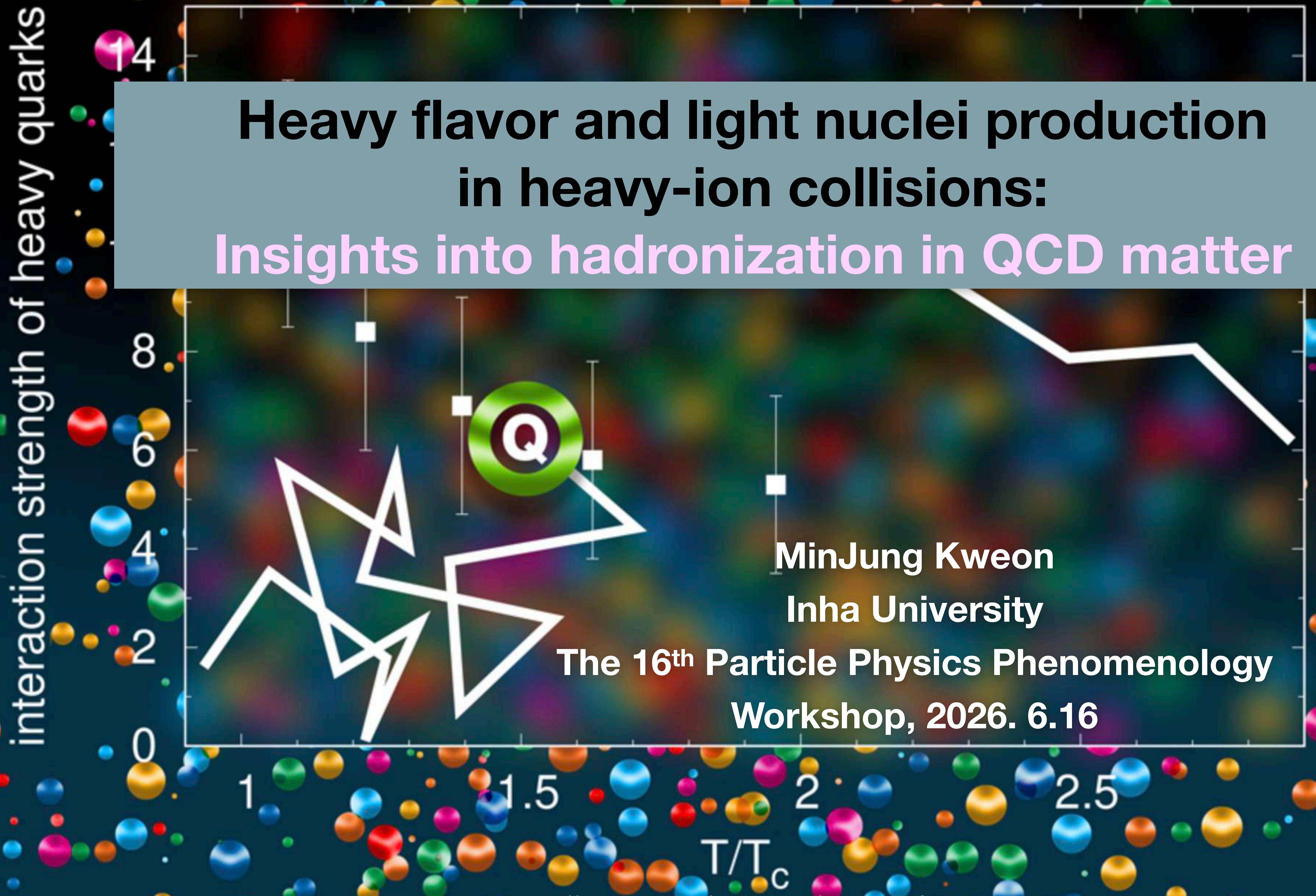
Heavy flavor and light nuclei production in heavy-ion collisions:
Insights into hadronization in QCD matter

MinJung Kweon

Inha University

The 16th Particle Physics Phenomenology Workshop, 2026. 6.16



https://www.bnl.gov/newsroom/news.php?a=121223

Cabibbo and Parisi: quark liberation at high T, 1975

T_H not maximum attainable, simply: for T > T_H quarks not confined any more!

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

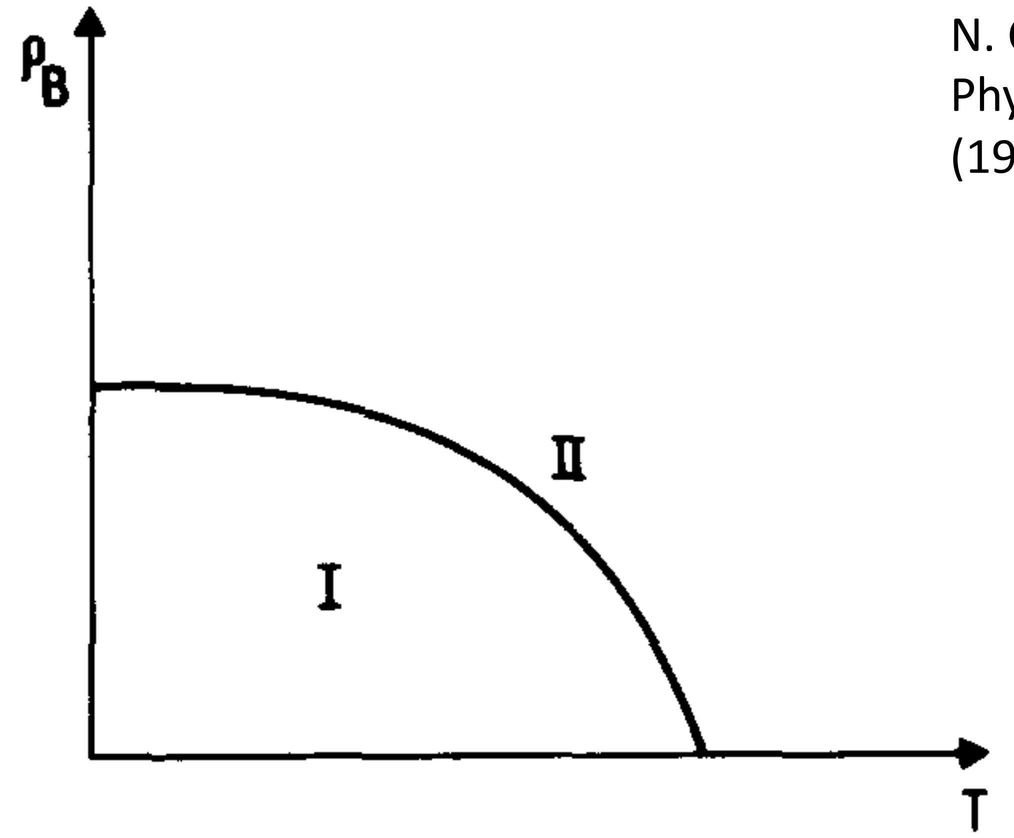


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

N. Cabibbo, C. Parisi
Phys. Lett. B 59
(1975) 67

First phase diagram for nuclear matter: Cabibbo, Parisi PL B59 (1975): "We suggest ... a different phase of the vacuum in which quarks are not confined"

Collins and Perry: "quark soup" in neutron stars?, 1975

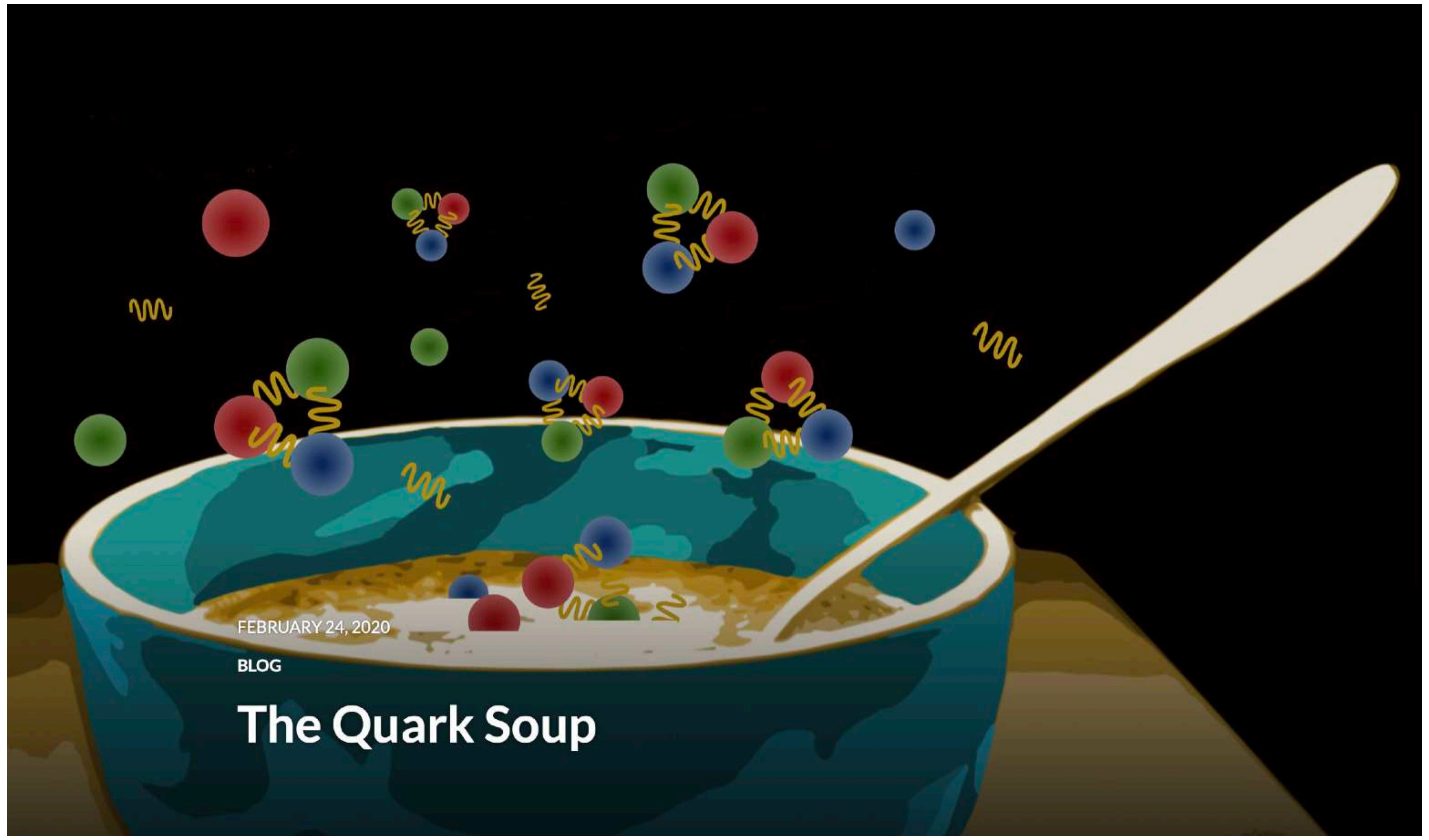
Volume 34, Number 21 PHYSICAL REVIEW LETTERS 26 May 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

There are several astrophysical and cosmological situations where one needs the equation of state for matter of densities greater than 10^{15} g cm^{-3}: in particular, the center of a neutron star,[1,2] the early phases of the big-bang universe,[3] and black-hole explosions.[4] However, such densities might at first sight appear to be outside the range of normal physics, so that nothing can



figures by Anastasia Ershova

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

The quarks become free at sufficiently high density.

Heavy-ion physics, and what we learned

Understanding the fundamental properties of strongly interacting quark gluon-plasma (QGP) is one of the key goals in high-energy nuclear physics.

What is the bulk behavior of QCD?

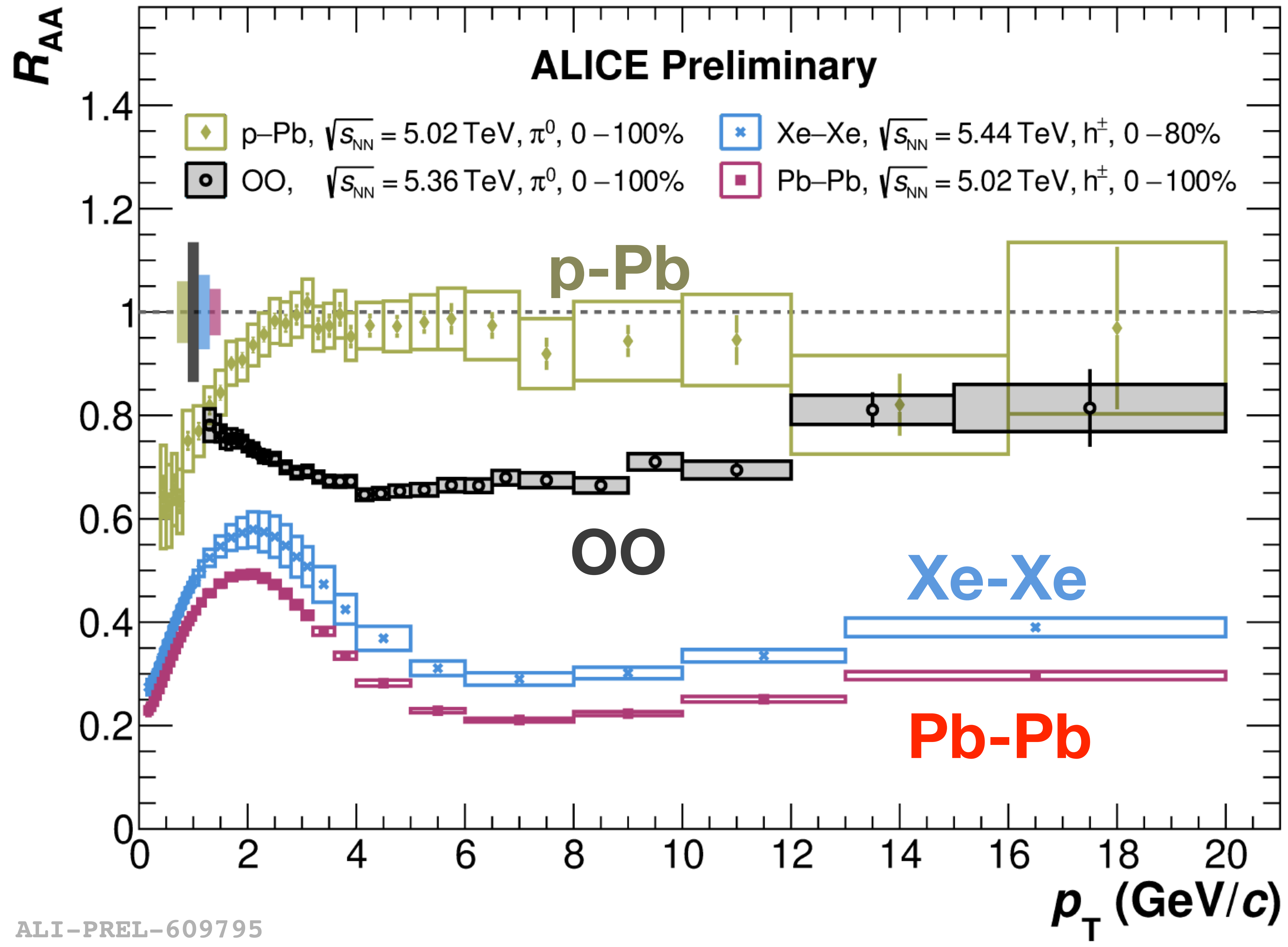
What are the collective features of QCD (Dynamics of heavy-ion collisions)?

How does the transition from confined matter to deconfined QGP occur?

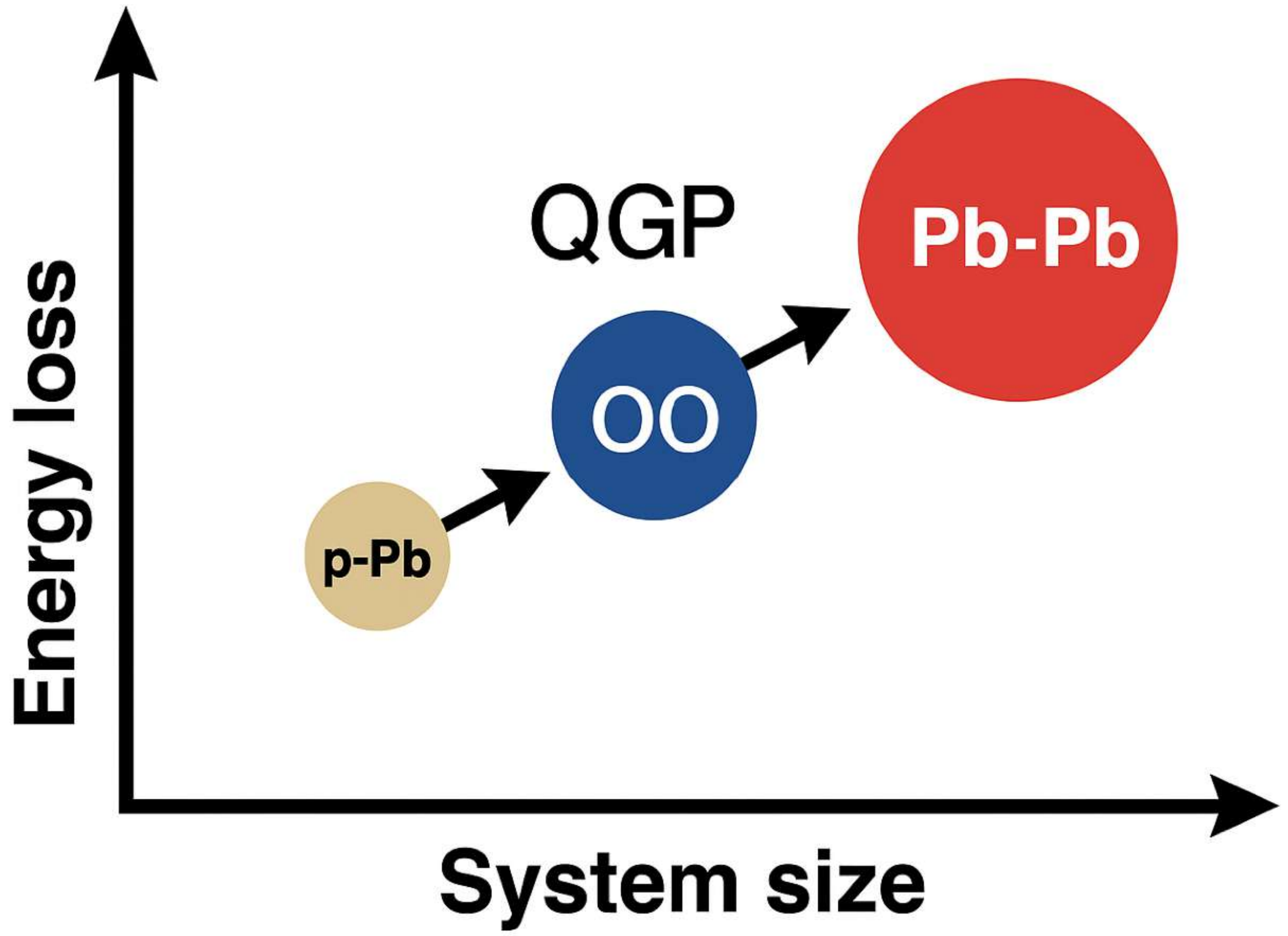
QGP as seen at the LHC

- Energy density > 10 GeV/fm^3
- Colour charge deconfined
- Strong energy loss for hard partons
- Hydro-dynamic expansion like a very-low viscosity liquid
- Hadronization as in thermal equilibrium

Probing QGP properties: In-medium energy loss



The Hottest Matter Ever Created: T > 10^{12} K!

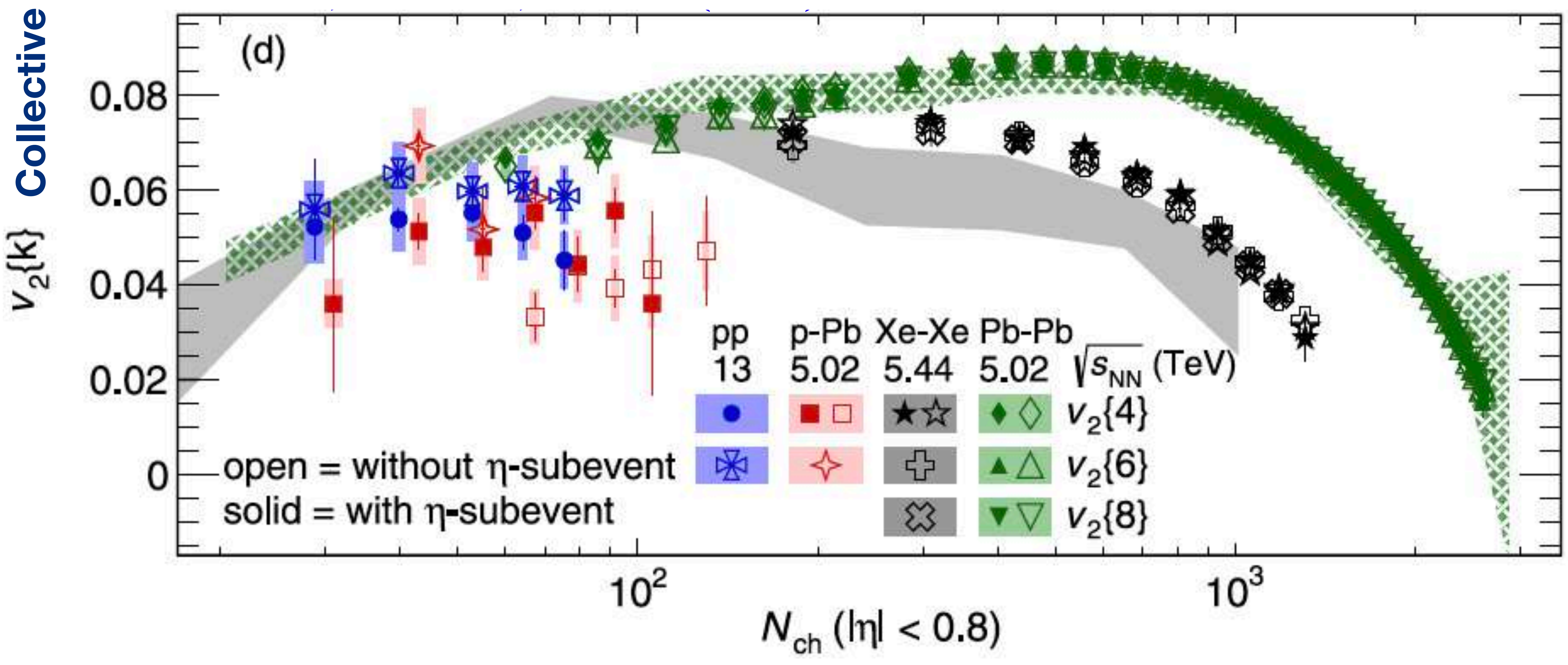


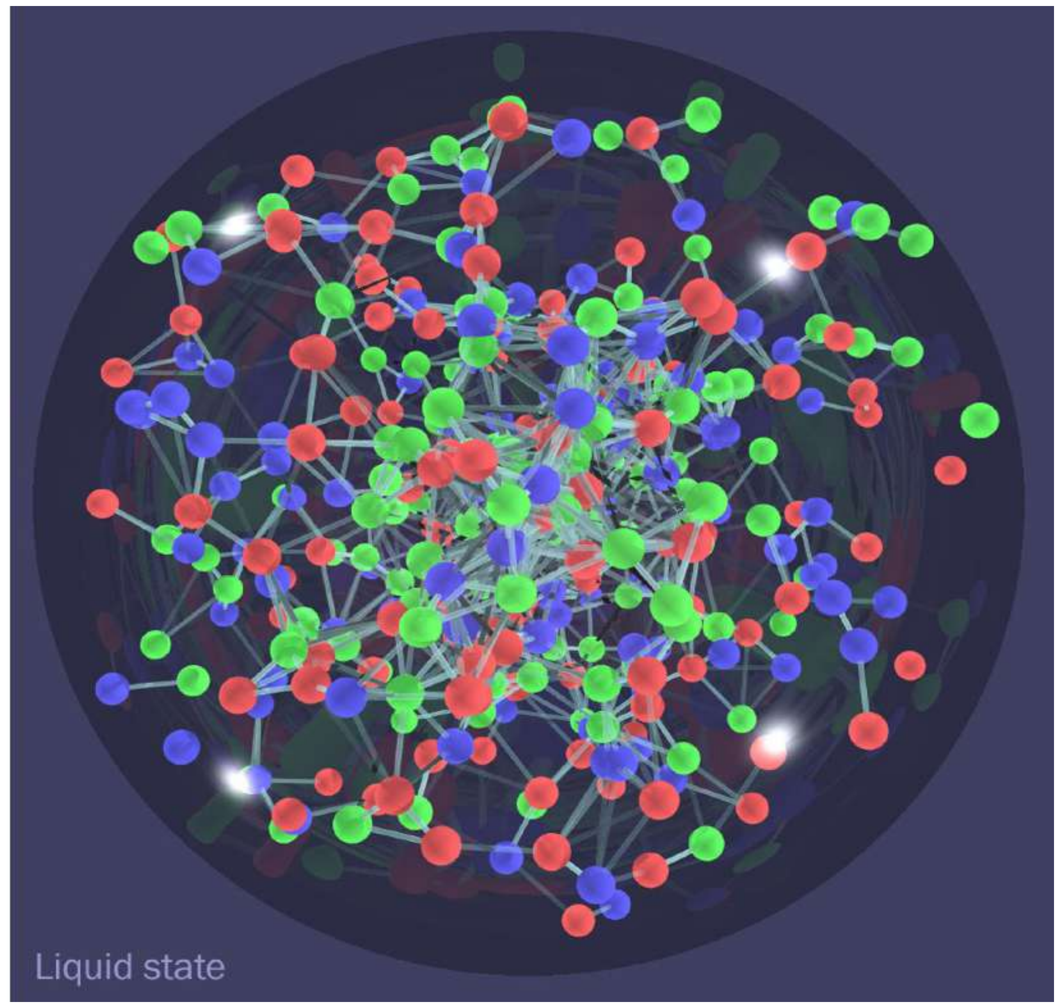
- The larger the system, the hotter and denser the QGP — leading to greater energy loss of traversing partons (R_{AA}<1)
- Energy loss patterns are observed even in light-ion (O–O) collisions → Providing a crucial clue to the question: can QGP be formed even in small systems?

Probing QGP properties: Collective flow and fluid-like behavior

A strongly coupled system that flows collectively — like a perfect fluid!

Collective flow



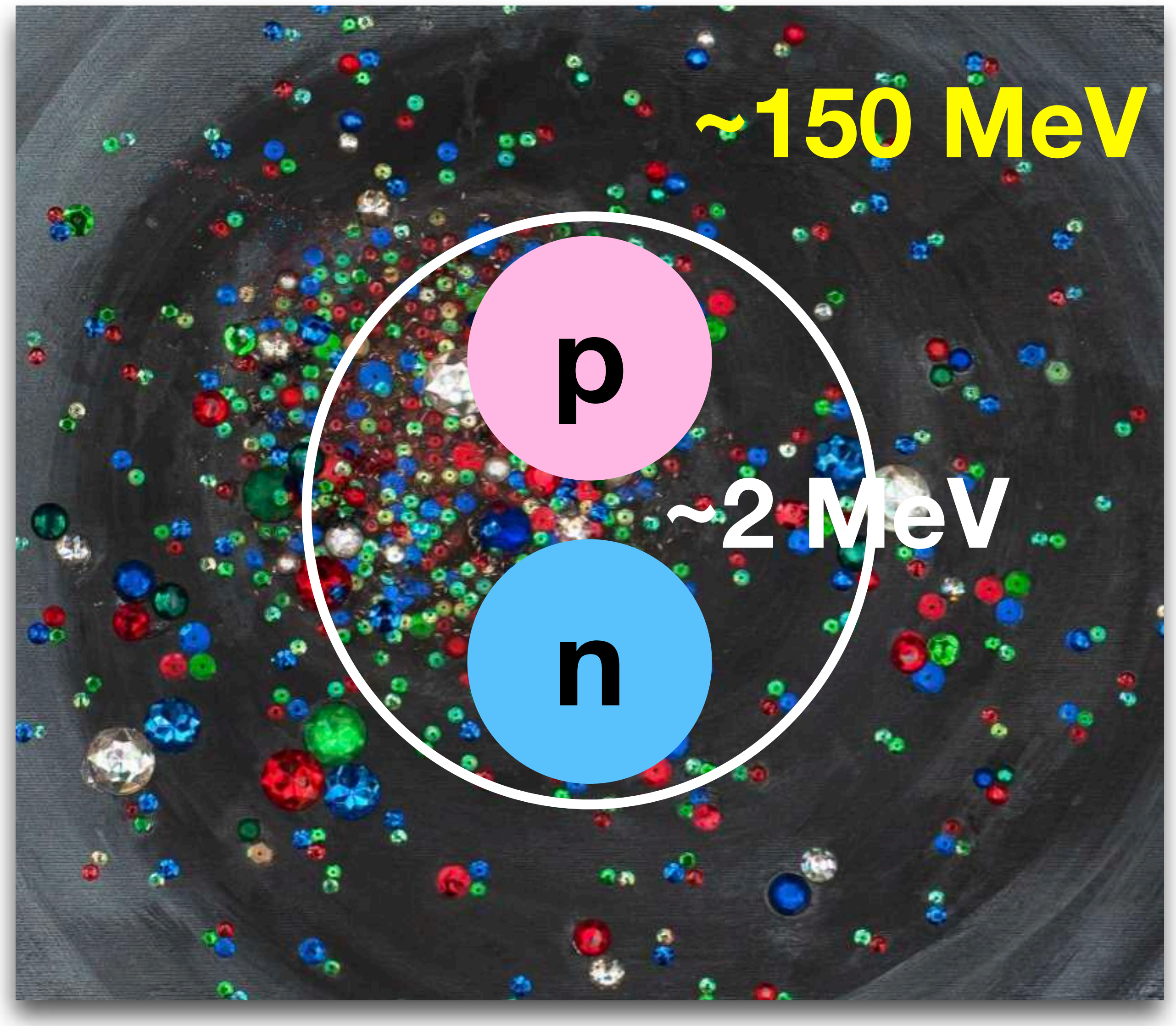


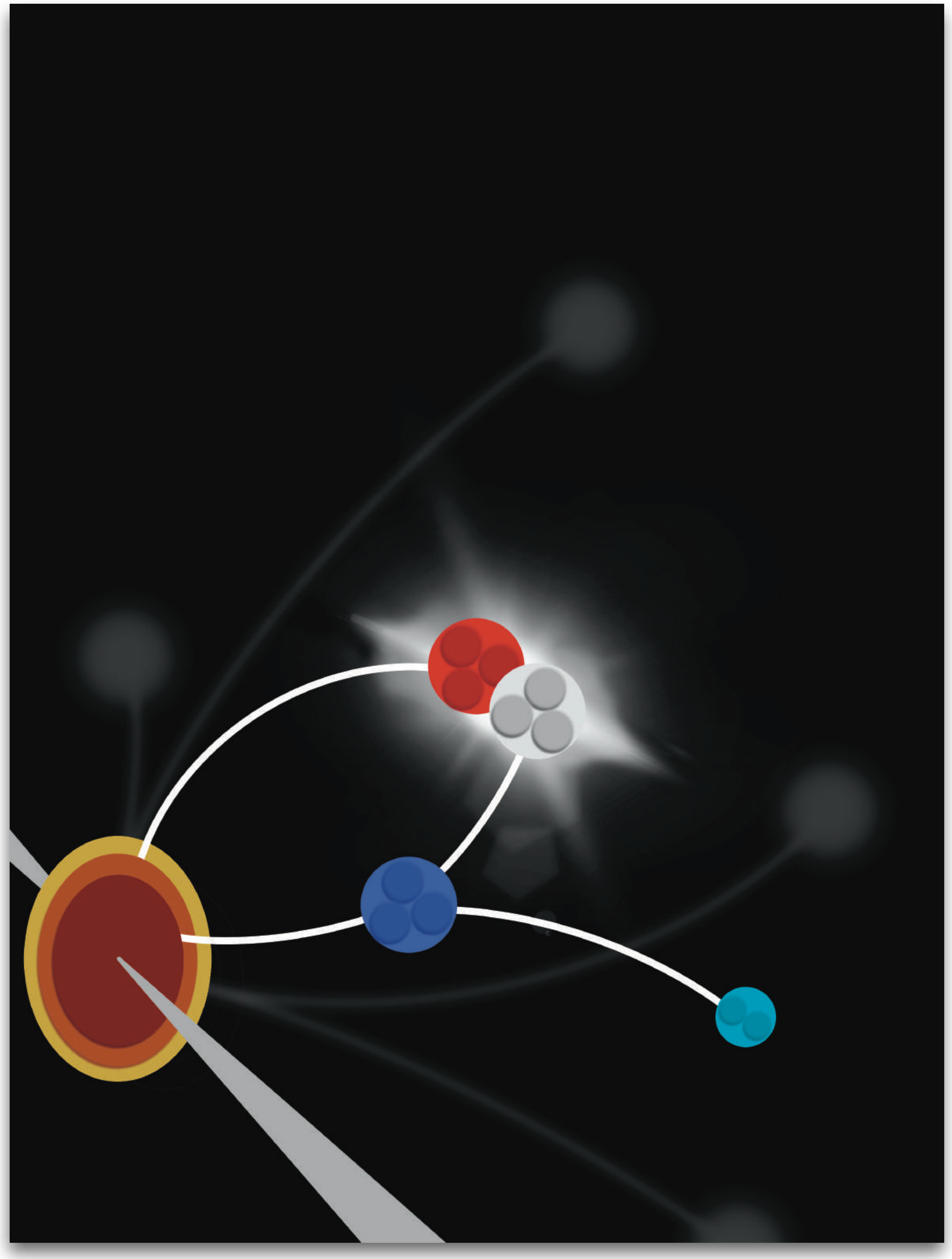
- Elliptic flow (v_2) increases with system size — the stronger the flow, the more pronounced the fluid-like behavior of the QGP
- When the number of produced particles is sufficiently large, elliptic flow emerges even in small systems → Collective fluid-like flow discovered even in small collision systems such as proton–proton collisions!

ALICE Unravels the Deuteron Production Mechanism: Nature, Dec. 2025

How does the deuteron — bound by only 2.2 MeV — form and survive in such an extreme environment?

Experimentally demonstrated that nucleons produced from the decay of short-lived resonances such as Δ, created immediately after the collision, coalesce to form deuterons!





ALICE

CERN

CERN-EP-2025-081
31 March 2025

Revealing the microscopic mechanism of deuteron formation at the LHC

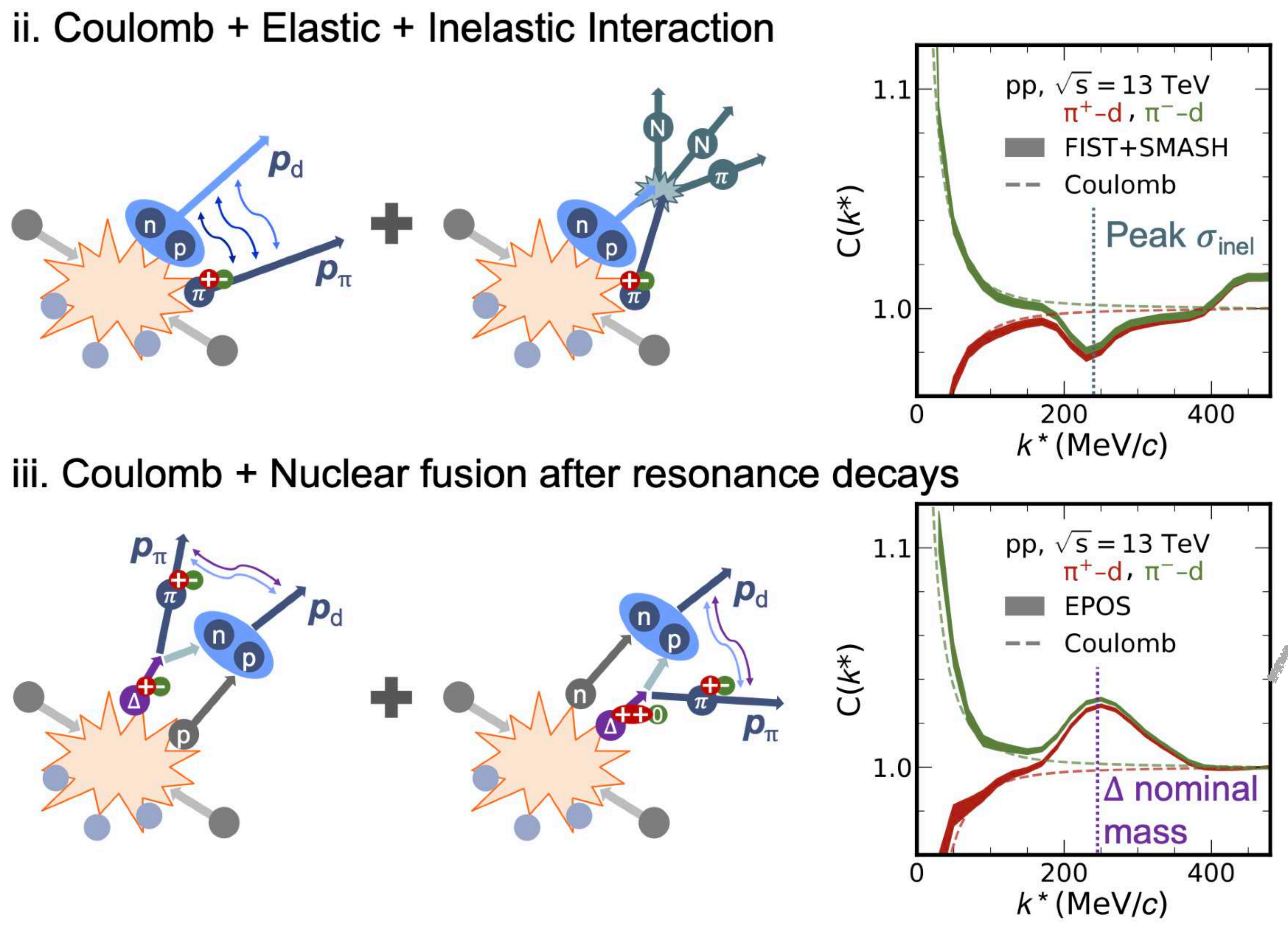
ALICE Collaboration*

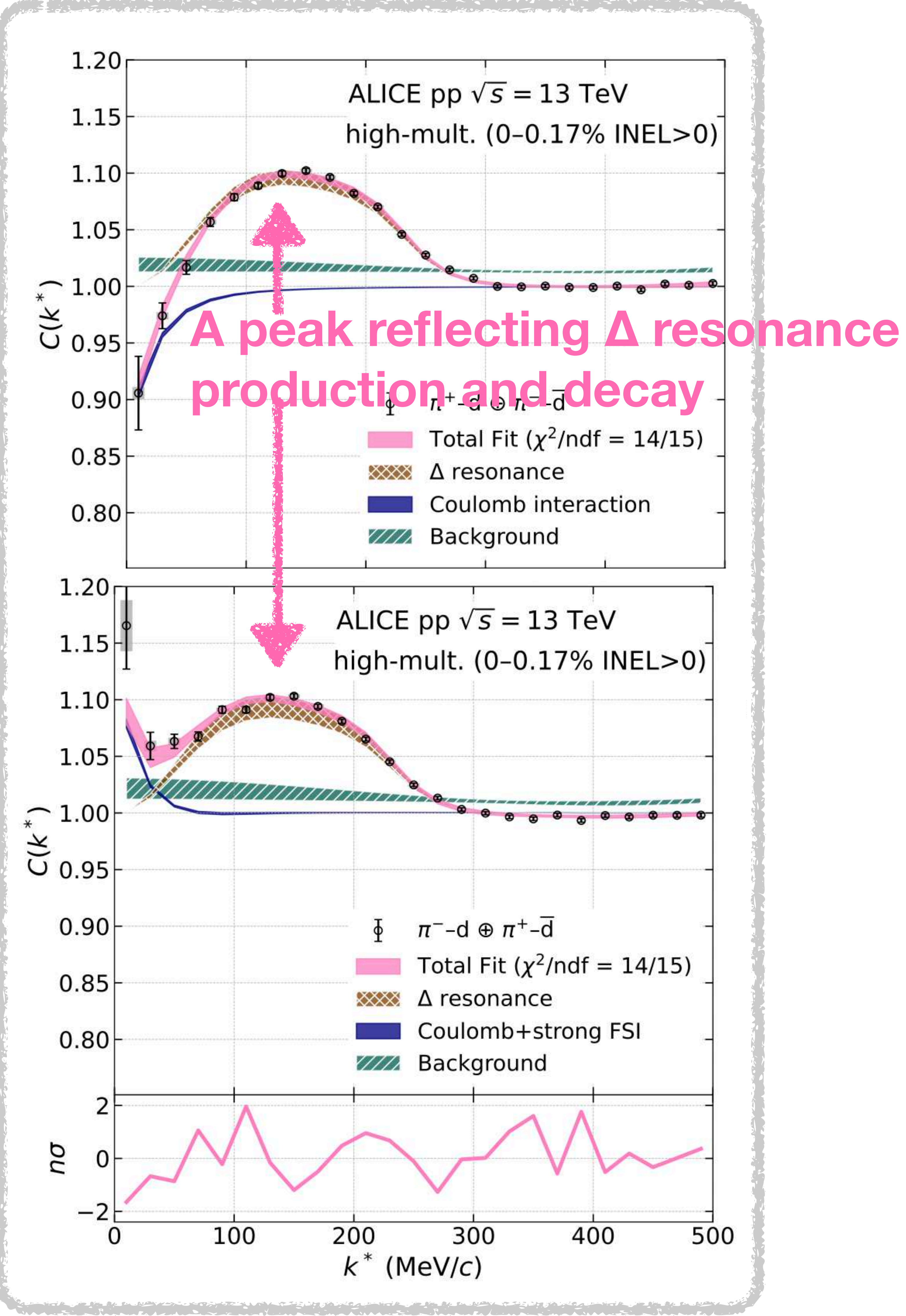
Abstract

The formation of light (anti)nuclei with mass number A of a few units (e.g., d, ^{3}He, and ^{4}He) in high-energy hadronic collisions presents a longstanding mystery in nuclear physics [1, 2]. It is not clear how nuclei bound by a few MeV can emerge in environments characterized by temperatures above 100 MeV [3–5], about 100,000 times hotter than the center of the Sun. Despite extensive studies, this question remained unanswered. The ALICE Collaboration now addresses it with a novel approach using deuteron–pion momentum correlations in proton-proton (pp) collisions at the Large Hadron Collider (LHC). Our results provide model-independent evidence that about 80% of the

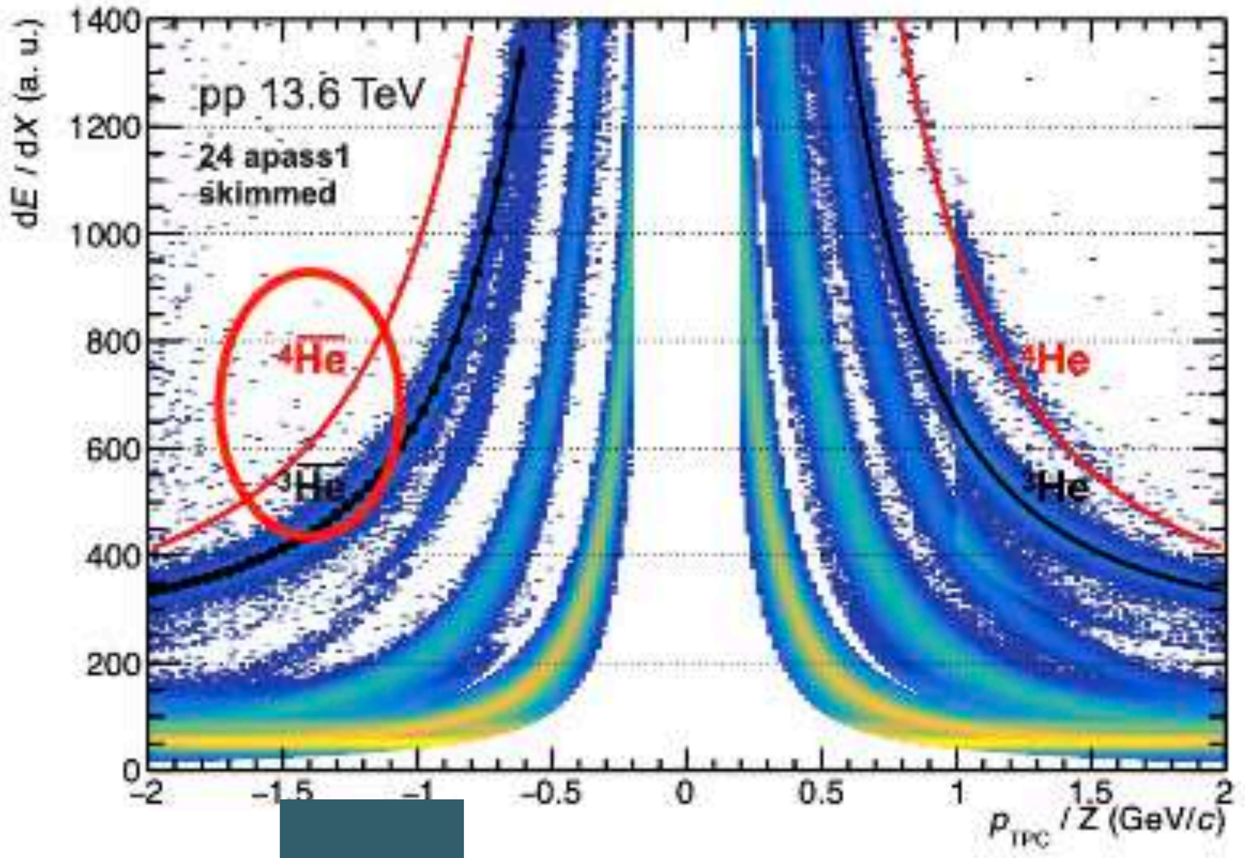
Deuteron production mechanism in pp collisions

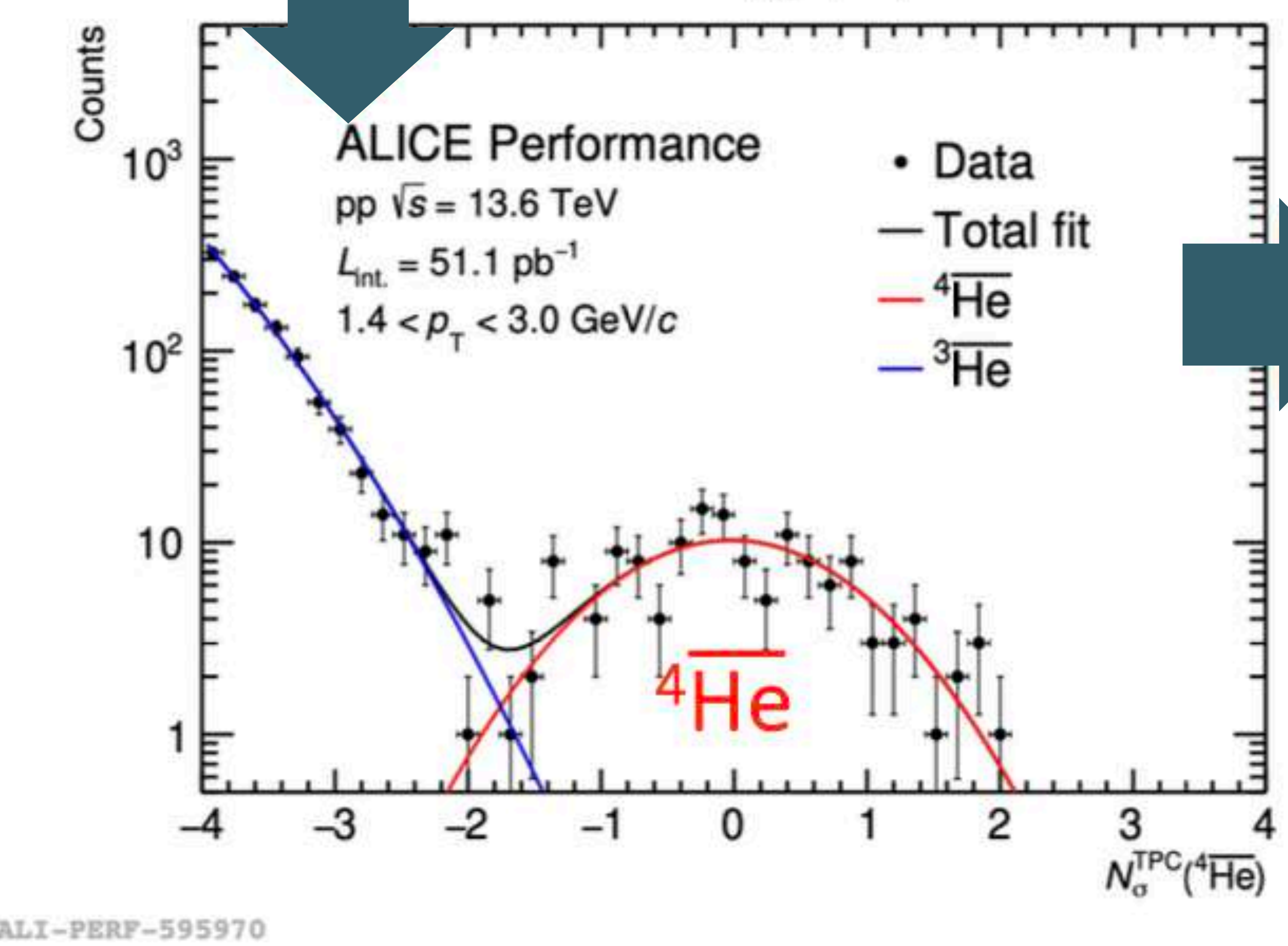
- **The actual microscopic mechanism of deuteron production is experimentally revealed through the π–d correlation function in heavy-ion collisions**
  Is Δ(1232) → N + π resonance decay the key pathway to deuteron formation?
  → Not simple coalescence — nearly 80% of deuterons are produced via coalescence of nucleons from Δ resonance decay



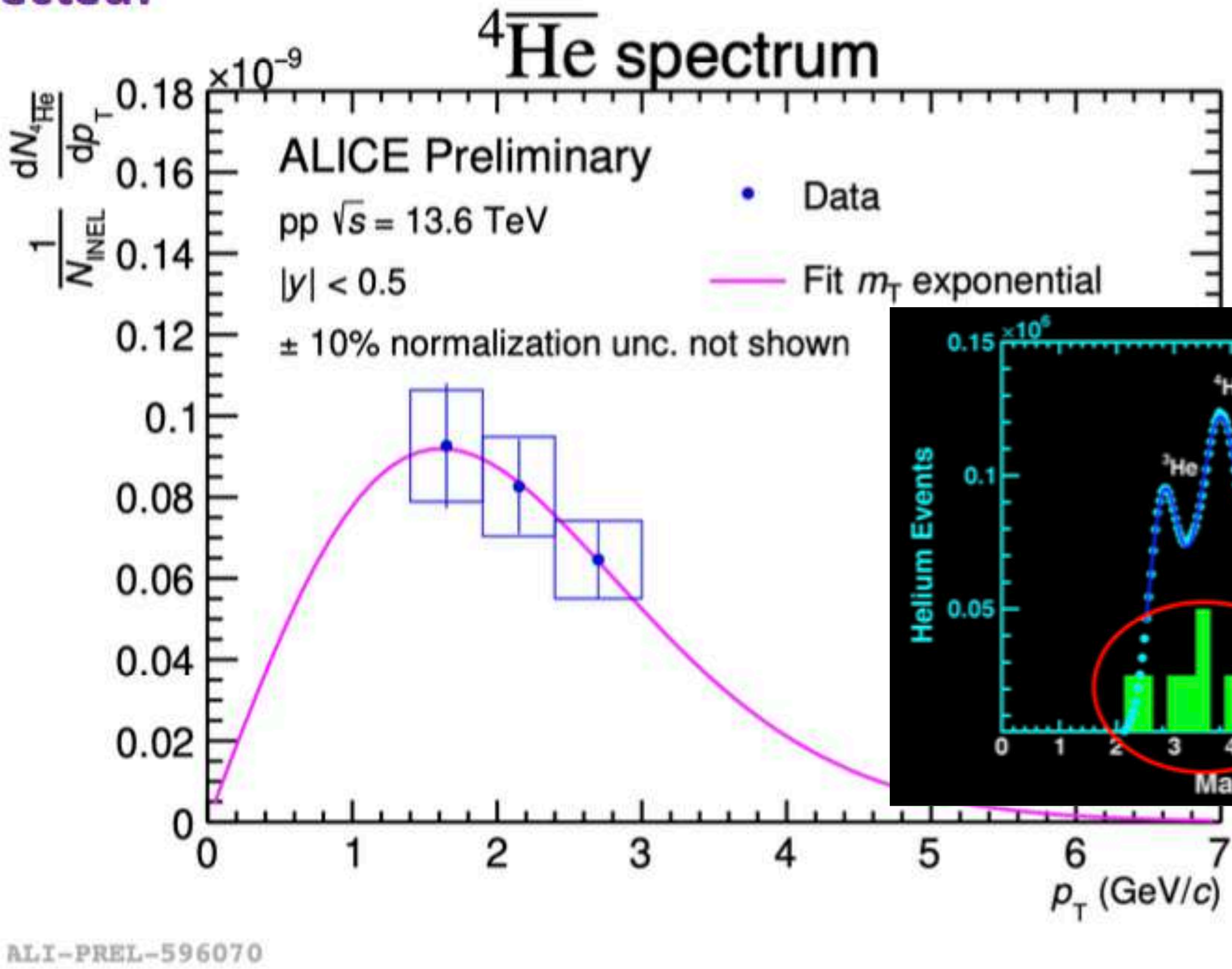


First observation of $^4\overline{\text{He}}$ in pp collisions

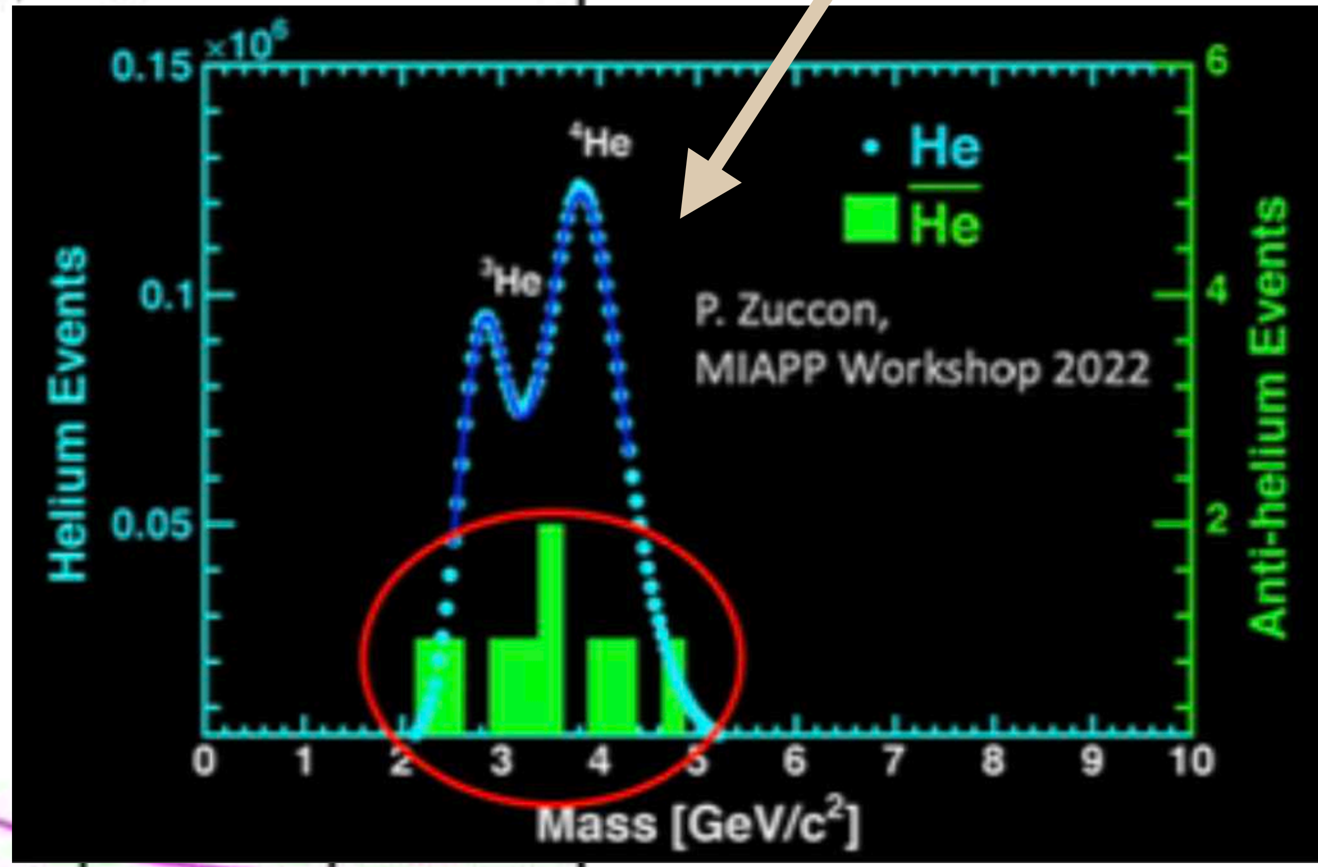




3 trillion events inspected!

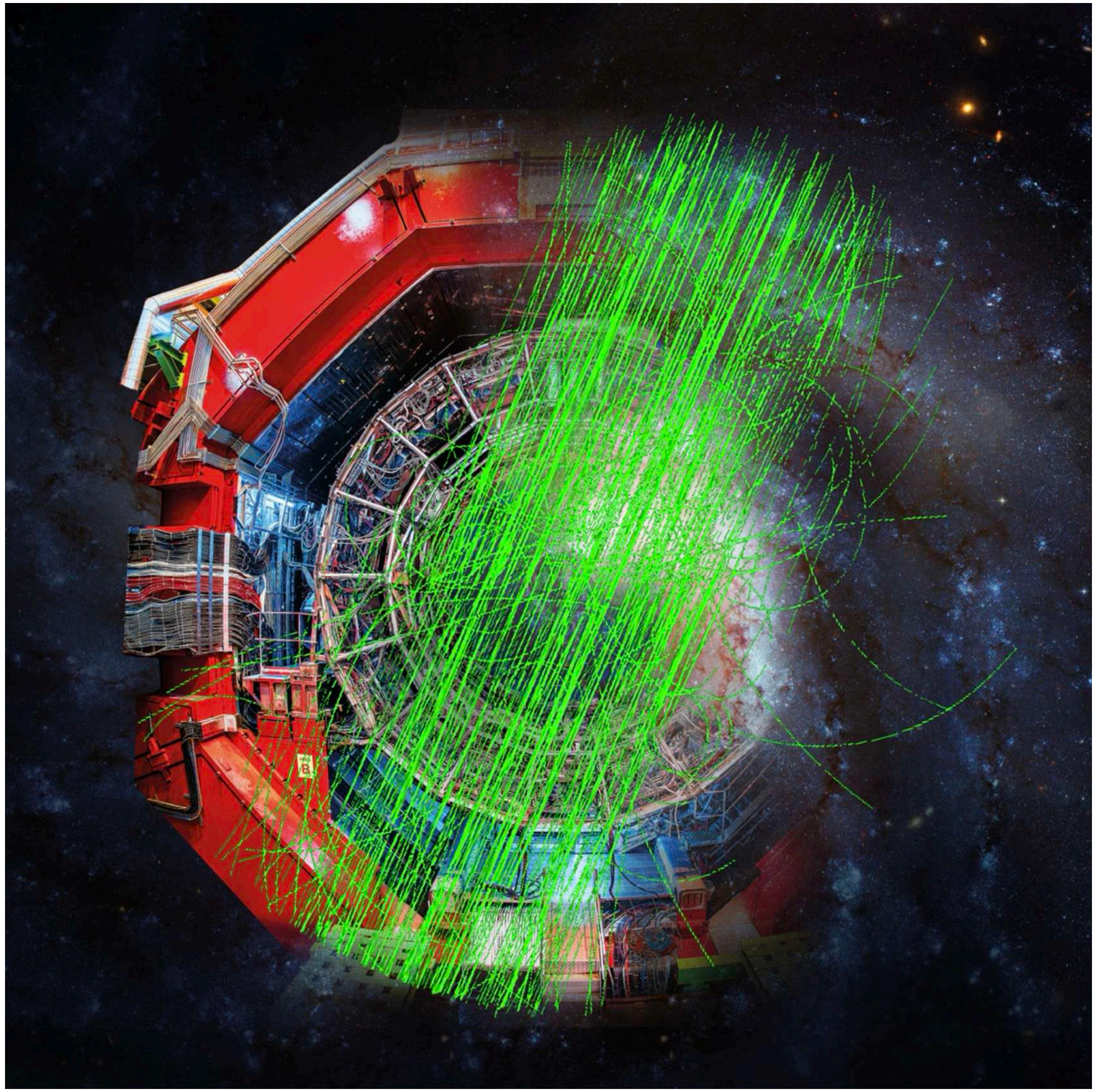


Anti-^{4}He events in AMS-02



- Clear anti-^{4}He peak in TPC dE/dx
- Important for anti-nuclei searches in space

Muon Multiplicity Distribution from 62.5 Days of Beam-Off Data



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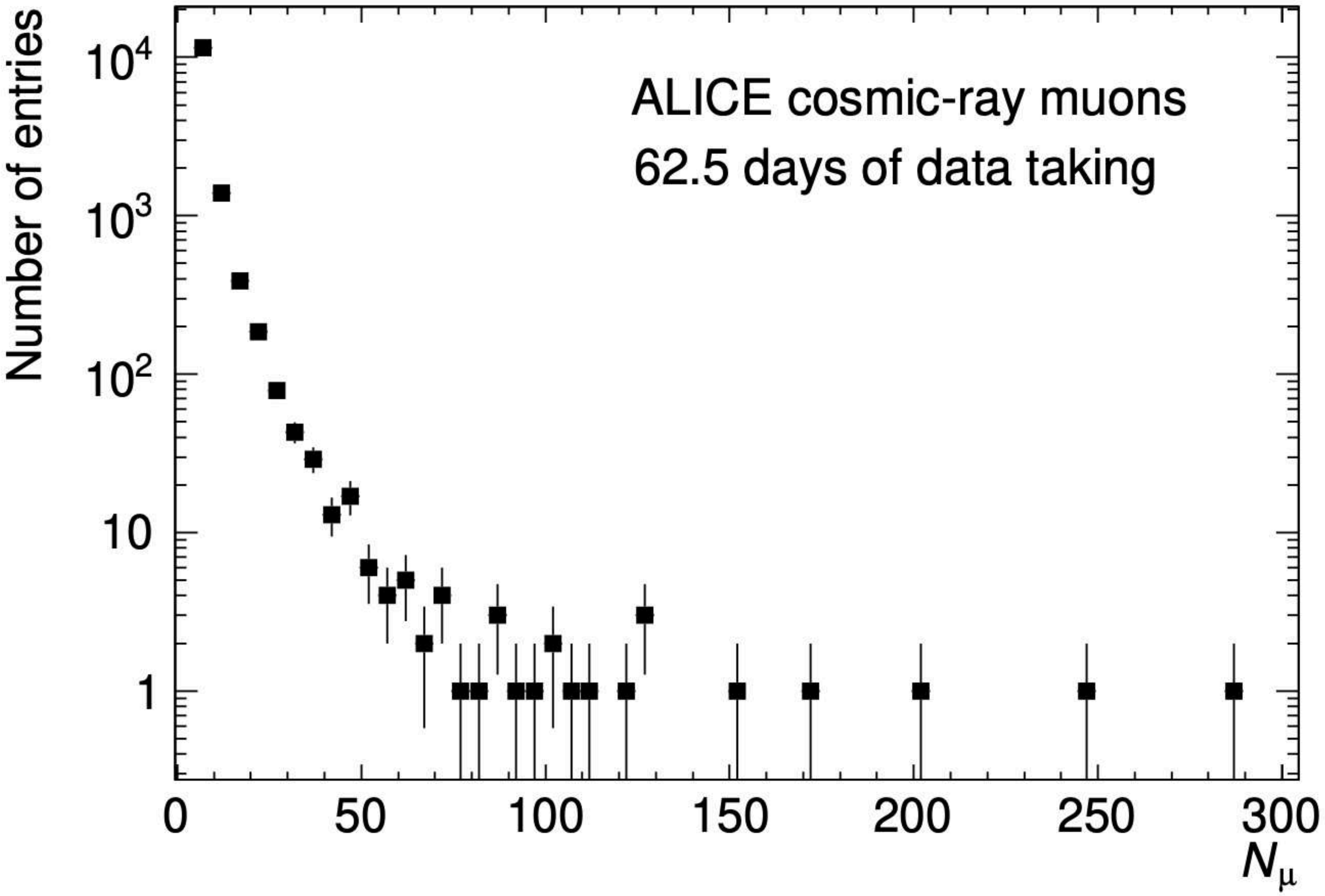
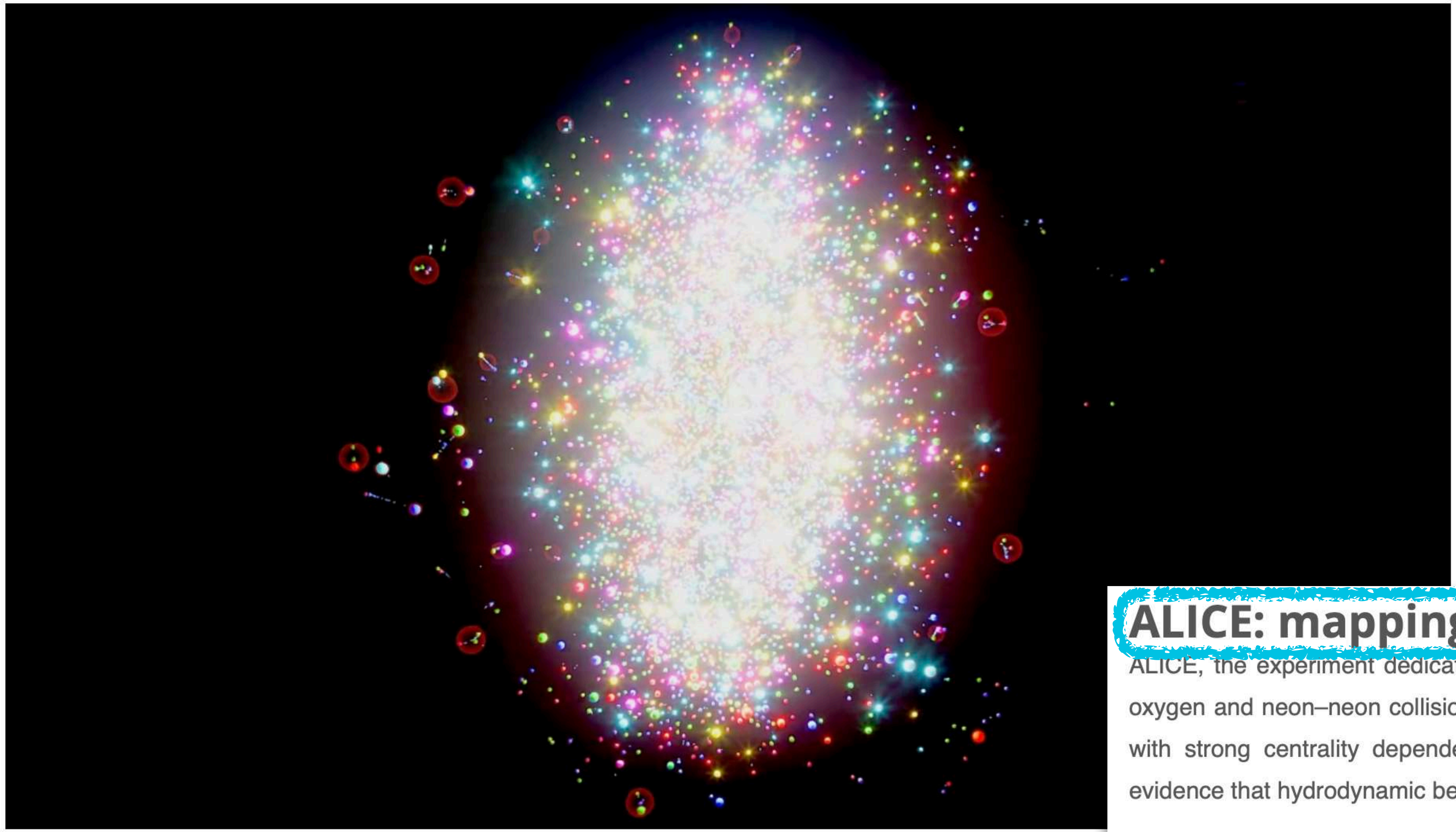


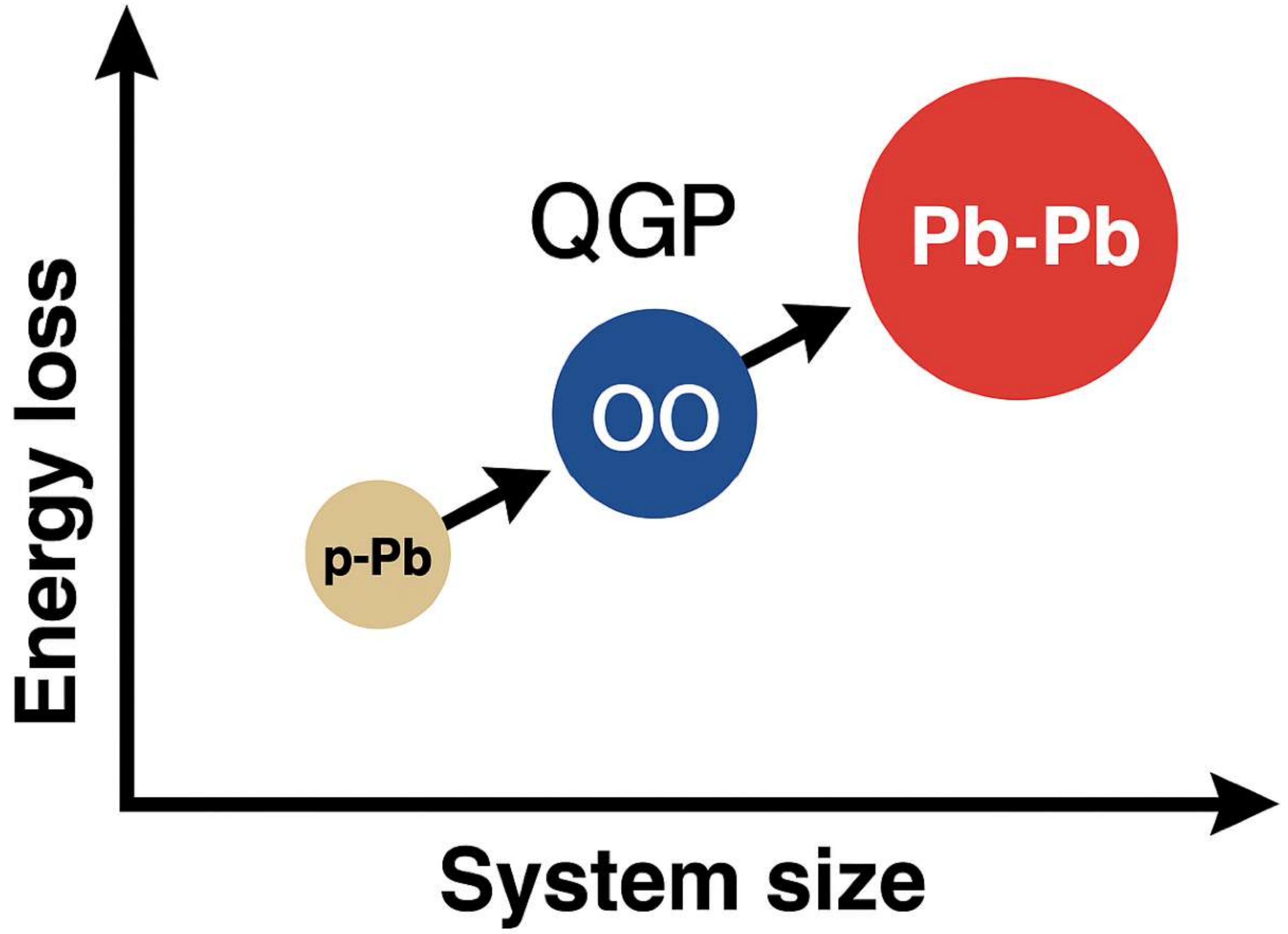
ALICE as a cosmic-ray detector: multi-muon bundles from extensive air showers (EAS) test hadronic physics at 10^{14}–10^{16} eV — the "knee" region of the cosmic-ray spectrum.

Beyond QGP, recent highlights!

Light ions at the LHC: first results from oxygen–oxygen and neon–neon collisions

Panos Charitos 6th Oct 2025



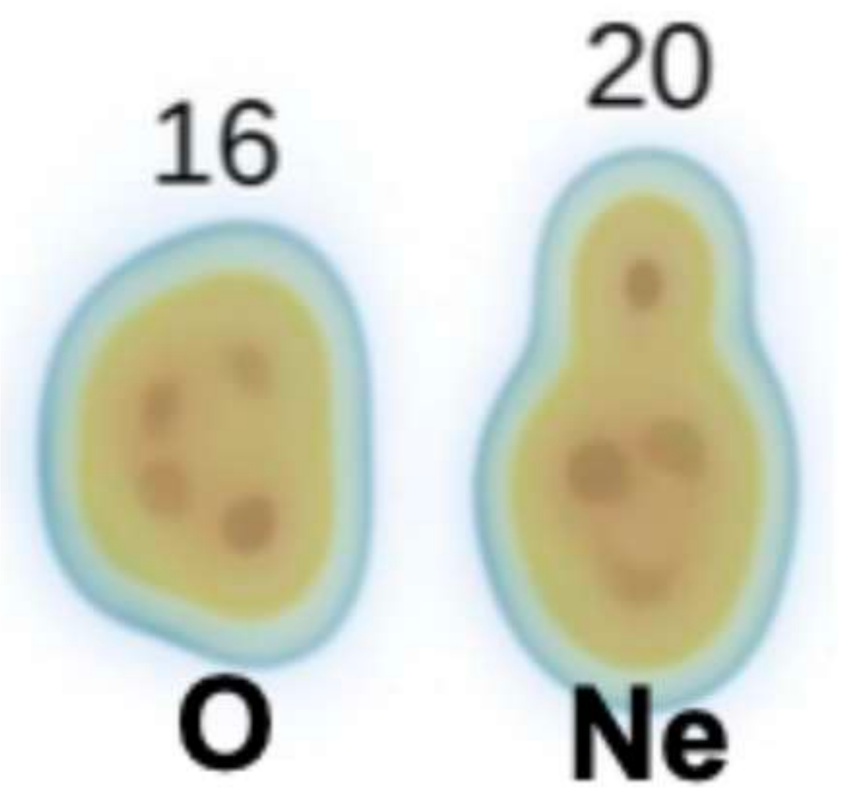


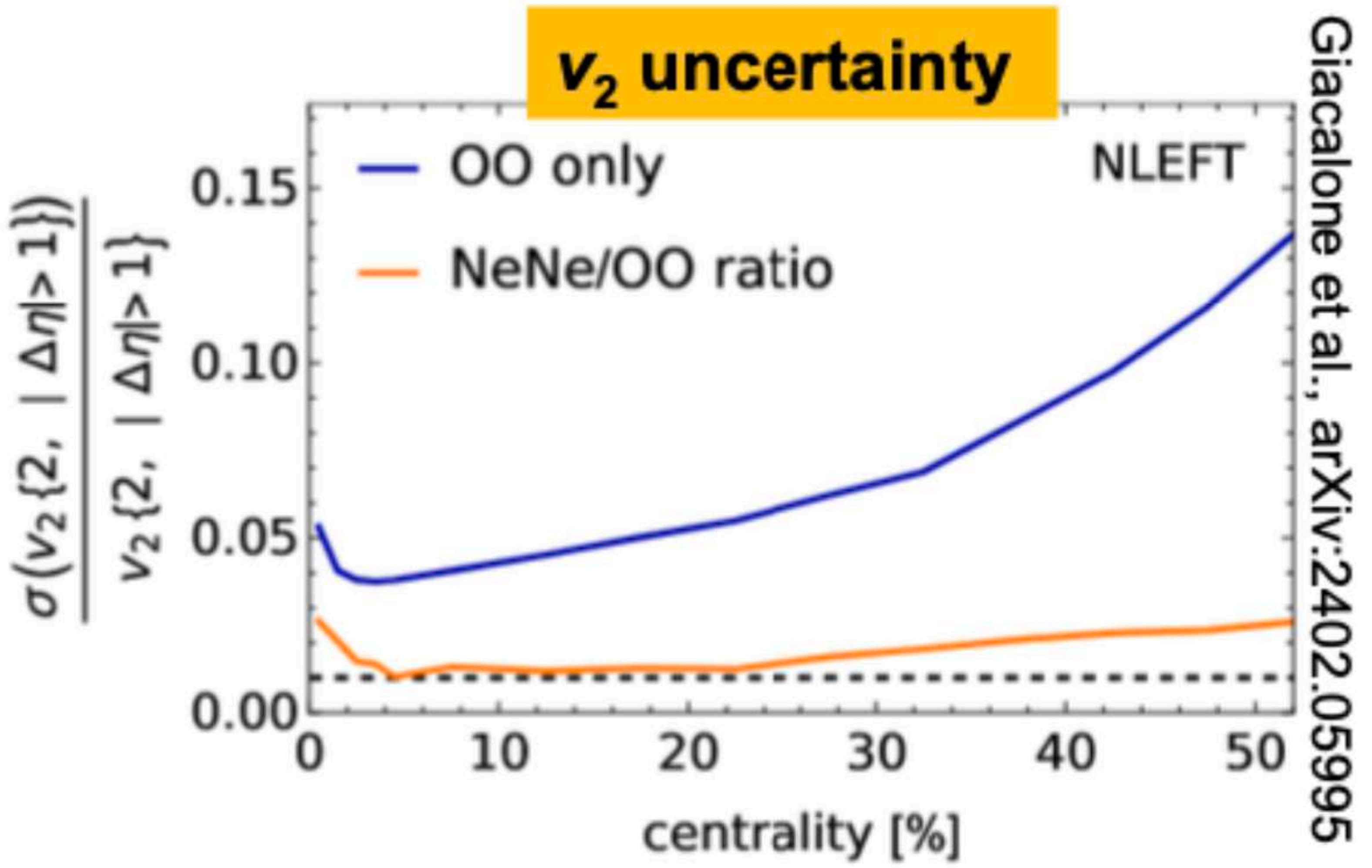
ALICE: mapping QGP across system sizes

ALICE, the experiment dedicated to heavy-ion physics, carried out a comprehensive programme of measurements in oxygen–oxygen and neon–neon collisions. The collaboration reported clear signals of elliptic (v_2) and triangular (v_3) flow in both systems, with strong centrality dependence and magnitudes comparable to those in heavier systems. These results strengthen the evidence that hydrodynamic behaviour emerges even in small collision systems.

ALICE also measured **charged-particle multiplicity distributions**, which are essential to characterising the initial conditions of the collisions. Together with **particle spectra** and the first nuclear modification factor (R_{AA}) studies in light-ion collisions, these results extend ALICE's longstanding programme of scanning QGP properties across system sizes, from Pb–Pb through Xe–Xe down to O–O and Ne–Ne. The measurements already show sensitivity to the nuclear structure of oxygen and neon, underlining ALICE's central role in establishing the minimal conditions for QGP formation.

Oxygen and Neon run at LHC



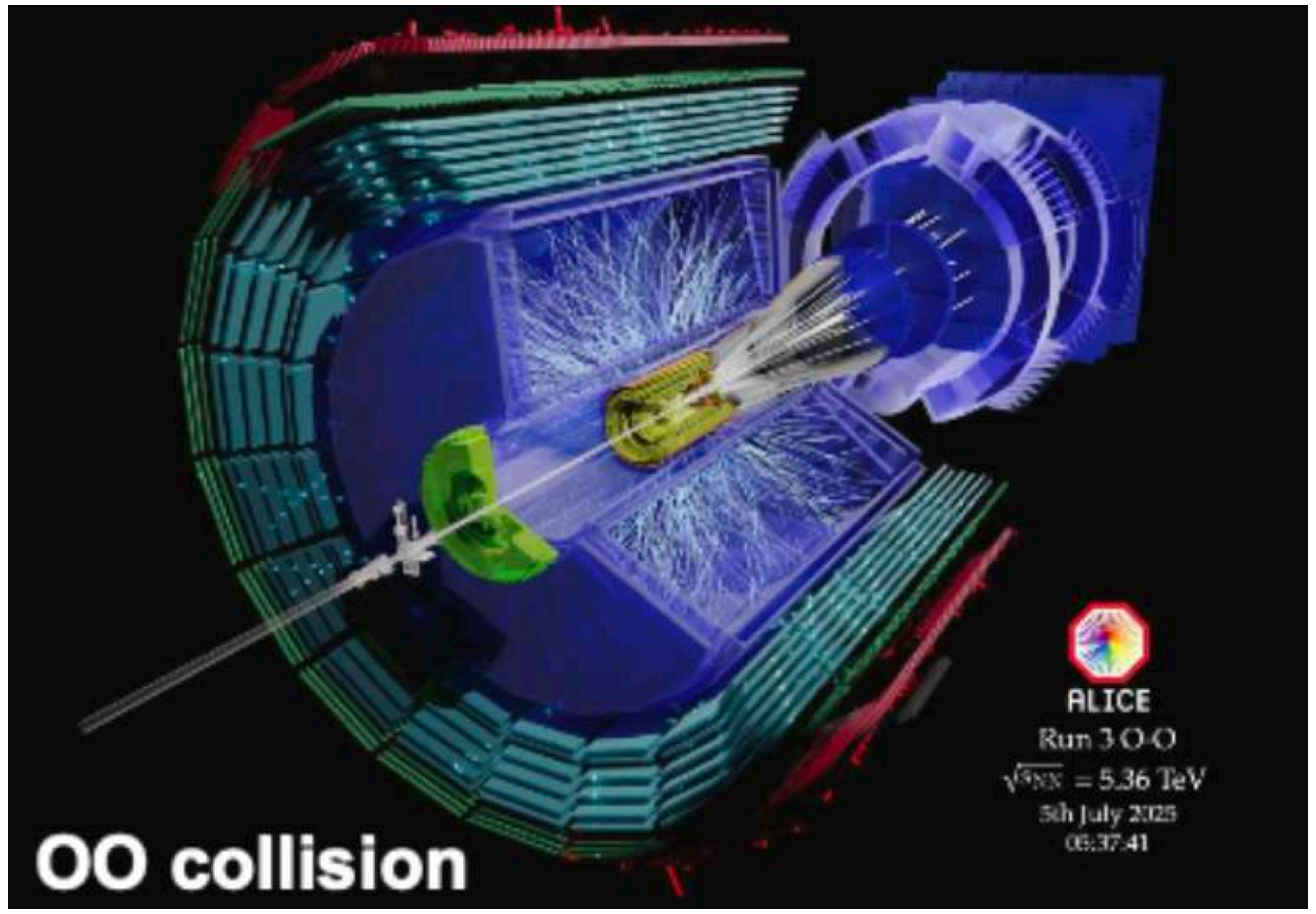


Special run week in July dedicated to collisions of **light lions (O and Ne)**

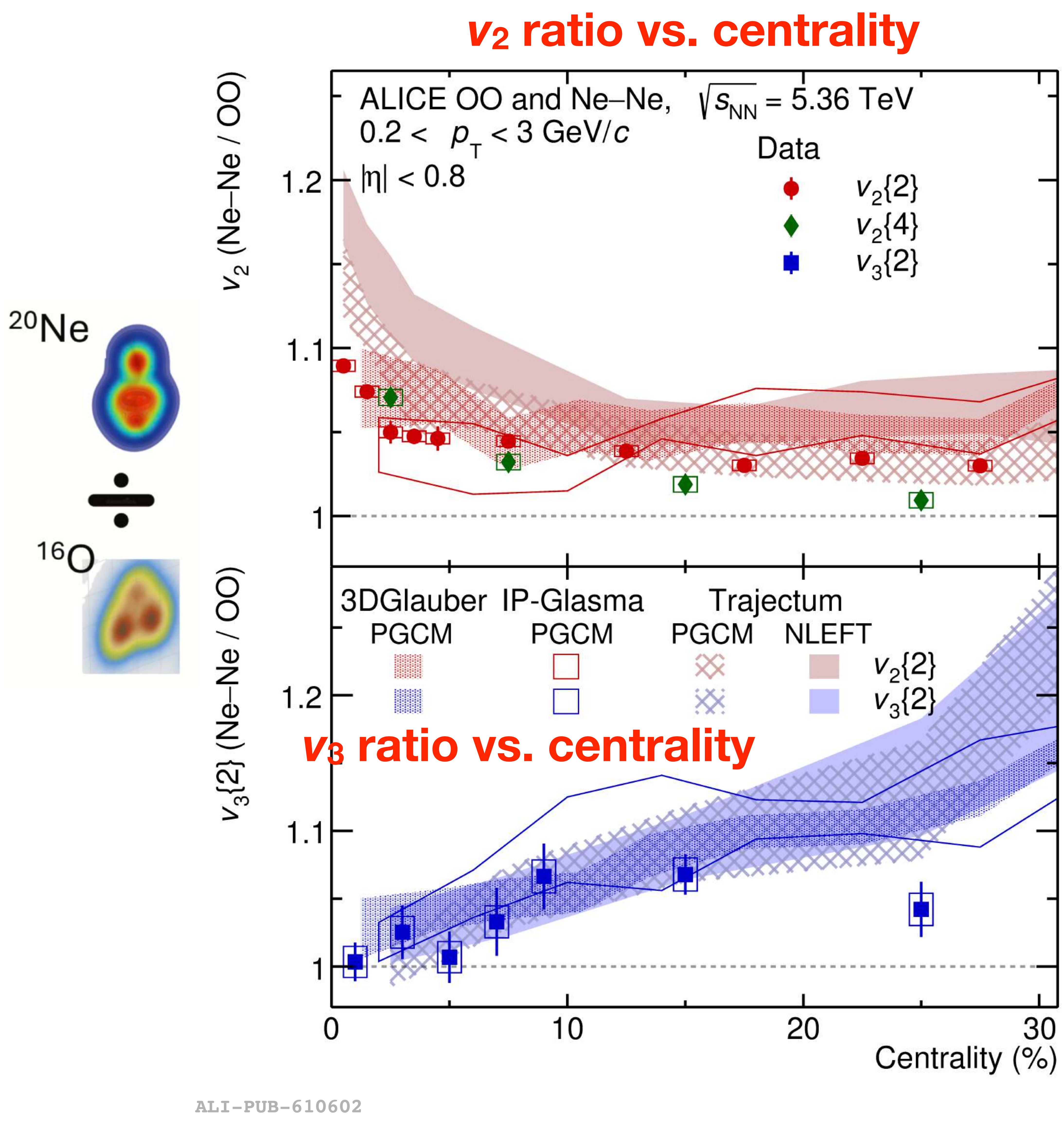
Modeling uncertainties cancel in light-ion ratio

LHC and ALICE performed with excellence

- pO: recored 7.27 nb^{-1} | $3x10^9$ events
- OO: recored 5.01 nb^{-1} | $6x10^9$ events
- NeNe: recored 0.84 nb^{-1} | 10^9 events



Oxygen and Neon: shape of the nucleus imprinted on the final-state flow



Ratios between OO and Ne-Ne reduces uncertainties (< 0.01 exp. for v_2)

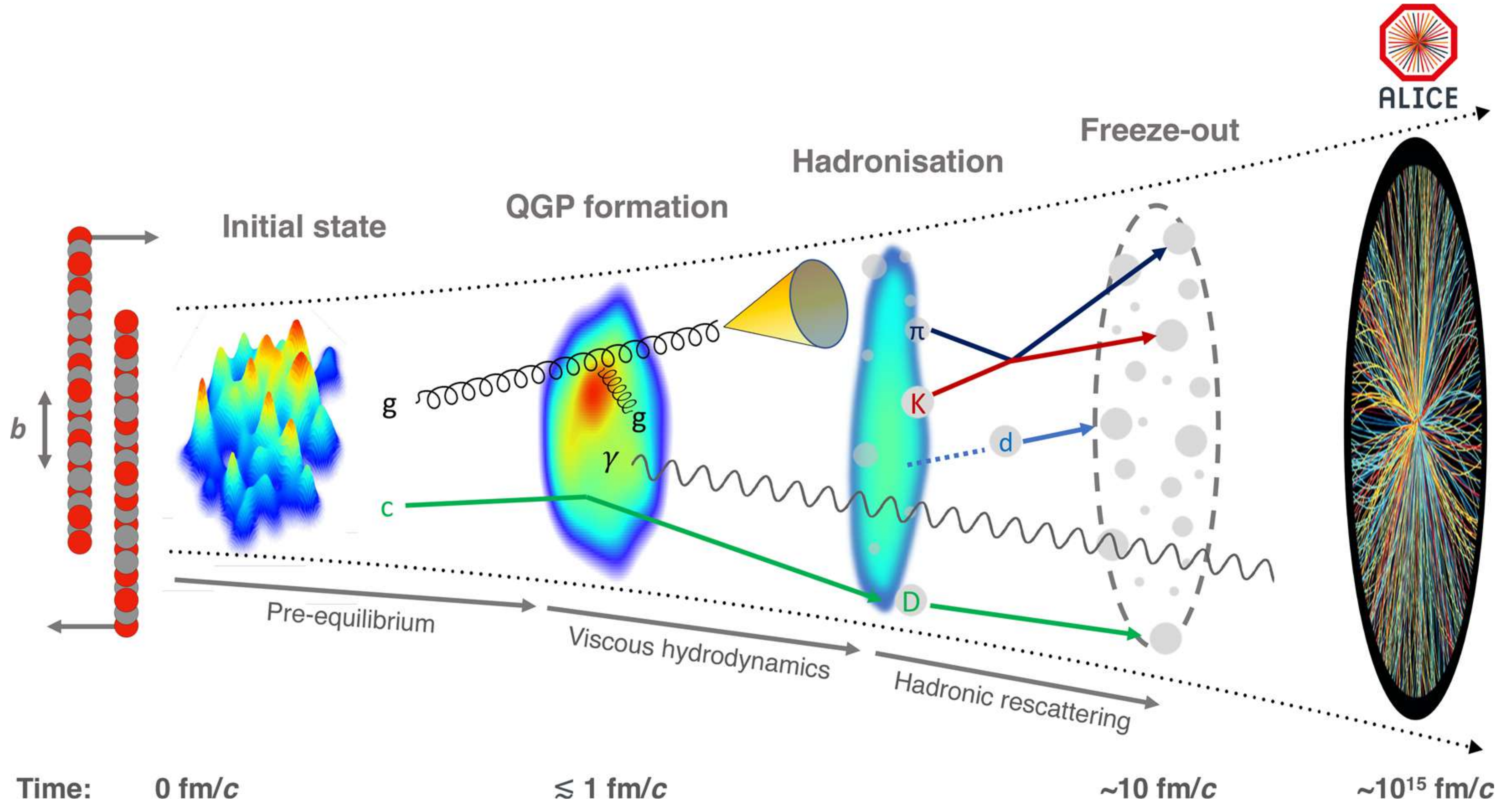
- v_2 peaks for central: stronger quadropole deformation of Ne compared to tetrahedral O
- v_3 increases with centrality: in ultra central collision, tetrahedral O leads to larger v_3

For the first time, the shape of ^{16}O and ^{20}Ne is directly read out from collective flow — bridging nuclear structure and heavy-ion physics

Moving back to QGP… we have differential, more views on the QGP

ALICE review paper

Eur. Phys. J. C 84, 813 (2024)



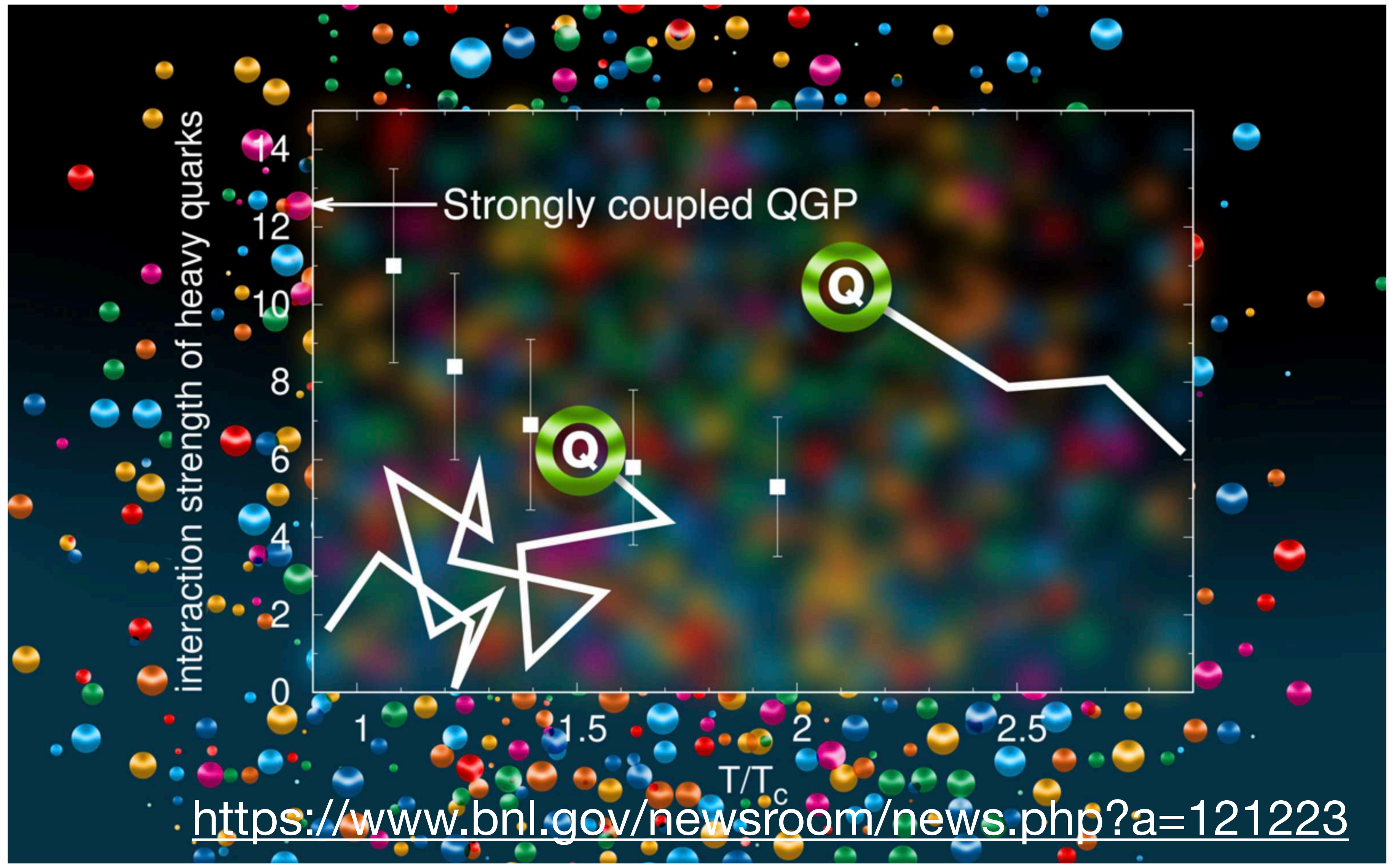
What do hard probes tell us about the QGP, and hadronization?

Suitable probes to understand QCD medium, heavy quarks

- Heavy-quark (HQ) mass is much larger than the nonperturbative QCD scale → produced mainly in initial hard scatterings (reasonably well described by perturbative QCD)

- However, the story is not easy since what we measure is …

  dynamics of heavy quarks from their creation at the onset of a heavy-ion collision through their evolution in the QCD medium until their detection as heavy hadrons



- We need a comprehensive description of the initial production of the heavy quarks, their interactions with the QGP, hadronization, and the interactions of heavy hadrons in the hadronic phase → rather complex to describe using first-principles QCD!

Heavy quark production in heavy-ion collisions: what we measure

$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes \left[P(\Delta E) \otimes D_{c\to D}(z)\right]$$

Initial-state effects

"Vacuum" parton spectra

Parton interaction with the medium

(Modified) hadronization

constrain models with measurements from p-Pb collisions

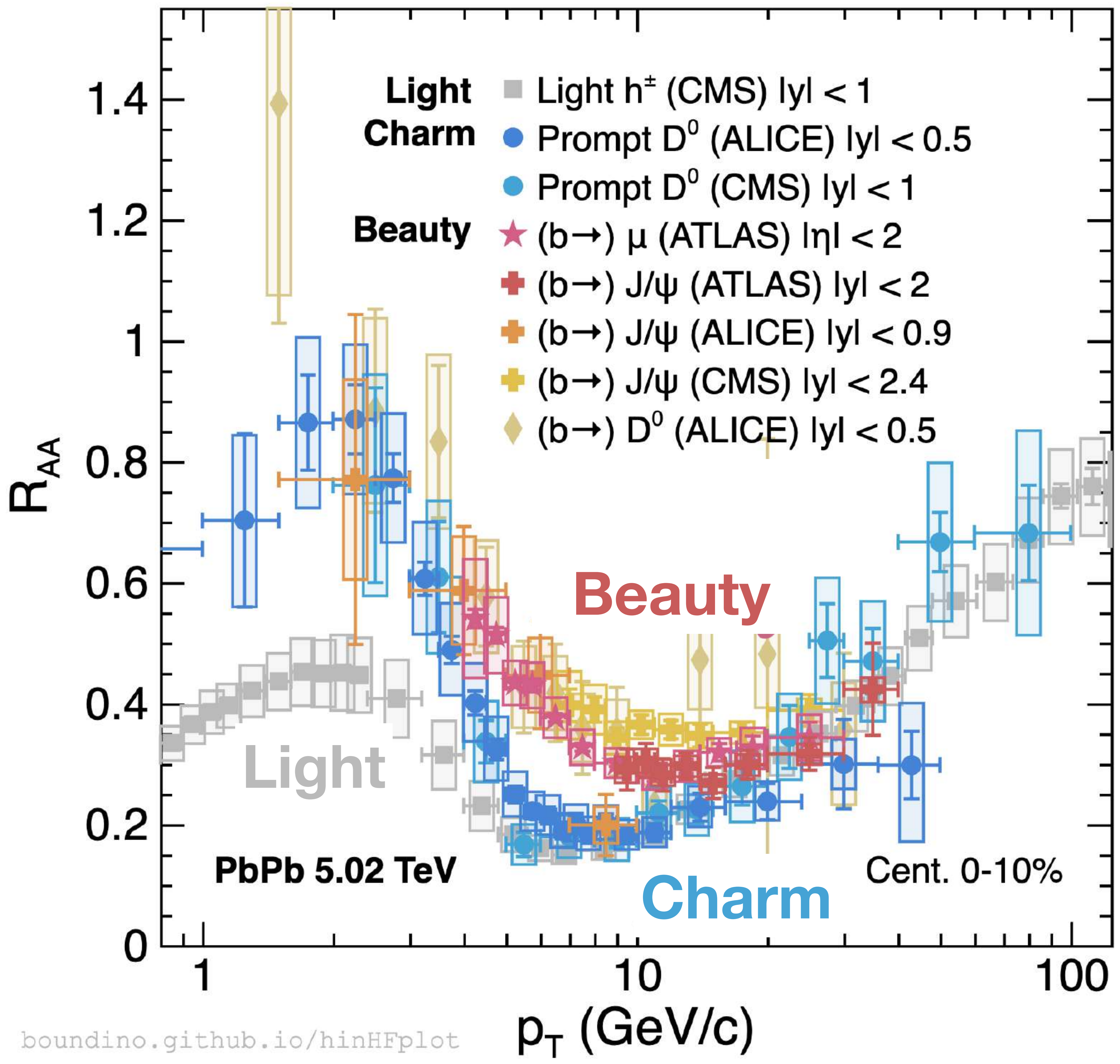
pp collisions

what we wanted to probe via heavy-ion collisions

dynamics in QGP: energy loss via radiative ("gluon Bremsstrahlung") and collisional processes

- color charge (Casimir factor)
- quark mass (dead-cone effect)
- path length and medium density

Mass and color charge dependence of energy loss: via R_{AA}

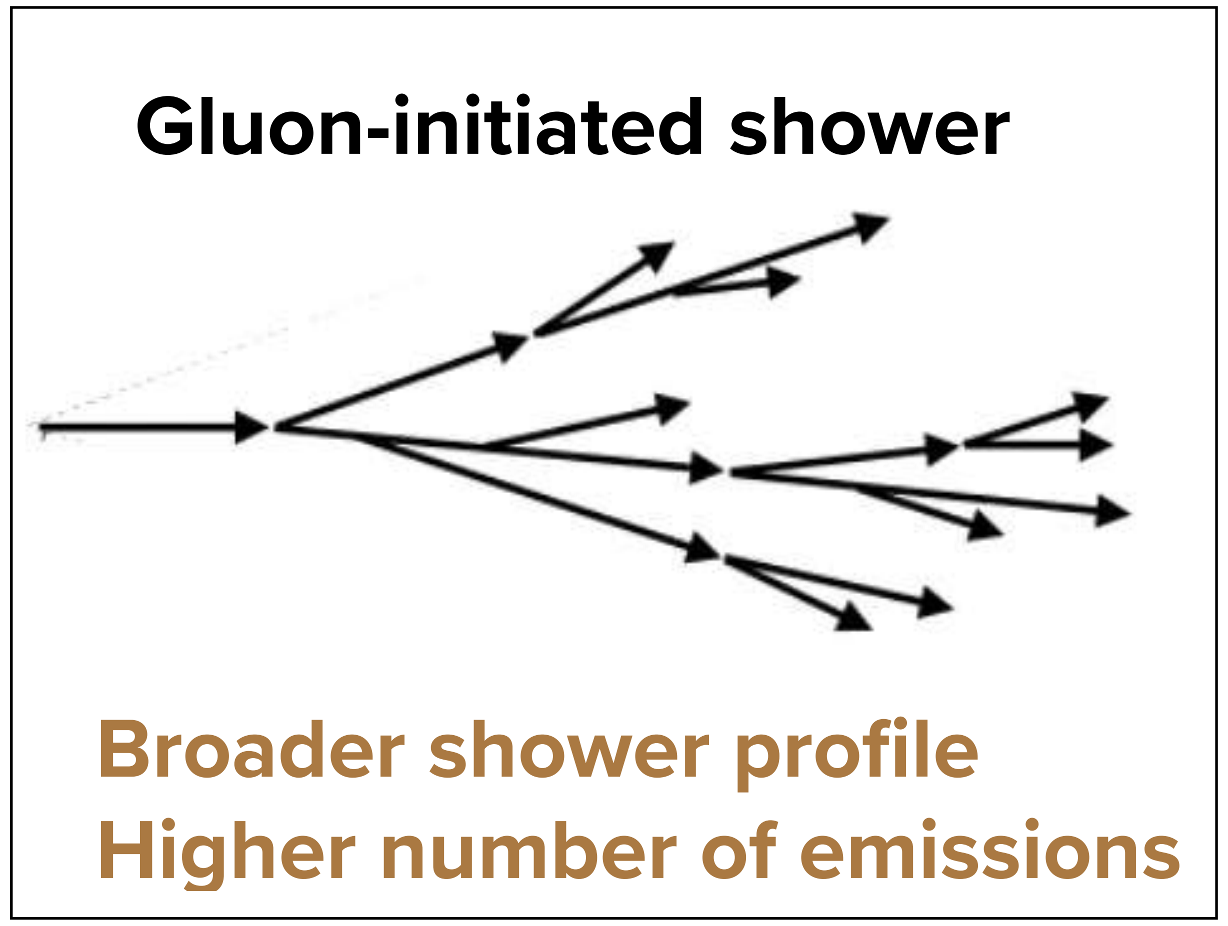


ATLAS PLB 829 (2022) 137077, ATLAS EPJC 78 (2018) 762
ALICE HEP 02 (2024) 066, ALICE JHEP 12 (2022) 126
CMS EPJC 78 (2018) 509

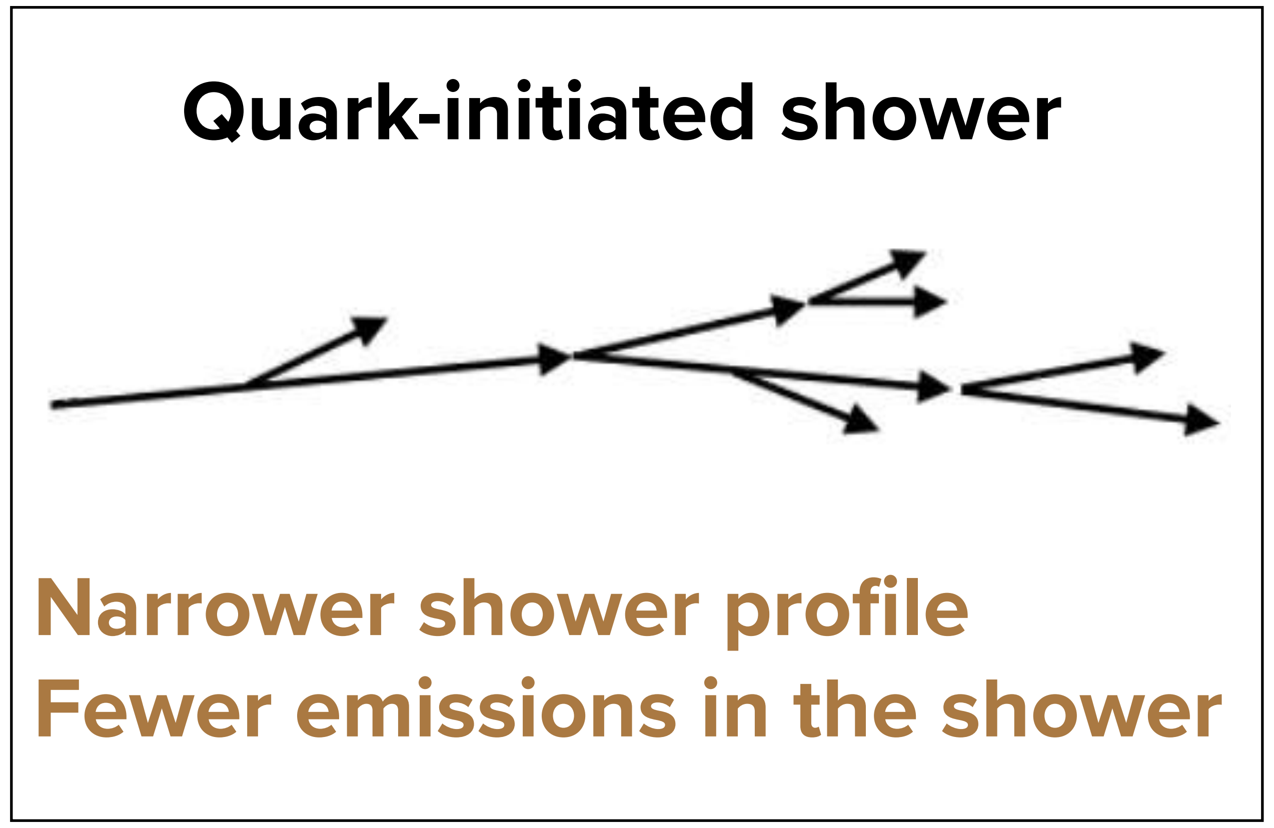
- Mass and color charge dependent suppression

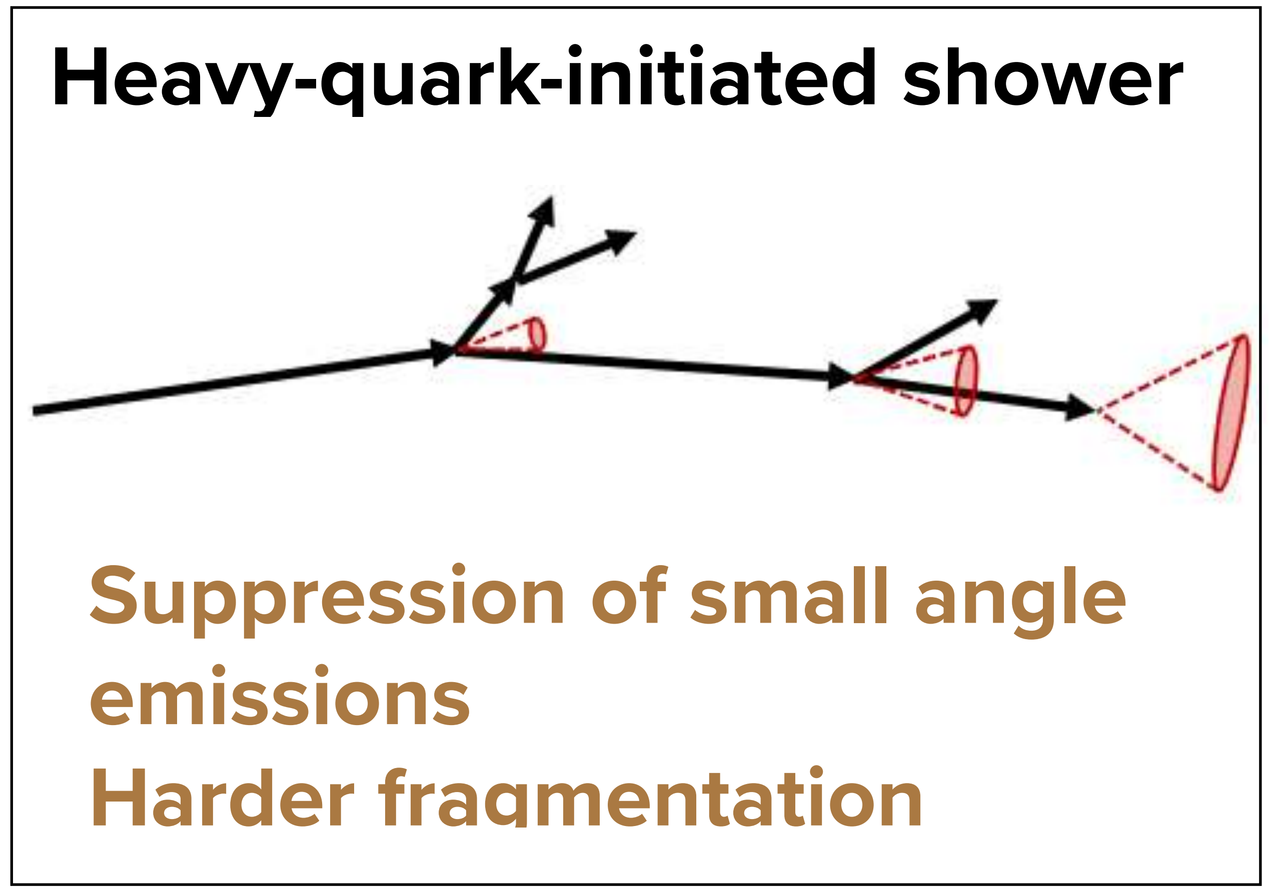
In terms of energy loss

Gluons > Light Quarks (u, d, s) > Charm Quarks (c) > Beauty Quarks (b)



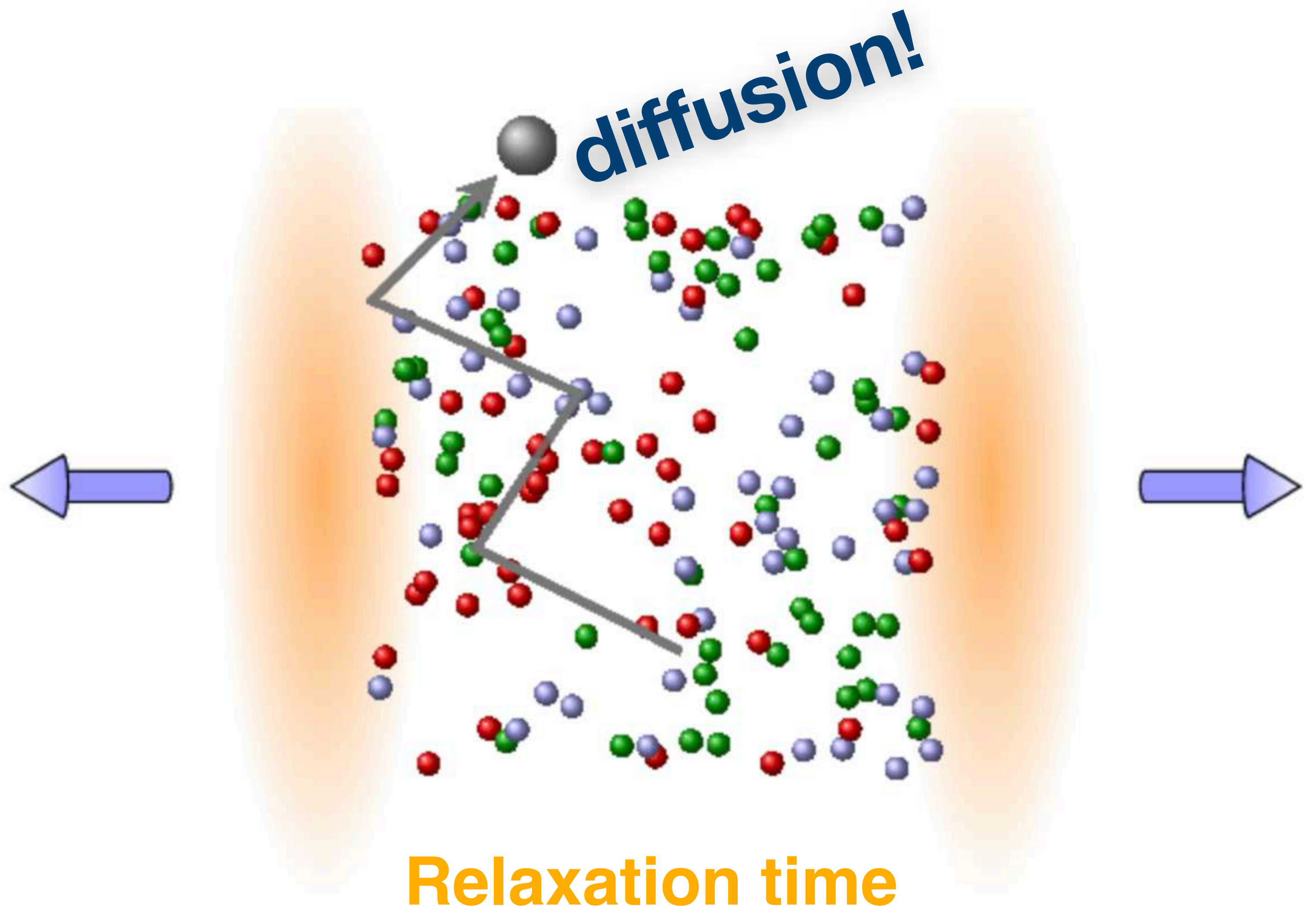
relevant to light quark suppression





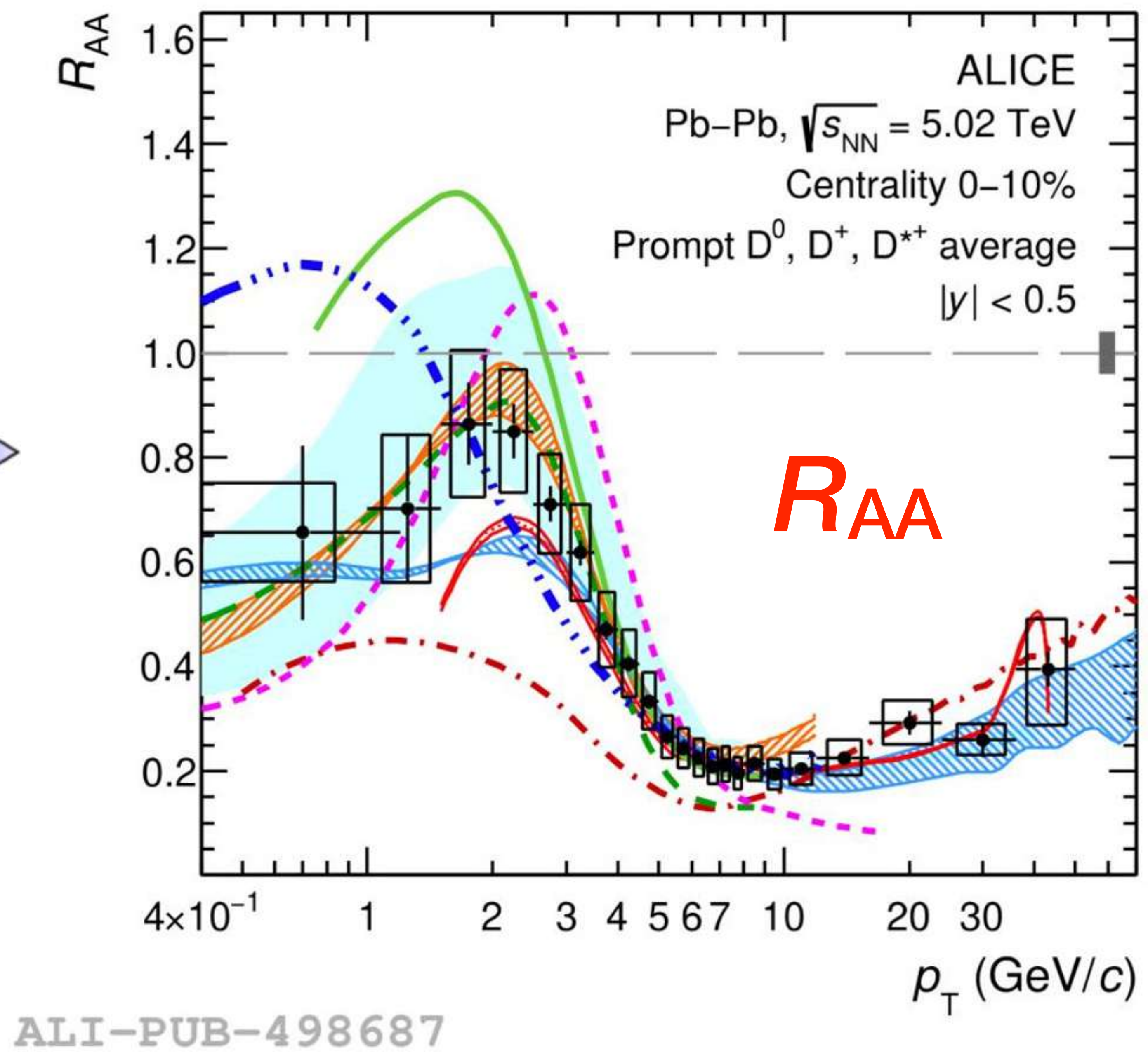
Charm quark diffusion in the medium

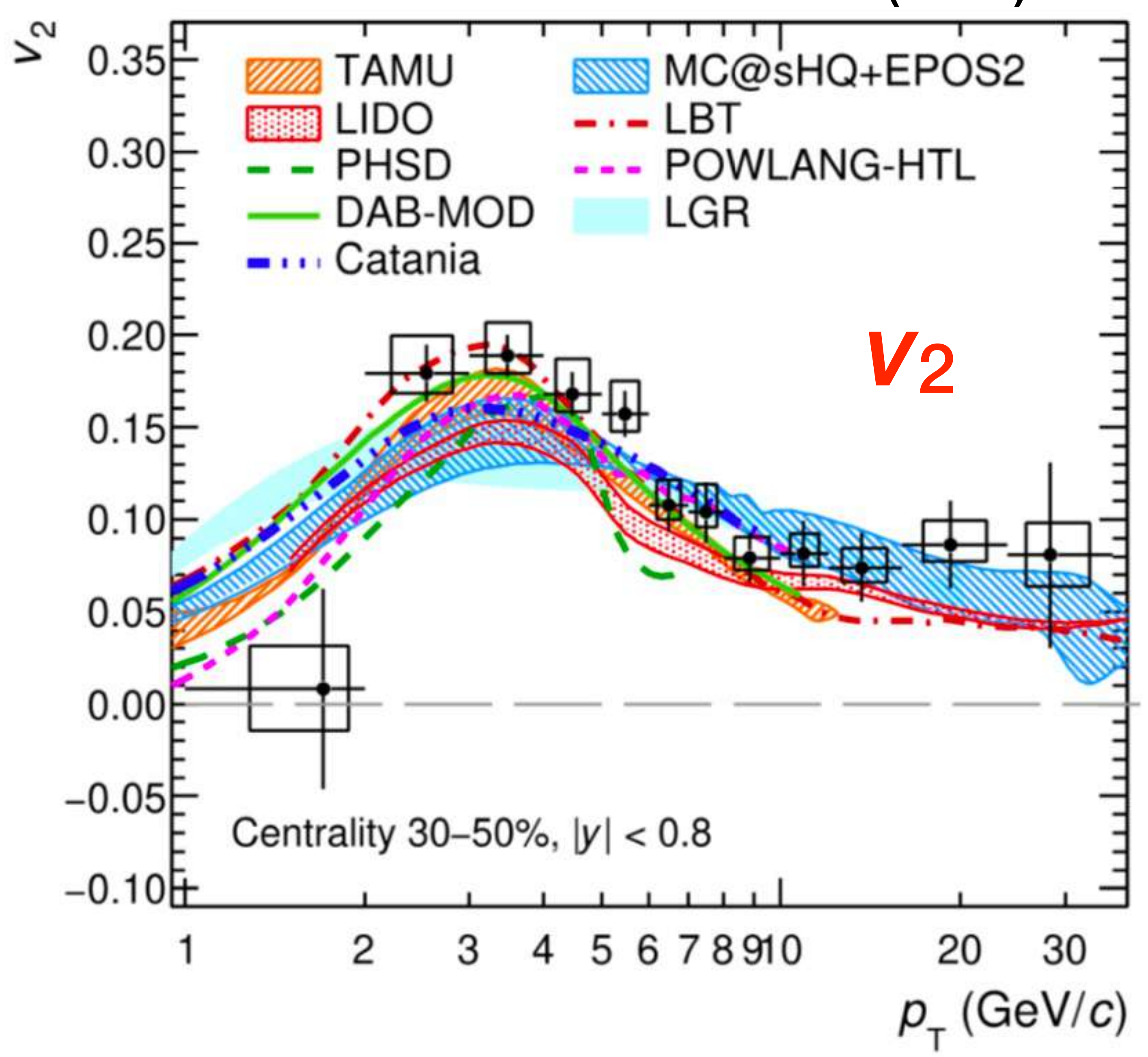
- Low-p_T region provides insight into the heavy-quark interactions with the medium (by diffusion, analogous to a 'Brownian motion')



$\tau_Q = (m_Q/T)D_s$

ALICE JHEP 01 (2022) 174





$1.5 < 2\pi D_s T_c < 4.5$ → direct access to heavy-flavour relaxation time: τ_{charm} ~ 3-8 fm/c

Note: hadronization is hard to control in the model…

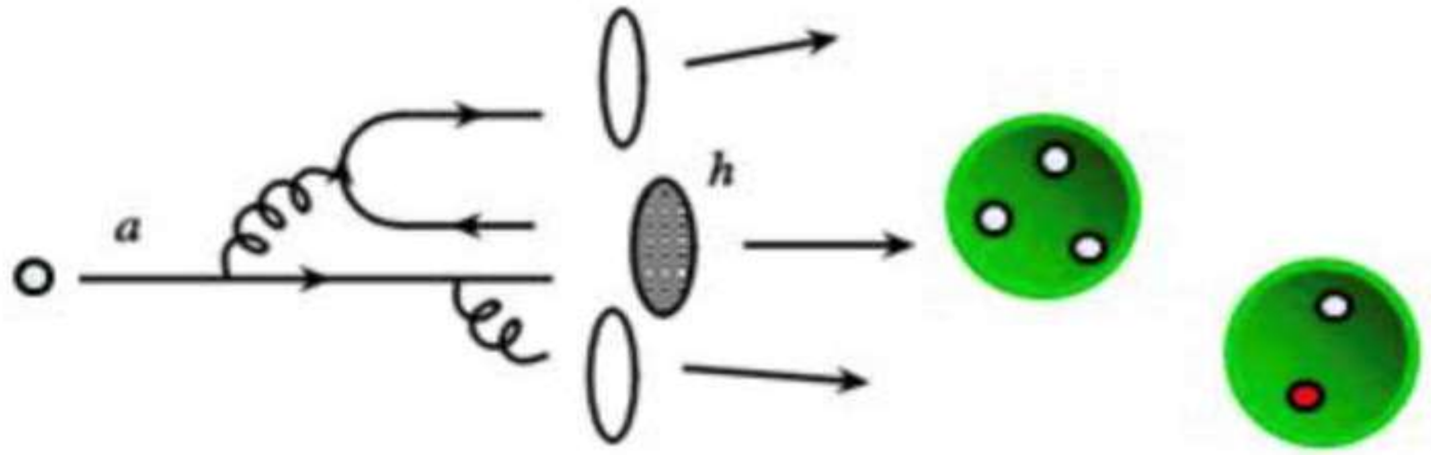
Heavy flavour production in medium: hadronization

Going back to the original assumption...

$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes \left[P(\Delta E) \otimes D_{c\to D}(z)\right]$$

Initial-state effects — "Vacuum" parton spectra — Parton interaction with the medium — (Modified) hadronization

- Fragmentation functions *D*(*z*) are phenomenological functions to parameterize the non-perturbative parton-to-hadron transition
  - → *z* = fraction of the parton momentum taken by the hadron h
  - → Do not specify the hadronisation mechanism
- Parametrized on data and assumed to be "universal"



extracted from experiments such as e^+e^- collisions, ex. Peterson

$$\mathcal{D}_{Q\to H}(z) \propto \frac{1}{z[1-\frac{1}{z}-\frac{\epsilon}{1-z}]^2}$$

$$\epsilon = m_q^2/m_Q^2$$

Fragmentation

Independent fragmentation of partons into hadrons is the standard way to describe hadronization in elementary collision systems (pp, e^+e^-)

$$E\frac{d\sigma_H}{d^3P_H} = E_p\frac{d\sigma_i}{d^3p_i} \otimes \mathcal{D}_{i\to H}(z) \qquad z = P_H/p$$

D(*z*) is non-perturbative quantity but it is considered to be universal and usually extracted from experiments such as e^+e^- collisions.

ex. Peterson

$$\mathcal{D}_{Q\to H}(z) \propto \frac{1}{z[1-\frac{1}{z}-\frac{\epsilon}{1-z}]^2} \qquad \epsilon = m_q^2/m_Q^2$$

ex. in PYTHIA with a modified Lund string fragmentation function

$$\mathcal{D}_{Q\to H} \propto \frac{1}{z^{1+rbm_Q^2}} z^{a_\alpha}\left(\frac{1-z}{z}\right)^{a_\beta} \exp\left(-\frac{bm_T^2}{z}\right)$$

Question on the universality

Fragmentation Issues

Fragmentation Function (FF):
provides information about the energy fraction which is transfered from quark to a given meson (the larger m_Q the harder the fragmentation function)

Questions to be answered:

▷ what's the **proper parametrization** of non-perturbative frag. function?

- Peterson: $f(z) \propto 1/[z(1 - \frac{1}{z} - \frac{\varepsilon}{(1-z)})^2]$
- Kartvelishvili: $f(z) \propto z^\alpha(1-z)$
- Lund symmetric: $f(z) \propto \frac{1}{z}(1-z)^a \exp(-\frac{bm_t^2}{z})$
- Bowler: $f(z) \propto \frac{1}{z^{1+r_b m_t^2}}(1-z)^a \exp(-\frac{bm_t^2}{z})$

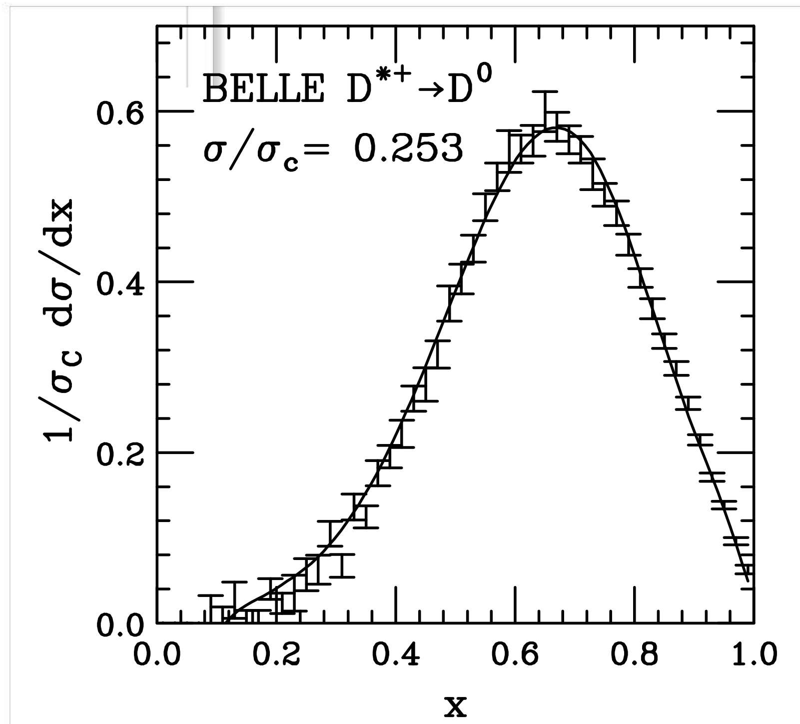
▷ is fragmentation function **universal**?
(i.e. are FF portable from e^+e^- to ep and pp?)

Zuzana Rúriková Charm Fragmentation Function June 7, 2006

▷ different observable definitions

▷ different center of mass energies, thus different pert. components as well

$\Longrightarrow$ **Direct shape comparison impossible!**



Fit to BELLE data
(Cacciari, Nason, Oleari)

▷ **Fitted parametrization:** $f(x) \propto \delta(1-x) + \frac{c}{N_{a,b}}(1-x)^a x^b$

▷ **ALEPH:** a= 2.4±1.2, b=13.9±5.7, c=5.9±1.7

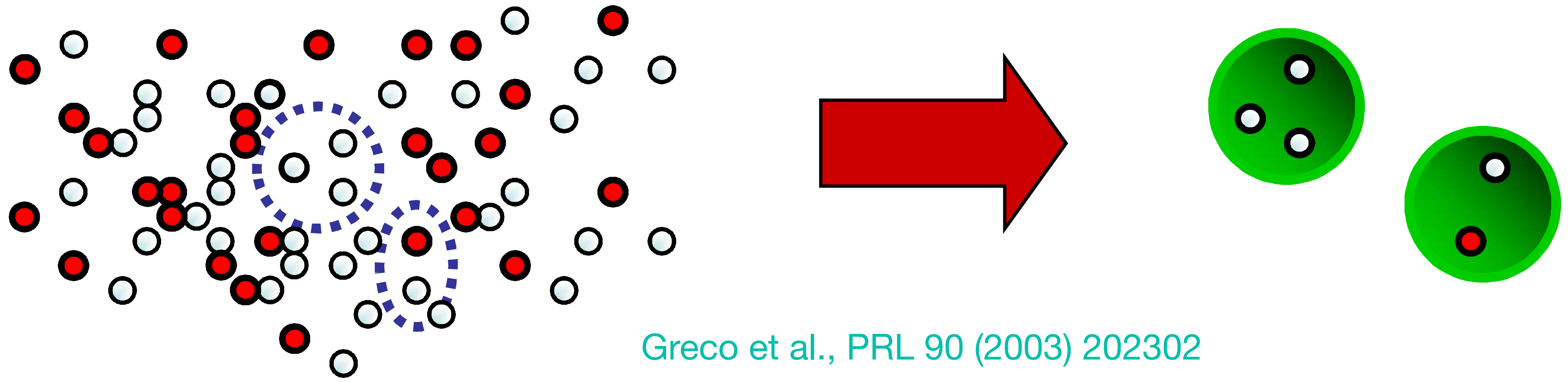
▷ **CLEO/BELLE:** a= 1.8±0.2, b=11.3±0.6, c=2.46±0.07

Fits not in agreement! Does universality of $\mathrm{FF_{np}}$ not hold?

Zuzana Rúriková Charm Fragmentation Function – June 7, 2006

Hadronization in medium

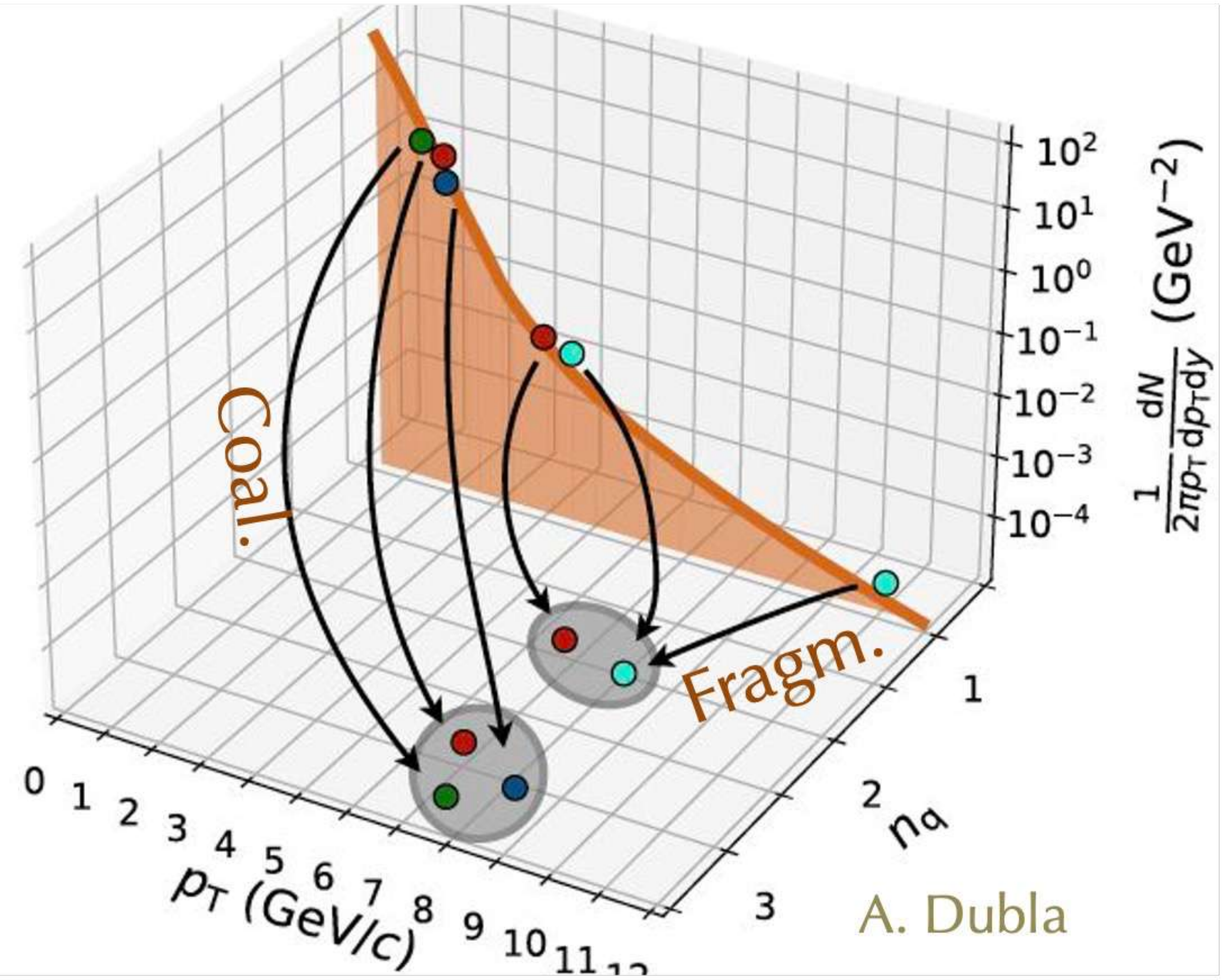
- Phase space at the hadronization is filled with partons
  - → Single parton description may not be valid anymore
  - → No need to create $q\bar{q}$ pairs via splitting / string breaking
  - → Partons that are “close” to each other in phase space (position and momentum) can simply recombine into hadrons



Greco et al., PRL 90 (2003) 202302

Fries et al., PRL 90 (2003) 202303

Hwa, Yang, PRC 67 (2003) 034902



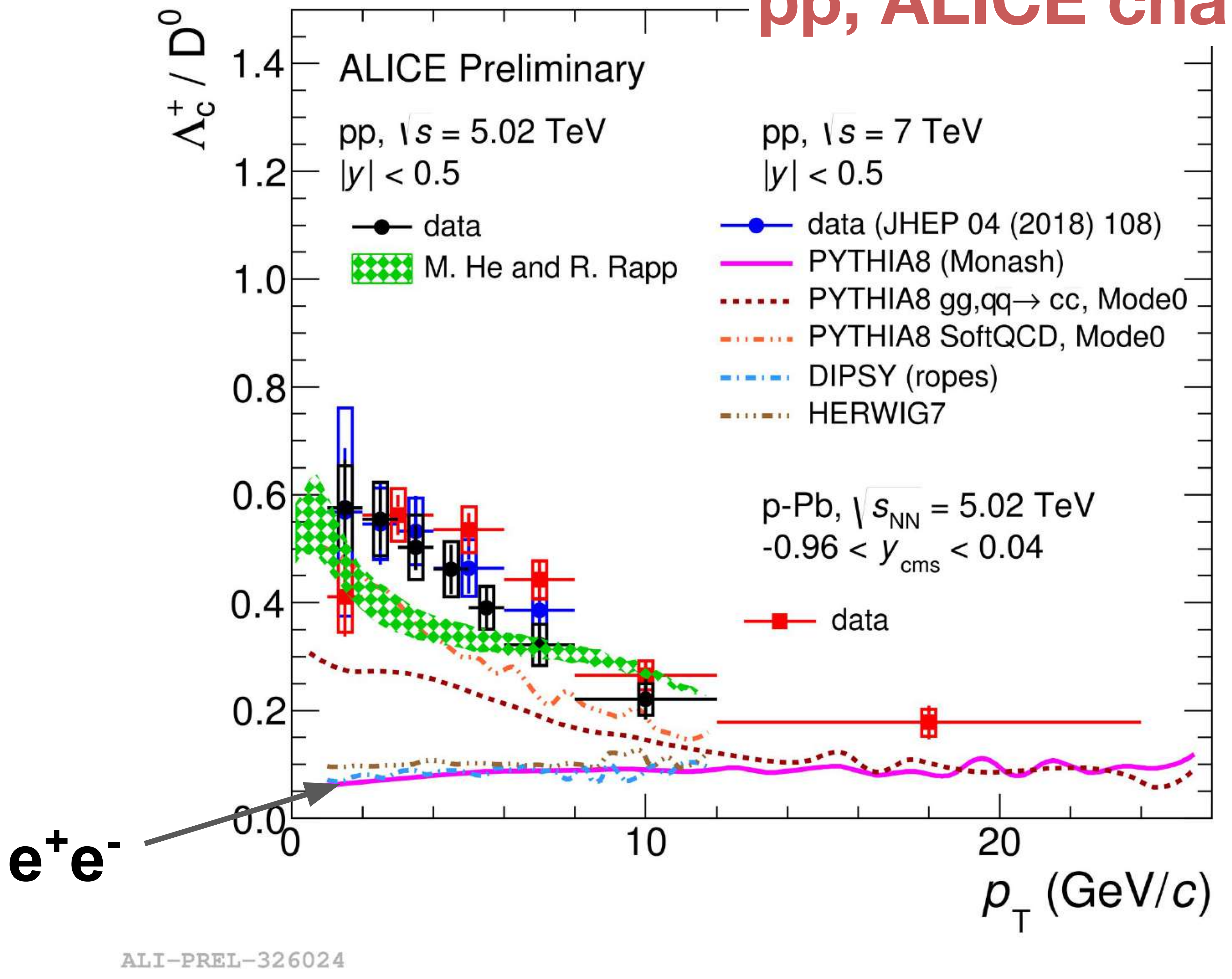
- Recombination vs. fragmentation:
  - → Competing mechanisms
  - → Recombination naturally enhances baryon/meson ratios at intermediate p_T

Hadronization in vacuum

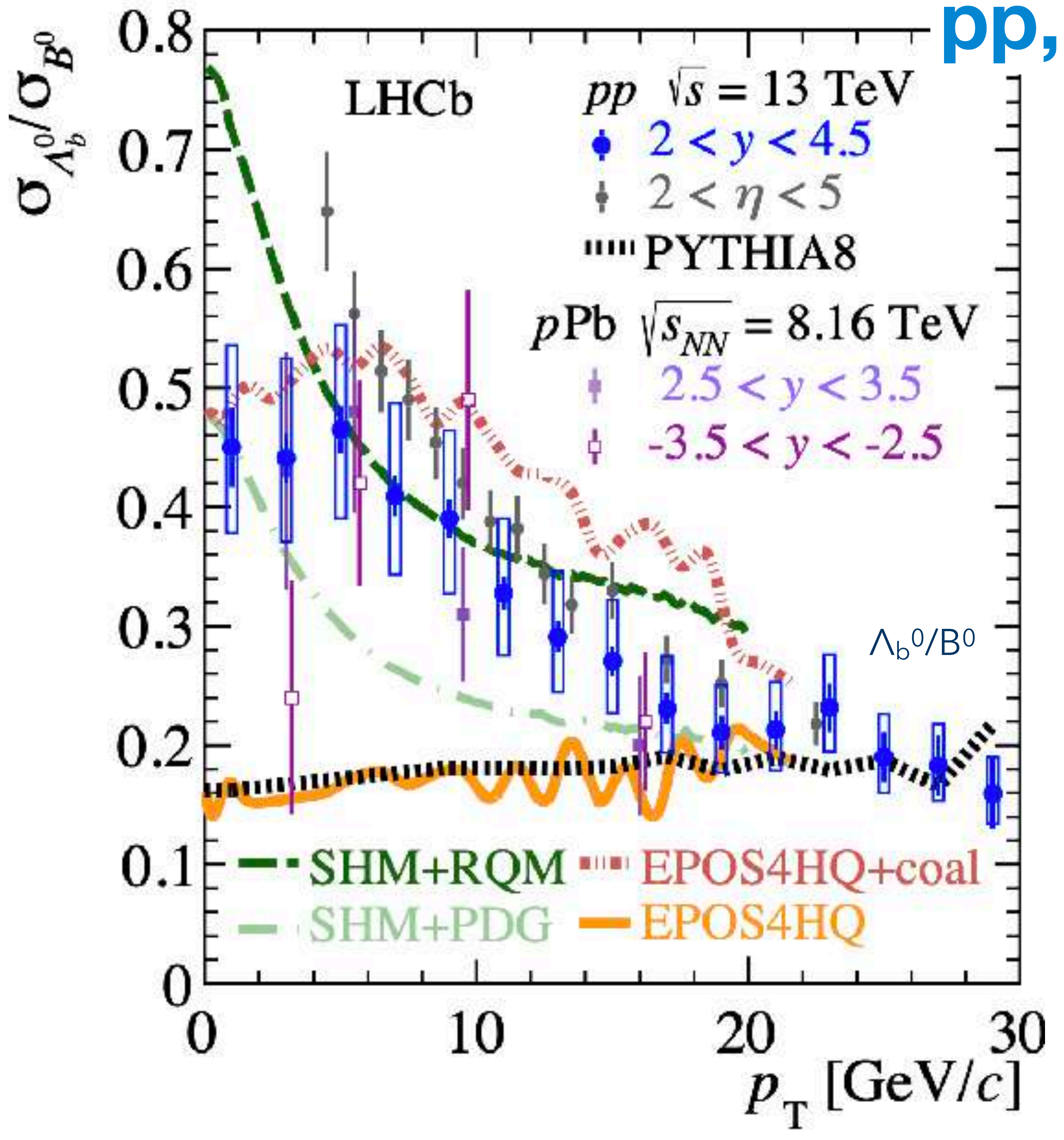
"Naive expectation: ratios of particle-species yields independent from collision system"

Surprises: Λ_c/D^0 ~0.5 (at intermediate p_T) not only in AA but even in pp → strong enhancement wrt e^+e^-

pp, ALICE charm



pp, LHCb beauty

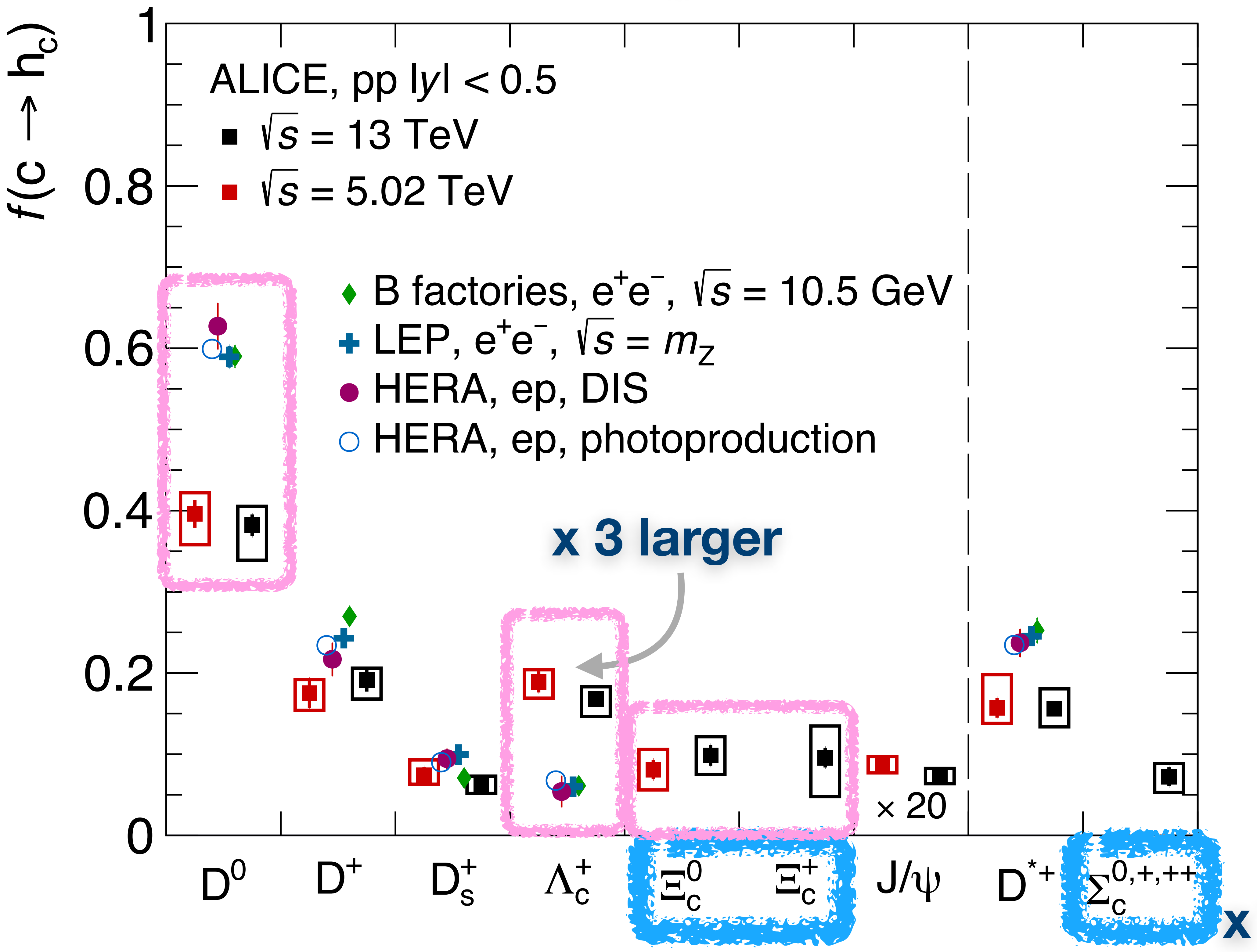


PRL 132, 081901 (2024)

Λ_b/B^0 → Similar trend in charm and beauty sectors!

Charm-quark fragmentation fraction

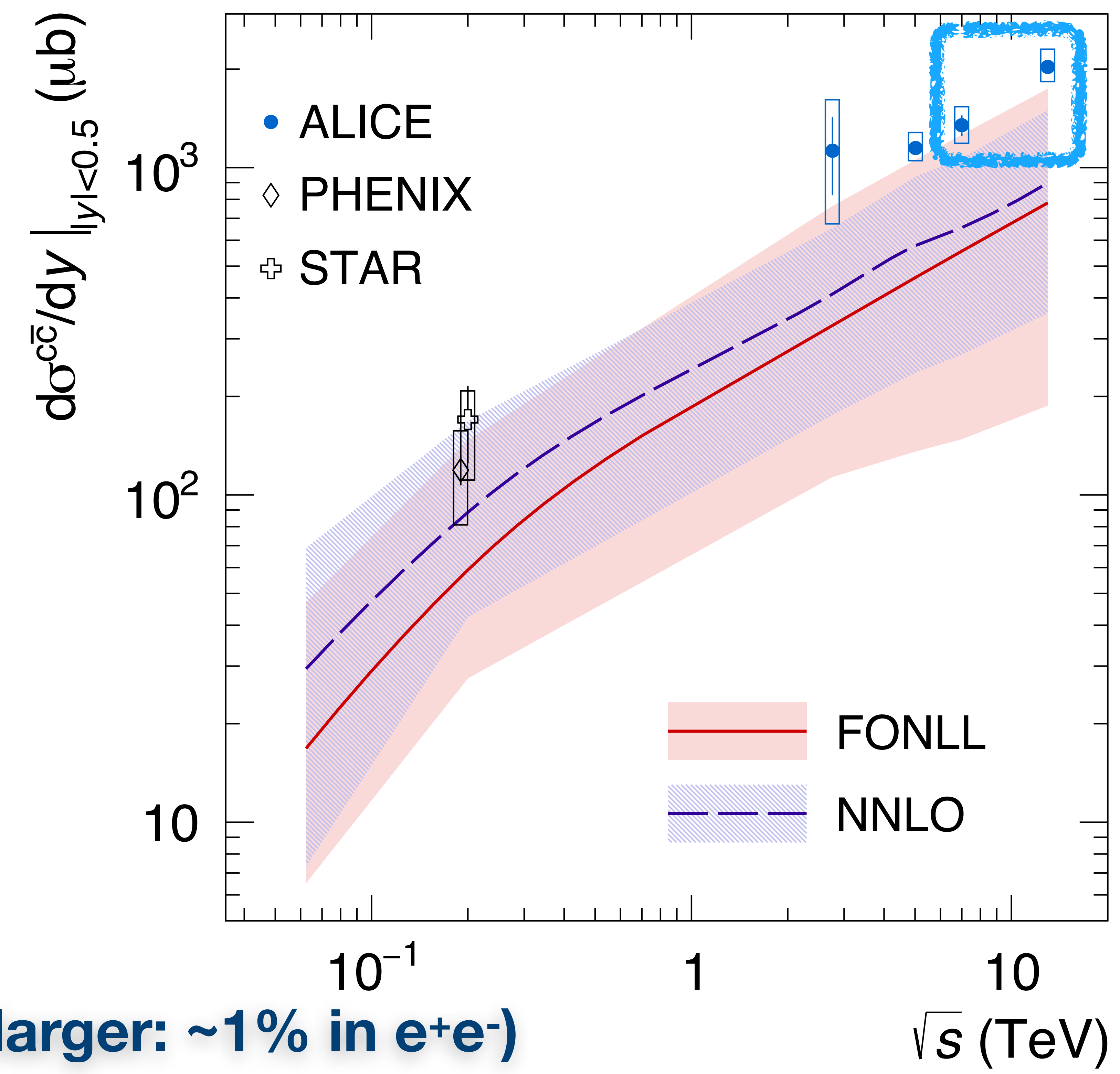
Normalized by the sum of the p_T-integrated cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+, Ξ_c^0, Ξ_c^+



x 3 larger

x 7 larger: ~1% in e^+e^-)

10% of total charm cross section (considered negligible in e^+e^-)



Used the sum of the p_T-integrated cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+, Ξ_c^0, Ξ_c^+

JHEP 12 (2023) 086

Σ_c^0: Larger feed-down to Λ_c^+ (40%, 17% in e^+e^-)

Baryon enhancement at the LHC with respect to e^+e^- collisions is caused by different hadronisation mechanisms at play in the parton-rich environment produced in pp collisions

Way of heavy-flavour hadronization, also in small systems?

- **Fragmentation**
  - → production from hard-scattering processes (PDF+pQCD)
  - → fragmentation functions: data parametrization, assumed universal

$$\sigma_{pp \to h} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to h}(z, Q^2)$$

Parton shower: String fragmentation (Lund model - PYTHIA) + color reconnection (interaction from different scattering), Cluster decay (HERWIG)

- **Coalescence:**
  - → recombination of partons in QGP close in phase space

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

$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i)\; f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\; \delta(p_T - \sum_i p_{iT})$$

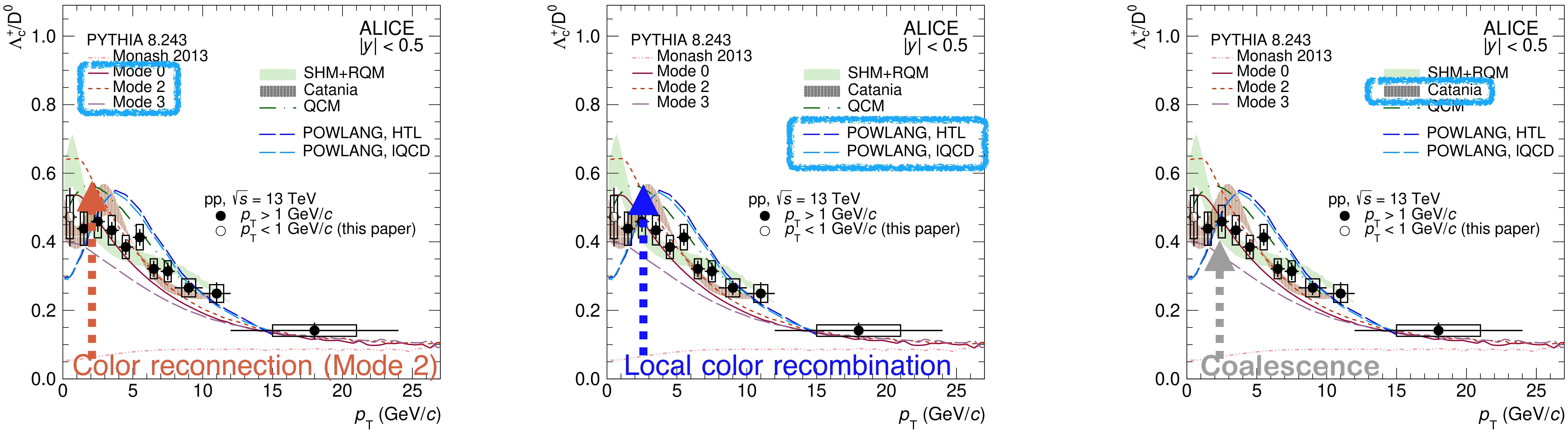
Have described first AA observations in light sector for the enhanced baryon/meson ratio and elliptic flow splitting

- **Statistical hadronization**
  - → equilibrium + hadron-resonance gas + freeze-out temperature
  - → production depends on hadron masses and degeneracy, and on system properties require total charm cross section

How do we explain? Heavy flavour baryon enhancement has driven…

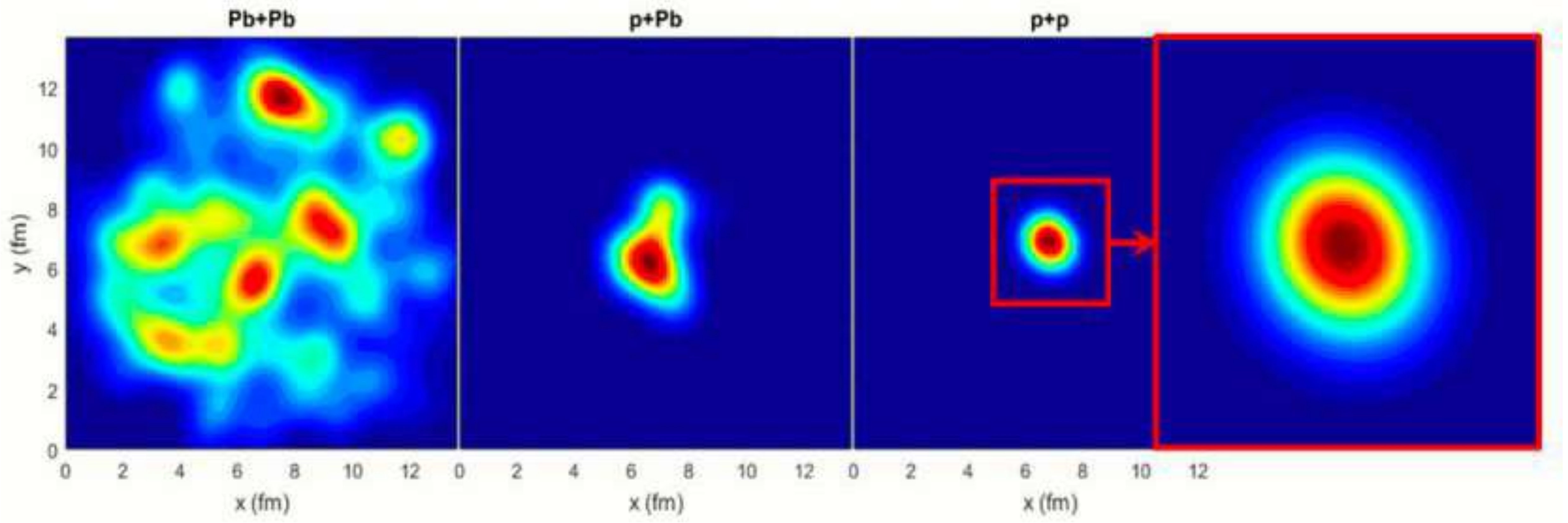
- Heavy-flavour hadronization stimulated the model developments
  - PYTHIA with Color Reconnection (CR) beyond Leading Color (LC) in pp
  - Catania: Coalescence+Fragmentation approach applied to pp
  - Local color recombination: POWLANG in AA and in pp
  - Inclusion of heavy-flavour Coalescence+Fragmentation in EPOS (pp & AA)

ALICE JHEP 12 (2023) 086



- Different hadronization mechanisms proposed!

As an example, in Catania, coalescence + fragmentation in pp



R. D. Weller, P. Romatschke, PLB 774 (2017) 351-356

Daring to assume a small fireball according **viscous hydro** applied to pp as in AA, but **size,time, flow given by hydro for pp**

p+p @ 5 TeV

- t_{pp}=1.7 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm^3

+ $f_c(p)$ from **FONNL distribution**

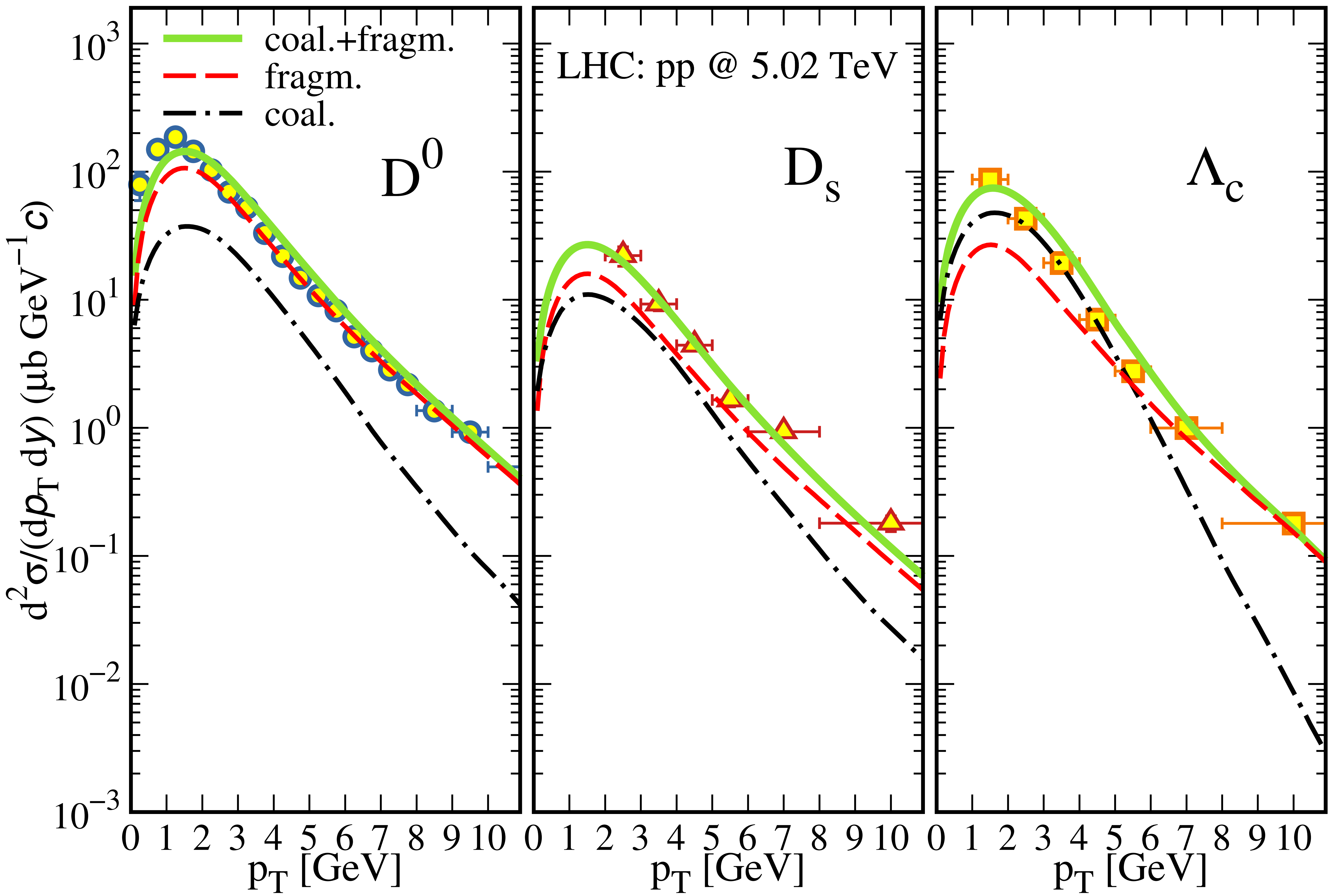
$$f_q(p) \sim \frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma_T\left(m_T - p_T \cdot \beta_T \mp \mu_q\right)}{T}\right)$$

+ same Wigner function widths $\sigma_{r,i}$ of hadrons in AA

$$f_H(x_{\mathrm{i}},;\ p_i) = \prod_{i=1}^{N_q-1} 8\ \exp\left(-\frac{x_{r,i}^2}{\sigma_{r,i}^2} - p_{r,i}^2\sigma_{r,i}^2\right)$$

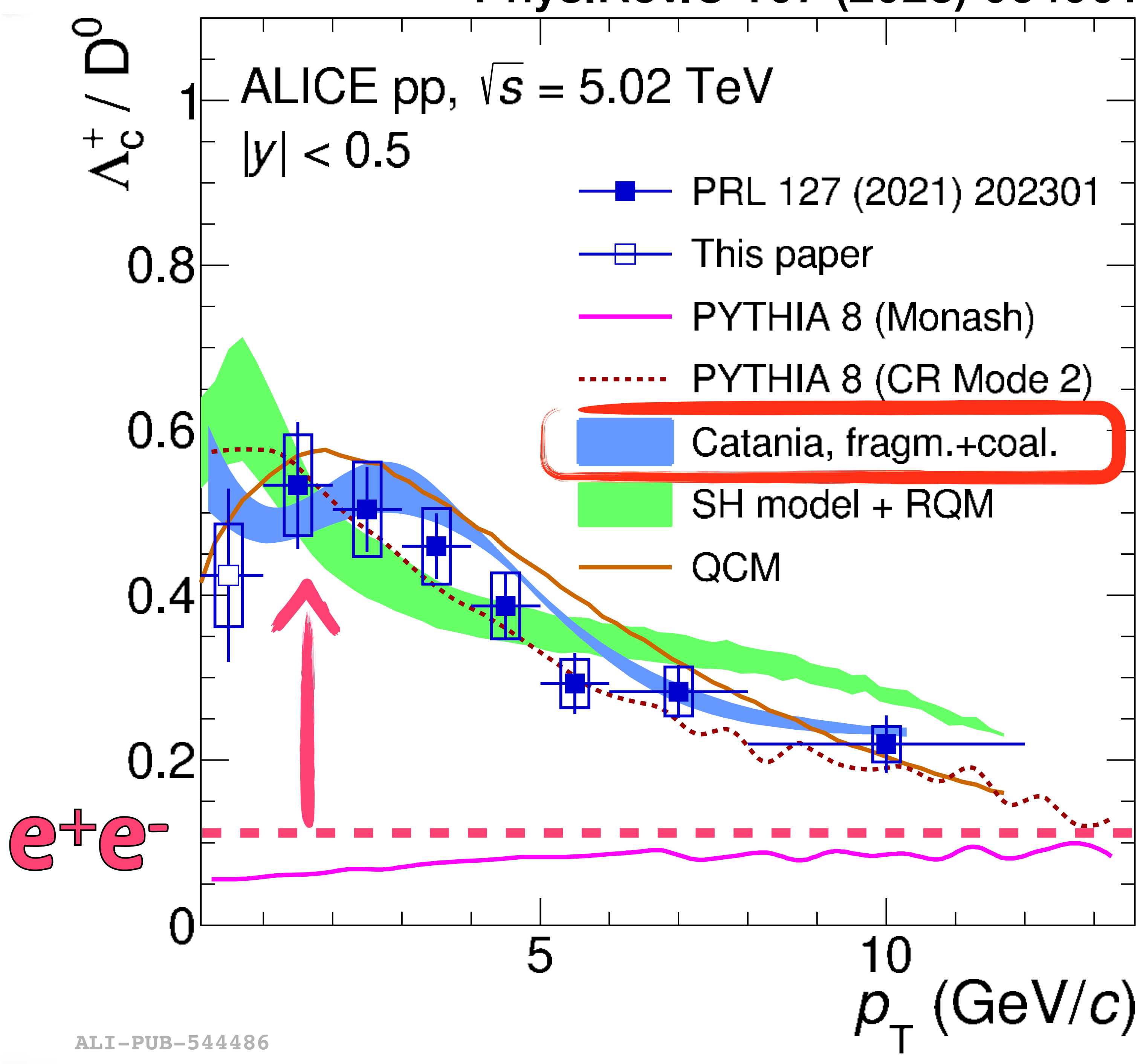
Coalescence in pp vs p_T in Catania

Phys. Lett. B 821 (2021) 136622



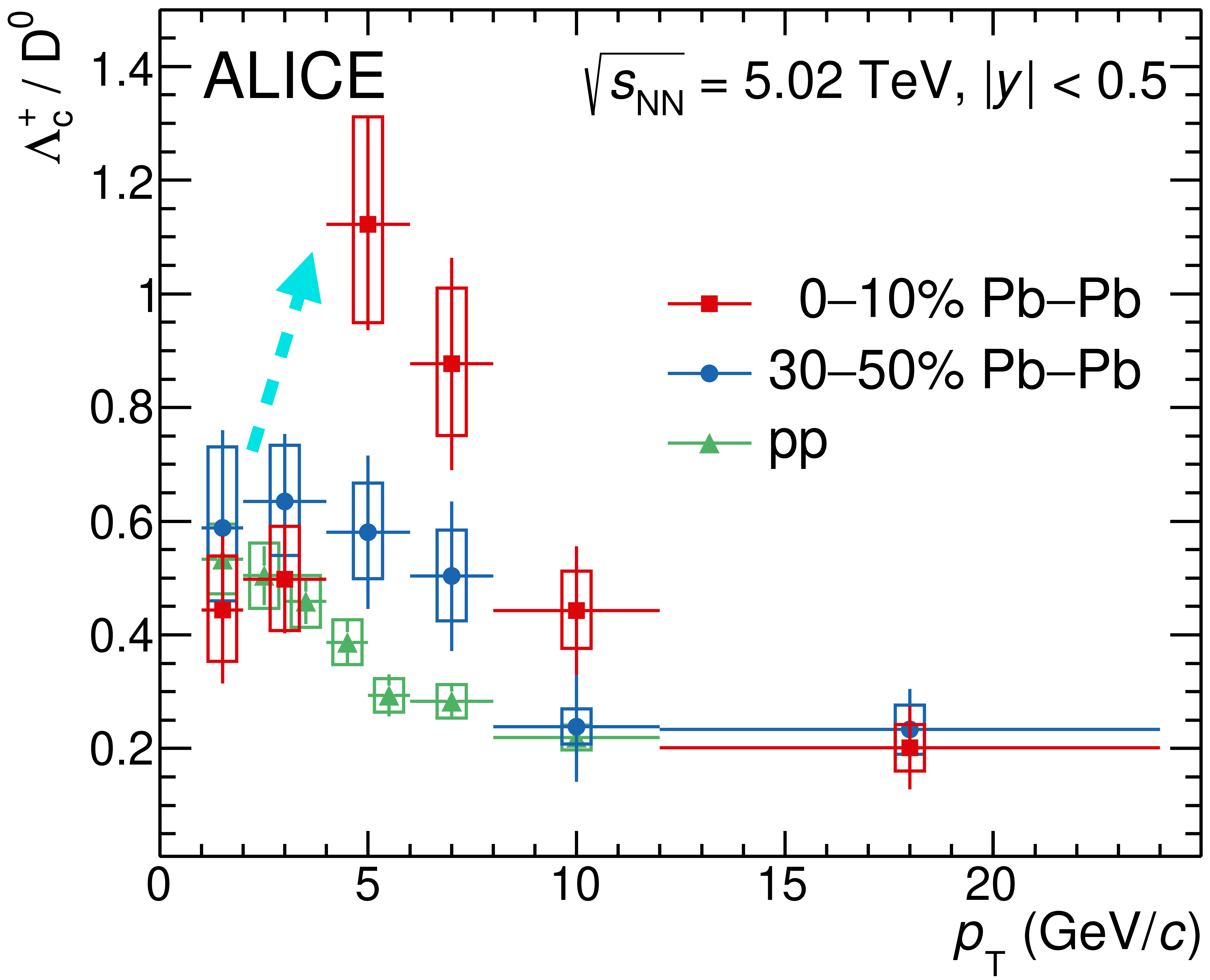
- All the coalescence does not affect significantly D^0, but is dominant for baryons Λ_c and Ξ_c

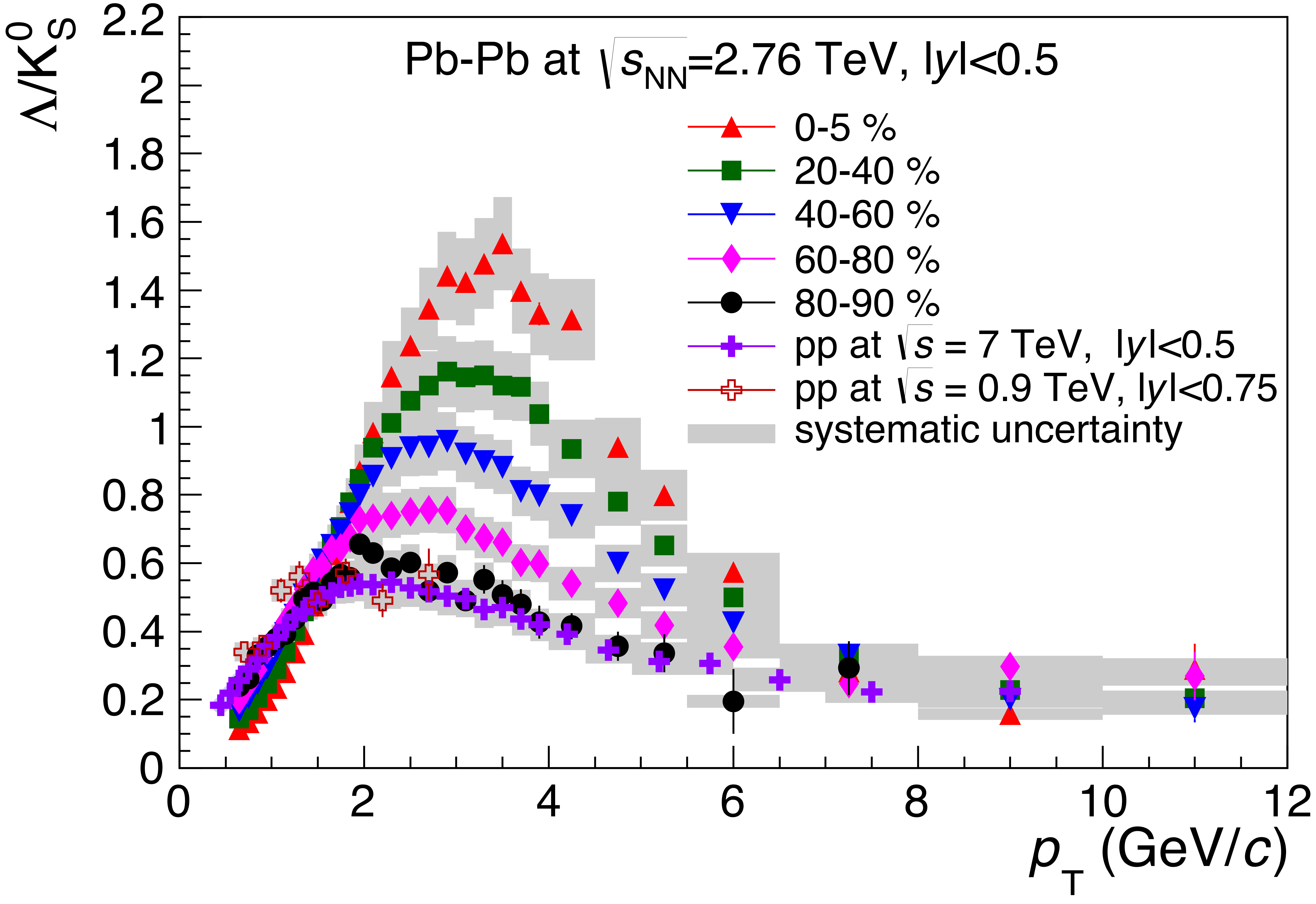
Phys.Rev.C 107 (2023) 064901



How about in Pb–Pb?

Physics Letters B 839 (2023) 137796

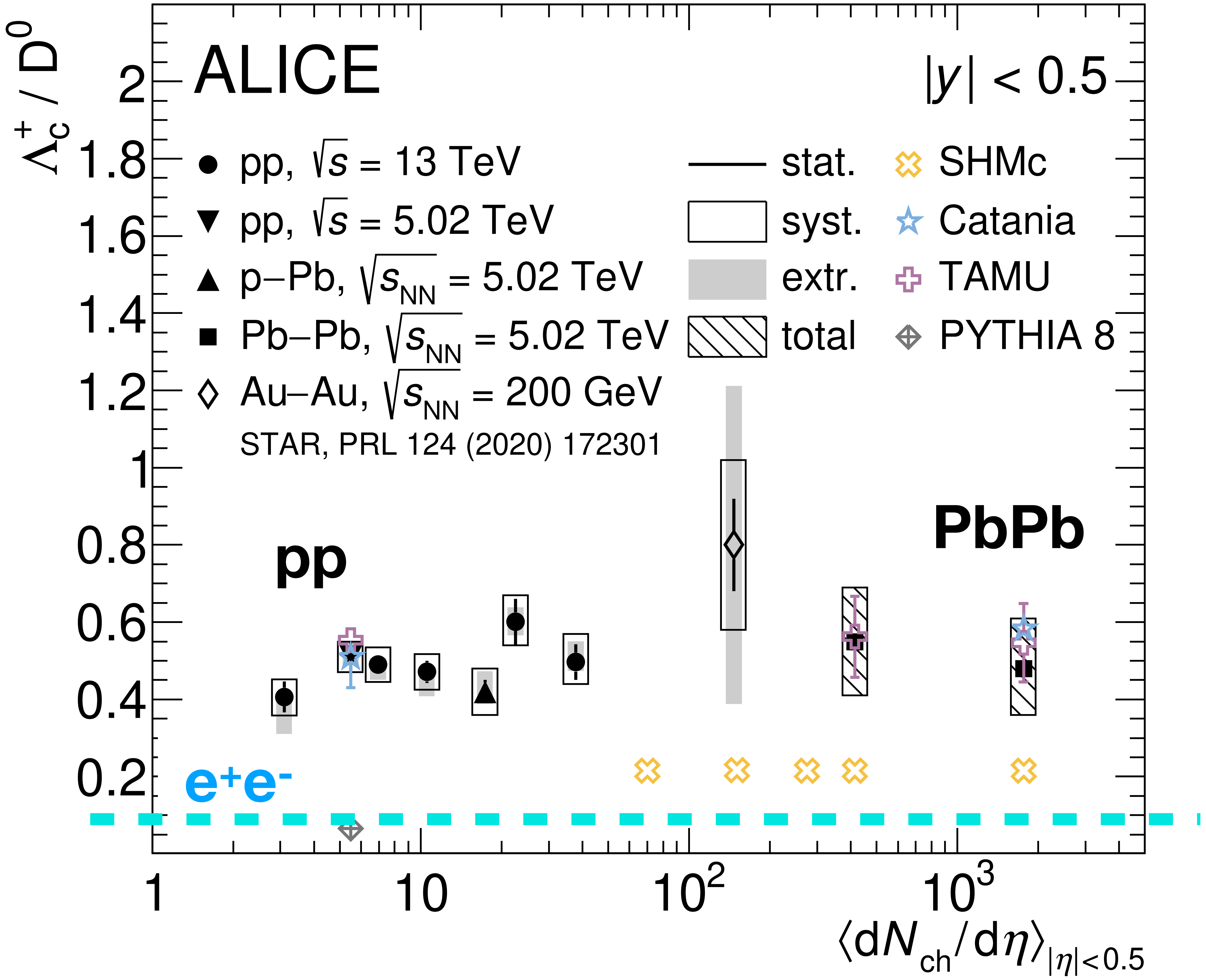




- Ratio increases from pp to mid-central and central Pb-Pb at intermediate p_T
- Trend qualitatively similar to what is observed for Λ/K_s^0 ratios

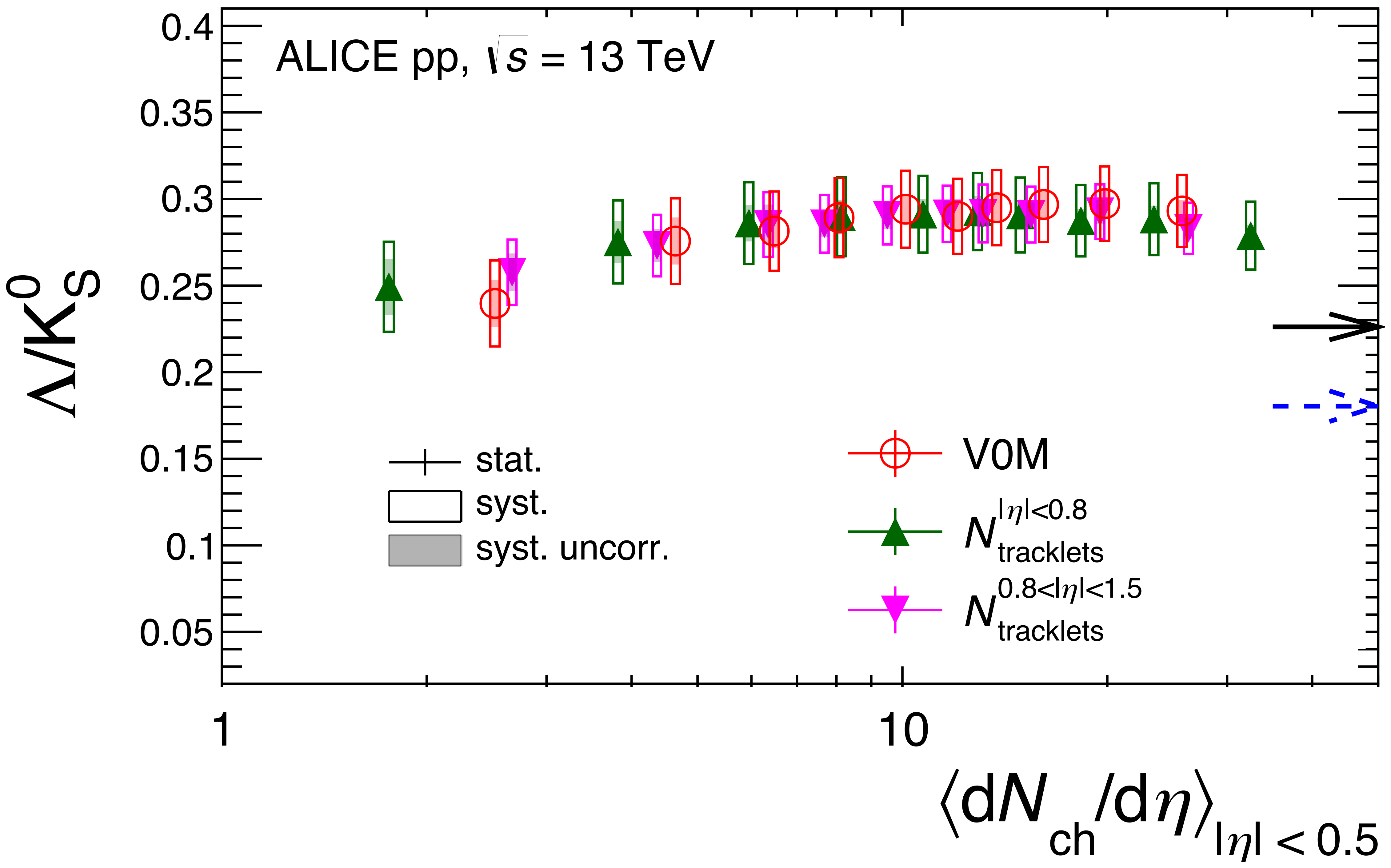
Where does the p_T differential enhancement come from?

p_T-integrated Λ_c^+/D^0 ratios

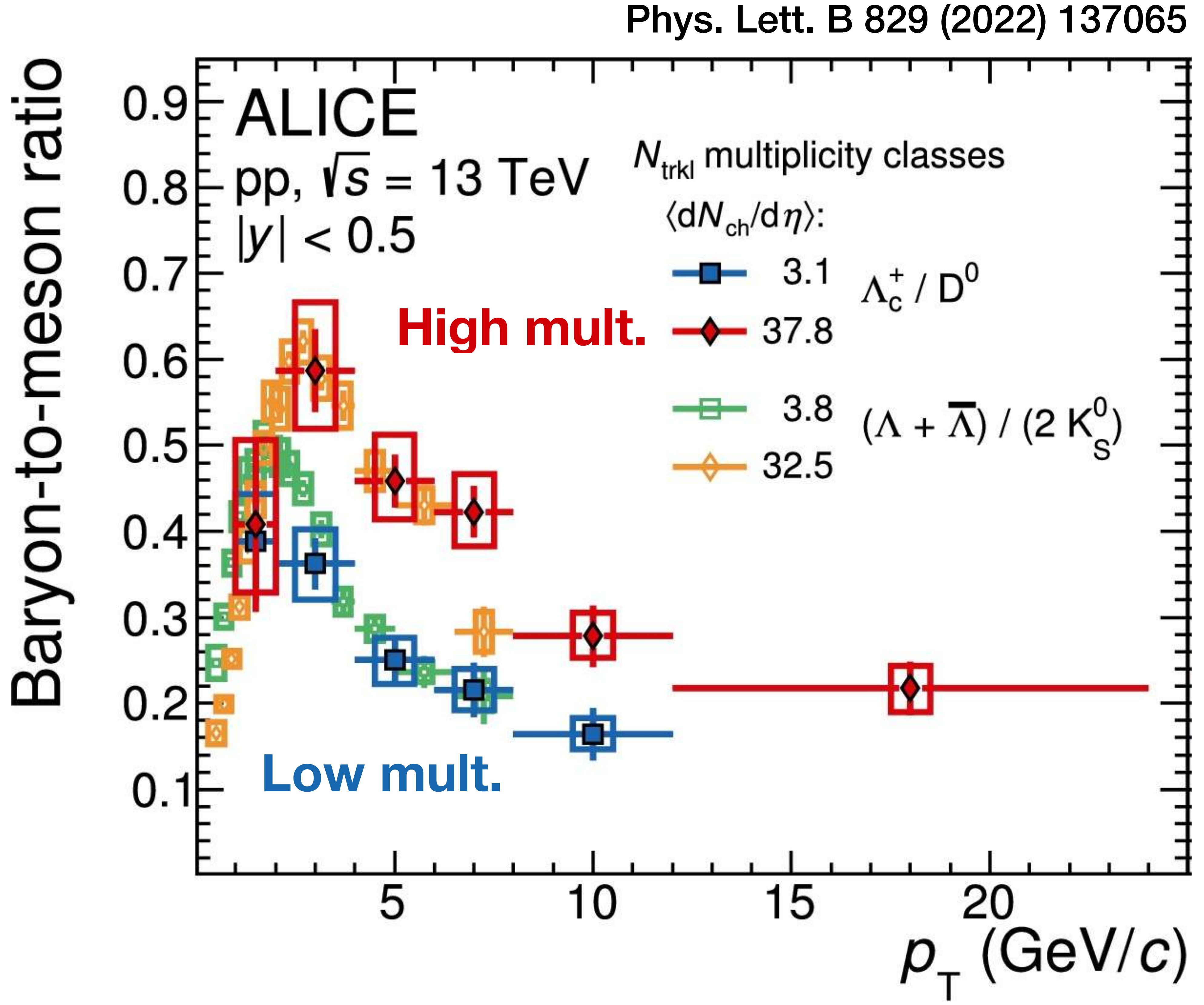


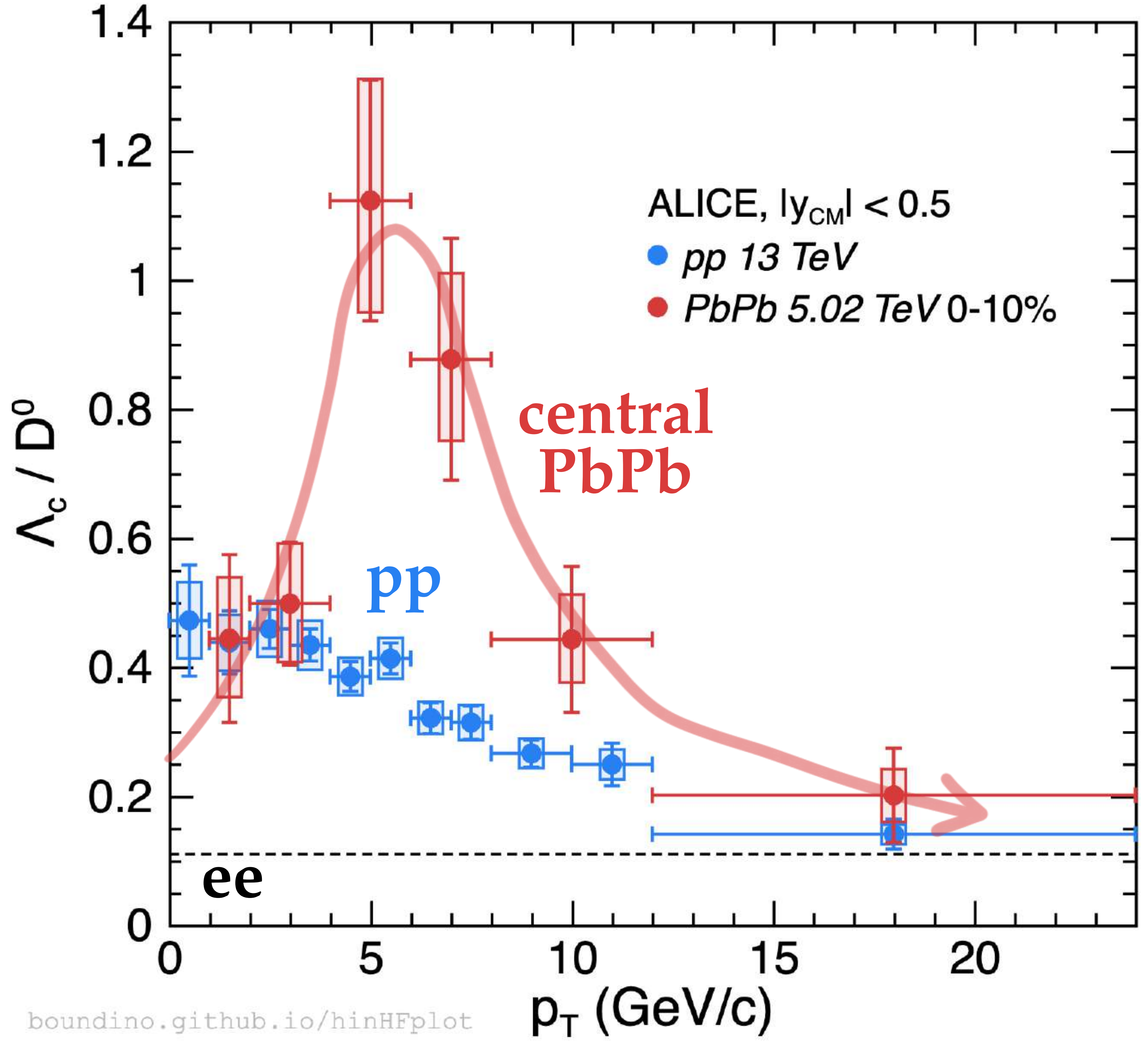
Phys. Lett. B 839 (2023) 137796

- Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?
- Modified mechanism of hadronization in all hadronic collision systems with respect to charm fragmentation tuned on e^+e^- and e^-p measurements?



p_T redistribution

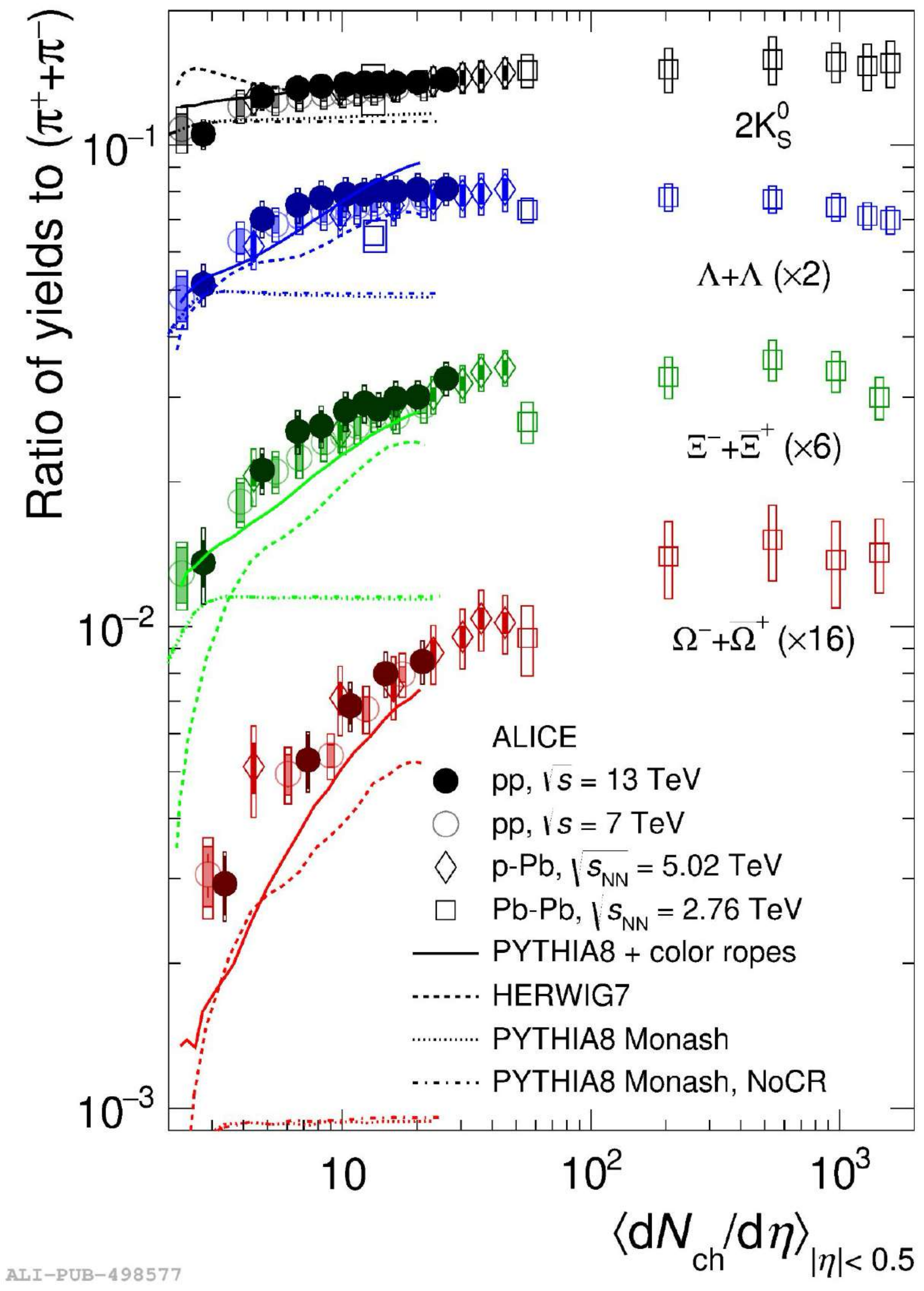




- Charm baryons/meson like for strangeness!
- Common mechanism for light- and charm-baryon formation in hadronic collisions? (unlikely) or coincidence in a redistribution?
- Shape changes dramatically in central PbPb → Strongest radial flow?

Role of strangeness in heavy-quark hadronization

Eur. Phys. J. C 80 (2020) 693



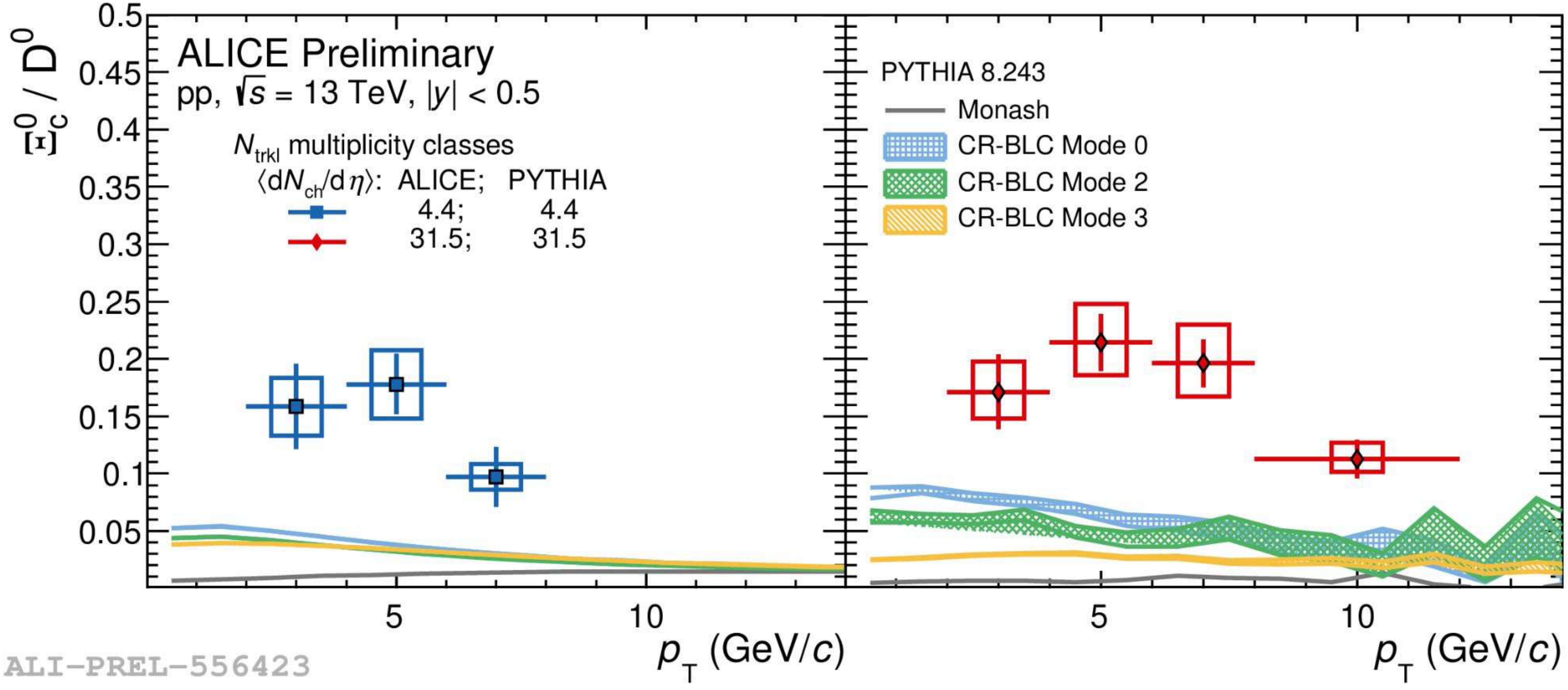
- Strangeness enhancement: yield-ratio between (multi)strange hadrons and pion larger in heavy-ion collisions than minimum-bias pp collisions

- Smooth increase vs. event multiplicity, without a clear collision-system dependence

- What do we learn from strange heavy hadron (D^0, Λ_c^+, Ξ_c^0,…) production about heavy-quark hadronization
  - ➡ evolve vs. event multiplicity?
  - ➡ sensitive to QGP-induced effects (e.g. strangeness enhancement, coalescence, *E*-loss, flow, …)?

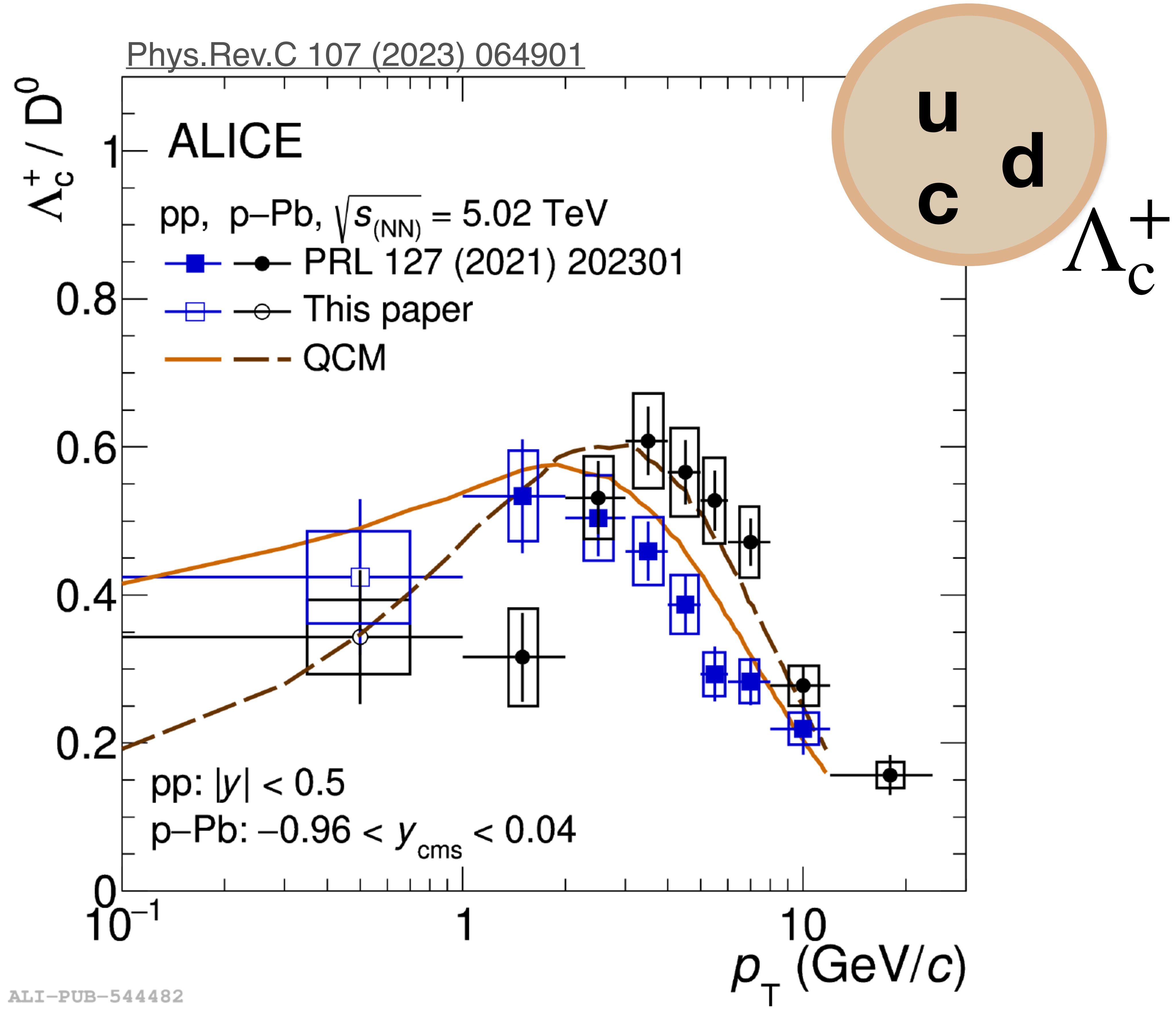
What about strangeness charm baryon?

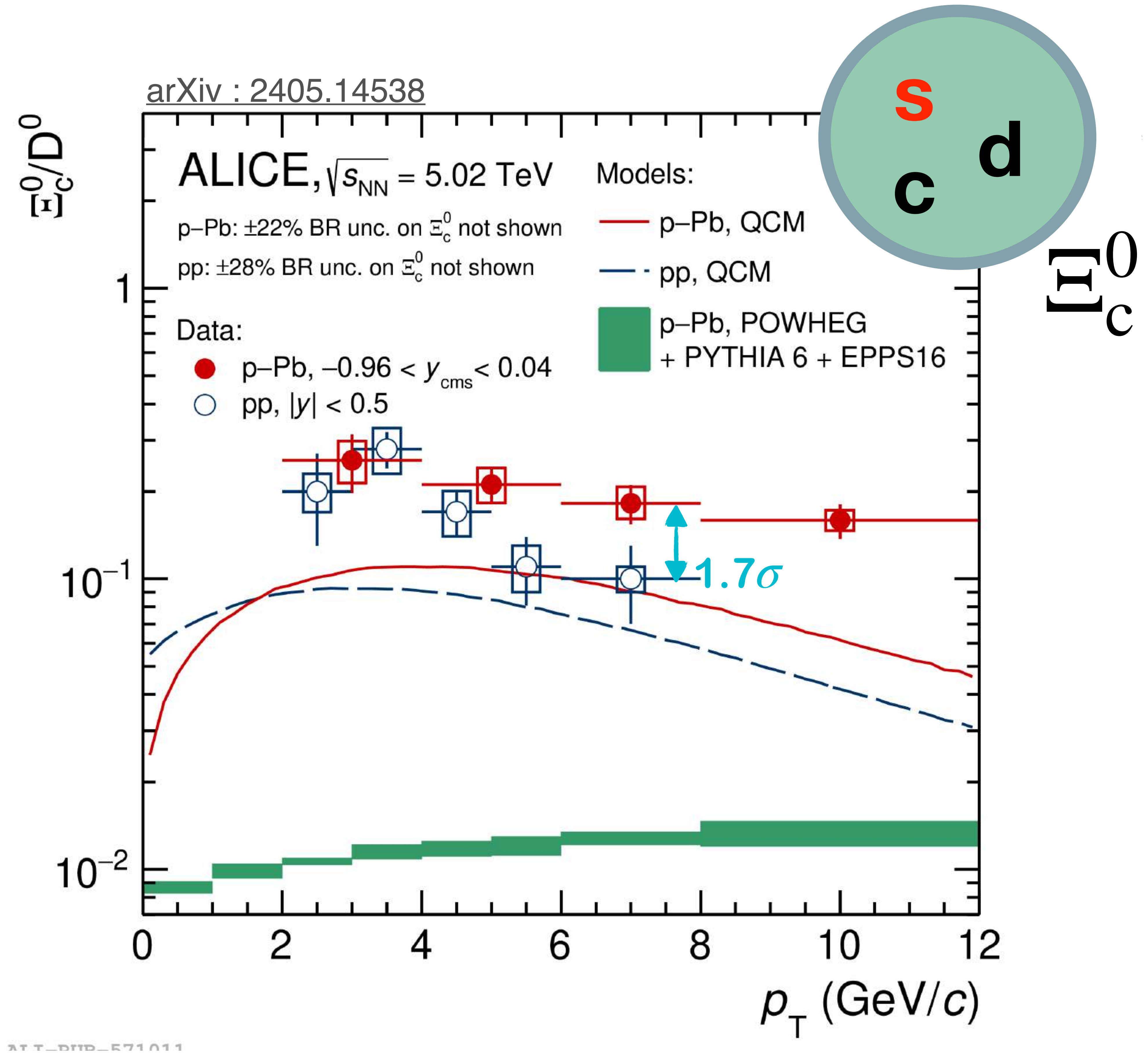
More challenges!



- Strong p_T dependence
- Enhancement compared to the measurement in e^+e^- and e^-p collisions

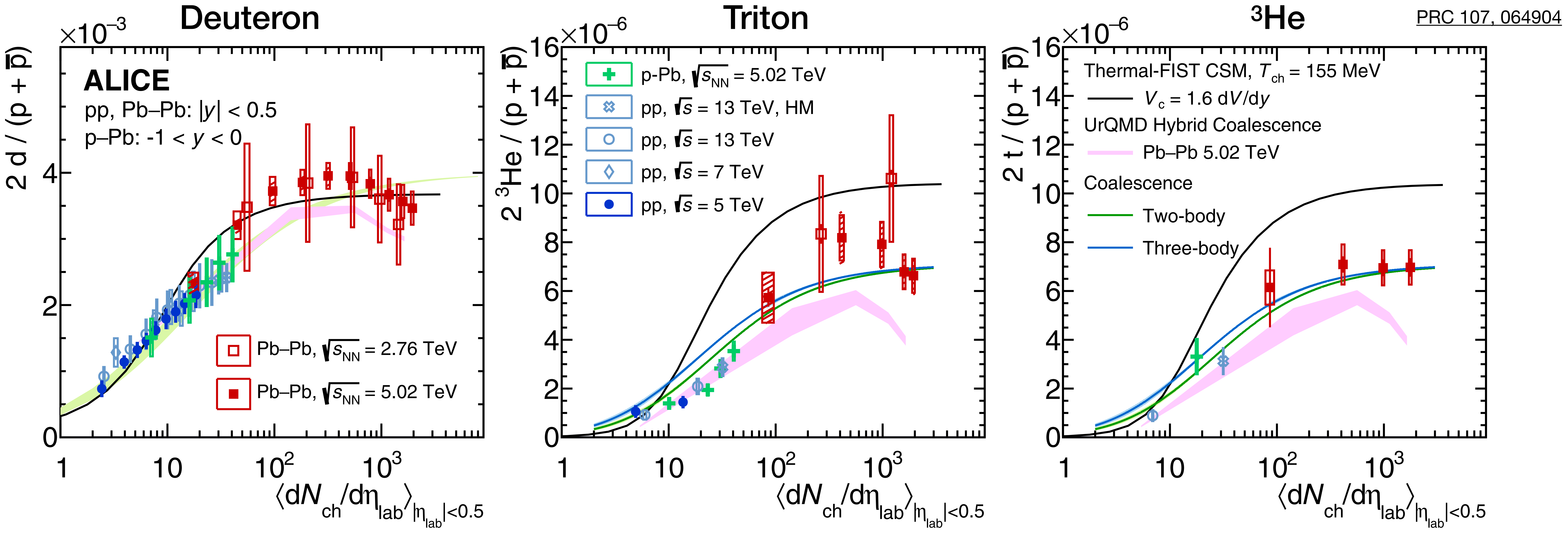
Challenging models





- Shift of distribution peak towards higher p_T could be attributed to radial flow
- QCM describes the magnitude of the ratio for Λ_c^+/D^0, but underestimate for Ξ_c^0

Light nuclei production

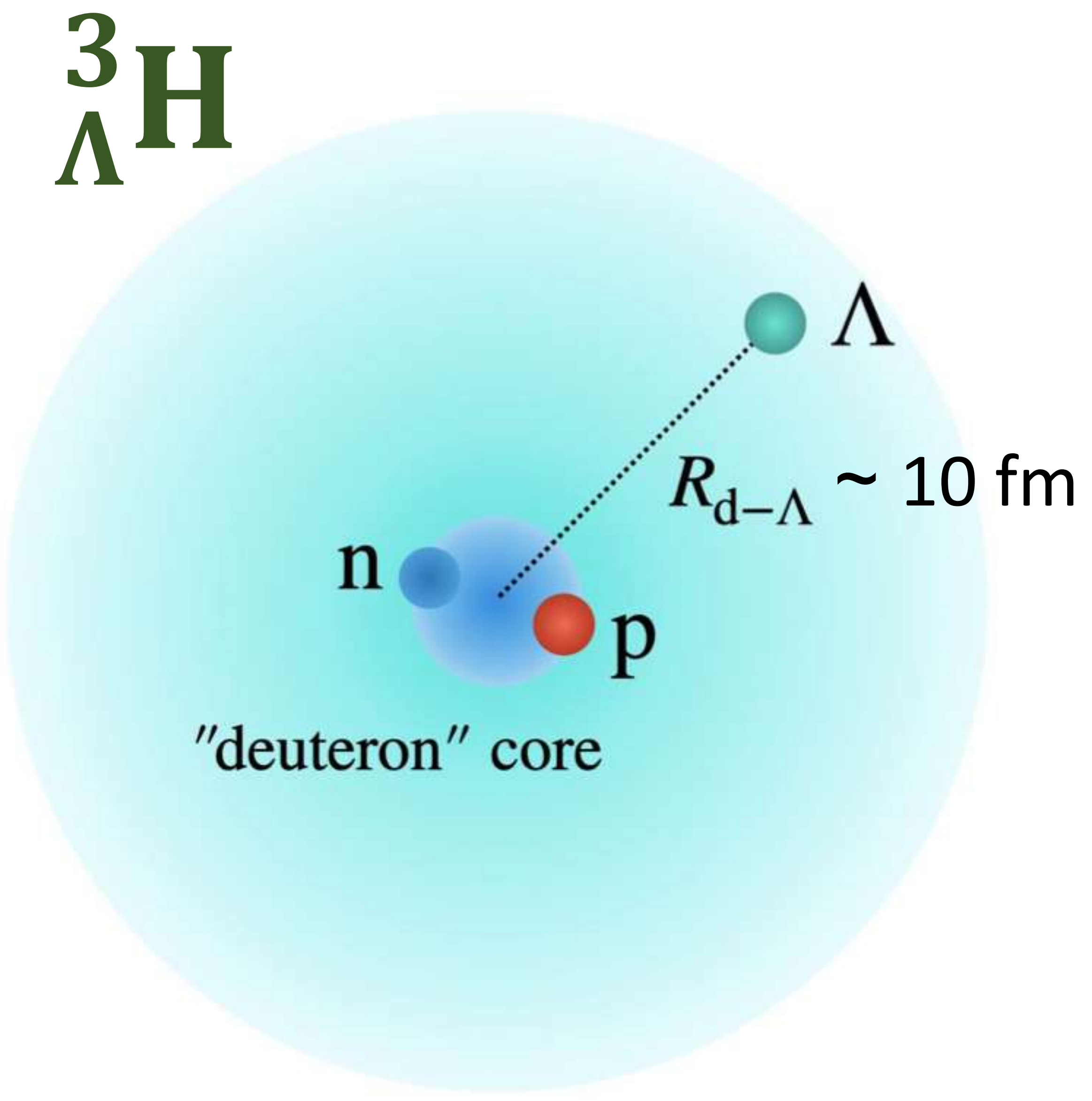


Thermal model prediction: Eur. Phys. J. A (2020) 56:280

Light nuclei: binding energy O(10 MeV)
expect dissociation in rescattering phase
+ formation via coalescence of baryons
⇒ different evolution vs density

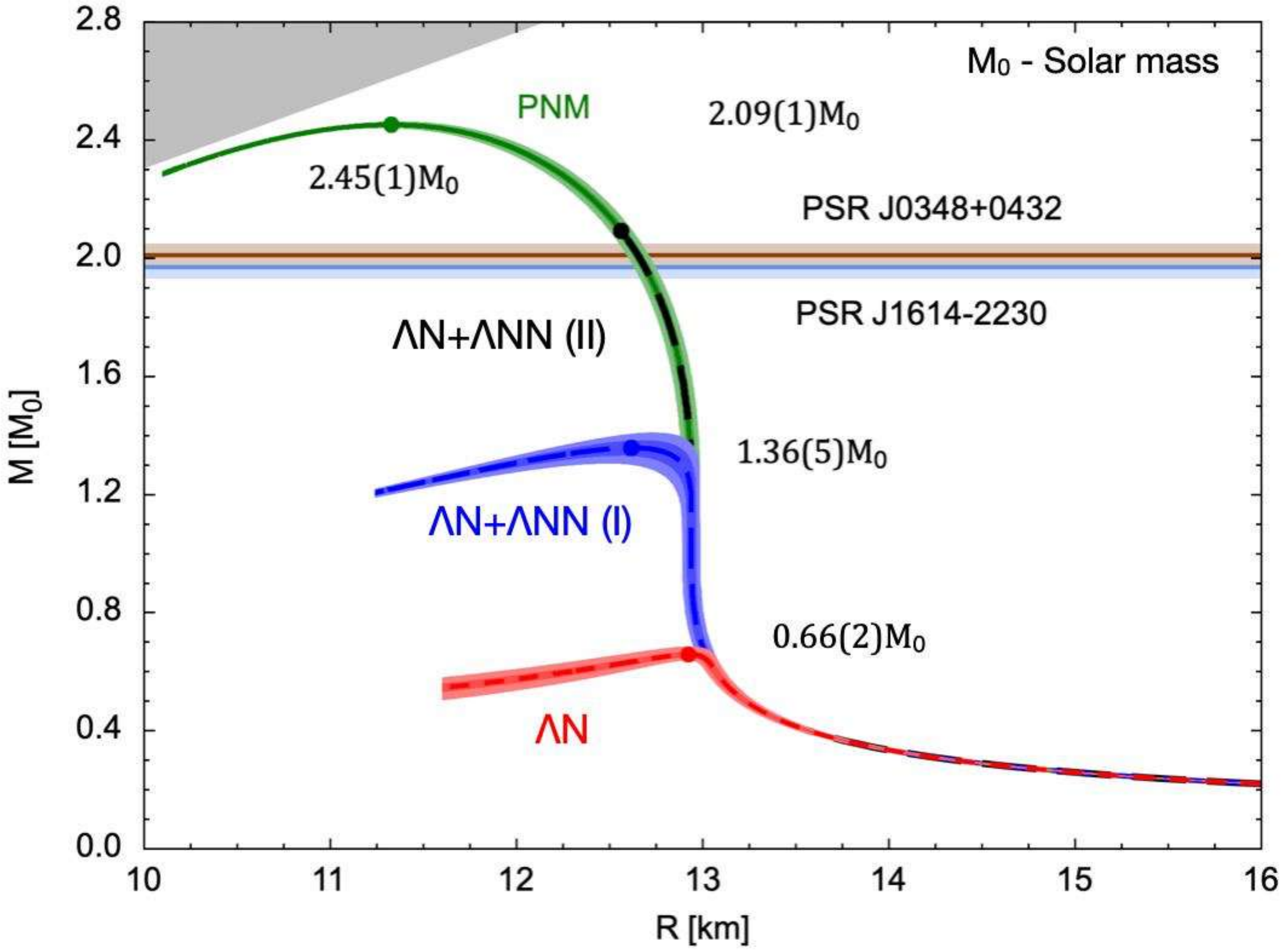
- Dependence of light-nuclei production on event multiplicity provides important insights into the mechanisms of light-nuclei formation
- ^{3}He, t favour coalescence models → likely formed through the coalescence of nucleons in the later stages of the collision

Hypertriton production, application to neutron star



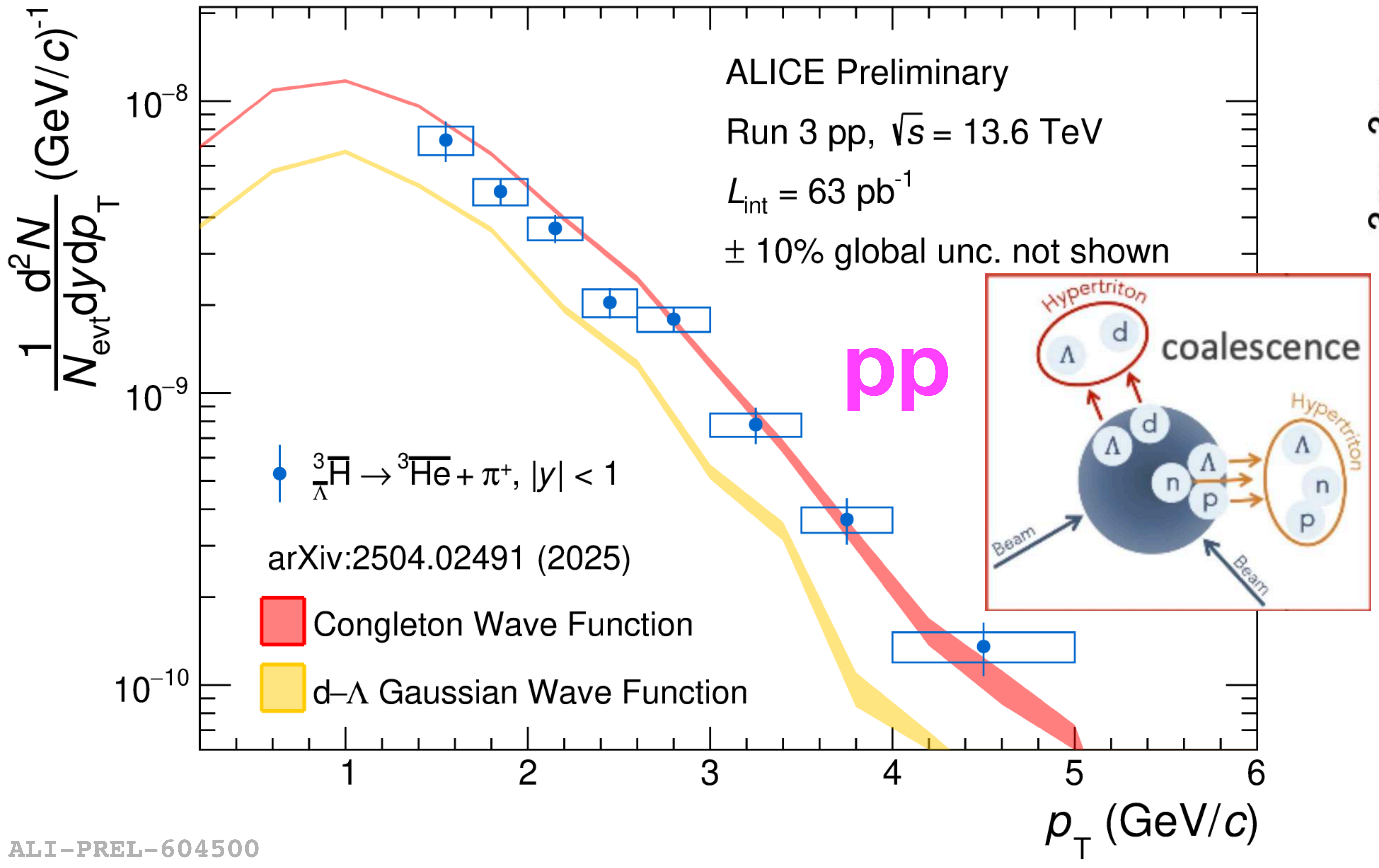
Lightest hyper nucleus

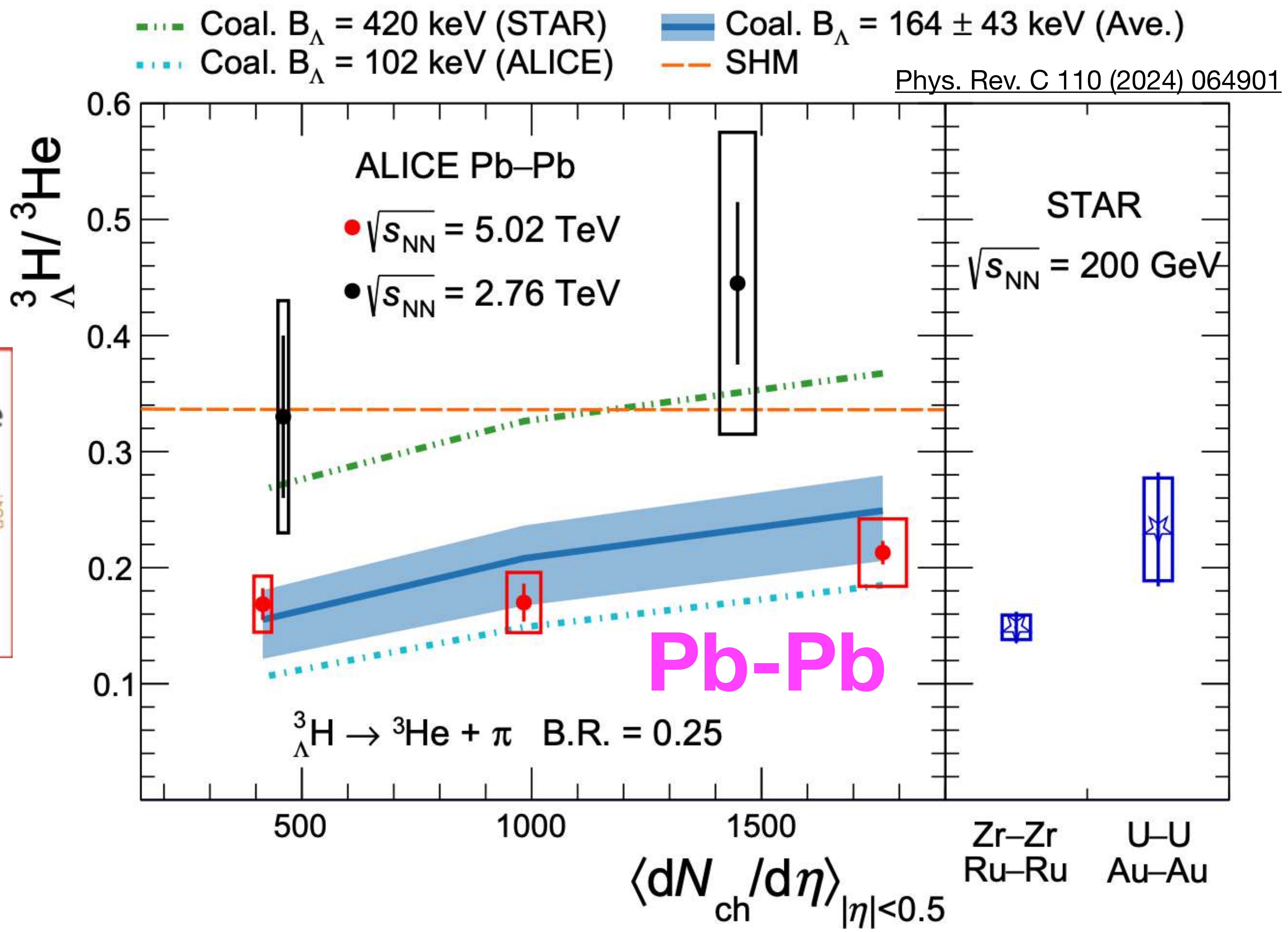
D. Lonardoni et al., PRL 114, 092301 (2015)



- At the LHC, $^{3}_{\Lambda}$H has been measured in pp, p-Pb, and Pb–Pb collisions
- $^{3}_{\Lambda}$H powerful probe for investigating the nucleon–Λ interaction
- Crucial for the calculation of the equation of state (EoS) and the neutron star mass-radius relation

Hypertriton production in pp & Pb–Pb collisions



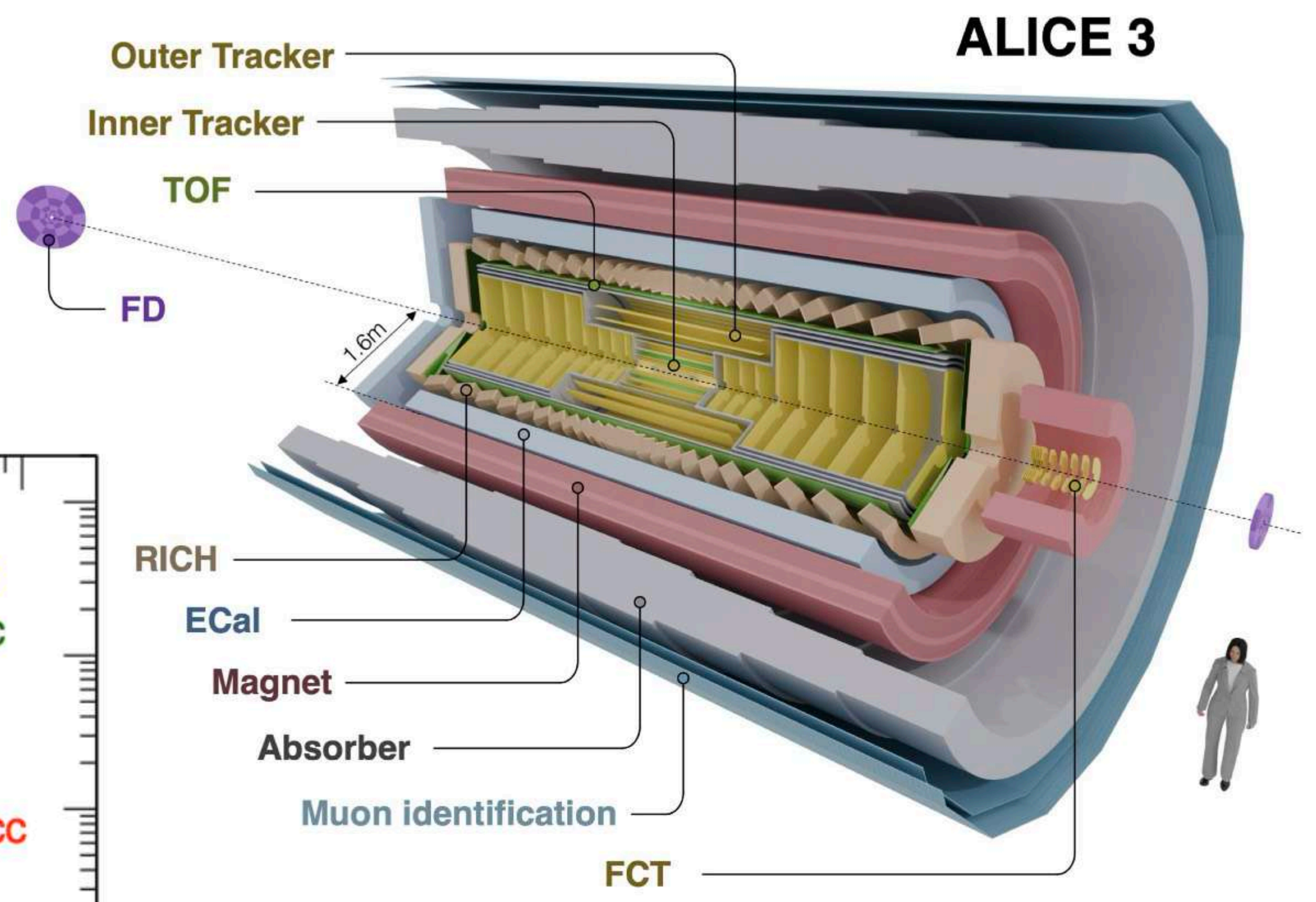


- Hypertriton production in pp & Pb-Pb collisions consistent with coalescence model → powerful tool to investigate the mechanism of nuclear production

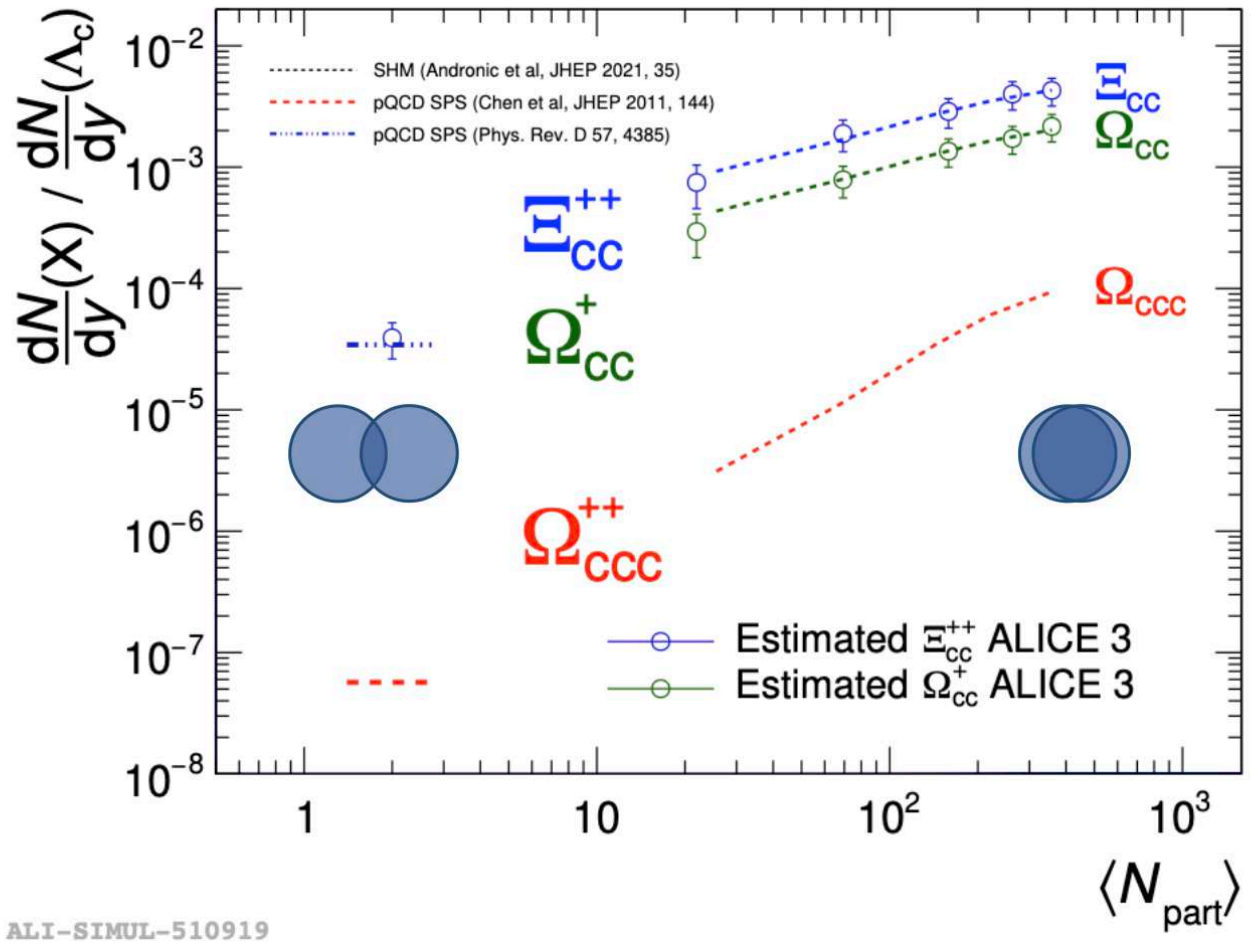
- **coalescence** → interplay between the spatial extension of the nucleus wavefunction and the system size
- **SHM** predicts a flat ratio: sensitive to their similar masses, but insensitive to their size

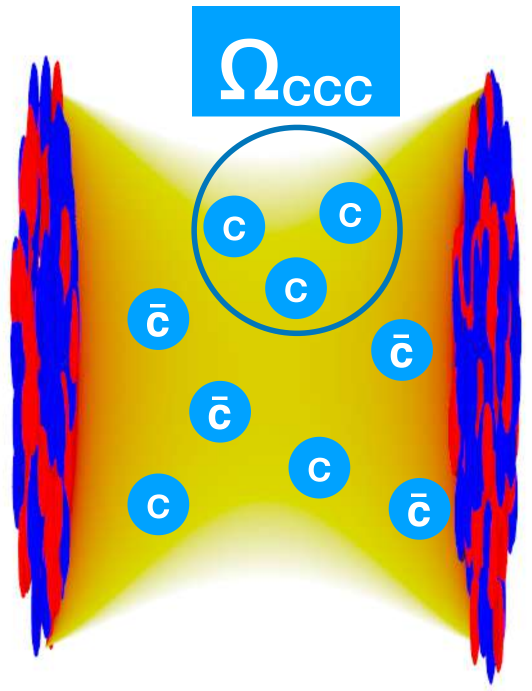
What is obvious?, what is vague, what is unknown, …

- Coalescence → a common framework for heavy-flavor hadronization from pp to AA?
- Other approaches such as PYTHIA-CR, POWLANG-LCN, … point also to
  - In medium local recombination
  - Large evolution from e^+e^- to pp while reshuffling in p_T from pp to AA



- Many open issues
  - Rapidity evolution
  - Extend to bottom
  - Effect on other observables (ex. v_2)
  - ….





→ Recombination models predicts

2-3 orders of magnitude enhancement in Pb-Pb

⇨ Unique ALICE 3 physics!



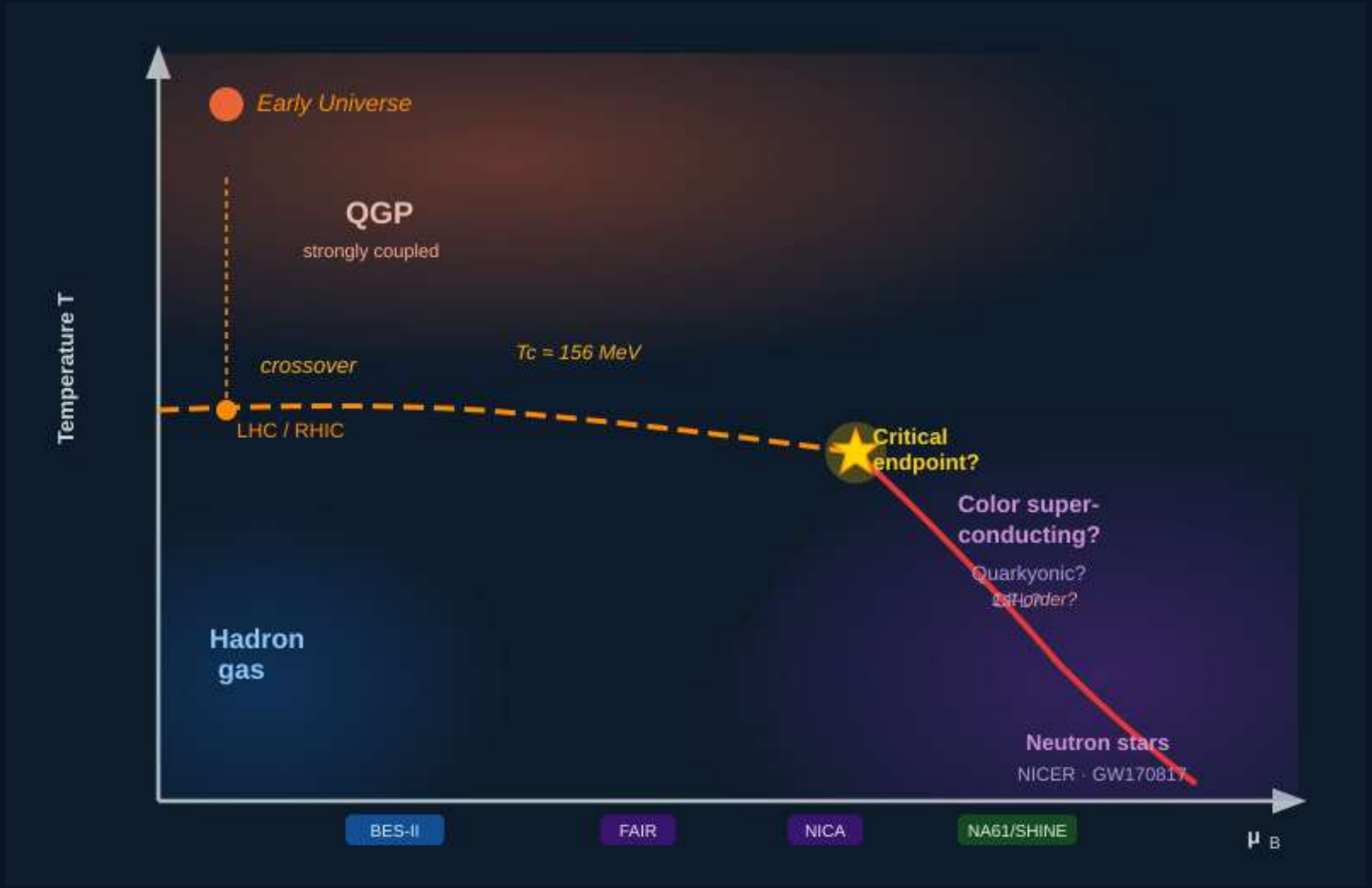
Thank you for your attention!

Extra Slides

QCD phase diagram (2026 perspective)

QCD Phase Diagram (2026 Perspective)

From qualitative ideas to quantitative constraints



✅ What We Know

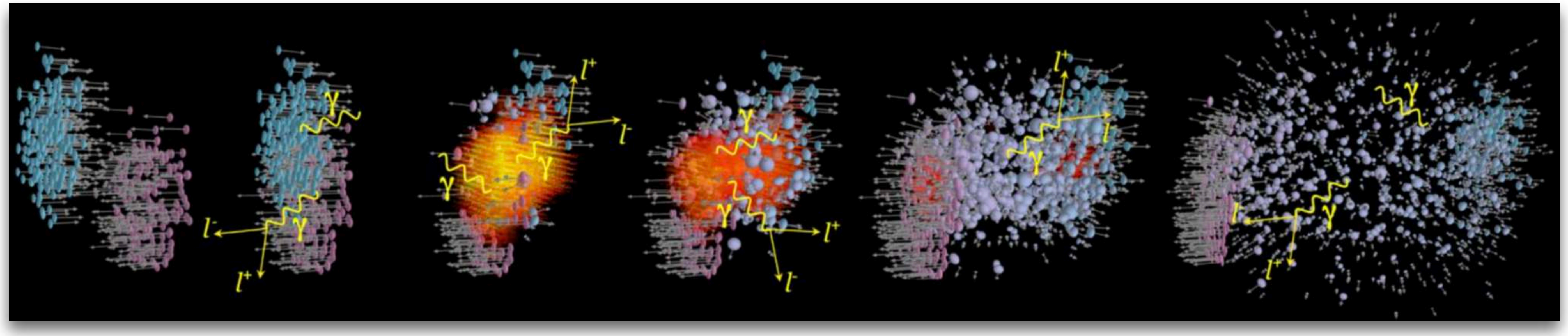
- Crossover at $\mu_B \approx 0$
- $T_c \approx 156$ MeV (lattice QCD)
- Strongly coupled QGP
- η/s close to KSS bound

❓ Open Questions

- Critical endpoint location
- First-order transition line
- Dense quark matter phases
- Color superconductivity
- Quarkyonic matter

The discovery era is largely complete at low baryon density — the next frontier is mapping the high-density region and determining transport properties of QCD matter.

Learn more… QCD medium evolution over time



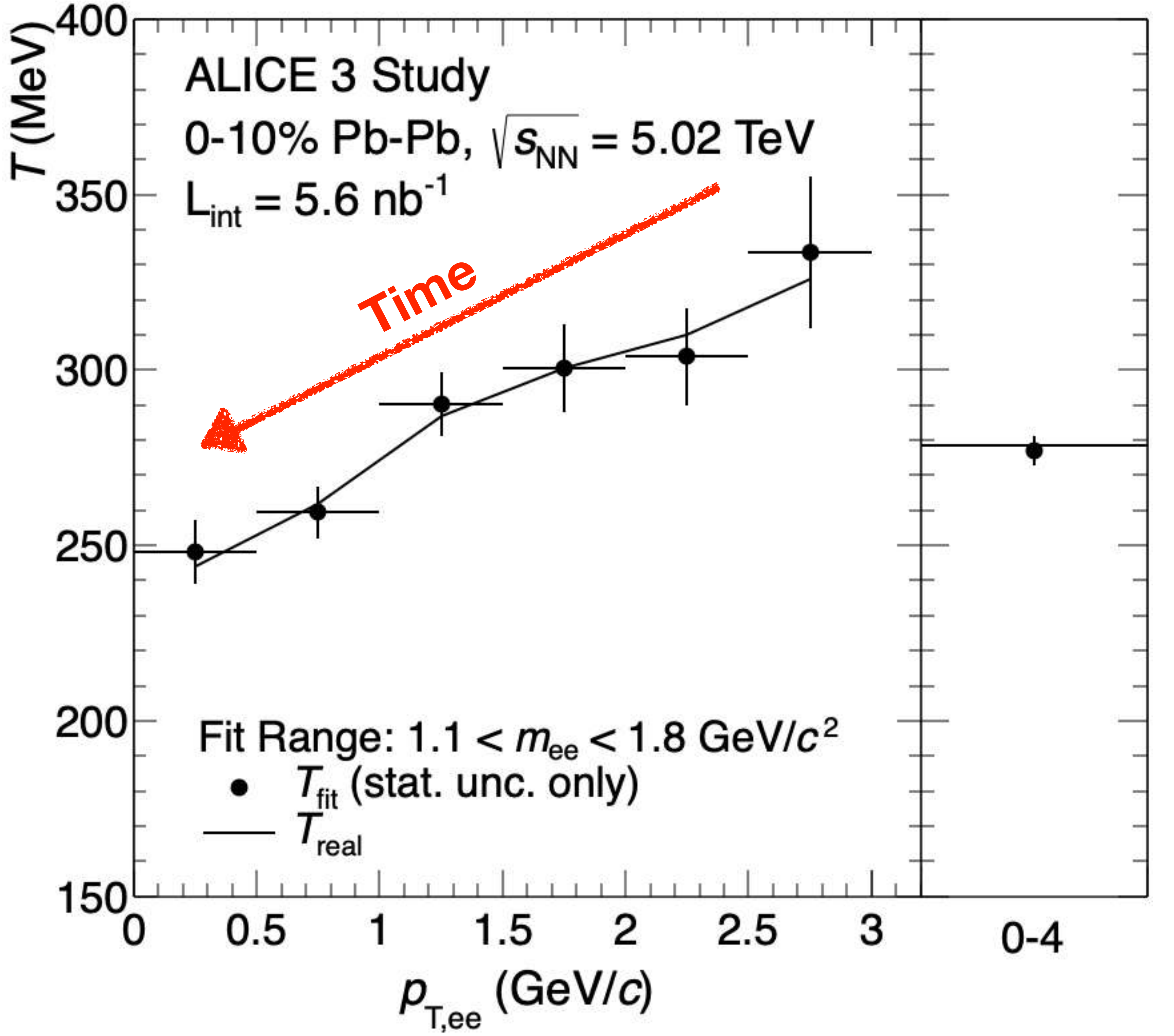
ALICE 3: probe time dependence of T

- Double differential spectra: T vs mass, $p_{T,ee}$

Measure time evolution of the QCD matter!

in 10-15 years

Expected statistical errors of T as a function of $p_{T,ee}$
ALICE 3, one month Pb-Pb

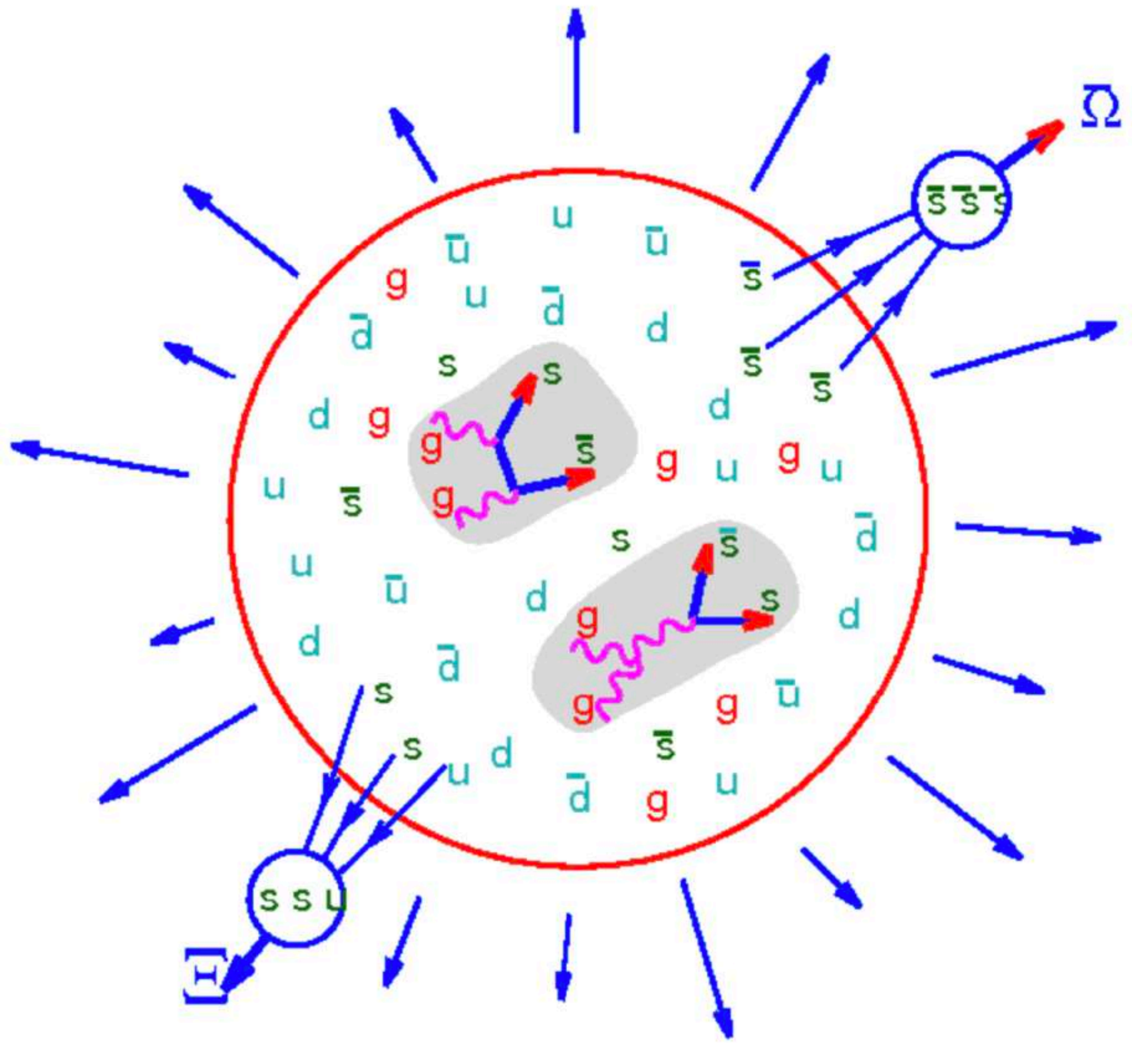


Two historic predictions

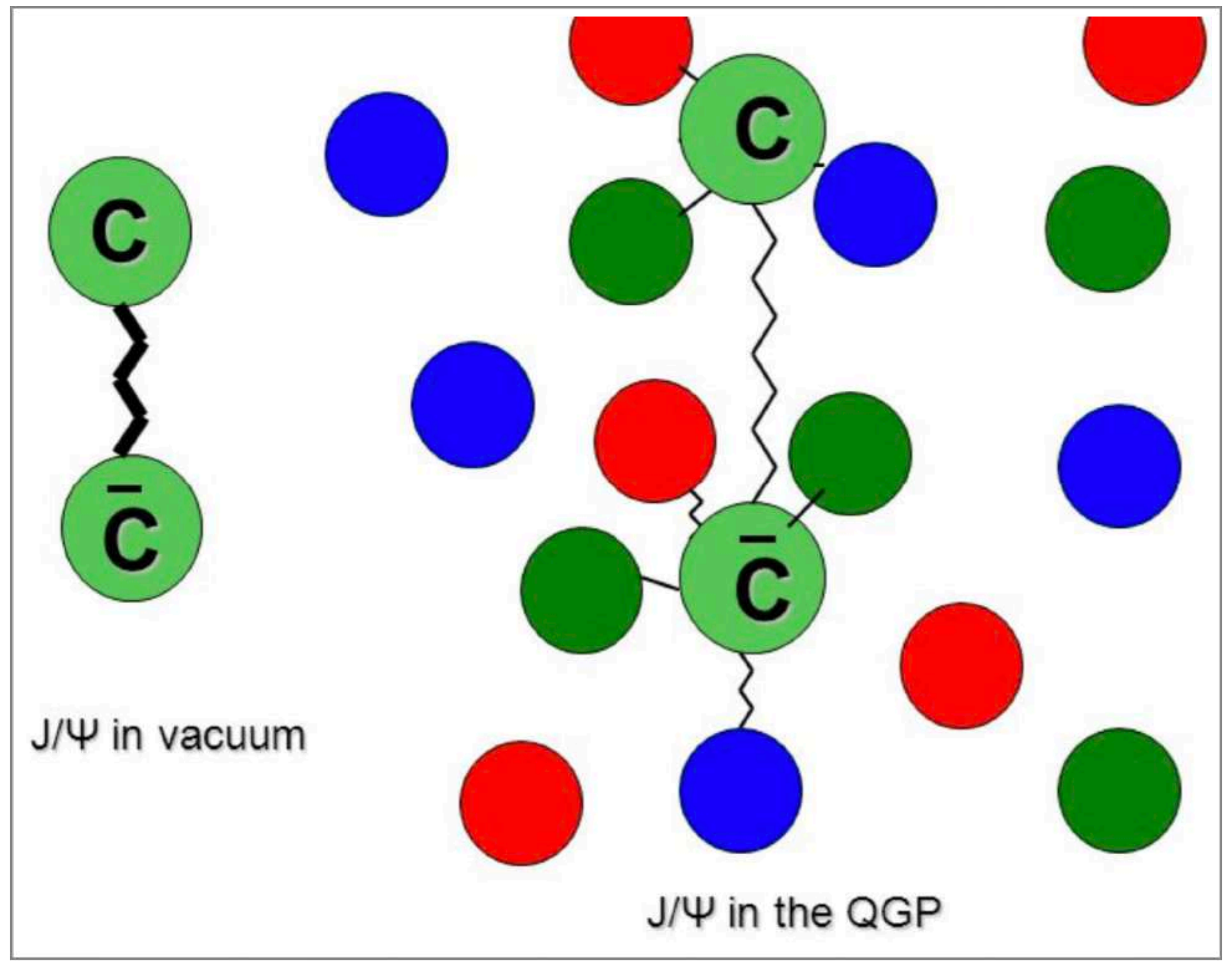
QGP phase, if existed, would obviously be very short-lived, how to observe it?

- is there a memory of the passage through the QGP phase?
- are there "signatures" of the QGP that we can look for in the final state?

two major proposals made in the 80's:



Strangeness enhancement



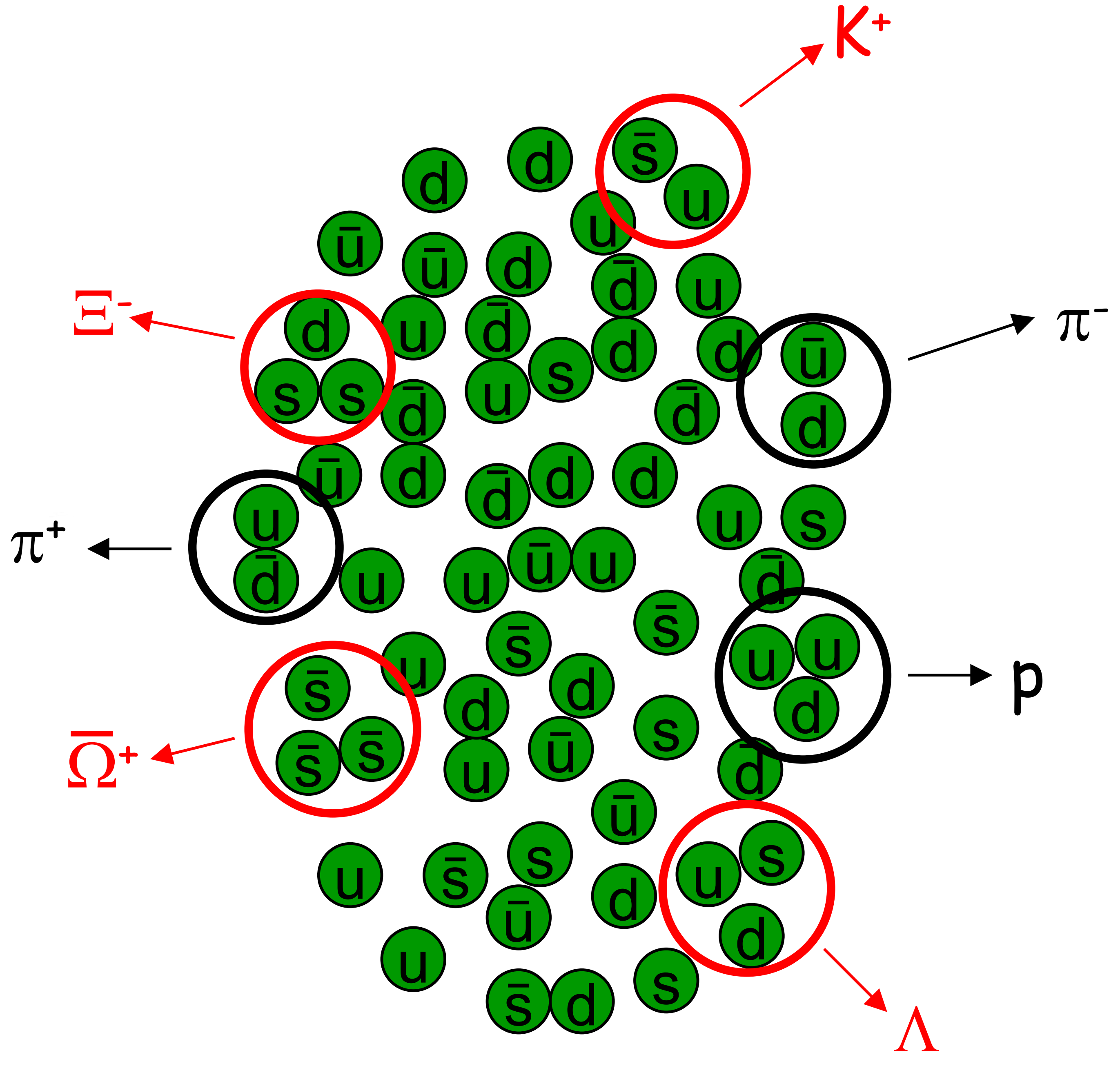
J/ψ suppression (Tetsuo Matsui and Helmut Satz)

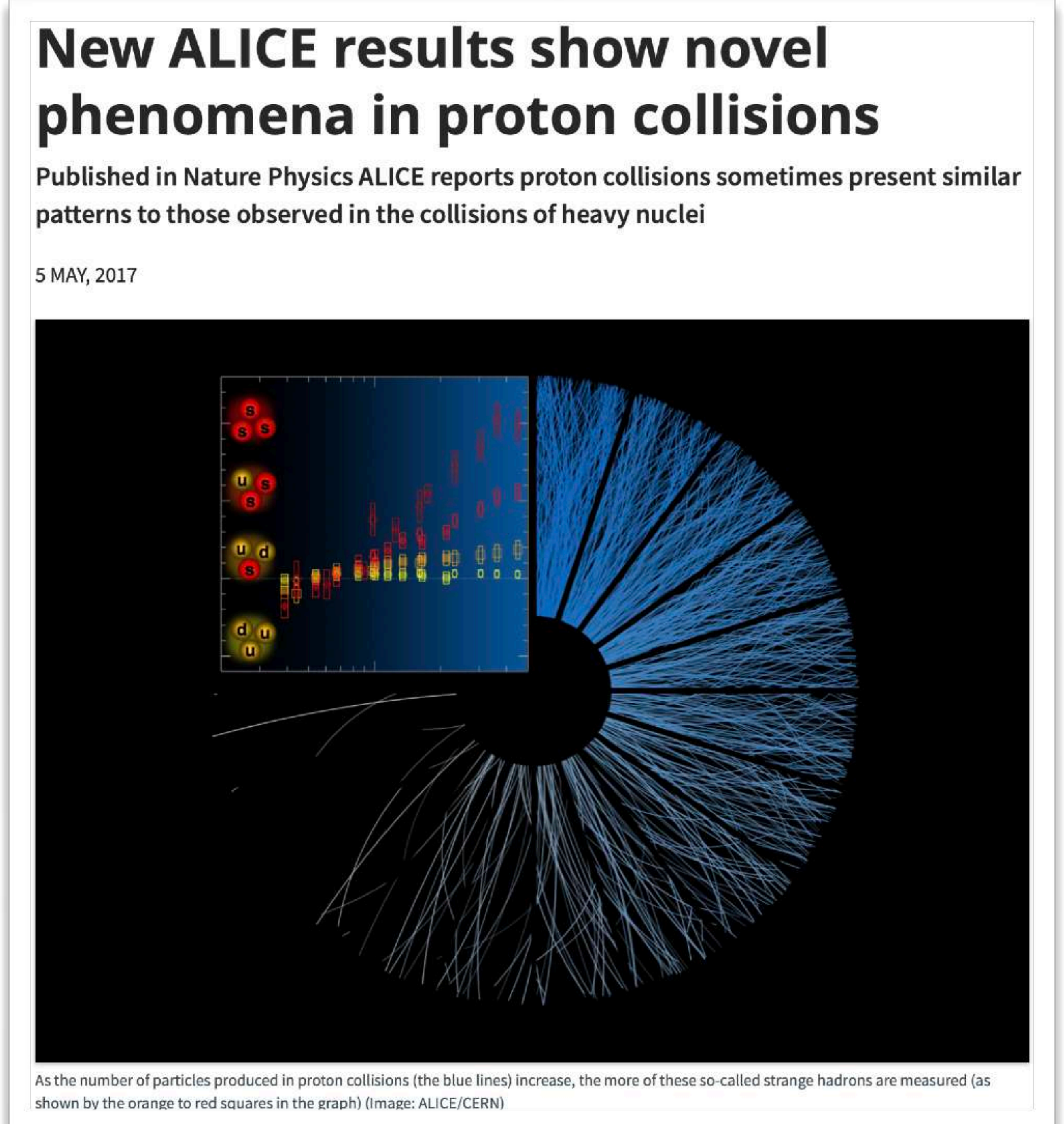
Strangeness enhancement

Restoration of chiral symmetry increase the strangeness production

- $m_s \sim 150$ MeV $\sim T_c$
- copious production of $s\bar{s}$ pairs, mostly by gg fusion

Recombination of the strangeness quarks: Strangeness production is dominated by the underlying event (soft/thermal), not jet fragmentation





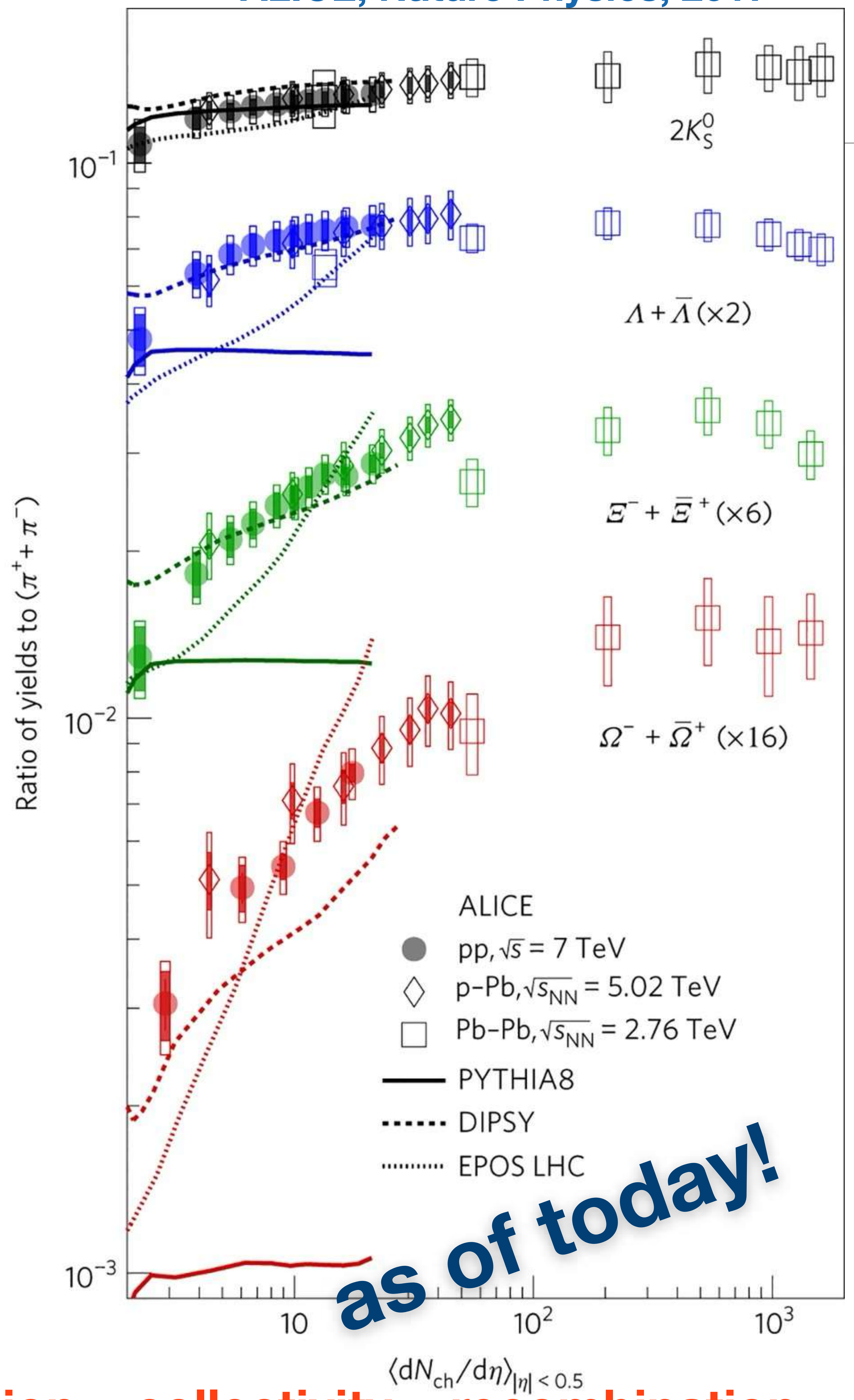
New ALICE results show novel phenomena in proton collisions

Published in Nature Physics ALICE reports proton collisions sometimes present similar patterns to those observed in the collisions of heavy nuclei

5 MAY, 2017

As the number of particles produced in proton collisions (the blue lines) increase, the more of these so-called strange hadrons are measured (as shown by the orange to red squares in the graph) (Image: ALICE/CERN)

ALICE, Nature Physics, 2017

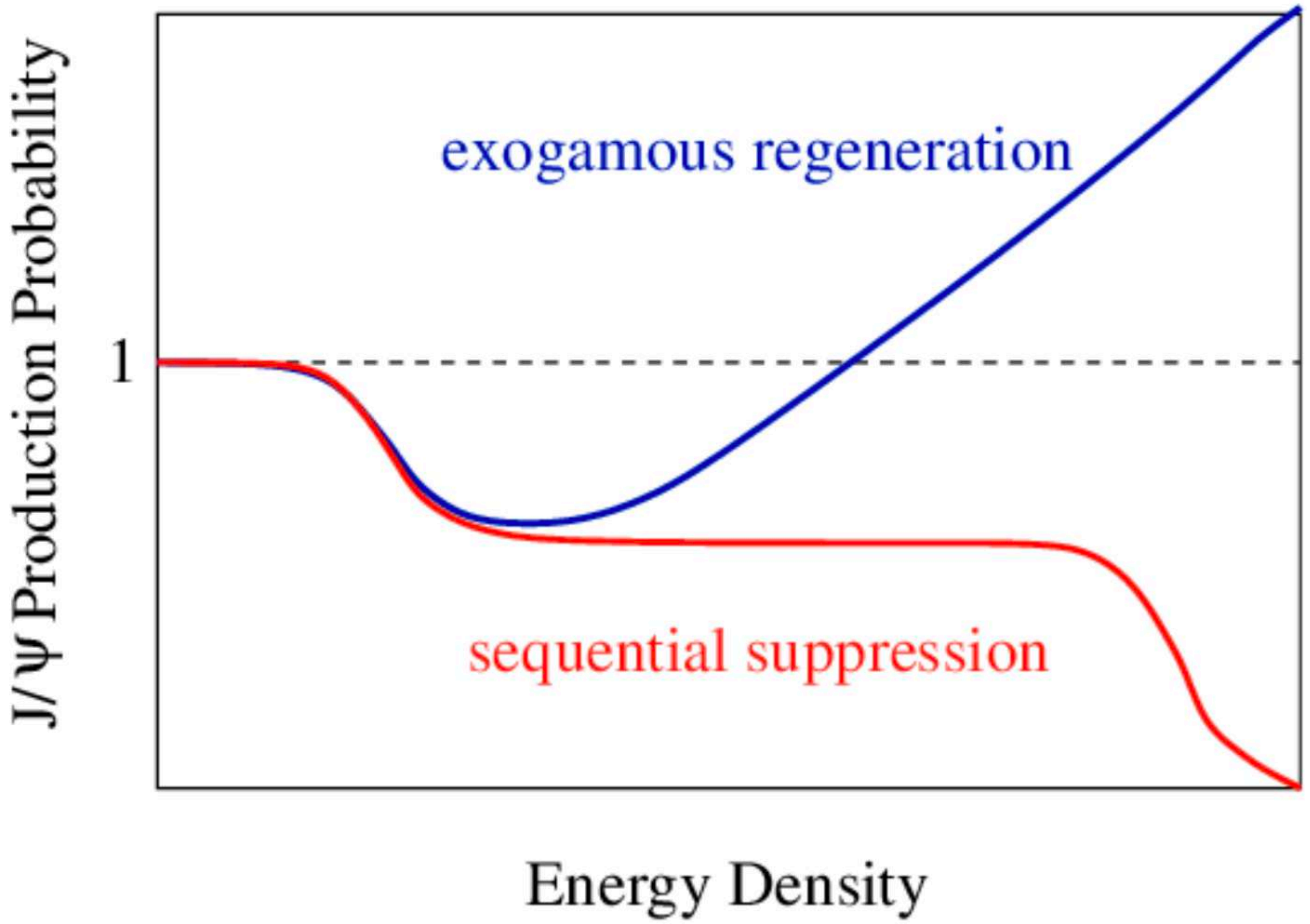


Canonical suppression + collectivity + recombination

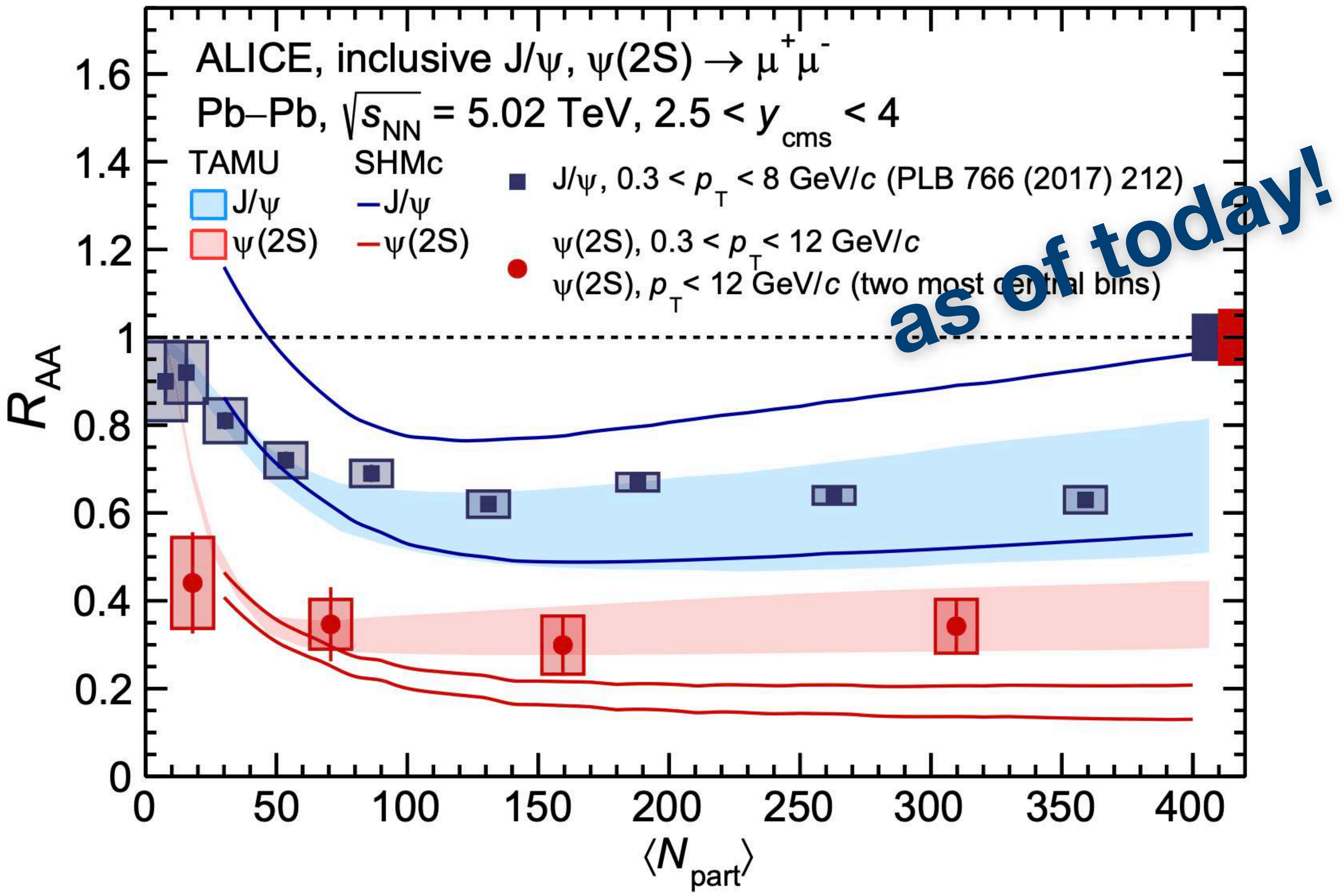
Quarkonium suppression

At T >> 0, high density of colour charge in the medium induces Debye screening

- at $T > T_D$, melting of quarkonia
- also regenerated…

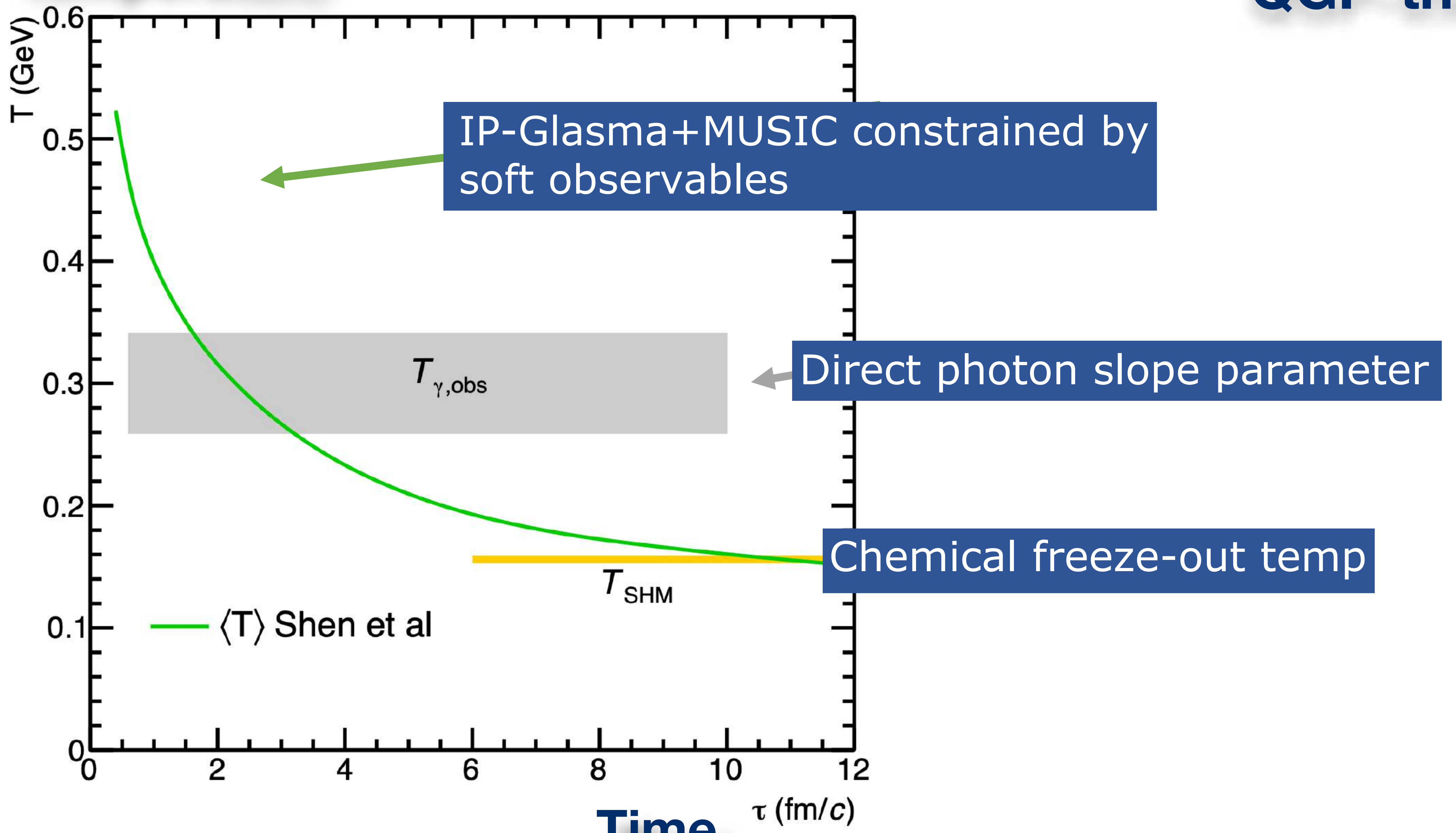


Phys. Rev. Lett. 132 (2024) 042301



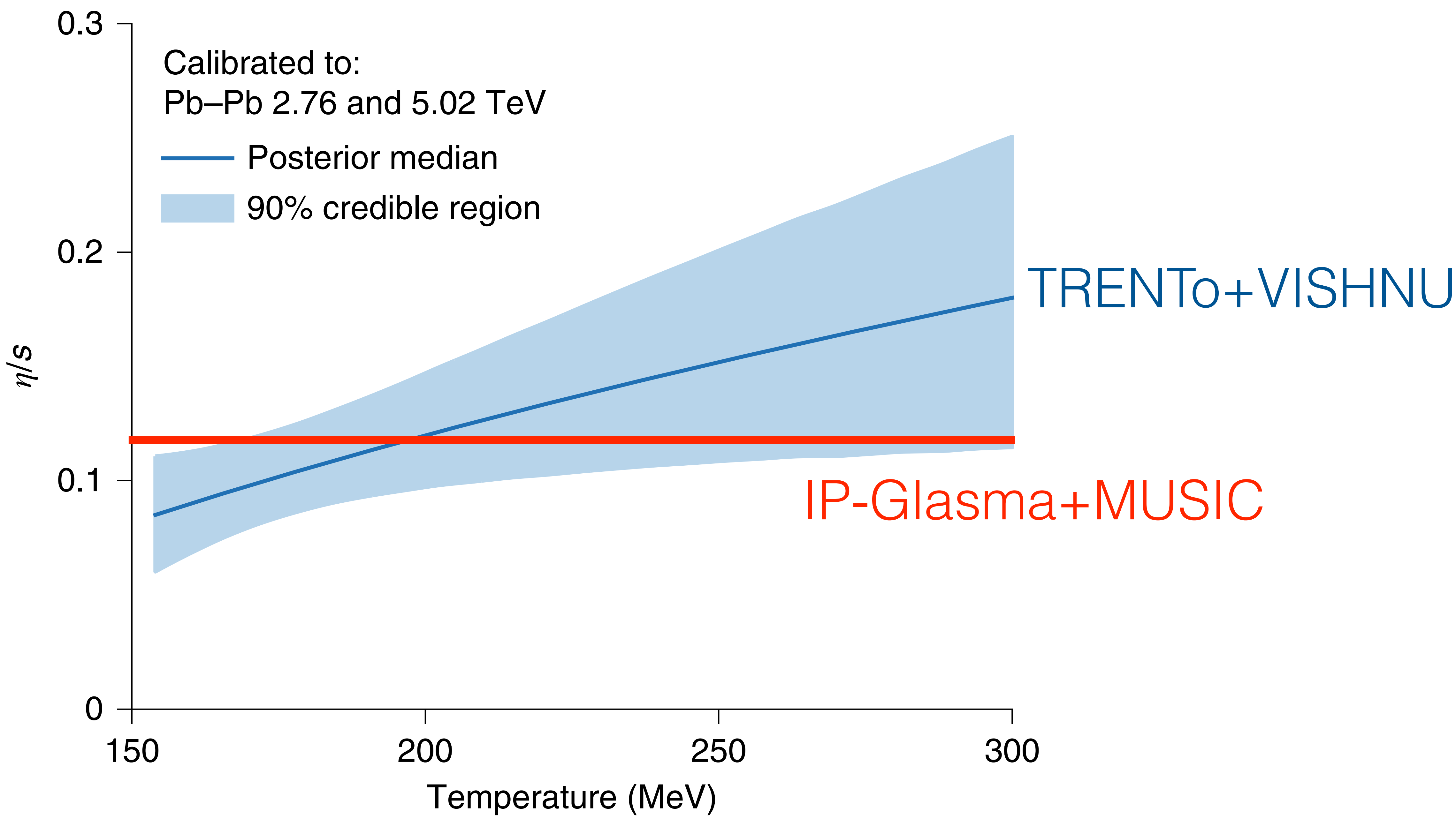
What did we learn about QGP properties, in short

Temperature



Time

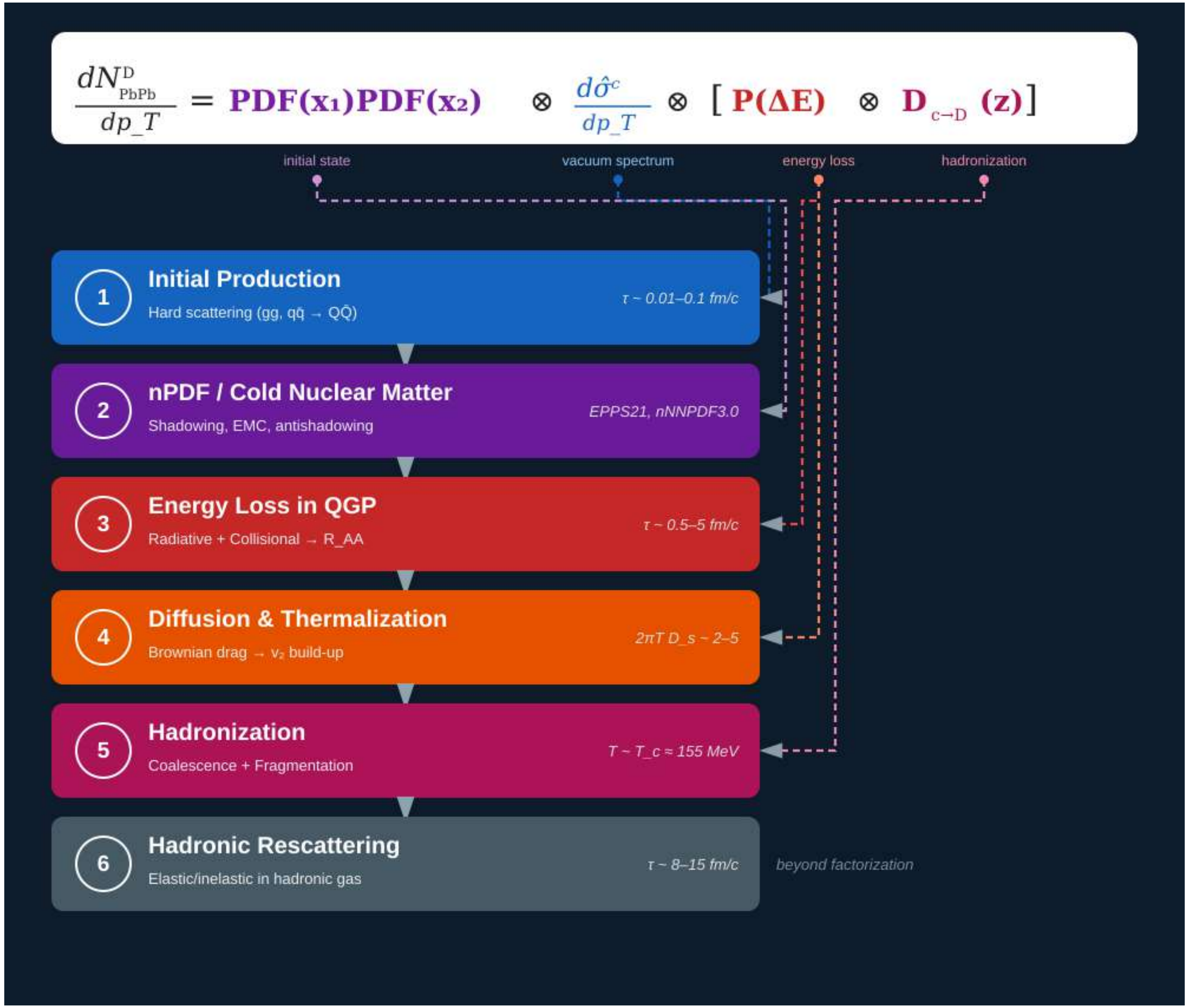
QGP-the most perfectly fluid liquid ever observed



$\hat{q}$, transport parameters, more…

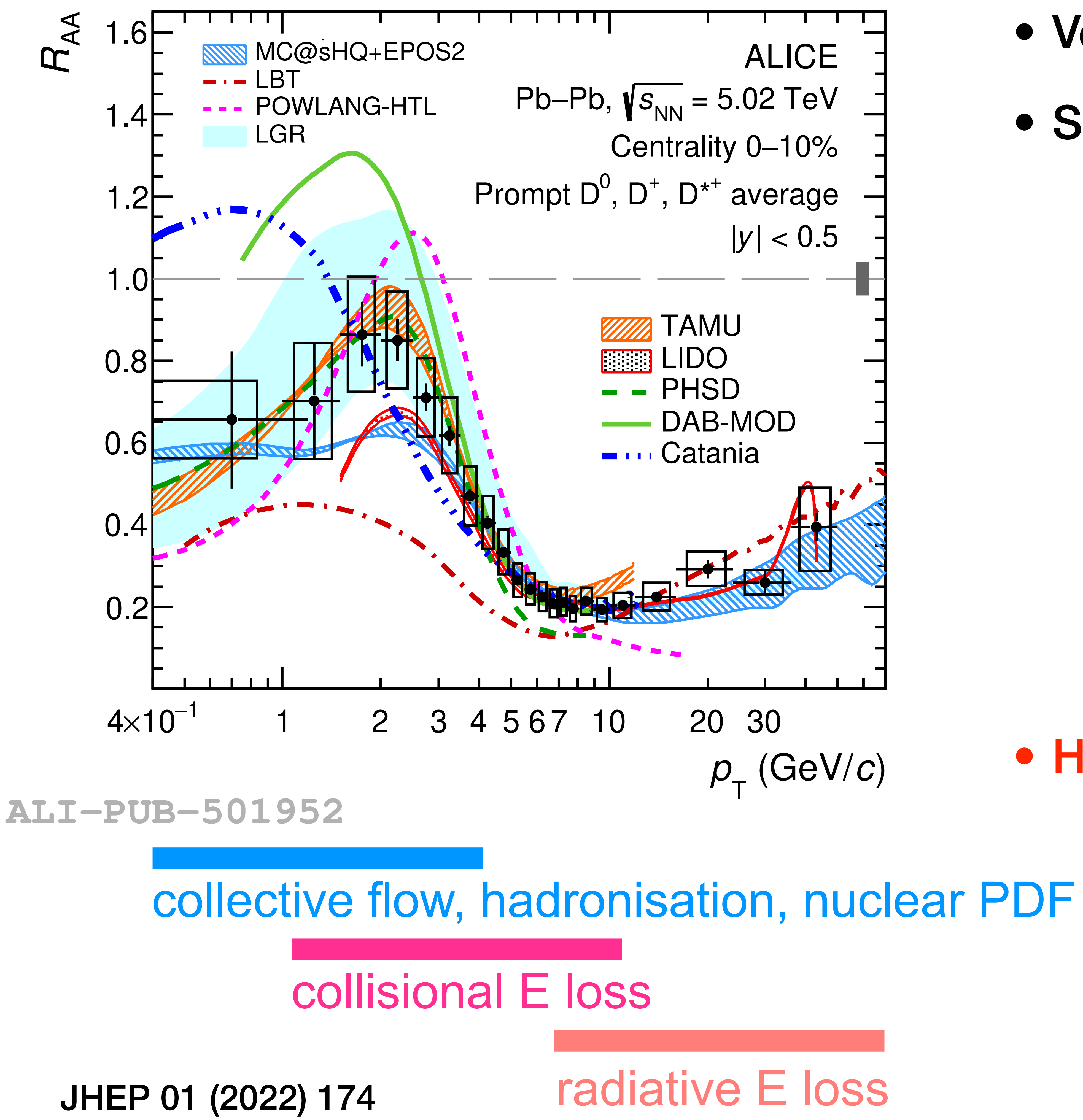
Not **“freely roaming” quarks and gluons, strongly-coupled to the point of having the minimal value of viscosity to entropy density ratio**

Heavy quark production in heavy-ion collisions: what we measure



Heavy flavour production in medium: where to see, what we see

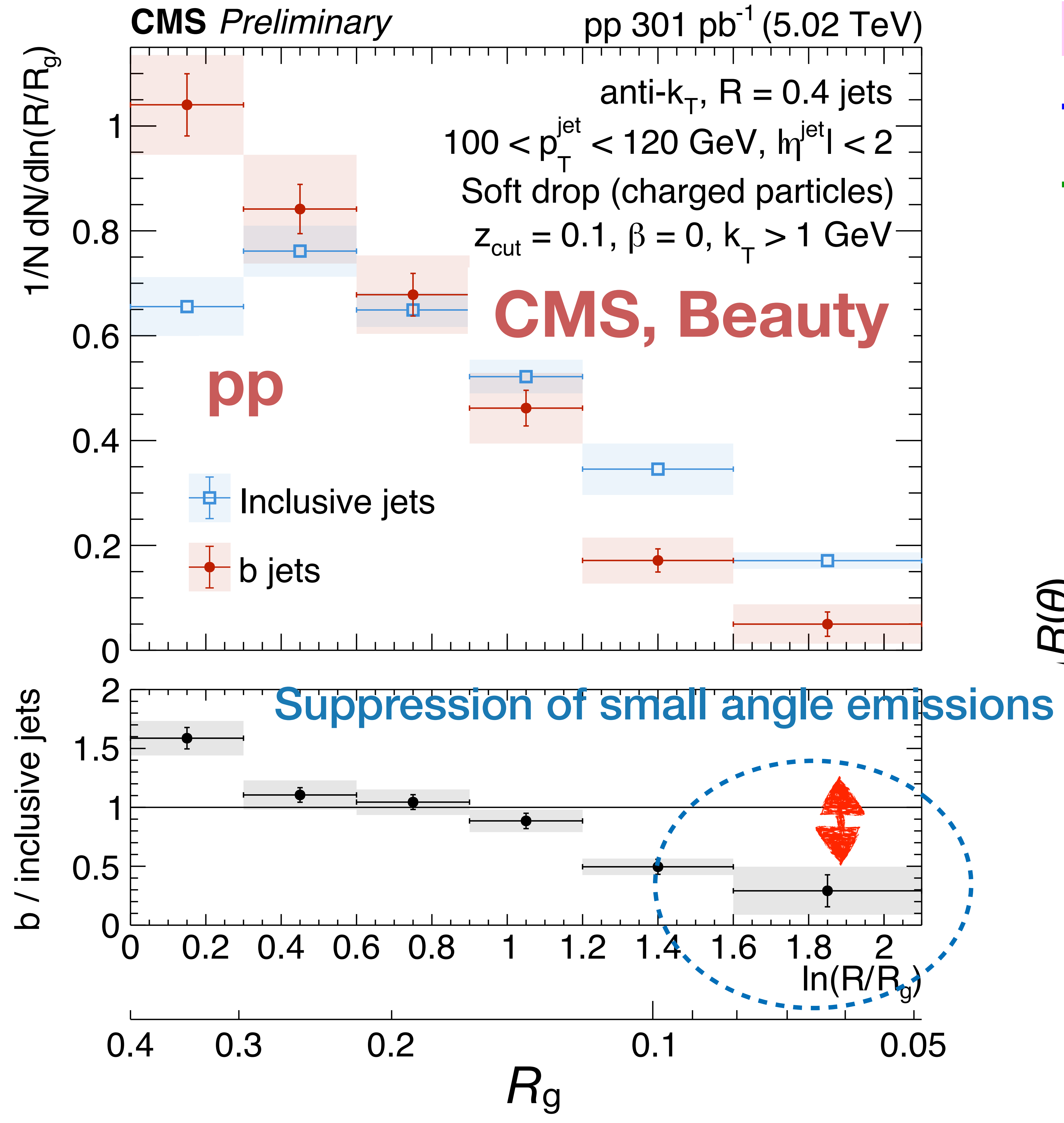
D meson R_{AA}

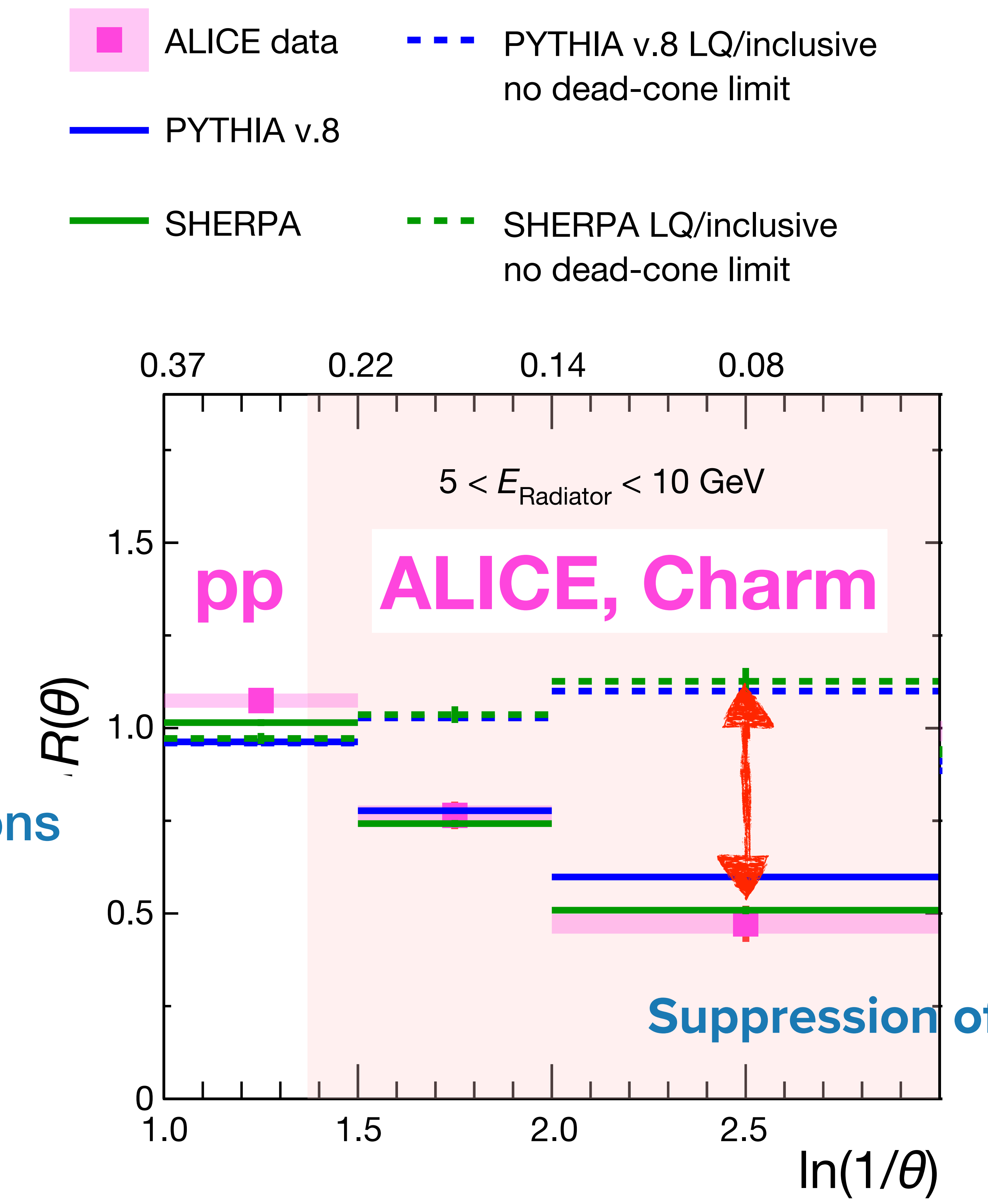


JHEP 01 (2022) 174

- Very strong coupling between heavy quarks and medium
- Strong suppressions are fairly described by transport models
  - nPDF changes the total yields
  - Suppression at low p_T via collisional energy loss
  - Suppression at high p_T via radiative energy loss (ΔE/E decreases)
  - Push by radial flow (low p_T to high p_T)
  - Hadronization picks light quark kinematics
- However, describing full p_T is still challenging...

Mass dependence of energy loss: via dead cone

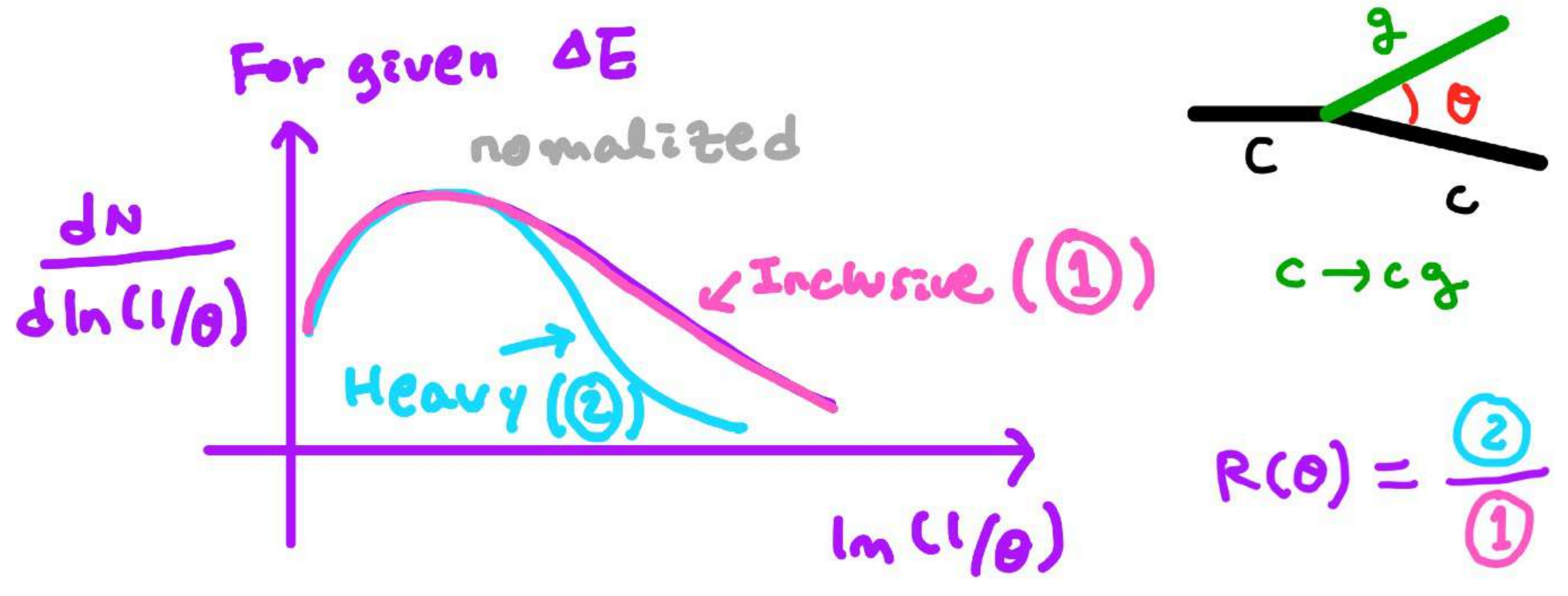




Suppression of c→cg splittings at small angles

The ratio of the splitting angle (θ) distributions

for D⁰-meson tagged jets & inclusive jets

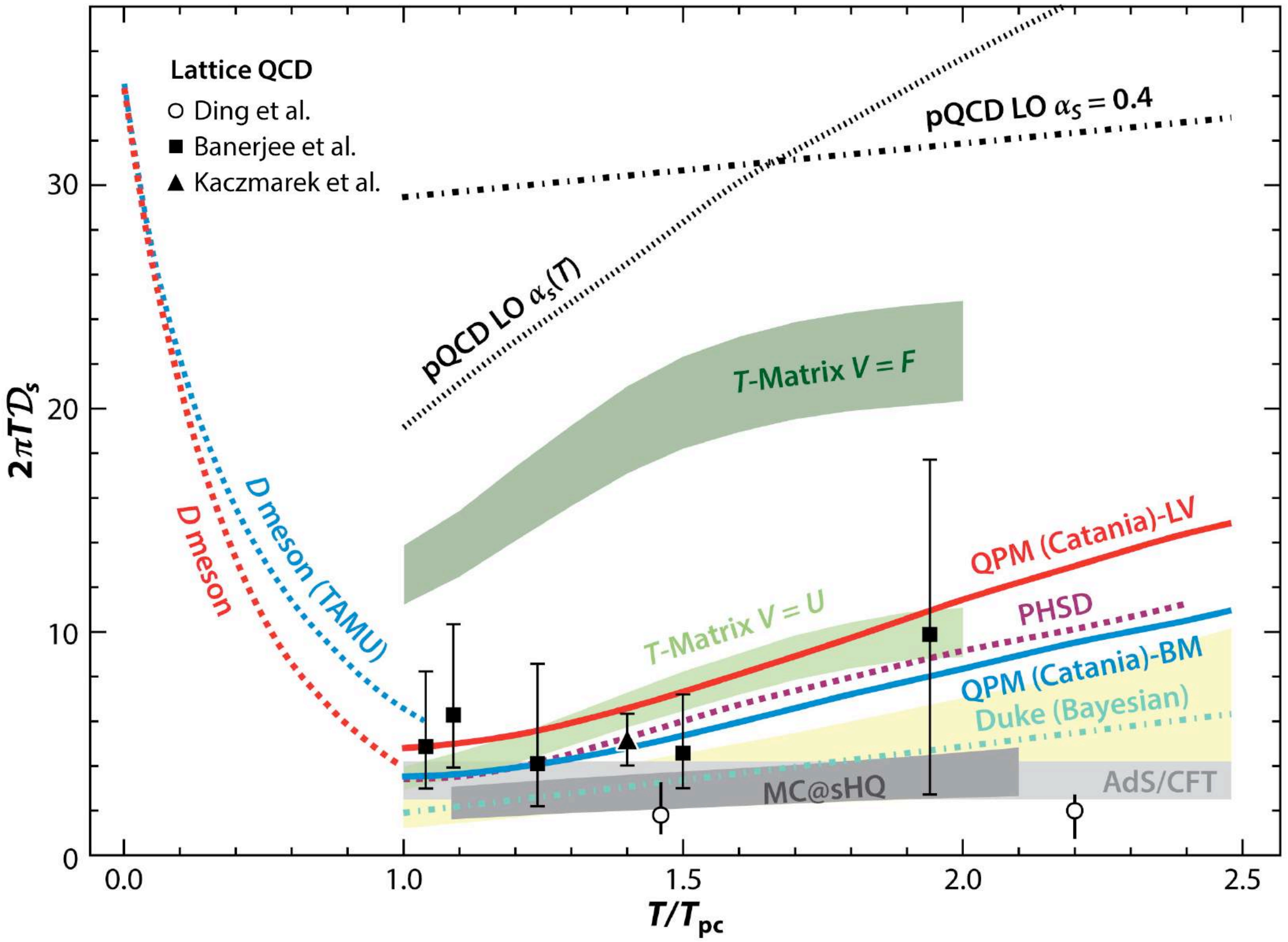


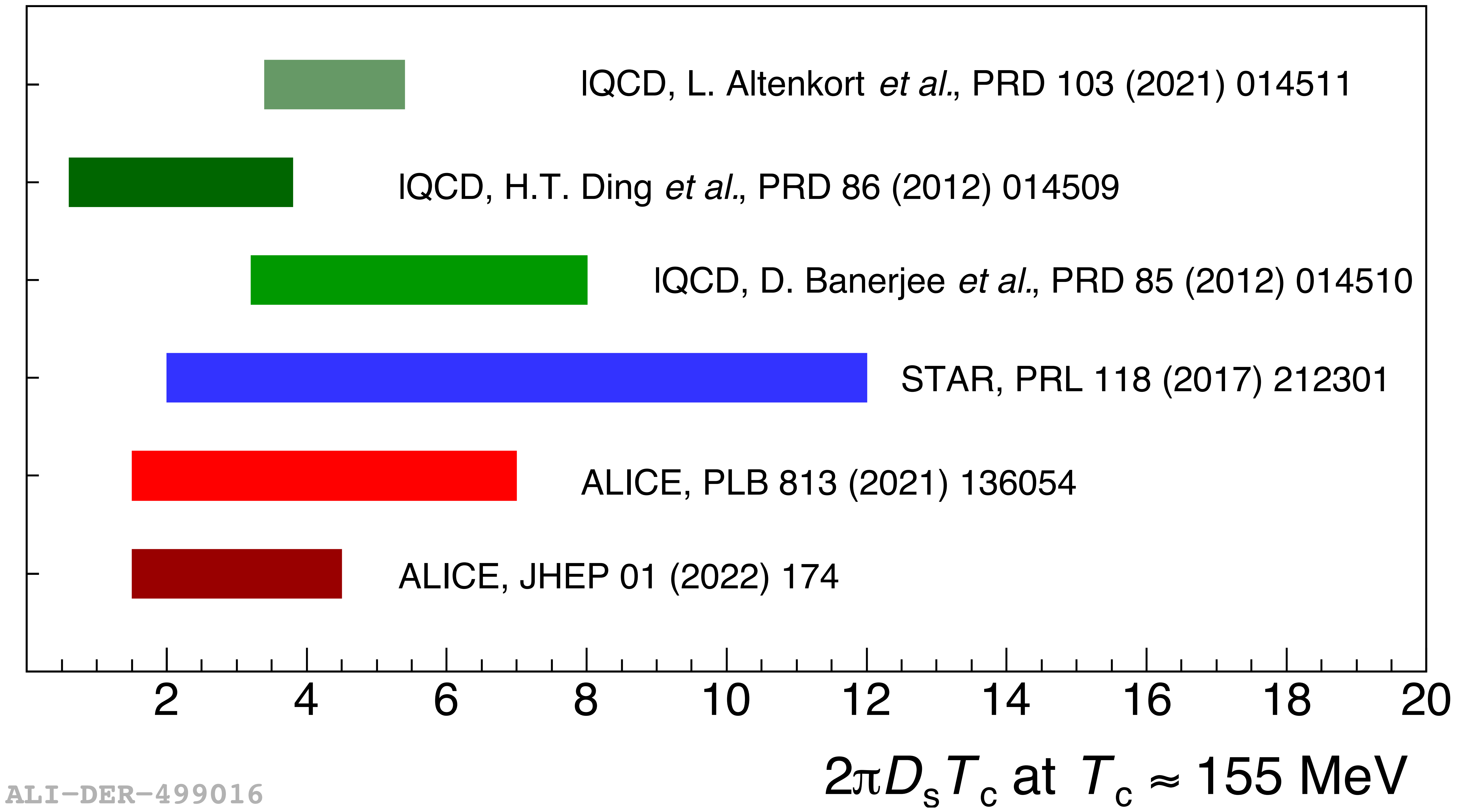
- Direct observation of dead cone in pp collisions
- The medium-induced radiation in a QGP can alter the same observables → to be understood to separate the contributions of parton mass effects and QGP-induced modifications.

ALICE Nature 605 (2022) 440, CMS CMS-PAS-HIN-24-007

Quantitative information via spacial diffusion coefficient

X. Dong et al., Ann.Rev.Nucl.Part.Sci. 69 (2019) 417





Relaxation time

$\tau_Q = (m_Q/T)D_s$ **$1.5 < 2\pi D_s T_c < 4.5$ → direct access to heavy-flavour relaxation time: τ_{charm} ~ 3-8 fm/c**

Note: hadronization is hard to control in the model…