Hadronization and coalescence in light and heavy flavor sector

F. Bellini (University and INFN, Bologna)

Padova, 26.11.2021

Terzo Incontro di Fisica con Ioni Pesanti alle Alte Energie 2021

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN
Istituto Nazionale di Fisica Nucleare

erc
European Research Council
Established by the European Commission

How does hadronic matter form starting from the fundamental building blocks of the standard model and laws of QCD?

A dive deep into the complexity of the quantum chromodynamics phenomenology, with one main (at least for the scope of this talk…) question in mind:

how does hadronization in-medium differ from hadronization in-vacuum?

From partons to hadrons

In pp collisions: ''textbook'' factorisation formalism (*divide et impera*)

- The non-perturbative PDFs and FFs are factorized and obtained via phenomenological fits to data
- pQCD used to calculate perturbative cross-sections
- At the LHC, more than one parton-parton interaction per pp collision

In AA collisions: hadronization is modified by the presence of a thermalised, strongly-interacting medium

- Light flavour bulk (low p_T) from hadronization of a QGP around T_{pc}, non-perturbative
- Heavy flavours and high p_T from early hard scatterings + interaction with the medium (to which extent?)

Hard probes: QCD factorization extended to AA

$$\underbrace{\sigma_{AA\to hX}}_{\text{Cross section in AA collisions}} = \underbrace{NPDF(x_a,Q^2)NPDF(x_b,Q^2)}_{\text{Nuclear Parton Distribution Functions (nPDFs)}} \otimes \underbrace{\sigma_{ab\to q}}_{\text{cross section in vacuum}} \otimes \underbrace{P(\Delta E)}_{\text{Parton interaction with medium}} \otimes \underbrace{D_{q\to h}(z_q,Q^2)}_{\text{Fragmentation Functions (FFs)}}$$

Cross section in AA collisions

Nuclear Parton Distribution Functions (nPDFs)
From proton to nuclear projectile/target
→ constrain with pA

cross section in vacuum

Parton interaction with medium

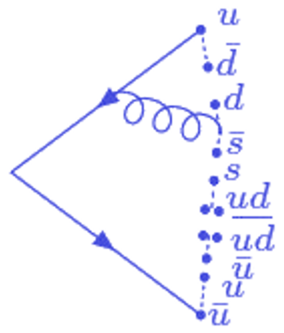
Fragmentation Functions (FFs)

Quark gluon plasma properties emerge with increasing from pp to AA collisions

System size
Multiplicity
Energy density

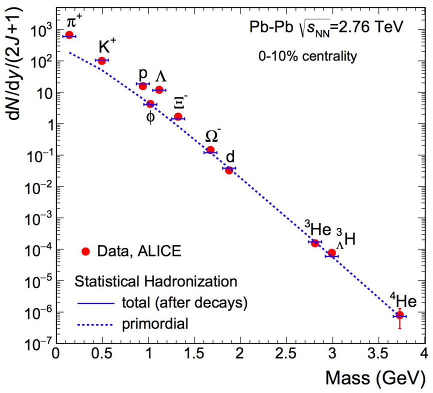
Can we find one unique picture (or a smooth transition across pictures) that explains the experimentally observed smooth trends in hadron production across systems?

How do models deal with hadronization?



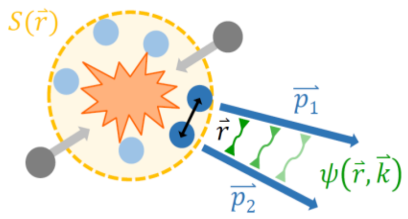
QCD-based MC generators: in-vacuum hadronization

- By string fragmentation (e.g. Lund model + color reconnection, ropes/junctions…)
- In hybrid approaches (e.g. core-corona), hydro description of a fireball complements
- …



Statistical hadronisation: hadronization out of a thermalised medium

- Yields depend on mass, temperature of the system and quantum numbers
- Quantum numbers conservation on average (Grand Canonical) or exact over a small causally-correlated volume (canonical)
- Composite objects (hyper- and anti-nuclei) treated as hadrons: no structure



Coalescence: cluster formation from the interaction among existing degrees of freedom

- Parton coalescence → partons from a fireball recombine into hadrons
- Hadron/nucleon level → nucleosynthesis
- Depends on the properties of the particle emitting source

Experimental overview: hadronization and coalescence in light and heavy flavor sector

Different classes of observables exhibit common features

Light flavour (u,d,s)

Heavy flavour (c,b)

Nuclear bound states

Today focus on the low and mid p_T

Smooth multiplicity dependence: light and strange hadrons

Some Improvement in description of strangeness enhancement effect with the inclusion of rope hadronization in Pythia

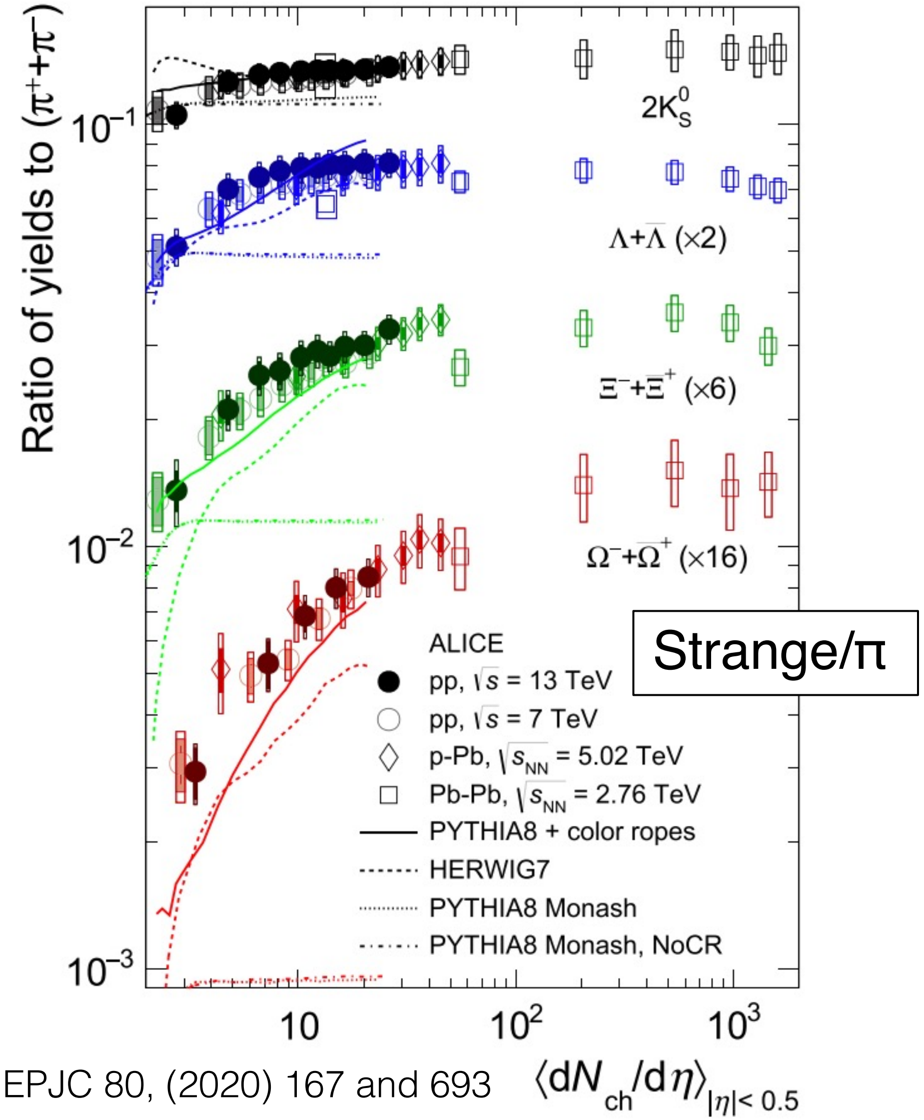
Bierlich et al., JHEP2015, 148 (2015)

However, **strangeness increase with multiplicity is still not understood**

→ new observables proposed and multi-differential analyses

to disentangle in/out-of-jets and initial/final state effects

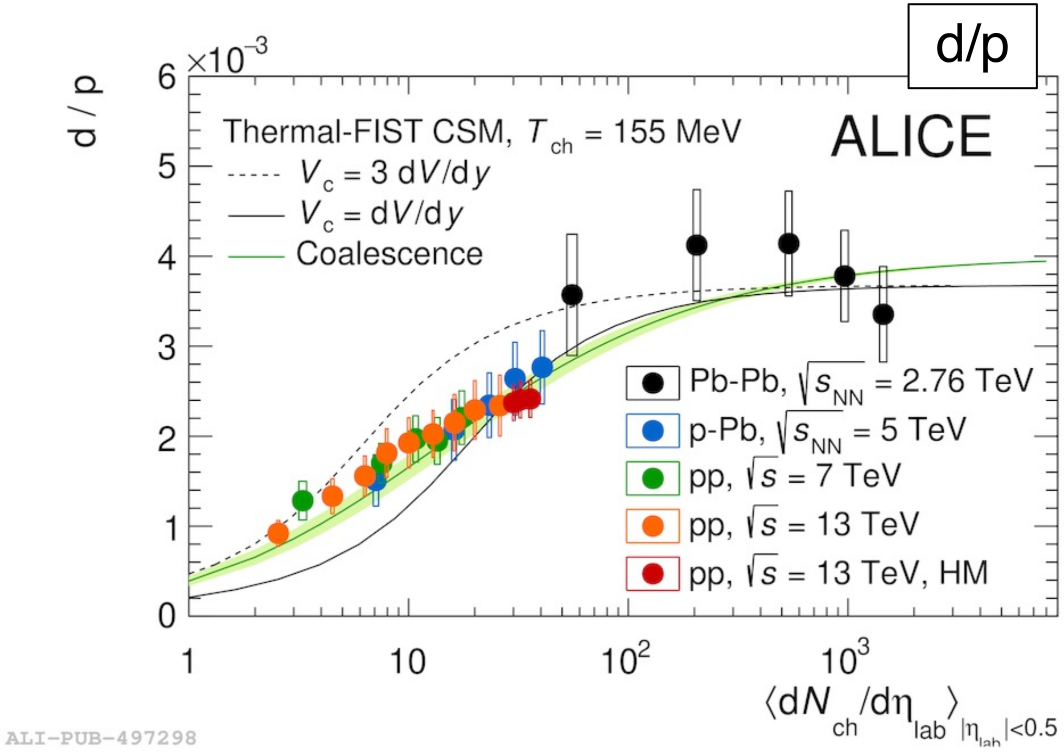
OPEN QUESTION: “**emergence**” in hadron production mechanism, **from microscopical ones** (string overlap, color reconnection) **to the onset of a QGP** (thermalization, equilibration)**?**



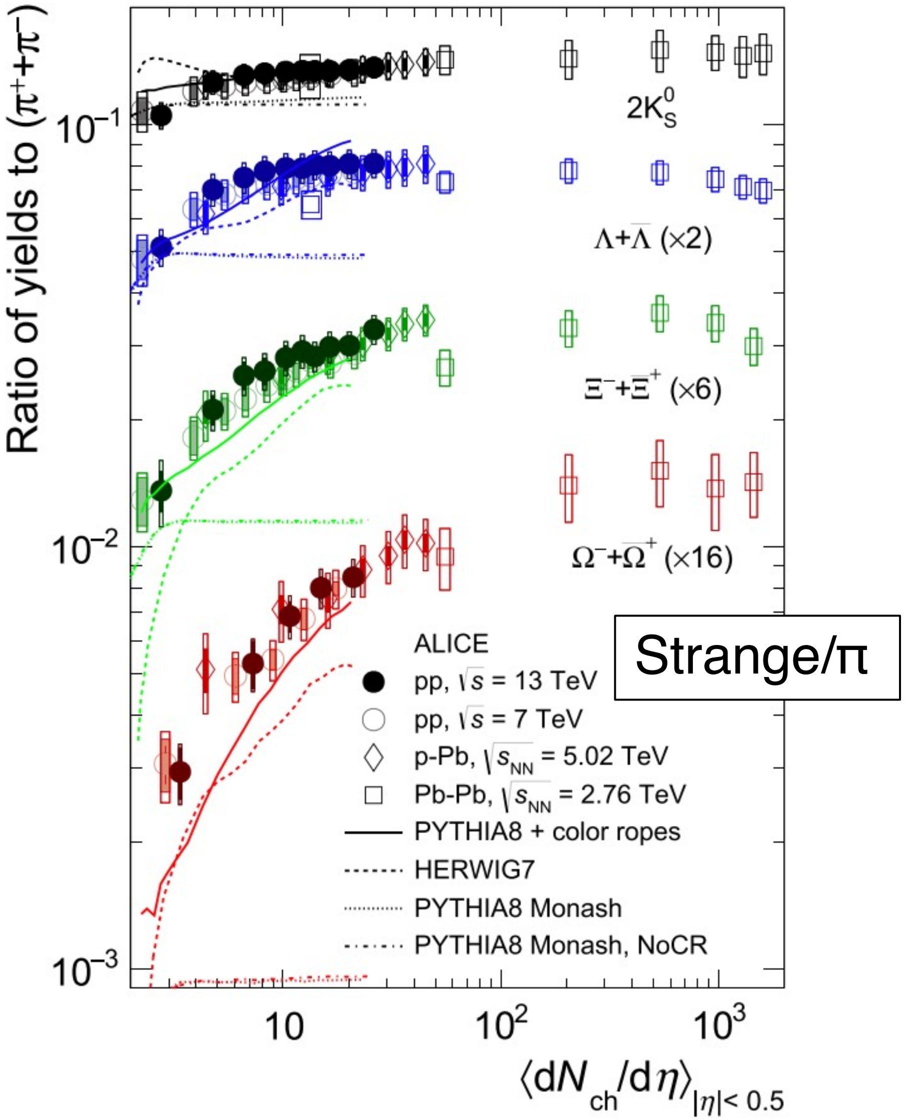
EPJC 80, (2020) 167 and 693

talk by L. Bianchi

Smooth multiplicity dependence: light nuclei



arXiv:2109.13026, EPJC 80 (2020) 889



Smooth trend observed also in the production of light nuclei.

QUESTION: Does it reflect a transition in production mechanisms and/or a consequence of emerging properties of the source?

Light flavour hadrons from QGP hadronization in Pb-Pb

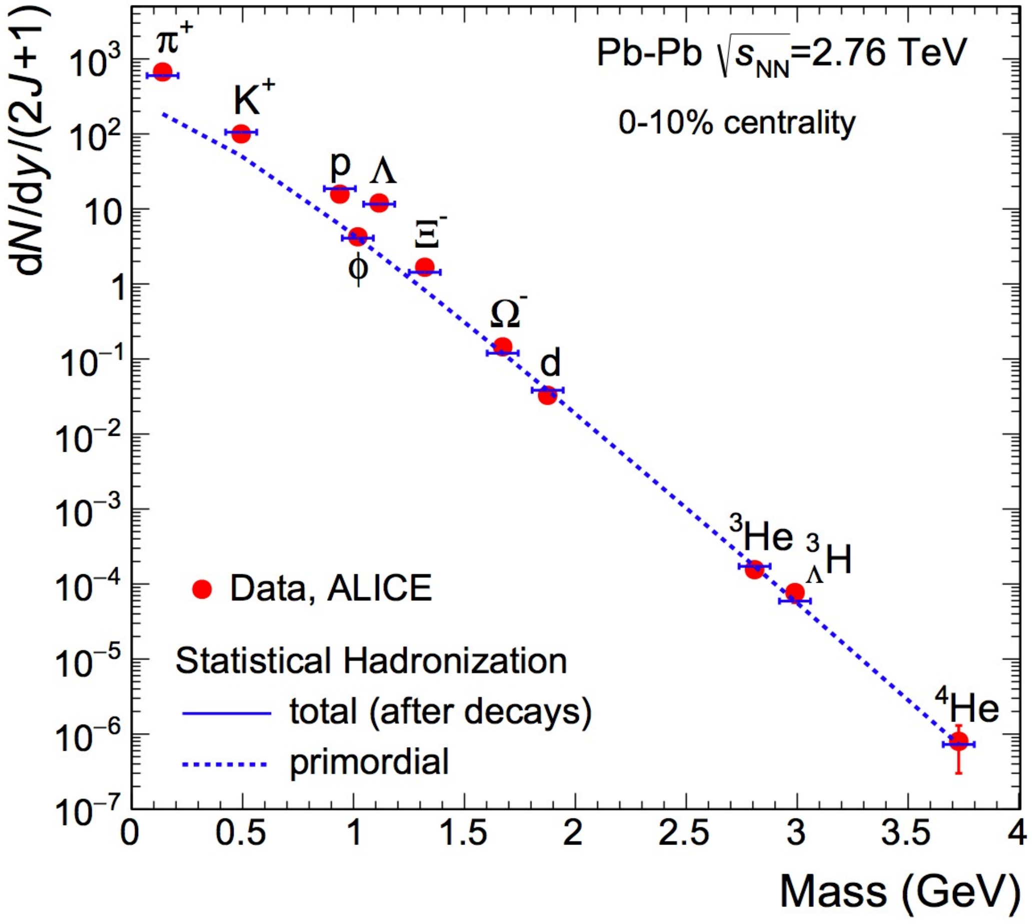
Success of the Grand Canonical statistical hadronization model in describing yields of light flavour hadron species over 10 orders of magnitude in central AA collisions

(including strangeness, light nuclei and hypernuclei)

→ bulk produced from the hadronization of a QGP in thermodynamical equilibrium

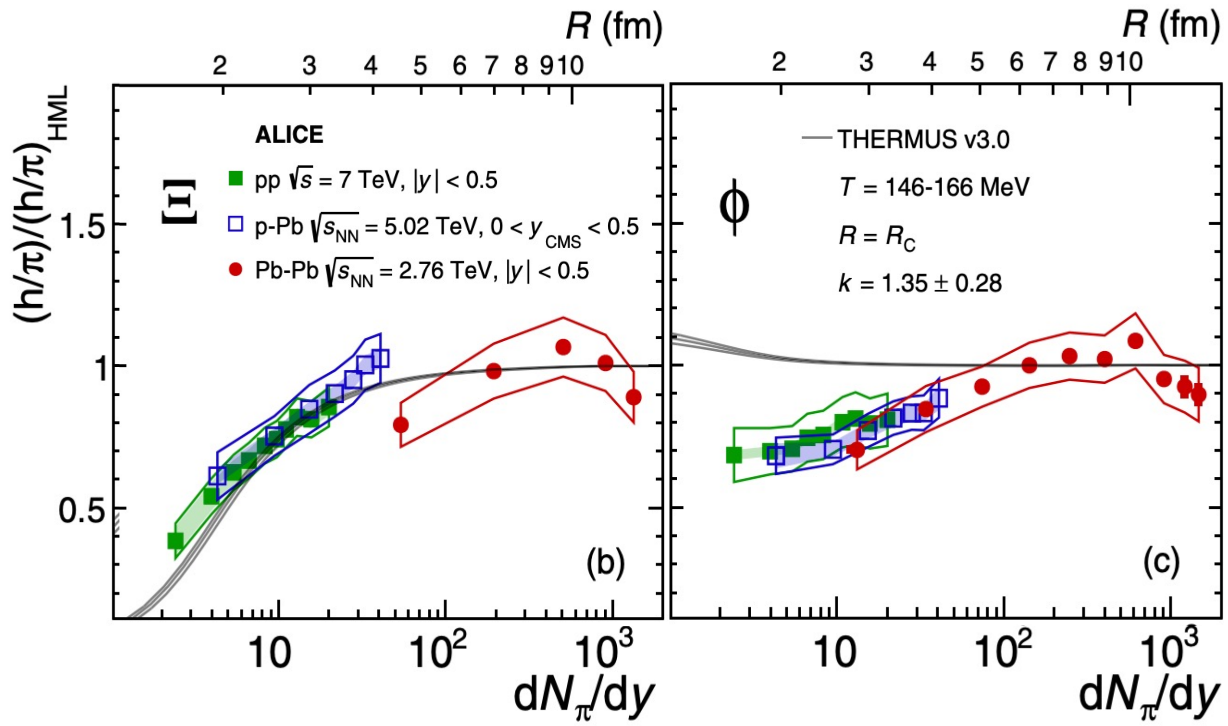
$T_{chemical}$ ~ 155 MeV

NB: bulk ↔ low p_T

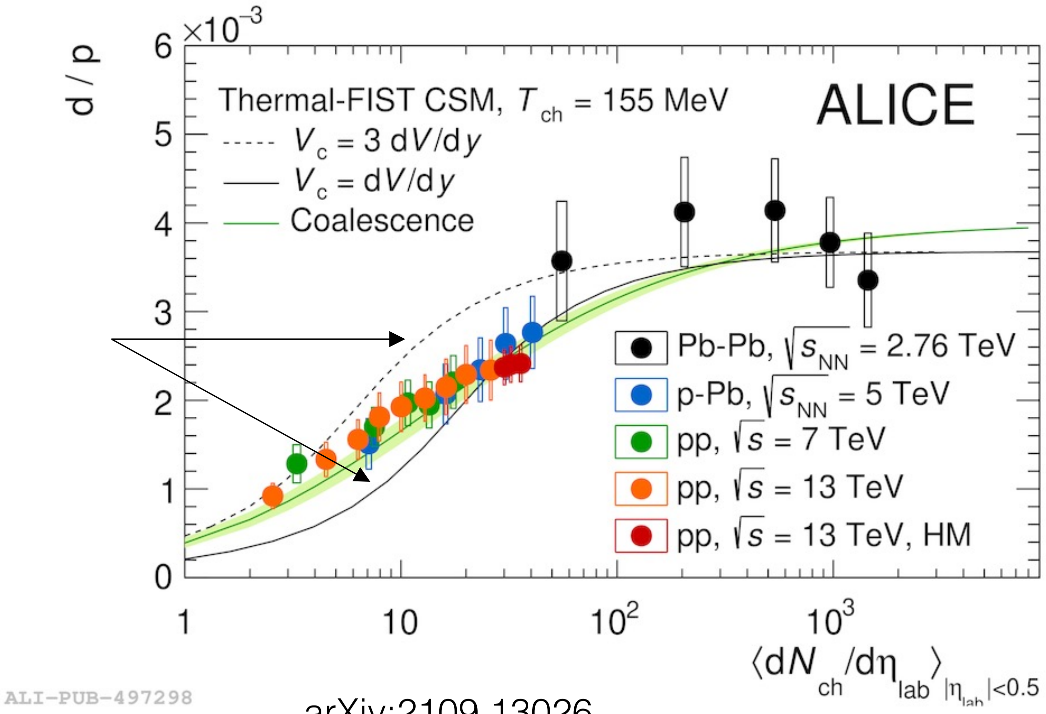


A. Andronic et al., Nature 561, 321 (2018)

Canonical statistical hadronization approach in small systems



ALICE, PRC 99, 024906 (2019)



arXiv:2109.13026

ϕ is the exception that does not fit in the canonical suppression picture that describes all other measured LF and strange hadrons from small to large systems.

Deuteron data show that a single correlation volume cannot reproduce them all, but more likely a **dynamical evolution of V_c** with increasing source size → can we access directly V_c?

Hadron production by fragmentation and recombination in Pb-Pb

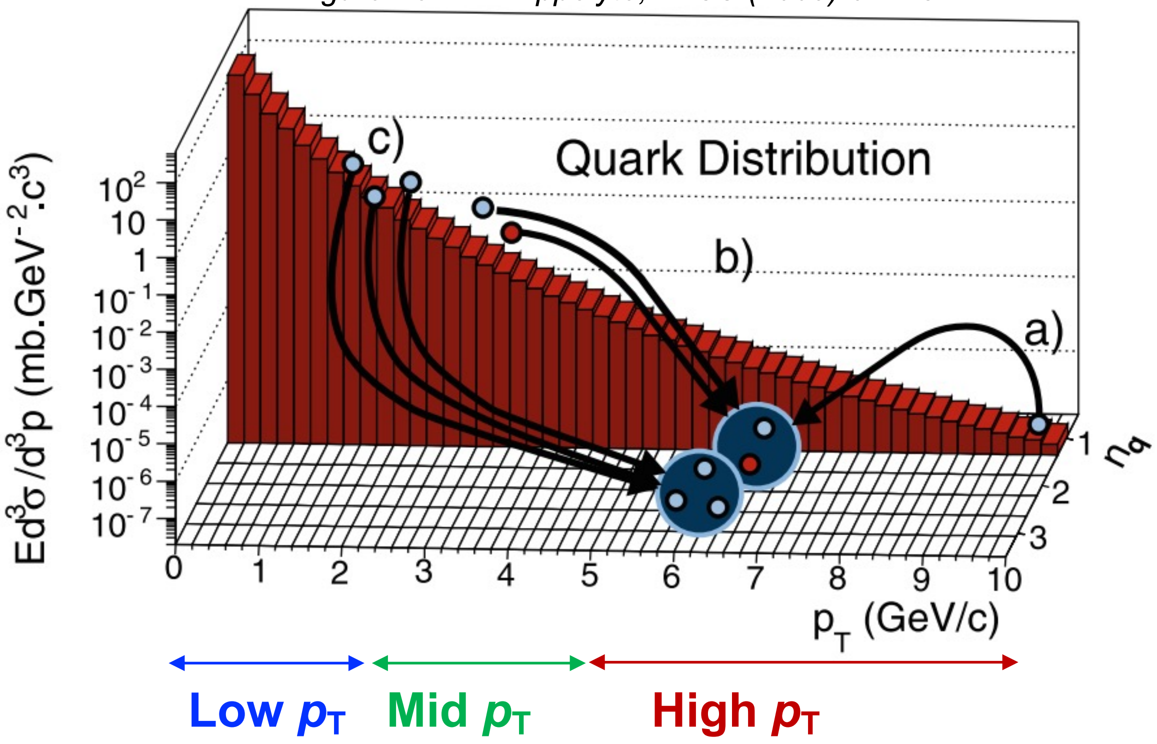
Ratios of production distribution of baryons to mesons are sensitive to competing particle production mechanisms, depending on transverse momentum

Fragmentation (a) of high-p_T partons into mid-p_T hadrons

Recombination (b,c) of low-p_T partons close in phase space into mid-p_T hadrons via coalescence

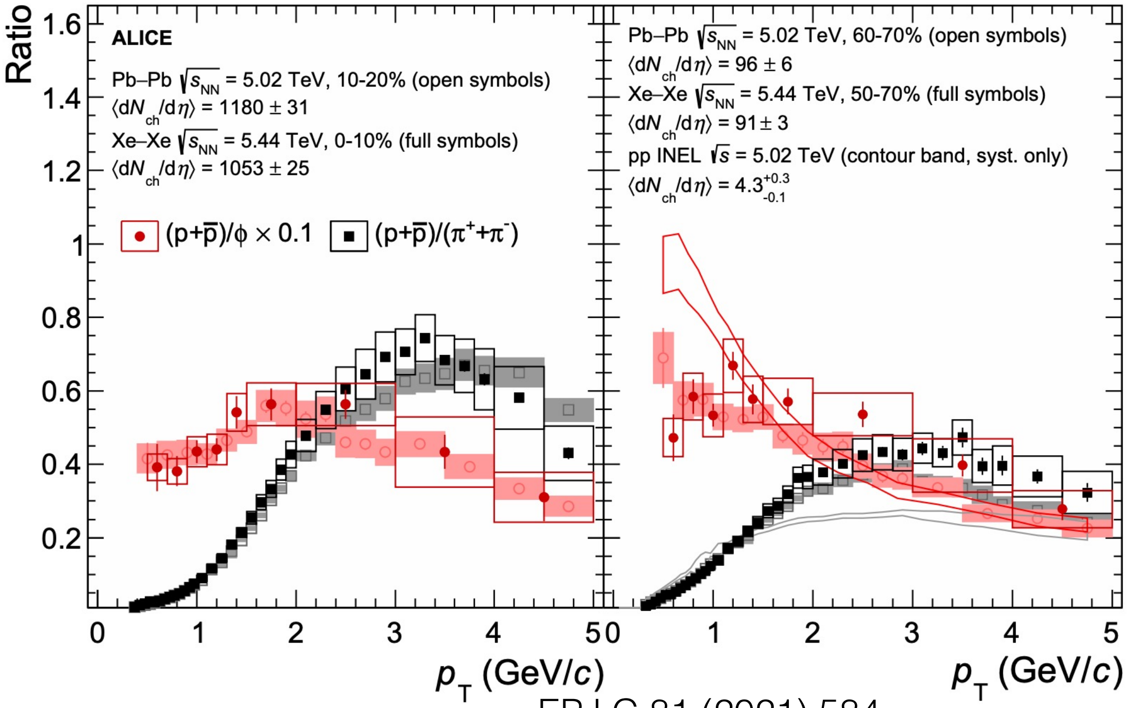
+ influence of **collective flow**

Figure from B. Hippolyte, EPJC (2009) 62: 237–242

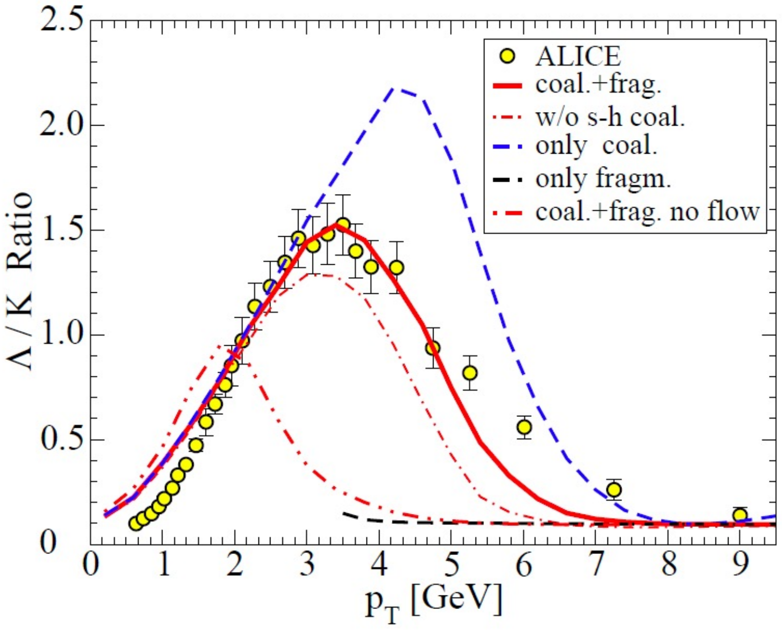


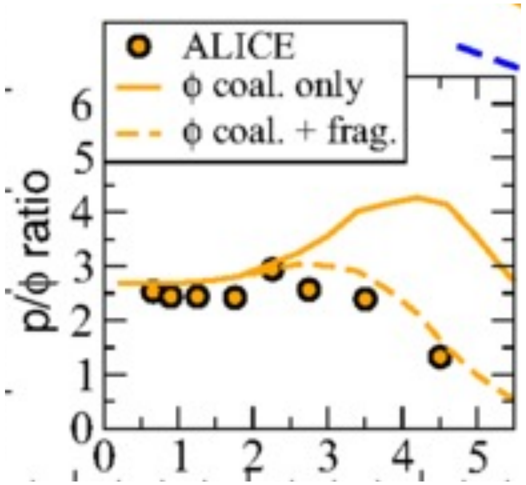
→ talk by S. Plumari

Light flavour baryon-to-meson production in AA



EPJ C 81 (2021) 584





V. Minissale et al., PRC 92 (2015) 054904

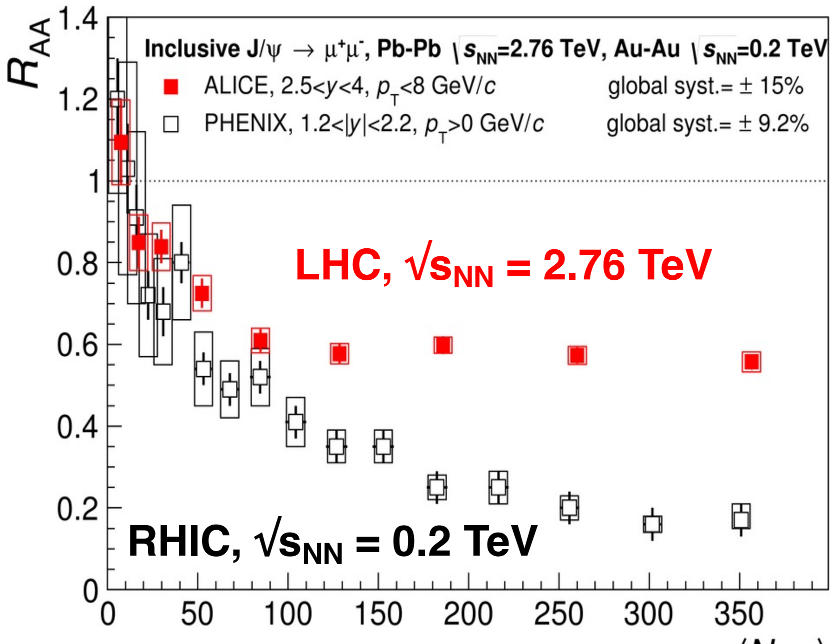
Baryon/meson enhancement at mid p_T observed and more evident for particle ratios where mass difference is larger, e.g. p/π, Λ/K^0_S and less evident for small Δm, e.g. p/ϕ

The flatness of the p/ϕ ratio in central AA collisions is consistent with predictions from hydrodynamics but can be accommodated by models with recombination.

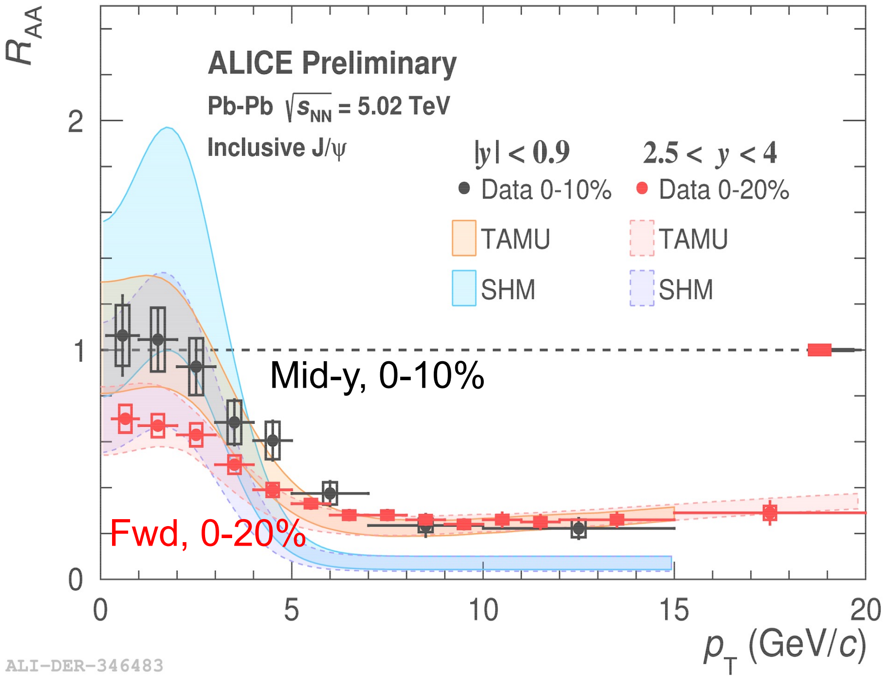
Charm production and recombination at the LHC

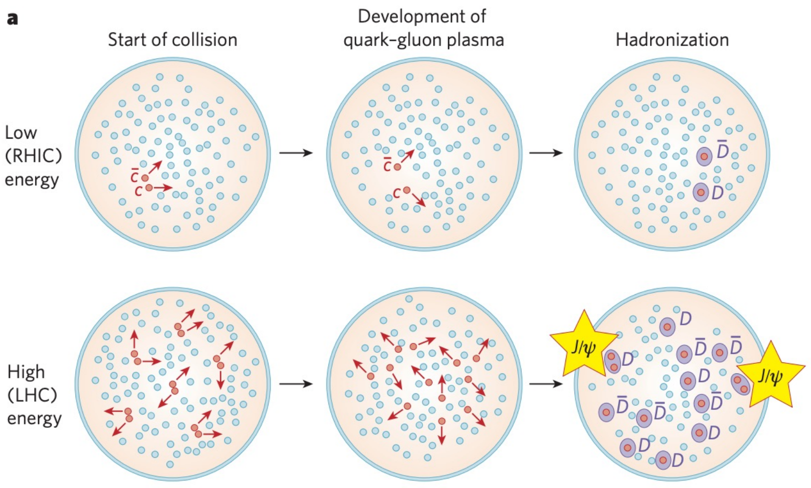
Increase with √s: ~100 $c\bar{c}$ per central Pb-Pb event at the LHC vs ~10 $c\bar{c}$ at RHIC
→ **(re)generation of charmonium** and charmed hadron production takes place at the phase boundary or in QGP

R_{AA}(LHC) > R_{AA}(RHIC), R_{AA} at midrapidity > R_{AA} at forward rapidity
The J/ψ recombination picture is confirmed by LHC data → signature of de-confinement



JHEP 05 (2016) 179



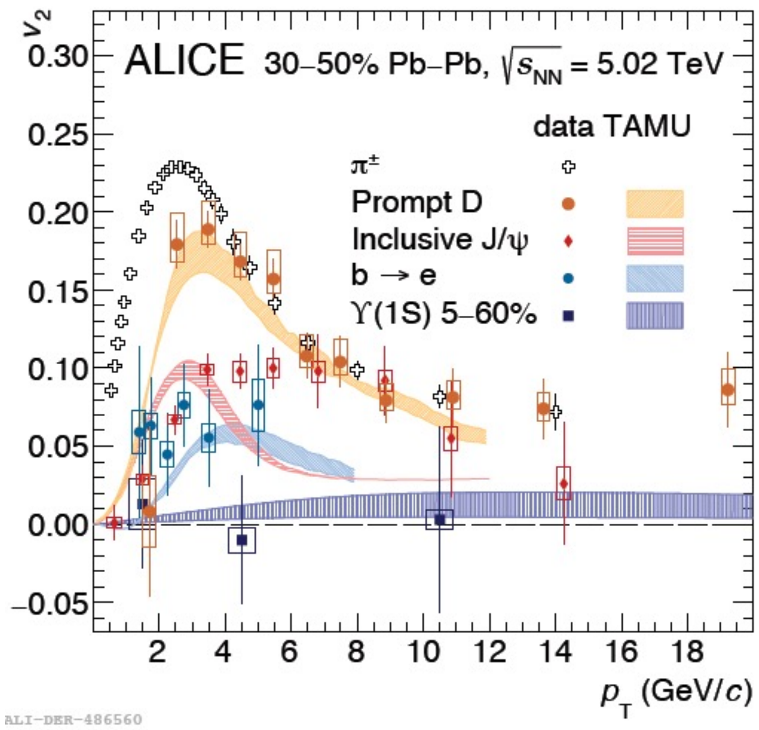


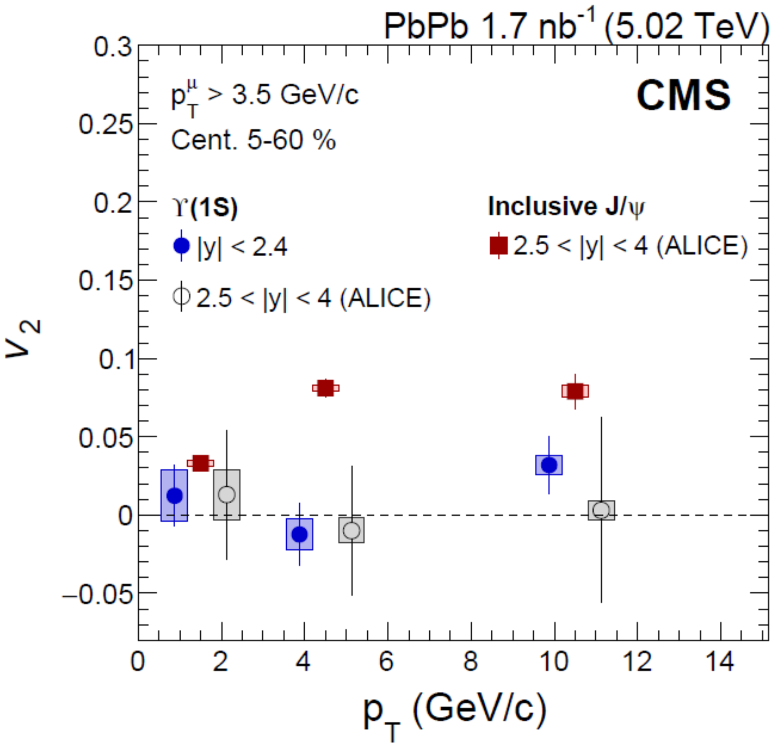
P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)

Charm and beauty: to flow or not to flow

Charm hadron flow and R_{AA} at low p_T suggest that **charm is partially thermalized at the LHC**
→ a **partially-equilibrated probe** of the late hadronization stages

Beauty seems to experience significantly less collectivity (if any) compared to charm
→ no significant evidence that beauty is even partially equilibrated with the medium



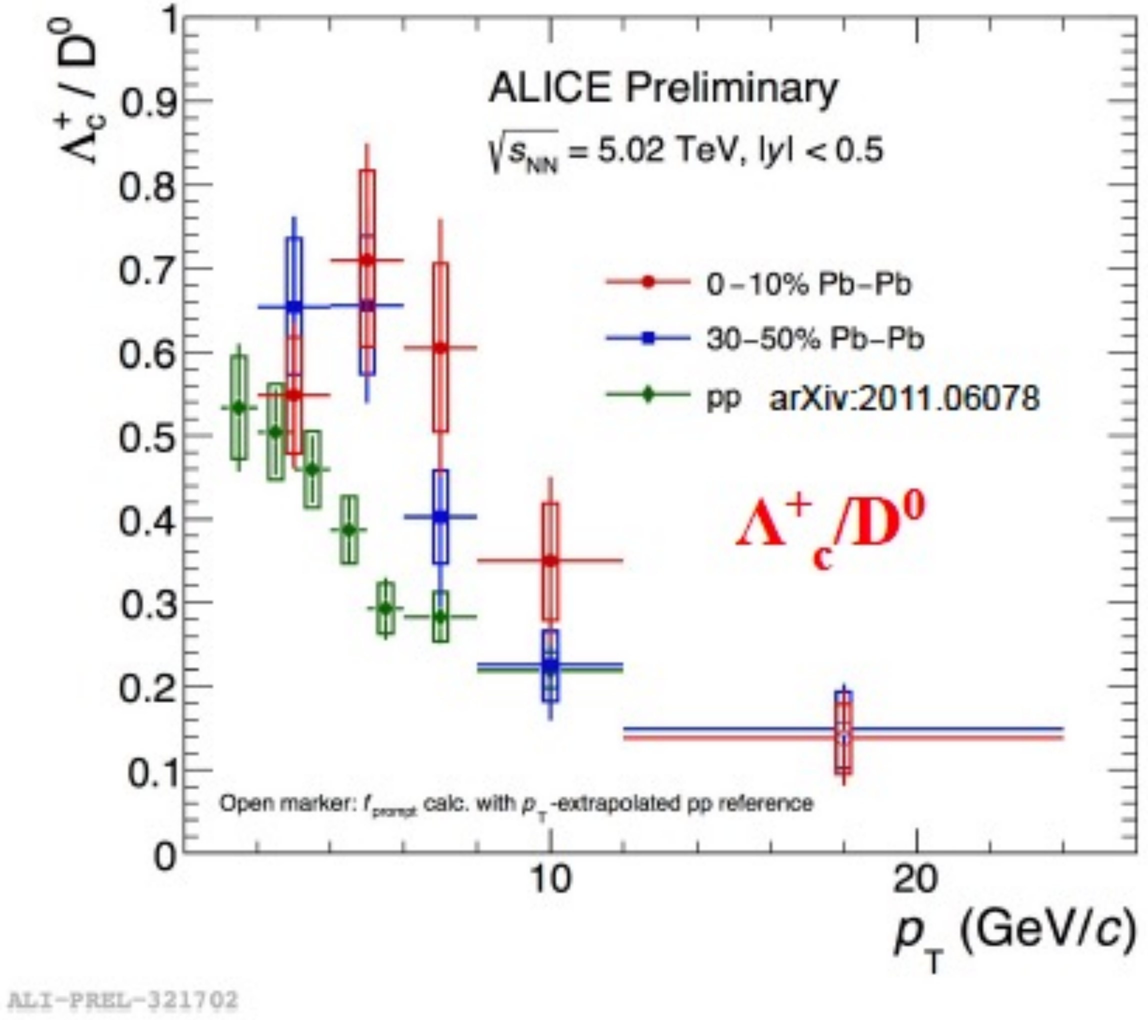


Heavy flavour hadronization in heavy-ion collisions

Investigate the possible modification of the charm fragmentation in presence of a medium with open heavy flavour mesons and baryons

Hint for an enhancement of Λ_c/D^0 wrt pp via recombination with light quark in the QGP, combined to the effect of flow and qualitatively similar to baryon enhancement observed in the LF sector.

→ Crucial to understand production in pp!



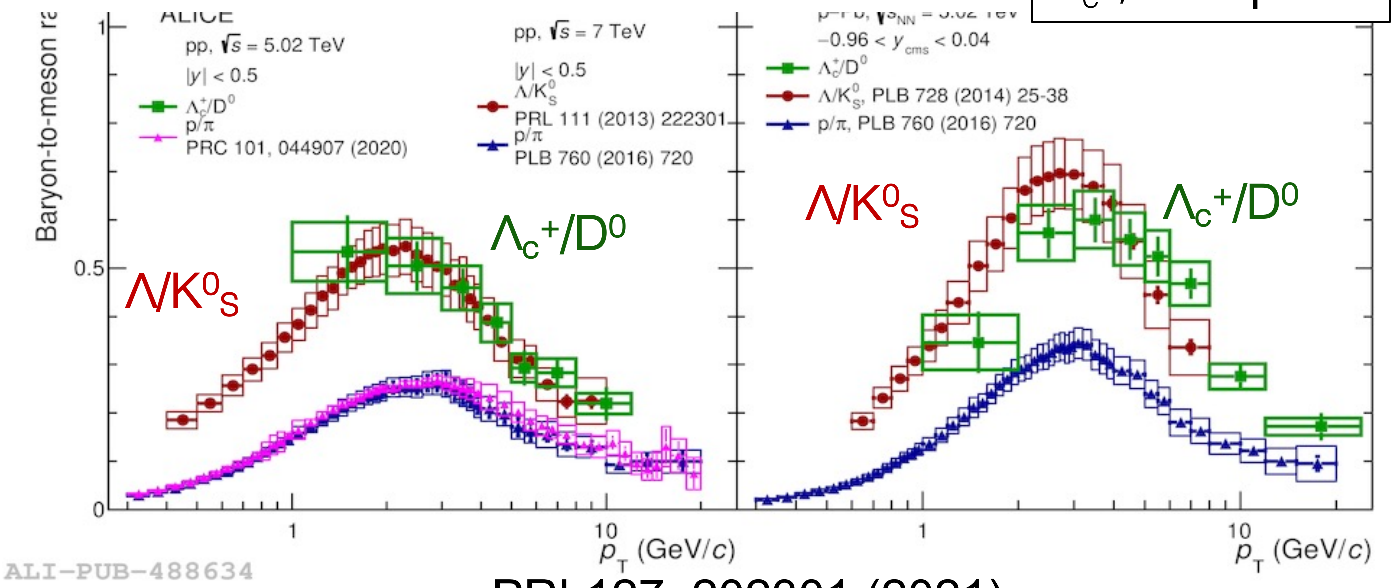
→ talk by M. Faggin

Charm fragmentation into baryons in pp

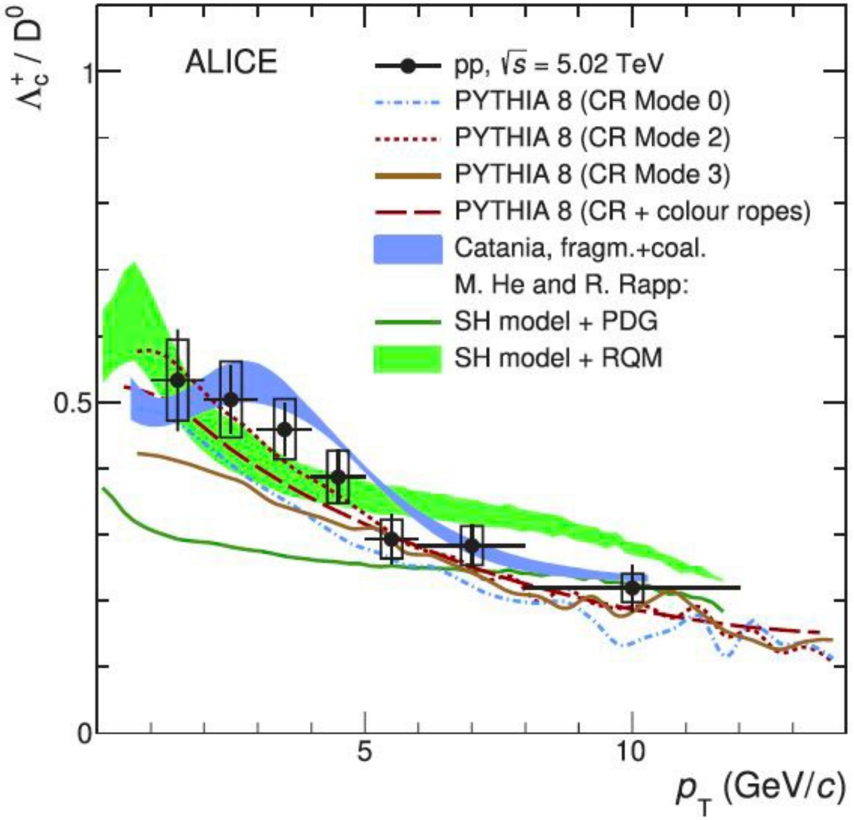
Λ_c^+/D^0 similar to the baryon/meson ratio in the LF sector

Data described by different approaches:
e.g. PYTHIA8 with String Formation beyond Leading Colour approximation and coalescence+vacuum fragmentation (Catania)

Λ_c^+/D^0 in **p-Pb**



PRL127, 202301 (2021)



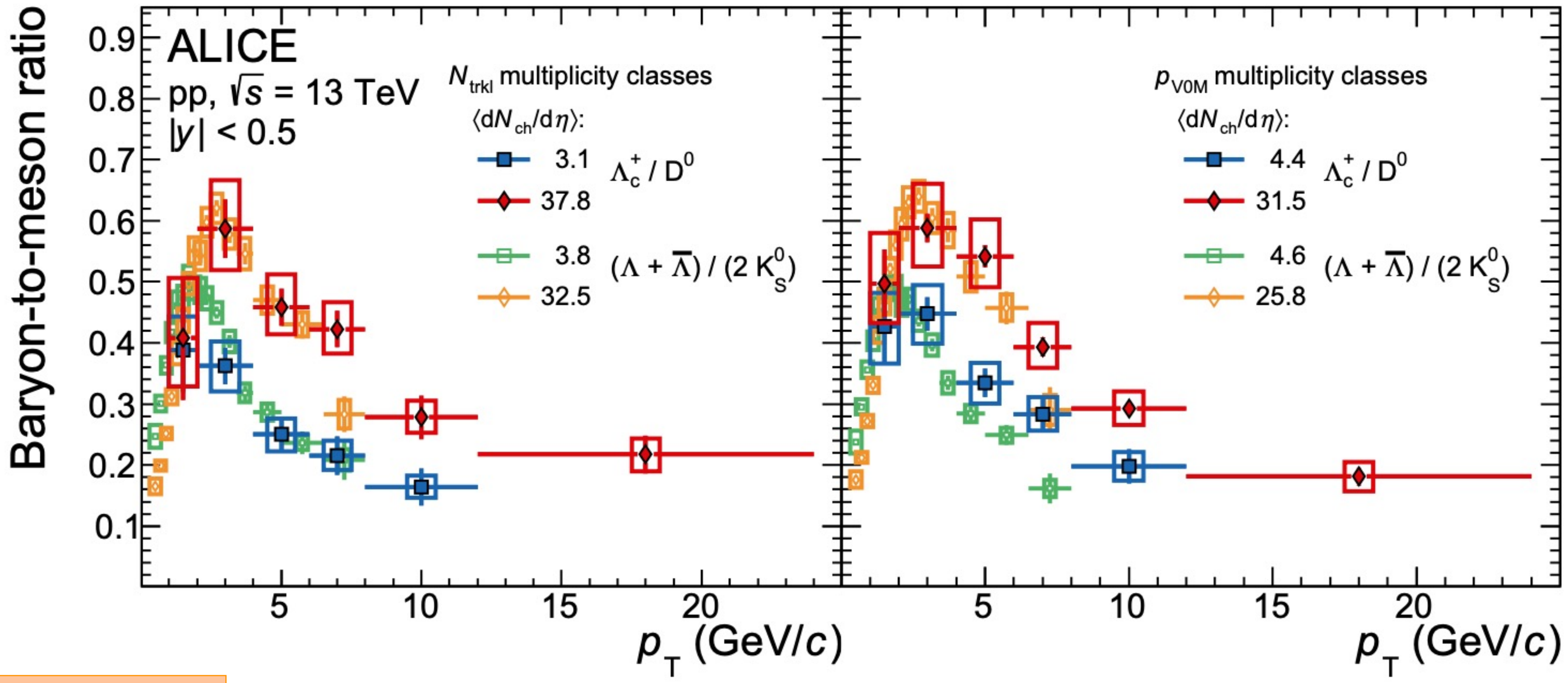
PYTHIA: JHEP 1508 (2015) 003 (new CR modes)
SHM+RQM: PLB 795 117-121 (2019) (additional charm states)
Catania: arXiv:2012.1200 (hadronization via coalescence)

→ talks by P. Skands, S. Plumari, M. Faggin, C.Terrevoli

Charm fragmentation into baryons in pp

Λ_c^+/D^0 similar to the baryon/meson ratio in the LF sector

→ Now tested also as a function of multiplicity



→ talk by C.Terrevoli

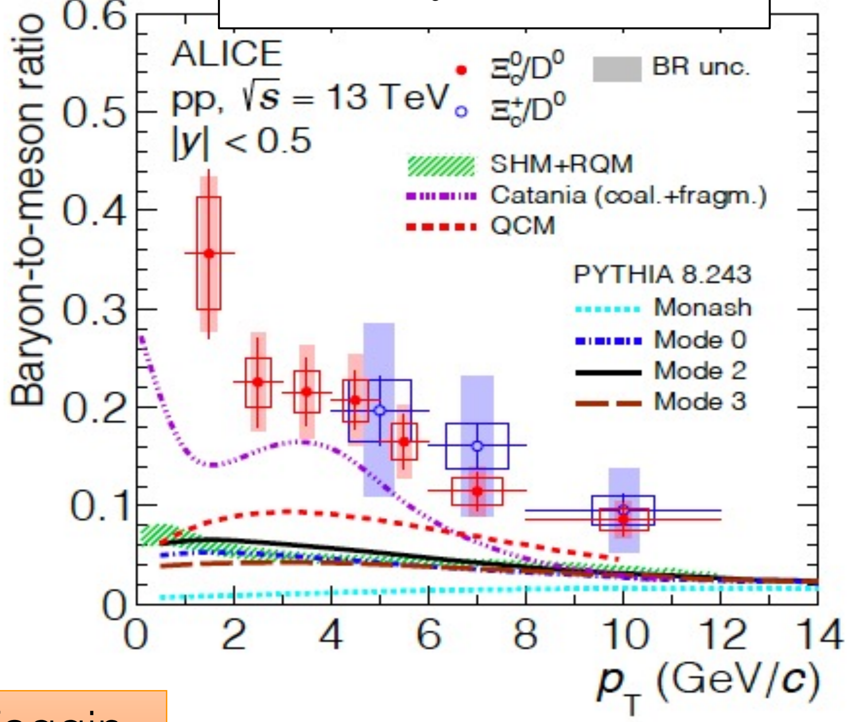
arXiv:2111.11948

Charm hadronization differs at the LHC

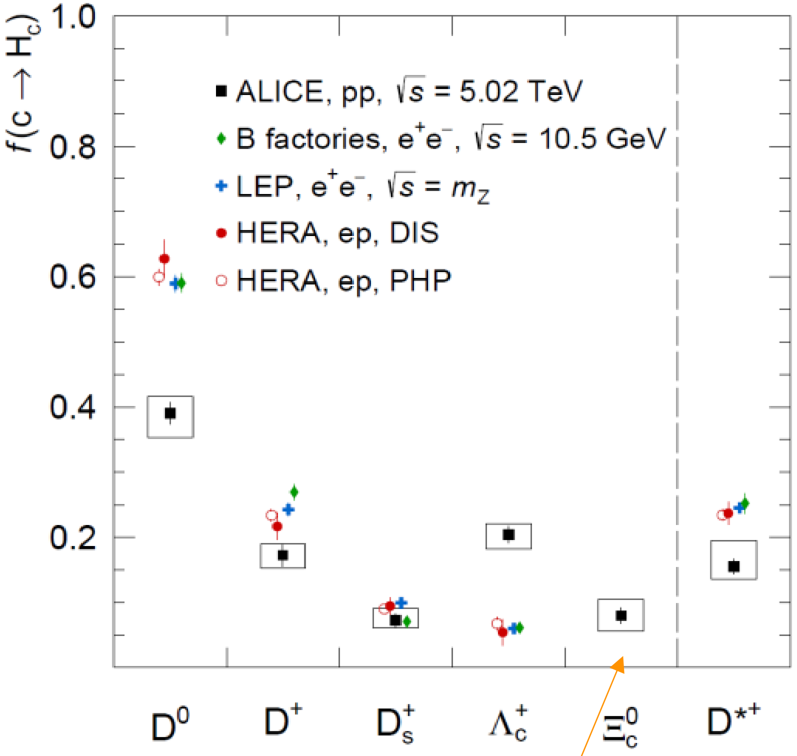
Charm FFs updated with latest data on charmed baryons in pp collisions

→ Evidence that universality (colliding-system independence) of parton-to-hadron fragmentation is broken

$\Xi^0_c \rightarrow \Xi^- e^+ \nu_e$, $\Xi^0_c \rightarrow \Xi^- \pi^+$
$\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^+$



f(c→H$_c$)



→ talk by M. Faggin

arXiv:2105.05187, arXiv:2106.08278

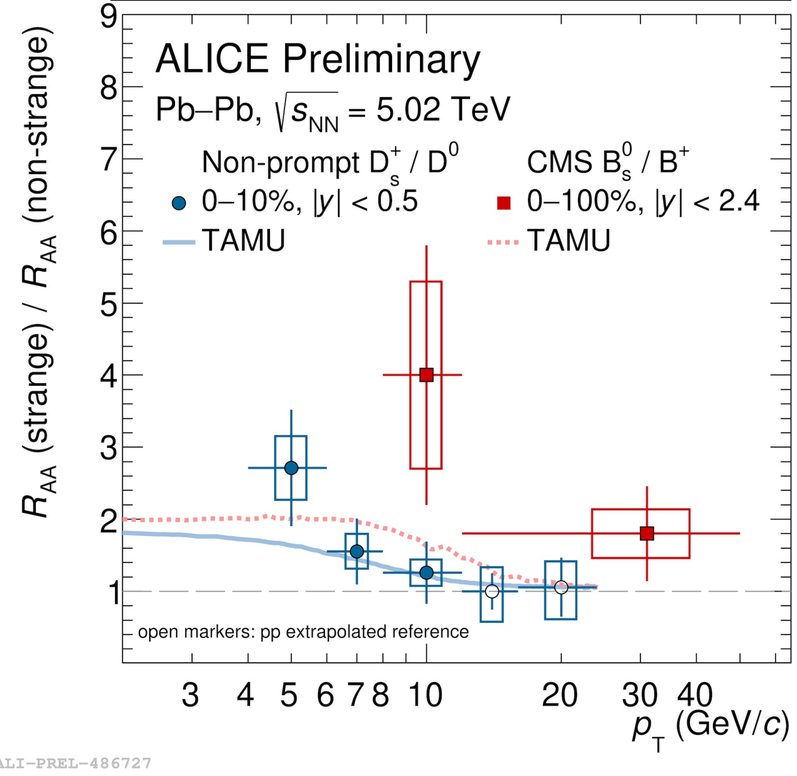
First measurement!

Open heavy flavour hadronization in heavy-ion collisions

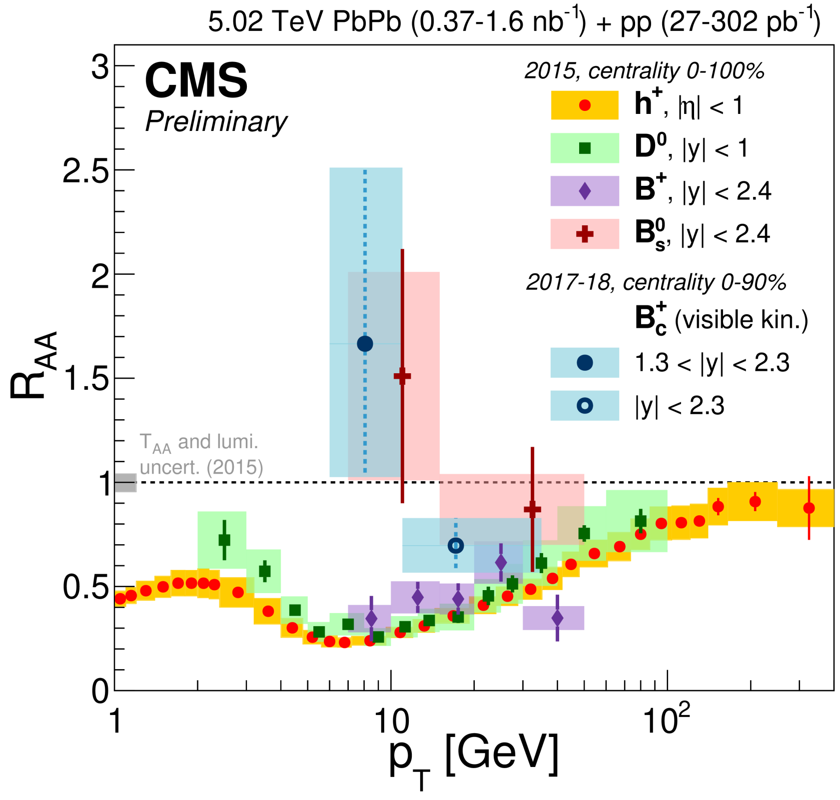
At low p_T, enhanced production of open heavy-flavour (D_s^+, B_s^0) with strangeness
→ **hadronisation via recombination in a strangeness-rich medium**

At mid p_T, B_s^0 and B_c^+ less suppresed than D, B, bottomonia and light hadrons
→ additional evidence that **recombination is at play?**

First measurement of non-prompt D_s^+/D^0 in central HI



First measurement of $B^+_c \rightarrow J/\psi+\mu+\nu_\mu$

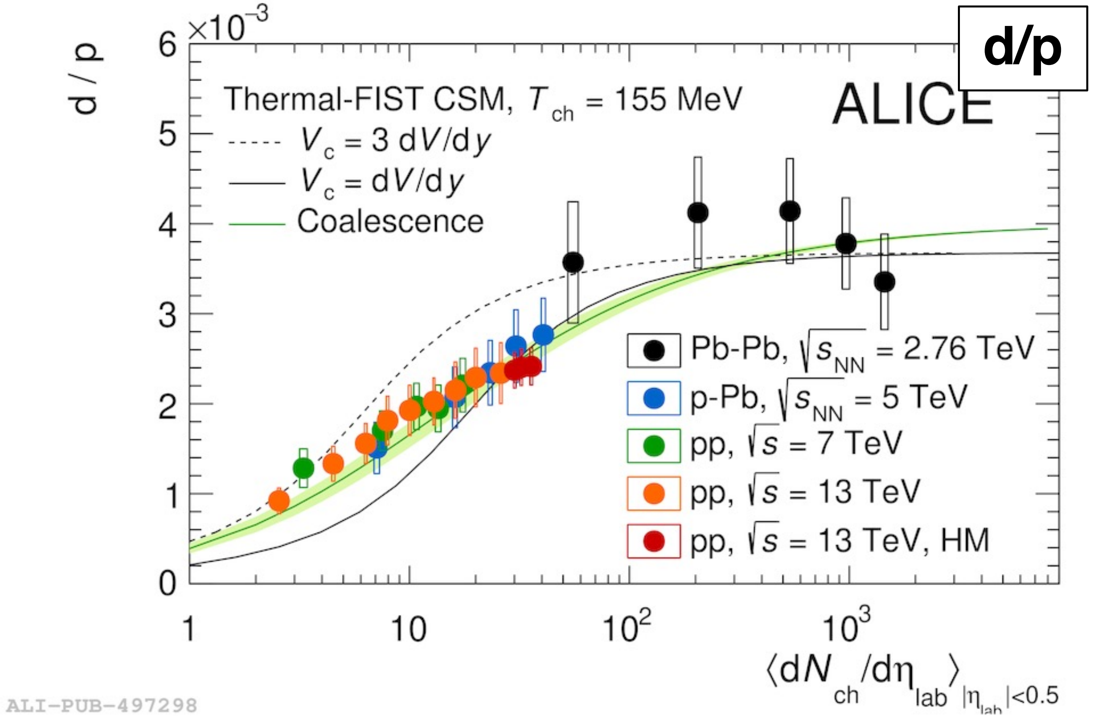


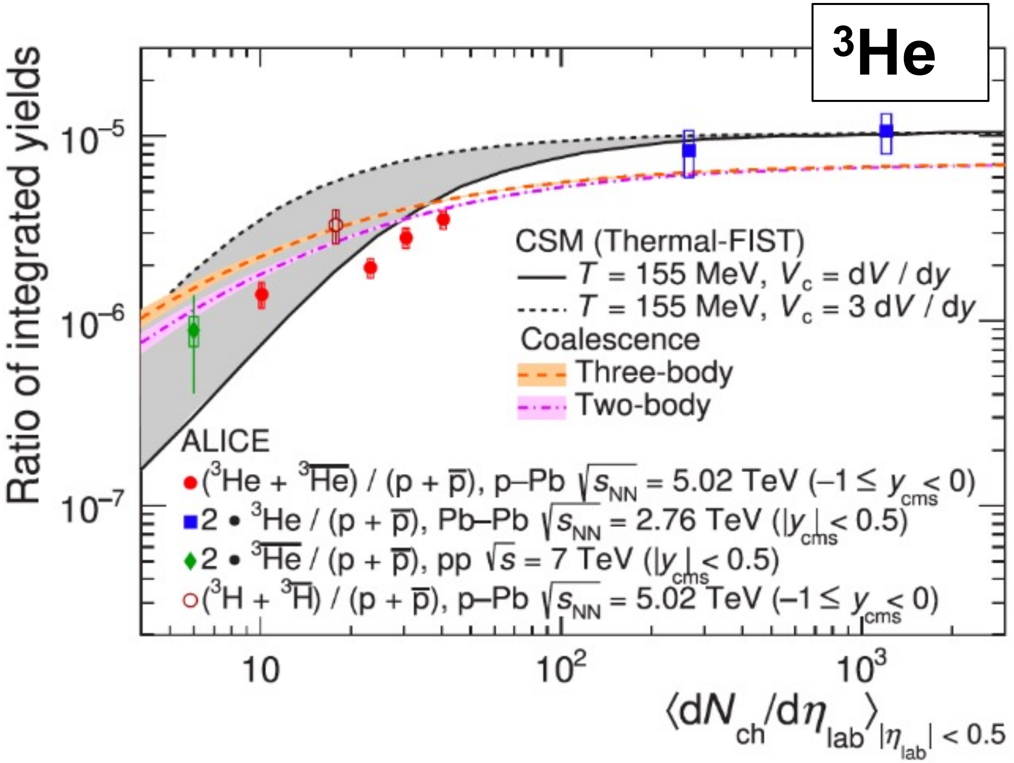
From hadrons to light (anti)nuclei

Smooth evolution of production of rare light nuclei as a function of the system size from pp to Pb-Pb

→ puzzle of the **survival of loosely bound states** (E_B ~ 2 MeV) in the hot hadron gas (T ~ 150-100 MeV) produced in heavy ion collisions

→ **nucleosynthesis in hadronic collisions**: statistical hadronization vs coalescence





arXiv:2109.13026, EPJC 80 (2020) 889

Nucleosynthesis by coalescence (in a nutshell)

By coalescence, nuclear clusters form when nucleons are close in phase space
- dependence on momentum
- dependence on the source size
- dependence on the nucleus internal structure

→ can be tested with a system-size (multiplicity) scan, by comparing different species!

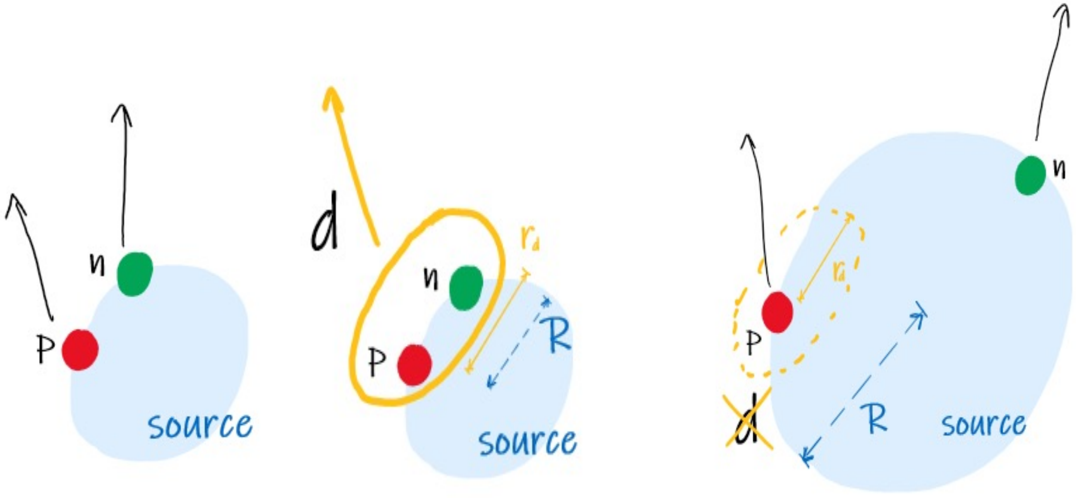
→ **crucial test with hypertriton** (Λpn): loosely bound (B_Λ~ 130 keV) and large (r ~ 10-14 fm)

$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+(\frac{r_A}{2})^2}\right)^{3/2(A-1)}$$

Nucleon transverse mass (including momentum)

Source radius

Nucleus radius



Nucleosynthesis by coalescence (in a nutshell)

By coalescence, nuclear clusters form when nucleons are close in phase space

- dependence on momentum
- dependence on the source size
- dependence on the nucleus internal structure

$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+\left(\frac{r_A}{2}\right)^2}\right)^{3/2(A-1)}$$

Nucleon transverse mass (including momentum)

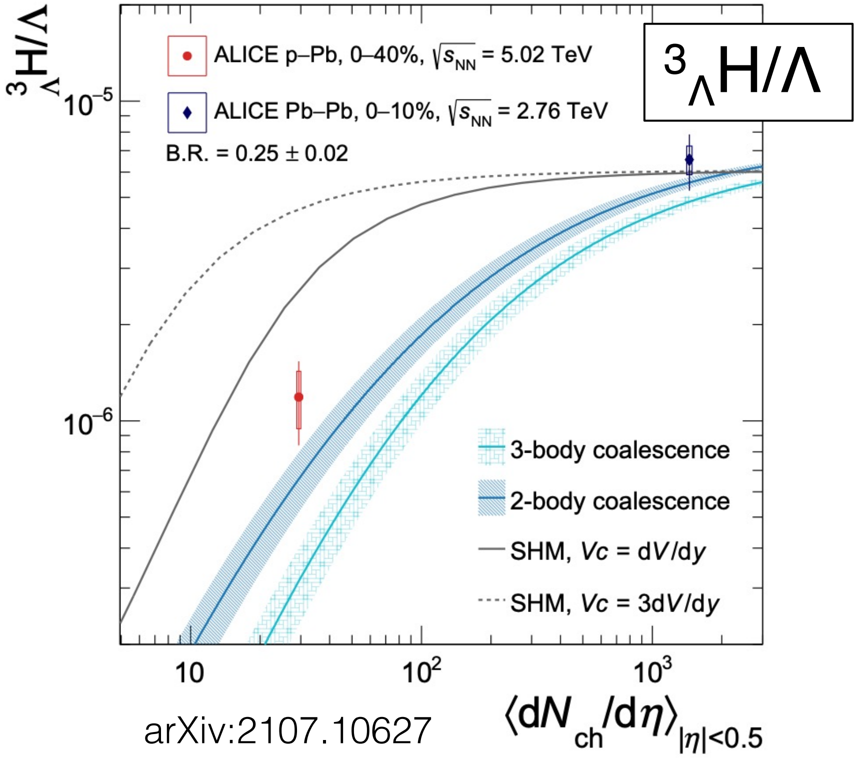
Source radius

Nucleus radius

→ can be tested with a system-size (multiplicity) scan, by comparing different species!

→ **crucial test with hypertriton** (Λpn): loosely bound (B_Λ~ 130 keV) and large (r ~ 10-14 fm)

→ **coalescence is supported by hypertriton data in small systems**



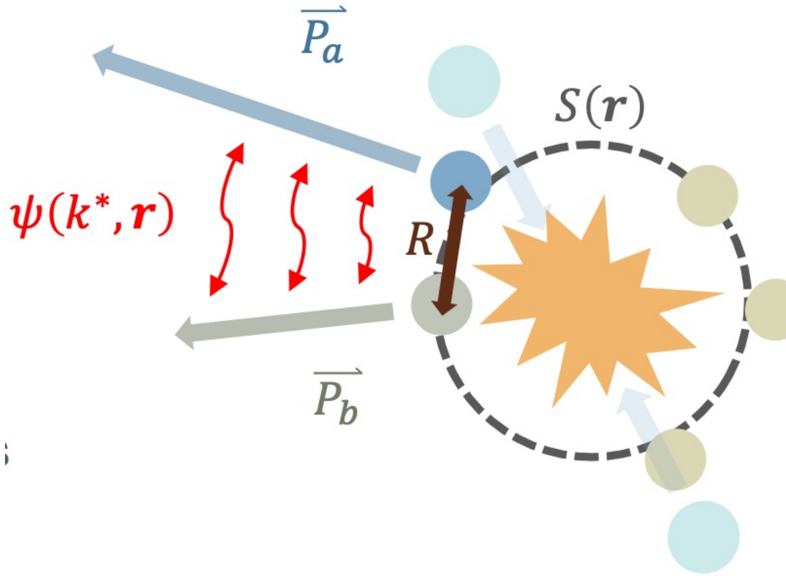
arXiv:2107.10627

A new approach to coalescence via femtoscopic correlations

Two-particle momentum correlations provide information about the final-state interaction among particles
[e.g., ALICE, Nature 588, 232–238 (2020), PLB 811 (2020) 135849]

Quantum-mechanical 2-body problem:

- Continuum solutions ⟶ information about the source
    - Two-particle momentum correlations used to measure size and lifetime of the system created in pp and heavy-ion collisions
- Discrete bound state solutions ⟶ coalescence
  [K.Blum, M. Takimoto, PRC 99, 044913 (2019); S. Bazak, S. Mrowczynski, EPJA 56, 193 (2020), K.Blum, FB, A. Kalweit, M.Puccio, PRC 103, 014907 (2021)]



Credits: ALICE/TUM

$$\mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2}(2\pi)^3 \int d^3\mathbf{r}\, |\phi_d(\mathbf{r})|^2\, \mathcal{S}_2(\mathbf{r}) \iff \mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2} \int d^3\mathbf{k}\, \mathcal{F}_d(\mathbf{k})\, \mathcal{C}_2(p, \mathbf{k})$$

Coalescence probability (d example)

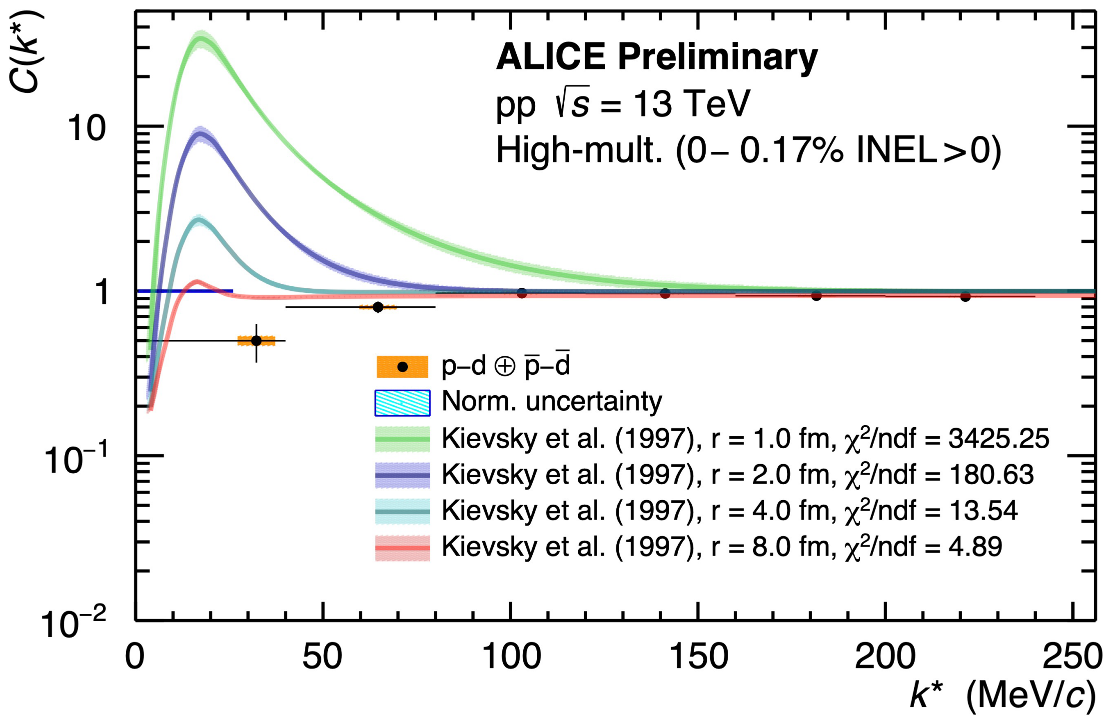
Nucleus wave function ⟺ Form factor

Source ⟺ Momentum correlation function

→ applications to cosmic ray physics and indirect dark matter searches

→ talk by L. Barioglio

Nuclei formation from the interaction point of view



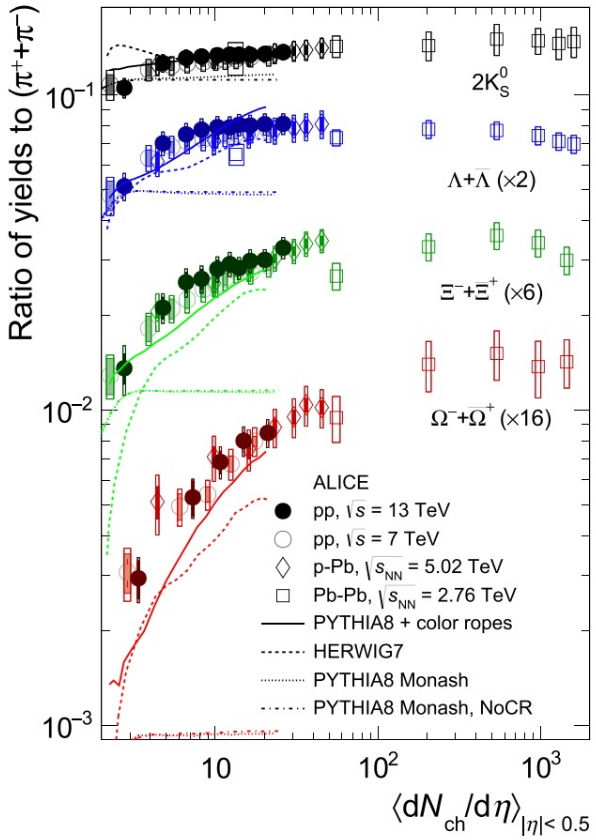
First measurement of the p-d correlation function in pp collisions at high energy shows a large disagreement with models at low pair momentum k*

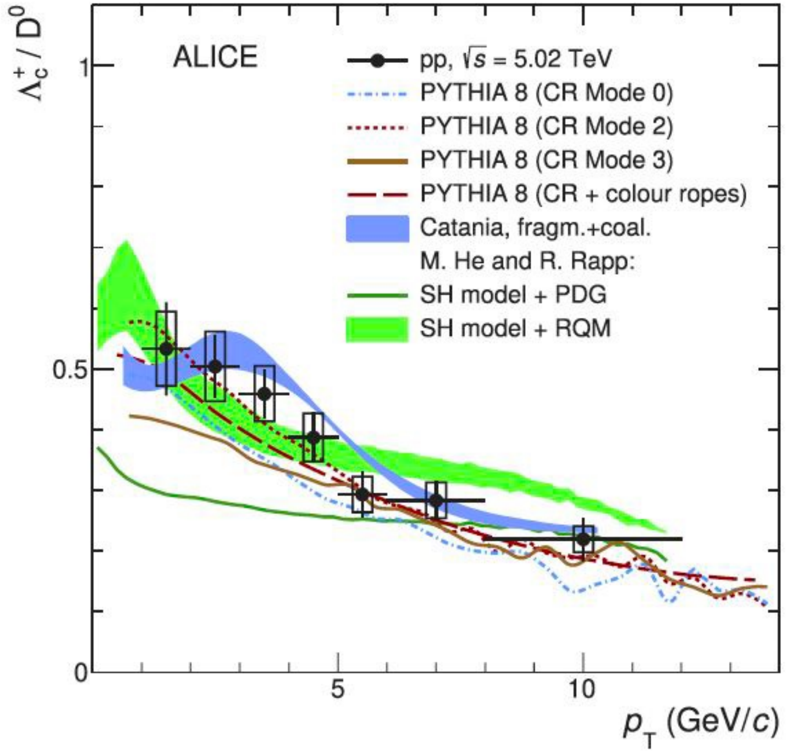
→ possible observation of ^{3}He formation at low k*?
→ consistent with later formation of deuterons

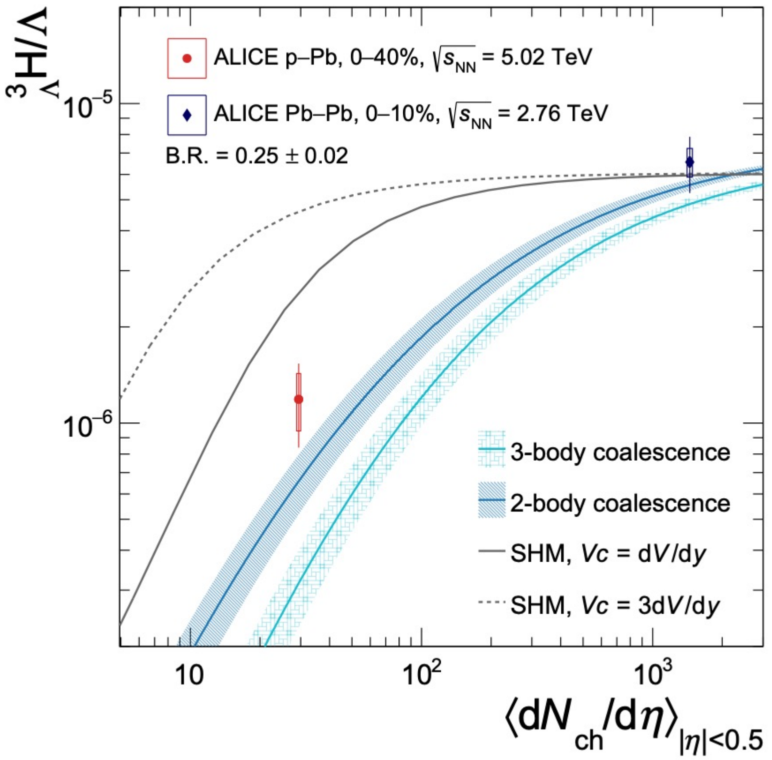
→ femtoscopic correlations as a powerful tool to study formation of bound nuclear states with more data at LHC Run 3

New measurements in the light and heavy flavour sector are powerful input to constrain models of hadronization in-medium and in-vacuum and particle production mechanisms

→ Interesting times ahead thanks to new data soon coming from the LHC Run 3!



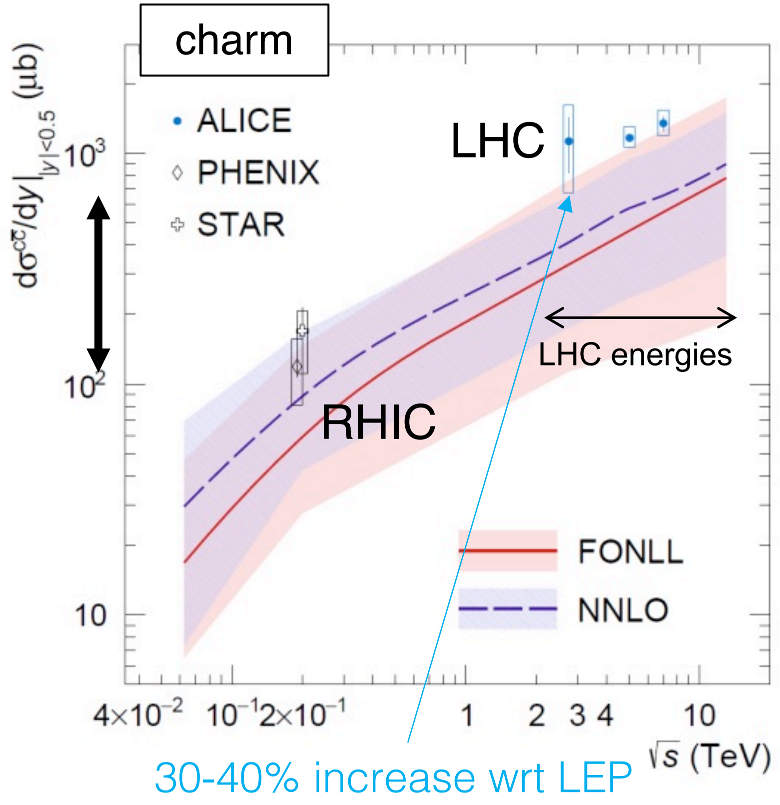




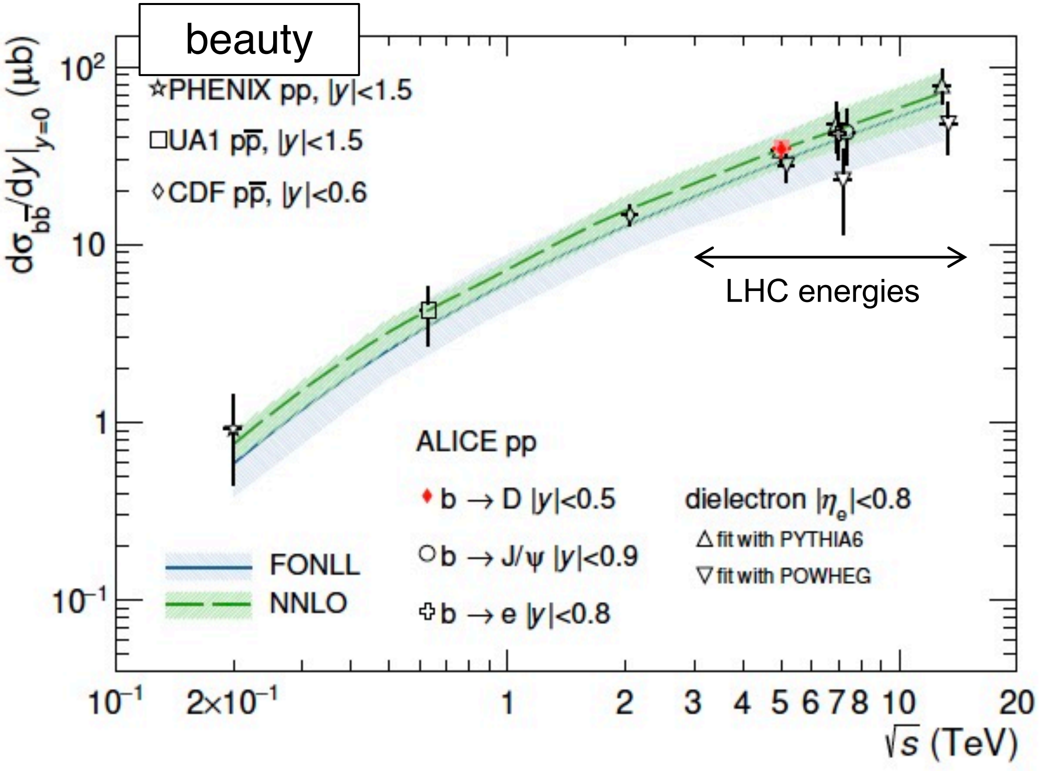
Thank you!

$c\bar{c}$ and $b\bar{b}$ cross section in pp collisions at the LHC

$c\bar{c}$ cross section at 5.02 TeV recently updated with latest measurements of charm mesons and **baryons**
Most precise measurement of $b\bar{b}$ cross section at 5.02 TeV with **non-prompt D mesons**
Measurements described by FONLL and NNLO calculations



arXiv:2105.06335



JHEP 05 (2021) 220

Accessing the strong potential among hadrons

Two-particle femtoscopic correlations provide information about

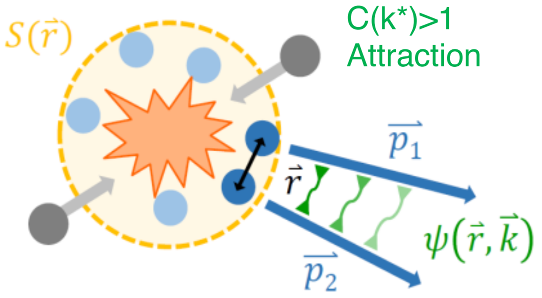
⟶ final-state interactions among hadrons

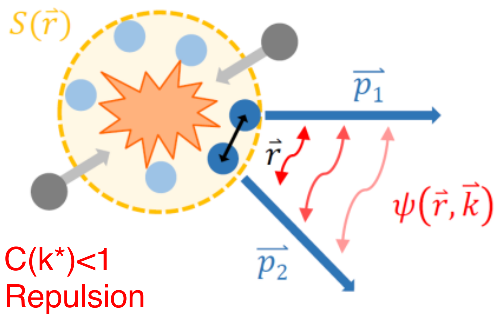
- direct comparison to ab initio **QCD calculations**

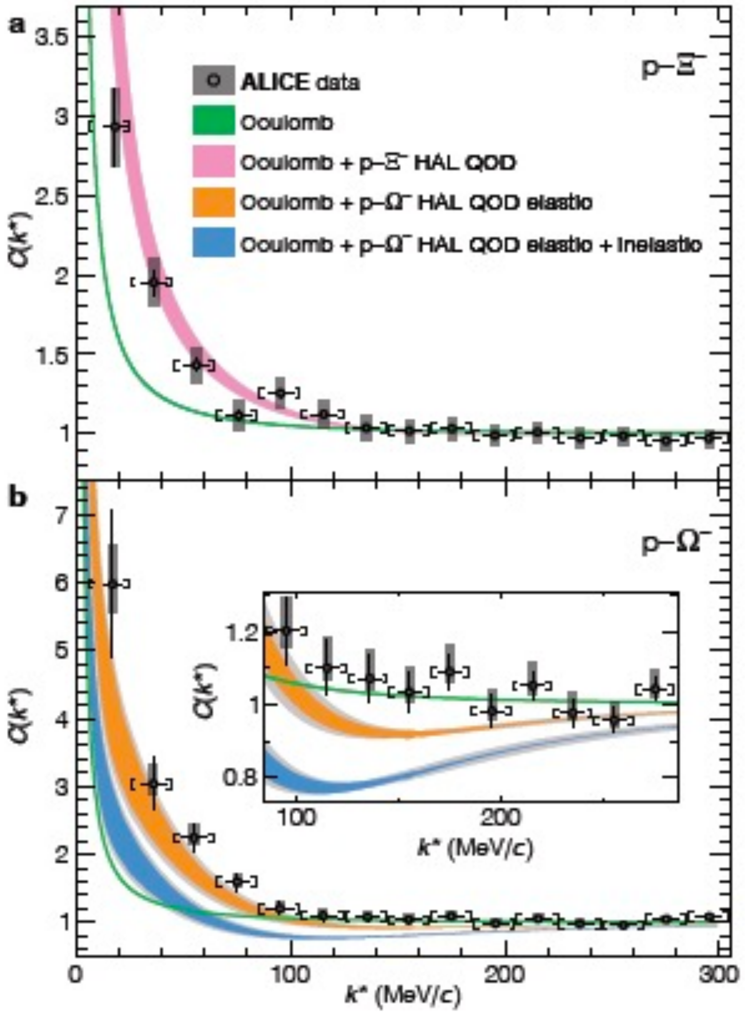
⟶ **source** (continuum) size and lifetime

⟶ **coalescence** (discrete bound state solutions)

A new and comprehensive programme of measurements in pp, p-A, AA at the LHC to **study of the residual strong interaction among (strange) hadrons and Y-N interaction** (relevant for neutron stars EoS)

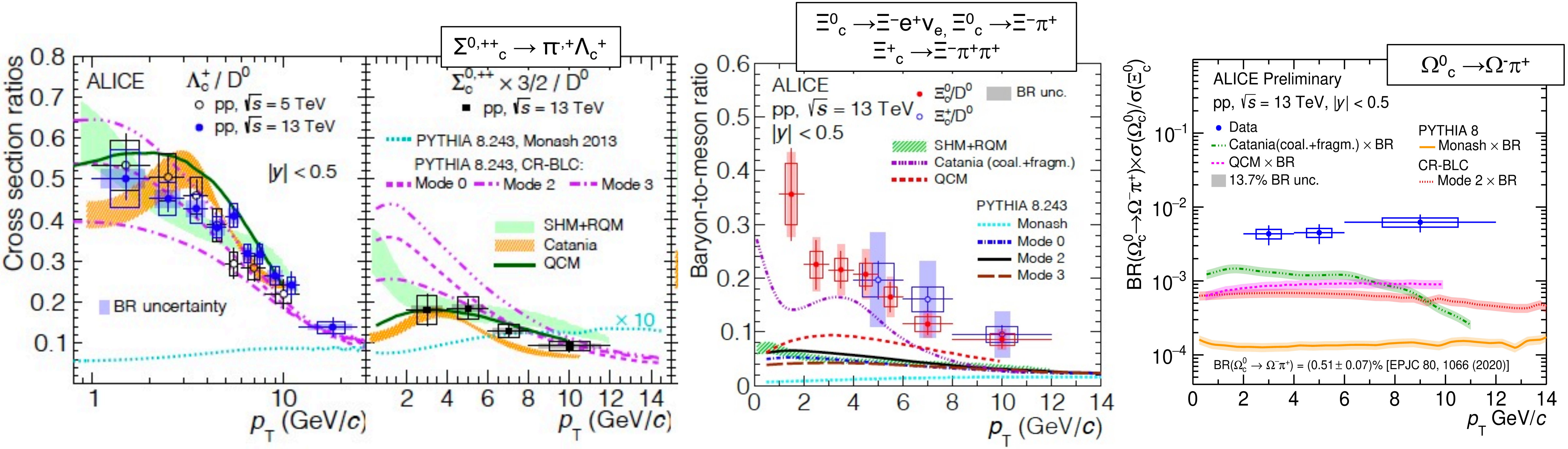






Nature 588 (2020) 232–238

Charming baryons



Modification of hadronization in presence of MPI and color reconnection (Pythia) or a hint that charm hadronisation in pp collisions involves coalescence (Catania model) of charm quark with light quarks?

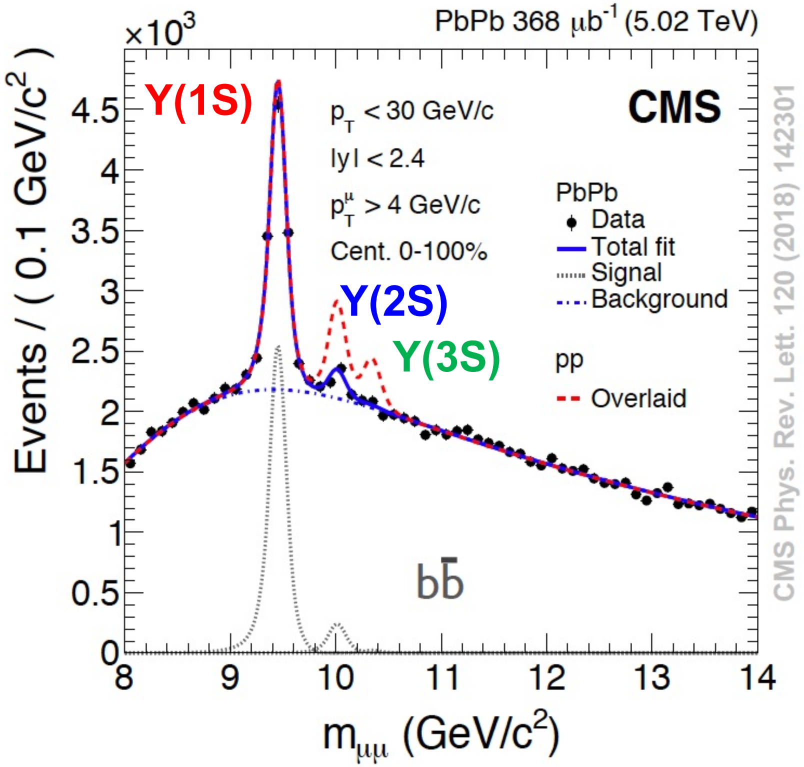
arXiv:2105.05616, arXiv:2105.05187, arXiv:2106.08278

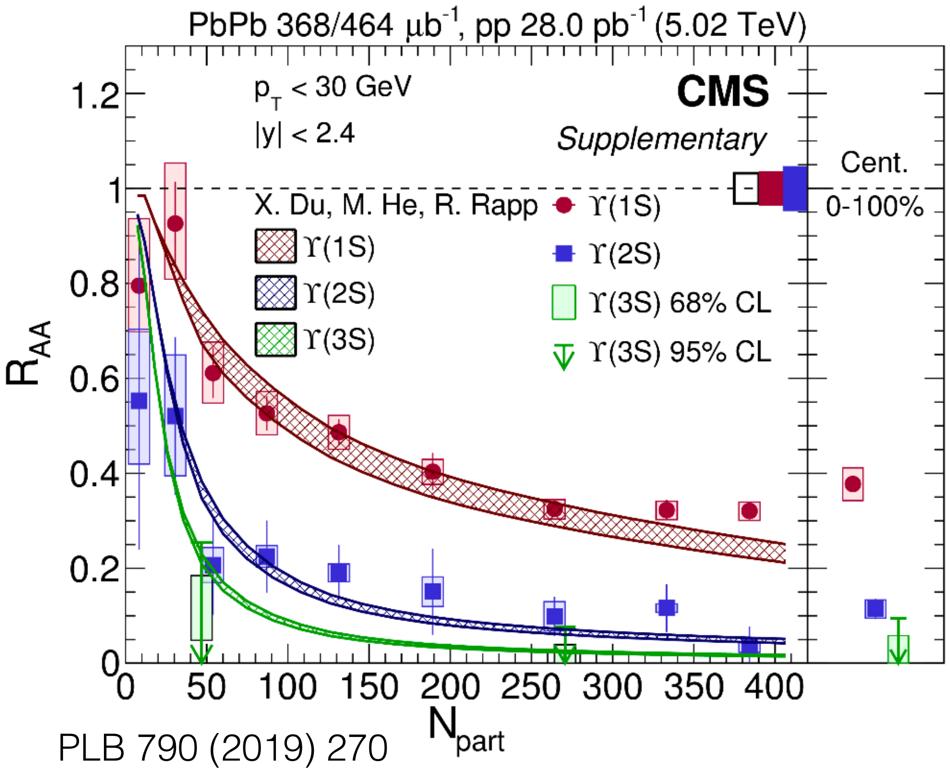
Sequential suppression of bottomonium states

Sequential suppression of excited bottomonium states observed

→ Centrality dependence consistent with **progressive suppression in a hotter medium**

→ Quarkonium as a **thermometer** for QGP





PLB 790 (2019) 270

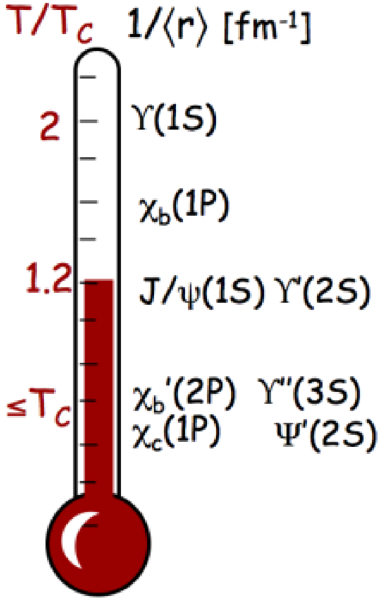


Figure: A. Mocsy
arxiv:0811.0337