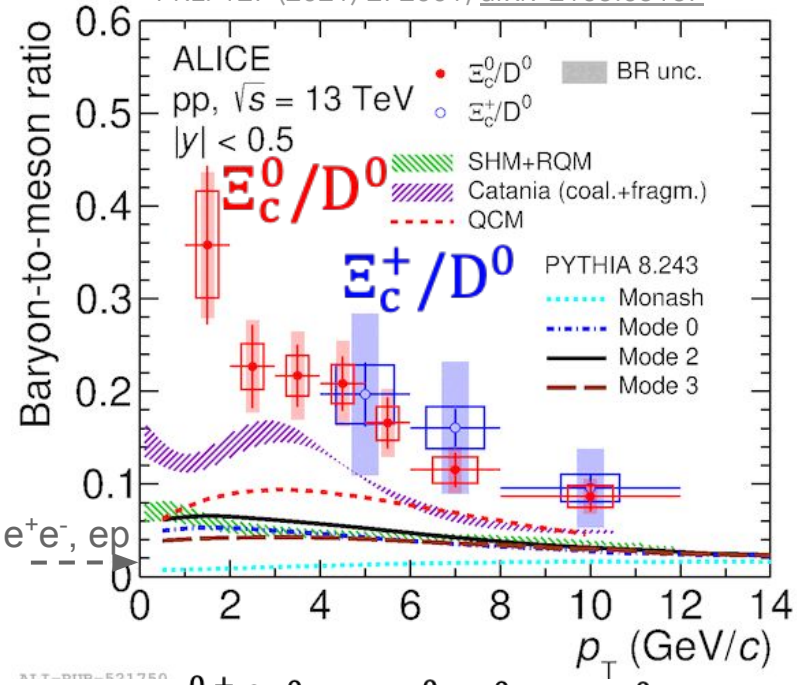
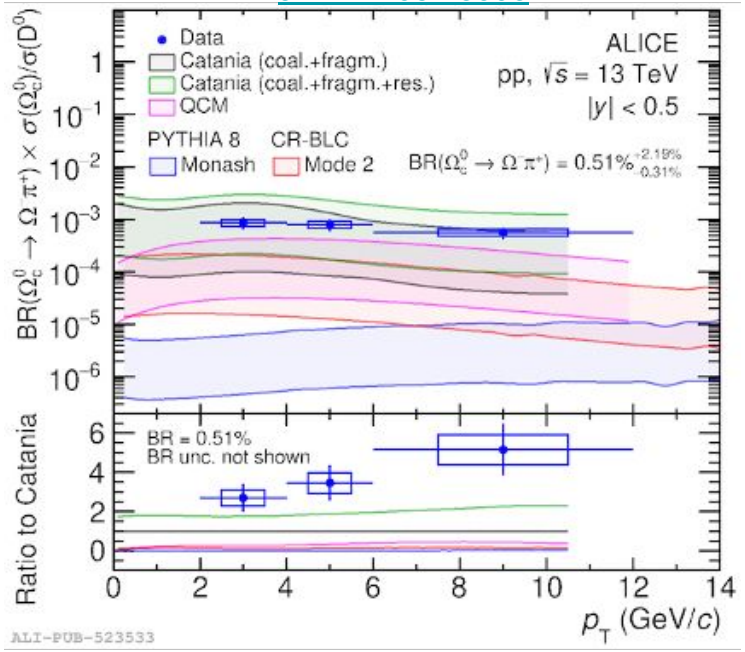
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

Charm-strange baryons: $\Xi_c^{0,+}$ and Ω_c^0

PRL. 127 (2021) 272001, arxiv 2105.05187



arXiv:2205.13993



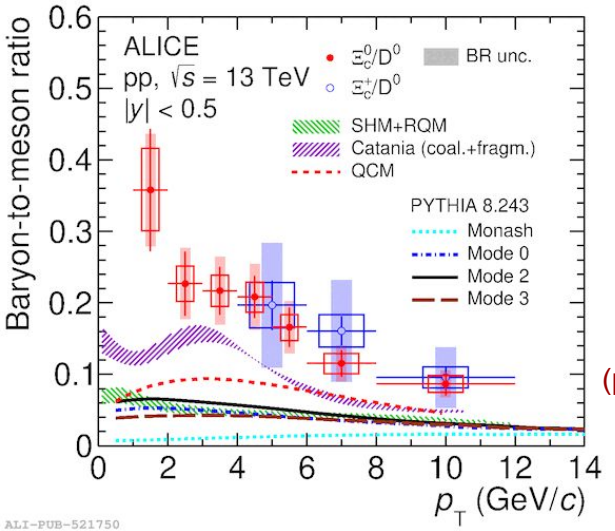
- Both $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0xBR($\Omega_c^0 \rightarrow \Omega^-\pi^+$) ratios significantly larger than in e^+e^- collisions
- Only **Catania** model (coalescence) close to the data.
- **PYTHIA8 with CR-BLC** (**Mode0,2,3**), **SHM+RQM, QCM** predict ratios significantly larger than what expected from e^+e^- and **Default PYTHIA8 (Monash)** but significantly underestimate the data.

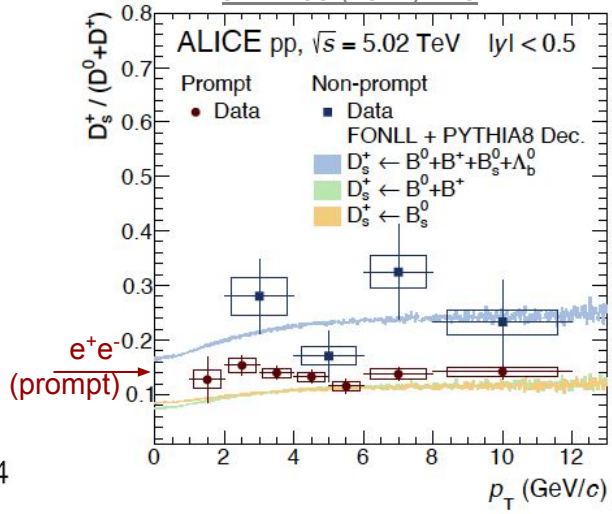
→ Additional challenges from strange (di)quark production

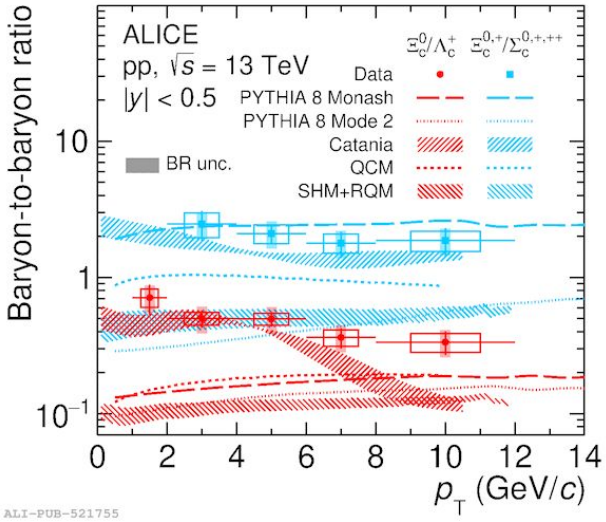
Not just a strange(ness) feature?

PRL. 127 (2021) 272001, arxiv 2105.05187

JHEP 05 (2021) 220





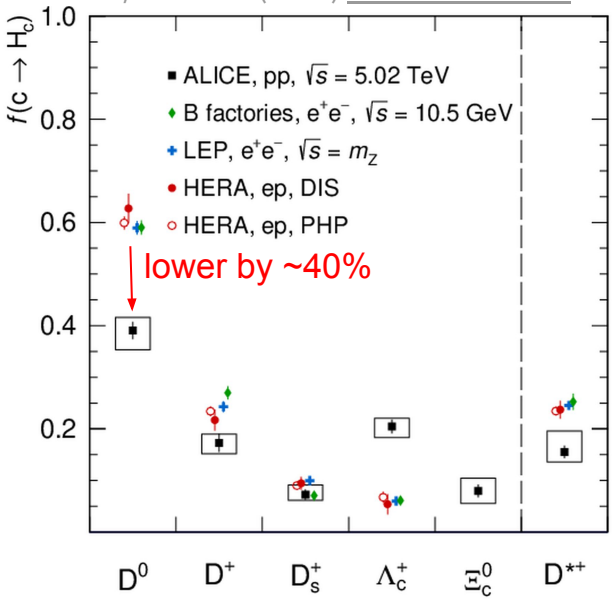


- Charm-strange baryon data underestimated by most models. Something anomalous with strange quarks?
- But **$D_s^+/(D^0+D^+)$ (prompt and non-prompt) compatible with expectations from e^+e^- … baryons are strange!**
  - Note Ξ_c^0/D^0 and Ξ_c^+/D^0 similar to D_s^+/D^0 (but large uncertainties)
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio described by default PYTHIA8 (Monash)! (by Catania as well)**
  → similar suppression in e^+e^-? Related to diquark rather than quarks?
  (note mass of spin-1 $(dd,ud,uu)_1$ diquarks might be similar to spin-0 $(us,ds)_0$ diquarks)
  Does this also connect to similarity of baryon-to-meson ratios in HF and LF sector?

- **$\Xi_c^{0,+}/\Lambda_c^+$** ratio underestimated by all models

Fragmentation fractions and charm cross section

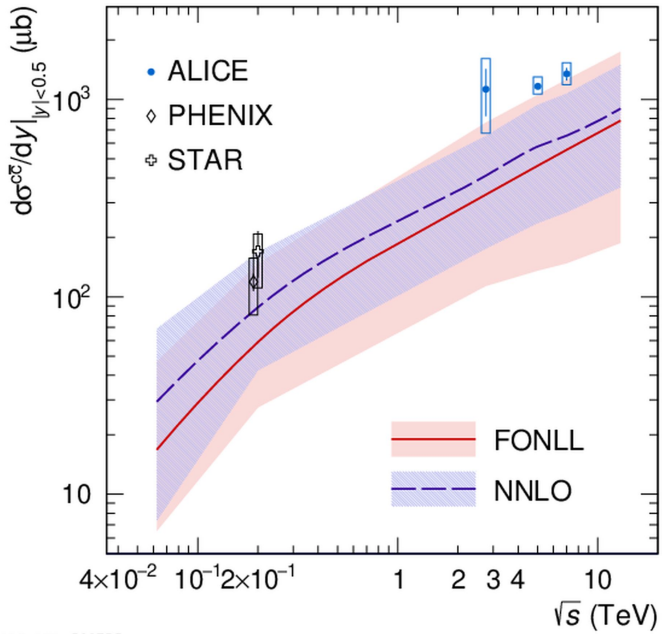
PRD 105, L011103 (2022) arxiv 2105.06335



Measured baryon-to-meson ratios imply **violation of universality of fragmentation fractions (FF) already in pp collisions**:

→ cannot rely on e^+e^- FF to get charm cross section from D meson data

→ new FF estimated from measured particle-species ratios

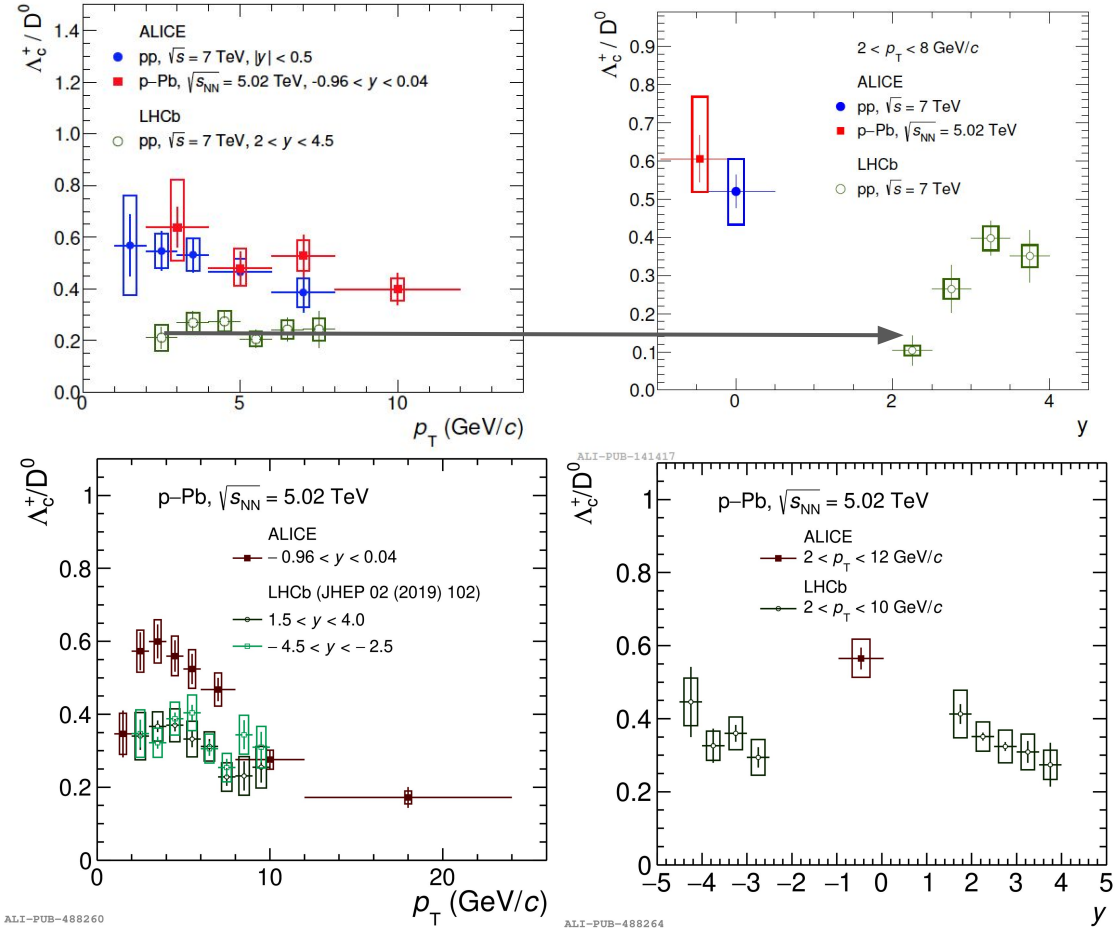


Total $c\bar{c}$ cross section at $|y|<0.5$ estimated at 5 TeV from all measured particle-species cross sections

About **40% higher values w.r.t. using e^+e^- FF**

On upper edge of FONLL and NNLO

Λ_c^+/D^0 vs. rapidity in pp (and p-Pb)



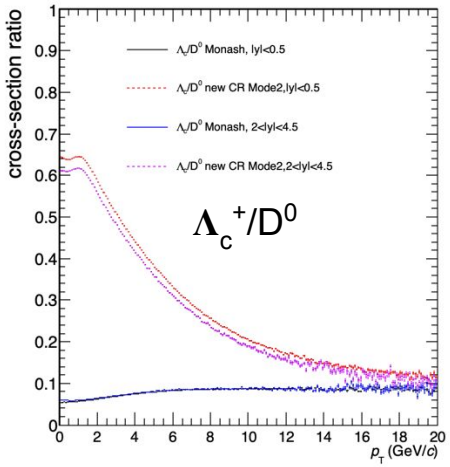
ALICE, JHEP 04 (2018) 108, PRC 104 054905 (2021) ,

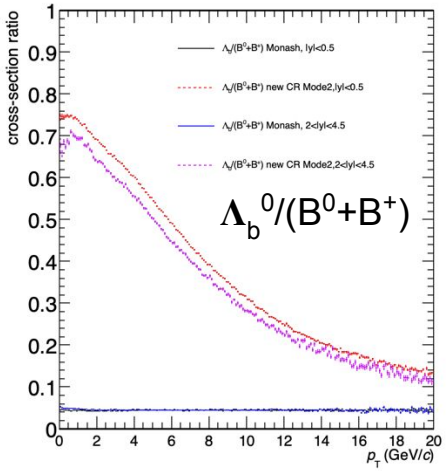
LHCb (pp), Nucl.Phys.B 871 (2013)
LHCb (p-Pb), JHEP 02 102 (2019)

Possible dependence on rapidity, especially in pp collisions

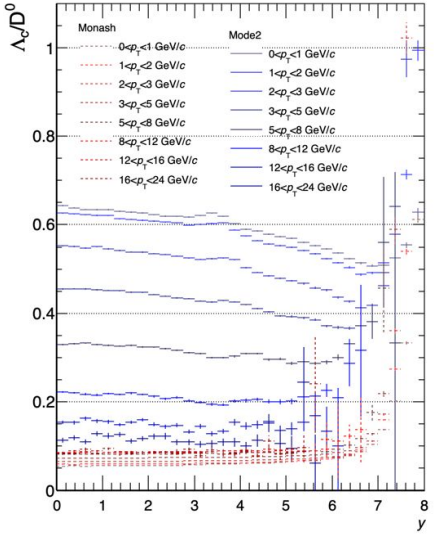
Probably run 3 data needed to clarify

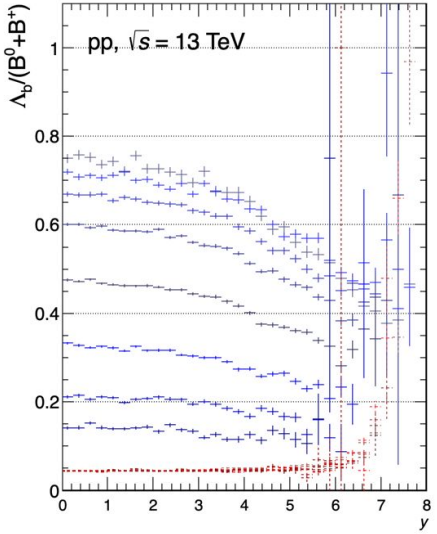
More on forward vs. mid rapidity: PYTHIA expectations





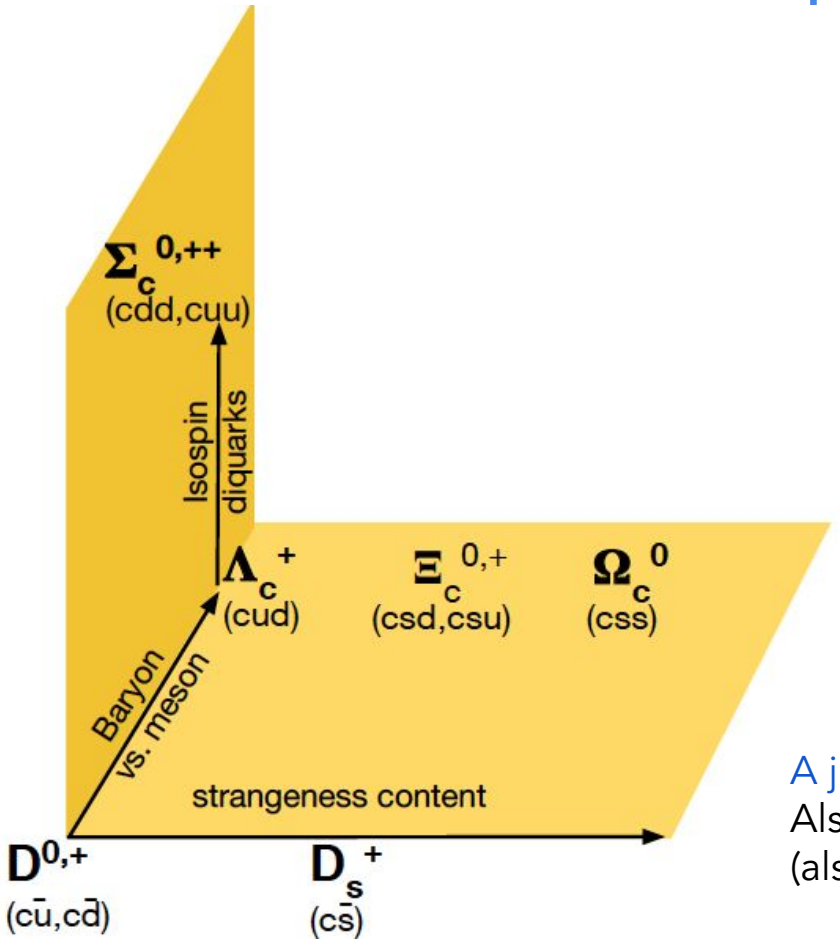
Small [none] difference on Λ_c^0/D^0 and Λ_b^0/B in ALICE and LHCb rapidity intervals expected from PYTHIA CR-BLC [Monash]





Stronger rapidity evolution starting at low p_T at y>4

Several arrows in the quiver



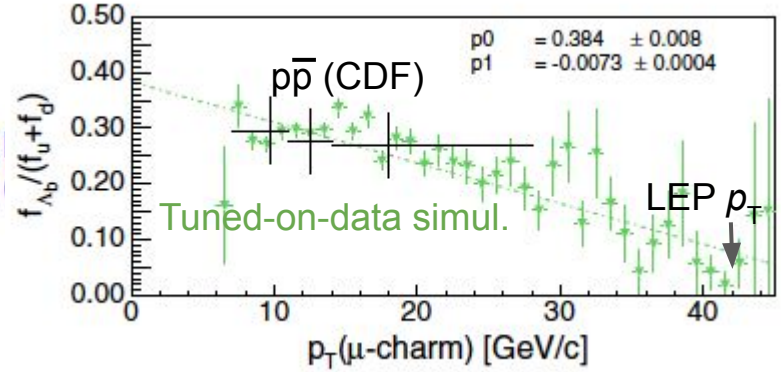
Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695
$B^{0,+}$	5.280
B_s^0	5367
Λ_b^0	5620

A jump in mass with beauty!
Also with non-prompt signals
(also leptons and J/Ψ)

Beauty baryons vs. mesons at LEP, Tevatron and LHC

HFLAV, EPJC 77 (2017) 895

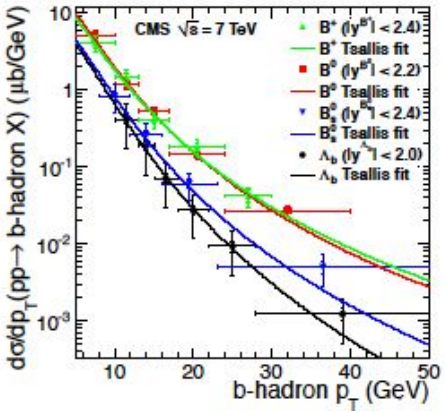
b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7



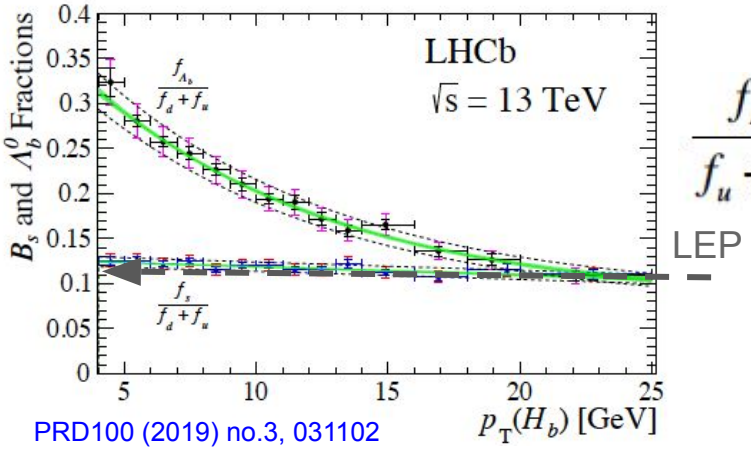
PRD 77 072003 (2008)

Suggest p_T-dependent fragmentation fraction, possibly influenced by hadronic environment

At LHC: precise Λ_b^0 measurements indicate clear dependence of baryon-to-meson ratio on p_T



CMS, PLB 714 (2012) 136



PRD100 (2019) no.3, 031102

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

At low p_T significantly higher (x3) than LEP data

B_s as at LEP

Similar trends in charm and beauty sectors

Beauty baryons vs. mesons at LEP, Tevatron and LHC

HFLAV, EPJC 77 (2017) 895

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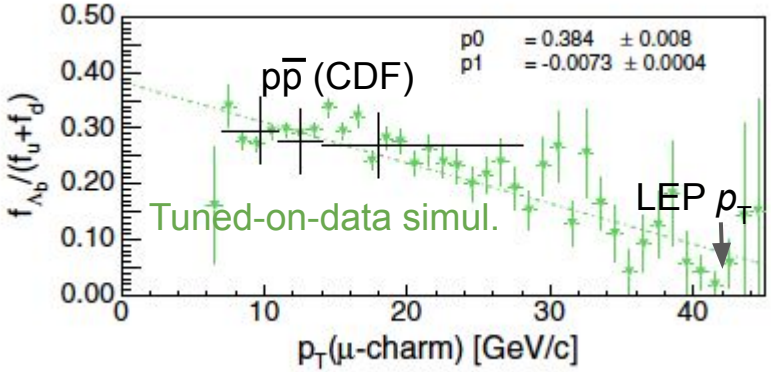

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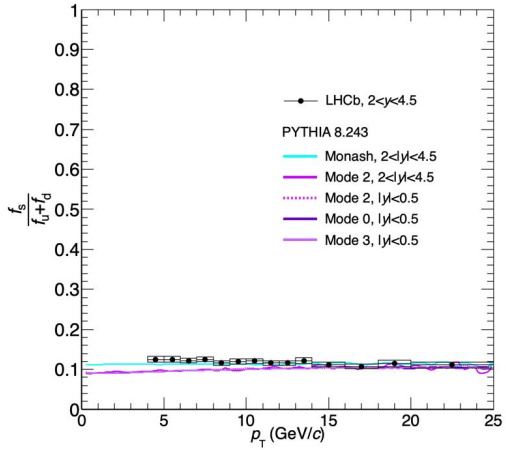
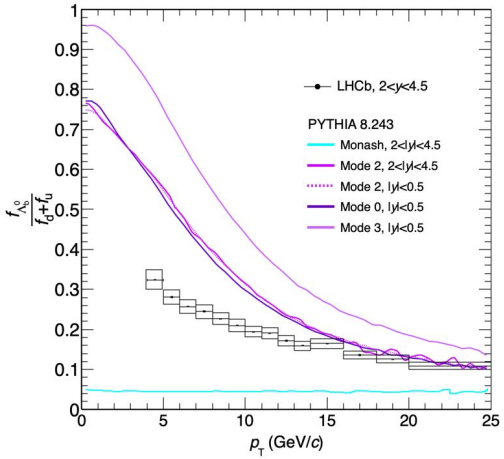
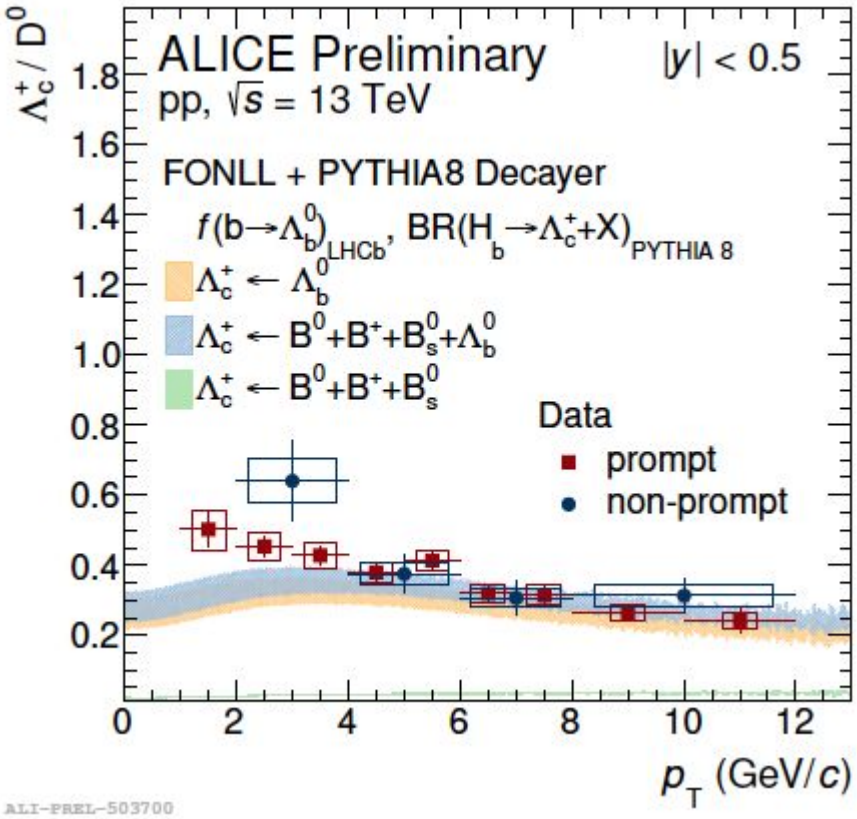


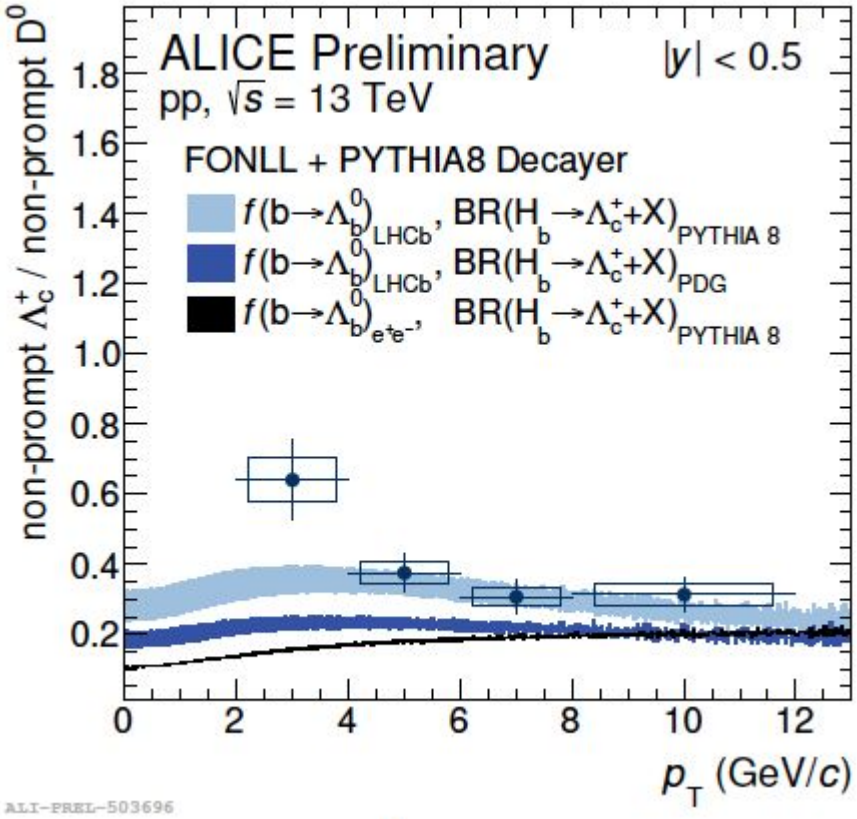


Default PYTHIA (Monash) reproduces B_s^0/B but fails for Λ_b^0/B (lower than LEP)

PYTHIA8 CR-BLC modes do not catch low p_T values

Forward vs. mid rapidity: Λ_b^0/B and non-prompt Λ_c^+/D^0

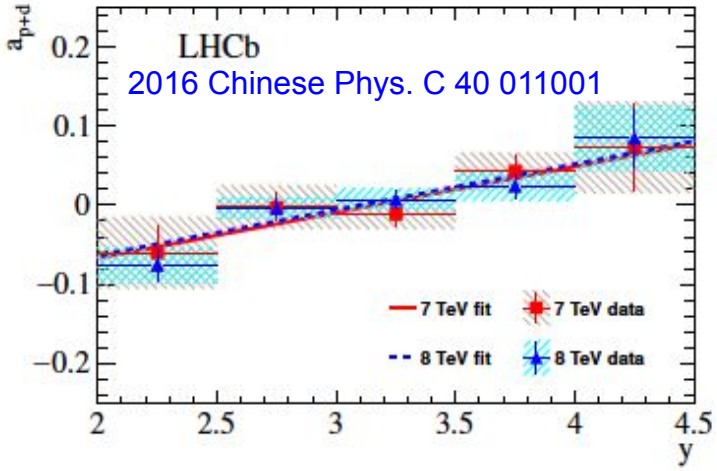




Beam remnants and drag effect, R_{AA}

Indication for a rapidity-dependent ratio of $\Lambda_b/\overline{\Lambda}_b$, suggesting some baryon-number transport from beam particles to $\Lambda_b \leftarrow$ **string drag/leading-quark effect?**

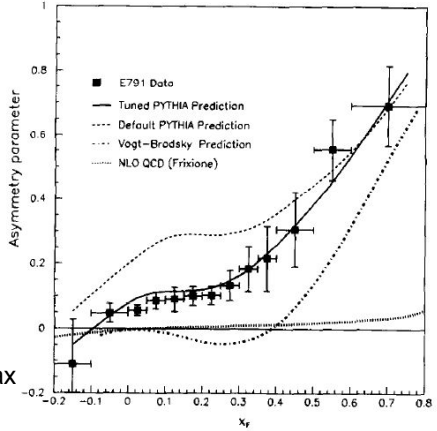
J.L. Rosner, PRD 90 014023 (2014); PRD 86 014011 (2012)



Similar effect observed for charm mesons (D^+) long ago in π-nucleus collisions (E791, E769, WA82)

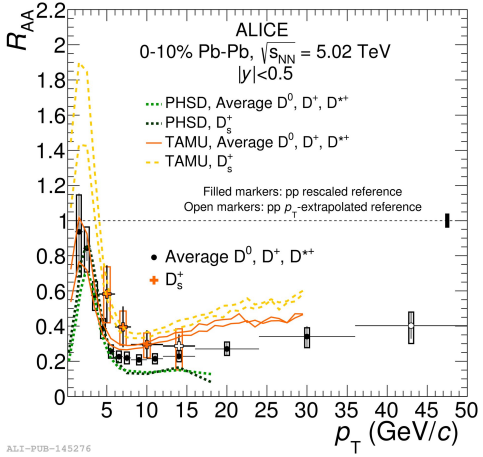
$$A(x_F, p_t^2) \equiv \frac{\sigma_L - \sigma_{NL}}{\sigma_L + \sigma_{NL}}.$$

E791, PLB 371 (1996) 157-162



$x_F = p_z/p_{z,\,max}$

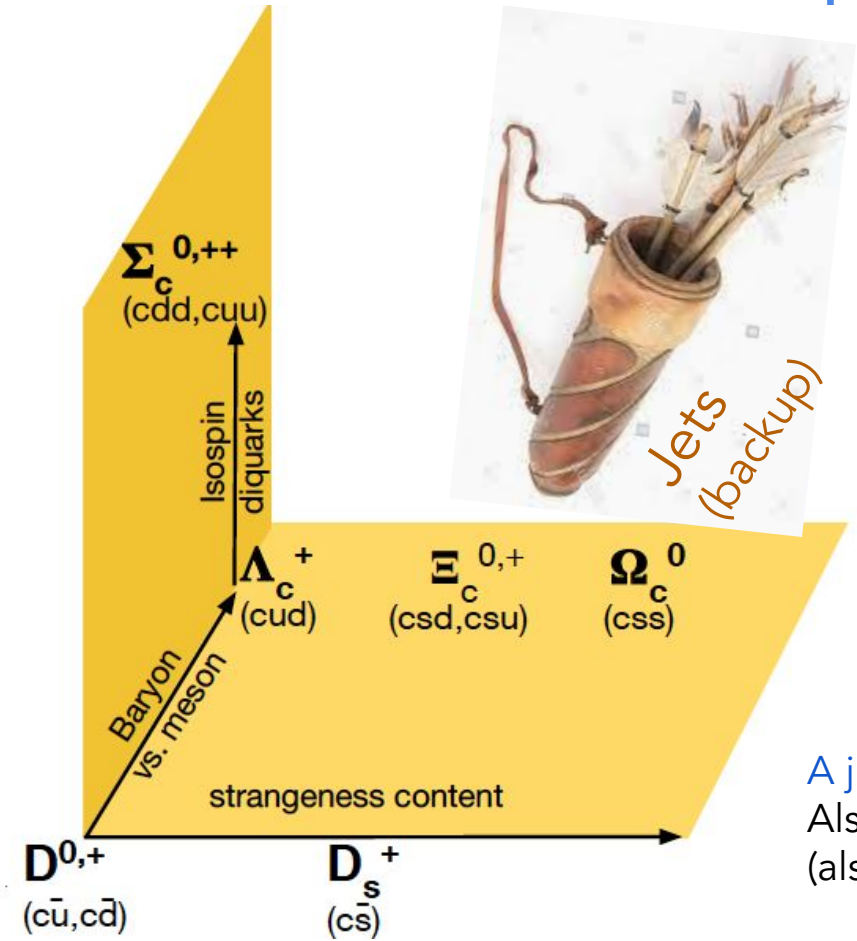
And the heavy-ion community knows that a medium matters...



Suggest that **hadronic environment plays a role**

Up to what extent? how does the hadronisation dynamics change in different systems?

Several arrows in the quiver

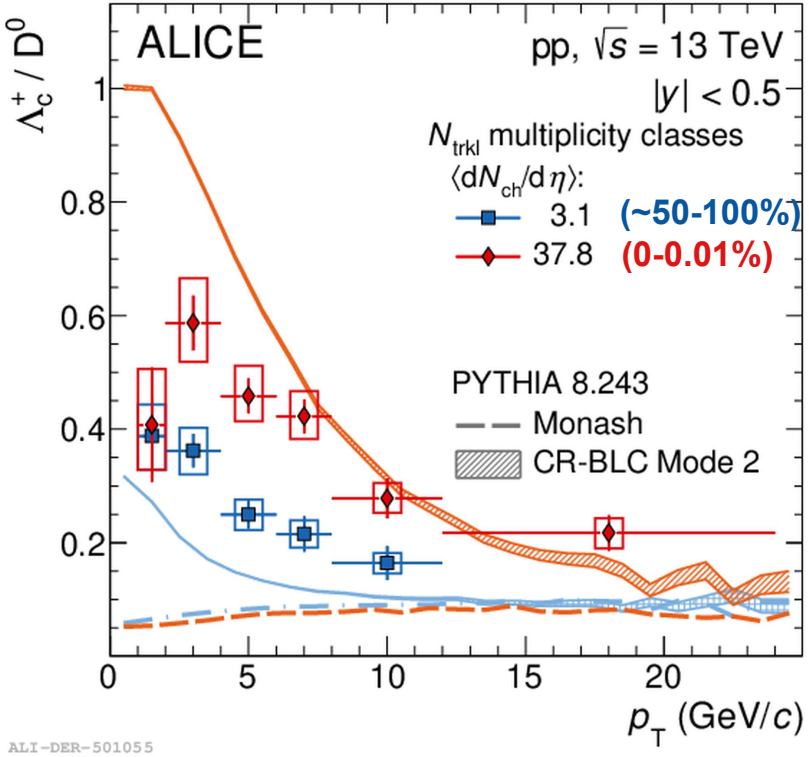


We can exploit multiplicity

Particle	Mass (GeV/c^2)
D^0	1.865
	1.870
	1.968
	2.286
	2.454
	2.470
Ξ_c	2.468
Ω_c^0	2.695
$B^{0,+}$	5.280
B_s^0	5367
Λ_b^0	5620

A jump in mass with beauty!
Also with non-prompt signals
(also leptons and J/Ψ)

Evolution with event activity in pp: Λ_c^+/D^0



Λ_c^+/D^0 increases with particle multiplicity at midrapidity

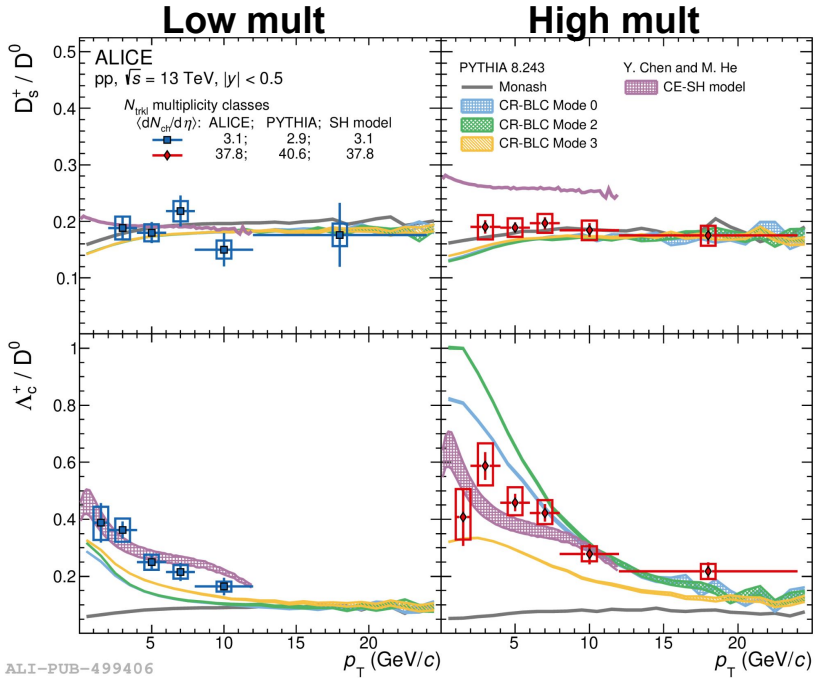
Trend expected by **PYTHIA8 with CR-BLC (Mode 2)**

→ confirms importance of Colour Reconnection in rich partonic environments

→ **interplay of Color Reconnection (CR) and Multiple Parton Interactions**

PLB 829 (2022) 137065, https://arxiv.org/abs/2111.11948

Evolution with event activity in pp: Λ_c^+/D^0 and D_s^+/D^0



Λ_c^+/D^0 increases with particle multiplicity at midrapidity

Trend expected by **PYTHIA8 with CR-BLC (Mode 2)**

→ confirms importance of Colour Reconnection in rich partonic environments

→ **interplay of Color Reconnection (CR) and Multiple Parton Interactions**

D_s^+/D^0 independent from multiplicity

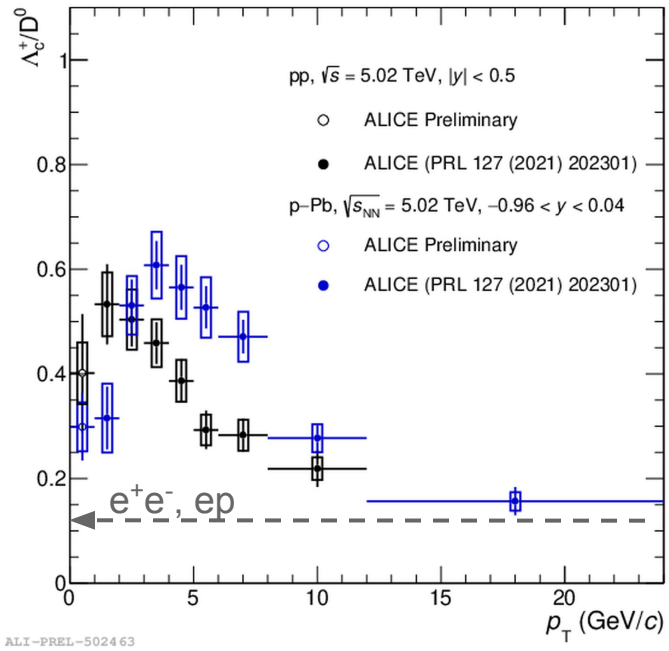
Canonical Ensemble-SH (+ RQM baryons) catches Λ_c^+/D^0 but not D_s^+/D^0 : ratios decrease at low mult from charm and strangeness number conservation in smaller volume

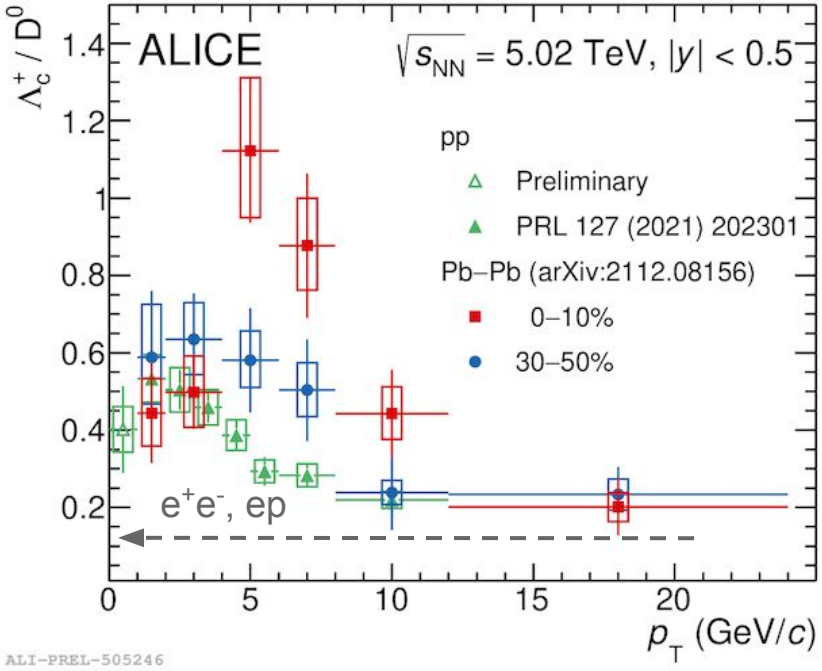
Do we have a smooth evolution with multiplicity from (e^+e^- to) pp to AA?

PLB 829 (2022) 137065, https://arxiv.org/abs/2111.11948

Λ_c^+/D^0 evolution with event activity: from pp to Pb-Pb

PRC 104 054905 (2021) , PRL 127 202301 (2021) , arxiv 2112.08156



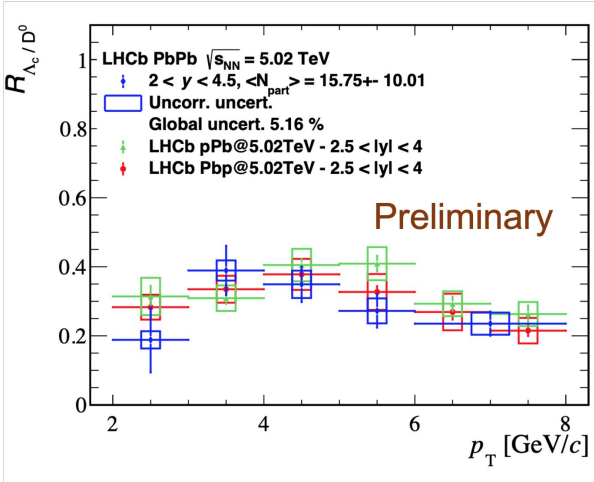


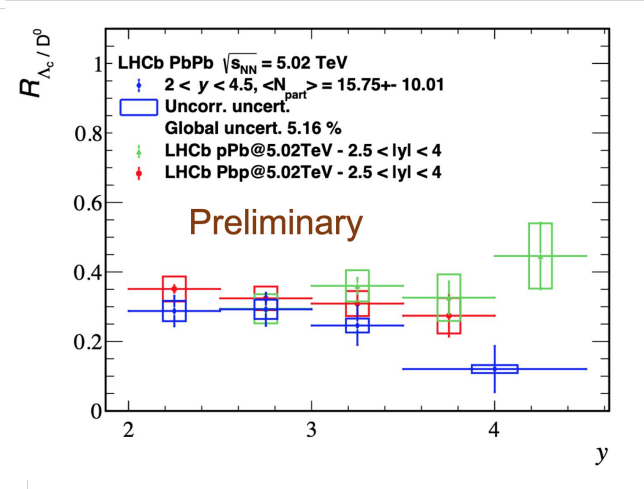
Evolution of Λ_c^+/D^0 ratio from pp to p-Pb to central Pb-Pb. Only a change of p_T shape?

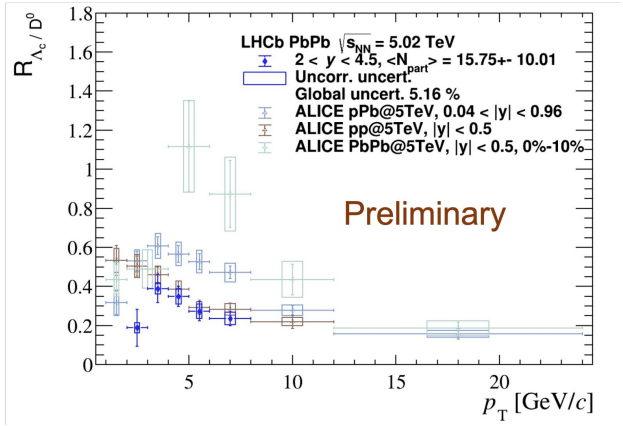
- Especially at low p_T: **larger "jump" from e^+e^- to pp than from pp to Pb-Pb**
- **p-Pb in-between pp and Pb-Pb**

Λ_c^+/D^0 evolution with event activity: from pp to Pb-Pb

LHCb-PAPER-2021-046 in preparation



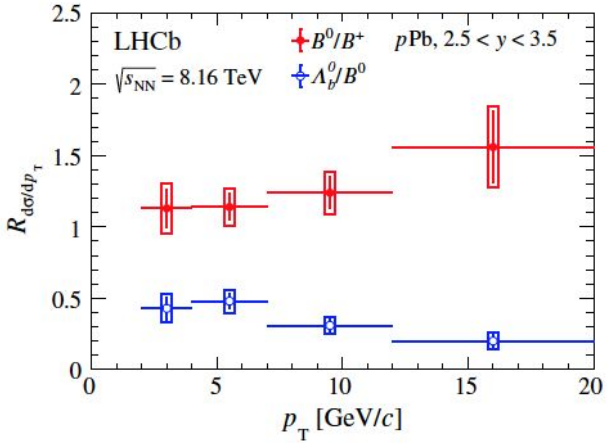


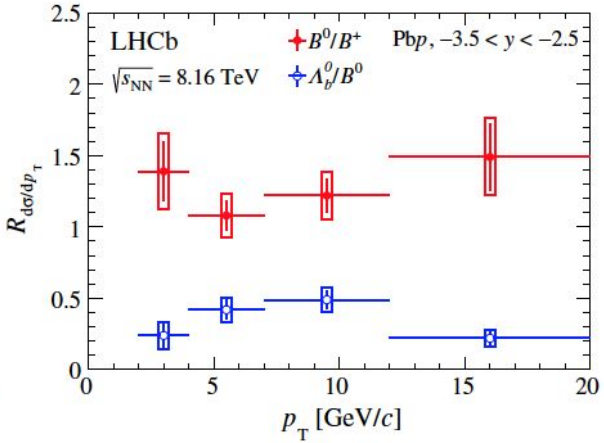


Λ_c^+/D^0 in peripheral (60-100%) Pb–Pb at forward rapidity has similar values than those of p–Pb

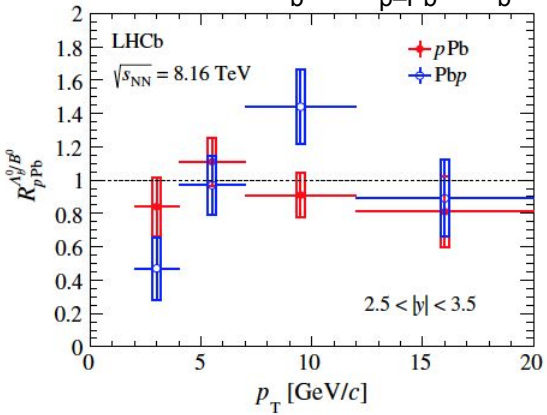
Lower than ALICE p–Pb data

Λ_b^0/B in p–Pb collisions





Double ratio $(\Lambda_b^0/B^0)_{p–Pb}$ /$(\Lambda_b^0/B^0)_{pp}$

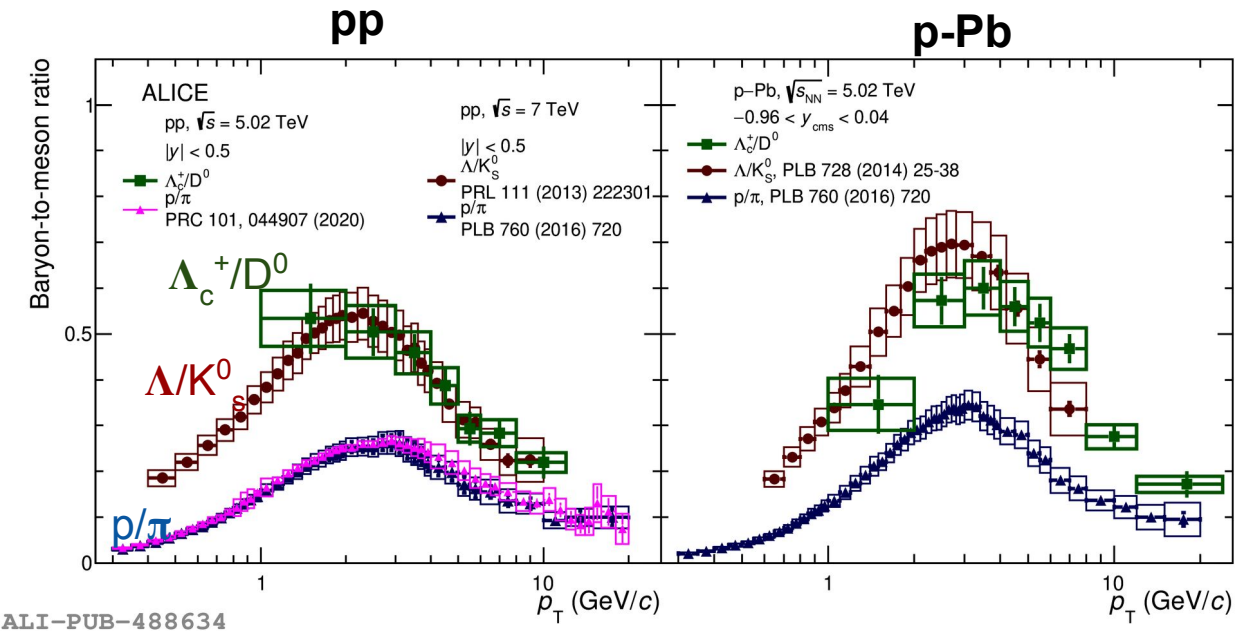


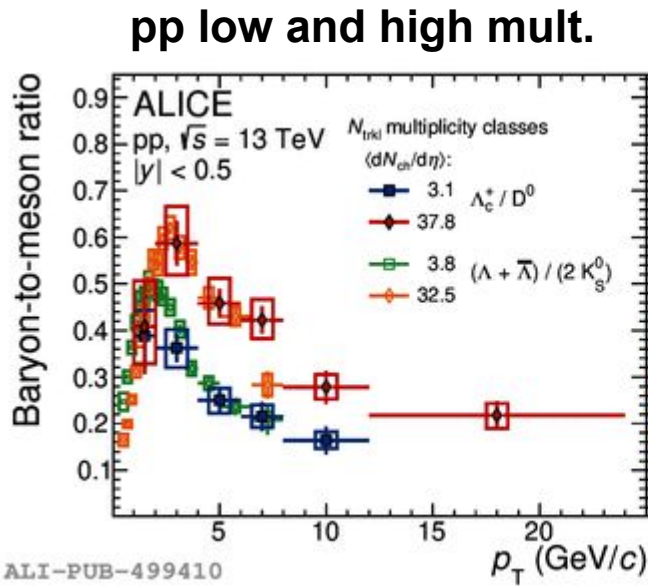
Λ_b^0/B ratio in p–Pb compatible with pp one

More precision needed to clarify possible hints of modification

Λ_c^+/D^0 compared with Λ/K_s^0 and p/π^+

PRC 104 054905 (2021) , PRL 127 202301 (2021), PLB 829 (2022) 137065



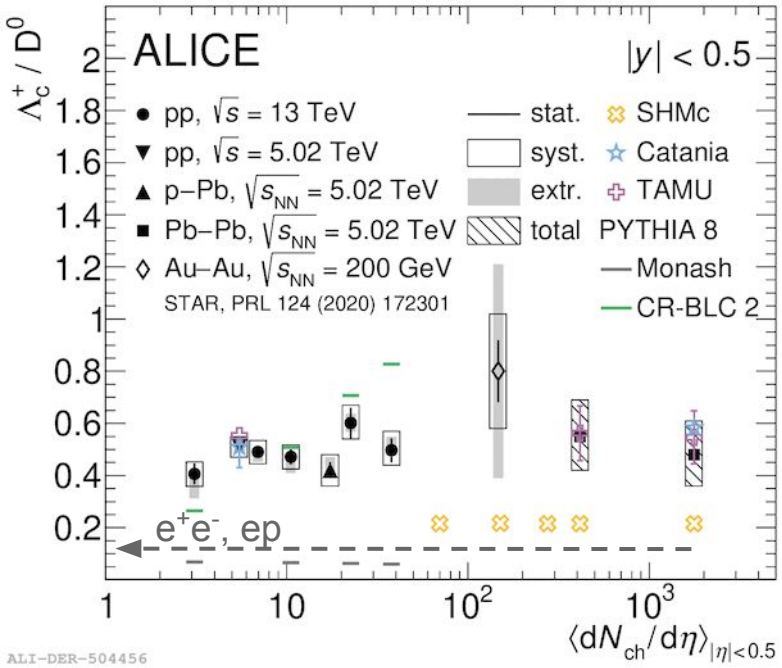


Similar p_T trend and evolution with multiplicity of baryon-to-meson ratios in light and heavy-flavour sector
Does light diquark formation play a role?

Diquarks are peculiar “objects” (aka quark-quark interactions)... can QCD measurements at the LHC provide inputs for EoS in neutron star?

Λ_c^+/D^0 evolution with event activity, p_T-integrated

PRC 104 054905 (2021) , PRL 127 202301 (2021), PLB 829 (2022) 137065, arxiv 2112.08156



No evidence of evolution of p_T-integrated Λ_c^+/D^0 ratio despite strong modification of p_T-differential trend. **Radial flow?**

Would not that be peculiar? Accidental?

Precision still limited

Significantly higher values than e^+e^-

STAR Au-Au data compatible with ALICE

PYTHIA8 CR-BLC expects increase with mult

SHMc (Pb–Pb) about flat trend but below data

TAMU, Catania: similar values in pp and Pb–Pb

Data uncertainty still large

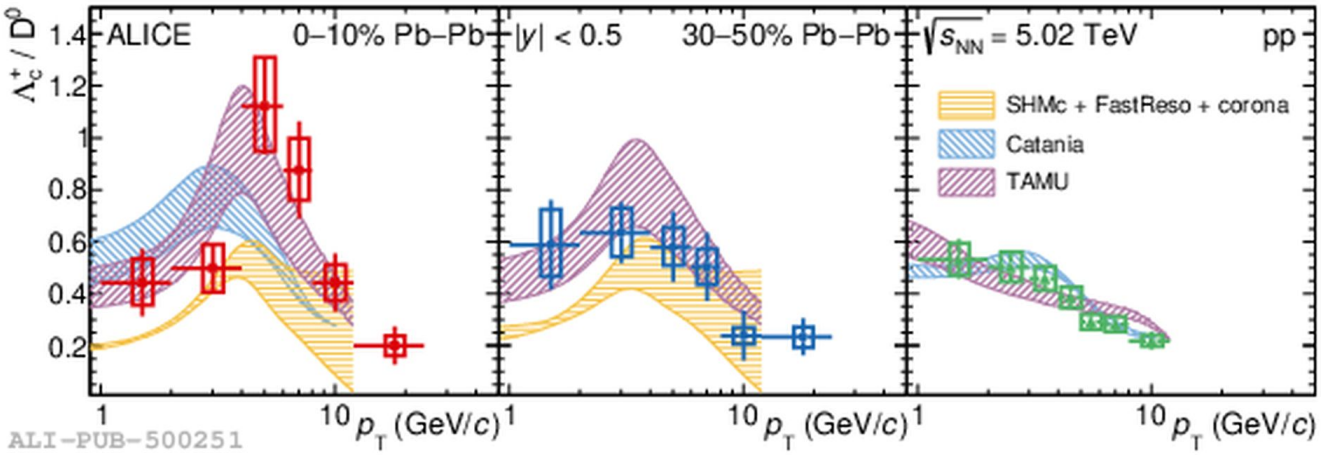
Lowest multiplicity still to be covered (run 3): recover e^+e^-?

→ more precise measurements from LHC new runs awaited

Λ_c^+/D^0 evolution with mult: can we learn from Pb-Pb?

Investigation of flow or medium effect easier in Pb-Pb than small systems?

arxiv 2112.08156

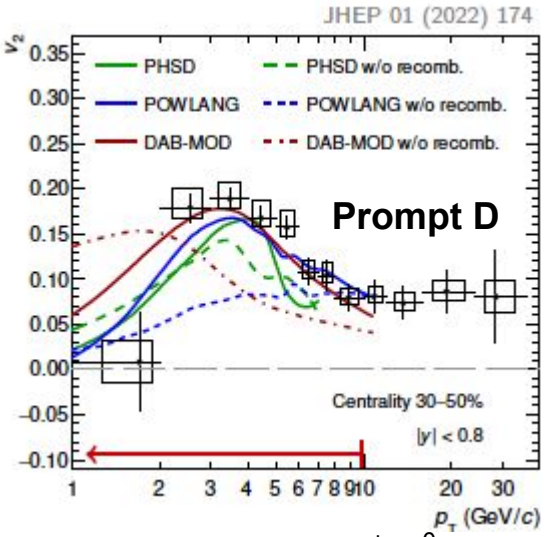


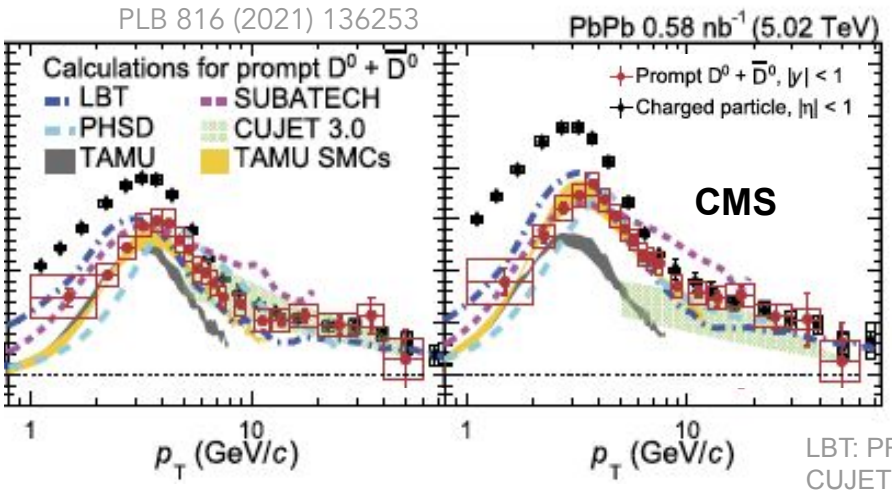
TAMU (hadronisation via Relativistic Resonant Scattering model + RQM states) and Catania (sudden coalescence + fragmentation) describe data within uncertainties

SHMc + FastReso + corona tends to underestimate data

Catania, EPJC 78 4 (2018) 348
TAMU, PRL 124, 4 (2020) 042301
SHM, JHEP 07 035 (2021)

Λ_c^+/D^0 evolution with mult: can we learn from Pb-Pb?





LBT: PRC 94 (2016) 014909
CUJET3.0: JHEP 02 (2016) 169
SUBATECH: PRC 91 (2015) 014904
TAMU: PLB 735 (2014) 445
TAMU SMCs: PRL124 (2020) 042301
PHSD: PRC 93 034906 (2016)
DAB-MOD: PRC 96 064903 (2017)
POWLANG: EPJC 75 3 121 (2015)

Models reproducing Λ_c^+/D^0 and D meson v_2 and R_{AA} include

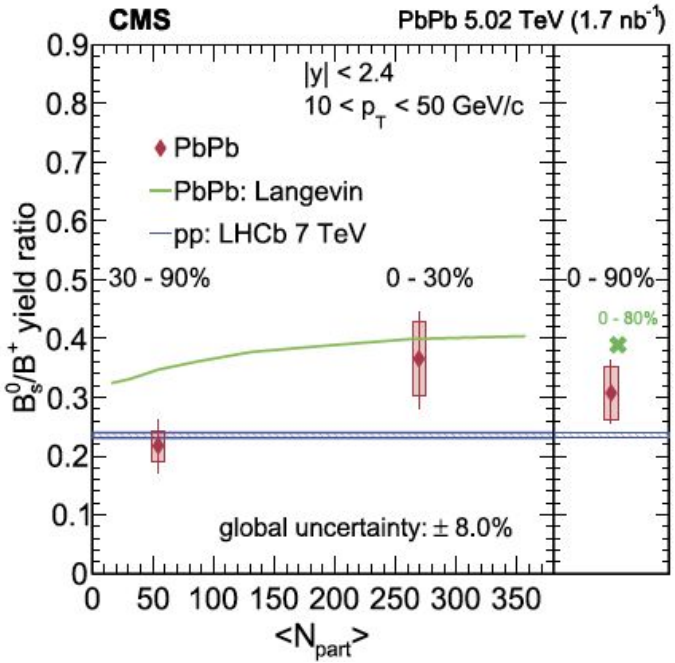
- Coalescence
- Space-momentum correlations (TAMU)

Both alter p_T spectra as well as relative hadron species abundances.
Flow-like effects observed for HF also in small systems.
→ interplay of medium flow and coalescence as cause of modification of the p_T-differential spectra w/o a large difference of the total yields? **Wouldn't it be too much accidental,** especially if extended to small systems?

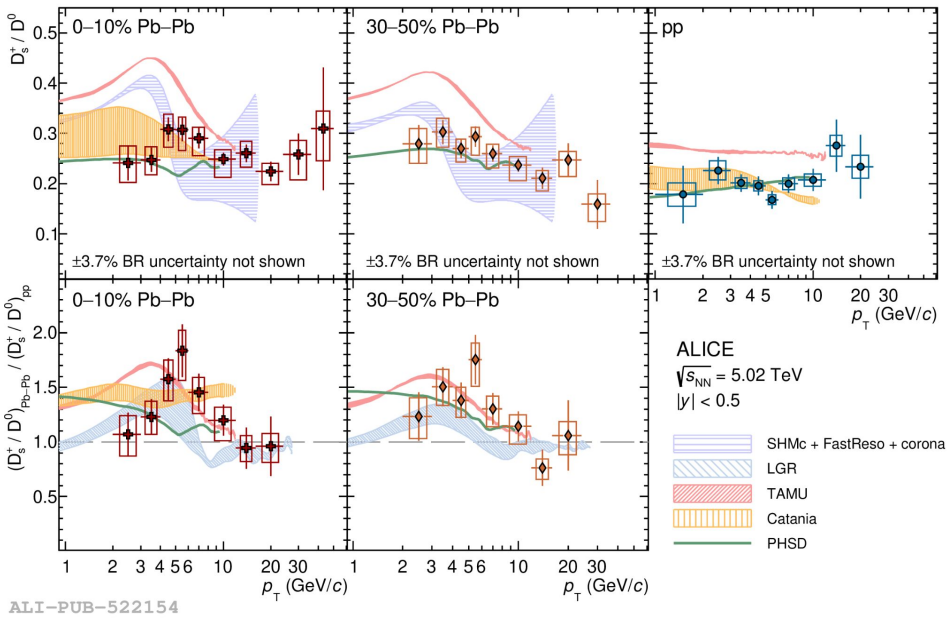
N.B. Hadronic phase expected to have small impact (models, femtoscopy data)

D_s^+ and B_s^0 in Pb–Pb collisions

PLB 829 (2022) 137062



PLB 827 (2022) 136986



Indication of higher strange/non-strange D and B meson ratios in Pb–Pb collisions
But Run 3 data needed to extend to lower p_T

Awaiting also Ξ_c data in Pb–Pb!

SHMc, JHEP 07 035 (2021)
LGR, EPJC 80 671 (2020)
PHSD, PRC 92, 014910 (2015)
TAMU: PRL 124, 042301 (2020)
Catania: EPJC 78, 348 (2018)

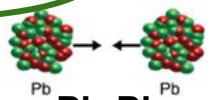
Summary: HF hadronisation in our QCD laboratories

Fragmentation functions universality violated already in pp collisions
Multiple parton interactions in pp build a system rich of quarks or gluons, dense enough to alter hadronisation w.r.t. e^+e^-

e^+e^- = "vacuum"

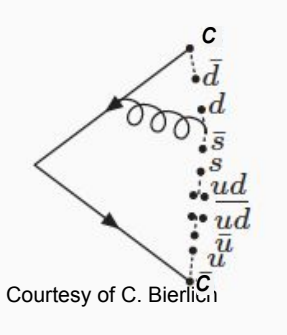
pp
~~not far from vacuum ~ many independent scatterings~~
(for HF at least)

MPI, system size

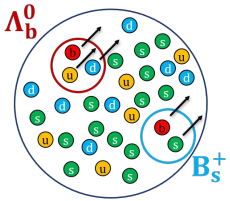


Pb-Pb
Complex, extended-size system,
Local equilibration
Flow

Dynamical model
"Local" dynamical constraints
(e.g. Lund string fragmentation, quarks and diquarks popping out from QCD potential)



Courtesy of C. Bierlich



(Semi)phenomenological models sufficient to describe relative particle abundances *once ingredients are tuned*?

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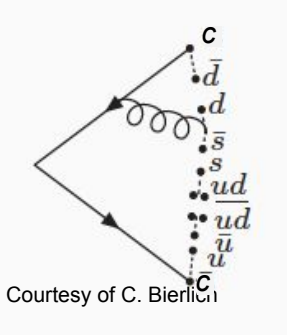
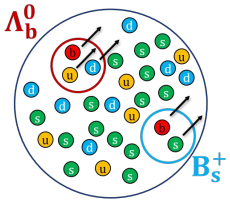


Courtesy of C. Bierlich

Where does e-A sit?



(Semi)phenomenological models sufficient to describe relative particle abundances *once ingredients are tuned*?

Summary

Could not cover other important topics that are related to HF hadronisation:

- HF jets and correlations
- Dependence of relative open-HF yields on multiplicity (dedicated talks in next days)
- multi-HQ particles, including B_c^+
- “exotic” states (X(3879), pentaquarks)

The detector upgrades, completed for Run3 and planned for the future, will boost the performance for all observables presented as well as for the above one.

ALICE3 apparatus (see LoI: http://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf?version=2) will allow to measure multi-charm baryons in heavy-ion collisions.

T. Sjostrand summary at LHCP:

https://indico.cern.ch/event/1109611/contributions/4686977/attachments/2447285/4194251/LHCP22Sjostrand.pdf

- Many poorly understood soft-physics aspects, notably
  - multiparton interactions,
  - colour reconnection, and
  - hadronization.
- LHC data has revolutionized the picture of soft physics:
  Goodbye jet universality!
- This has led to a renewed phenomenology interest:
  Welcome new mechanisms!
- Still some way to go before a new unified picture is in place, covering the evolution from e^+e^- to low-n_{ch} pp to AA.

Open points… my personal list

- Can the expected validity range of factorisation approach in pQCD-based calculation be well defined?
- D_s^+/D^0 does not change much from e^+e^- to pp, contrary to $\Xi_c^{0,+}/D^0$ and $\Sigma_c^{0,+,++}/D^0$, both increasing more than Λ_c^+/D^0, with $\Sigma_c^{0,+,++}/\Xi_c^{0,+}$ staying not far from e^+e^-
  - Higher-mass states
  - Diquark-formation suppression in e^+e^- or easier diquark-formation in hadronic collisions?
    - diquark role in Pb-Pb for EoS?
  - how much the production rate of a given hadronic state can depend on its internal structure?
- Relativistic Quark Model: several baryon states not yet observed
  - which collision system better suited for searching them? why not seen in e^+e^-?
  - expected rates? (e.g. SHM expectation as a baseline?)
  - which decays? (mostly strong decays to lower-mass states + pions)
- Low-mult pp vs. e^+e^-
  - Modification of hadronisation mechanisms
  - Yields vs. mult, MPI vs. edge effects
- Different models may describe differently similar effects, adopting different point of views
  - PYTHIA with CR beyond LC, Coalescence, SHM all imply departure from “standard” fragmentation and universality assumption
  - Can we connect them?
- Models including both fragmentation and coalescence often assume that fragmentation kicks in when coalescence probability results small (“leftover” c-quarks are fragmented): is there a foundation behind this?

Open points… my personal list

- p_T-integrated vs. p_T-differential multiplicity evolution of Λ_c^+/D^0
  - Flow? Unnecessary coincidence of getting p_T-int =1… or not?
  - Hadronic part expected small, theory + femto studies

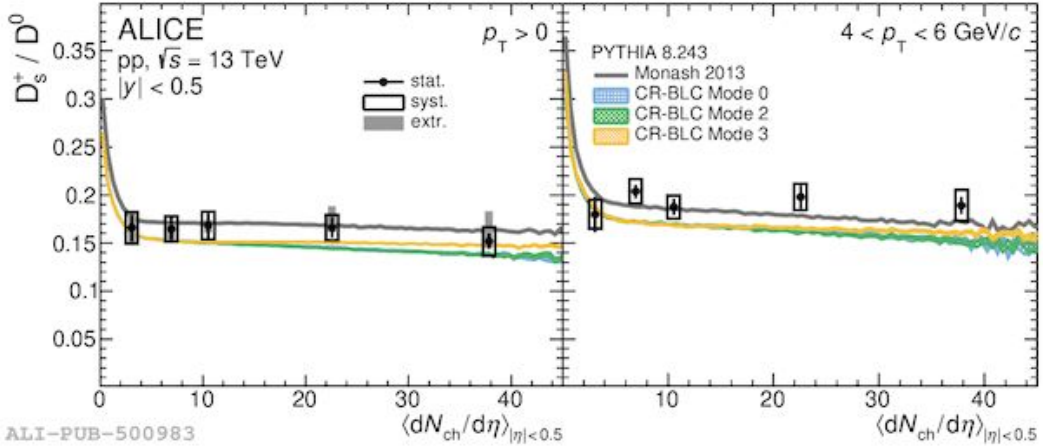
- What can we learn from
  - correlation measurements (production yields, angular and momentum correlations)
    - of HF-signal pairs
    - HF - light flavour (e.g. Λ_c^+-p vs. Λ_c^+ - $\overline{p}$)
  - HF jets, in particular: momentum fraction and radial profile of D-tagged, Λ_c^+-tagged jets?

- Exotic states (X(3872), pentaquarks):
  - how can we further understand their nature?
  - which additional information can the measurement of their production yields in different collision systems add?
  - could femtoscopy measurements help? (= could femtoscopy measurements of D-pion, D-p, Λ_c-pion, Σ_c-pion constrain the hadronic potential in such a way to provide information useful also for the molecular picture of these states?)

Extra

Λ_c^+/D^0 and D_s^+/D^0 vs. multiplicity

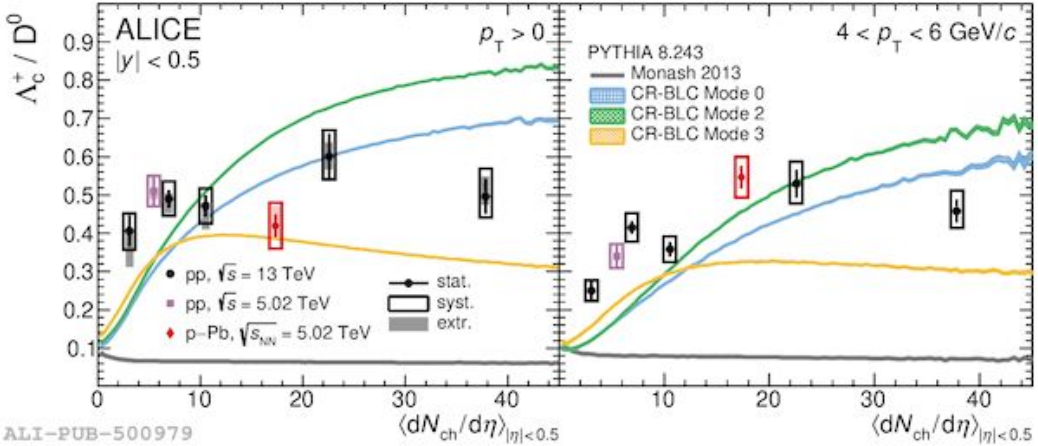
PLB 829 (2022) 137065



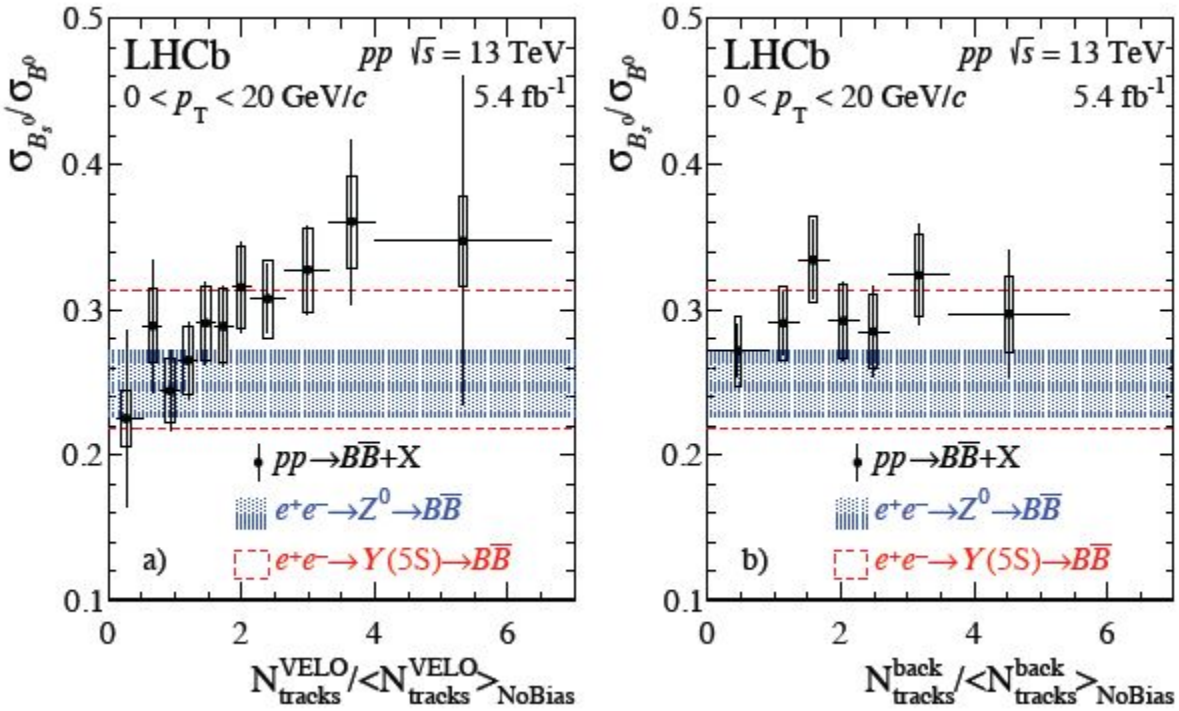
Both Λ_c^+/D^0 and D_s^+/D^0 p_T-integrated data do not show a significant dependence with multiplicity

Λ_c^+/D^0 increases with multiplicity at intermediate p_T

Run 3 data needed for precise assessment



B_s^0/B^0 vs. multiplicity at forward rapidity



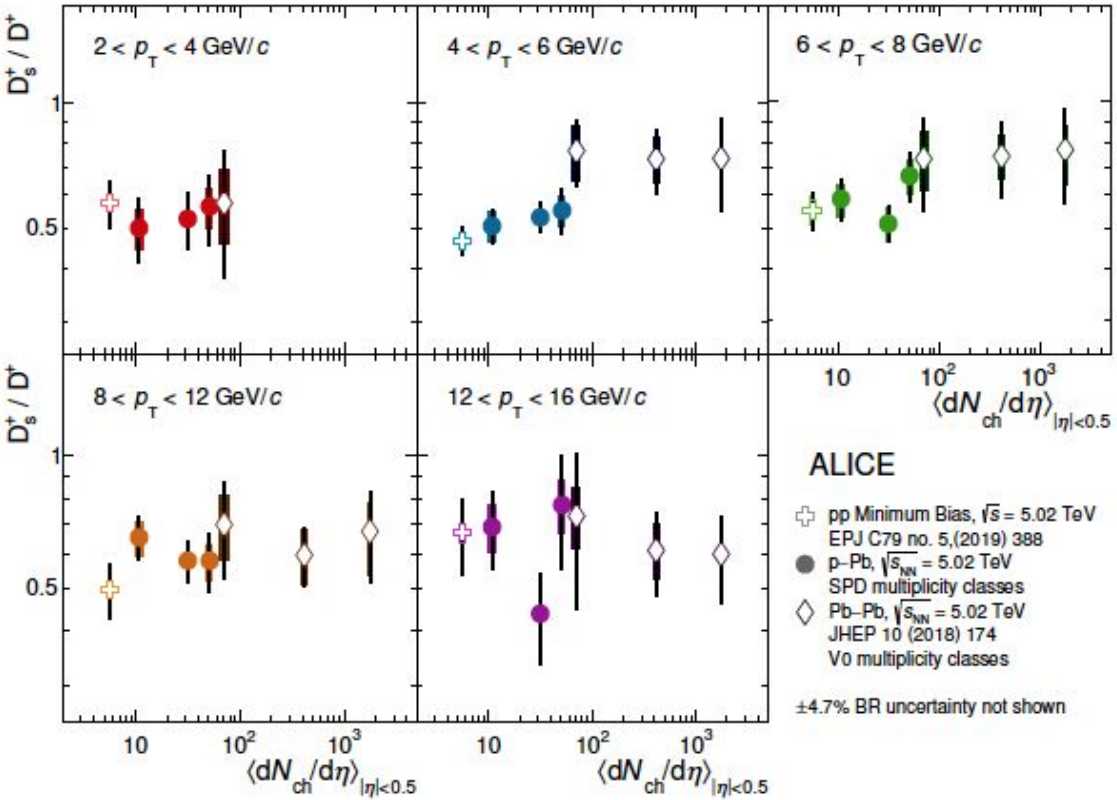
https://arxiv.org/pdf/2204.13042.pdf

Indication of a possible dependence of B_s^0/B^0 ratio on event multiplicity

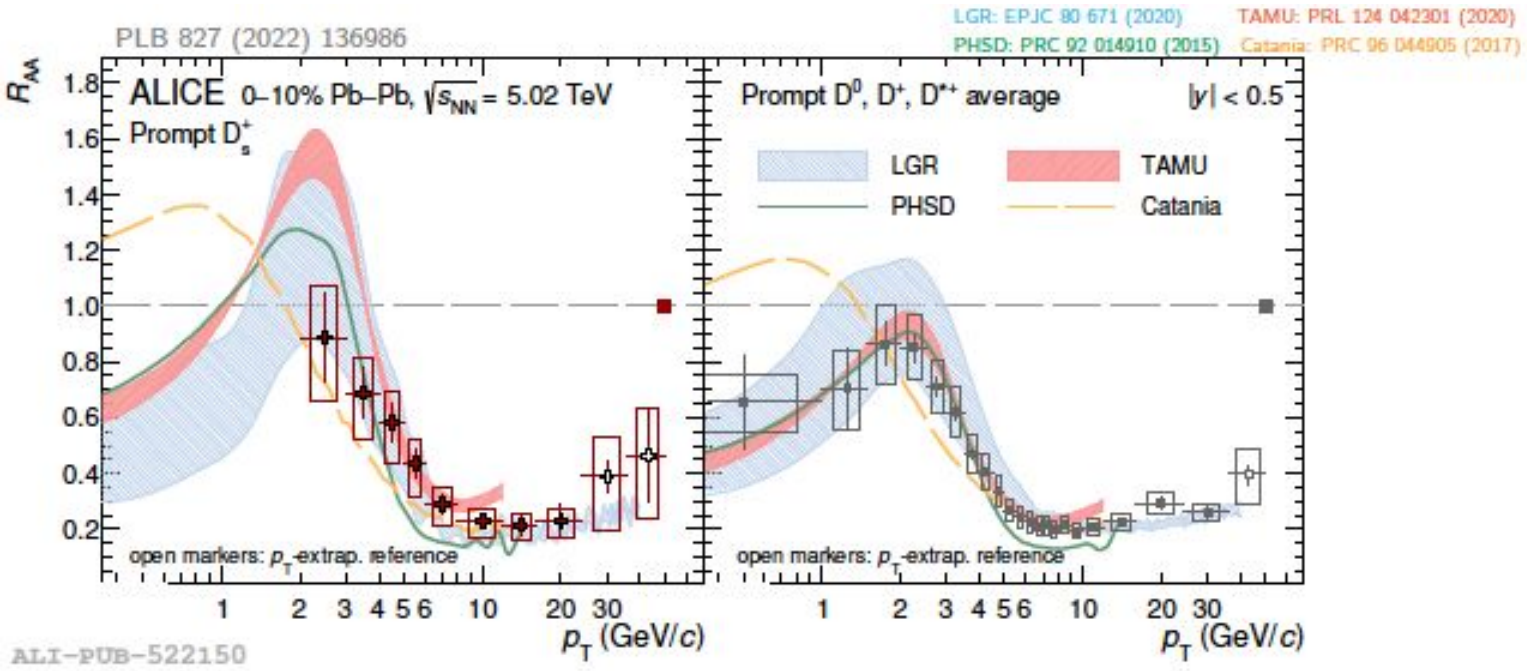
- At low pt
- Not observed when multiplicity estimated far from B mesons

D_s^+/D^+ vs. multiplicity, pp, p–Pb, Pb–Pb

JHEP 12 (2019) 092

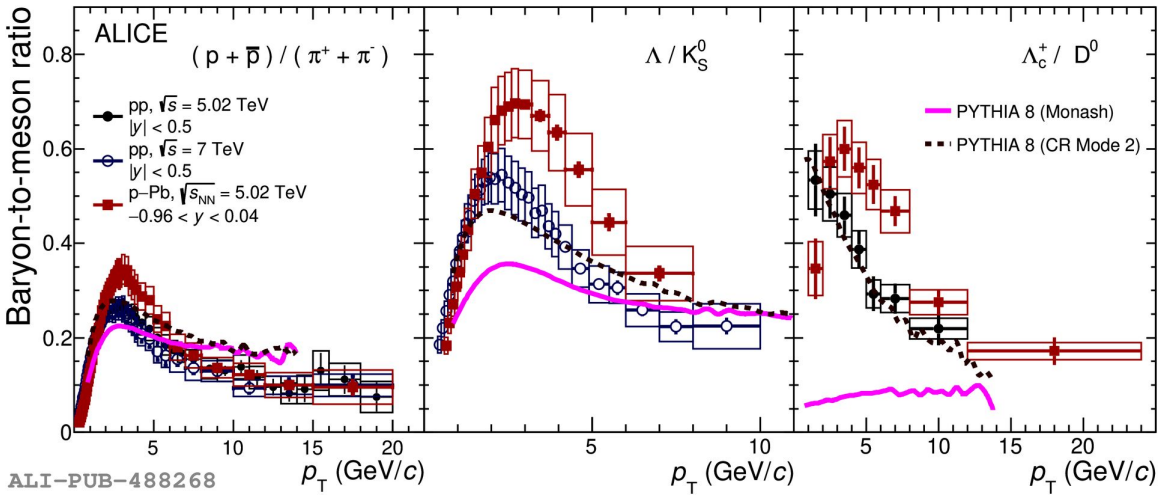


Strange and non-strange D R_{AA} vs. models



Λ_c^+/D^0 compared with Λ/K_S^0 and p/π^+

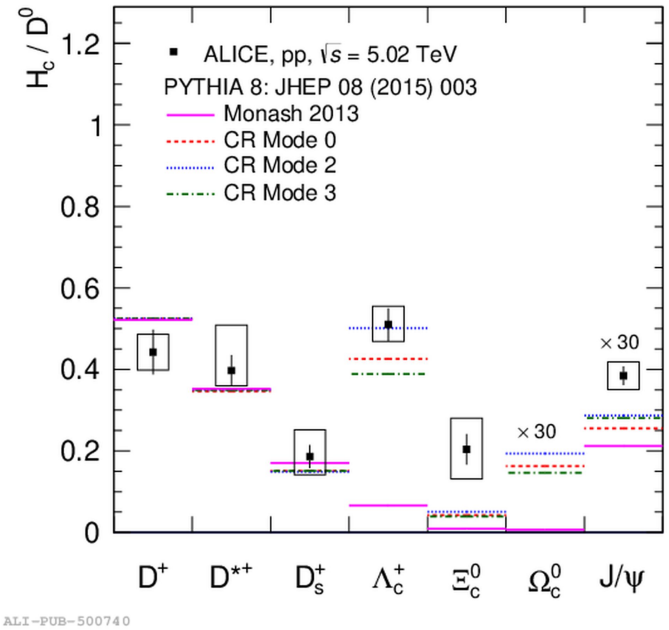
PRC 104 054905 (2021)

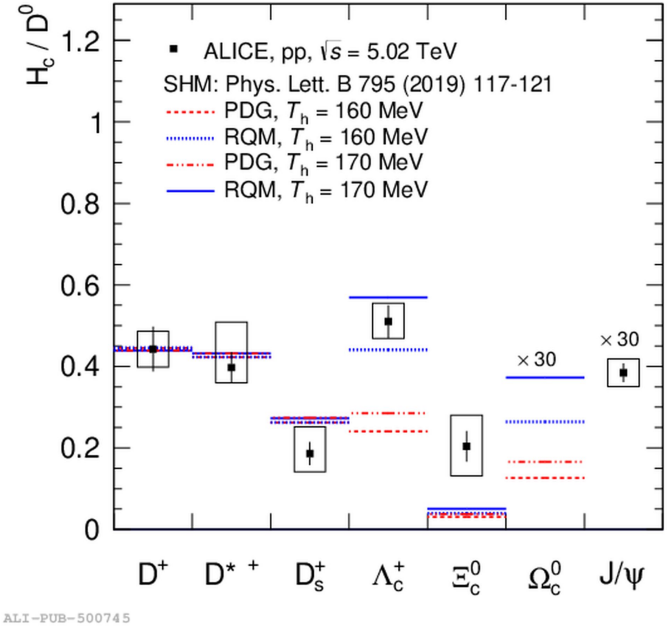


PYTHIA8 with CR-BLC better catching both charm and light-flavour baryon-to-meson ratios

Fragmentation fractions (normalised to D^0) vs. models

PRD 105, L011103 (2022) arxiv 2105.06335



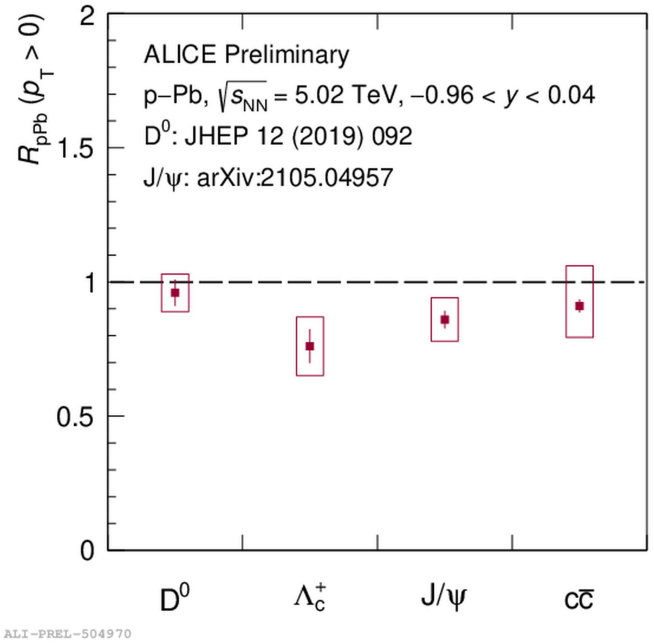


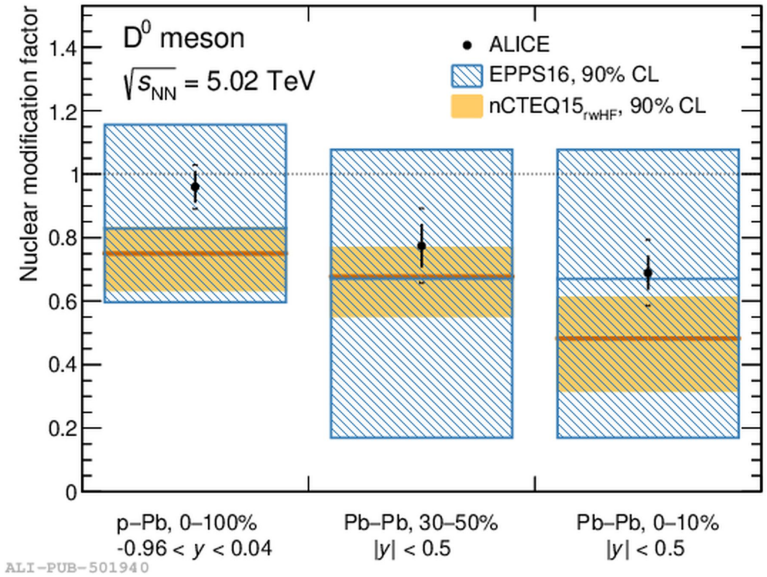
PYTHIA8: same conclusion as from p_T-differential studies.

Statistical Hadronisation Model:

- Λ_c^+ data described only if additional baryon states from RQM assumed
- Ξ_c^0 underestimated (final assessment needs new and more precise measurement down to lower p_T)

Side note: hadronisation, binary scaling and nPDF



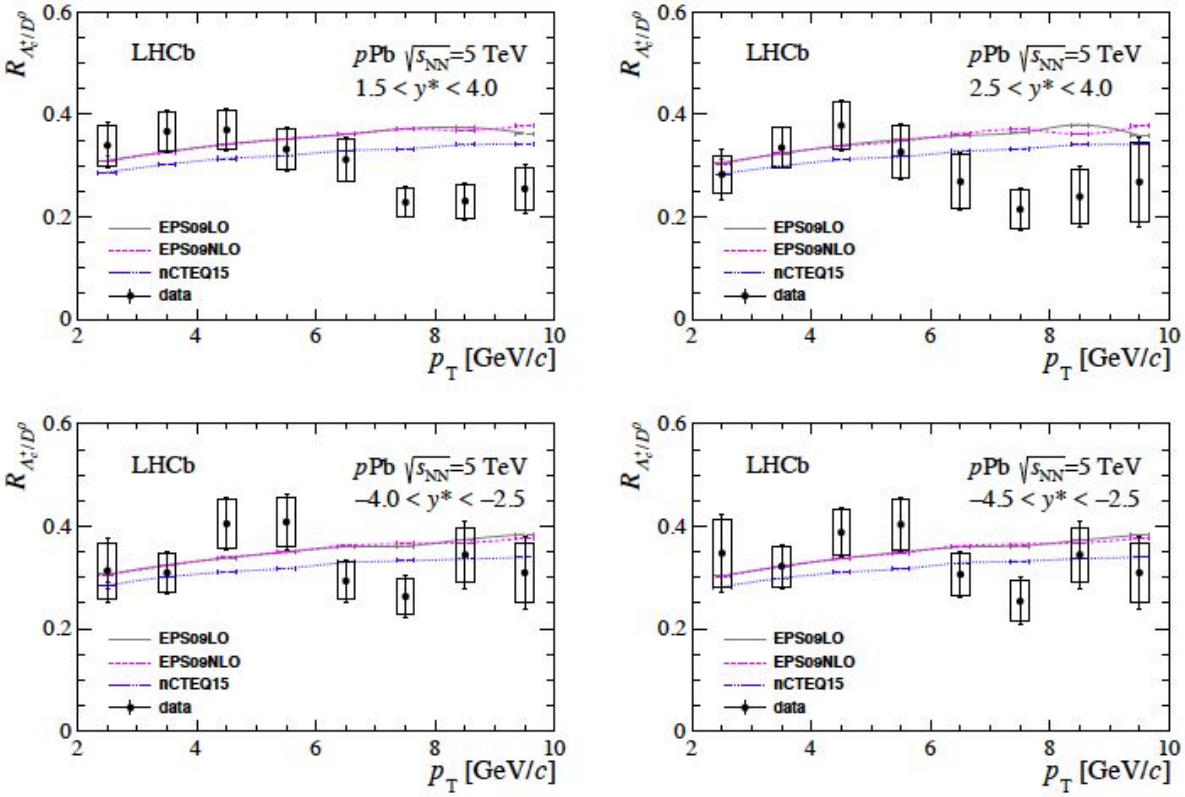


Test of binary scaling for HQ requires measurements of HF-baryon production in Pb-Pb

This, along with the determination of nPDF, is important for the interpretation of HF data in Pb-Pb collisions.

Λ_c^+/D^0 vs. rapidity in p-Pb collisions

JHEP 02 (2019) 102

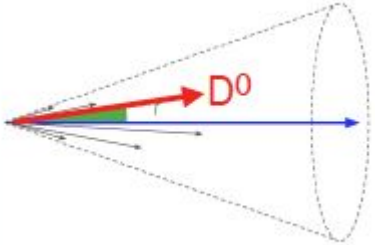


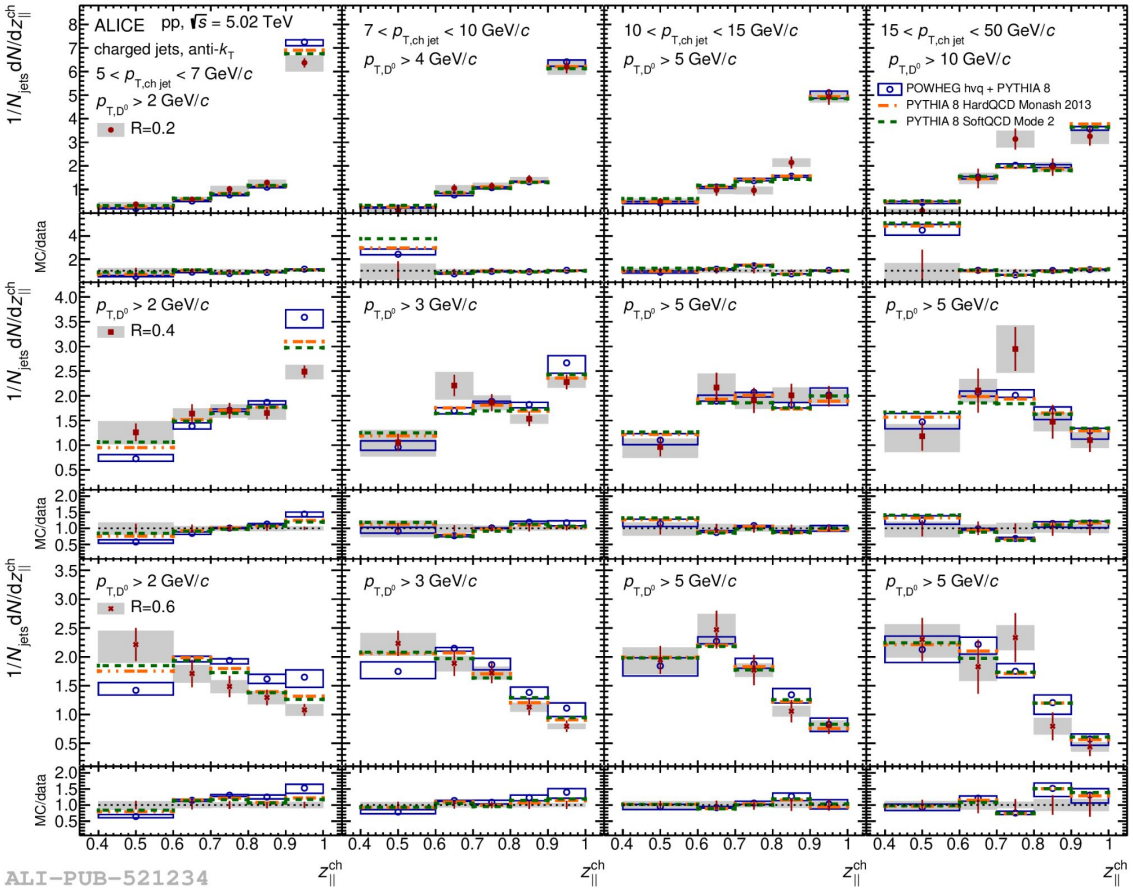
HF-hadron tagged jets

Interplay of production process, parton shower and hadronisation

Hint of softer fragmentation in data than in models

$$z_{\parallel}^{ch} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$



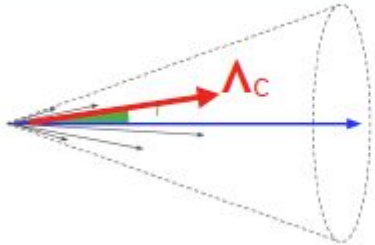


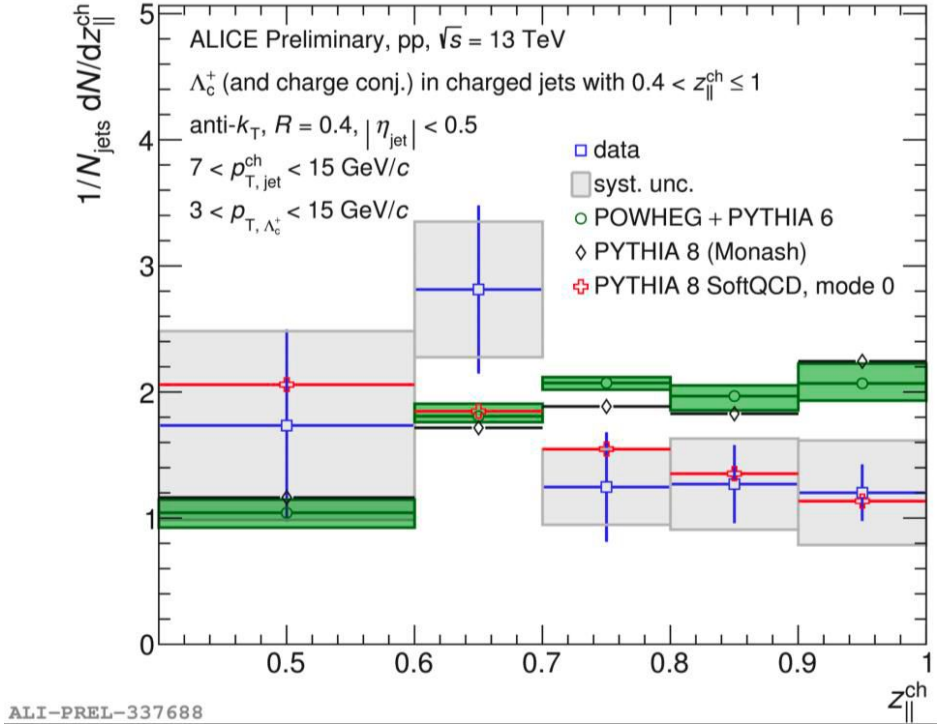
HF-hadron tagged jets

Interplay of production process, parton shower and hadronisation

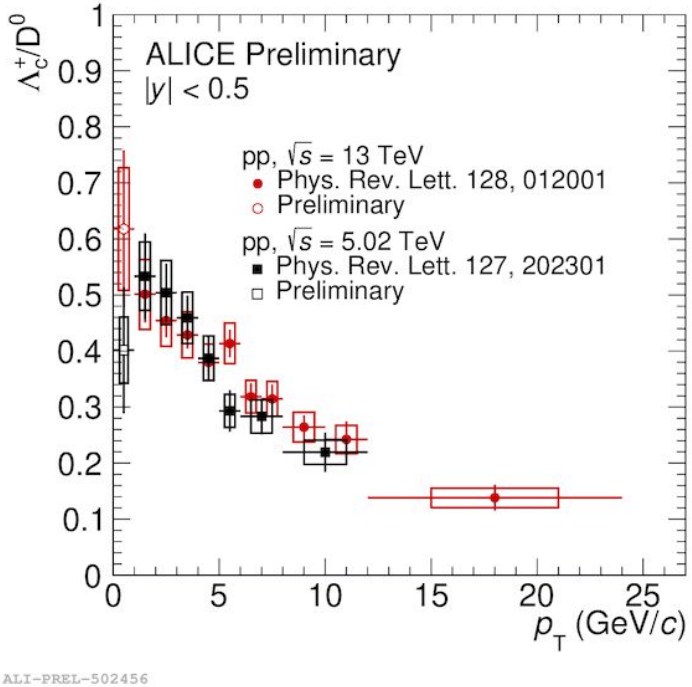
Softer fragmentation in data than in default PYTHIA8, PYTHIA8 with CR-BLC closer to the data

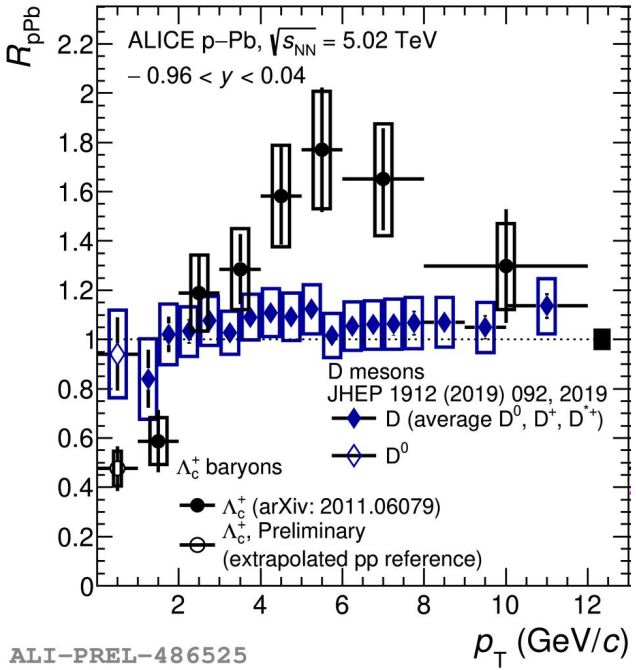
$$z_{//}^{ch} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$





More on Λ_c^+/D^0 in pp at 5, 13 TeV an in p-Pb collisions





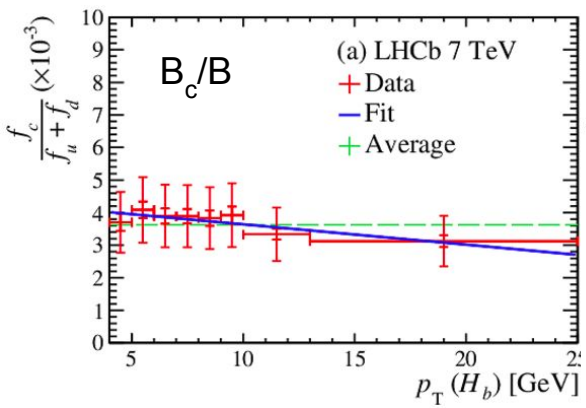
Run 3 data needed to conclude on trend below 1 GeV/*c*

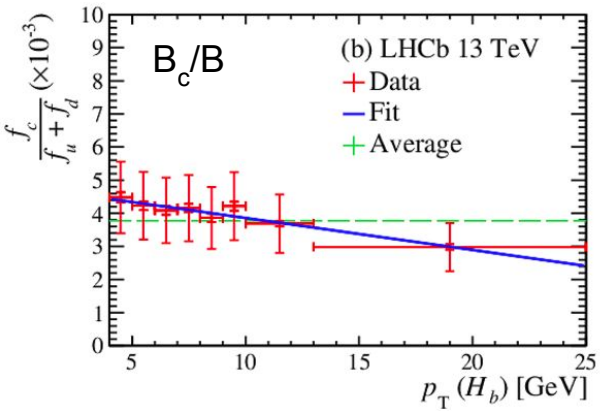
Mass effect or baryon effect?

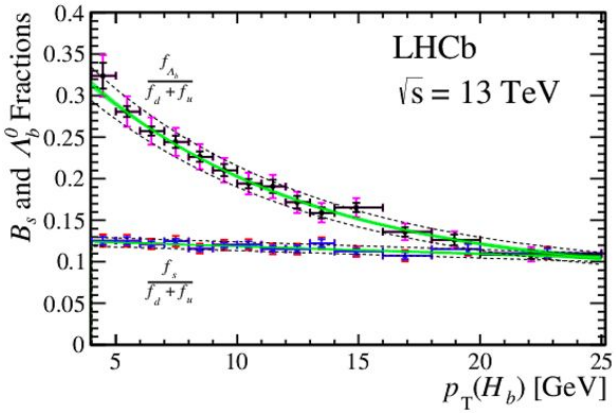
Typically baryons have larger mass
Baryon production requires the production of an antibaryon (→ an antiproton)

⇒ Energy cost larger for baryons than meson
→ impact on e^+e^- data?

Not main point: similar Λ_c/D at Z^0 and Υ peaks





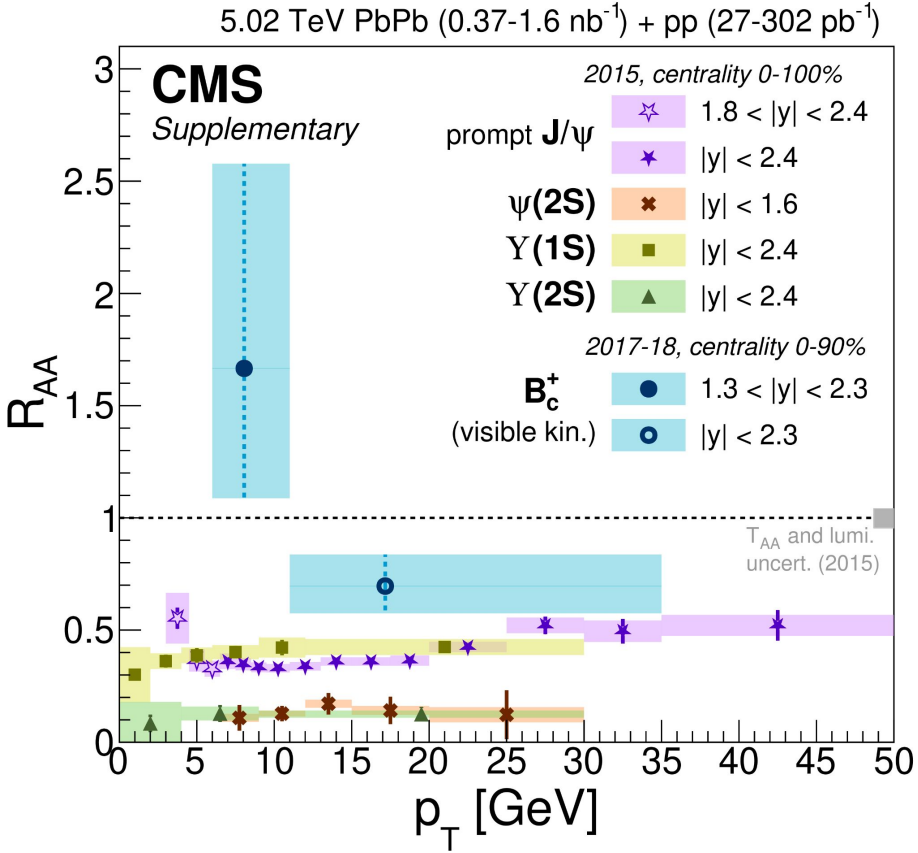


B_c mass >> Λ_b mass + requires another charm meson in the event (D mass >> p mass) → even stronger constraints to phase space from B_c than Λ_b

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? (caveat: feed-down, comes later)

B_c^+ nuclear-modification factor

PRL 128 (2022) 252301



B_c^+ less suppressed than quarkonia?
Production dominated by recombination in both pp and Pb-Pb?

Ω_c^0 lifetime(s)

Hard to reconcile theoretical expectations with recently measured values from LHCb and Belle II

→ sensitivity to description of hadron structure and quark interactions

J. Gratrex, B. Melic, I. Nisandzic
https://arxiv.org/pdf/2204.11935.pdf

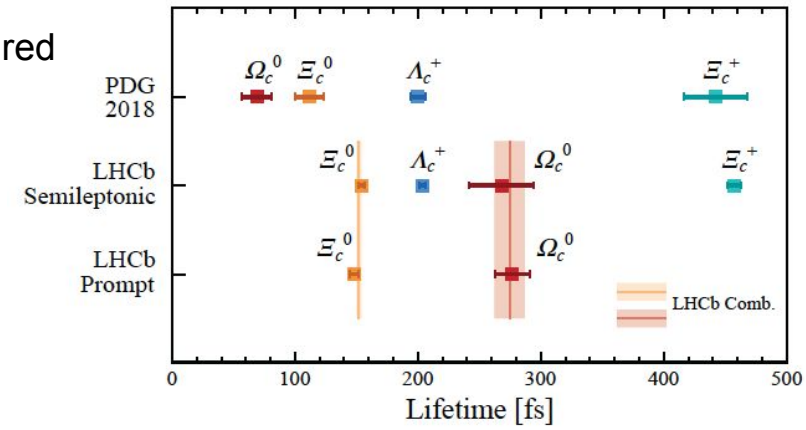
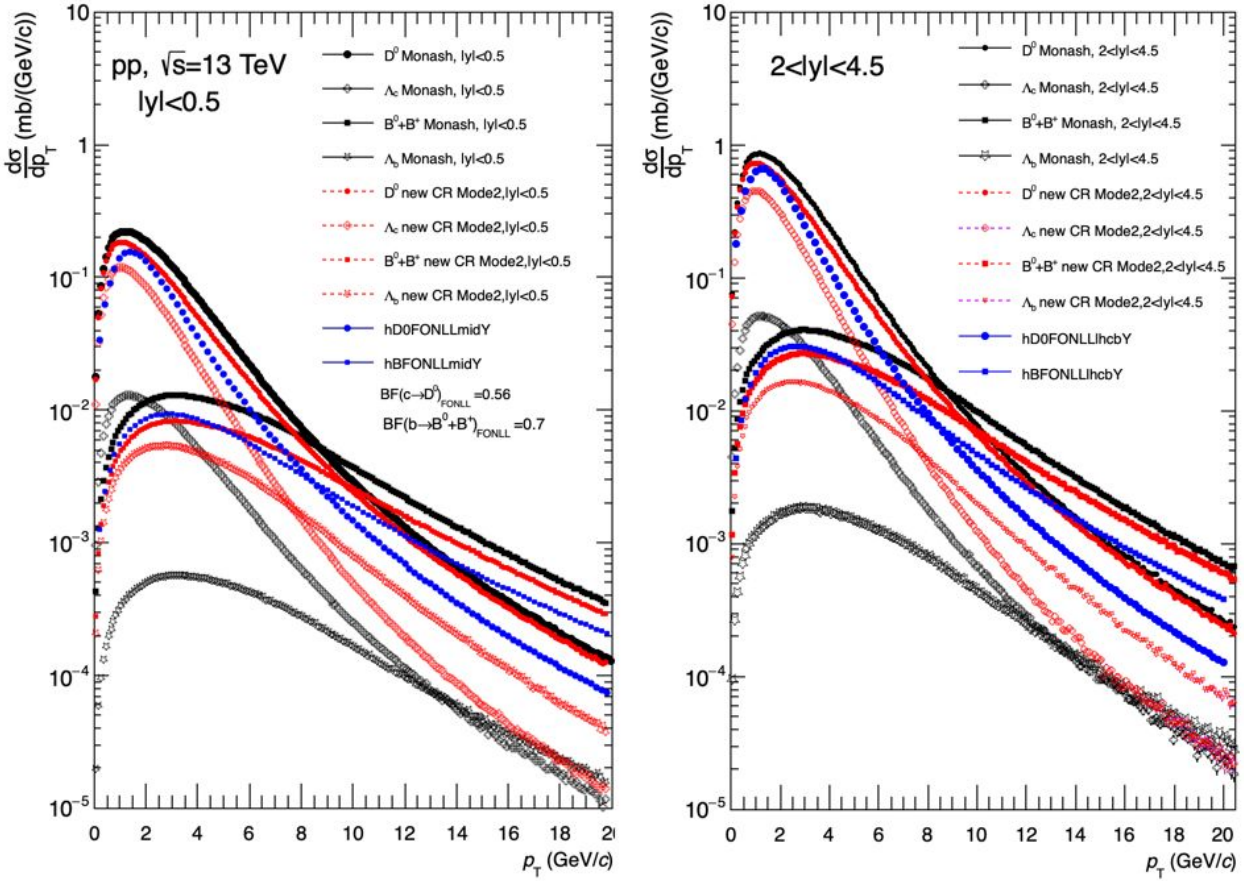


Figure from H.Y Cheng,
arXiv:2111.09566

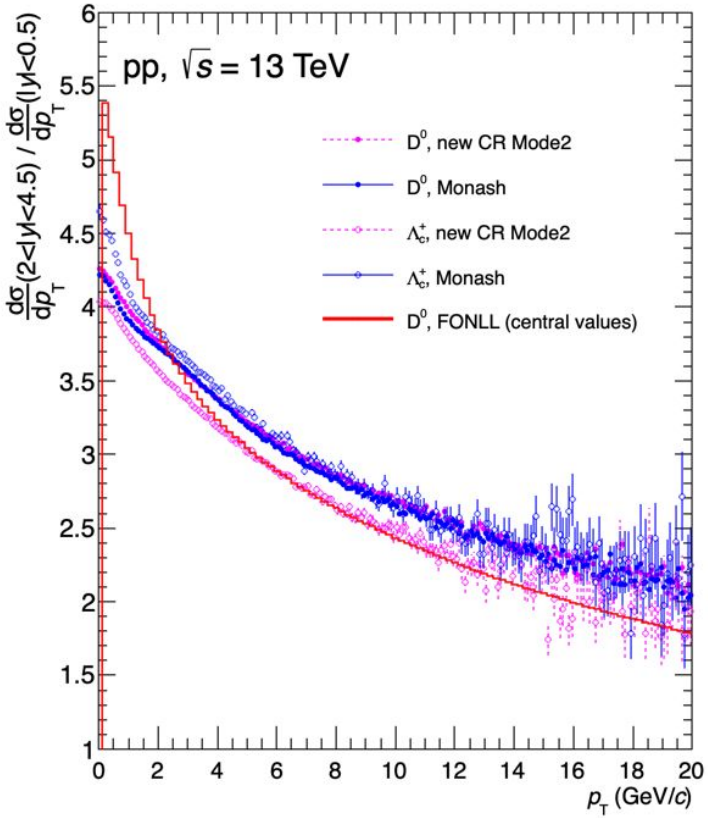
LHCb (most recent):
https://arxiv.org/pdf/2109.01334.pdf

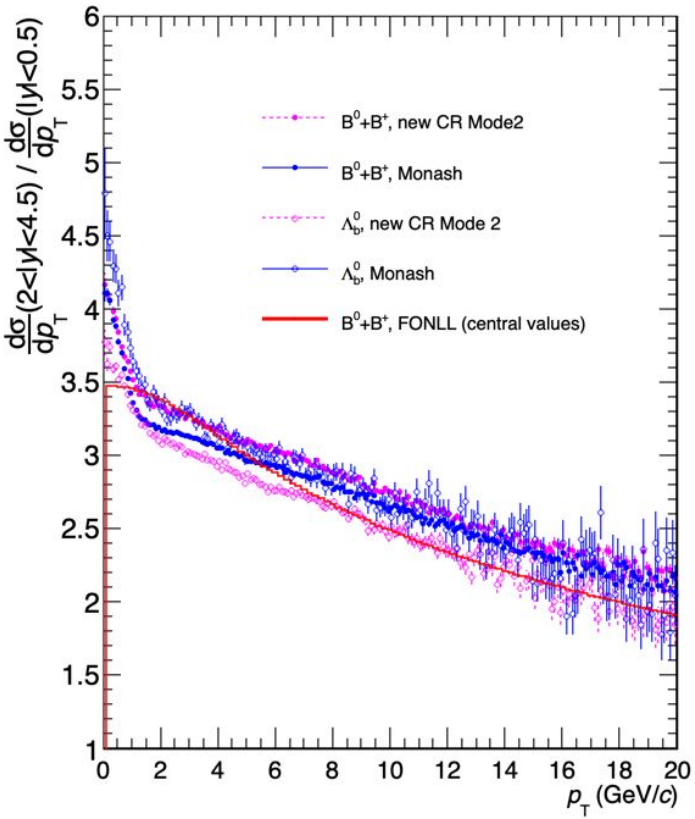
Belle II confirms LHCb data:
https://arxiv.org/pdf/2208.08573.pdf

More on forward vs. mid rapidity

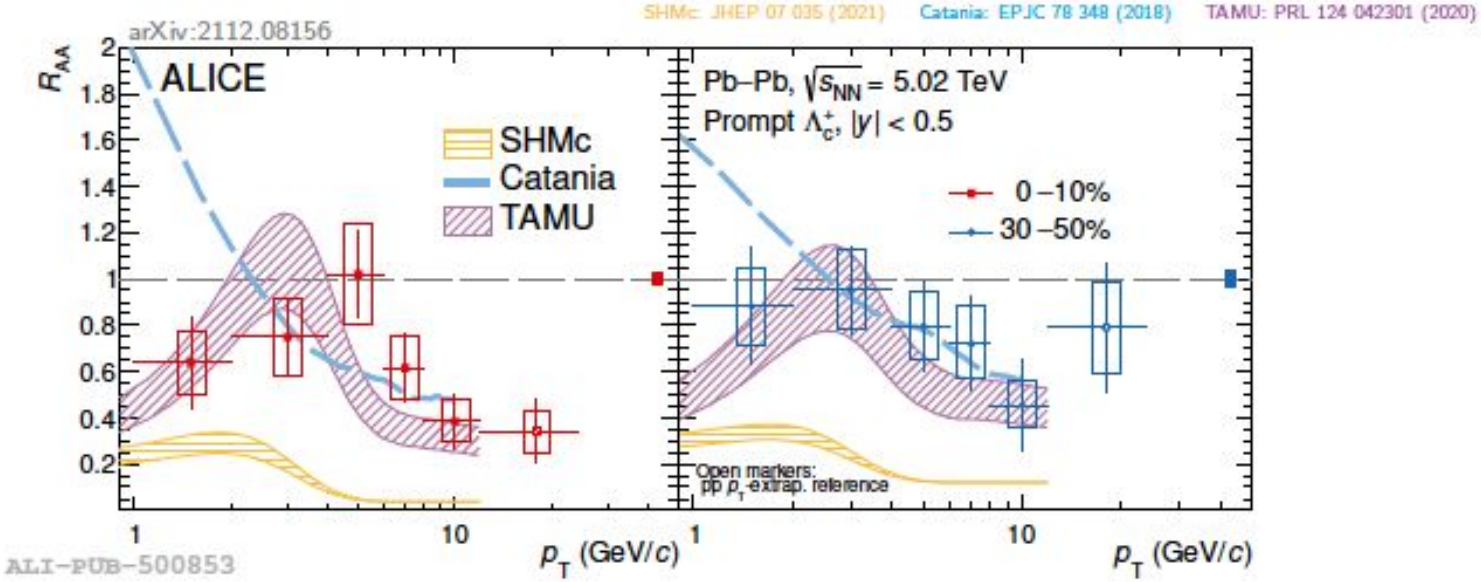


More on forward vs. mid rapidity

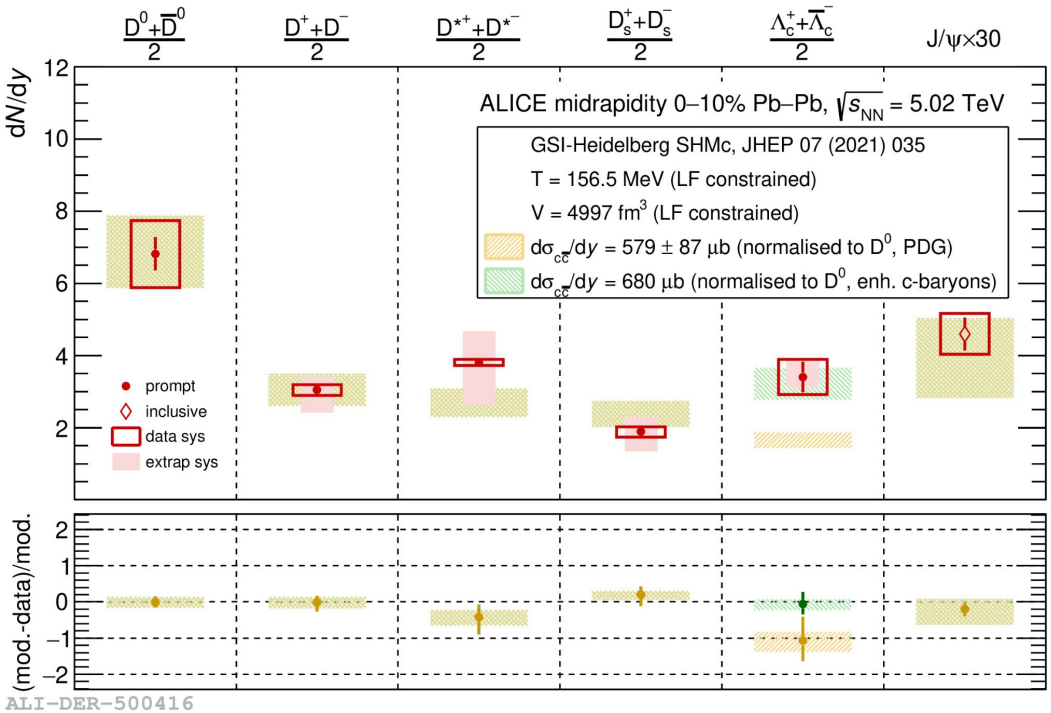




Λ_c^+ R_{AA} vs. models

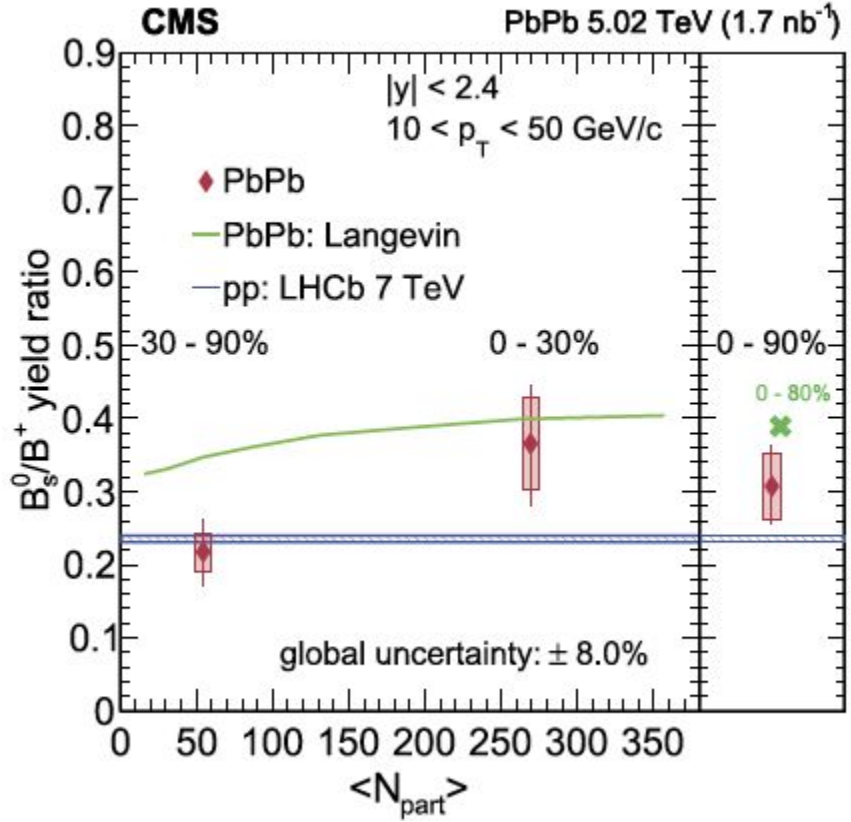


Charm-hadron yields vs. SHM in Pb–Pb collisions

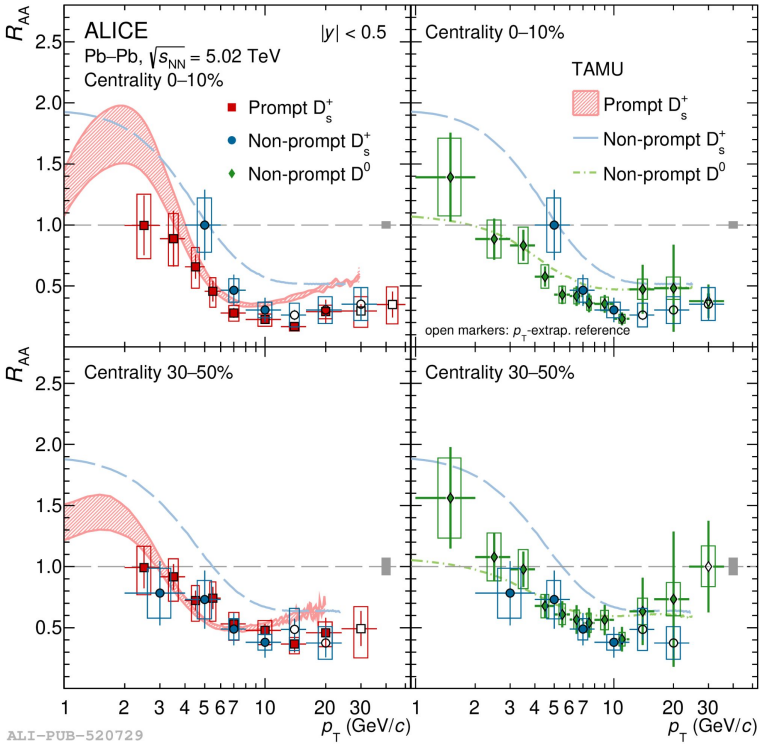


B_s^0 and non-prompt D_s^+ in Pb–Pb collisions

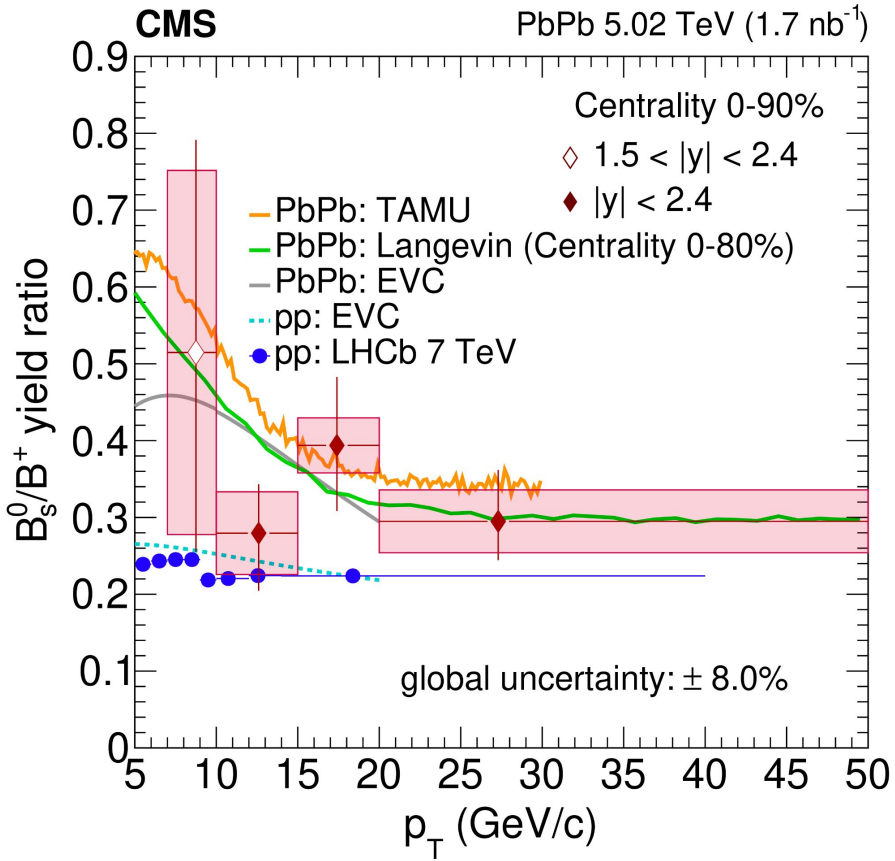
PLB 829 (2022) 137062



arxiv: 2204.10386

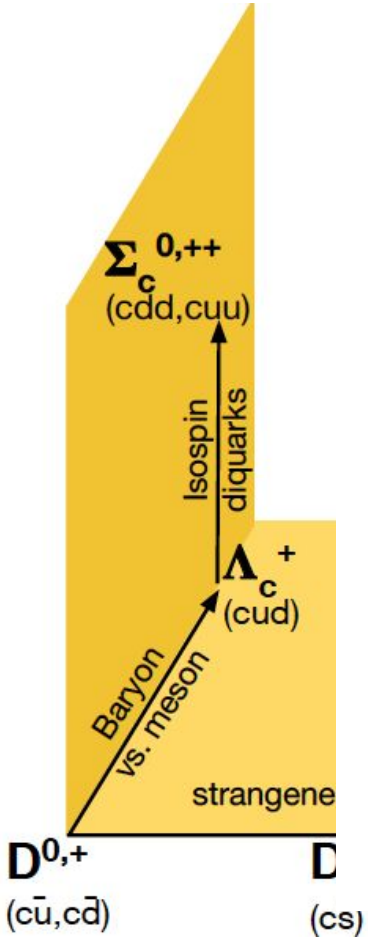


B_s^0 and non-prompt D_s^+ in Pb–Pb collisions



TAMU, PLB 735 (2014) 445
Langevin, PLB 807 (2020) 135561
EVC, EPJC 78 (2018) 344

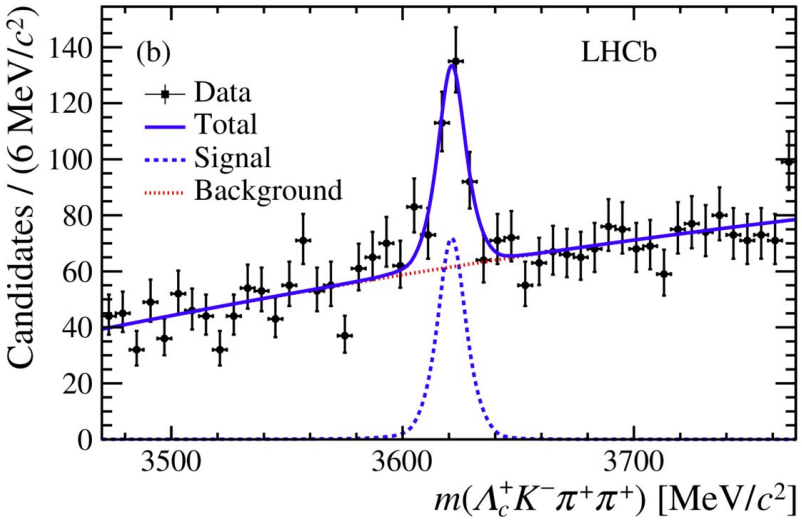
Several arrows in the quiver



Double (Triple?) heavy-quark states…

Particle	Mass (GeV/c^2)
	1.865
	1.870
	1.968
	2.286
	2.454
	2.470
	2.468
	2.695
	5.280
	5367
	5620

First steps towards measurement of Ξ_c^{++} production



CHIN. PHYS. C44 (2020) 022001

$$\mathrm{BR}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\Bigg|_{4<p_T<15\ \mathrm{GeV}/c} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

PYTHIA8 beyond Leading Colour

JHEP 1508 (2015) 003

Primordial yields

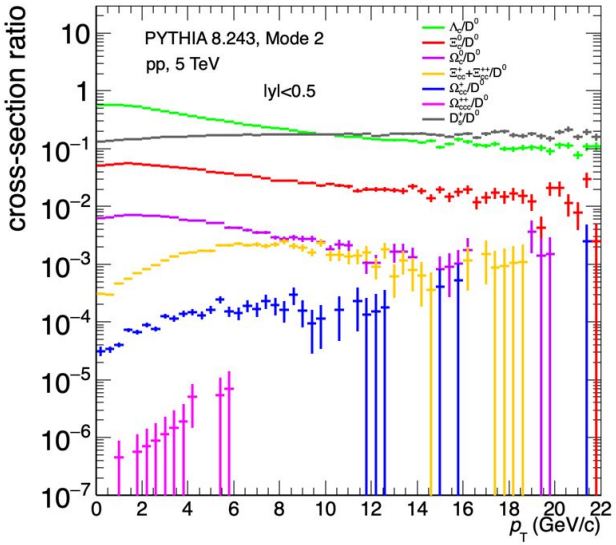
Particle	New CR	Old CR
D^+	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^+	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^0	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$
Σ_c^{*++}	$2.2 \cdot 10^{-3}$	$9.5 \cdot 10^{-4}$
Σ_c^{*+}	$2.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-4}$
Σ_c^{*0}	$2.2 \cdot 10^{-3}$	$9.1 \cdot 10^{-4}$
ccq^7	$2.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-7}$
B^+	$1.6 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
Λ_b^0	$8.2 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
Σ_b^+	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$

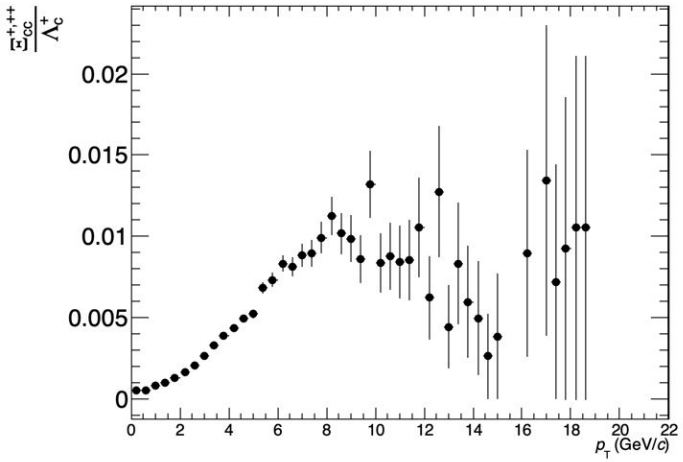
Double (and triple) charm production can set powerful constraints to hadronisation

As well as to 3-quark potentials (sensitive to “pure 3 quark” force?)

J. Vijande et al., Phys.Rev.D 90 (2014) 9, 094004
Y. Koma et al., Phys.Rev.D 95 (2017) 9, 094513
N. Sakumichi et al., Phys.Rev.D 90 (2014) 11, 111501

First steps towards measurement of Ξ_c^{++} production





PYTHIA8 beyond Leading Colour

JHEP 1508 (2015) 003

Primordial yields

Particle	New CR	Old CR
D^+	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^{+}	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^{0}	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$
Σ_c^{*++}	$2.2 \cdot 10^{-3}$	$9.5 \cdot 10^{-4}$
Σ_c^{*+}	$2.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-4}$
Σ_c^{*0}	$2.2 \cdot 10^{-3}$	$9.1 \cdot 10^{-4}$
ccq^7	$2.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-7}$
B^+	$1.6 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
Λ_b^0	$8.2 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
Σ_b^+	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$

LHCb, CHIN. PHYS. C44 (2020) 022001 :

$$\mathrm{BR}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\Bigg|_{4<p_T<15\ \mathrm{GeV}/c} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

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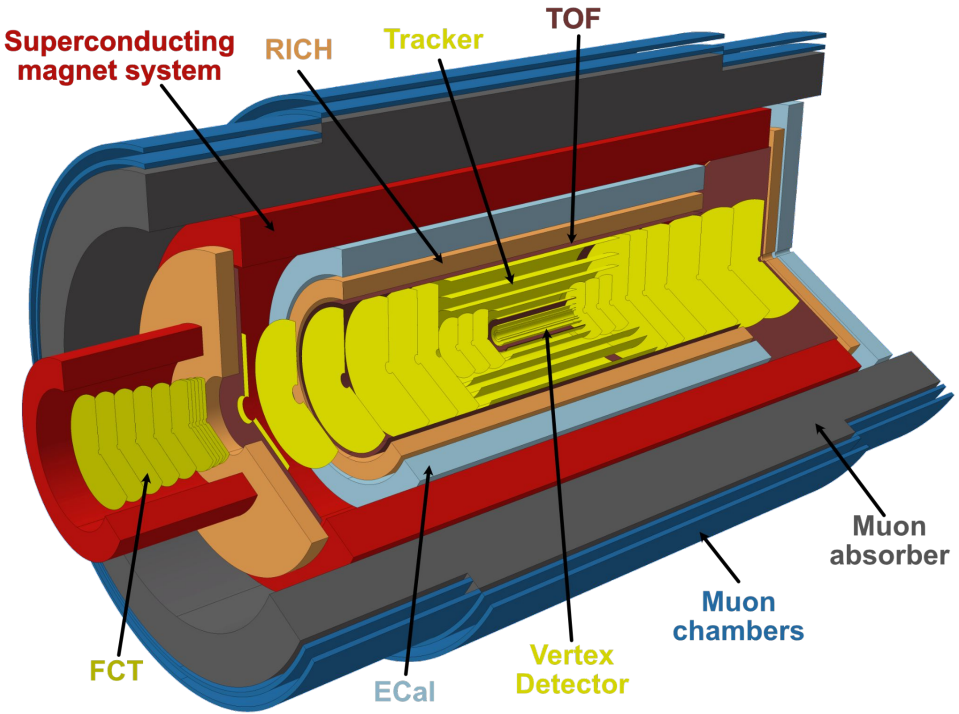
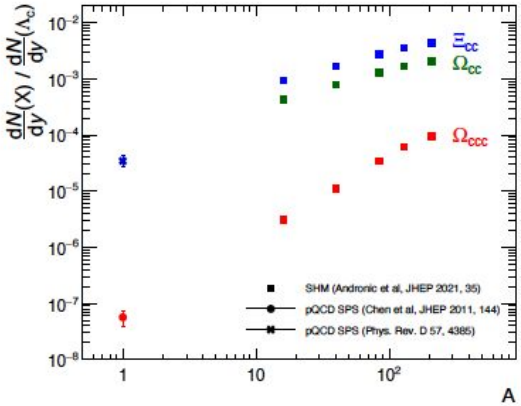
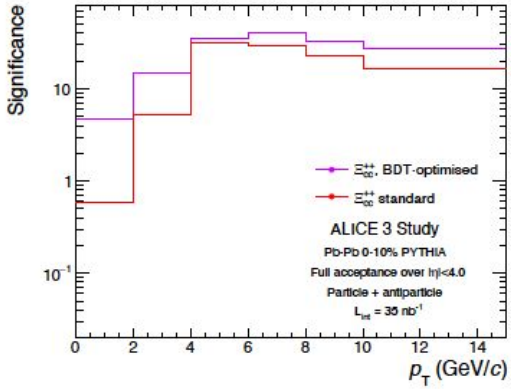
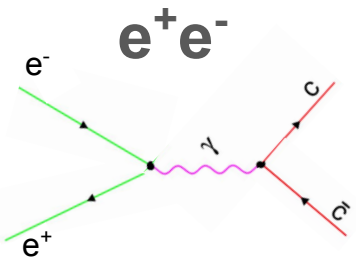
Future prospects: multicharm with ALICE3

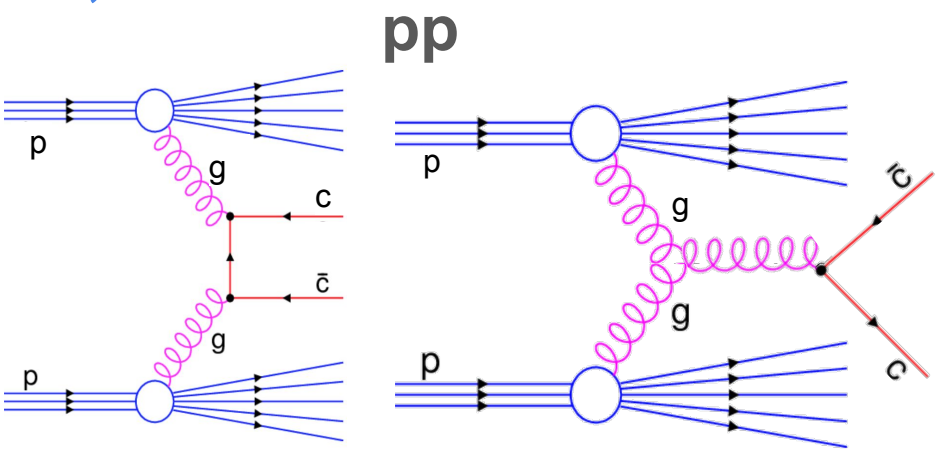


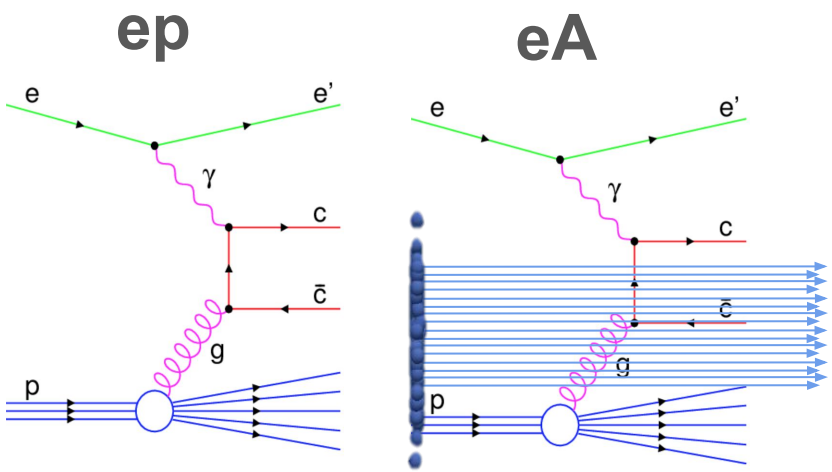




At EIC: different processes, different environments







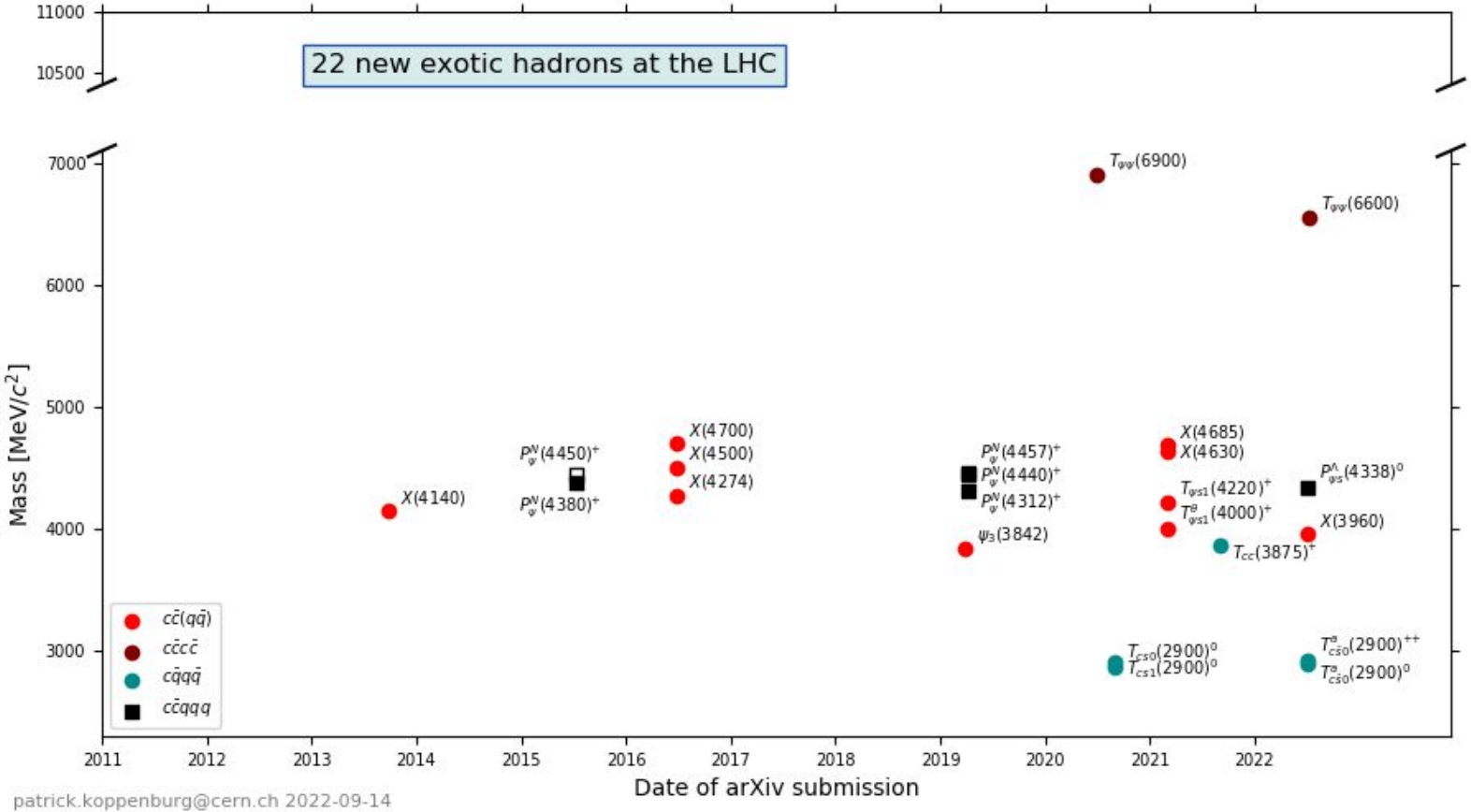
Different production processes → different colour topologies
(sketches only some LO terms, also 3 jet events in ee and ep)

Different environments

→ **different features** can be probed, also exploring phase space
(e.g. beam remnant effects)

Exotic hadrons at LHC

https://www.nikhef.nl/%7Epkoppenb/particles.html



patrick.koppenburg@cern.ch 2022-09-14