Measurements of Light-flavor Hadron Production with ALICE

Alberto Calivà on behalf of the ALICE Collaboration

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UNIVERSITÀ DEGLI STUDI DI SALERNO

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

CERN

ALICE

Introduction

Light-flavor hadrons: bulk of particle production in high-energy hadronic collisions at the LHC

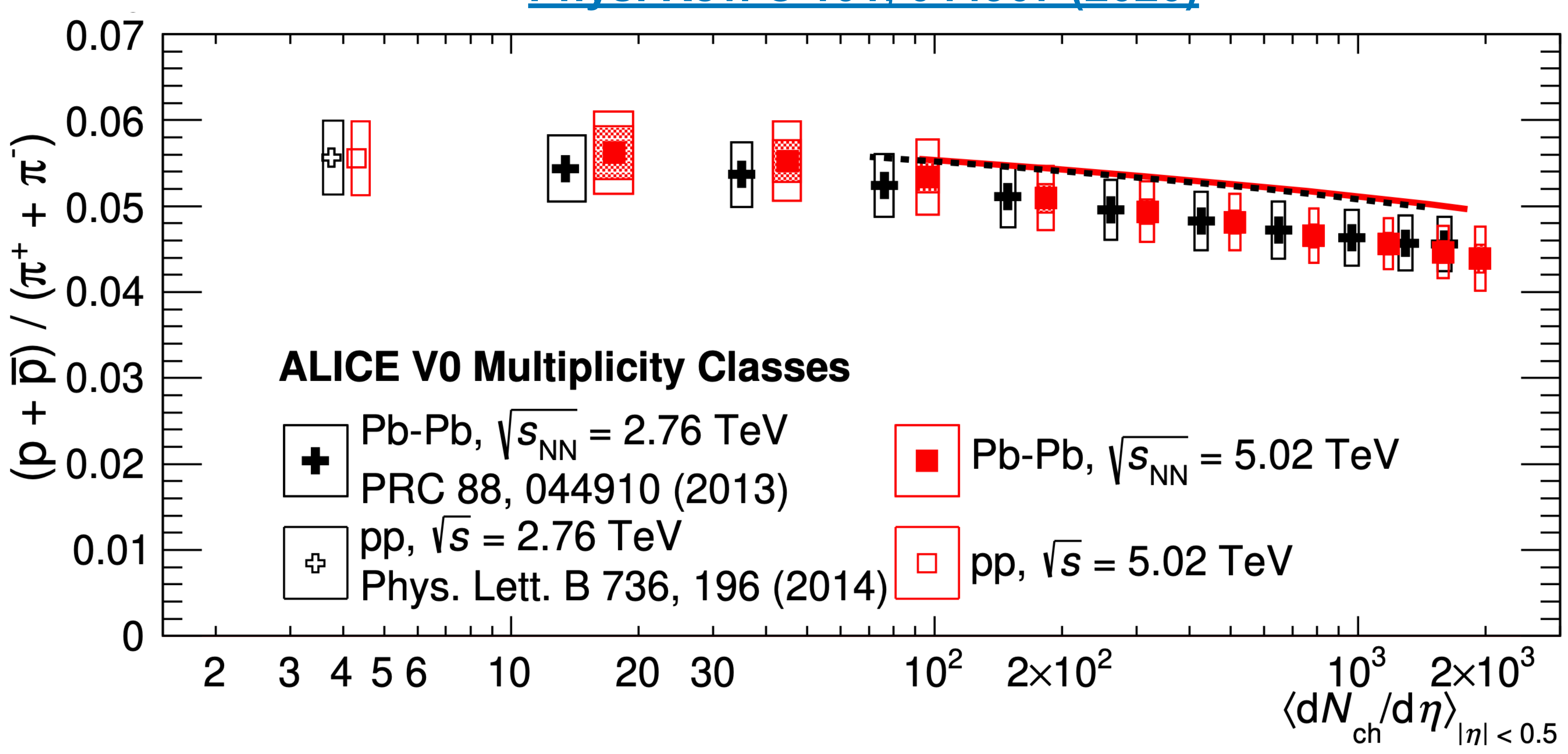
Multi-differential measurements of their production yields provide information on a large variety of phenomena such as

- hadronization mechanism
- strangeness enhancement
- hadronic interactions
- collectivity effects
- …

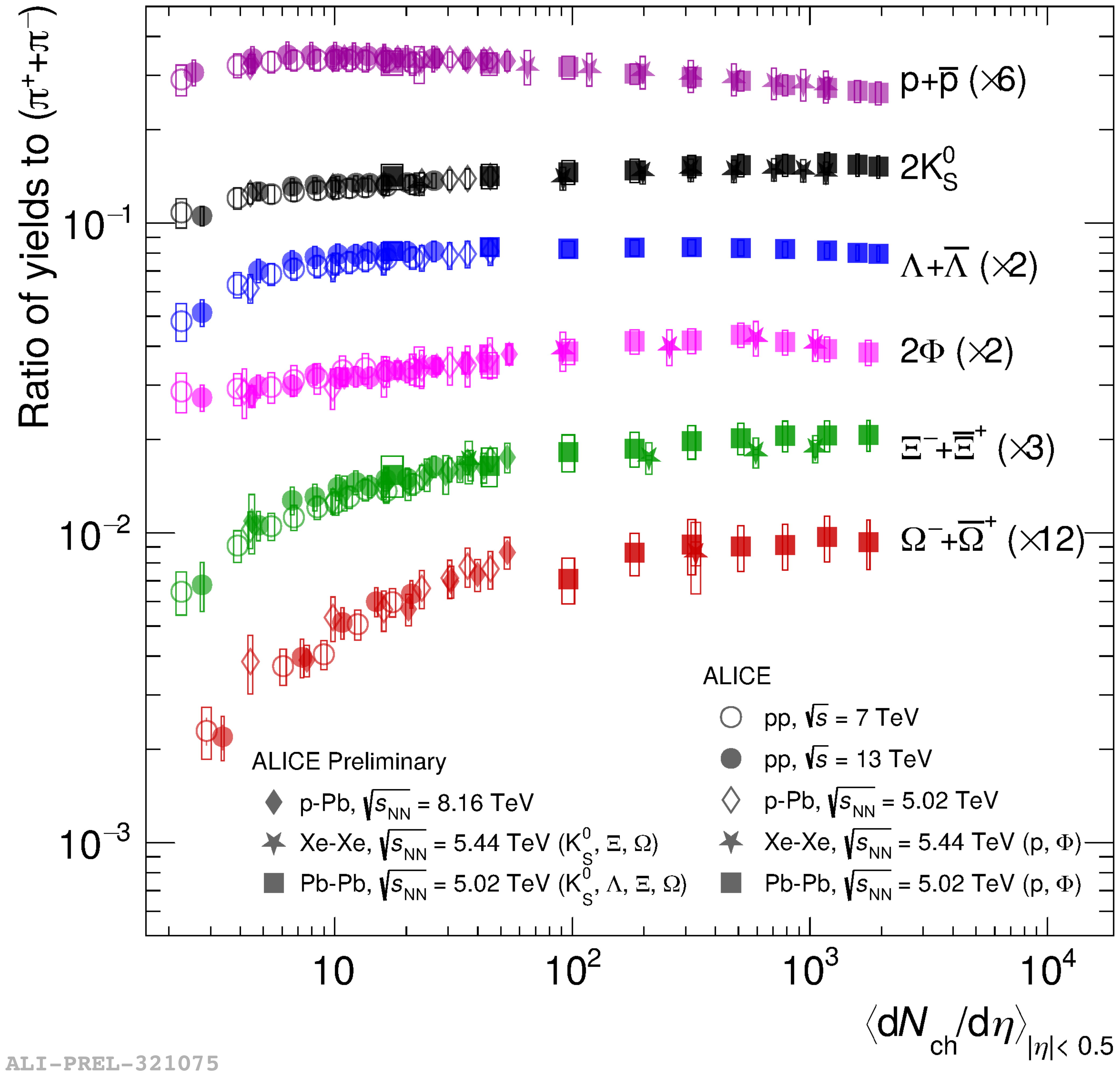
Universal scaling of yields and hadron chemistry with charged-particle multiplicity

smooth transition from pp to AA collisions

[Phys. Rev. C 101, 044907 (2020)]



Strangeness enhancement



Ratio of (multi-)strange hadron yields and pion yields:

- Smooth evolution with multiplicity across different collision systems and energies
- Steep rise at low multiplicity ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \lesssim 50$)
- Decreasing slope with increasing multiplicity until saturation at $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \approx 100$
- Larger increase for hadrons with larger strangeness content

Different phenomenological models are used to describe this effect

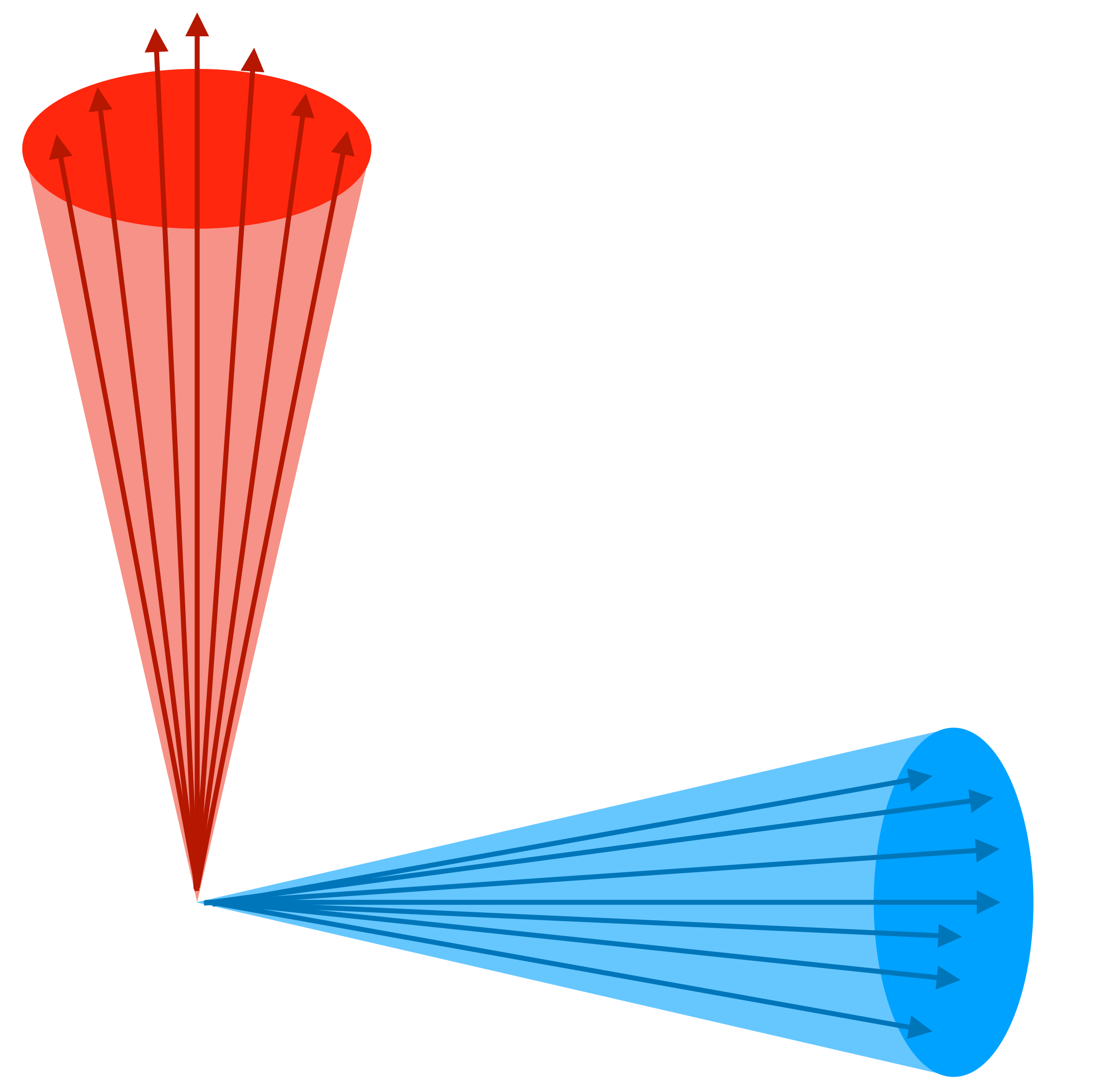
→ not fully understood

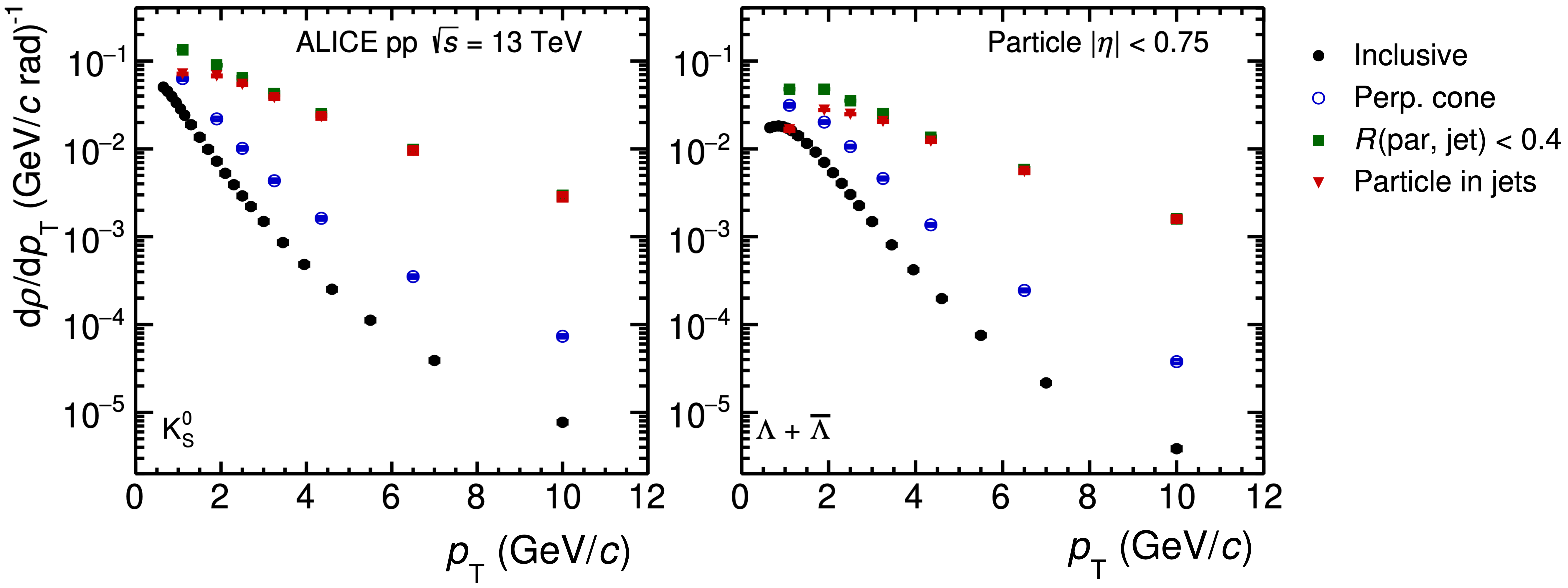
[Nature Phys. 13, 535–539 (2017)]

[Eur. Phys. J. C 80, 167 (2020)]

Strangeness in and out of jets

arXiv:2211.08936 (2022)



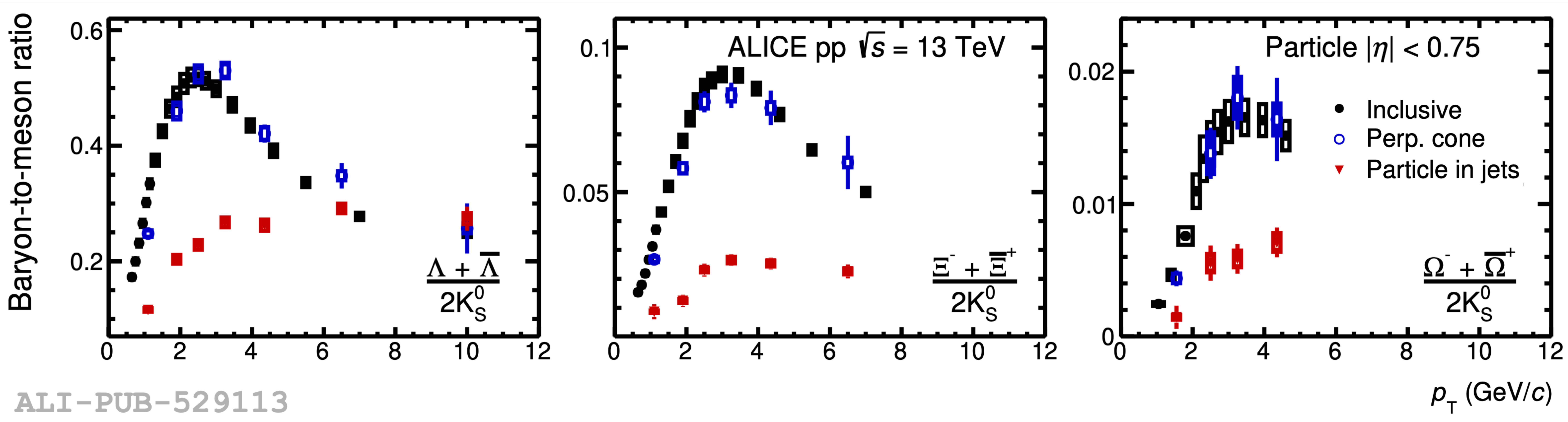


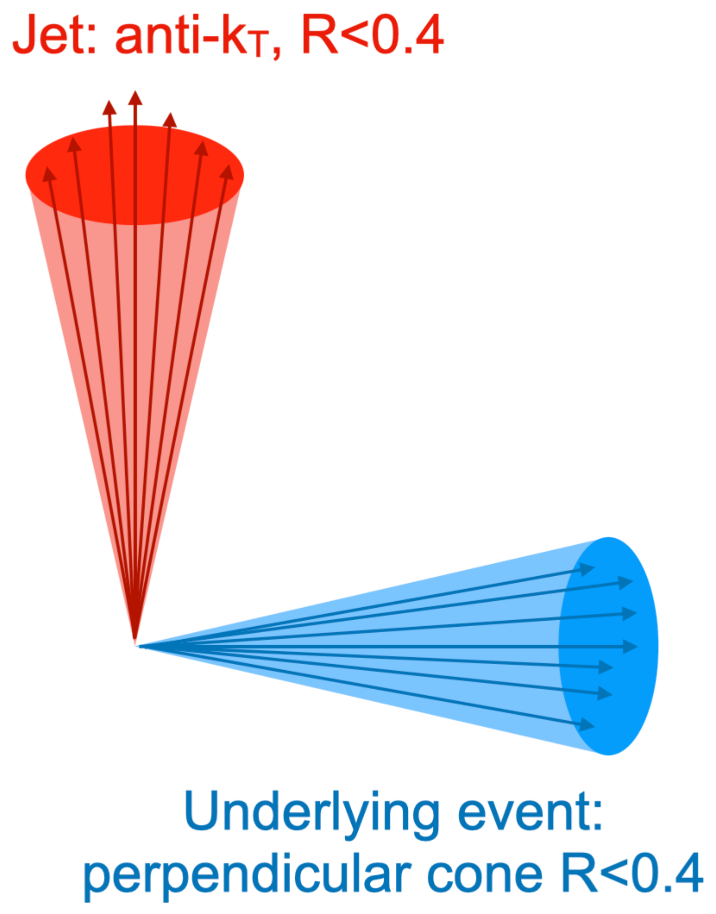
Λ, K^0_S , $\Xi^{\pm}$ and $\Omega^{\pm}$ production in pp collisions and p-Pb collisions with a hard scattering > tagged by a charged jet with $p_{T,jet}$ > 10 GeV/c

- p_T spectra of strange hadrons inside jets are less steep wrt UE
- p_T-differential density in inclusive measurements lower and softer than those in the UE
  → in this measurement events with $p_{T,jet}$ > 10 GeV/c are selected

Baryon-to-meson ratios

arXiv:2211.08936 (2022)



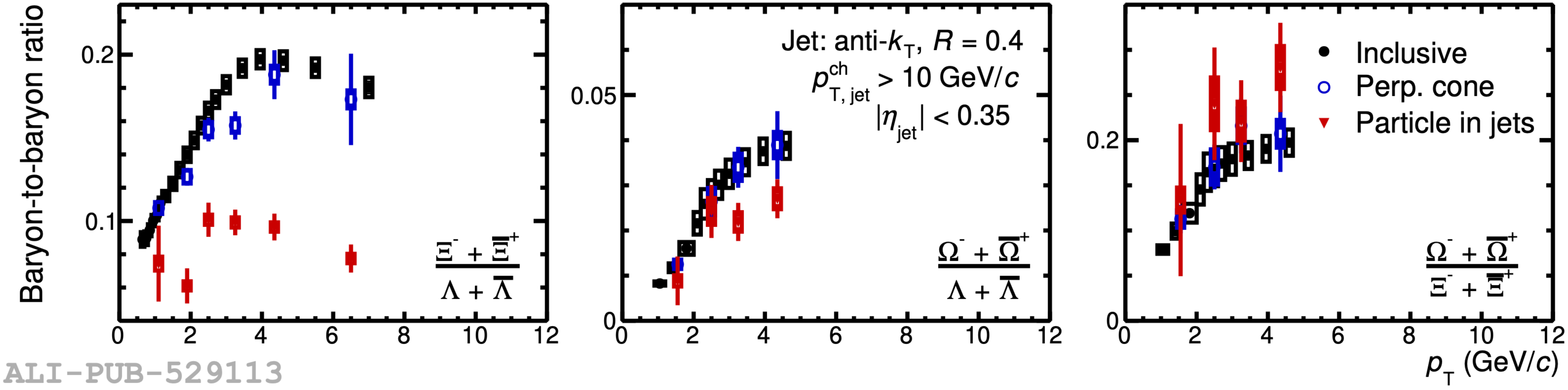


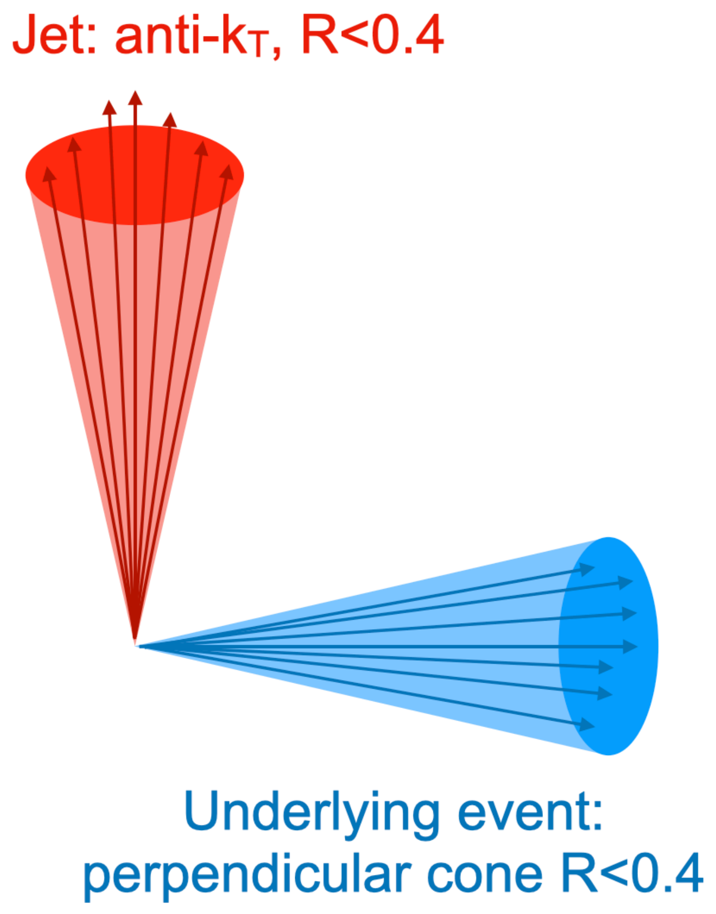
Baryon-to-meson ratios

- Different values at low p_T in jets and in the UE
- Enhancement at intermediate p_T not present within jet
  → different production mechanisms?
- Baryon-to-meson ratio in the UE consistent with inclusive ratio

Baryon-to-baryon ratios

arXiv:2211.08936 (2022)



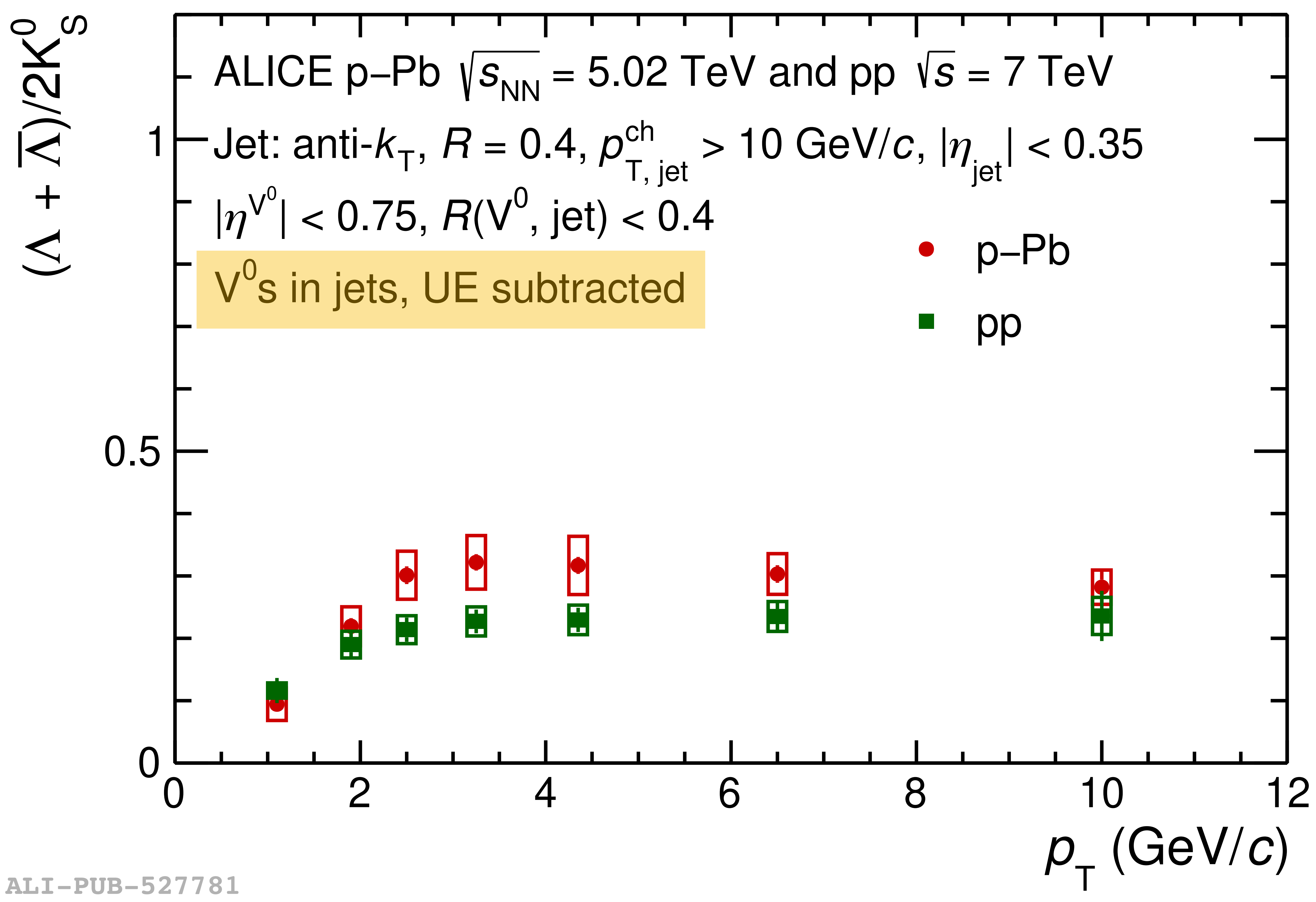


Baryon-to-baryon ratios

- Different values in jets and in the UE except for Ω/Ξ (large uncertainties in jets)
  $\rightarrow$ different production mechanisms?
- Inclusive measurements consistent with those in the UE for all ratios

Λ/K^0_S: pp vs. p-Pb collisions

Phys. Lett. B 827 (2022) 136984



Λ/K^0_S measured in p-Pb collisions systematically higher for $2 < p_T < 8$ GeV/c wrt that in pp collisions.

→jet fragmentation in p-Pb collisions not happening in the vacuum?

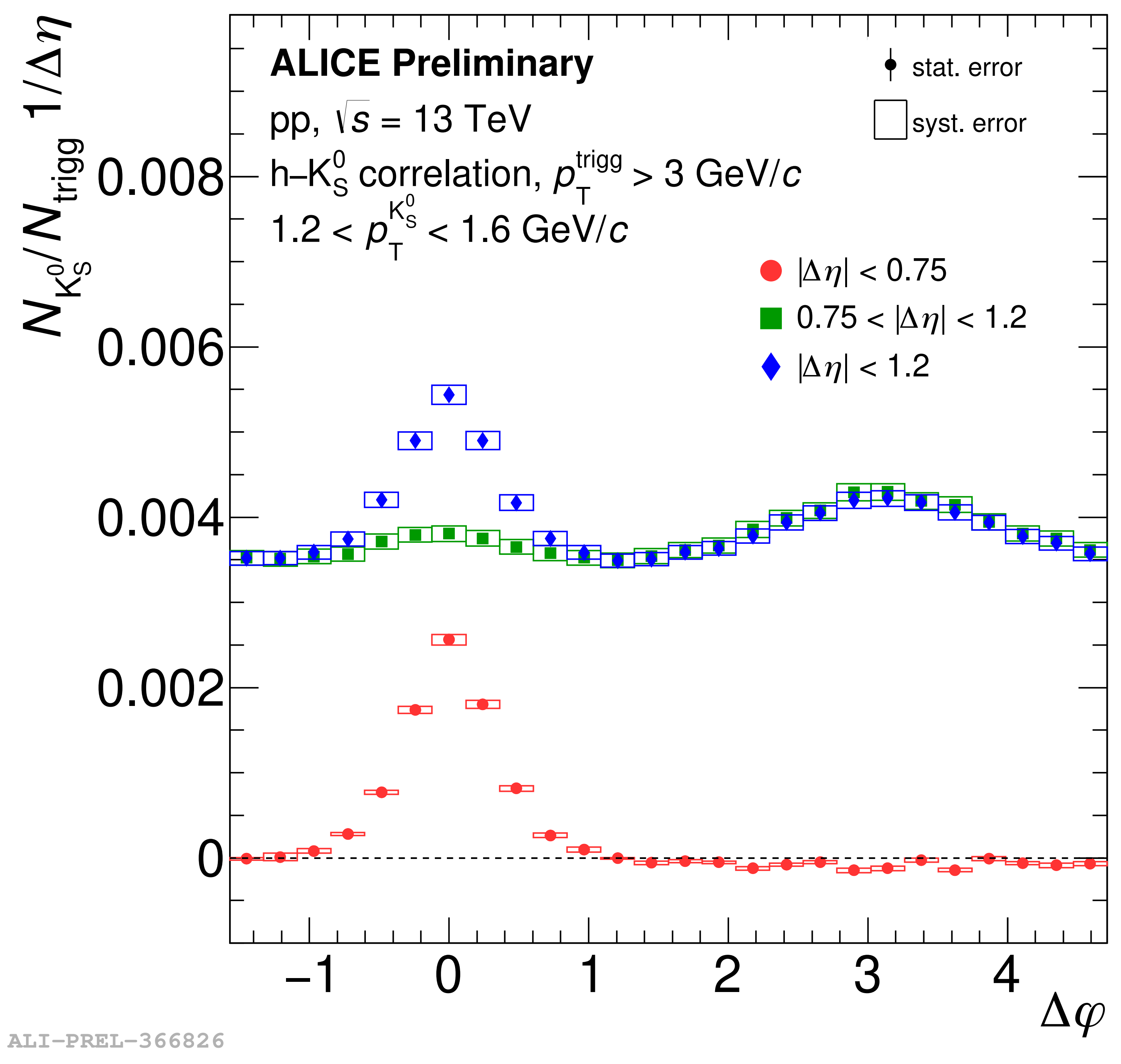
However, the difference is not significant (less than 2σ)

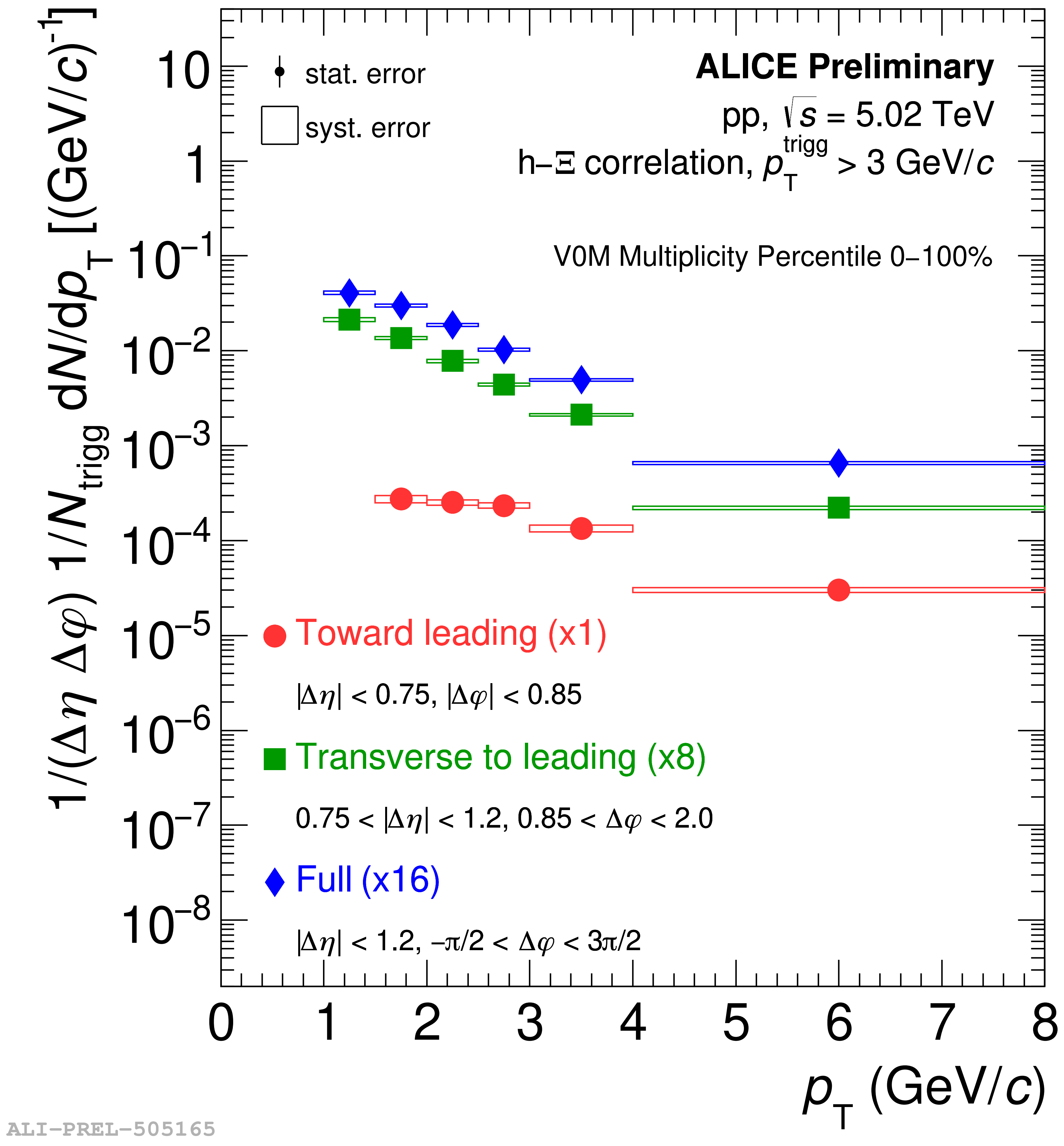
→ will be studied with higher precision in Run 3

Strangeness with two-particle correlation

Strangeness production in and out of jet via two-particle correlation method:

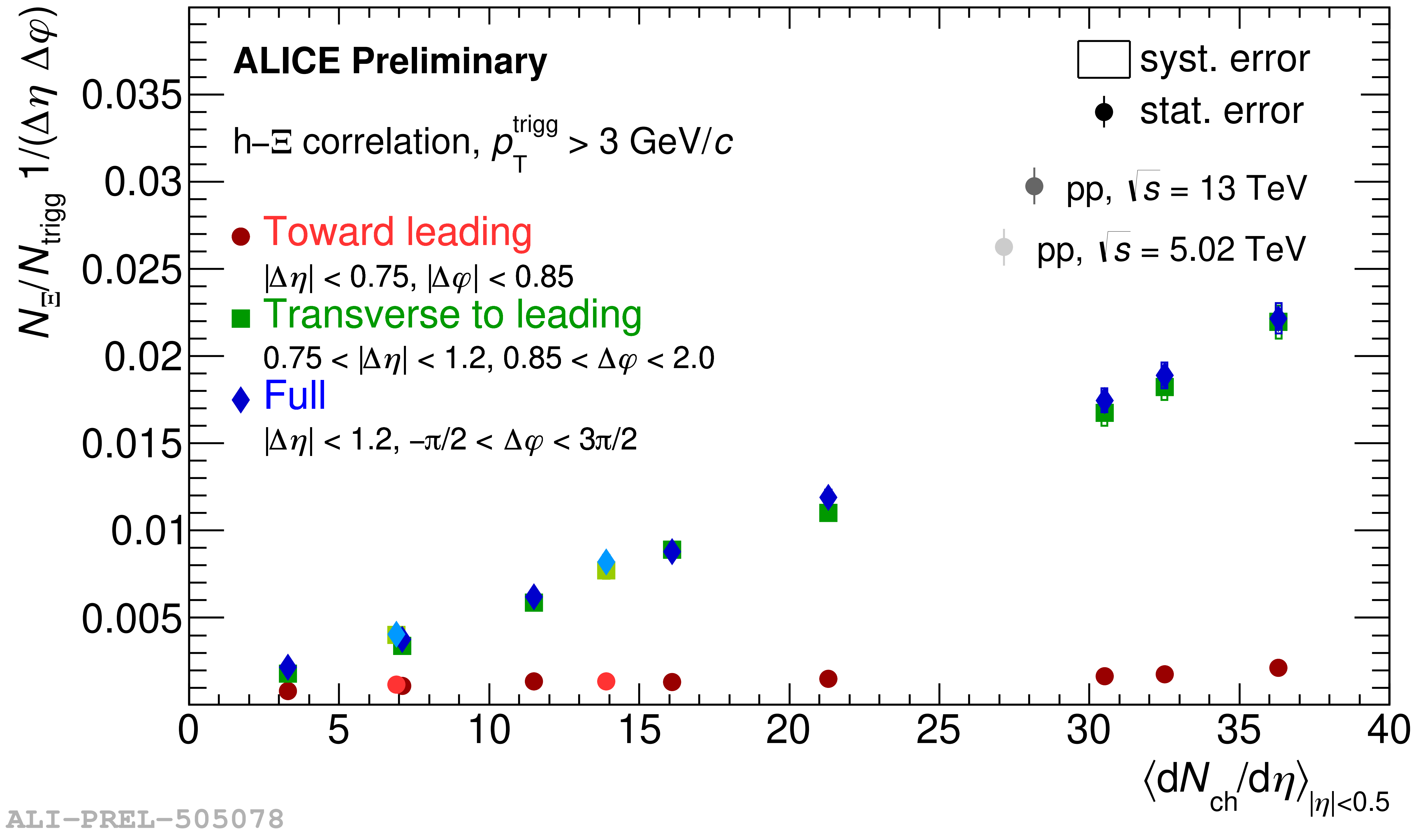
- Trigger primary particle as proxy for the jet (highest p_T and p_T > 3 GeV/c)
- $\Delta\eta$ and $\Delta\phi$ of strange hadron wrt trigger particle define in-jet and out-of-jet regions





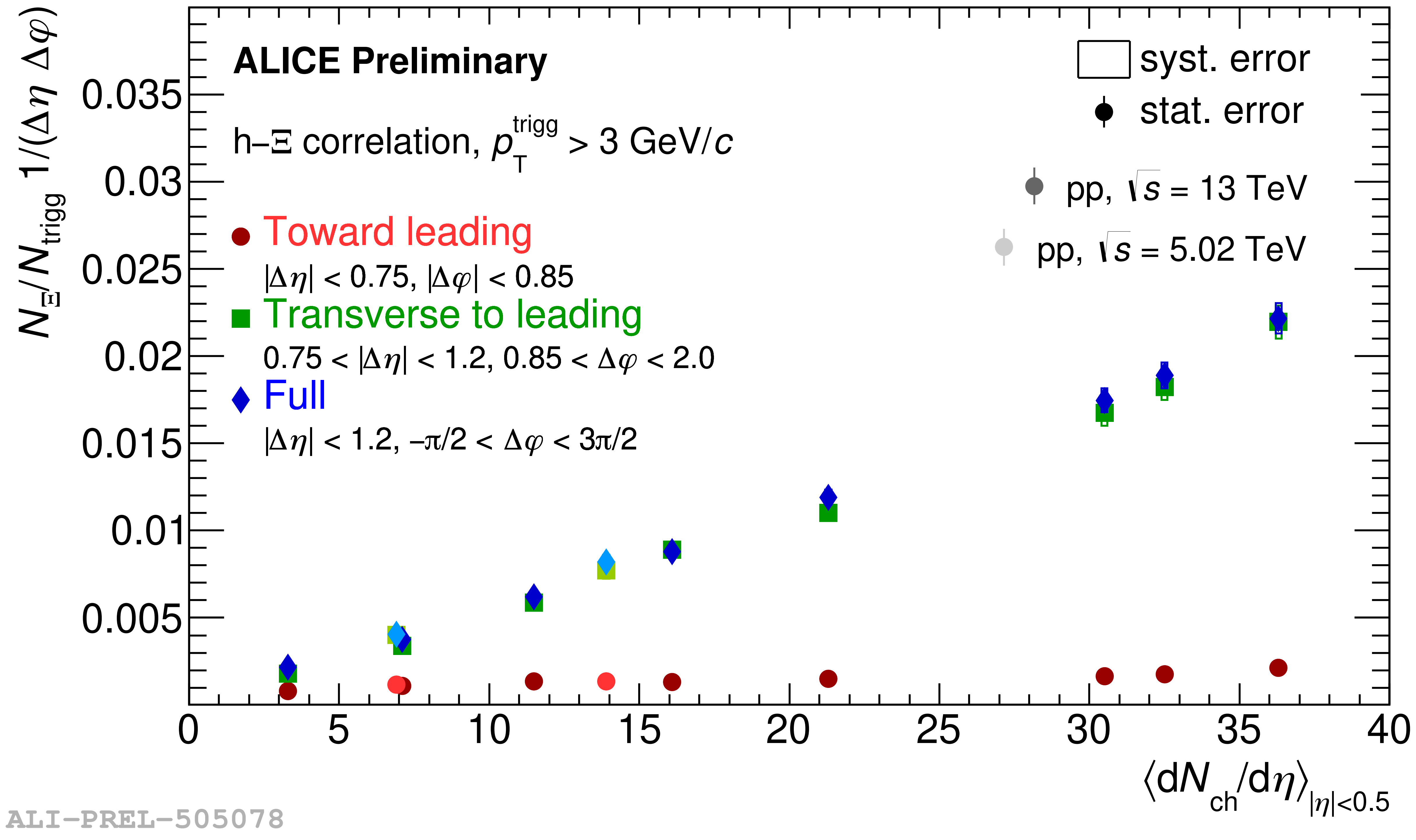
- K^0_S and $\Xi^{\pm}$ production toward and transverse to leading studied in different event multiplicity classes
- Toward leading p_T spectra are harder than those transverse to leading

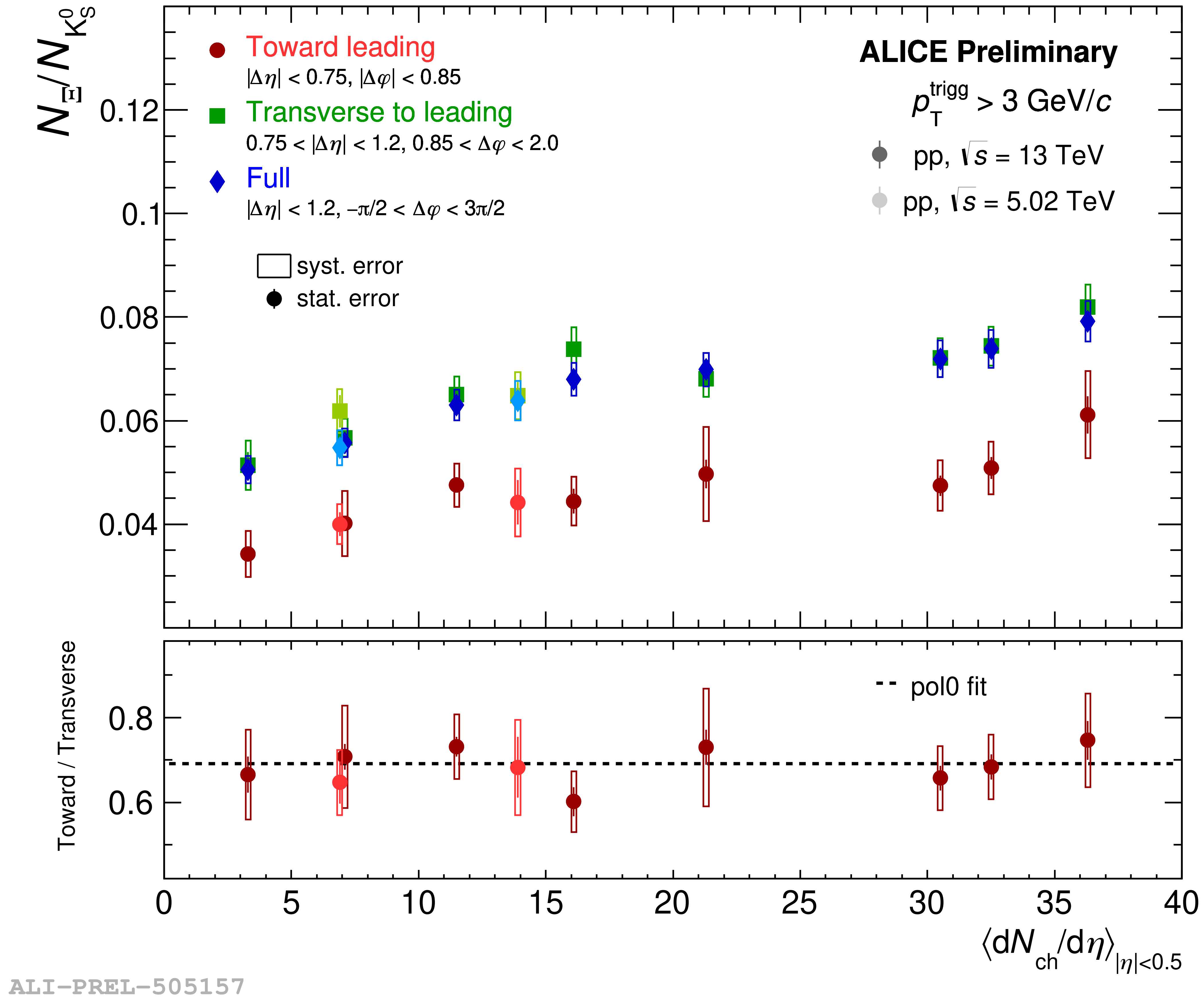
Strangeness enhancement in and out of jets



- Full and transverse-to-leading yields of strange hadrons show a similar rise with multiplicity
- Weak multiplicity dependence of the toward-leading yield

Strangeness enhancement in and out of jets





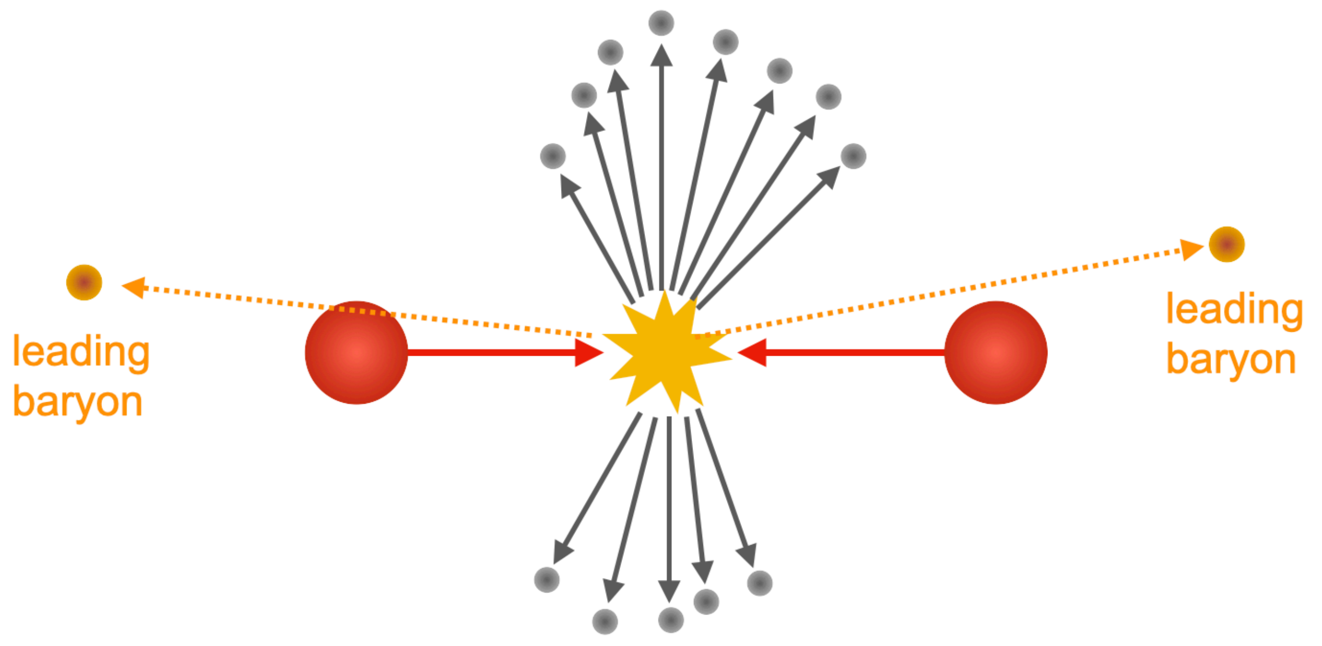
- Full and transverse-to-leading yields of strange hadrons show a similar rise with multiplicity
- Weak multiplicity dependence of the toward-leading yield

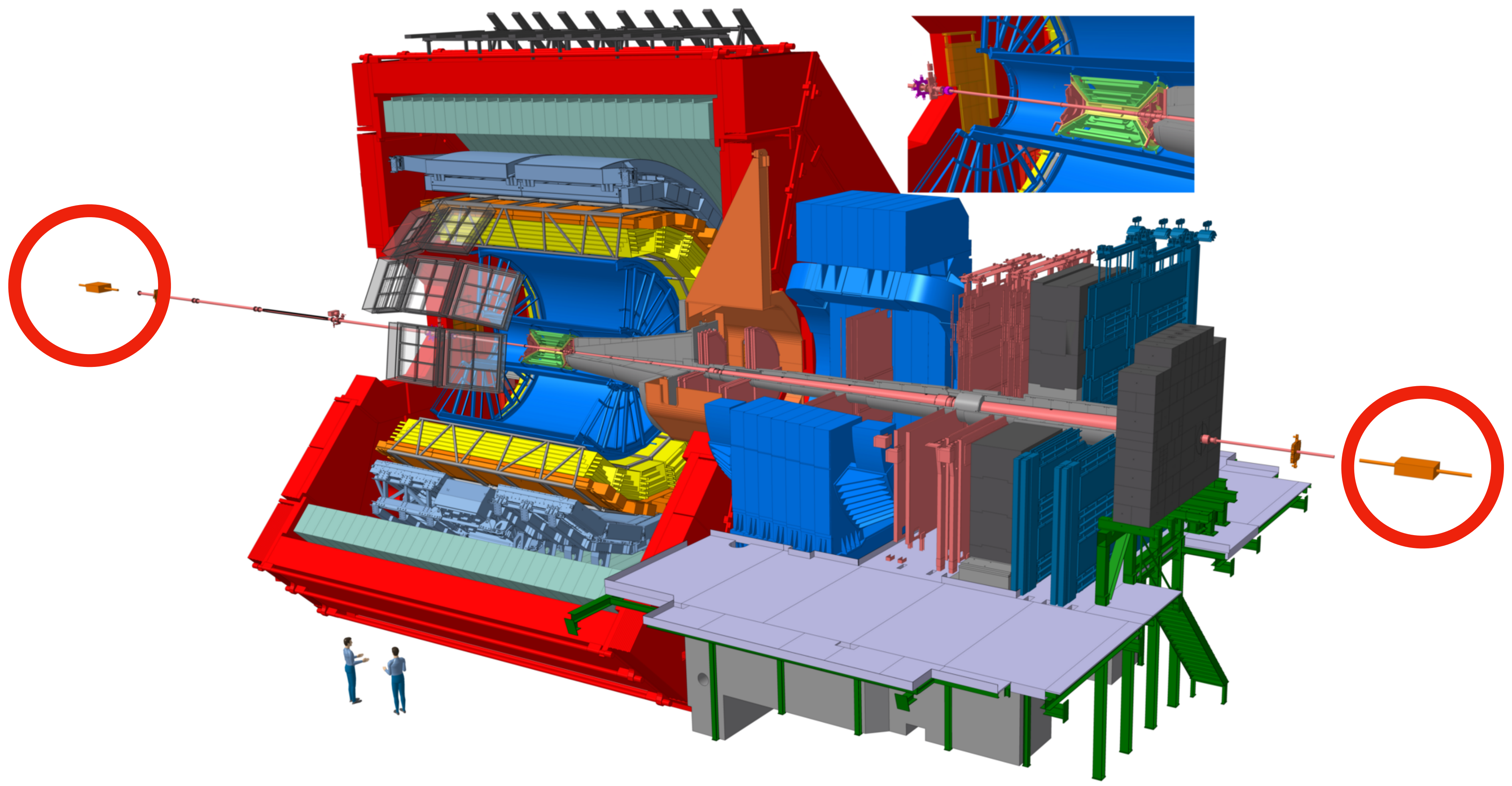
- Full $\Xi^{\pm}/K^0_s$ ratio consistent with transverse-to-leading ratio
- Strangeness enhancement both in and out-of-jet on two different levels

Effective energy

Forward emission of baryons in pp collisions reduces the **effective energy**, i.e. the energy available for particle production

$\rightarrow E_{\text{eff}} < \sqrt{s}$





Energy of leading baryons can be measured using the Zero-Degree Calorimeters (ZDC)

$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}} \approx \sqrt{s} - E_{\text{ZDC}}$$

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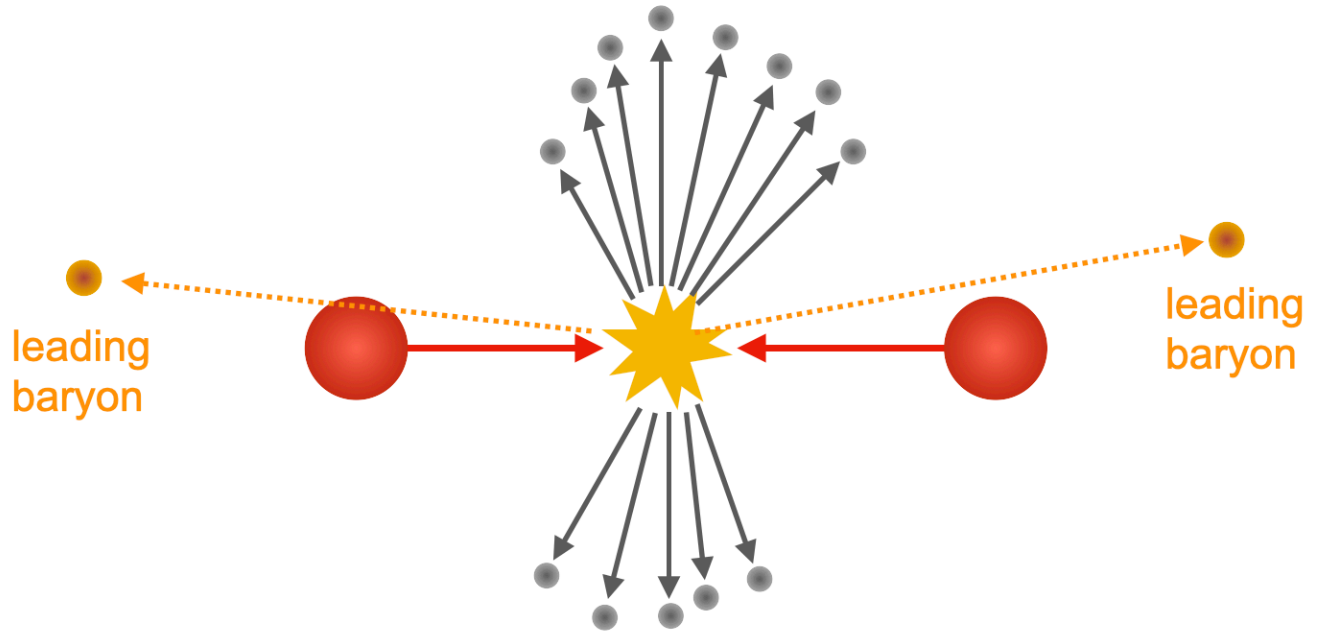

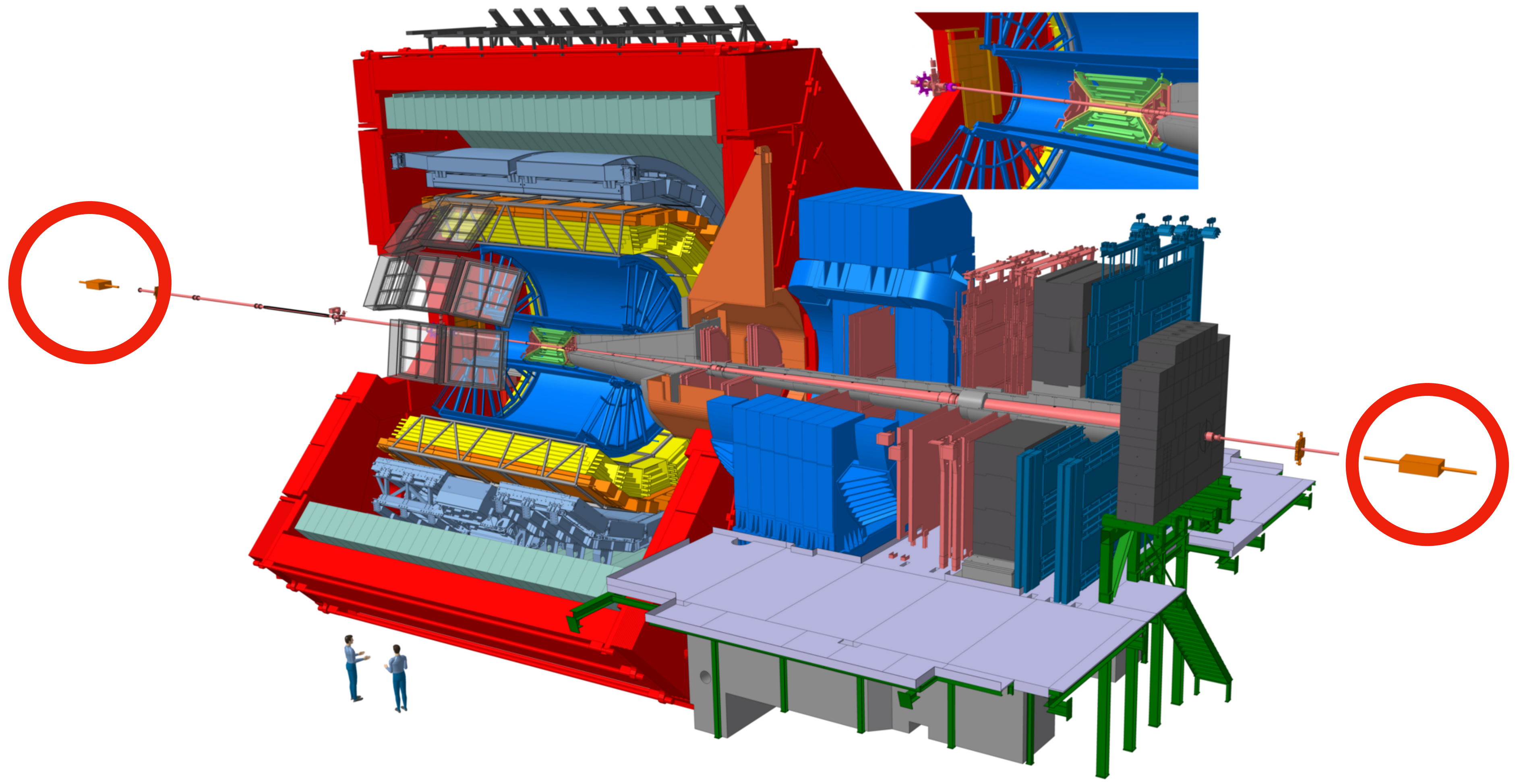

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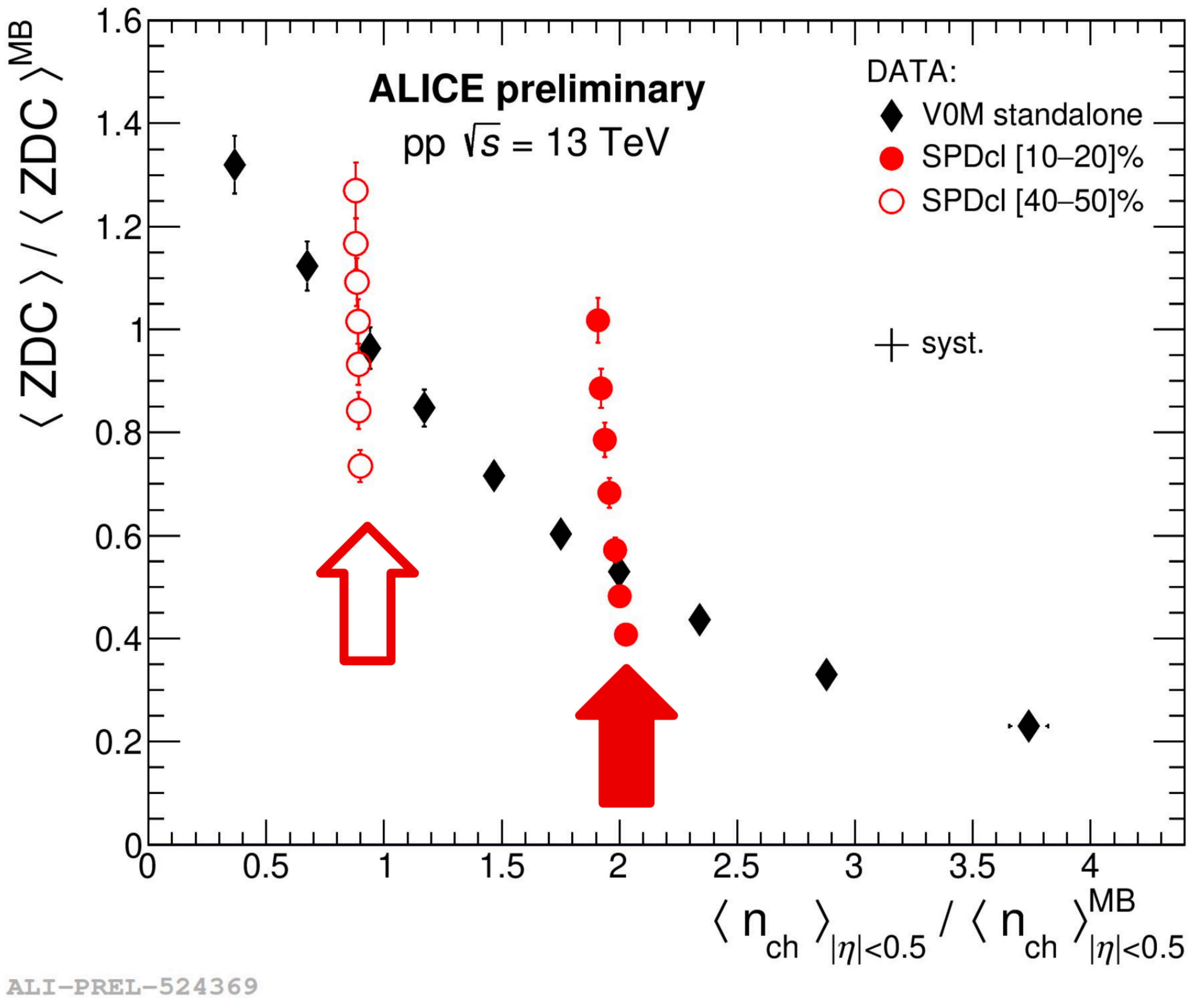
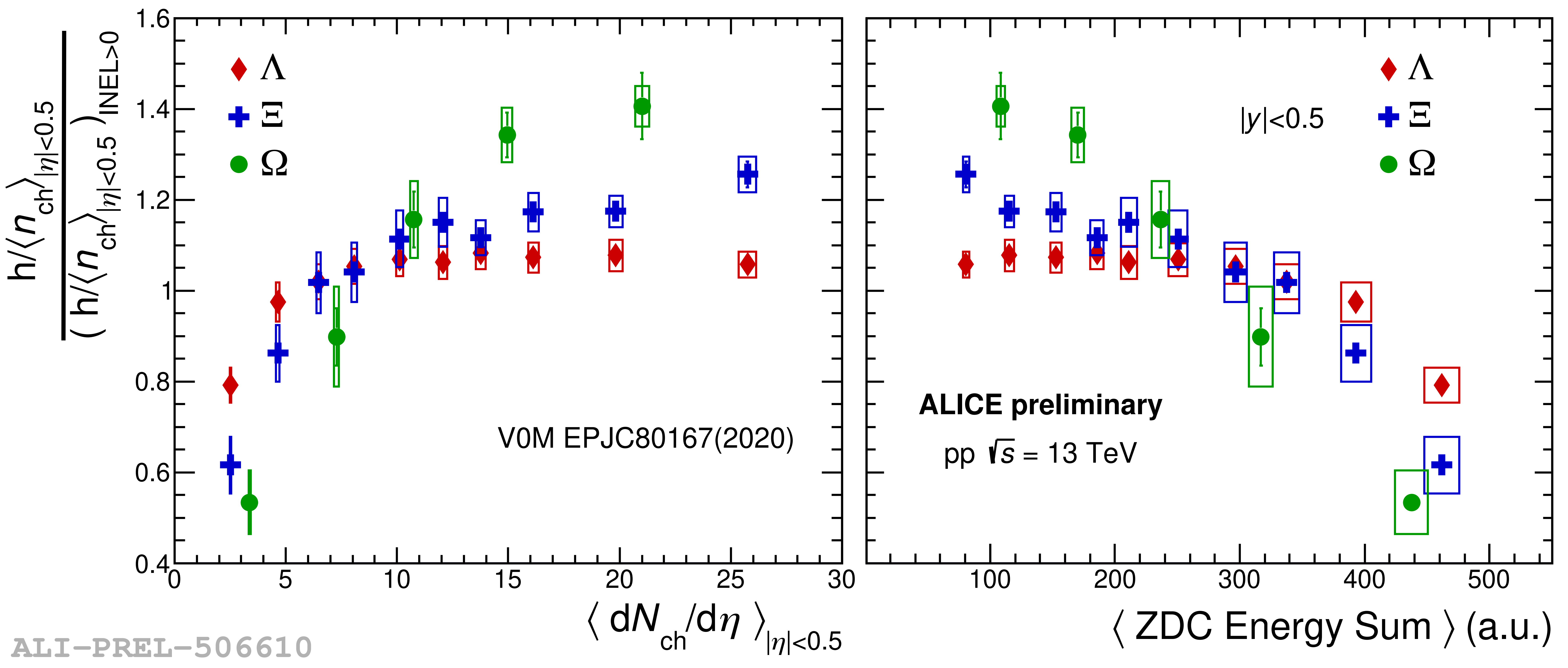


Forward energy (E_{ZDC}) is anti-correlated with the charged-particle multiplicity at mid-rapidity $\langle n_{\text{ch}} \rangle_{|\eta|<0.5}$ measured using SPD clusters

Strangeness production measured as a function of effective energy by fixing $\langle n_{\text{ch}} \rangle_{|\eta|<0.5}$ (2 values)

Strangeness vs. effective energy

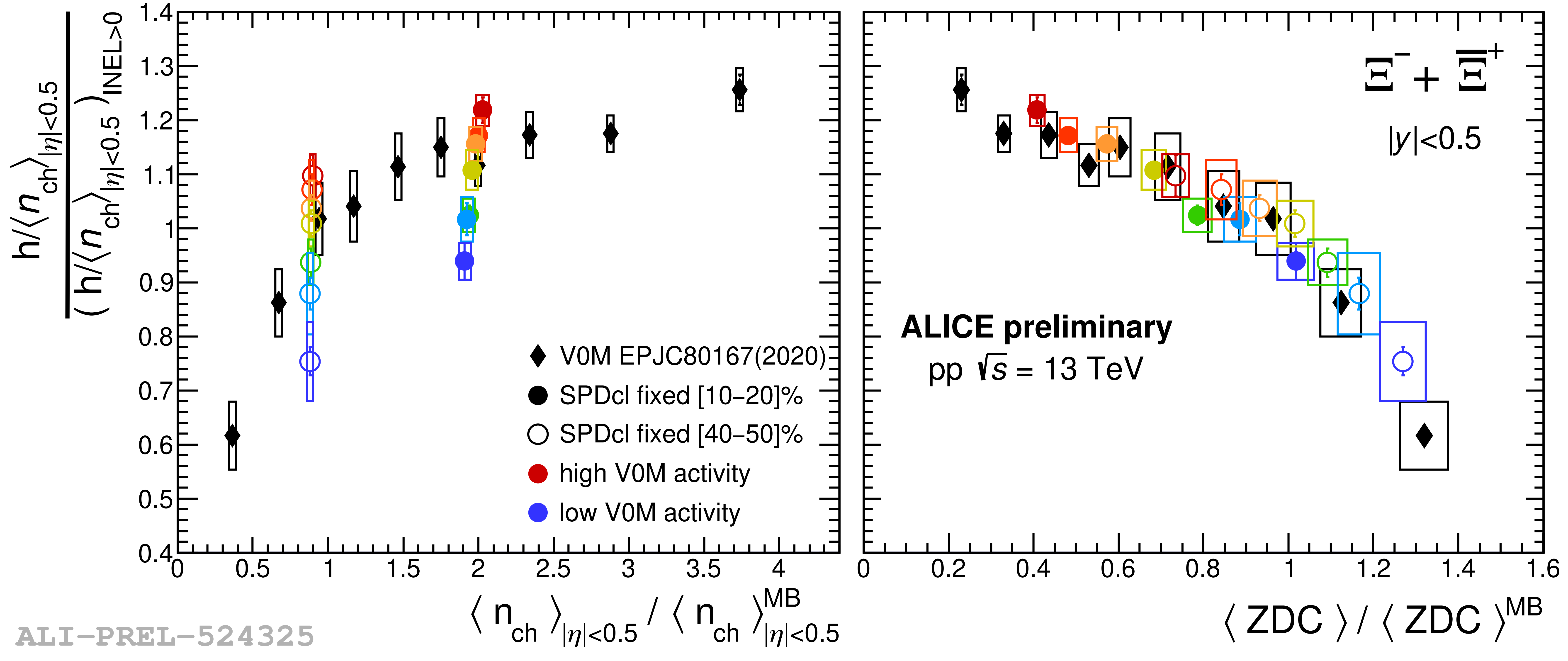


Strangeness production per charged particle:

- increases with charged-particle multiplicity at midrapidity (left)
- is anti-correlated with the ZDC energy (right)

Stronger variation for baryons with larger strangeness content

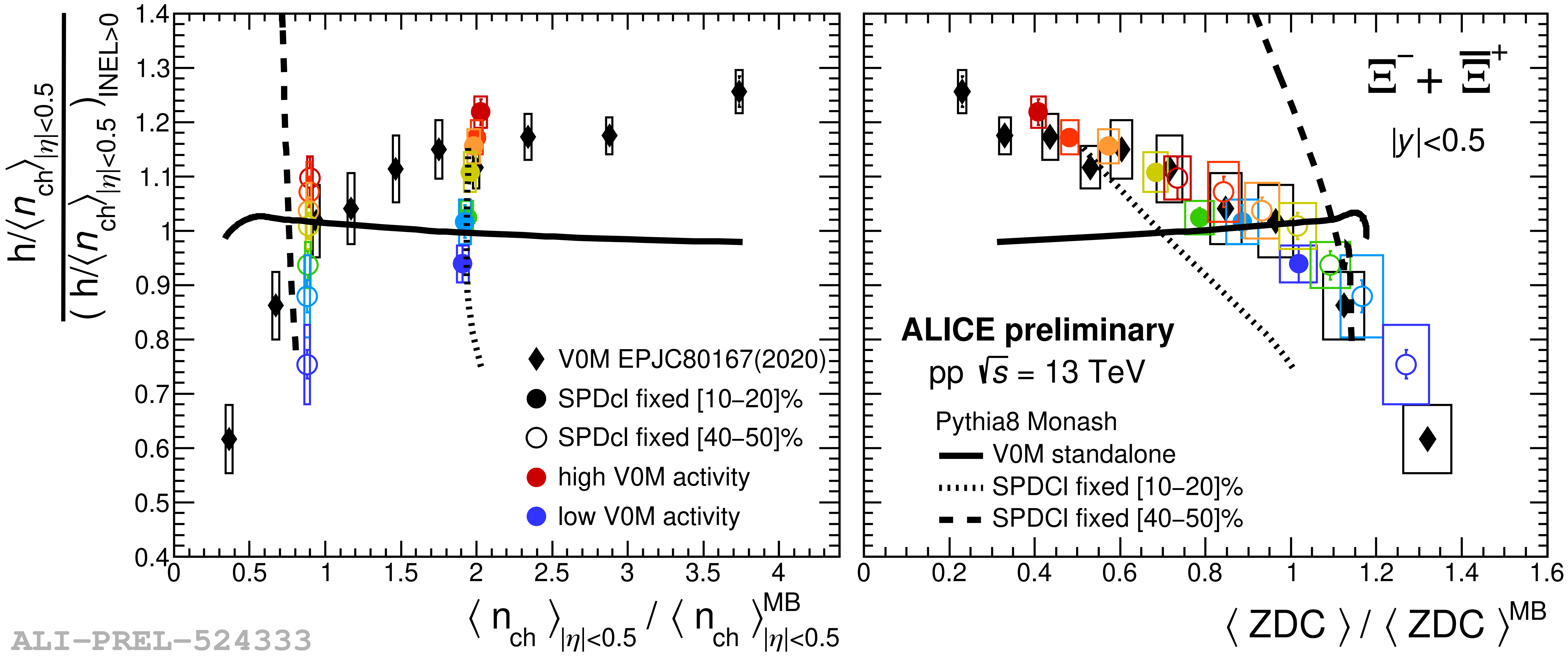
Strangeness vs. effective energy



Strange hadron yields per charged particle increases with the E_{eff} for fixed $\langle n_{\mathrm{ch}} \rangle_{|\eta|<0.5}$

Scaling with E_{eff} consistent for the two multiplicity classes within uncertainties

Strangeness vs. effective energy

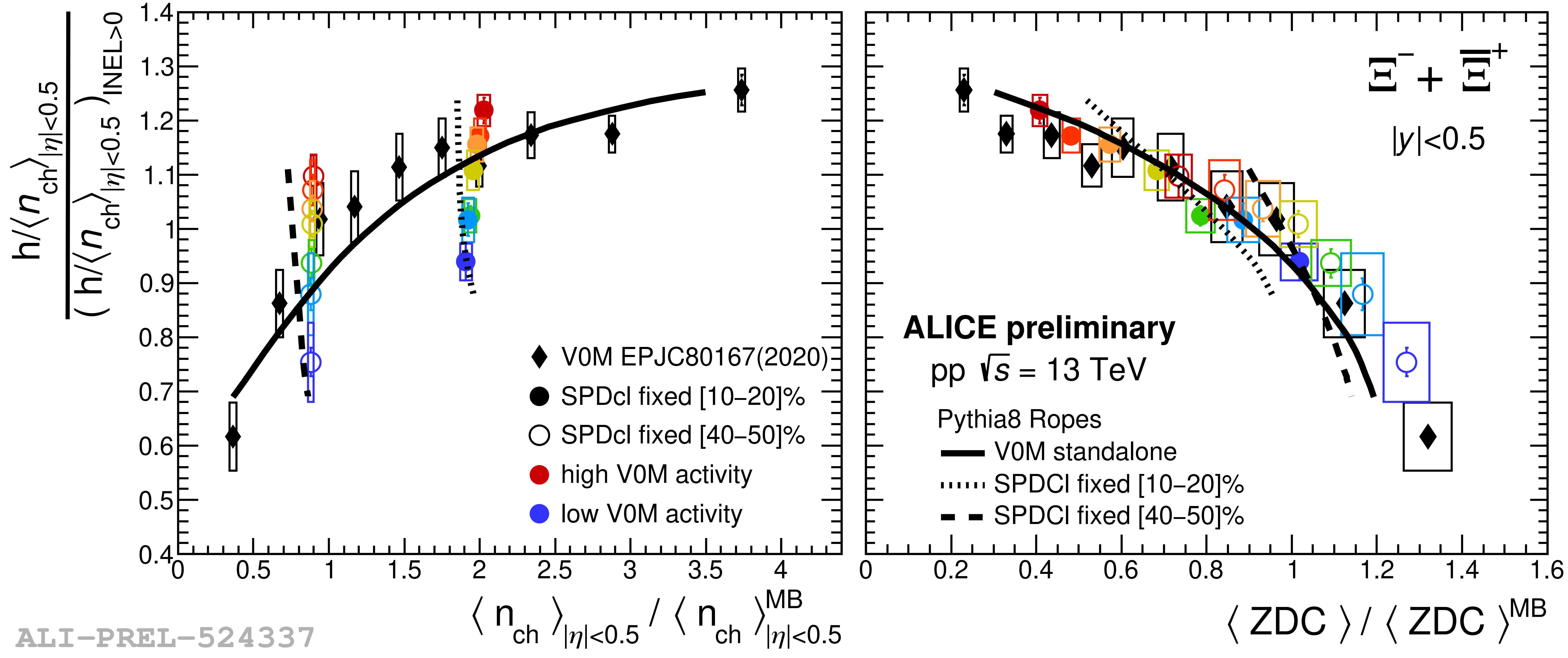


Strange hadron yields per charged particle increases with the E_{eff} for fixed $\langle n_{\mathrm{ch}} \rangle_{|\eta|<0.5}$

Scaling with E_{eff} consistent for the two multiplicity classes within uncertainties

Pythia Monash 2013 fails to reproduce the results

Strangeness vs. effective energy

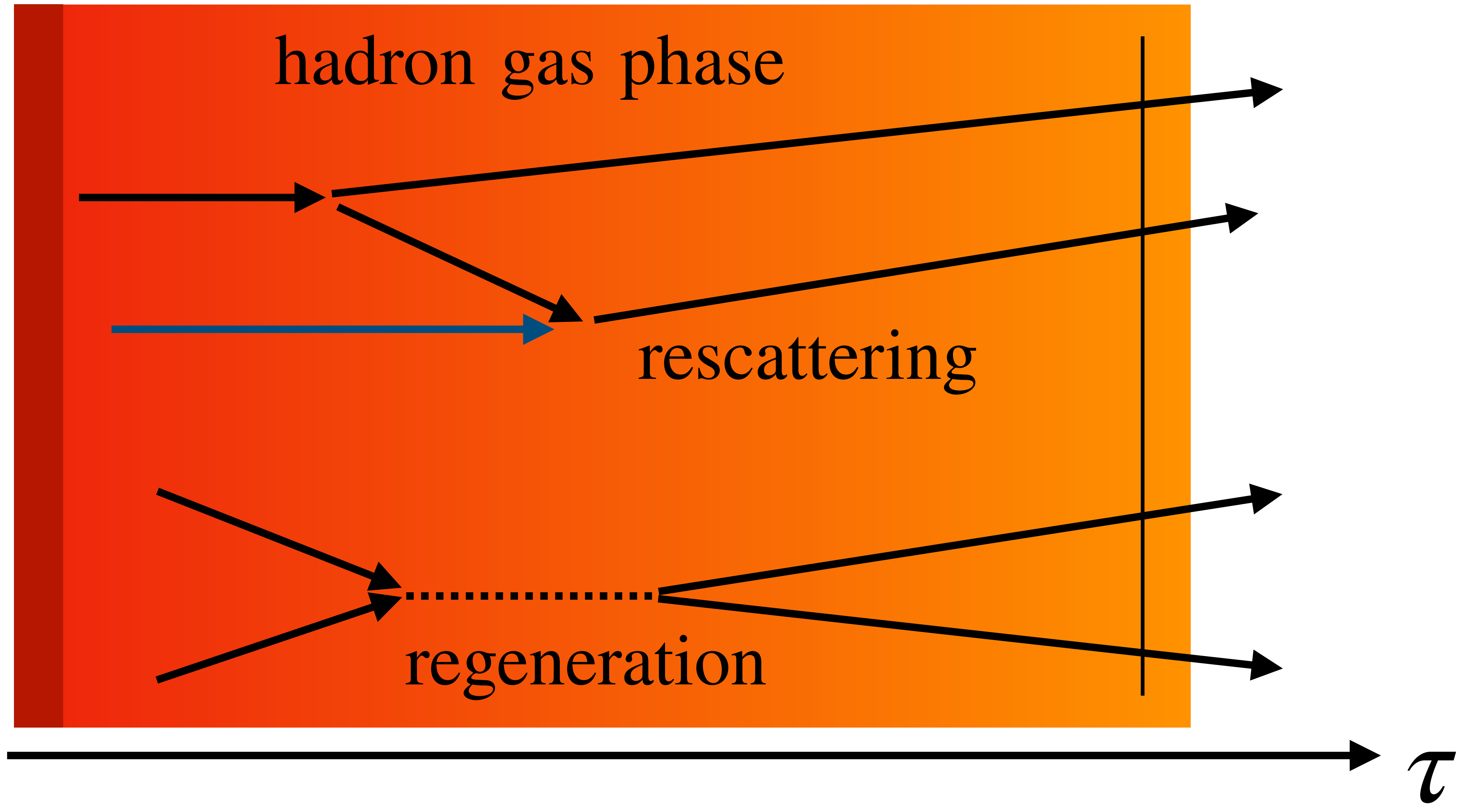


Strange hadron yields per charged particle increases with the E_{eff} for fixed $\langle n_{ch}\rangle_{|\eta|<0.5}$

Scaling with E_{eff} consistent for the two multiplicity classes within uncertainties

Trend well described by Pythia8 Ropes (p_T distributions not reproduced)

Short-lived resonances



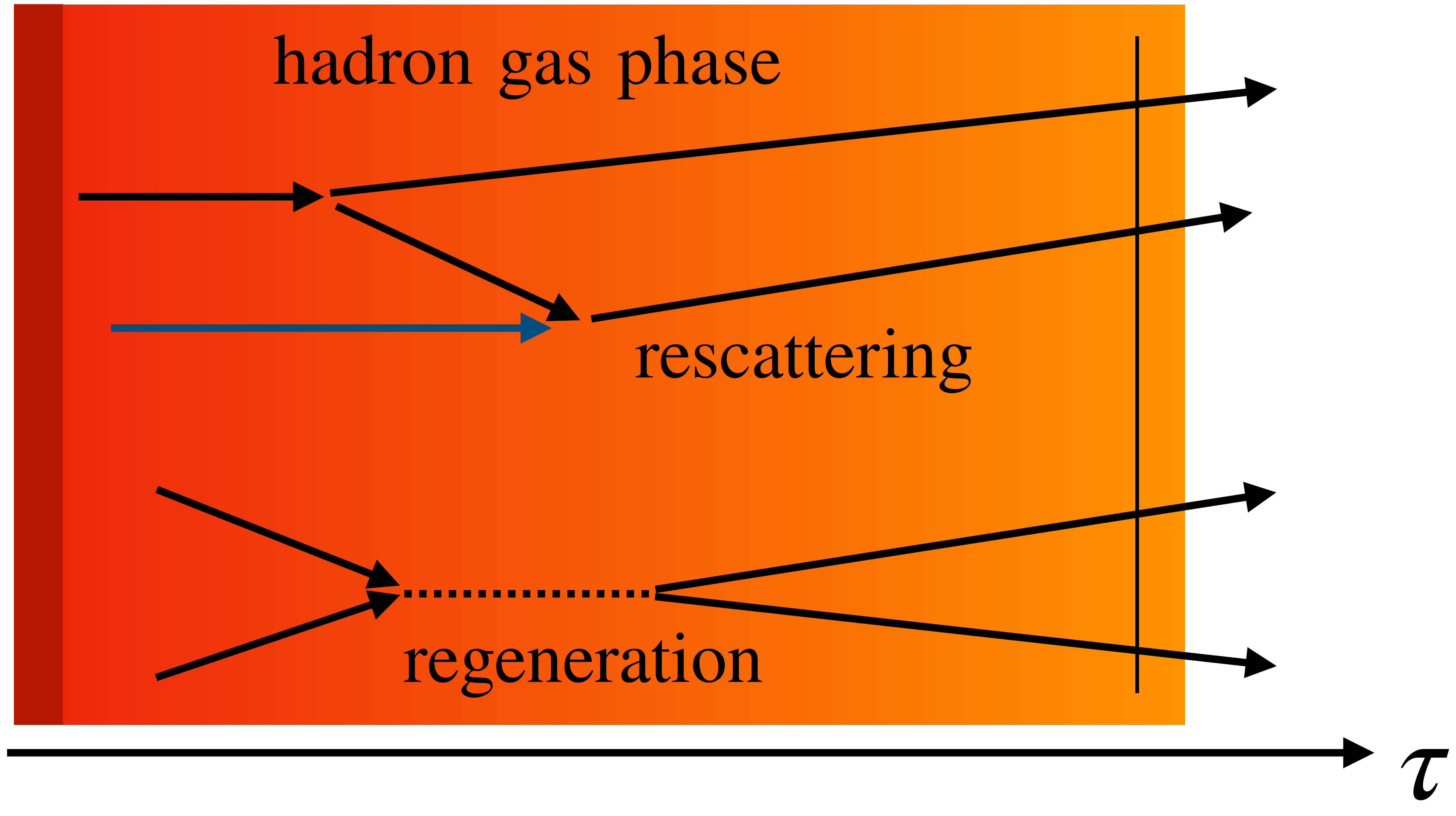
Hadronic resonances have lifetimes comparable to that of the hadron gas phase (few fm/c)

→ reconstructed yields and p_T spectra affected by re-scattering and re-generation effects

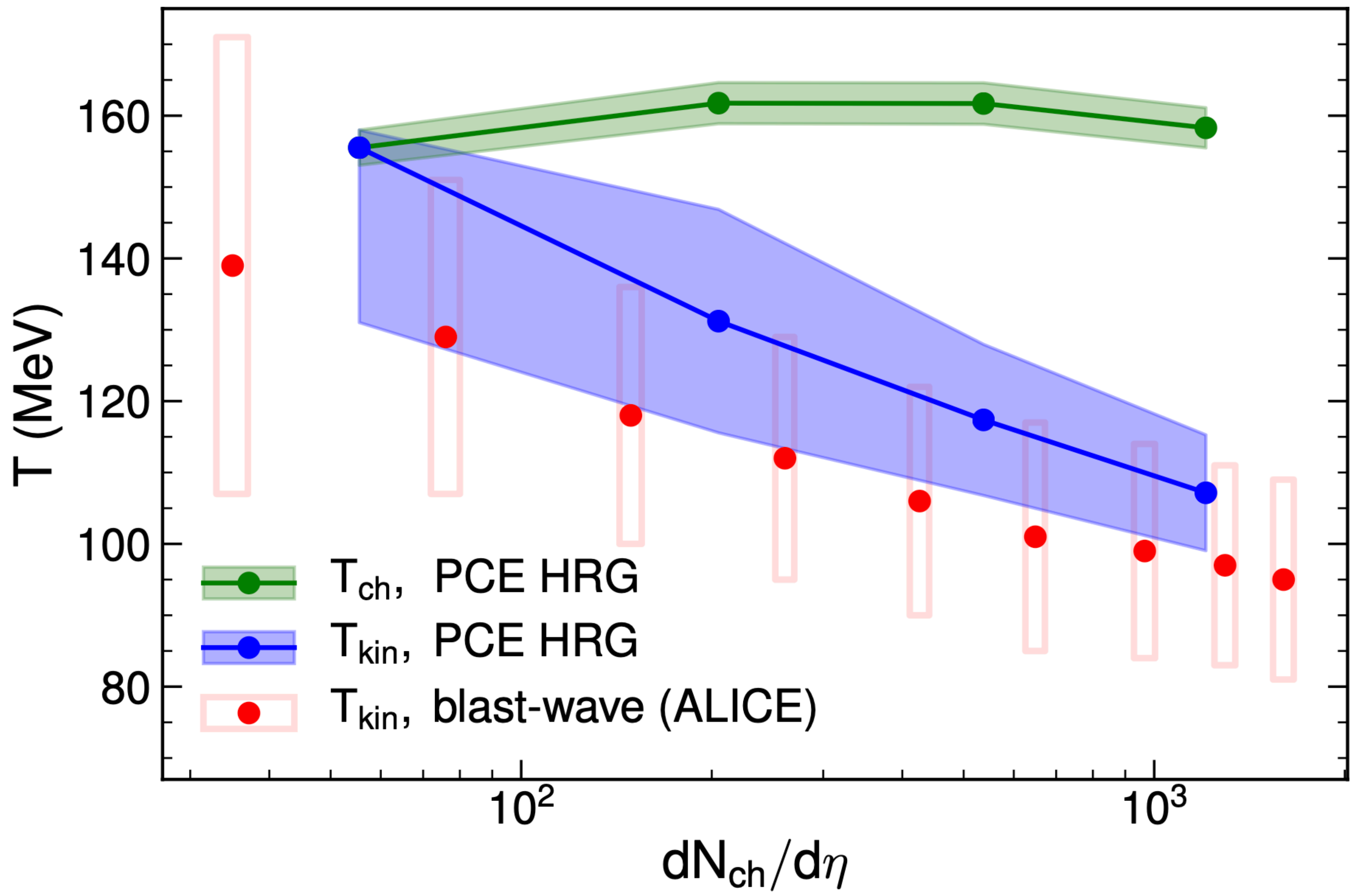
Relative contribution of these competing effects depends on:

- The resonance lifetime relative to that of the hadron gas
- The resonance mean free path
- The density of the hadronic medium

Short-lived resonances



[Phys. Rev. C 102, 024909 (2020)](#)



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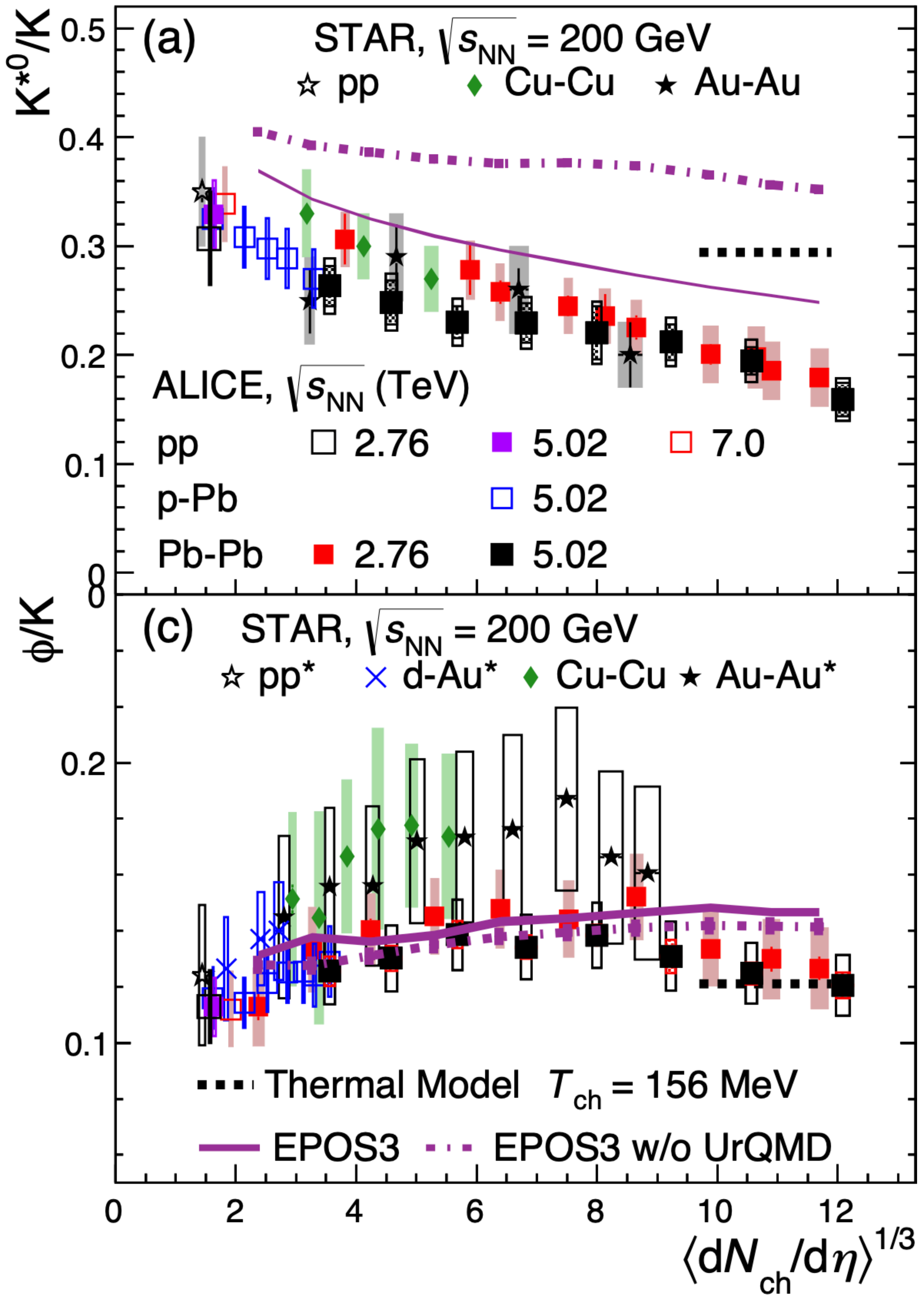
Resonances can be used to extract T_{kin} using hadron resonance gas model in partial chemical equilibrium

→ no assumptions regarding the flow velocity profile and the freeze-out hypersurface

→ consistent results with Blast-wave fits

Rescattering and regeneration

[Phys. Rev. C 106 (2002) 034907](#)

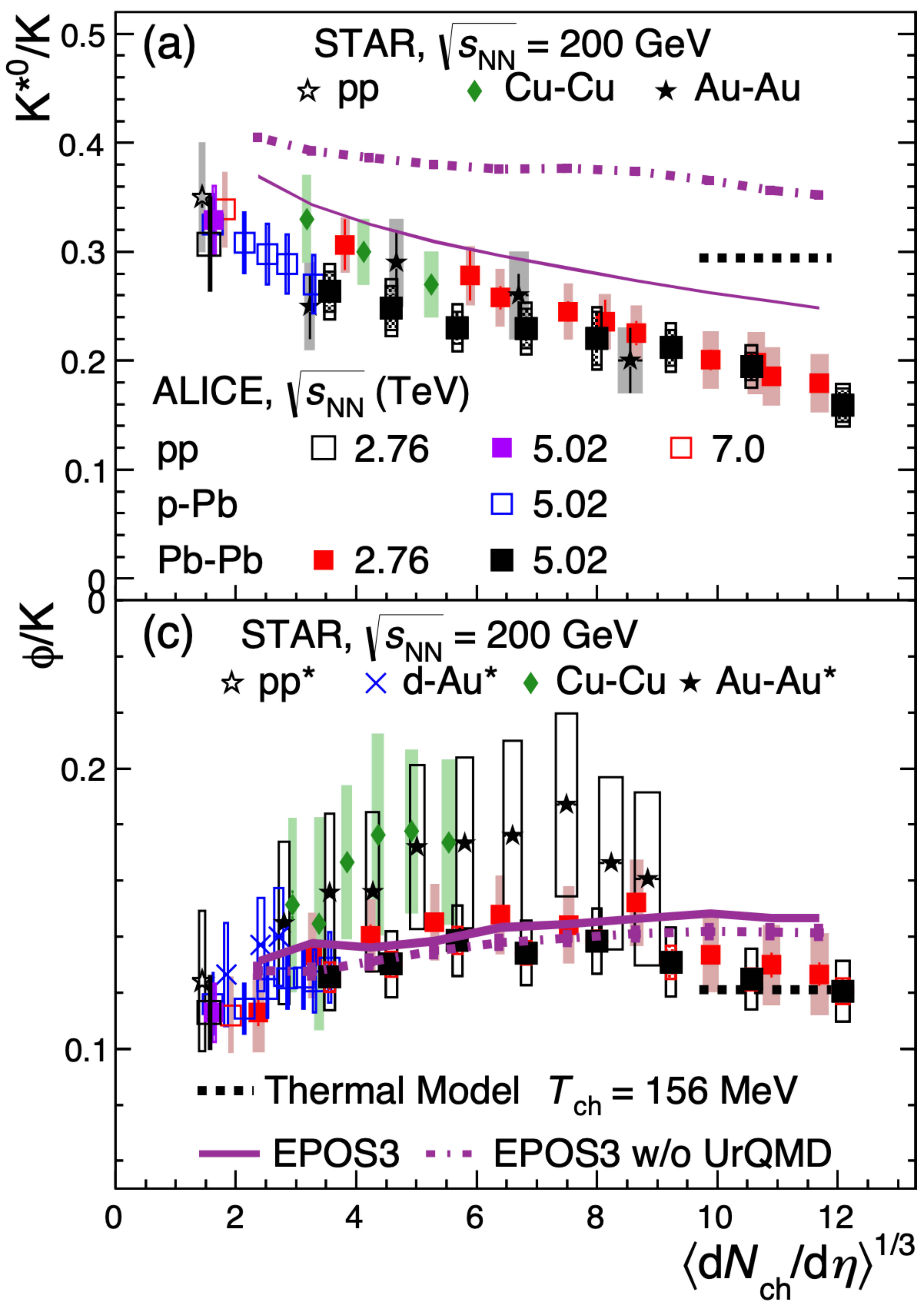


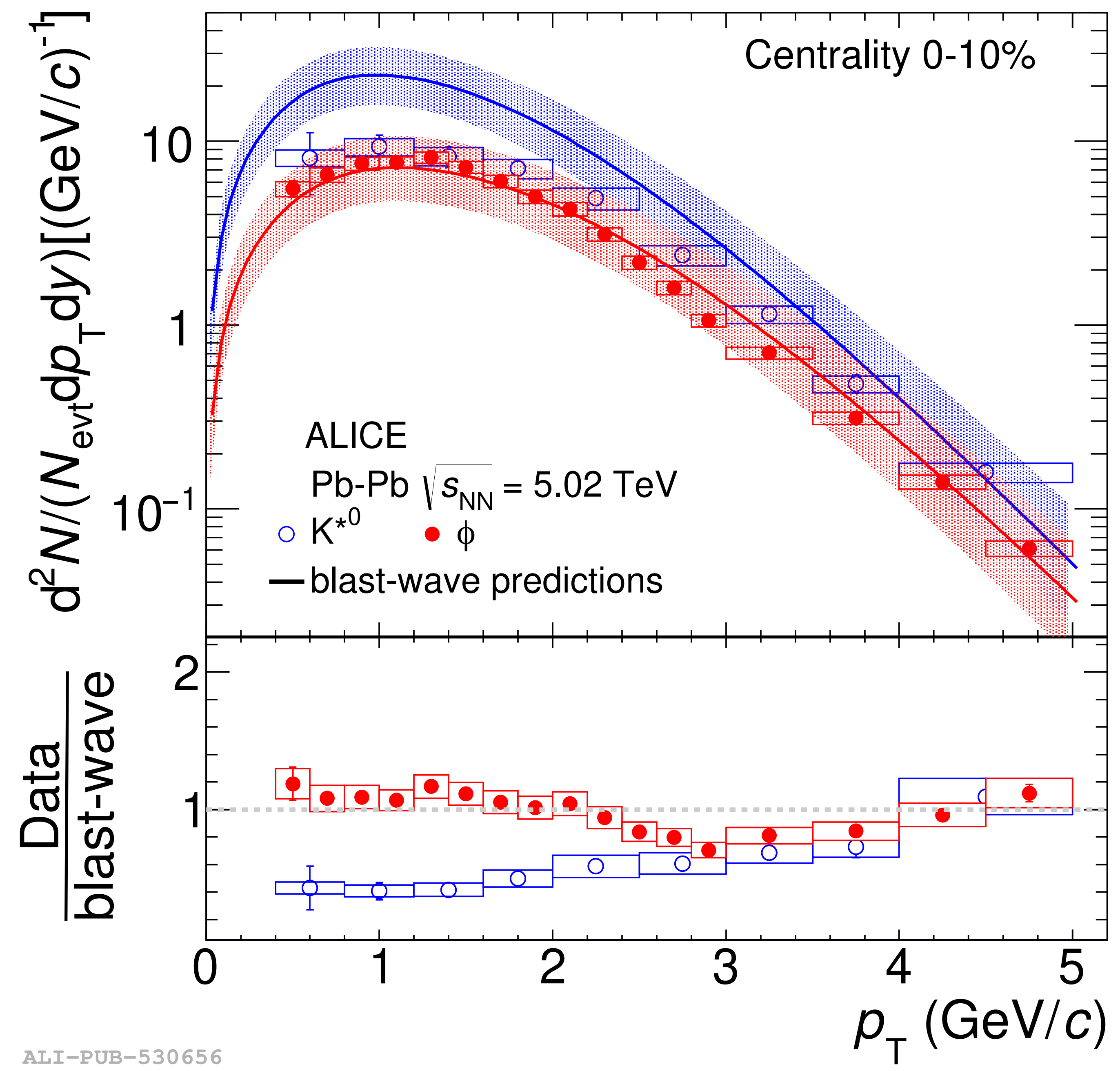
Rescattering and regeneration effects studied by measuring yield ratios of different resonances to corresponding stable hadron vs. $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$

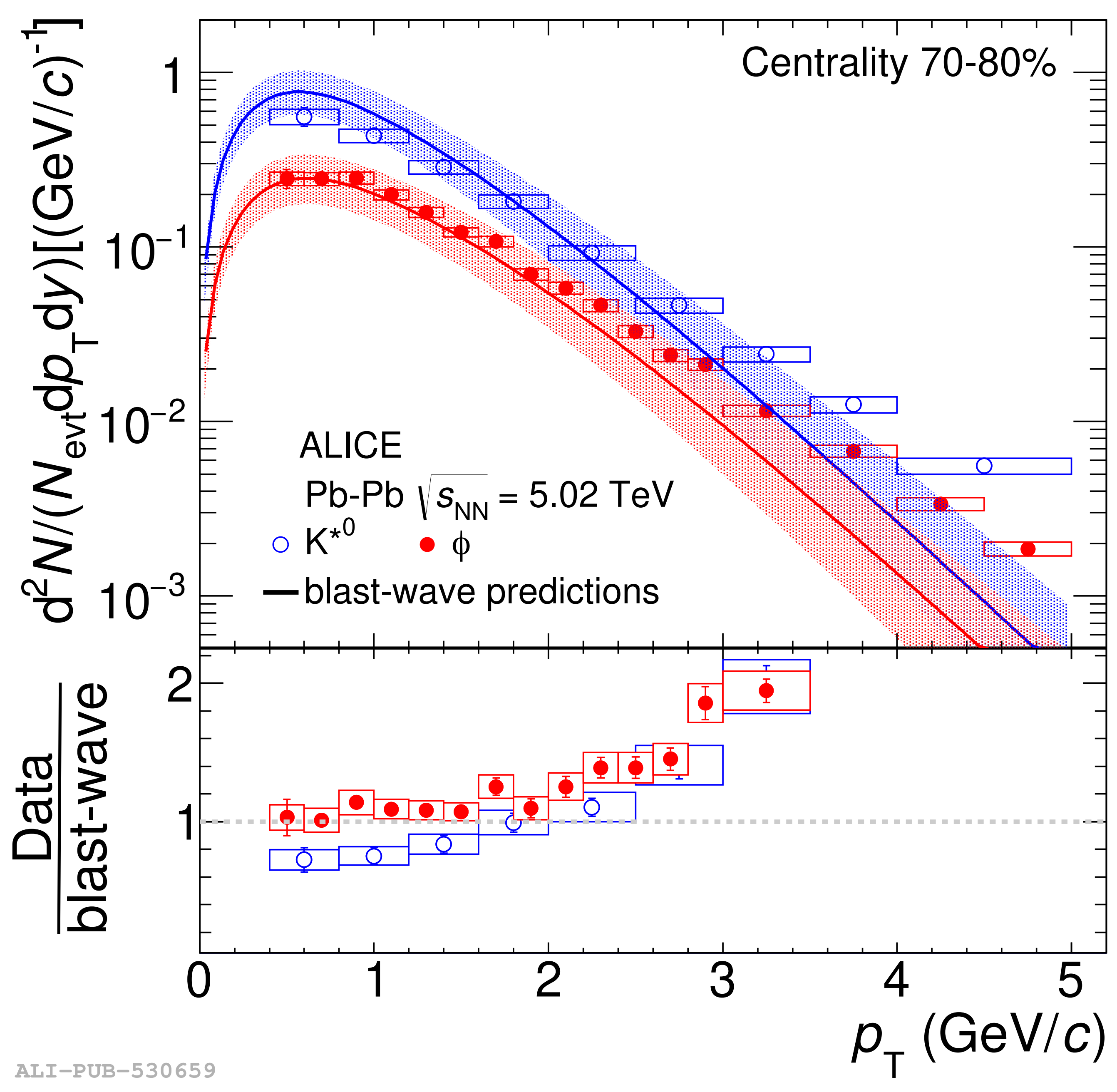
- Significant suppression of K^*/K with increasing multiplicity
- Almost flat trend for ϕ/K

Rescattering and regeneration

[Phys. Rev. C 106 (2002) 034907]







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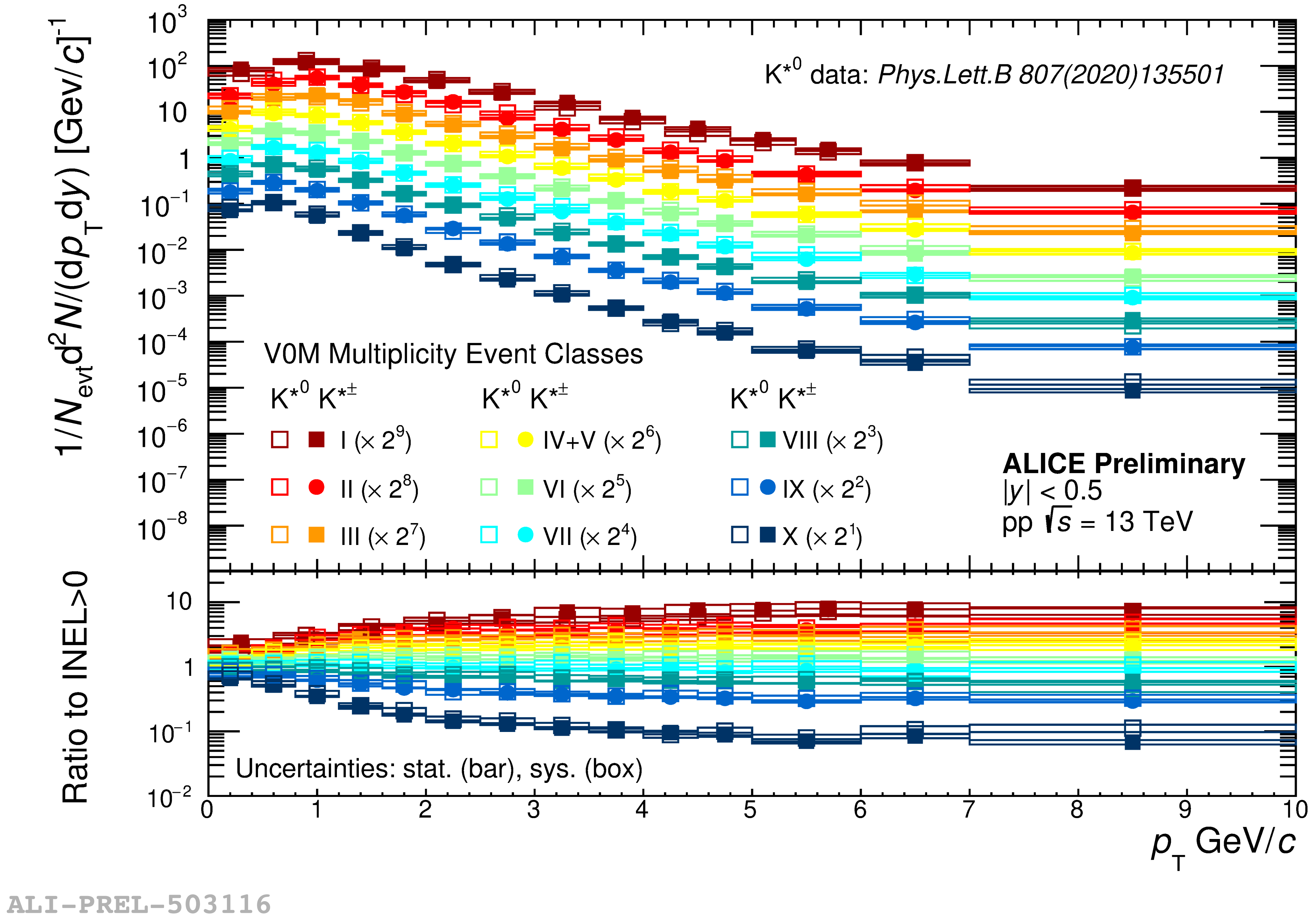
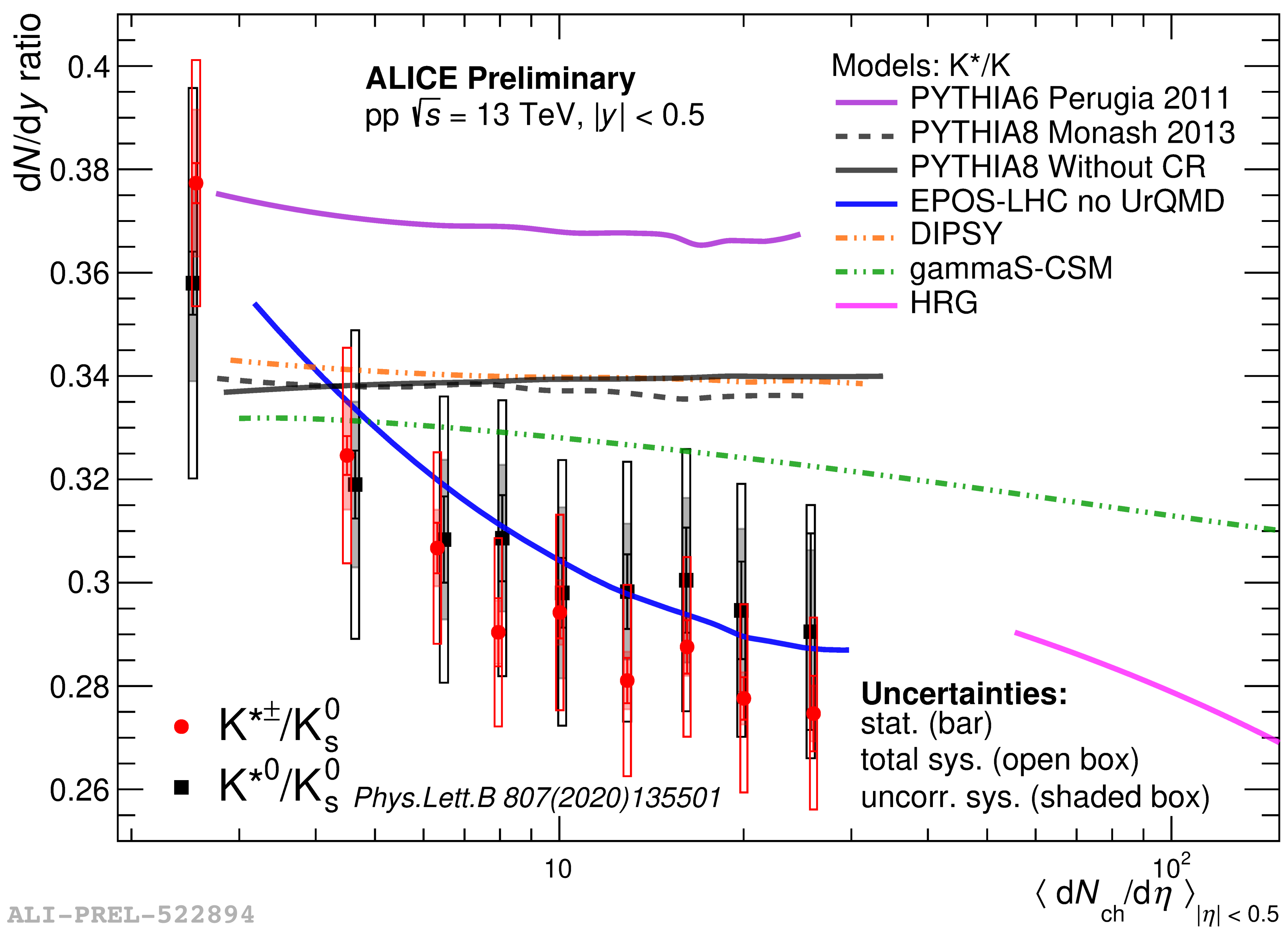
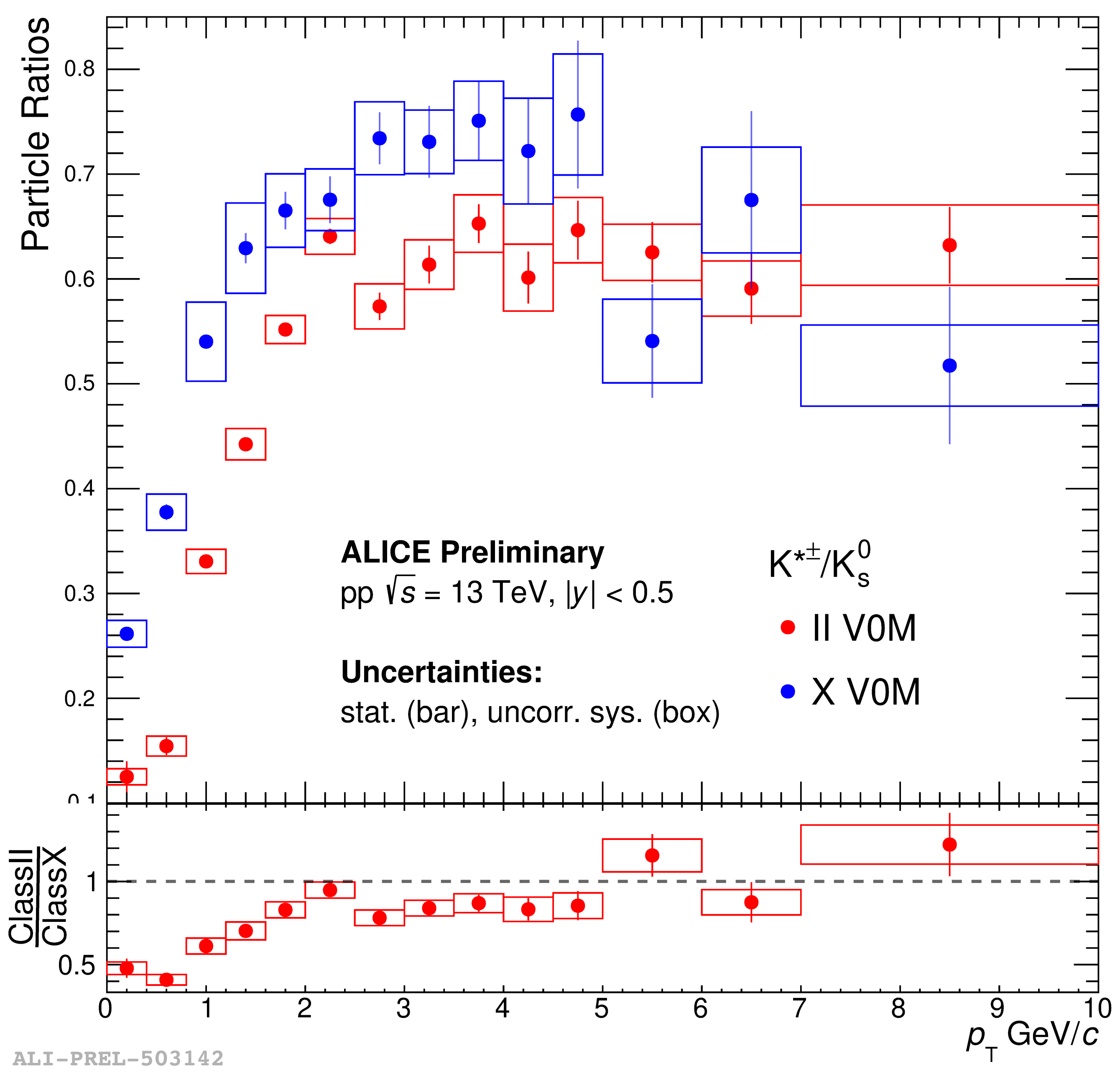
Effects of hadronic interactions with the medium are stronger in more central collisions and at low p_T

Resonances in small systems





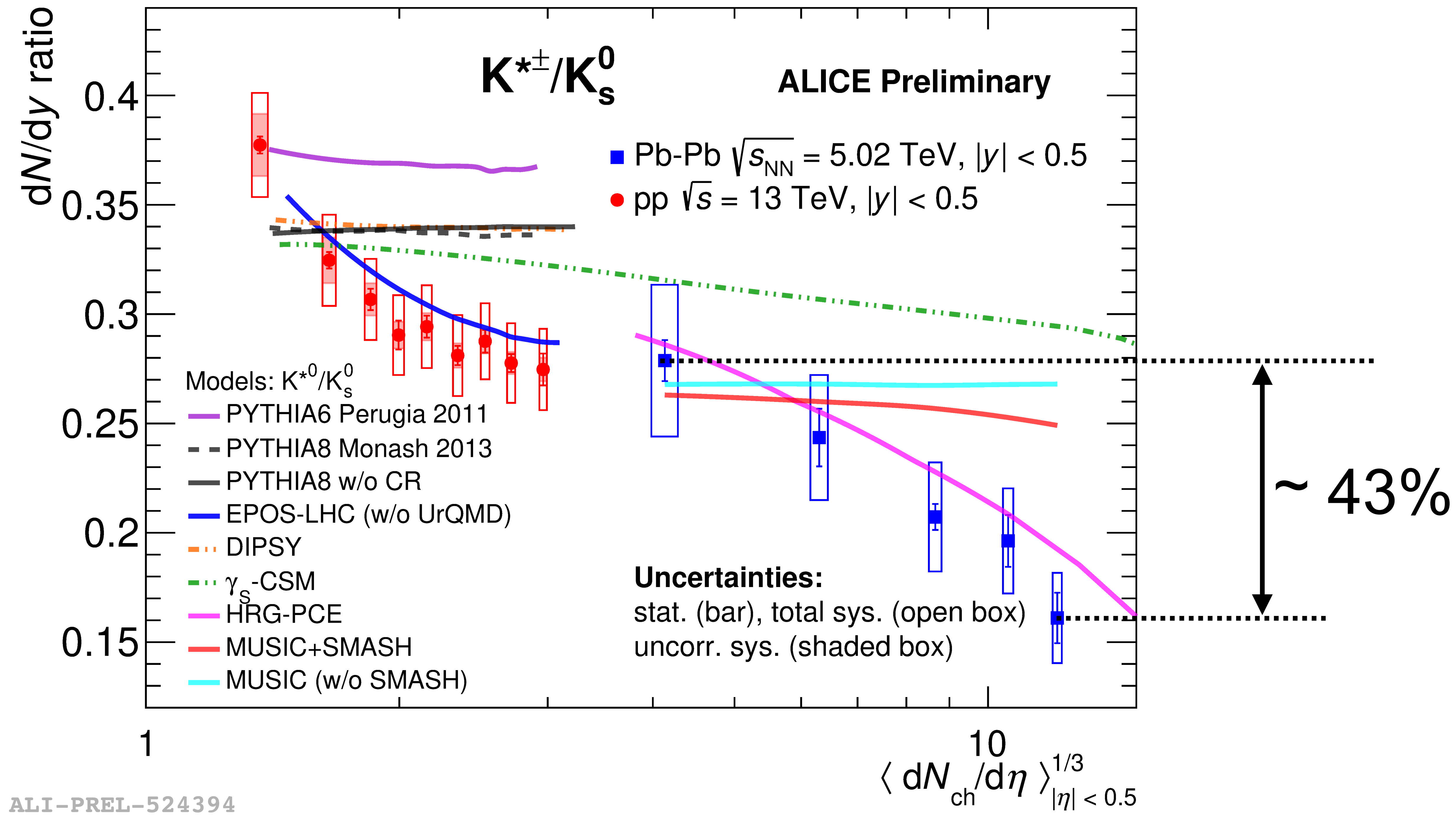


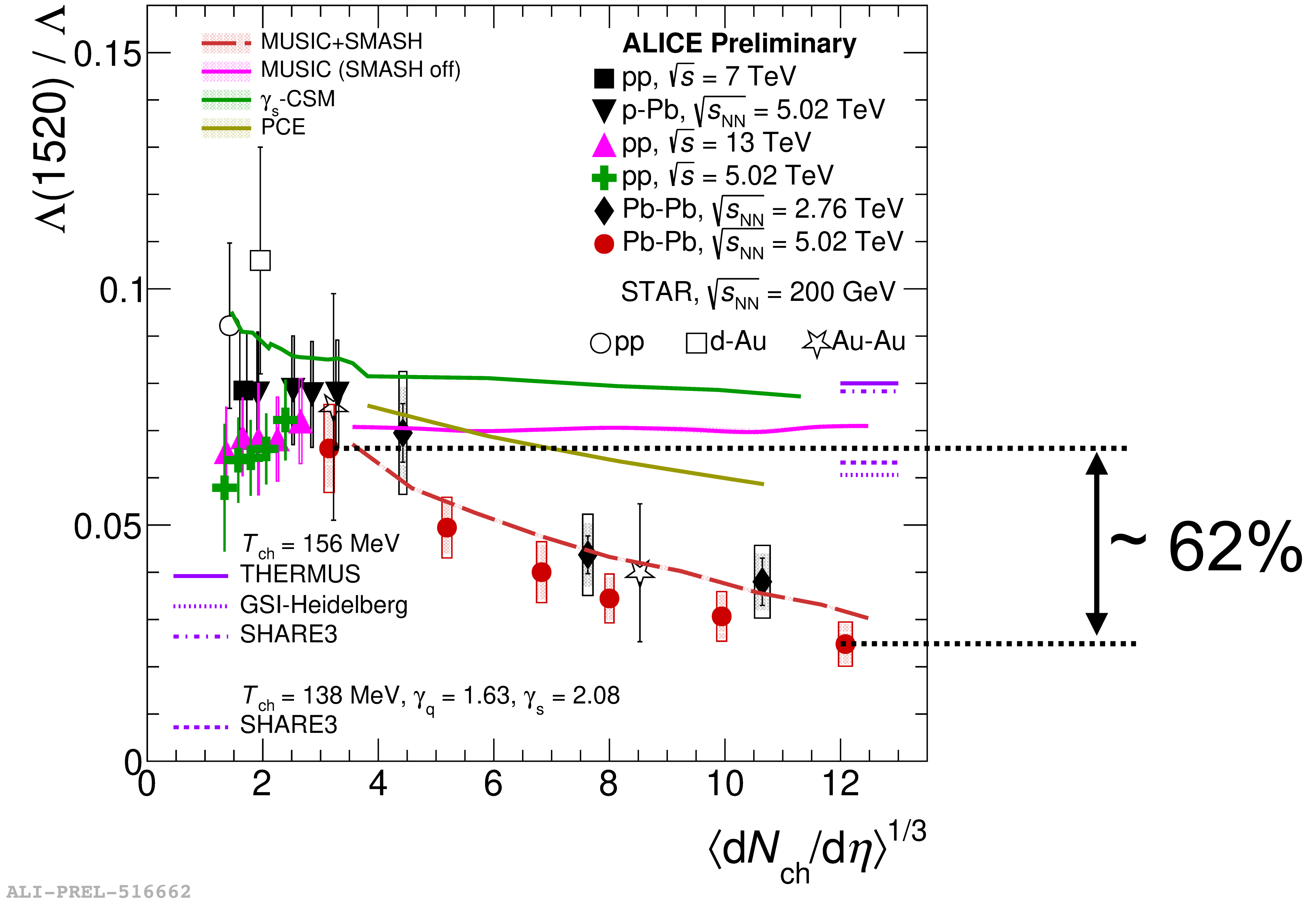
Measurement of K* production in pp collisions shows effects that are similar to heavy-ion collisions:

- Hardening of p_T spectra + shift of the maximum (similar to radial flow)
- Suppression of K^*/K ratio with increasing multiplicity
- Stronger suppression for higher multiplicity at low p_T

→ Short-lived hadronic phase in small collision systems?

Resonances with different lifetimes



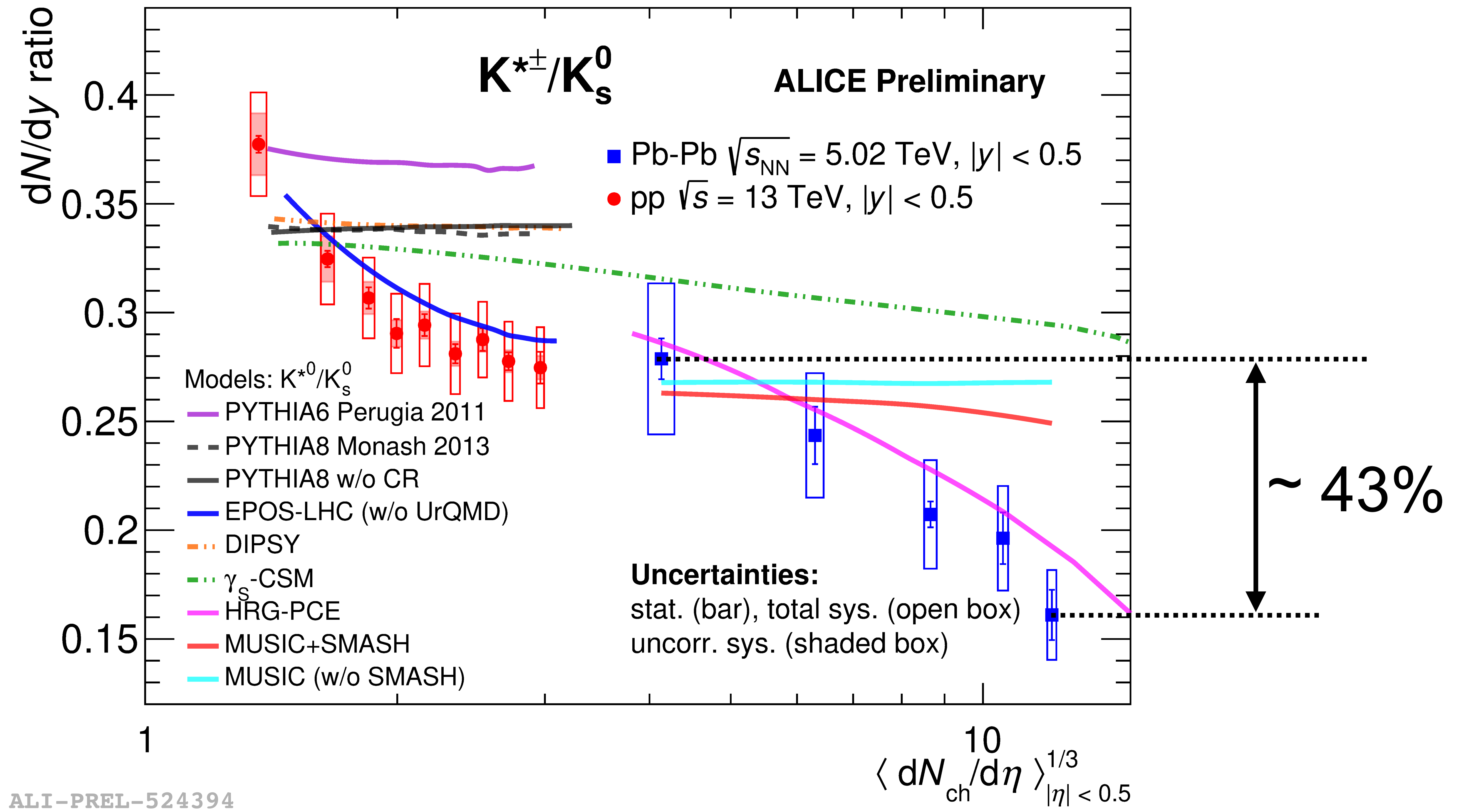


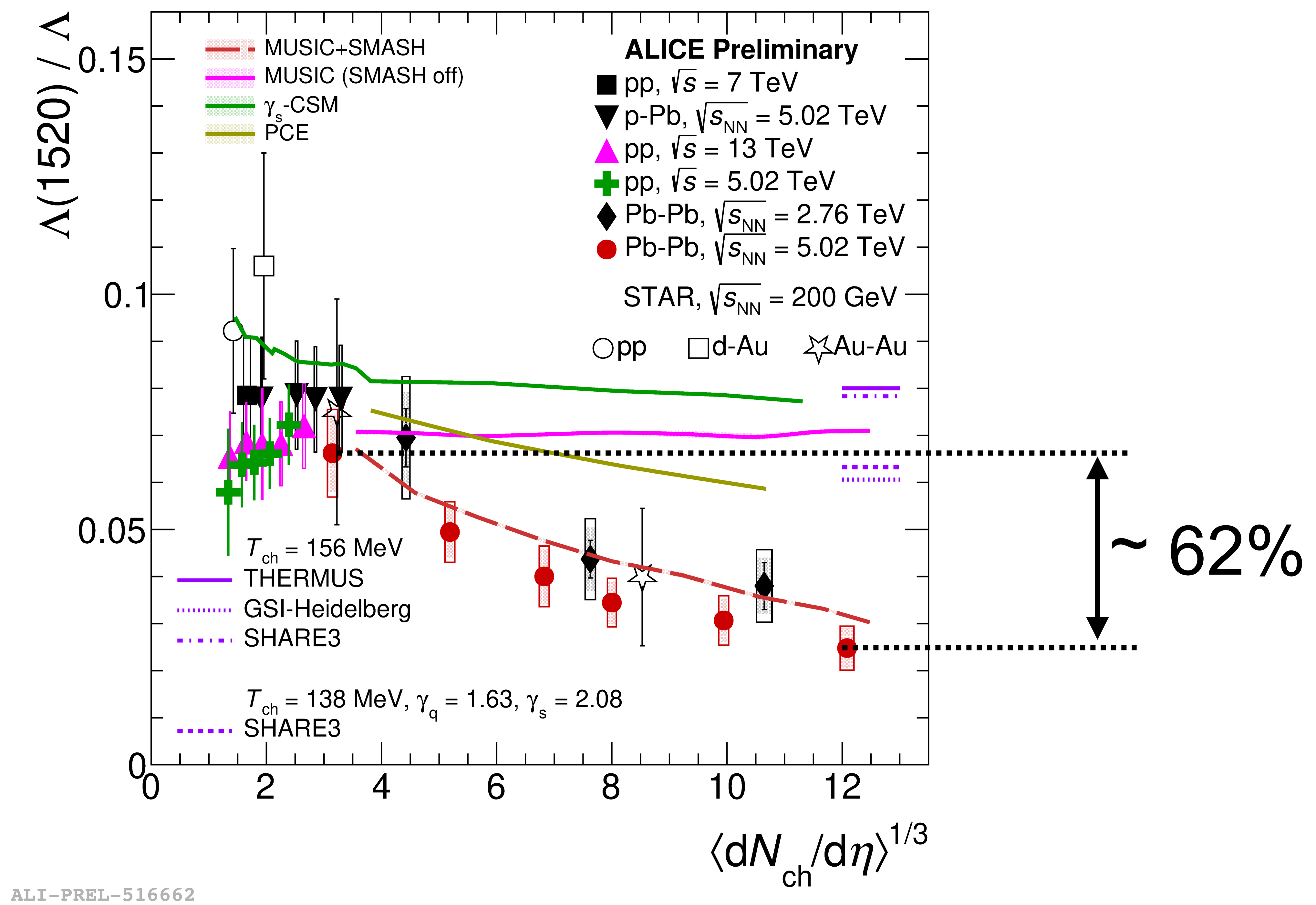
Interplay between rescattering and regeneration does not depend only on the resonance lifetime

$$\tau_{K^*} = (4.17 \pm 0.04)\ \text{fm/c}$$
$$\tau_{\Lambda^*} = (12.6 \pm 0.8)\ \text{fm/c}$$

Larger suppression for Λ^*/Λ wrt K*/K despite Λ^* has longer lifetime
→ lifetime is not a good predictor

Resonances with different lifetimes





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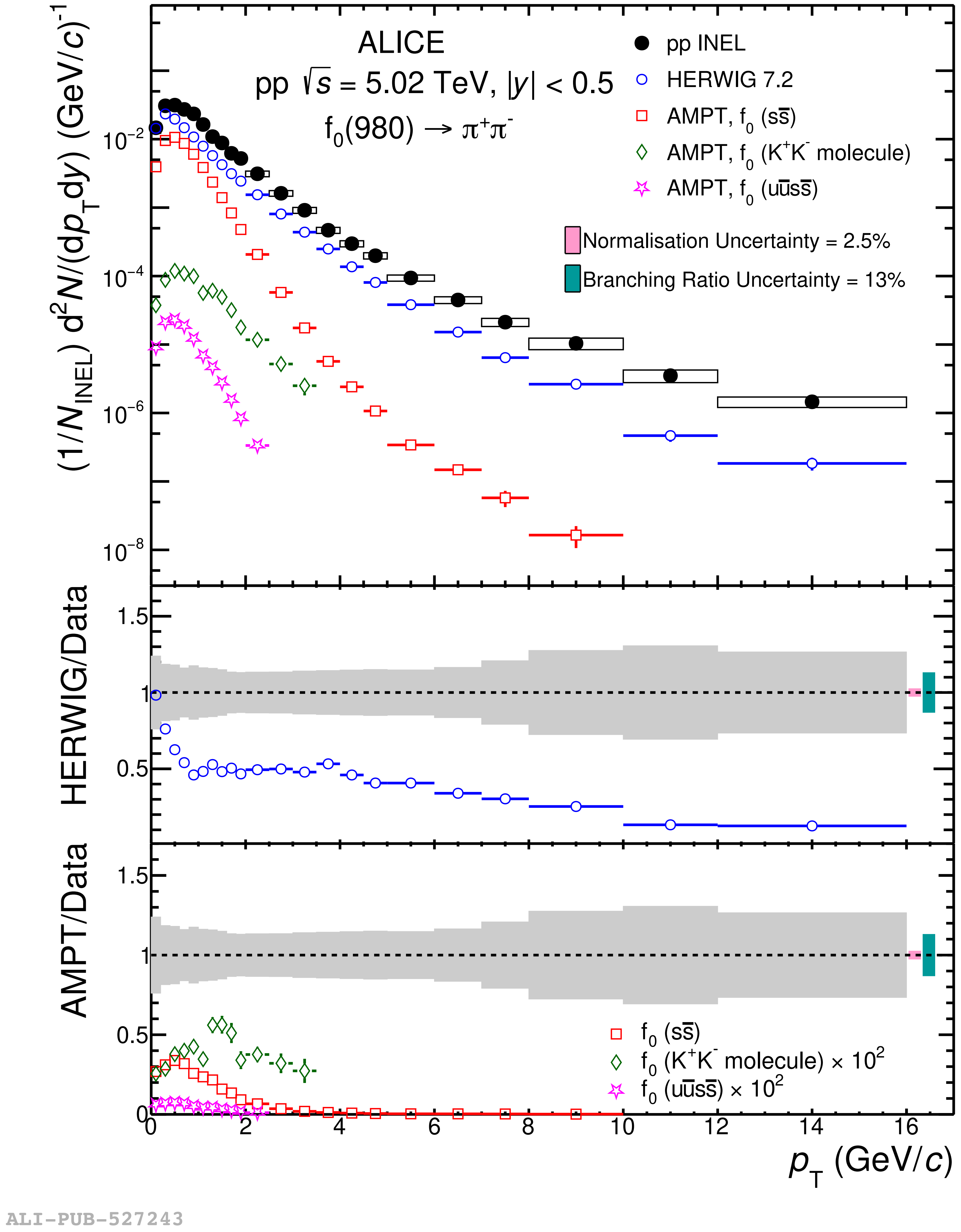
Larger suppression for Λ^*/Λ wrt K*/K despite Λ^* has longer lifetime
→ lifetime is not a good predictor

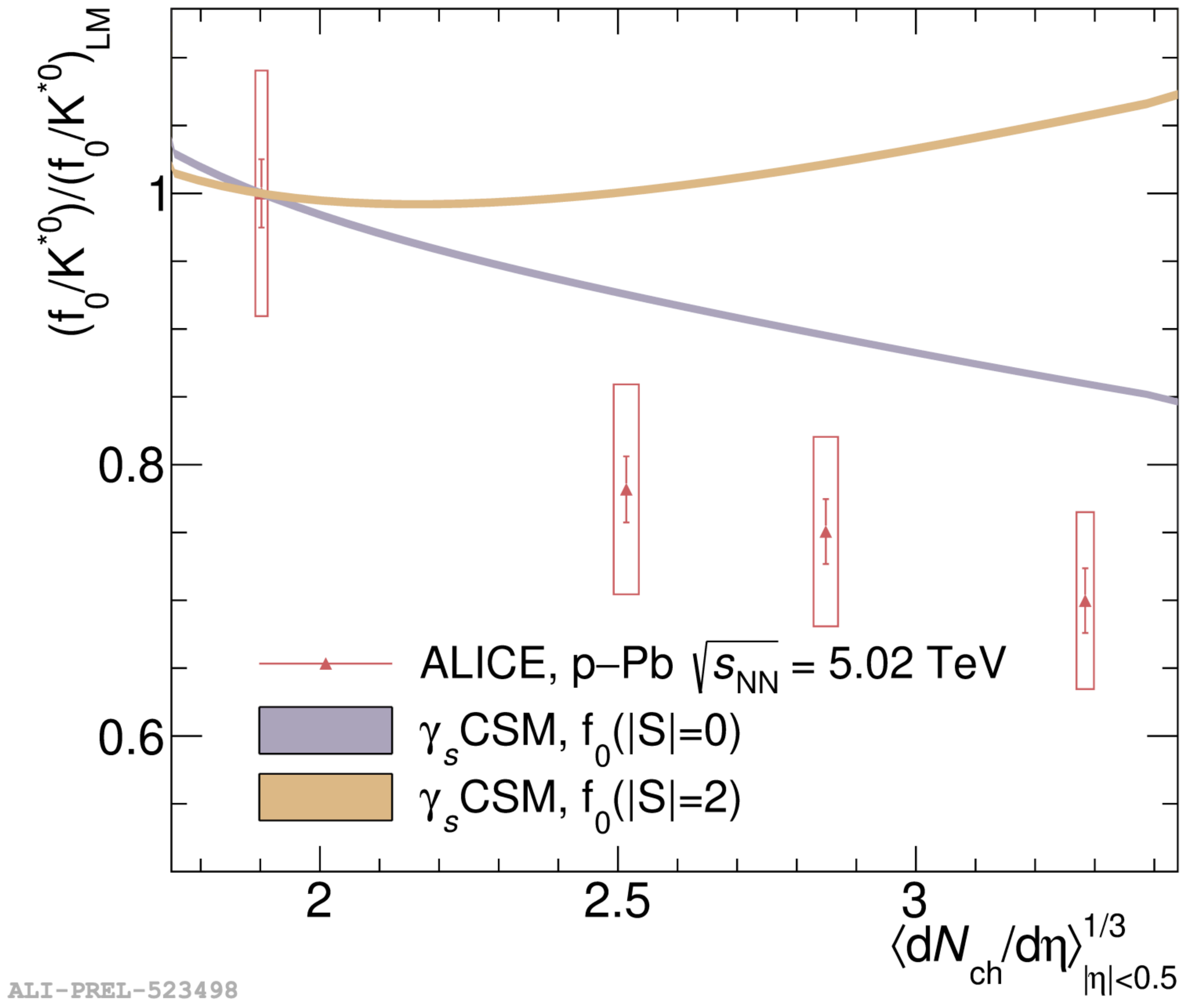
Lower regeneration probability for higher mass: Λ^*/Λ dominated by rescattering of decay daughters
Models do not simultaneously describe both K^*/K and Λ^*/Λ

Exotic resonances

[arXiv:2206.06216 [nucl-ex]]



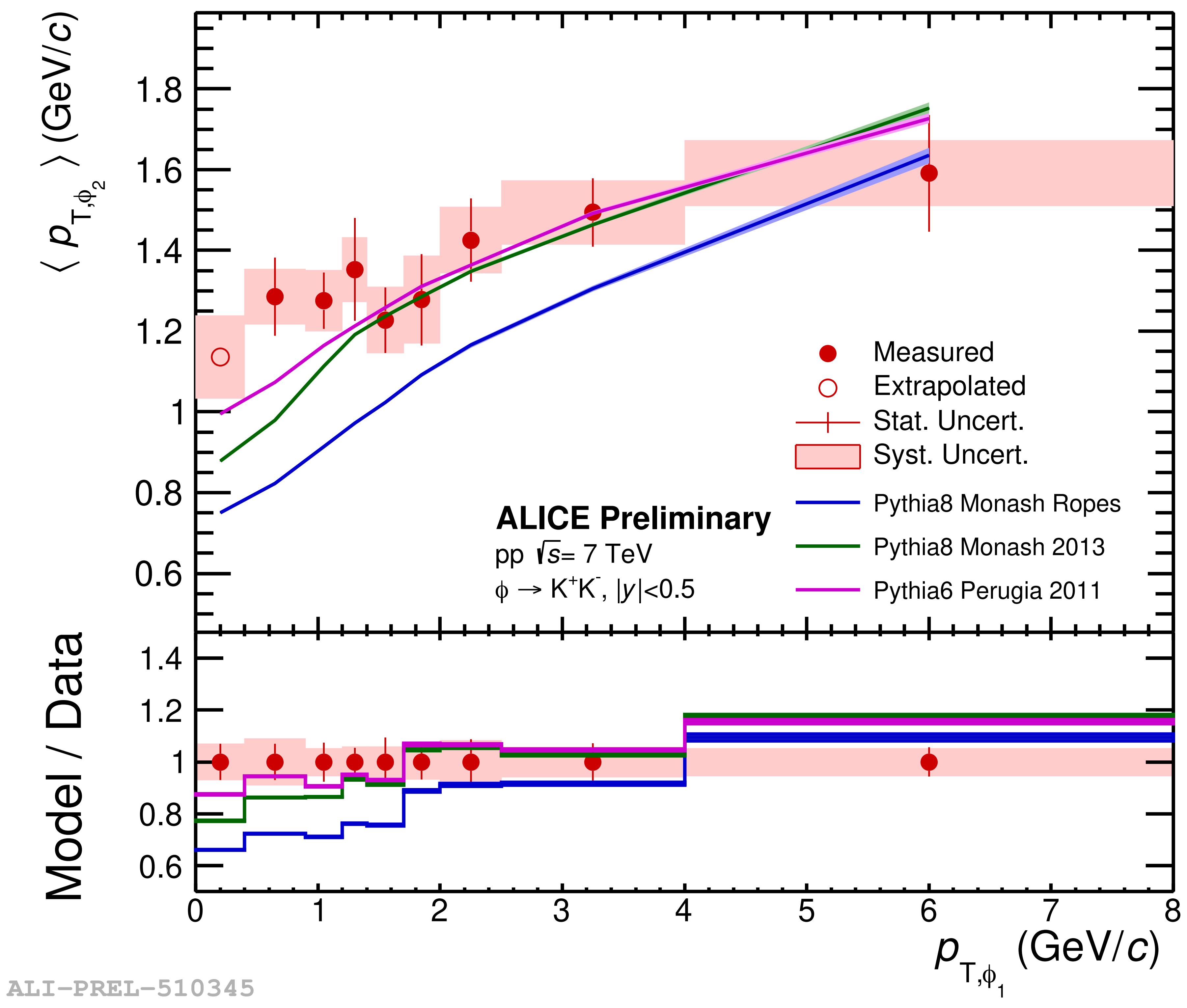
Vovchenko et al, PRC 100 (2019) 5, 054906

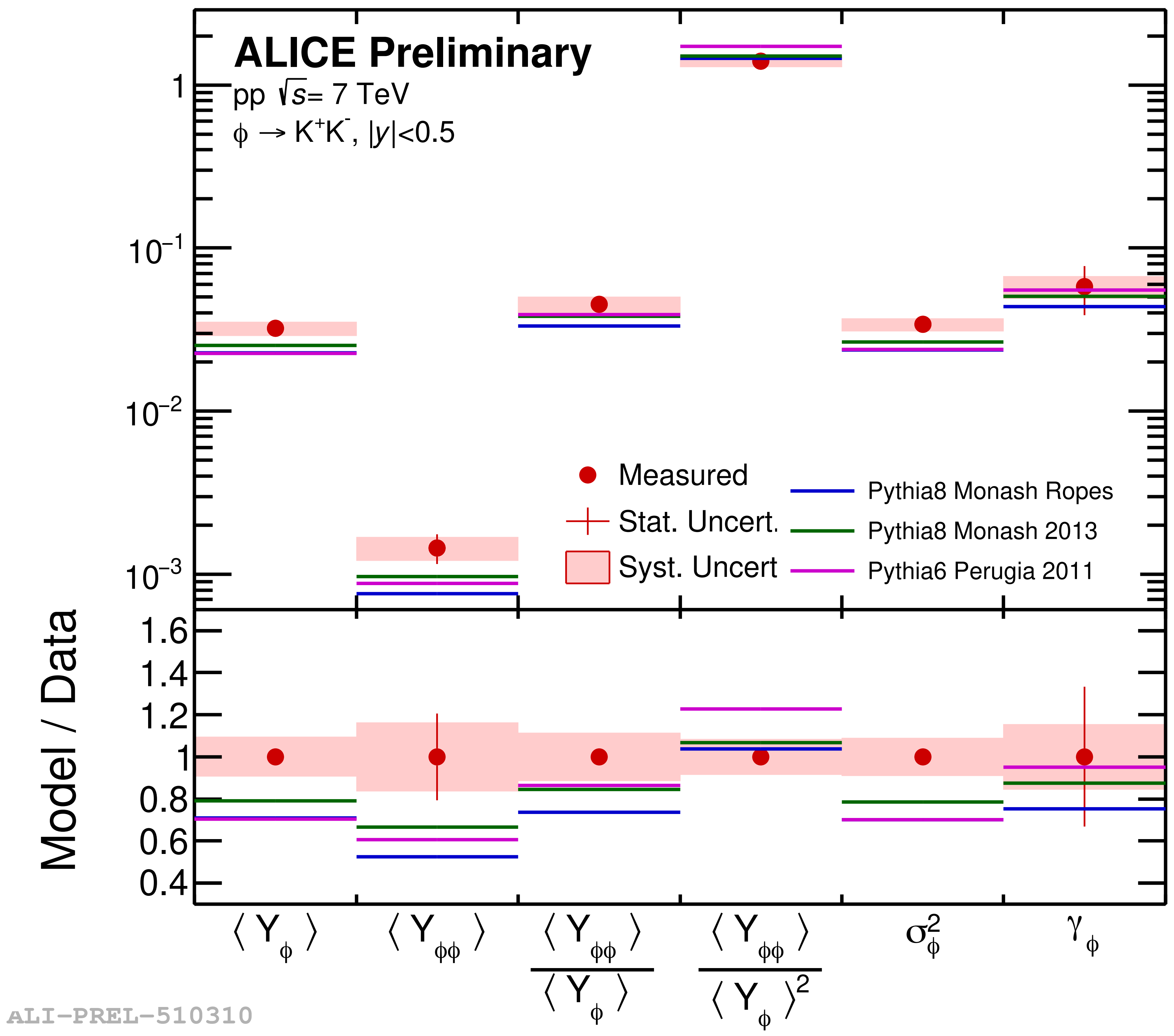


Measurements of $f_0(980)$ production in different collision systems used to study its internal structure

Different scenarios are tested: $s\bar{s}$, KK molecule, tetraquark
→ No conclusive statement

Double-ϕ production

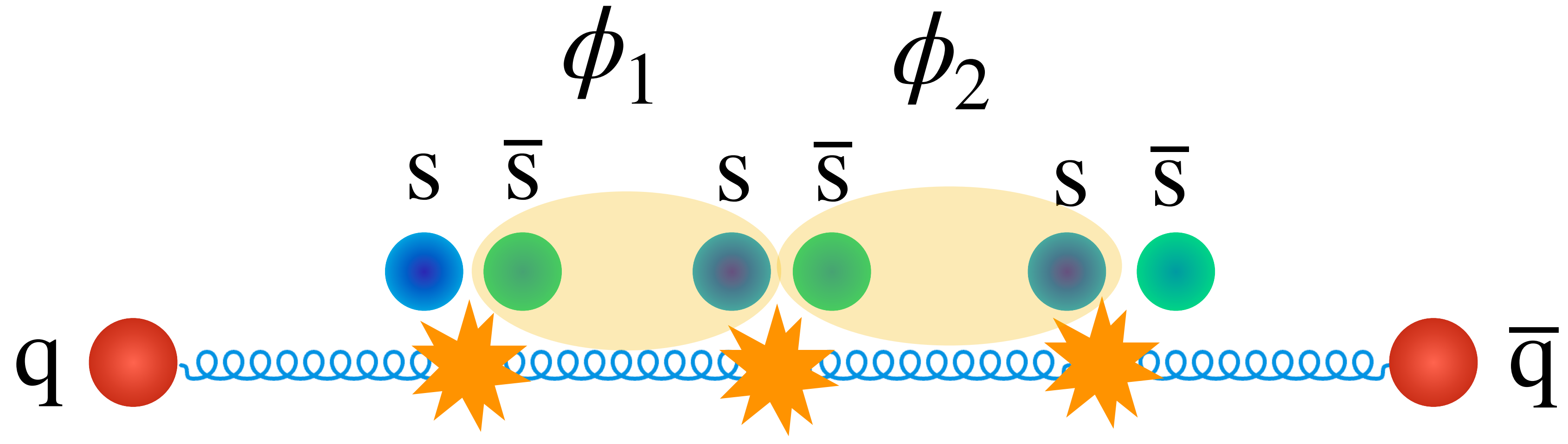




$$\gamma_\phi = \frac{\sigma_\phi^2}{\langle Y_\phi \rangle} - 1$$

Measurement of ϕ-meson pair production used to constrain particle production models

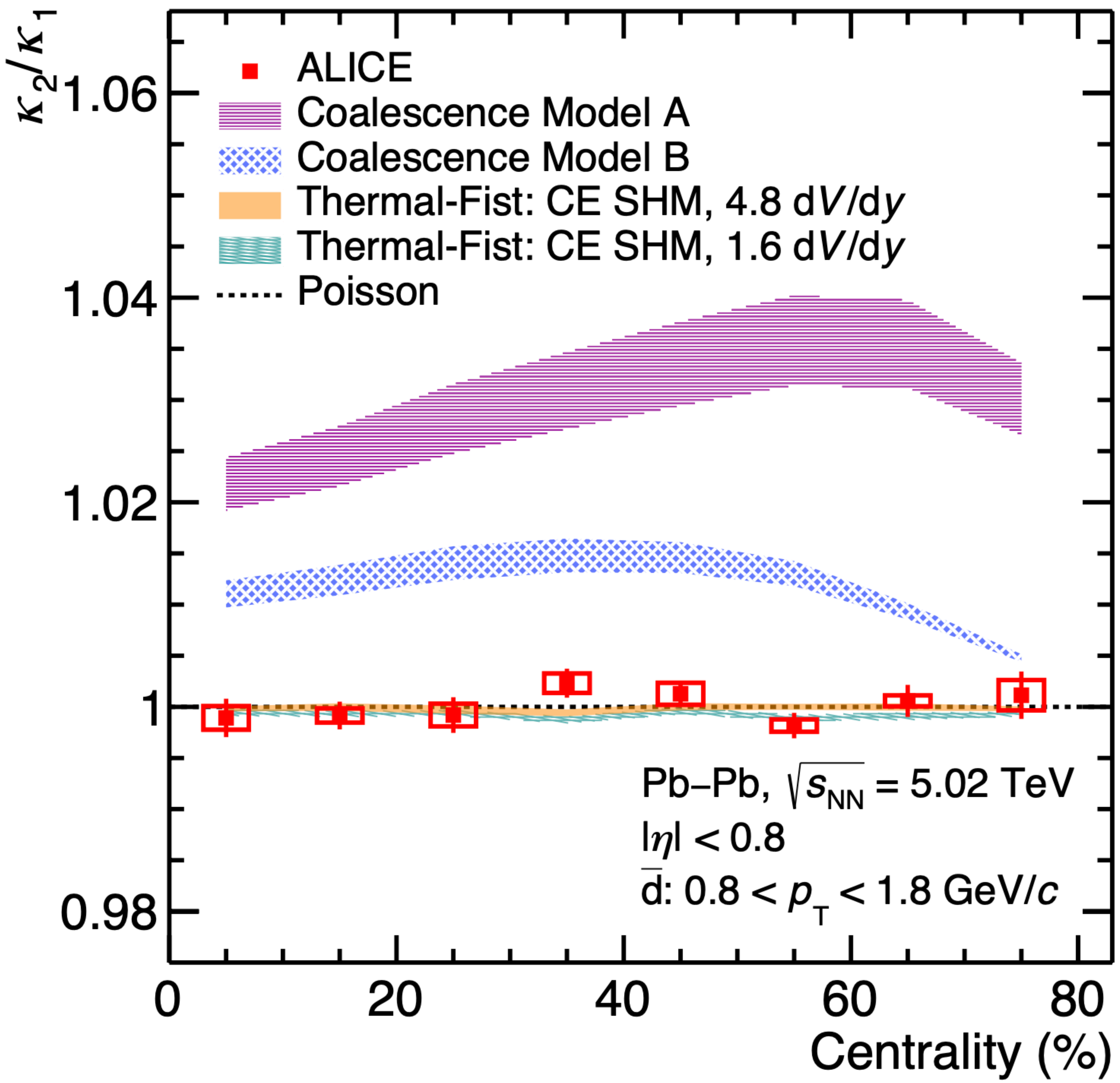
> average yield of single and double-ϕ underestimated by different tunes of Pythia8



three string breaking events coming from the same $q\bar{q}$ pair

Deuteron number fluctuations

arXiv:2204.10166 [nucl-ex]



New observable based on event-by-event (anti)deuteron fluctuations to distinguish SHM and coalescence

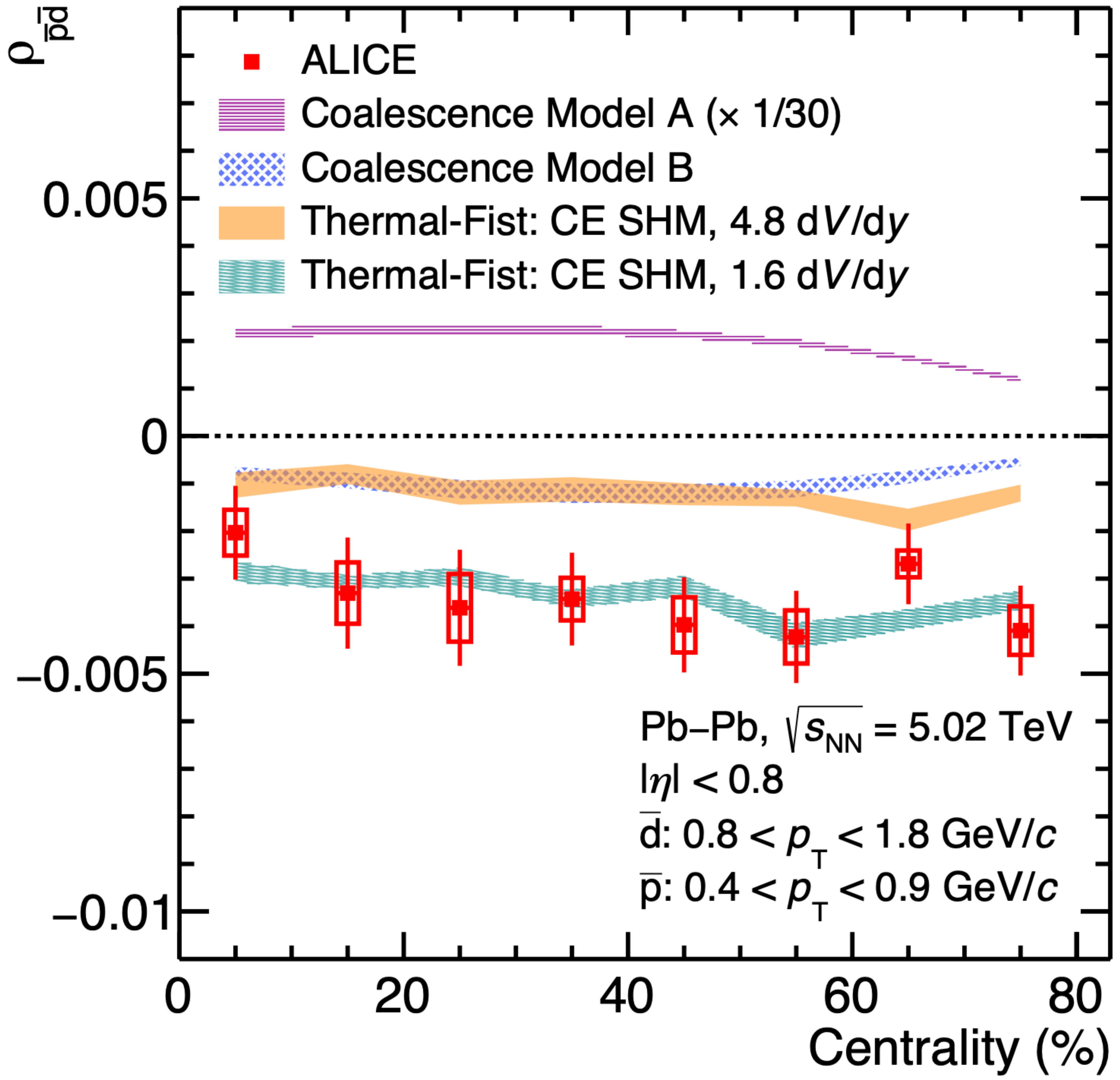
$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

Cumulant ratio favors canonical statistical model

Coalescence Model A: full correlation of *p* and *n*
Coalescence Model B: independent *p* and *n* fluctuations

Correlation volume

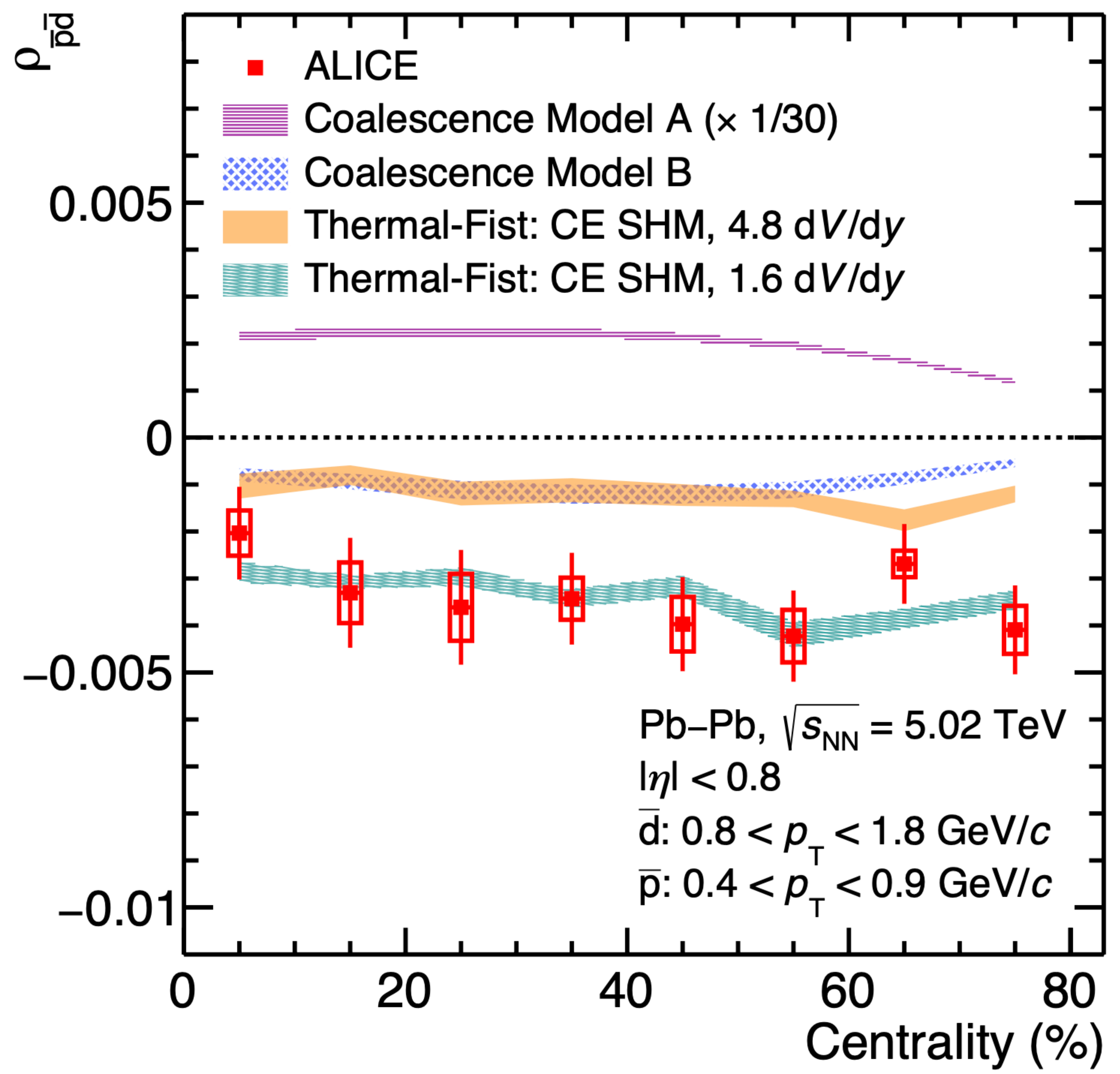
arXiv:2204.10166 [nucl-ex]



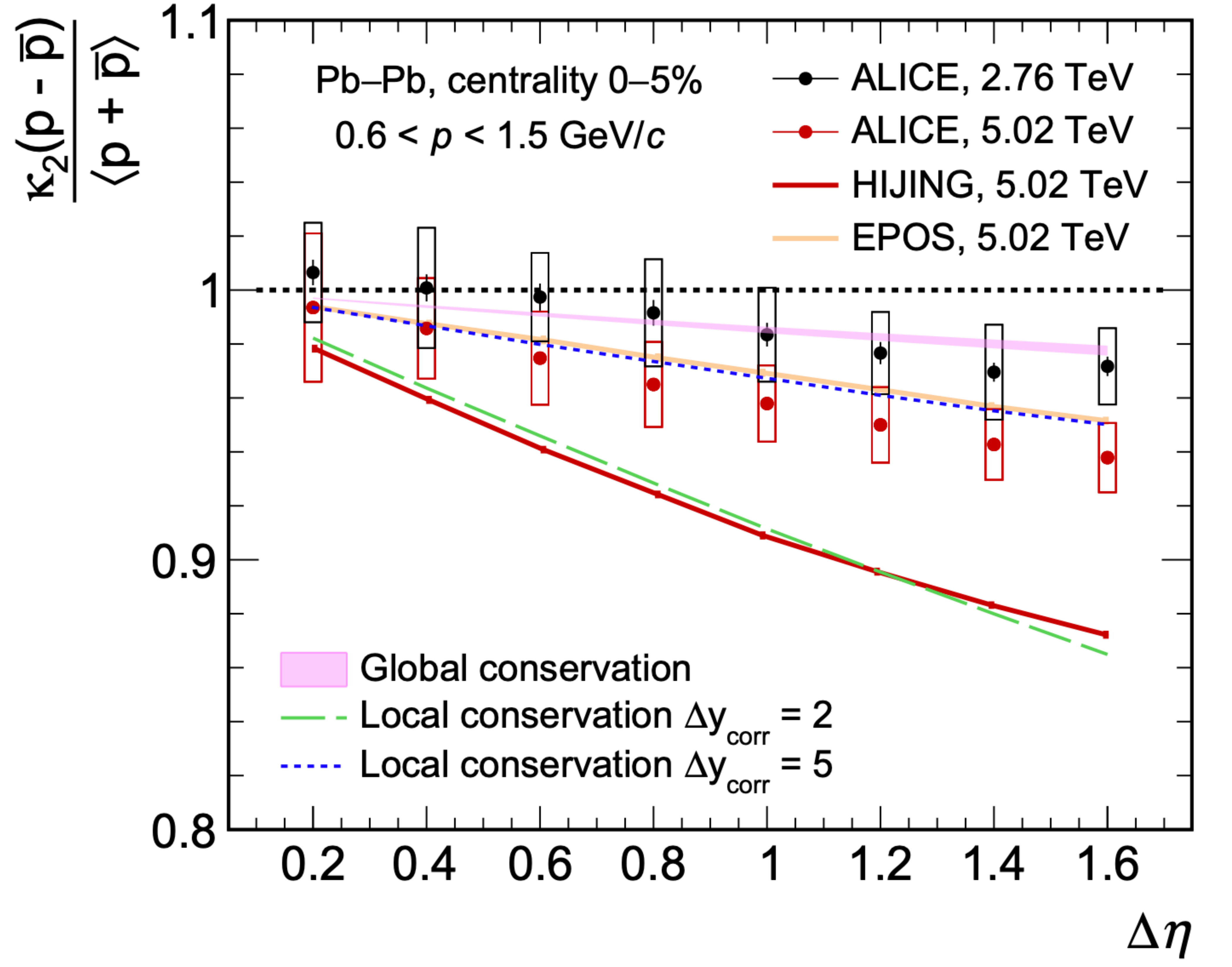
Pearson correlation $\rho_{\bar{p}\bar{d}}$ clearly indicates a correlation volume for baryon number conservation of 1.6 units of rapidity

Correlation volume

arXiv:2204.10166 [nucl-ex]



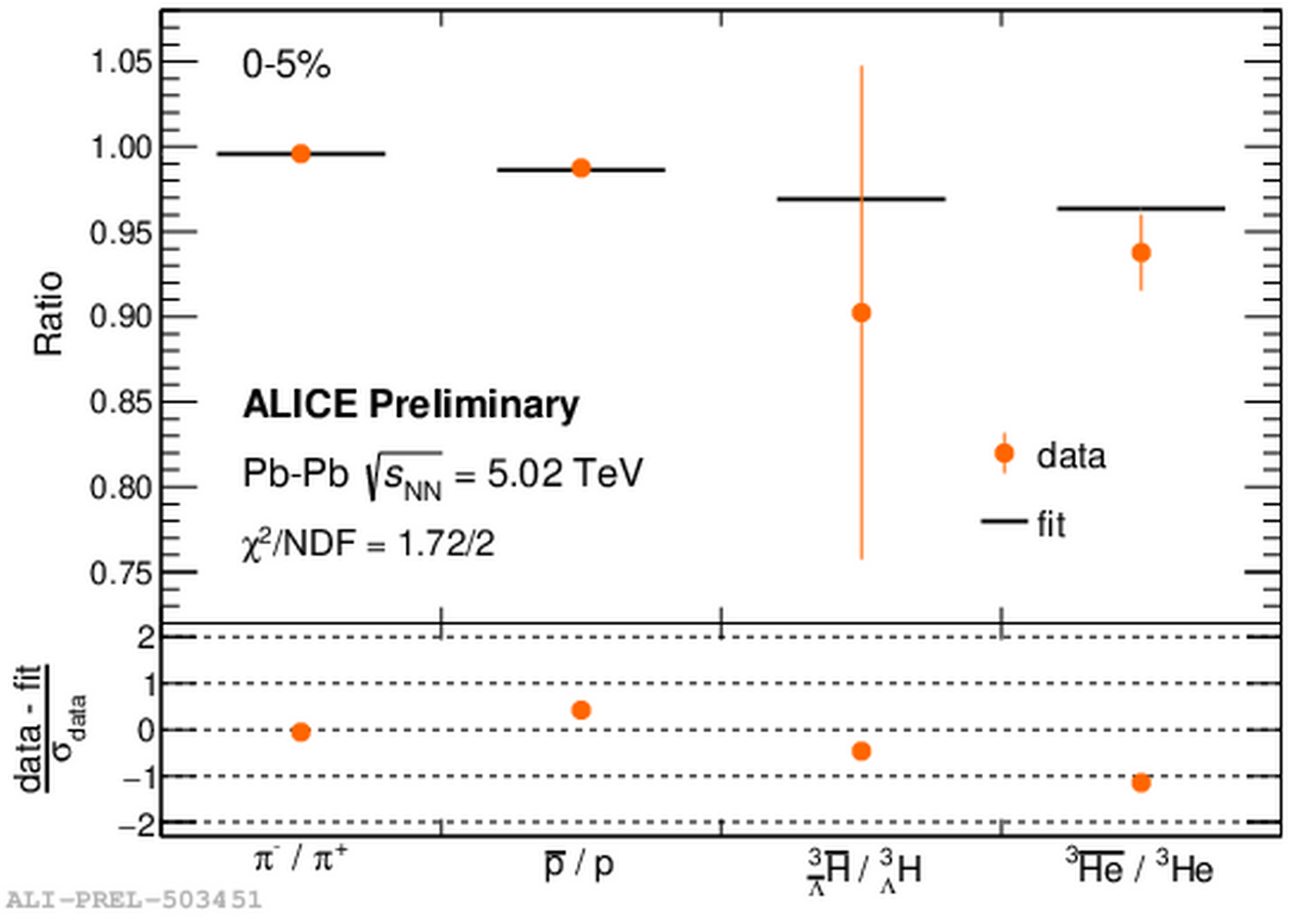
arXiv:2206.03343 [nucl-ex]

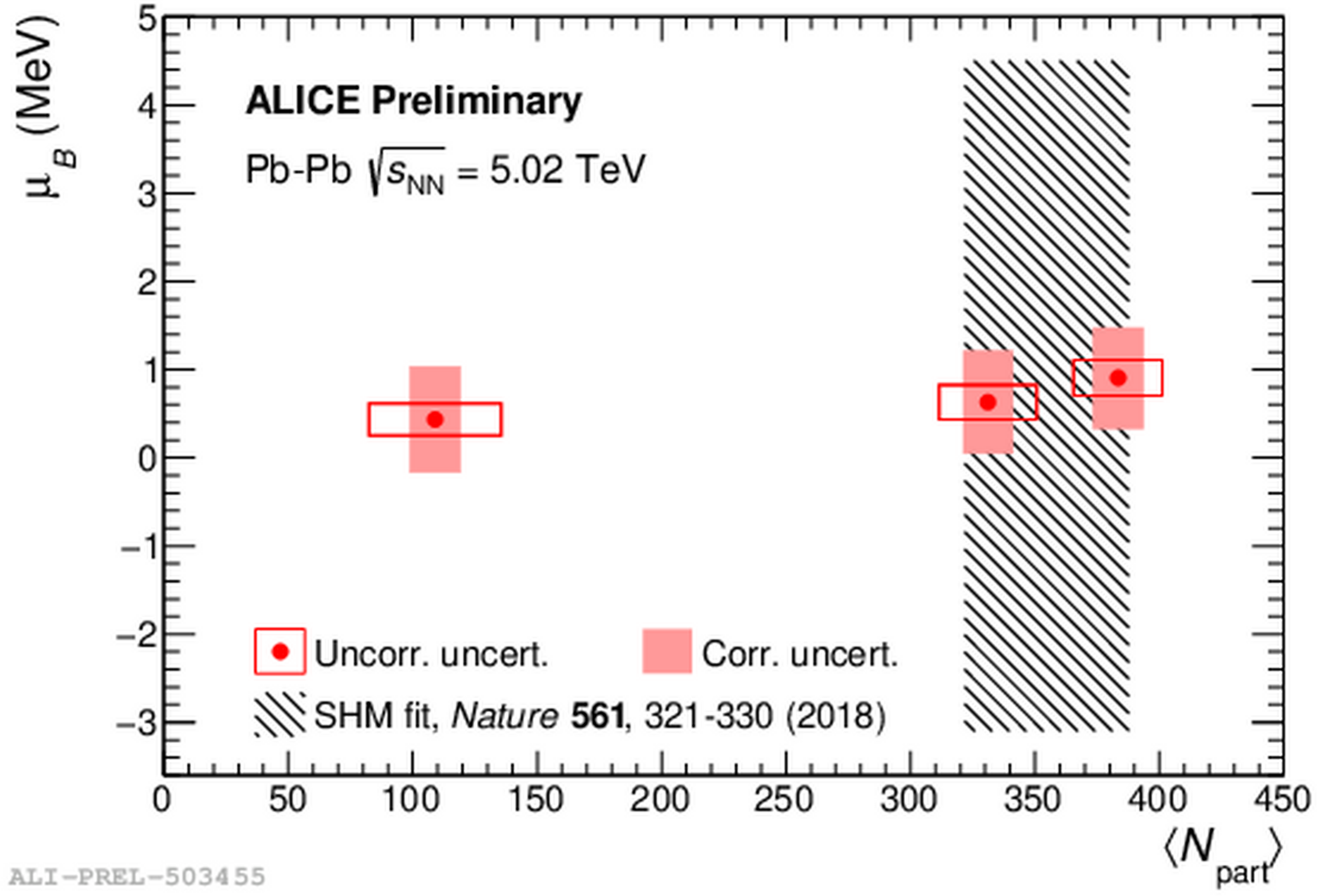


Pearson correlation $\rho_{\overline{p}\overline{d}}$ clearly indicates a correlation volume for baryon number conservation of 1.6 units of rapidity

> different from net-proton fluctuation results (Δy_{corr} = 5)

Precise μ_B measurement at LHC





New measurement of antimatter/matter imbalance at the LHC

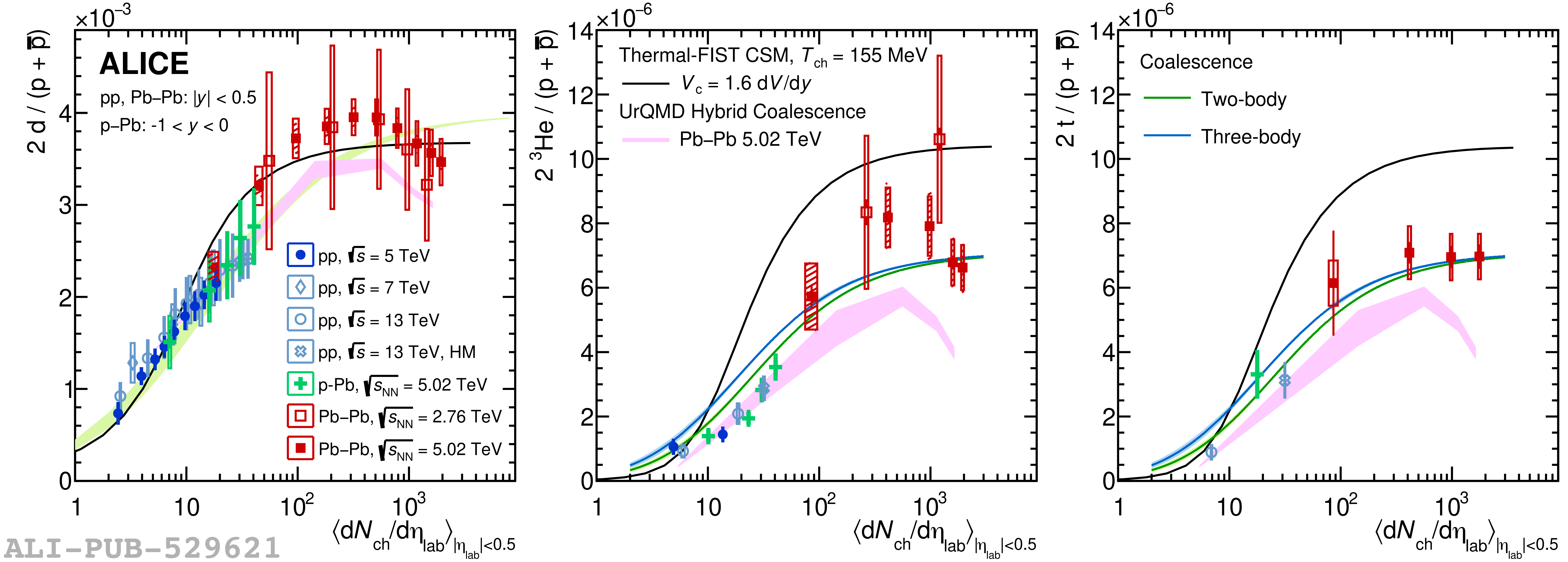
$$\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

Uncertainties reduced wrt thermal model fit by one order of magnitude

> direct cancellation of correlated uncertainties in antimatter-to-matter ratios

Light nuclei production

arXiv:2211.14015 [nucl-ex]

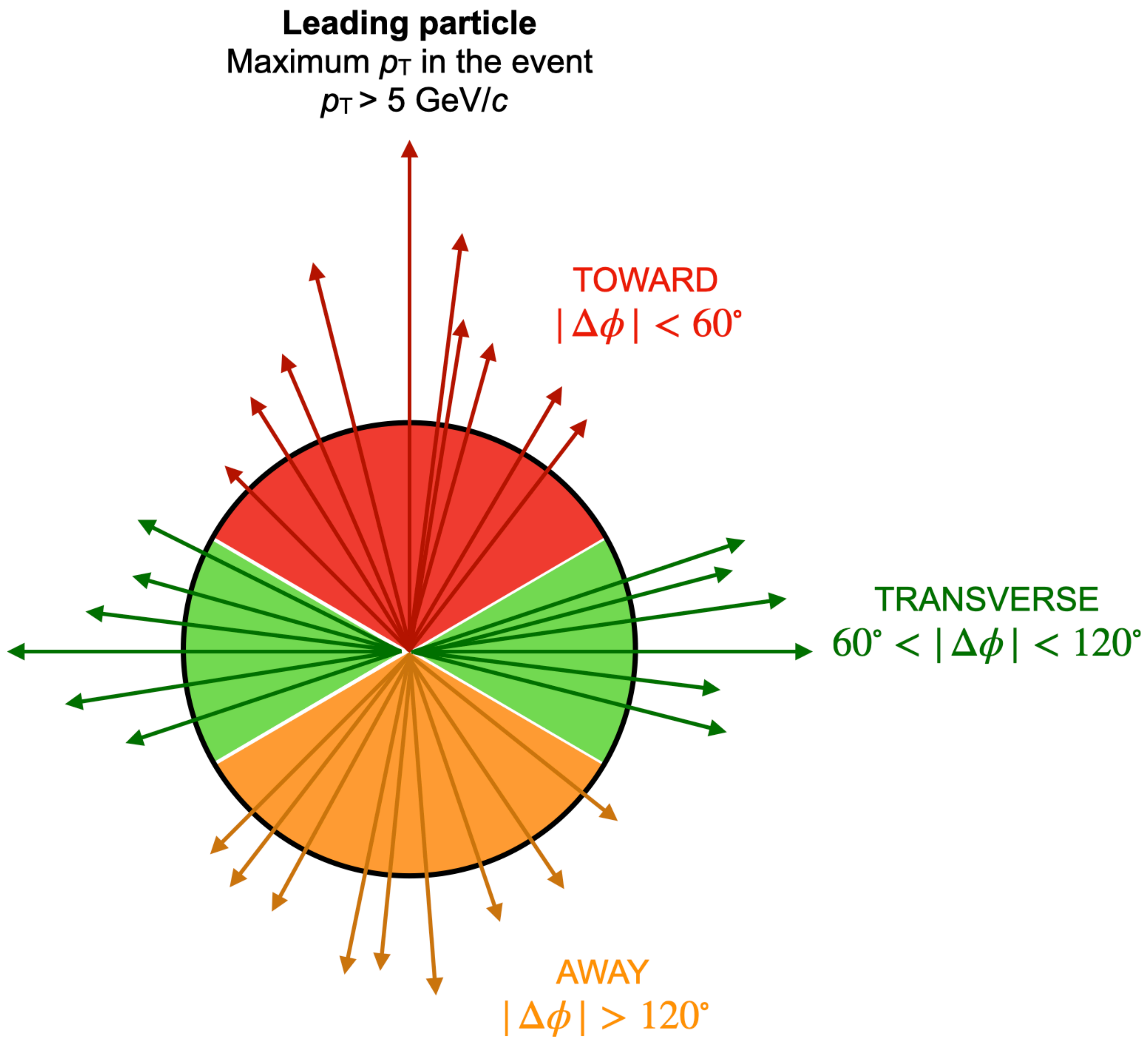


Closing in on the production mechanism of light (anti)nuclei via production measurements in different collision systems and energies

New results in Pb-Pb collisions with smaller uncertainties → entered the precision era!

Data challenge the existing models (thermal model and coalescence)

Hadron production vs. R_T

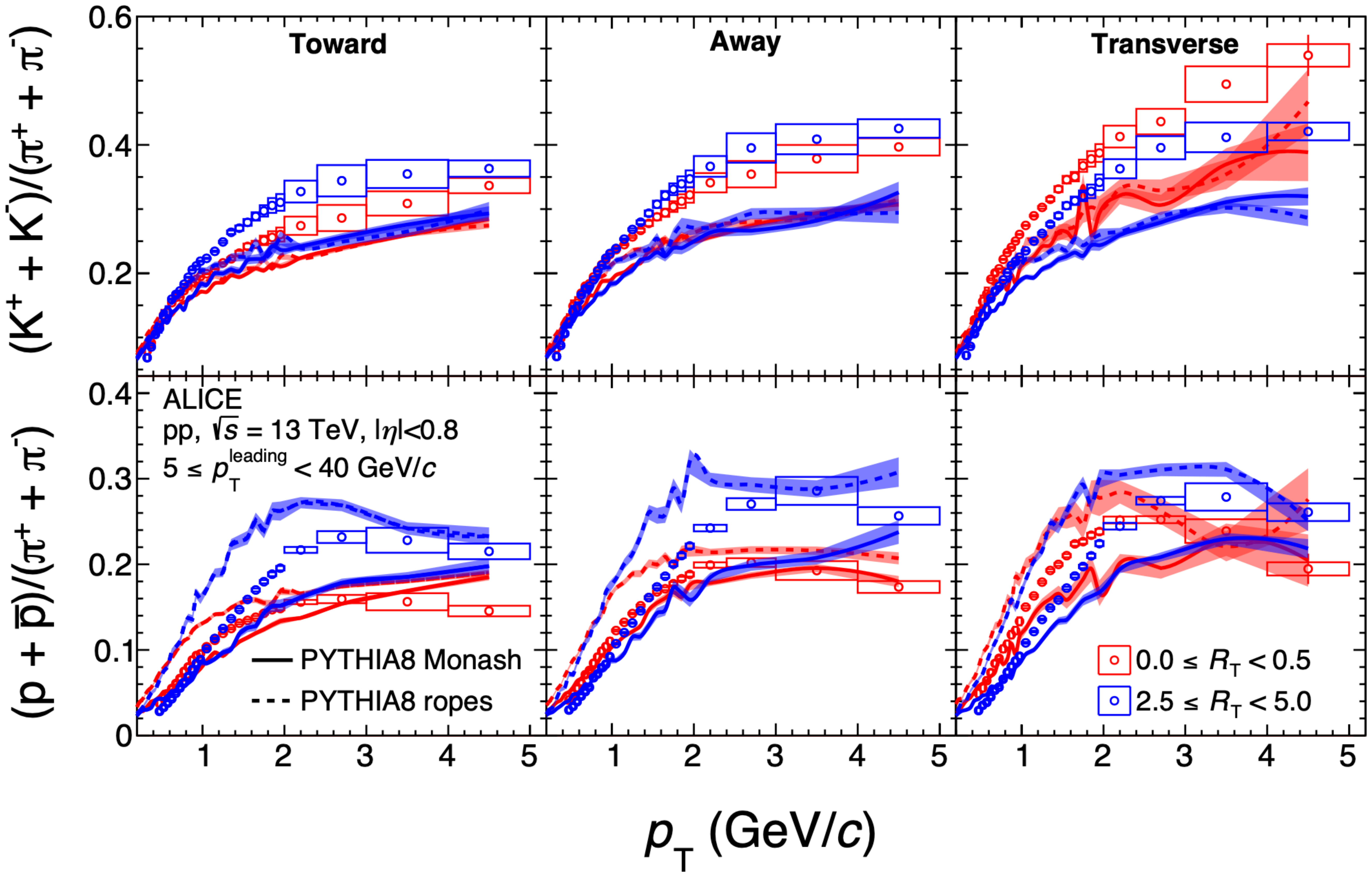


Underlying event activity classifier

$$R_T = \frac{N_T^{ch}}{\langle N_T^{ch} \rangle}$$

charged-particle multiplicity in the transverse region

arXiv:2301.10120 [nucl-ex]

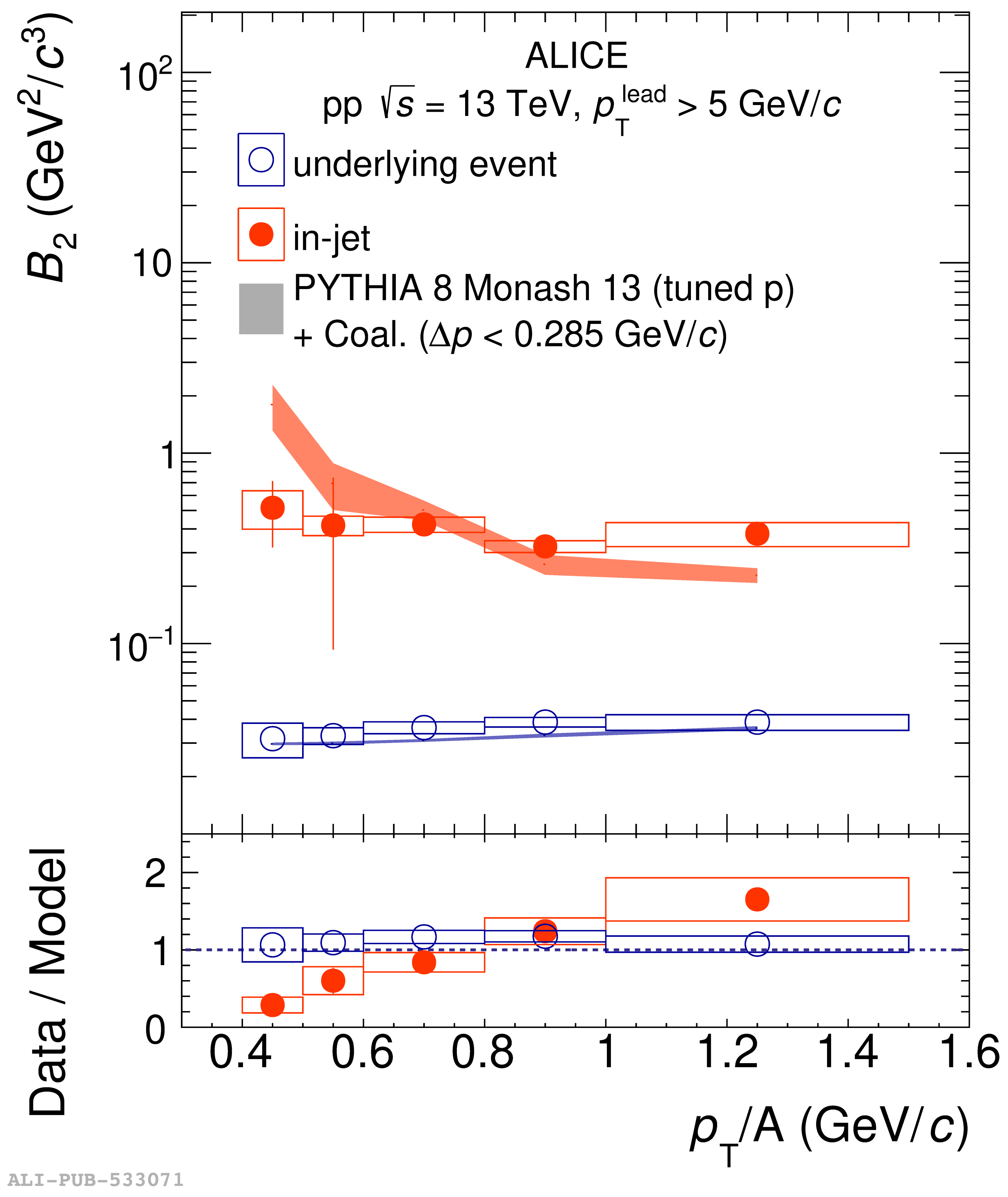


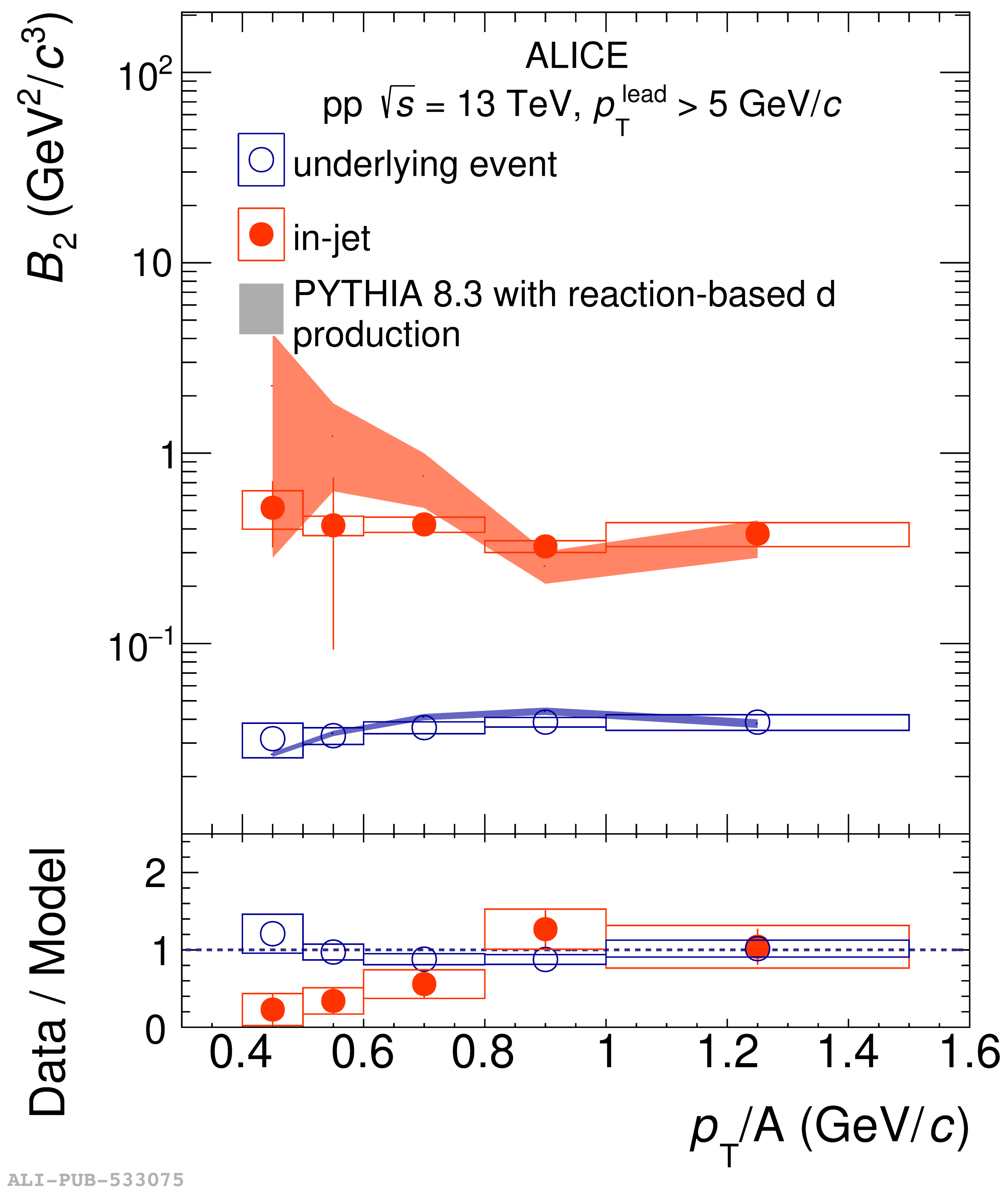
Different relative hadron abundances and p_T dependence in different regions and R_T intervals

→ different production mechanisms in hard-scattering and soft-QCD processes?

Enhanced coalescence probability in jets

arXiv:2211.15204 [nucl-ex]



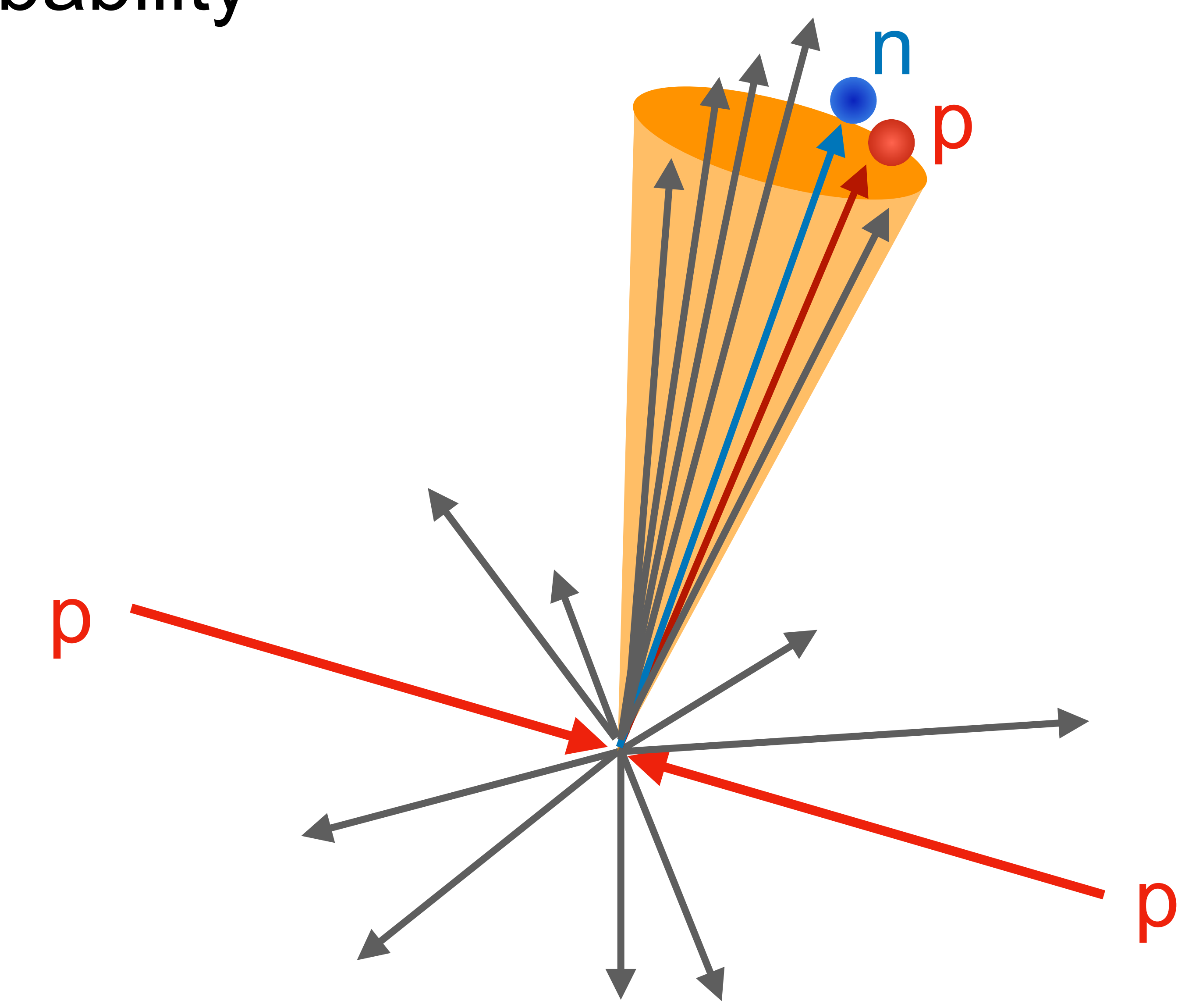


- In jet: Toward - Transverse
- Underlying Event: Transverse

Coalescence parameter

$$B_2 = \left(\frac{1}{2\pi p_T^d}\frac{d^2N_d}{dydp_T^d}\right) \Big/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dydp_T^p}\right)^2$$

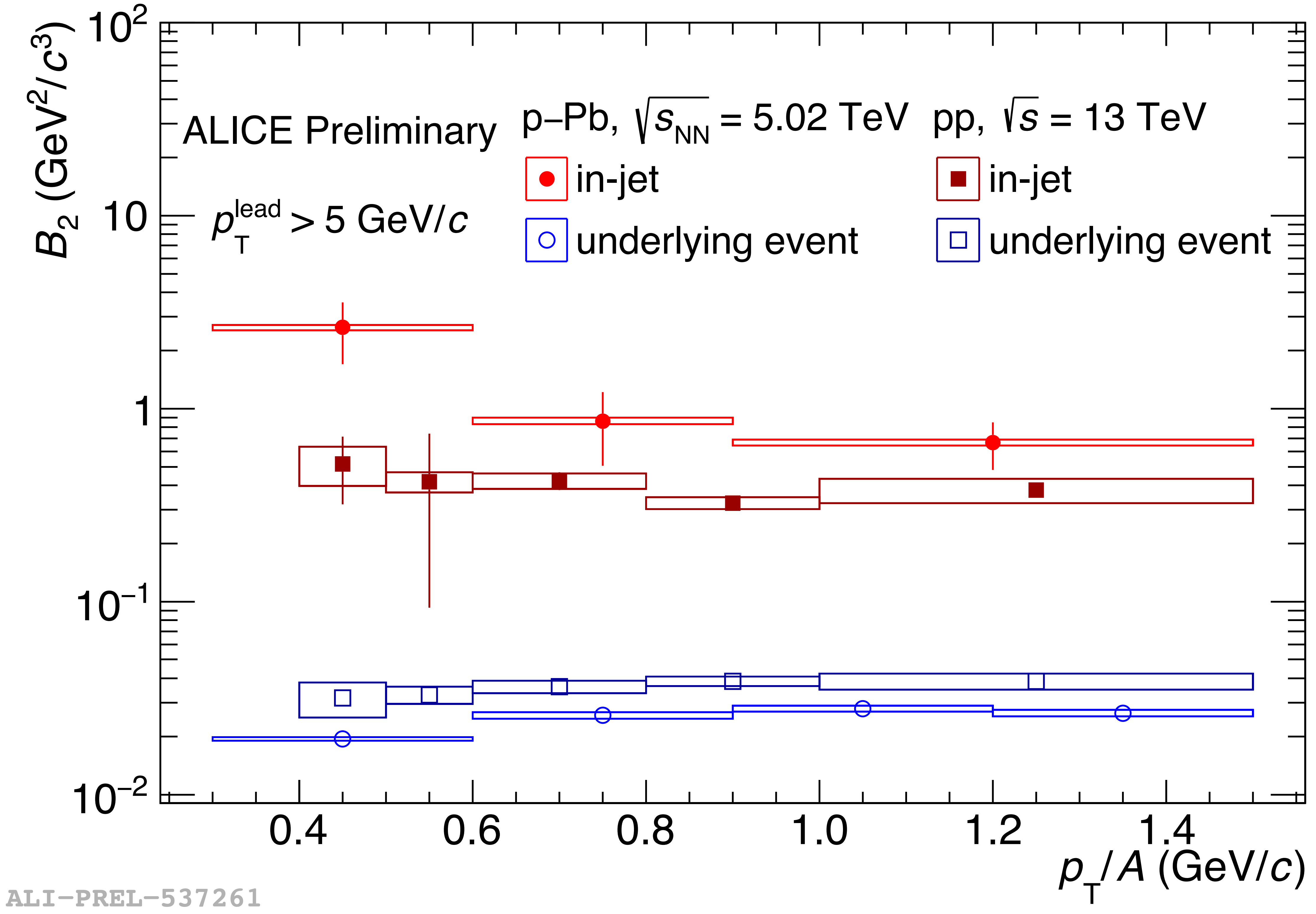
Proportional to the deuteron coalescence probability



Enhanced deuteron coalescence probability in jets
→ nucleons are closer in phase space within jets wrt UE

Results qualitatively described by nucleon coalescence and reaction-based deuteron production (e.g., $p + n \rightarrow d + \gamma$) implemented in PYTHIA 8.3

Nuclei production in and out of jets



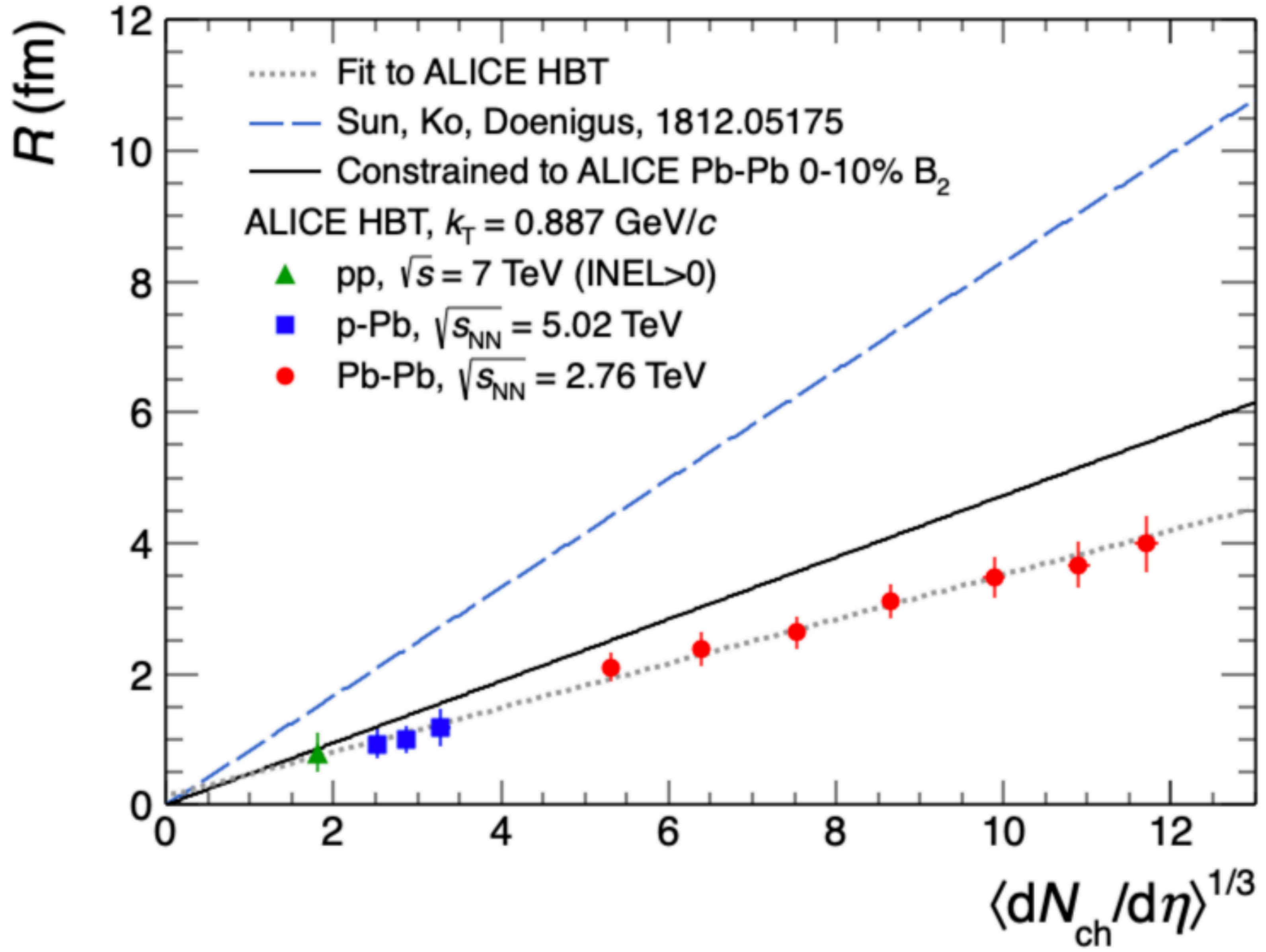
Larger difference between B_2^{jet} and B_2^{UE} in p-Pb wrt pp collisions

Underlying event $B_2^{\mathrm{UE}}(\mathrm{p-Pb}) < \mathrm{B}_2^{\mathrm{UE}}(\mathrm{pp})$

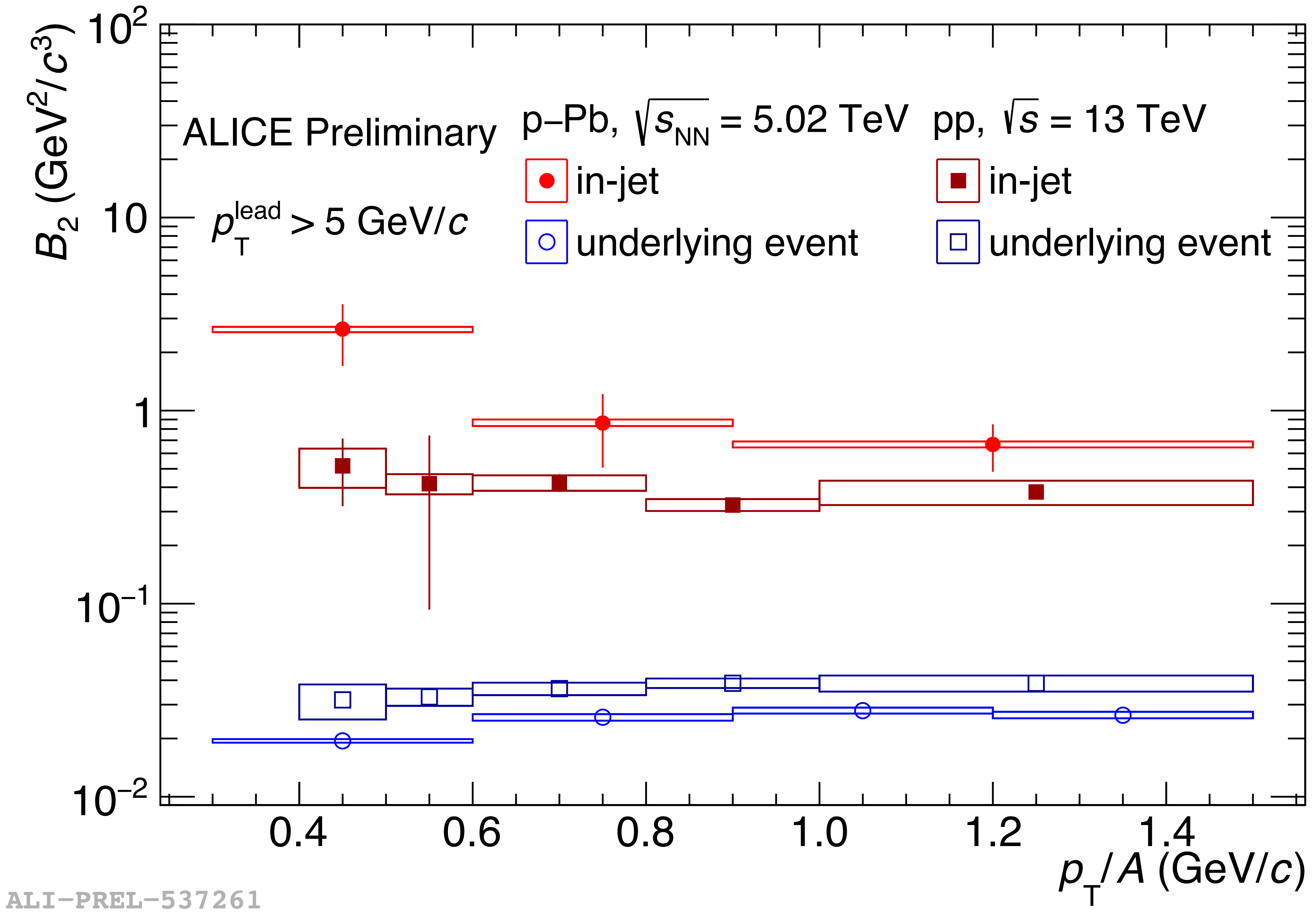
- particle-emitting source is larger in p-Pb wrt pp collisions
- larger average distance between nucleons

→ smaller coalescence probability

Phys. Rev. C 99, 054905 (2019)



Nuclei production in and out of jets



Larger difference between B_2^{jet} and B_2^{UE} in p-Pb wrt pp collisions

Underlying event $B_2^{UE}(\mathrm{p-Pb}) < \mathrm{B}_2^{UE}(\mathrm{pp})$

- particle-emitting source is larger in p-Pb wrt pp collisions
- larger average distance between nucleons

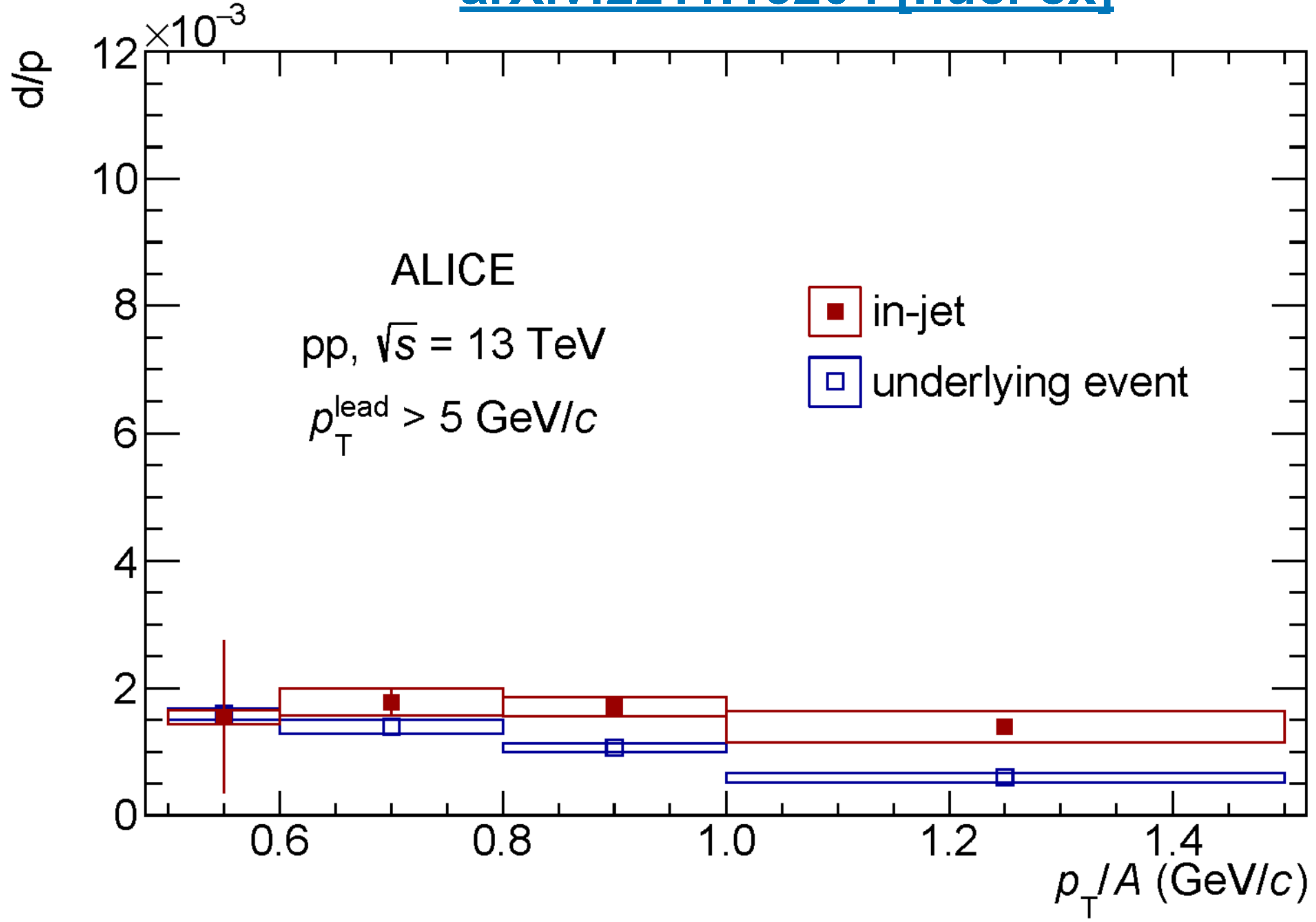
→ smaller coalescence probability

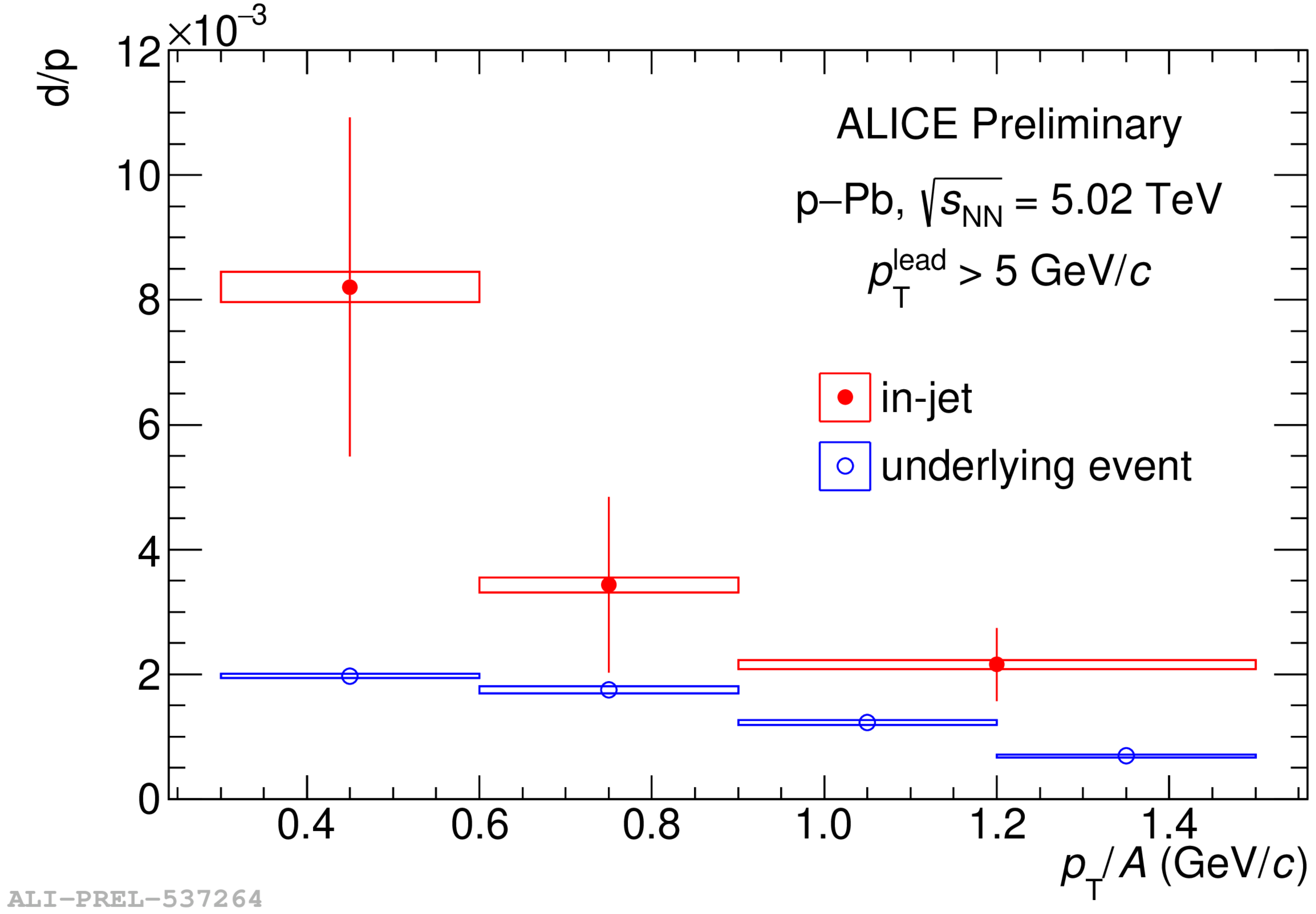
In jet $B_2^{in-jet}(\mathrm{p-Pb}) > \mathrm{B}_2^{in-jet}(\mathrm{pp})$

- Stronger momentum correlations between nucleons in p-Pb wrt pp collisions?
- Larger baryon density in p-Pb wrt pp collisions?
- …

d/p in jet: pp vs. p-Pb

arXiv:2211.15204 [nucl-ex]





Hint of a larger d/p within jets in p-Pb wrt pp collisions
→ jets in p-Pb not fragmenting in the vacuum?

Different hadron abundances might affect coalescence probability

Summary

Detailed characterization of a large variety of phenomena on hadron production

LHC Run 3: entering the precision era of hadron production measurements
> multi-differential measurements
> rare probes

Exciting times are ahead