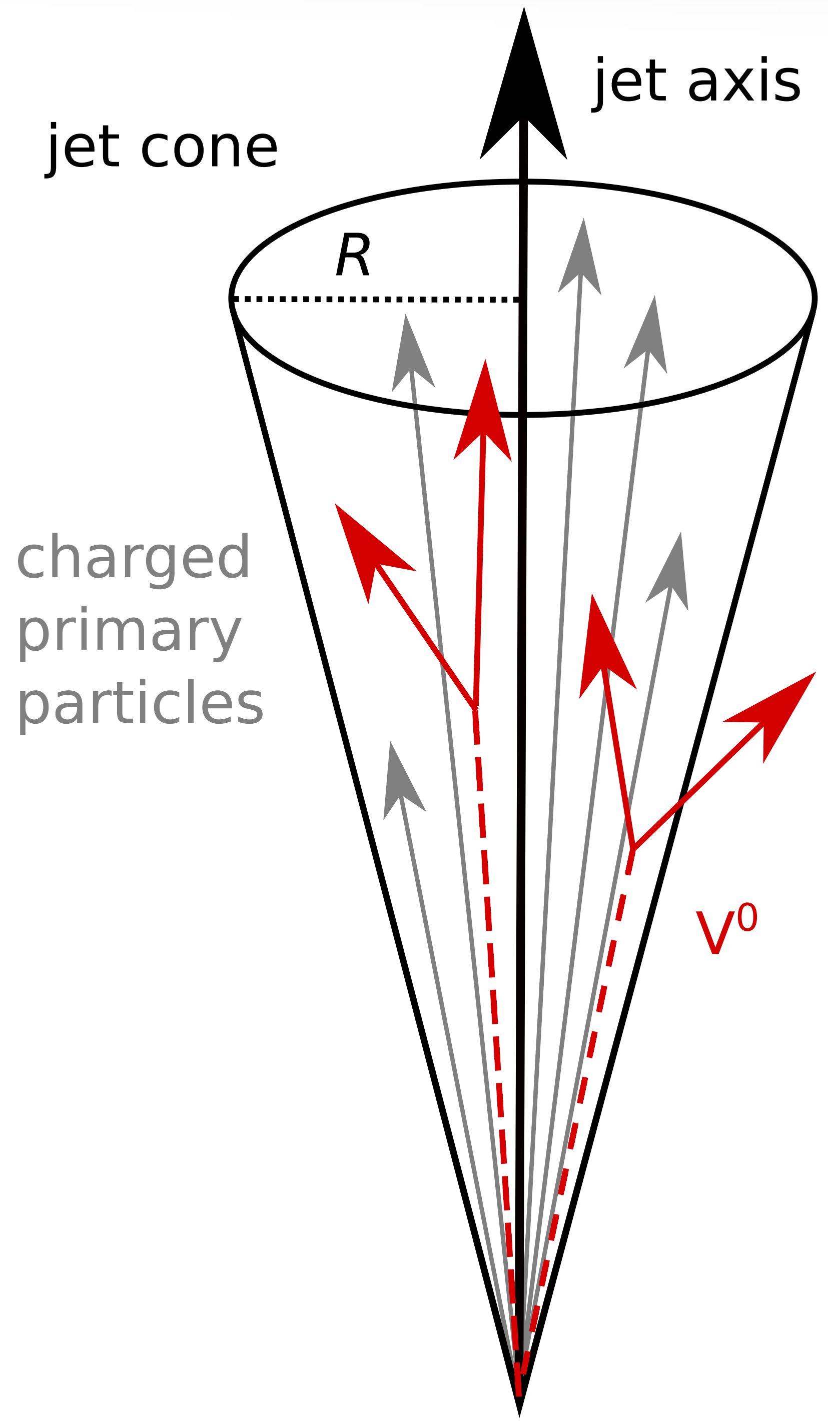
Strangeness in jets and in the underlying event in hadronic collisions at the LHC

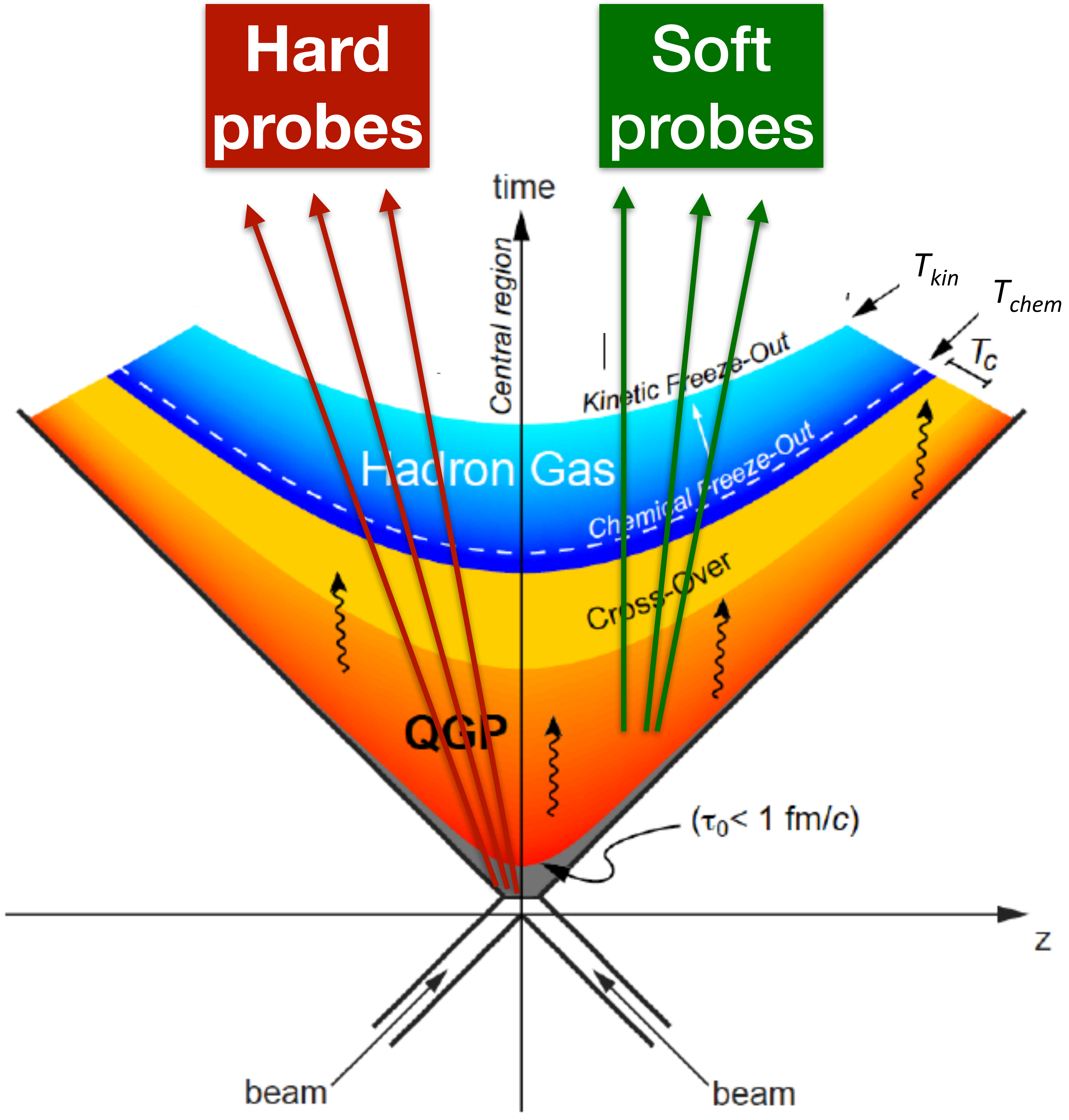
Xiaoming Zhang for the ALICE Collaboration

Central China Normal University



CERN seminar, 1st June 2021

Quark-gluon plasma



Heavy-ion collisions probe the strongly-interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density

Hard probes created at initial stage of the collision

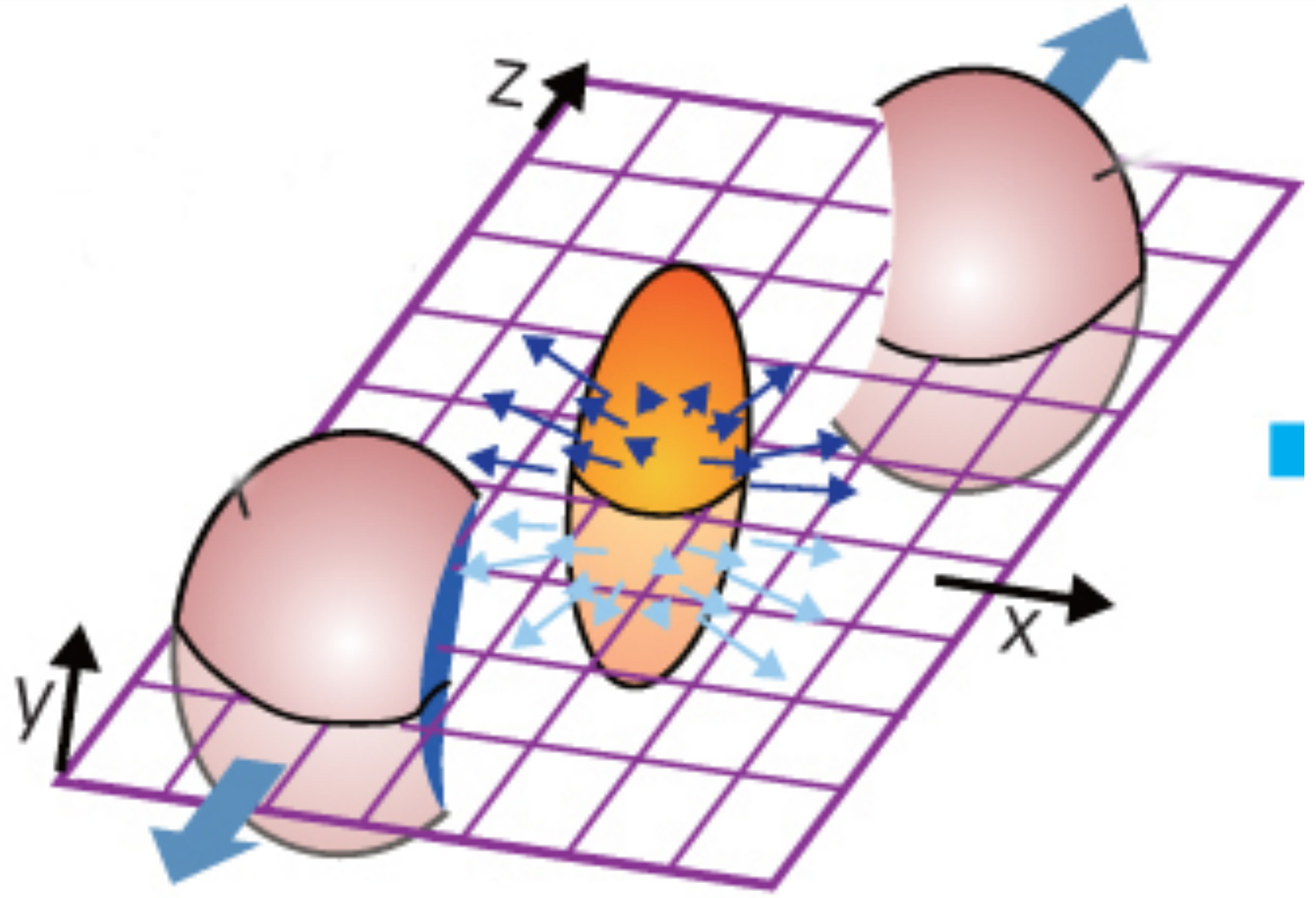
➡ QGP tomography

Soft probes created in the "fireball"

➡ Fingerprint of the QGP evolution

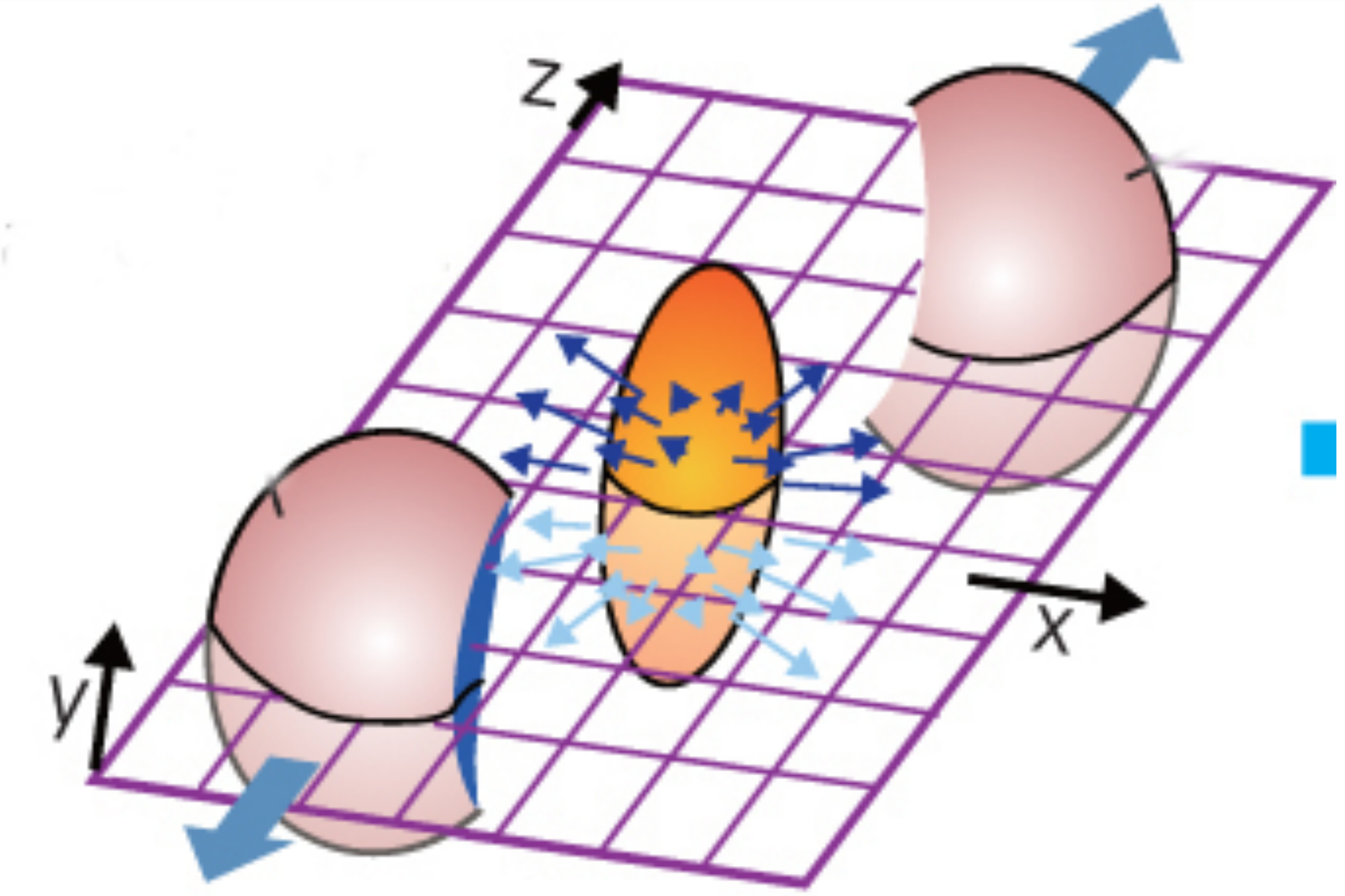
Collective properties

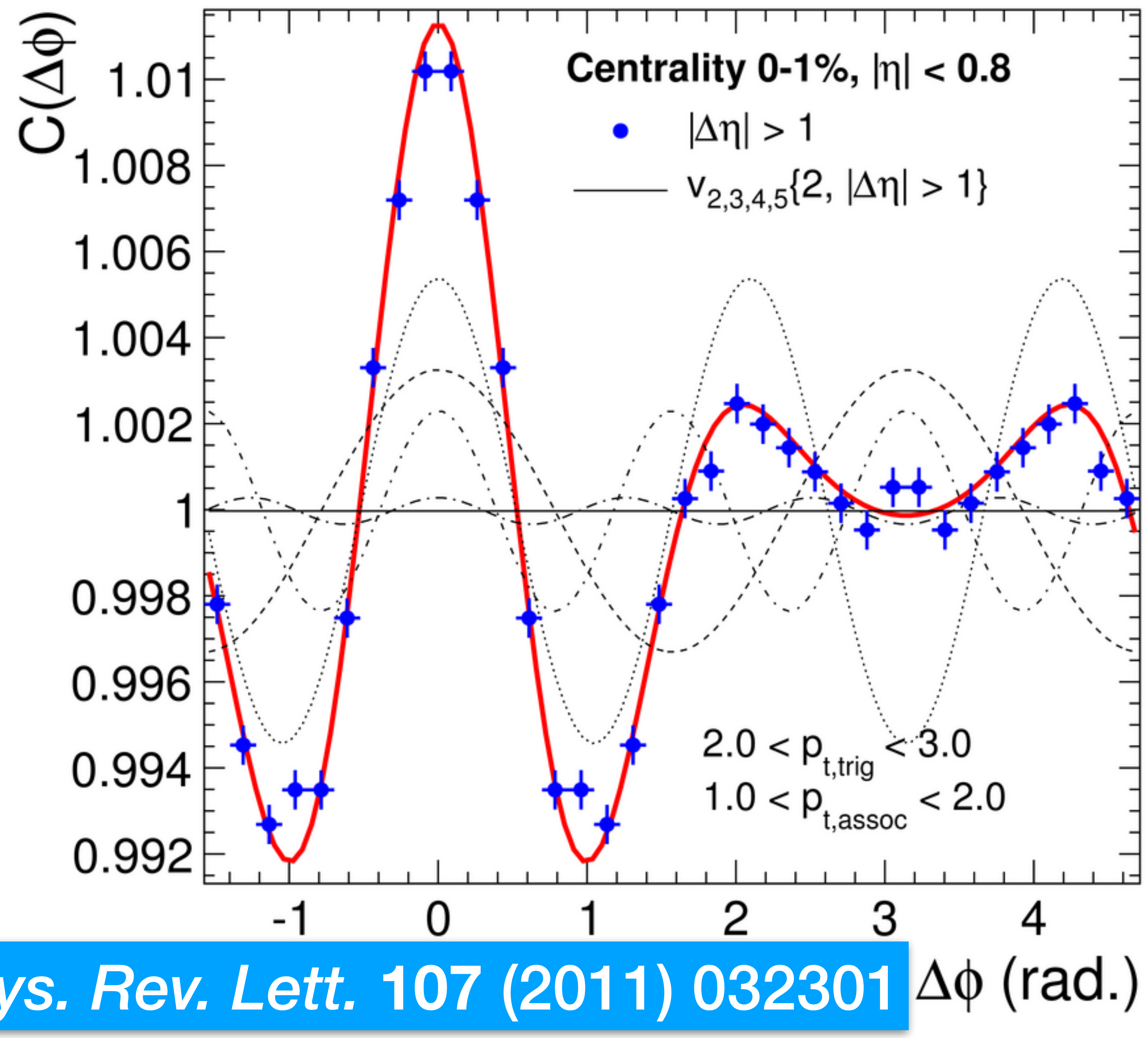
Collective expansion



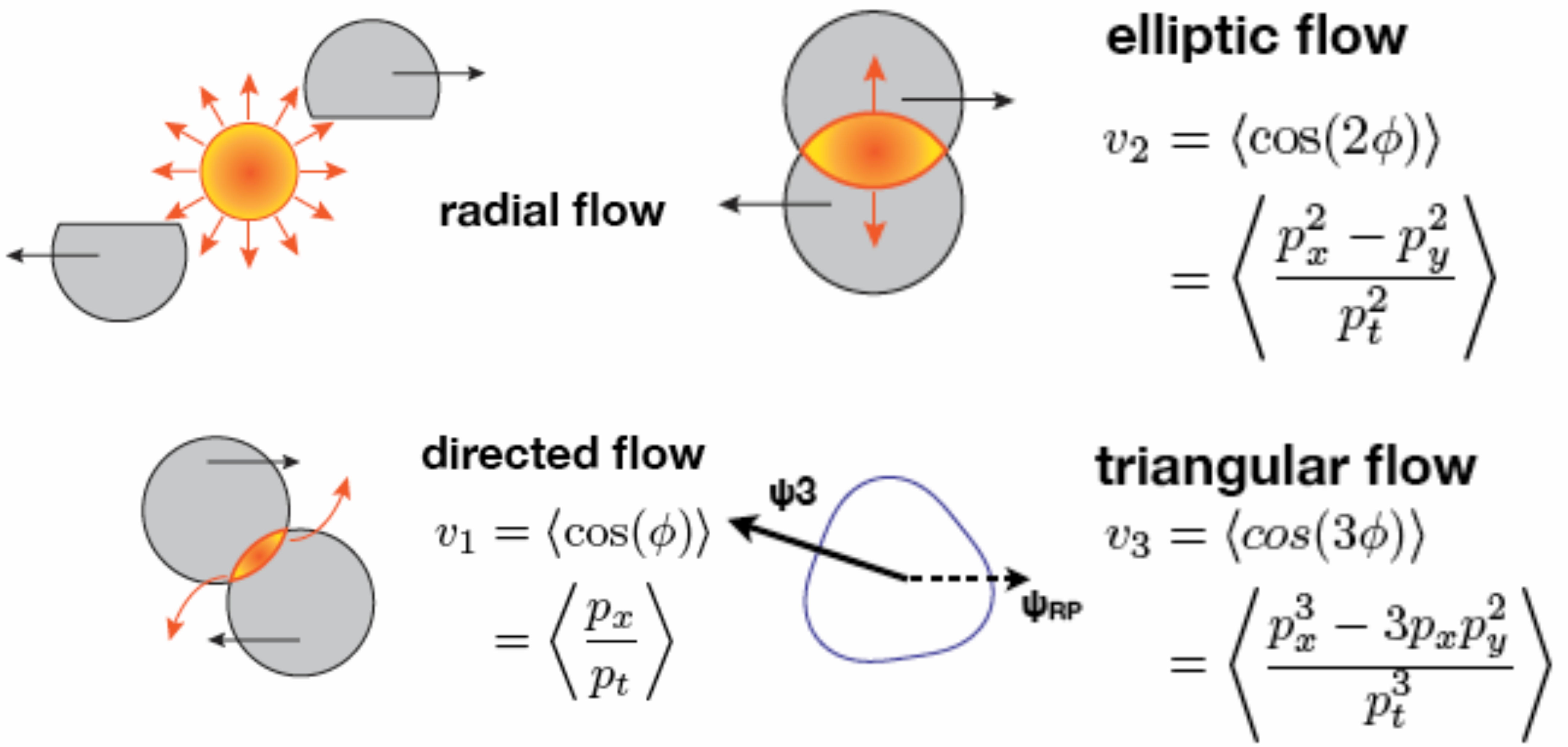
Collective properties

Collective expansion — results in complex azimuthal structure of final state particles





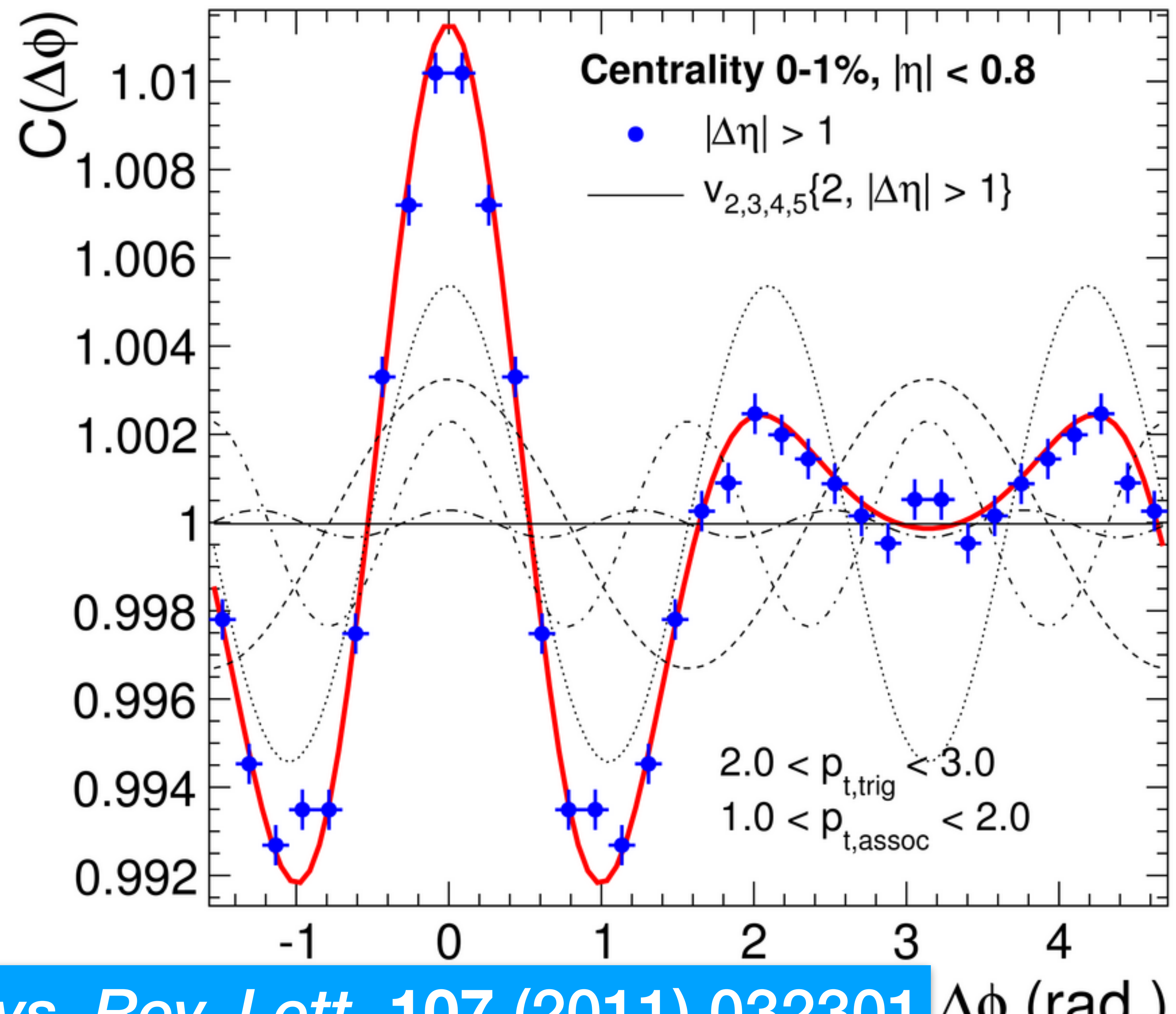
ALICE *Phys. Rev. Lett.* 107 (2011) 032301

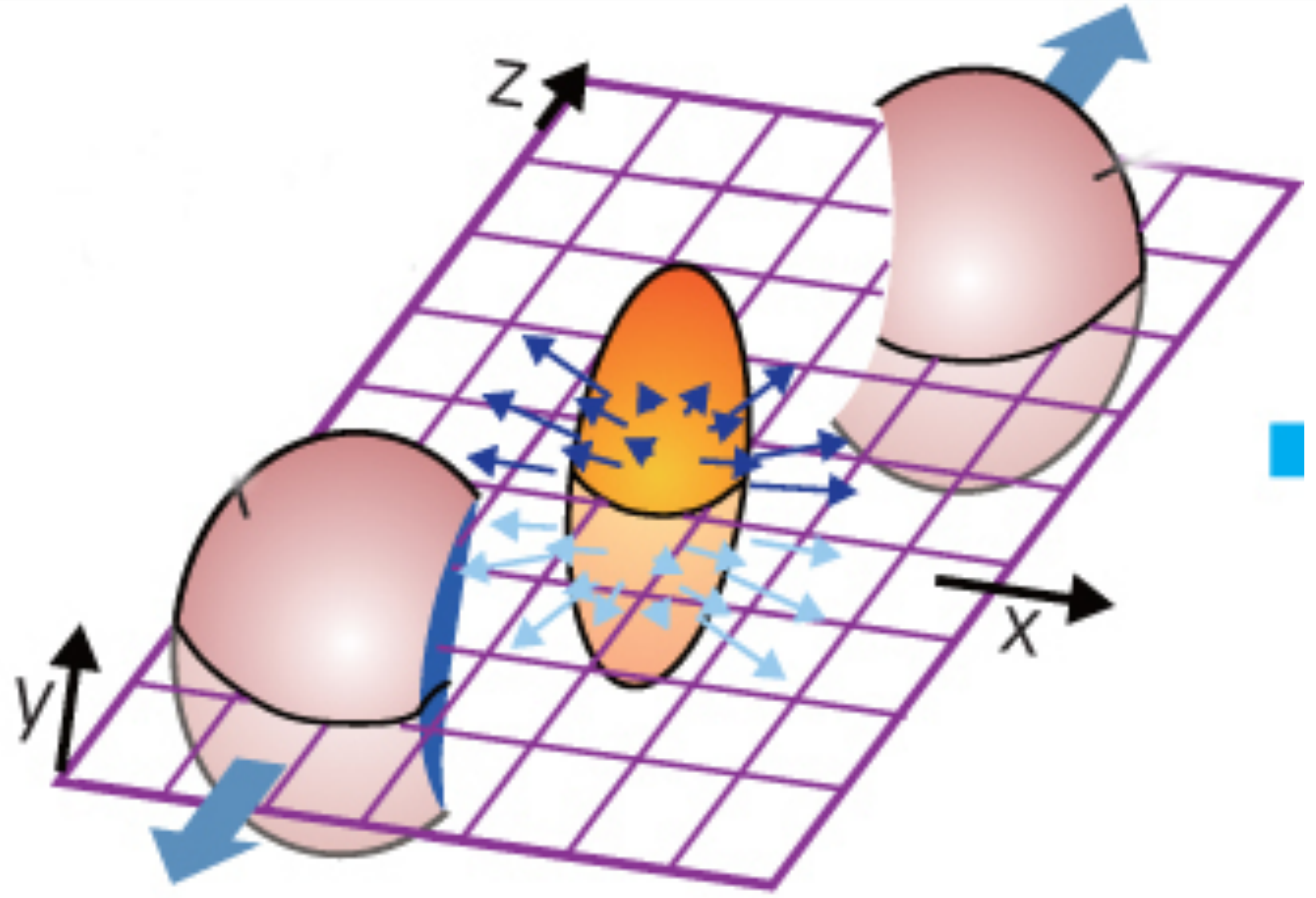


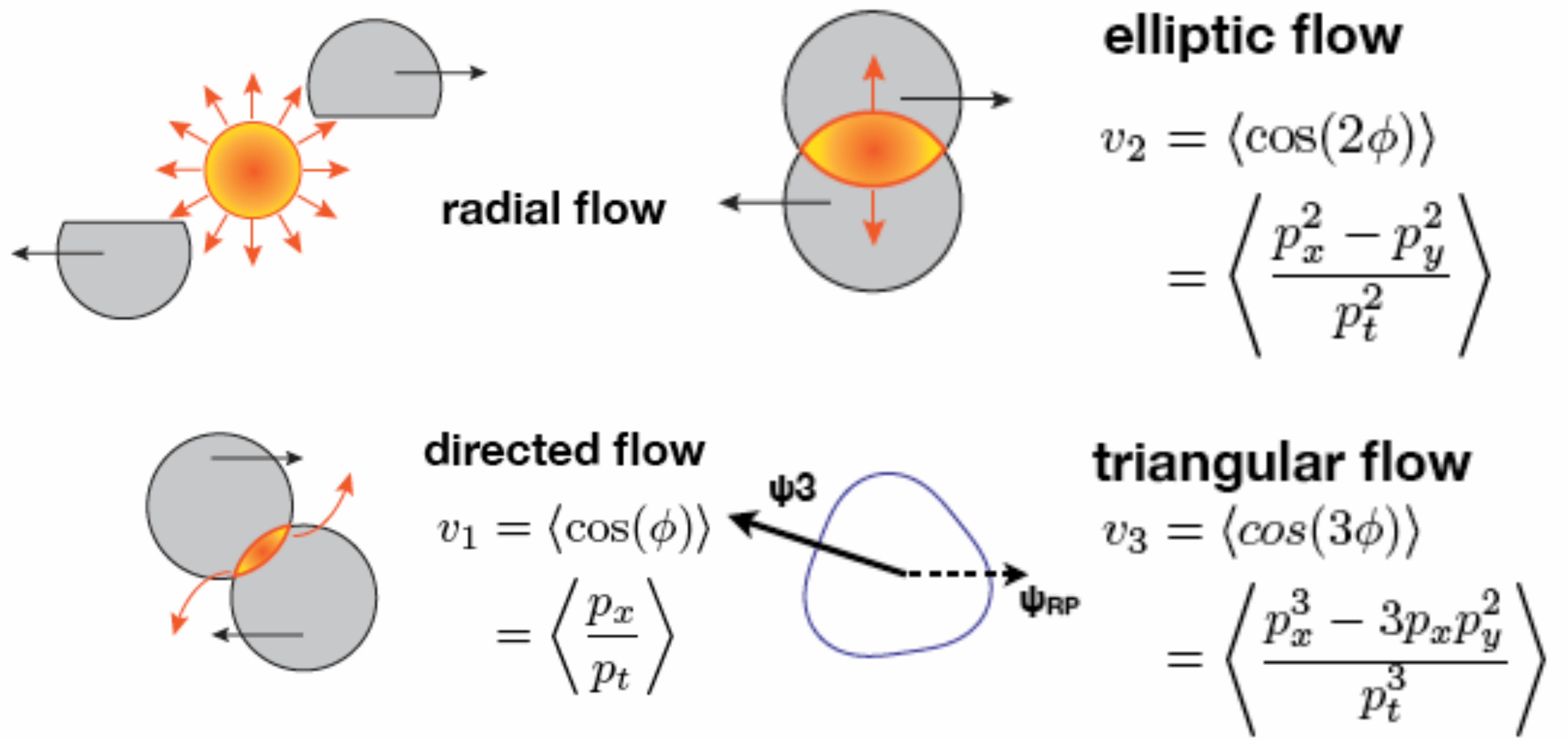
Collective properties

Collective expansion — results in complex azimuthal structure of final state particles

➡ Interactions in medium, access to medium properties, e.g. viscosity, equation of state





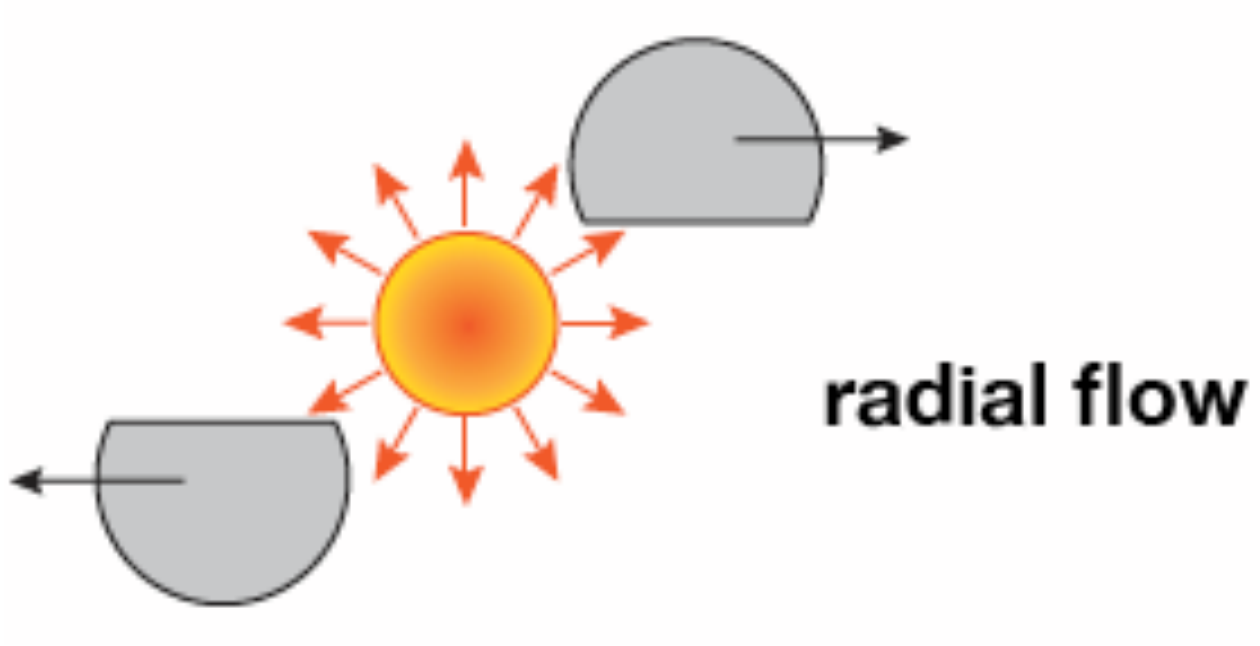


ALICE *Phys. Rev. Lett.* **107** (2011) 032301

Radial flow

Collective expansion

➡ “Zero order” — radial flow

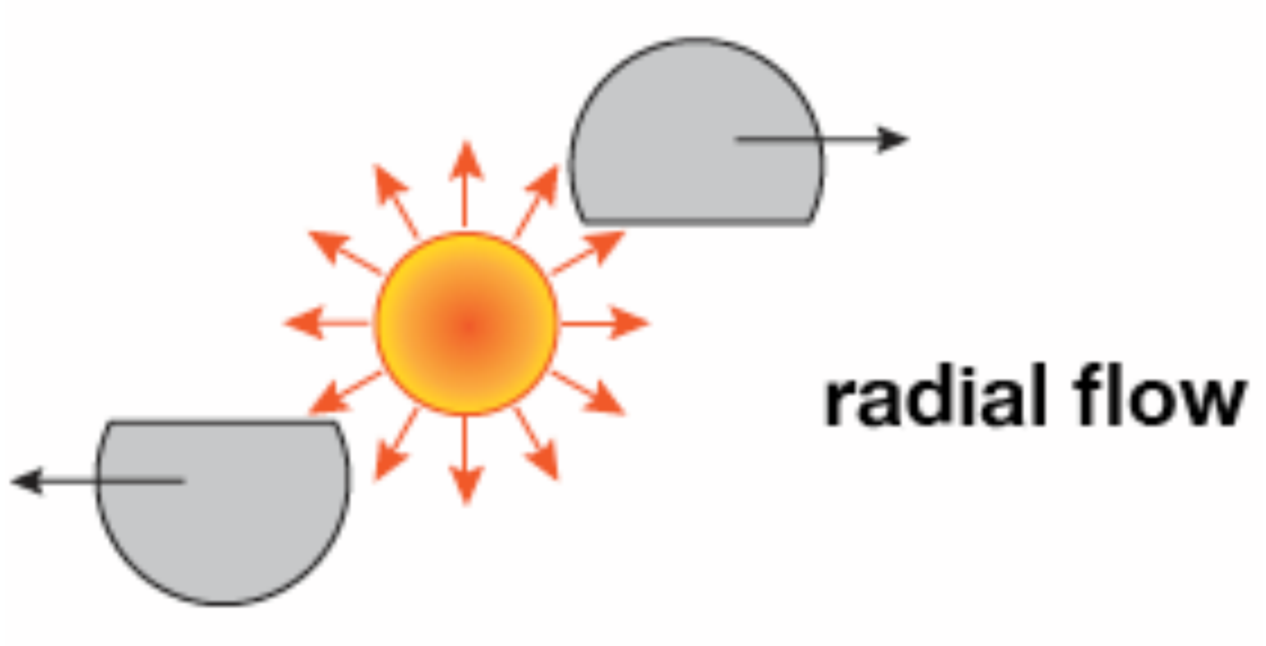


Radial flow

ALICE

Collective expansion

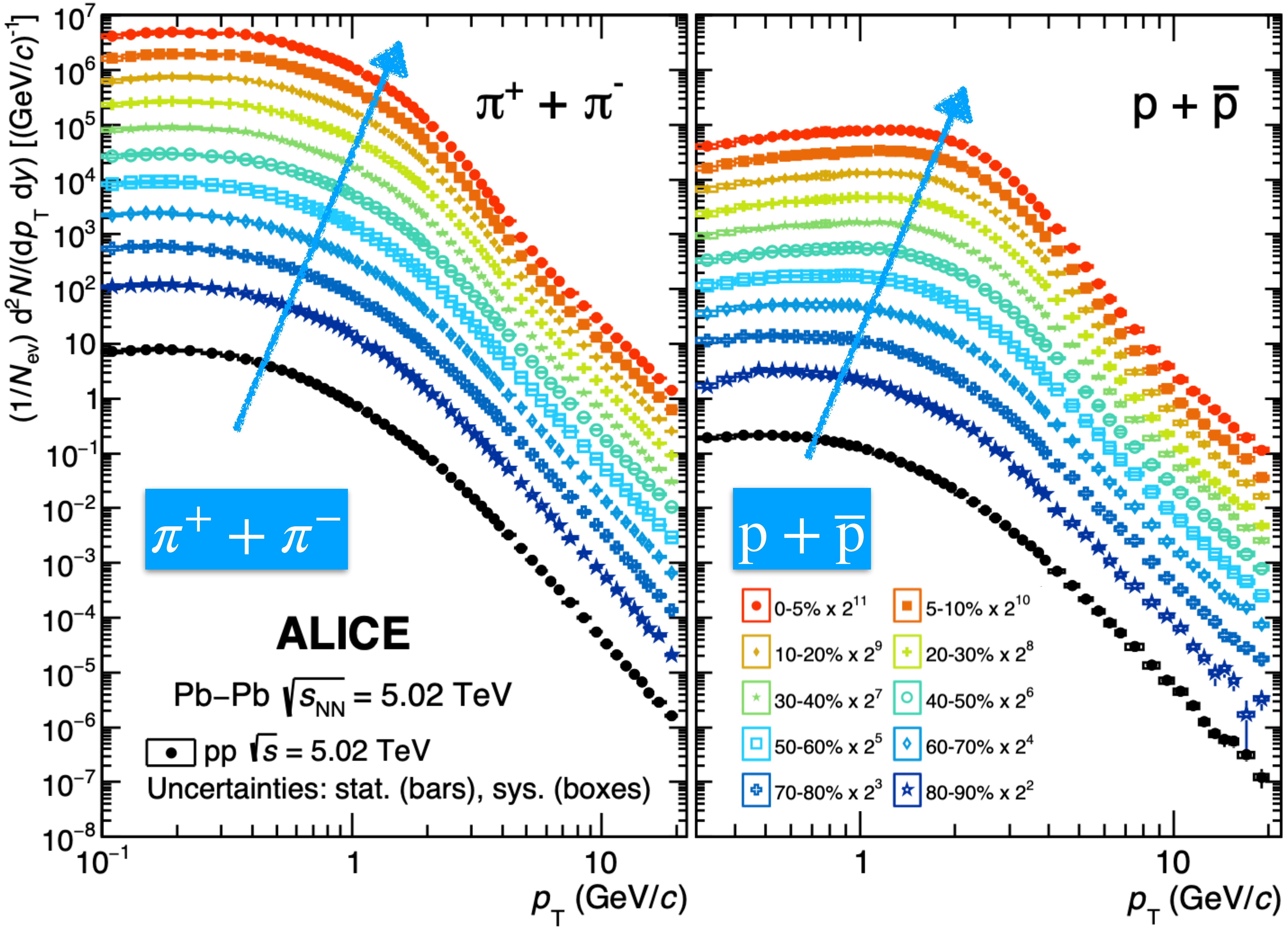
➡ “Zero order” — radial flow



➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

p_0: initial momentum
β: flow velocity
m: particle mass

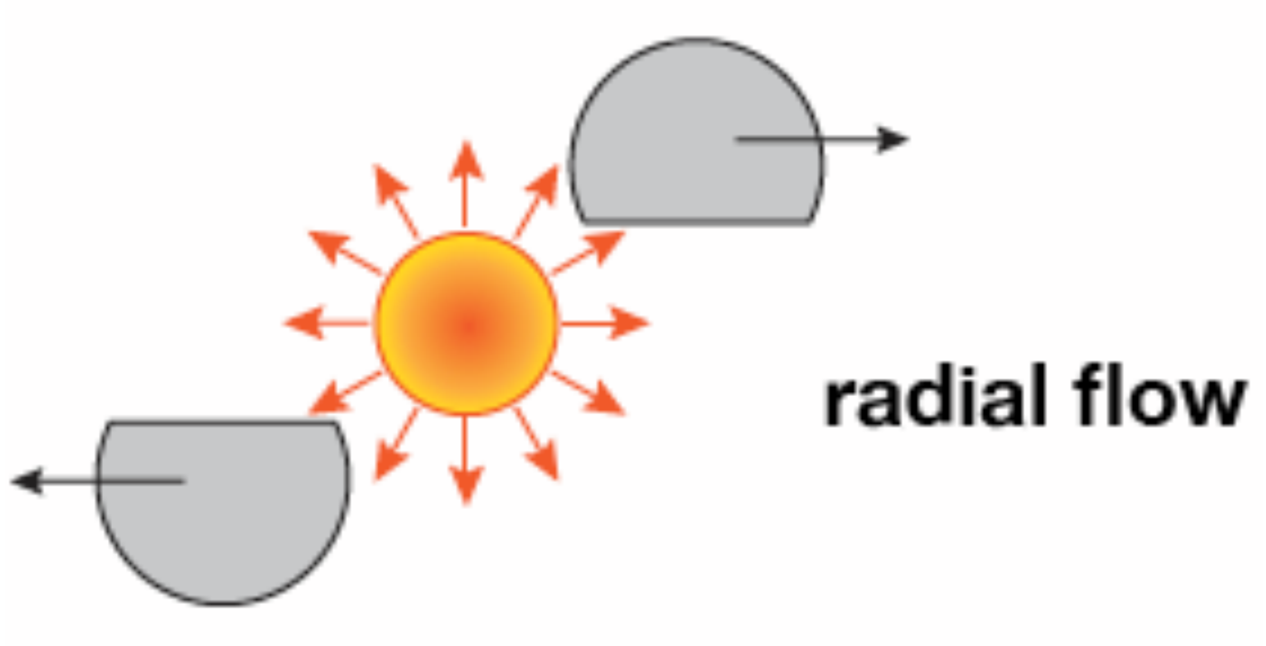


ALICE *Phys. Rev.* C101 (2020) 044907

Radial flow

Collective expansion

➡ "Zero order" — radial flow

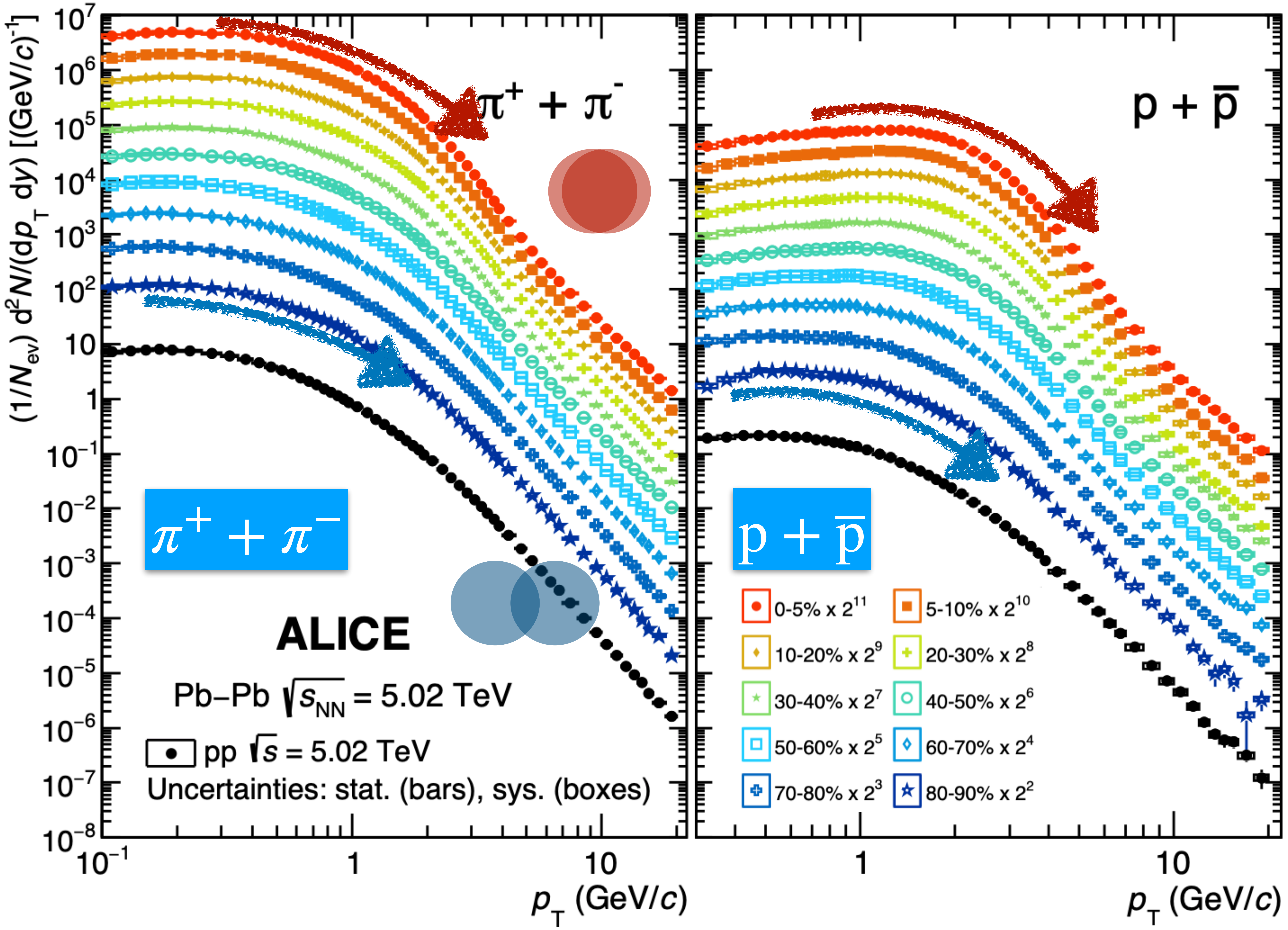


➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

p_0: initial momentum
β: flow velocity
m: particle mass

➡ More pronounced in central collisions

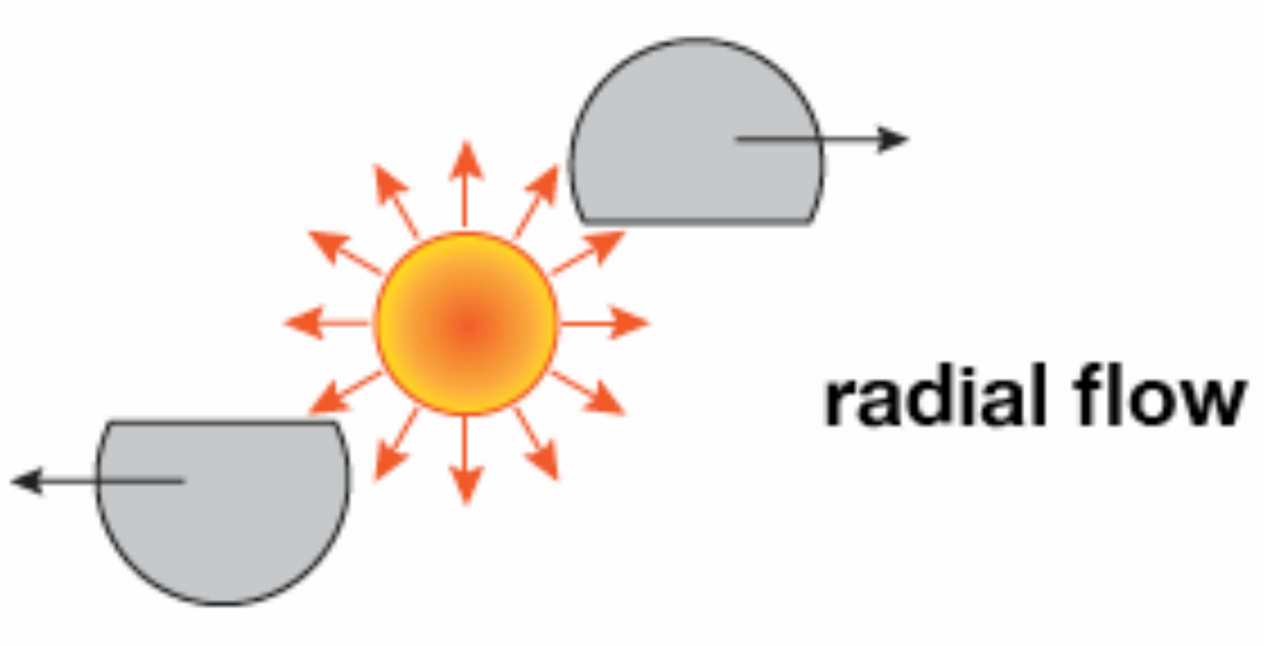


ALICE *Phys. Rev.* C101 (2020) 044907

Radial flow

Collective expansion

➡ "Zero order" — radial flow

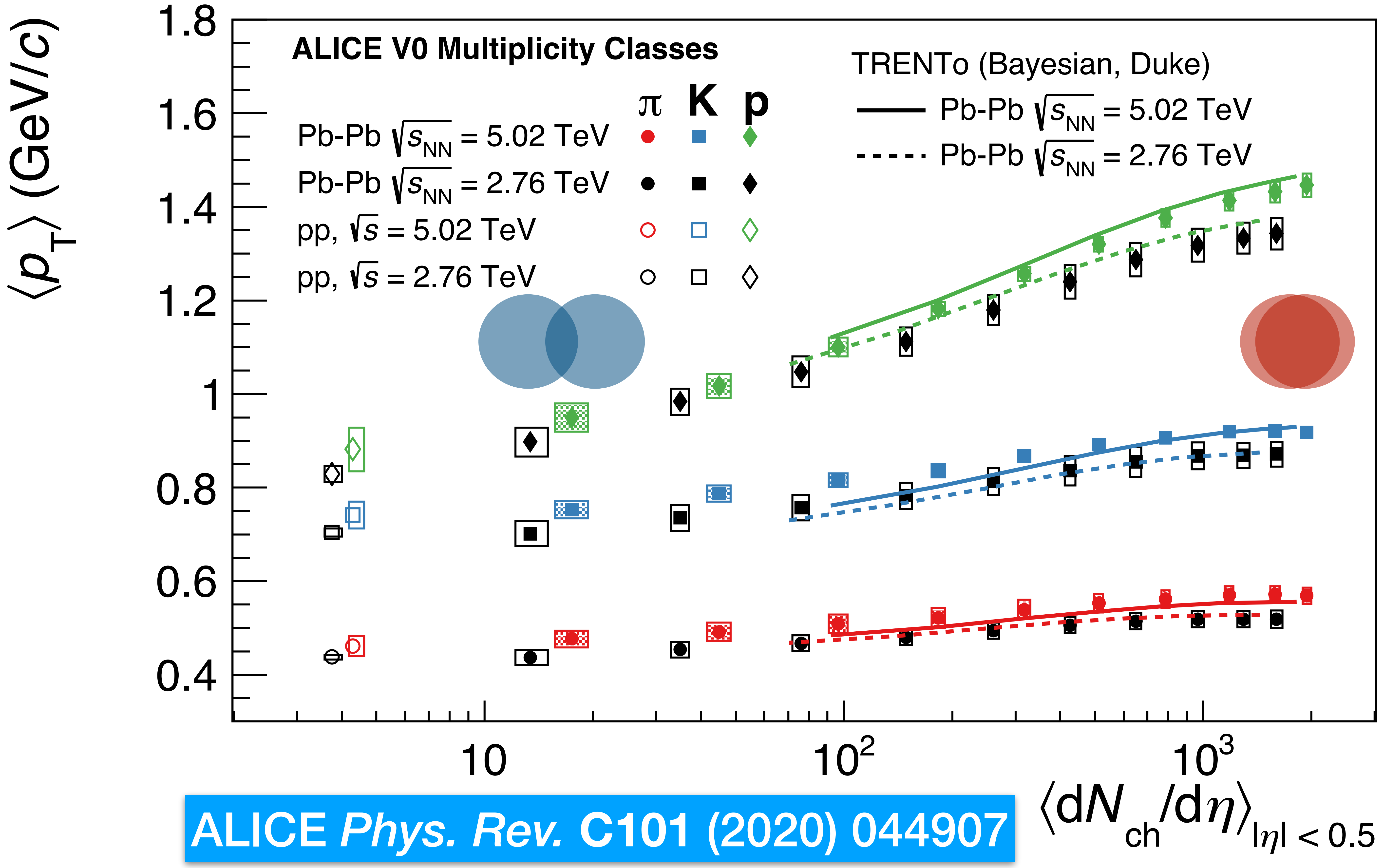


➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

p_0: initial momentum
β: flow velocity
m: particle mass

➡ More pronounced in central collisions

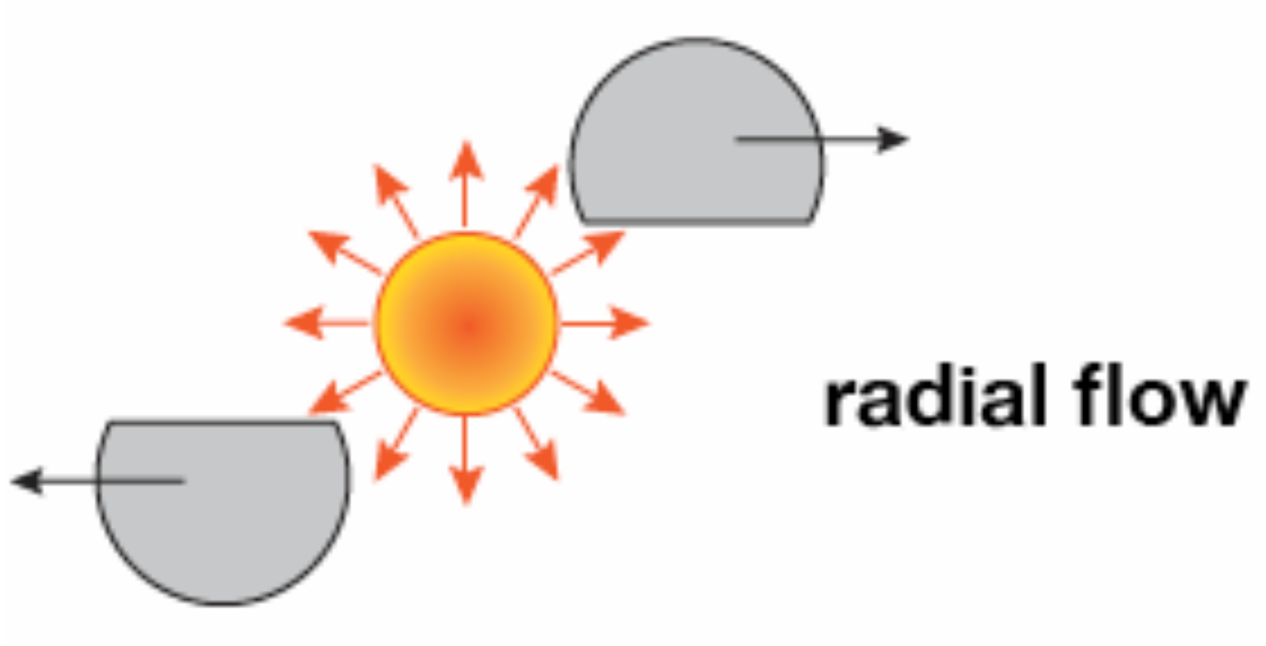


ALICE *Phys. Rev.* C101 (2020) 044907

Radial flow

Collective expansion

➡ "Zero order" — radial flow



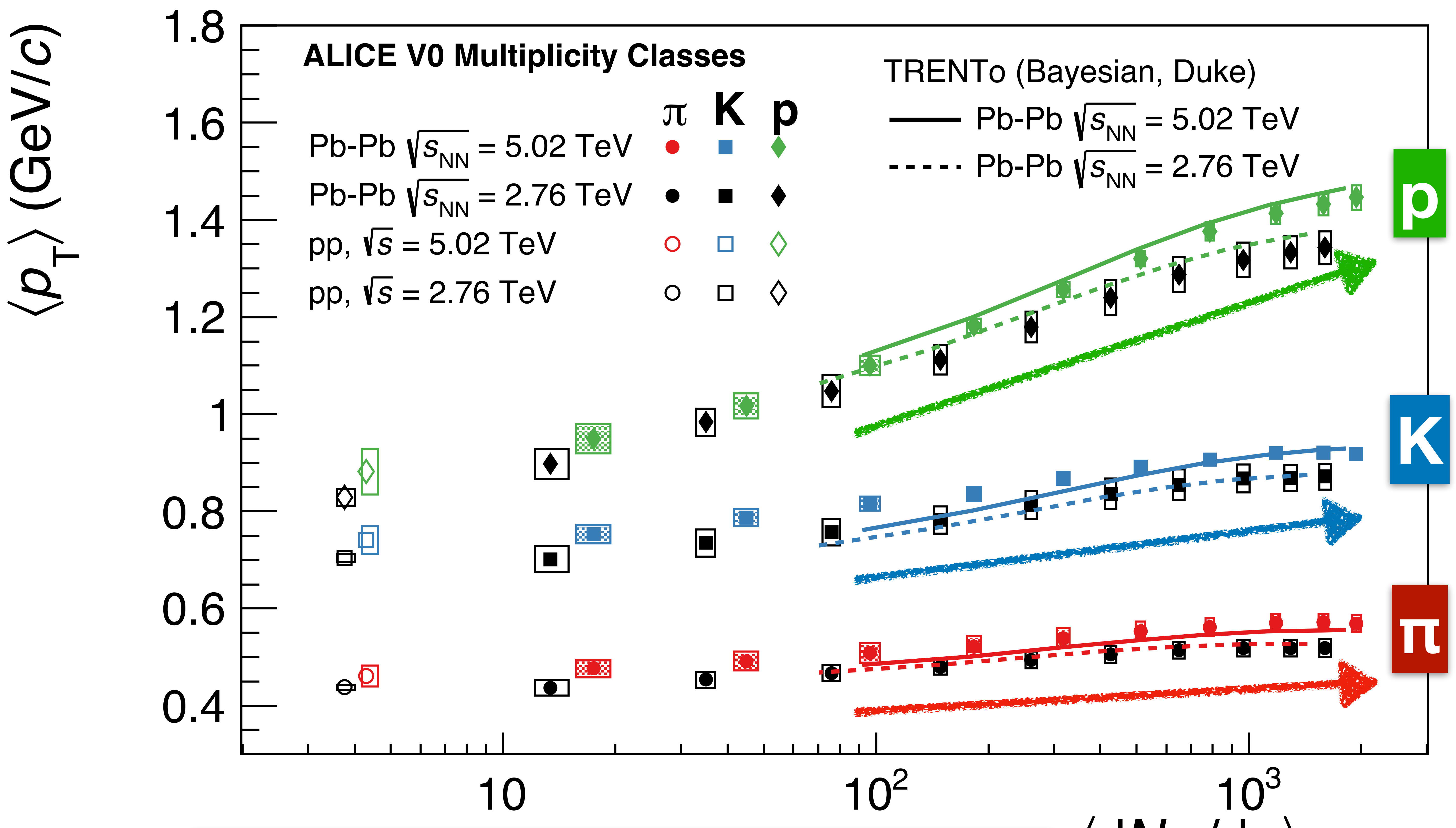
➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

***p_0*: initial momentum**
***β*: flow velocity**
***m*: particle mass**

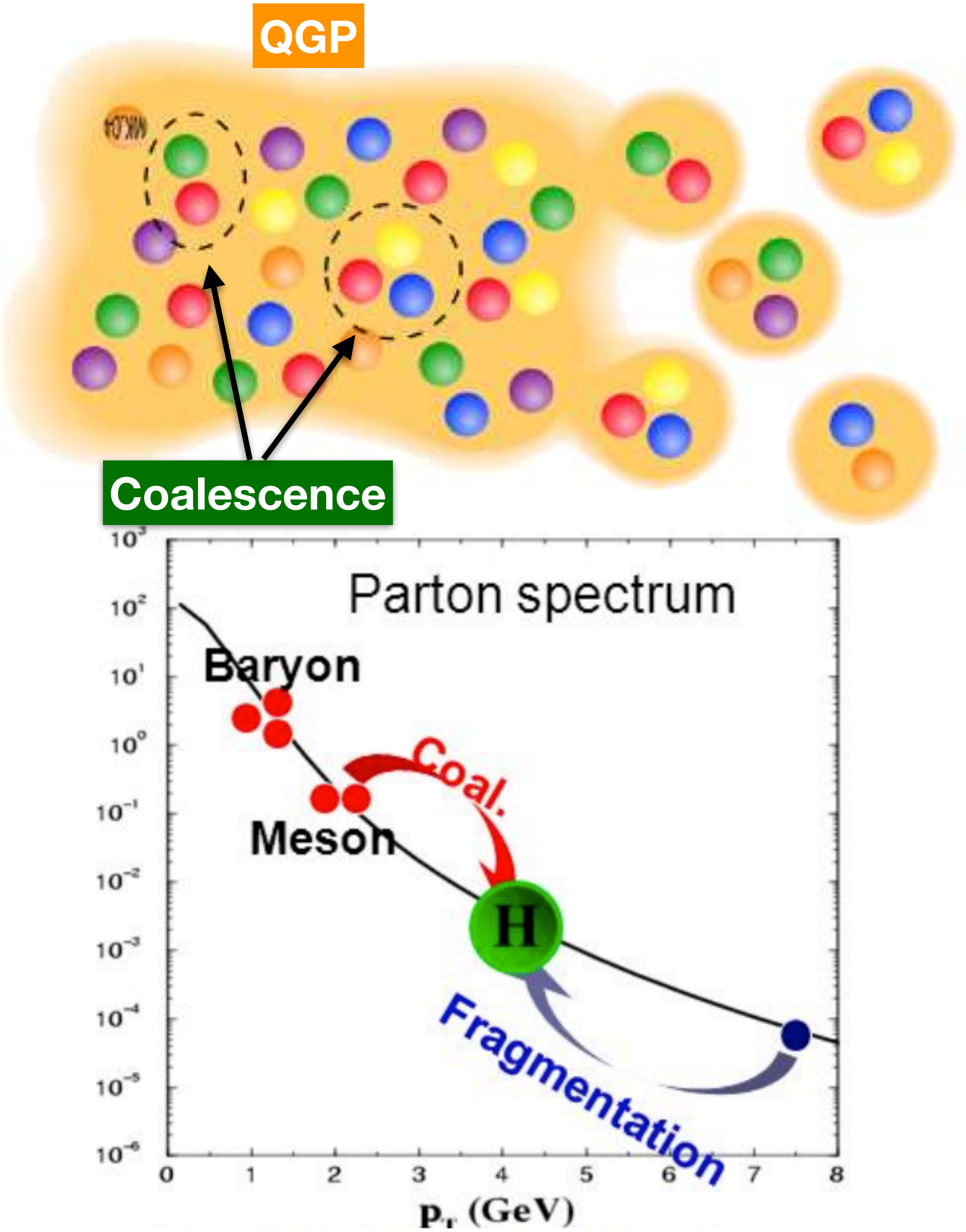
➡ More pronounced in central collisions

➡ Mass dependence



ALICE *Phys. Rev.* C101 (2020) 044907

Hadronization in heavy-ion collisions



Fragmentation — hadrons from high p_T (hard) partons

Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

➡ $p_{T,hadron} \simeq n\, p_{T,parton}$, n = 2 (meson), 3 (baryon)

➡ Sensitive to baryon and meson species

➡ Baryons from lower momenta partons (denser)

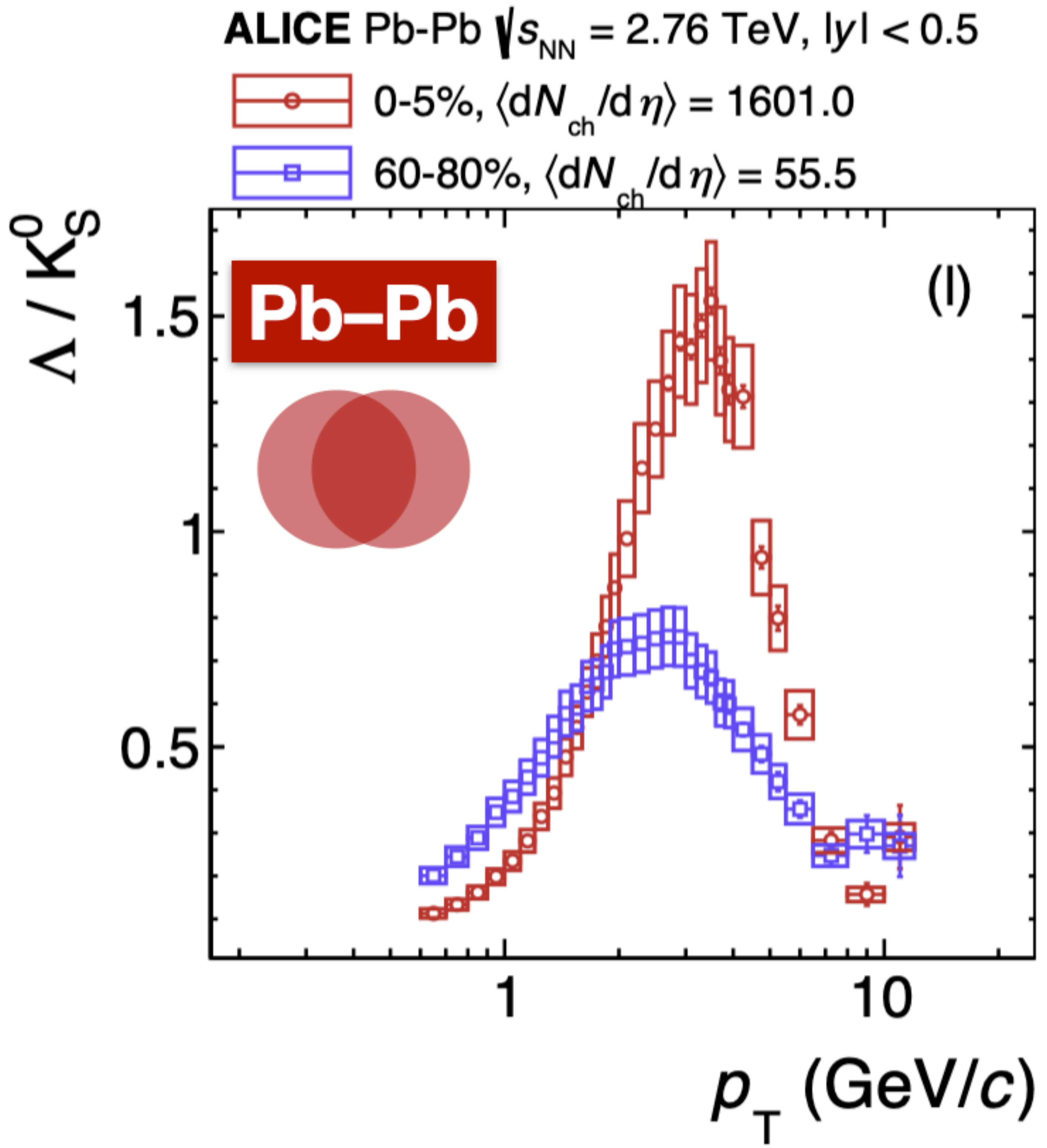
Rapp *et al. Phys. Lett.* **B655** (2007) 126
Greco *et al. Phys.Rev.* **C92** (2015) 054904
Ko *et al. Phys. Lett.* **B792** (2019) 132

Baryon-to-meson enhancement

Baryon-to-meson ratio (Λ/K_S^0) increases at intermediate p_T in central Pb–Pb collisions w. r. t. peripheral ones

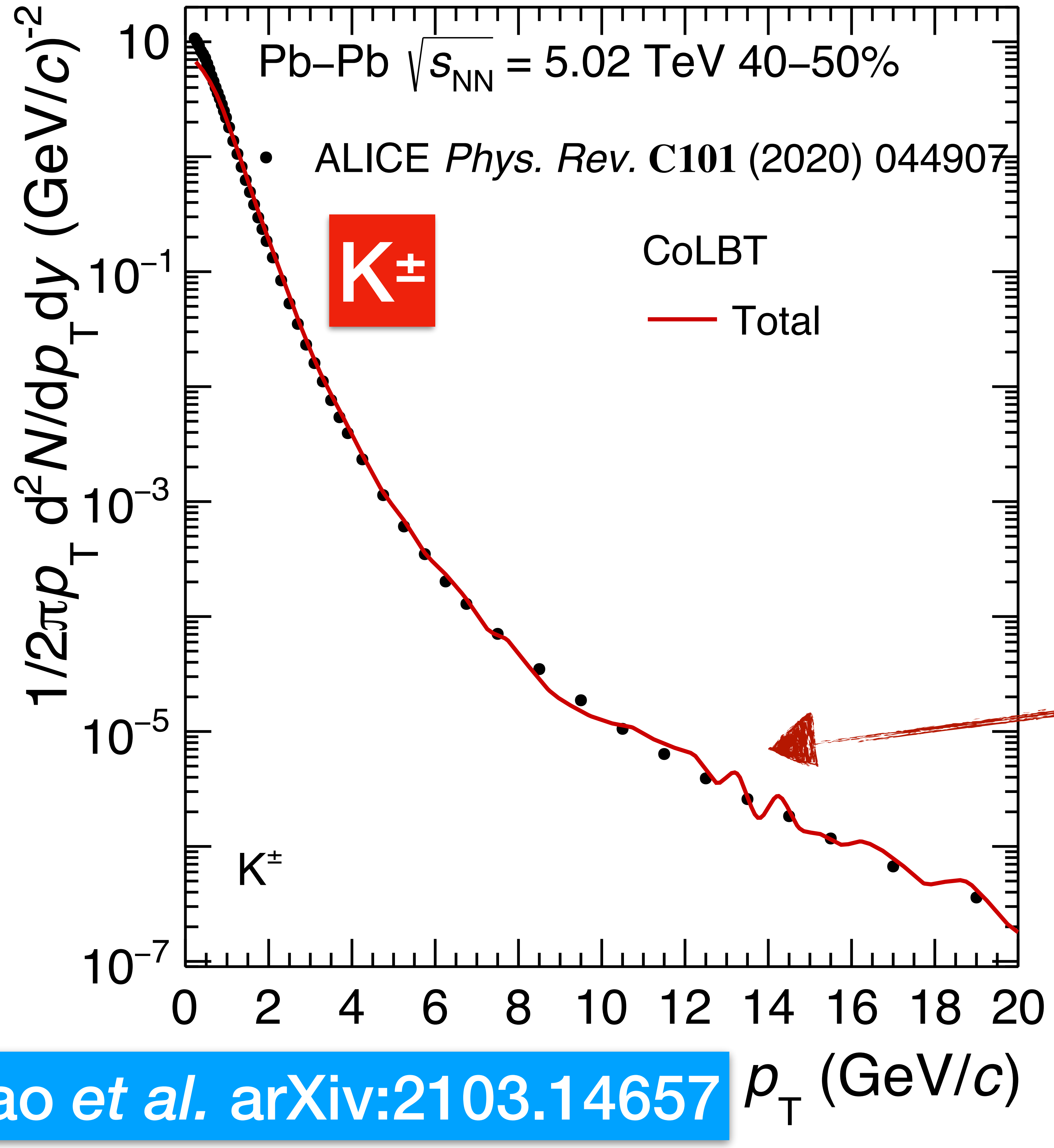
➡ Interplay of radial flow and coalescence

➡ Reflect QGP effects in heavy-ion collisions



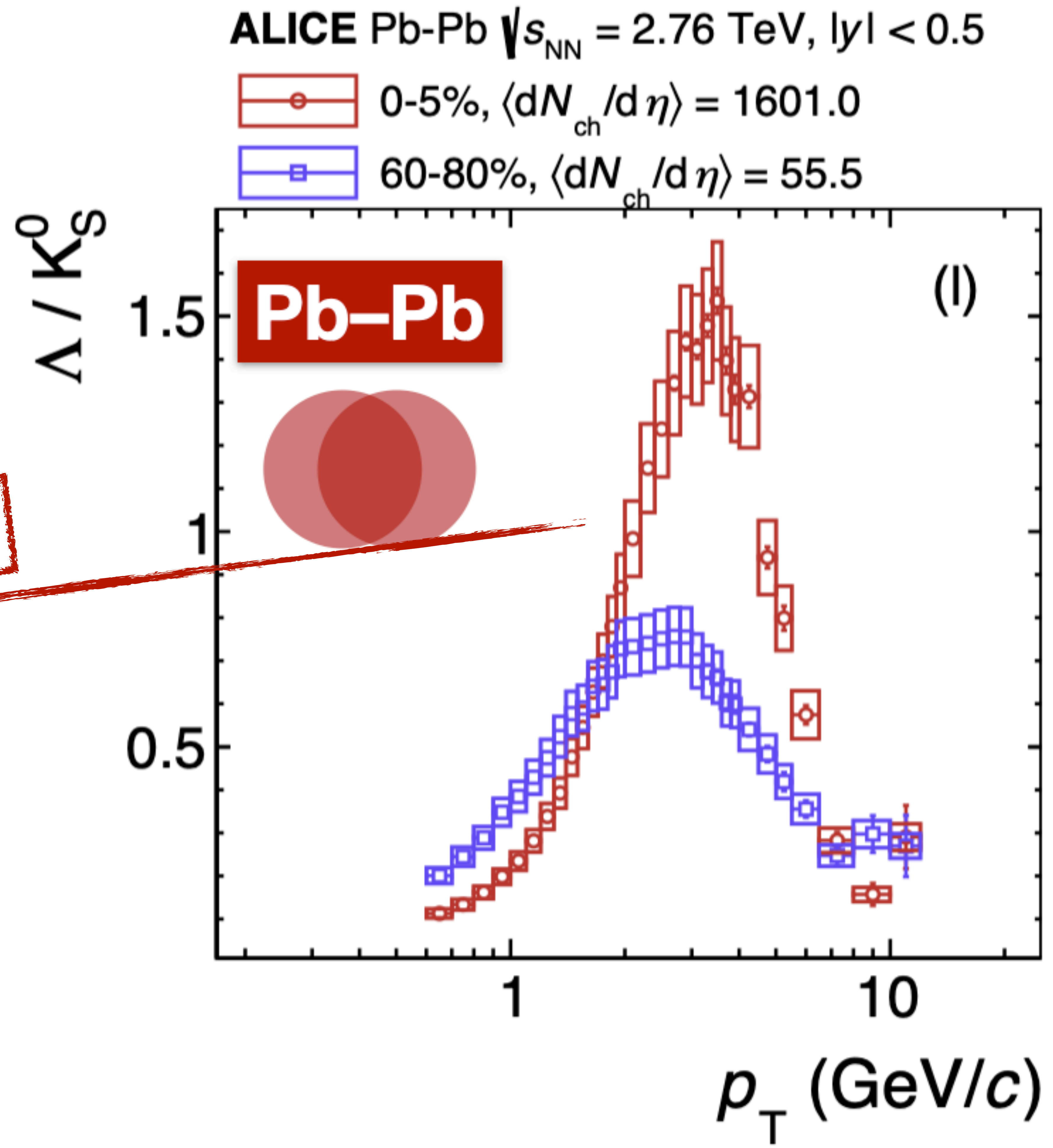
ALICE *Phys. Rev.* **C99** (2019) 024906

Baryon-to-meson enhancement



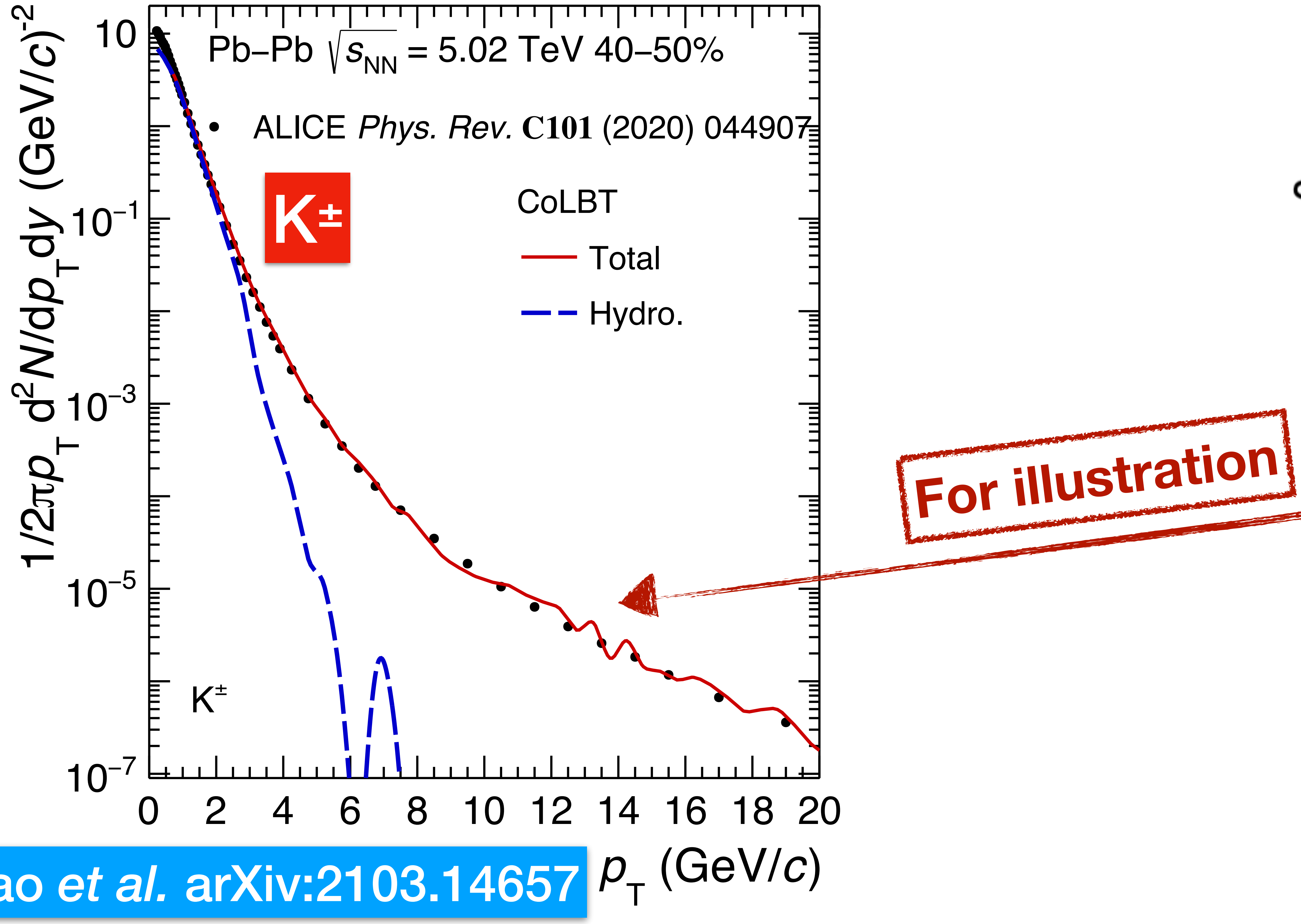
Zhao *et al.* arXiv:2103.14657

For illustration

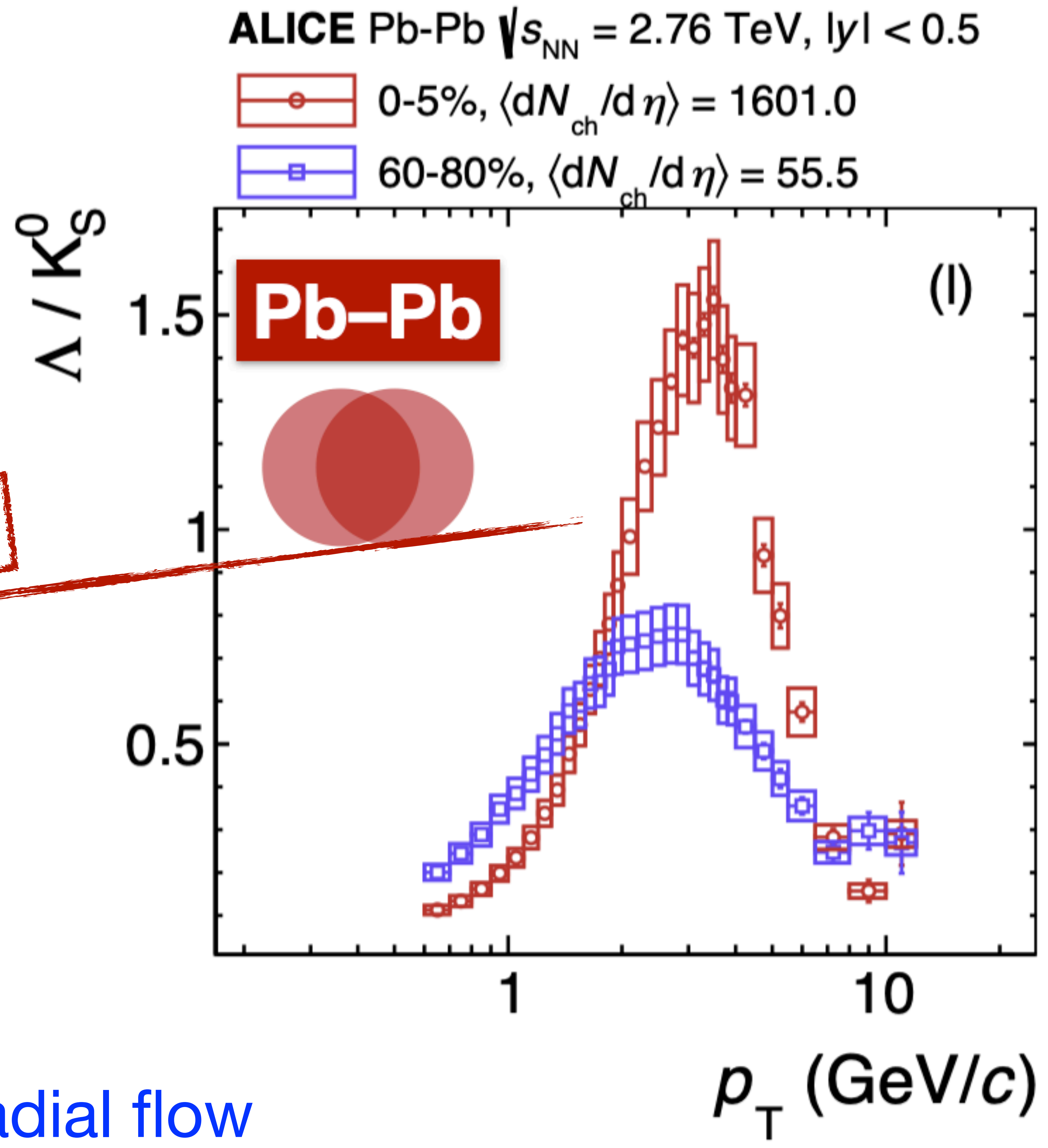


ALICE *Phys. Rev.* C99 (2019) 024906

Baryon-to-meson enhancement



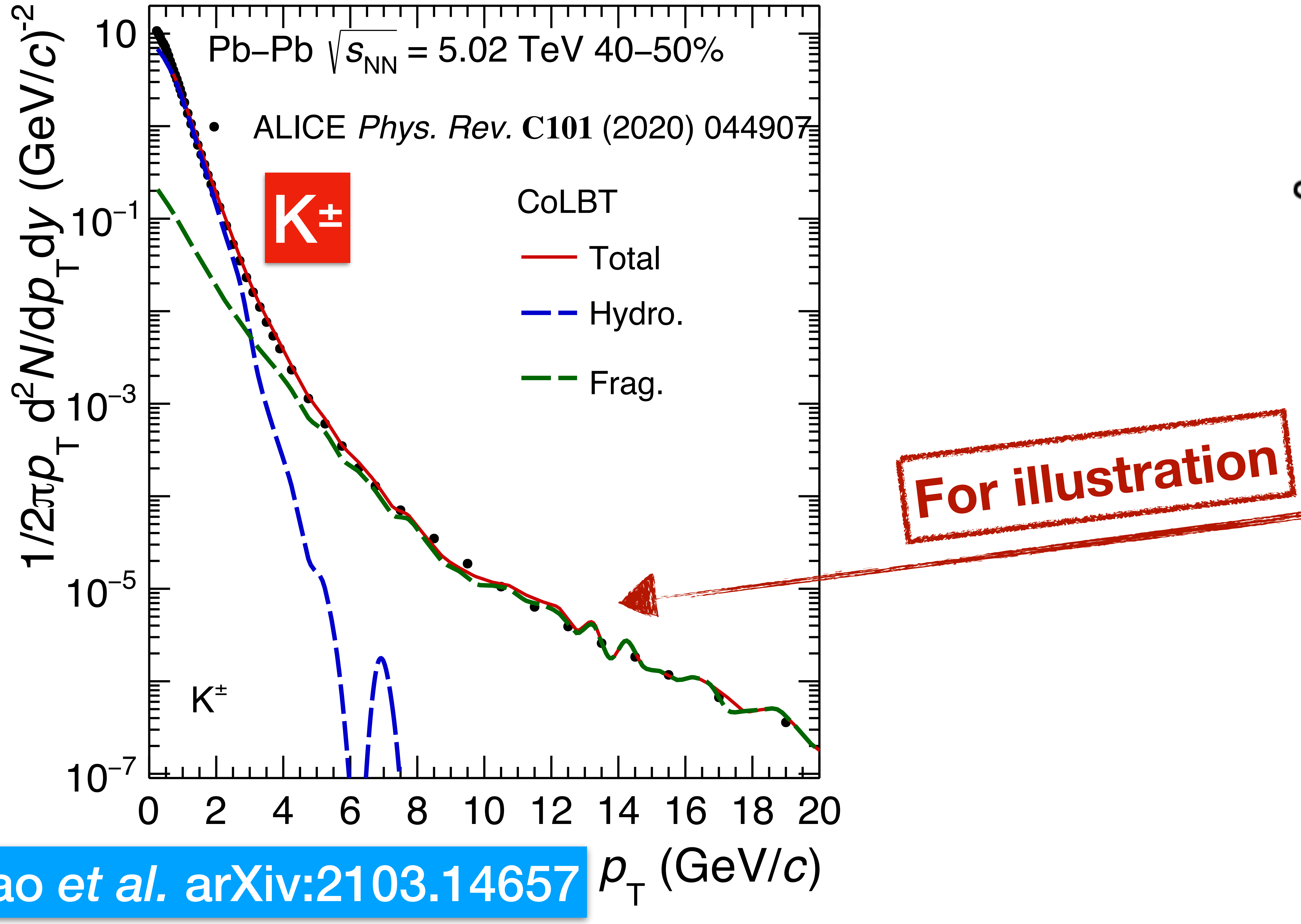
Zhao *et al.* arXiv:2103.14657



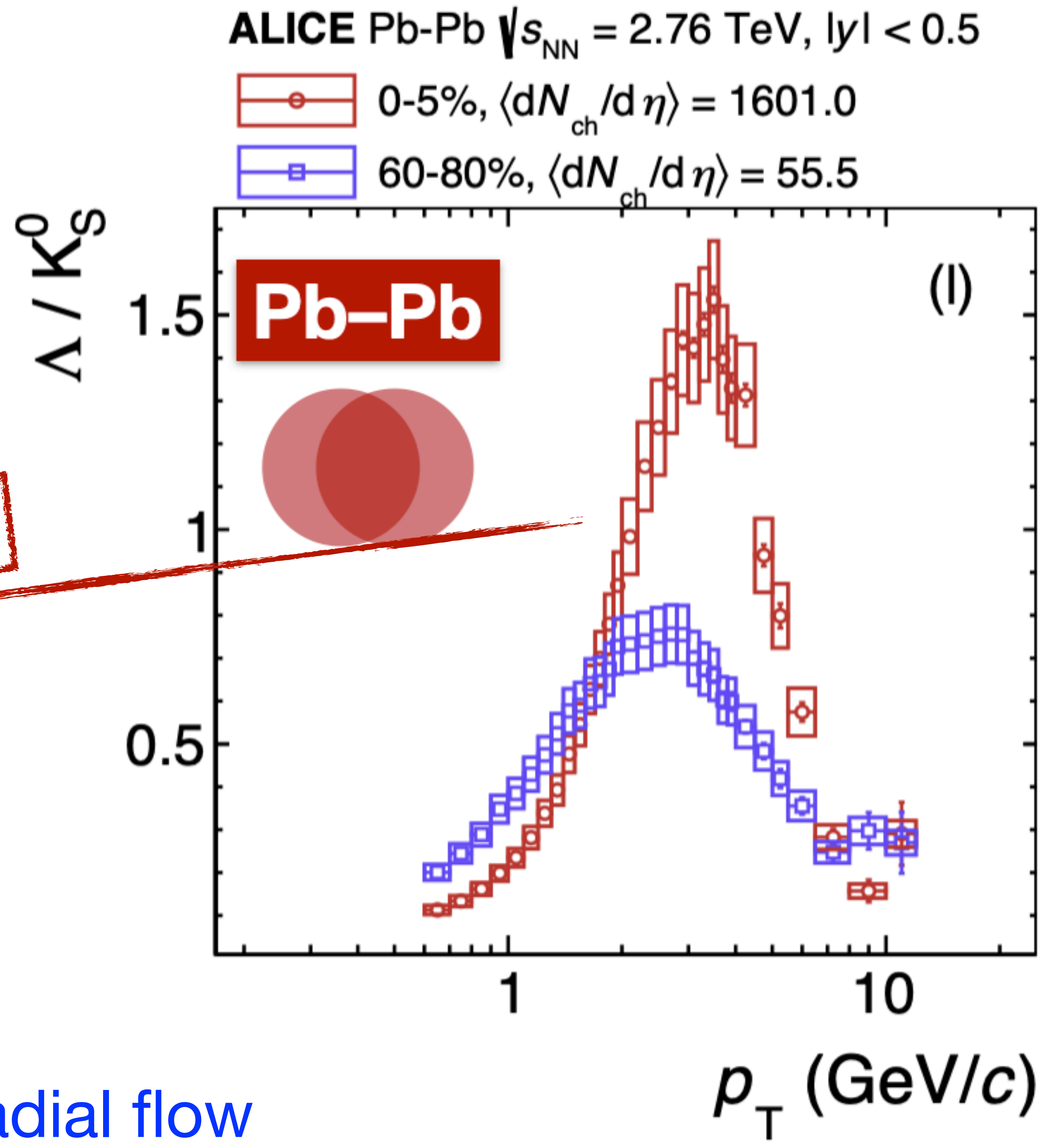
Hydrodynamics contribution from thermal parton — radial flow

ALICE *Phys. Rev.* C99 (2019) 024906

Baryon-to-meson enhancement



Zhao *et al.* arXiv:2103.14657

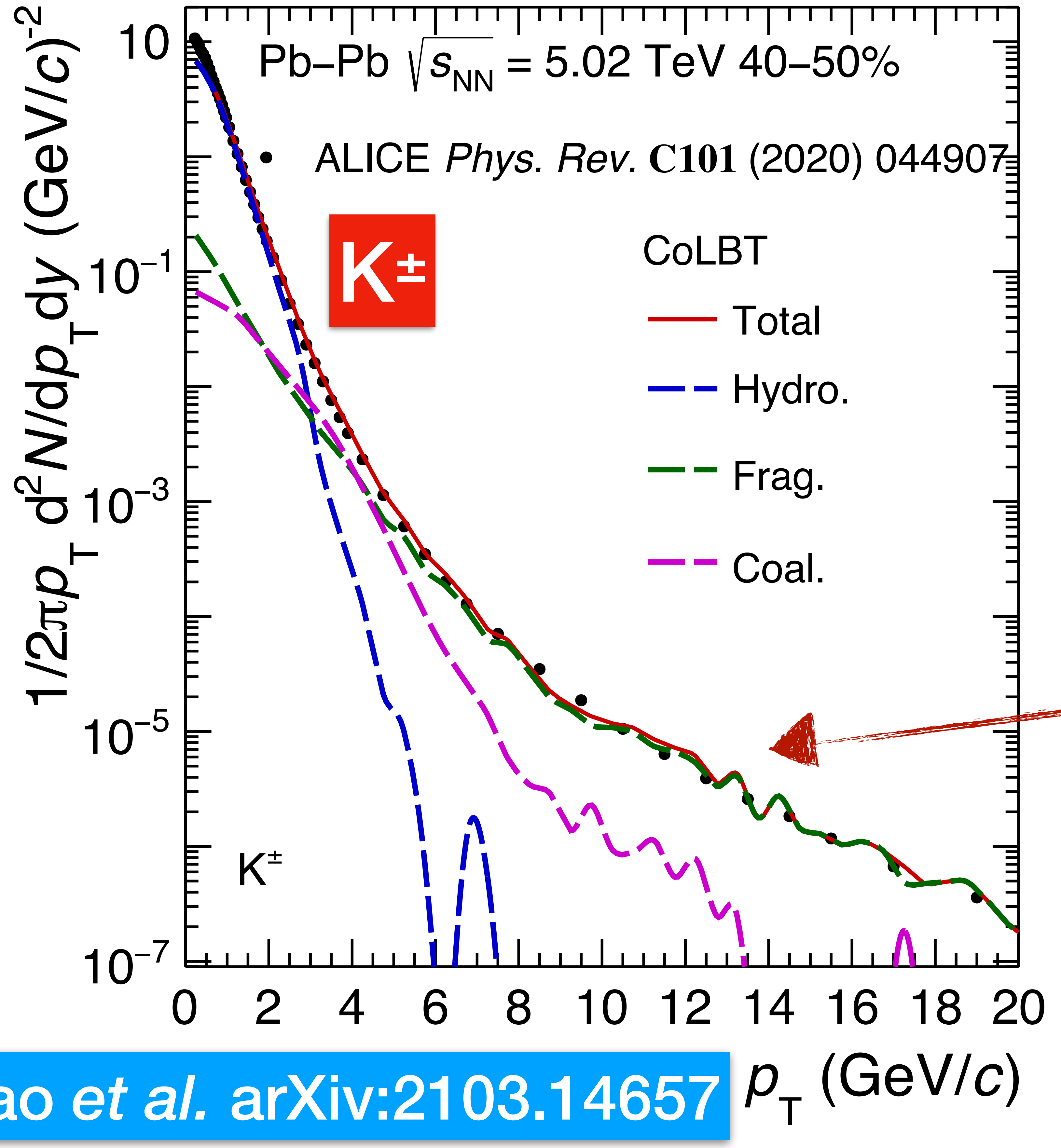


ALICE *Phys. Rev.* **C99** (2019) 024906

Hydrodynamics contribution from thermal parton — radial flow

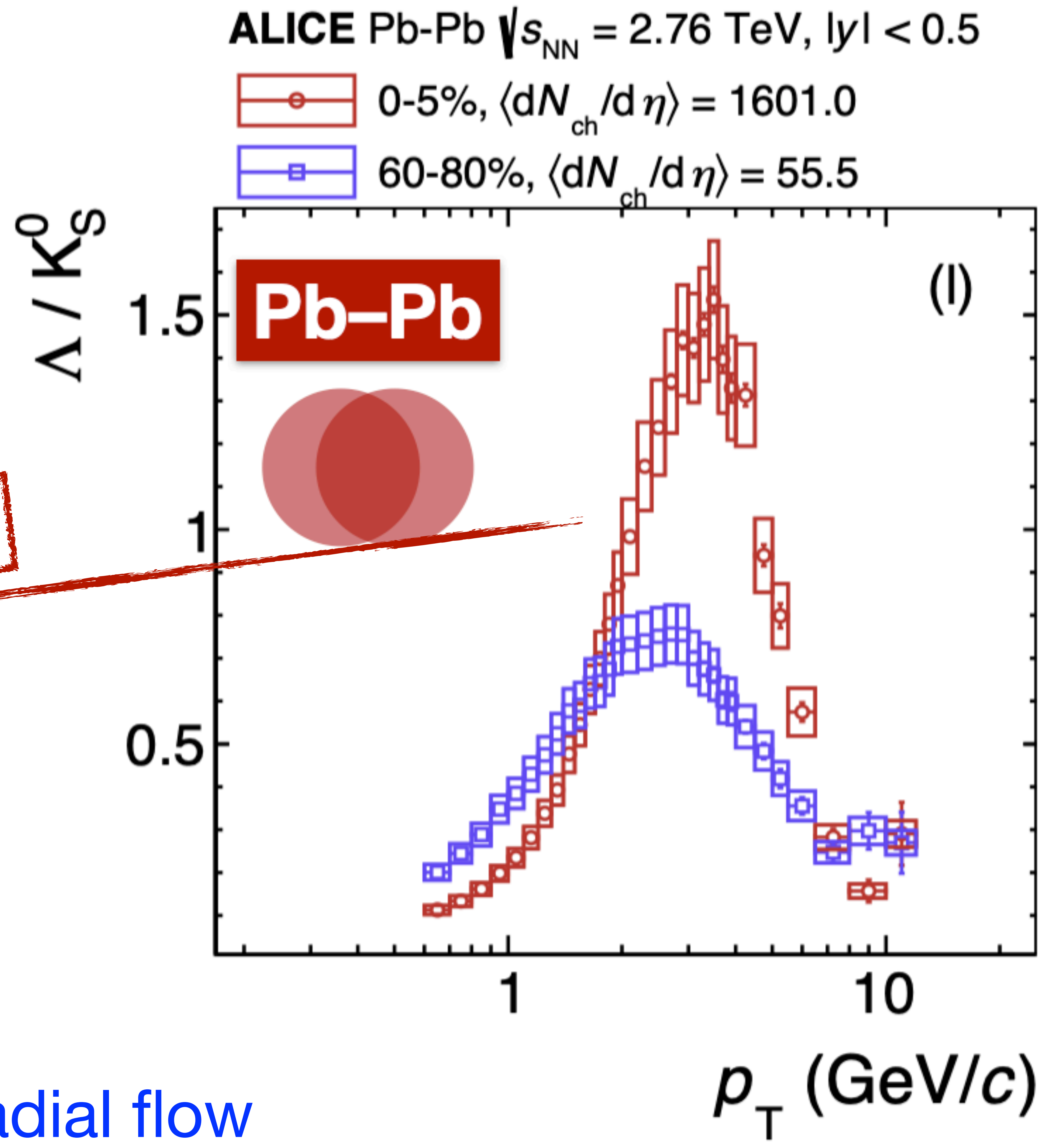
Fragmentation hard parton hadronization at QGP surface

Baryon-to-meson enhancement



Zhao *et al.* arXiv:2103.14657

For illustration



ALICE *Phys. Rev.* **C99** (2019) 024906

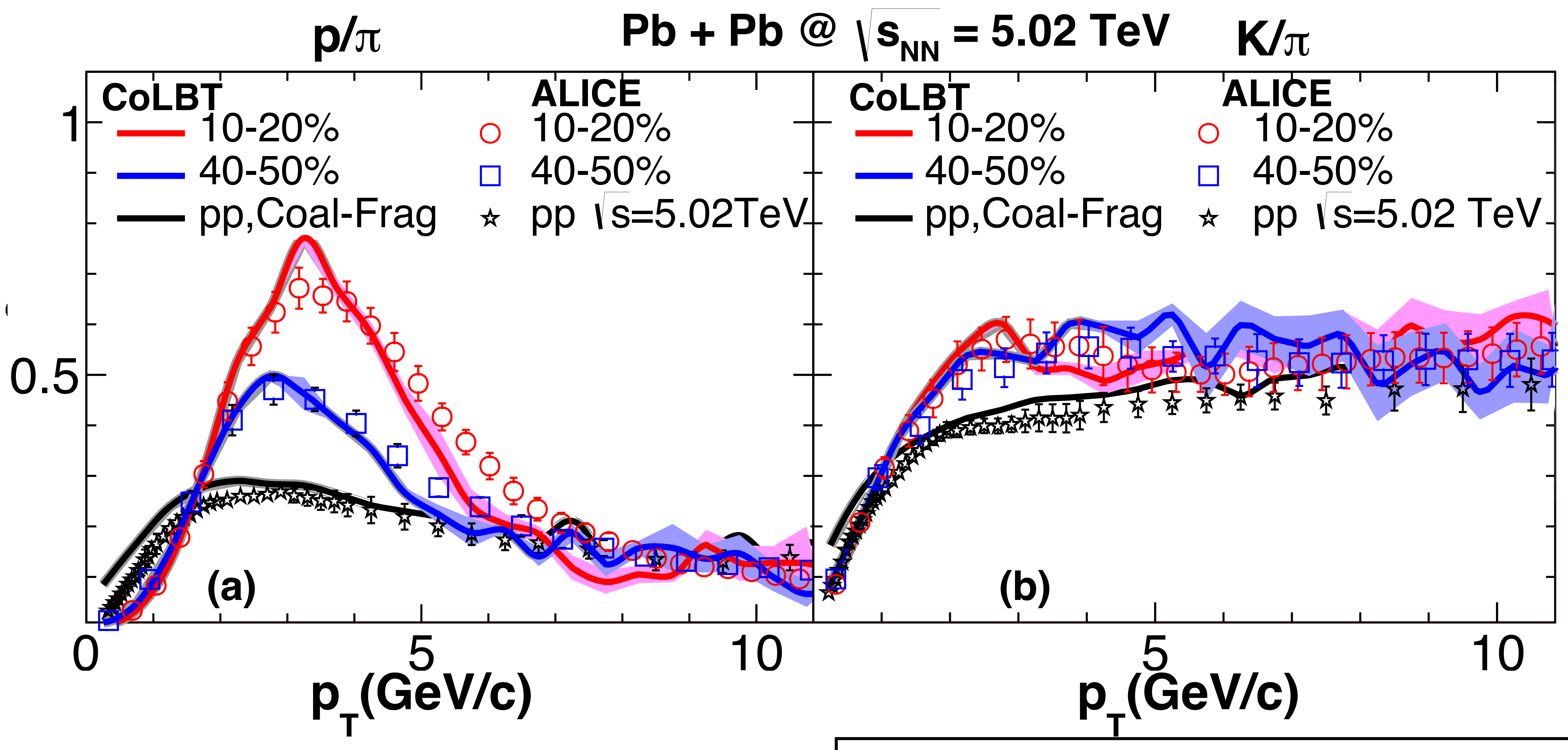
Hydrodynamics contribution from thermal parton — radial flow

Fragmentation hard parton hadronization at QGP surface

Coalescence interplay of thermal and hard partons

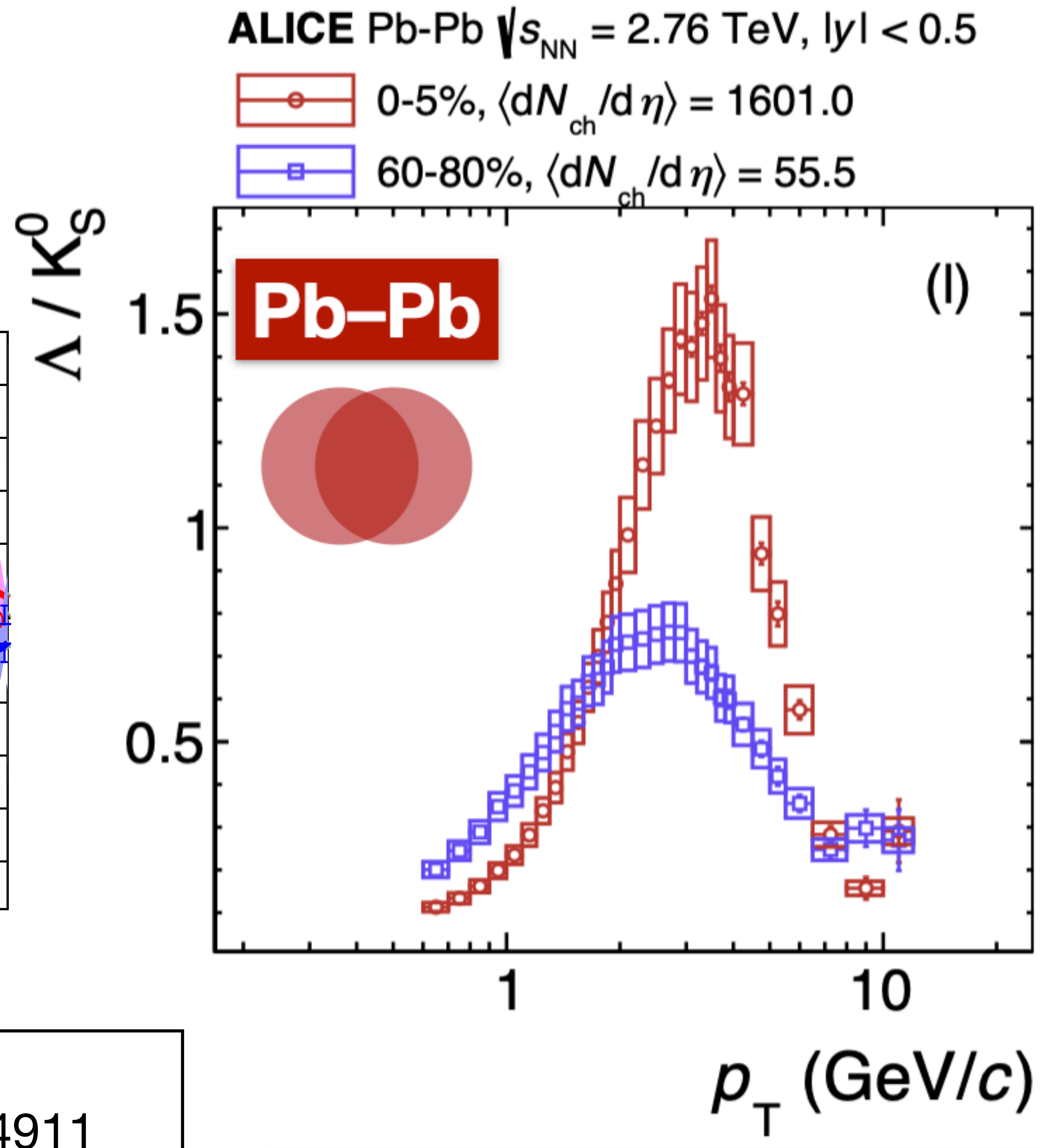
Baryon-to-meson enhancement

Hard parton contribution is important to describe the particle ratios in data



Zhao *et al.* arXiv:2103.14657

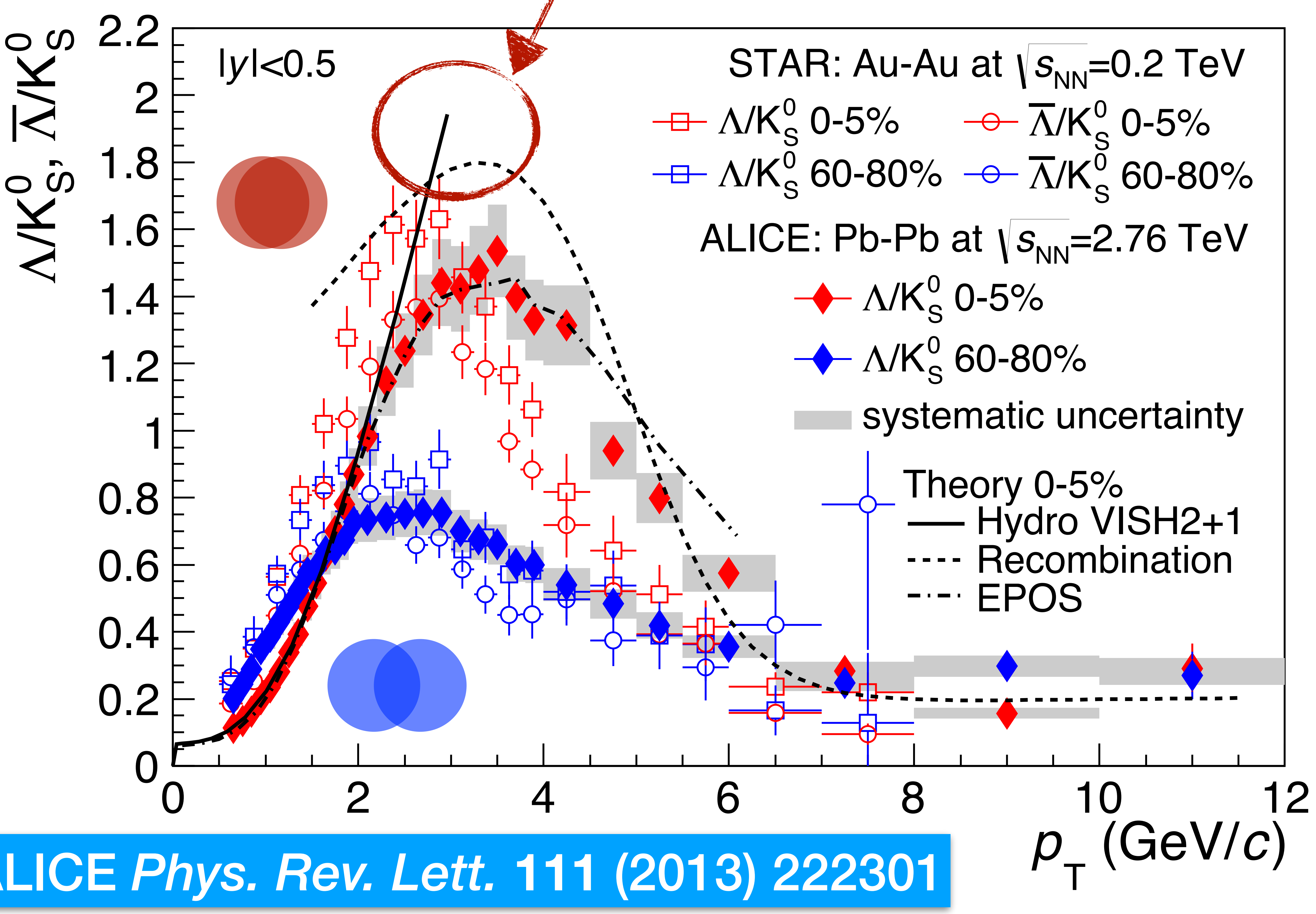
Similar implementation
LIDO *Phys. Rev.* **C100** (2019) 064911
MC@sHQ *Phys. Rev.* **C89** (2014) 014905
Catania *Phys. Lett.* **B805** (2020) 135460
POWLANG-HTL *JHEP* **1802** (2018) 043



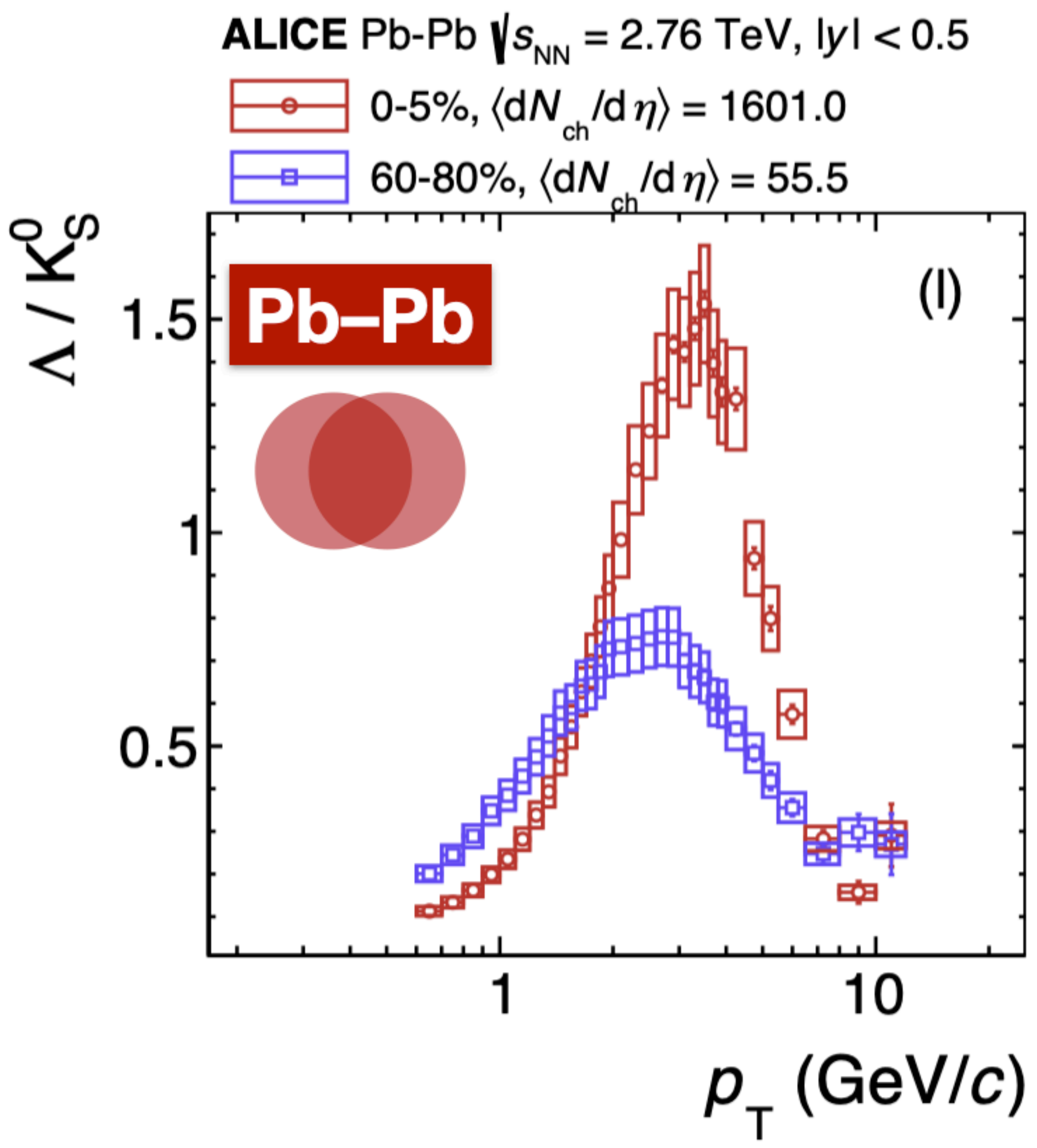
ALICE *Phys. Rev.* **C99** (2019) 024906

Baryon-to-meson enhancement

It leads large deviation from data if consider the soft component only

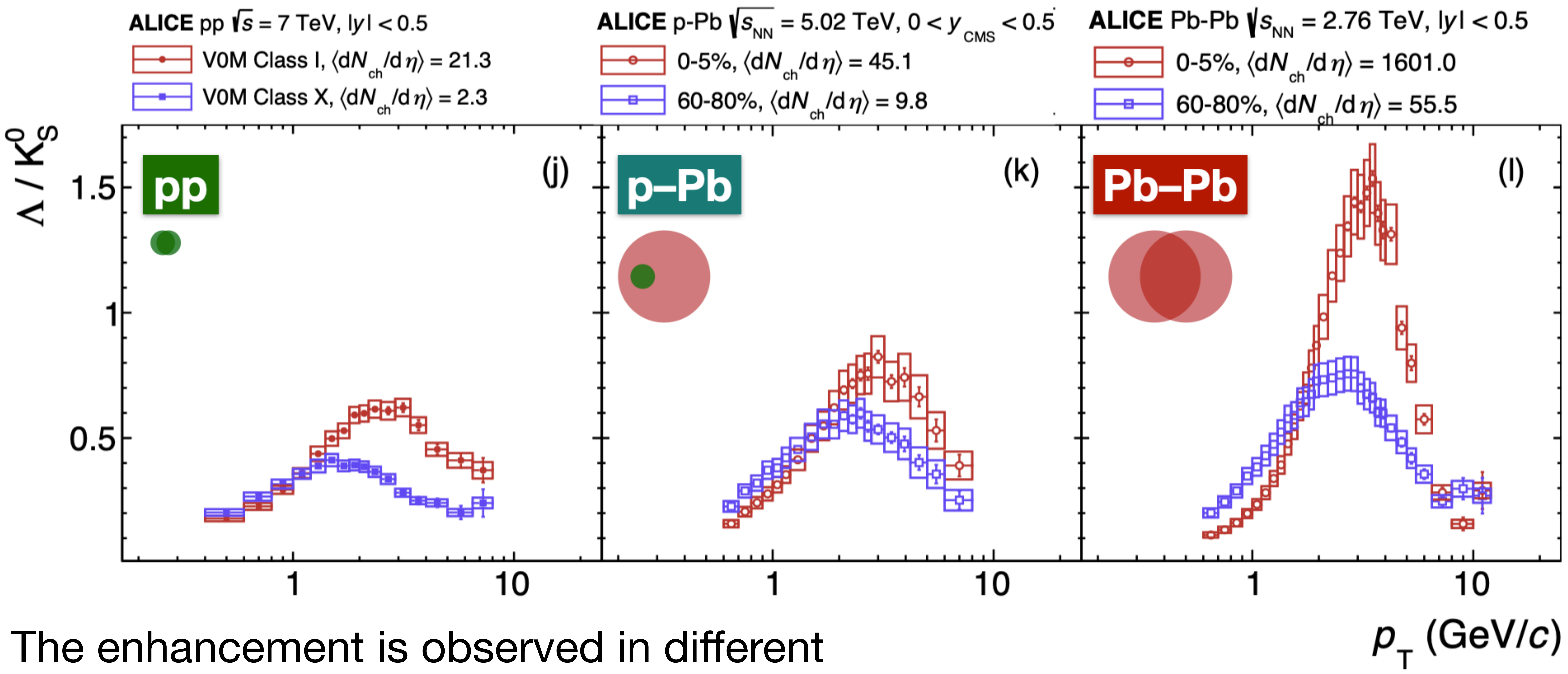


ALICE *Phys. Rev. Lett.* 111 (2013) 222301



ALICE *Phys. Rev.* C99 (2019) 024906

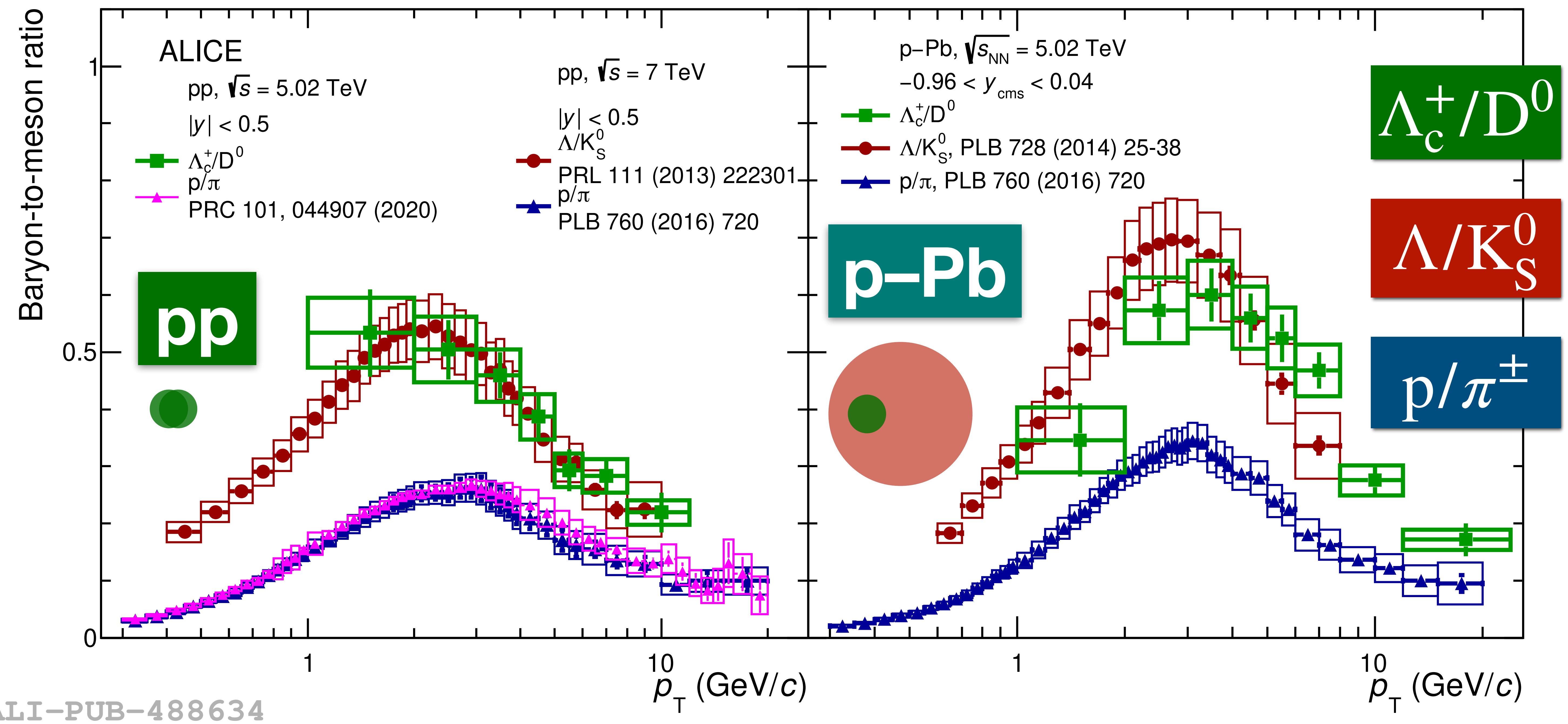
Baryon-to-meson enhancement



The enhancement is observed in different collision systems (Pb–Pb, p–Pb and pp) at high multiplicities

ALICE *Phys. Rev.* **C99** (2019) 024906

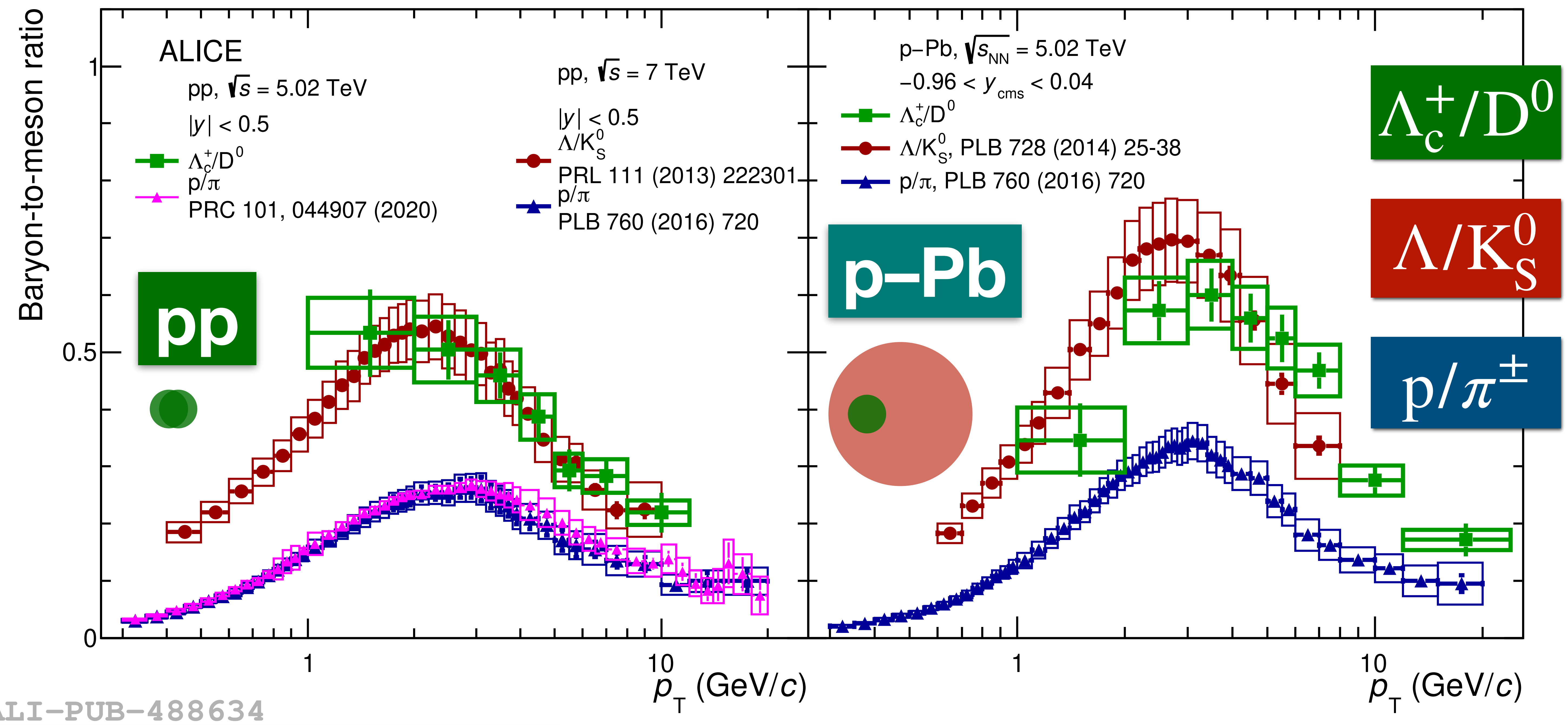
Baryon-to-meson enhancement



ALICE arXiv:2011.06079
arXiv:2011.06078

Similar behavior observed also in **charm sector** in small system (pp and p–Pb) collisions

Baryon-to-meson enhancement

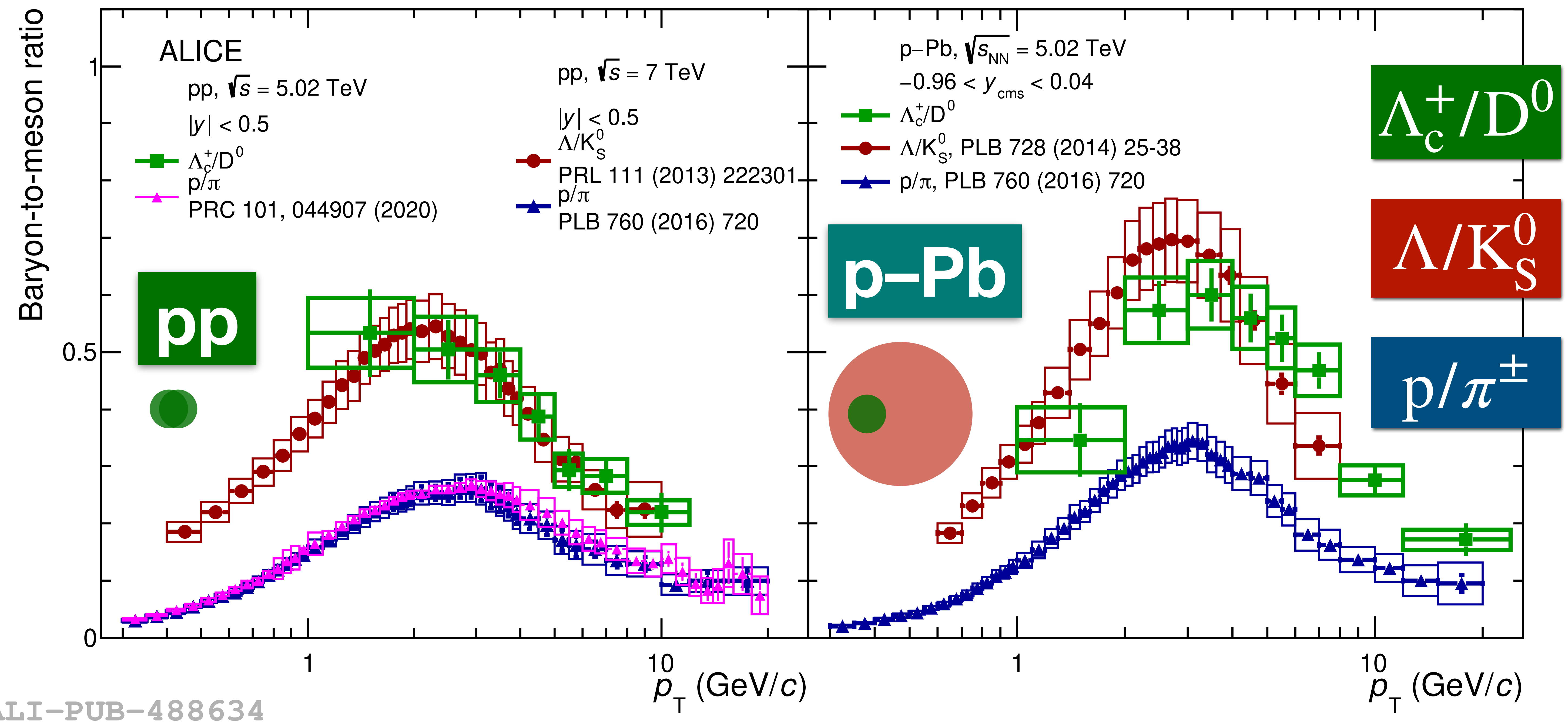


ALICE arXiv:2011.06079
arXiv:2011.06078

To provide constraints on particle production mechanisms in all collision systems, it is important to separate particles from hard and soft processes

Similar behavior observed also in **charm sector** in small system (pp and p–Pb) collisions

Baryon-to-meson enhancement



ALICE arXiv:2011.06079
arXiv:2011.06078

Similar behavior observed also in **charm sector** in small system (pp and p–Pb) collisions

To provide constraints on particle production mechanisms in all collision systems, it is important to separate particles from hard and soft processes

We concentrate on strange hadrons with ALICE in this presentation

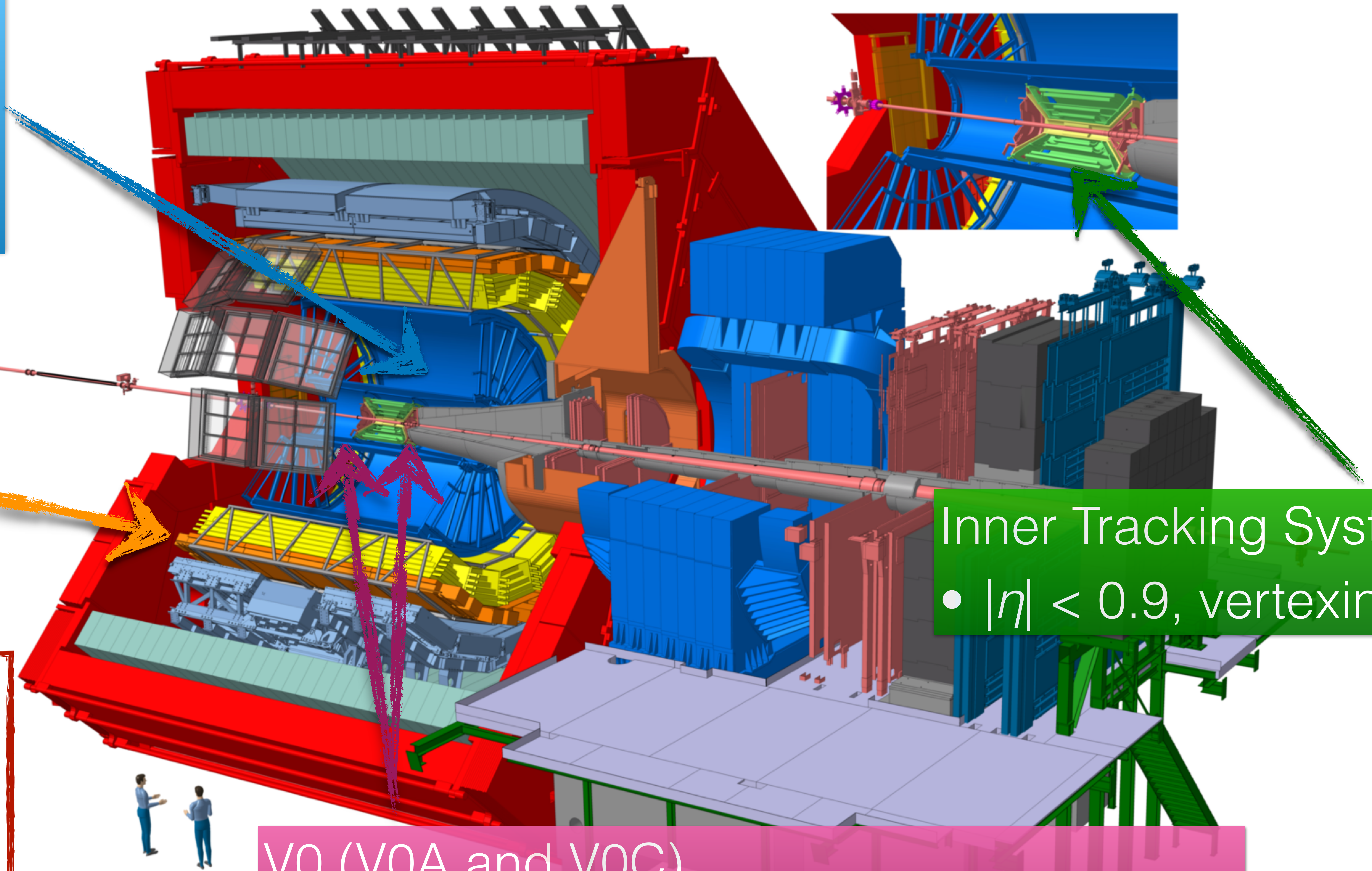
ALICE at the LHC

Time Projection Chamber (TPC)

- $|\eta| < 0.9$
- Charged-particle tracking and identification (PID)

Time of Flight (TOF)

- $|\eta| < 0.9$
- Triggering, pileup rejection, PID



Inner Tracking System (ITS)

- $|\eta| < 0.9$, vertexing

Data samples

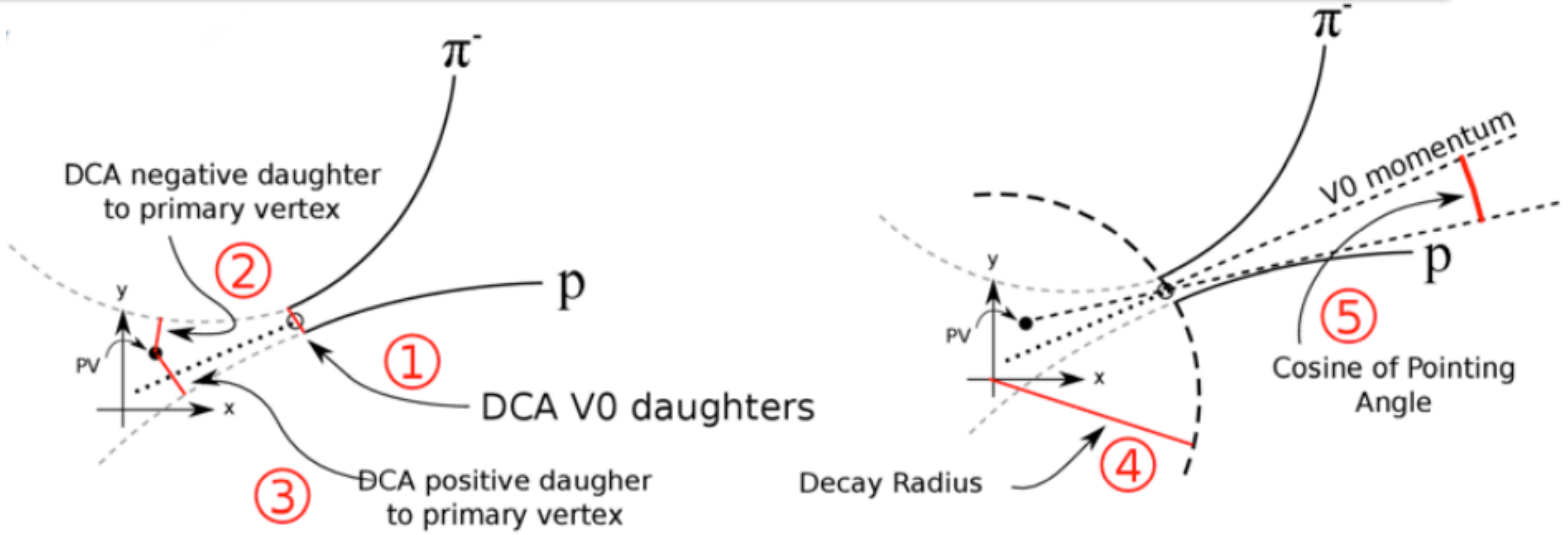
- pp at $\sqrt{s}$ = 7 and 13 TeV
- p–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

V0 (V0A and V0C)

- V0A: $2.8 < \eta < 5.1$, V0C: $-3.7 < \eta < -1.7$
- Triggering and multiplicity determination

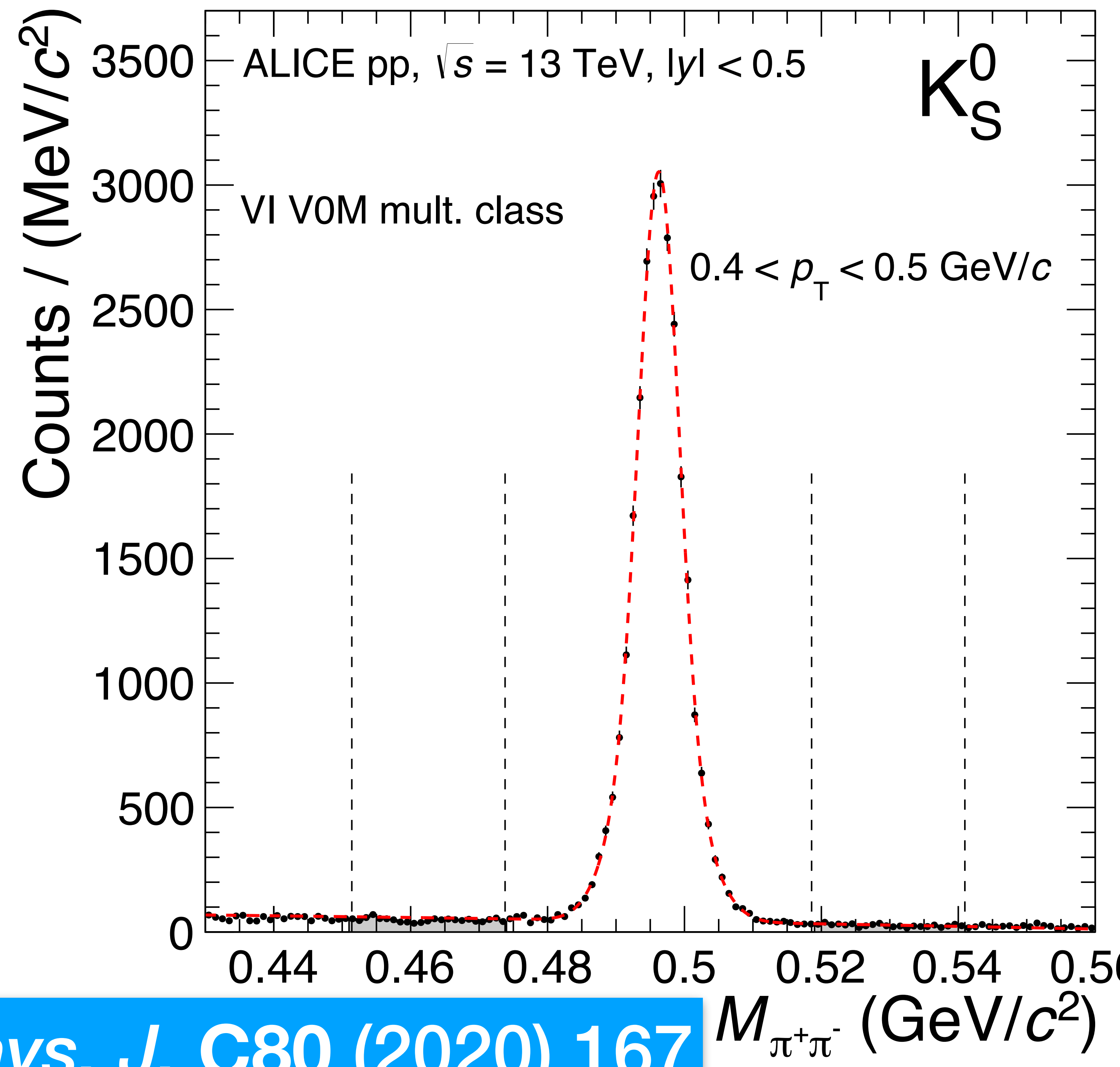
Strange particle reconstruction

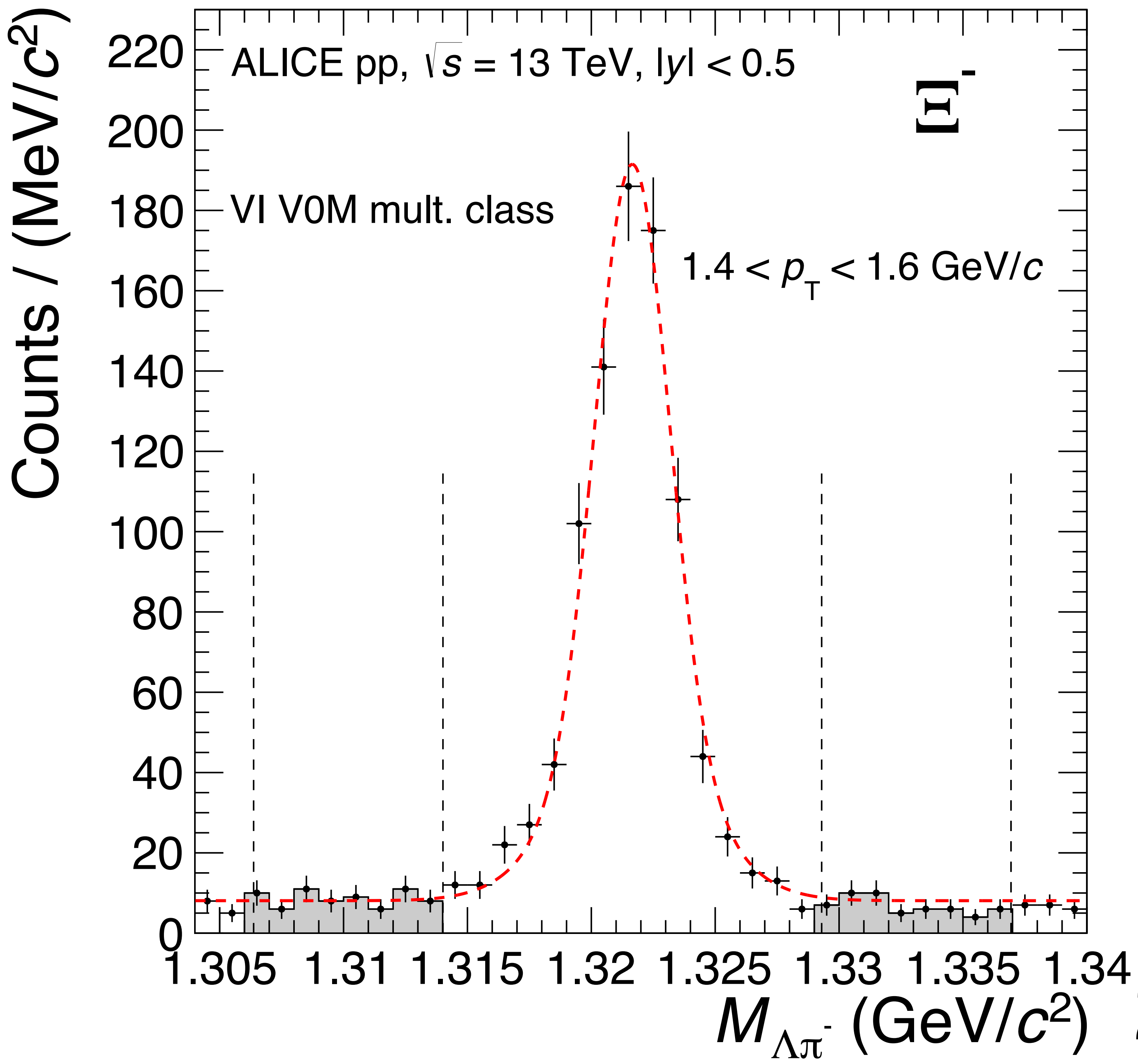
- $K_S^0 \rightarrow \pi^+\pi^-$ (BR 69.2%)
- $\Lambda \rightarrow p\pi^-$ (BR 63.9%)
- $\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^+\pi^-$ (BR 63.9%)



Candidate selection

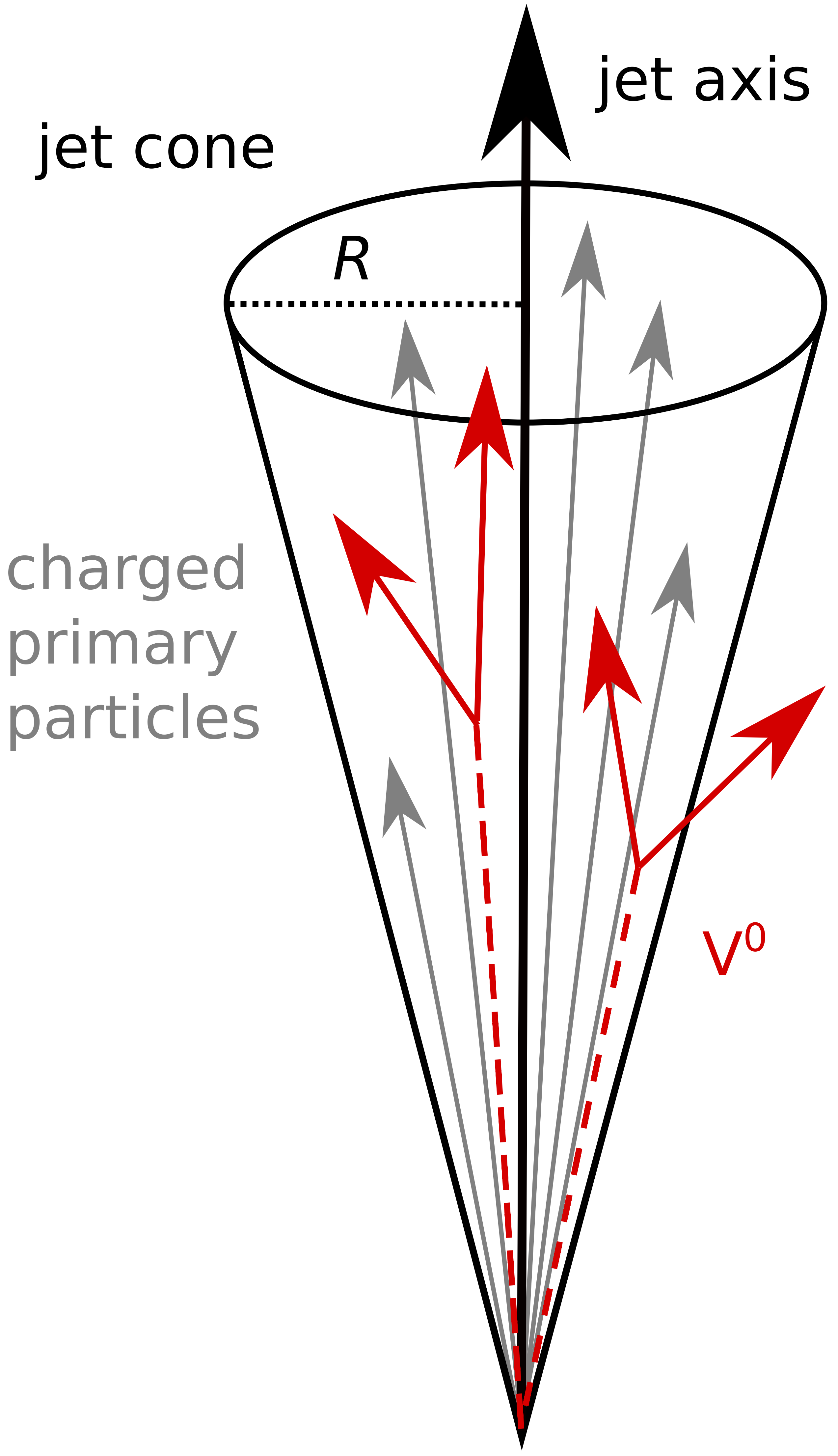
- Pairs/triplets of tracks with proper charge-sign combination
- Particle identification of decay tracks
- Geometrical and kinematic selections based on decay topology





ALICE *Eur. Phys. J.* C80 (2020) 167

Tag hard processes using jets



Charged-particle jet reconstruction

- Jet finder: anti-k_T, R = 0.4
- $p_{T,track}$ > 0.15 GeV/c, $|\eta_{track}|$ < 0.9
- $p^{ch}_{T,jet}$ > 10, 20 GeV/c, $|\eta_{jet}|$ < 0.35

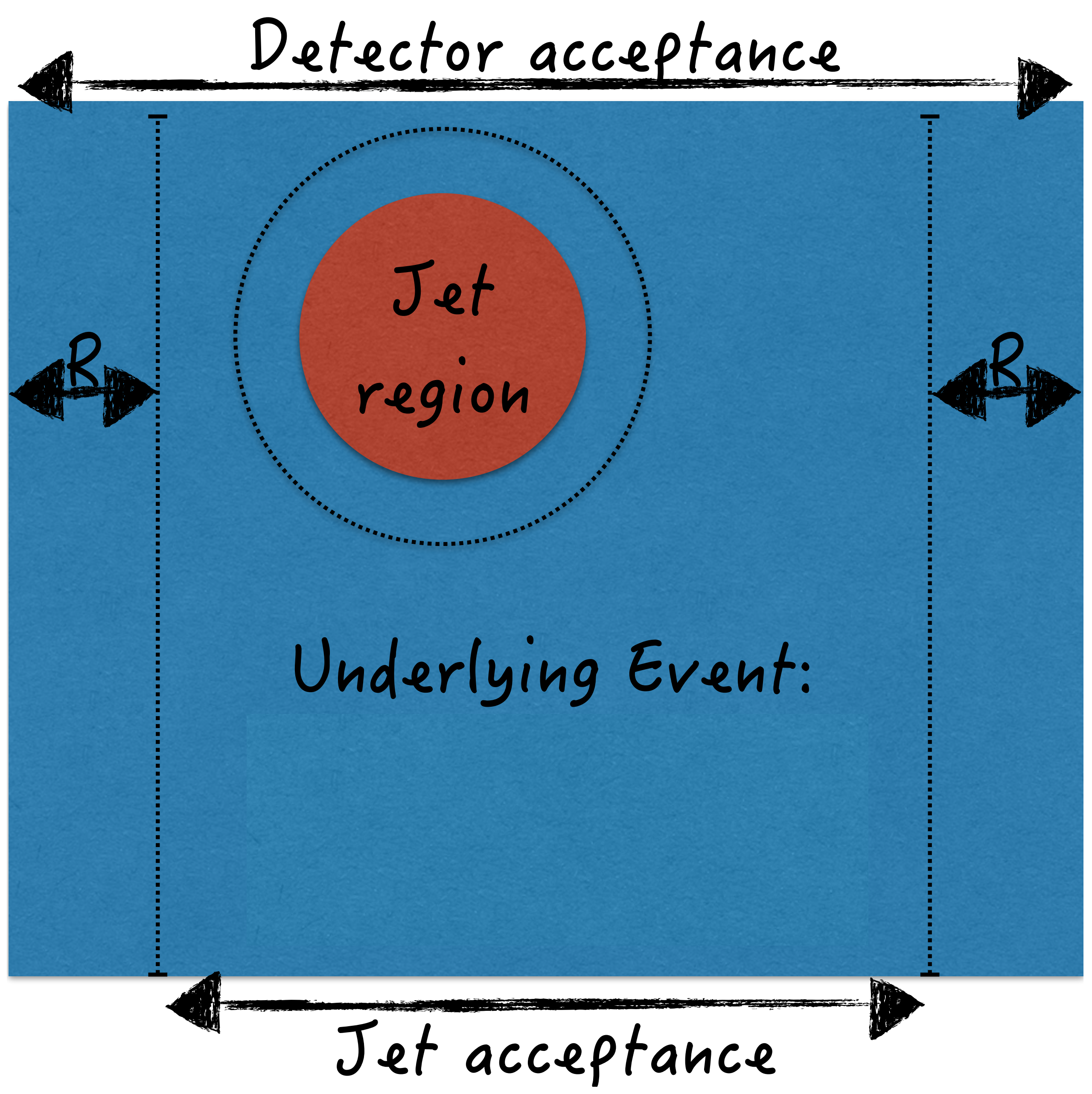
Strangeness-jet matching

- Strange particles in jet cone (JC selection)

➡ $R(\mathrm{S,jet}) = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 0.4$

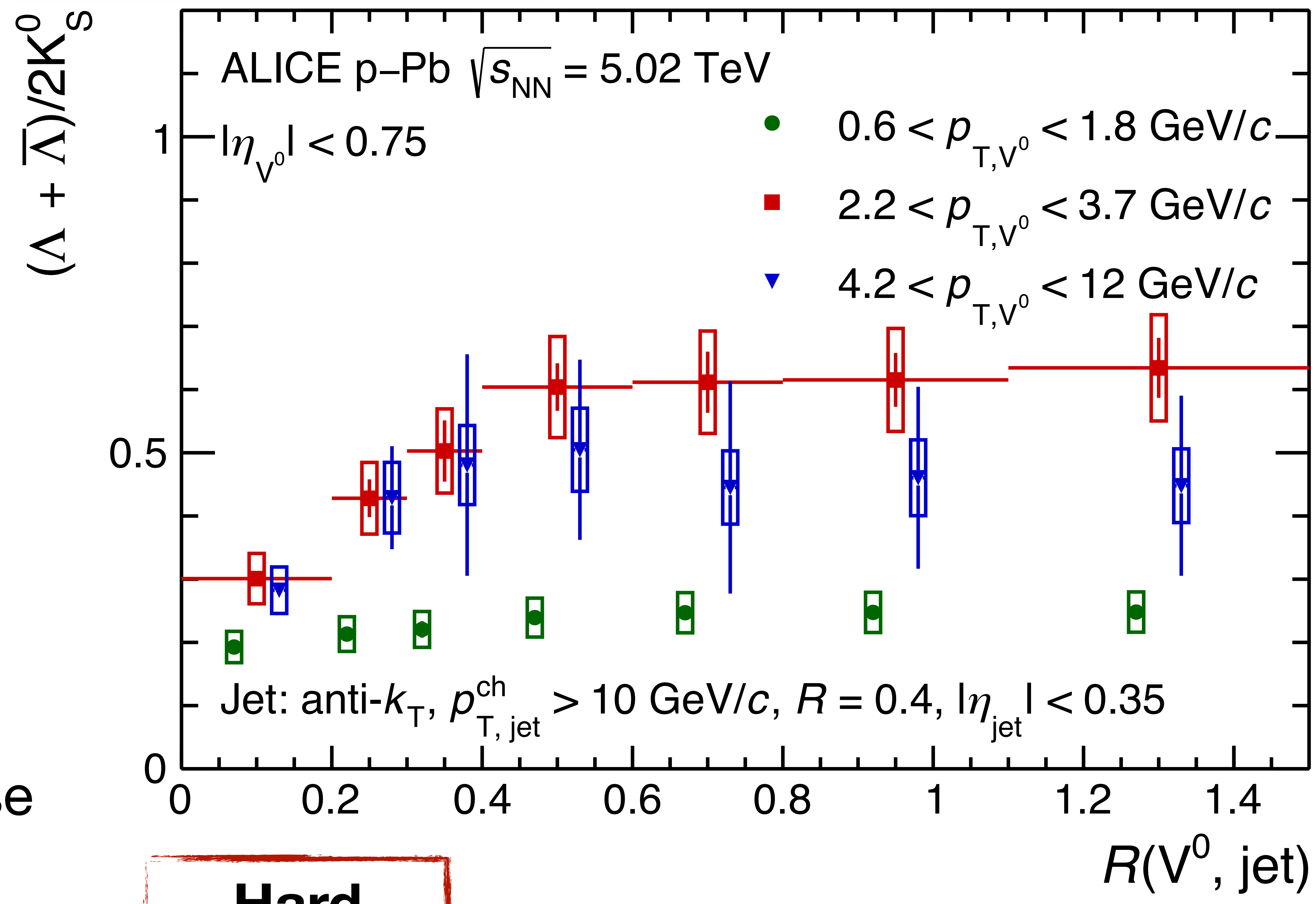
- Caveat still remaining underlying event (UE) contribution in the JC selection

R(S,jet)-dependent Λ/K_S^0 ratio



- Λ/K_S^0 ratio without UE subtraction
- Lack of enhancement close to the jet axis
- The enhanced Λ/K_S^0 ratio is not associated with the jets

ALICE arXiv:2105.04890



Intermediate p_T

High p_T

Low p_T

Hard processes dominant → **UE dominant**

Tag hard processes using jets

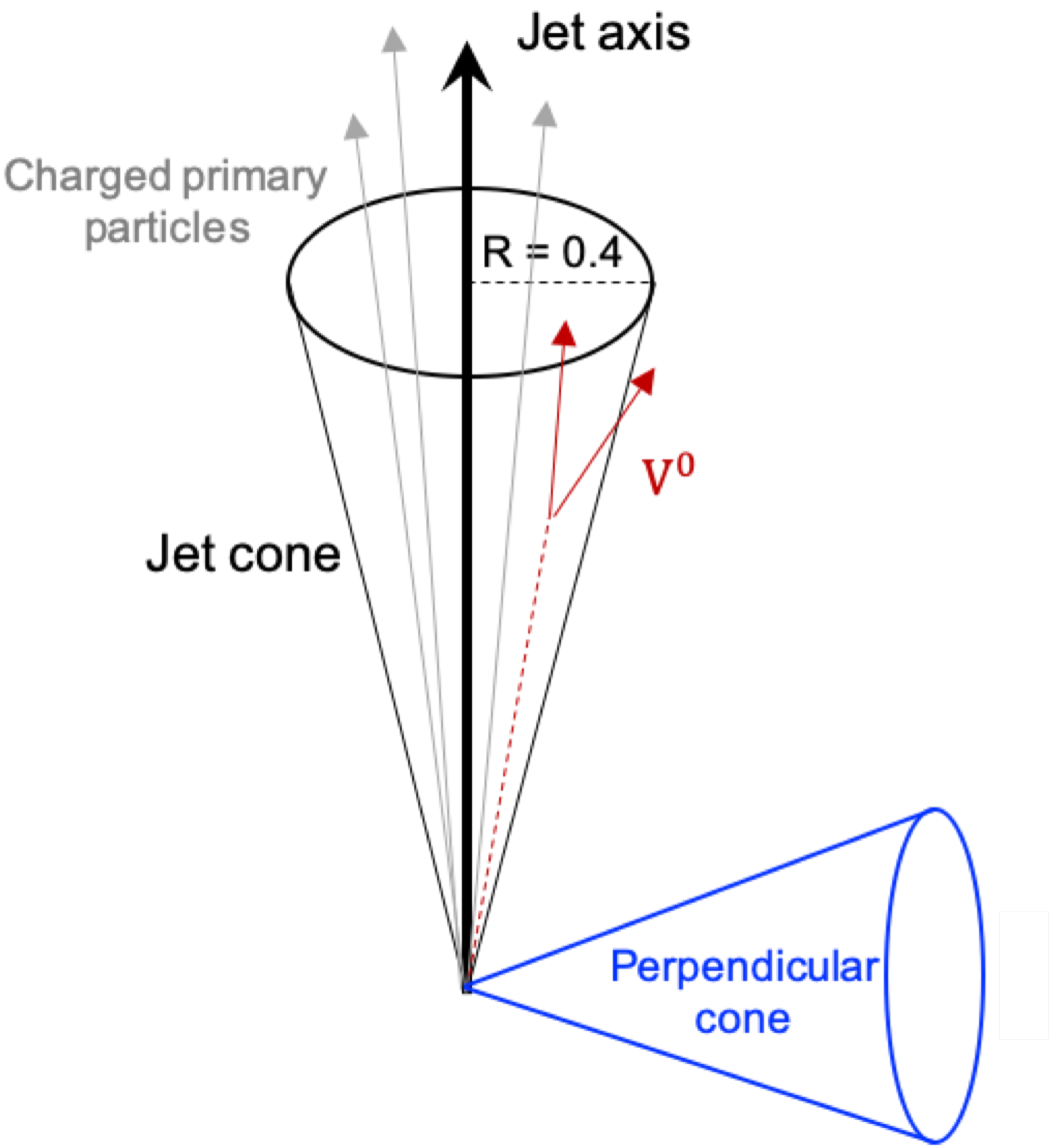
UE contribution subtraction

- UE contribution is obtained in perpendicular cone (PC selection)
- Density distribution

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

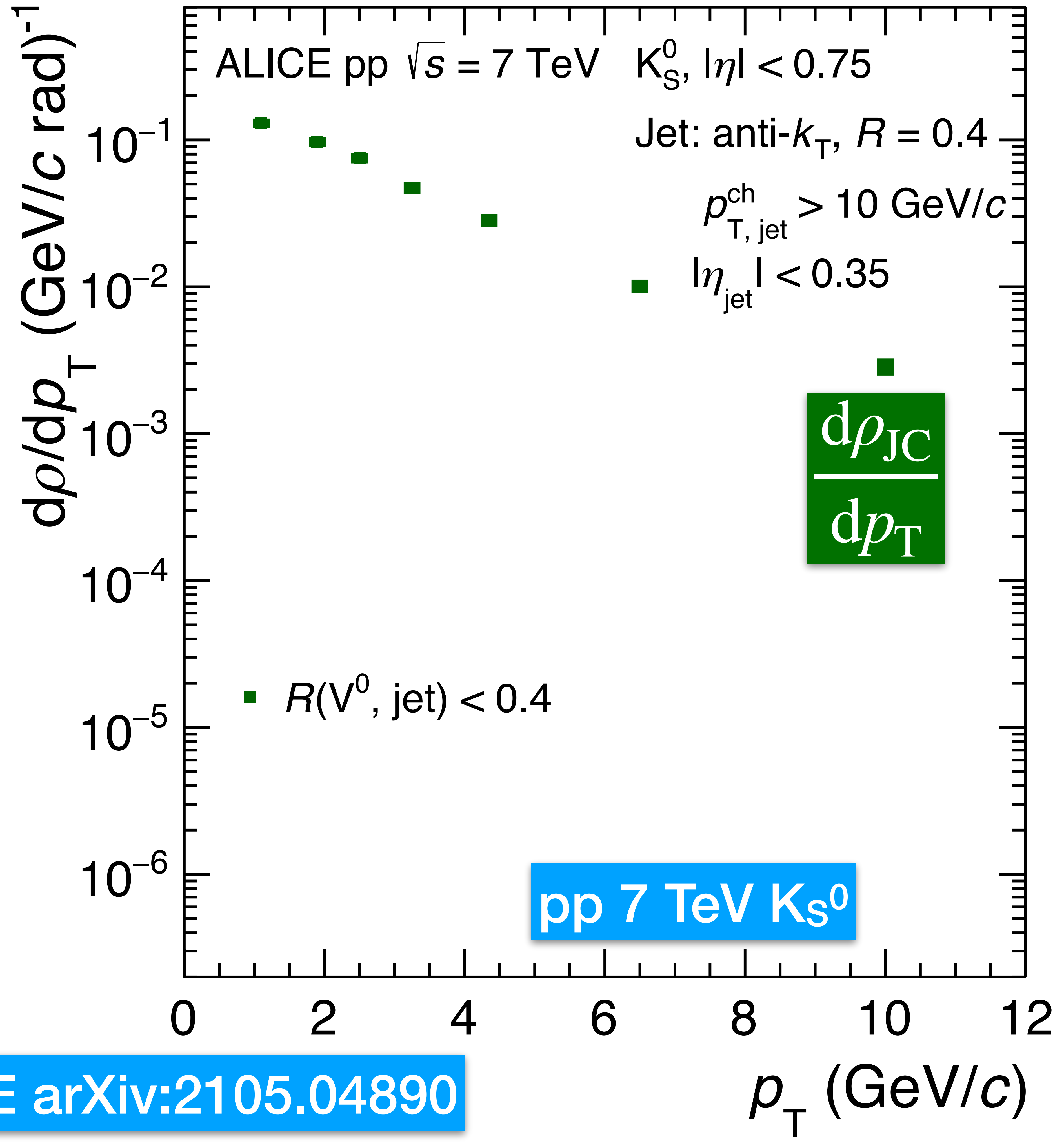
- Strange particles in jets (JE particles)

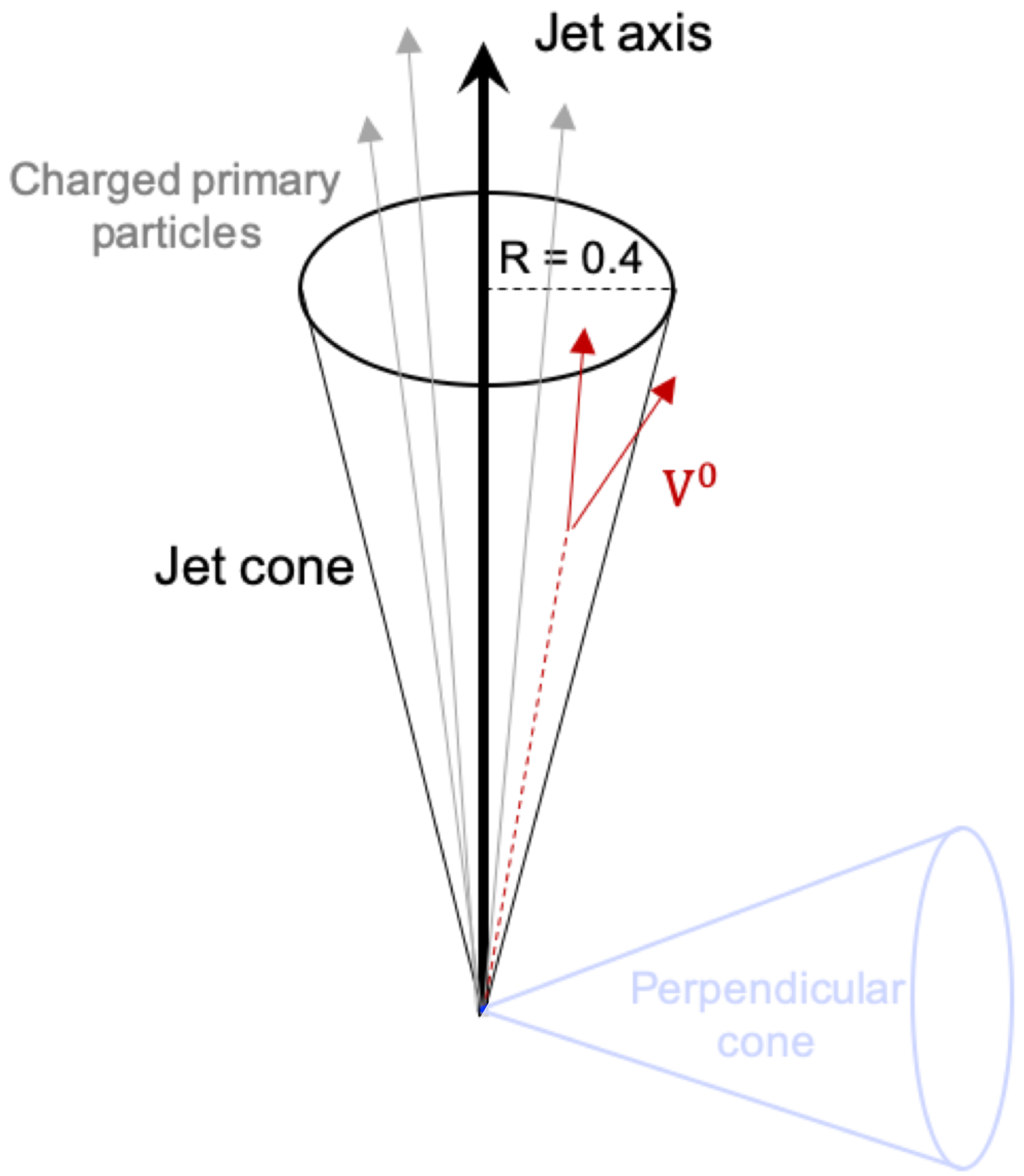
$$\frac{d\rho_{JE}}{dp_T} = \frac{d\rho_{JC}}{dp_T} - \frac{d\rho_{UE}}{dp_T}$$



Strangeness in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

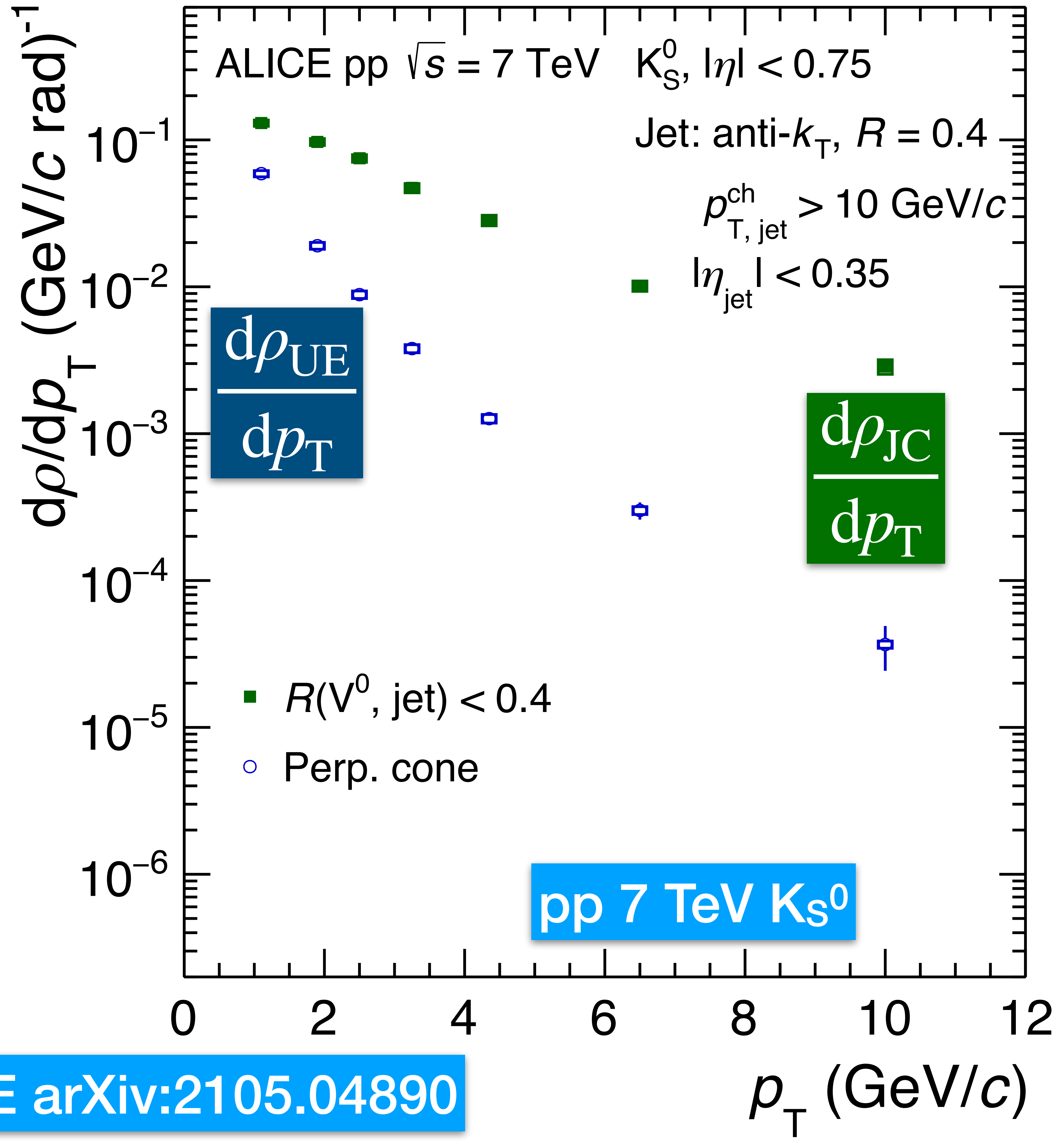


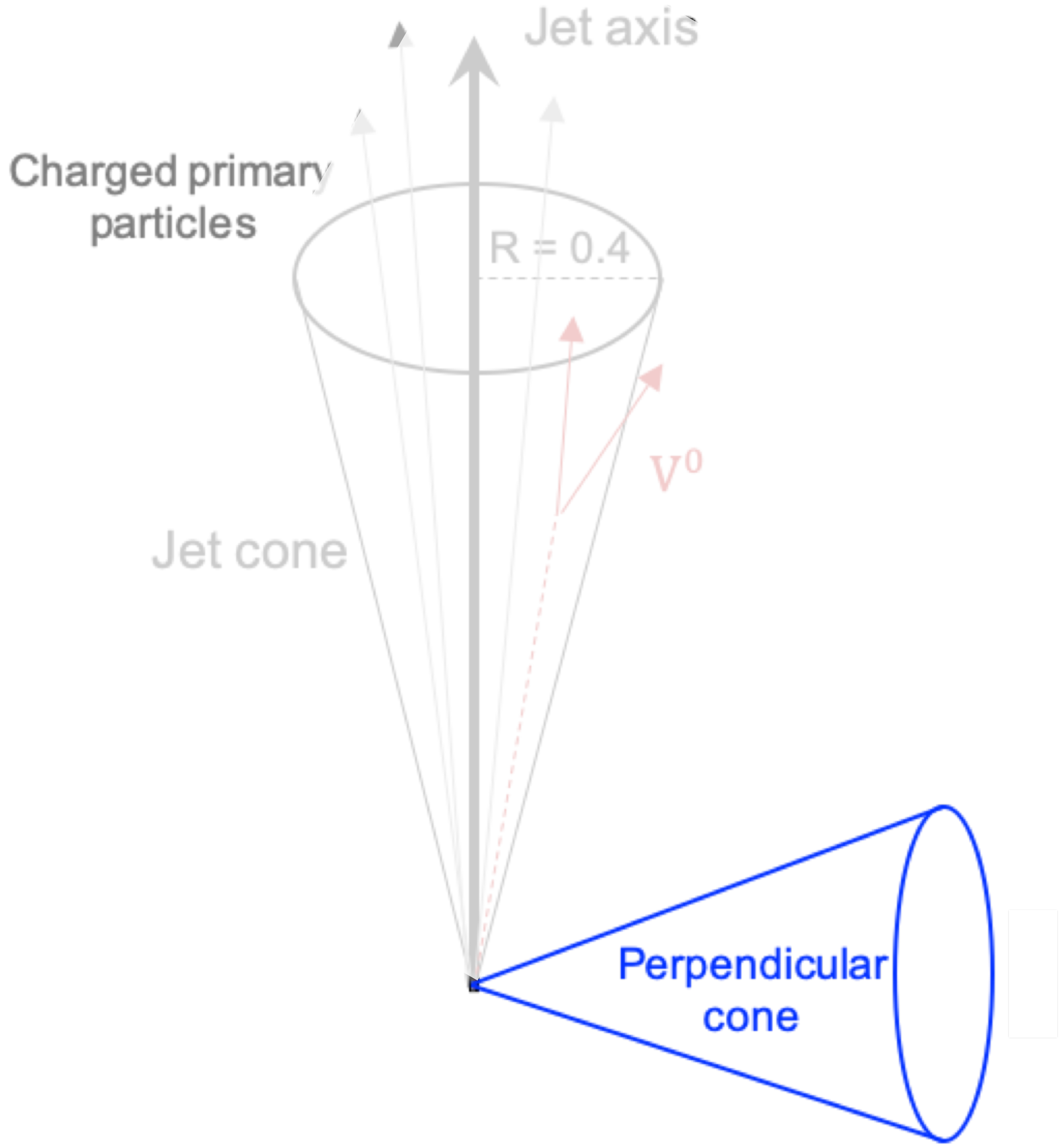


ALICE arXiv:2105.04890

Strangeness in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

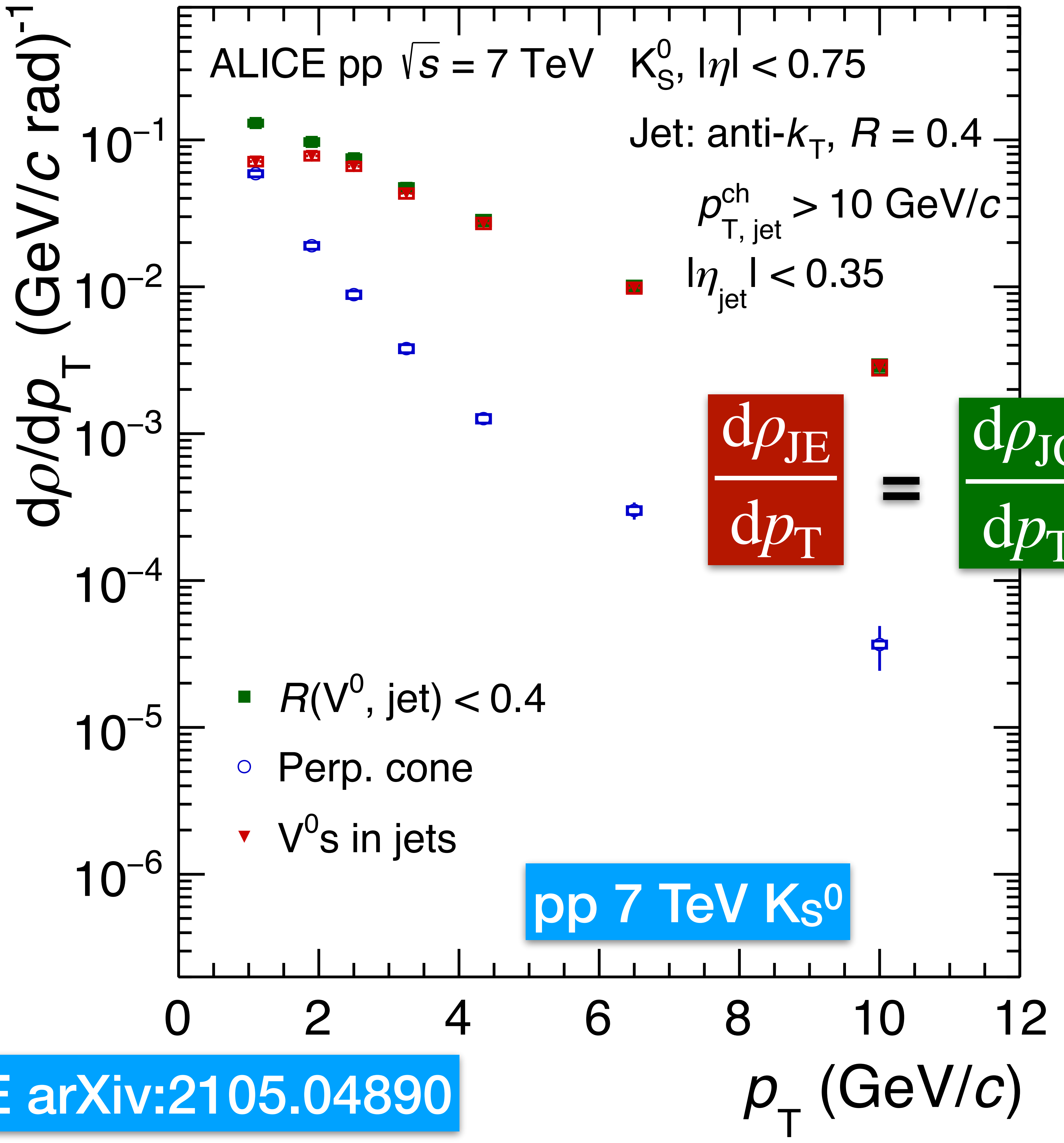




ALICE arXiv:2105.04890

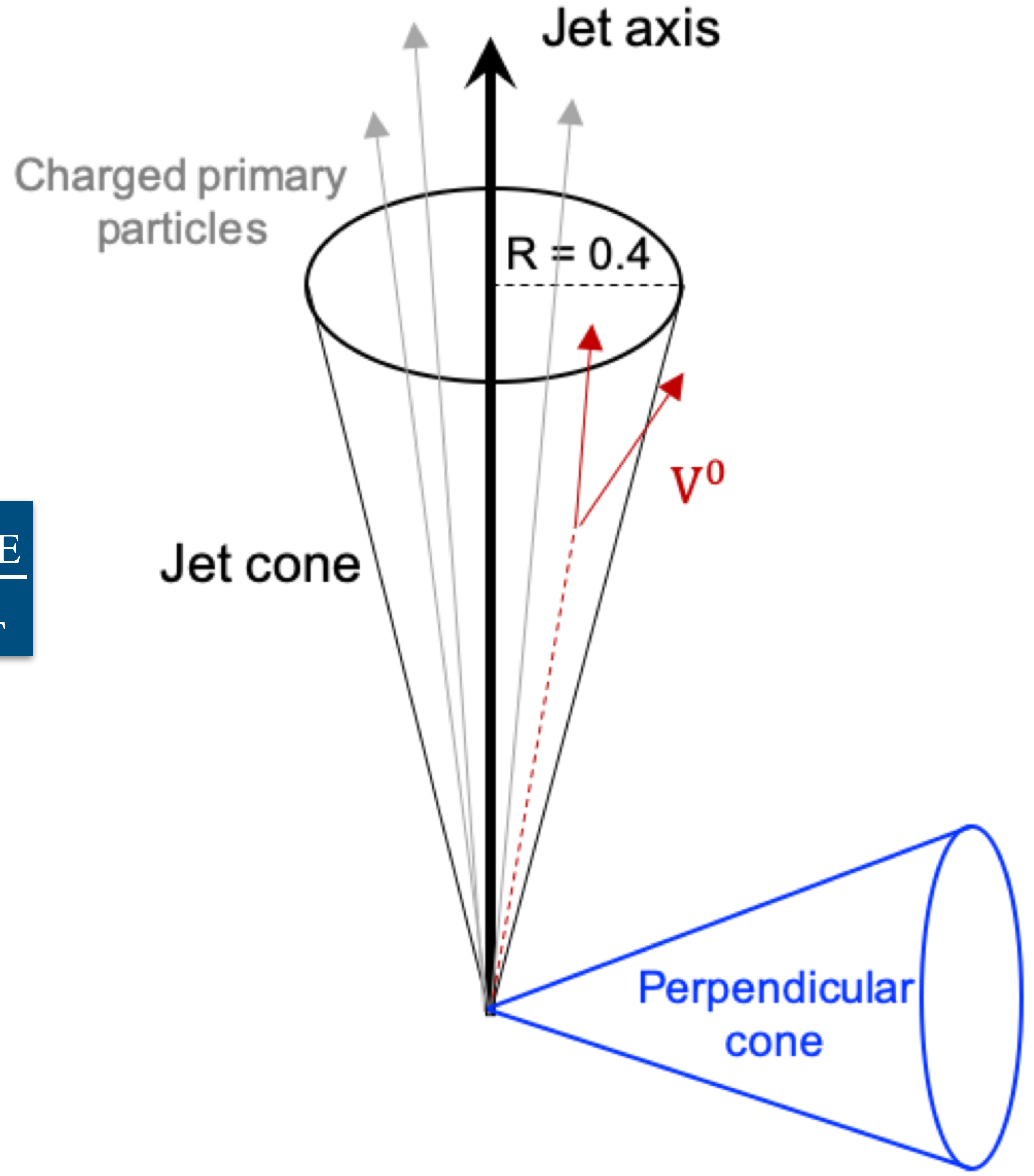
Strangeness in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$



$$\frac{d\rho_{JE}}{dp_T} = \frac{d\rho_{JC}}{dp_T} - \frac{d\rho_{UE}}{dp_T}$$

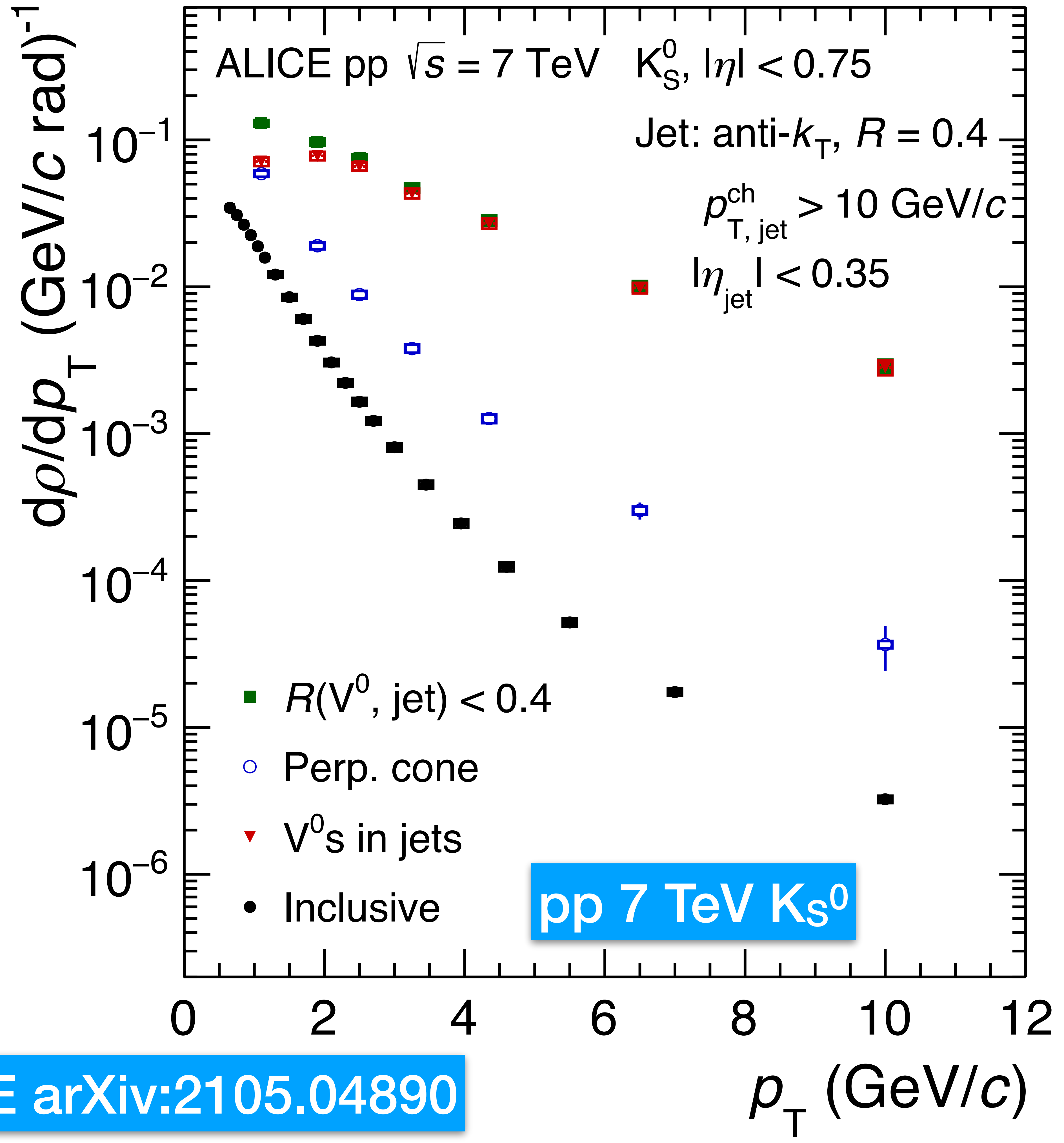
pp 7 TeV K_S^0



ALICE arXiv:2105.04890

Strangeness in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

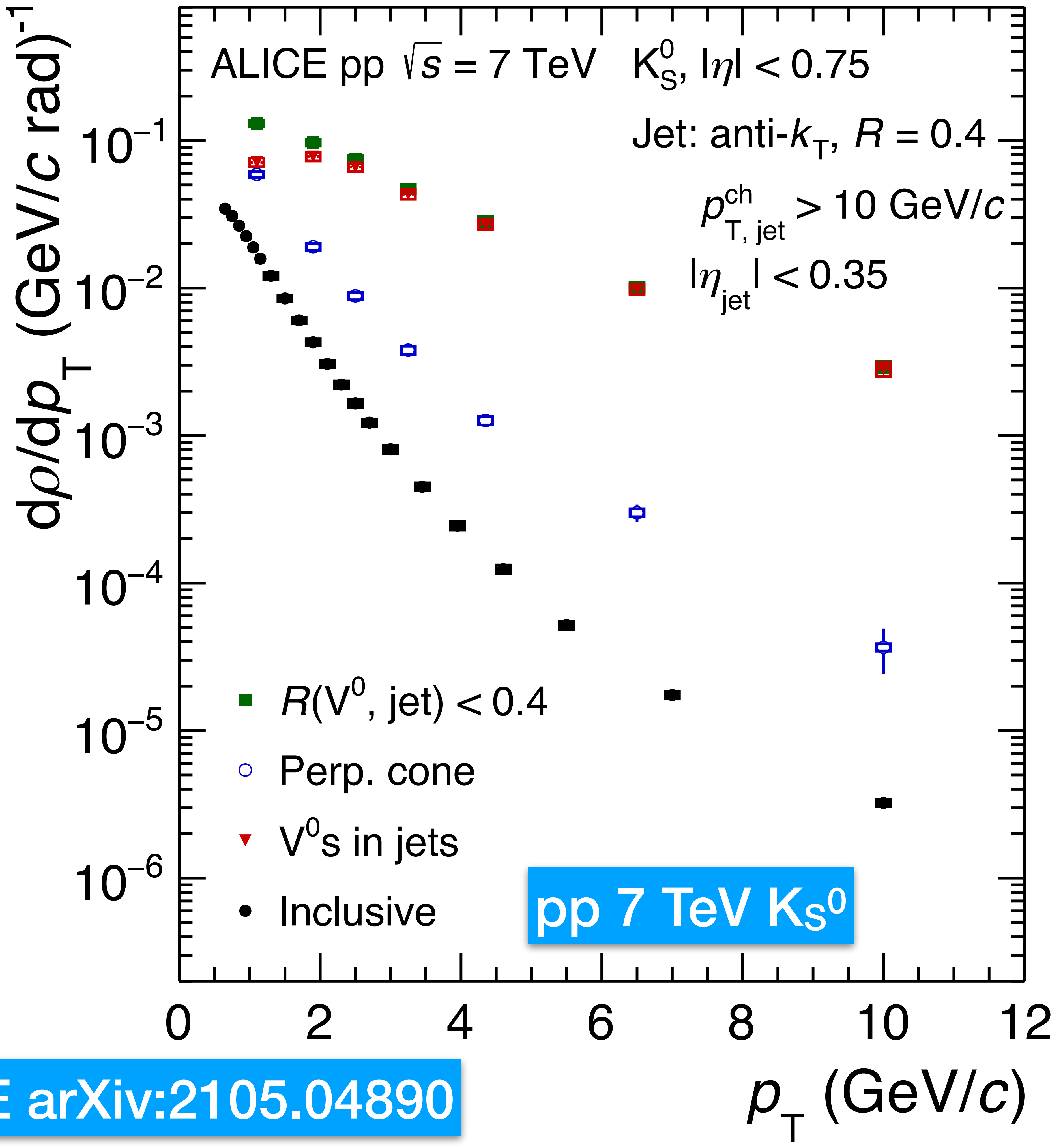


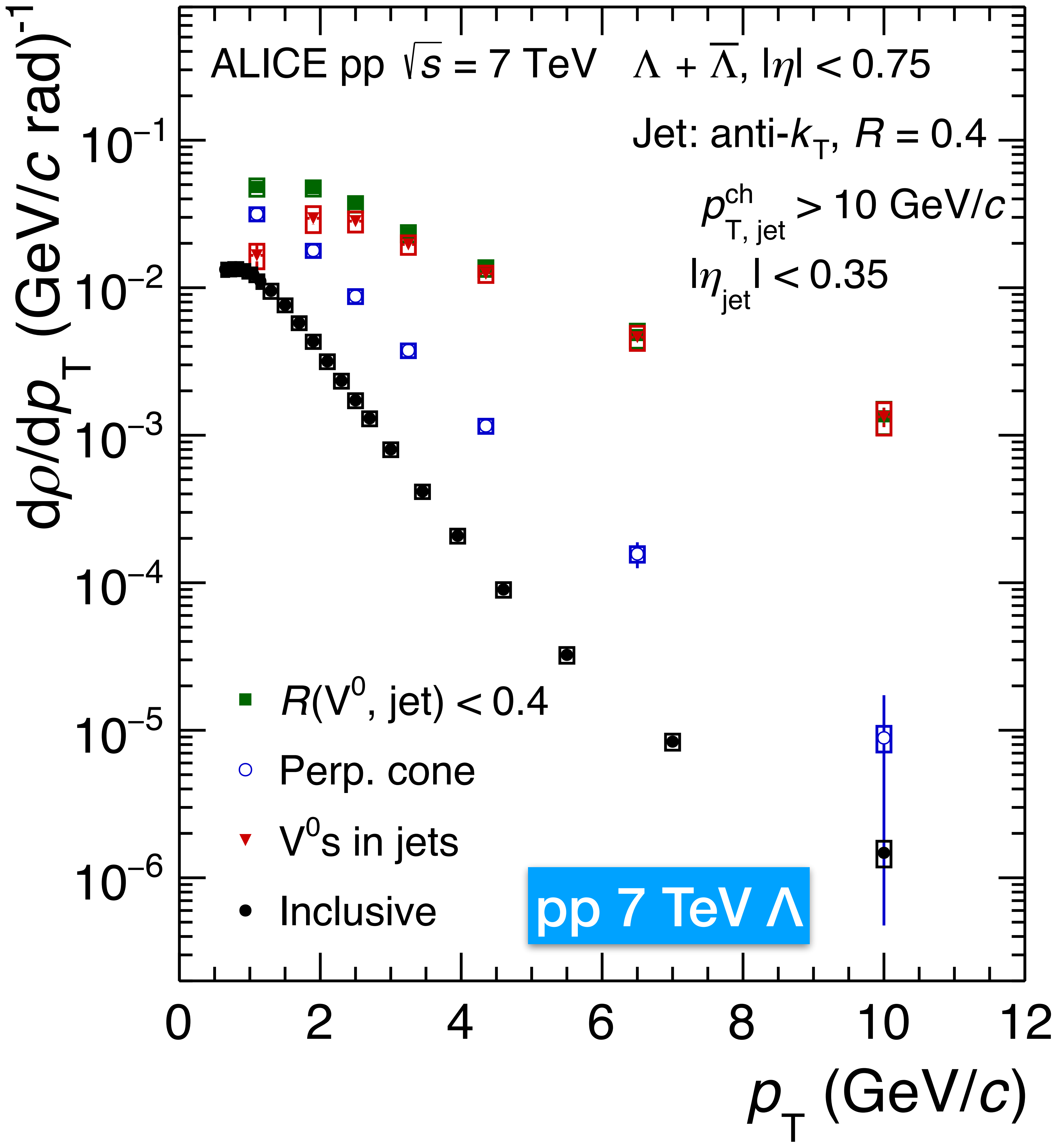
ALICE arXiv:2105.04890

- UE background is dominant at low p_T
- p_T-differential production density in jets (JE particles) is harder than that in UE (PC selection)
- The inclusive density distribution is softer than the UE — jet selection bias

Strangeness in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

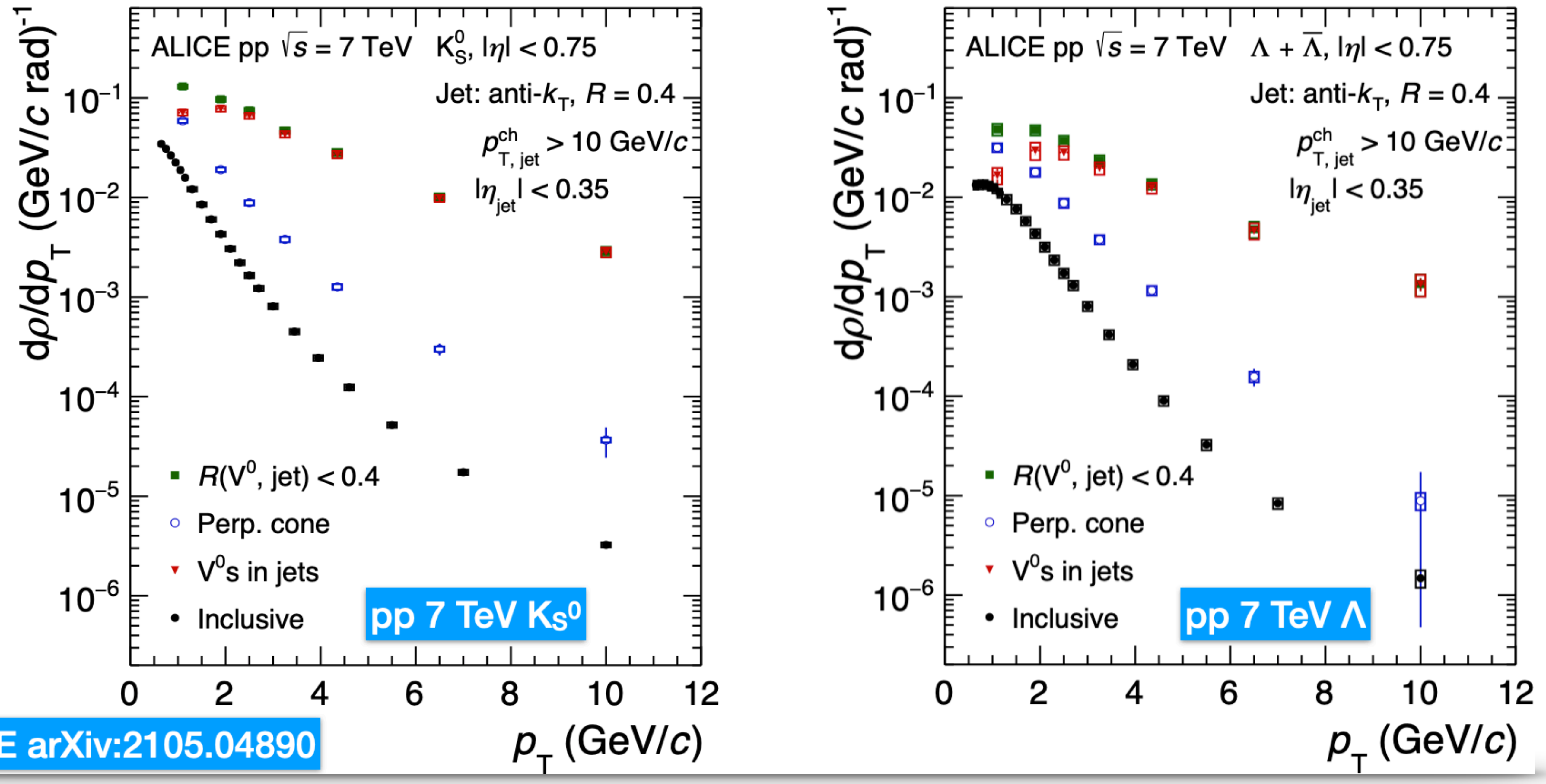




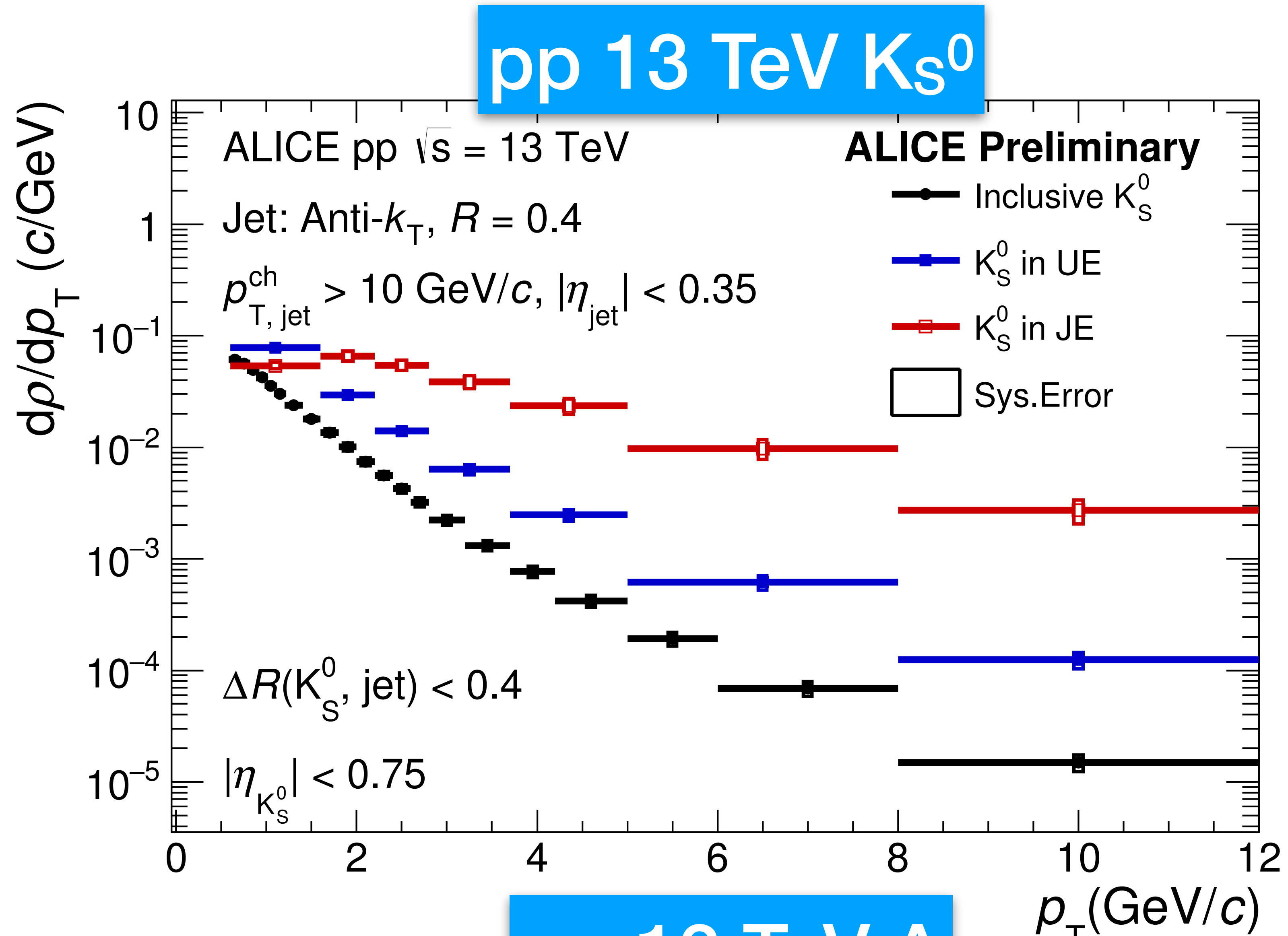
ALICE arXiv:2105.04890

K_S^0 and Λ production — energy dependence

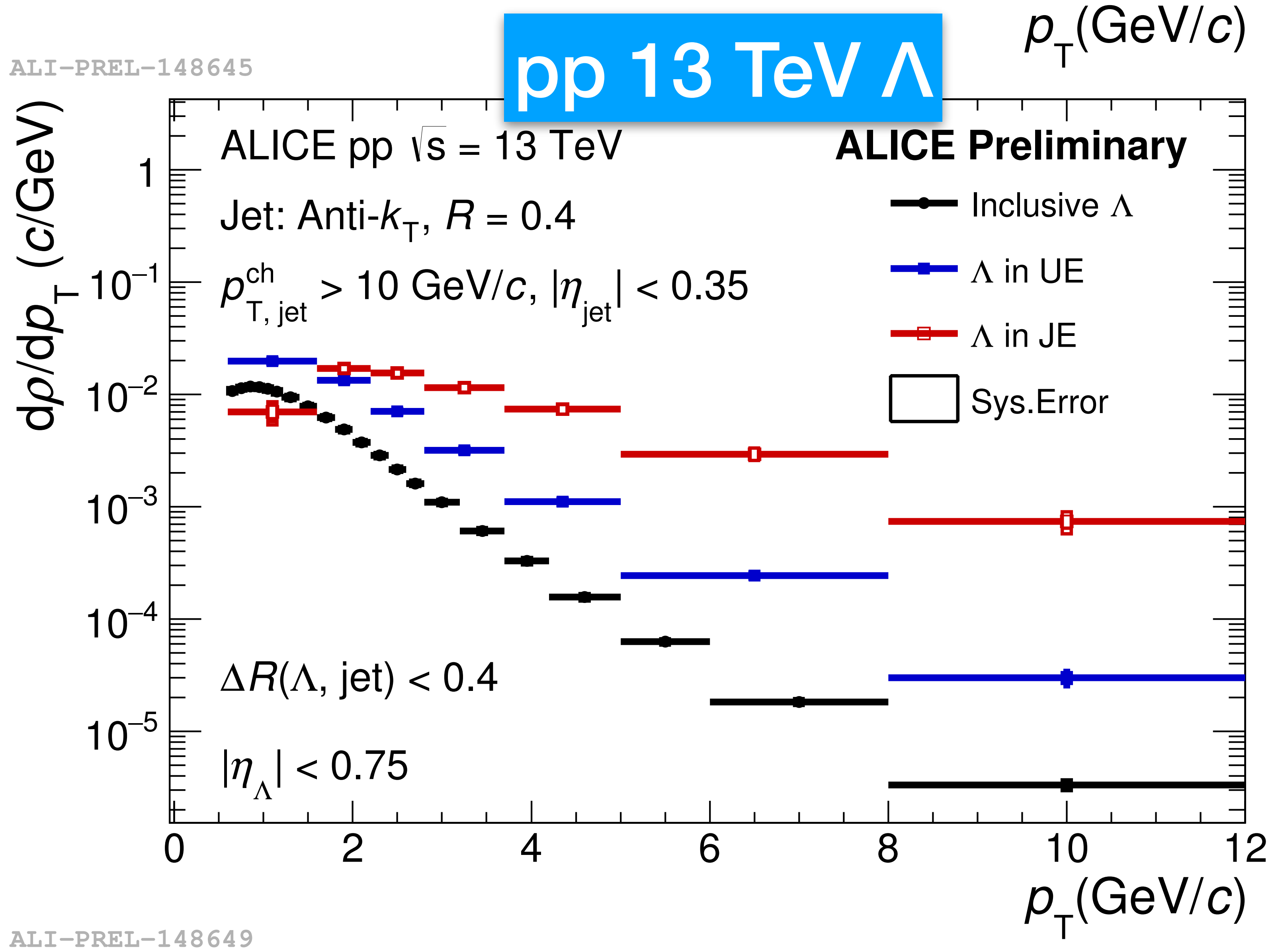
$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{<\text{Area acceptance}>} \times \frac{dN}{dp_T}$$



ALICE arXiv:2105.04890



ALI-PREL-148645



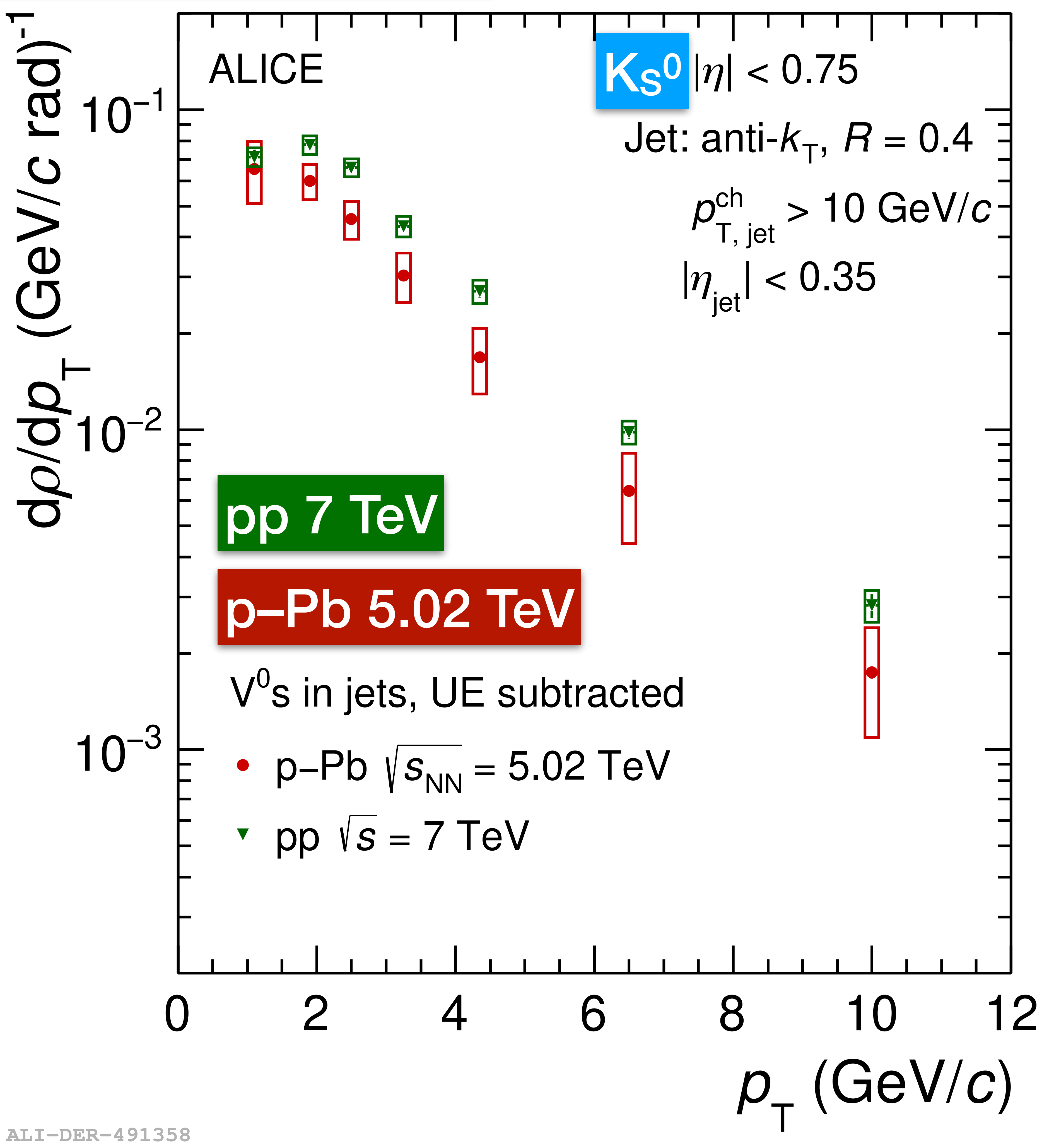
ALI-PREL-148649

- Results at 7 TeV and 13 TeV are consistent

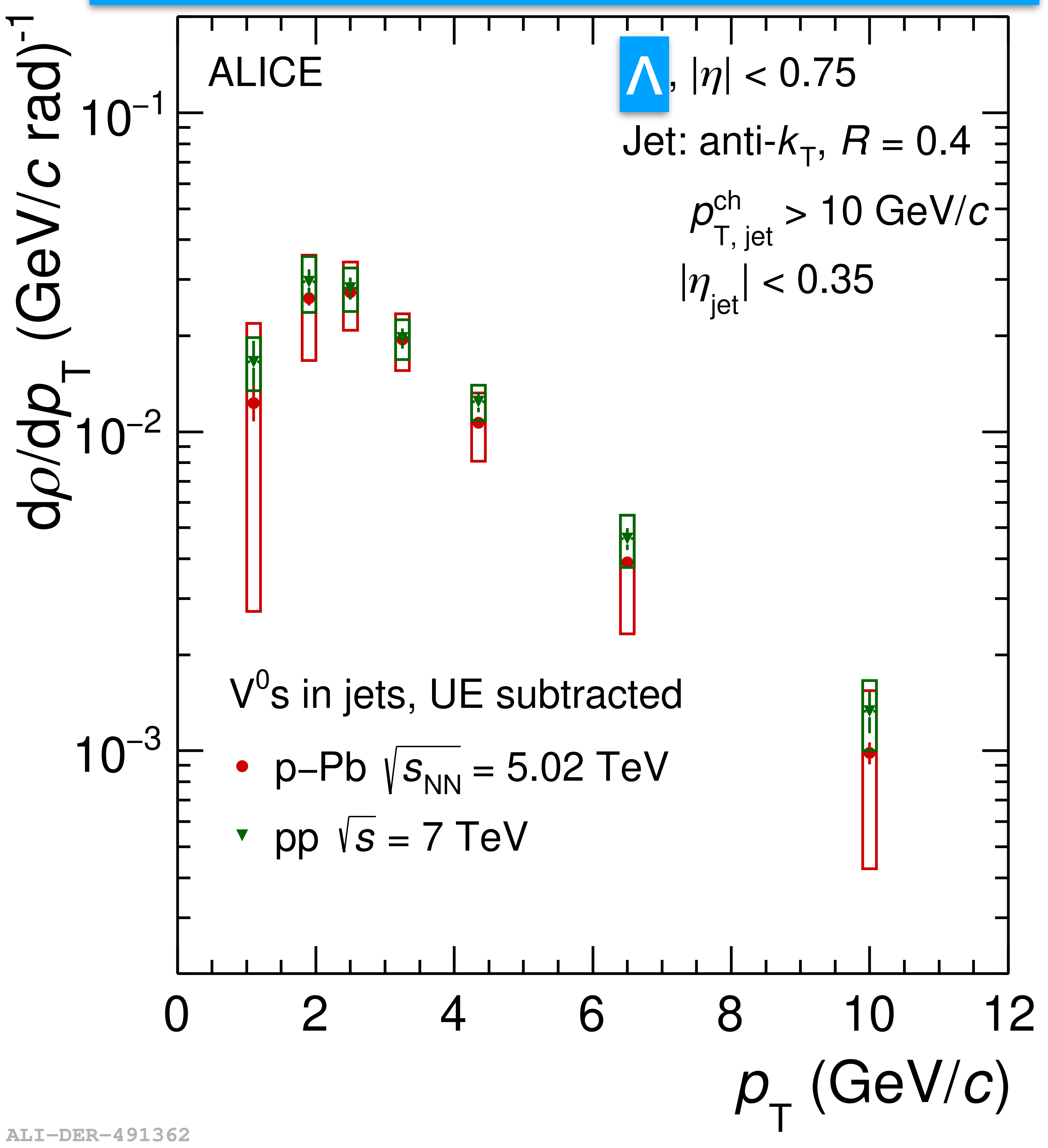
➡ Weak energy dependence

K_S^0 and Λ production — system dependence

ALICE arXiv:2105.04890

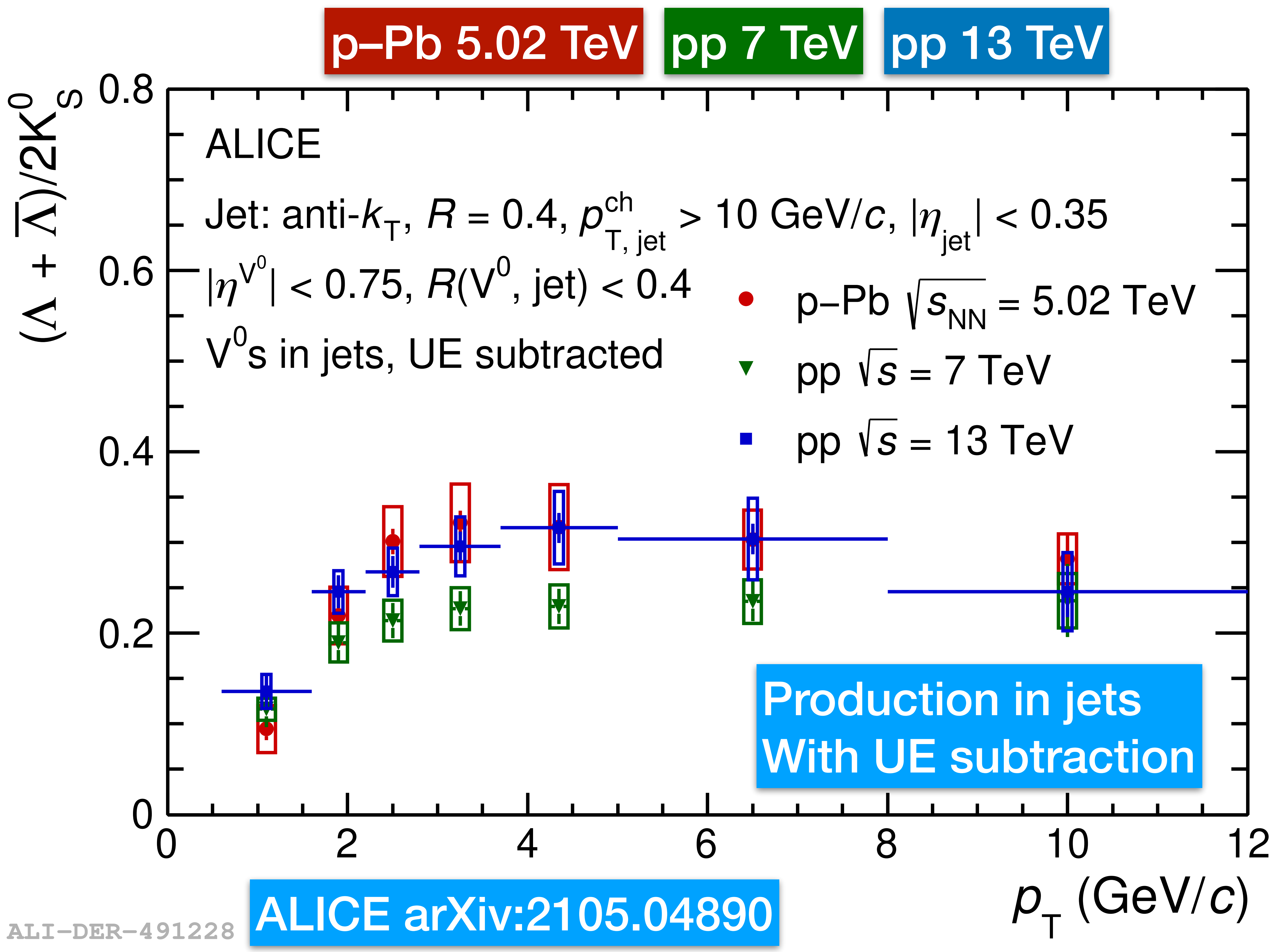


Production in jets with UE subtraction



- Weak collision system dependence for particles produced in jets

Λ/K_S^0 ratio in pp and p–Pb

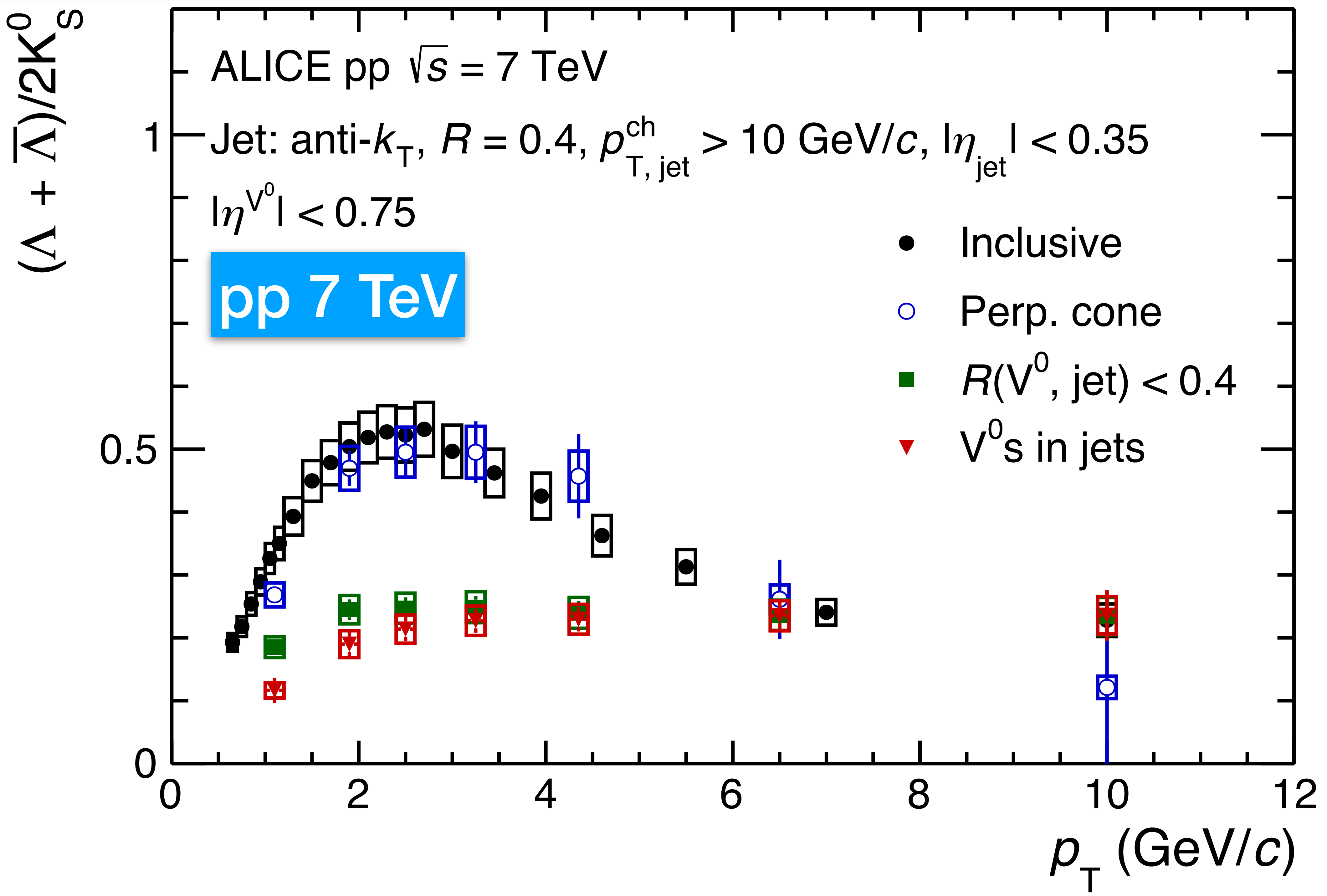


ALICE arXiv:2105.04890

- In pp collisions: results at 7 TeV are consistent with those at 13 TeV within uncertainties — no (visible) energy dependence
- < 2σ deviation at intermediate p_T between pp and p–Pb

Λ/K_S^0 ratio in pp and p–Pb

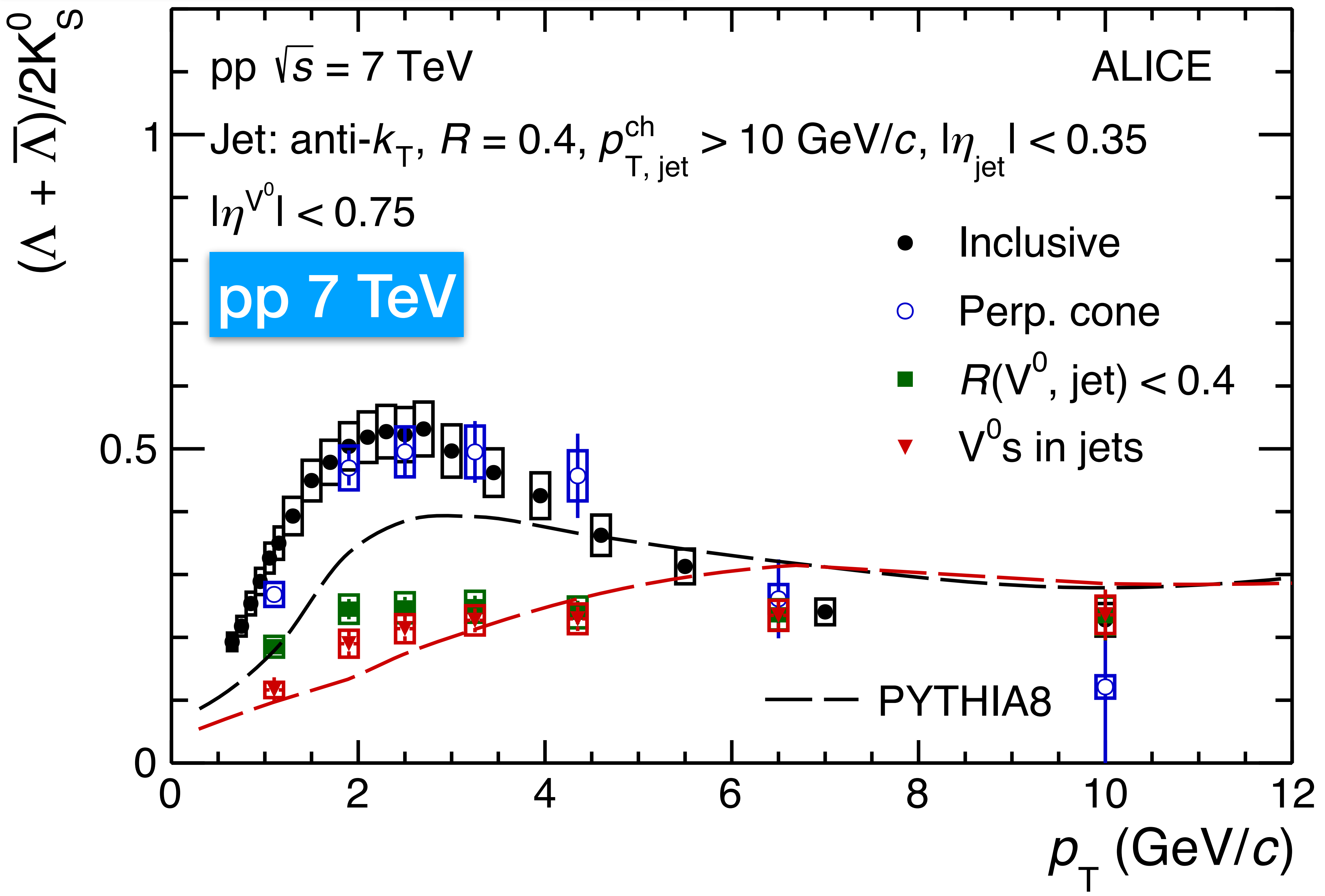
ALICE arXiv:2105.04890



- Ratio in jets does not show a maximum at intermediate p_T, ratio with UE selection is systematically higher than the inclusive in $2 < p_T < 5$ GeV/c

Λ/K_S^0 ratio in pp and p–Pb

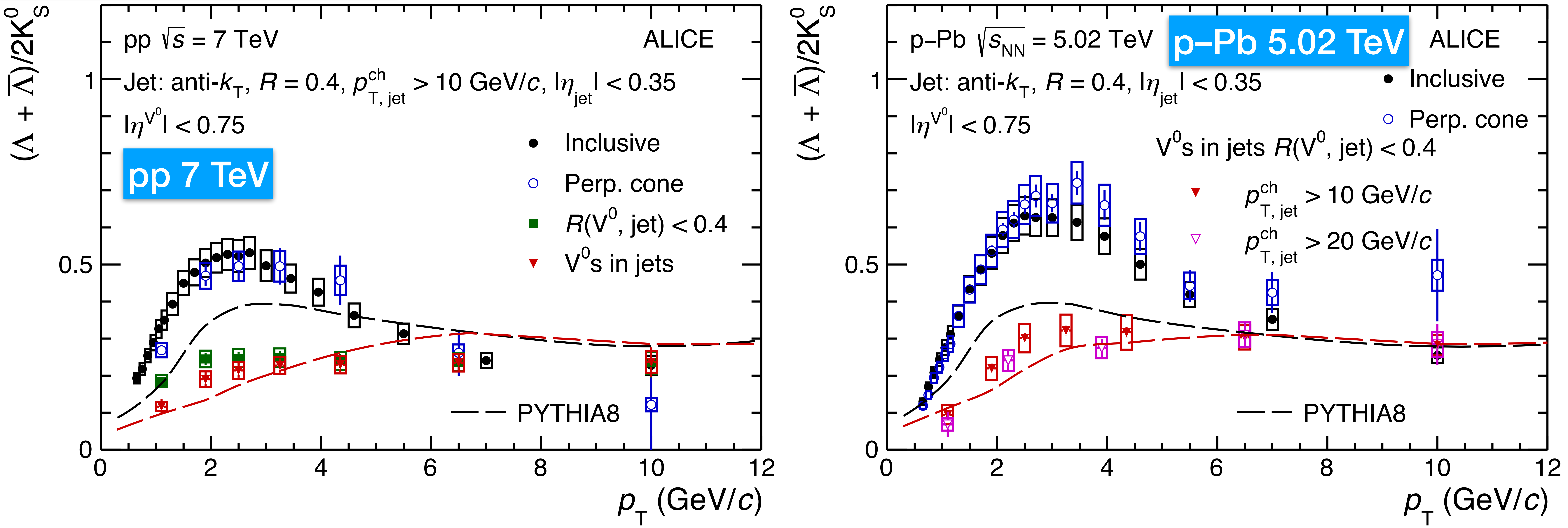
ALICE arXiv:2105.04890



- Ratio in jets does not show a maximum at intermediate p_T, ratio with UE selection is systematically higher than the inclusive in $2 < p_T < 5$ GeV/c
- PYTHIA 8 hard QCD is consistent with ratio in jets but does not reproduce the inclusive ratio at low and intermediate p_T

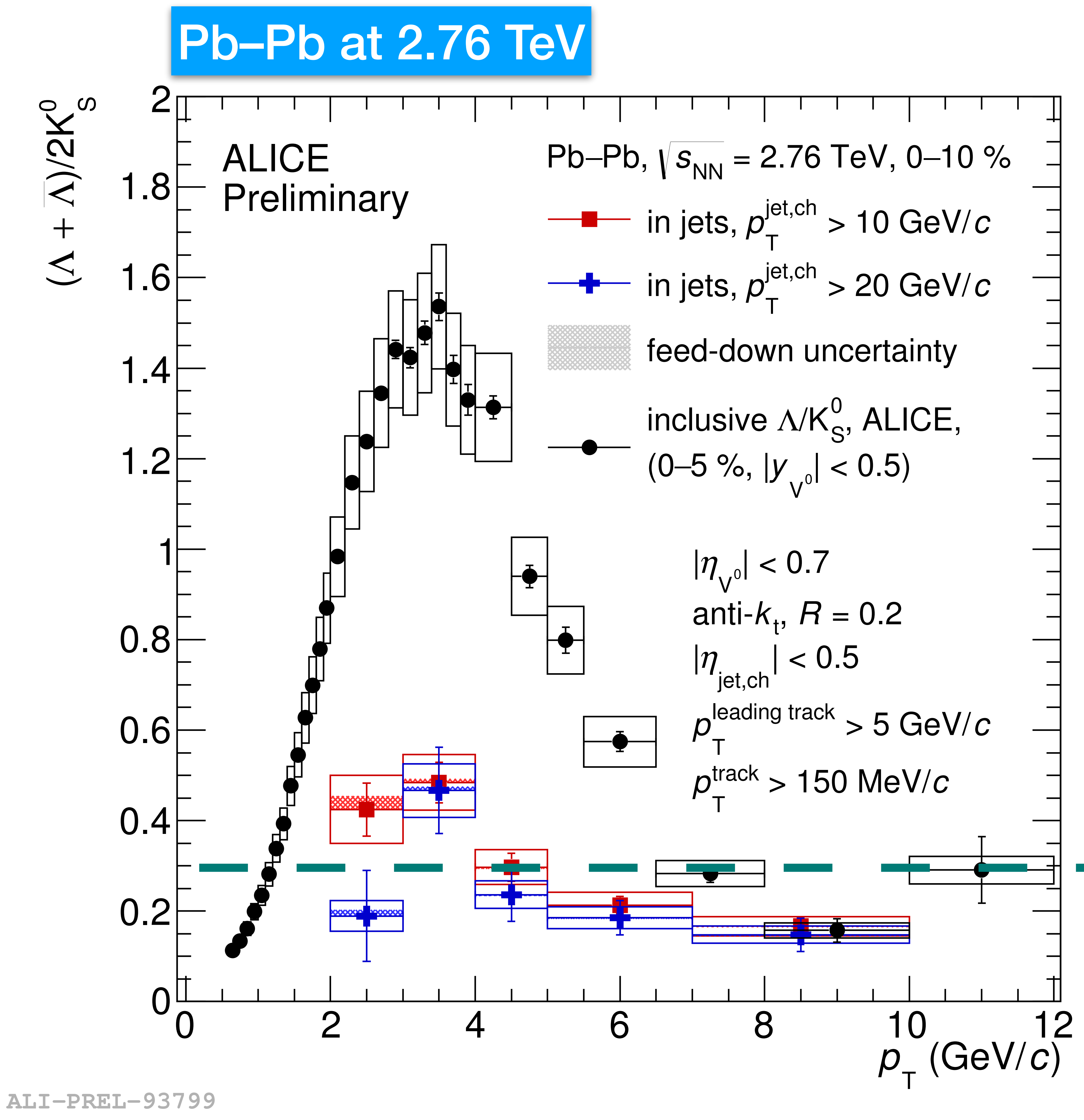
Λ/K_S^0 ratio in pp and p–Pb

ALICE arXiv:2105.04890

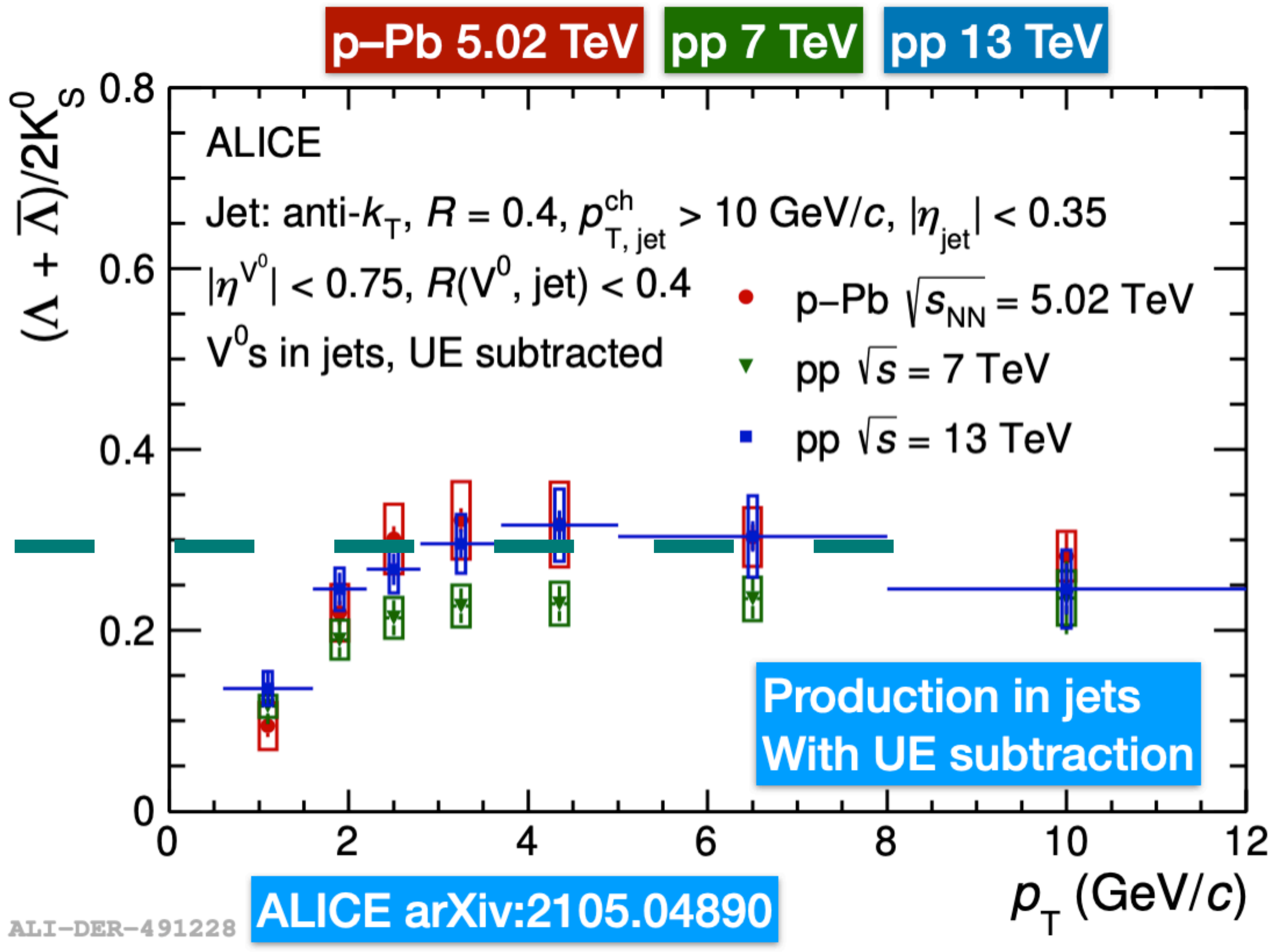


- Ratio in jets does not show a maximum at intermediate p_T, ratio with UE selection is systematically higher than the inclusive in $2 < p_T < 5$ GeV/c
- PYTHIA 8 hard QCD is consistent with ratio in jets but does not reproduce the inclusive ratio at low and intermediate p_T

Λ/K_S^0 ratio in Pb–Pb

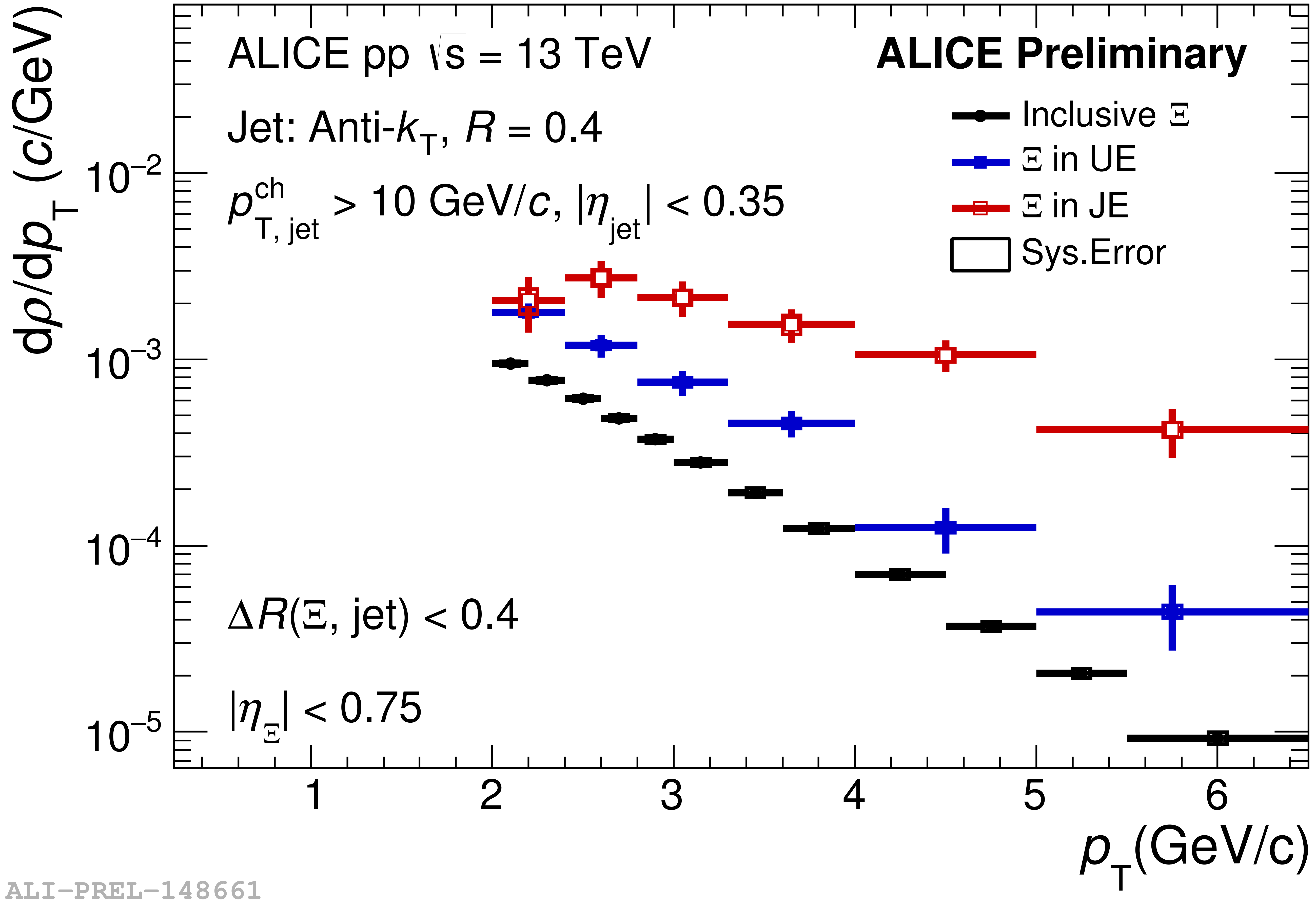


- Pb–Pb collisions: Λ/K_S^0 ratio at intermediate p_T is suppressed in jets when compared to inclusive production
- Ratio in jets in Pb–Pb is similar as that in pp and p–Pb



Ξ± production in jets and UE

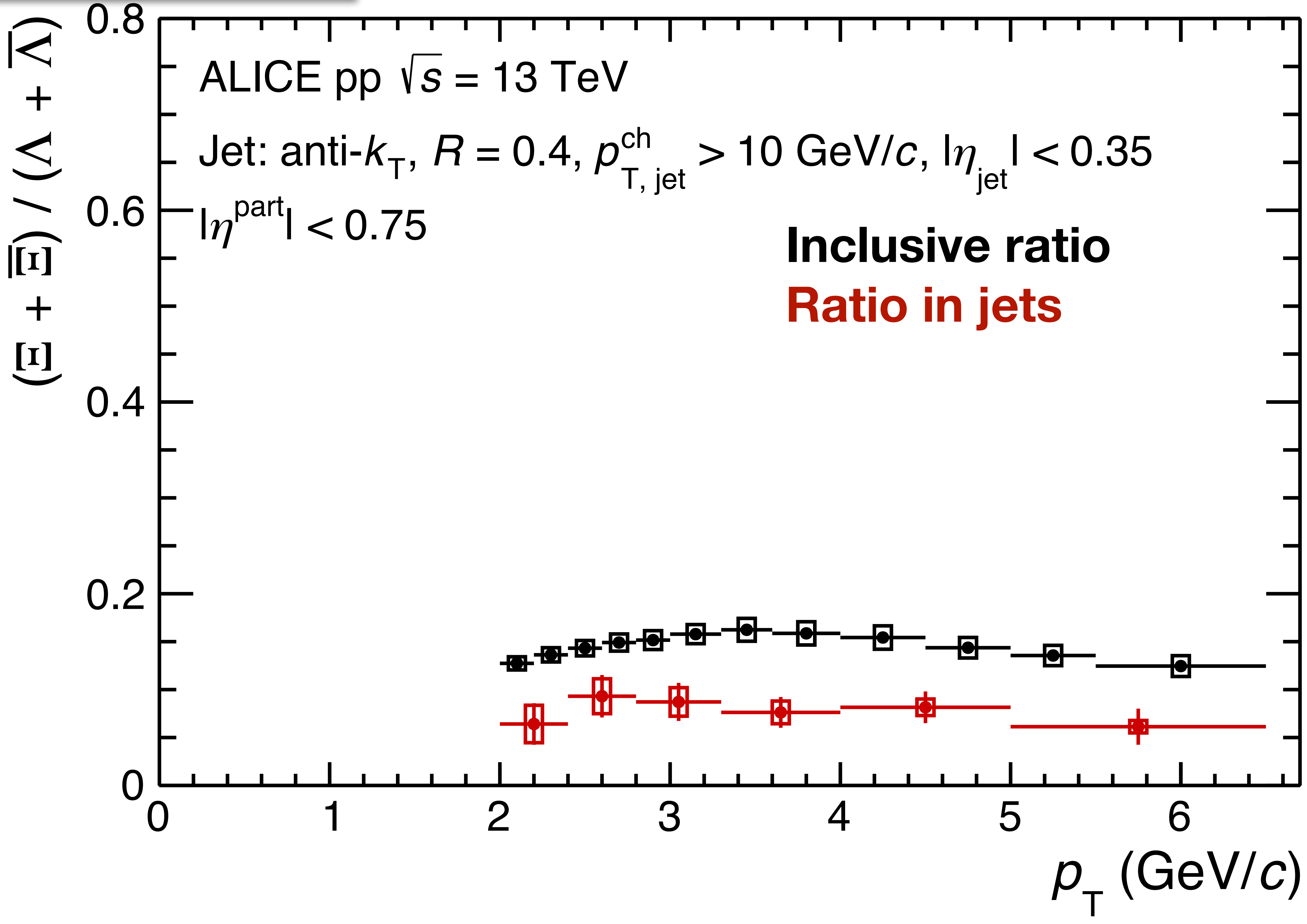
pp 13 TeV Ξ±



- pp 13 TeV — study extend to the multi-strange sector (Ξ±) with higher statistics

Ξ±/Λ ratio in jets

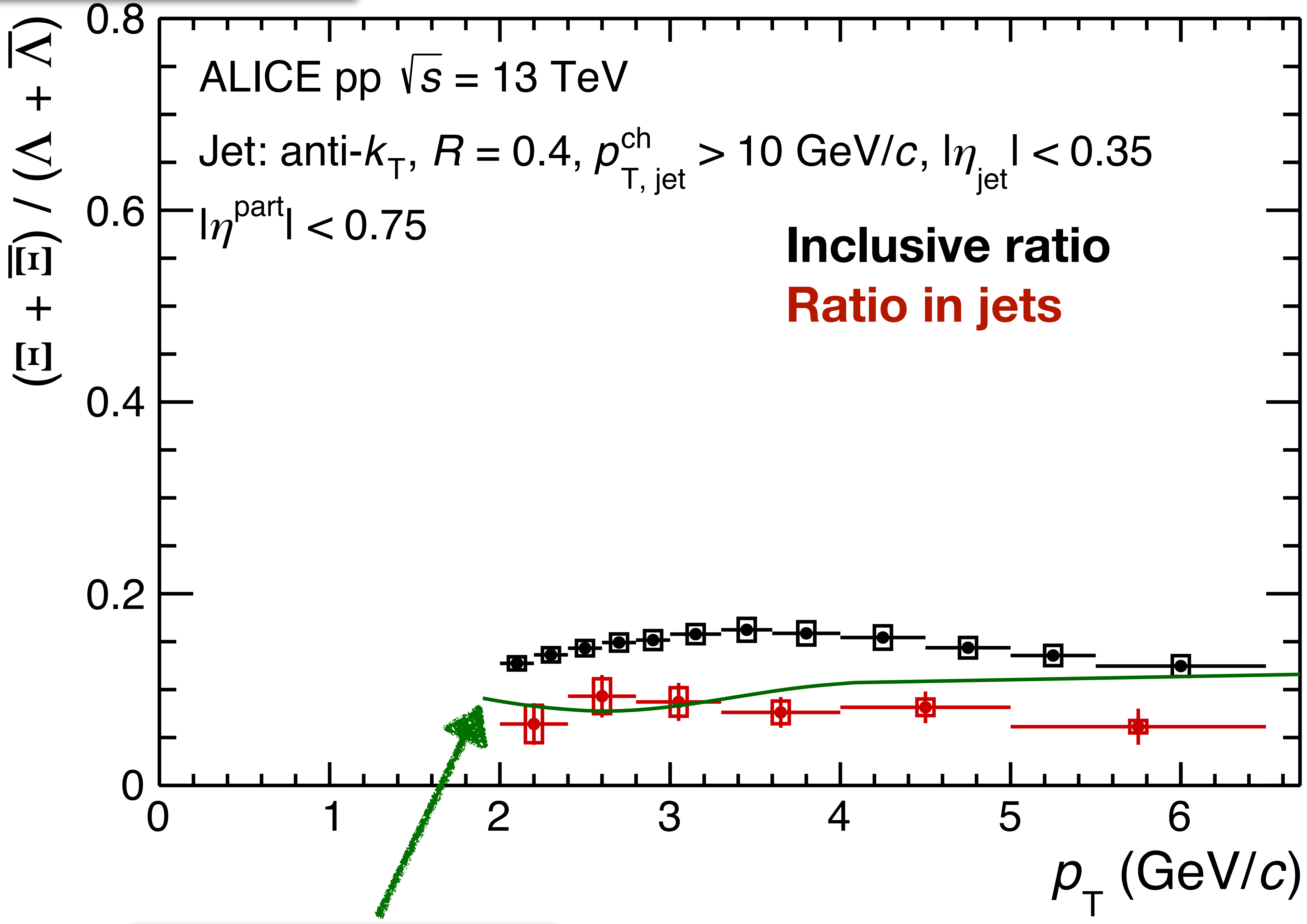
pp 13 TeV Ξ± / Λ



- Increase on baryon-to-baryon (Ξ±/Λ) ratio at intermediate-p_T suppressed in jets

Ξ±/Λ ratio in jets

pp 13 TeV Ξ± / Λ

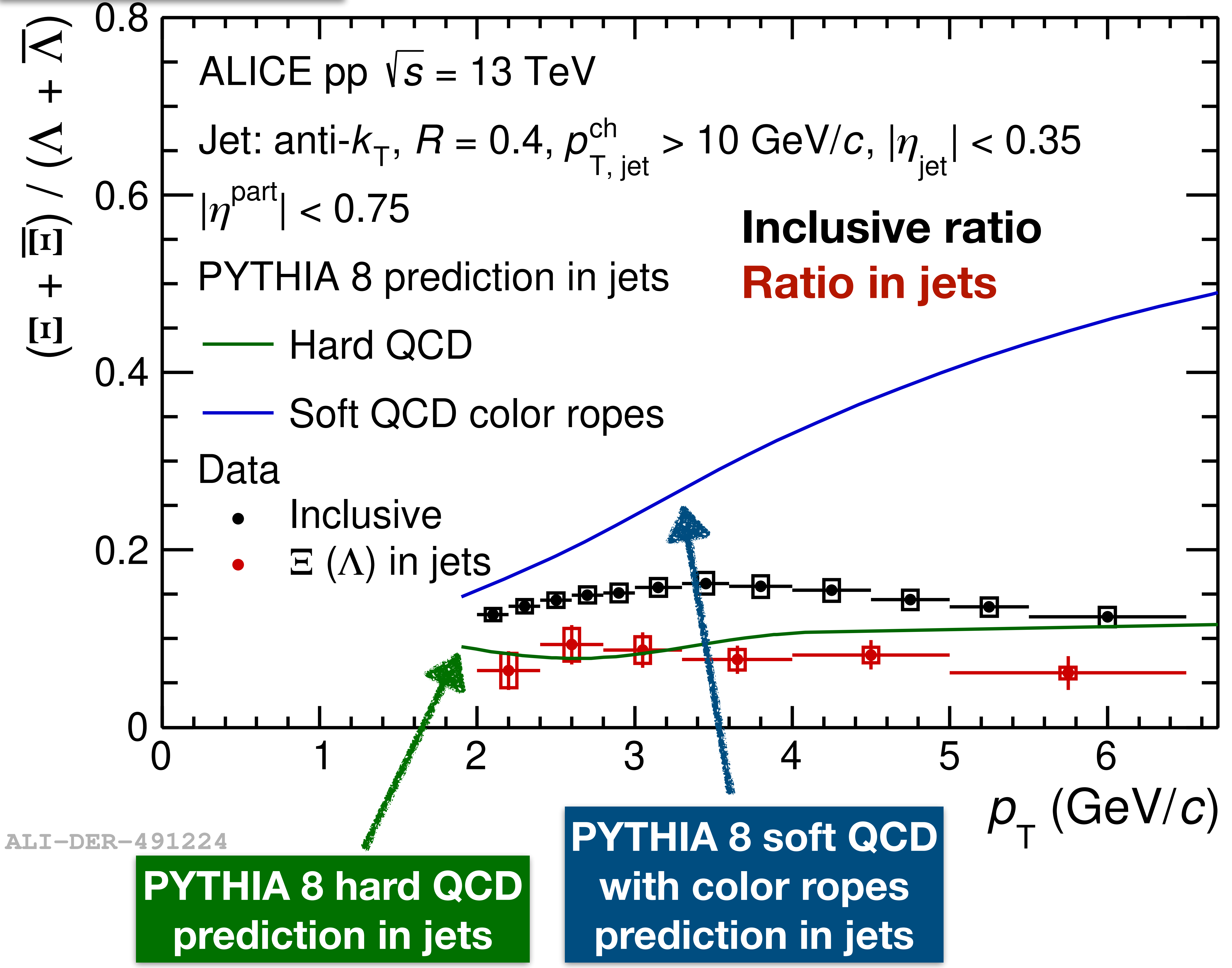


PYTHIA 8 hard QCD prediction in jets

- Increase on baryon-to-baryon (Ξ±/Λ) ratio at intermediate-p_T suppressed in jets
- PYTHIA 8 hard QCD generally reproduces ratio in jets

$\Xi^{\pm}/\Lambda$ ratio in jets

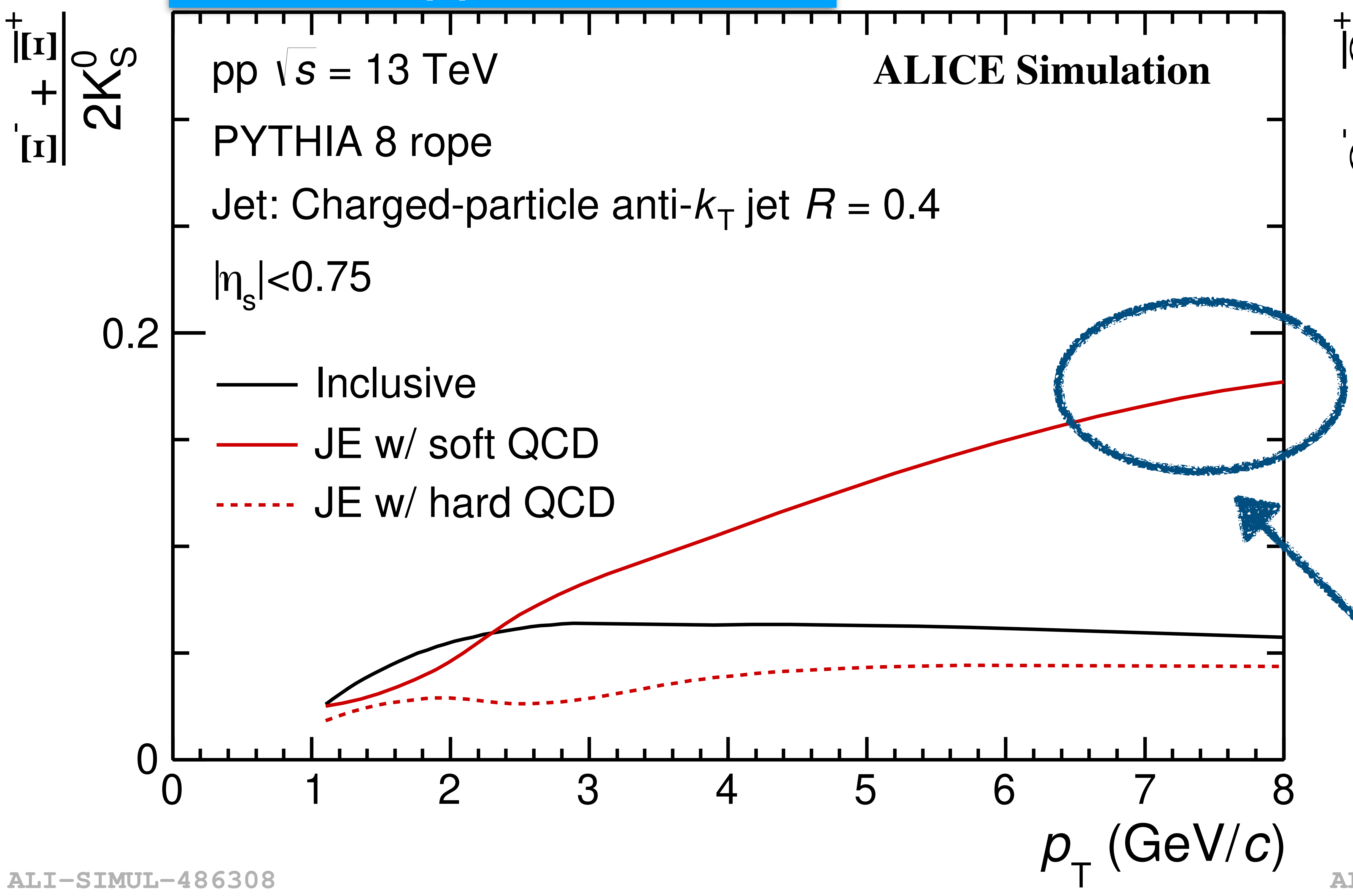
pp 13 TeV $\Xi^{\pm}$ / Λ



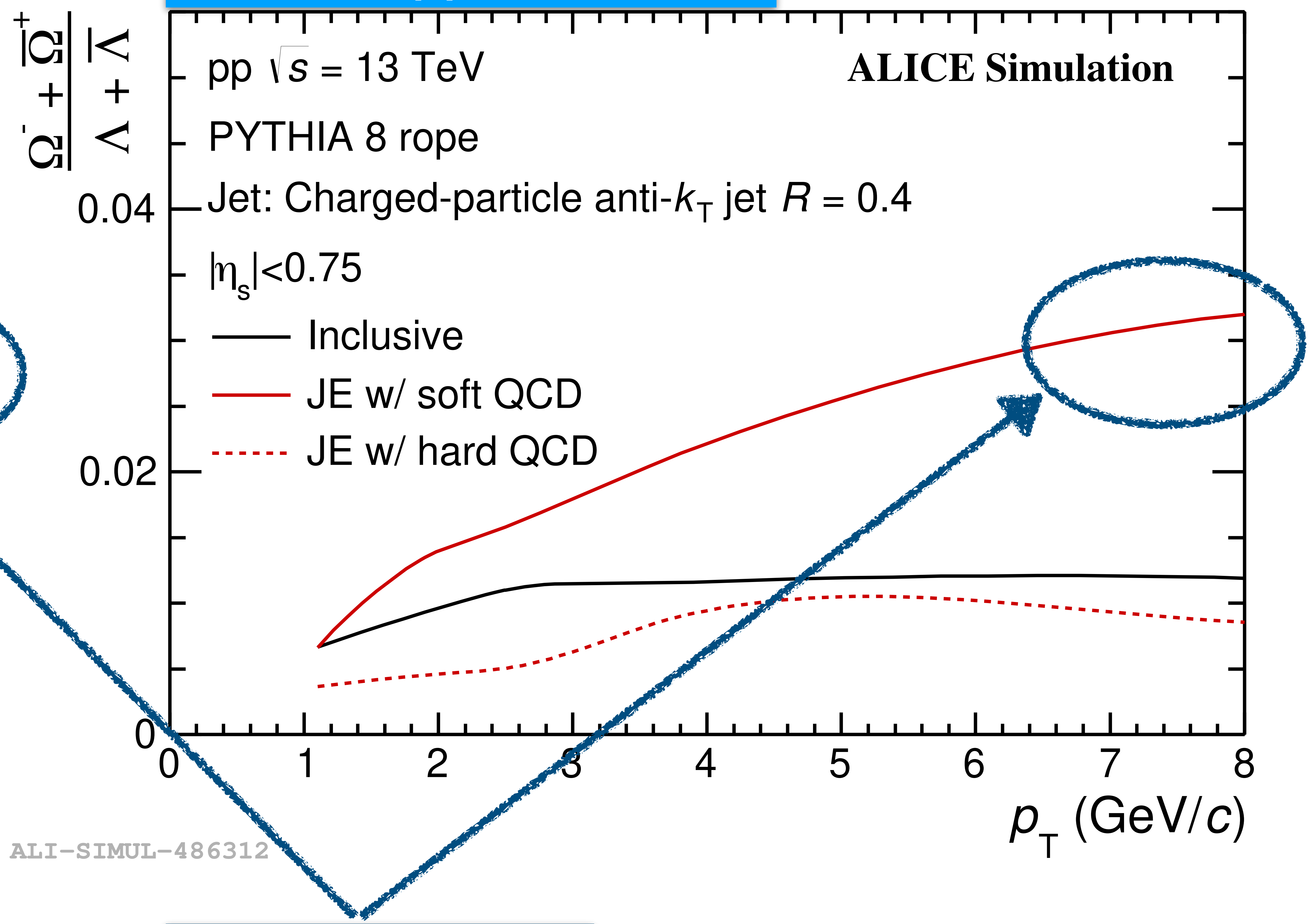
- Increase on baryon-to-baryon ($\Xi^{\pm}/\Lambda$) ratio at intermediate-p_T suppressed in jets
- PYTHIA 8 hard QCD generally reproduces ratio in jets
- PYTHIA 8 soft QCD overestimate data — especially at high p_T
  - ➡ Mechanism reproduces charmed baryon-to-meson ratio can not reproduce the strange baryon-to-baryon ratio in jets

Ω-baryon: PYTHIA predictions

PYTHIA 8 pp 13 TeV $\Xi^{\pm}/K_S^0$



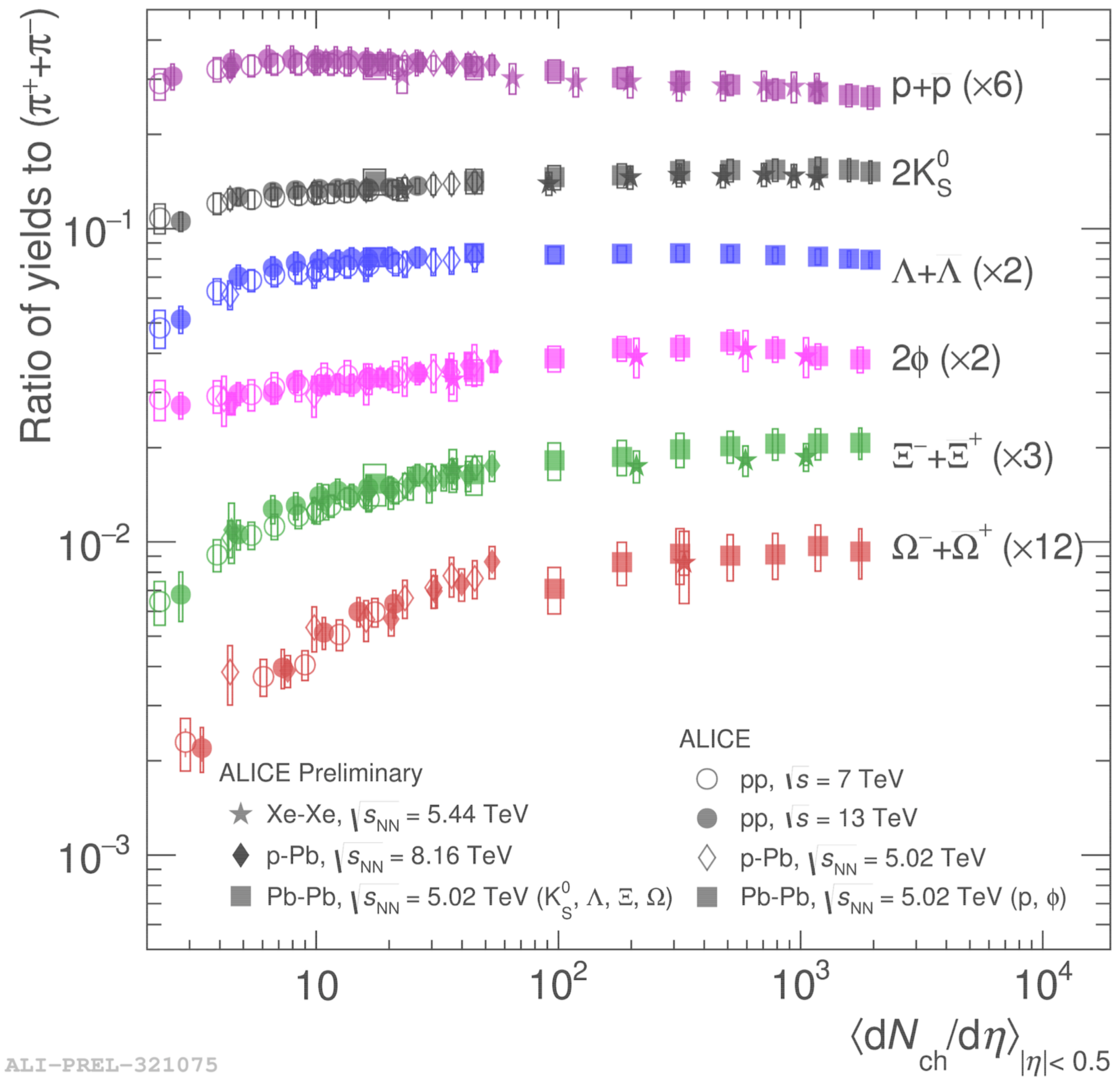
PYTHIA 8 pp 13 TeV $\Omega^{\pm}/\Lambda$



PYTHIA 8 soft QCD with color ropes prediction in jets

Next step extend the study to Ω-baryon

Particle ratio — multiplicity dependence



ALICE *Nature Phys* 13 (2017) 535
ALICE *Eur. Phys. J.* C80 (2020) 167

(Multi-)strange hadron to pion yield ratio

➡ Smooth evolution with charged-particle multiplicity across different collision systems (Pb–Pb, p–Pb and pp)

➡ No collision energy dependence at the LHC

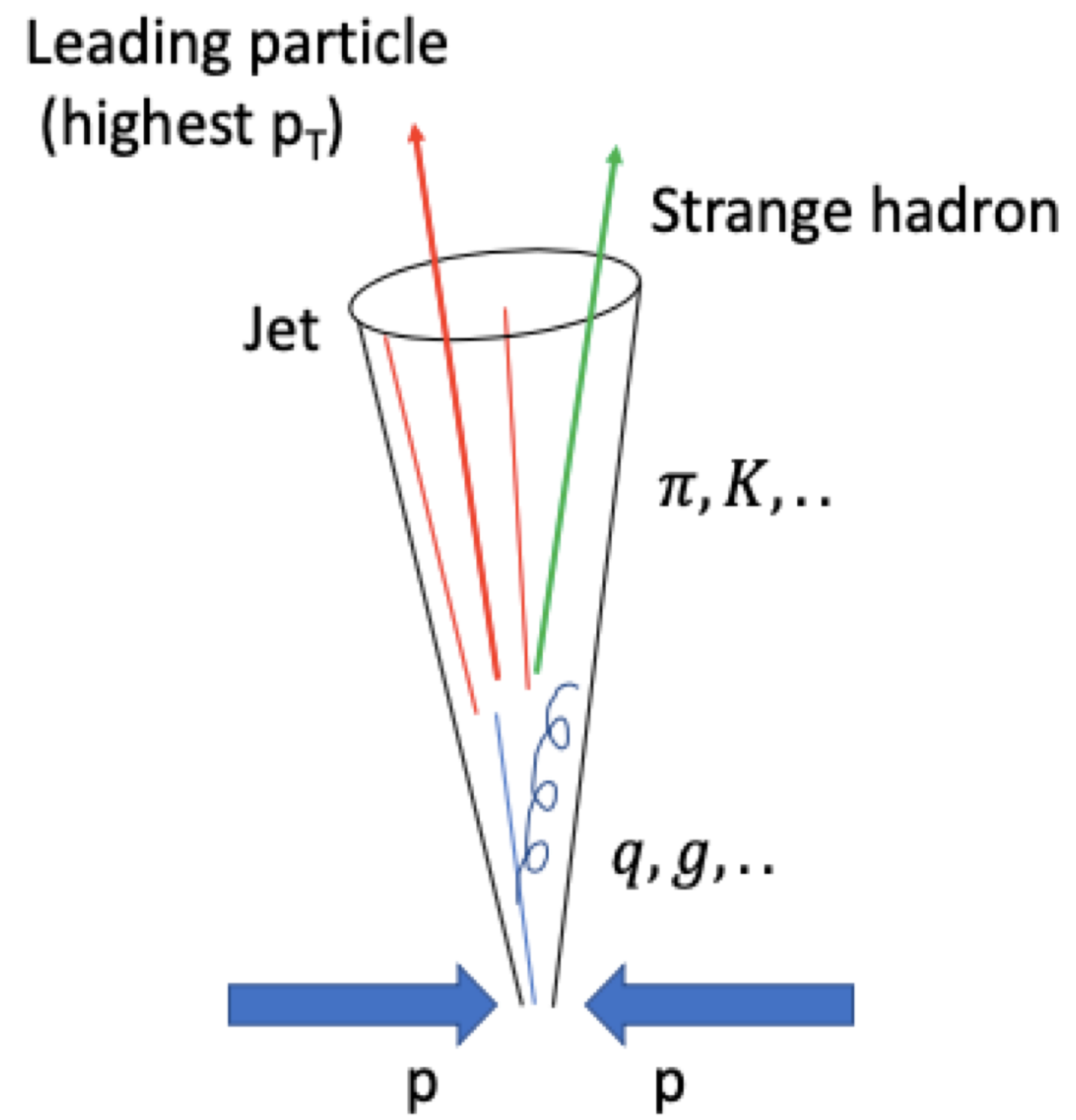
➡ Enhancement is stronger with larger strangeness content ($\Omega^{\pm} > \Xi^{\pm} > \Lambda$)

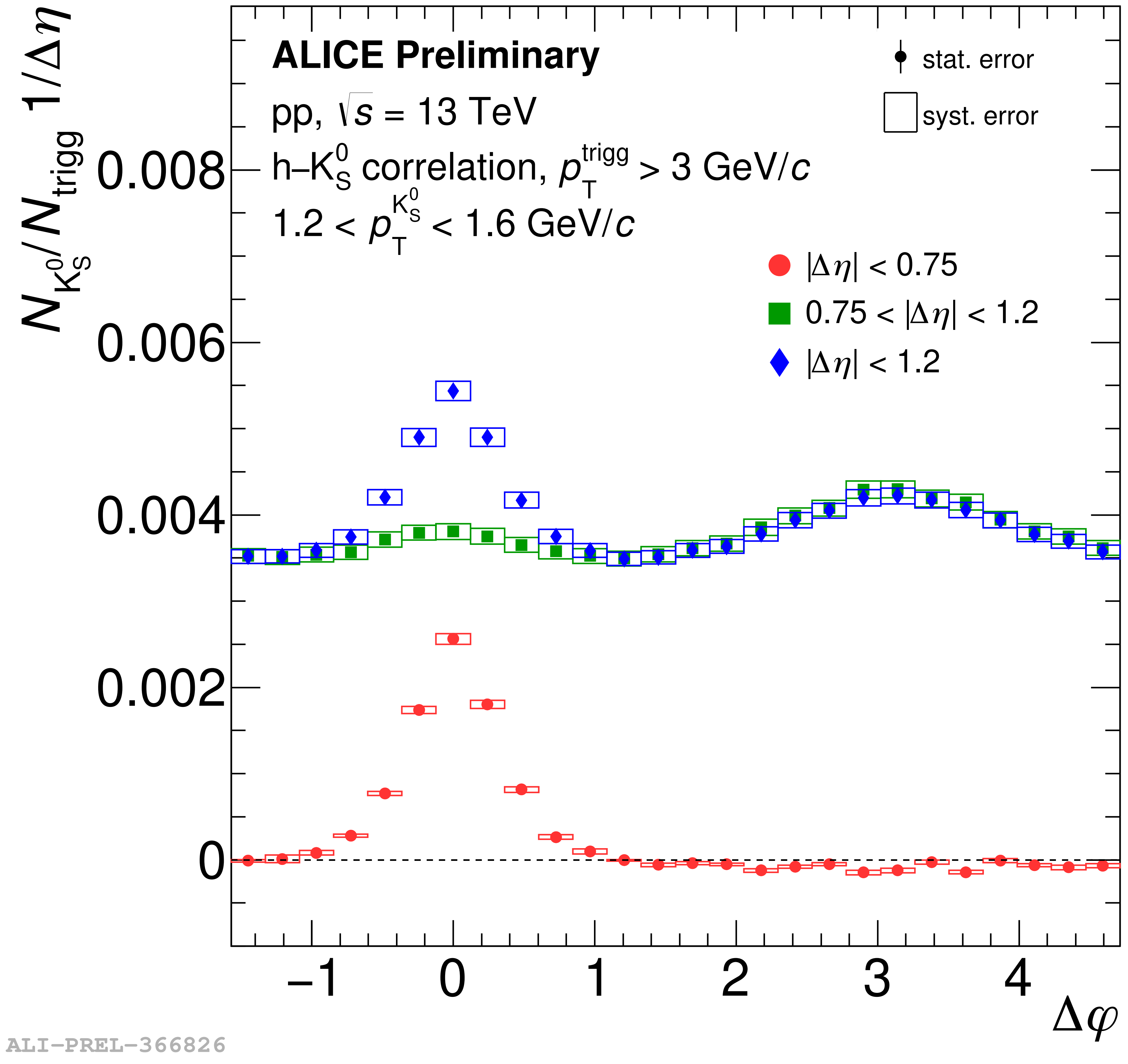
Possible explanation

- Canonical Statistical Model (CSM) [Vovchenko *et al. Phys. Rev.* **C100** (2019) 054906]
  - ➡ Exact conservation of charges in correlation volume
- Core–Corona two-component model [Kanakubo *et al. Phys. Rev.* **C101** (2020) 024912]
  - ➡ Evolution from thermal QGP to string fragmentation
- Ropes hadronization [Nayak *et al. Phys. Rev.* **D100** (2019) 074023]
  - ➡ Overlapping strings at high energies

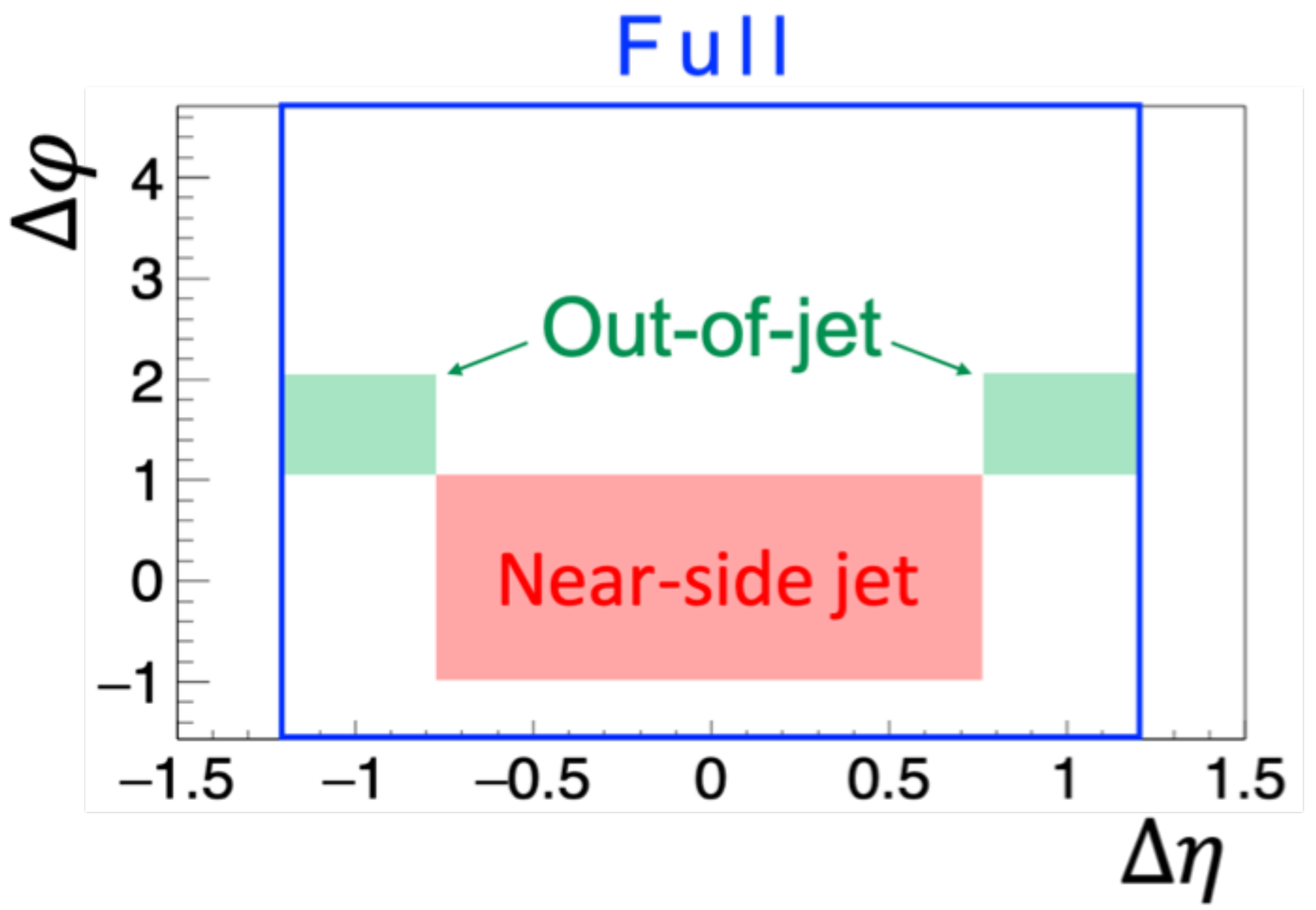
Two-particle angular correlations

- Explore the multiplicity dependence in pp collisions





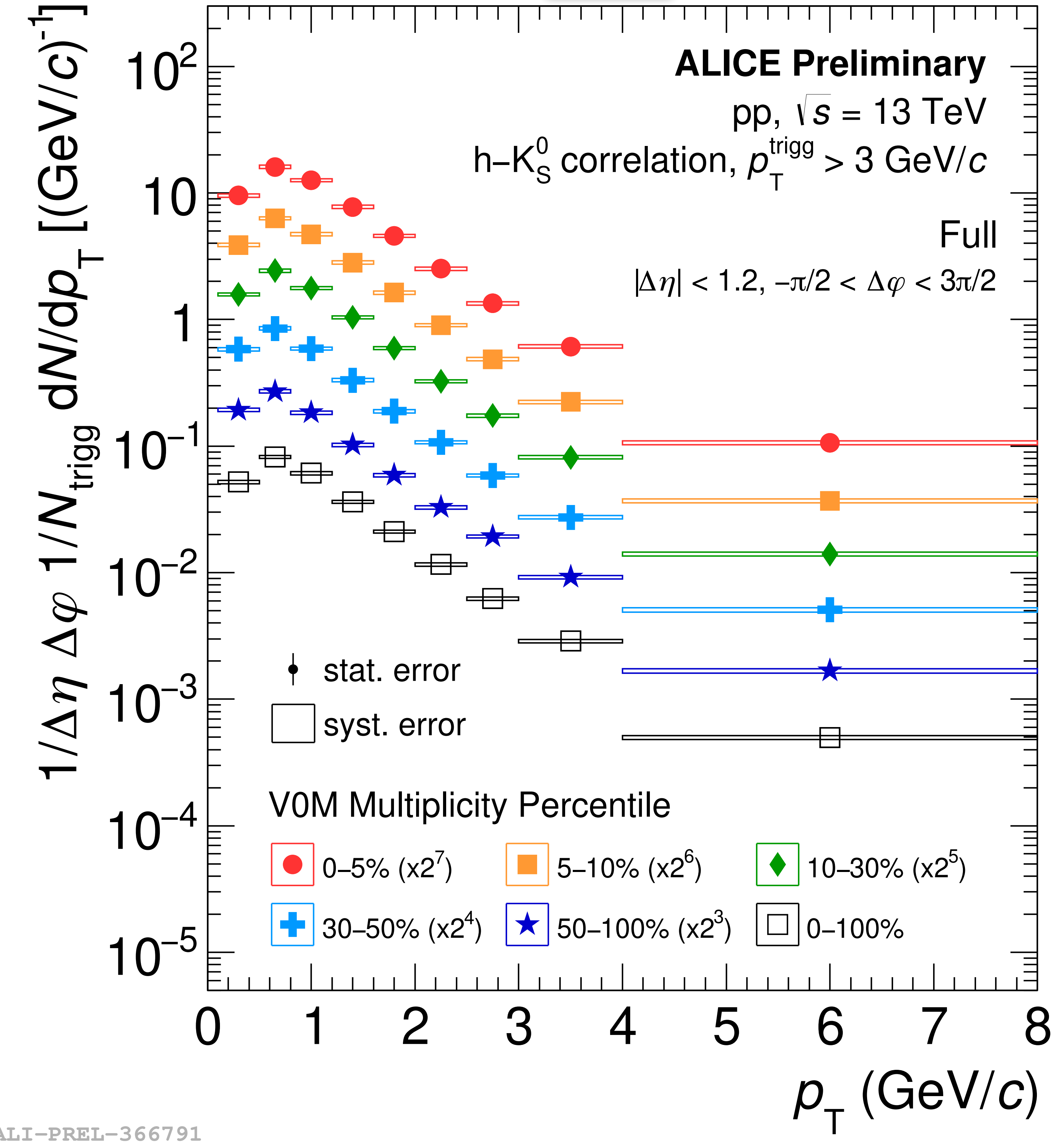
Focus on $\Xi^{\pm}$ in events selected by hard scatterings ($p_{T,trigger}$ > 3 GeV/c)



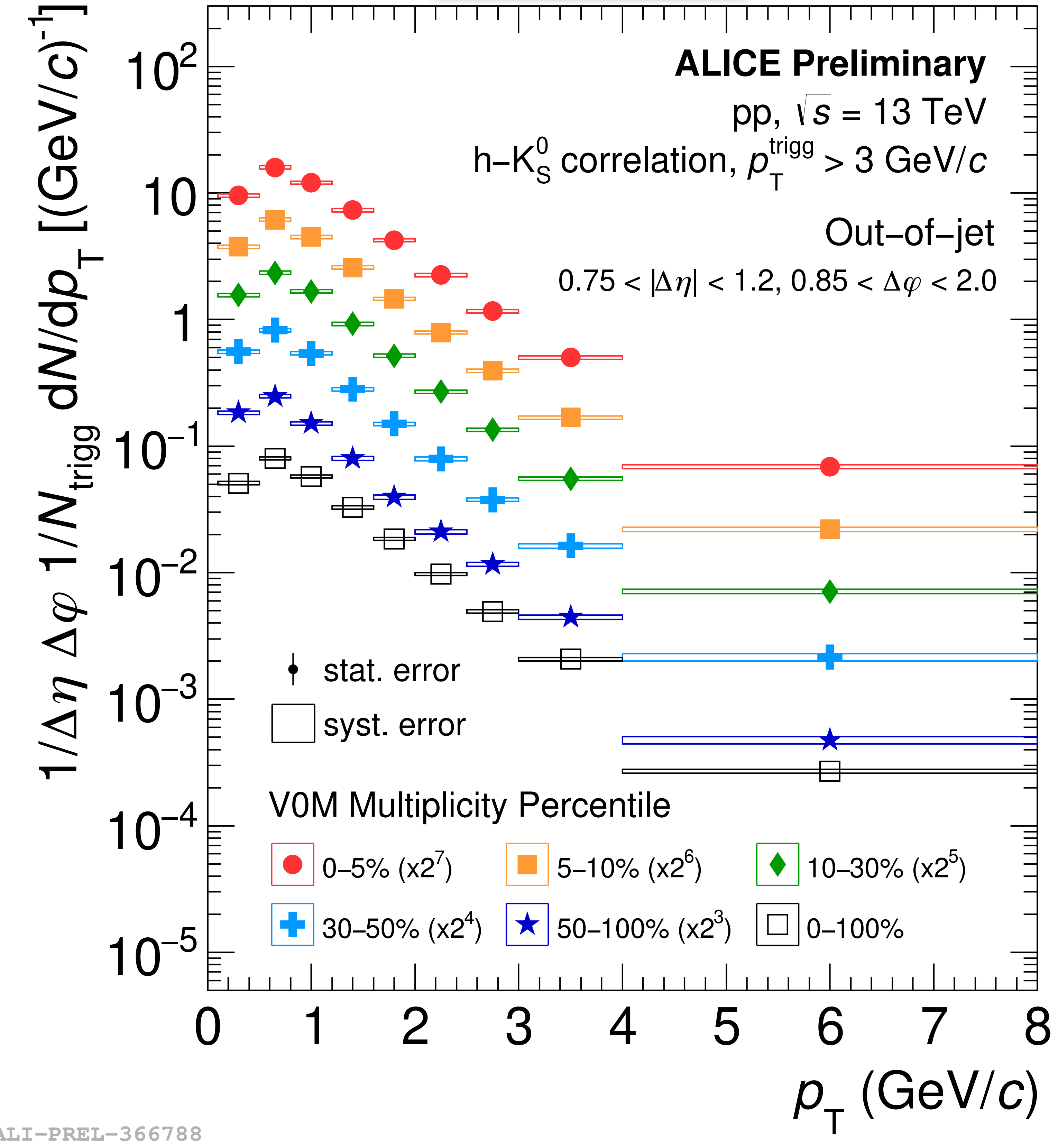
K_S^0 production in and outside jets

ALICE

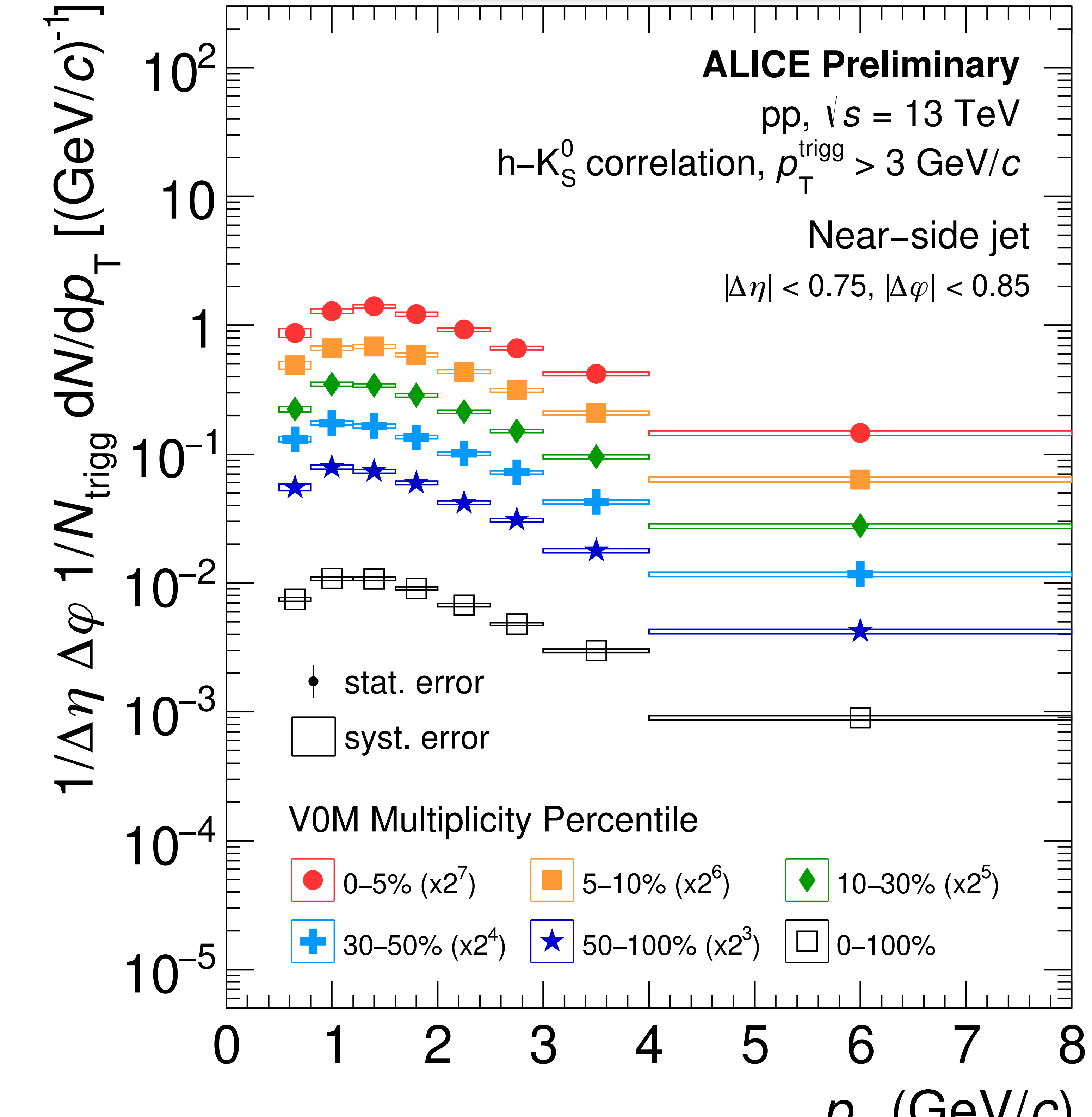
Full



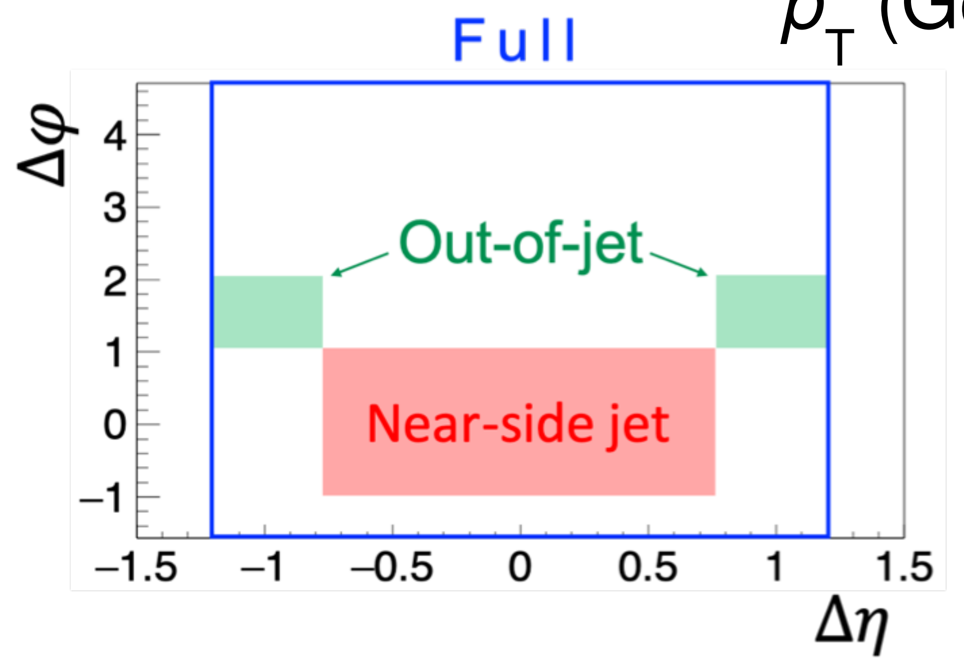
Out-of-jet



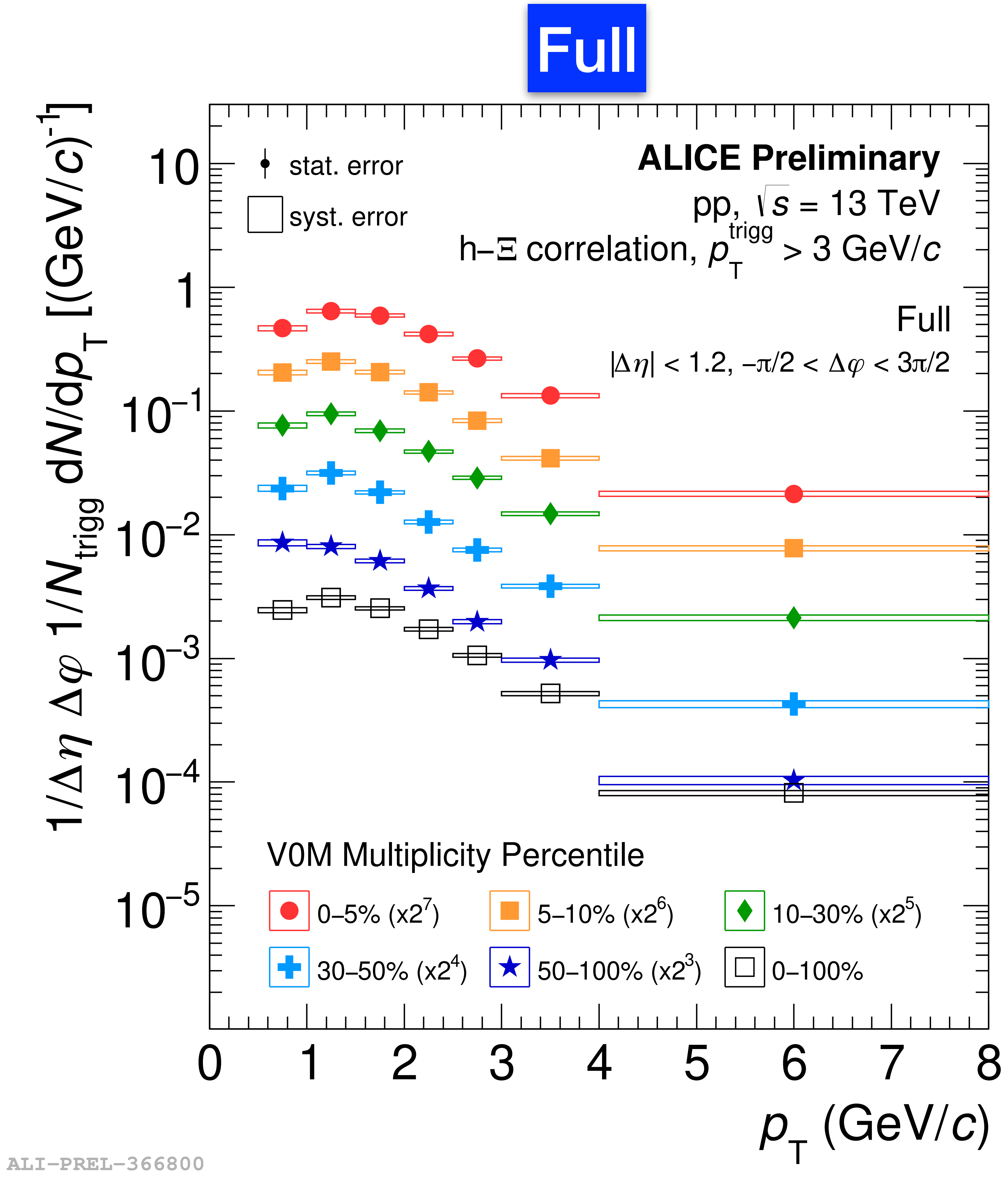
Near-side jet

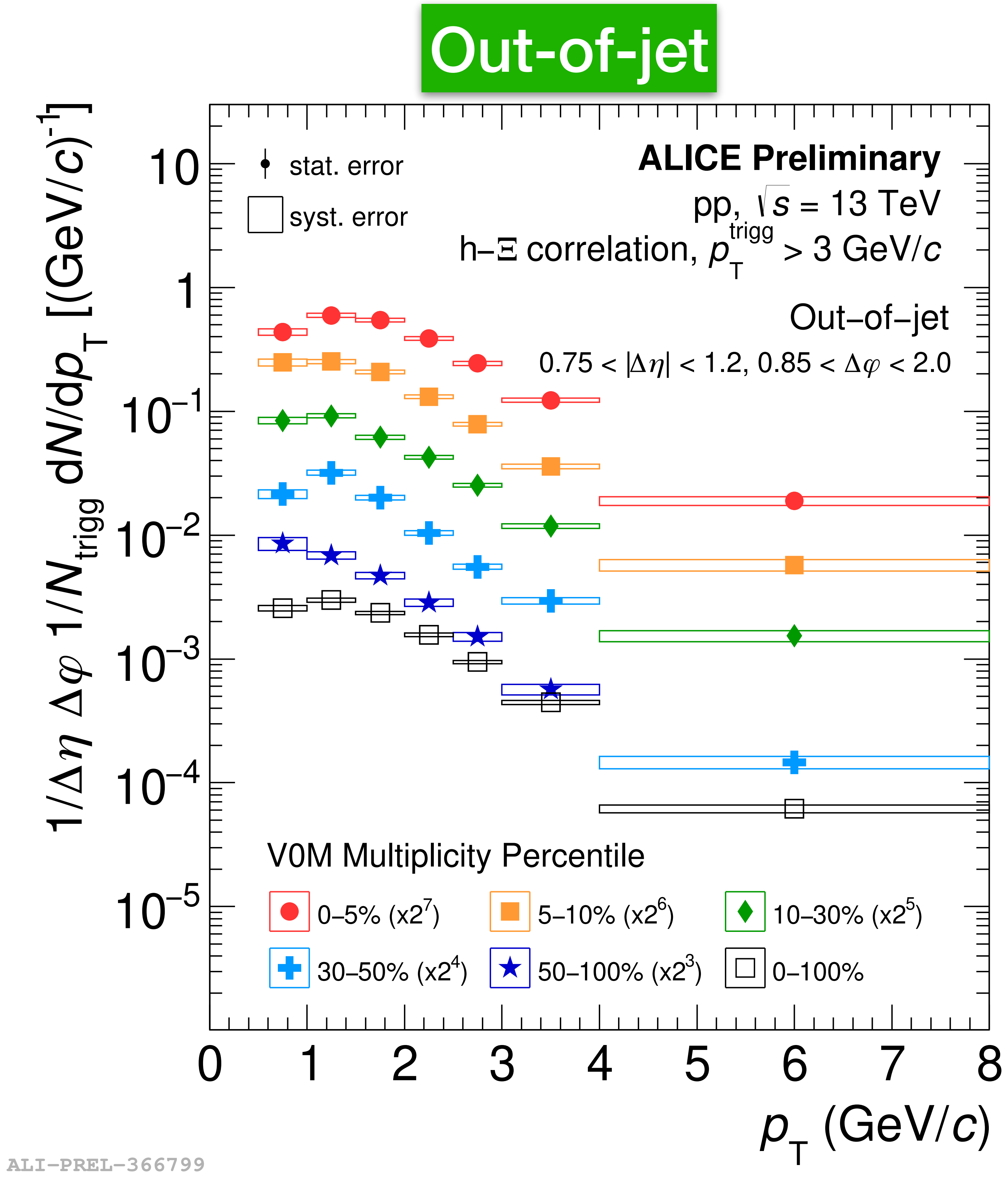


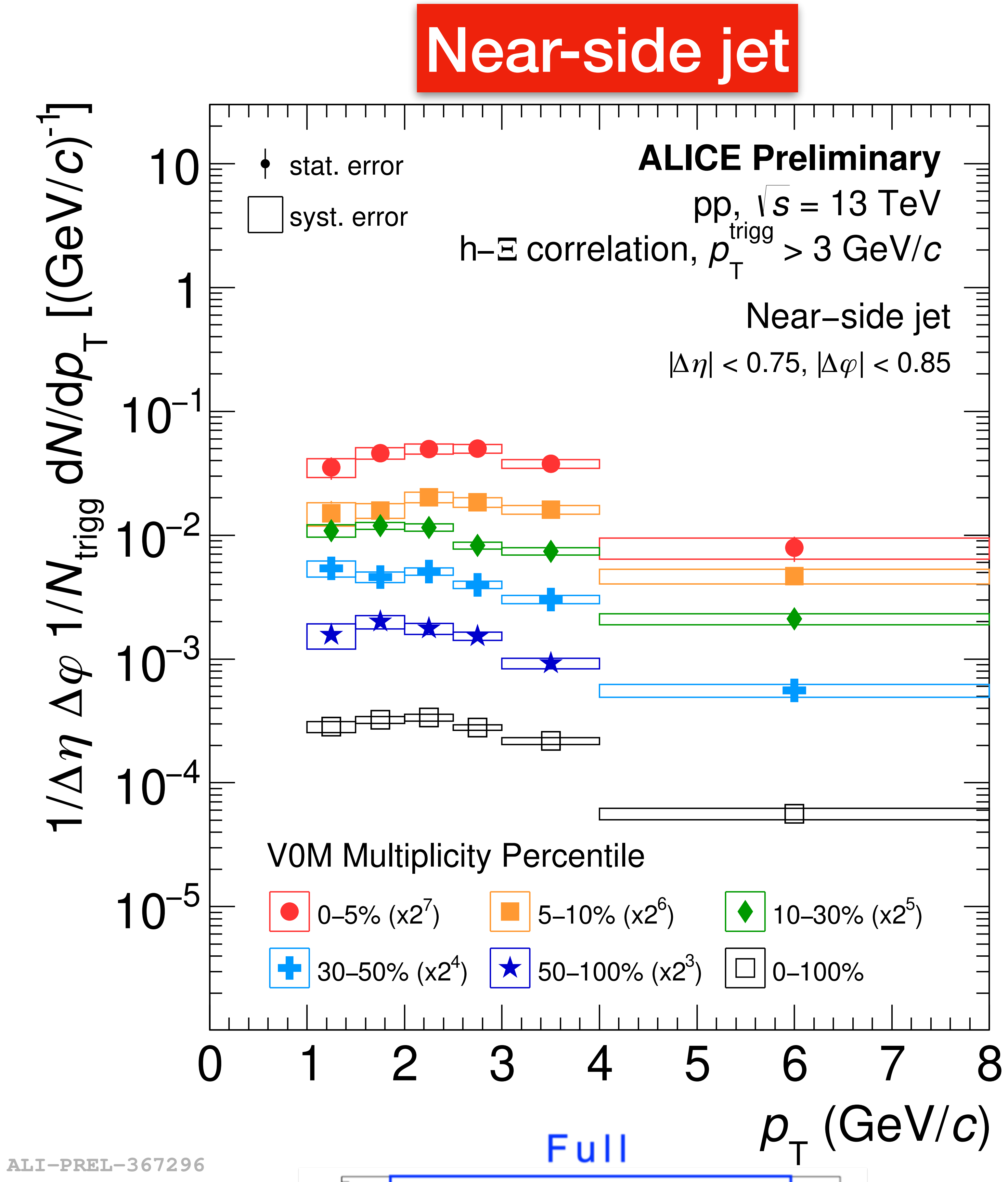
- K_S^0 spectra in jets are harder than those produced out of jets

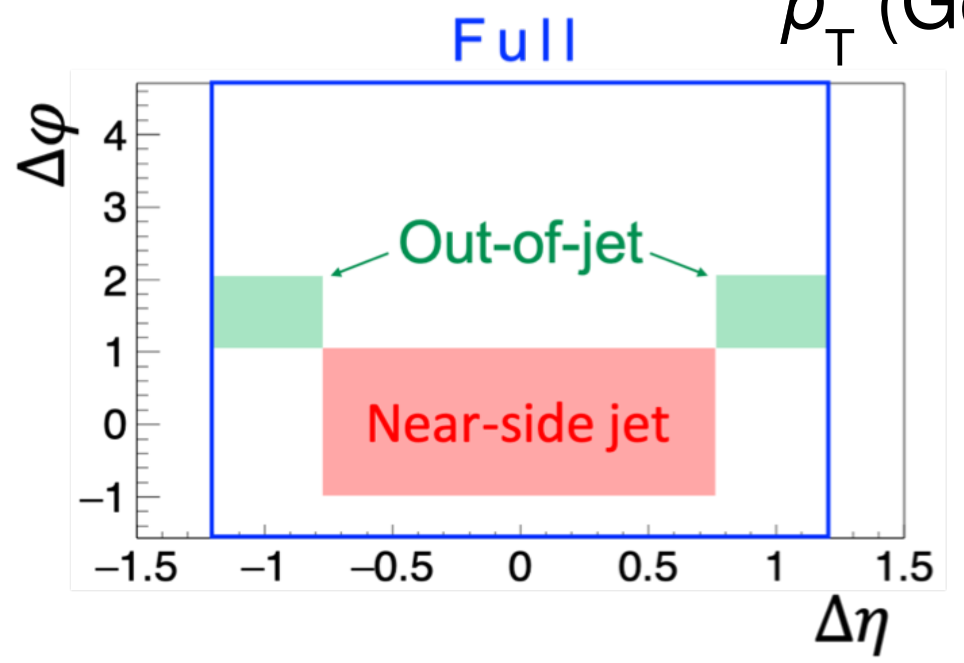


Ξ± production in and outside jets



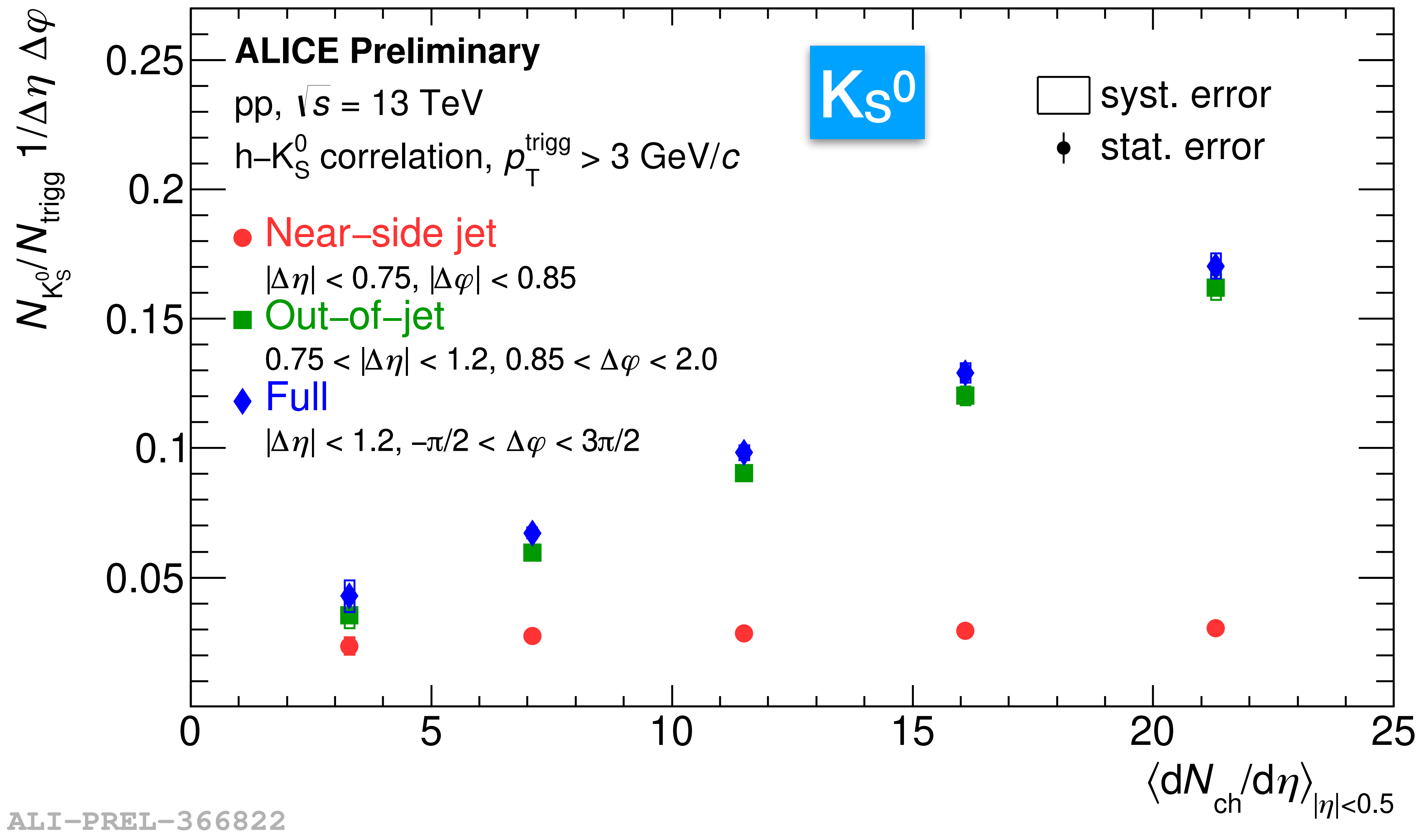


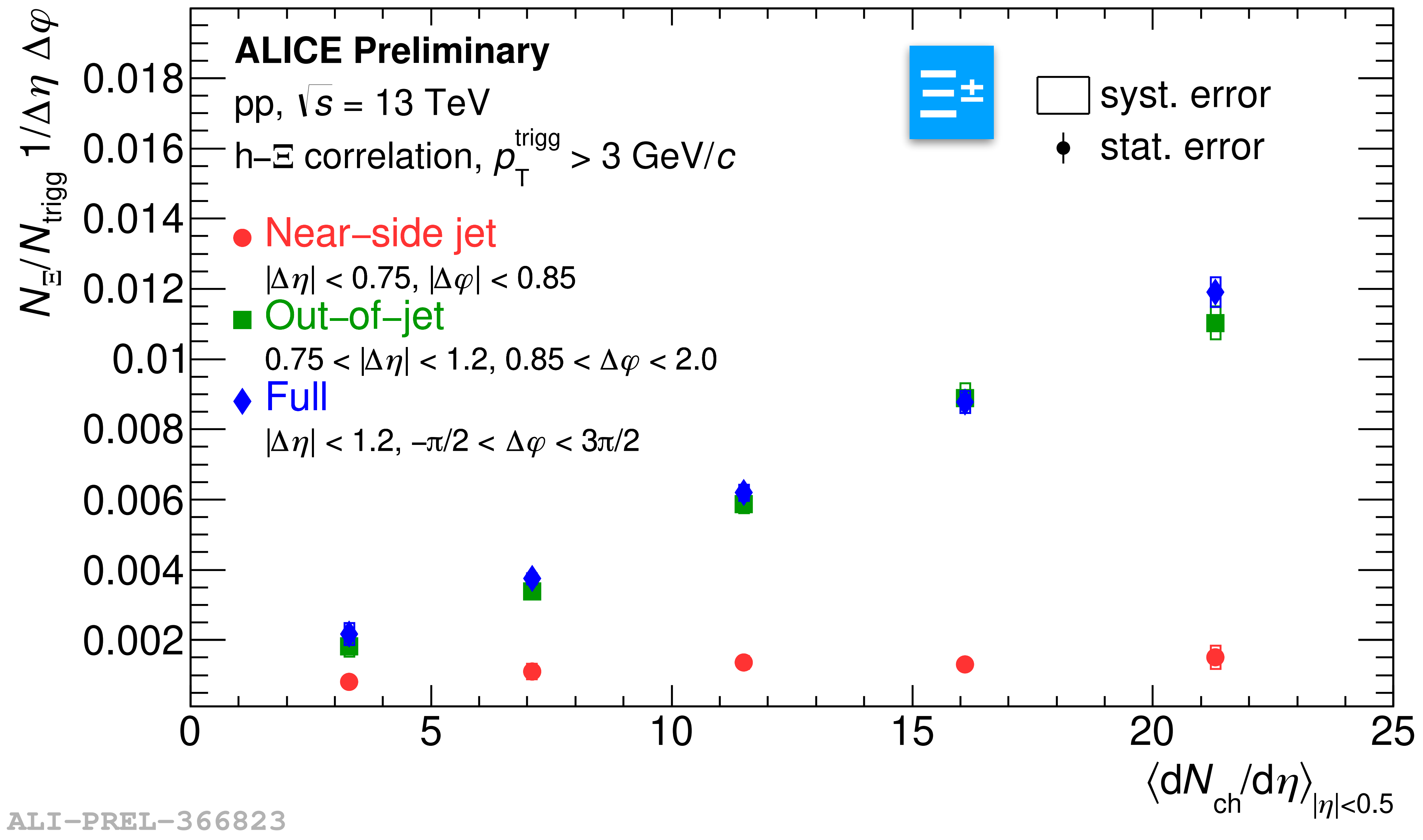




- Similar as K_S^0, spectra in jets are harder than those produced out of jets

Multiplicity dependence

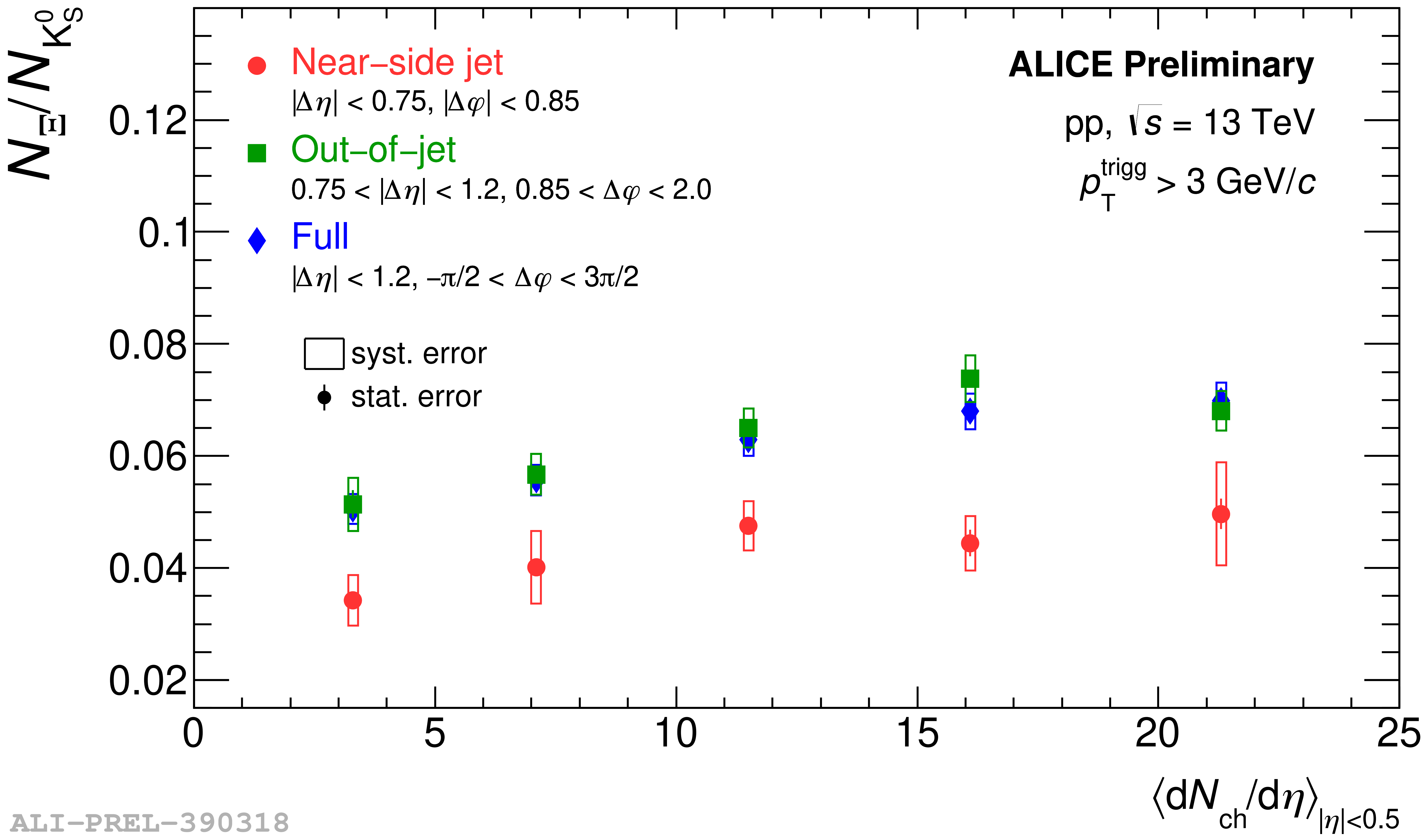




- Both the full yield and the out-of-jet yield increase with the multiplicity
- Near side jet yield has mild to no-evolution with multiplicity

➡ The contribution of out-of-jet production relative to near-side jet production increases with multiplicity

Multiplicity dependence



- Out-of-jet production is the dominant contribution to $\Xi^{\pm}/K_S^0$ full yield ratio enhancement in events with a hard scattering ($p_{T,trigger}$>3 GeV/c)

Conclusions

Strange particle production associated to hard processes and the underlying events is studied via two approaches

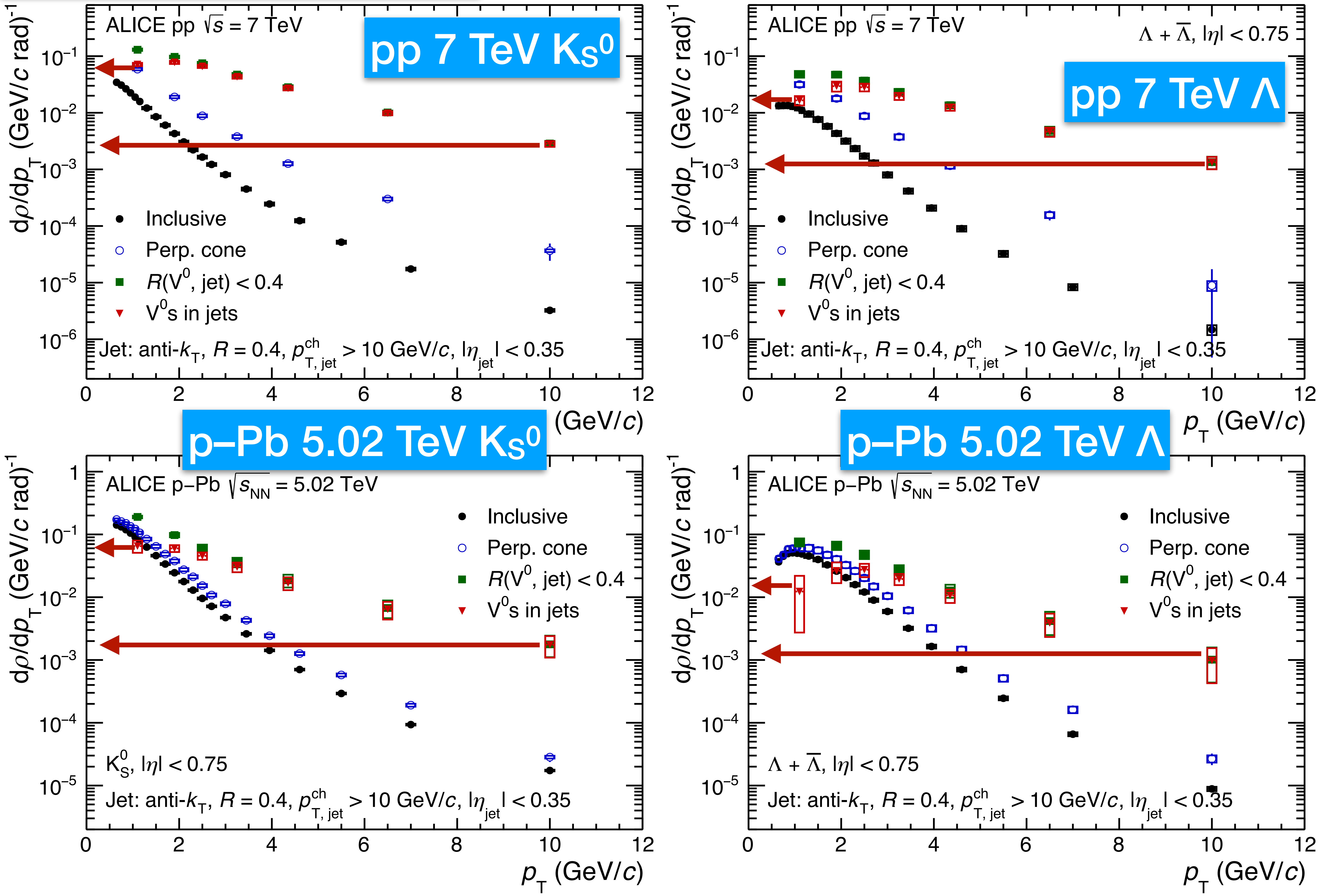
- Tagged hard processes using reconstructed jets
  - ➡ The Λ/K_S^0 increase at intermediate p_T is not present within the jets, but is related to the Underlying Event (UE)
  - ➡ PYTHIA 8 soft QCD mode gives a strong increase in particle ratios at high p_T when multi-strange particles are considered, not consistent with data
- Angular correlations of in-jet and outside-jet production
  - ➡ The $\Xi^{\pm}/K_S^0$ ratio measured out of jets increases with multiplicity and a hint of increase is observed in the near-side jet
- The inclusive ratio enhancement absent in jets, out-of-jet production is the dominant contribution to strange particle production

Extra

Strange particles in jets and UE

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Area acceptance} >} \times \frac{dN}{dp_T}$$

ALICE arXiv:2105.04890



- Similar density distributions in jets between pp and p–Pb
- No significant modification on jet fragmentation in min bias p–Pb collisions