ALICE Overview

MinJung Kweon
on behalf of the ALICE Collaboration
Inha University

The XVIth Quark Confinement and the Hadron Spectrum Conference
August 22th, 2024

Honoring the Legacy

Contributions of T. D. Lee and J. D. Bjorken to High-Energy Nuclear Physics

Tsung-Dao Lee
(24 Nov 1926 – 4 Aug 2024)

James Daniel Bjorken (Bj)
(22 Jun 1934 – 6 Aug 2024)

This week, we are deeply saddened by the loss of two towering giants in physics:

T. D. Lee won the Nobel Prize in Physics in 1957, alongside Chen-Ning Yang, for their work on parity violation in weak interactions. He is one of the founding fathers of our field.

J.D. Bjorken is renowned for the Bjorken scaling phenomenon, pivotal in developing the quark model and QCD. He along with Sheldon Glashow also predicted the existence of a fourth flavor of quark, which they called charm. He worked out the concepts of heavy-ion collisions, i.e. hydrodyanmical flow and energy loss in one of the top cited papers in our field.

The ALICE newsletter No. 320

Creating hot and dense matter

T.D. Lee (1975) suggested to distribute a high amount of energy over a relatively large volume

⇨ Collisions of nuclei at very high energy

- Temperature of the produced “fireball” $O(10^{12}$ K)
  - $10^5 \times$ T of the centre of the Sun
  - ≈T of the Universe 10^{-5} s after Big Bang

Study nuclear matter at extreme conditions of temperature and density

Since the 70’s nuclear physicists were already colliding heavy ions

- UNILAC (GSI), Super-Hilac and Bevalac (Berkeley), Synchrophasotron (Dubna)
- to reach T_c, higher-energy accelerators were needed ⇨ ultrarelativistic AA collisions

Since then…

Rev. Mod. Phys., Vol. 47, No. 2, April 1975

Abnormal nuclear states and vacuum excitation*†

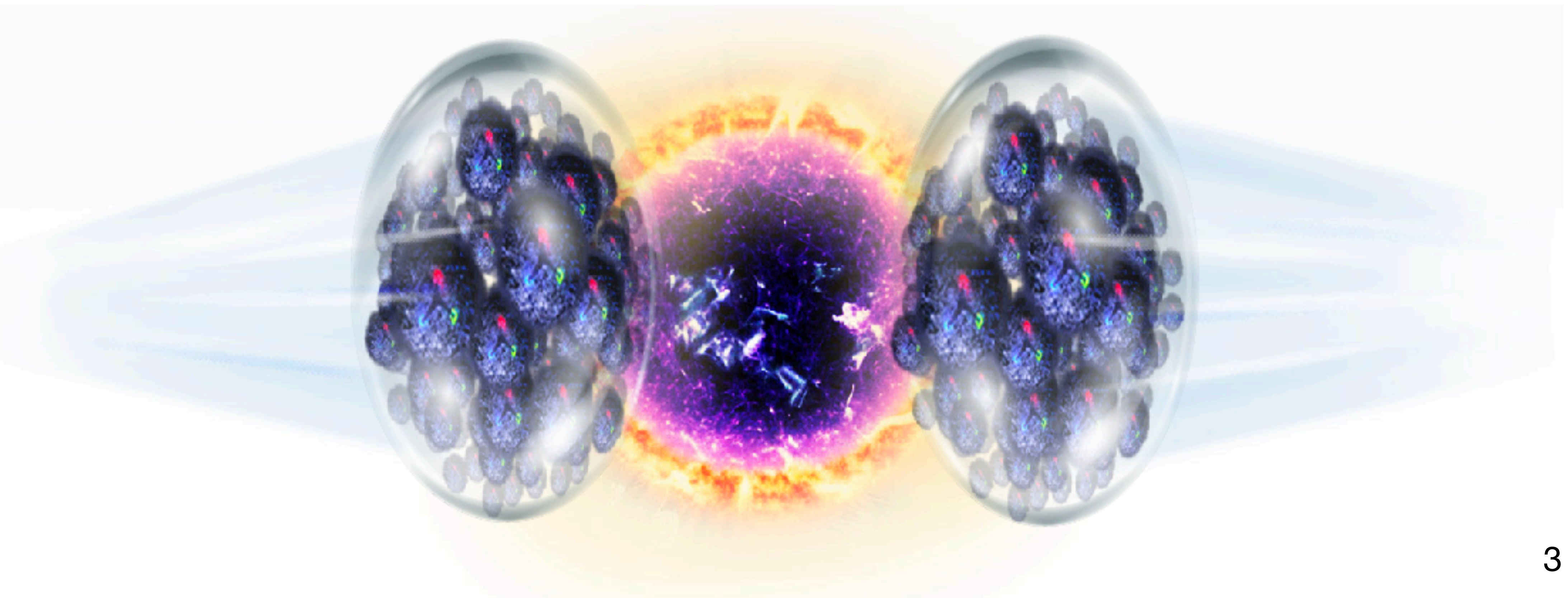
T. D. Lee

Physics Department, Columbia University, New York, New York 10027

We examine the theoretical possibility that at high densities there may exist a new type of nuclear state in which the nucleon mass is either zero or nearly zero. The related phenomenon of vacuum excitation is also discussed.

I. INTRODUCTION

In this talk, I would like to discuss some of my recent theoretical speculations, made in collaboration with G. C. Wick. As you shall see, these speculations suggest the possible existence of some rather interesting physical objects, hitherto unobserved.[1] An effective way to search for these new objects is through the use of high-energy heavy ions, which is the subject matter of this meeting.



The Large Hadron Collider (LHC) at CERN
LHC
SPS
~10 Km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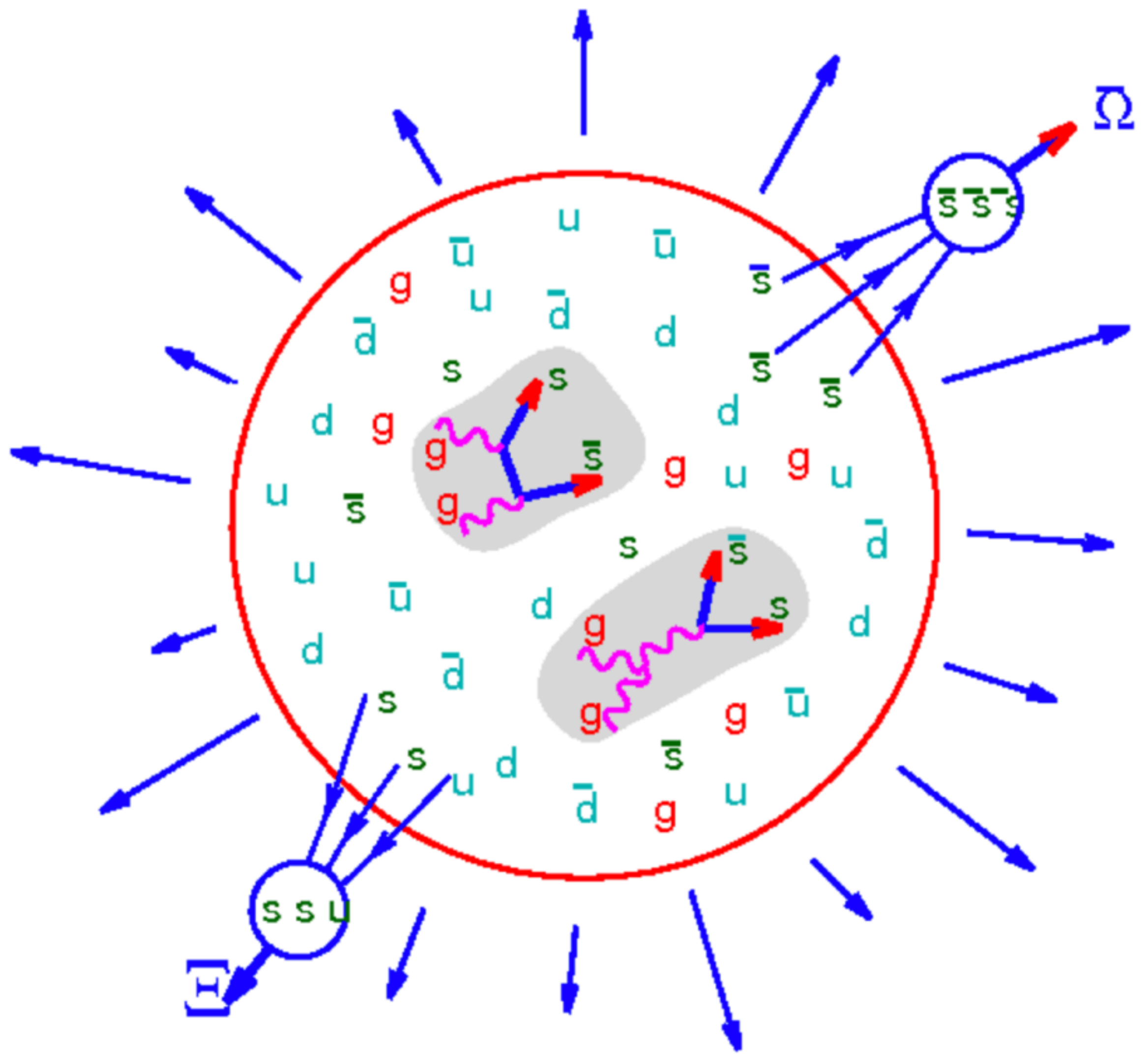
Starting from two historic predictions

Quark-gluon plasma (QGP) phase, if existed, would obviously be very short-lived, how to observe it?

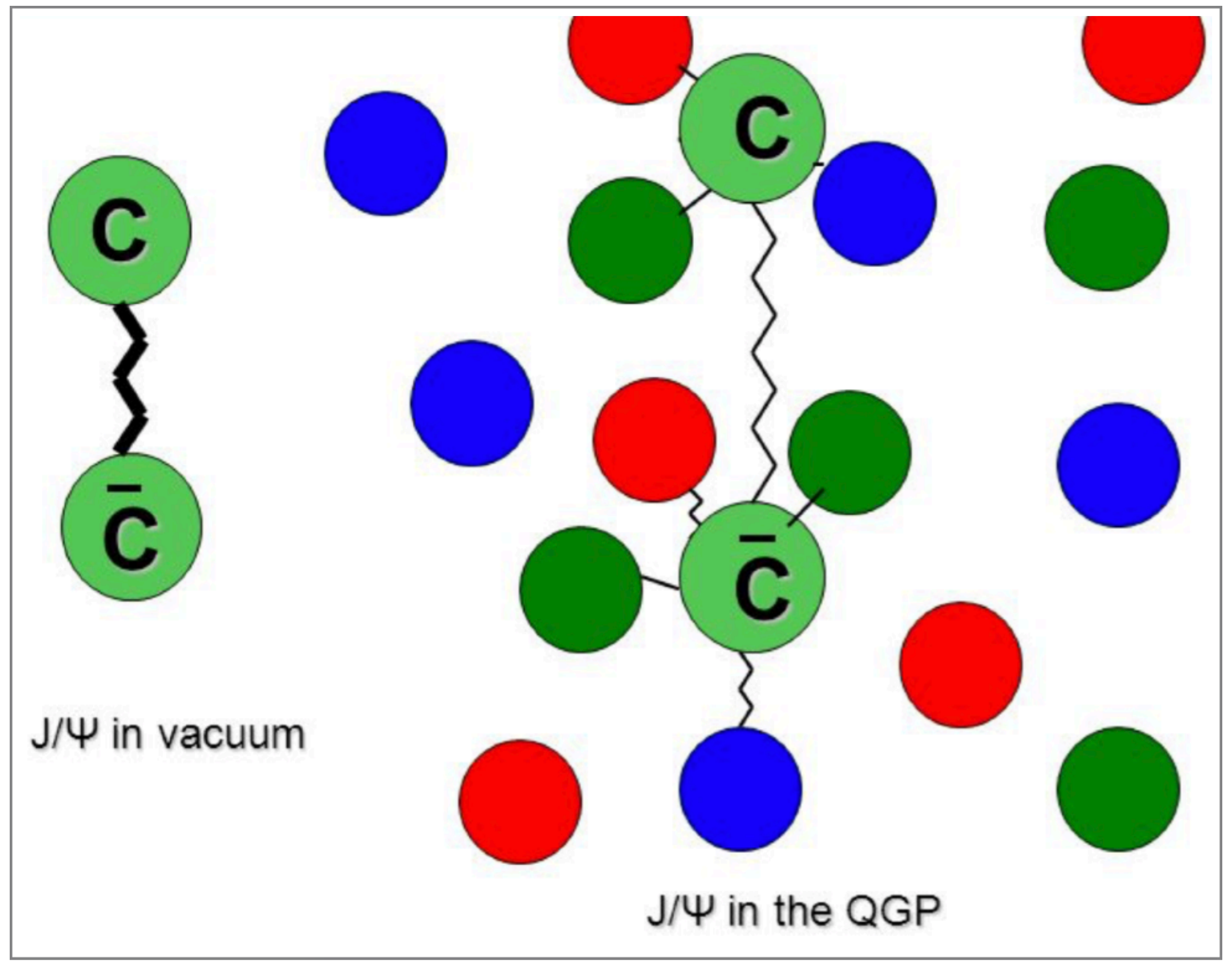
- is there a memory of the passage through the QGP phase?
- are there “signatures” of the QGP that we can look for in the final state?

two major proposals made in the 80’s:



Strangeness enhancement

P. Koch, B. Müller and J. Rafelski
Phys. Rep. 142, 167 (1986)



J/ψ suppression

T. Matsui and H. Satz
Phys.Lett.B 178 (1986) 416-422.

Strangeness enhancement

Francesca Ercolessi, Monday 15:00

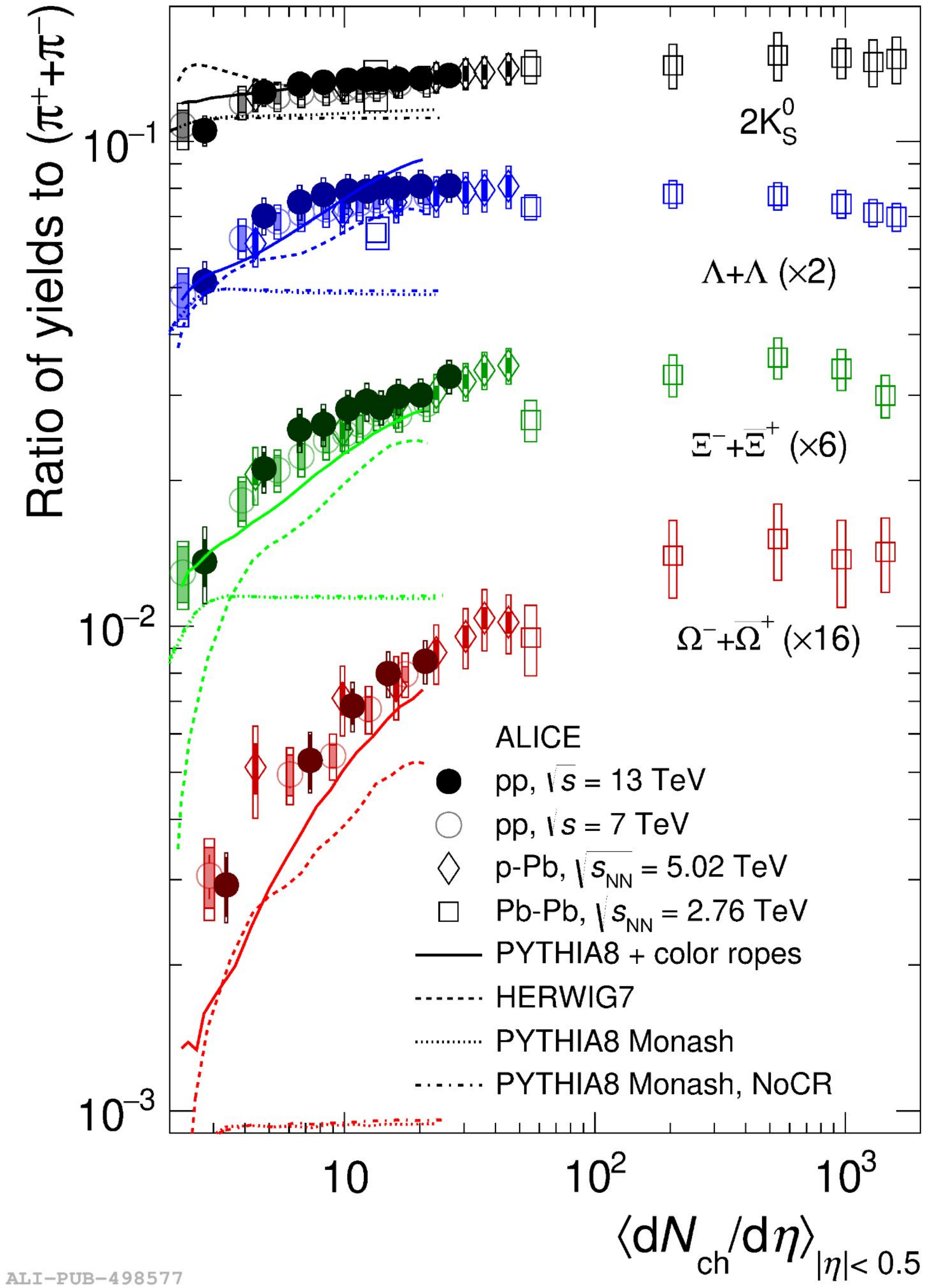
In Pb-Pb, restoration of chiral symmetry increase the strangeness production

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

Recombination of the strangeness quarks

- 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 (from small systems like pp to large systems like Pb-Pb)

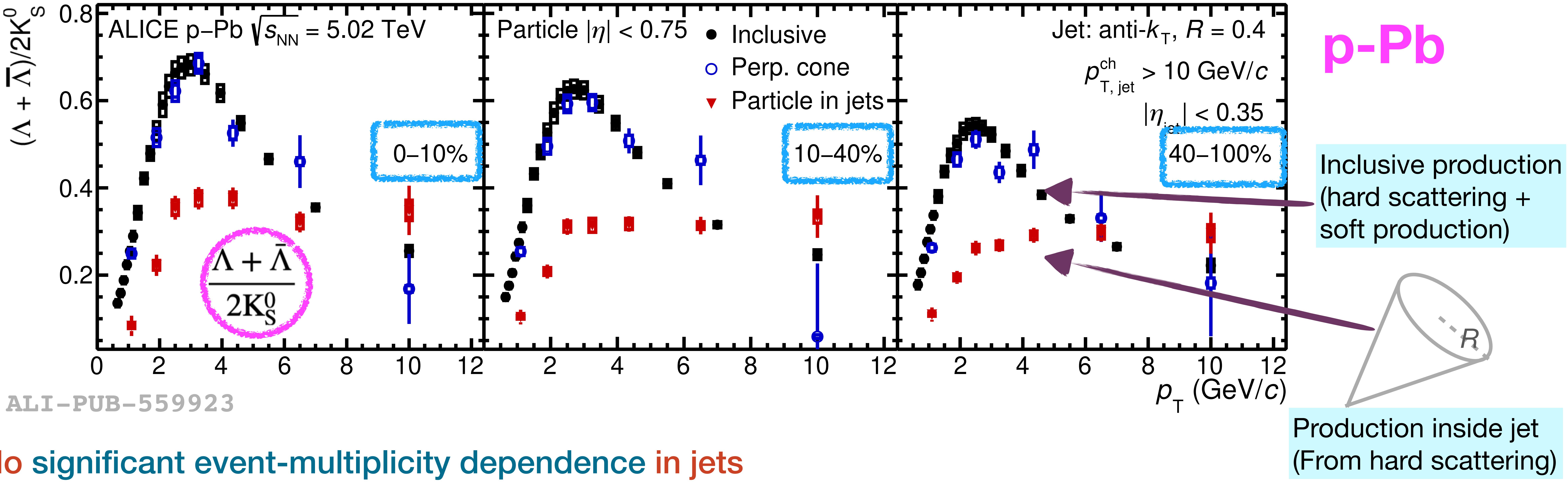
Eur. Phys. J. C 80 (2020) 693



Strangeness enhancement, in small systems!

- What is the microscopic origin of strangeness enhancement in pp & p-Pb collisions?
- Is it related to hard processes, such as jets, to the underlying event, or to both?

JHEP 07 (2023), 136



- No significant event-multiplicity dependence in jets

→ enhancement is limited to the soft particle production. Provide novel constraints on the underlying particle-production mechanisms!

Strangeness enhancement, in small systems!

- What is the microscopic origin of strangeness enhancement in pp & p-Pb collisions?
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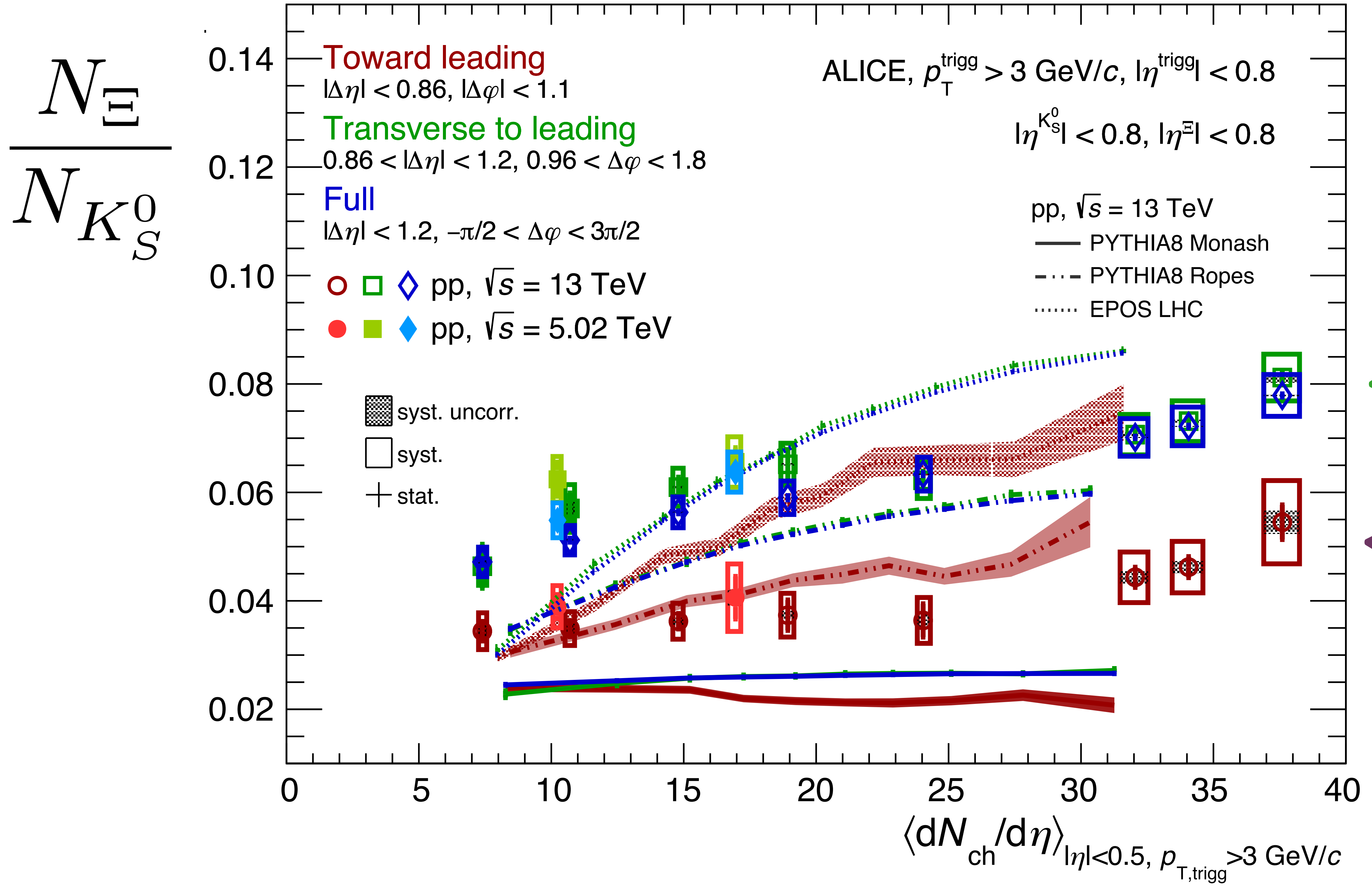
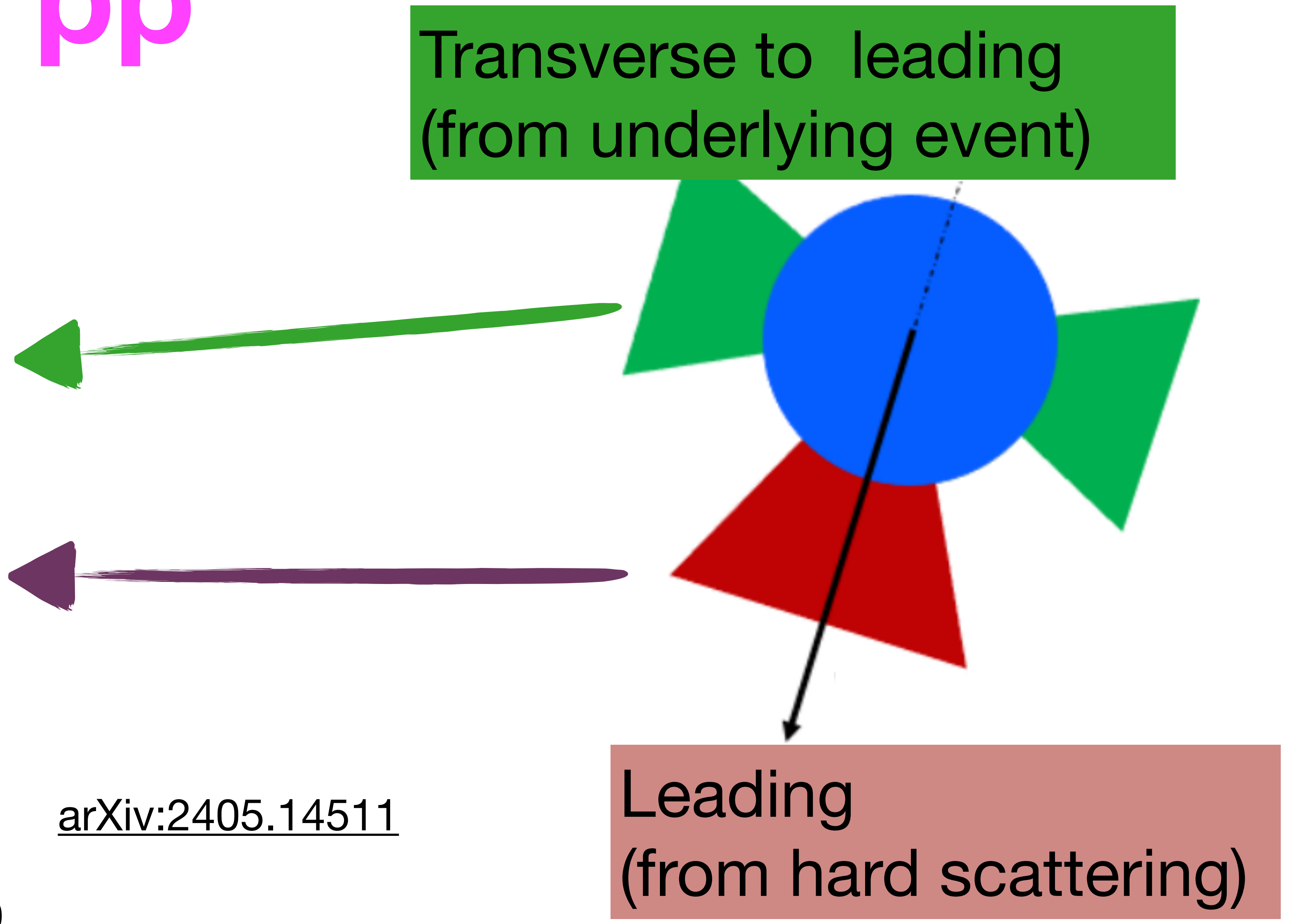


pp



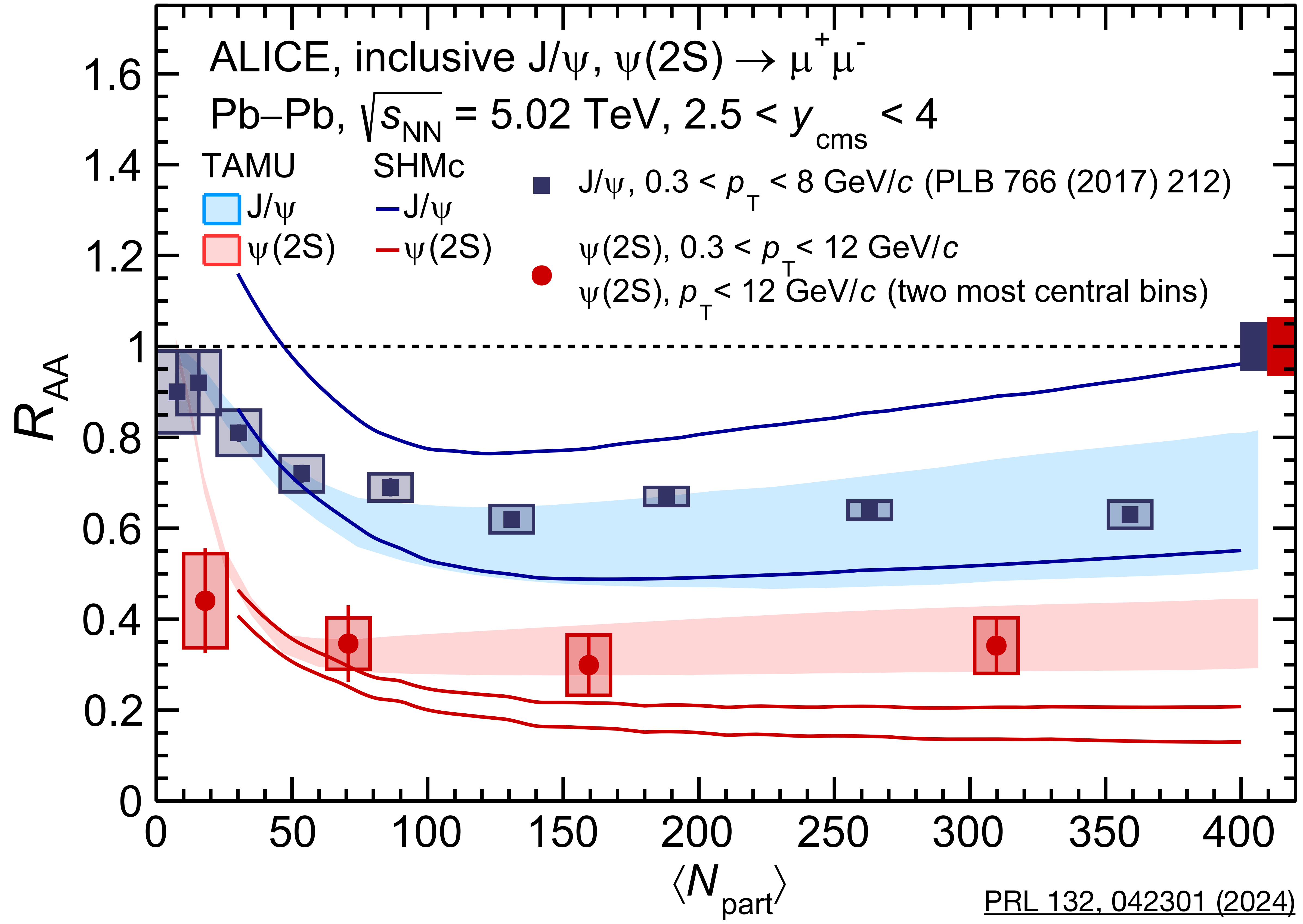
arXiv:2405.14511

- Relative production of Ξ wrt K^0_S is favored in transverse-to-leading processes
  → insight into the strangeness enhancement effect (hard scattering processes or in the underlying event)

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…



PRL 132, 042301 (2024)

- Suppression of J/ψ and ψ(2S) in Pb-Pb collisions relative to pp collisions as a function of the collision centrality.
- Clear hierarchy of suppression of J/ψ and ψ(2S): suppressed by a factor of ~2 wrt J/ψ → weaker binding energy

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

Quarkonium suppression, also regeneration?

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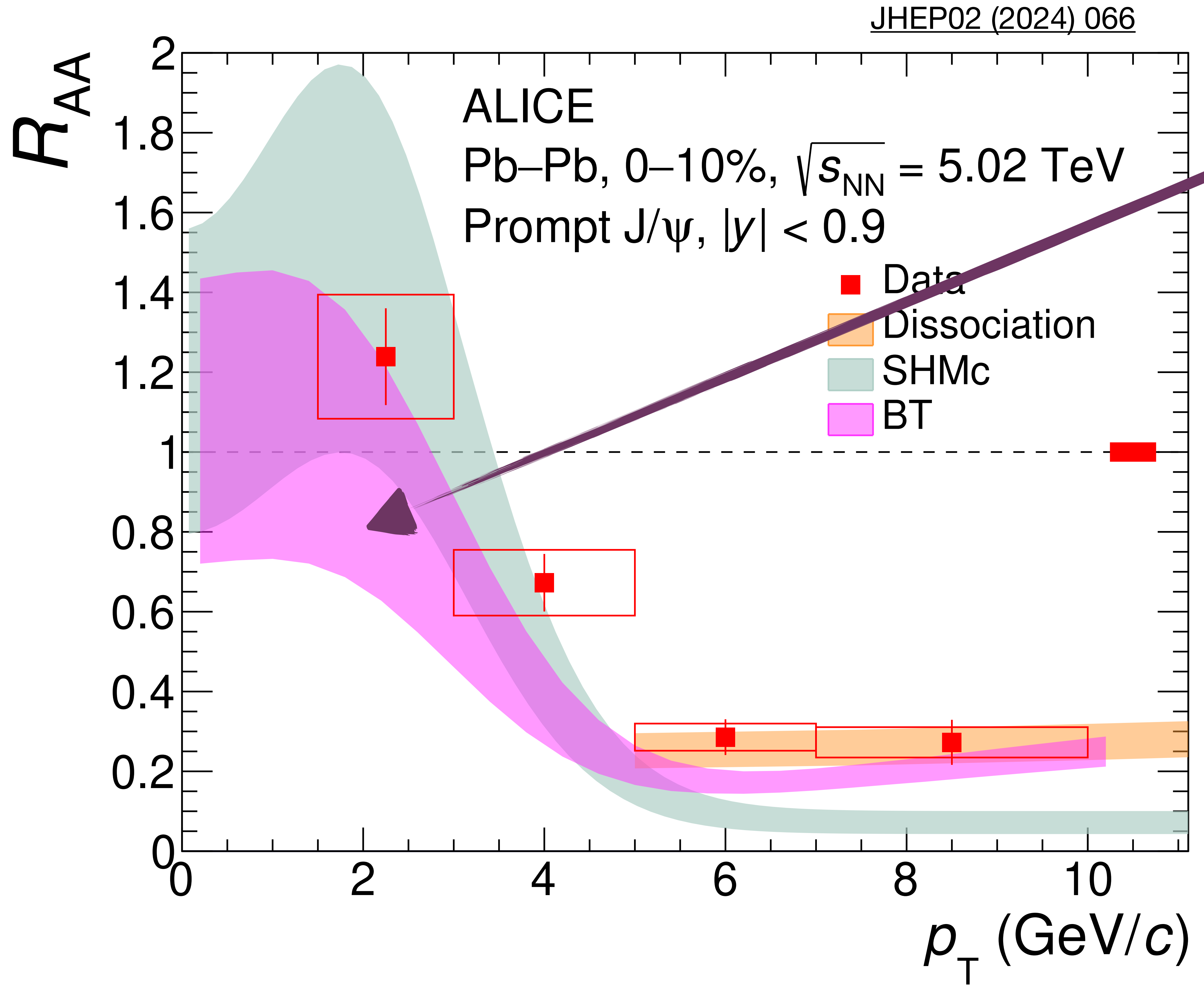
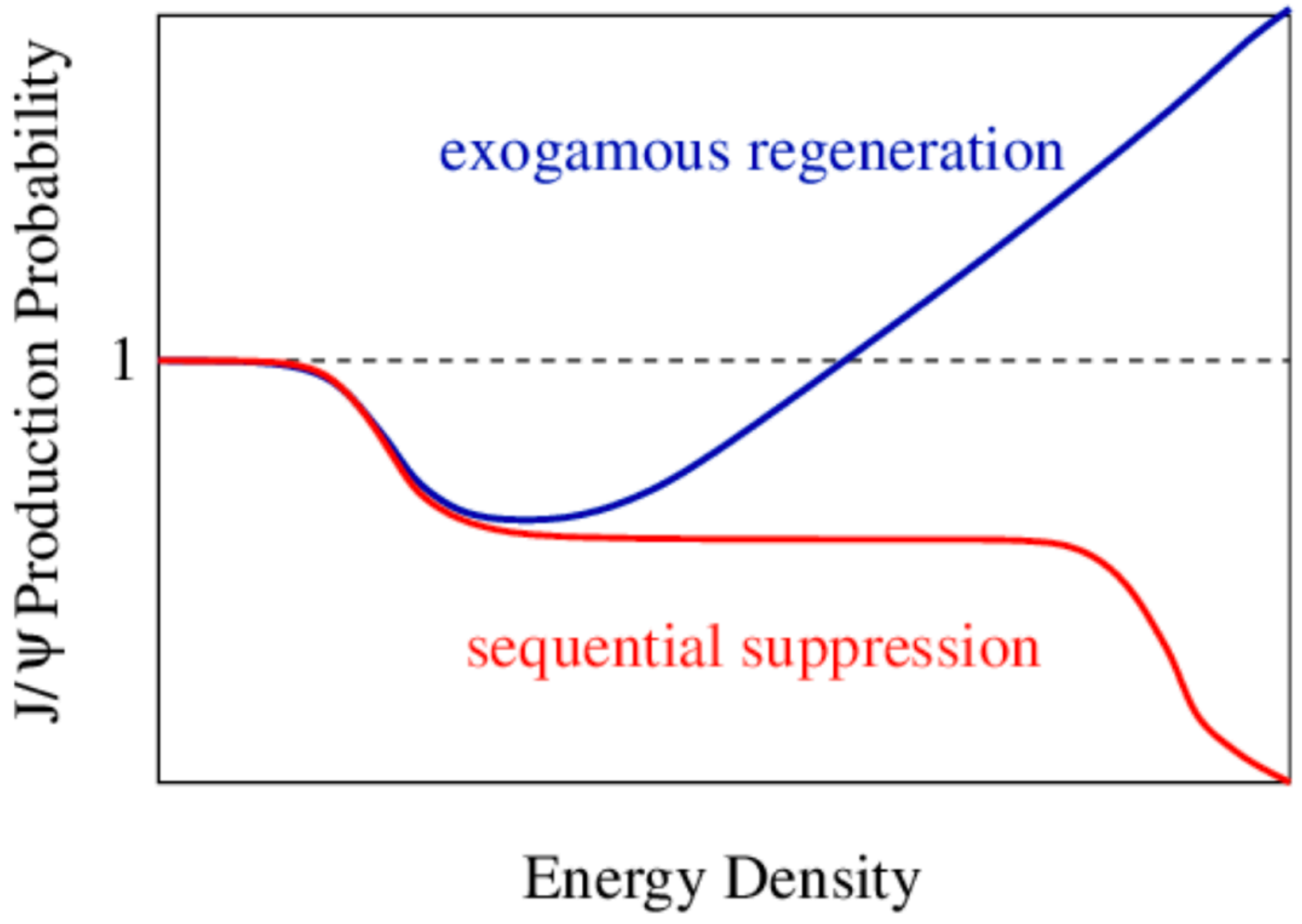


Boltzmann transport model (BT), including terms of dissociation and regeneration



- Models including **regeneration** can describe the **rising trend** towards low p_T

Quarkonium suppression, also regeneration?

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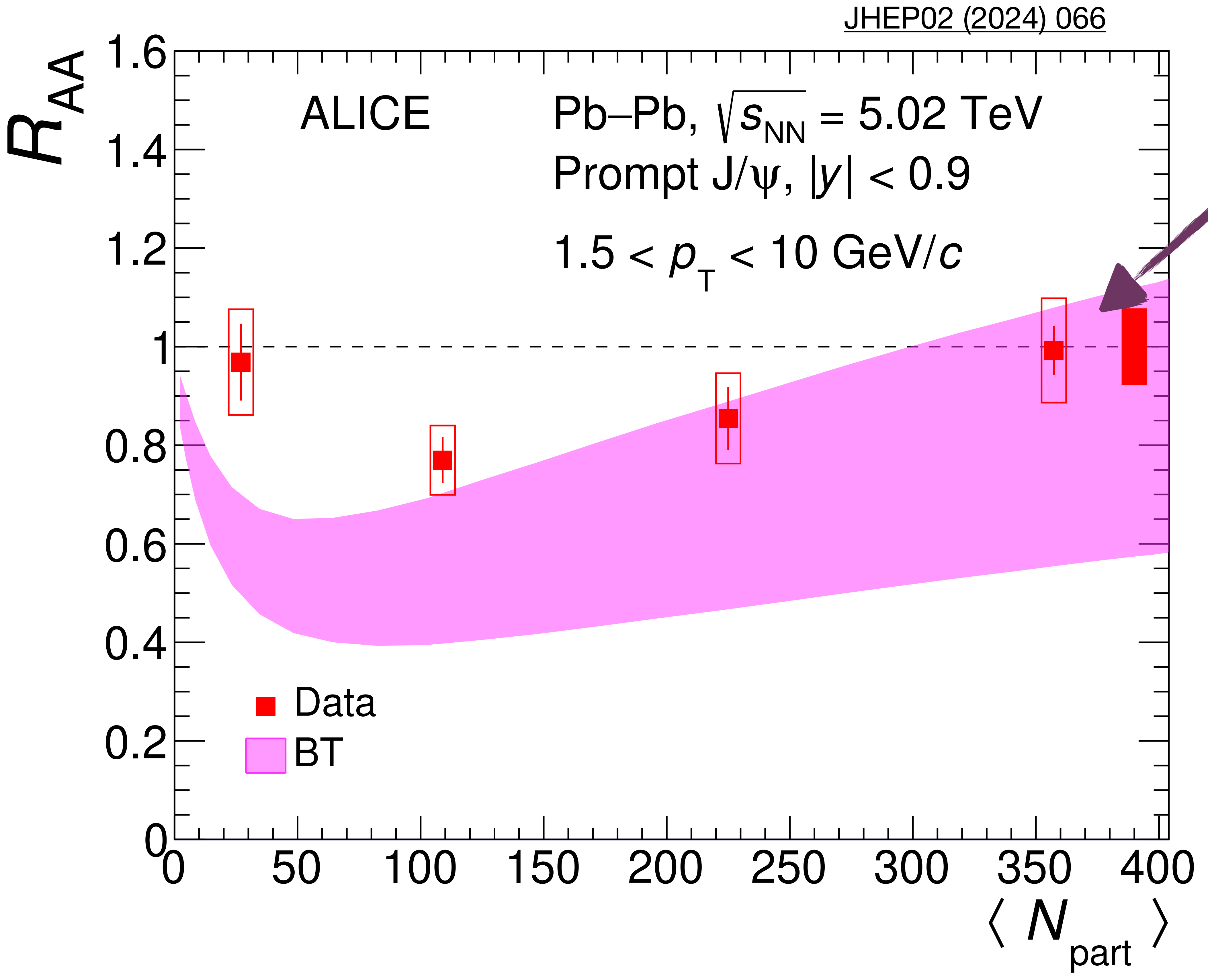

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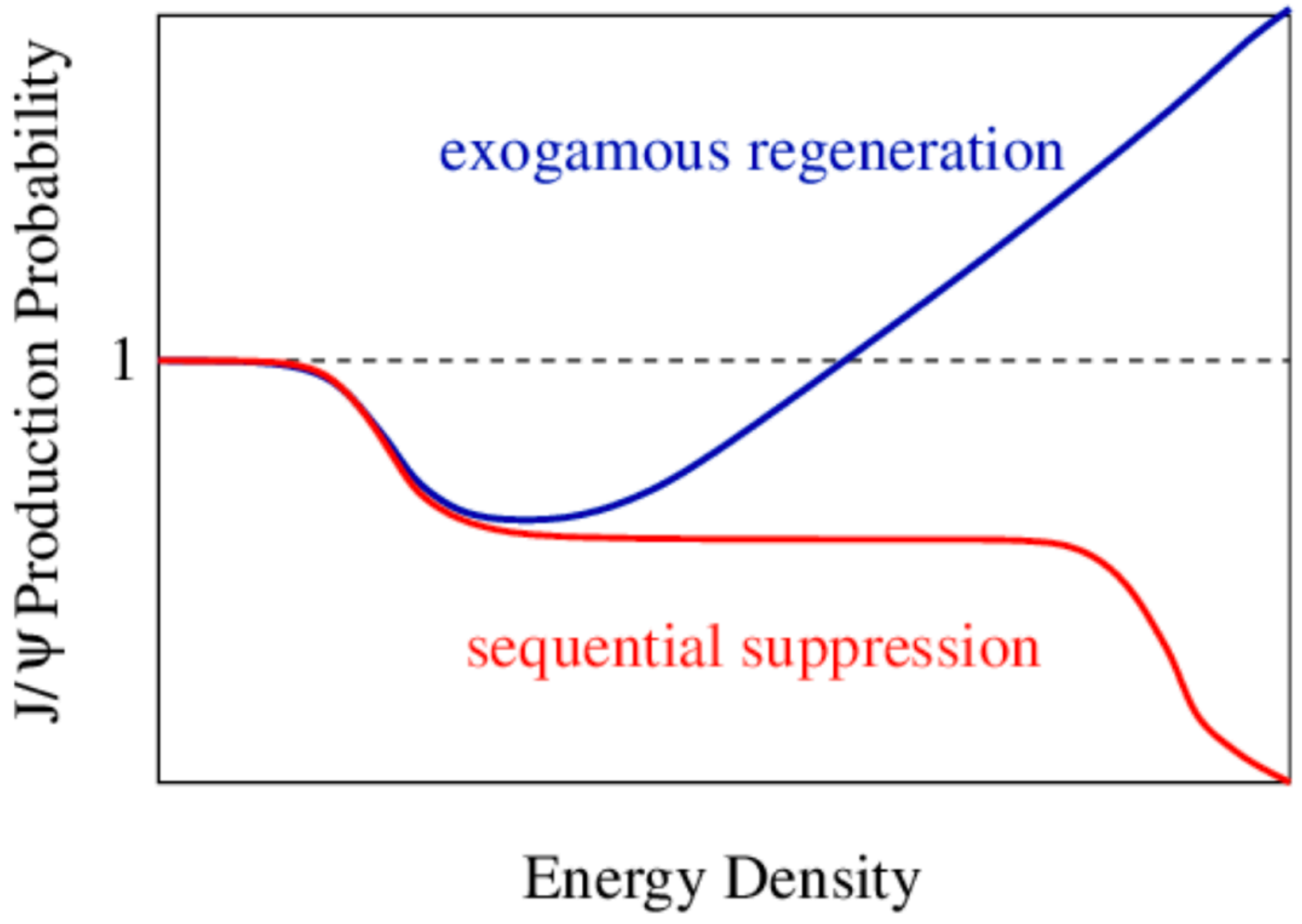
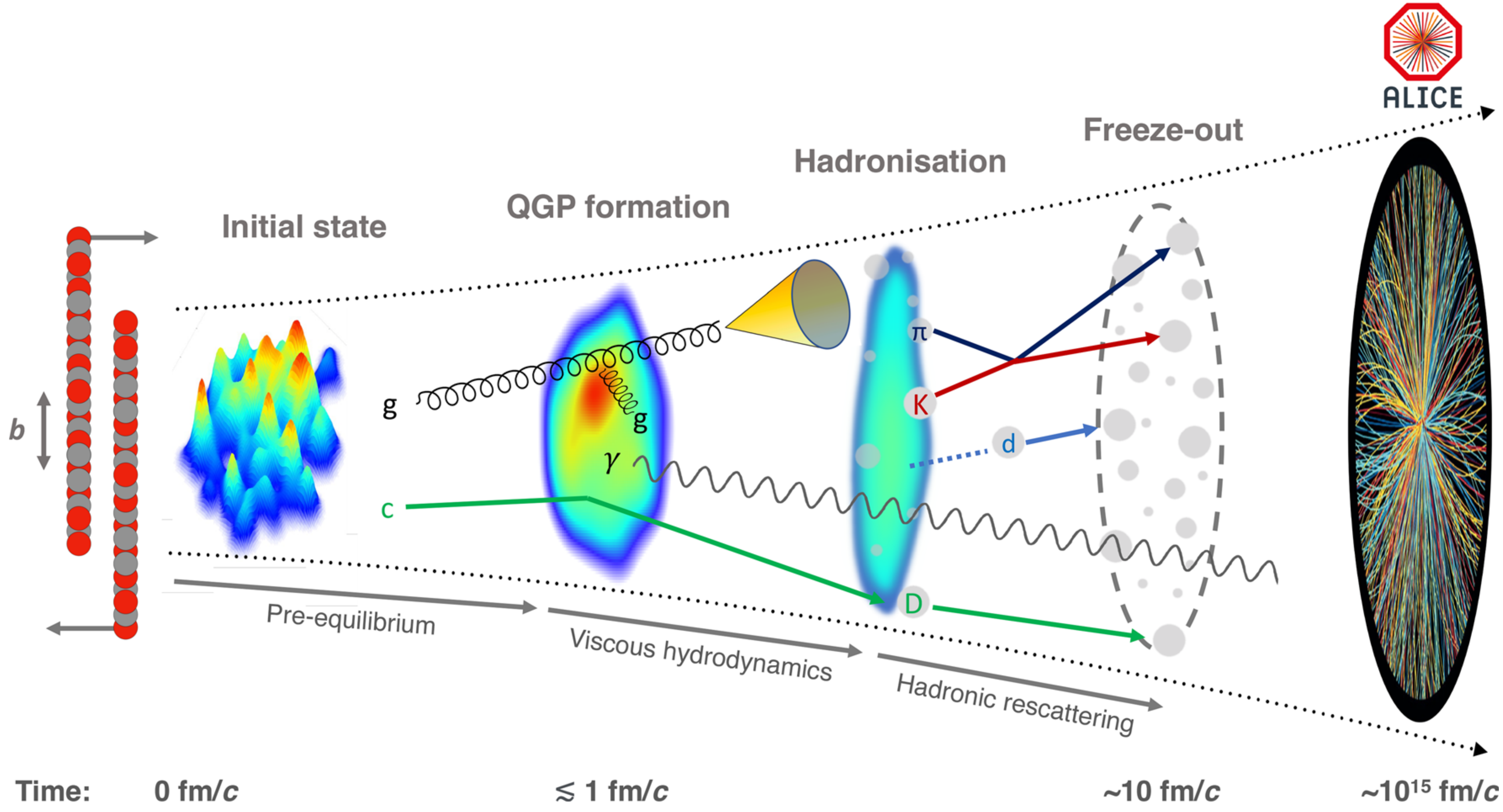


- Models including **regeneration** can describe the **rising trend** towards low p_T and with increasing centrality

We have differential, more views on the QGP

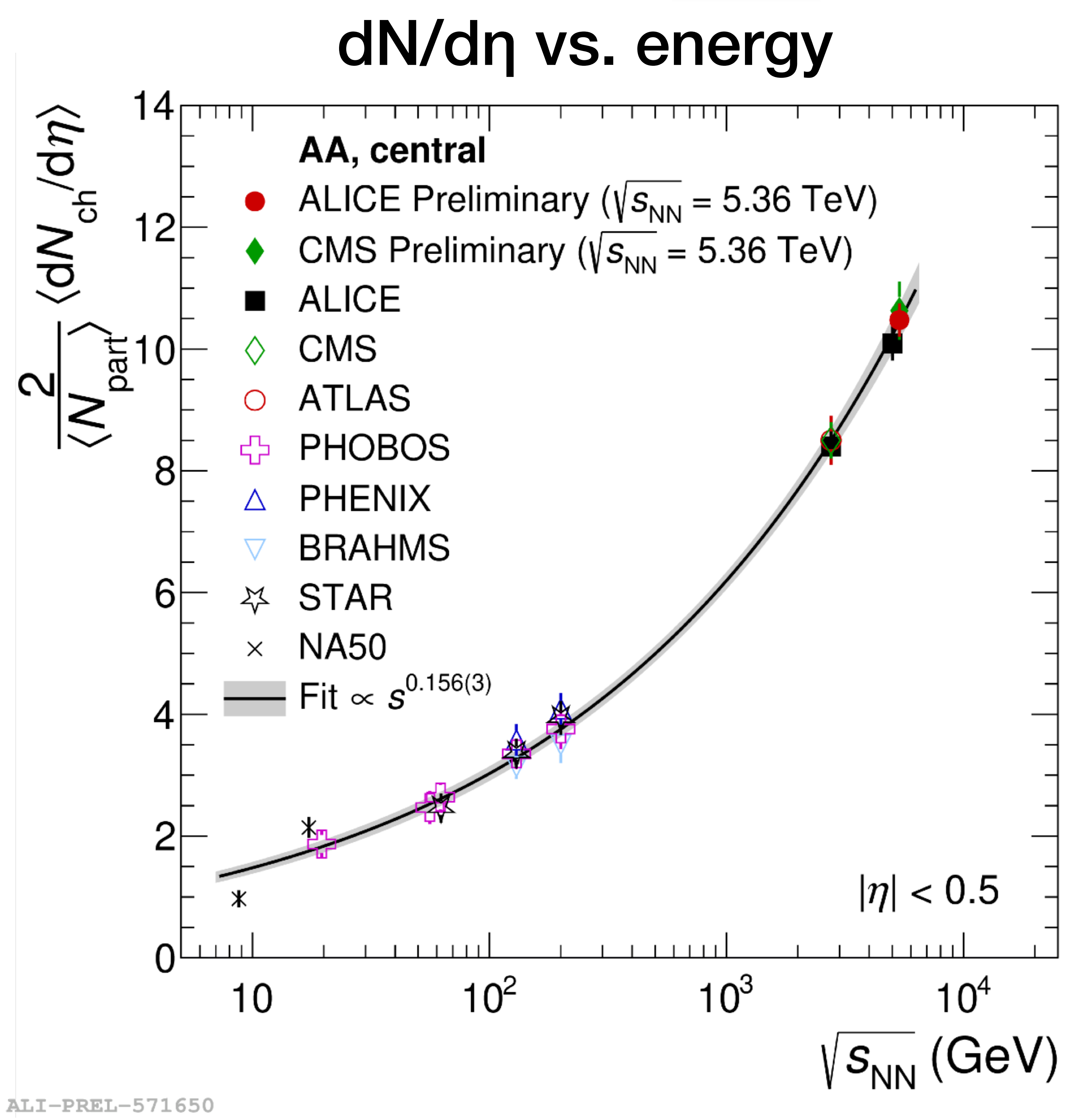


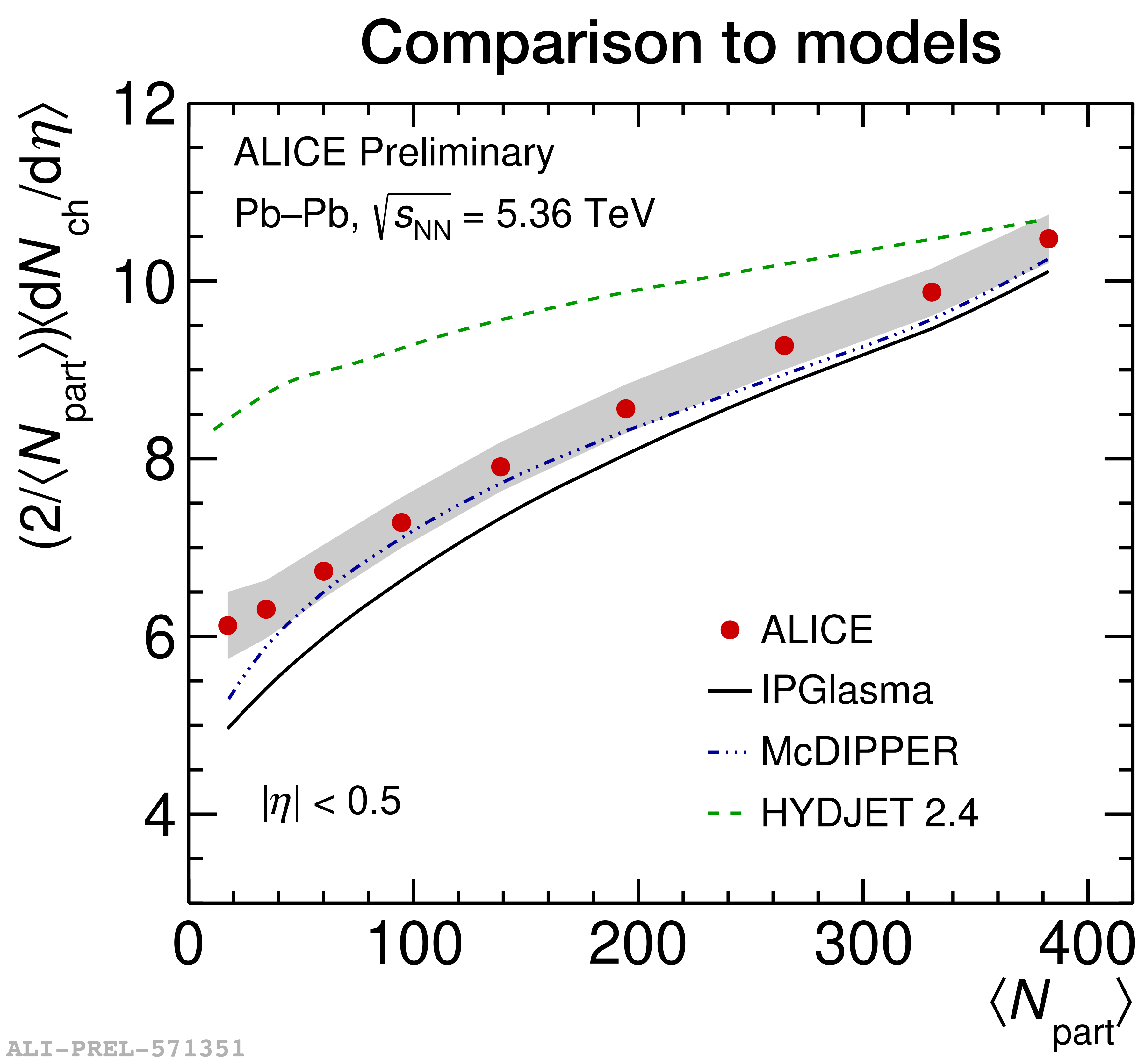
ALICE review paper

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

Will introduce selective topics providing perspectives along the stage

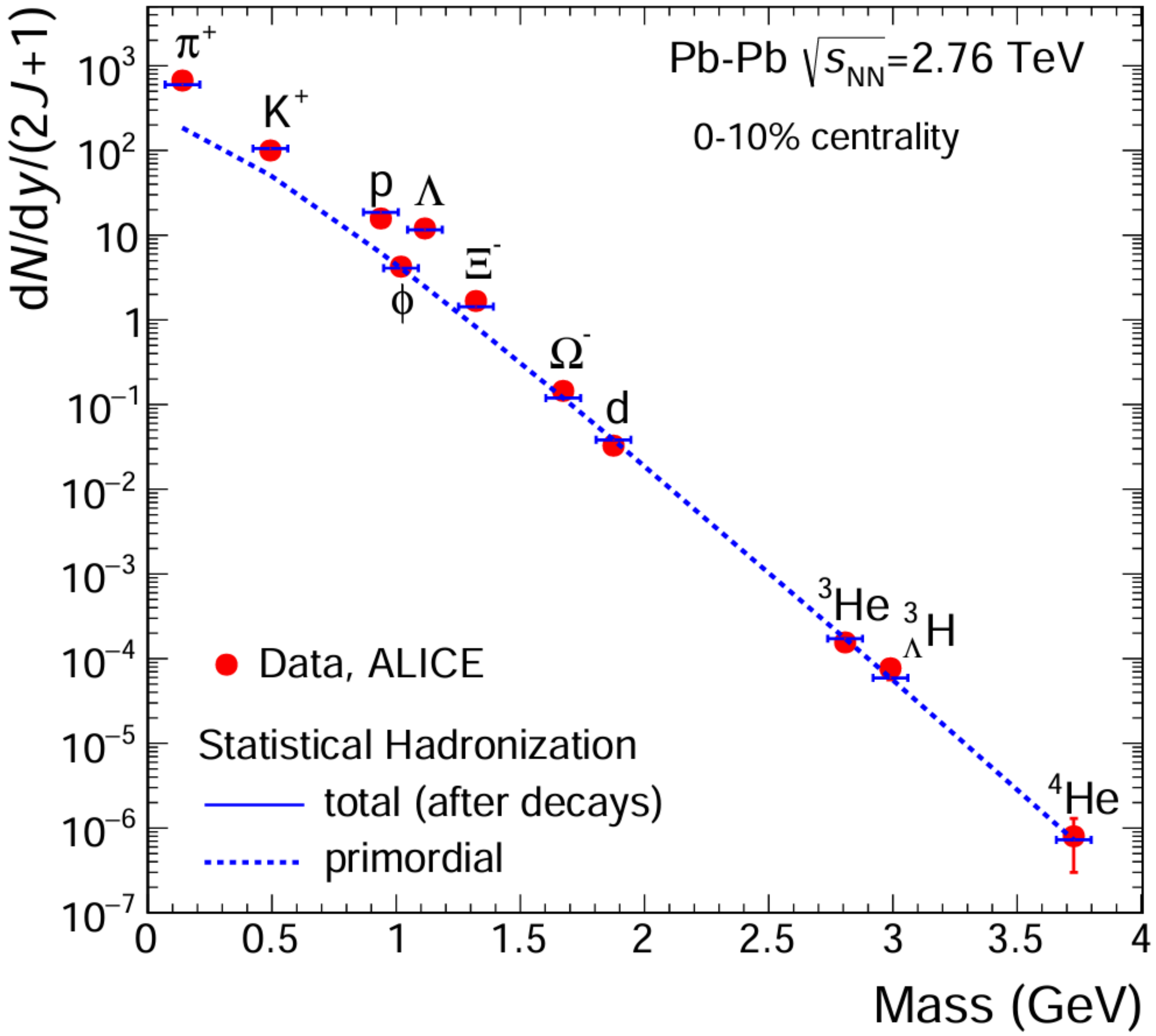
Particle production: multiplicity





- The good agreement among different experiments suggests a universal behavior in particle production as a function of energy in heavy-ion collisions
- How well different models capture the measured particle production? → key experimental constraints for model validation

Particle production in heavy-ion collisions



Andronic A., et al. Nature 561, 321-330

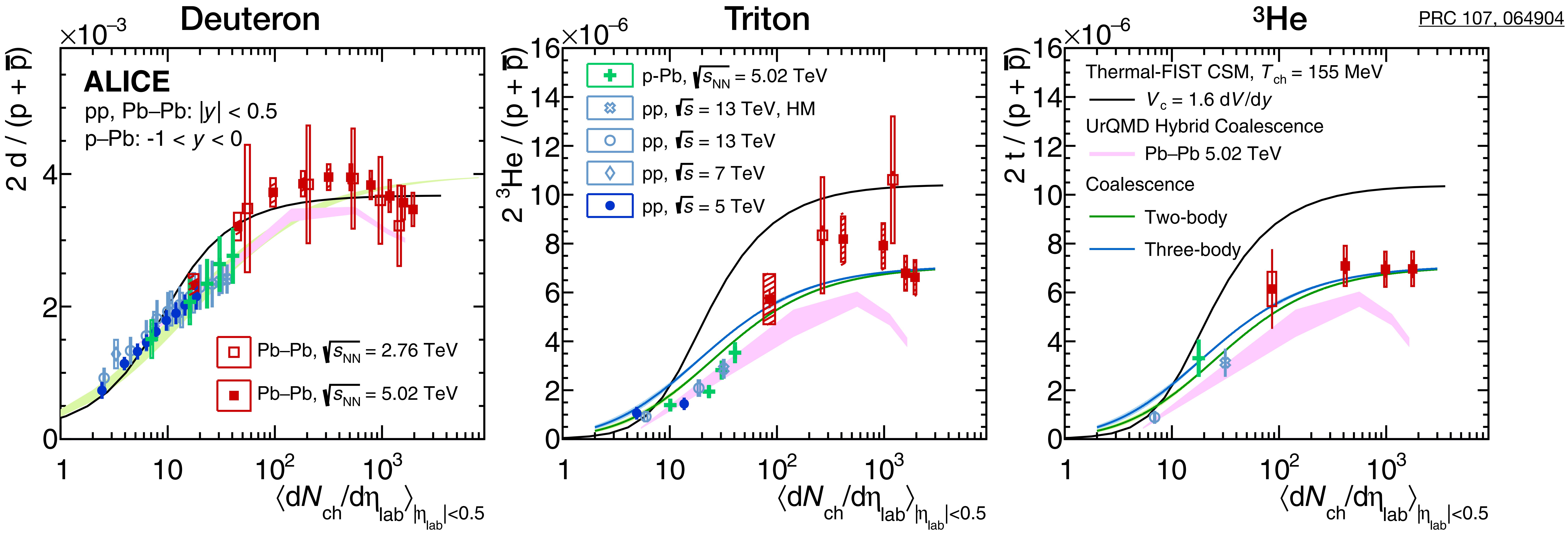
- Particle production in heavy-ion collisions follow statistical hadronization:

$$N \propto (2J+1)e^{-m/T}$$

- The yields depend solely on the mass and temperature, consistent with a thermal model. →supporting the thermal nature of the hadronization process.

Light nuclei production

Francesca Ercolessi,
Monday 15:00

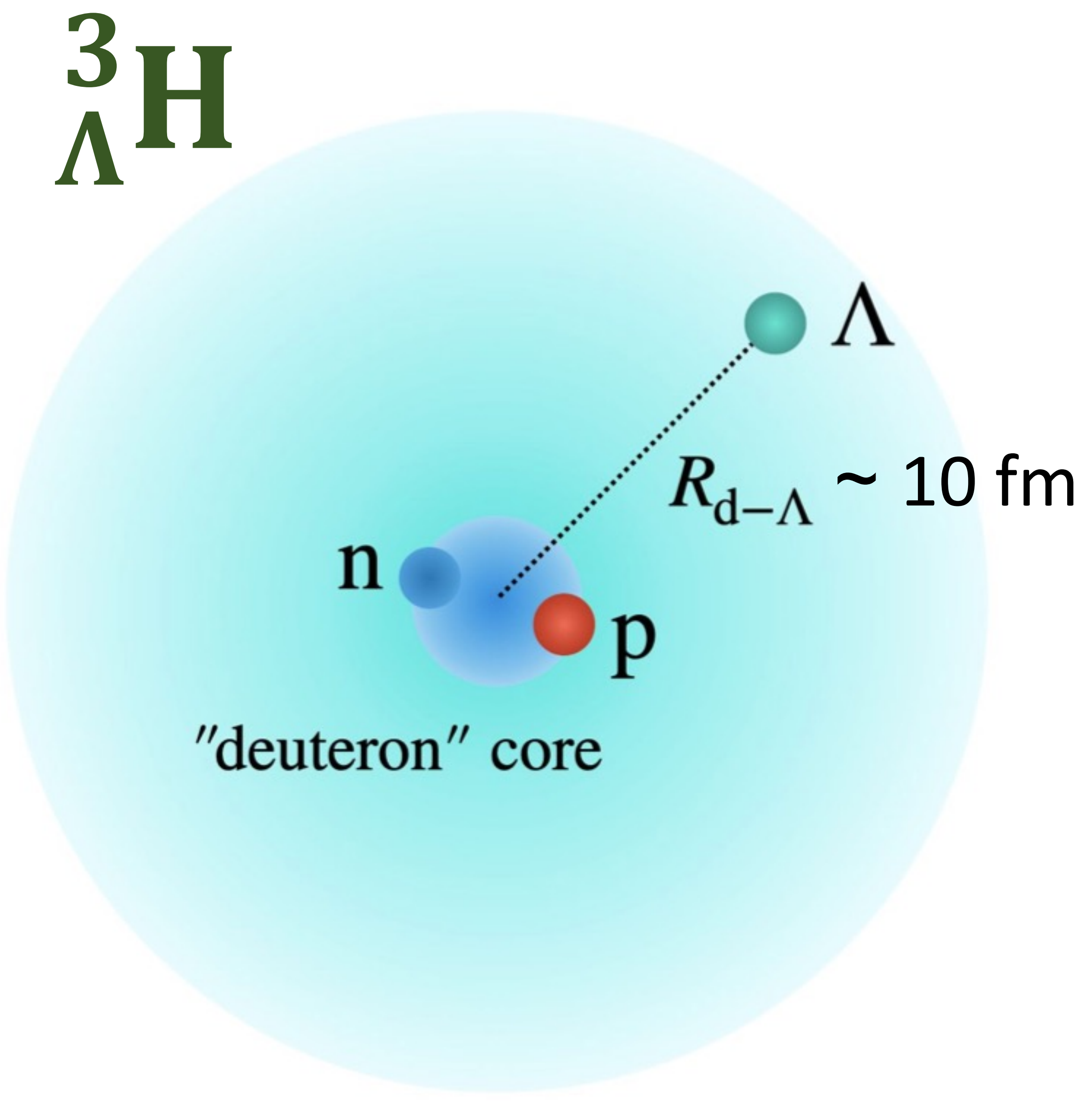


Thermal model prediction: Eur. Phys. J. A (2020) 56:280

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

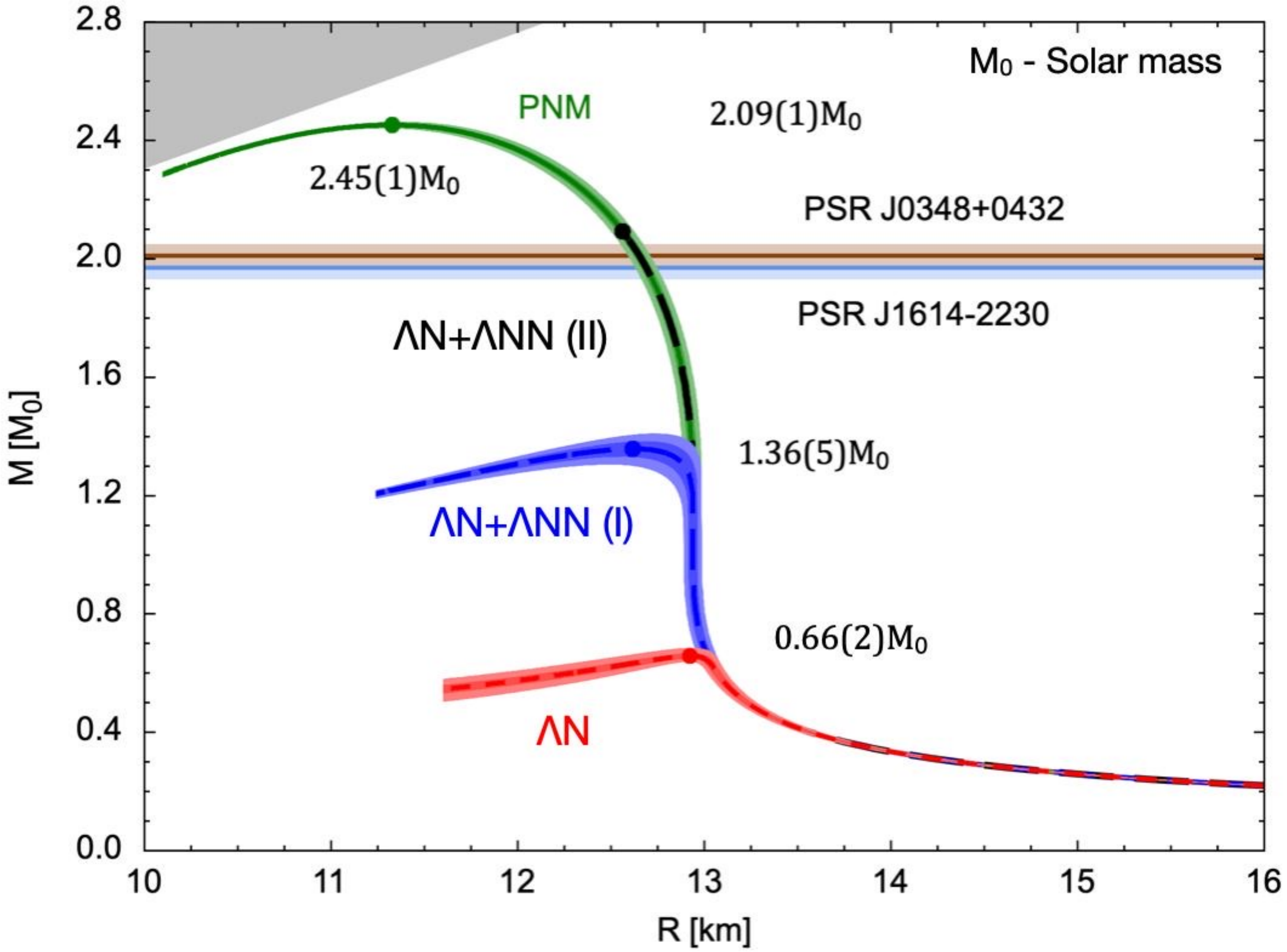
- Dependence of light-nuclei production on event multiplicity provides important insights into the mechanisms of light-nuclei formation
- ^{3}He, t favour coalescence models → likely formed through the coalescence of nucleons in the later stages of the collision

Hypertriton production, application to neutron star



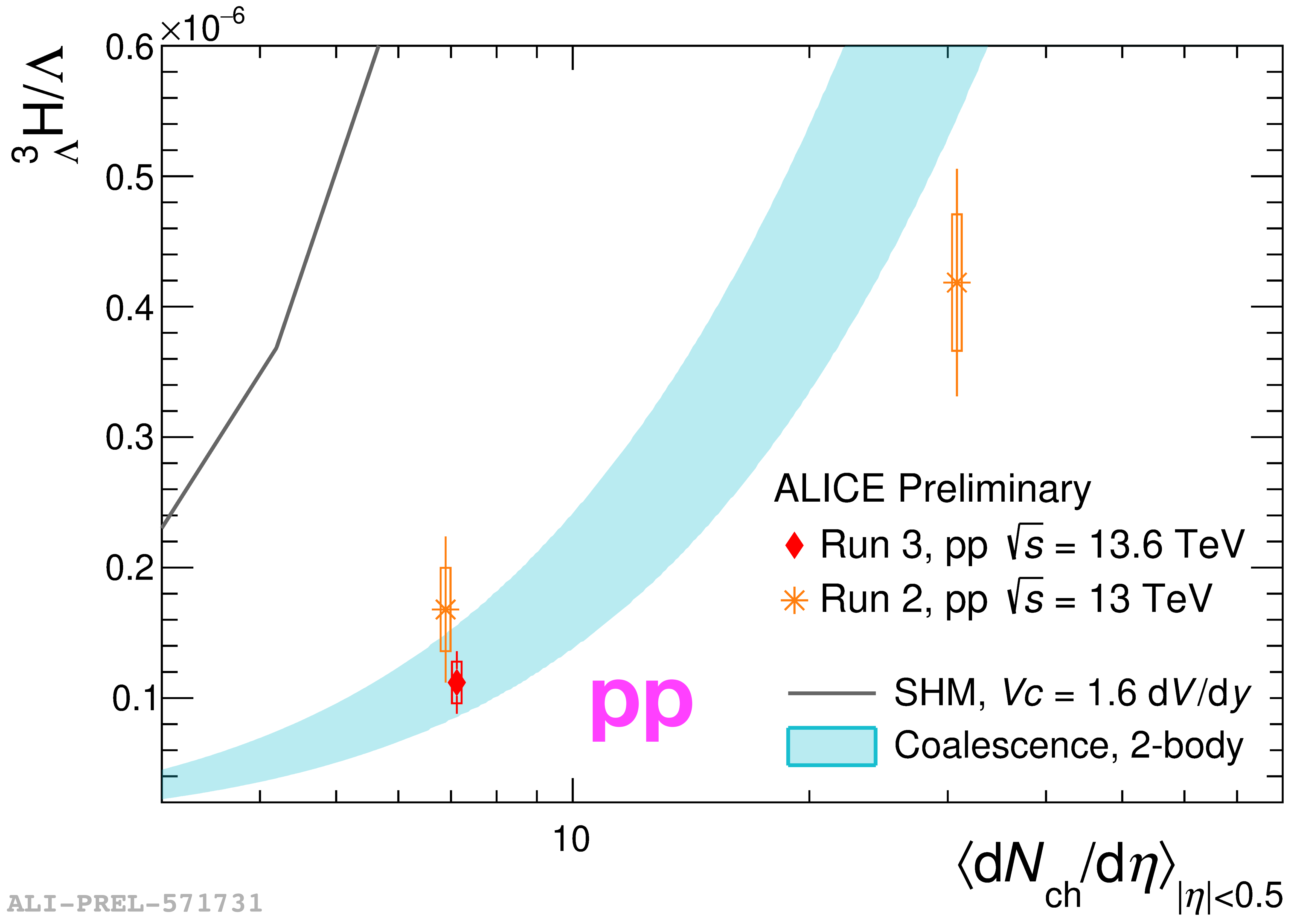
Lightest hyper nucleus

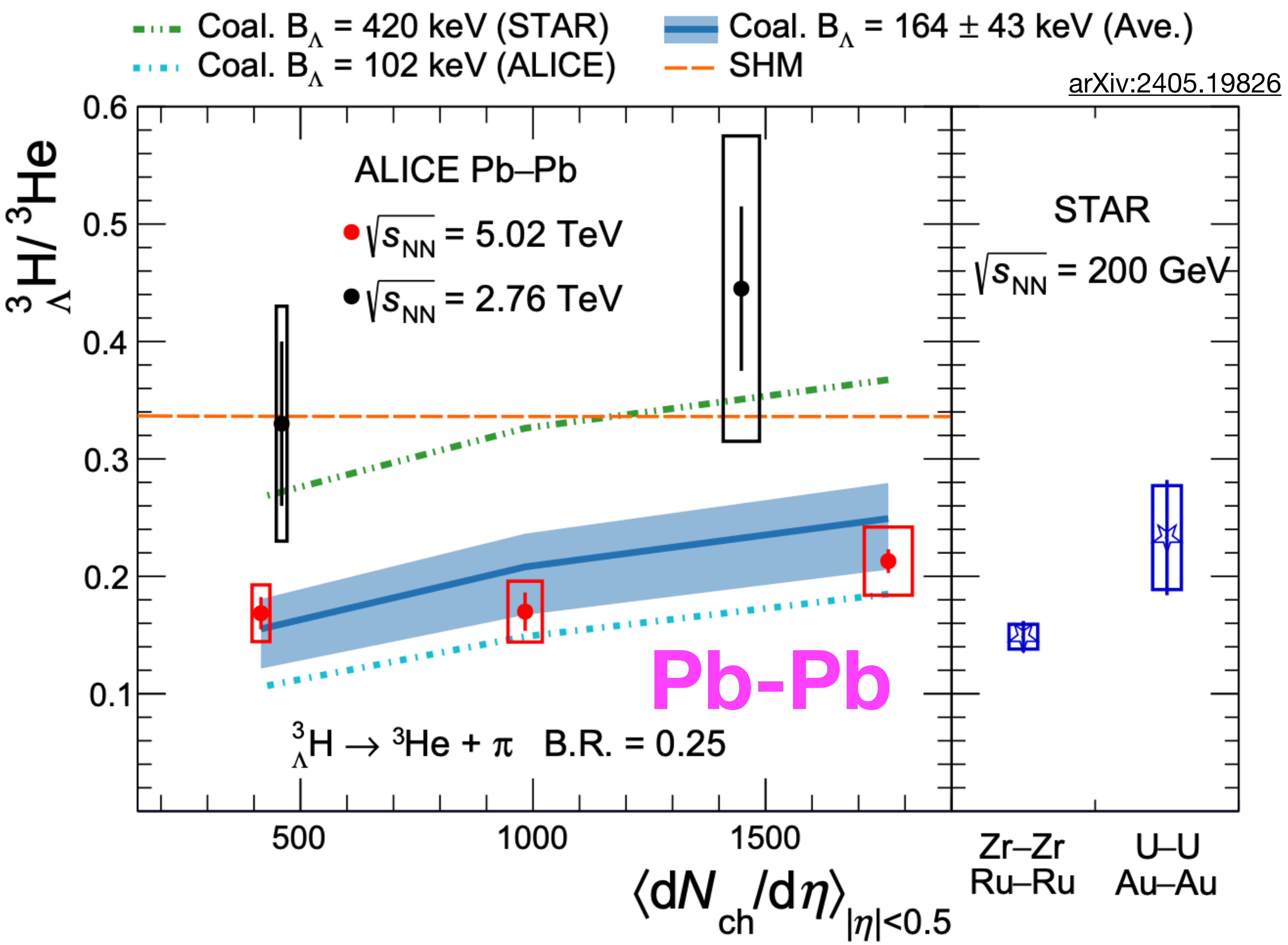
D. Lonardoni et al., PRL 114, 092301 (2015)



- 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

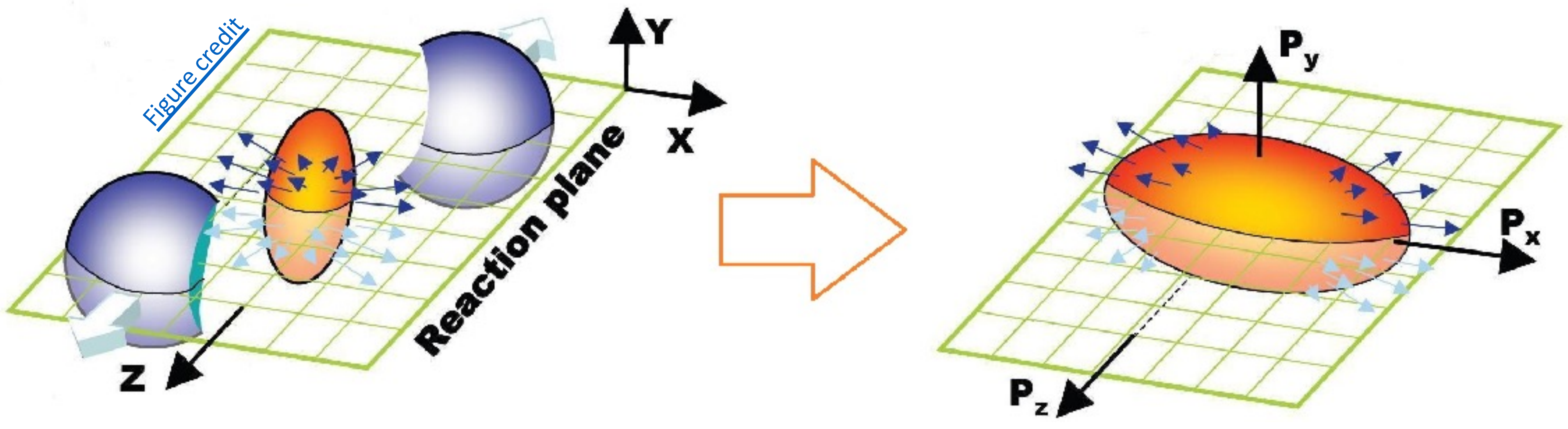
- **coalescence** → interplay between the spatial extension of the nucleus wavefunction and the system size
- **SHM** predicts a flat ratio: sensitive to their similar masses, but insensitive to their size

Studying QGP with elliptic flow

Eccentricity in the initial state of a heavy-ion collision is converted to momentum anisotropy in the final state distributions of particles by the pressure gradients:

- elliptic flow v_2: second-order coefficient

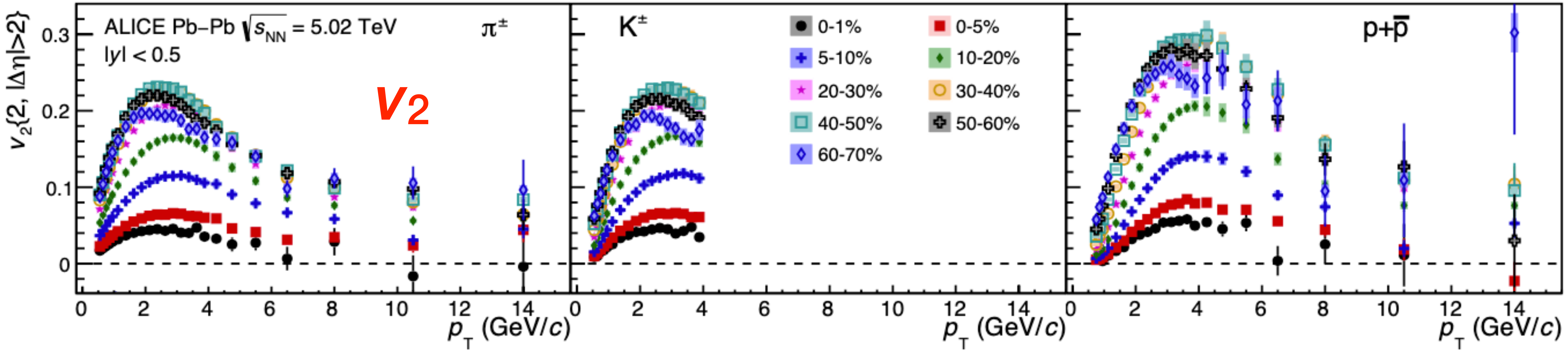
→ probe the transport coefficients of the QGP (i.e. shear viscosity and bulk viscosity), the initial state of the collisions and its fluctuations



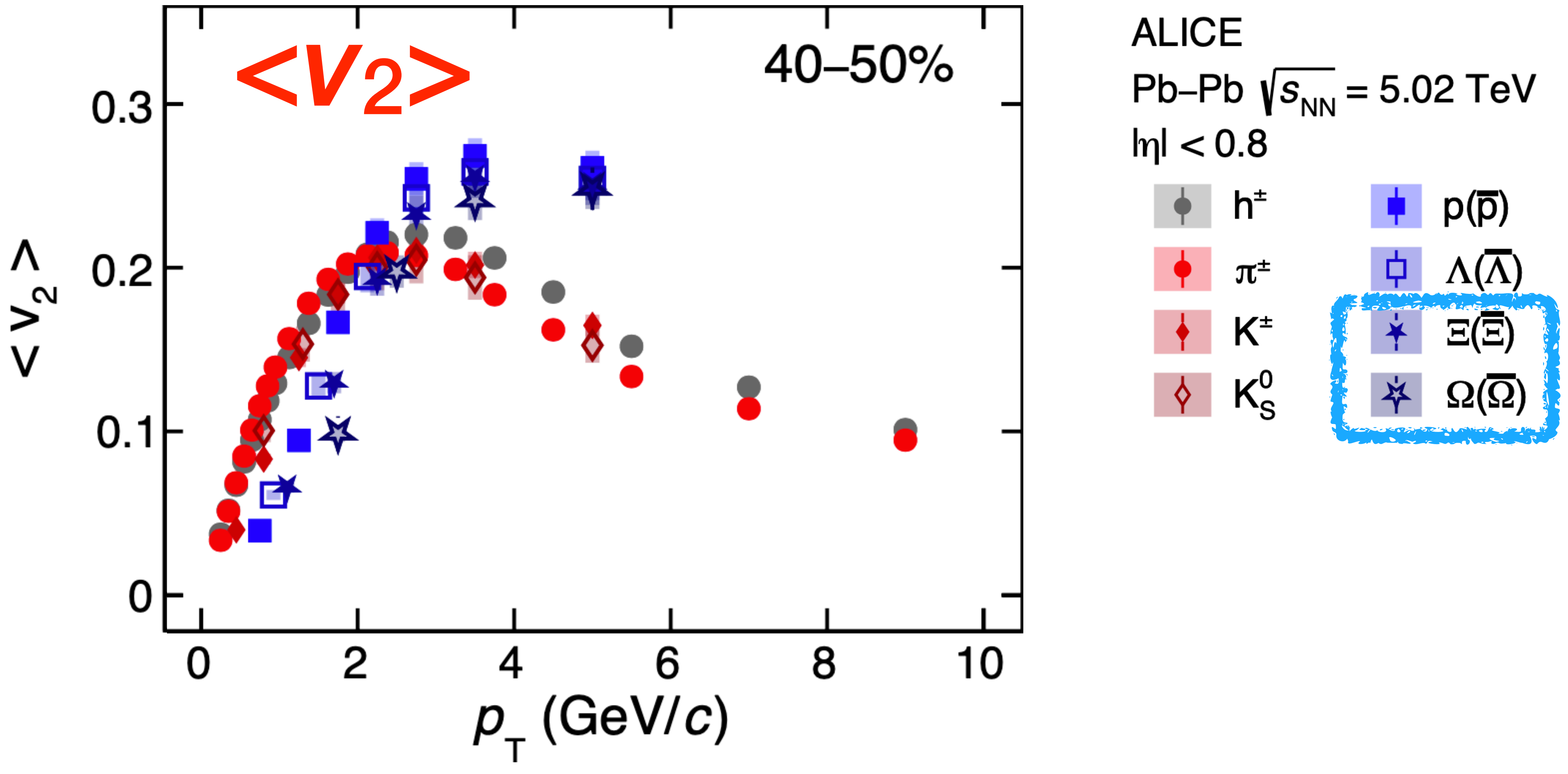
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

$$v_2 = \langle\cos[2(\varphi - \Psi_2)]\rangle$$

Elliptic flow of hadrons



JHEP 09 (2018) 006

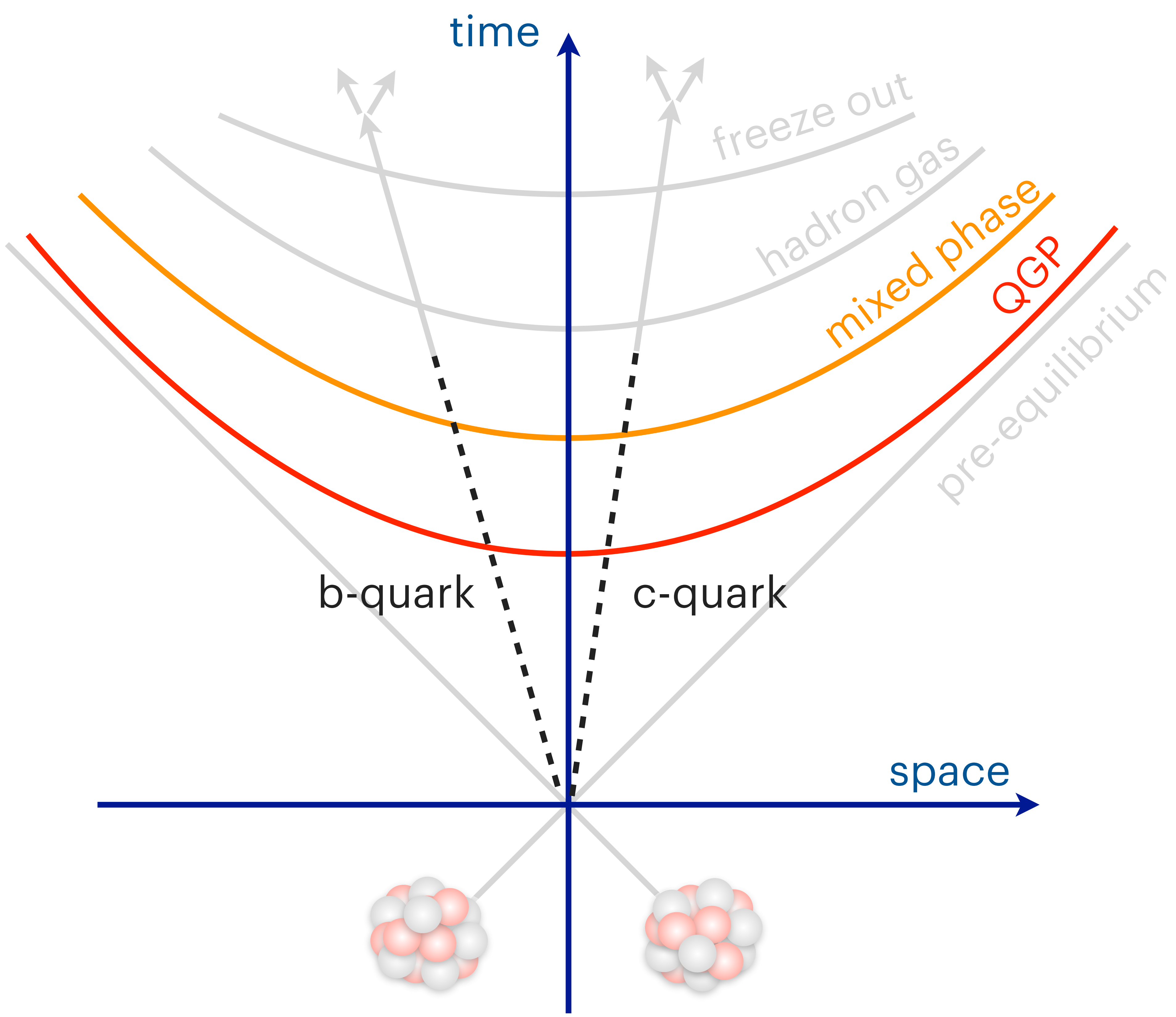


JHEP 05 (2023) 243

- Strongly centrality dependent → peripheral collisions (40-50%) showing more pronounced anisotropy
- Heavier particles have a smaller v_2 at lower p_T → mass ordering (same for multi-strange hadrons) due to interplay between elliptic and radial flow
- Meson and baryon grouping at the intermediate p_T → interpreted as evidence that quark degrees of freedom dominate the stage when v_2 develops

→ Insights into the viscosity of the QGP and the degree of thermalization of the system

Heavy quark interaction with the medium



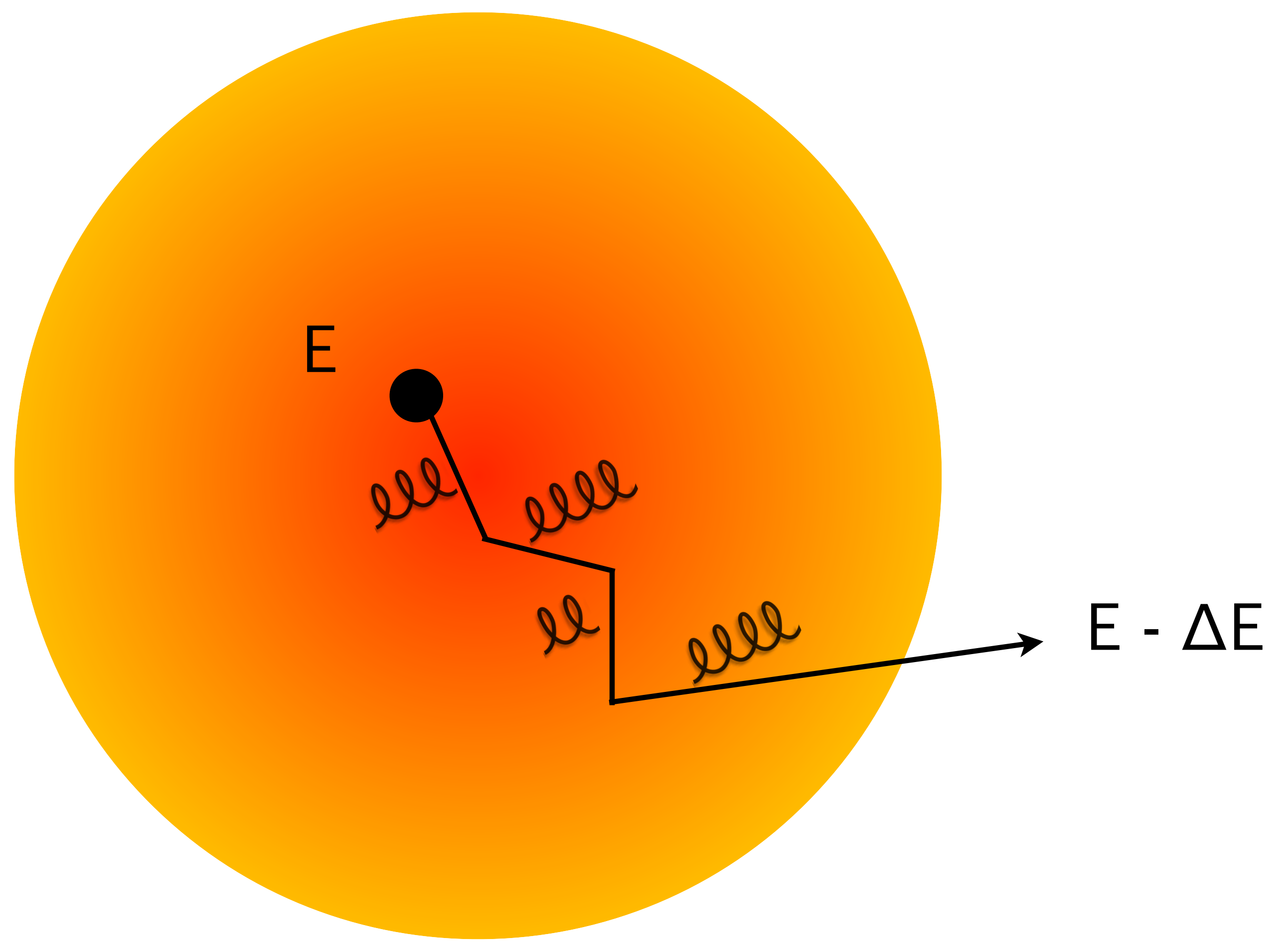
$\tau_{HF} \simeq \hbar/m \simeq$ 0.05-0.1 fm/c

$\tau_{QGP\ form}$ (LHC) $\simeq$ 0.3 fm/c

$\tau_{QGP\ lifetime} \simeq$ 10 fm/c

F.M. Liu et al., PRC 89, 034906 (2014)

ALICE, PLB 696 (2011) 328-337

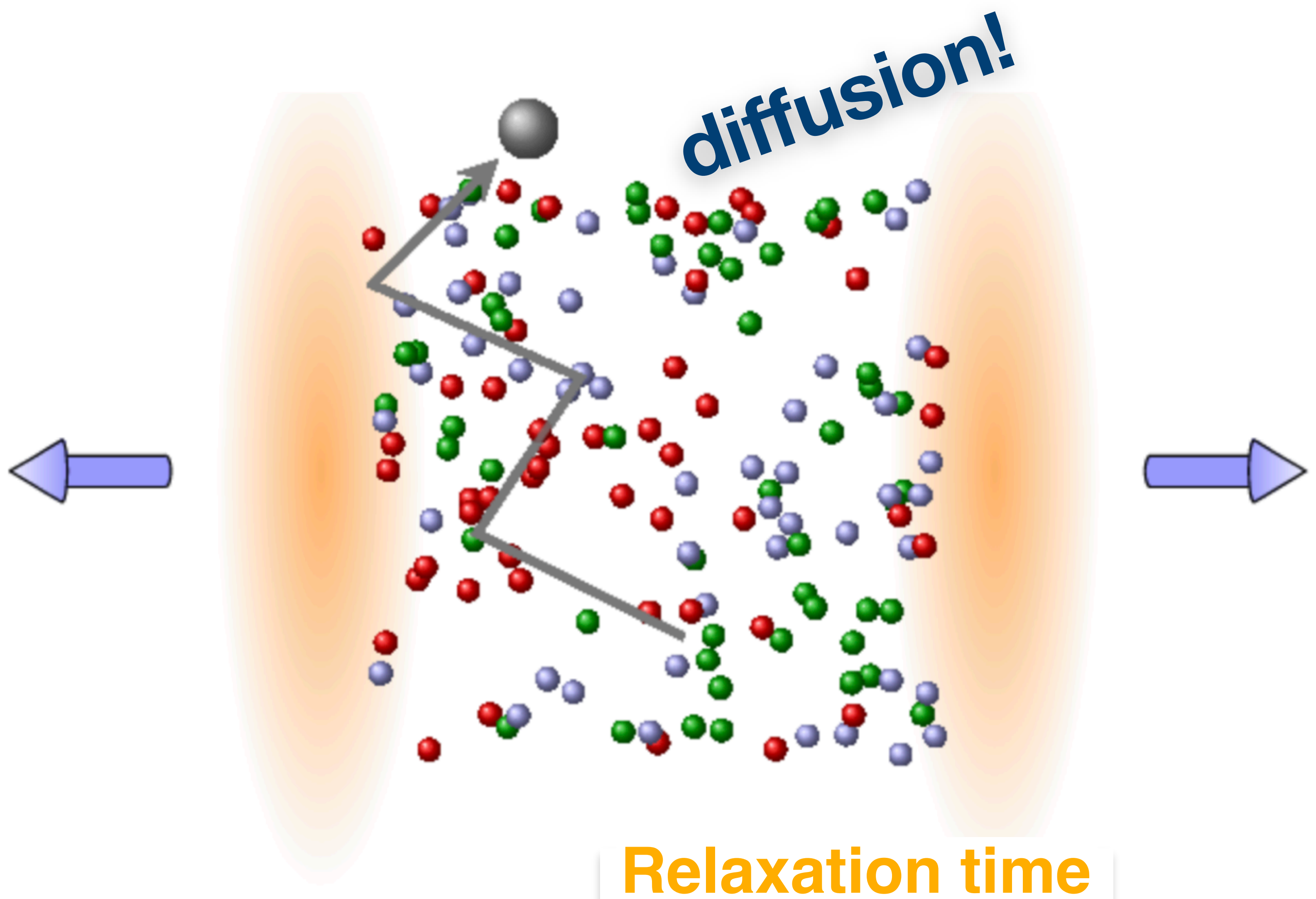


Heavy quarks interact with QGP constituents

- Energy loss via elastic collisions and/or radiative processes
- low-p_T heavy-quarks thermalisation in the medium?

Charm quark transport in the medium

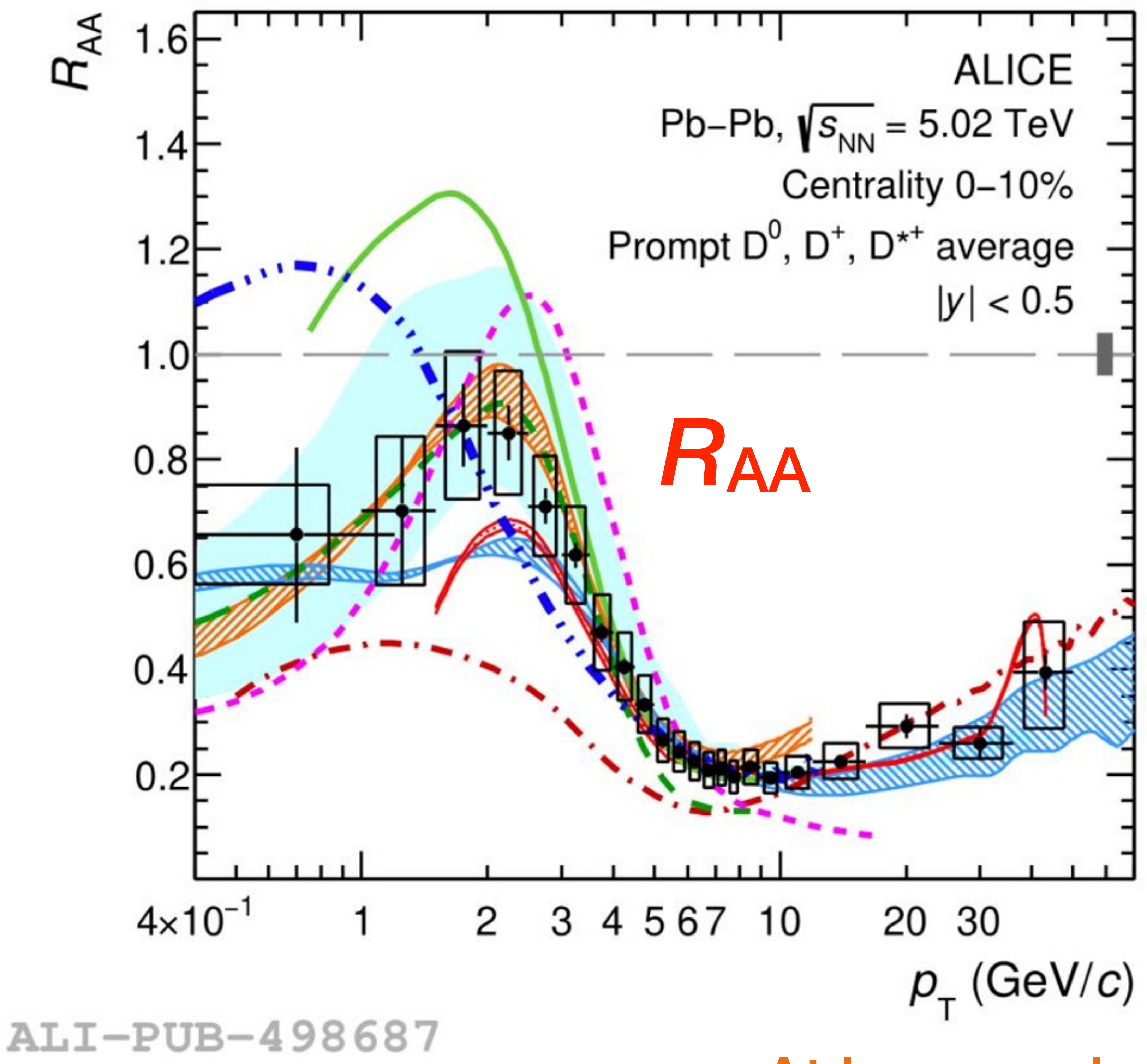
- The low-p_T region provides insight into the heavy-quark interactions with the medium
- Comparison of R_{AA} and v_2 with transport models

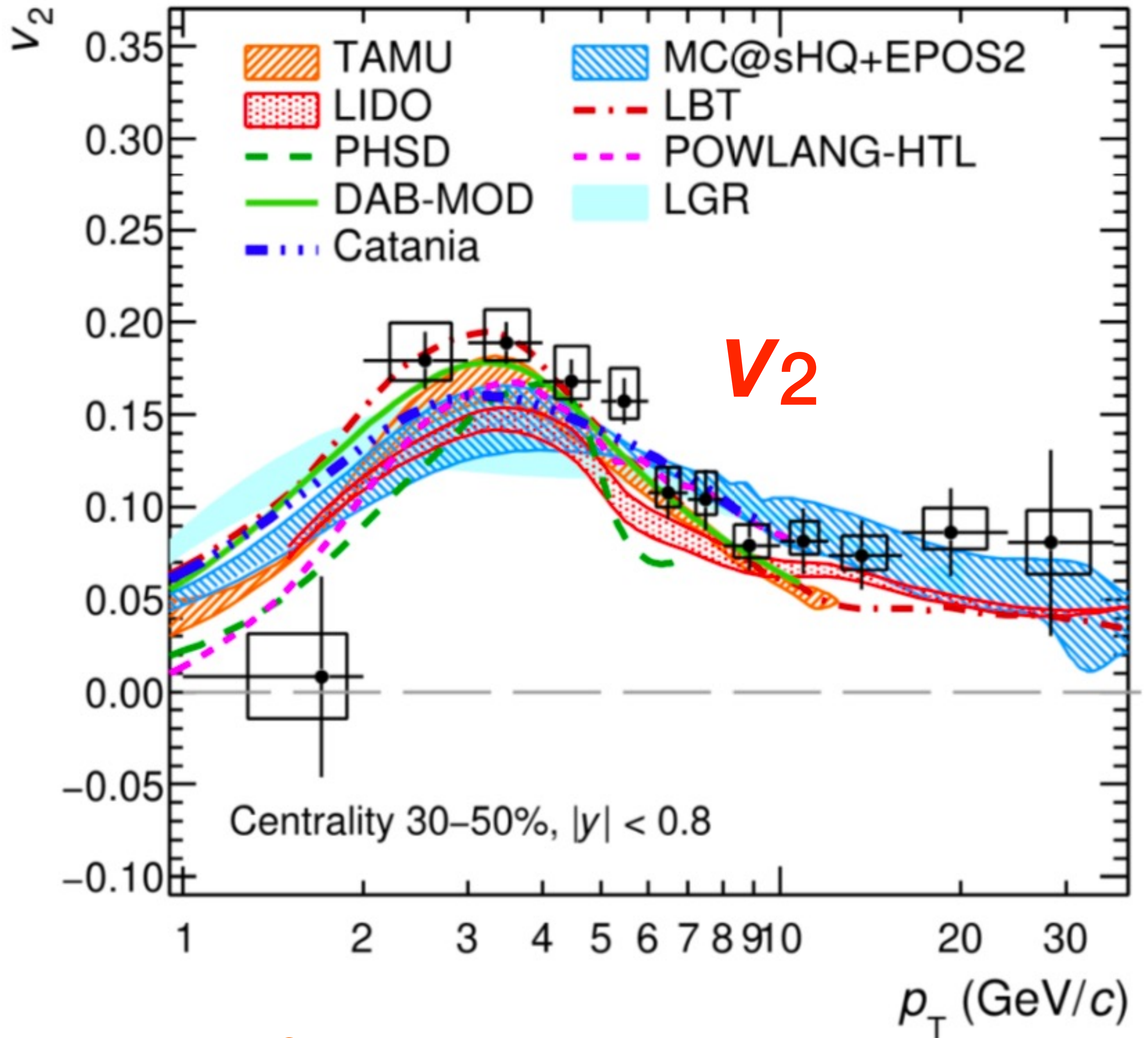


Relaxation time

$\tau_Q = (m_Q/T)D_s$

JHEP01 (2022) 174



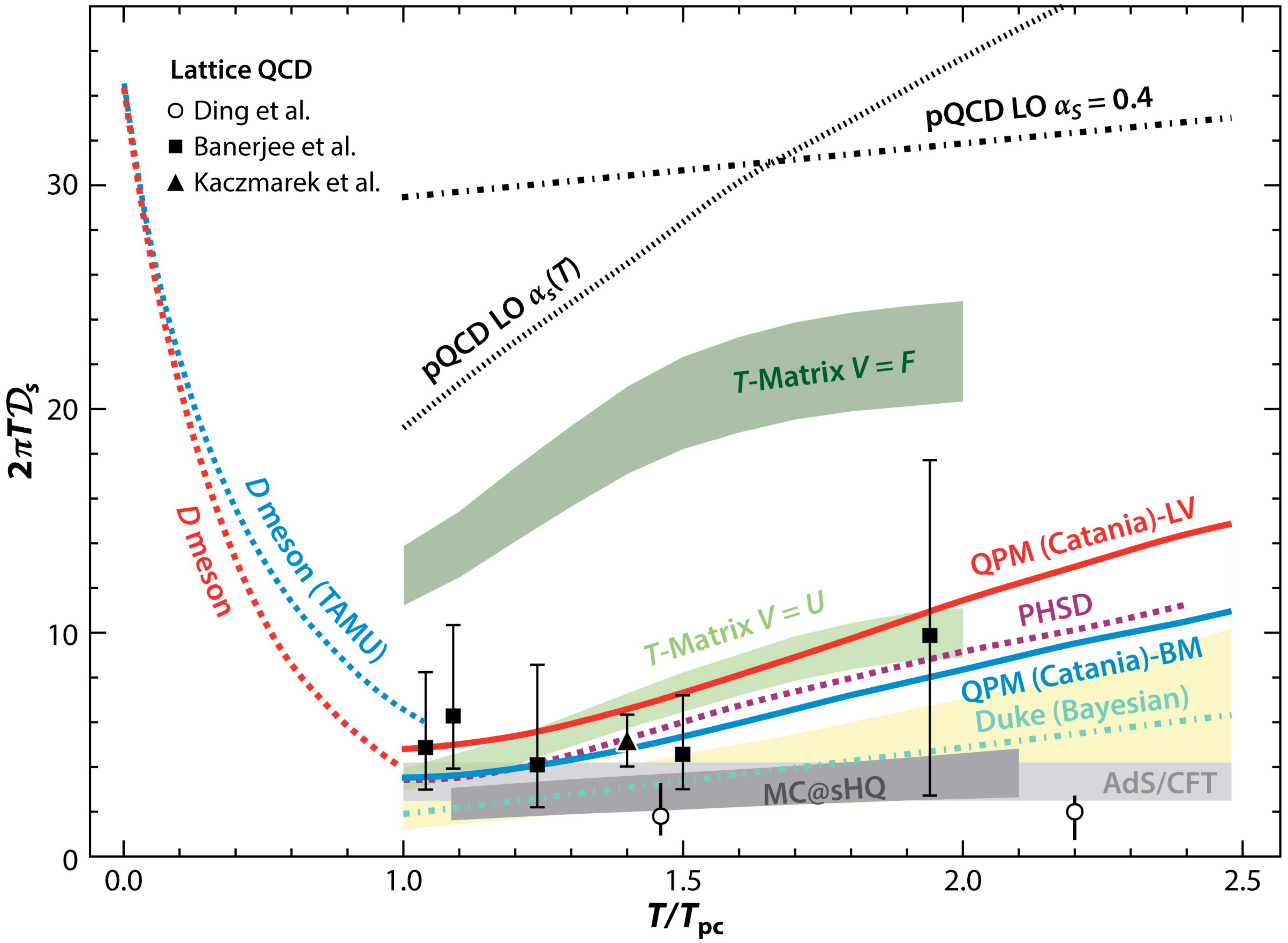


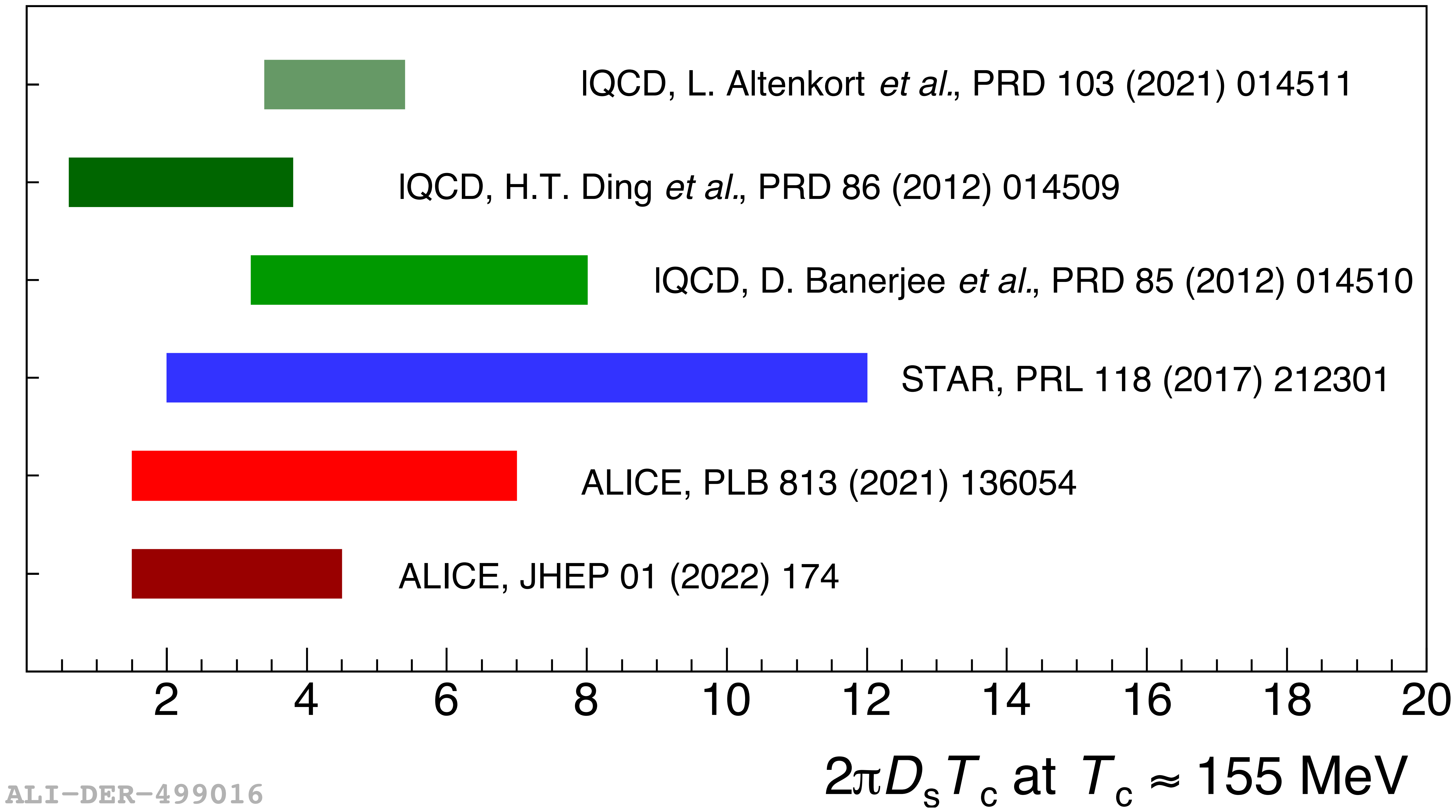
At low-p_T, also shadowing & bulk evolution of the medium

- Charm quark interacts with the medium via collisional and radiative processes in Pb-Pb collisions
- Charm quarks are thermalised with medium → collective motion

Quantitative information via spacial diffusion coefficient

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





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

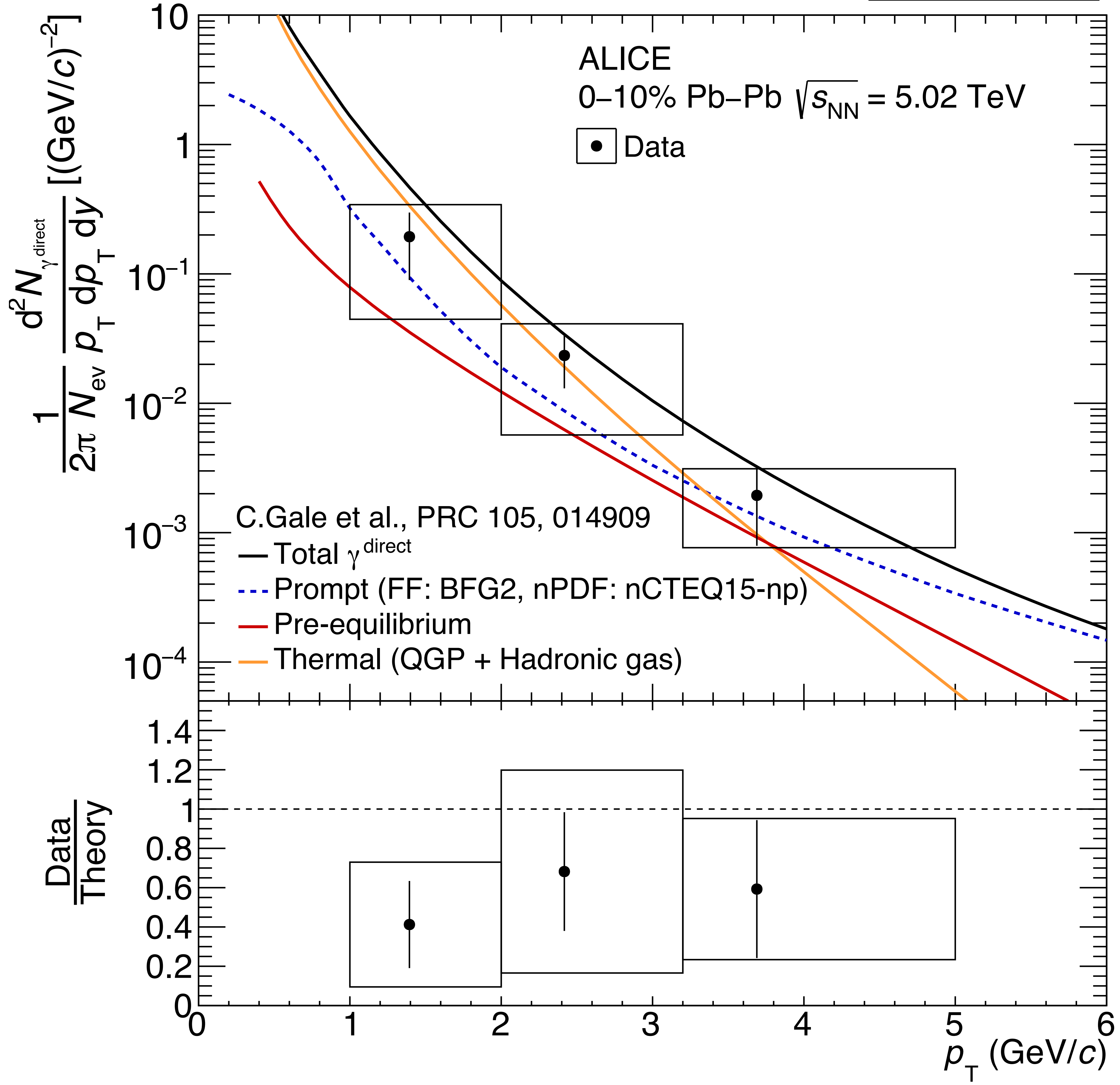
Virtual direct photon production

Direct photon-production mechanisms:

- prompt photons: originating from initial hard scatterings (high p_T)
- pre-equilibrium photons: reflecting the dynamics before the QGP reaches full thermalization (inter mediated p_T)
- thermal photons: emitted by the QGP and the hadronic gas (low p_T)

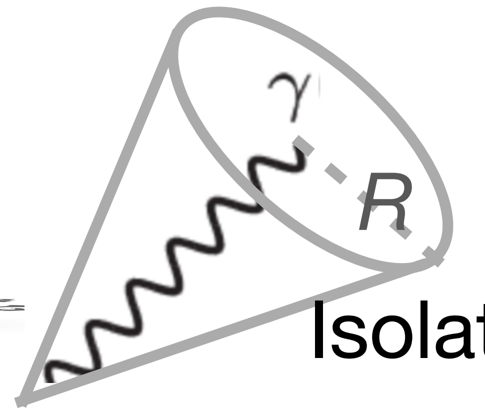
→ provides strong evidence for the formation and evolution of the QGP, as well as the role of various stages in the photon-emission process.

arXiv:2308.16704



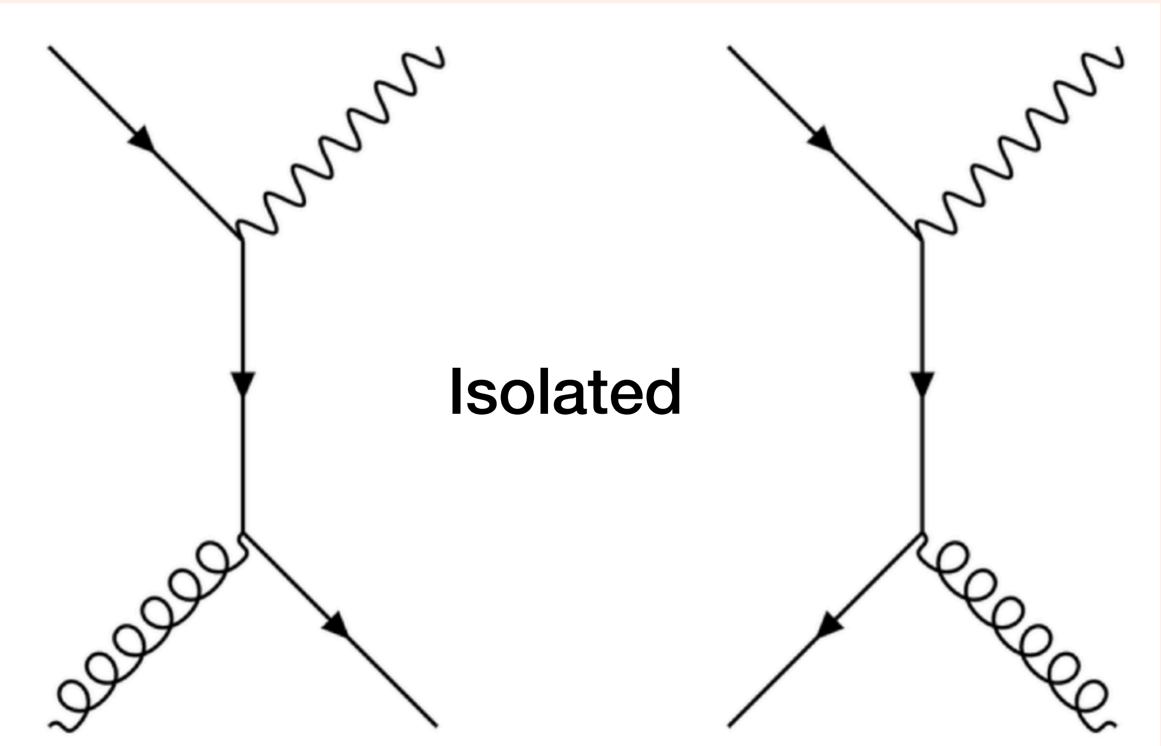
- Agreement between the data and the model across different p_T ranges → models capture the key processes of photon production in the complex environment of a heavy-ion collision.

Isolated photon production

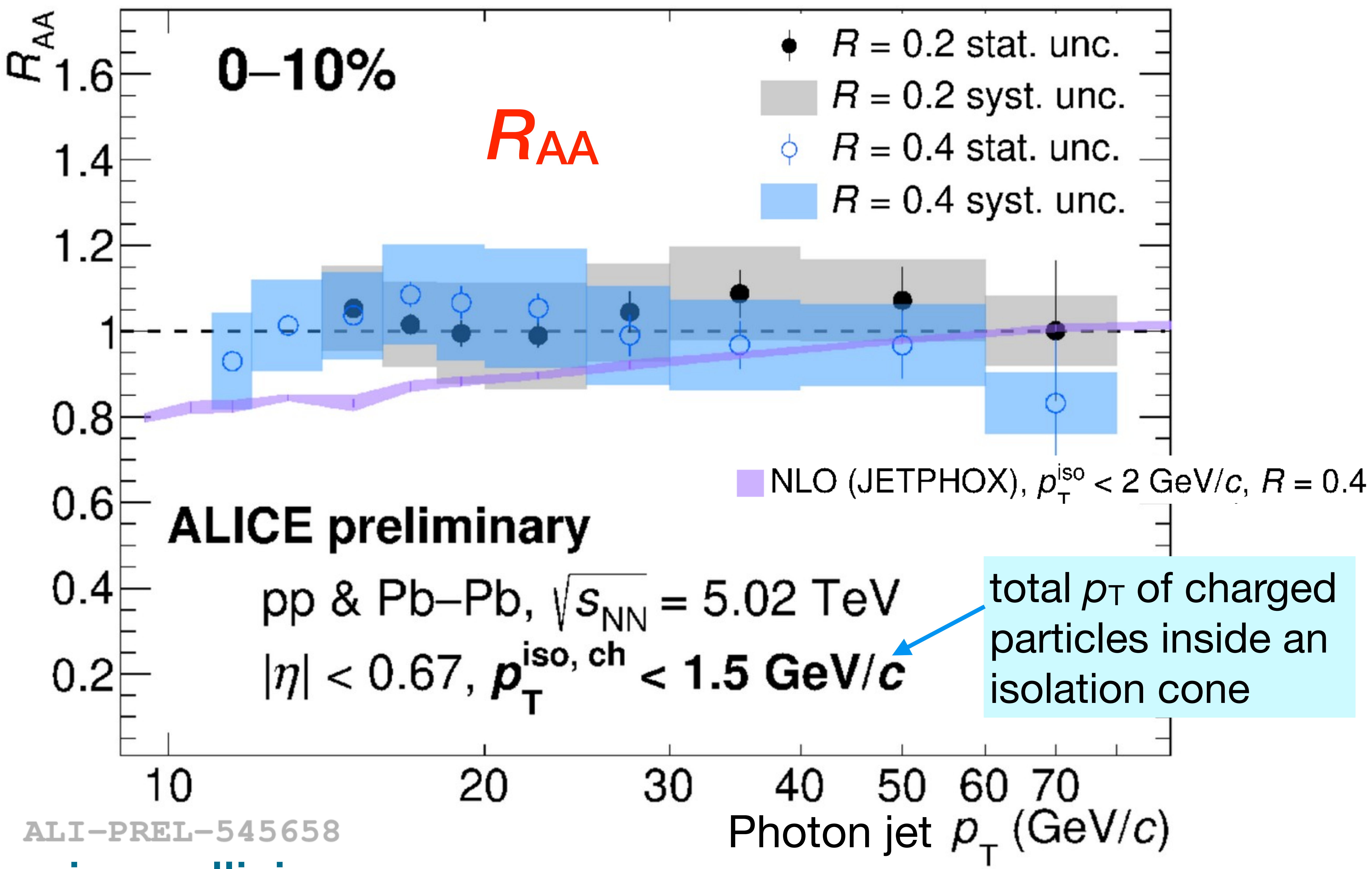


Isolated photon production:

- Direct photons (prompt) are mostly isolated



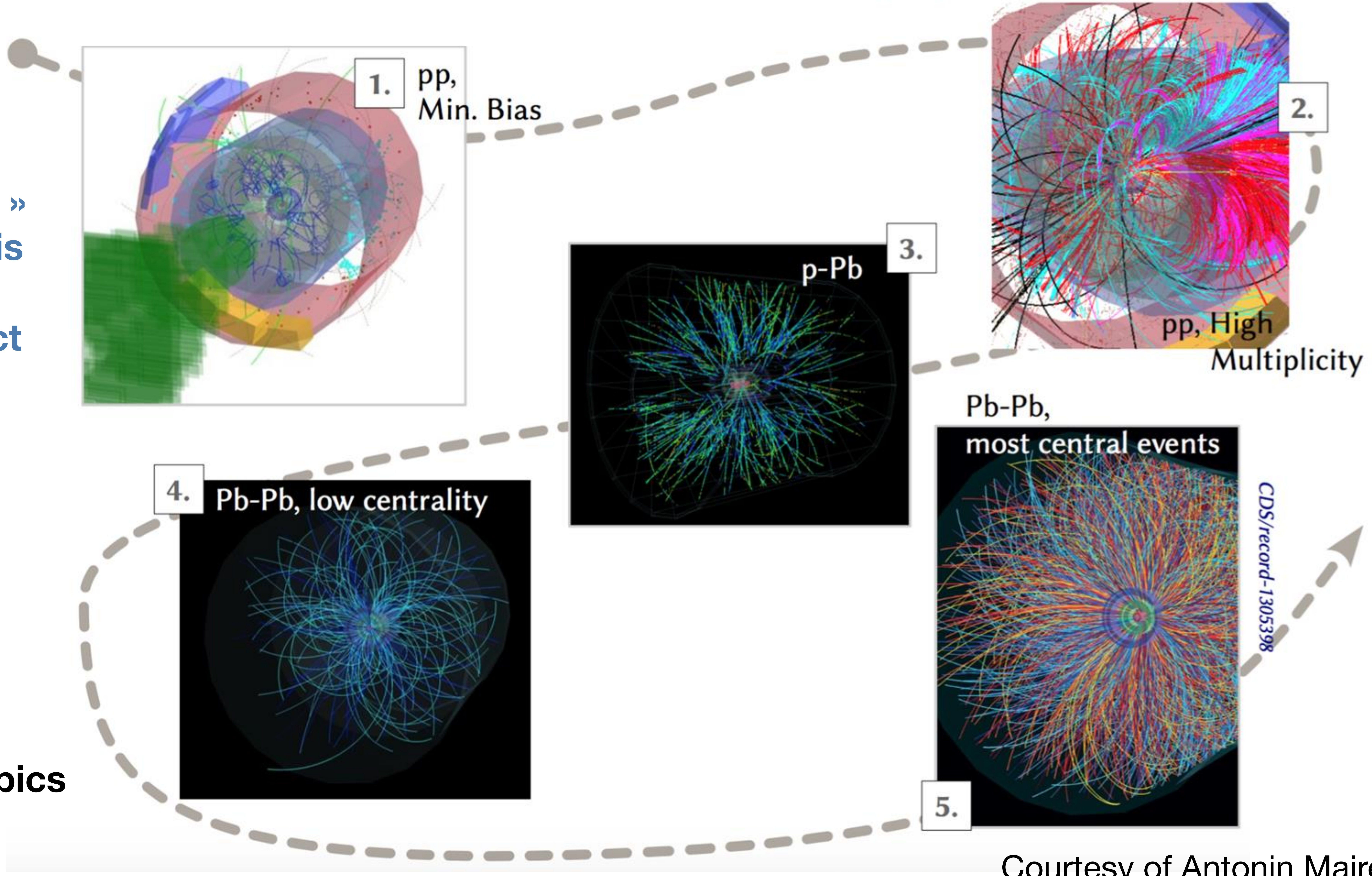
Compton scattering   Annihilation processes



- No direct-photon suppression in the central heavy-ion collisions
- Consistent with the expectation that direct photons should escape the medium without significant interaction → probe for studying the initial stages of heavy-ion collisions, less affected by the hot and dense medium.

From large to small system

The name « small systems » appeared at LHC Run I, it is now a session at Quark Matter, it is a recent aspect of heavy-ion physics



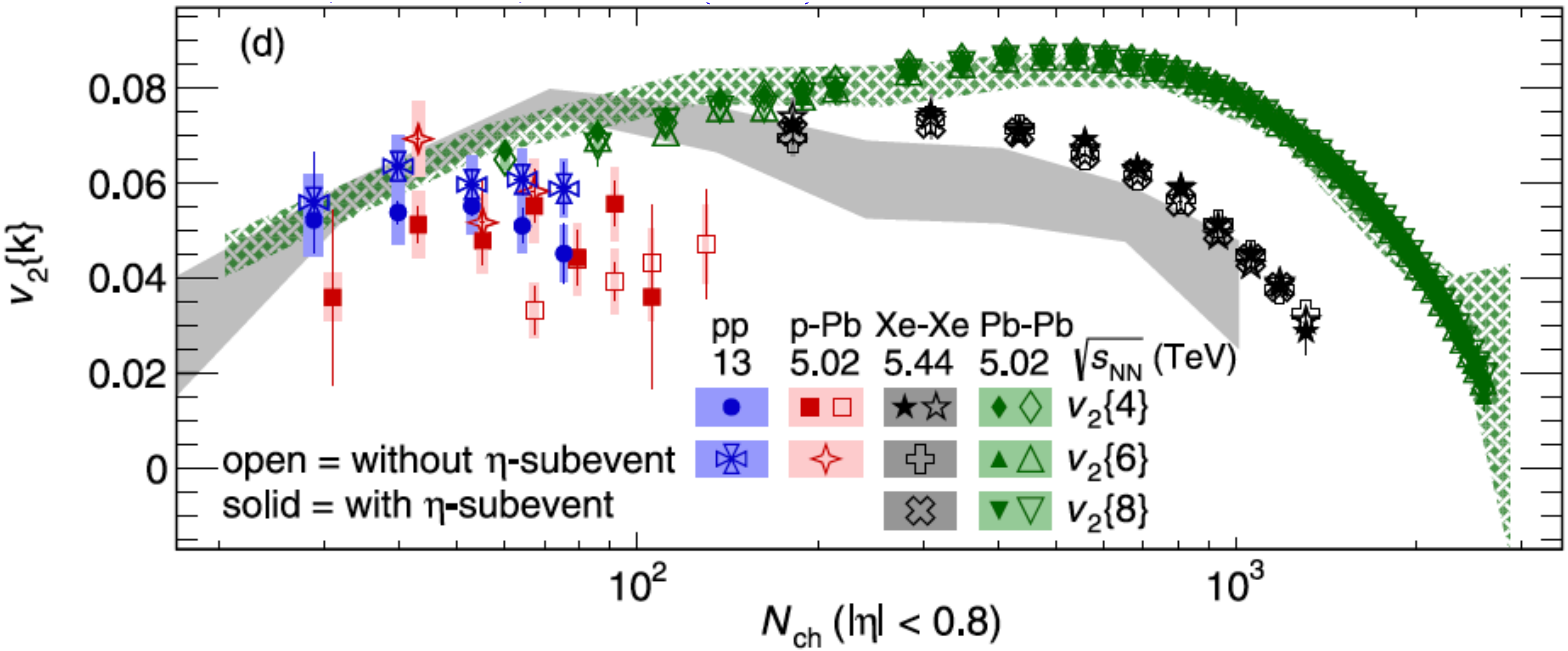
Will introduce selective topics

Courtesy of Antonin Maire

Elliptic flow in small systems

Observation of flow in small system:

- Measure elliptic flow as a function of the charged particle multiplicity for different systems
- Nature of particle correlations in high-energy collisions

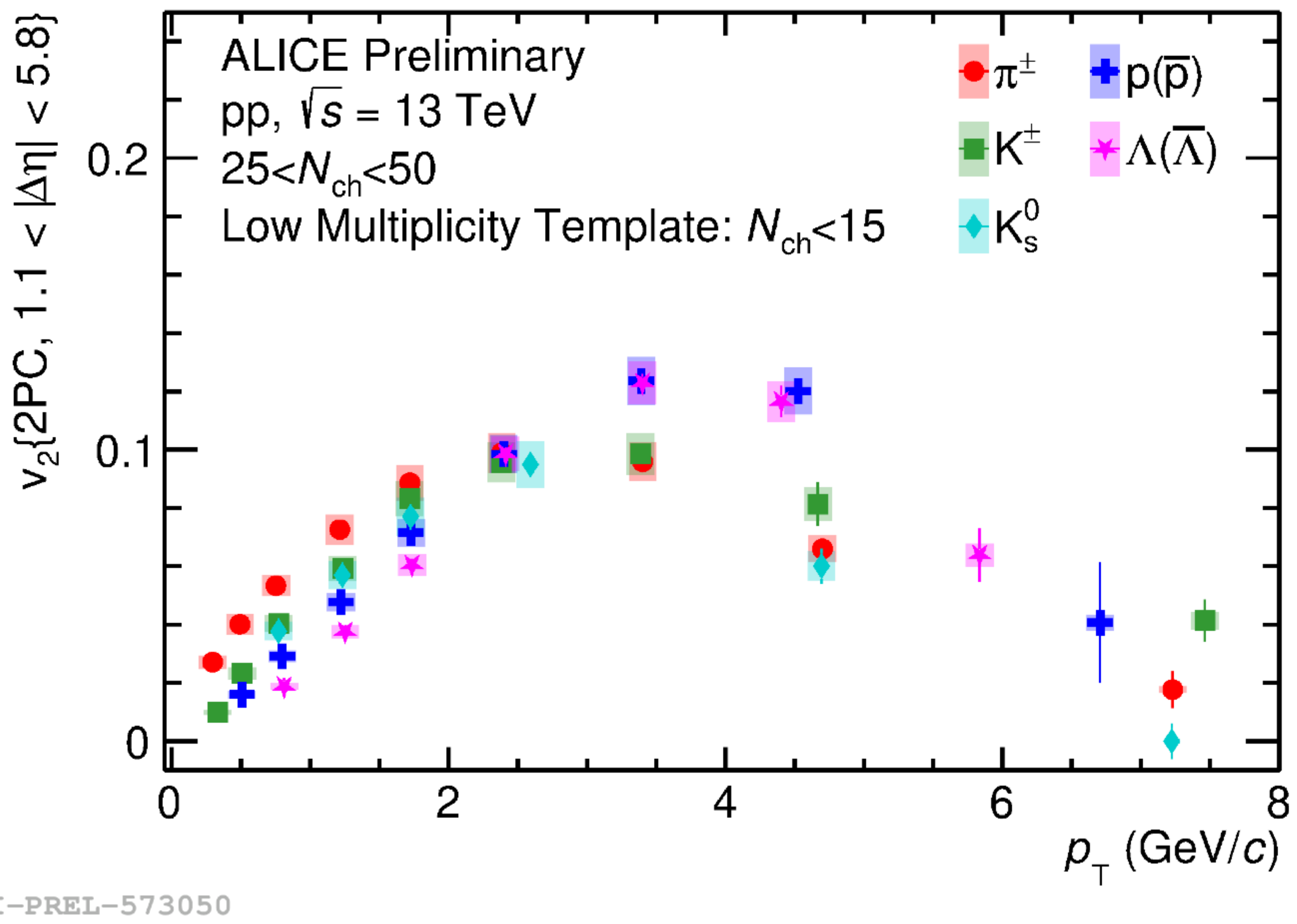


PRL123, 142301 (2019)

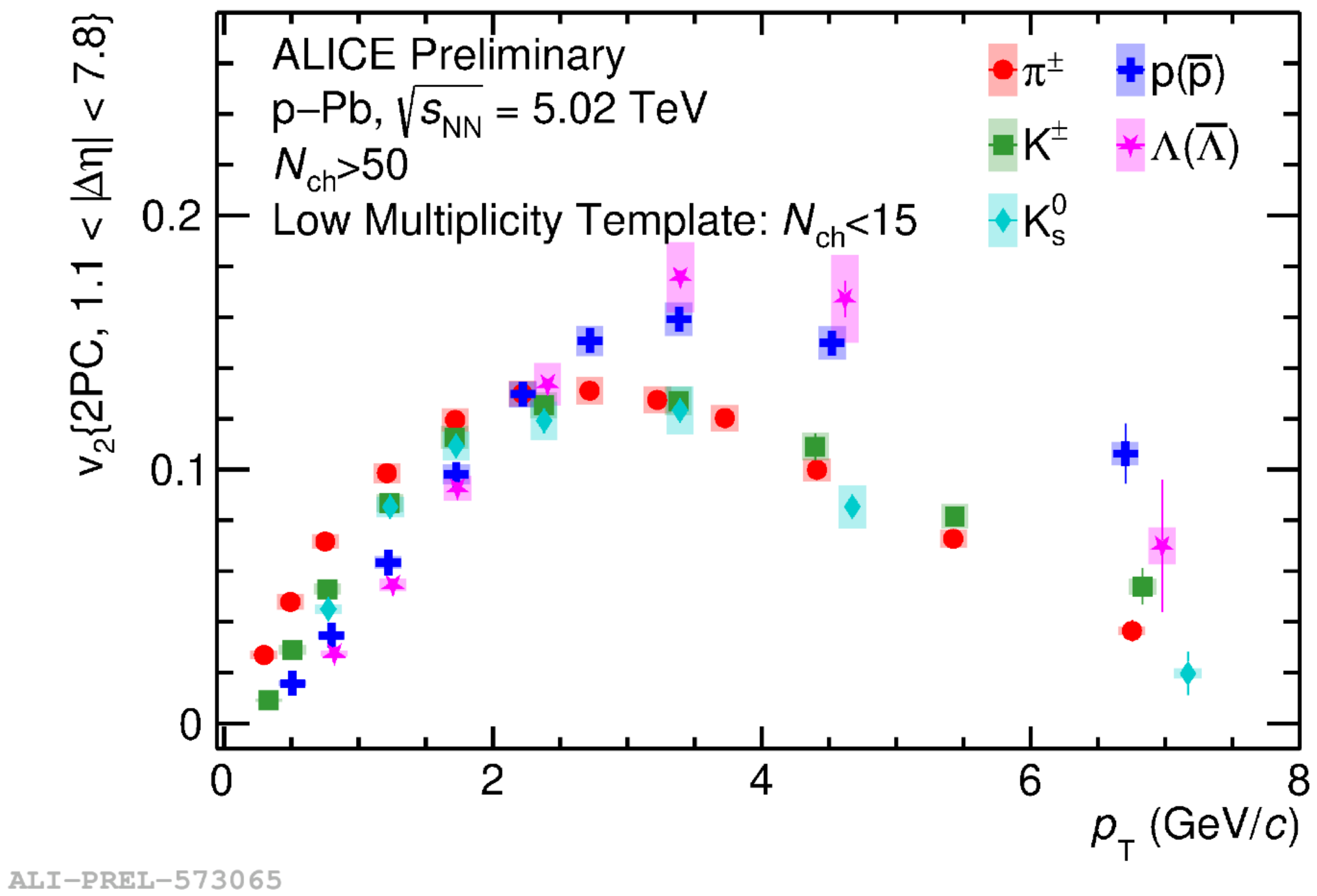
Is the measurement the consequence of the evolution of a hydrodynamic fluid?

Elliptic flow in small systems, similar to Pb–Pb?

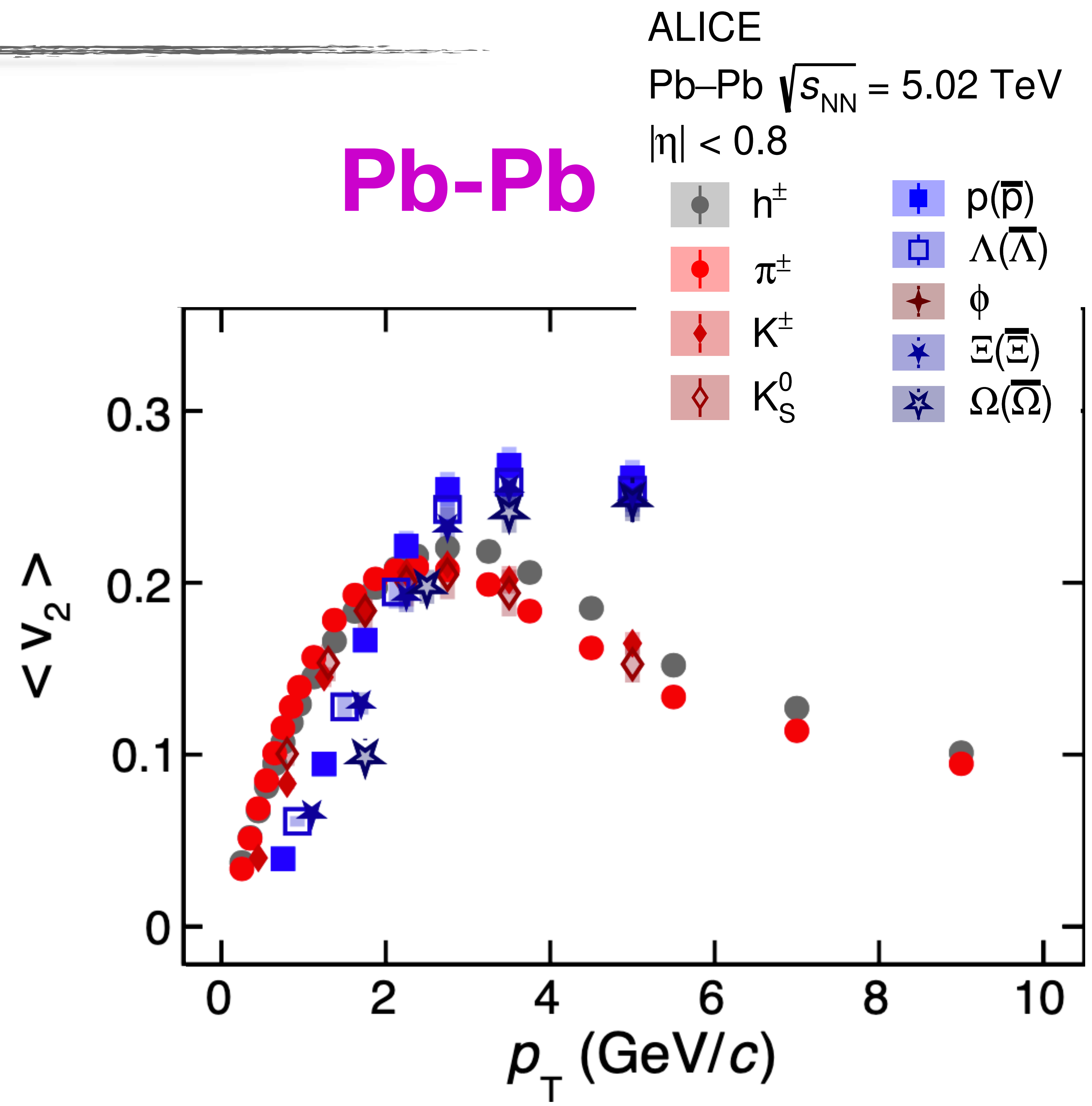
pp



p-Pb



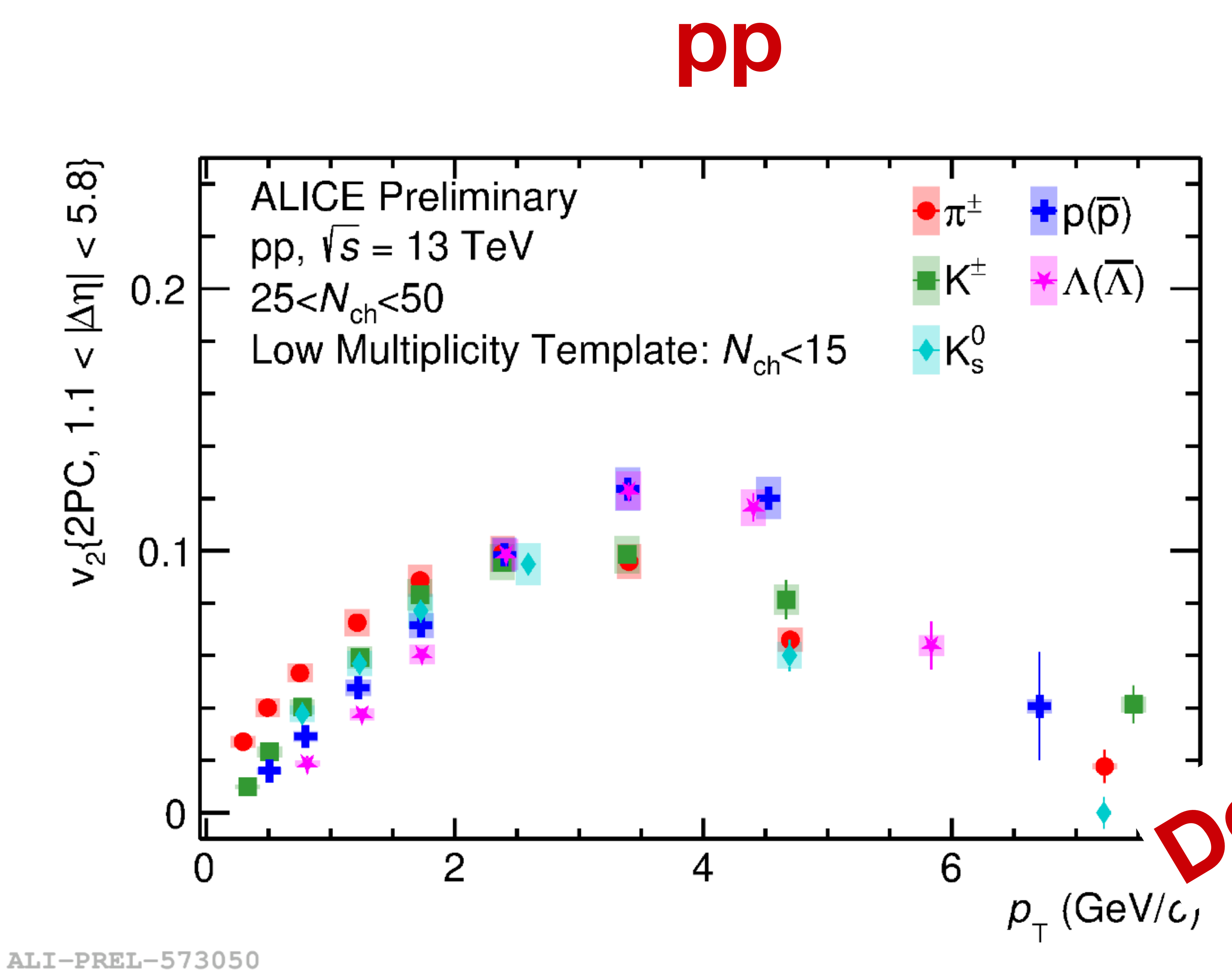
Pb-Pb

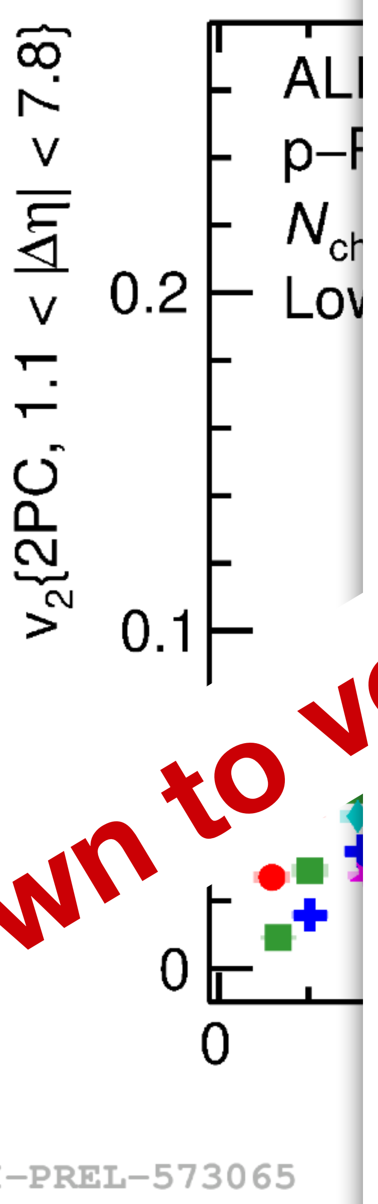


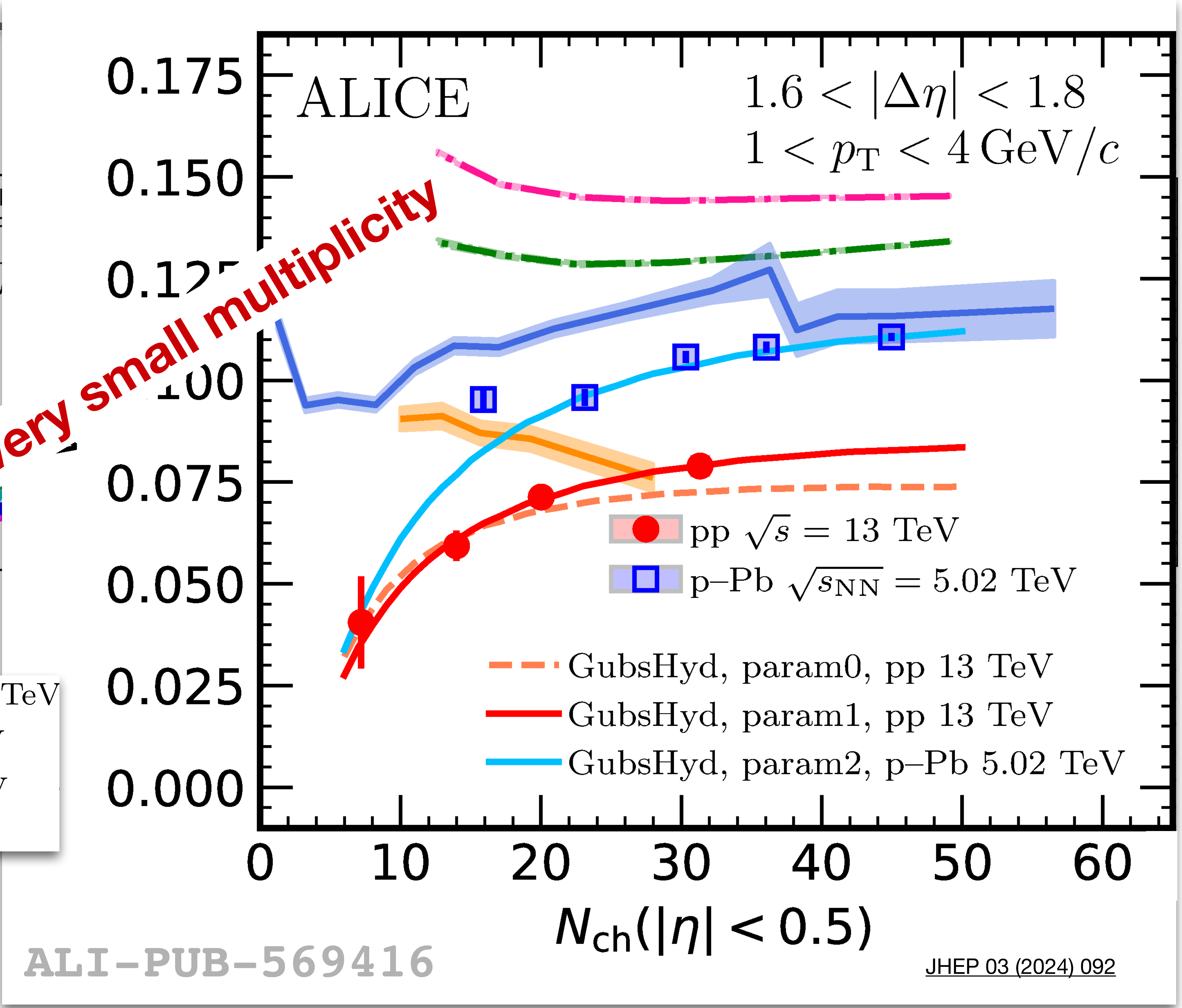
JHEP 05 (2023) 243

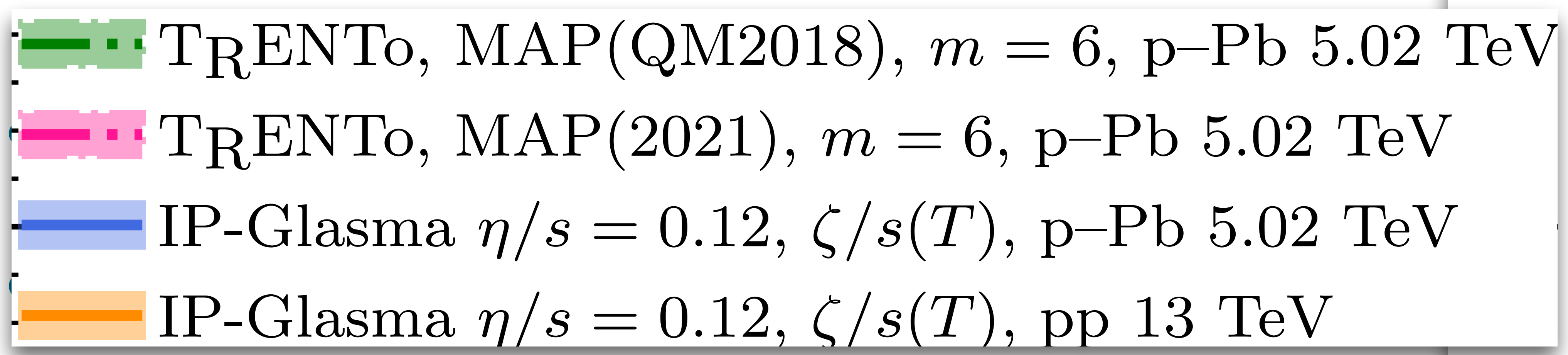
- Similar observations in Pb-Pb, high multiplicity p-Pb and pp collisions!
- Low p_T (p_T < 3 GeV/c) - Mass ordering
- Intermediate p_T (3 < p_T < 6 GeV/c): baryon-meson grouping, splitting between baryons and mesons v_2

Elliptic flow in small systems, similar to Pb–Pb?





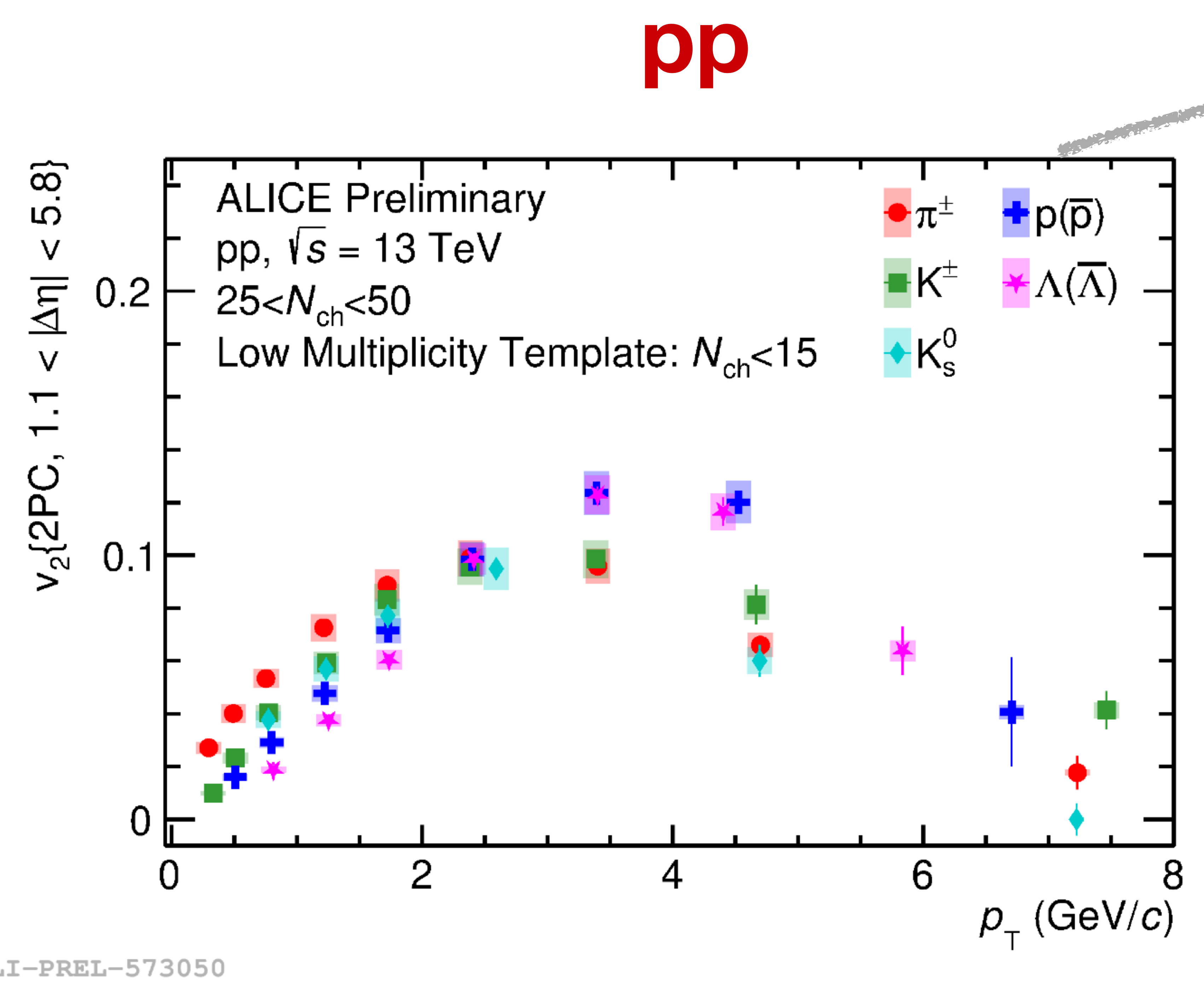


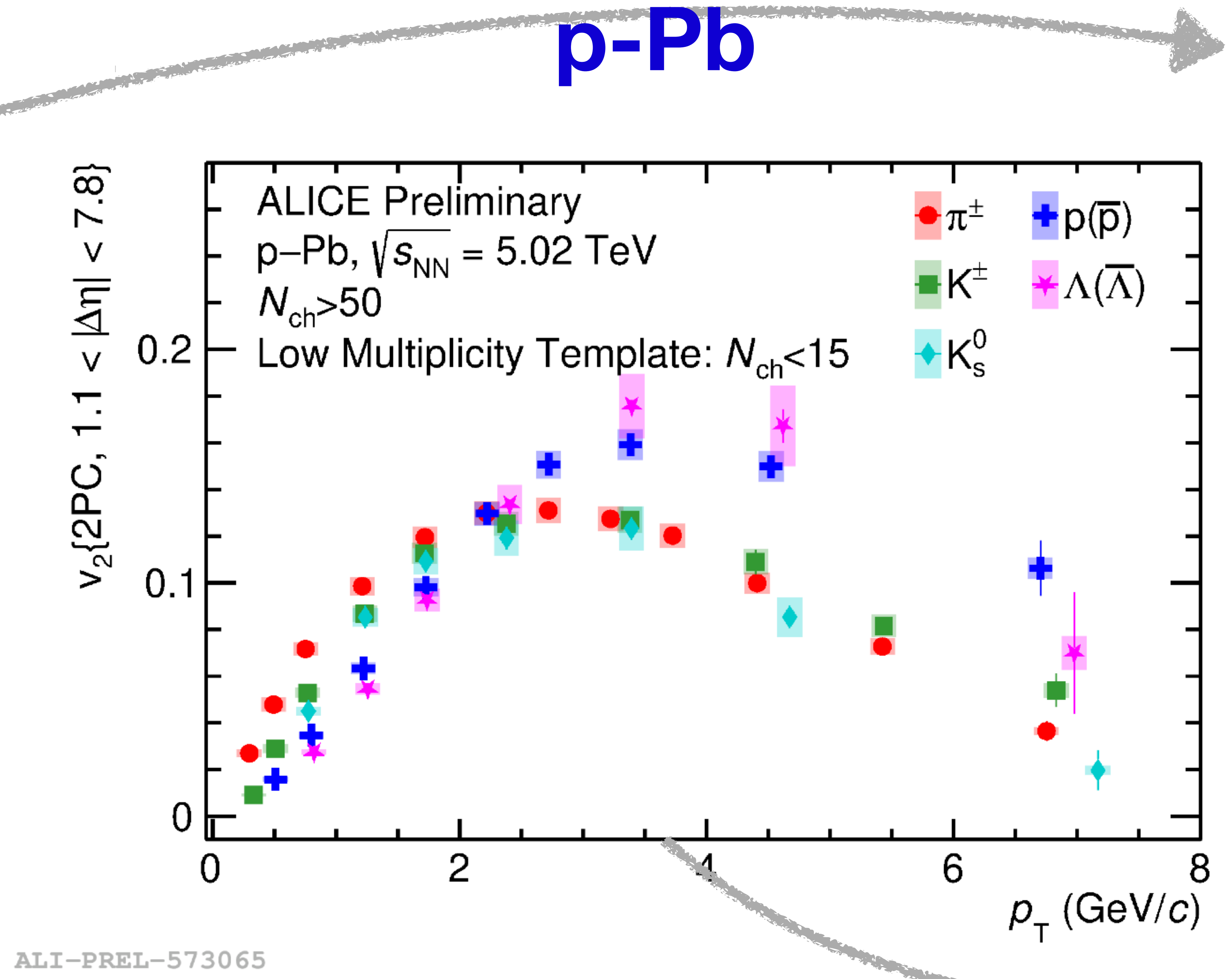


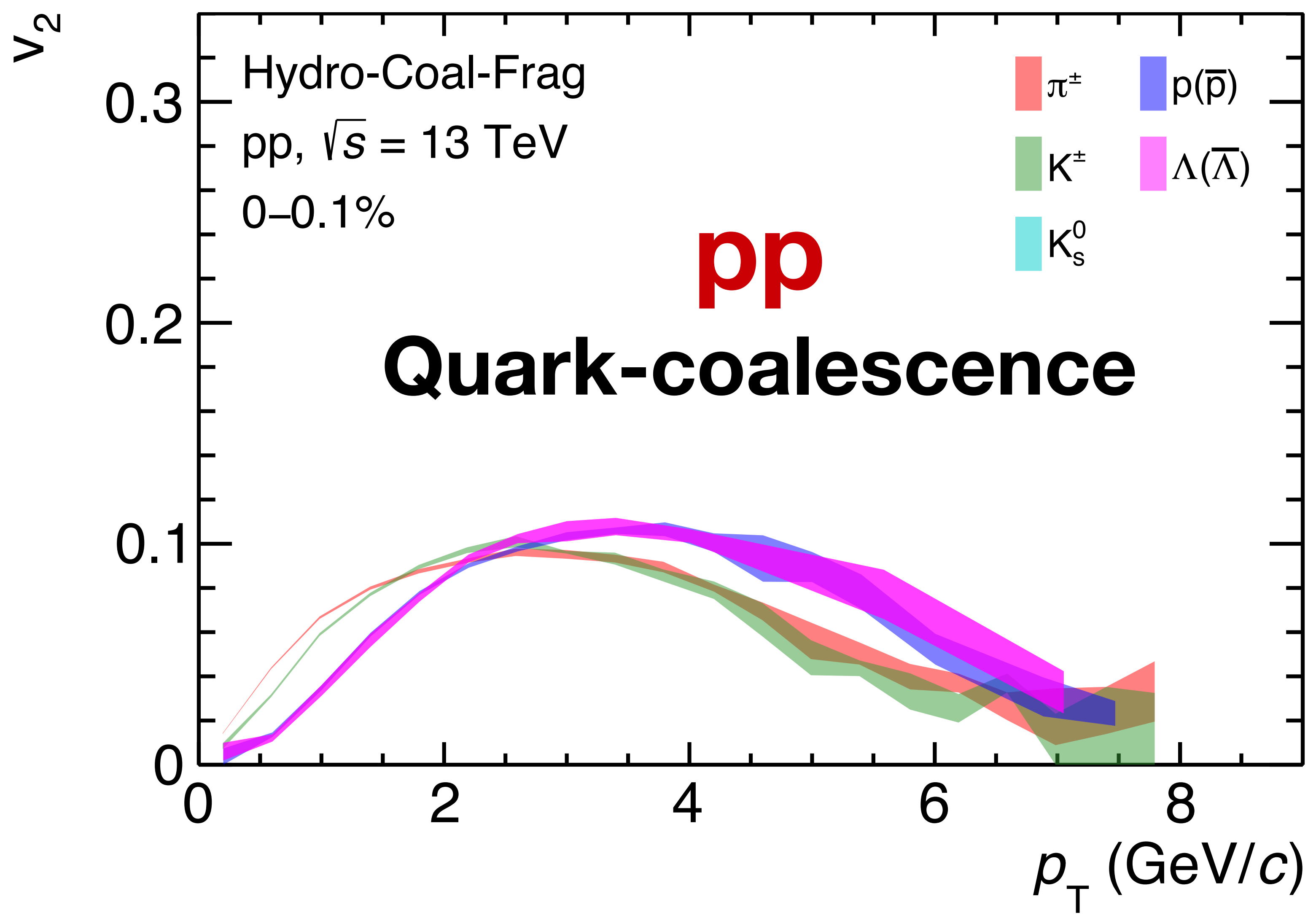
- Intermediate p_T ($3 < p_T < 6$ GeV/c): baryo

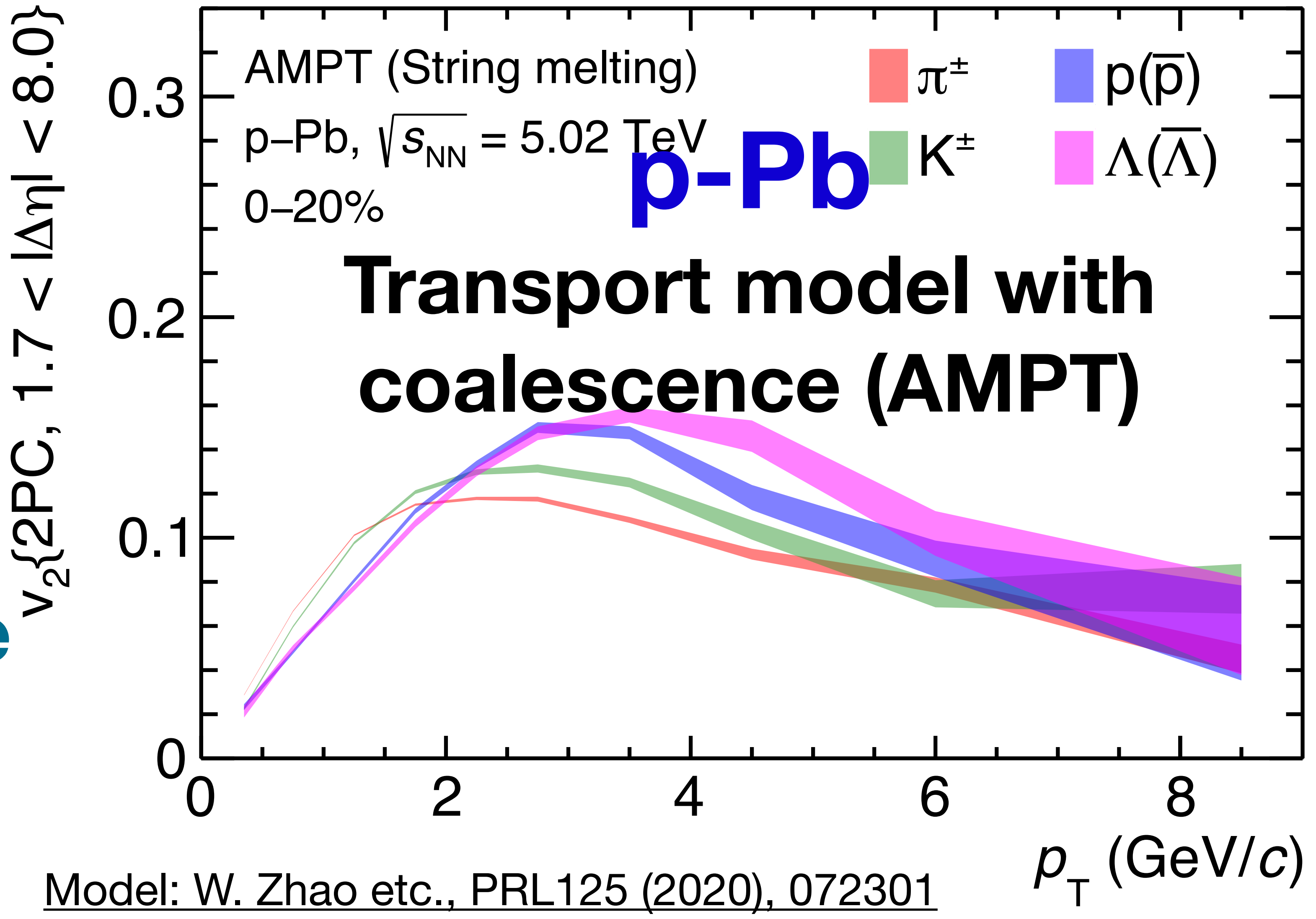
JHEP 03 (2024) 092

Elliptic flow in small systems: model comparisons









- With quark-coalescence in pp: successfully reproduces baryon/meson grouping and splitting
- In p-Pb, transport model with coalescence predicts only mass dependence

→ thorough investigations, including careful data and model comparisons, are needed to understand the underlying mechanism

Model: W. Zhao etc., PRL125 (2020), 072301
Y. Wang etc, arXiv:2401.00913
S. Tang etc, Nucl. Sci. Tech. 35 (2024) 32

Hadronization in vacuum, in medium

Fragmentation functions are phenomenological functions to parameterize the non-perturbative parton-to-hadron transition

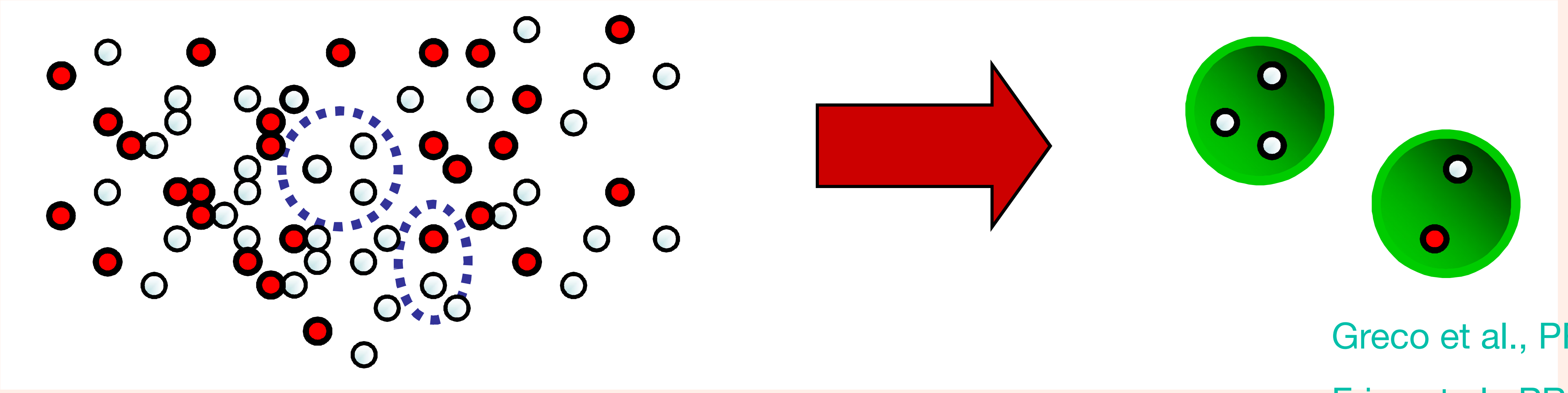
- Parametrized on data and assumed to be “universal”

In vacuum

Phase space at the hadronization is filled with partons:

- Single parton description may not be valid anymore
- Partons that are “close” to each other in phase space (position and momentum) can simply recombine into hadrons

In medium



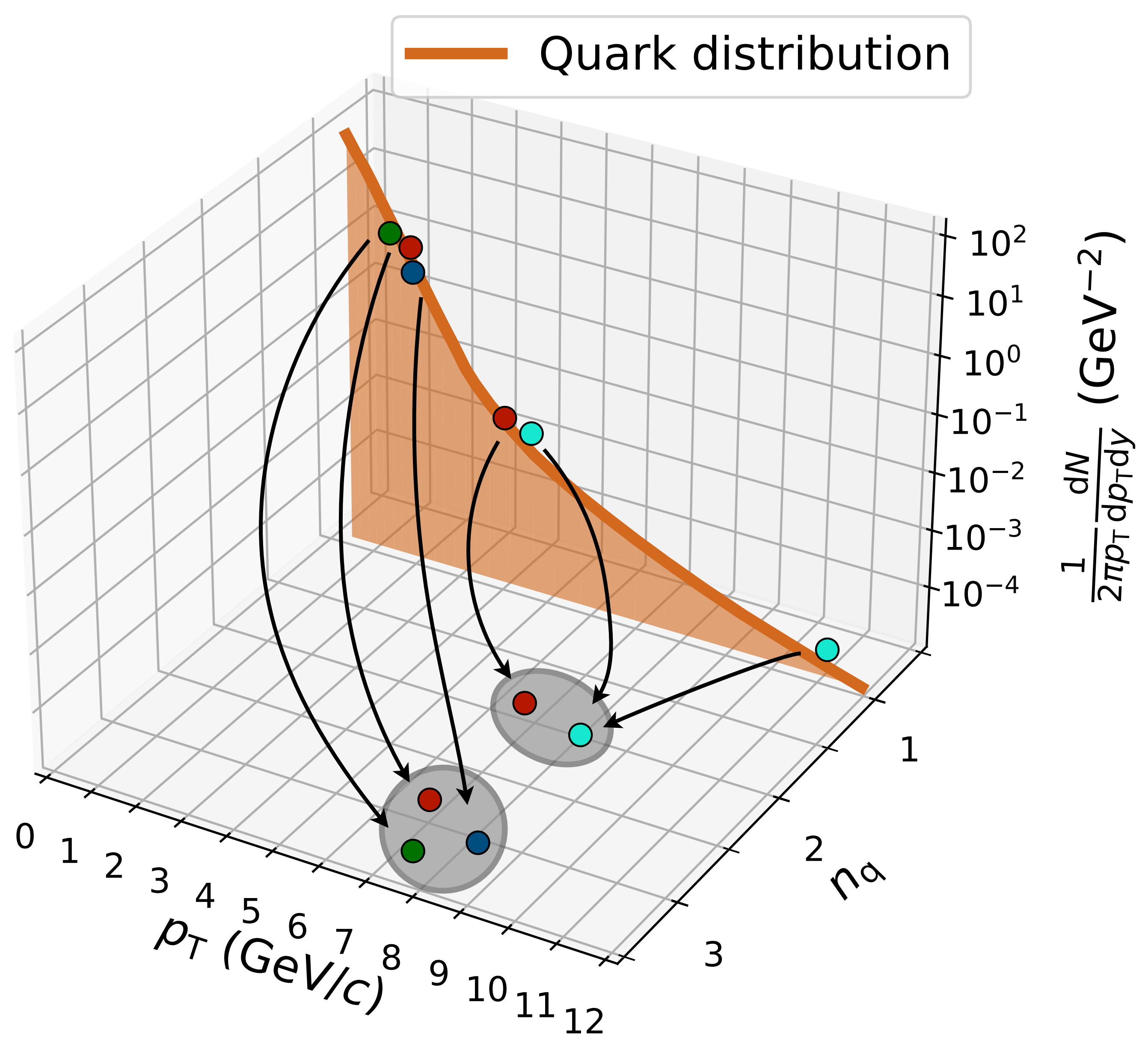
Greco et al., PRL 90 (2003) 202302

Fries et al., PRL 90 (2003) 202303

Hwa, Yang, PRC 67 (2003) 034902

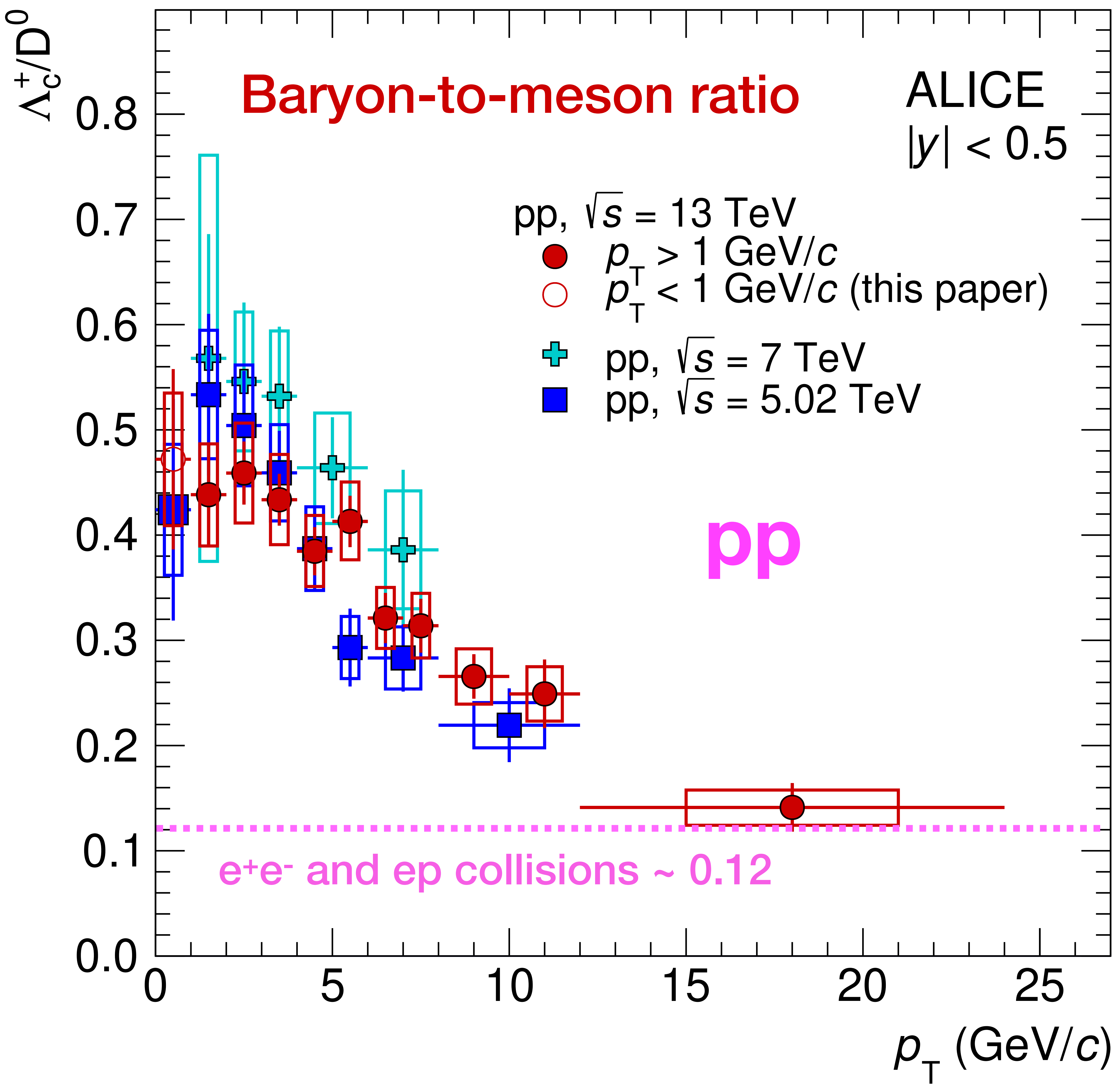
Recombination vs. fragmentation:

- Competing mechanisms
- Recombination naturally enhances baryon/meson ratios at intermediate p_T



Charm baryon vs. meson production in pp

JHEP 12 (2023) 086



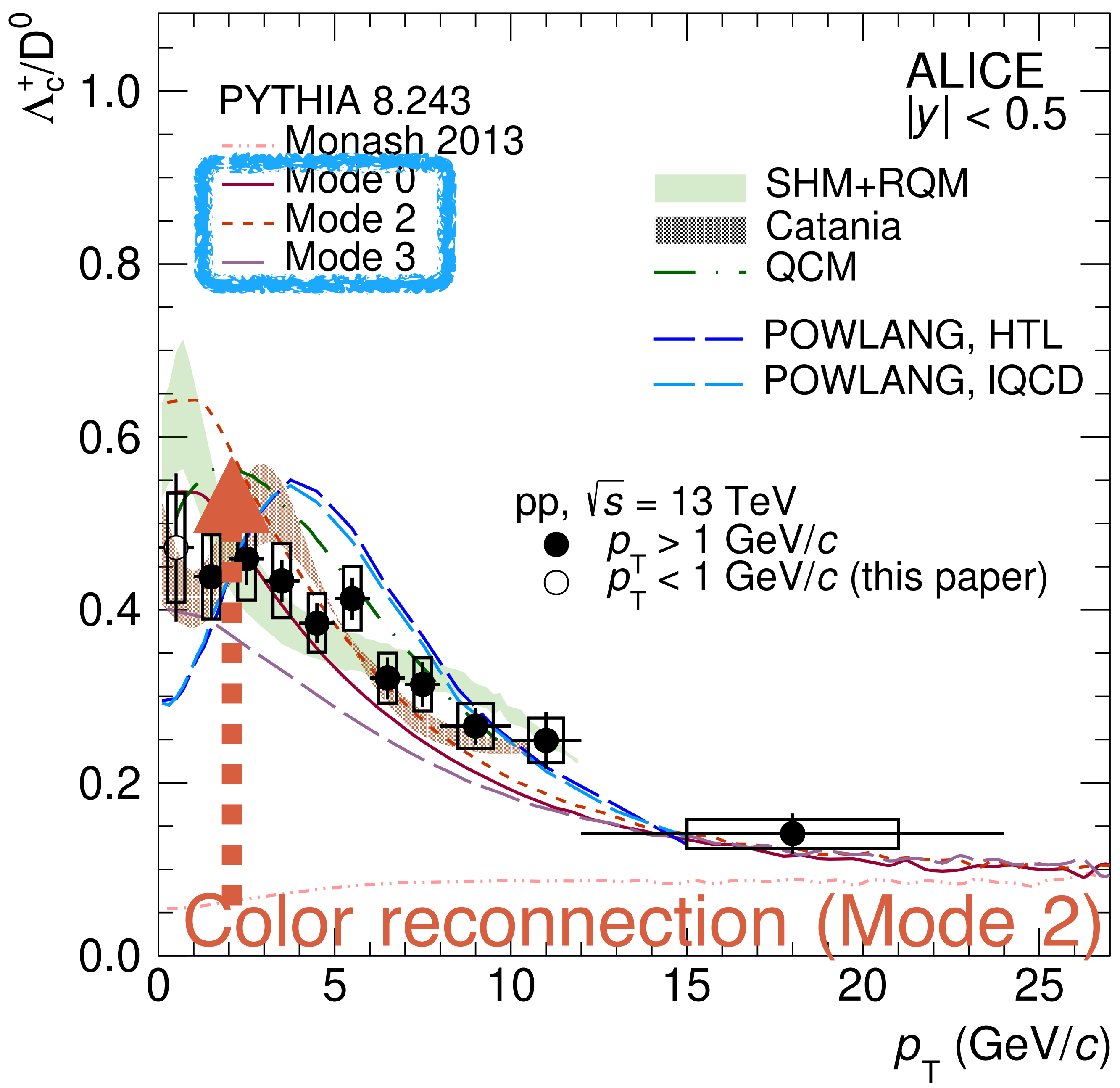
- Strong p_T dependence in charm sector
- Enhancement compared to the measurement in e^+e^- and e^-p collisions

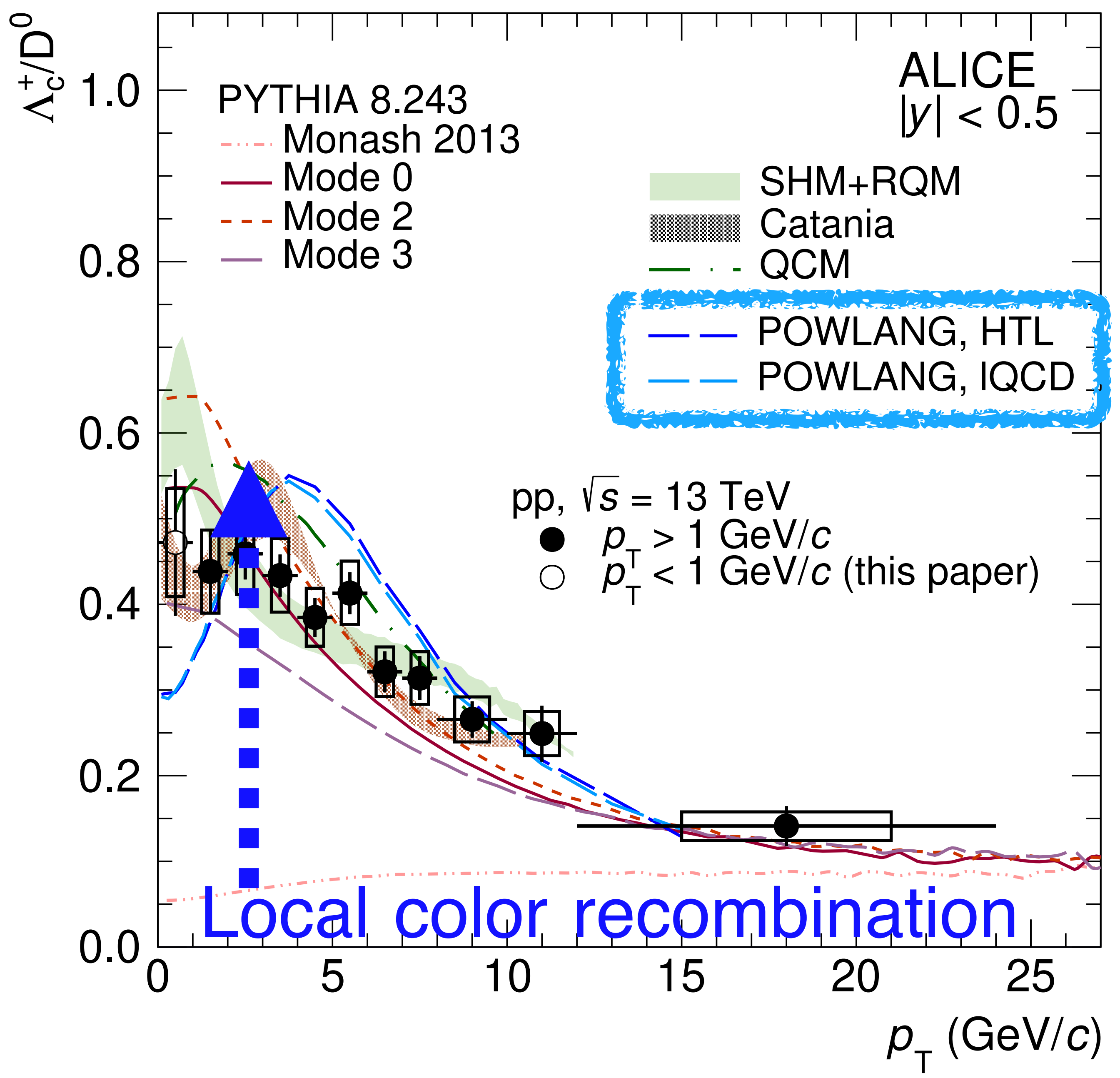
Naive expectation:

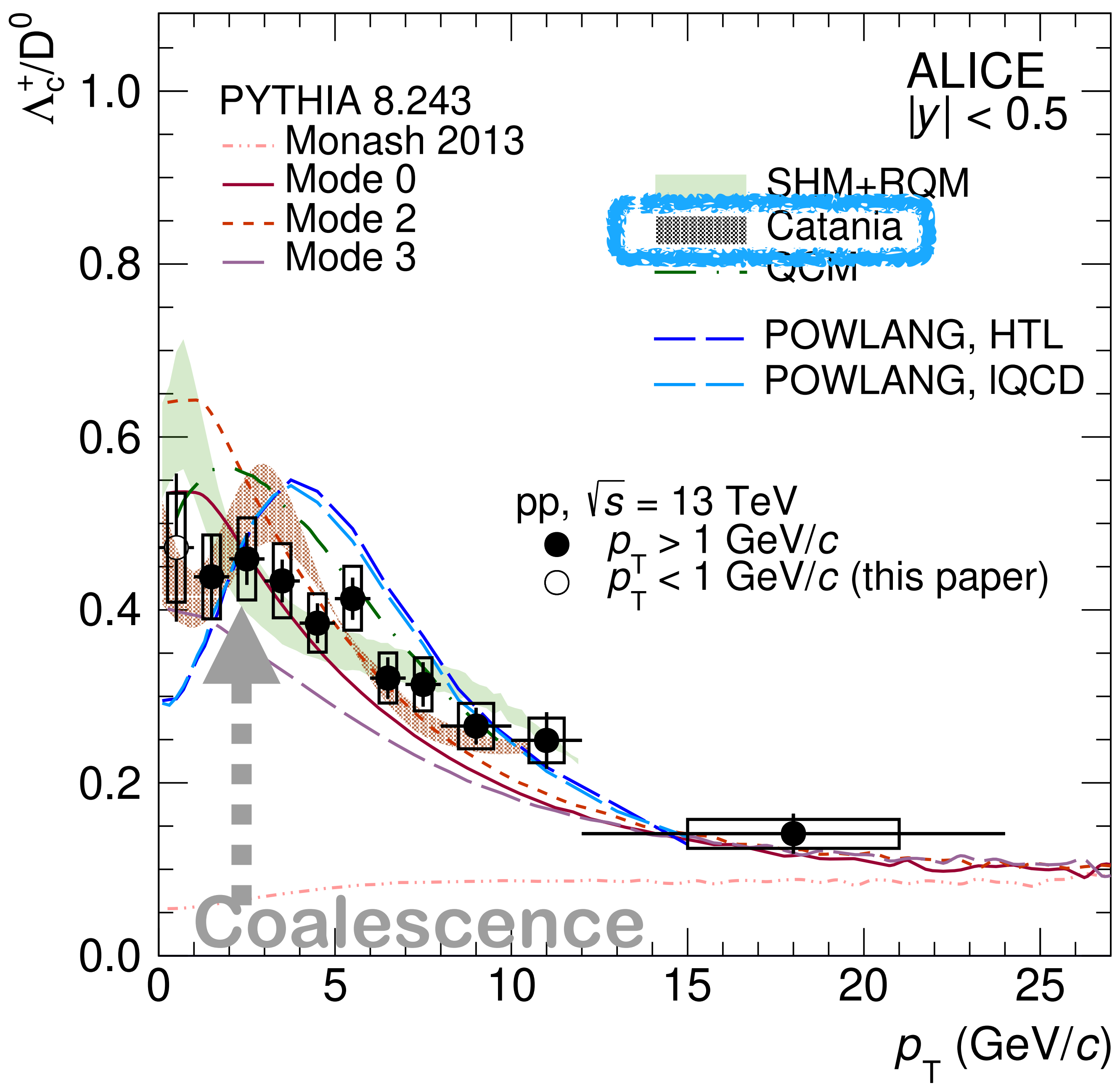
ratios of particle-species yields independent from collision system

How do we explain in the charm sector

- 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)

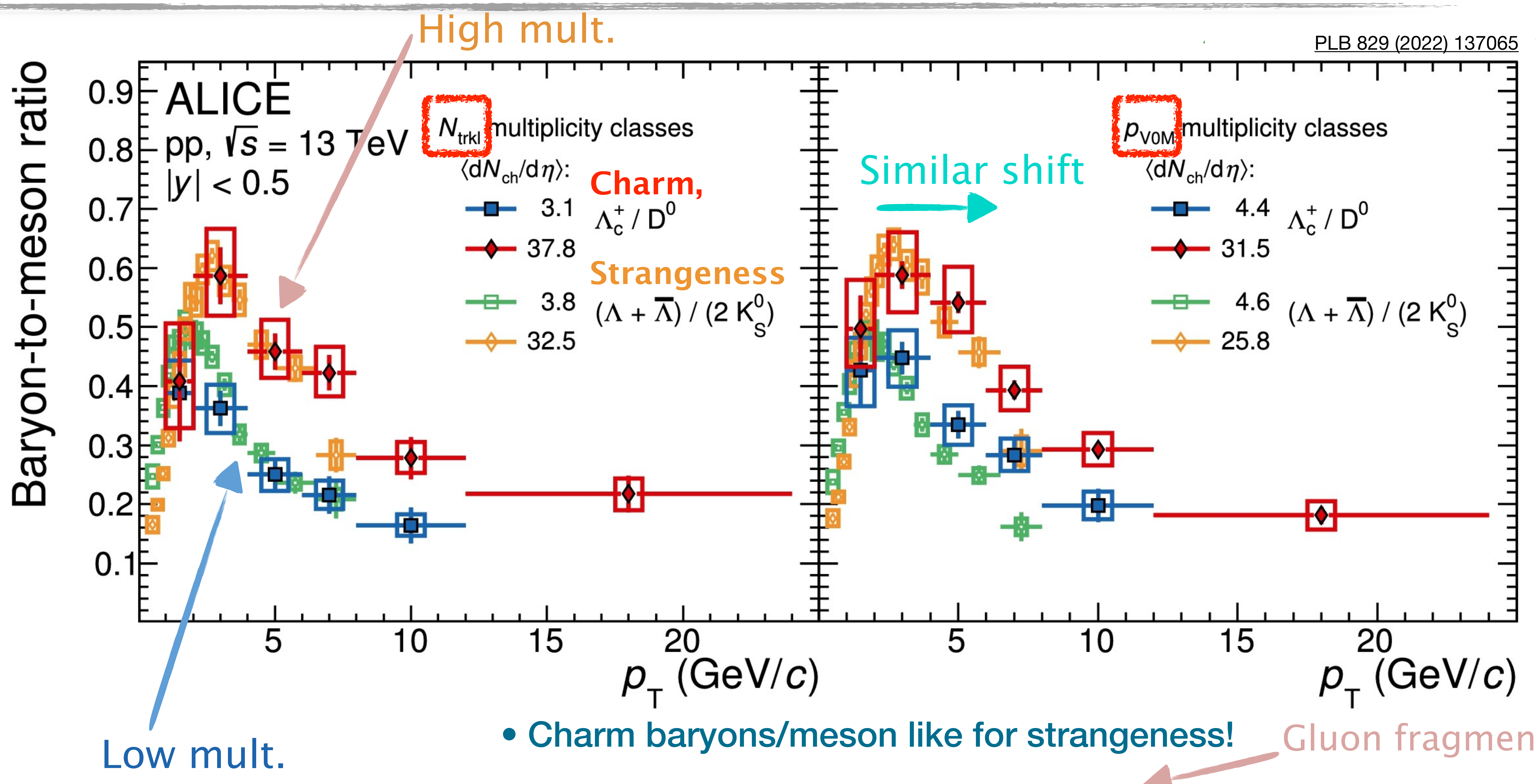






- Different hadronization mechanisms proposed!
- Similar to the light flavor sector?

Charm vs. light baryon-to-meson ratio



pp

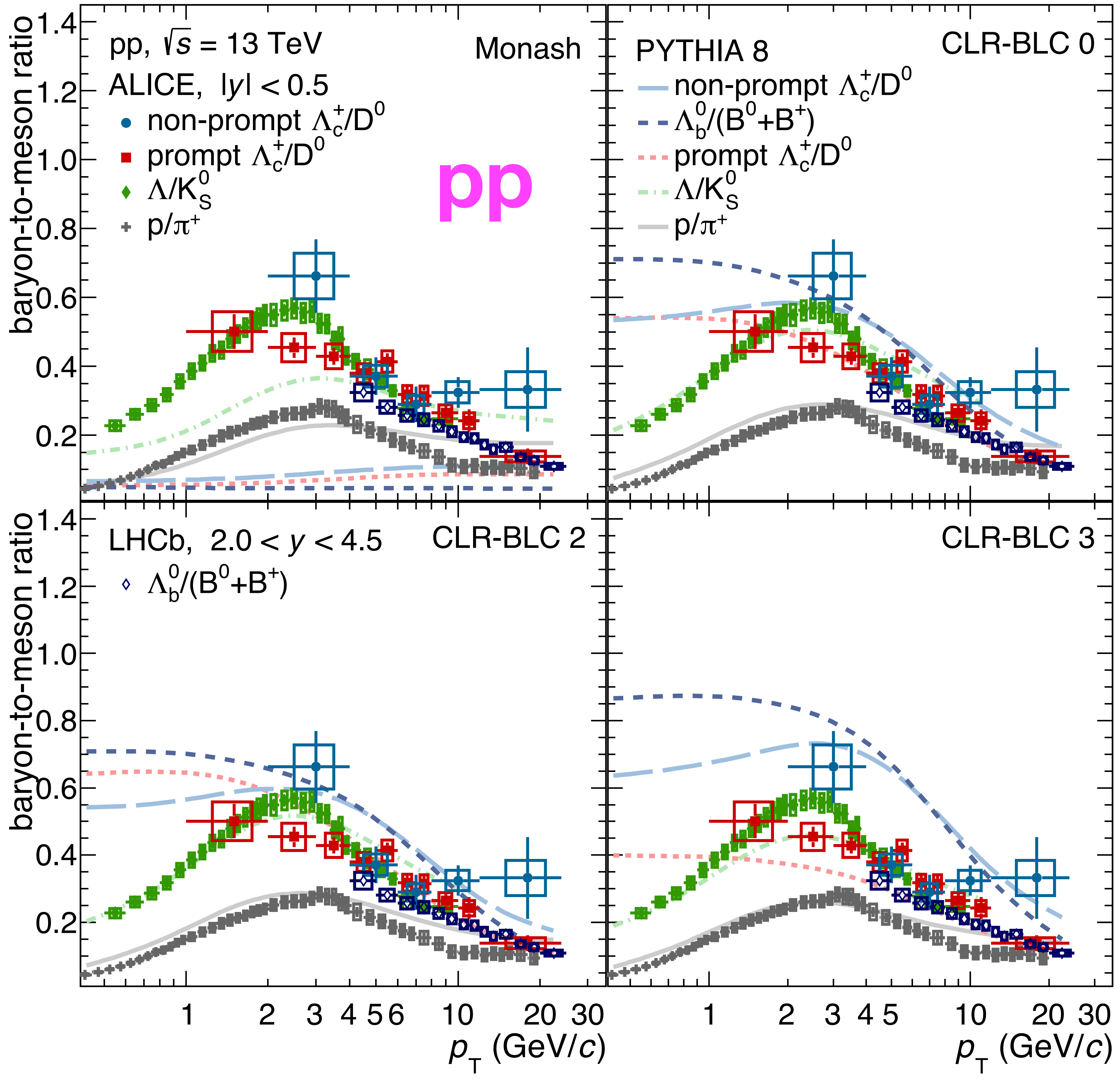
- Charm baryons/meson like for strangeness!
- Hint at a common mechanism for light- and charm-baryon formation in hadronic collisions at LHC energies.

Gluon fragmentation…

Charm quark fragmentation…

Baryon-to-meson ratios of different flavors

Phys. Rev. D 108, 112003 (2023)



- All the measurements for beauty, charm, and strange hadrons show a similar trend as a function of p_T and are compatible within the uncertainties

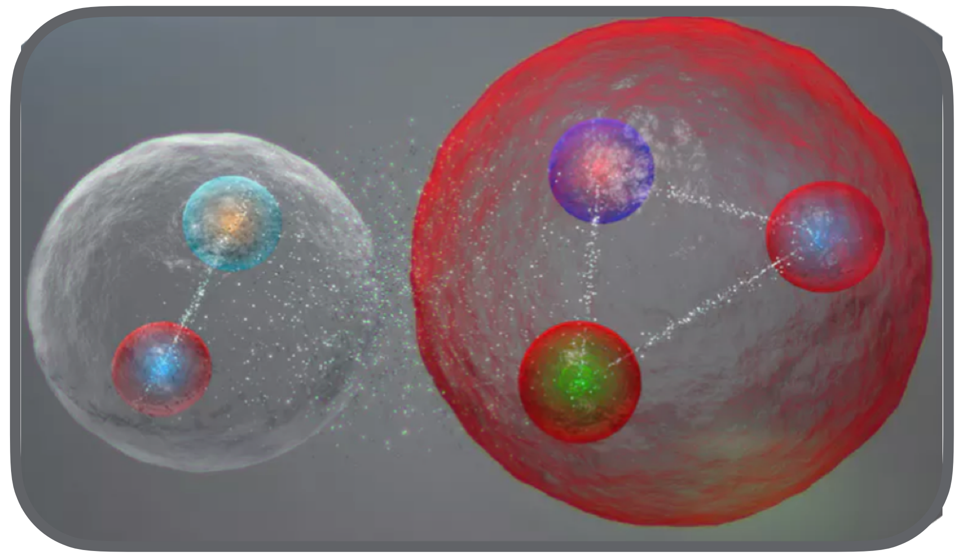
→ Similar baryon-formation mechanism among light, strange, charm and beauty hadrons?

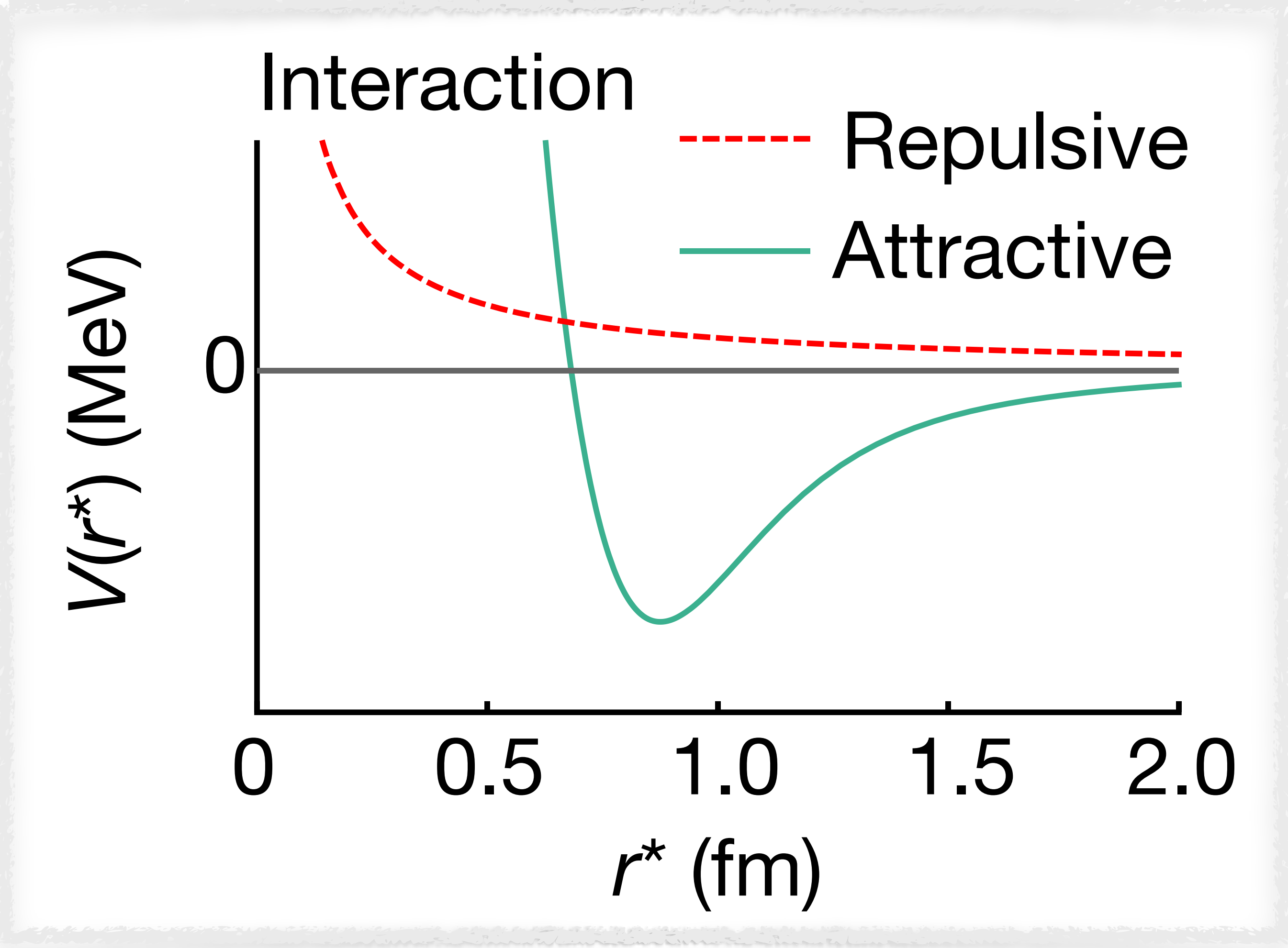
- non-prompt Λ_c^+/D^0
- prompt Λ_c^+/D^0
- Λ/K^0_S
- p/π^+
- $\Lambda_b^0/(B^0+B^+)$

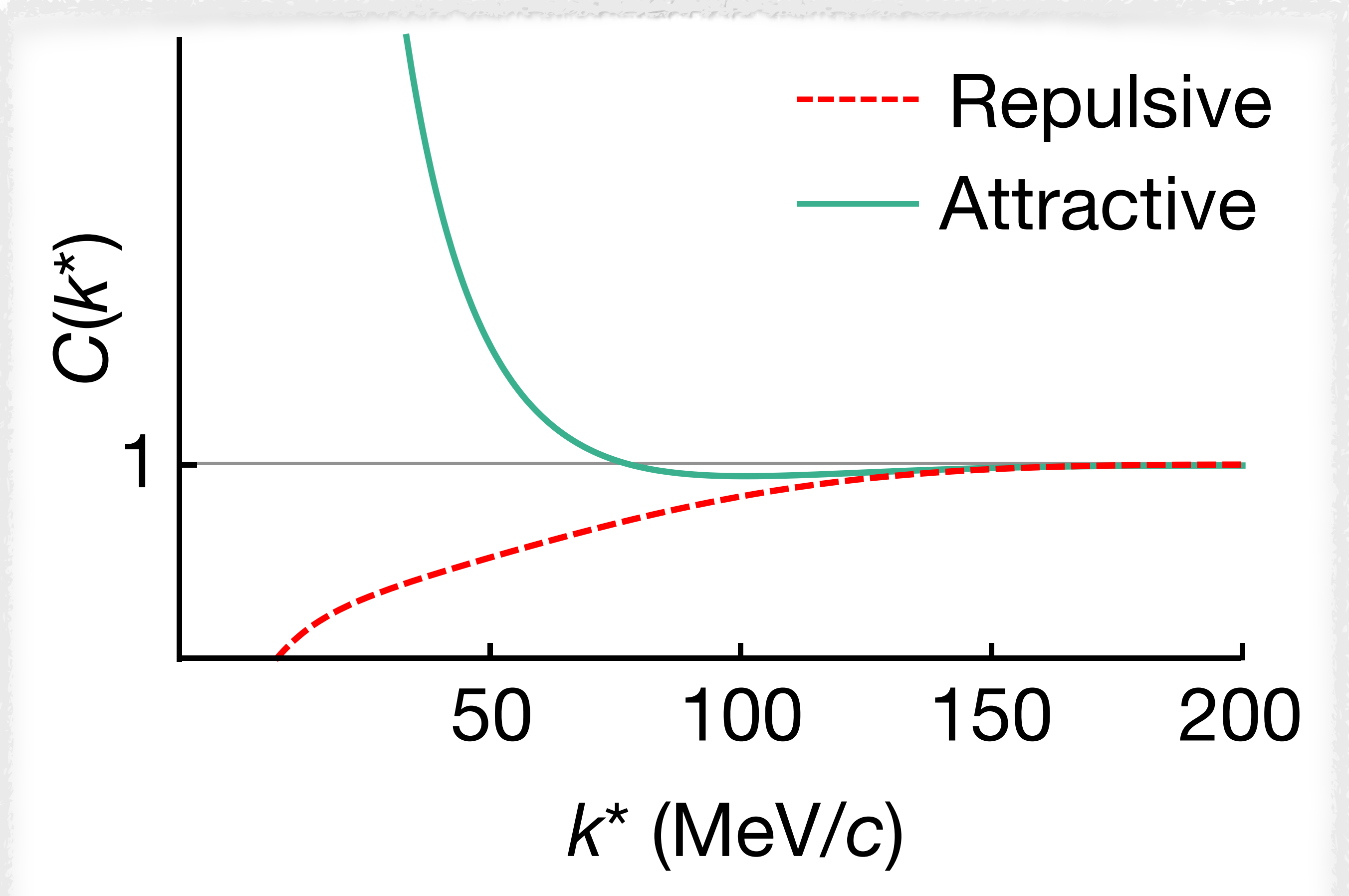
Note: for LHCb, different normalization & should consider decay kinematics (for the other case)
* These three tunes are characterized by different constraints on the time dilation and causality

Measuring hadron interaction potentials via correlations

What we want to know: The interaction between hadrons at the 1 fm scale.

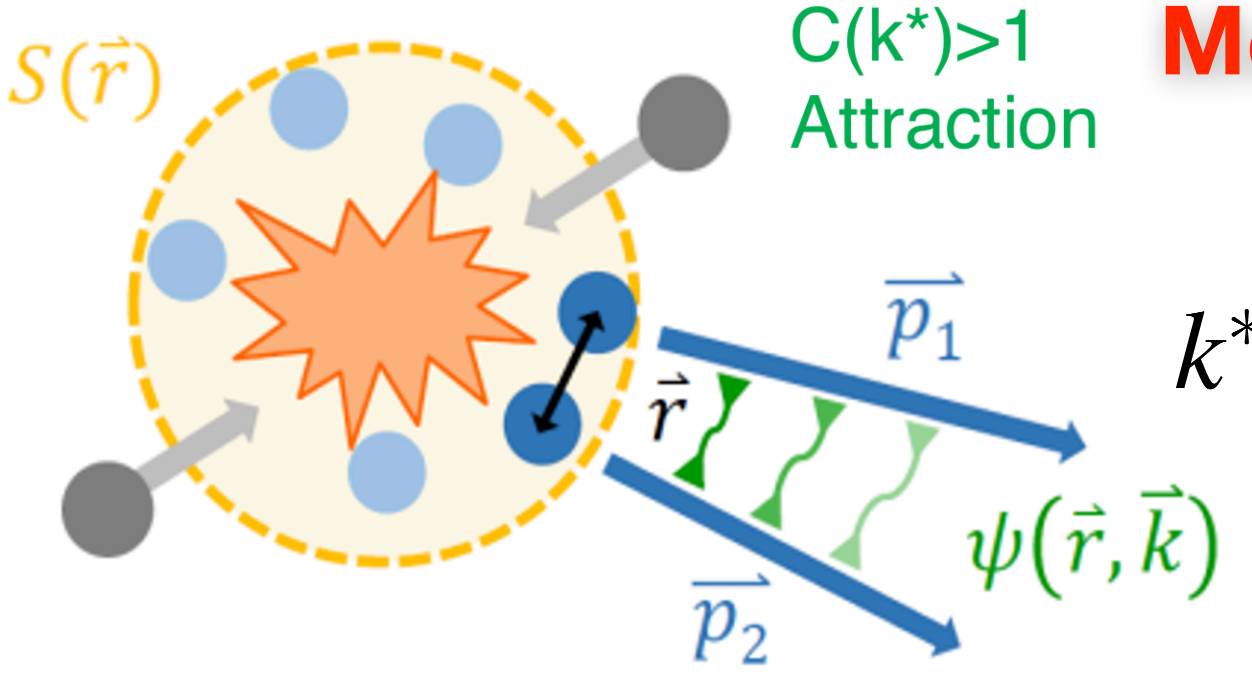






Correlation function

Generally, through the scattering of two particles...



Momentum correlations of low-k pairs

$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$

p* : p in the pair rest frame

$$C(k^*) = \int S(r^*) |\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^3 r^*$$

$$C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Correlation function depends on source distribution and interaction potential:

Gives access hadron-interaction potentials of unstable hadrons

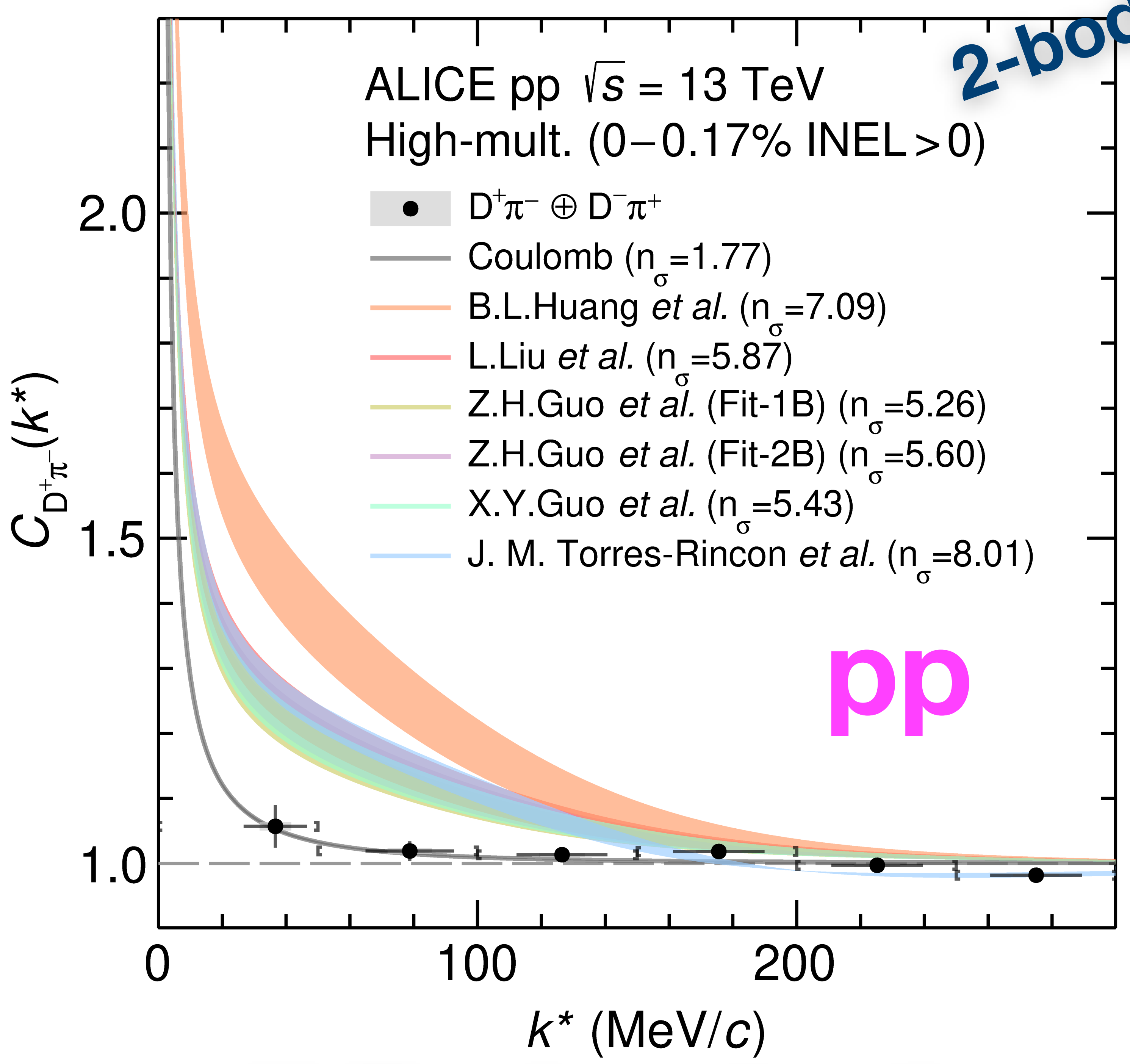
→ Connections to hadron and nuclear physics

Femtoscopy: two, three-body interactions

2-body interaction

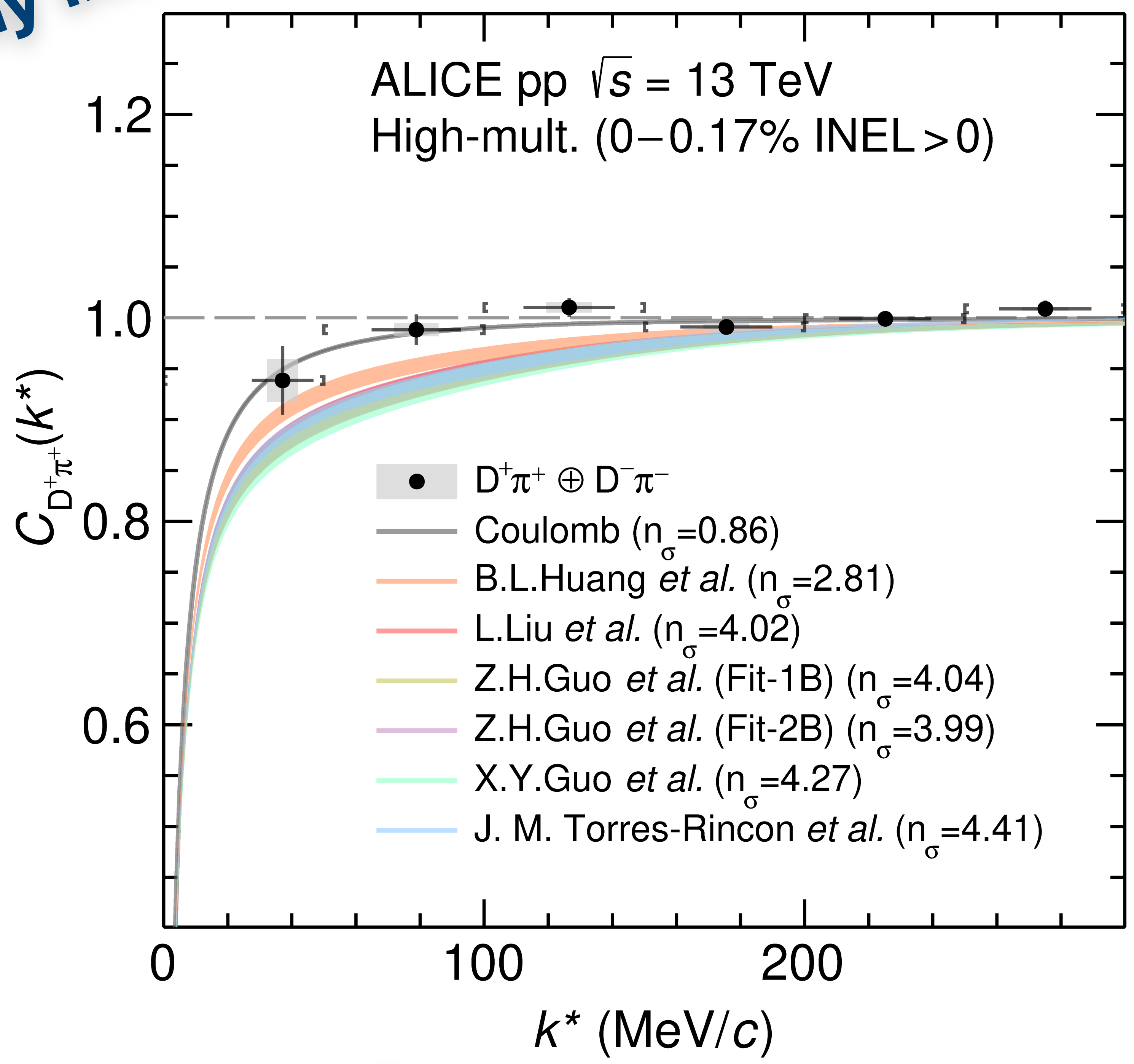
$D^+\pi^-$ + $D^-\pi^+$

arXiv:2401.13541



Unlike sign: attractive

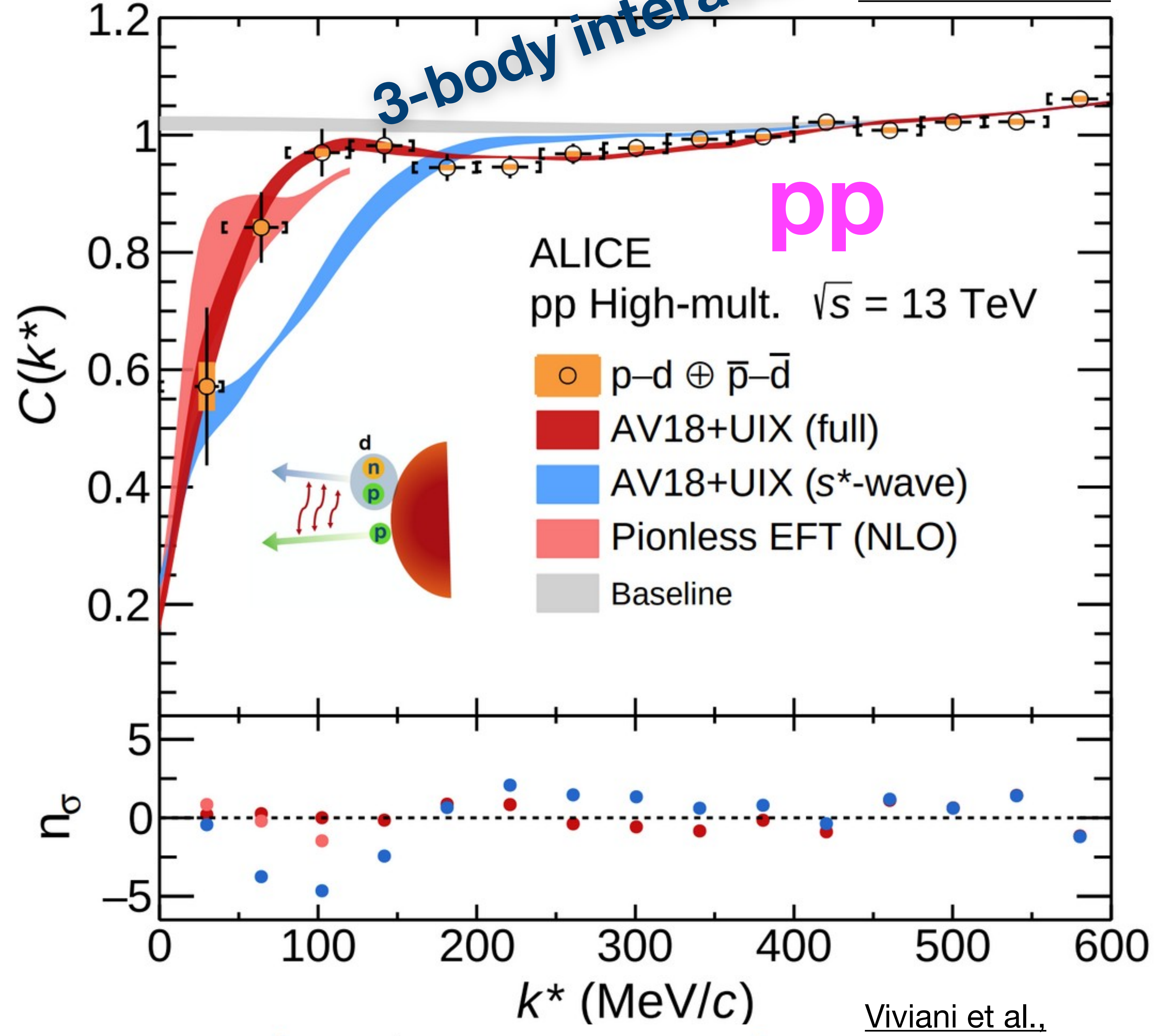
$D^-\pi^-$ + $D^+\pi^+$



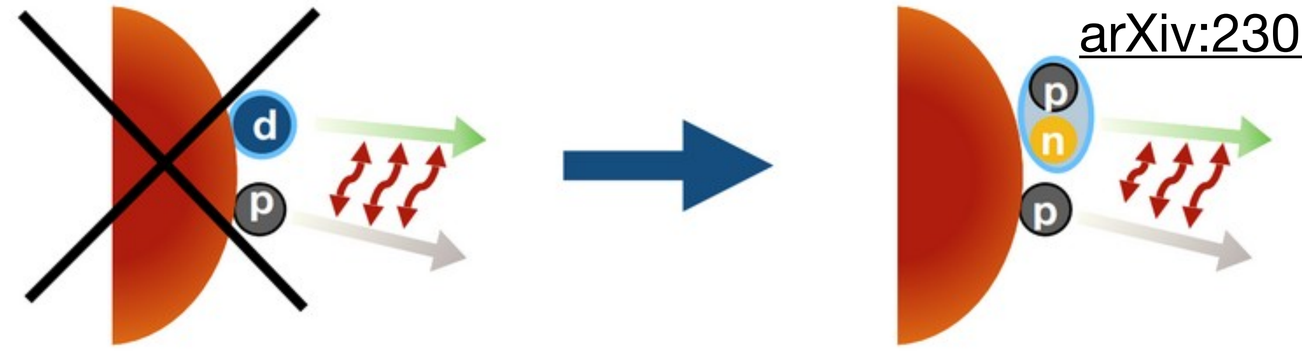
Like sign: repulsive

3-body interaction

arXiv:2308.16120



Viviani et al., arXiv:2306.02478v1

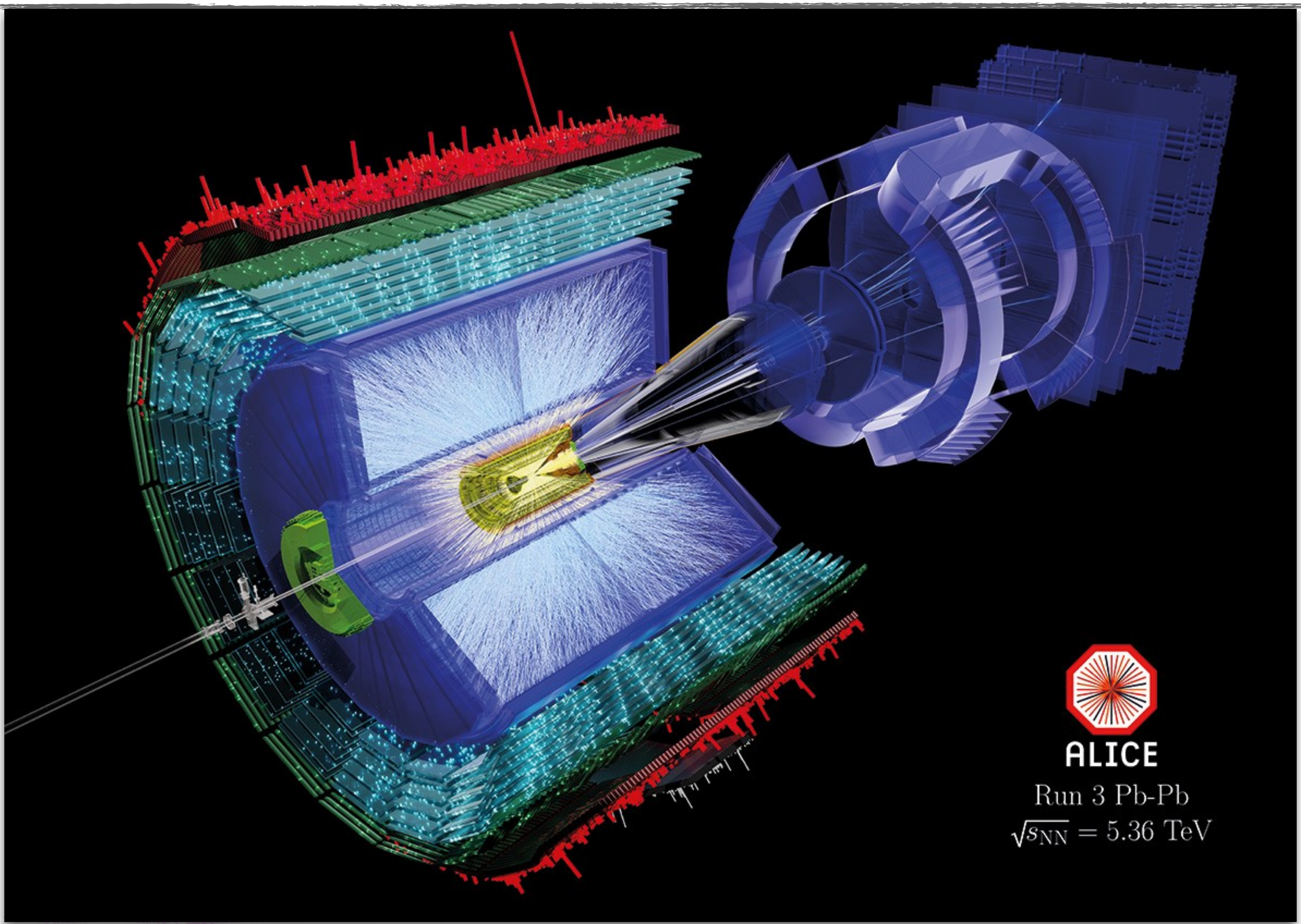


- Coulomb interaction dominates: limited contribution from strong interactions
- Lattice-based theory calculations predict stronger interactions

Wioleta Rzesa, Monday 14:30

- Only a full three-body calculation that accounts for the internal structure of the deuteron can explain the data

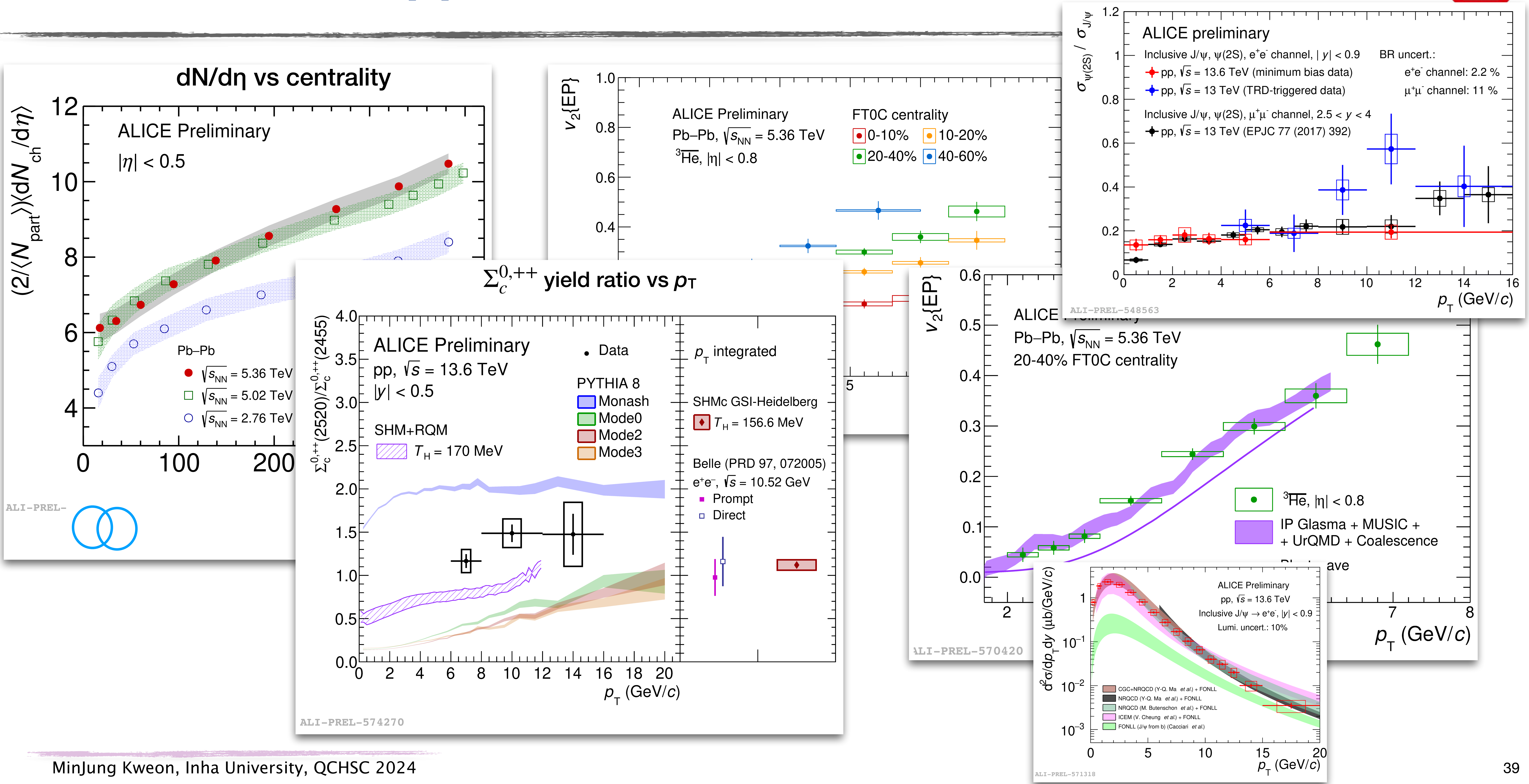
ALICE in Run 3 (ongoing)



- Major upgrades installed in 2019- 2021
- In production since 2022
- 50x increase in readout rate
- 3 to 6x improvement in pointing resolution
- Secondary vertexing for forward muons

ALICE upgrades: arXiv:2302.01238
ITS: NIM 1032(2022)166632
TPC: JINST 16 P03022 (2021)
MFT: CDS link
FIT: NIM 1039 (2022) 167021

Run 3 results in pp and Pb–Pb collisions, more to come



Summary

- Through a wide range of collision systems and energies, ALICE provides crucial insights into the behavior of QGP, particle-production mechanisms, and the strong interaction at unprecedented energy scales.

- Key results from Run 1, Run 2 highlight the experiment's contributions to understanding the early universe and the fundamental forces governing hadronic matter

- With the ongoing Run 3, we anticipate acquiring even more detailed information, further enhancing our understanding of the early universe and the fundamental forces that govern hadronic matter.

⇨ Stay tuned!

Future for Heavy Ions & ALICE 3
Dieter Roehrich, Tursday 14:30

ALICE pp 13.6 TeV
Period LHC22m, Run 523308
14th August 2022

Thank you for your attention!

Extra Slides

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)

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

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

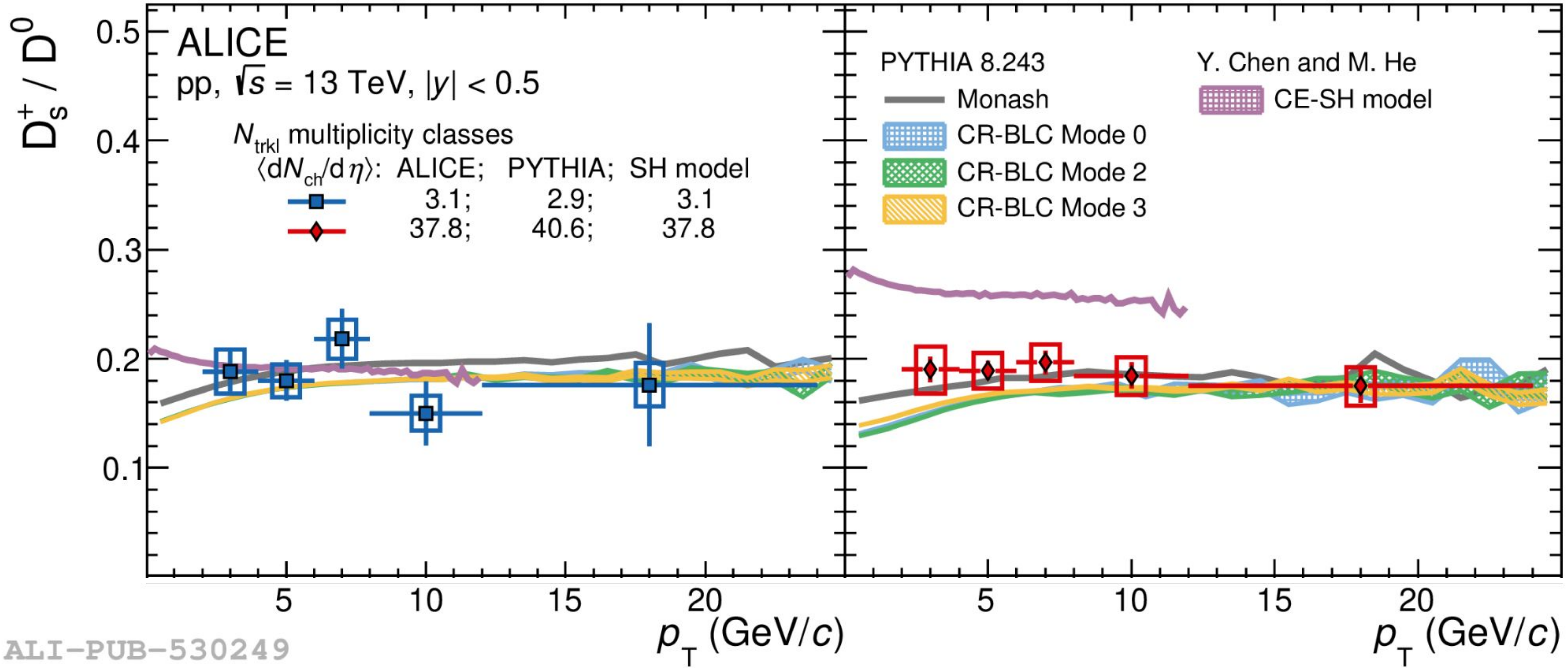
$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3}\; f_q(x_i, p_i)\; f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\; \delta(p_T - \sum_i p_{iT})$$

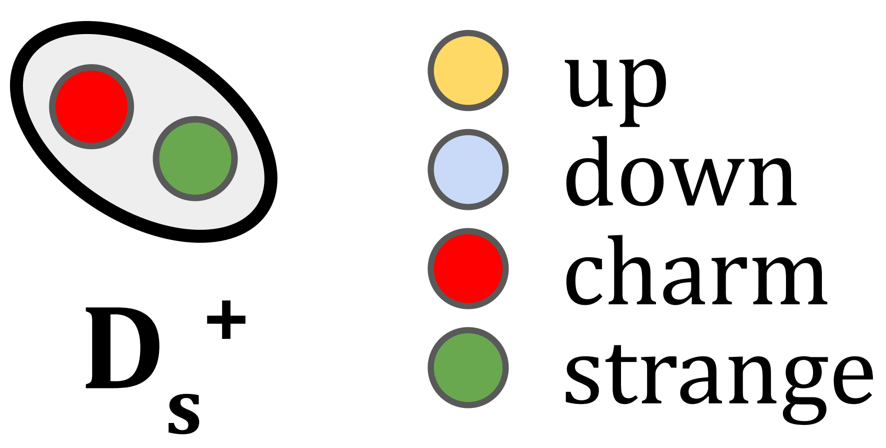
Have described first AA observations in light sector for the enhanced baryon/meson ratio and elliptic flow splitting

- **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

D_s^+: strange charm meson

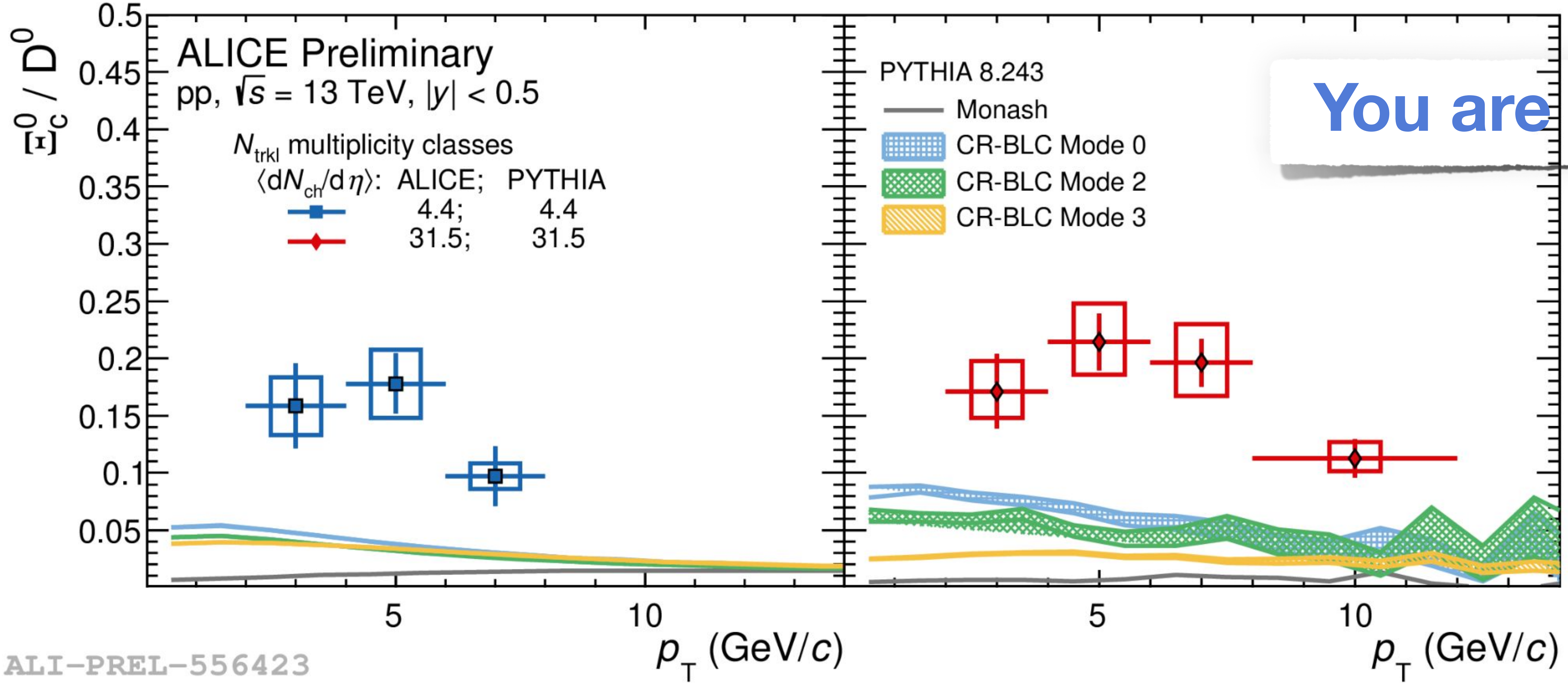
Phys.Lett.B 829 (2022) 137065

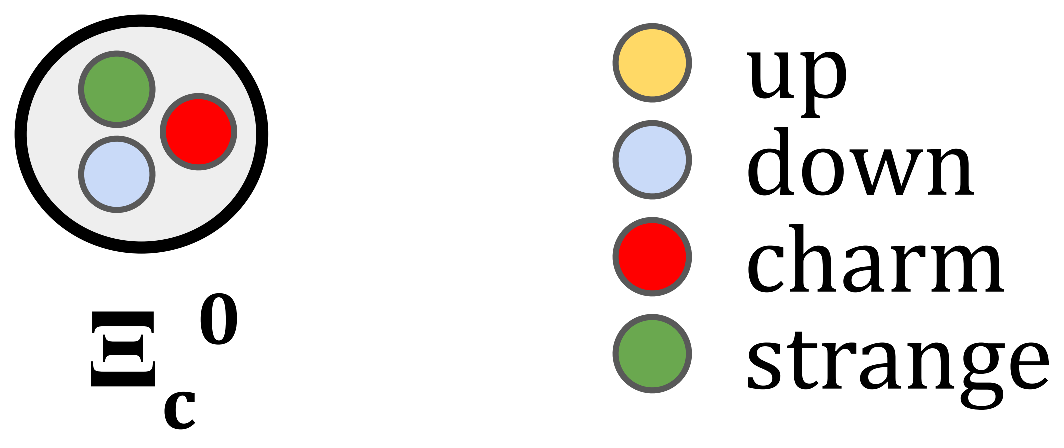




- D_s^+/D^0 ratio are independent of p_T
- No strong multiplicity dependency
- Comparable with measurement at e^+e^- and e^-p collisions

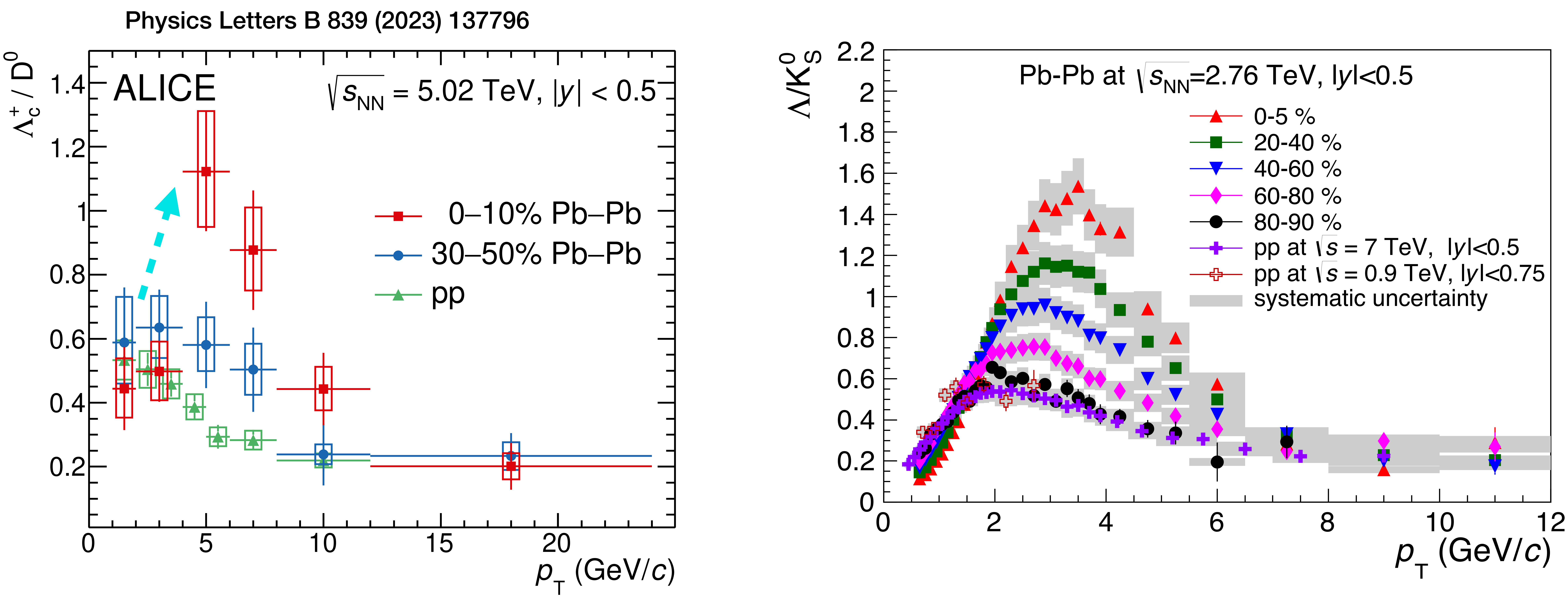
What about strangeness charm baryon?





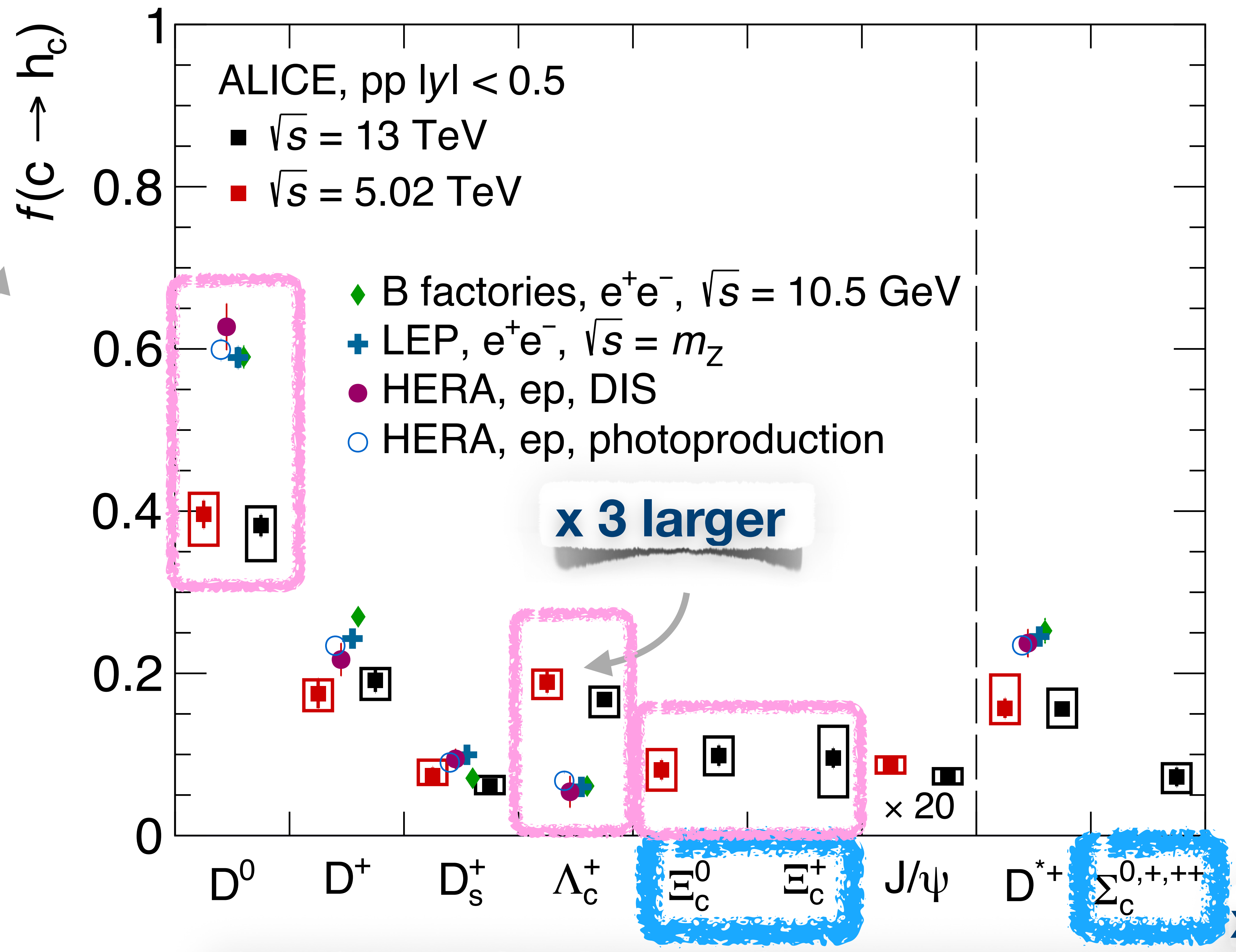
- Strong p_T dependence
- Enhancement compared to the measurement in e^+e^- and e^-p collisions

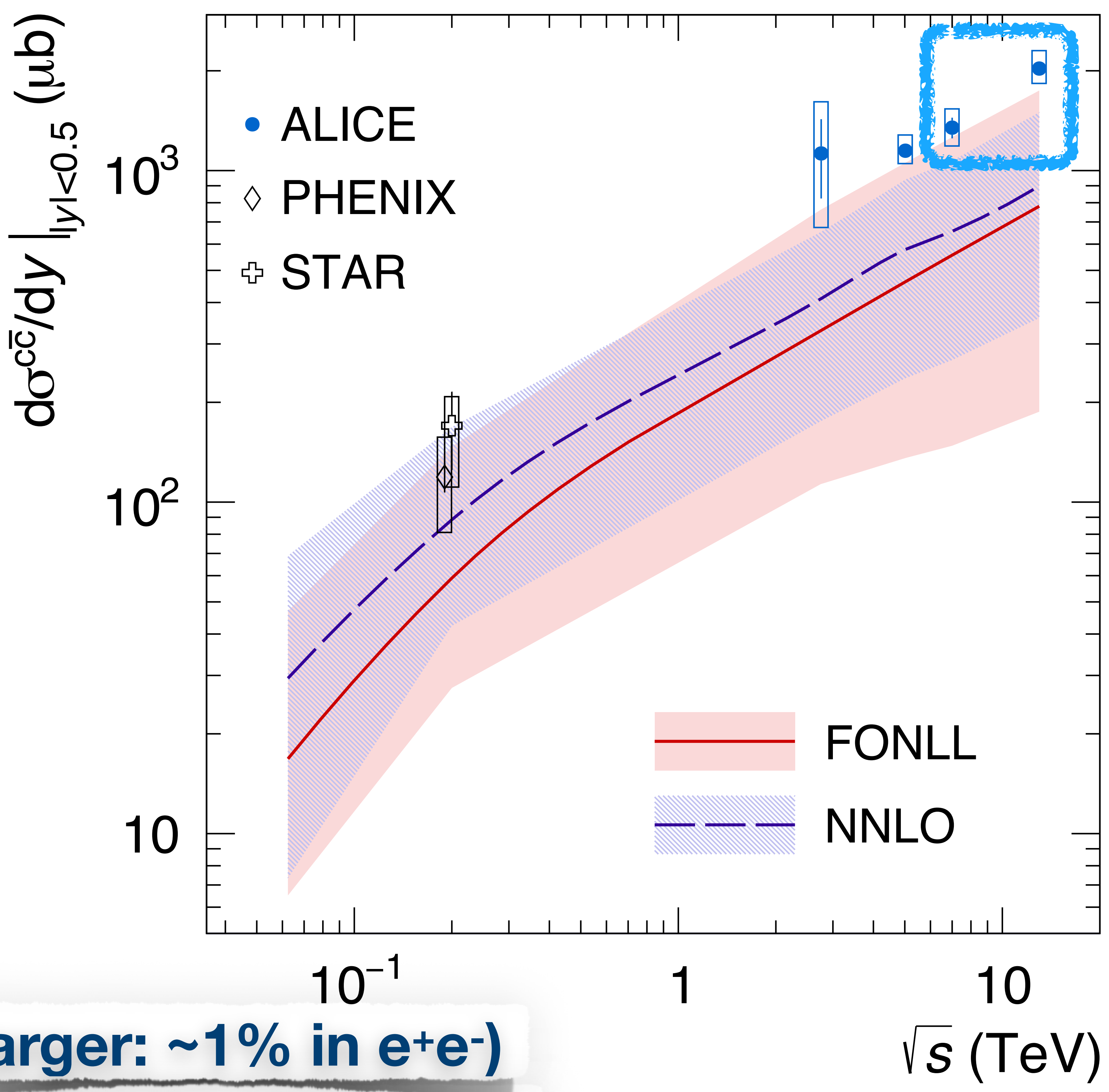
How about in Pb–Pb?



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

Charm-quark fragmentation fraction





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

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

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

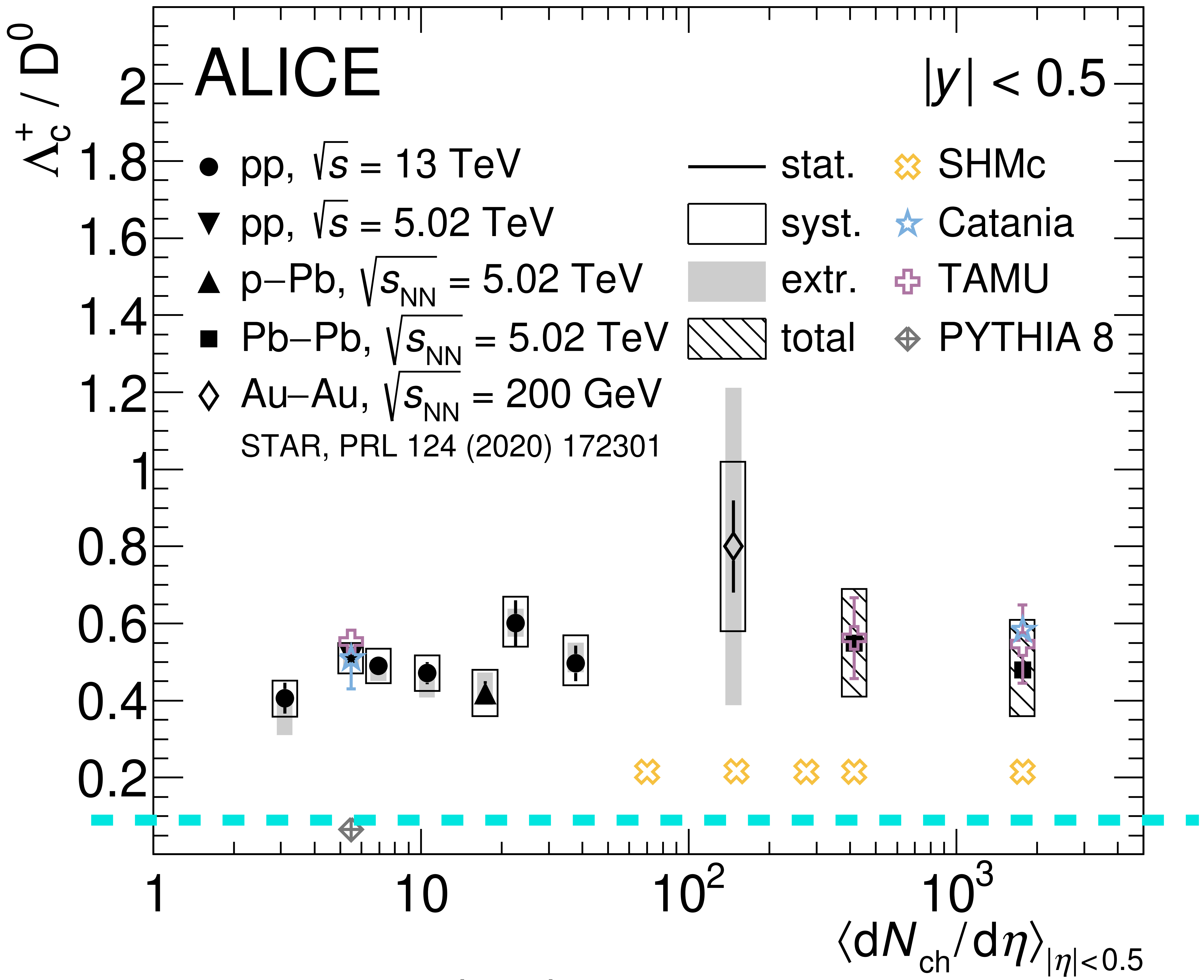
Σ_c^0: Larger feed-down to Λ_c^+ (40%, 17% in e^+e^-)

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^+

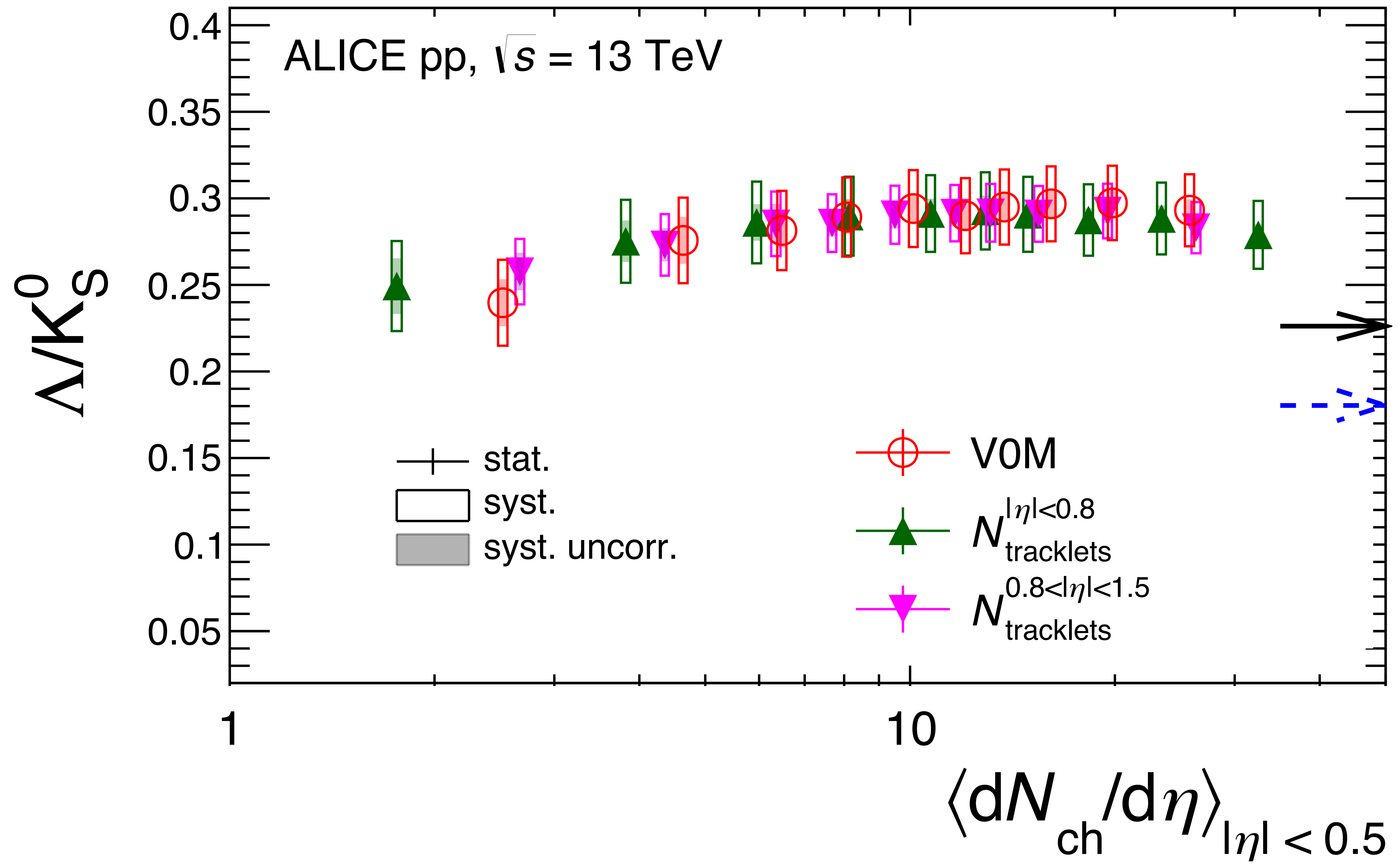
Conclusion: baryon enhancement at the LHC with respect to e^+e^- collisions is caused by different hadronisation mechanisms at play in the parton-rich environment produced in pp collisions

Where does the p_T differential enhancement come from?

p_T–integrated and to $p_T > 0$ extrapolated Λ_c^+/D^0 ratios



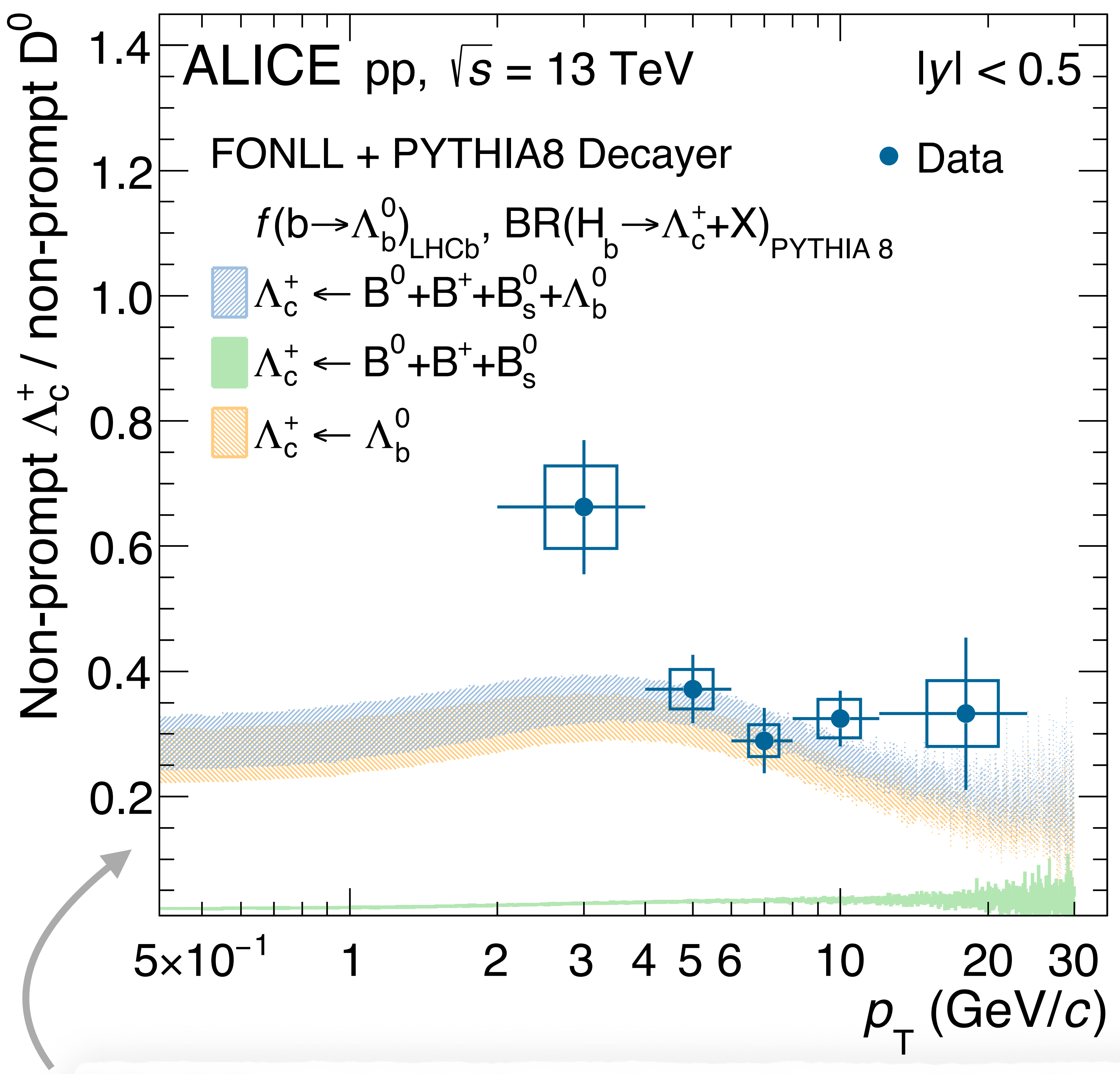
Physics Letters B 839 (2023) 137796

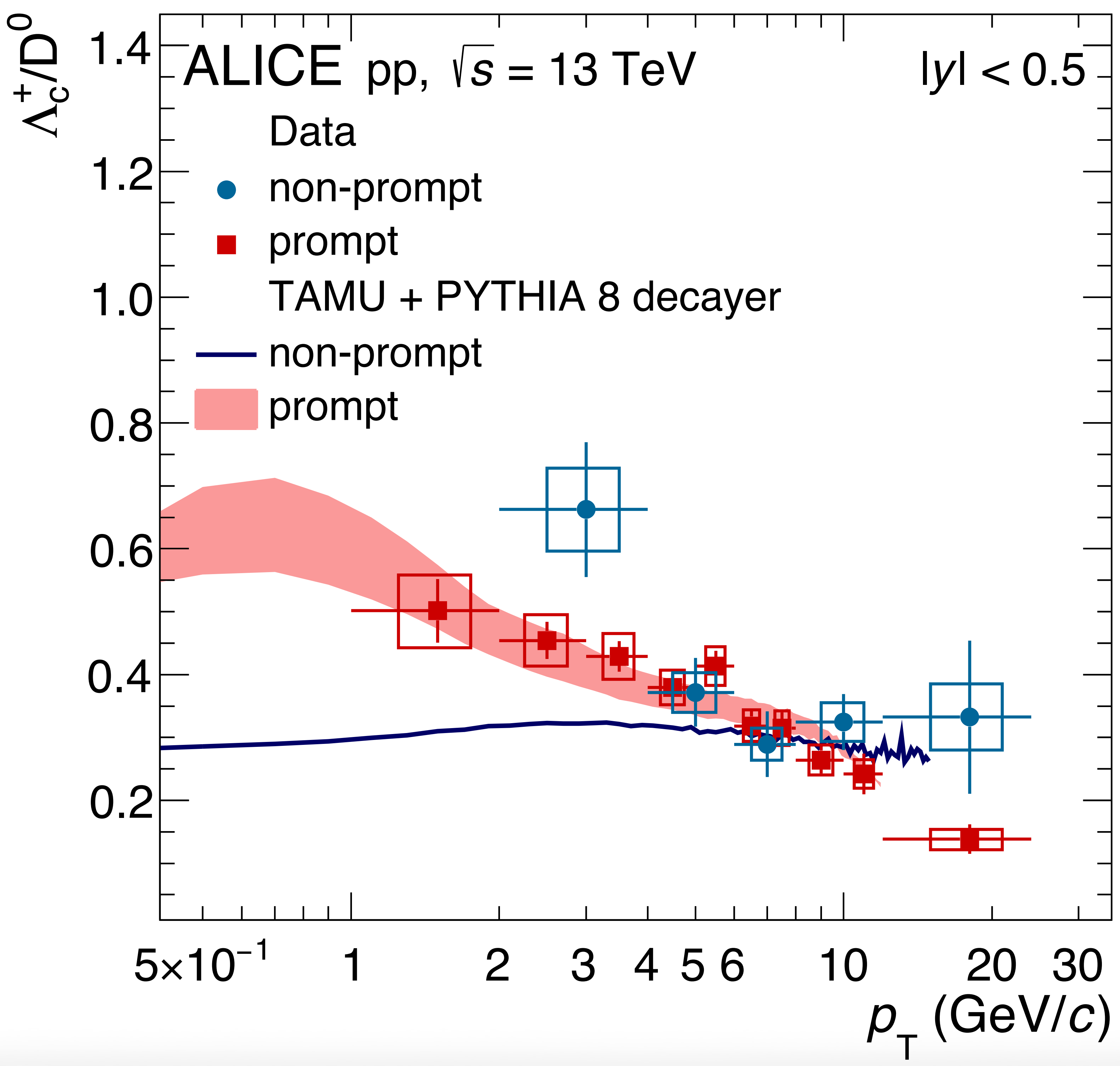


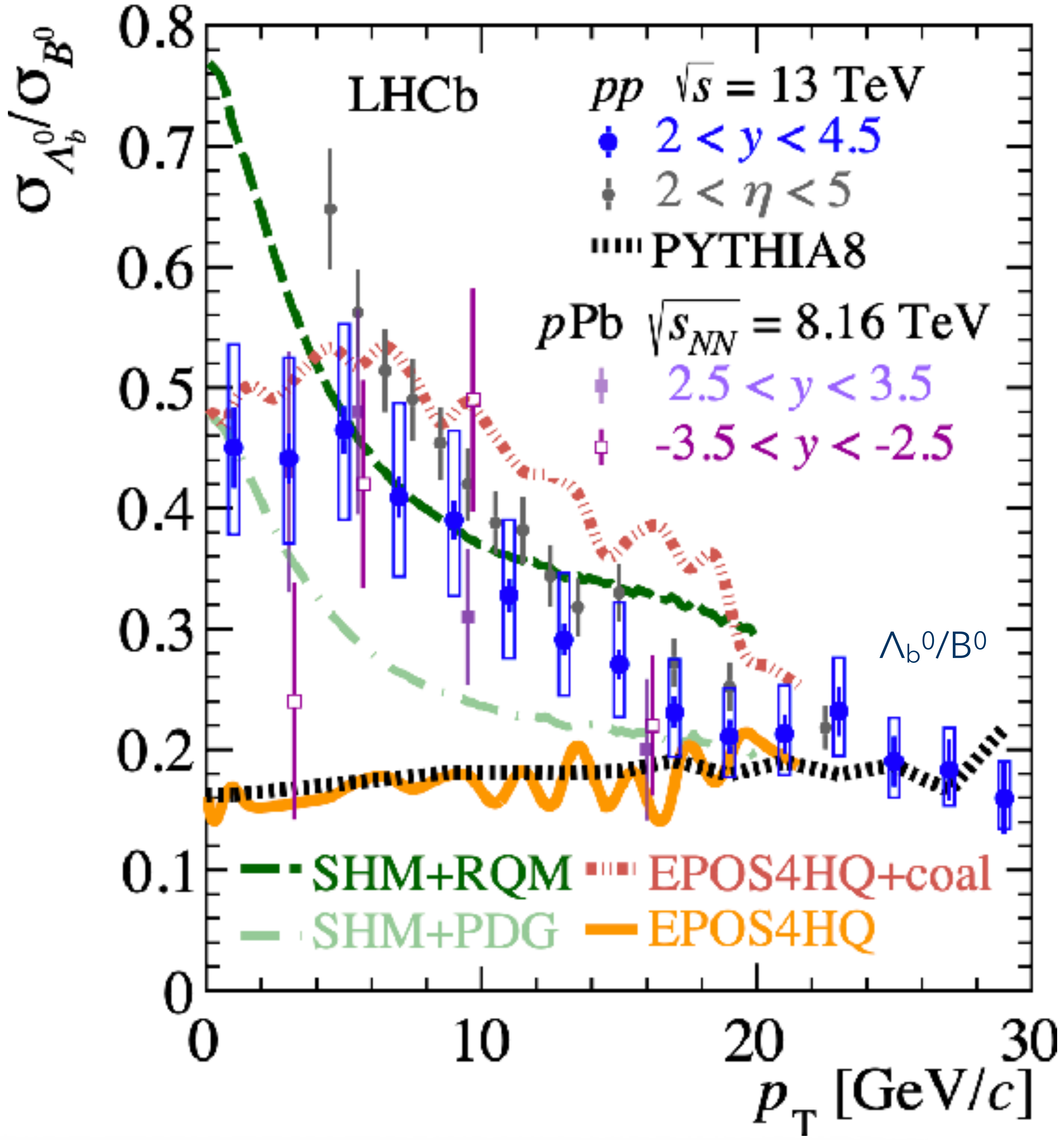
- Modified mechanism of hadronization in all hadronic collision systems with respect to charm fragmentation tuned on e^+e^- and e^-p measurements?
- Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?

Moving to beauty sector

Phys. Rev. D 108, 112003 (2023)







FONNL calculations based on using fragmentation fraction from e^+e^- and $f(b \rightarrow \Lambda_b^0)/f(b \rightarrow B)$ LHCb measurement

Non-prompt Λ_c^+ largely from the beauty baryons: good to investigate beauty baryon hadronization via non-prompt Λ_c^+

Note: should consider different decay kinematics
→ slightly modify p_T dependence

Similar trend to the charm measurement!

Beauty-quark fragmentation fraction

Phys. Rev. D 108, 112003 (2023)

Table 2: $p_{\rm T}$-integrated Λ_c^+/D^0 production ratio measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13$ TeV and in e^+e^- collisions at LEP [68] for prompt and non-prompt production.

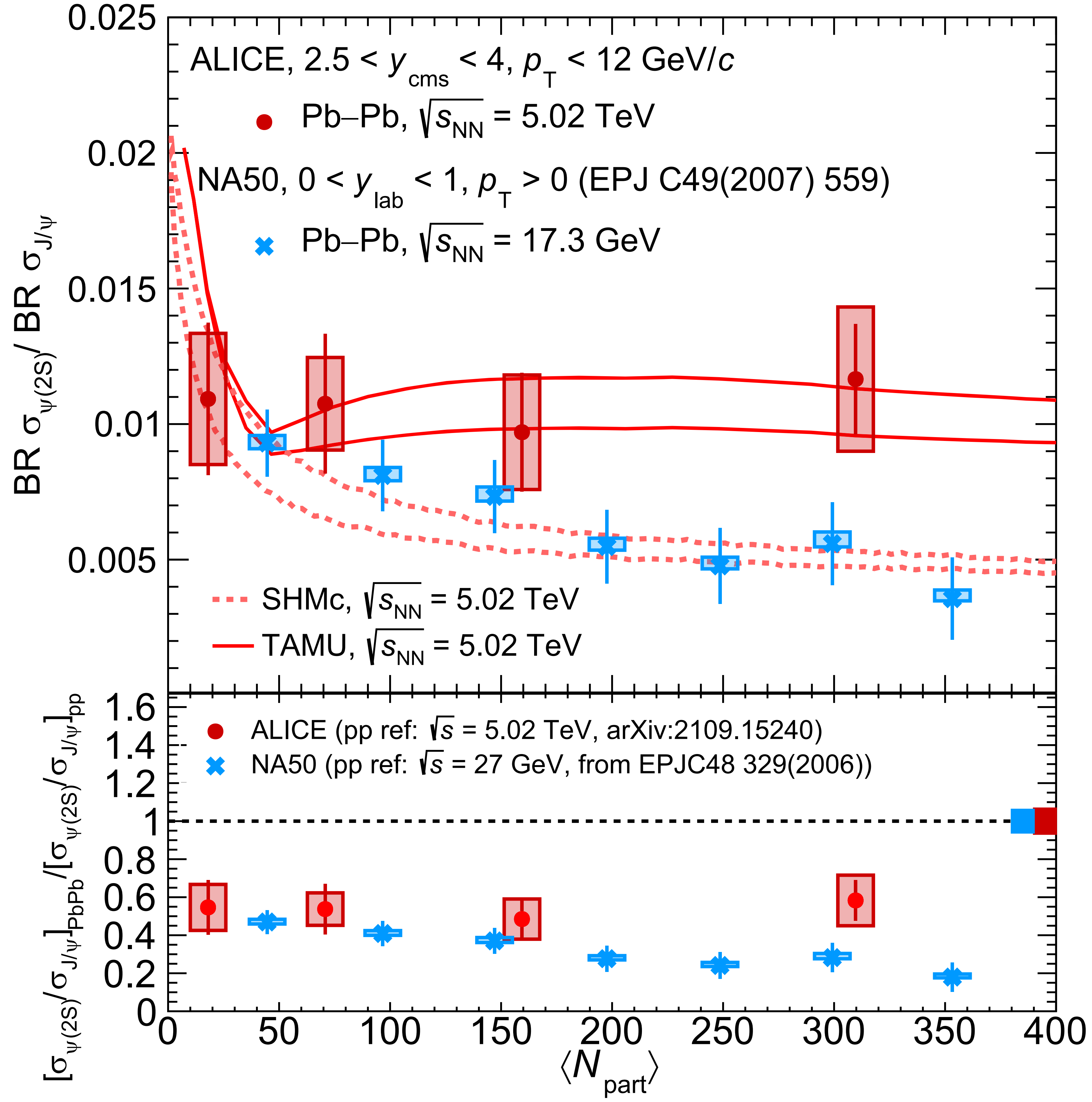
	pp	e^+e^-
	ALICE	LEP average [68]
prompt Λ_c^+/D^0	$0.49 \pm 0.02(\text{stat})^{+0.05}_{-0.04}(\text{syst})^{+0.01}_{-0.03}(\text{syst})$ [60]	0.105 ± 0.013
non-prompt Λ_c^+/D^0	$0.47 \pm 0.06(\text{stat}) \pm 0.04(\text{syst})^{+0.03}_{-0.04}(\text{extrap})$	0.124 ± 0.016

Significantly higher than that measured in e^+e^-

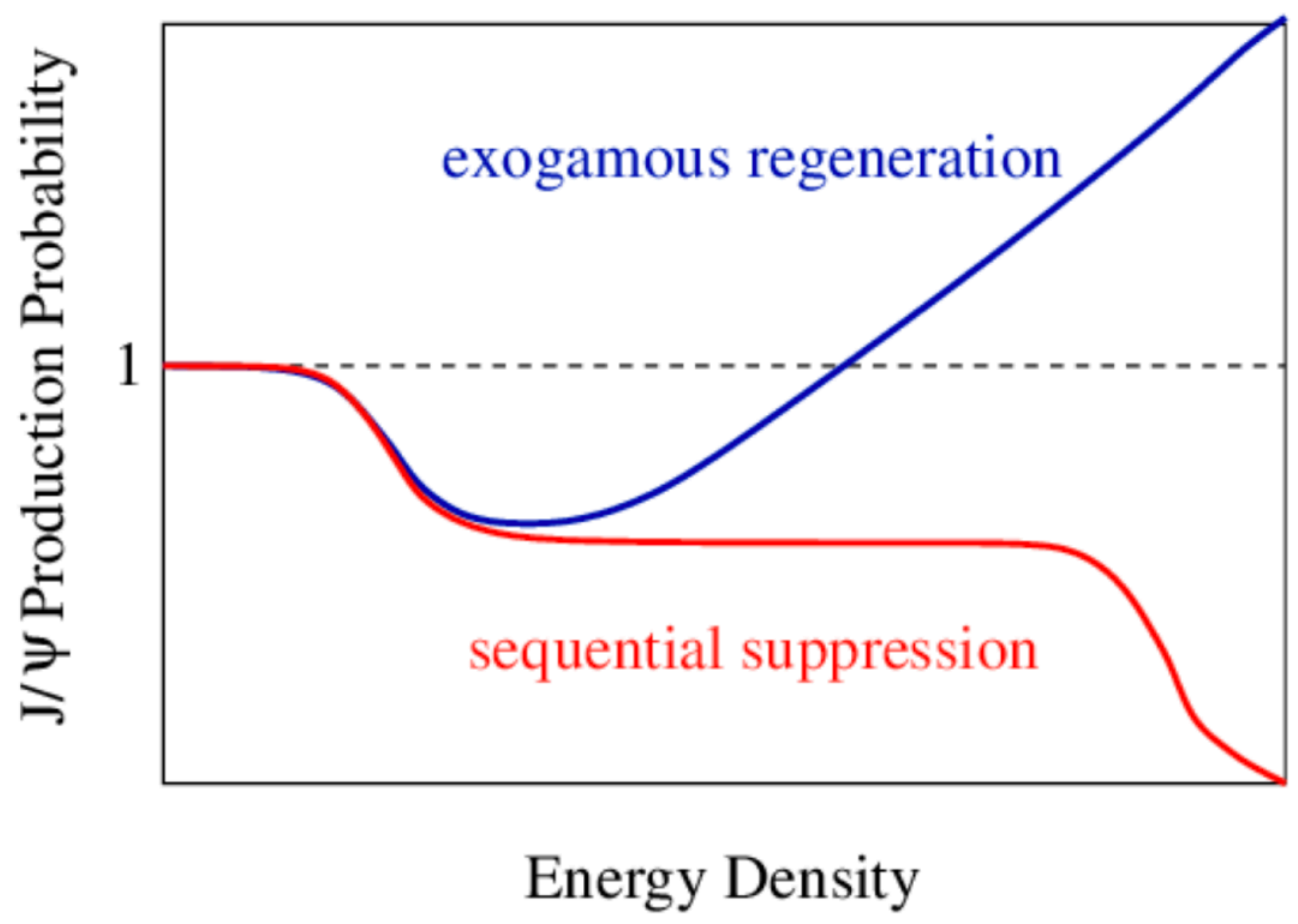
Quarkonium suppression

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

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



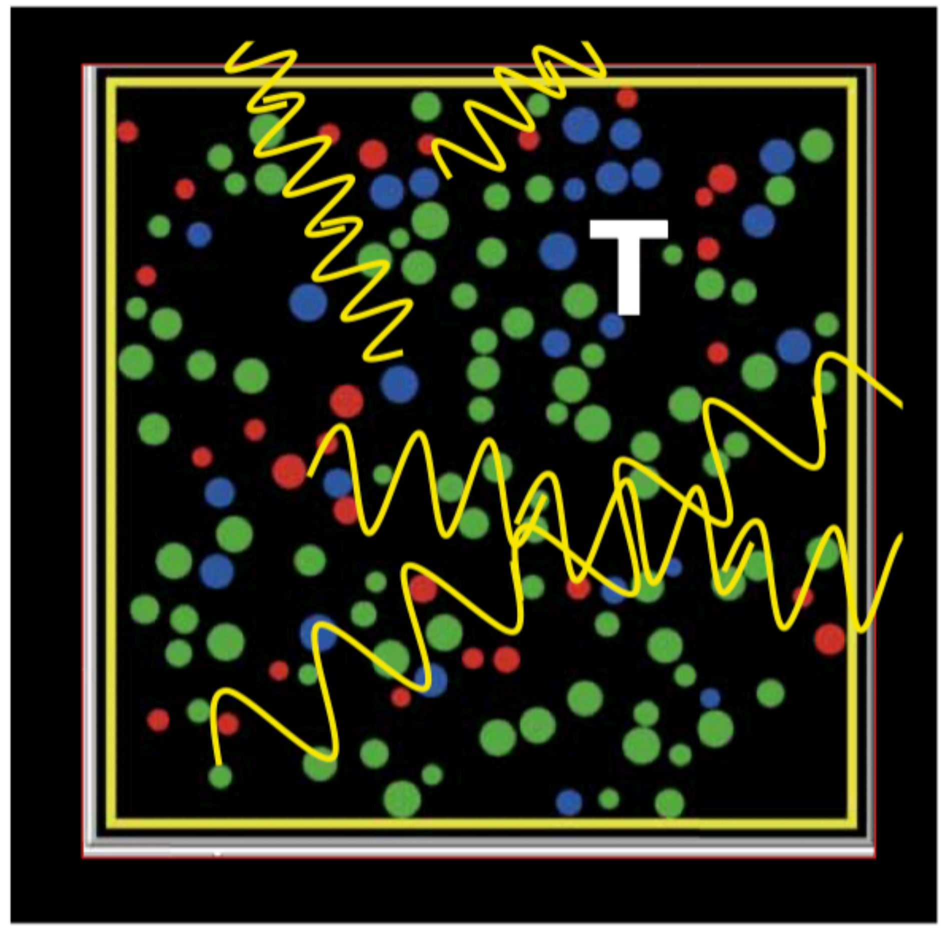
PRL 132, 042301 (2024)

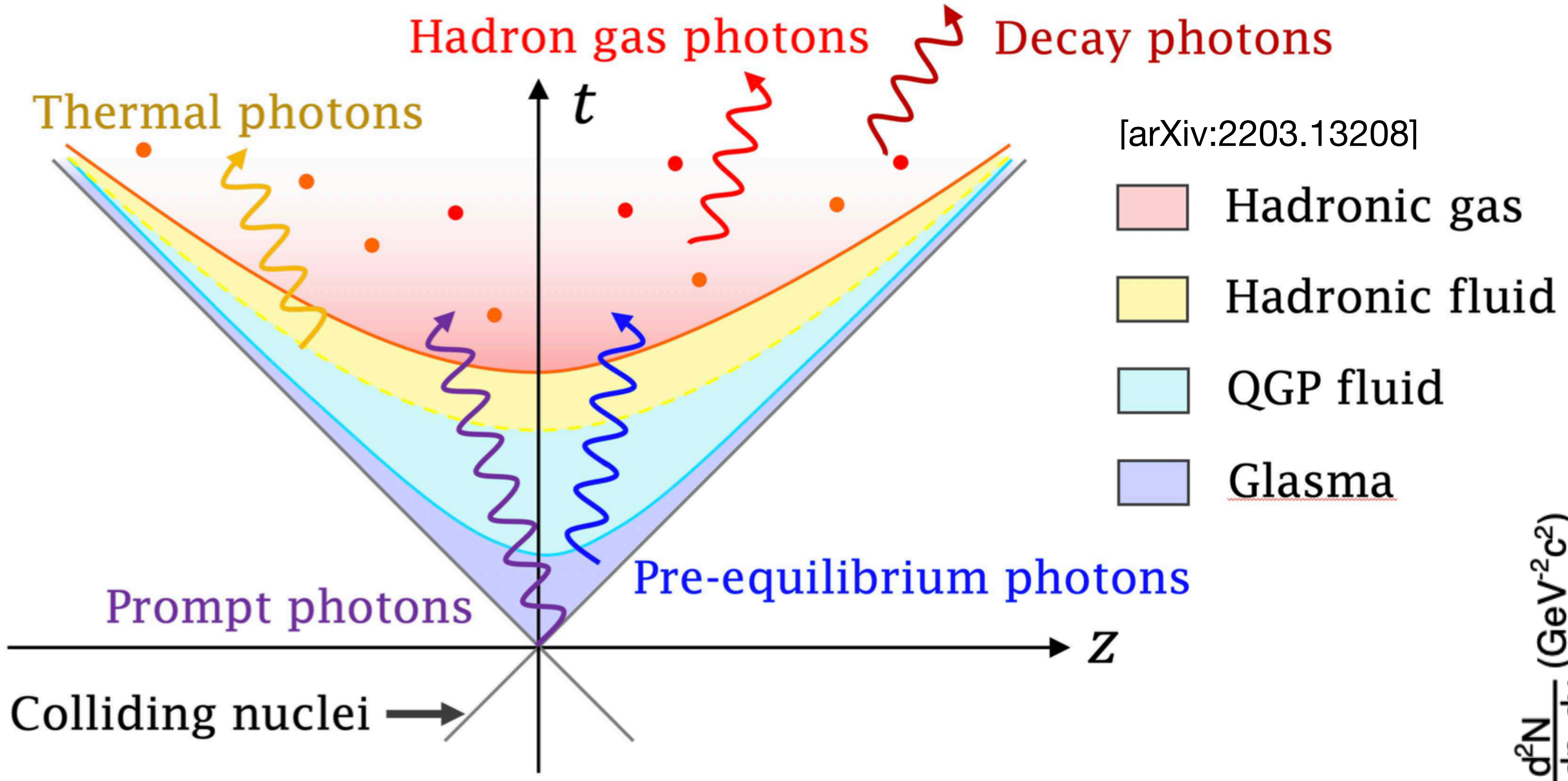


- Compared with the NA60 results → regeneration effect?

Hot QCD medium, temperature

QGP emits thermal photons
(power proportional to T^4)



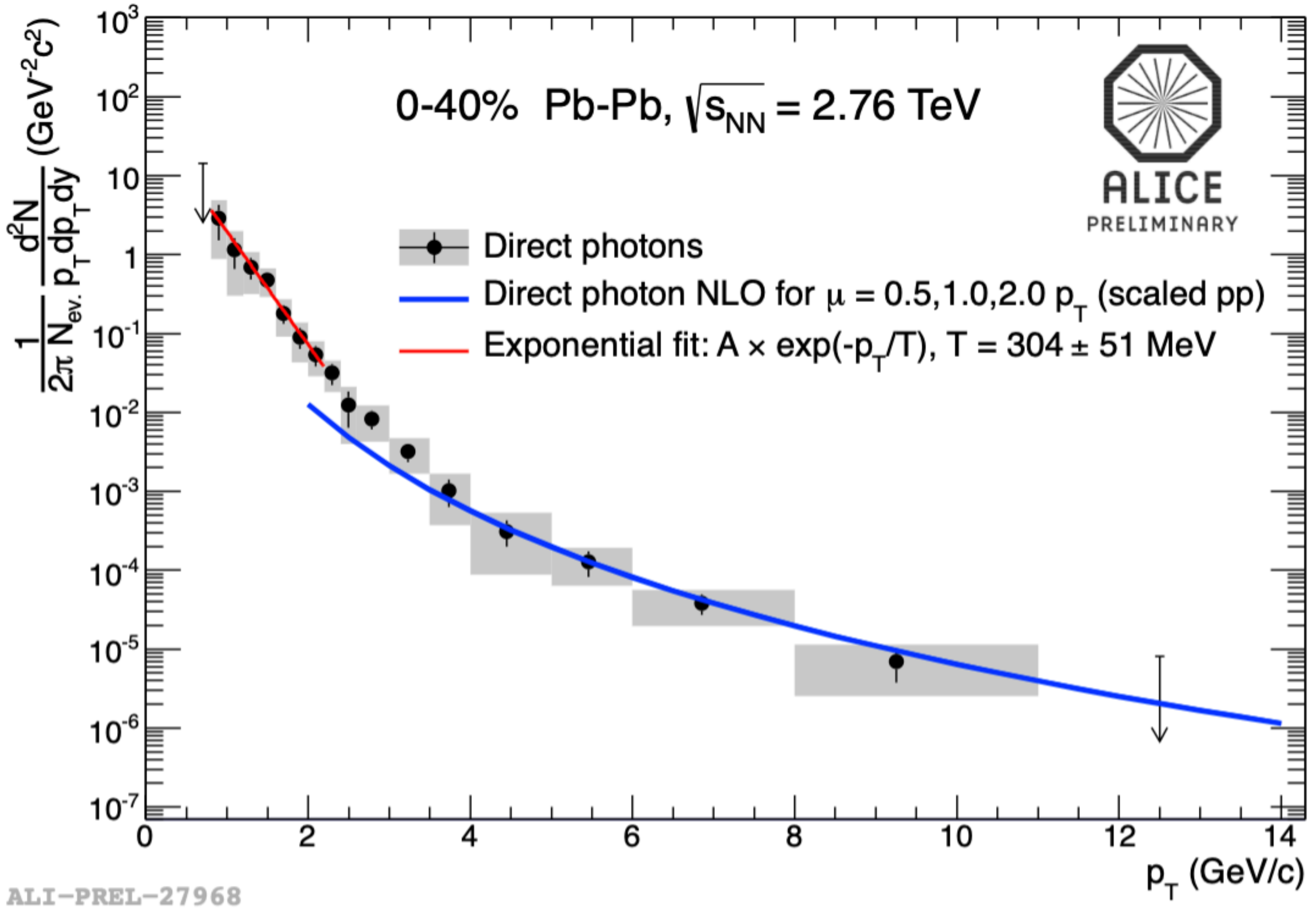


fit: $A\exp(-p_T/T)$

$T = 304 \pm 51^{\mathrm{stat+sys}}\,\mathrm{MeV}$

~ 5-6 Trillion Kelvin

Mixture over the evolution…



Charm and beauty creation