Hadronization mechanisms
(via heavy-flavour hadrons): Experiment

A. Rossi, INFN Padova

Hard Probes 2023, Aschaffenburg, 30th March 2023

INFN
Istituto Nazionale
di Fisica Nucleare

Introduction

Hadronisastion is a fundamental process in nature

- High-energy particle physics
- Astrophysics (neutron stars, early Universe, cosmic-ray physics, …)

Soft QCD processes involved → intrinsically non-perturbative

Heavy quarks, formed in initial hard scatterings, are “calibrated probes” of hadronisation

- different hadron species
- different collision systems

→ lever arm to investigate different hadronisation mechanisms

Viceversa, constraining hadronisation fundamental to understand energy loss, collective phenomena, transport

Only a selection of new and recent results (among many)

- Focus on open-HF hadronisation: HF baryon formation not understood in proton-proton collisions
- Quarkonia
- Exotic states

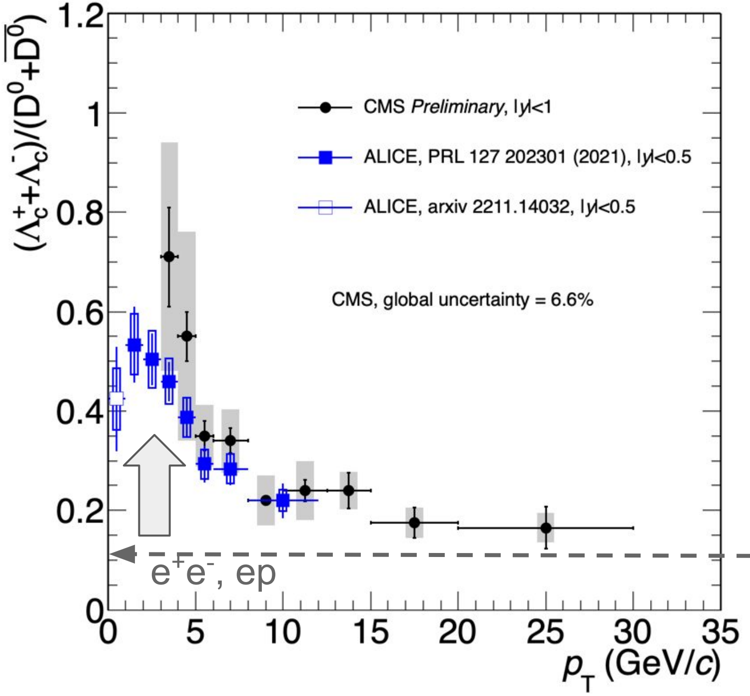
→ K. Smith, M. Espinosa, this morning

If you do not find an important result or your preferred one, my apologies!

Thanks for inputs and discussions to
A. Andronic, R. Arnaldi, A. Dainese, A. Dubla, Y. Sara Amhis, R. Rapp, J. Wang, J. Wilkinson

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

Y. Zhang, Tuesday
A. S. Kalteyer, Wednesday



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

Significantly decreasing with p_T , approaching e^+e^- at high p_T

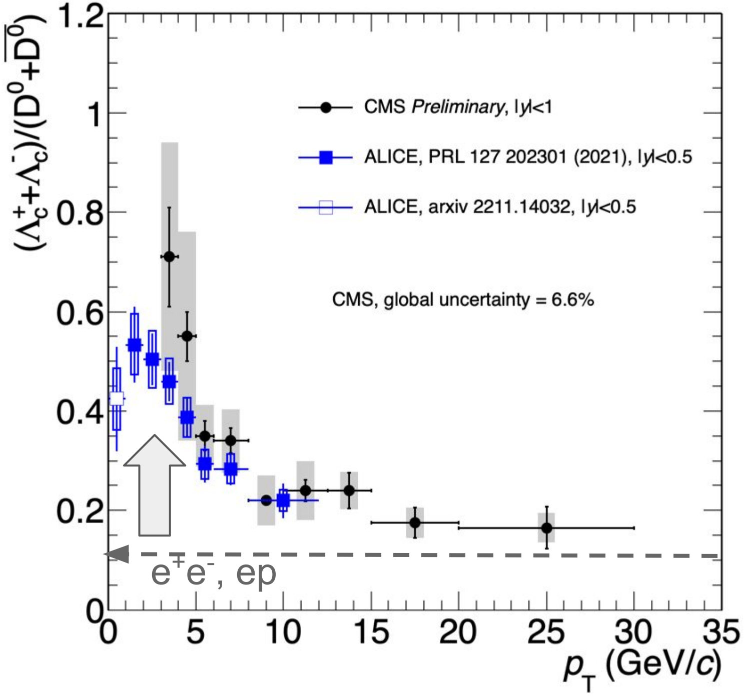
	Λ_c^+/D^0 ± stat. ± syst.	System	$\sqrt{s}$ (GeV)	Notes
ALICE	$0.51 \pm 0.04 \pm 0.04^{+0.01}_{-0.02}$	pp	5020	$p_T > 0, \lvert y \rvert < 0.5$
ALICE	$0.43 \pm 0.03 \pm 0.05^{+0.05}_{-0.03}$	p–Pb	5020	$p_T > 0, -0.96 < y < 0.04$
CLEO [16]	$0.119 \pm 0.021 \pm 0.019$	e^+e^-	10.55	
ARGUS [15, 17]	0.127 ± 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, $\lvert\eta\rvert < 1.6$

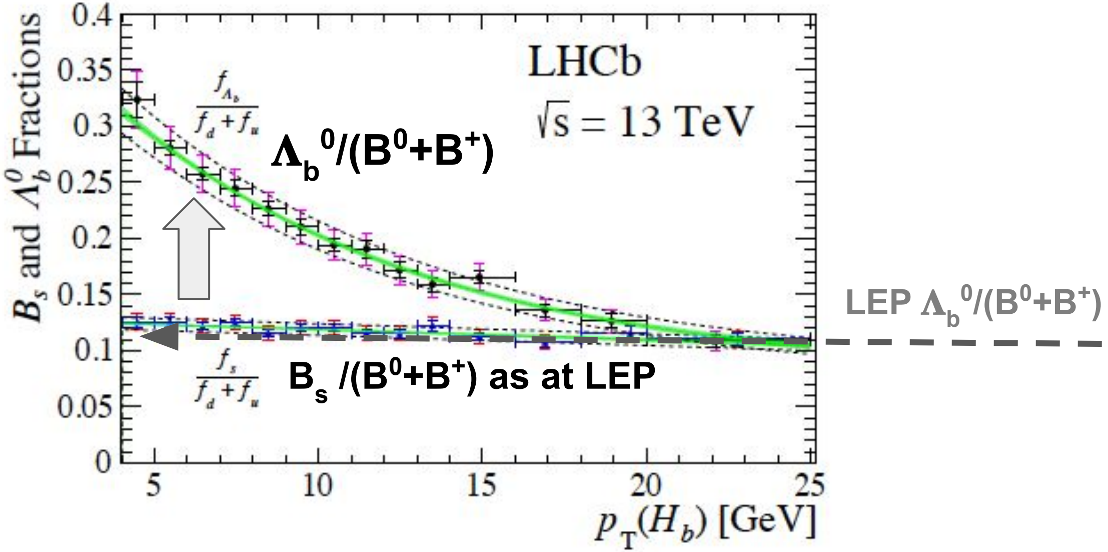
ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032
CMS, PAS-HIN-21-004

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

Y. Zhang, Tuesday
A. S. Kalteyer, Tuesday

PRD100 (2019) no.3, 031102





Similar trend in charm and beauty sectors

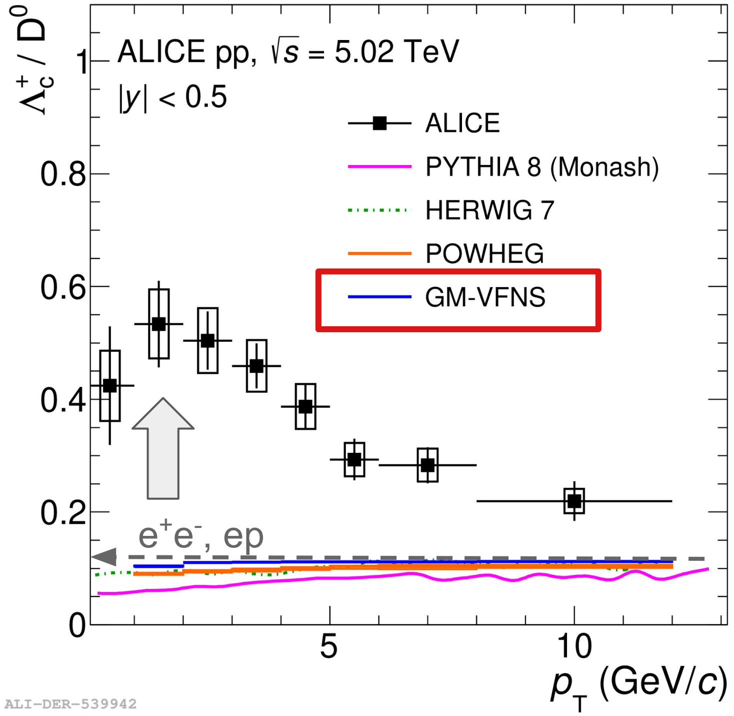
b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7

HFLAV, EPJC 77 (2017) 895

$p\bar{p}$: CDF
PRD 77 072003 (2008)

ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032
CMS, PAS-HIN-21-004

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



Data far from **pQCD-based calculations** based on **factorisation** approach**,** which works well for mesons (plethora of results at RHIC, Fermilab, LHC,...)

Hadronisation → 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.

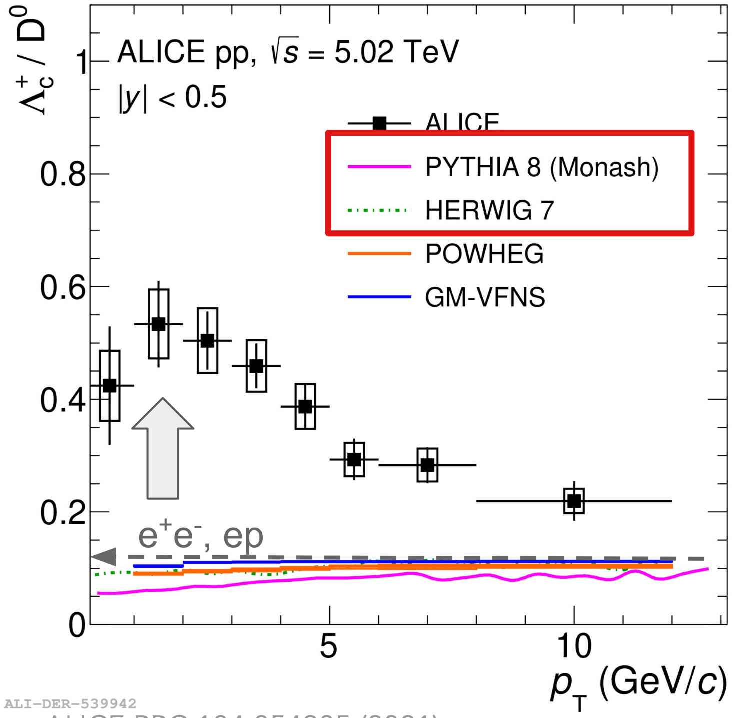
Naïve expectation: ratios of particle-species yields independent from collision system

→ **Universality of fragmentation function does not hold already in pp collisions**

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

fragmentation function

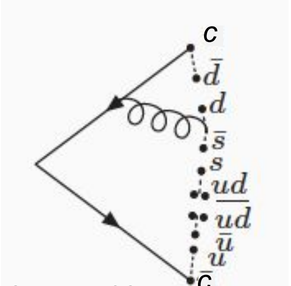
Λ_c^+/D^0 ratio in pp collisions vs. models (2)



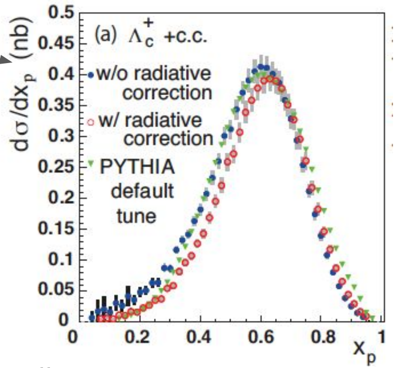
ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

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 e^+e^- data ~ fragmentation functions used in pQCD-based calculations



Courtesy of C. Bierlich

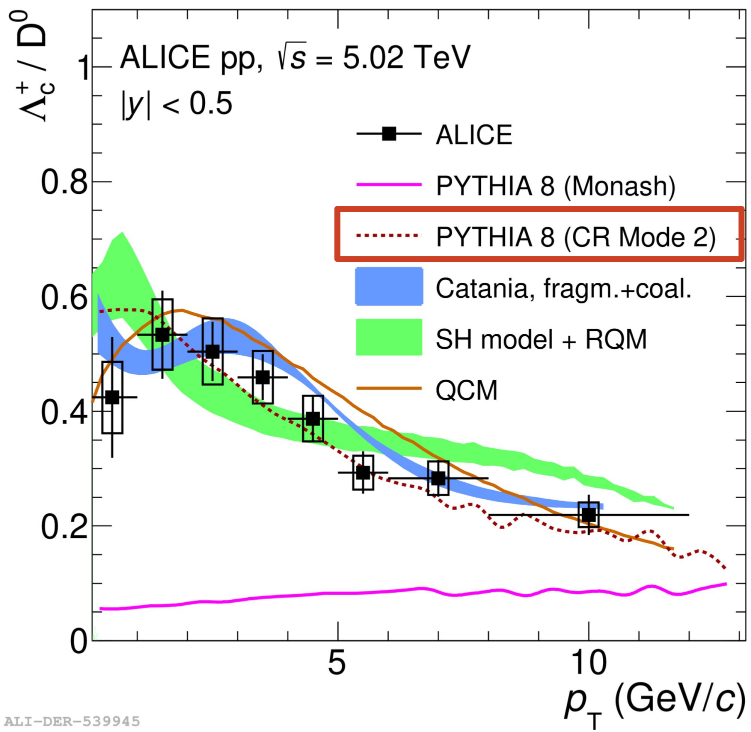


Belle, PRD 97, 072005 (2018)

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

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

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



ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

Data described by:

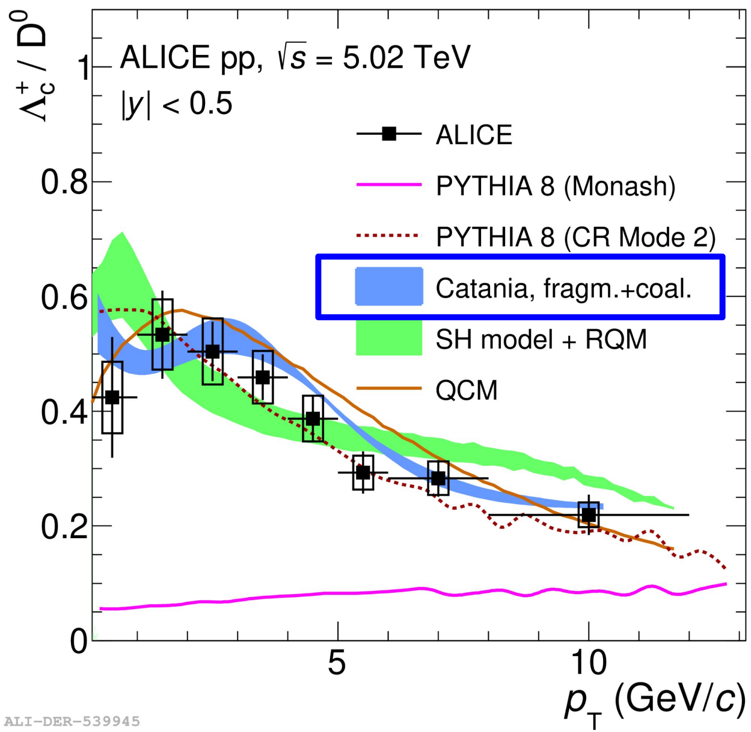
PYTHIA8 with String Formation beyond Leading Colour approximation (JHEP 1508 (2015) 003).
More complete and realistic (=closer to QCD) colour-reconnection (CR) scheme
- **"...*between which partons do confining potentials arise?*"**

Junction reconnection topologies → enhance baryons.

(b) Type II: junction-style reconnection

Support need of abandoning independent hadronisation of different MPI
A hadronic environment matters

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



ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

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

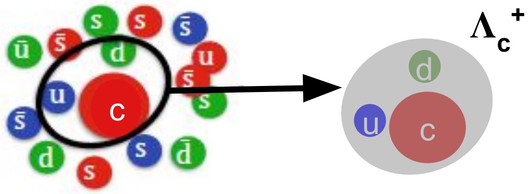
"Sudden" (fixed temperature) coalescence:

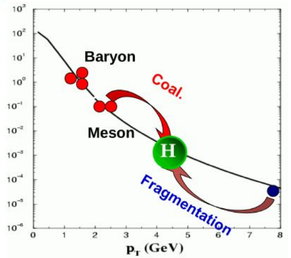
f_q = phase-space distributions of quarks in the system

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

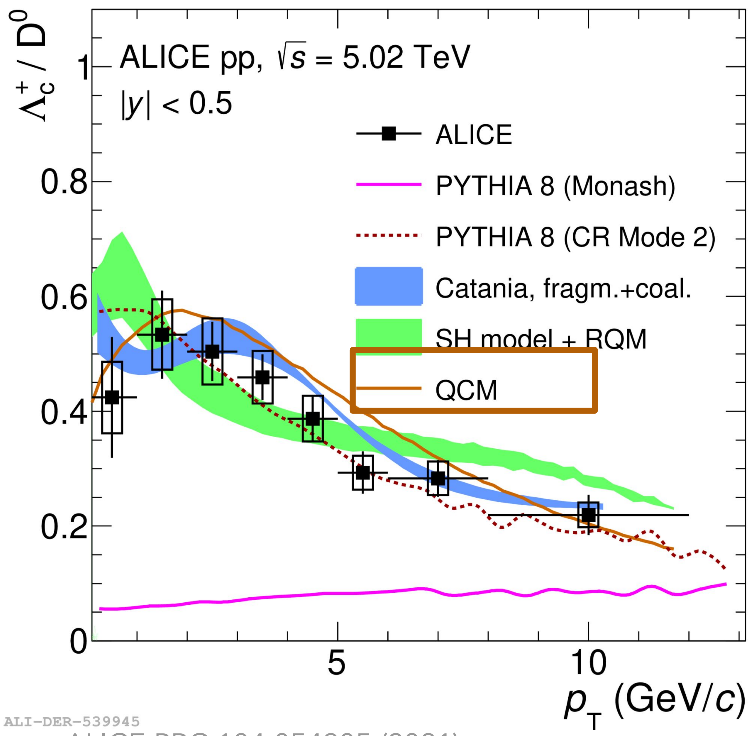
$$\times f_H(x_1 ... x_{N_q}, p_1 ... p_{N_q}) \, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right)$$

f_H = phase-space distributions of quarks within hadron





Λ_c^+/D^0 ratio in pp collisions vs. models (5)



ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

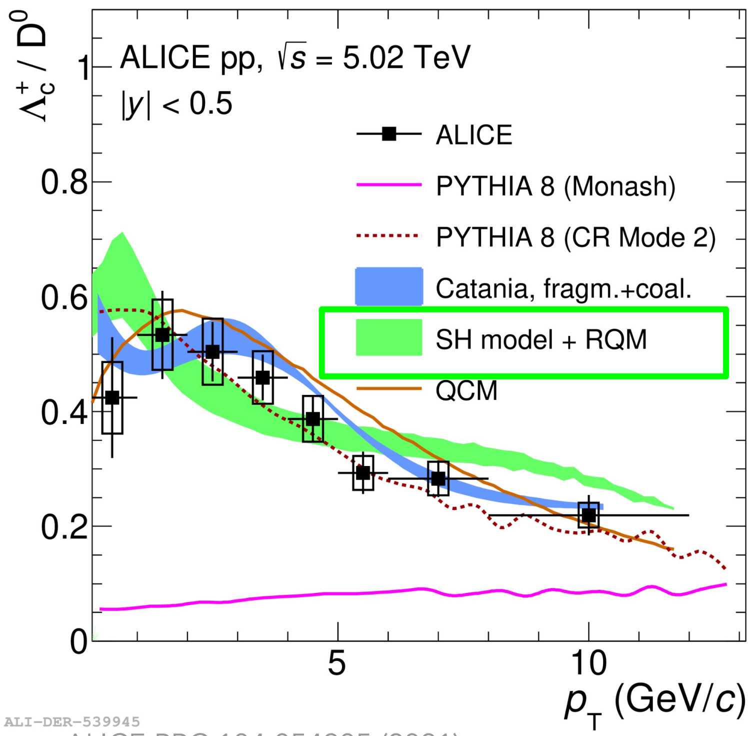
Data described by:

PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

QCM: recombination model based on statistical weights + "equal quark-velocity" (EPJC 78, 2018 4, 344)

Λ_c^+/D^0 ratio in pp collisions vs. models (6)



ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

Data described by:

PYTHIA8 with String Formation beyond Leading Colour

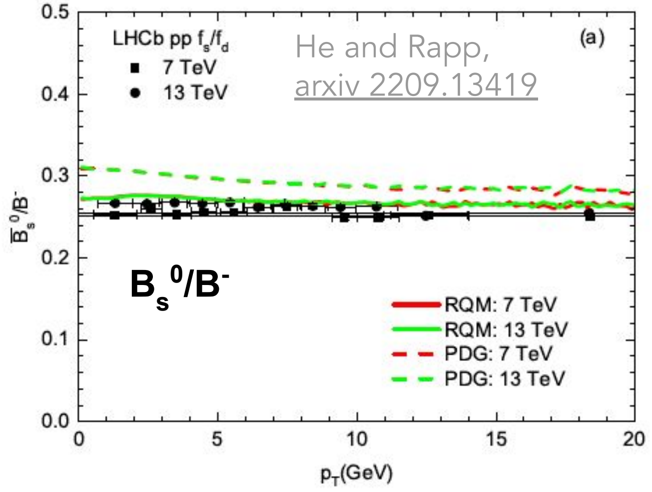
Catania model: coalescence + "vacuum" fragmentation

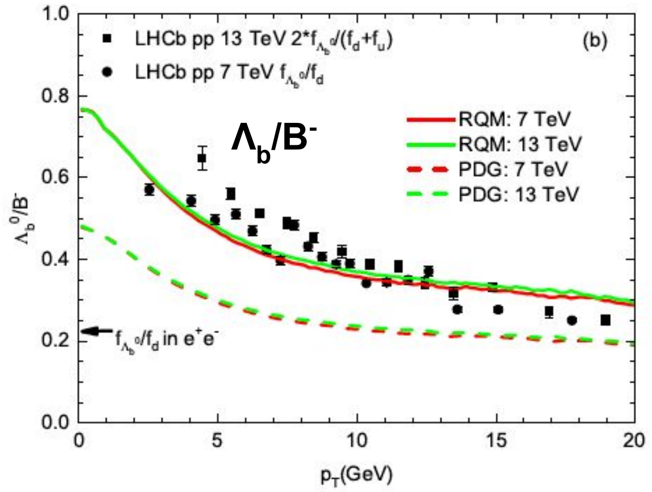
QCM: recombination model based on statistical weights + "equal quark-velocity" (EPJC 78, 2018 4, 344)

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 Relativistic Quark Model)

→ 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





ions vs. models (6)

Data described by:

PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

QCM: recombination model based on statistical weights + "equal quark-velocity" (EPJC 78, 2018 4, 344)

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 Relativistic Quark Model)

→ PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c

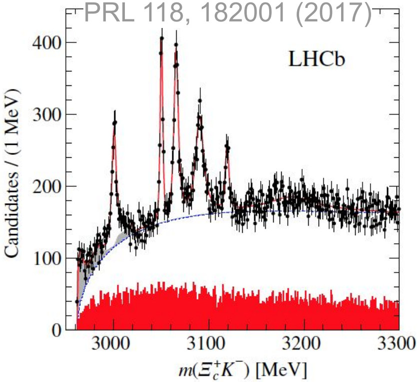
→ RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

Works also for beauty

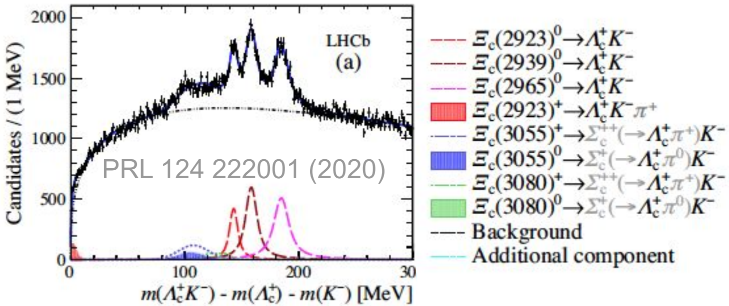
Do these states exist?
Why not discovered in e^+e^-?

Higher-mass states: new states popping up

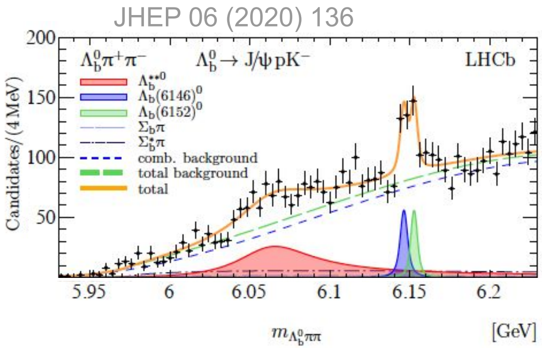
Ω_c excited states

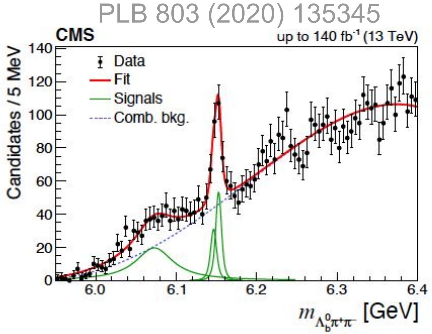


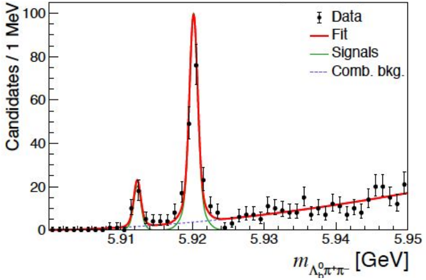
Ξ_c excited states



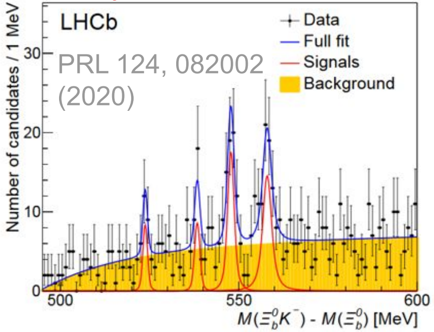
Λ_b excited states

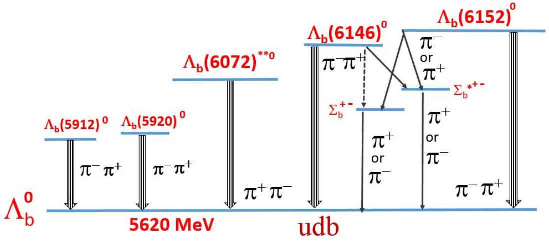






Ω_b excited states





Many states with relatively narrow widths, Γ~10 MeV

Also several lifetime measurements, very important spectroscopy results

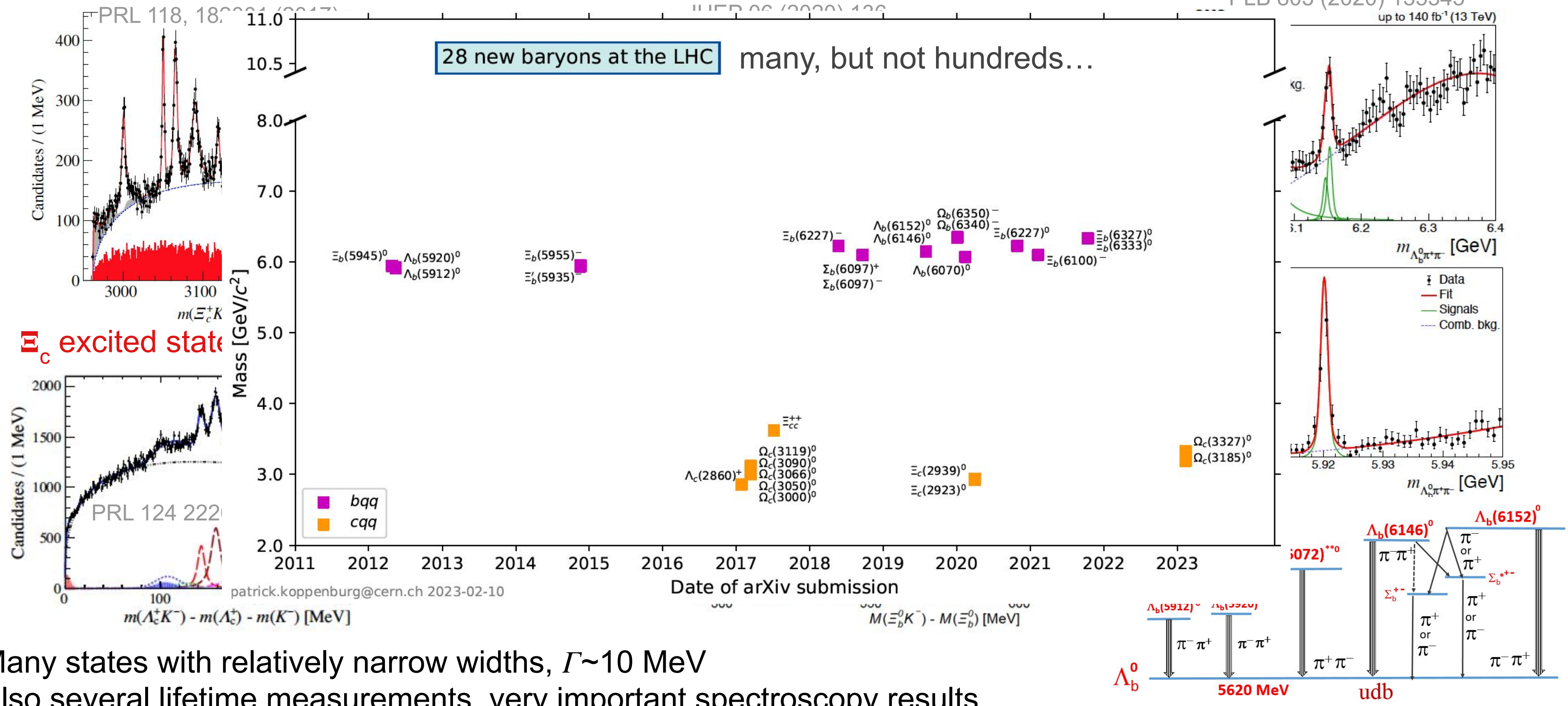
Typically not measurements of (prompt) cross sections. Prospects?

Higher-mass states: new states popping up

Ω_c excited states

Λ_b excited states

Ξ_c excited states



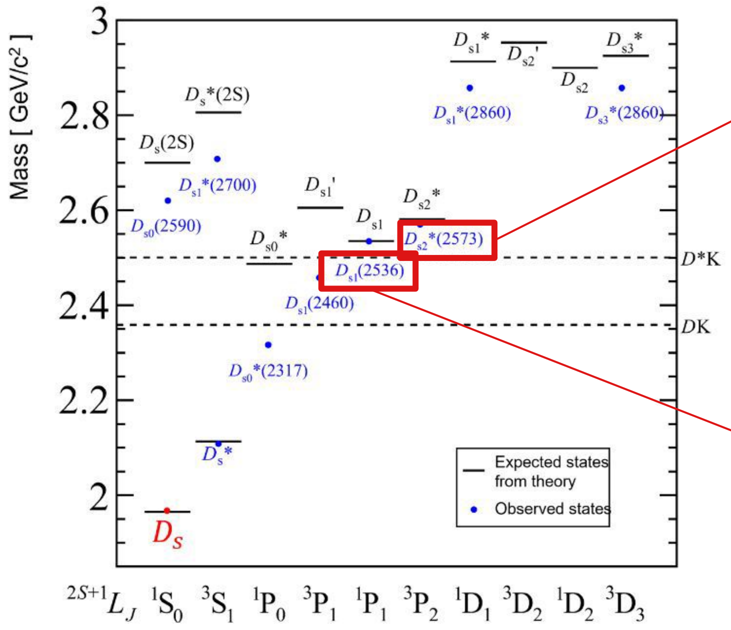
Many states with relatively narrow widths, Γ~10 MeV

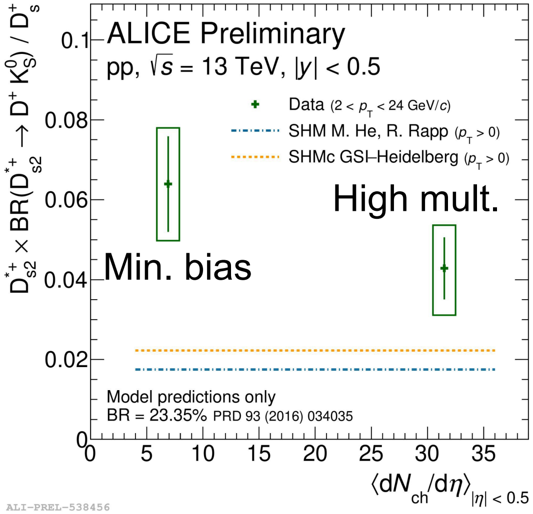
Also several lifetime measurements, very important spectroscopy results.

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

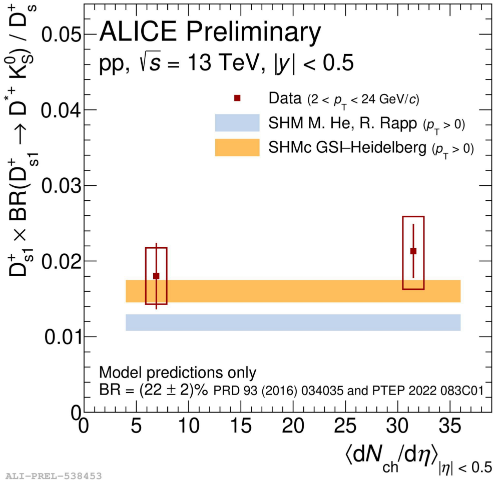
Excited D_s mesons

S. Politano, Wednesday





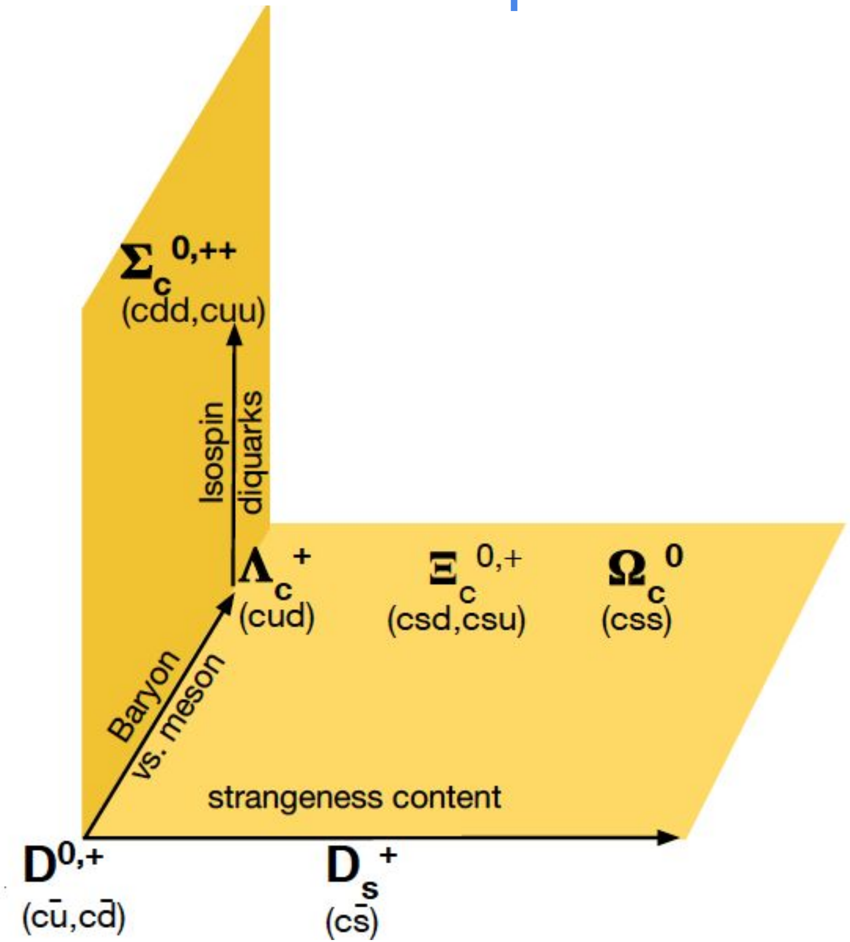
$\Gamma \sim 16.9$ MeV
$\tau \sim 11.6$ fm/c



$\Gamma \sim 0.92$ MeV
$\tau \sim 219$ fm/c

(More precise) studies of multiplicity dependence of states with different widths may reveal possible role of hadronic rescattering.

Several arrows in the quiver

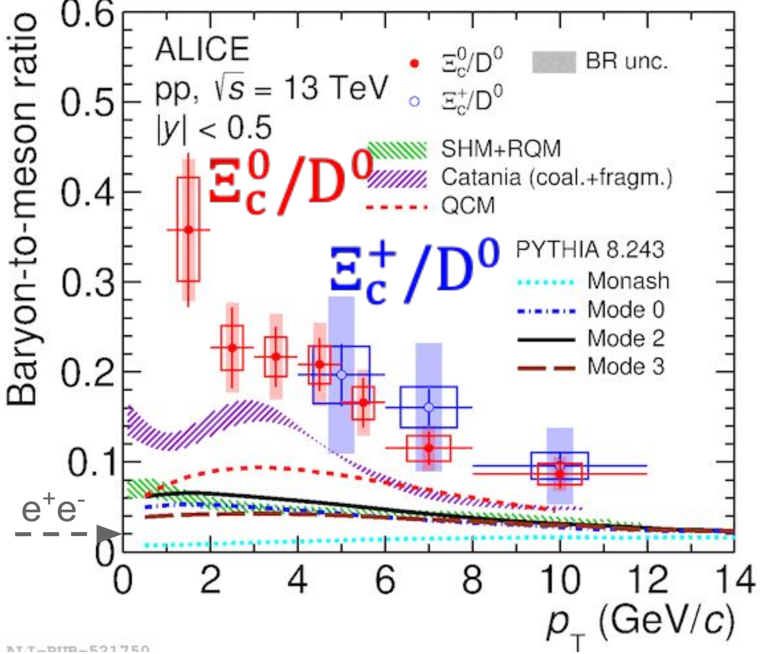


Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

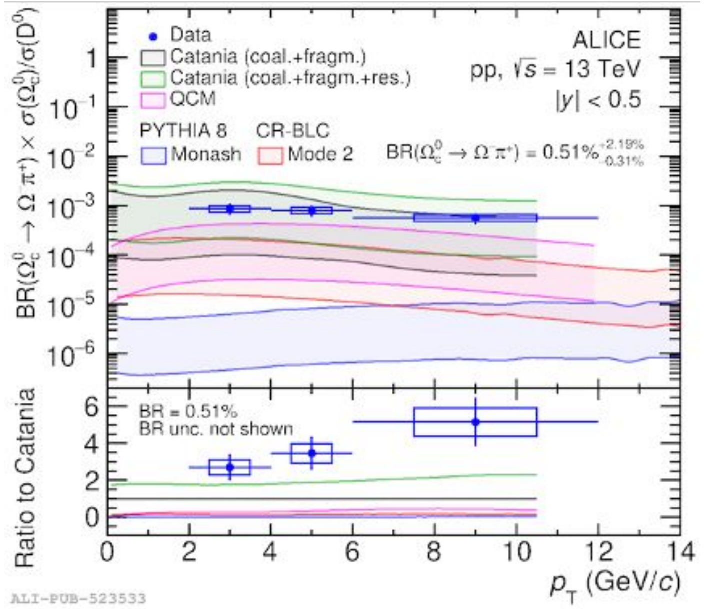
Charm-strange baryons: $\Xi_c^{0,+}$ and Ω_c^0

A. S. Kalteyer , Wednesday

PRL. 127 (2021) 272001



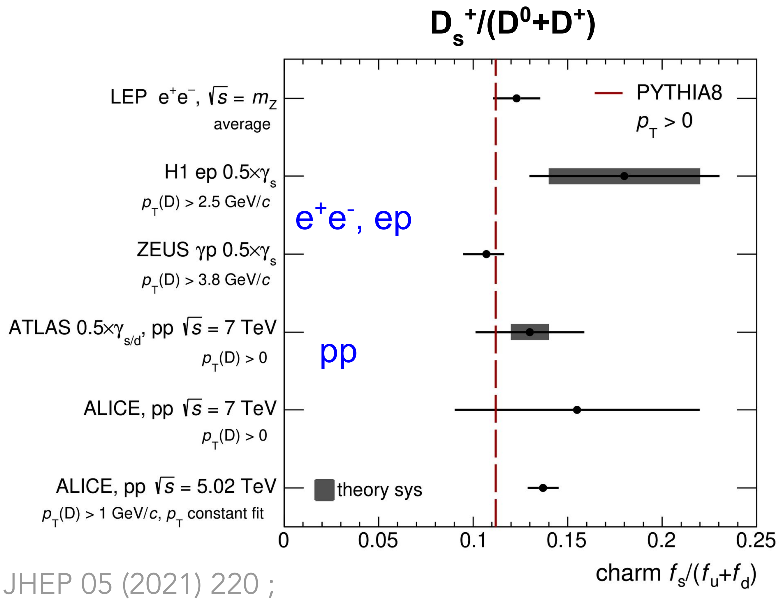
arXiv:2205.13993



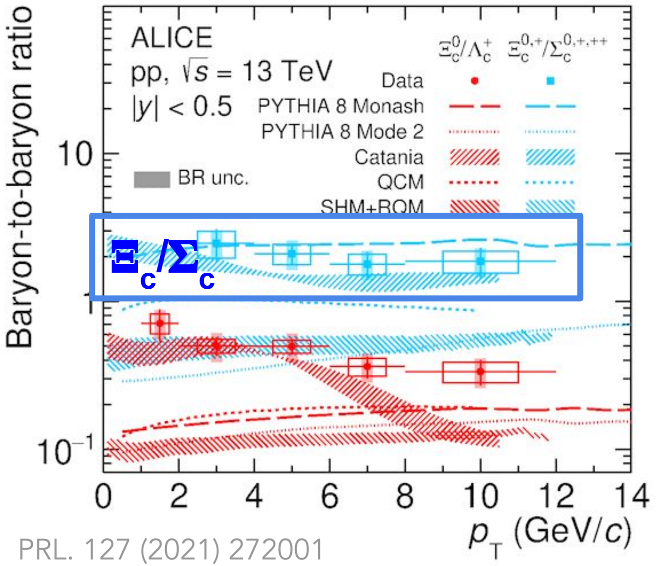
- Both $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0x BR($\Omega_c^0 \to \Omega^-\pi^+$) ratios significantly larger than in e^+e^- collisions
- Only **Catania** model (coalescence) close to the data.

→ Additional challenges from strange-quark production?

Baryon-to-baryon: $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$



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



PRL. 127 (2021) 272001

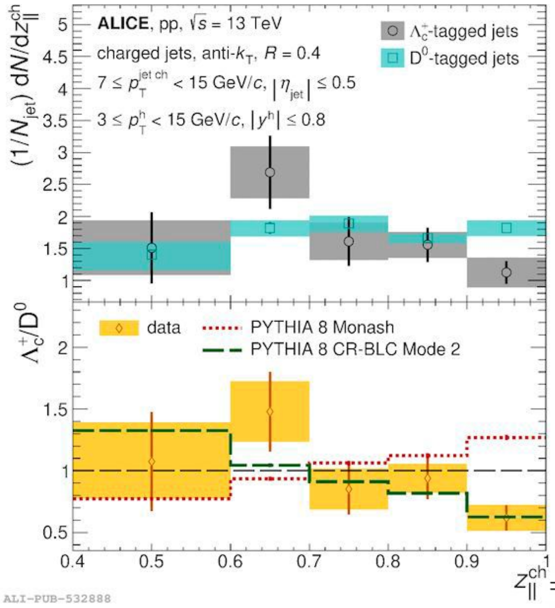
- **$D_s^+/(D^0+D^+)$ (prompt and non-prompt) compatible with expectations from e^+e^-**

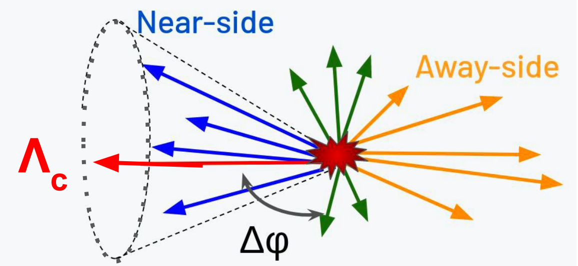
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio close to default PYTHIA8, which strongly underestimates their production! (described by Catania as well)**
  → similar suppression in e^+e^-? Related to diquark rather than quarks?
  (note mass of spin-1 $(dd,ud,uu)_1$ diquarks might be similar to spin-0 $(us,ds)_0$ diquarks)

Jets and correlations

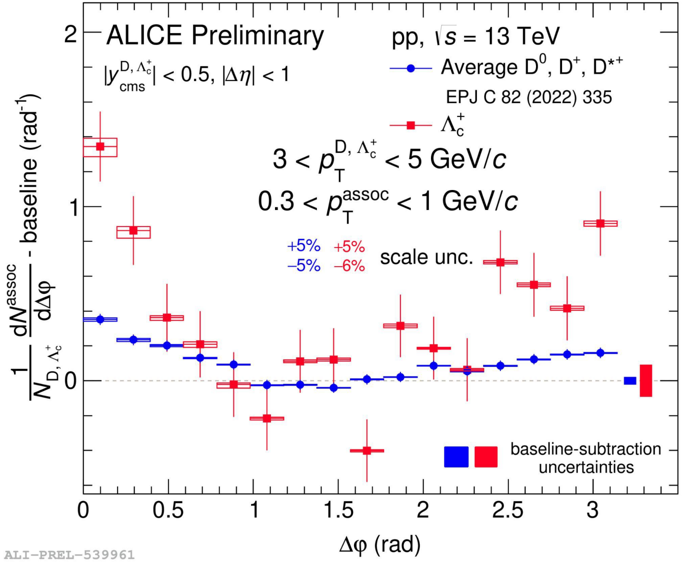
A. Palasciano, Wednesday

ALICE, arXiv:2301.13798





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

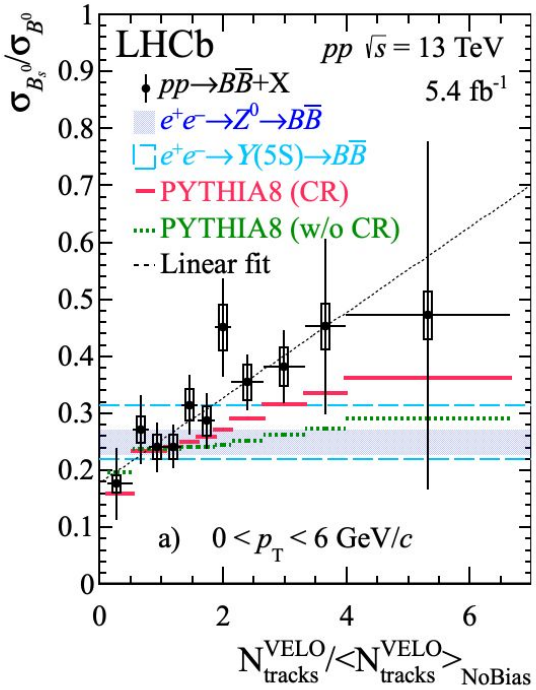


- Jets: indication of **softer fragmentation c→Λ_c than c→D**
- Coherent with higher associated yield in the nearside of Λ_c^+ - hadron azimuthal correlations w.r.t. D-hadron
  … away side surprisingly high!!! No straightforward explanation
  Higher-mass states + decay kinematics? Production process?

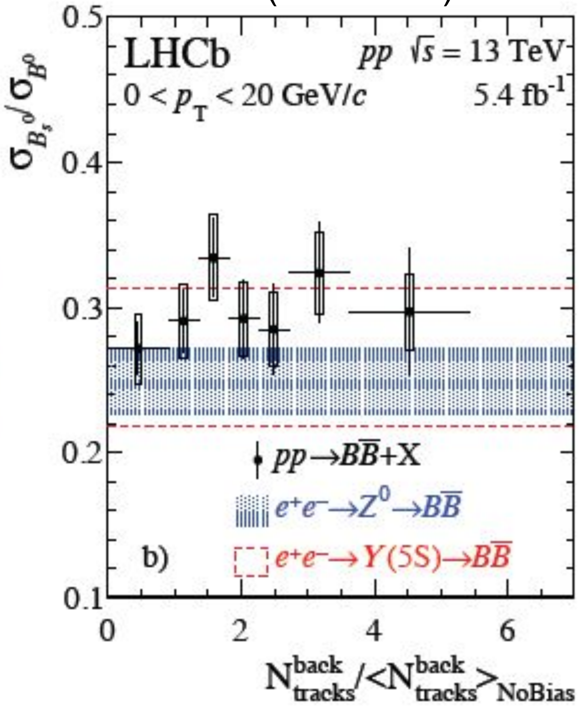
Evolution with event activity in pp: B_s^0/B^0 at forward *y*

C. Gu, Tuesday

All VELO tracks



Only backward VELO tracks (far from B)



LHCb, arxiv 2204.13042

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

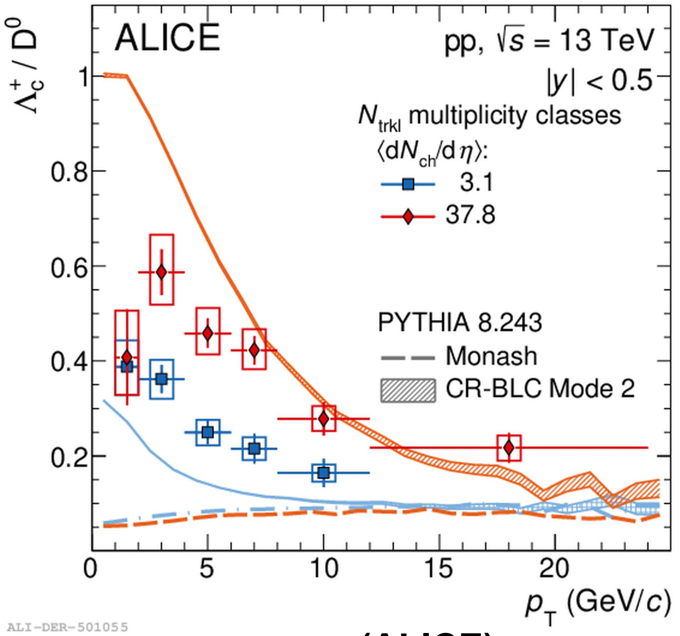
- Stronger than PYTHIA expectation at low p_T
- Not observed when multiplicity estimated far from B mesons

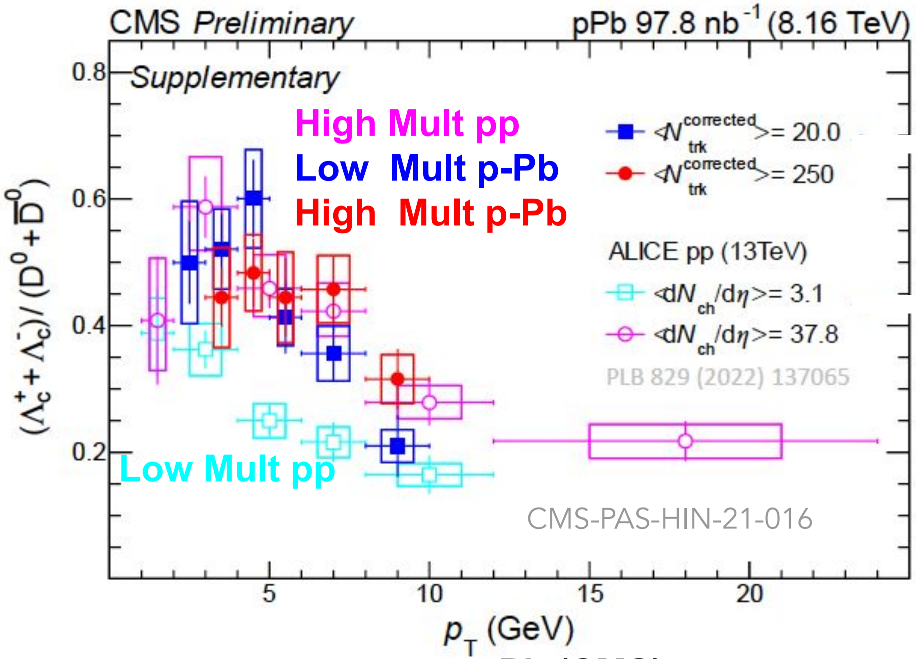
N.B. D_s^+/D^0 at mid-*y* not increasing with multiplicity (backup)

Evolution with event activity in pp and p-Pb: Λ_c^+/D^0

Y. Zhang, Tuesday

PLB 829 (2022) 137065





pp (ALICE):

Λ_c^+/D^0 increases with multiplicity from p_T>2 GeV/c

Qualitatively reproduced by **PYTHIA8 with CR-BLC**

→ interplay of CR and MPI

p-Pb (CMS):

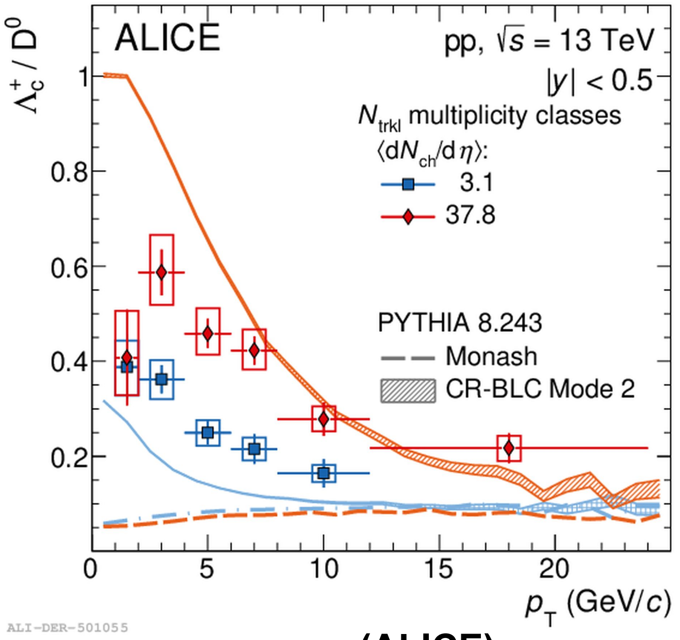
Λ_c^+/D^0 does not evolve significantly with multiplicity

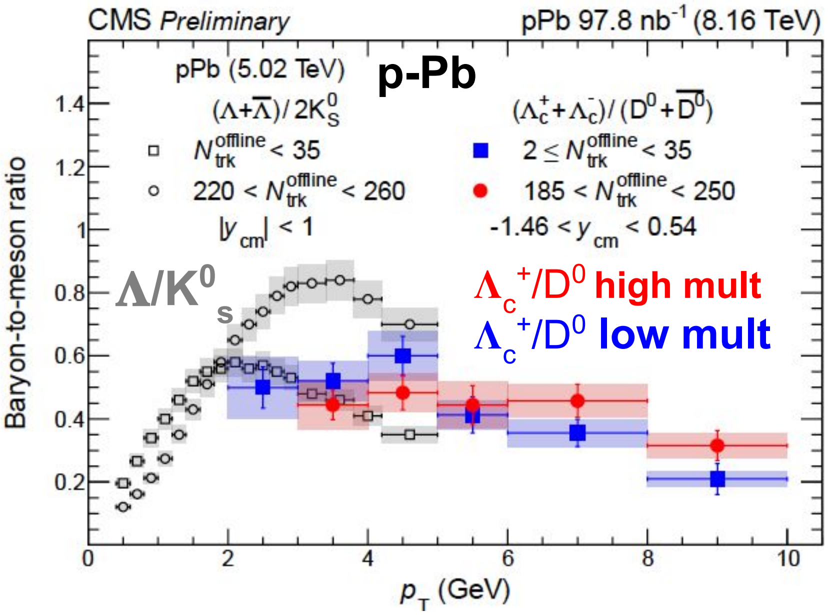
Close to ALICE pp high-multiplicity data

Evolution with event activity in pp and p-Pb: Λ_c^+/D^0

Y. Zhang, Tuesday

PLB 829 (2022) 137065





pp (ALICE):

Λ_c^+/D^0 increases with multiplicity from p_T>2 GeV/c

Qualitatively reproduced by **PYTHIA8 with CR-BLC**
→ interplay of CR and MPI

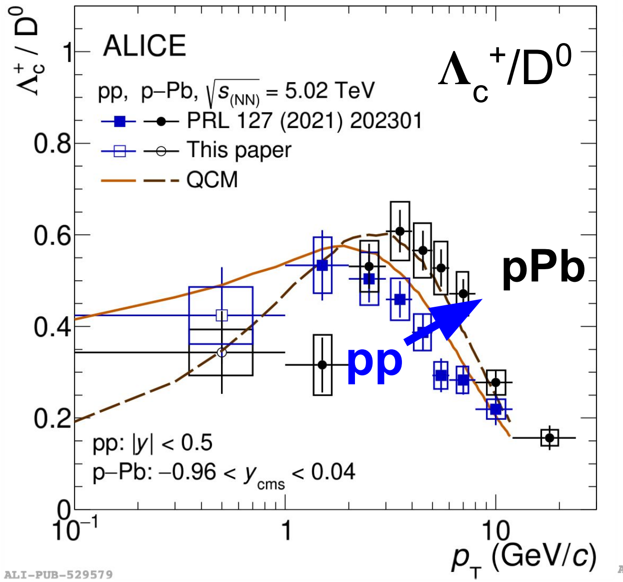
p-Pb (CMS):

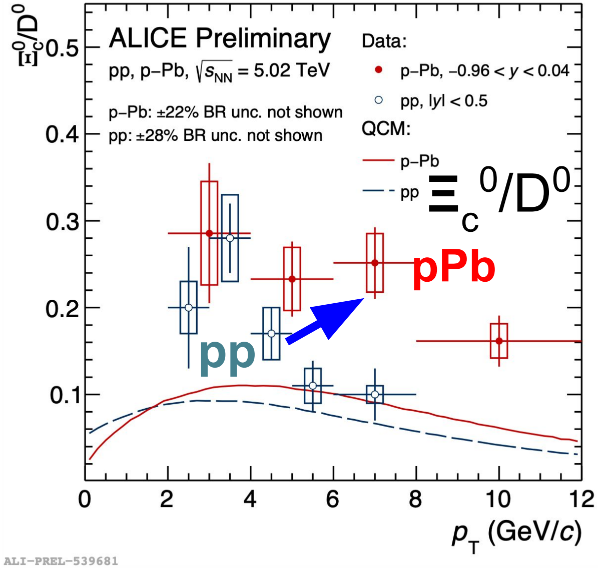
Λ_c^+/D^0 does not evolve significantly with multiplicity
Close to ALICE pp high-multiplicity data
Breaking the similarity with Λ/K^0_s observed in pp (see backup)

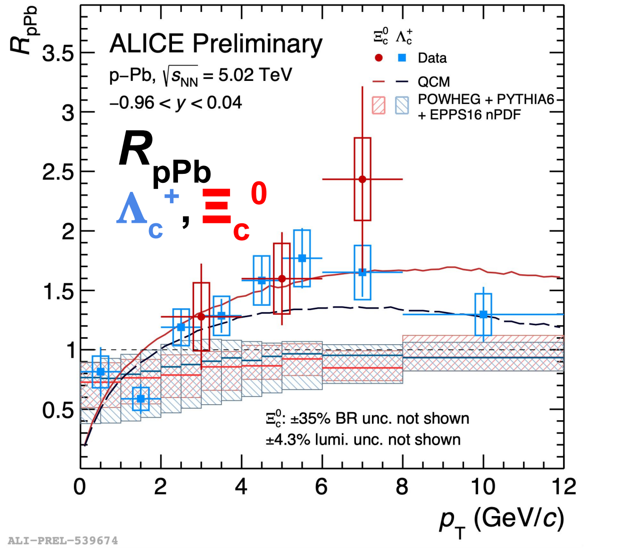
Evolution with event activity: pp vs. p-Pb

PRC 104 054905 (2021) , PRL 127 202301 (2021), arxiv 2211.14032

R. Litvinov, Tuesday
A. S. Kalteyer Tuesday





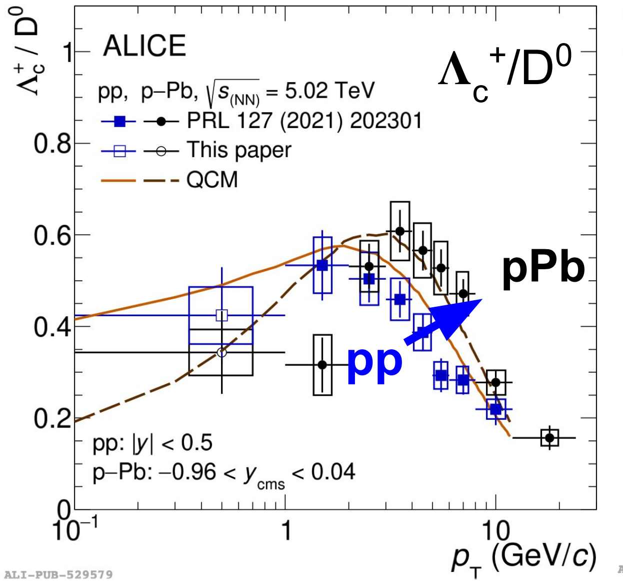


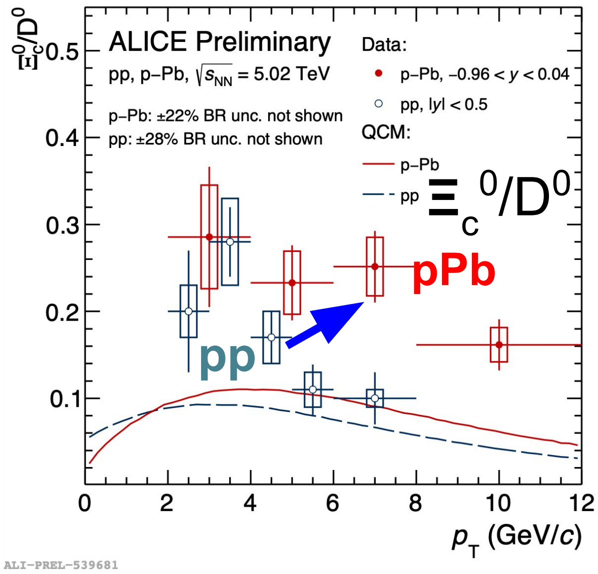
- Similar push towards higher p_T of Λ_c^+/D^0 and Ξ_c/D^0 ratio from pp to p-Pb?
  - R_{pPb} described by QCM within uncertainties QCM: PRC 97 064915 (2018)

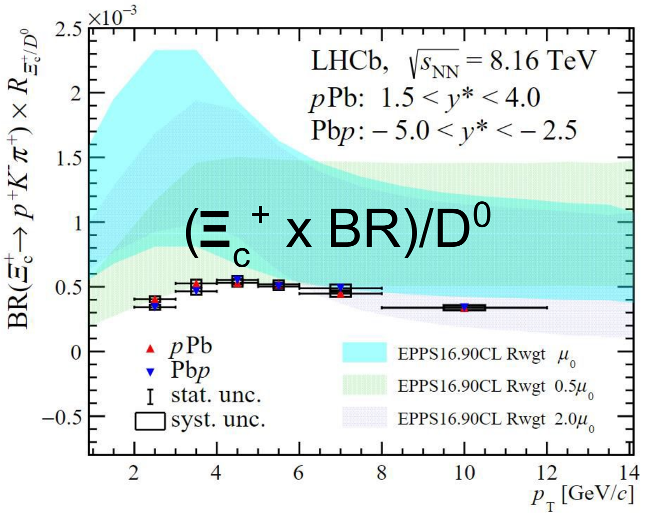
Evolution with event activity: pp vs. p-Pb

R. Litvinov, Tuesday
A. S. Kalteyer Tuesday

PRC 104 054905 (2021) , PRL 127 202301 (2021), arxiv 2211.14032

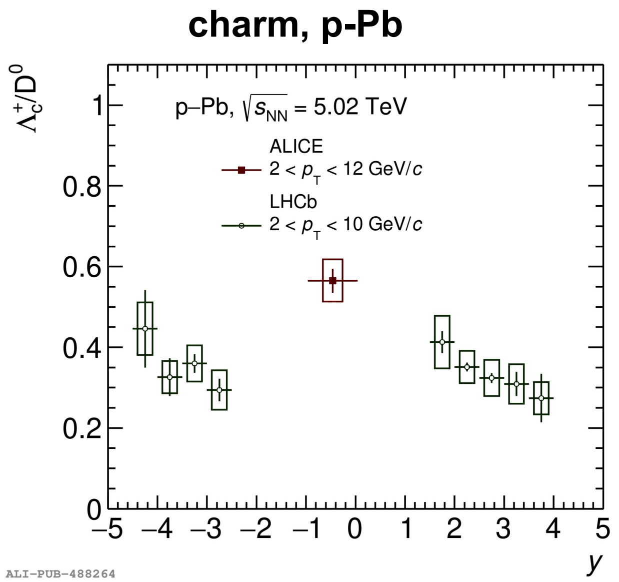






- Similar push towards higher p_T of Λ_c^+/D^0 and Ξ_c/D^0 ratio from pp to p-Pb
  - R_{pPb} described by QCM within uncertainties QCM: PRC 97 064915 (2018)
- Branching ratio (and data) uncertainties limit comparison of ALICE and LHCb data, useful to study rapidity dependence

Rapidity dependence



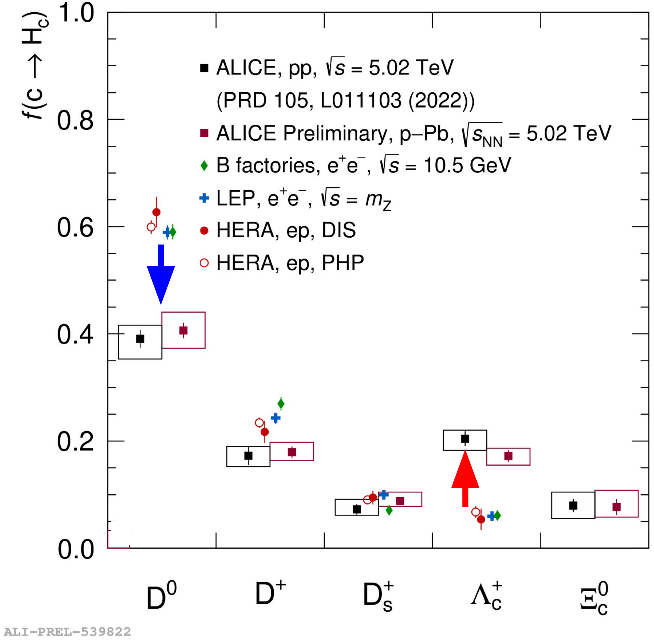
Possible trend, to be revisited with run 3 data (also in pp)?

What should we expect in coalescence models and SHM? Flat?

ALICE, JHEP 04 (2018) 108
ALICE, PRC 104 054905 (2021)
LHCb (pp), Nucl.Phys.B 871 (2013)
LHCb (p-Pb), JHEP 02 102 (2019)

Fragmentation fractions from all ground-state baryons

PRD 105 (2022) 1, L011103, arxiv 2211.14032



Direct measurement of all ground-state baryons
(Ξ_c^+ similar to Ξ_c^0, checked at 13 TeV)
→ new Fragmentation Fractions

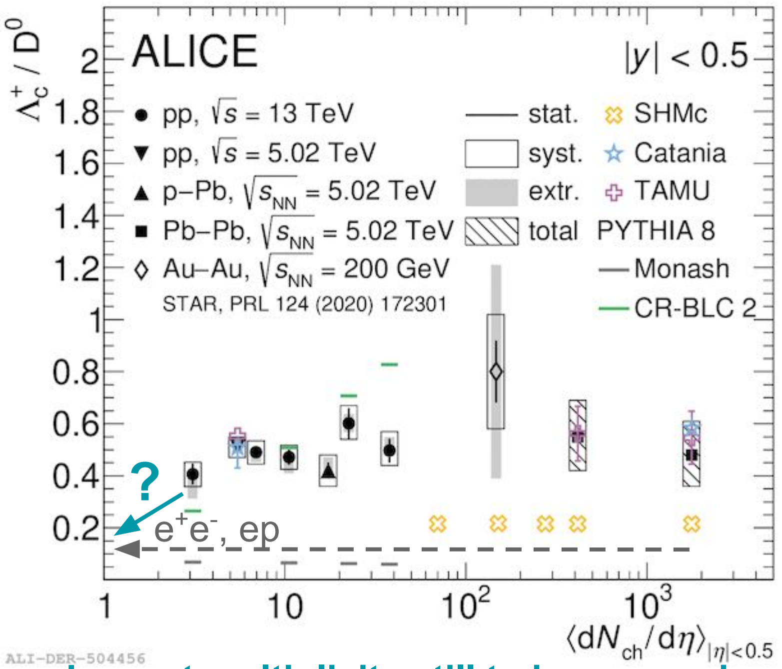
Large increase for c→ Λ_c^+ and c→Ξ_c^0 w.r.t e^+e^-

More than 1/3 of charm quarks go to baryons!

No significant modification of p_T-integrated yield ratios from pp to p-Pb

Λ_c^+/D^0 from pp to central AA: 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.

Data uncertainty large

Significantly higher values than e^+e^-

STAR Au-Au data compatible with ALICE

PYTHIA8 CR-BLC expects increase with multiplicity

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

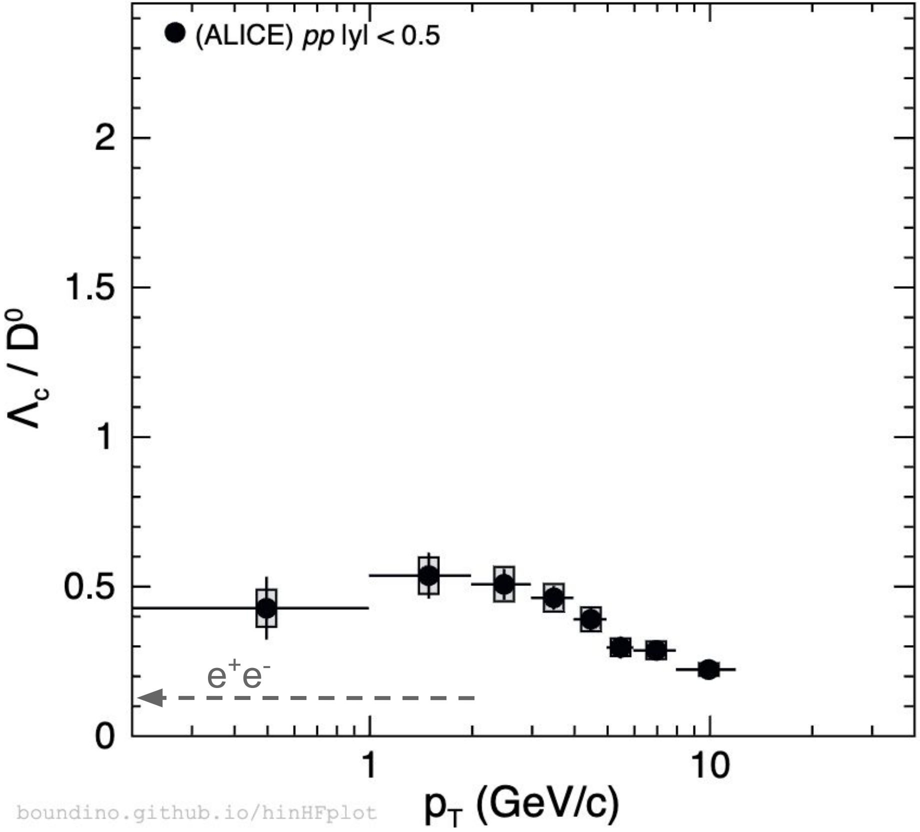
TAMU, Catania: similar values in pp and Pb–Pb

Lowest multiplicity still to be covered: recover e^+e^-?

→ more precise measurements from LHC new runs awaited

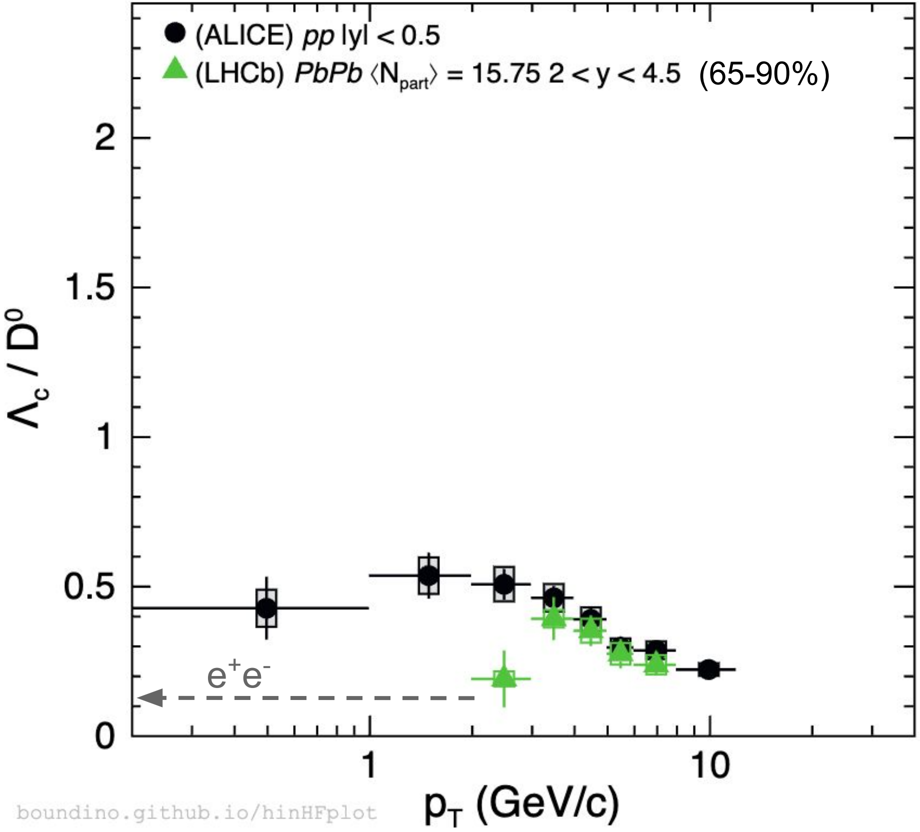
Λ_c^+/D^0 from pp to central AA: p_T-differential

A. S. Kalteyer Tuesday



Λ_c^+/D^0 from pp to central AA: p_T-differential

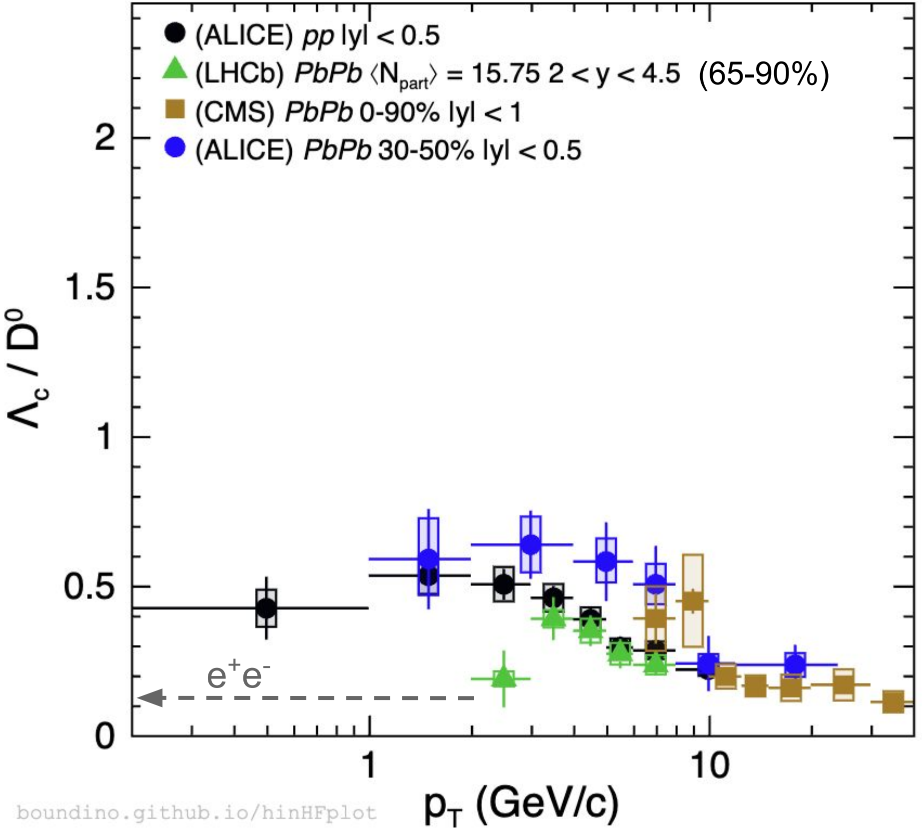
A. S. Kalteyer Tuesday
R. Litvinov, Tuesday



boundino.github.io/hinHFplot

Λ_c^+/D^0 from pp to central AA: p_T-differential

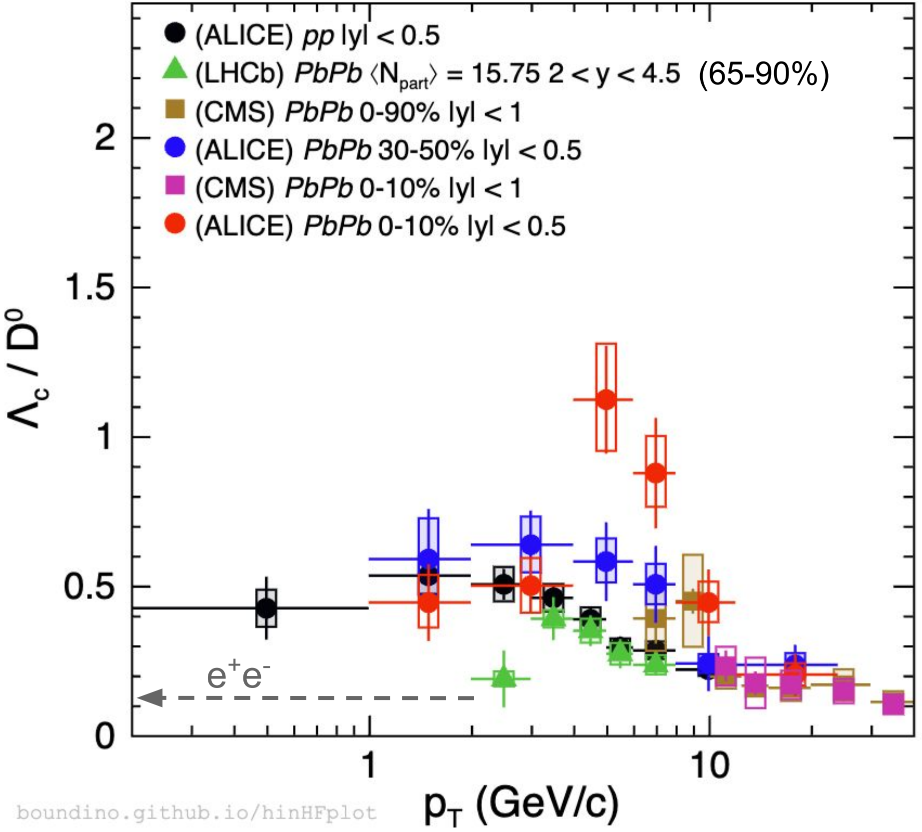
A. S. Kalteyer Tuesday
R. Litvinov, Tuesday
S. Chandra, M. Stojanovic, Poster



boundino.github.io/hinHFplot

Λ_c^+/D^0 from pp to central AA: p_T-differential

A. S. Kalteyer Tuesday
R. Litvinov, Tuesday
S. Chandra, M. Stojanovic, Poster



boundino.github.io/hinHFplot

Significant evolution of p_T-differential yield ratio

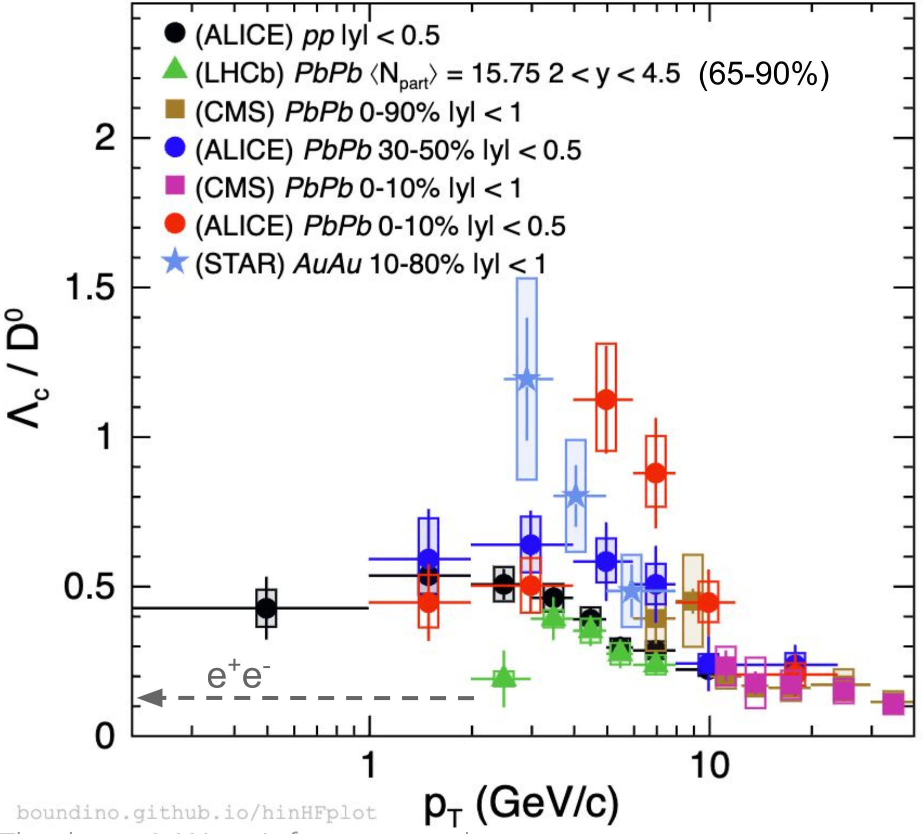
Biggest jump from e^+e^- to pp

"Radial-flow" like peak ← coalescence?

ALICE pp, PRL 127 (2021) 202301
LHCb Pb-Pb, arXiv:2210.06939
CMS Pb-Pb, CMS-PAS-HIN-21-004
ALICE Pb-Pb, arXiv:2112.08156

Λ_c^+/D^0 from pp to central AA: p_T-differential

A. S. Kalteyer Tuesday
R. Litvinov, Tuesday
S. Chandra, M. Stojanovic, Poster



Thanks to J. Wang's fantastic tool

Significant evolution of p_T-differential yields

Biggest jump from e^+e^- to pp

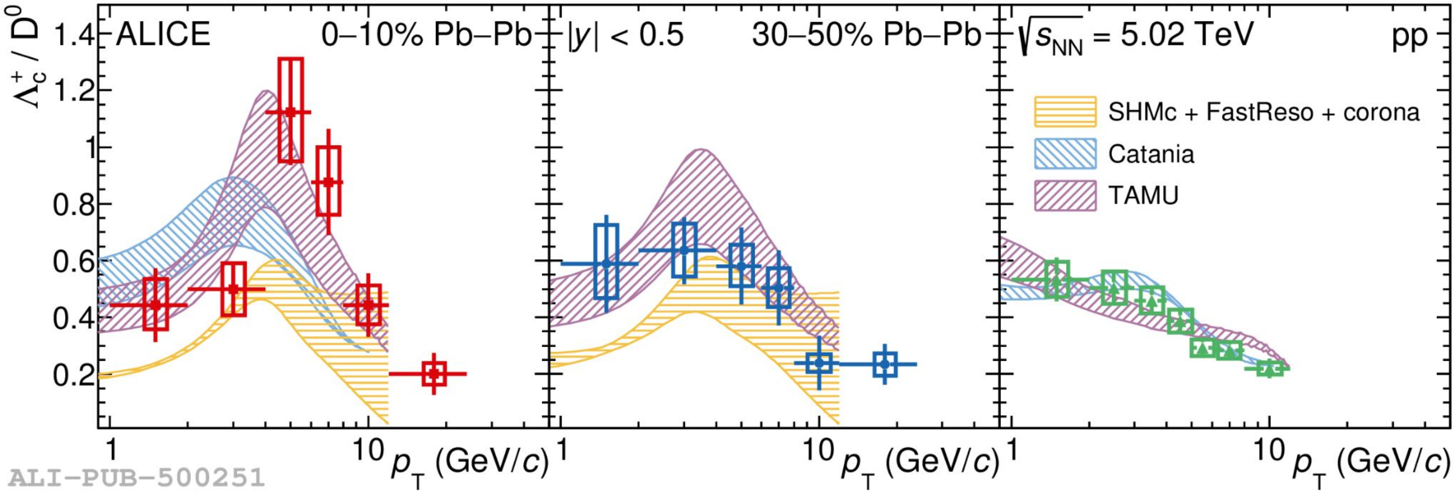
"Radial-flow" like peak ← coalescence?

Large ratio also at STAR, "shifted" in p_T w.r.t. LHC

ALICE pp, PRL 127 (2021) 202301
LHCb Pb-Pb, arXiv:2210.06939
CMS Pb-Pb, CMS-PAS-HIN-21-004
ALICE Pb-Pb, arXiv:2112.08156
STAR Au-Au, PRL 124 (2020) 172301

Λ_c^+/D^0 in Pb-Pb vs. models

arxiv 2112.08156



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

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

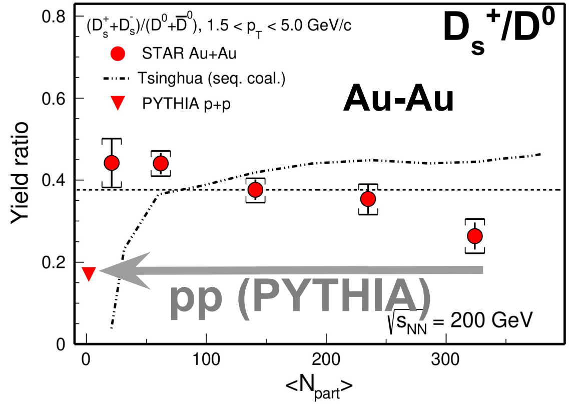
SHMc + FastReso + corona tends to underestimate data

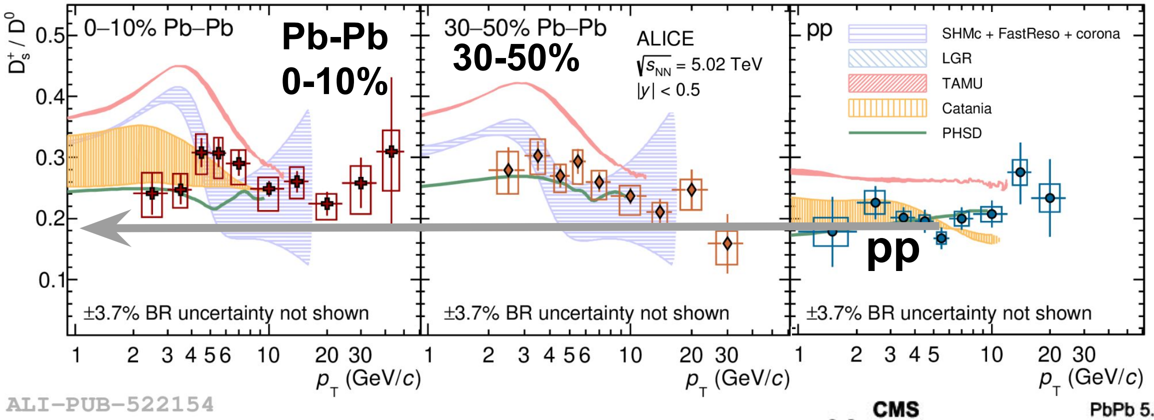
Important specific constraints to model features (hadronisation, space-momentum correlations) needed to describe D meson flow and R_{AA}

More in Beraudo's talk (next one!)

D_s^+ and B_s^0 in nucleus-nucleus collisions

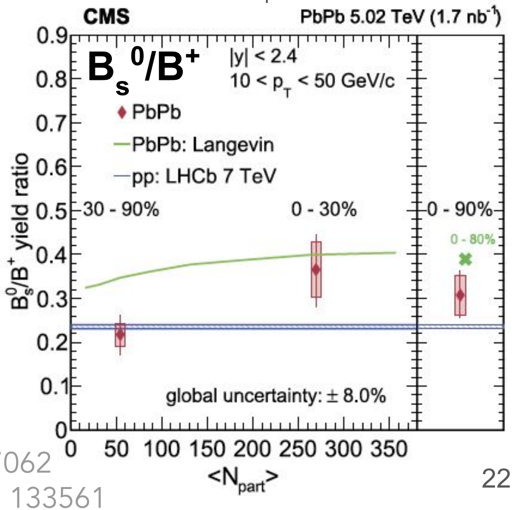
Tzu-An Sheng, Thursday





Indication of higher D_s^+/D^0 ratio in Au–Au at RHIC and Pb–Pb at LHC w.r.t. pp

Also hint for higher B_s^0/B^+ at the LHC



More data needed to extend at lower p_T

Awaiting Ξ_c in Pb–Pb!

STAR, PRL 127 092301 (2021)
Tsinghua, arxiv 1805.10858, Springer Proc. Phys. 250 (2020) 275-278

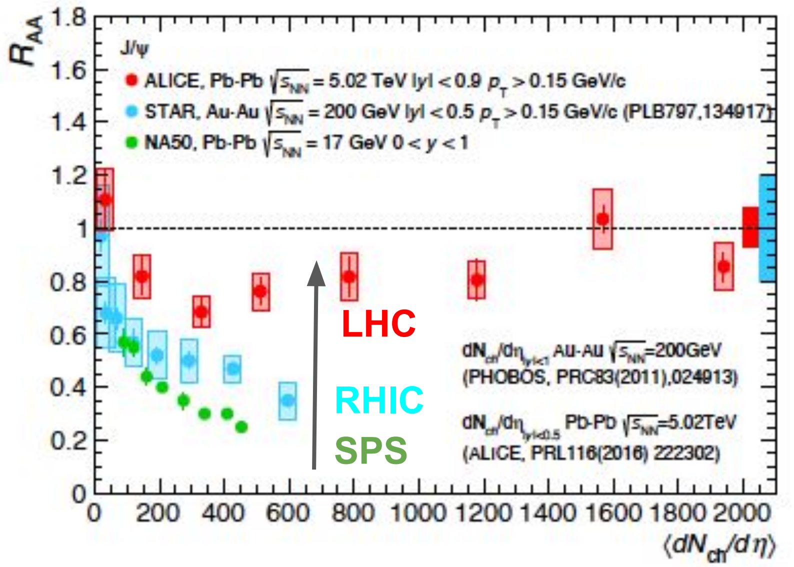
ALICE, PLB 827 (2022) 136986
SHMc, JHEP 07 035 (2021)
LGR, EPJC 80 671 (2020)
PHSD, PRC 92, 014910 (2015)
TAMU: PRL 124, 042301 (2020)
Catania: EPJC 78, 348 (2018)

CMS, PLB 829 (2022) 137062
Langevin: PLB 807 (2020) 133561

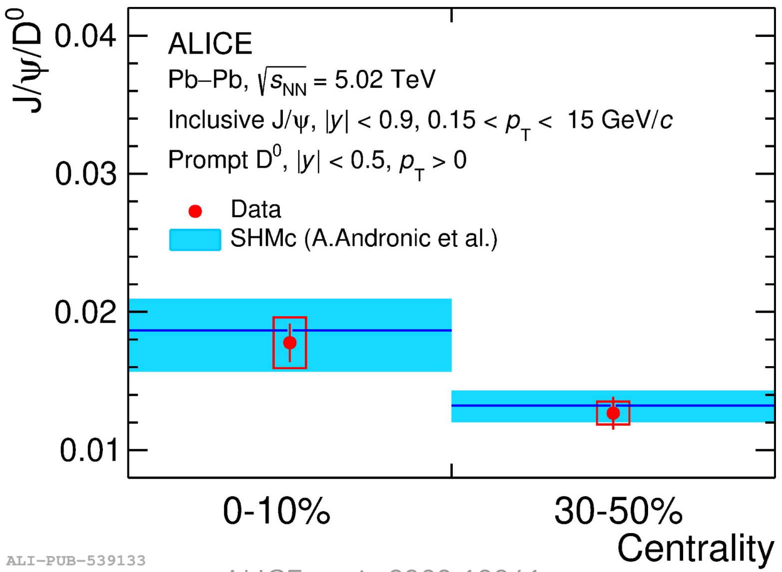
Quarkonia regeneration

→ **K. Smith, M. Espinosa, this morning**
Pengzhong Lu,Tuesday

- Debye screening & dynamic dissociation → loss of initial $Q\overline{Q}$ colour connection & suppression
- **Regeneration via recombination**
  - **J/ψ in line with statistical hadronisation model expectation at LHC energies**



ALICE, arxiv:2211.04384

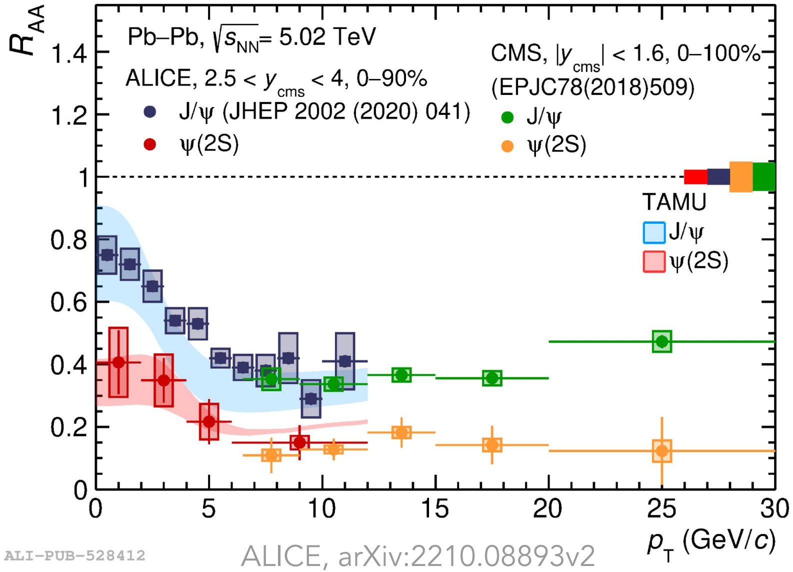


ALICE, arxiv:2303.13361

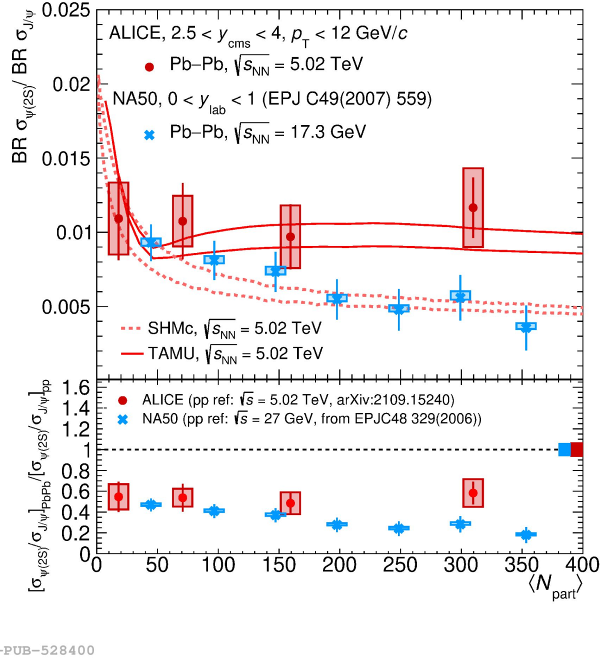
Quarkonia regeneration

V. Feuillard, Thursday

- Debye screening & dynamic dissociation → loss of initial $Q\bar{Q}$ colour connection & suppression
- **Regeneration via recombination**
  - J/ψ in line with statistical hadronisation model expectation at LHC energies
  - **relevant also for low-p_T ψ(2S)**
    - Data described by TAMU transport model, SHMc tends to underestimate ψ(2S)/J/ψ ratio in central collisions



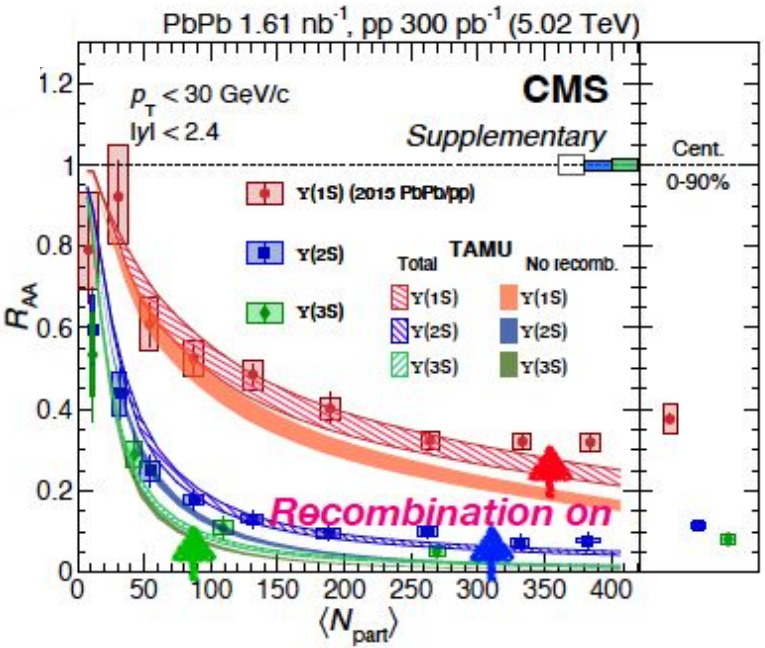
ALICE, arXiv:2210.08893v2



Quarkonia regeneration

JaeBeom Park, Tuesday

- Debye screening & dynamic dissociation → loss of initial $Q\overline{Q}$ colour connection & suppression
- **Regeneration via recombination**
  - J/ψ in line with statistical hadronisation model expectation at LHC energies
  - relevant also for low-p_T ψ(2S)
    - Data described by TAMU transport model, SHMc tends to underestimate ψ(2S)/J/ψ ratio in central collisions
  - **relevant also for bottomonia?**



CMS, HIN-21-007

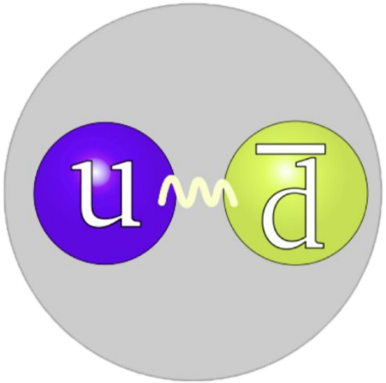
TAMU: PRC 96 (2017) 054901

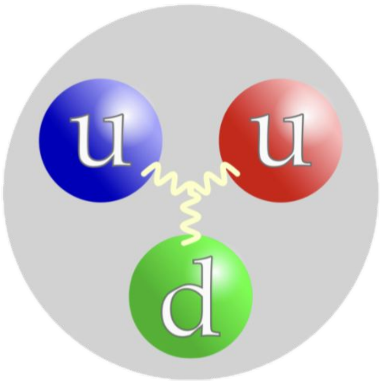
Exotic states → **K. Smith, this morning**

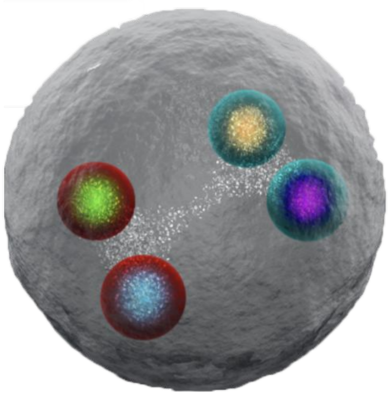
Understanding "exotic"-state production yields and formation mechanism

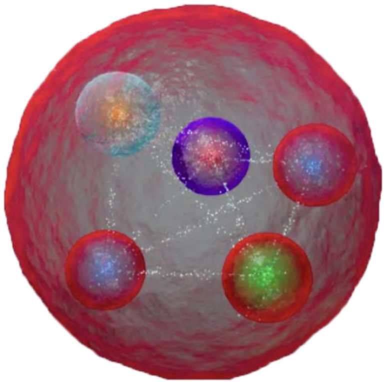
Understanding their nature
- Compact objects (tetra/pentaquarks)
- Meso-barionic molecules
- Hybrid..

Insight into hadronisation processes in different collision systems





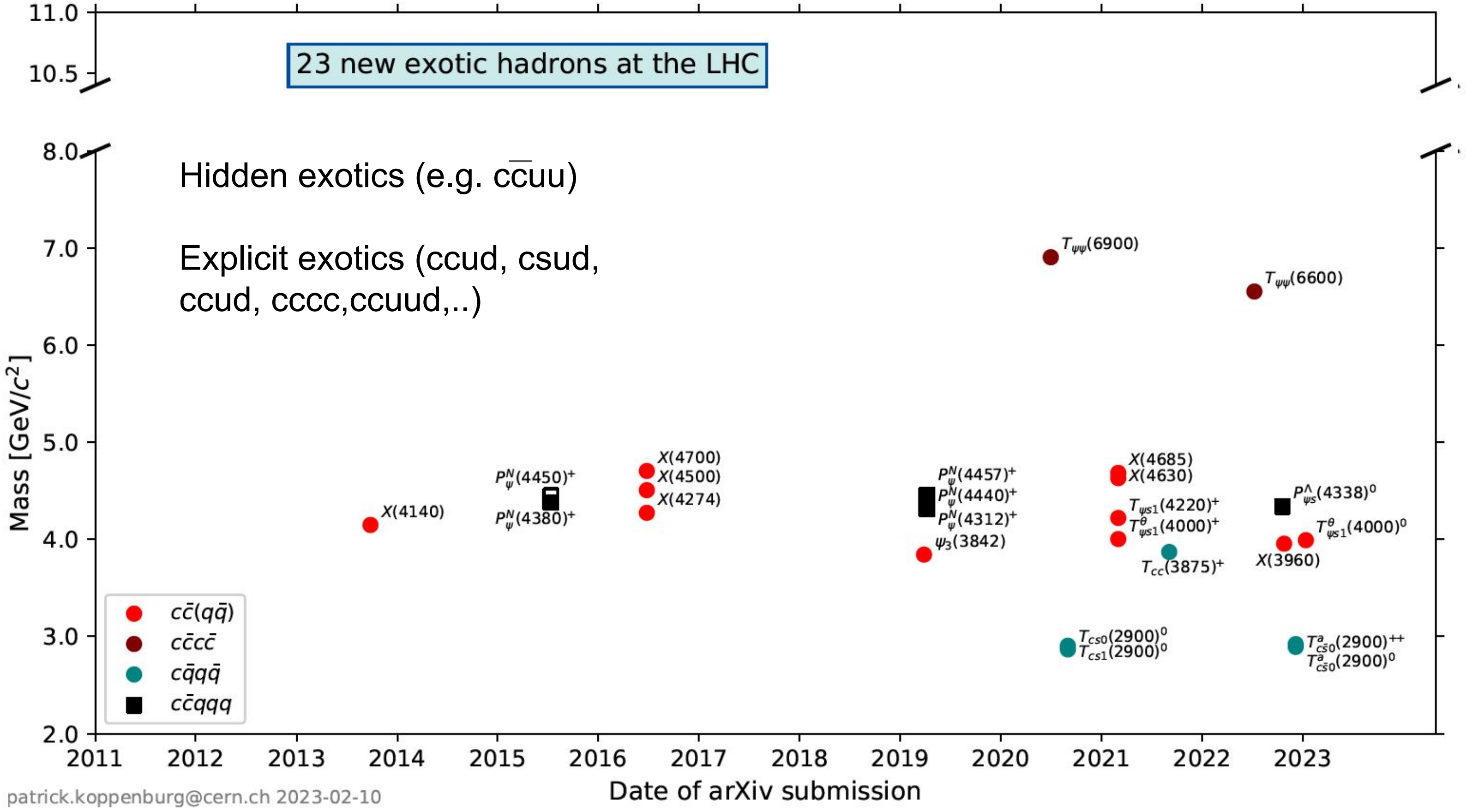




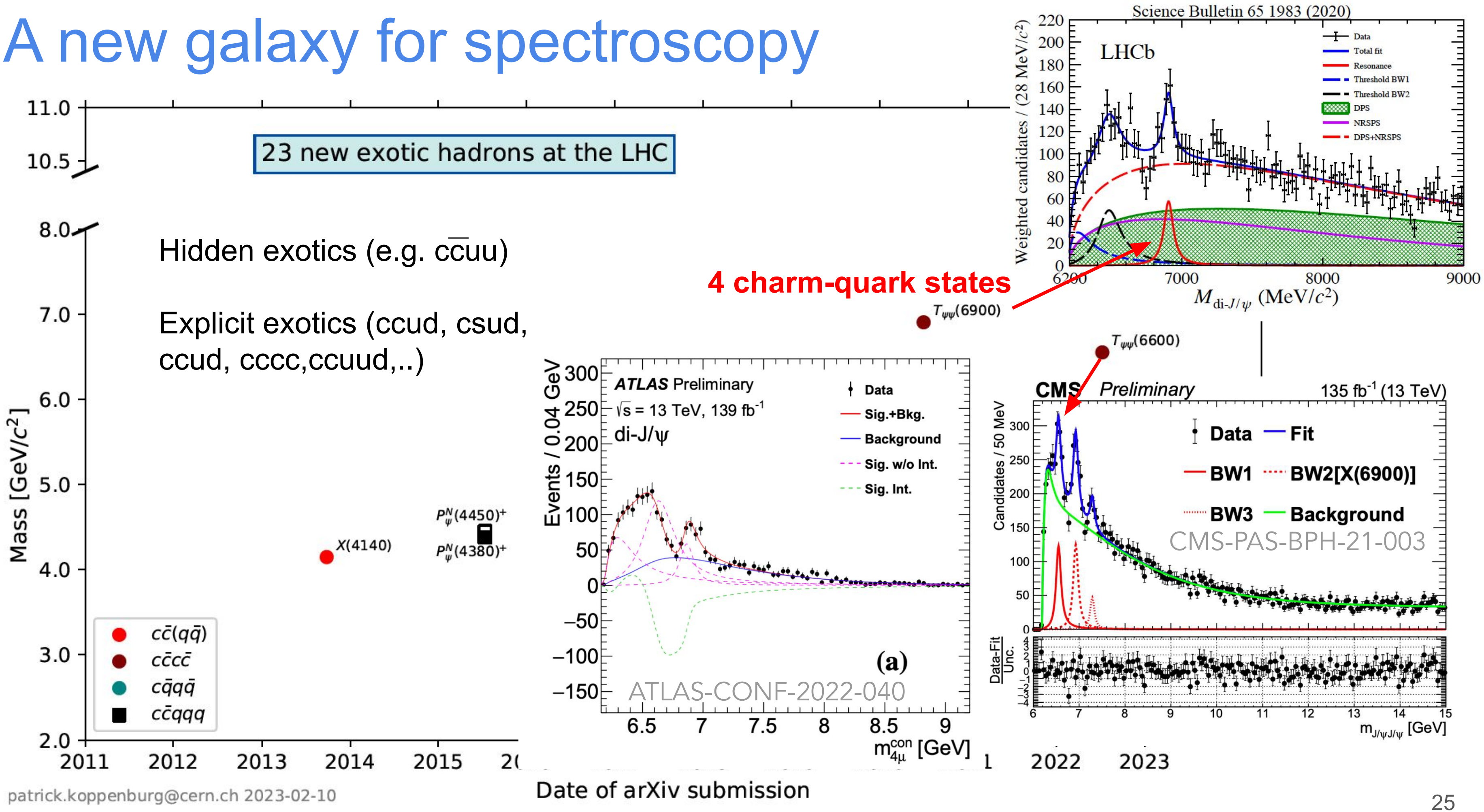
A new galaxy for spectroscopy

Hidden exotics (e.g. $c\bar{c}uu$)

Explicit exotics (ccud, csud, ccud, cccc,ccuud,..)



A new galaxy for spectroscopy

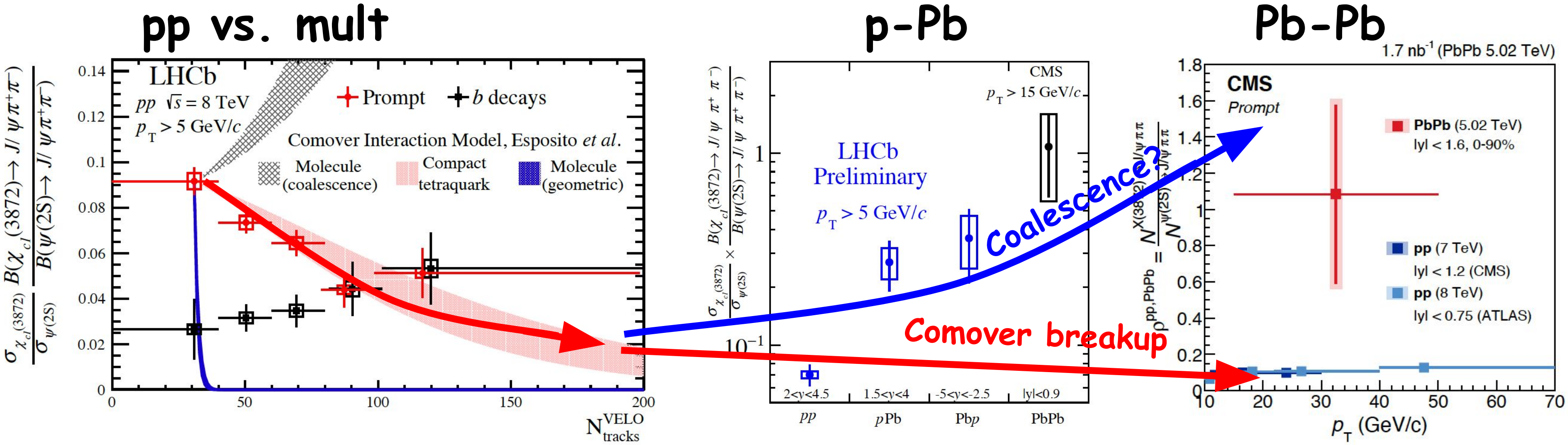


X(3872)/ψ(2S) in different collision systems

C. L. Gomez, Wednesday

CMS, PRL 128 (2022) 032001

LHCb, PRL 126 (2021) 092001



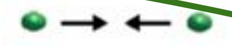
ψ(2S) suppressed in p-Pb and Pb-Pb (R_{AA}~0.1 at high p_T): better to use a different reference?

Coalescence likely to be an important mechanism of X(3872) production in nuclear collisions, compensating breakup from interaction with comovers

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^-

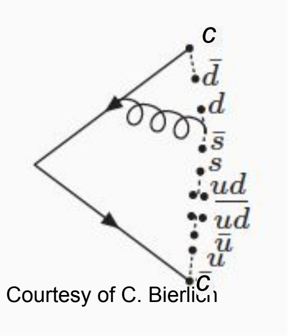
e^+e^- = "vacuum"



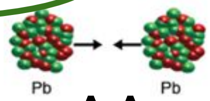
pp
~~not far from vacuum ~ many independent scatterings~~
(for HF at least)

MPI, system size

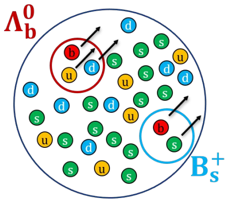
Dynamical model
"Local" dynamical constraints
(e.g. Lund string fragmentation, quarks and diquarks popping out from QCD potential)



Courtesy of C. Bierlich



A-A
Dense, extended-size system
Equilibrium
Flow



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

What's next (and my personal wishlist)

Run 3-4 at the LHC: quantum leap in precision for HF measurements in pp and Pb-Pb
+ Λ_b, Ξ_c in Pb-Pb
+ new measurements of jets and correlations
→ **fundamental tests to constrain models!**

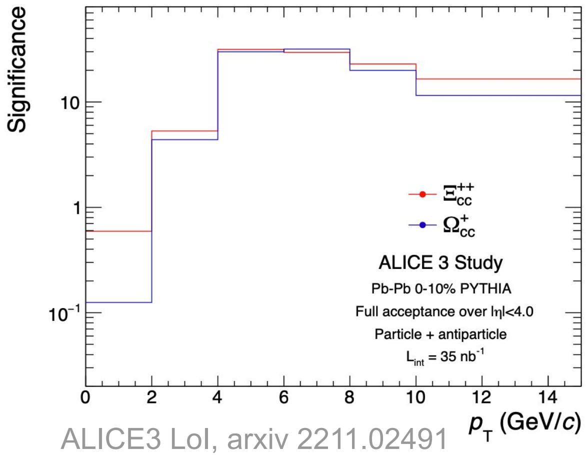
Understand role of diquarks

Not only high multiplicity and nucleus-nucleus:
We need to check if (and "where") we recover LEP!
→ low multiplicity, high p_T

Flow in small systems: what's the role of coalescence?

Spectroscopy & production measurement of excited states

Double charm in AA with ALICE3
… though need to wait beyond run 4
→ Compelling test for coalescence and SHM in Pb-Pb



ALICE3 LoI, arxiv 2211.02491

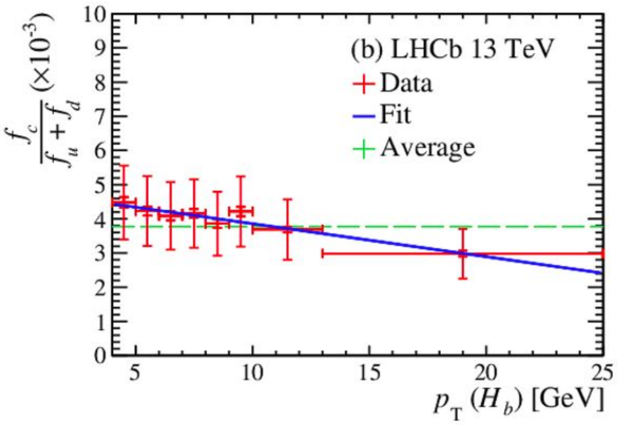
A. Grelli, Tuesday

Extra

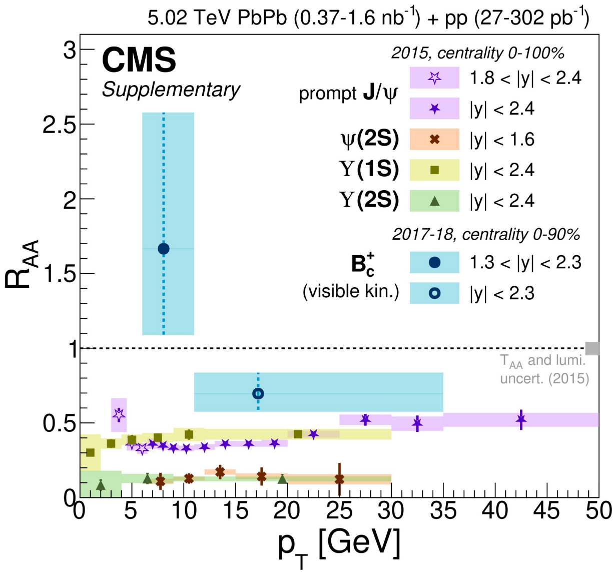
B_c^+ nuclear-modification factor

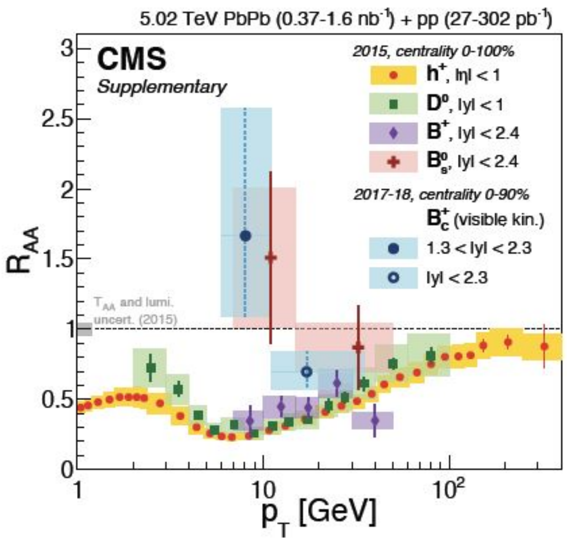
Tzu-An Sheng, Thursday

LHCb, PRD100 (2019) 112006



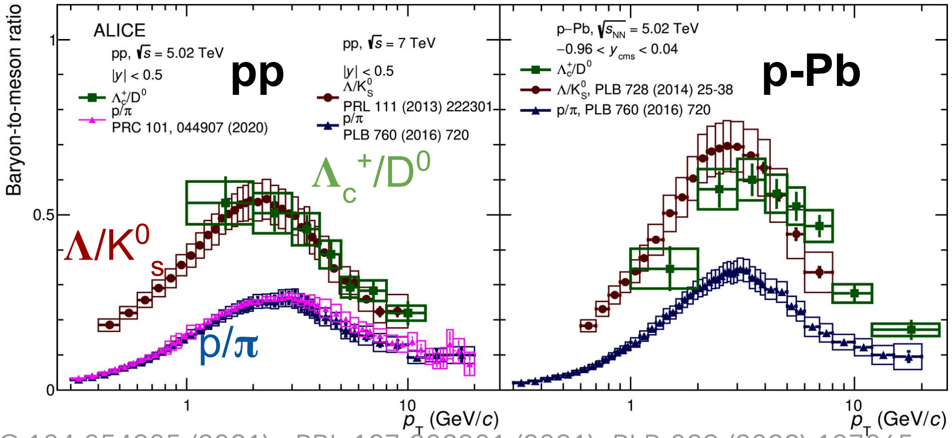
CMS, PRL 128 (2022) 252301



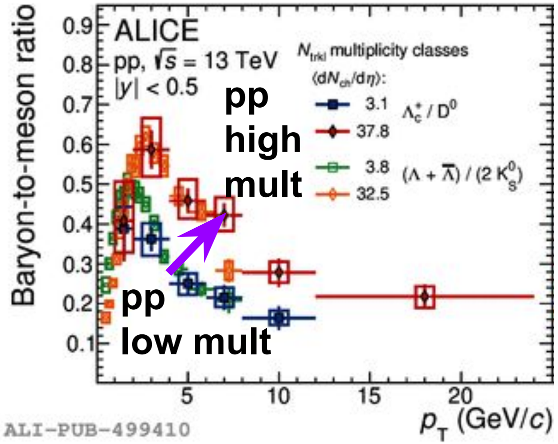


- B_c^+ production in pp not yet theoretically well understood
  - Contribution from **double-parton-scattering possibly large in pp**: U. Egede et al., Eur. Phys. J. C 82, 773 (2022)
- Enhanced in Pb-Pb at low p_T? Less suppressed than other quarkonia?
- Production dominated by recombination in both pp and Pb-Pb?

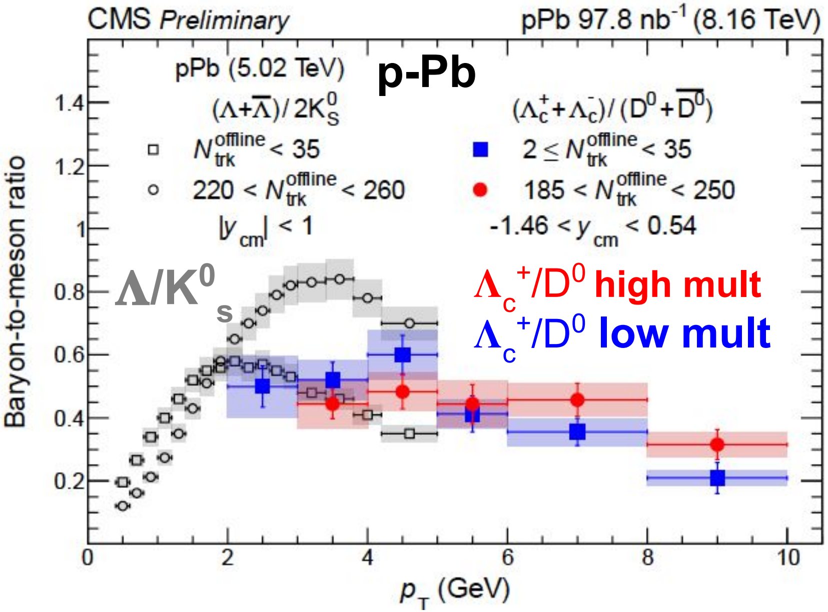
Similarity of charm and light-flavour baryon-to-meson ratios?



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



Y. Zhang, Tuesday



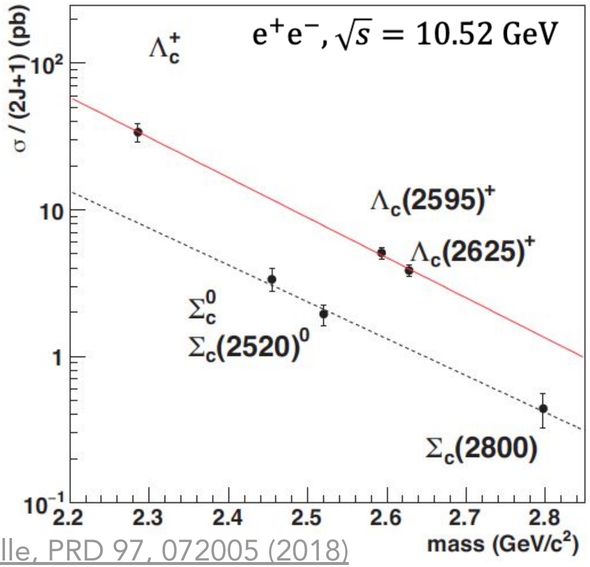
Λ_c/D^0 vs. Λ/K_s^0: **striking similarity in pp collisions**, also vs. multiplicity

Weaker in p-Pb min. Bias

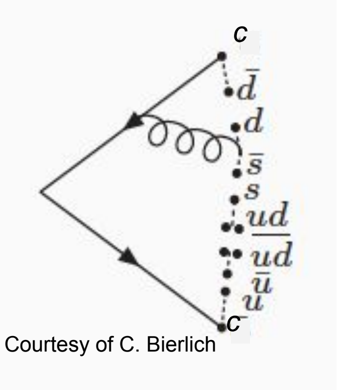
Lost in p-Pb vs. multiplicity with new CMS data

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

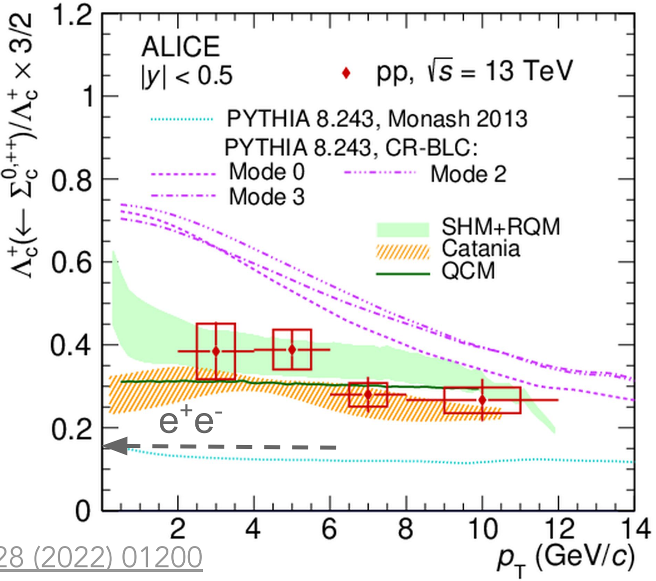
e$^+$e$^-$ collisions



Belle, PRD 97, 072005 (2018)



pp collisions

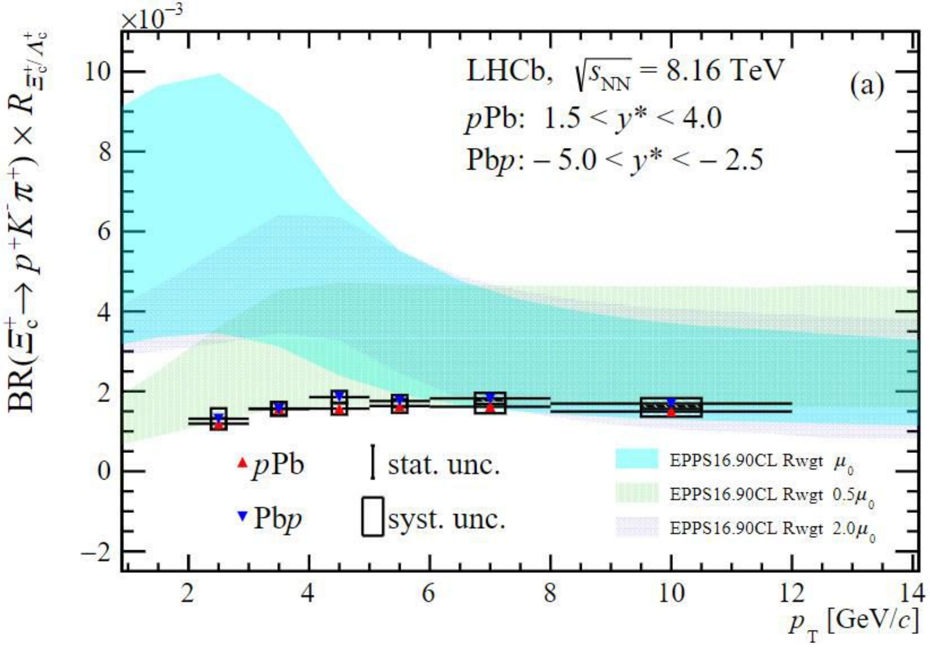


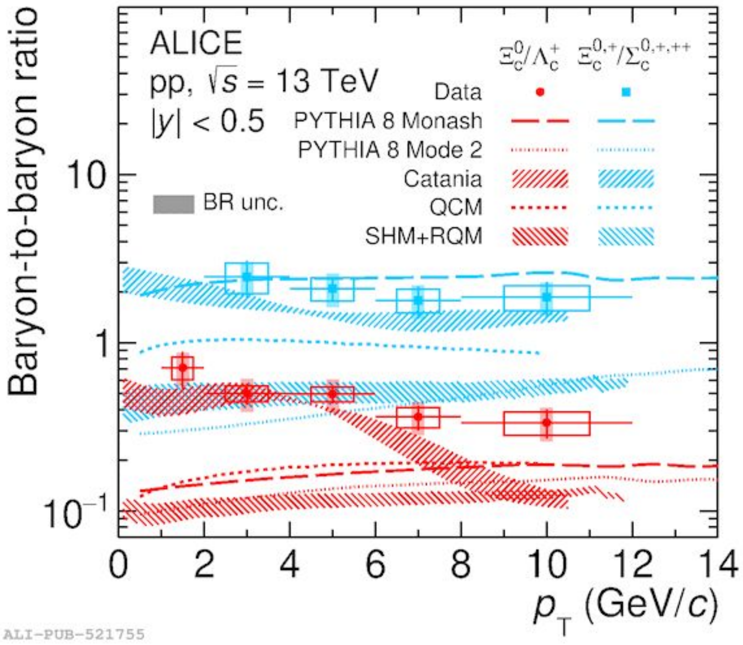
PRL 128 (2022) 01200

Σ_c states suppressed w.r.t. Λ_c states
In string fragmentation: from heavier diquark-antidiquark pair from vacuum
Λ_c (isospin = 0) needs spin = 0 diquark $(ud)_0$
Σ_c (isospin = 1) needs spin = 1 diquark $(ud,dd,uu)_1$ which is heavier than $(ud)_0$

$\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feed-down about twice larger than in e$^+$e$^-$
→ $\Sigma_c^{0,+,++}$ "enhancement" larger than Λ_c^+ one
→ **$\Sigma_c^{0,+,++}$ produced differently in pp than e$^+$e$^-$**
→ **suppression from $(ud,dd,uu)_1$ diquark creation reduced/absent**, as comparison to models suggests

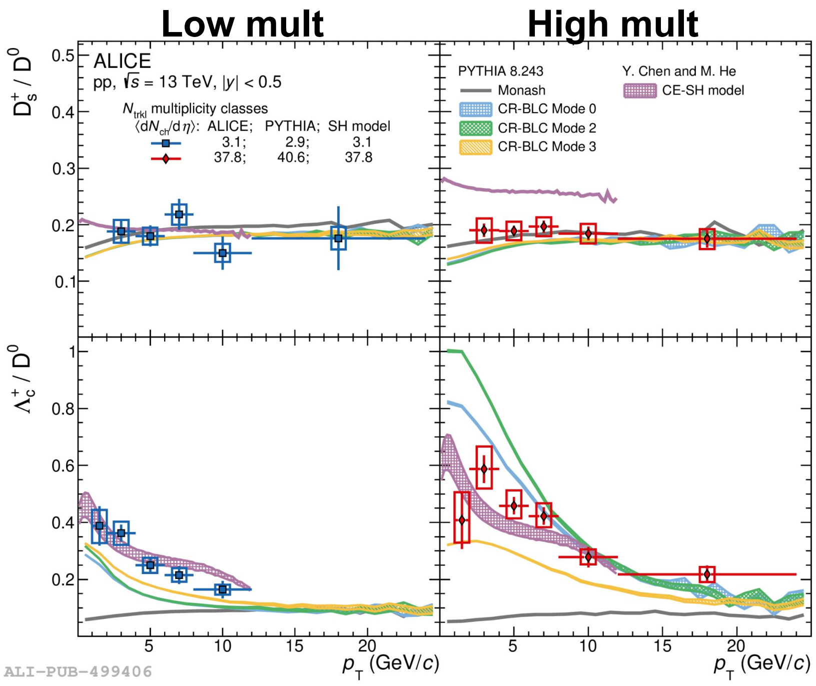
Ξ_c / Λ_c^+ in p-Pb: ALICE vs. LHCb





BR ~0.45%-1.1% → likely LHCb below ALICE

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



D_s^+/D^0 independent from multiplicity

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

Trends qualitatively reproduced by **PYTHIA8 with CR-BLC** → interplay of Color Reconnection (CR) and Multiple Parton Interactions

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

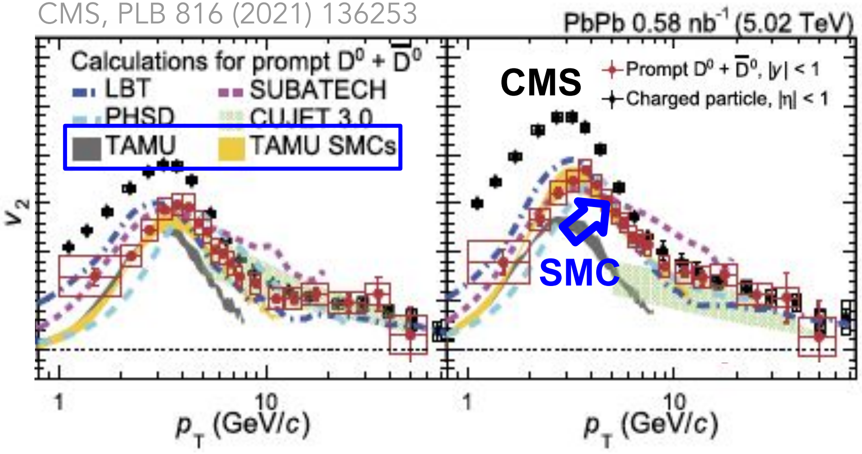
PLB 829 (2022) 137065, https://arxiv.org/abs/2111.11948

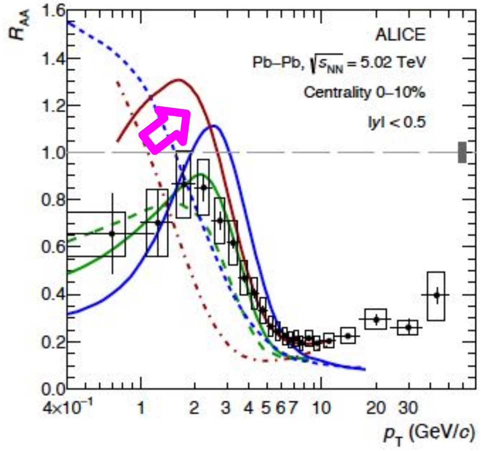
Hadronisation impact on D meson R_{AA} and flow

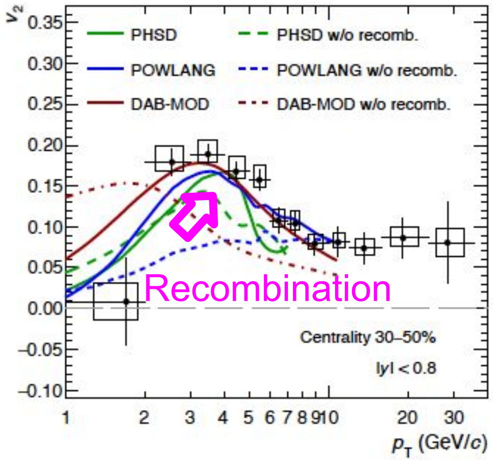
More in Beraudo's talk (next one!)

ALICE, JHEP 01 (2022) 174

CMS, PLB 816 (2021) 136253







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

- Recombination
- Medium expansion
  - Space-momentum correlations (TAMU SMCs vs. TAMU)

Interplay of hadronisation with medium expansion

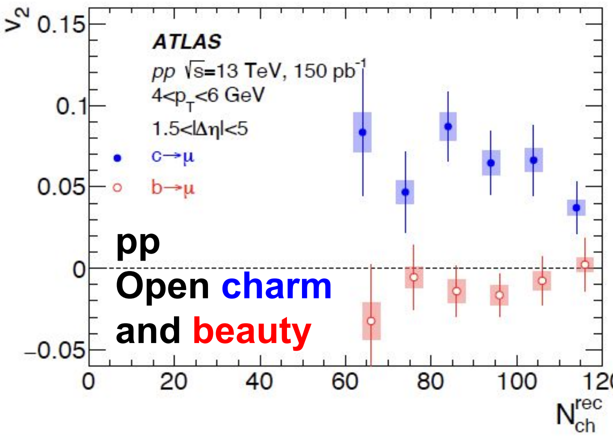
N.B. Hadronic phase expected to have small impact (models, femtoscopy data)

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)

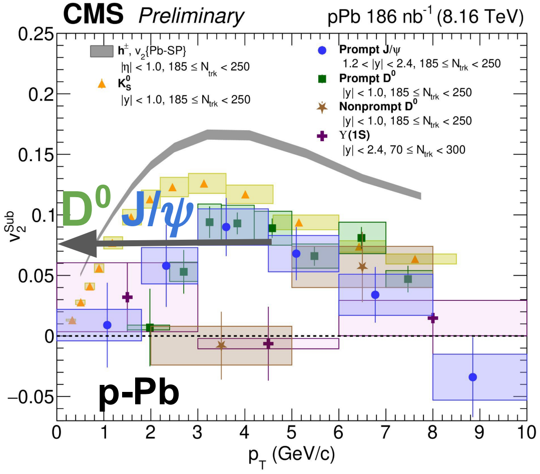
Charmonia and open HF flow in small systems

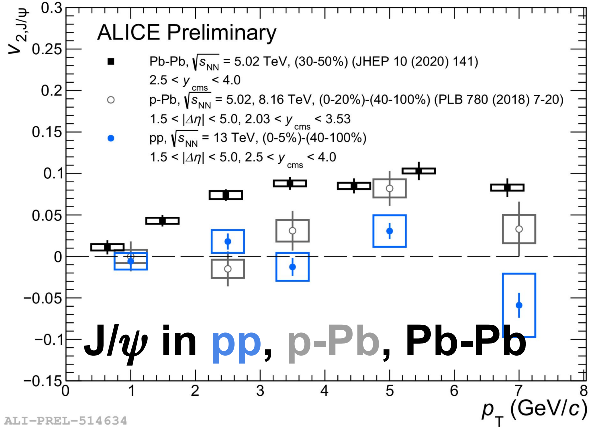
K. Lee, Tuesday

ATLAS, PRL 124 (2020) 082301



CMS-PAS-HIN-21-001





Does coalescence contribute to open HF flow in small systems as a result of charm recombination with flowing light quarks?

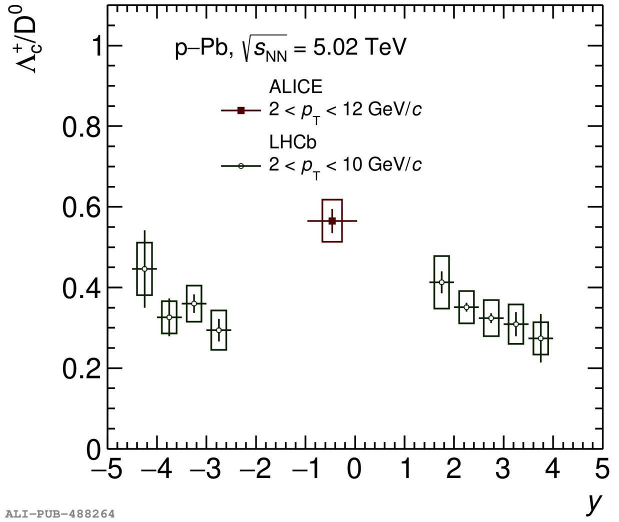
However, also J/ψ flows in p-Pb collisions… also other effects needed

Evolution of charm and beauty flow across collision systems can set important constraints to hadronisation

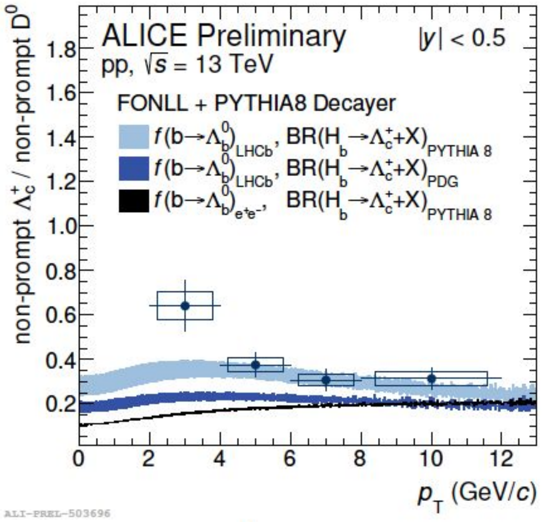
Rapidity dependence

A. S. Kalteyer, Tuesday

charm, p-Pb



beauty, pp



Possible trend, to be revisited with run 3 data (also in pp)?

Beauty: non-prompt Λ_c^+ ALICE data consistent with LHCb Λ_b^0 data
→ low p_T region to be explored with run 3 data

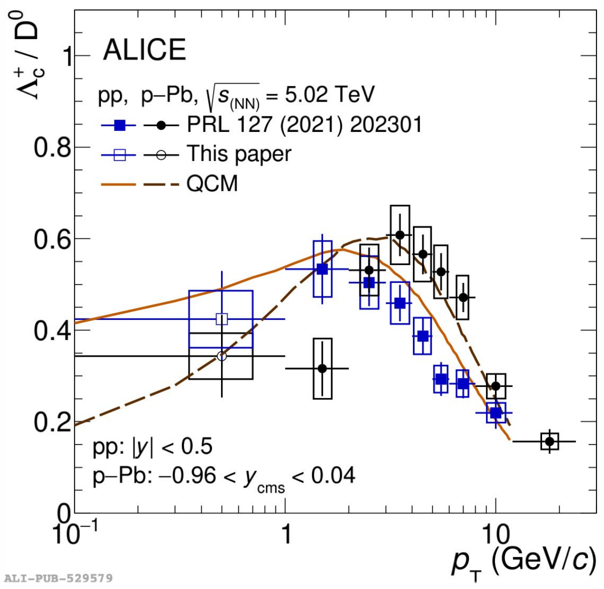
What should we expect in coalescence models and SHM? Flat?

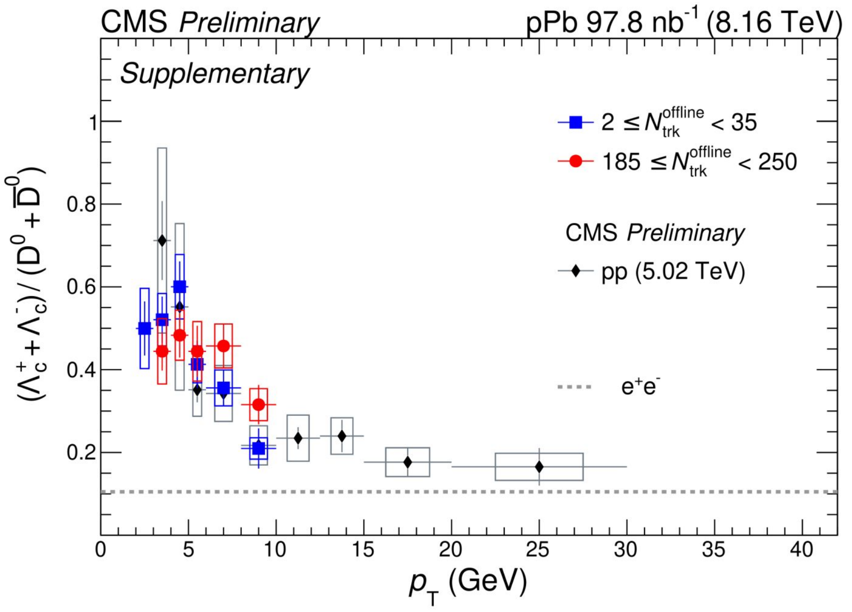
ALICE, JHEP 04 (2018) 108
ALICE, PRC 104 054905 (2021)
LHCb (pp), Nucl.Phys.B 871 (2013)
LHCb (p-Pb), JHEP 02 102 (2019)

Evolution with event activity: pp vs. p-Pb

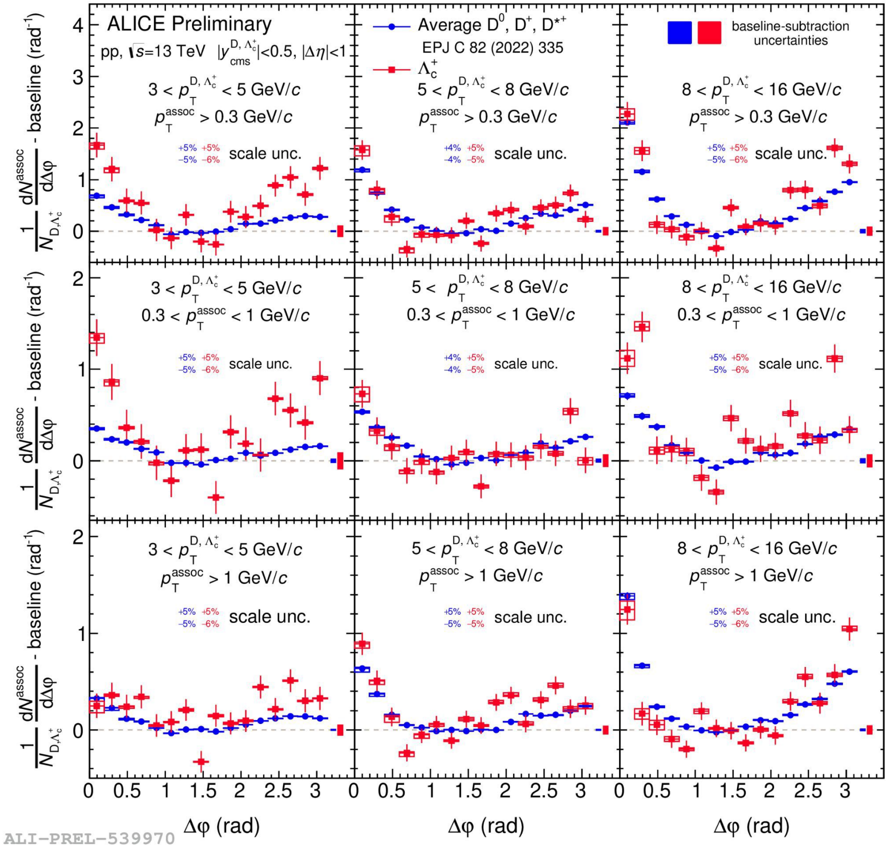
R. Litvinov, Tuesday
A. S. Kalteyer, Wednesday

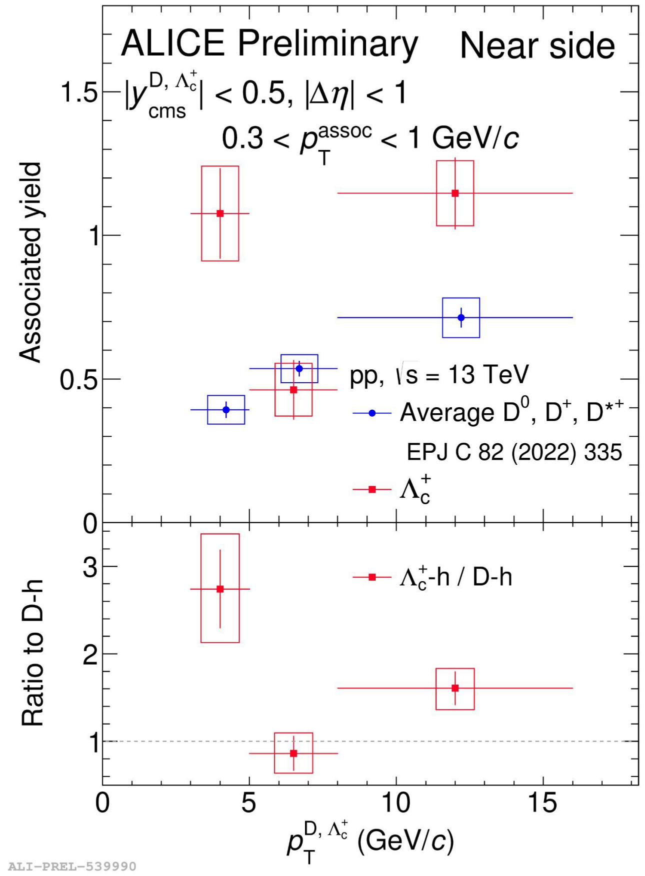
PRC 104 054905 (2021) , PRL 127 202301 (2021), arxiv 2211.14032



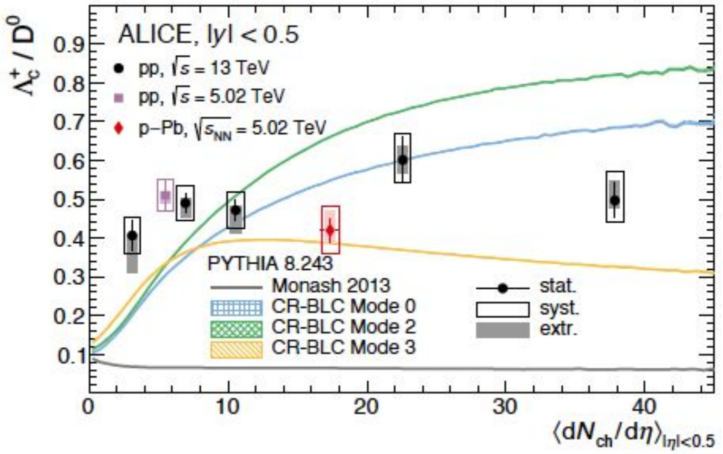


Azimuthal correlations: Λ_c^+-h vs. D-h





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

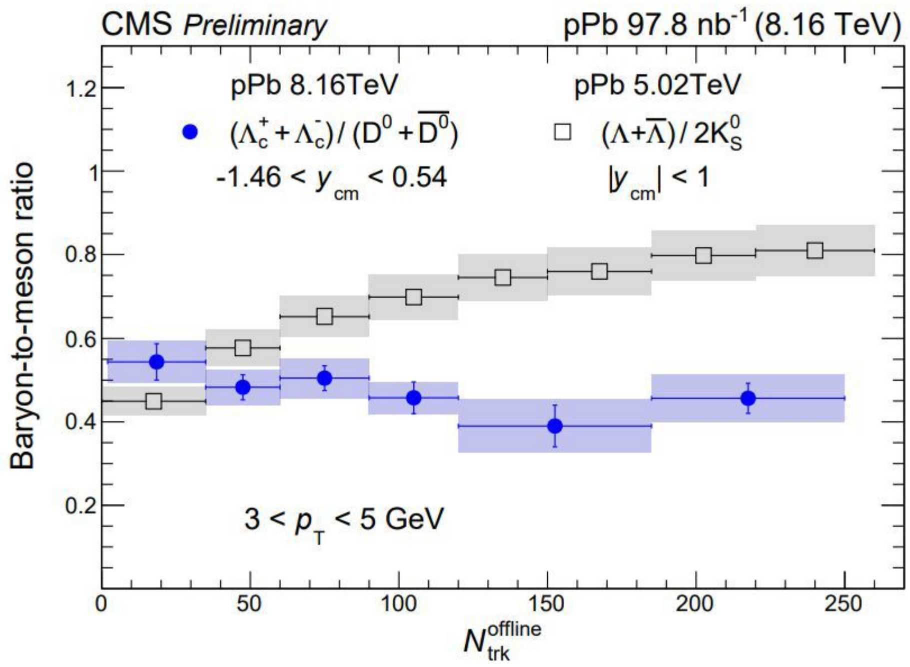


p_T-integrated ratio: no evidence of multiplicity dependence

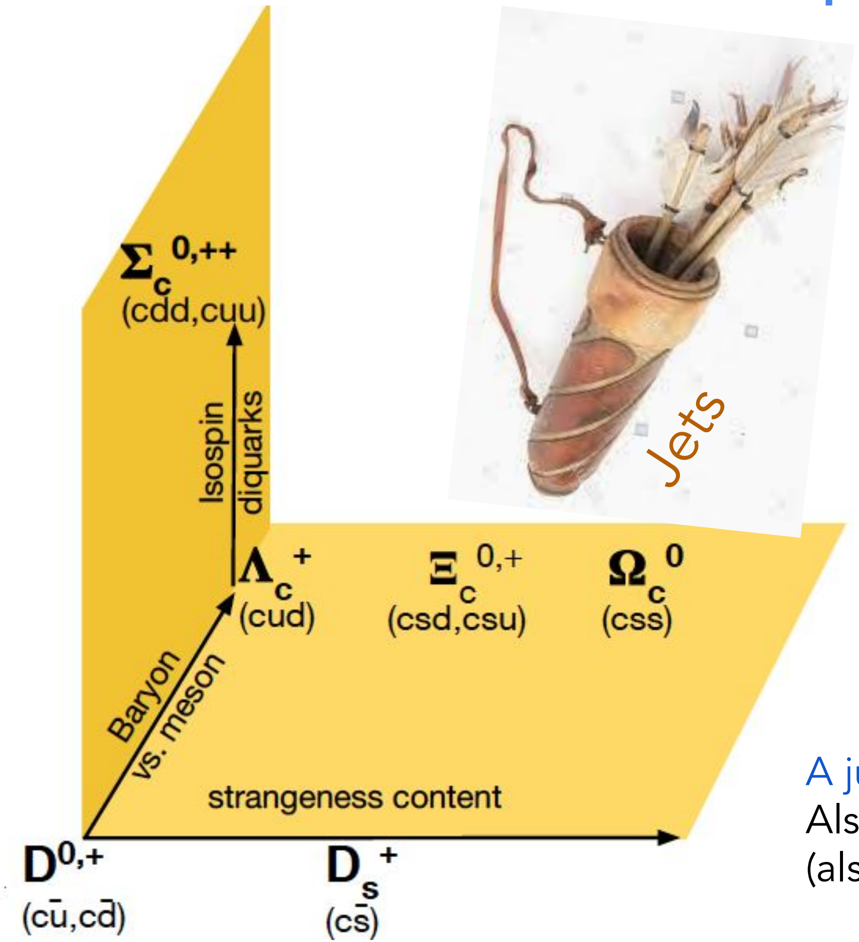
Contrary to expectations from PYTHIA8 with CR-BLC

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

Baryon-to-meson ration: HF vs. LF in p-Pb collisions



Several arrows in the quiver

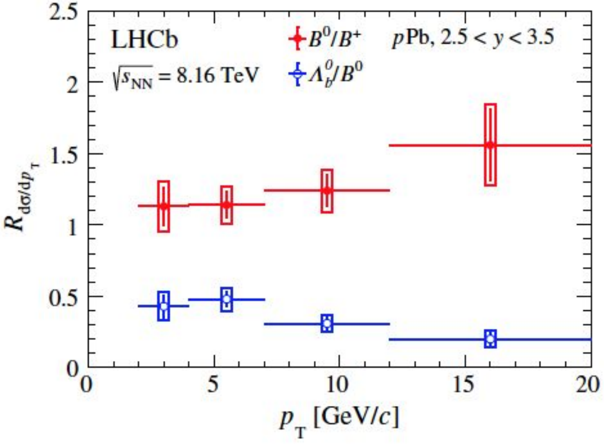


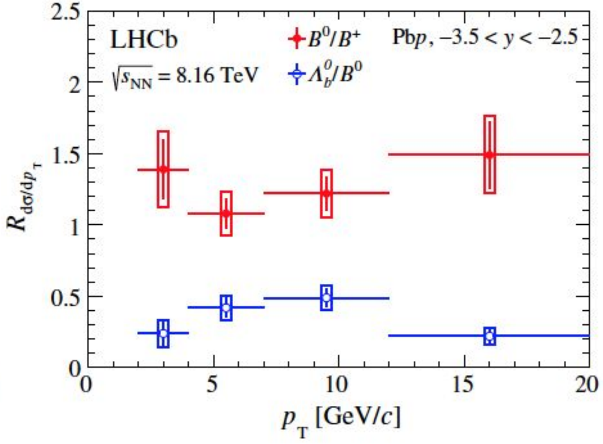
We can exploit multiplicity

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

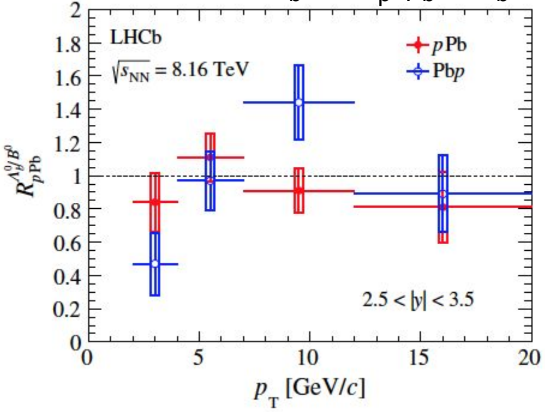
Particle	Mass (GeV/c^2)
D^0	1.865
	1.870
	1.968
	2.286
	2.454
	2.470
[illegible]	2.468
Ω_c^0	2.695
$B^{0,+}$	5.280
B_s^0	5367
Λ_b^0	5620

Λ_b^0/B in p–Pb collisions





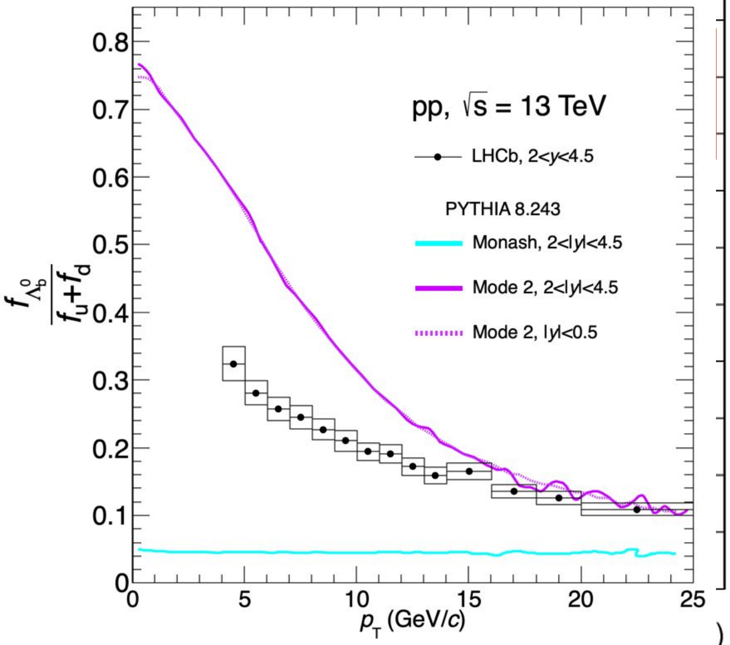
Double ratio $(\Lambda_b^0/B^0)_{p\text{–}Pb}$ /$(\Lambda_b^0/B^0)_{pp}$



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 ratio in pp collisions vs. models (2)



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

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.

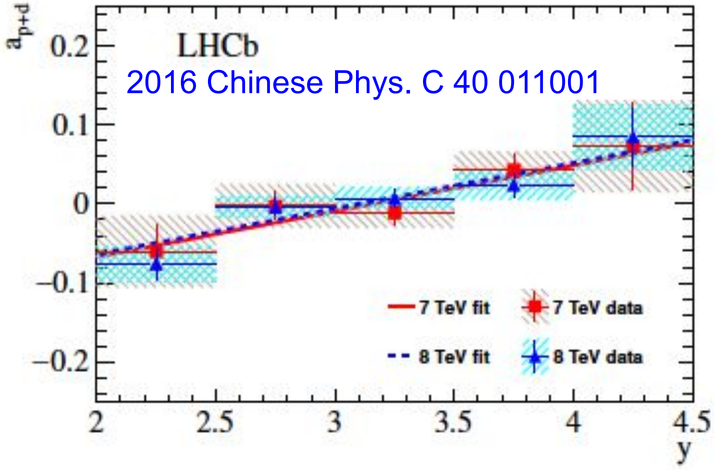
(b) Type II: junction-style reconnection

Support need of abandoning independent fragmentation of different MPI
A hadronic environment matters

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)

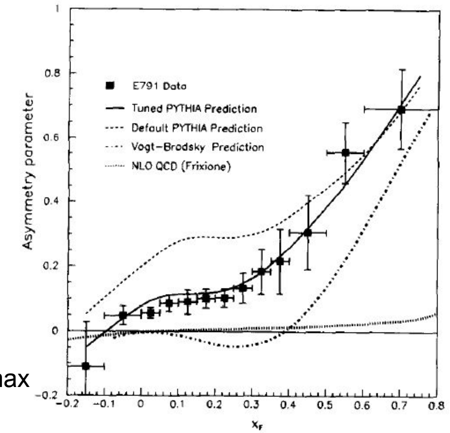


2016 Chinese Phys. C 40 011001

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

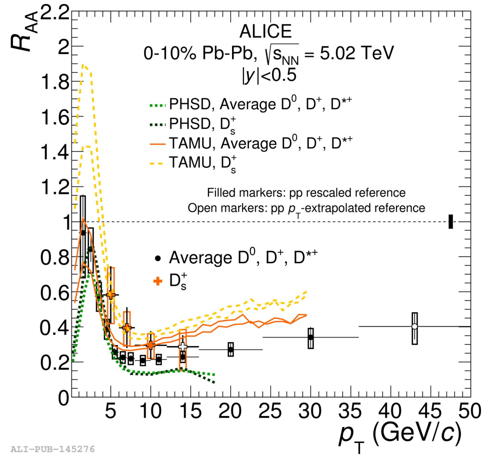
$$A(x_F, p_t^2) \equiv \frac{\sigma_L - \sigma_{NL}}{\sigma_L + \sigma_{NL}}.$$

E791, PLB 371 (1996) 157-162



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

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

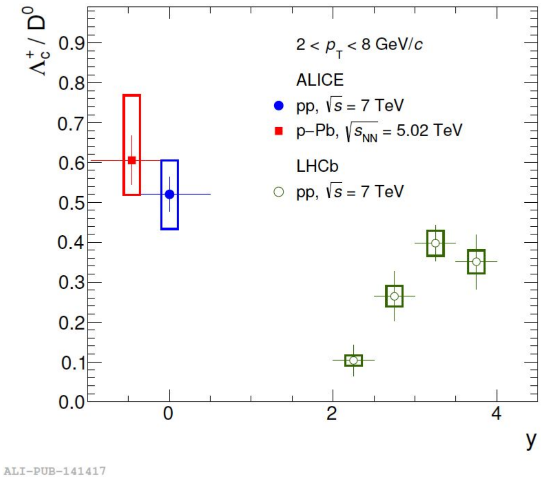


Suggest that **hadronic environment plays a role**

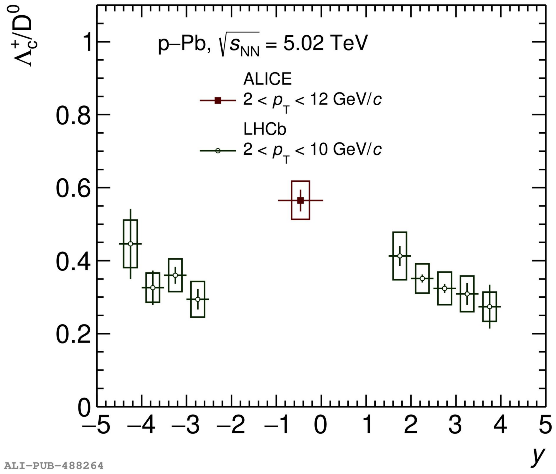
Up to what extent? how does the hadronisation dynamics change in different systems?

Rapidity dependence

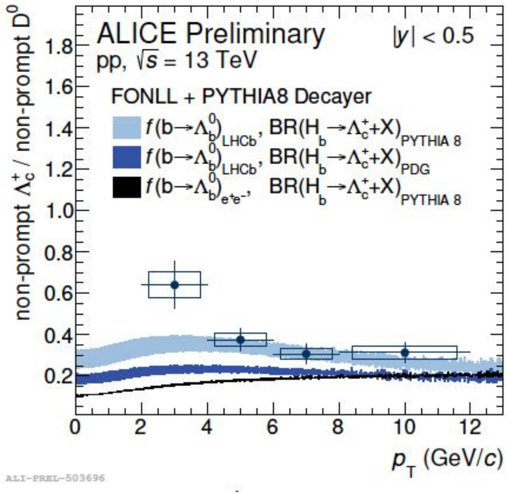
charm, pp



charm, p-Pb



beauty, pp



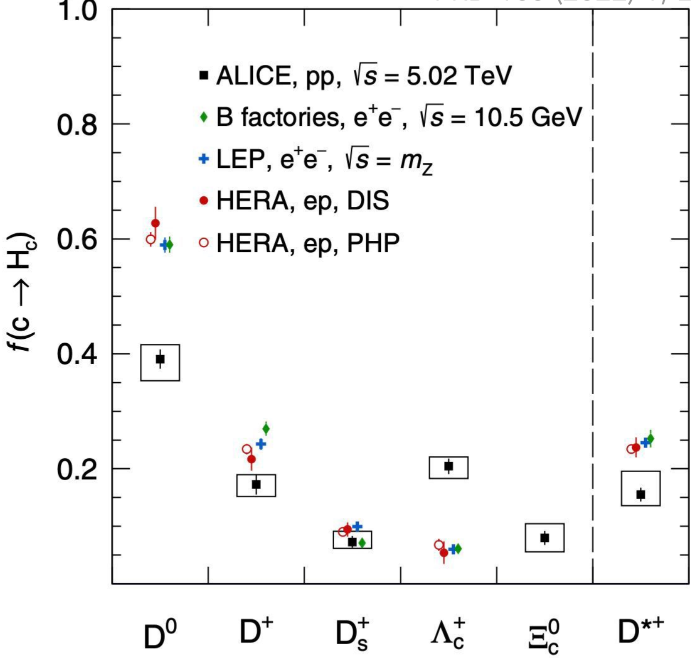
Not clear for charm (especially in pp), to be revisited with run 3 data?

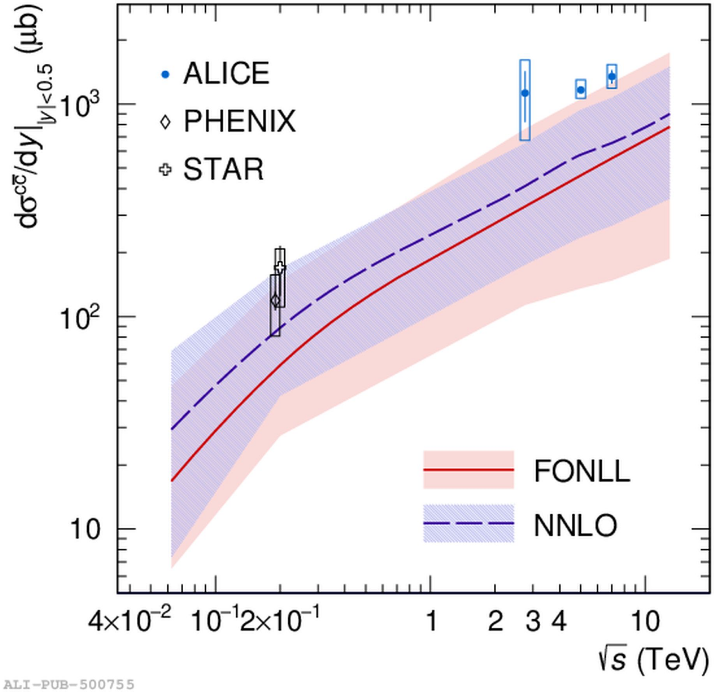
Beauty: non-prompt Λ_c^+ ALICE data consistent with LHCb Λ_b^0 data
→ low p_T region to be explored with run 3 data

ALICE, JHEP 04 (2018) 108
ALICE, PRC 104 054905 (2021)
LHCb (pp), Nucl.Phys.B 871 (2013)
LHCb (p-Pb), JHEP 02 102 (2019)

Fragmentation fractions from all ground-state baryons

PRD 105 (2022) 1, L011103

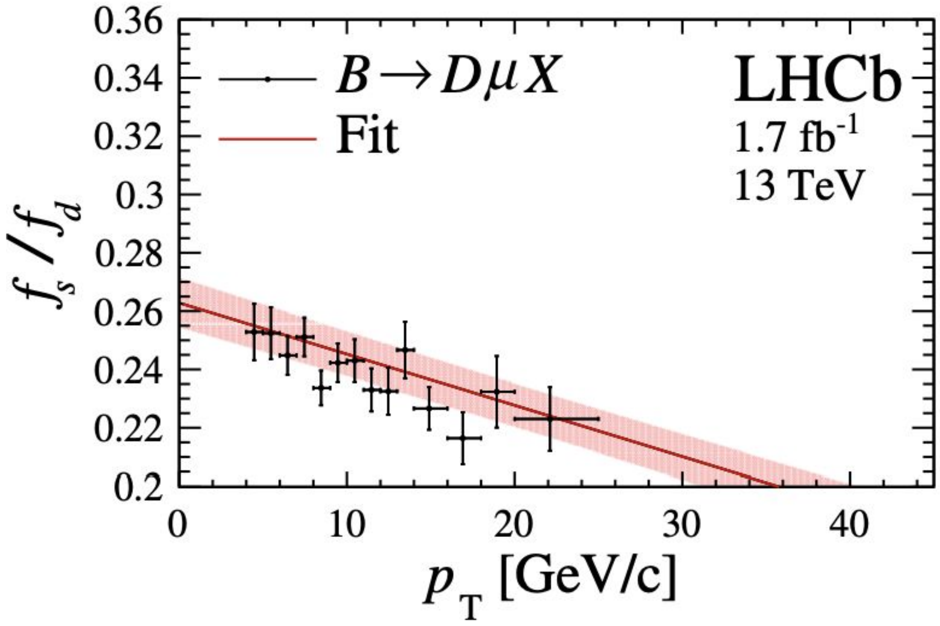


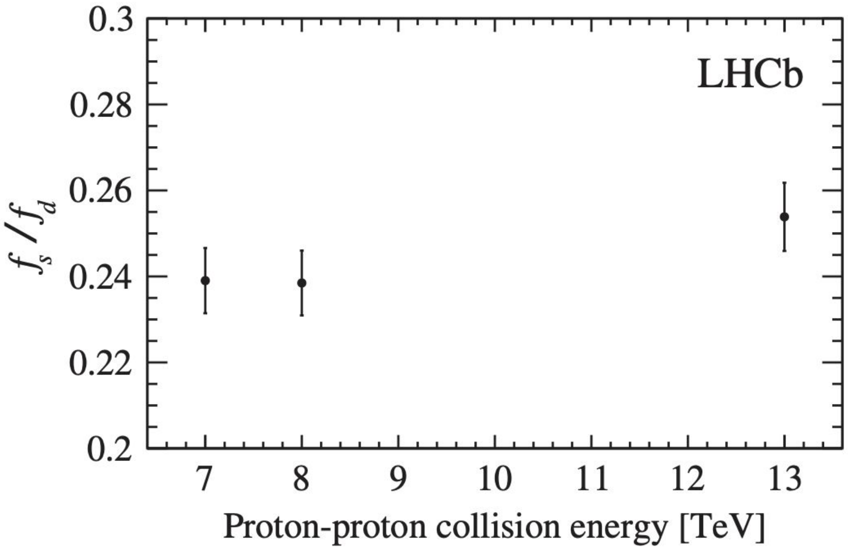


Direct measurement of all ground-state baryons
(Ξ_c^+ similar to Ξ_c^0, checked at 13 TeV)
Large increase for Λ_c^+ and Ξ_c^0
→ new Fragmentation Fraction

Measurement of total charm cross section:
about **40% higher values w.r.t. using e$^+$e$^-$ FF**
On upper edge of FONLL and NNLO

B_s^0/B vs. collision energy





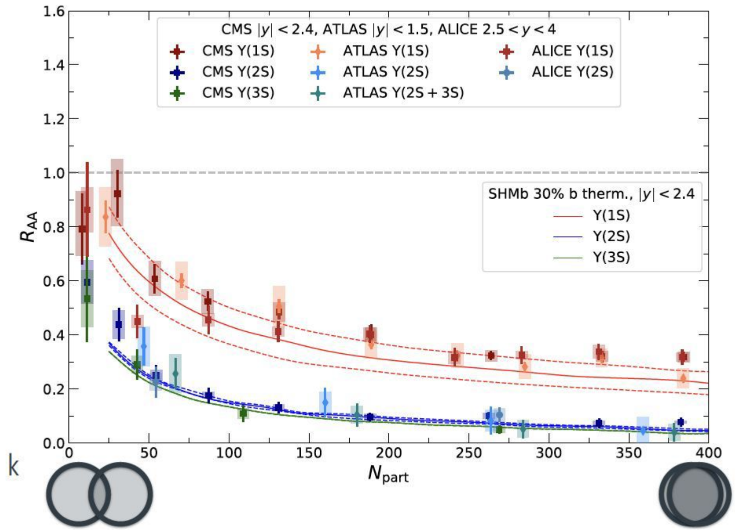
B_s^0/B slightly dependent on p_T and on collision energy

PRD104 (2021) 032005

Quarkonia, regeneration

JaeBeom Park, Tuesday

- Debye screening & dynamic dissociation → loss of initial QQ colour connection & suppression
- **Regeneration via recombination**
  - in line with statistical hadronisation model expectation at LHC energies, mainly at low p_T
  - relevant also for low-p_T ψ(2S)
    - Data described by TAMU transport model, SHMc tends to underestimate ψ(2S)/J/ψ ratio in central collisions
  - **relevant also for bottomonia?**



SHMb: *Acta Phys.Polon.Supp.* 16 (2023)

SHM describes bottomonia if 30% of beauty quarks thermalise

N.B.
Additional (unobserved) states (RQM) would further reduce expected bottomonia yields