Overview of recent results on strange and heavy-flavor particle production with ALICE at the LHC

Xiaoming Zhang
Central China Normal University

QCD物理研讨会暨基金委重大项目学术交流会
29–31 July 2022, Qingdao, China

Brief discussion of recent results on strange particle production in small systems with ALICE at the LHC

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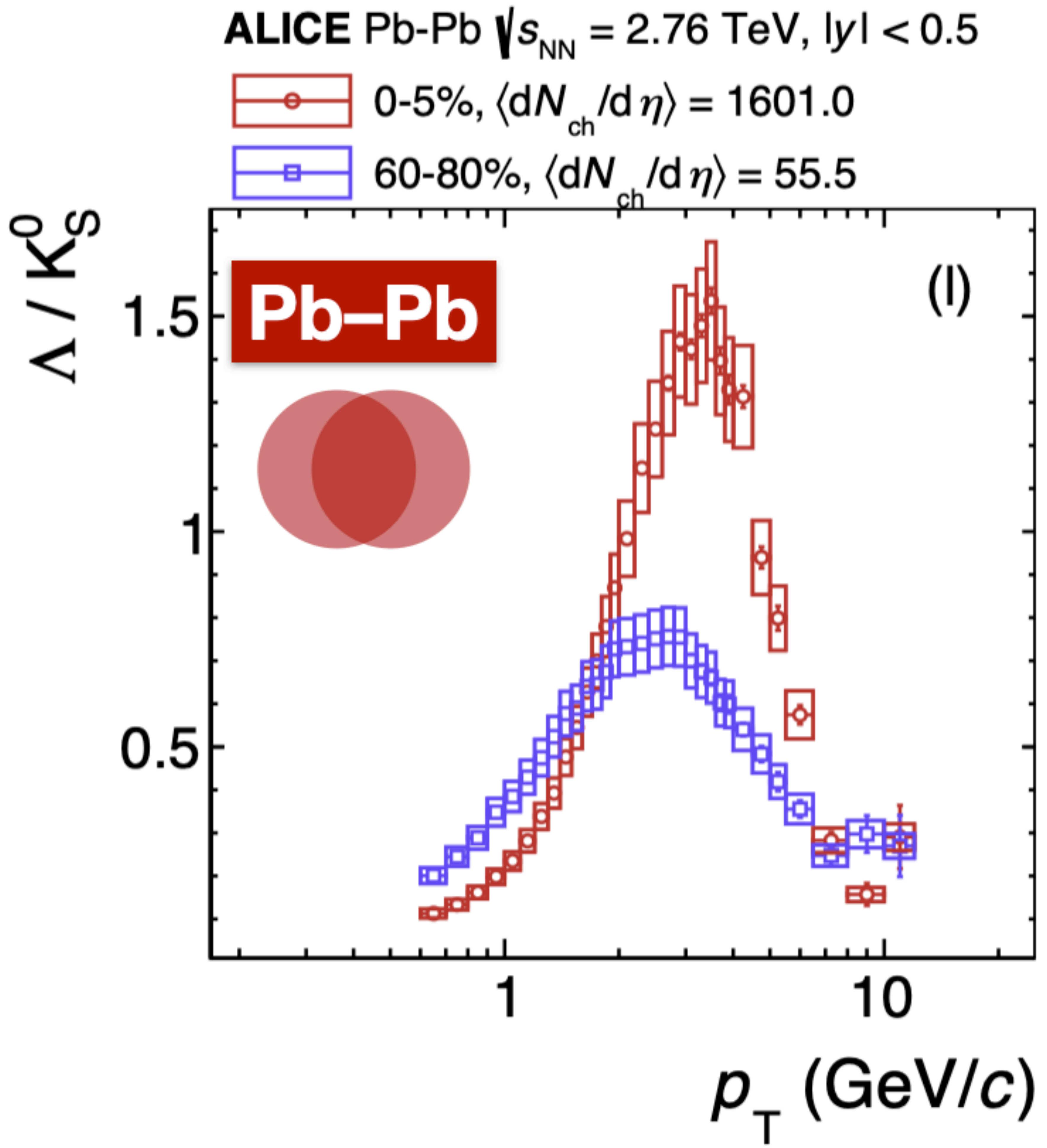
Baryon-to-meson enhancement

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

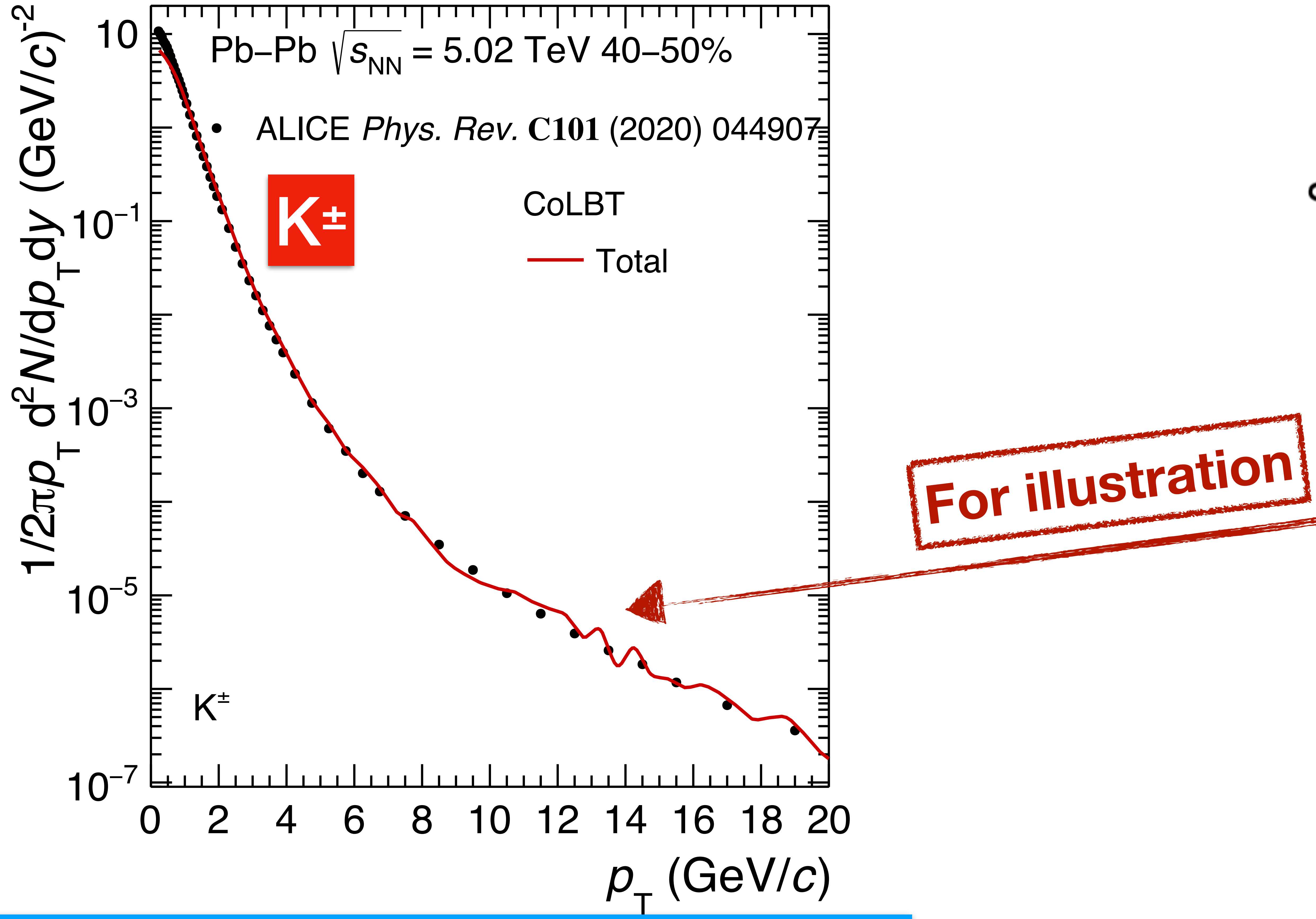
➡ Interplay of radial flow and coalescence

➡ Reflect QGP effects in heavy-ion collisions

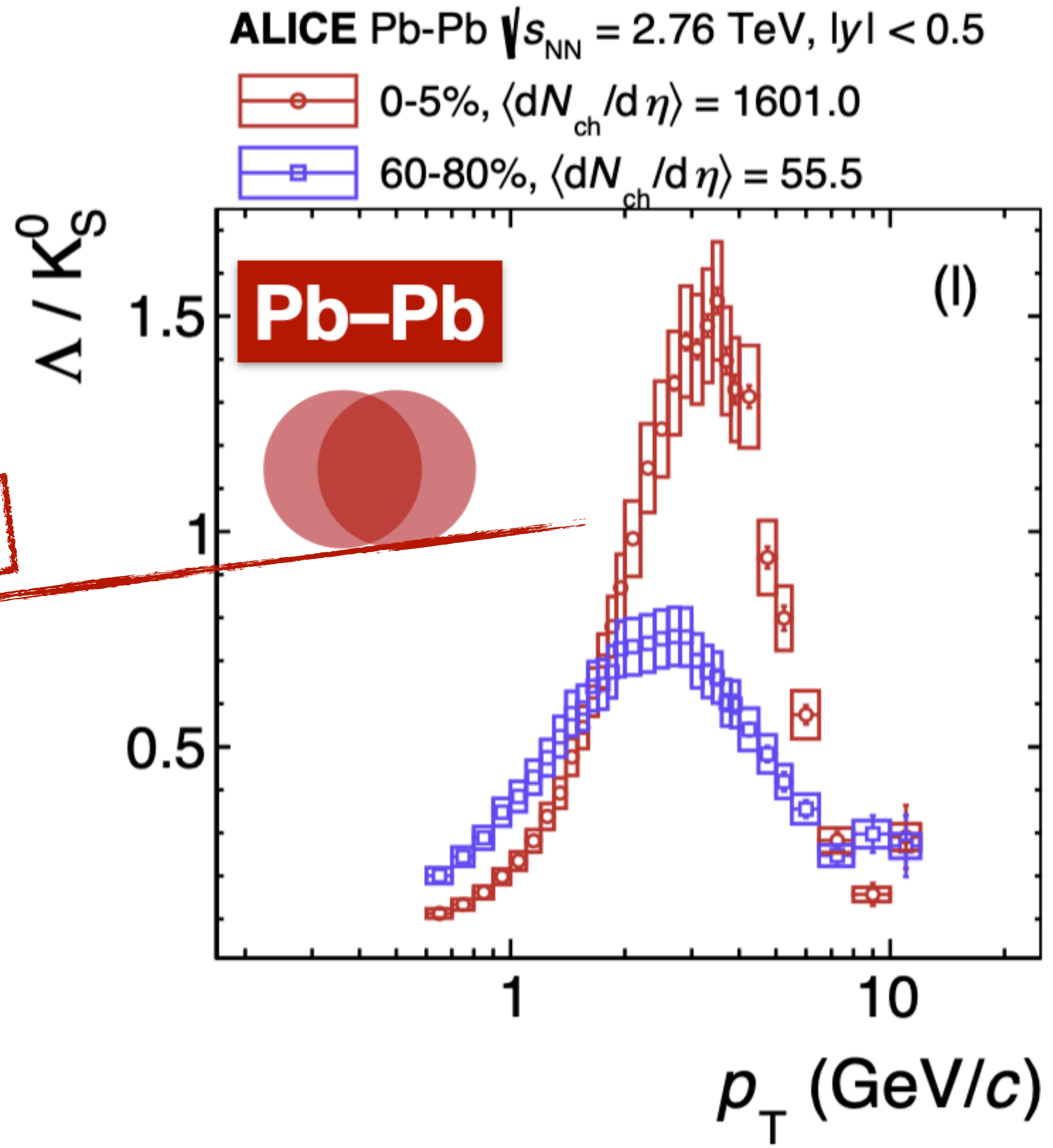


ALICE *Phys. Rev.* **C99** (2019) 024906

Baryon-to-meson enhancement



Zhao *et al.* *Phys. Rev. Lett.* **128** (2022) 022302



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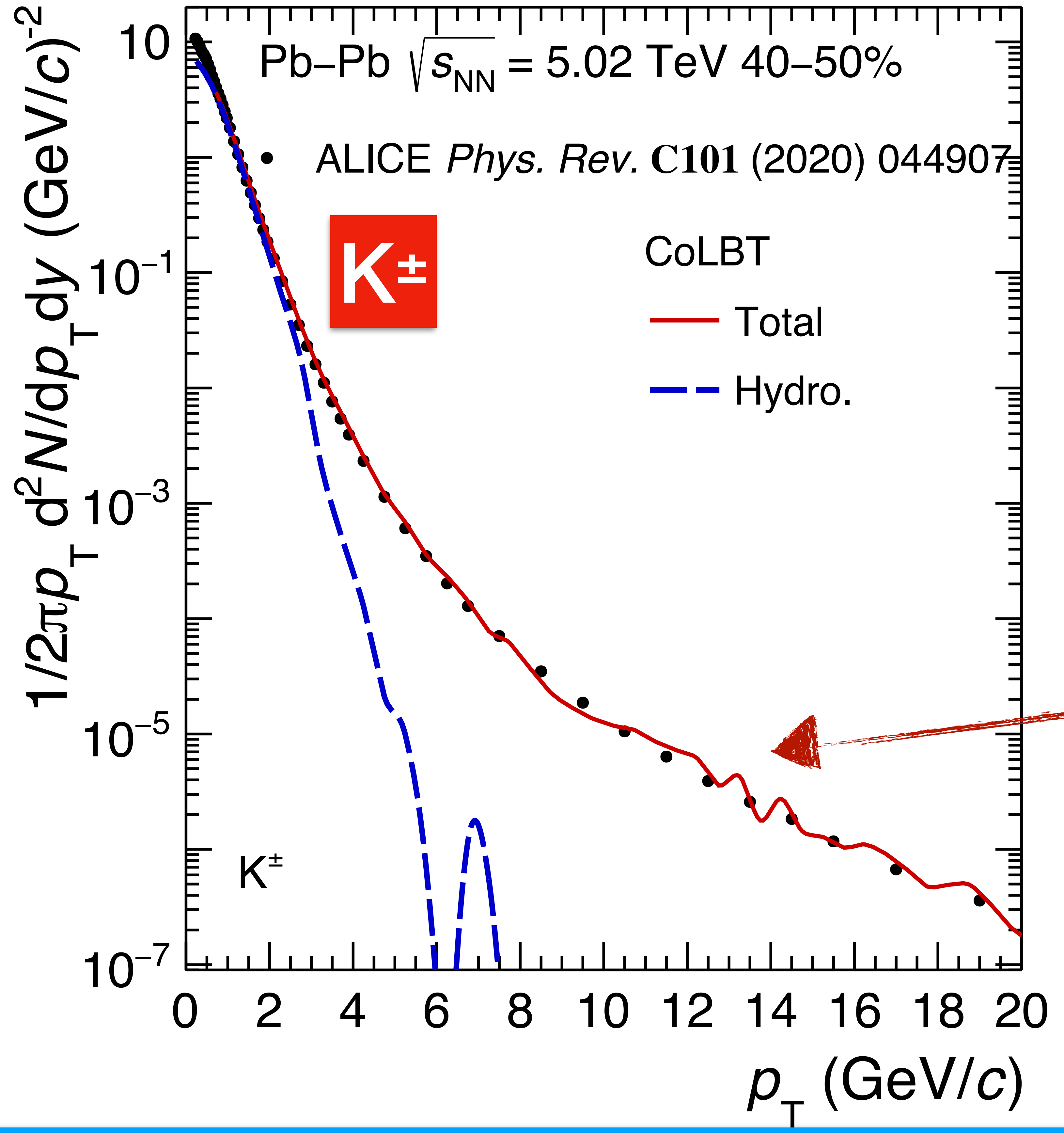

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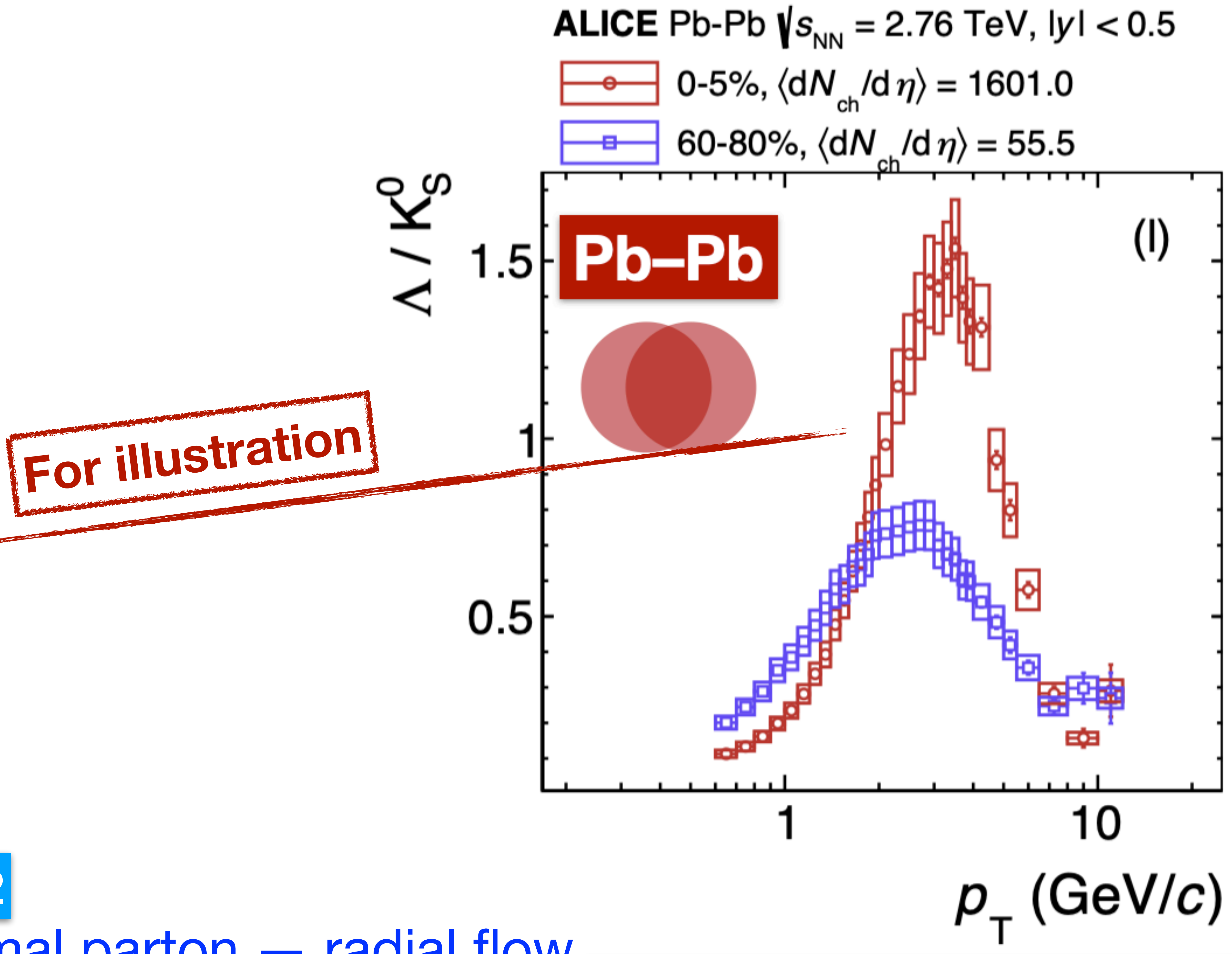
Hydrodynamics contribution from thermal parton — radial flow



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

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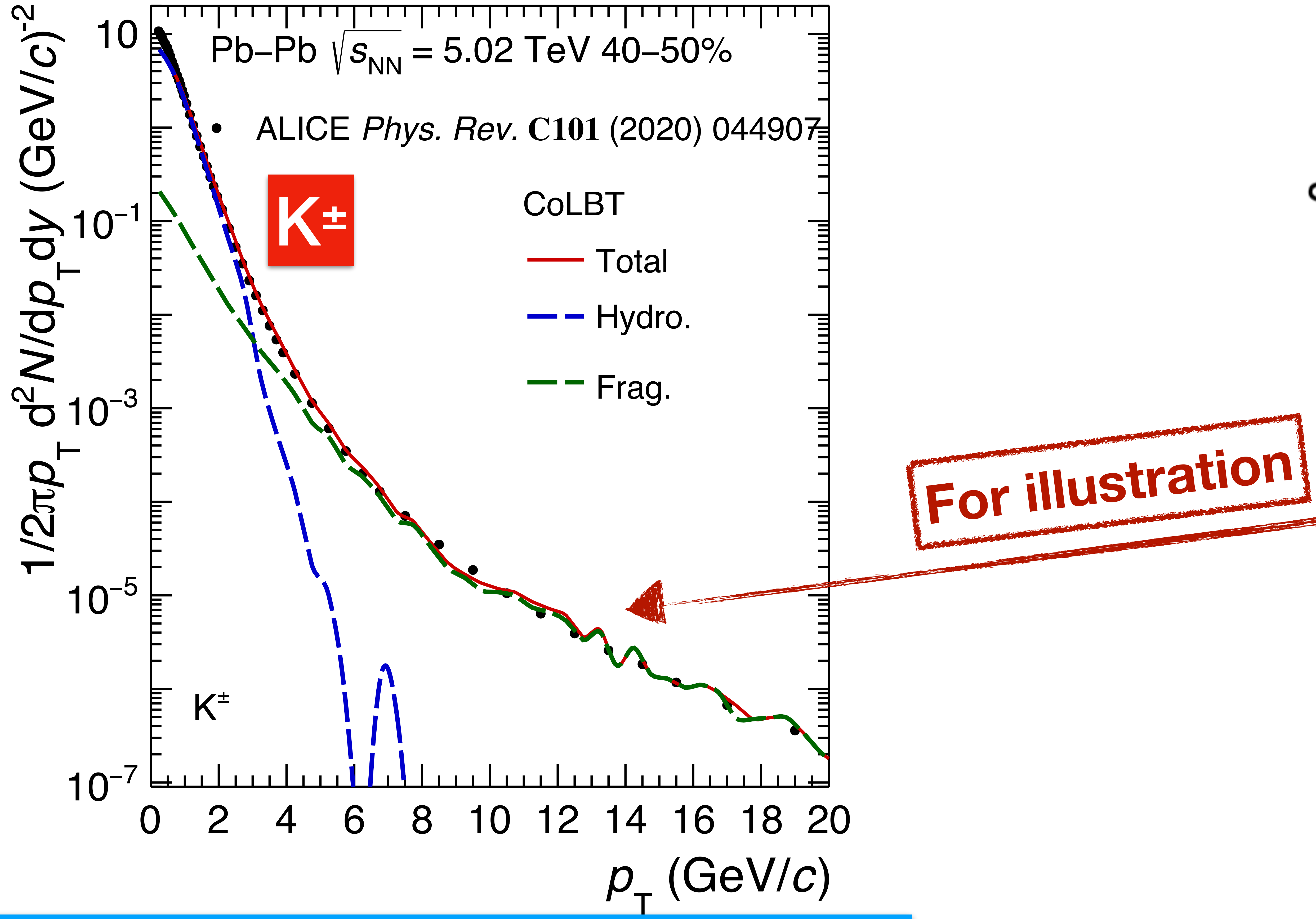

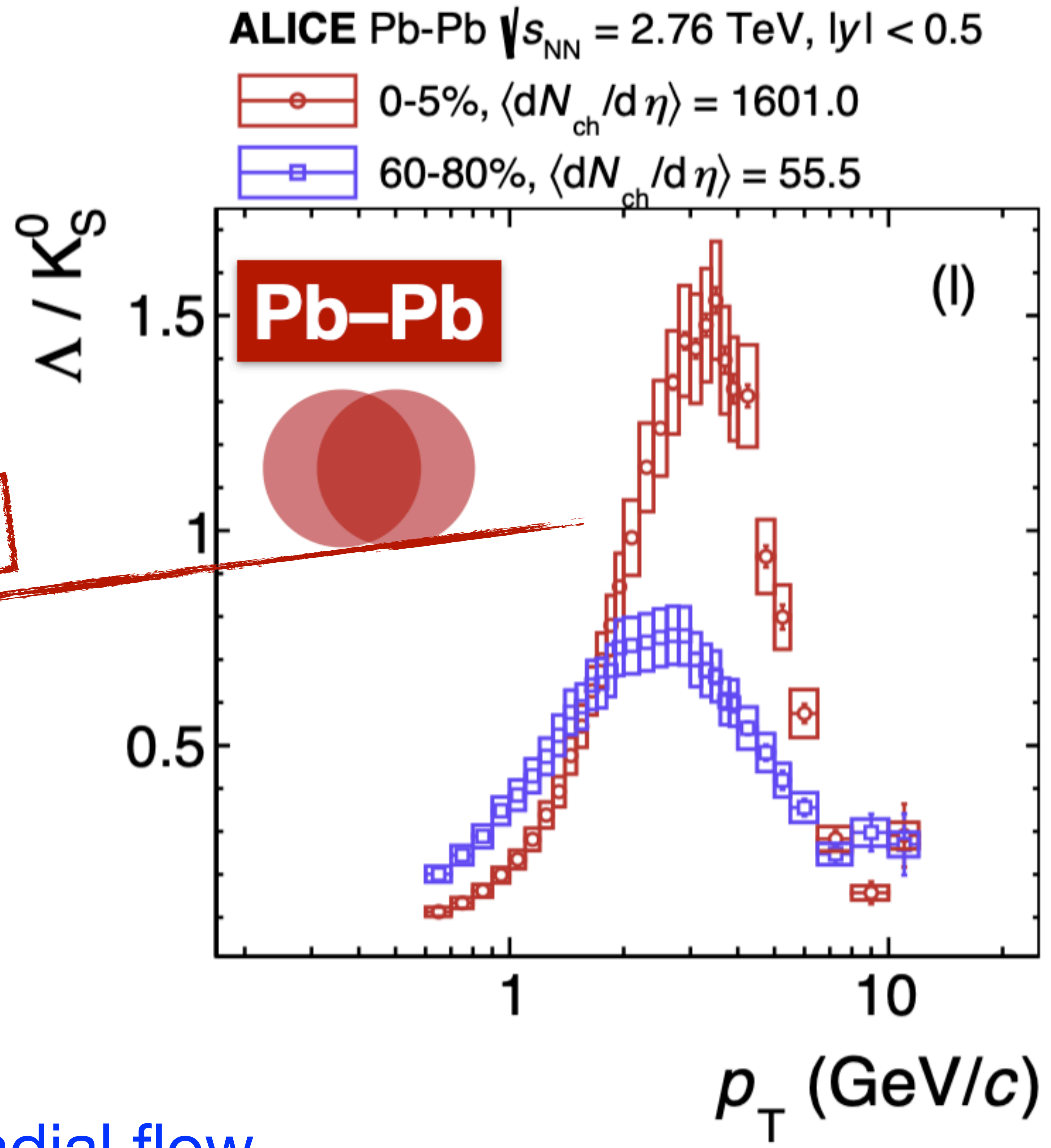

Zhao *et al.* *Phys. Rev. Lett.* **128** (2022) 022302

Hydrodynamics contribution from thermal parton — radial flow

Fragmentation hard parton hadronization at QGP surface

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

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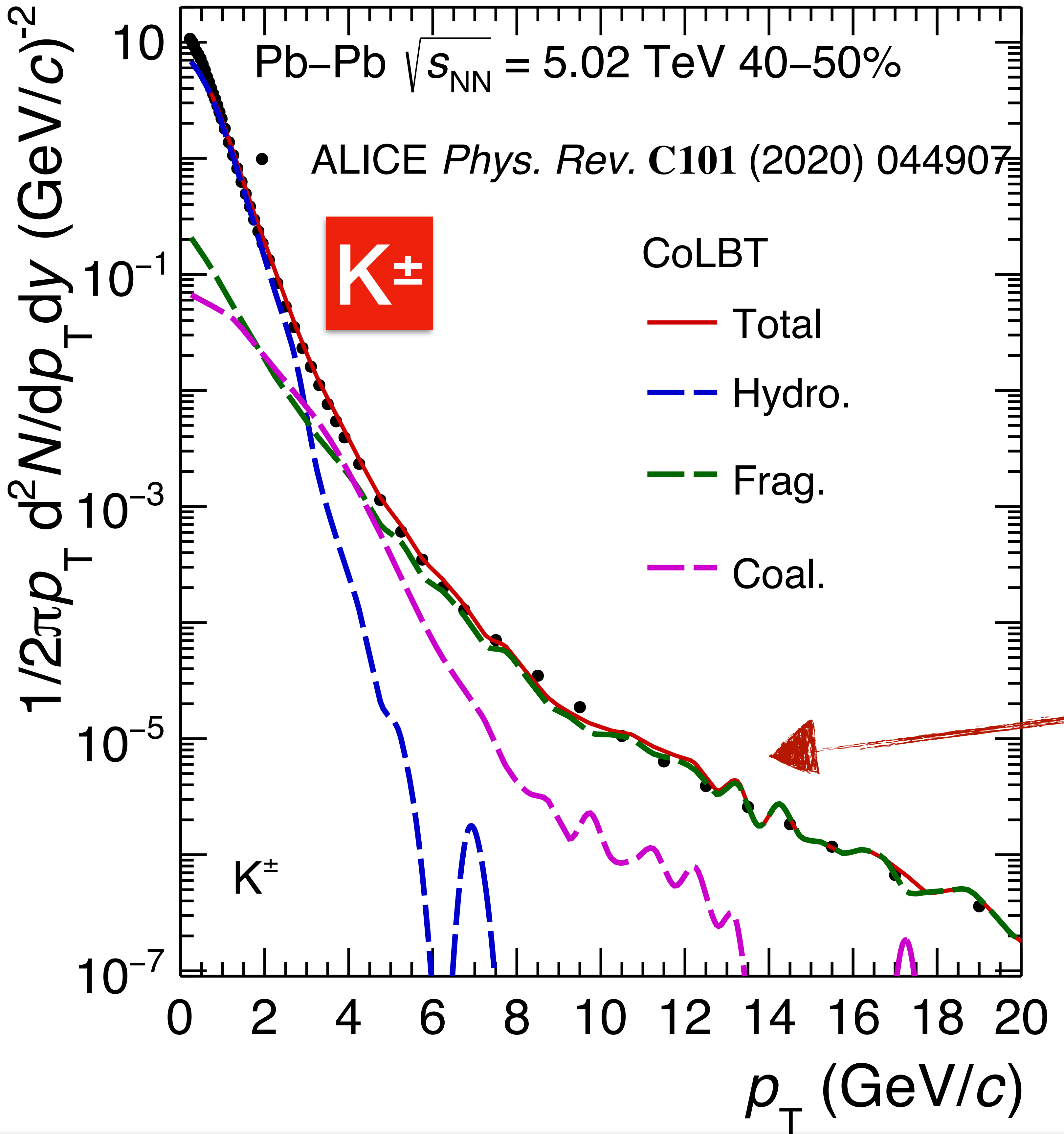
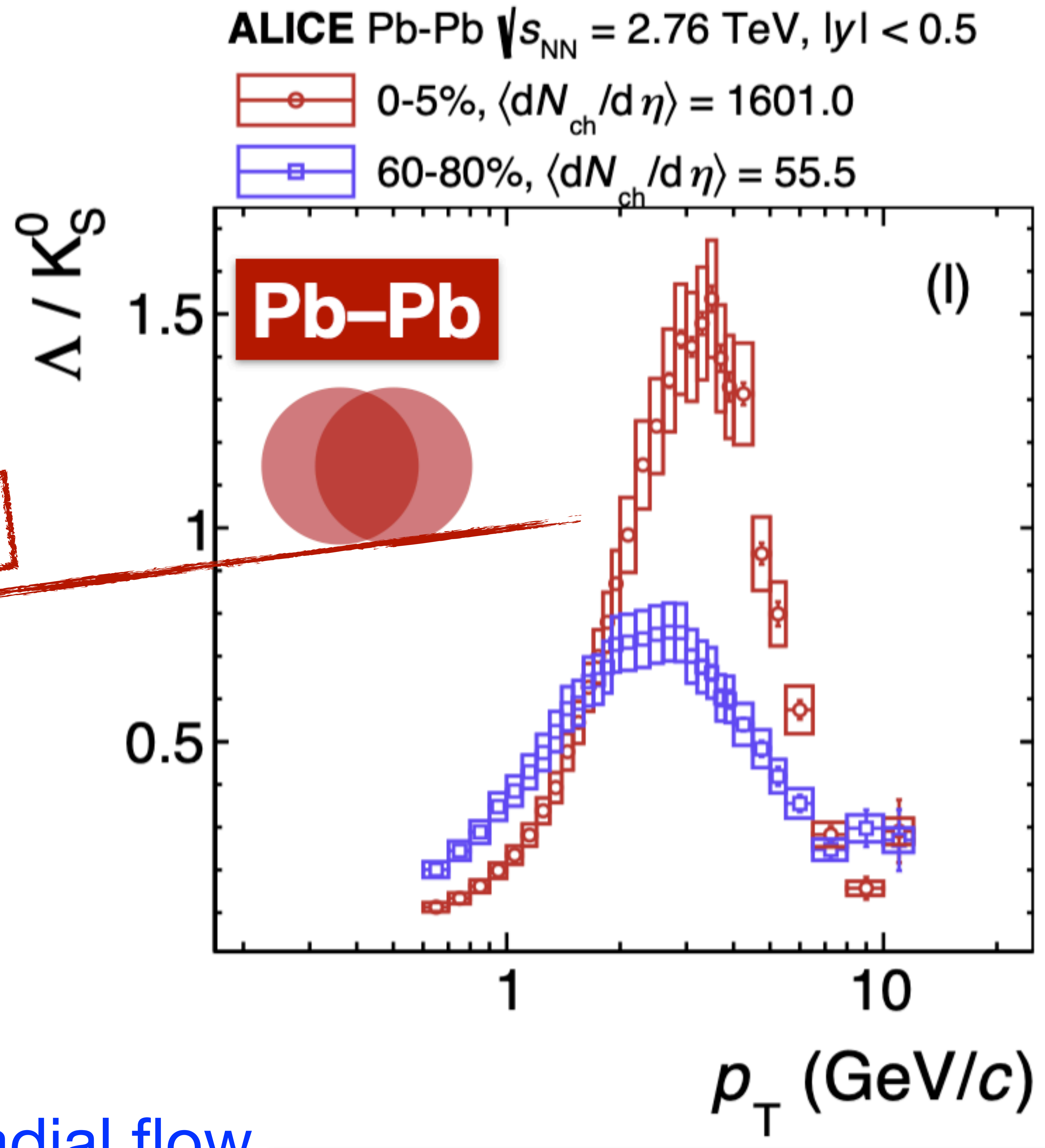


Zhao *et al. Phys. Rev. Lett.* **128** (2022) 022302

For illustration



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

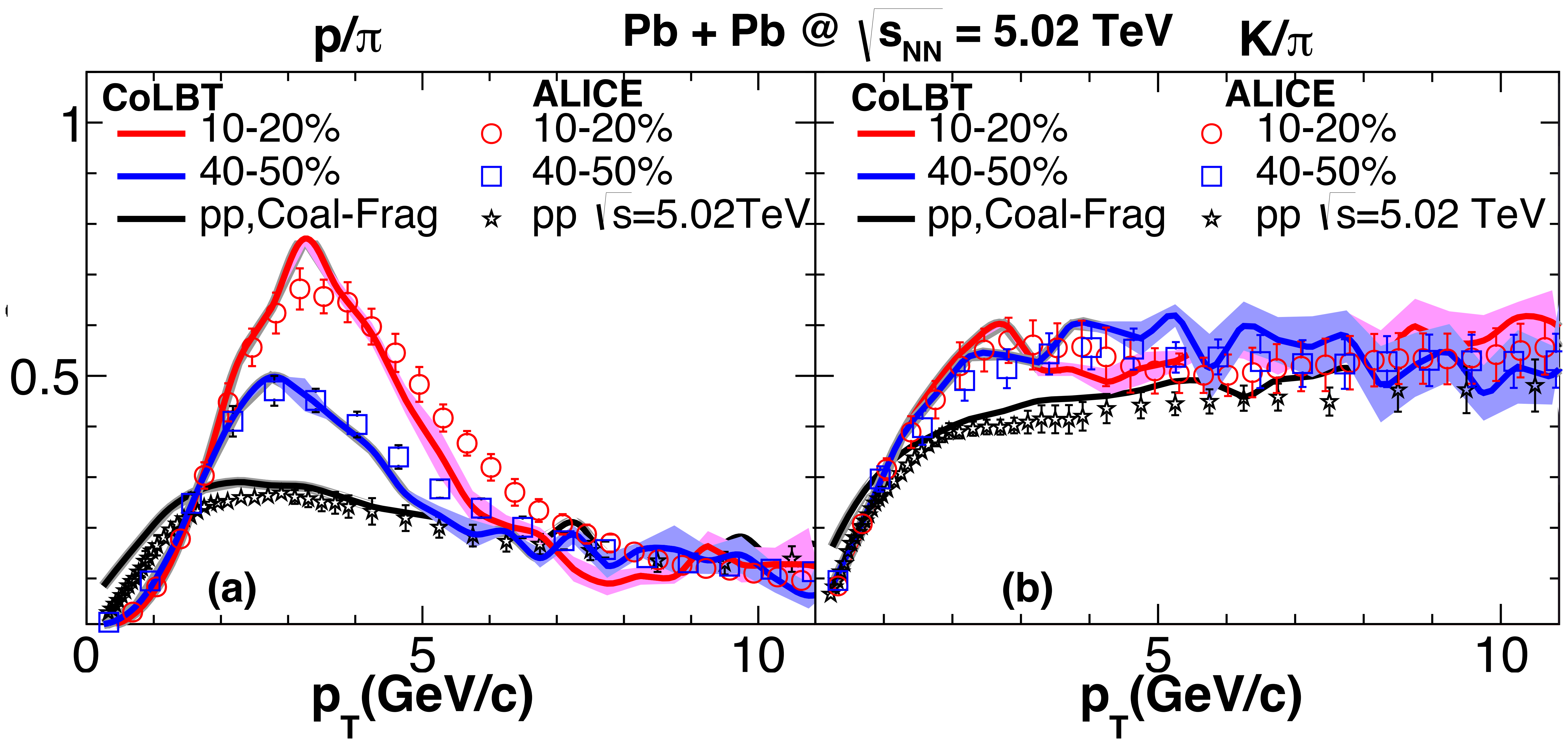
Hydrodynamics contribution from thermal parton — radial flow

Fragmentation hard parton hadronization at QGP surface

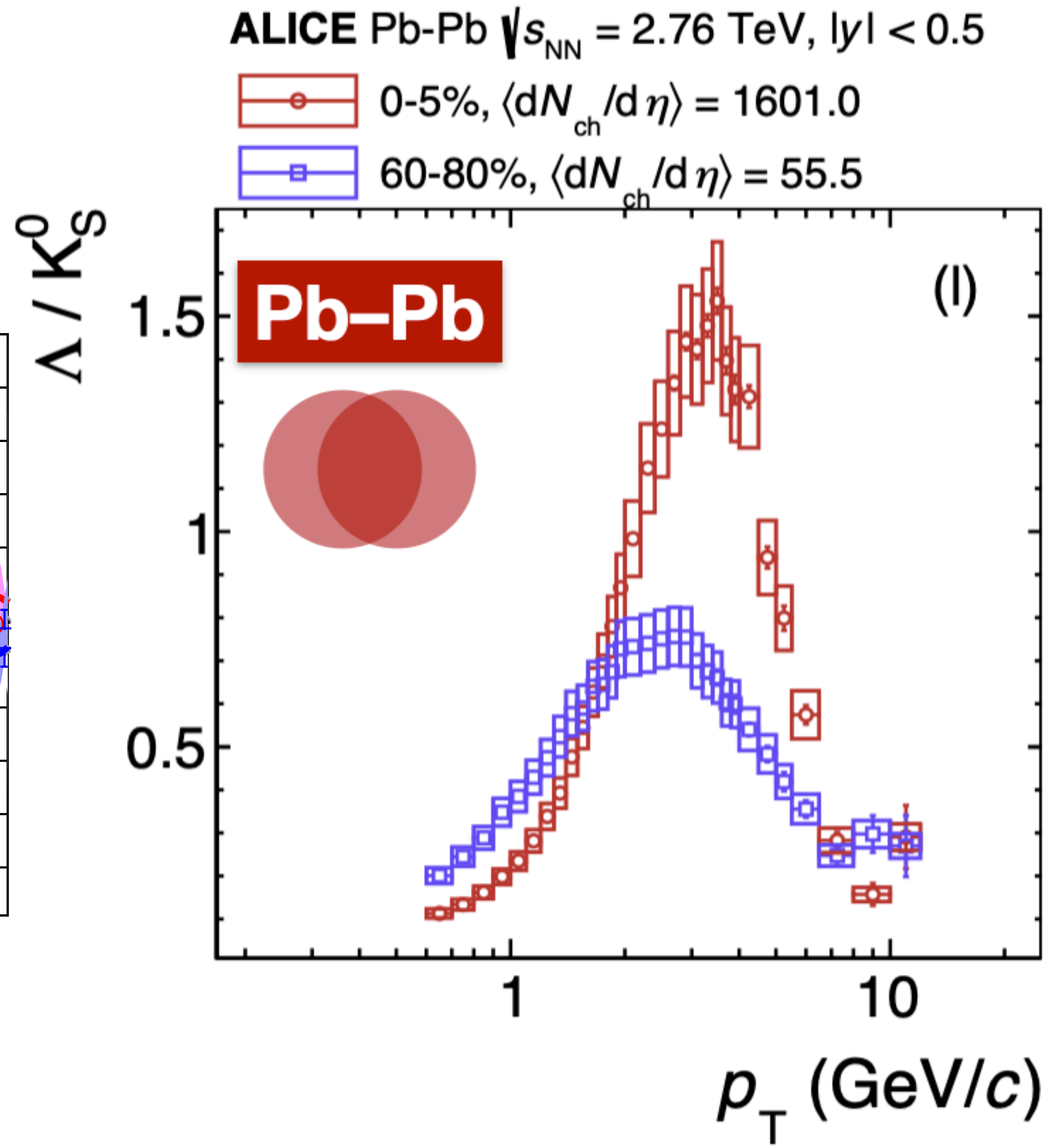
Coalescence interplay of thermal and hard partons

Baryon-to-meson enhancement

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



Zhao *et al. Phys. Rev. Lett.* **128** (2022) 022302



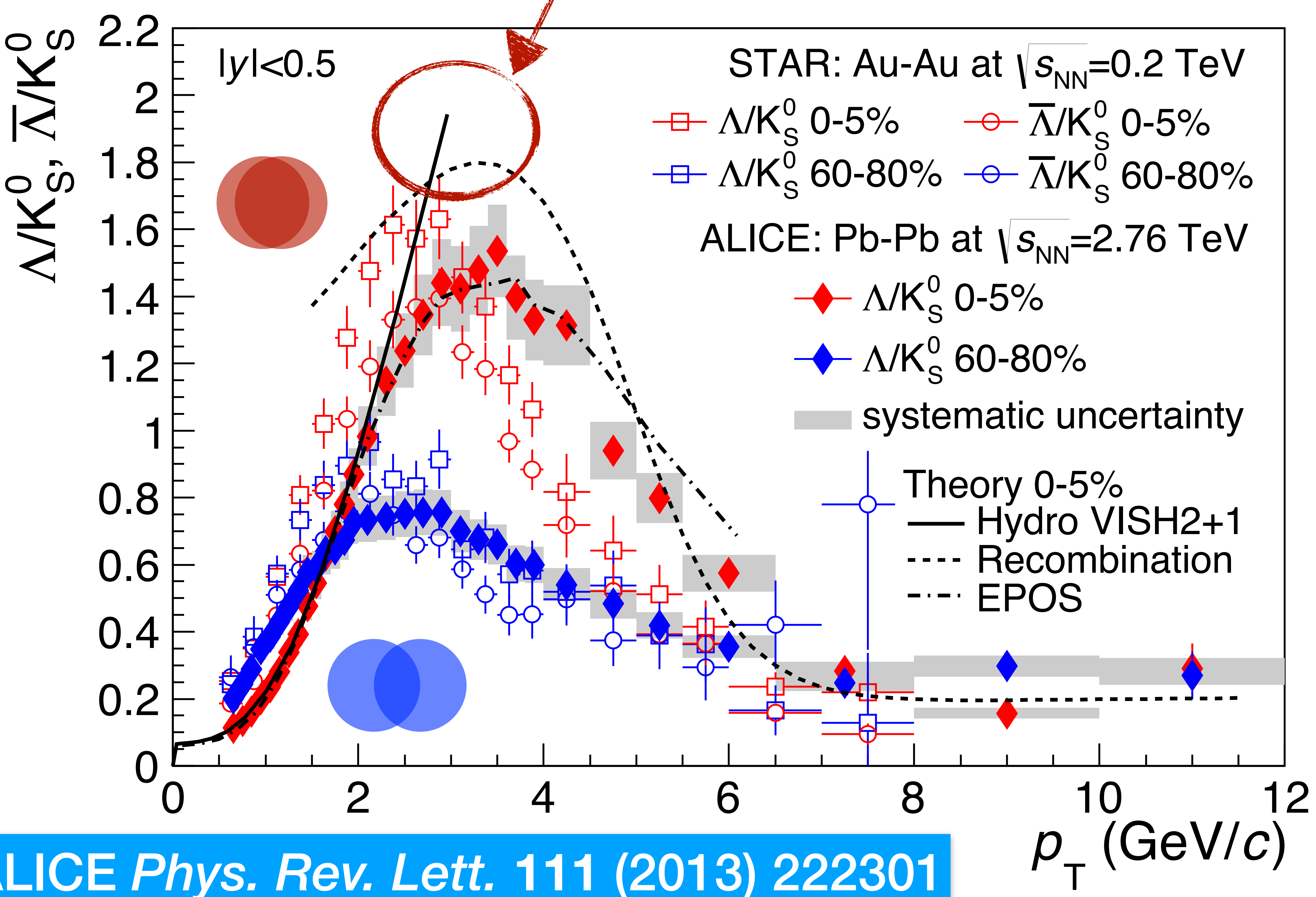
ALICE *Phys. Rev.* **C99** (2019) 024906

Similar implementation
LIDO *Phys. Rev.* **C100** (2019) 064911
MC@sHQ *Phys. Rev.* **C89** (2014) 014905

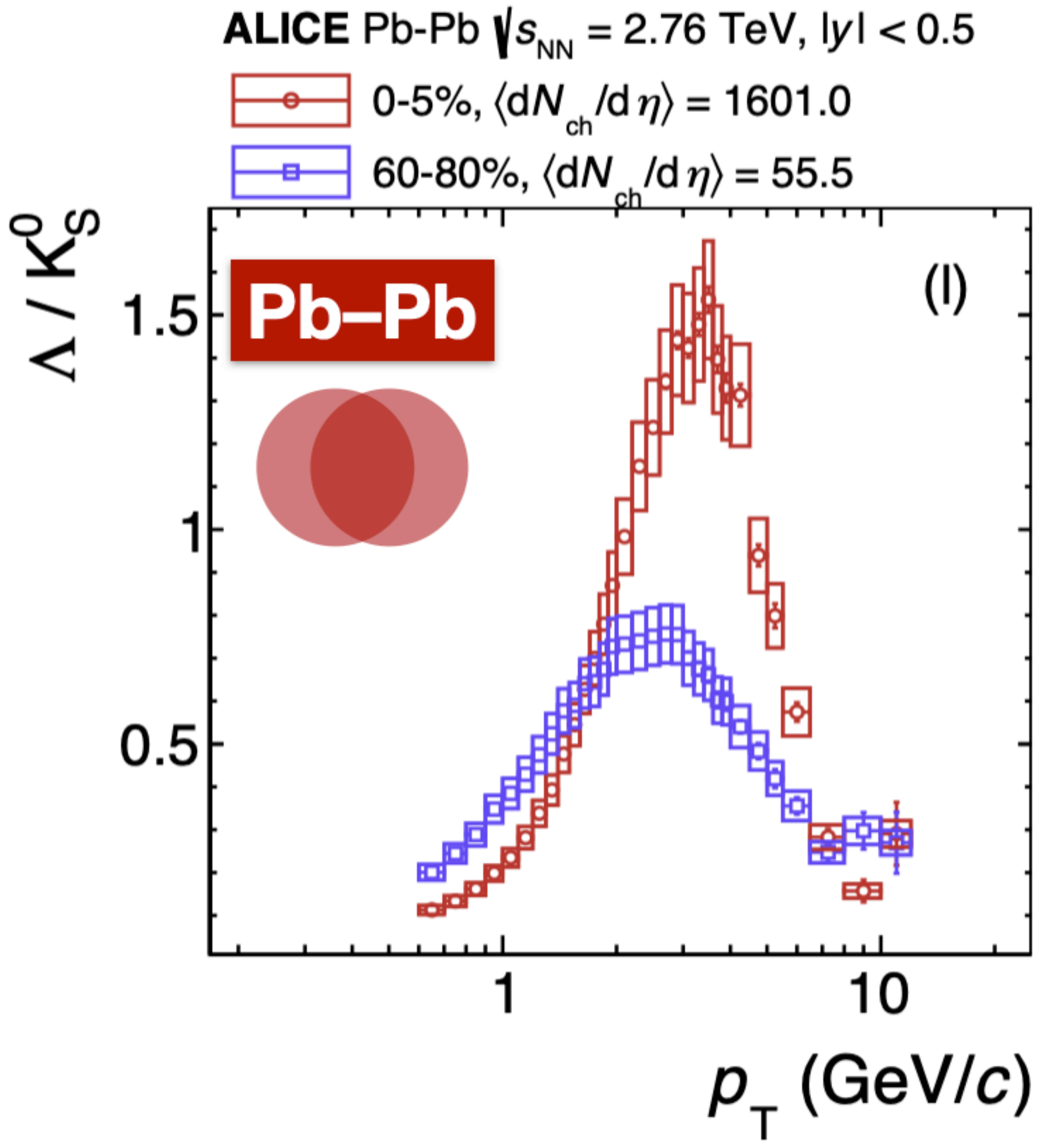
Catania *Phys. Lett.* **B805** (2020) 135460
POWLANG-HTL *JHEP* **1802** (2018) 043

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

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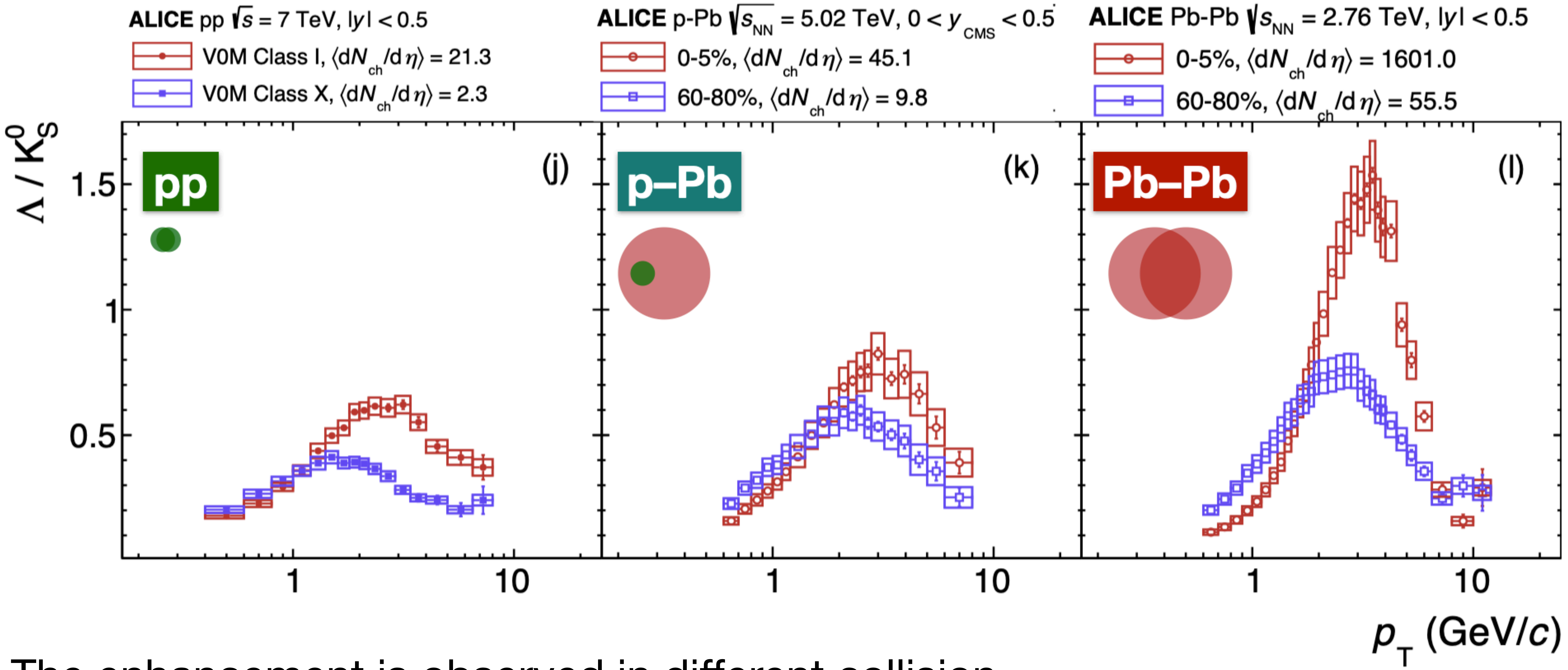
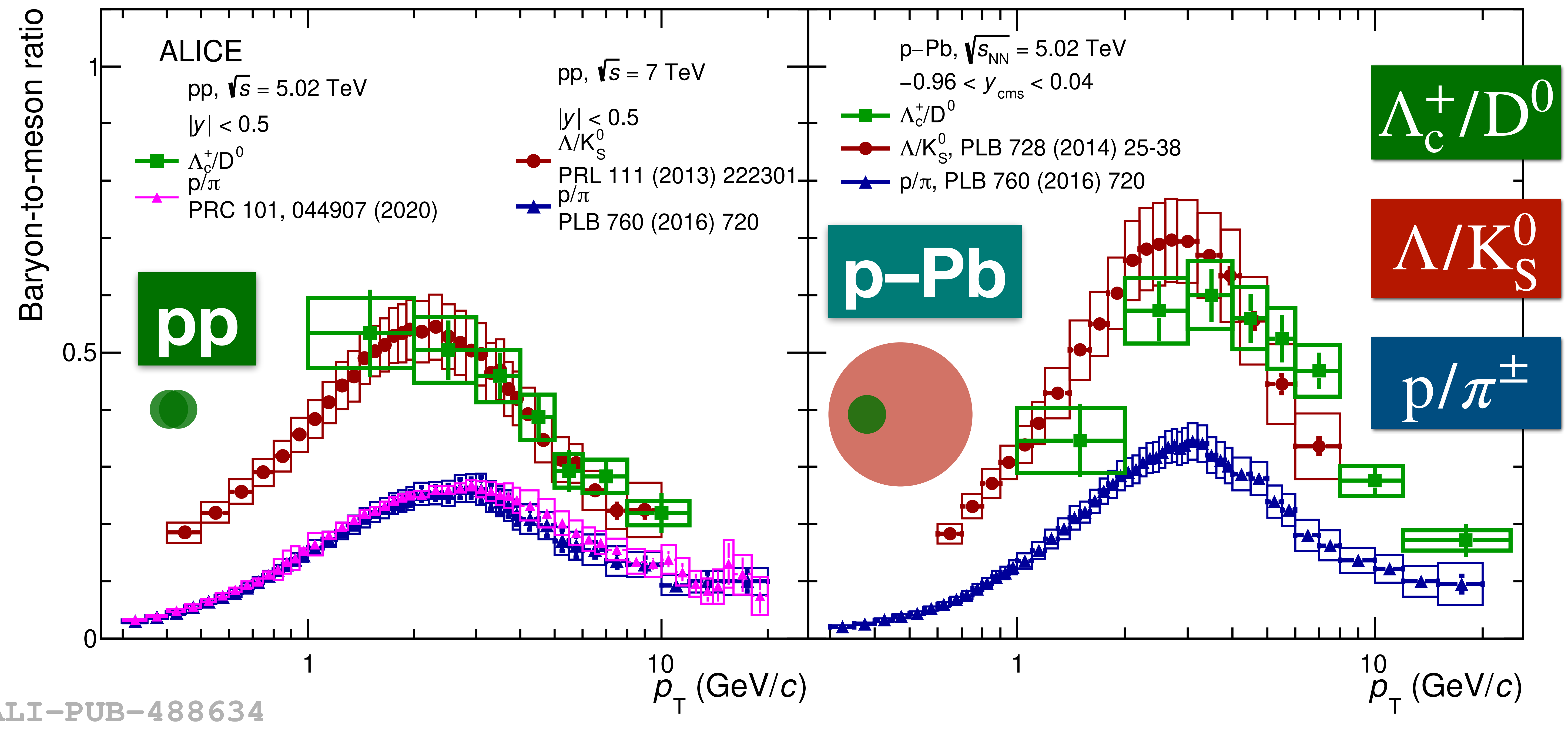


The enhancement is observed in different collision systems (Pb–Pb, p–Pb and pp) at high multiplicities

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

Baryon-to-meson enhancement



ALICE *Phys. Rev.* C104 (2021) 054905
Phys. Rev. Lett. 127 (2021) 202301

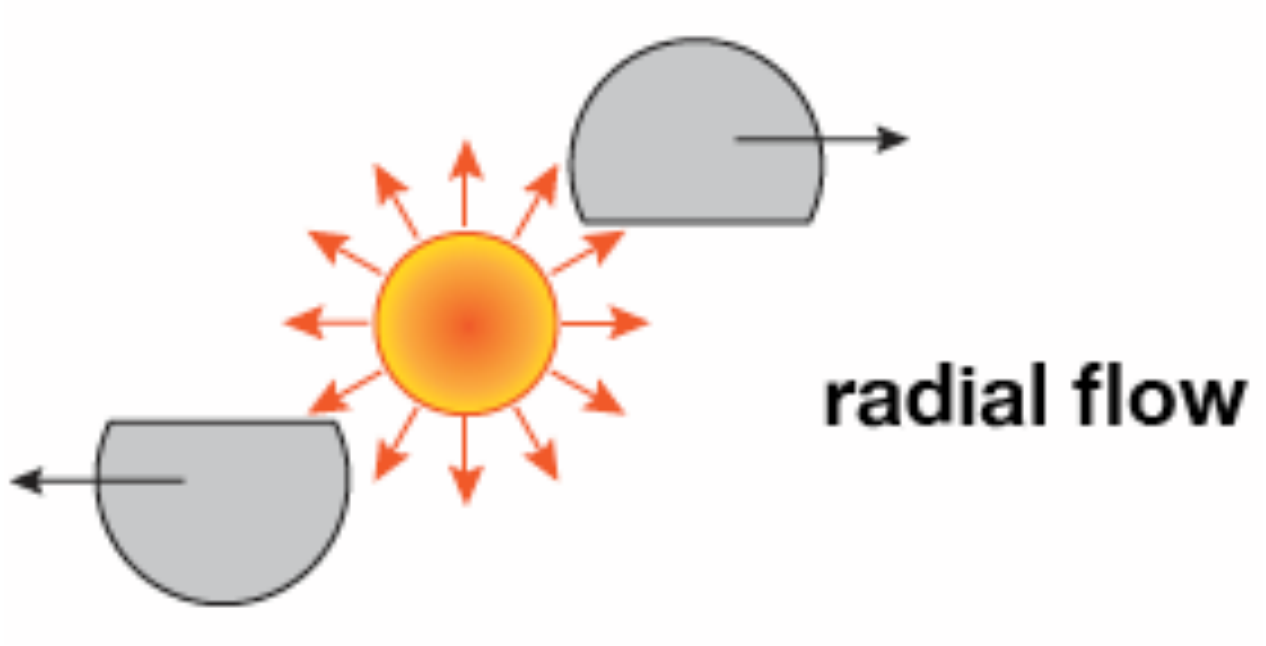
To provide constraints on particle production mechanisms in all collision systems, it is important to separate particles from hard and soft processes

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

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

Radial flow

Collective expansion

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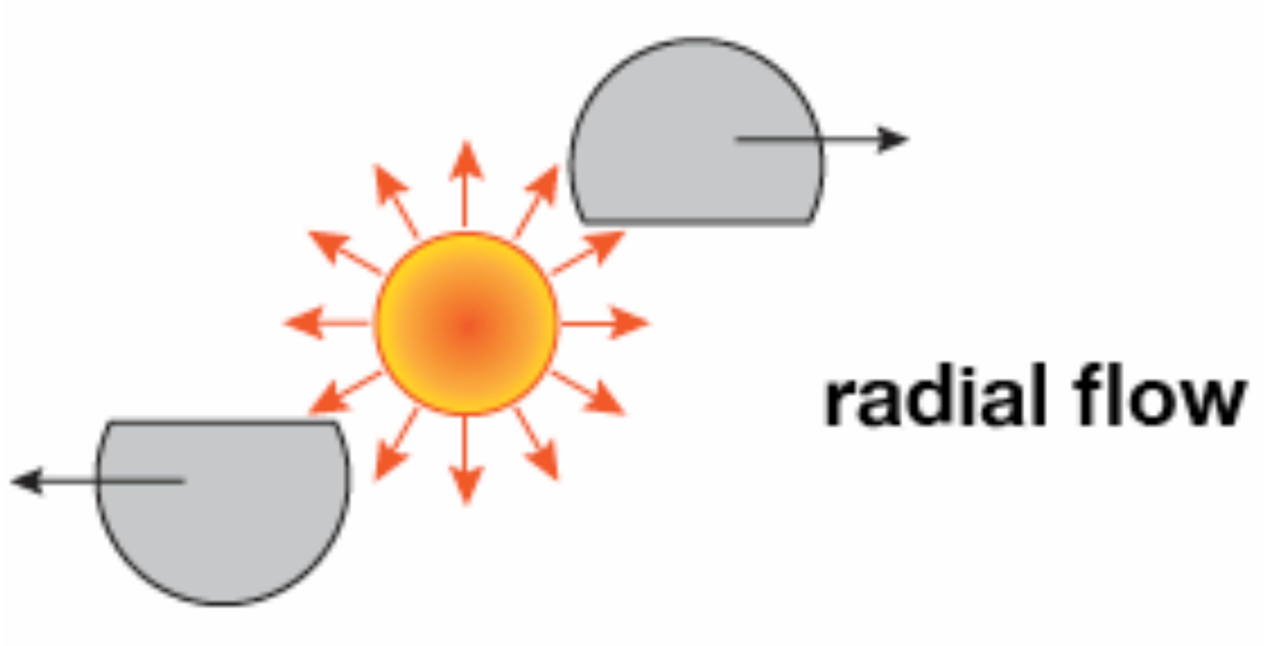

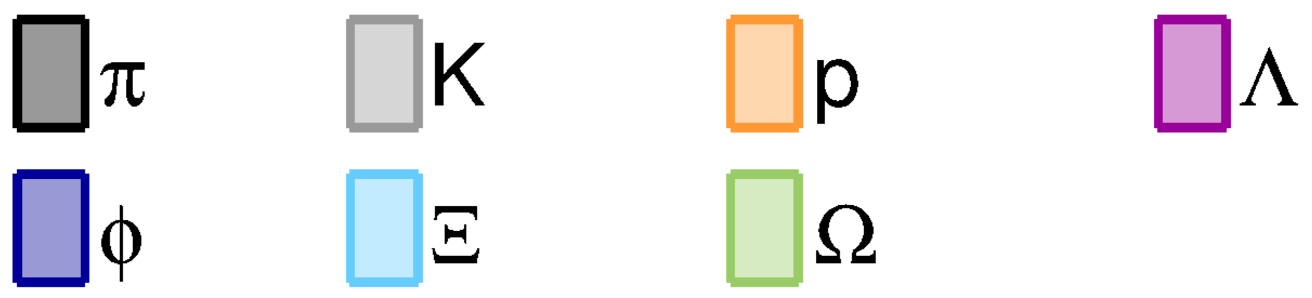

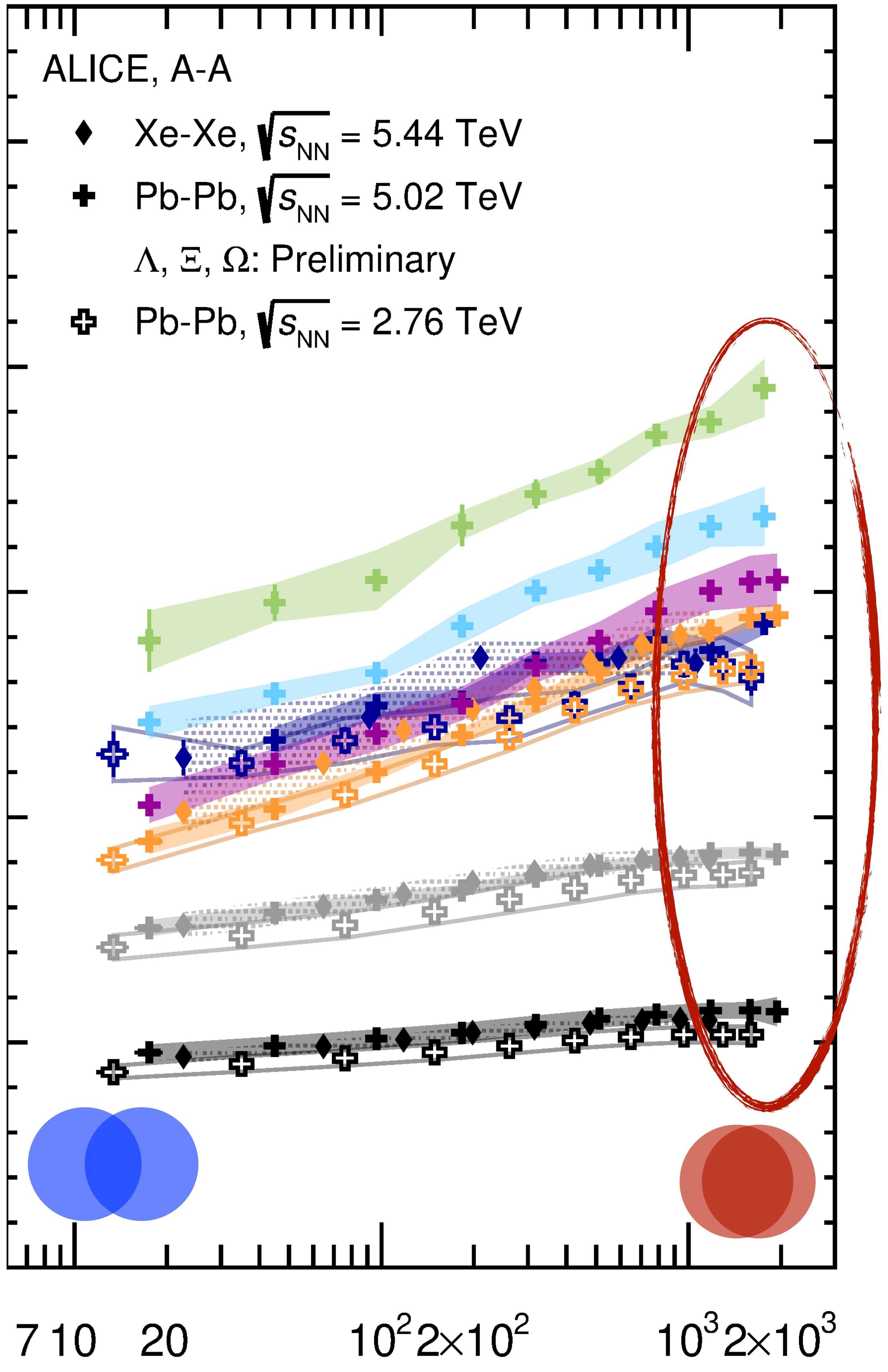

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Mean p_T of strange particles

Collective expansion

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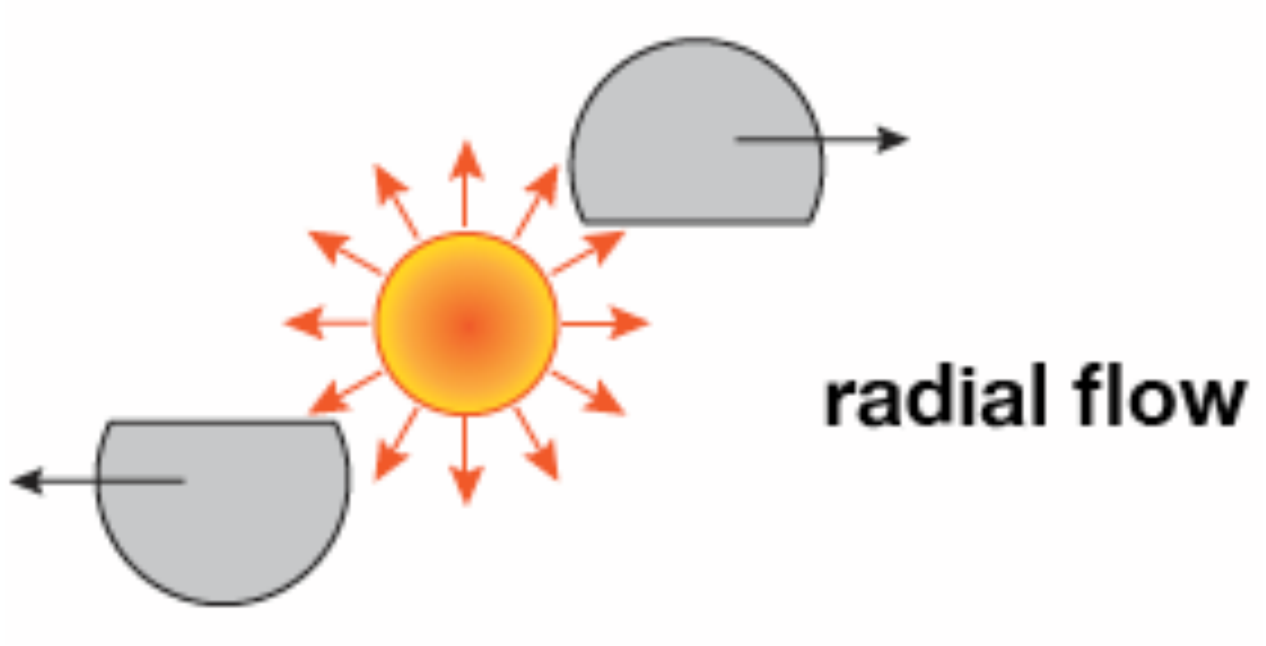

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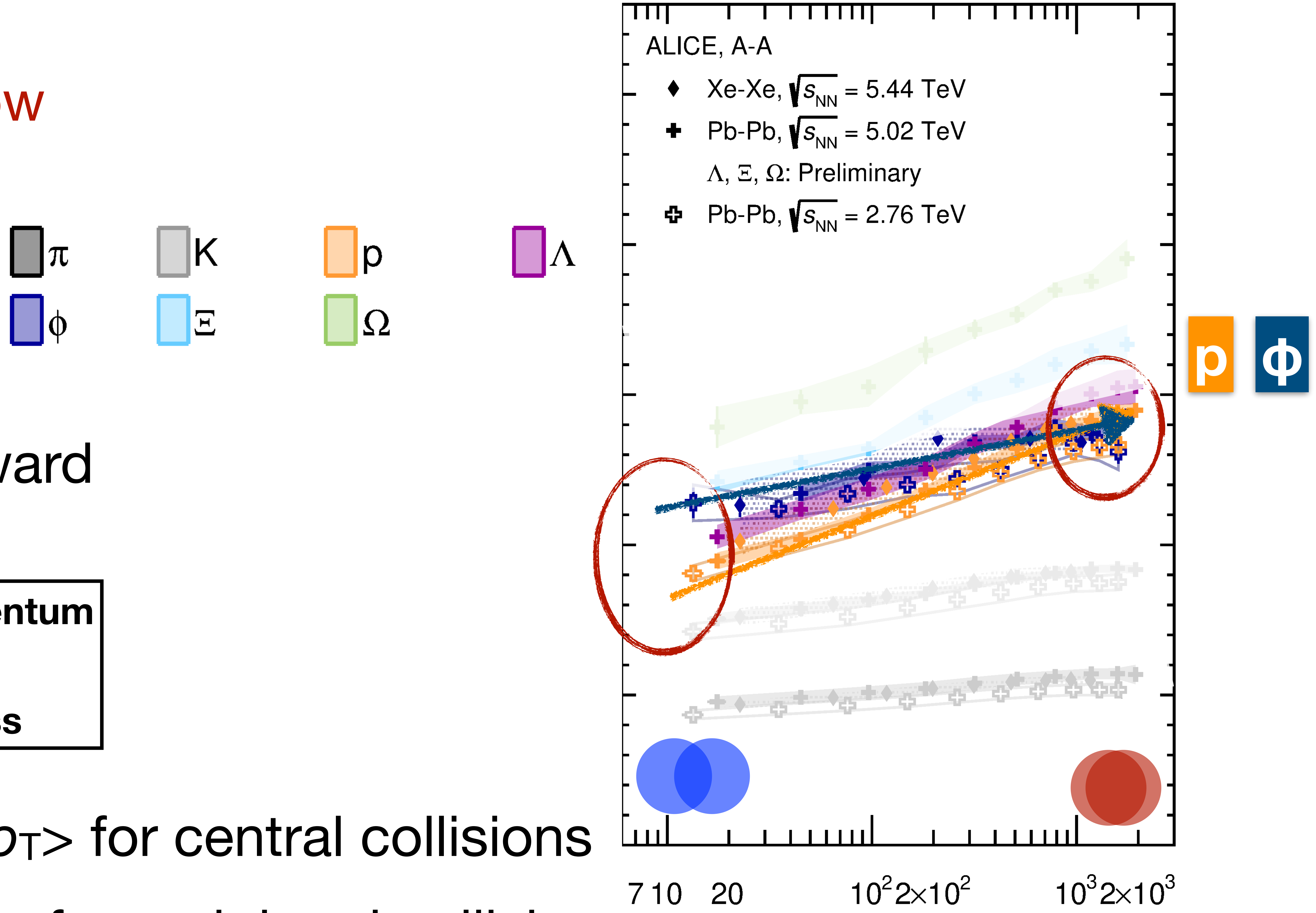
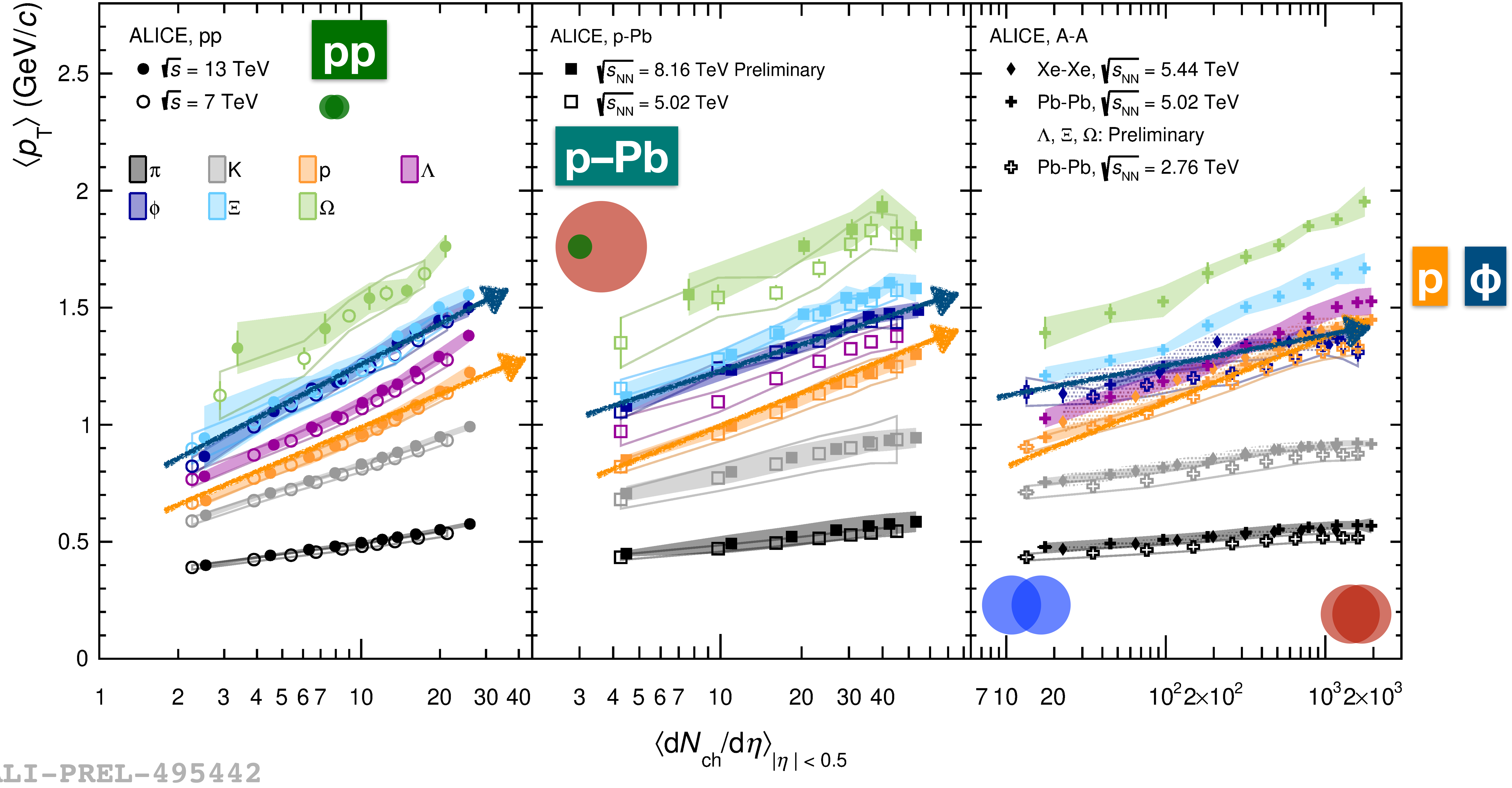


- Similar mass has similar <p_T> for central collisions
- Mass ordering breaks down for peripheral collisions

Mean p_T of strange particles



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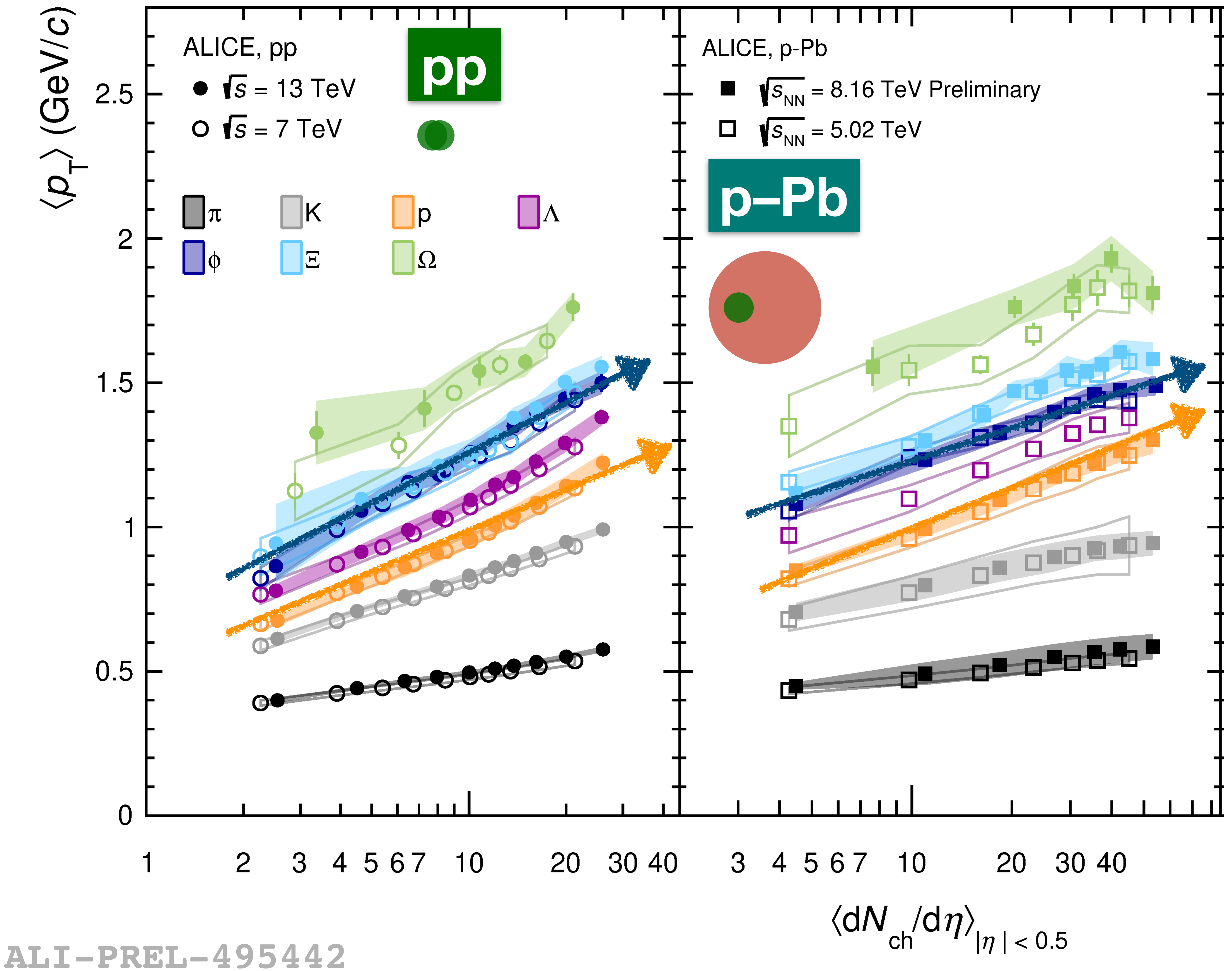
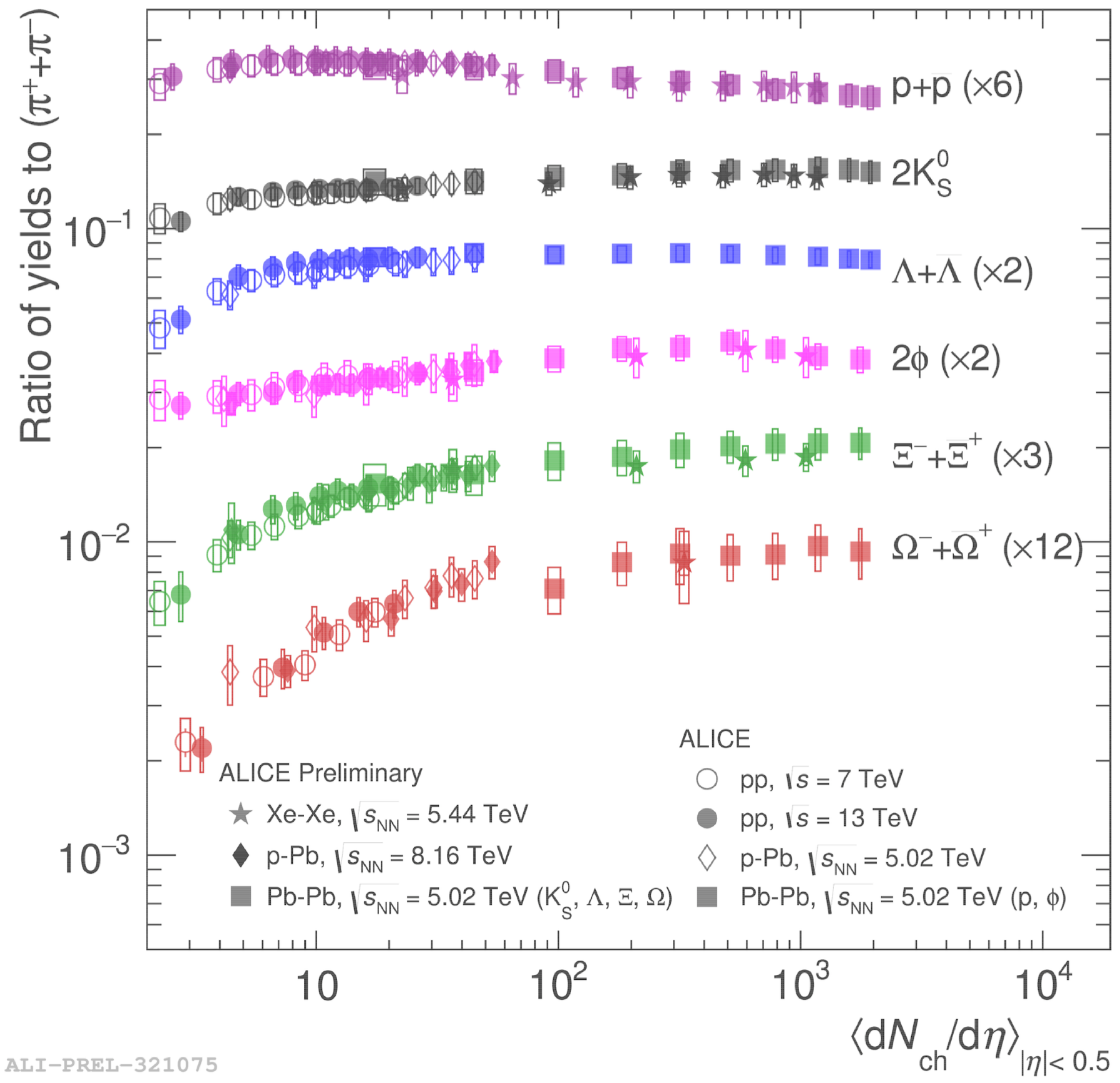


- Is hydro scenario validated in small systems (?)
- Are strange particles mainly produced in hard processes or in underlying processes (?)
- Is the strangeness production also correlated to the initial stage of the collisions (?)

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

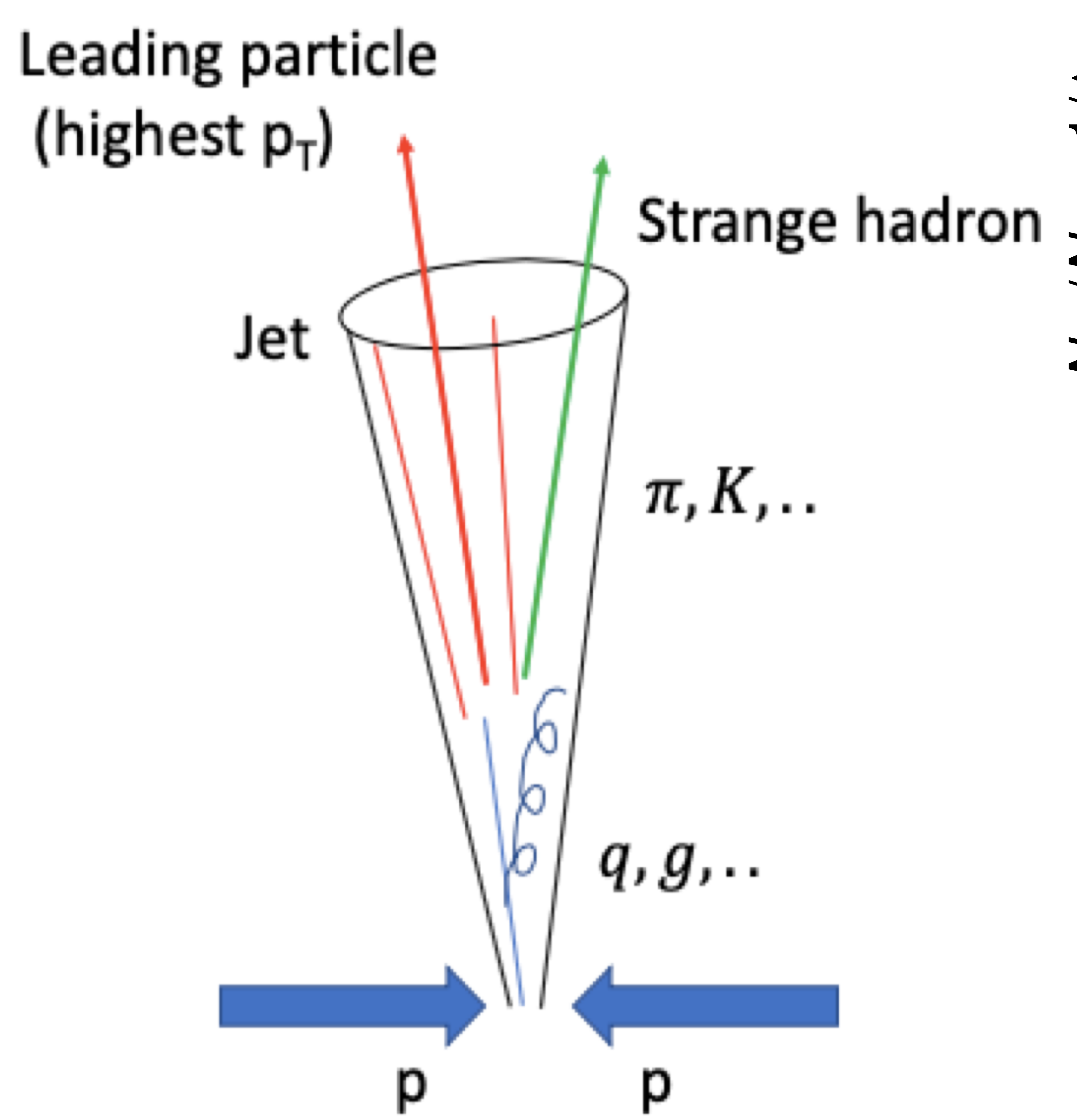
➡ Enhancement is stronger with larger strangeness content ($\Omega^{\pm} > \Xi^{\pm} > \Lambda$)

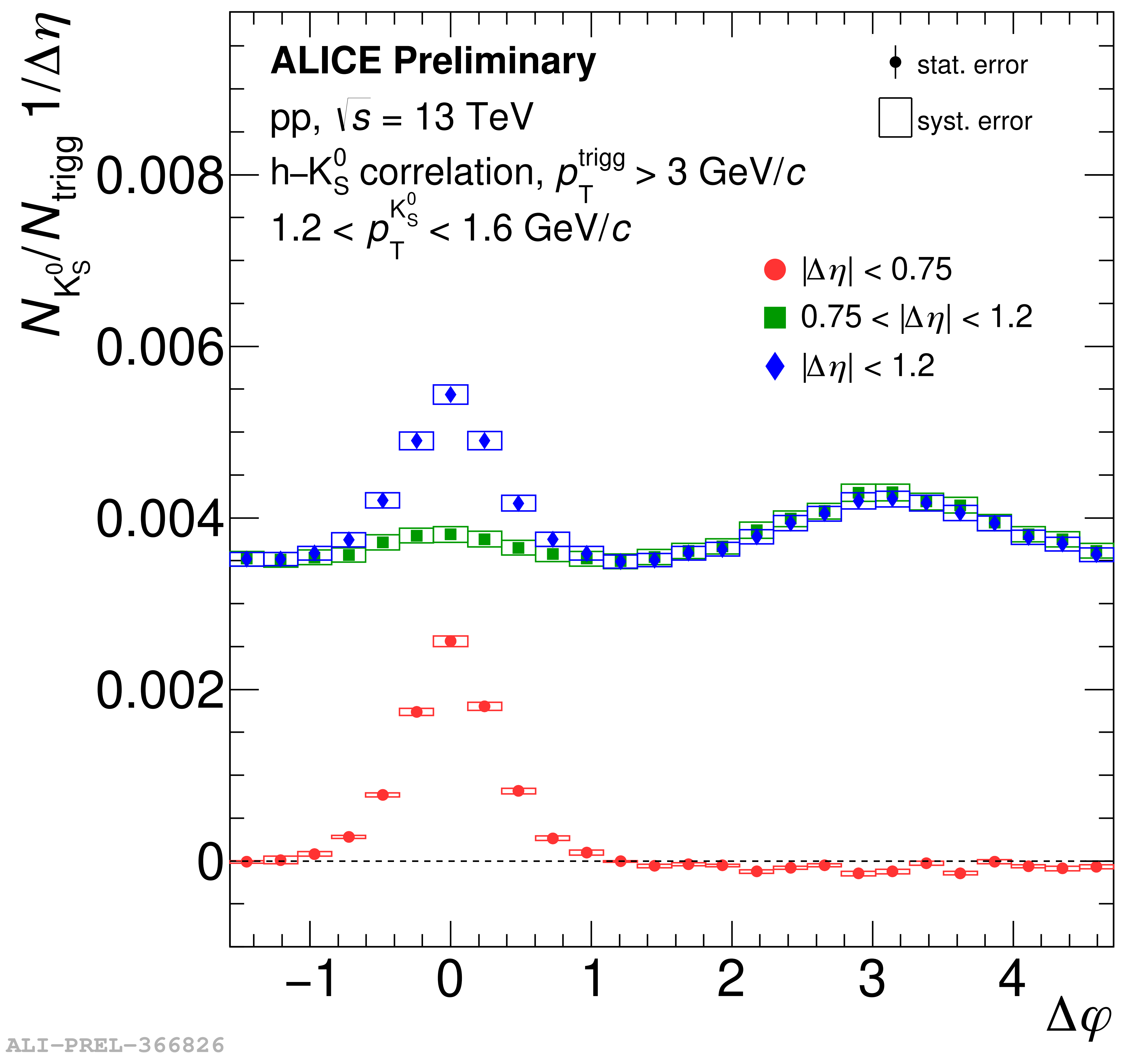
Possible explanation

- 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

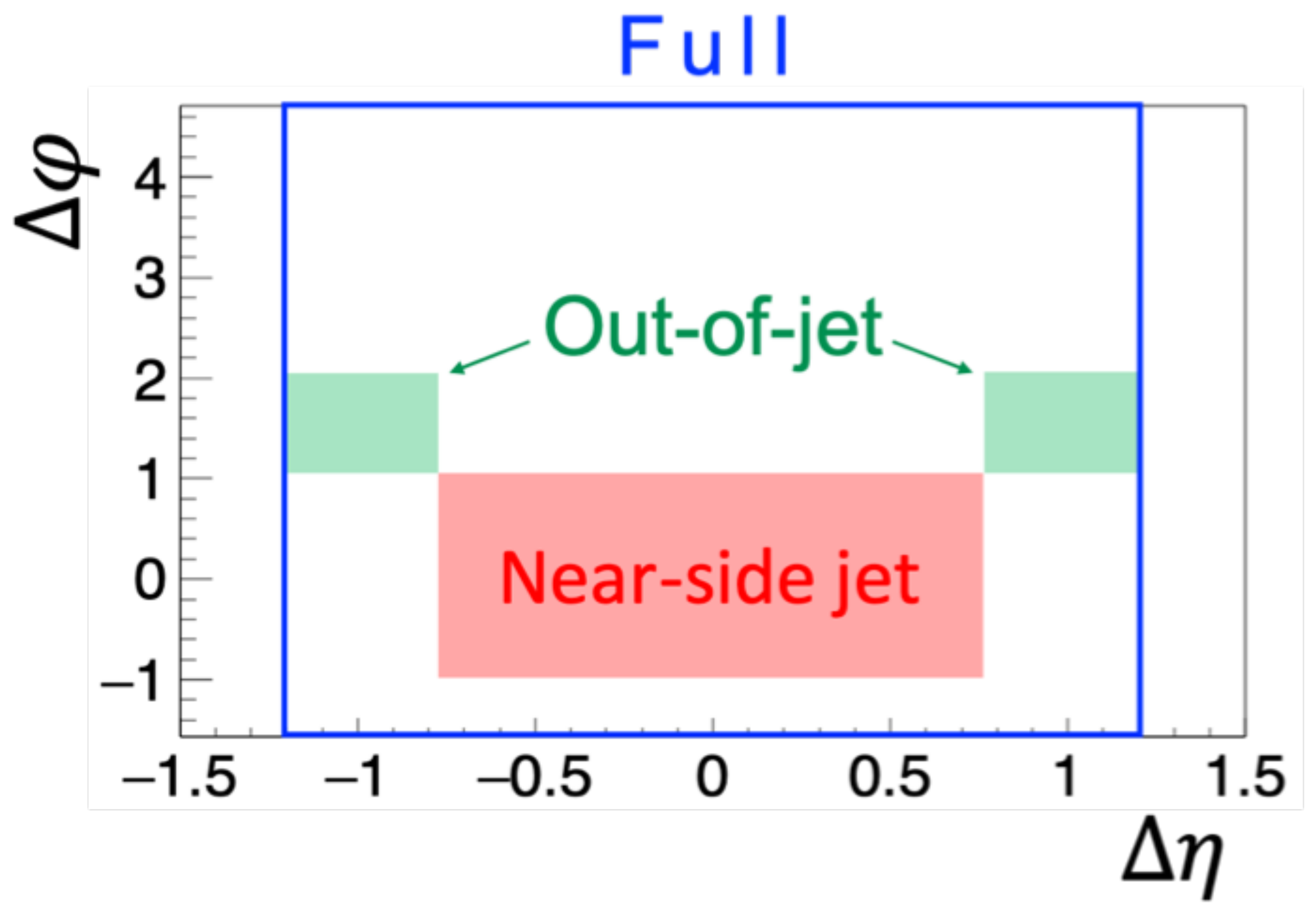
Two-particle angular correlations

- Explore the multiplicity dependence in pp collisions

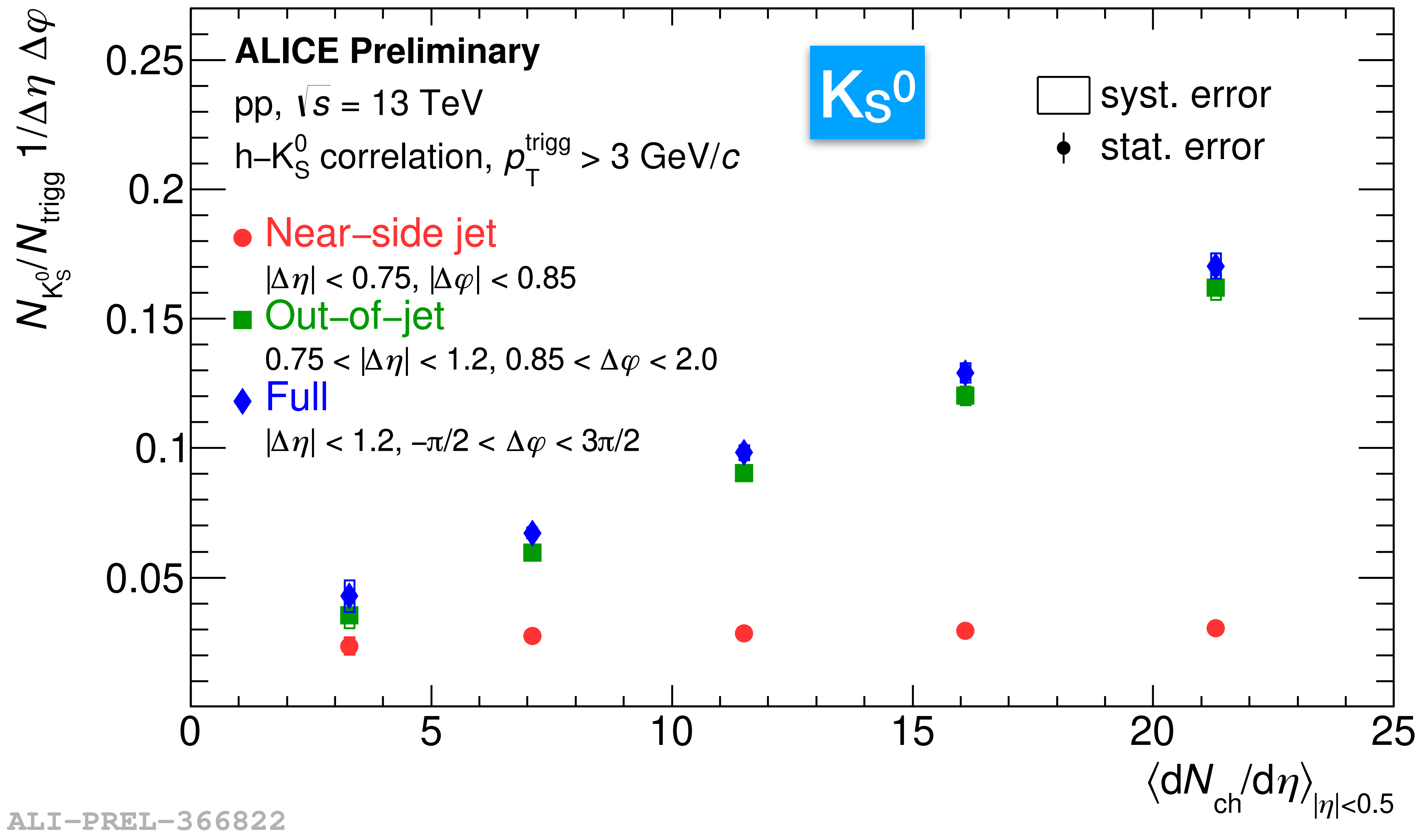


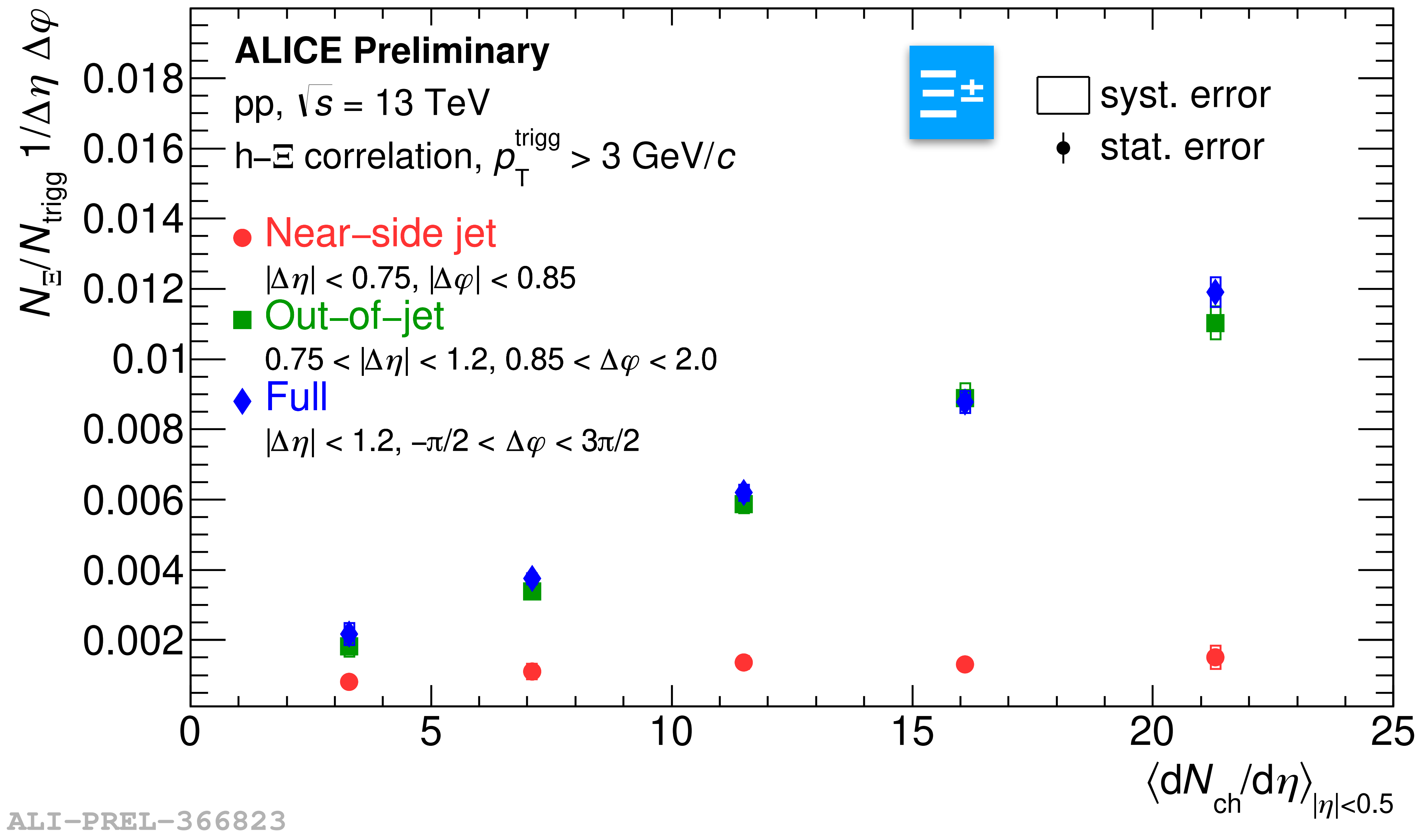


Focus on $\Xi^{\pm}$ in events selected by hard scatterings ($p_{T,trigger}$ > 3 GeV/c)



Multiplicity dependence

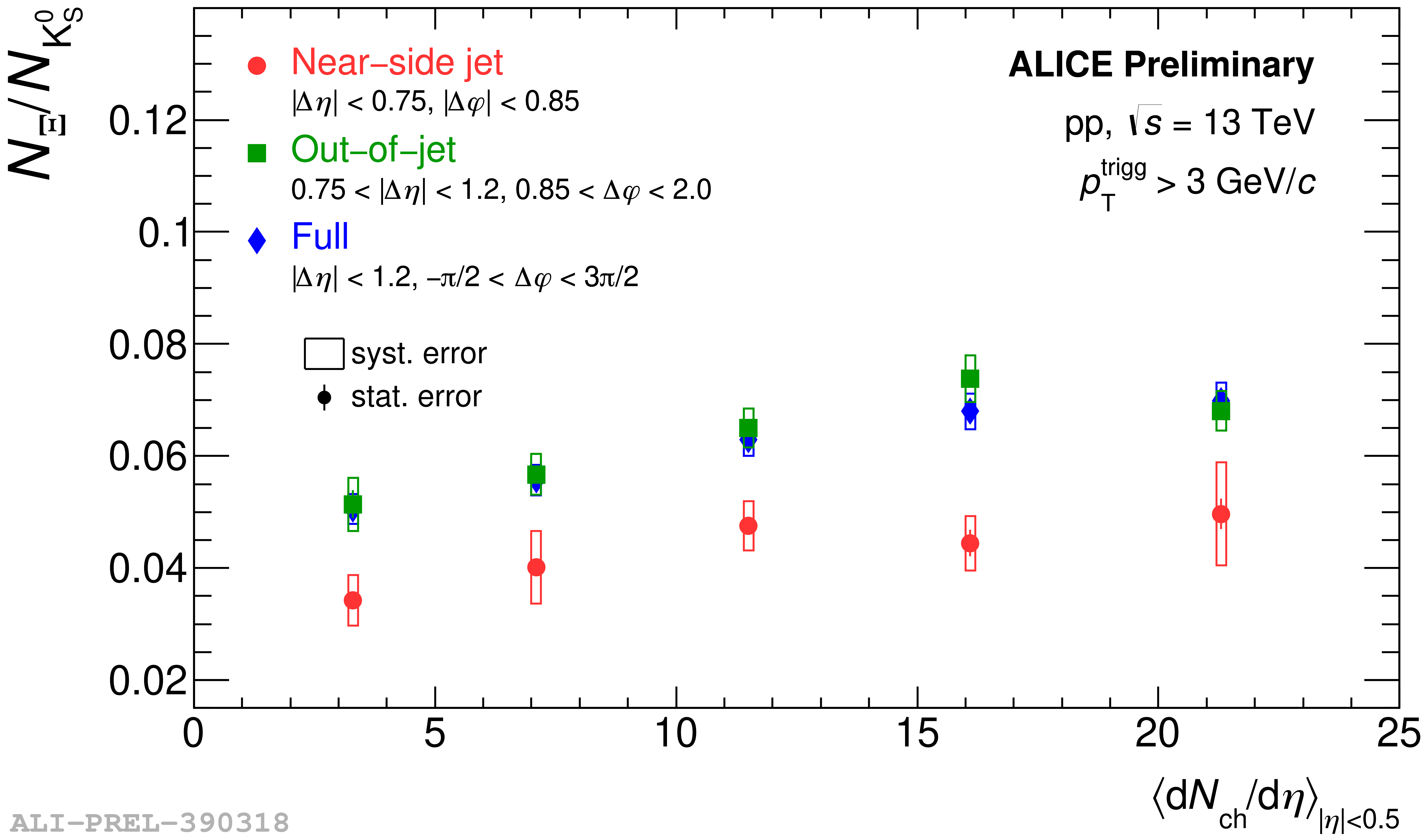




- Both the full yield and the out-of-jet yield increase with the multiplicity
- Near side jet yield has mild to no-evolution with multiplicity

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

Multiplicity dependence

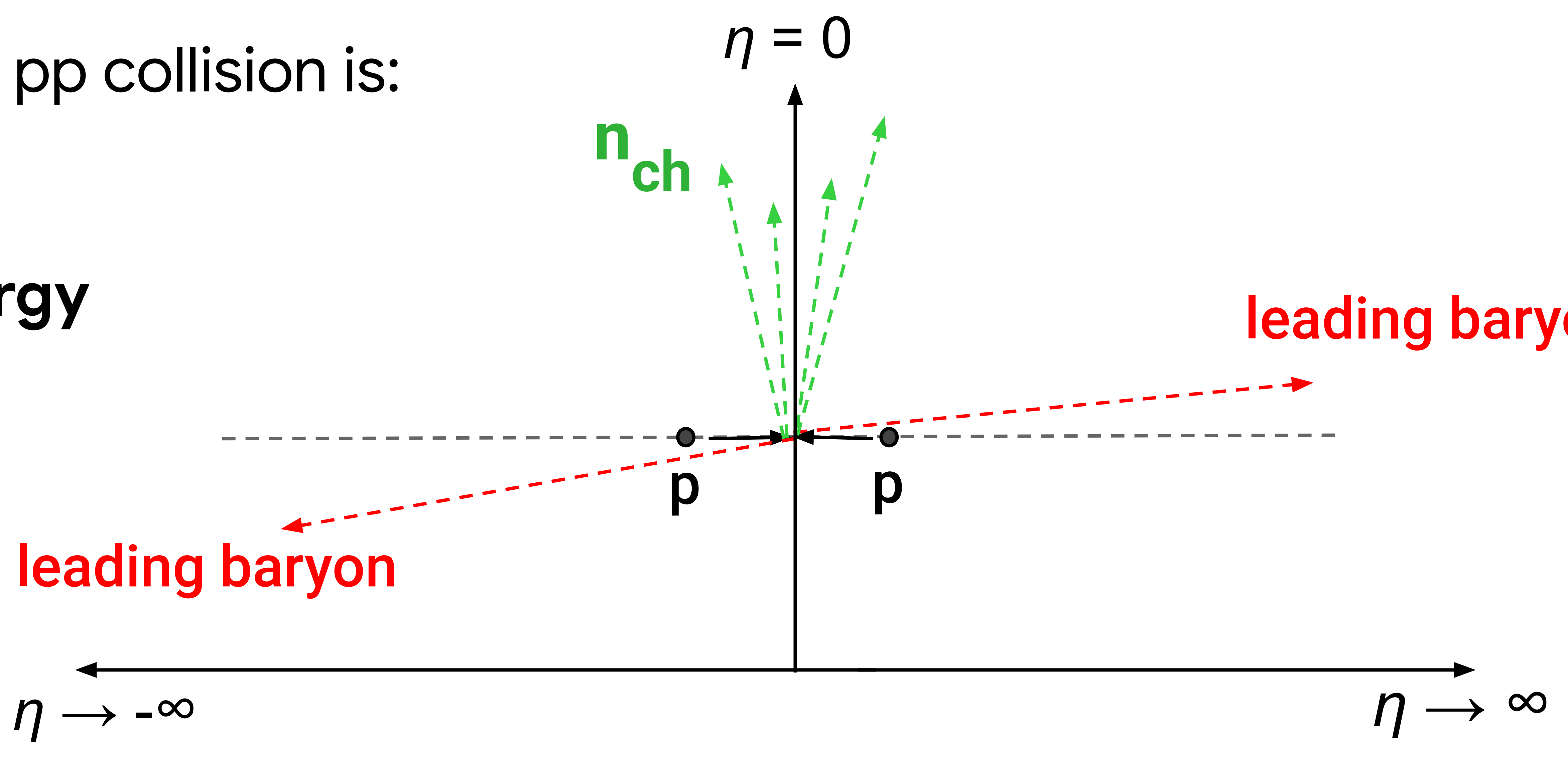


- Out-of-jet production is the dominant contribution to $\Xi^{\pm}/K_S^0$ full yield ratio enhancement in events with a hard scattering ($p_{T,trigger}$>3 GeV/c)

Concept of effective energy

The **charged-particle multiplicity** produced in a pp collision is:

- characteristic of the **hadronic final** state
- strongly correlated to the **initial effective energy**



EFFECTIVE ENERGY

energy available for particle production in the **initial stages** of the pp collision

$E_{\mathrm{EFF}} < \sqrt{s}$ due to **leading baryon emission** at forward rapidity

A. Akindinov et al., Eur. Phys. J. C 50, 341-352 (2007)

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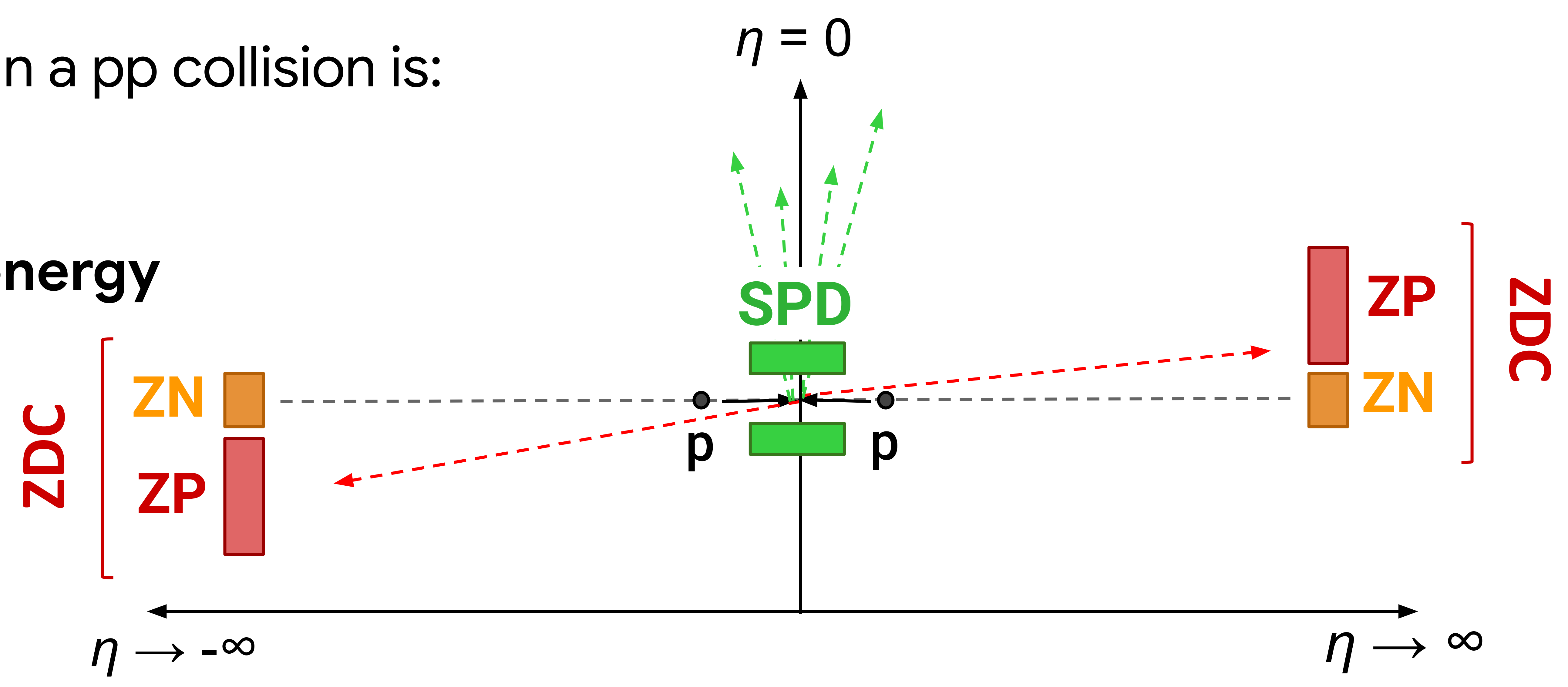

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ALICE can measure:

- midrapidity multiplicity (**SPD**)
- leading energy (**ZDC**)

$$E_{\rm eff} = \sqrt{s} - E_{\rm leading} \simeq \sqrt{s} - E_{\rm ZDC}$$

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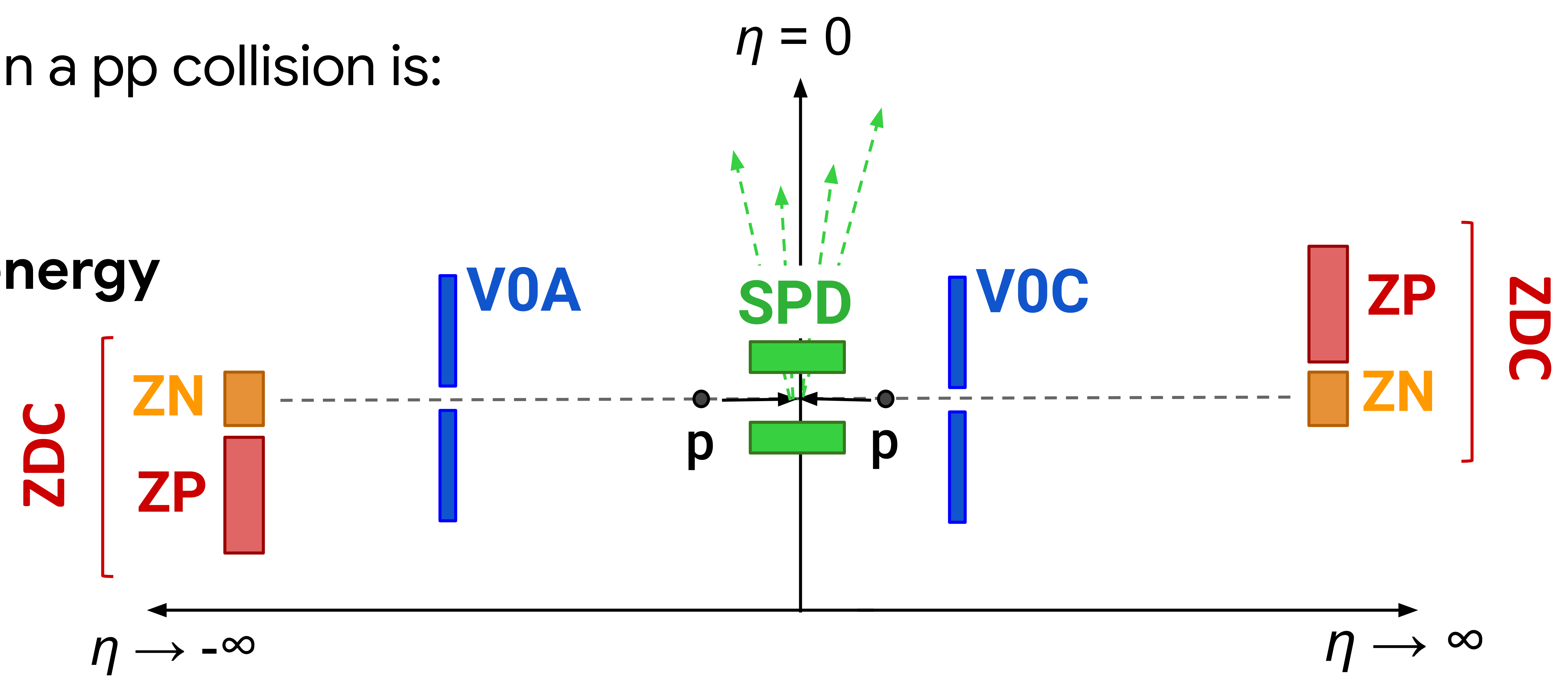

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- multiplicity (**V0M** = V0A+V0C)

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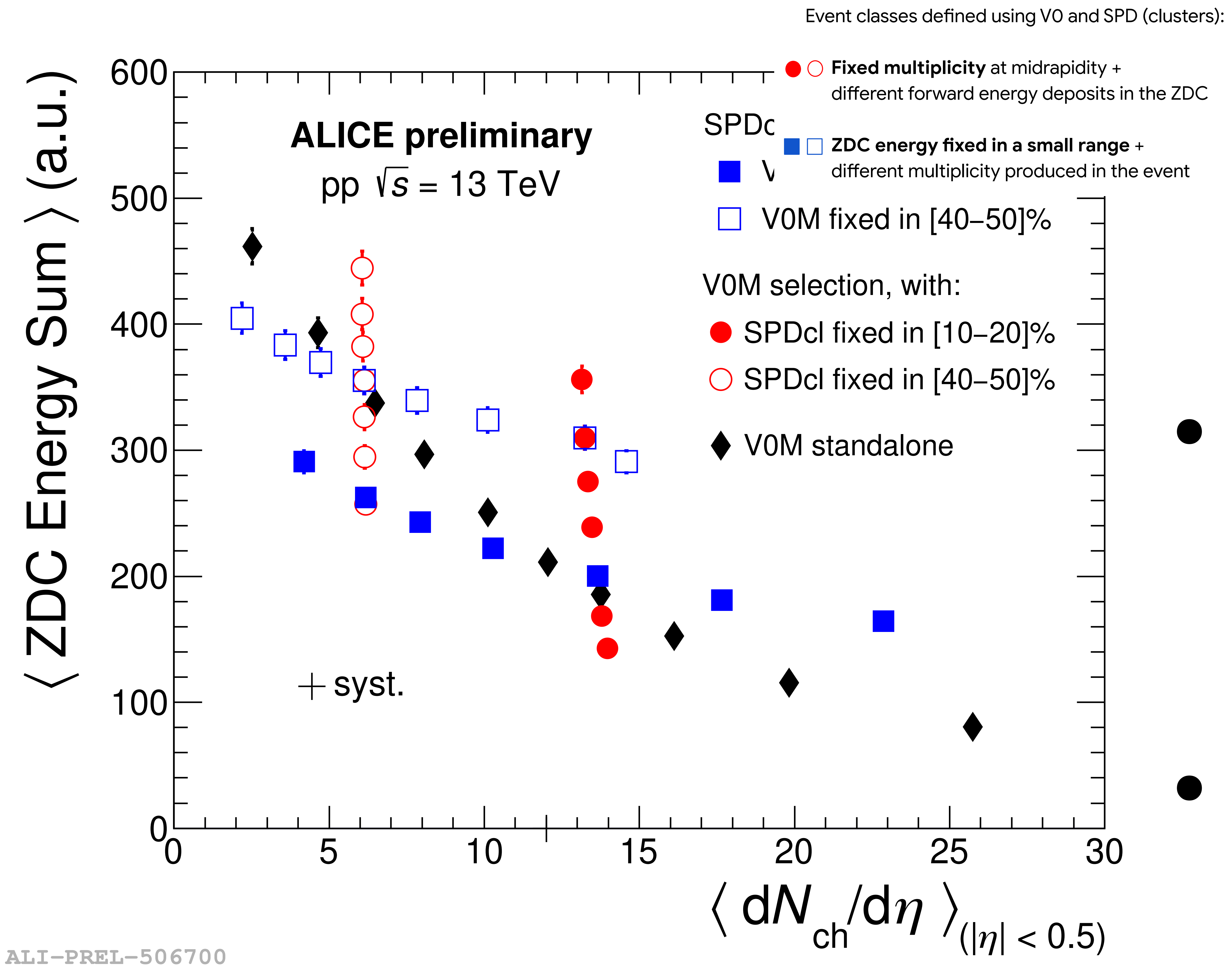
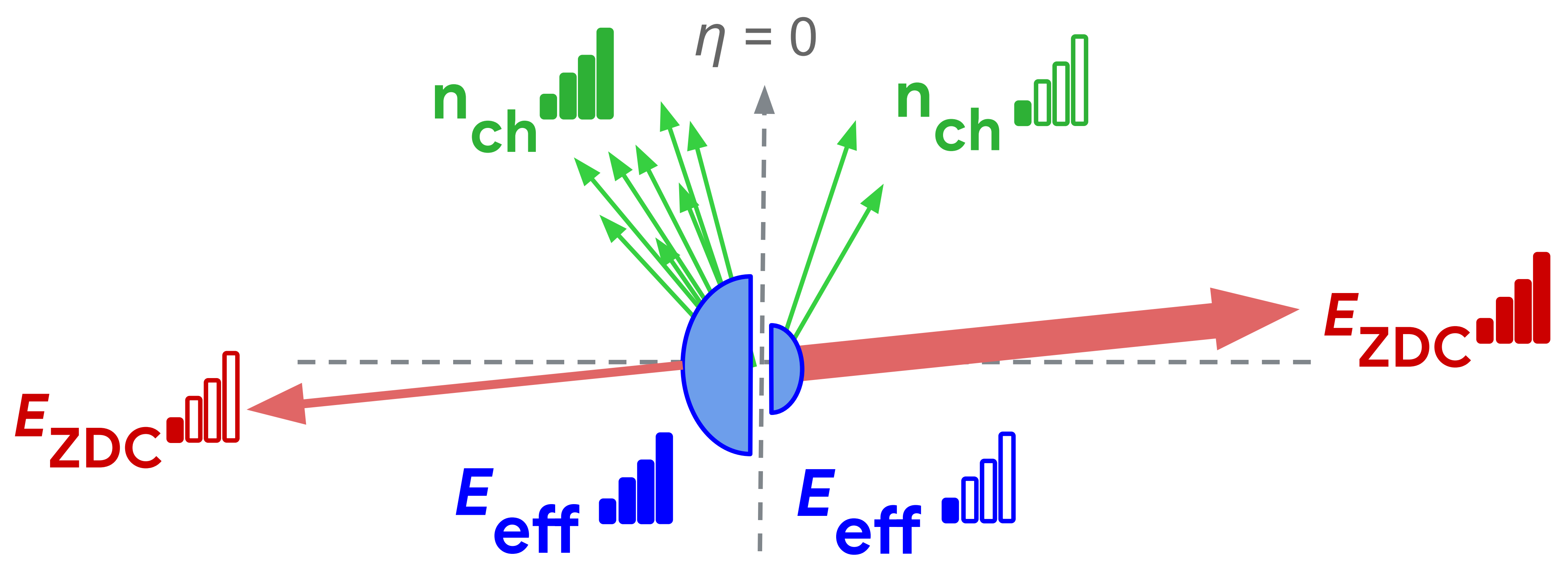
Multi-differential event classes



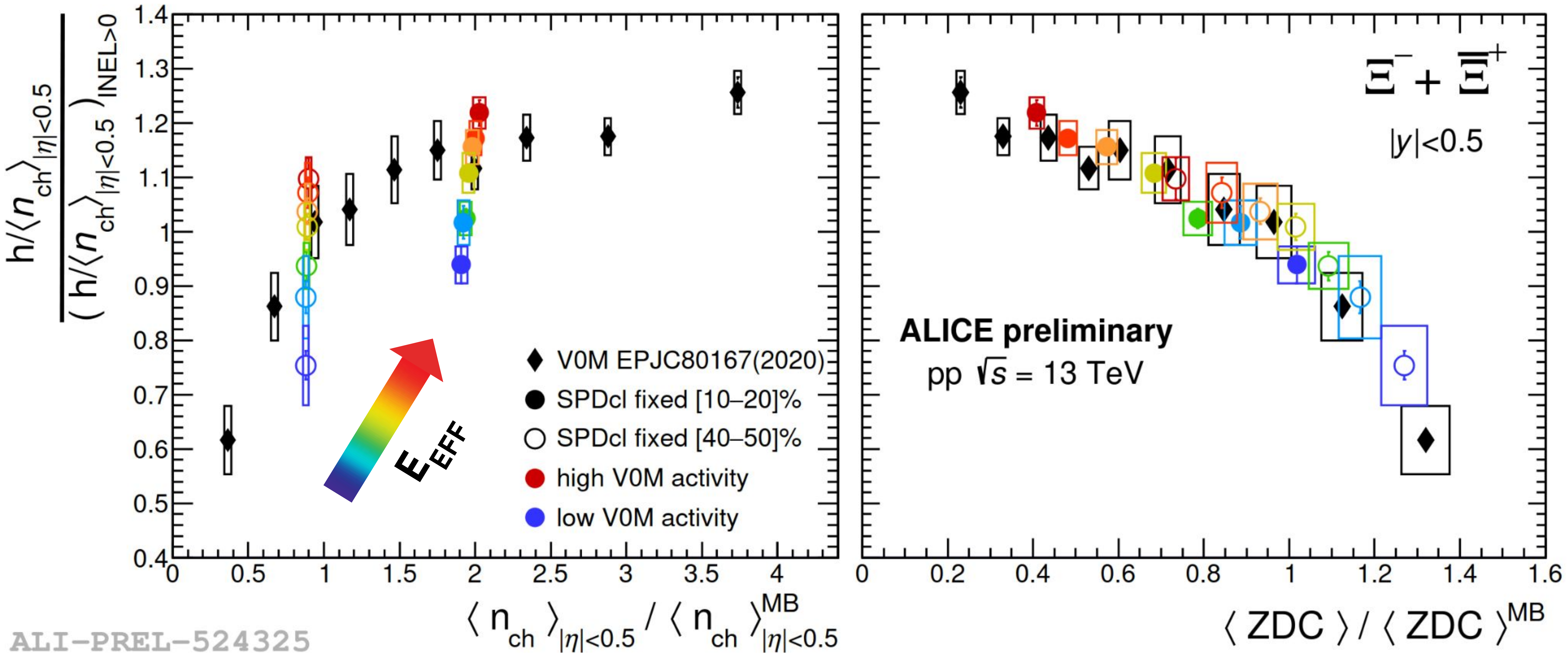


- Fixed midrapidity multiplicity class: effective energy (anti-)correlated with forward multiplicity
- Fixed forward multiplicity class: effective energy insensitive to midrapidity multiplicity

Fixed midrapdity multiplicity

In events with the same particle multiplicity produced:

- **increase** in Ξ production per charged particle is observed for **decreasing forward energy** (ZDC)
- scaling trends with ZDC energy are **compatible within uncertainties**



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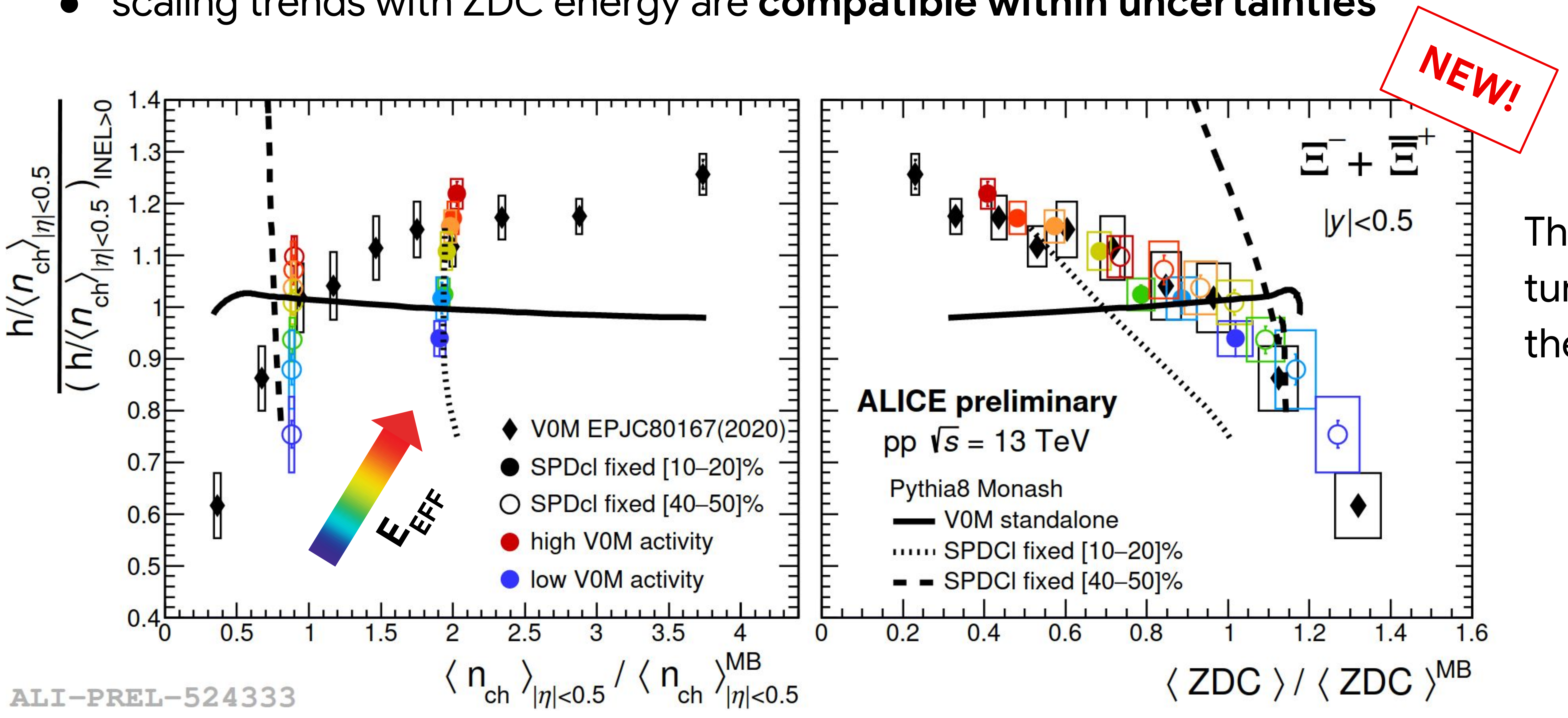

The **Pythia Monash 2013** tune **fails to reproduce** the results

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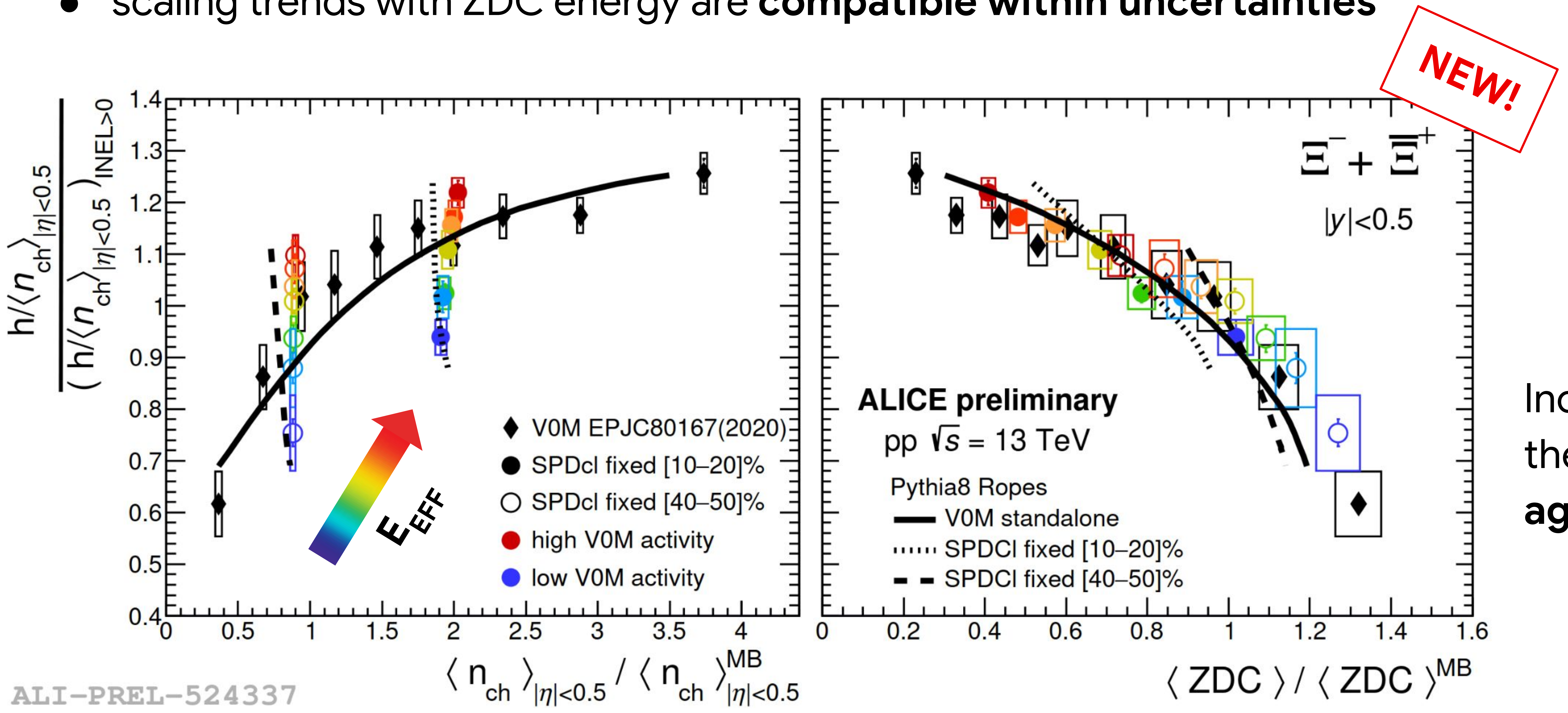
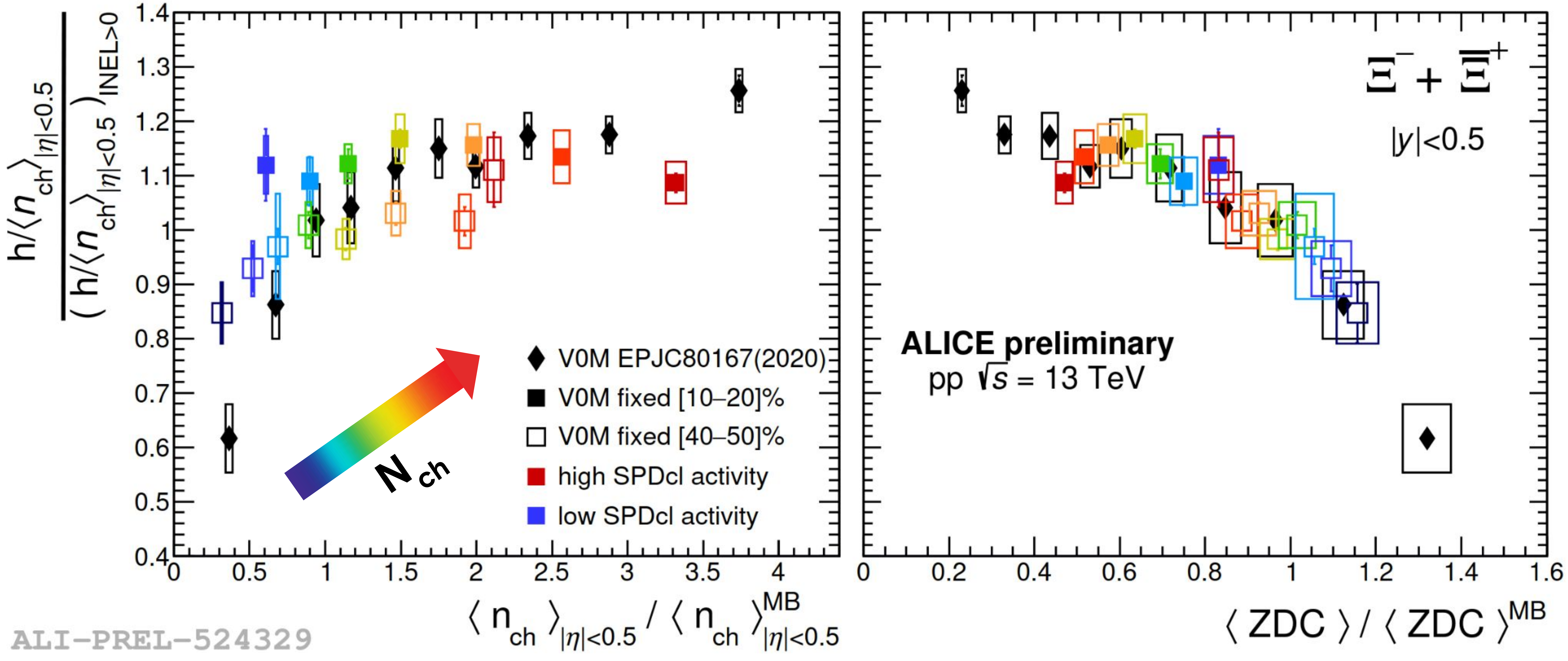


Including **Color Ropes** in the model **improves the agreement** with data

Fixed forward rapidity multiplicity

In events with ZDC energy deposits fixed in a small range:

- strangeness **enhancement with multiplicity is reduced** (left)
- within the small ZDC energy range, scaling **trends** are **compatible** within uncertainties (right)



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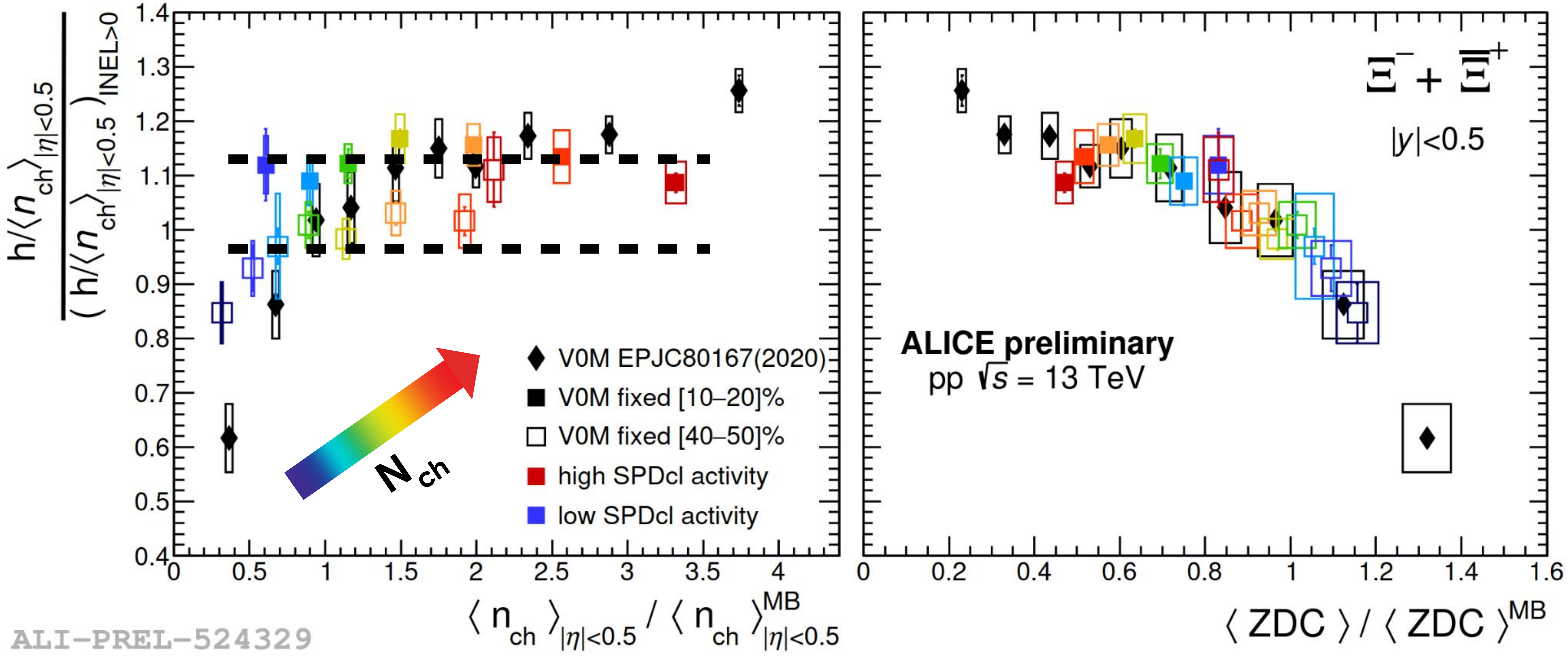

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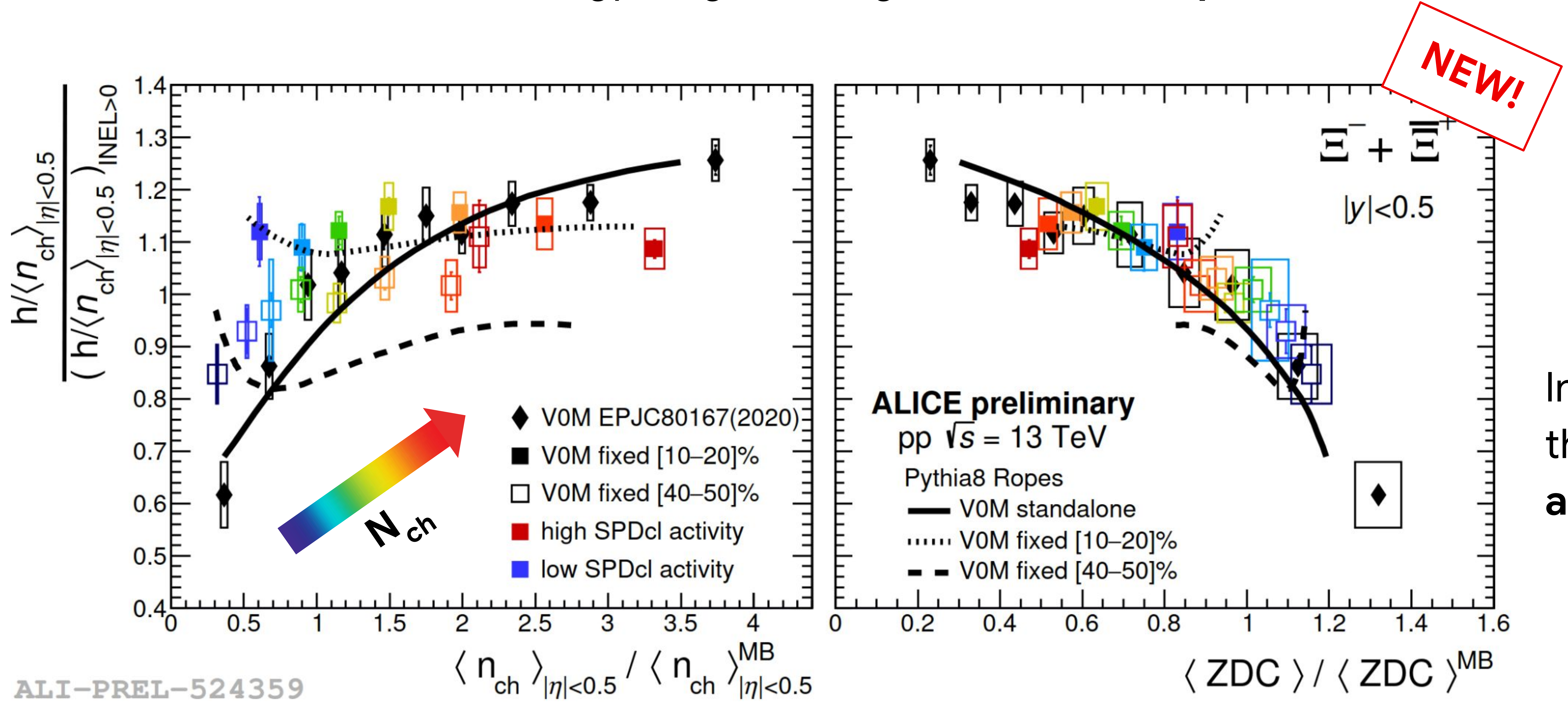

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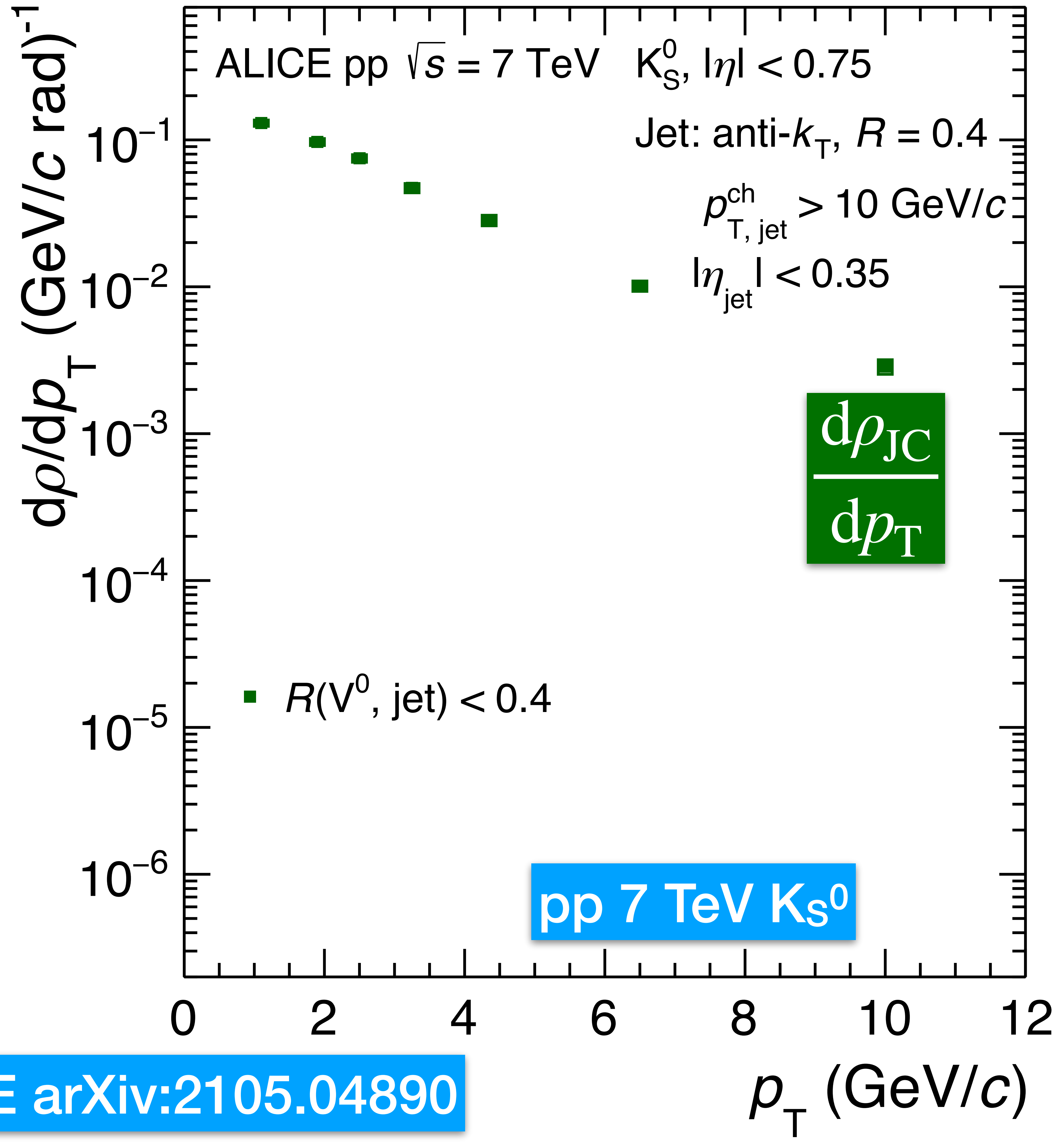
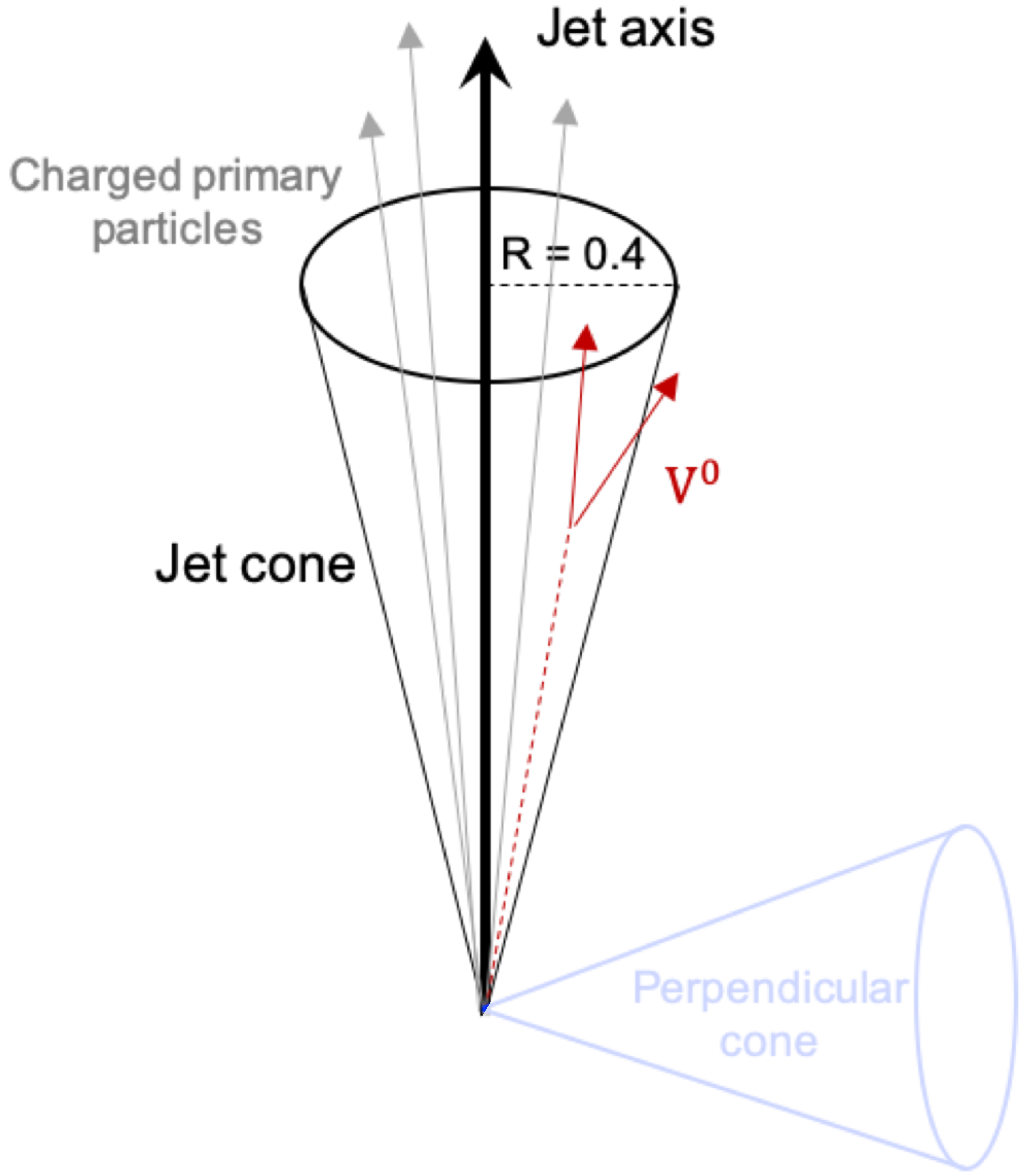
Strangeness in jets and UE

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





ALICE arXiv:2105.04890

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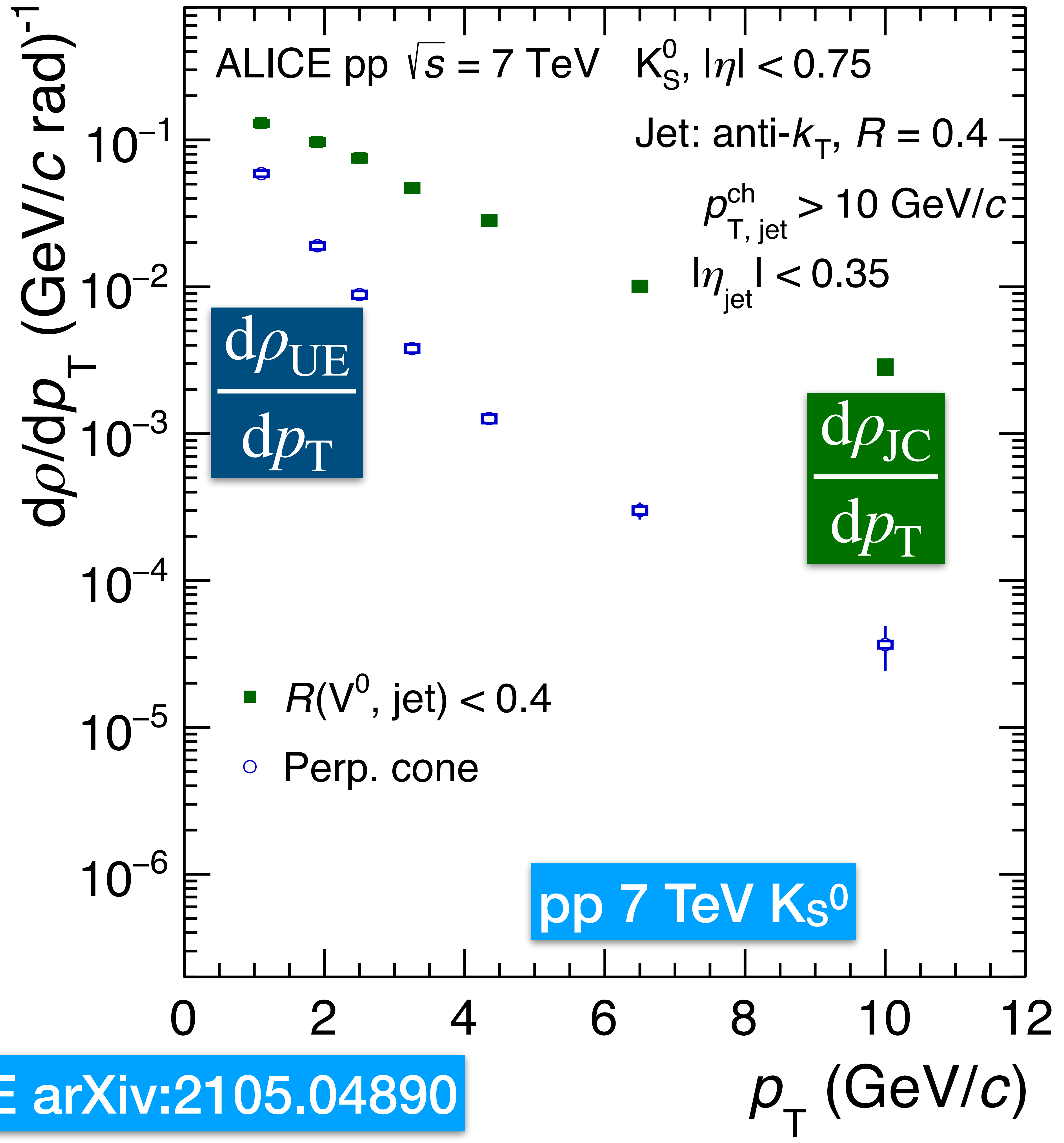

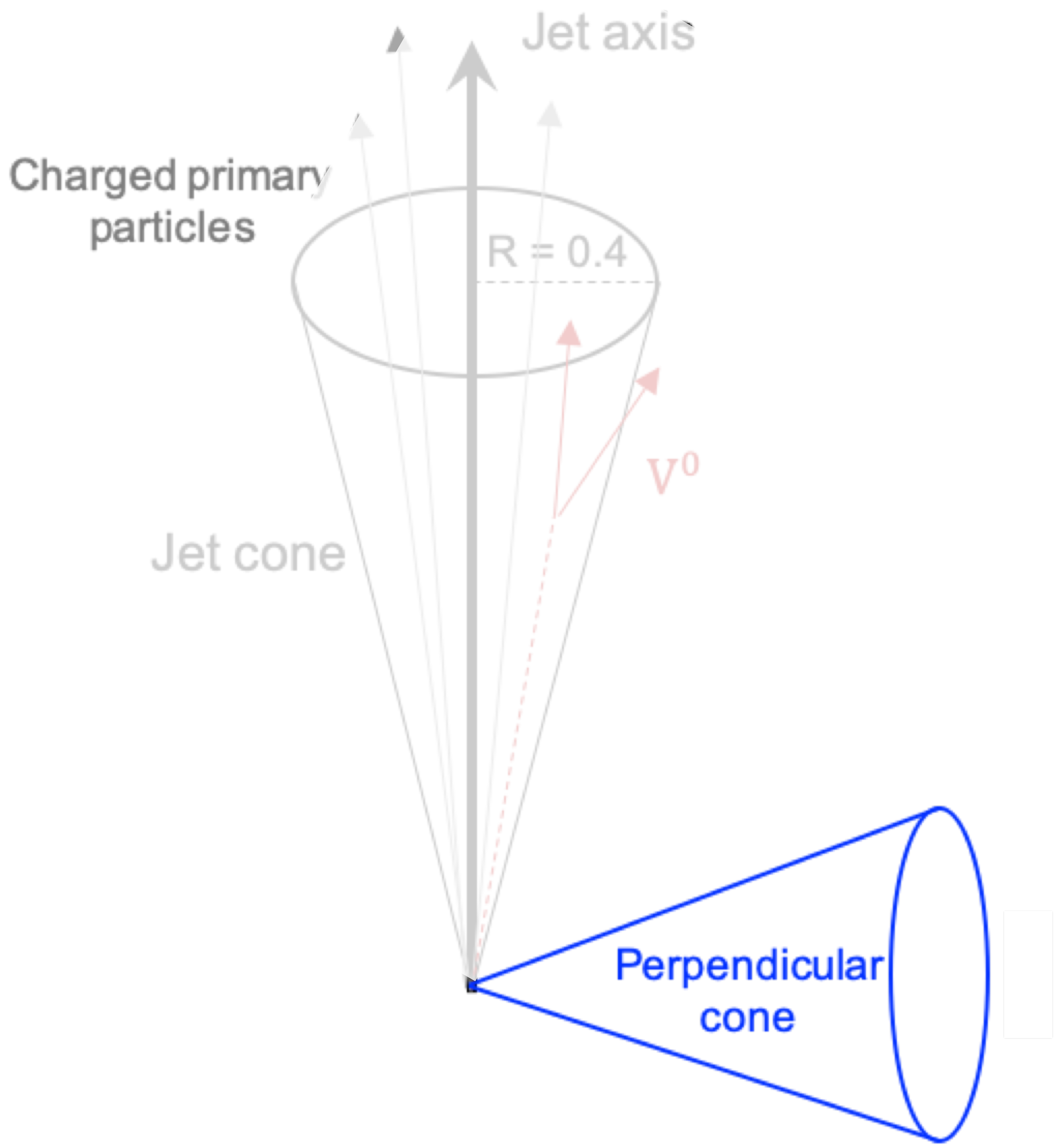

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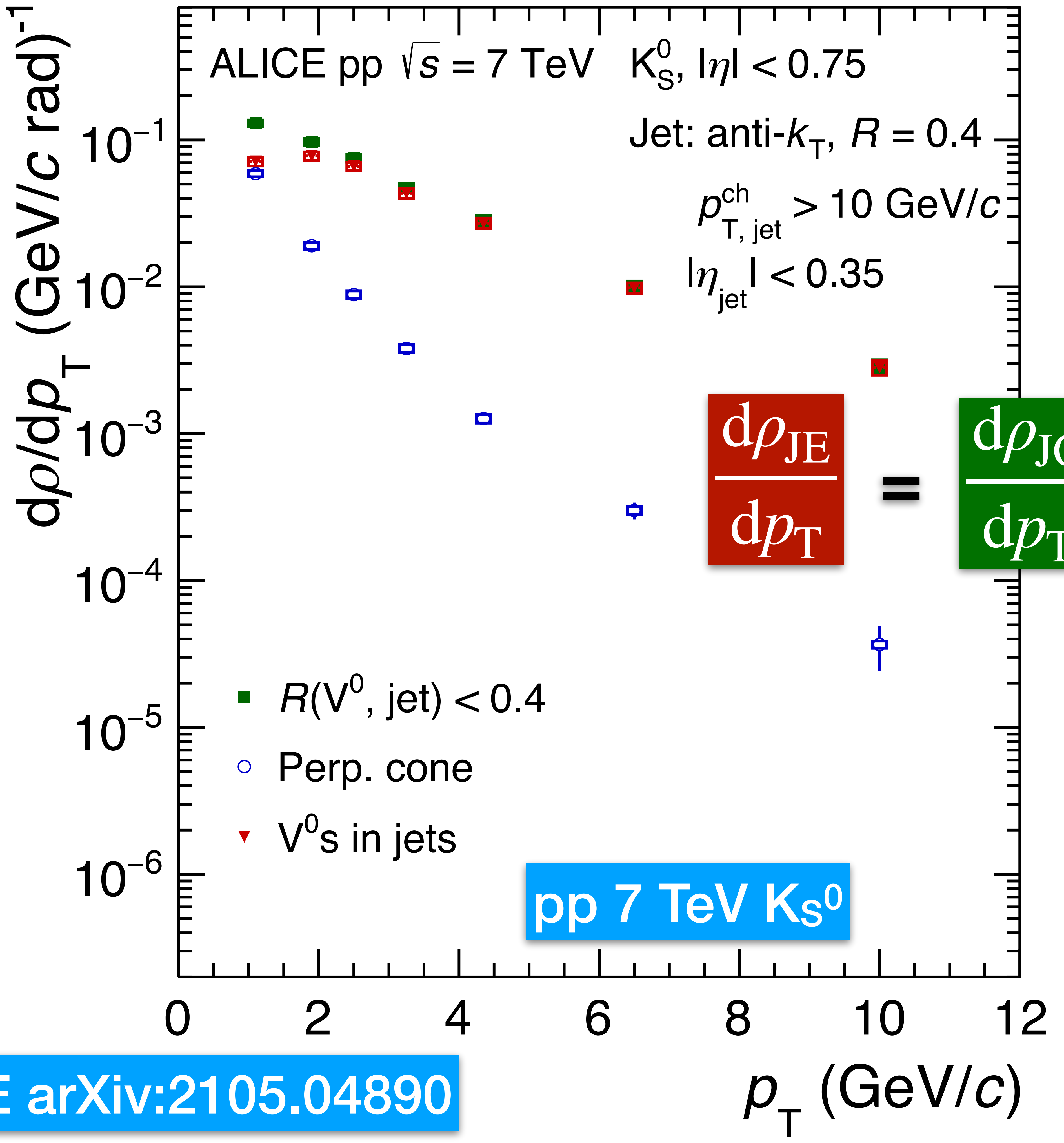
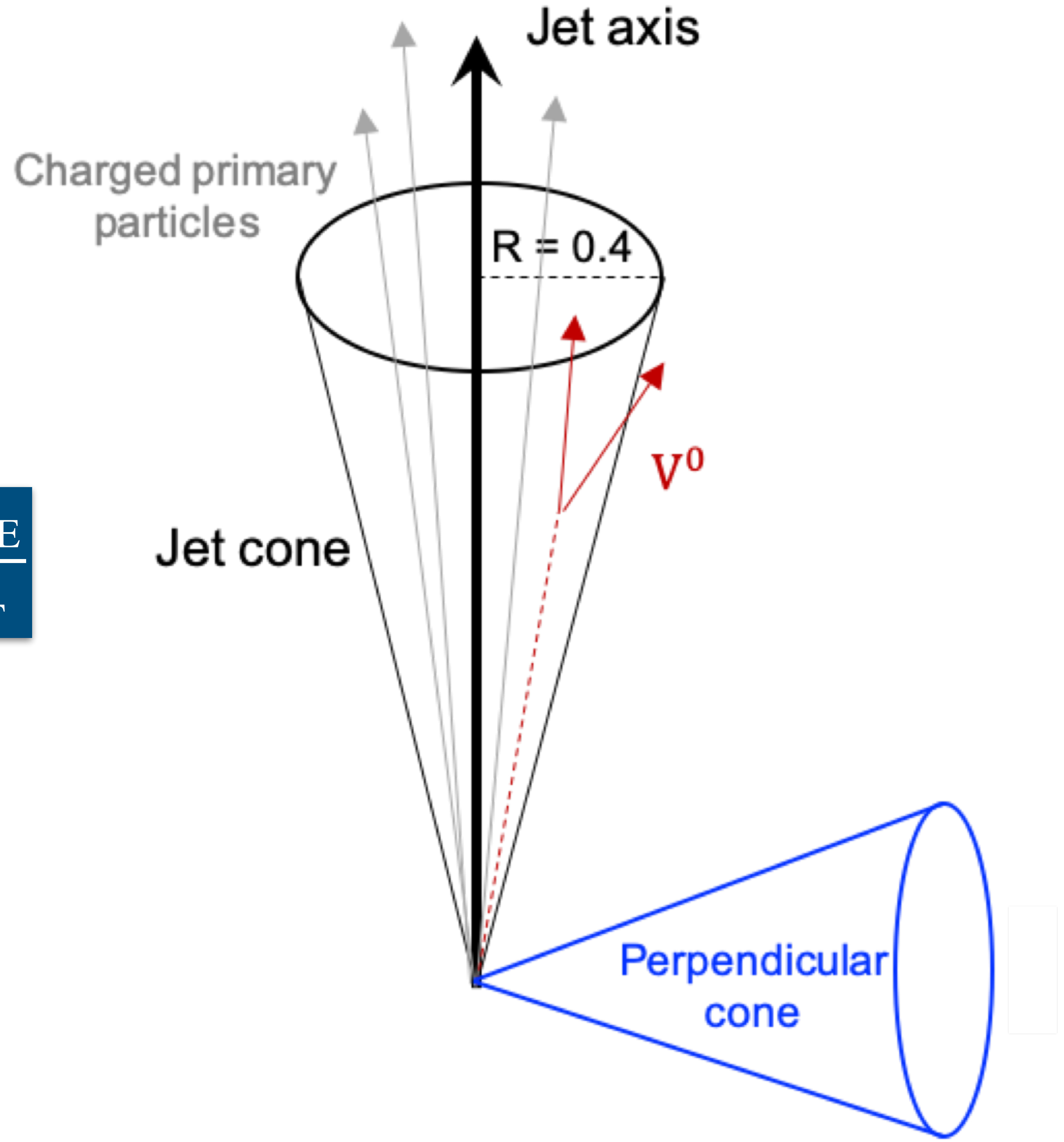


$$\frac{d\rho_{JE}}{dp_T} = \frac{d\rho_{JC}}{dp_T} - \frac{d\rho_{UE}}{dp_T}$$



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Λ/K_S^0 ratio in pp and p–Pb

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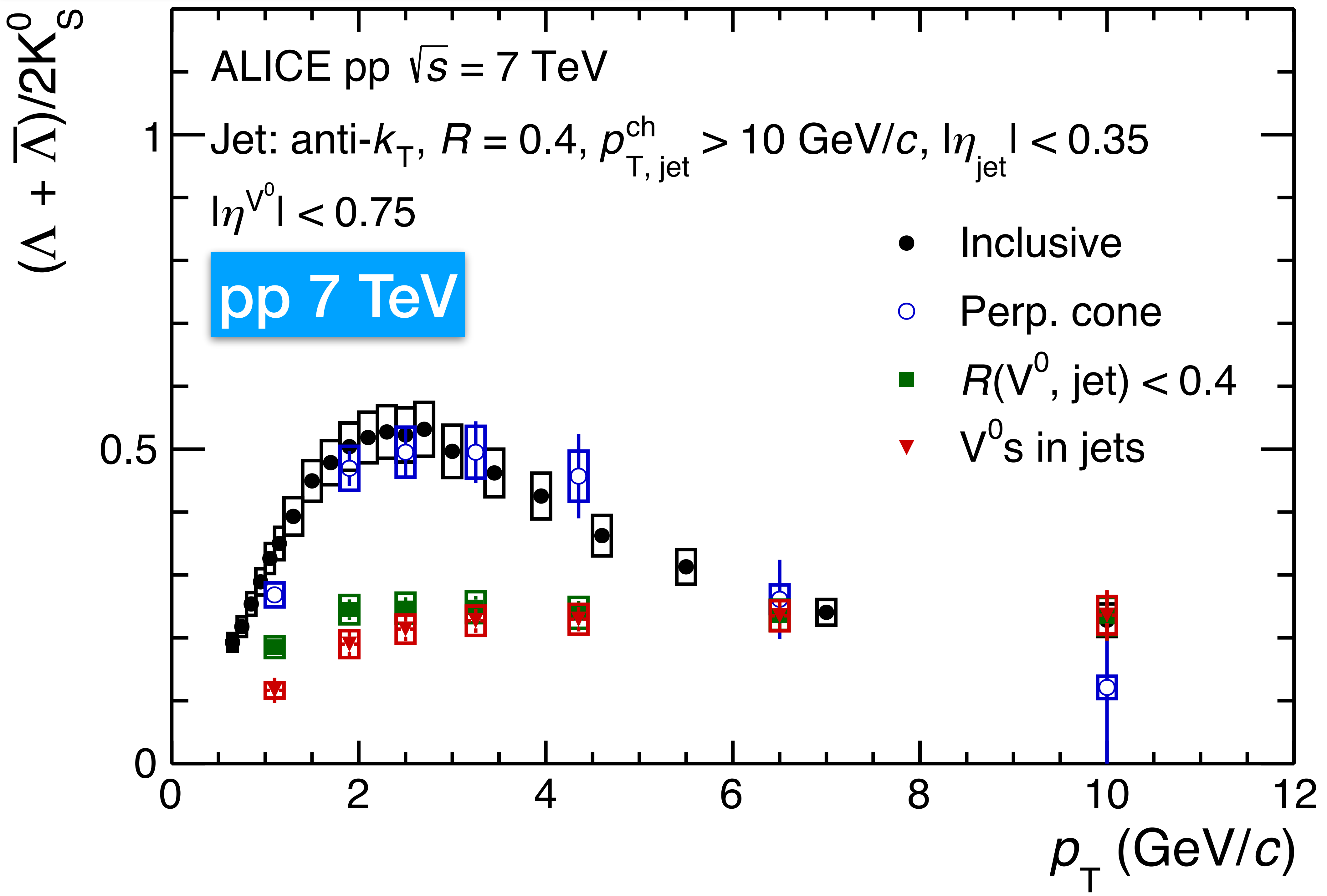

- Ratio in jets does not show a maximum at intermediate p_T, ratio with UE selection is systematically higher than the inclusive in $2 < p_T < 5$ GeV/c

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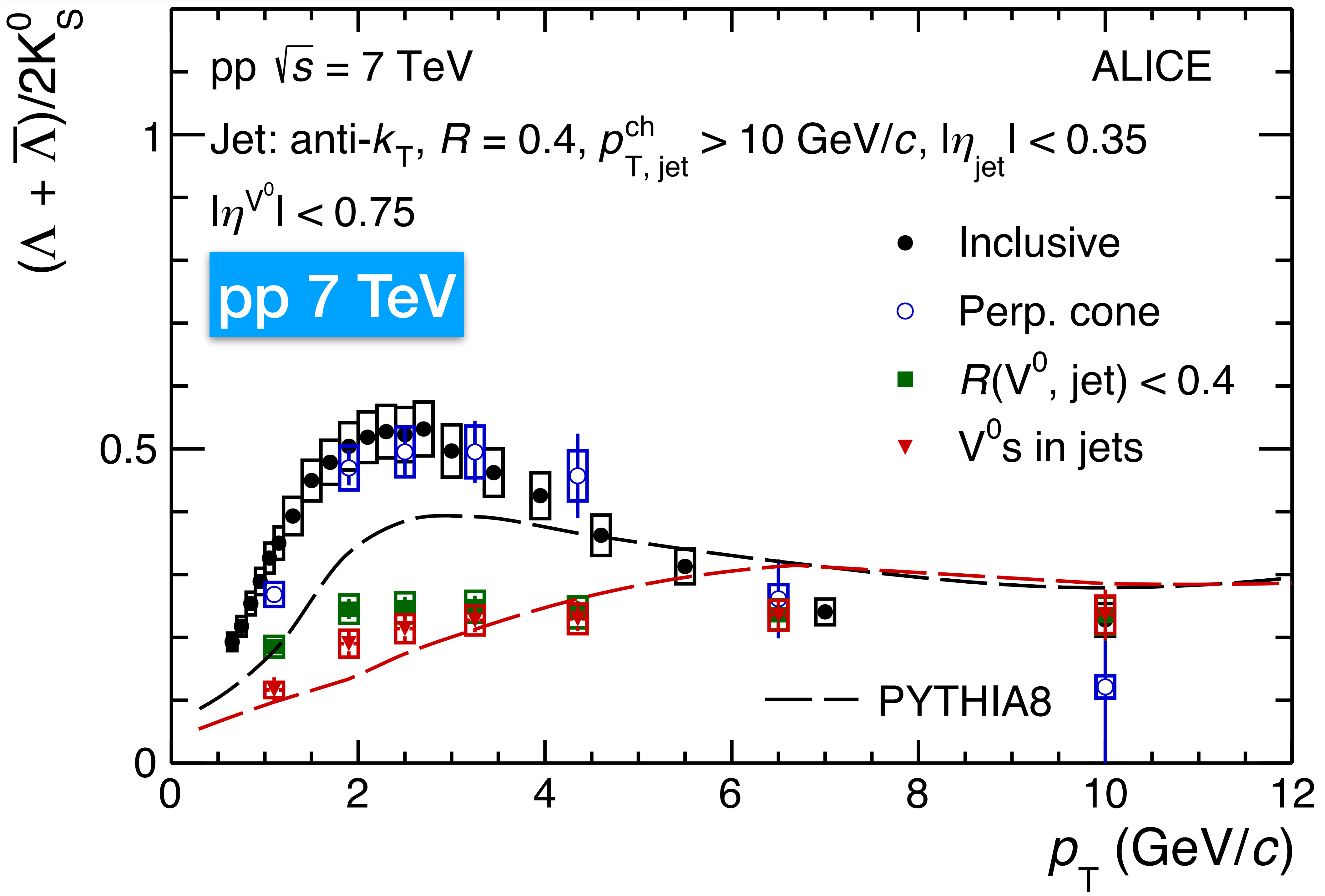

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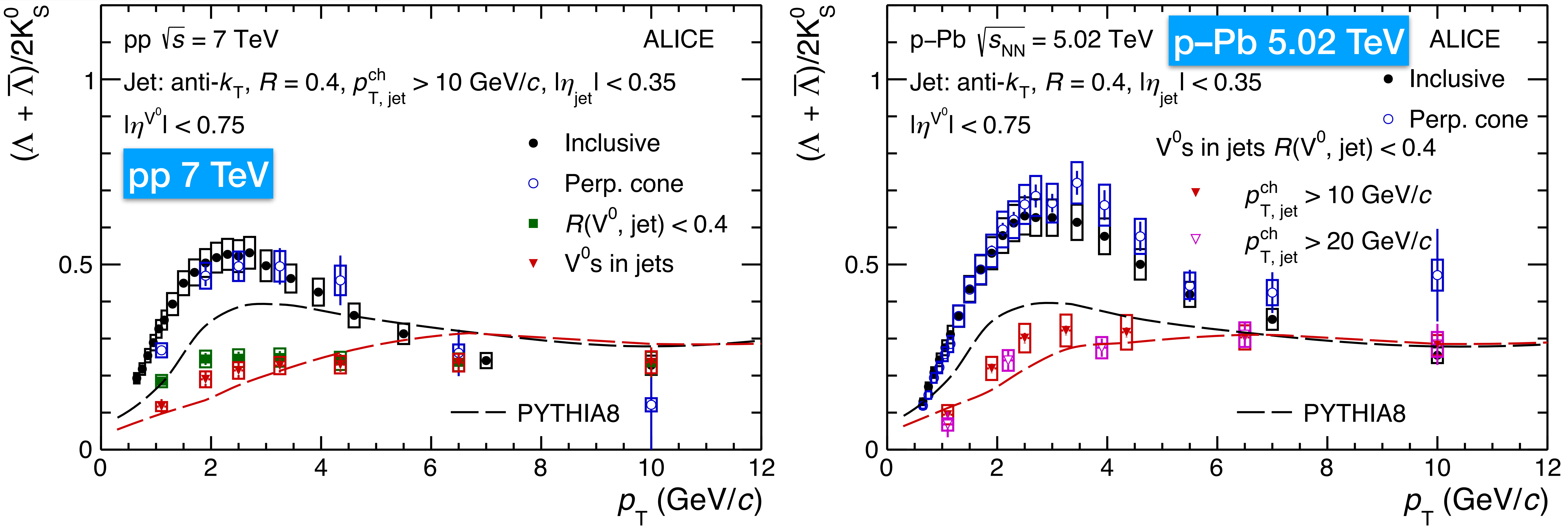
- PYTHIA 8 hard QCD is consistent with ratio in jets but does not reproduce the inclusive ratio at low and intermediate p_T

Λ/K_S^0 ratio in pp and p–Pb

ALICE arXiv:2105.04890



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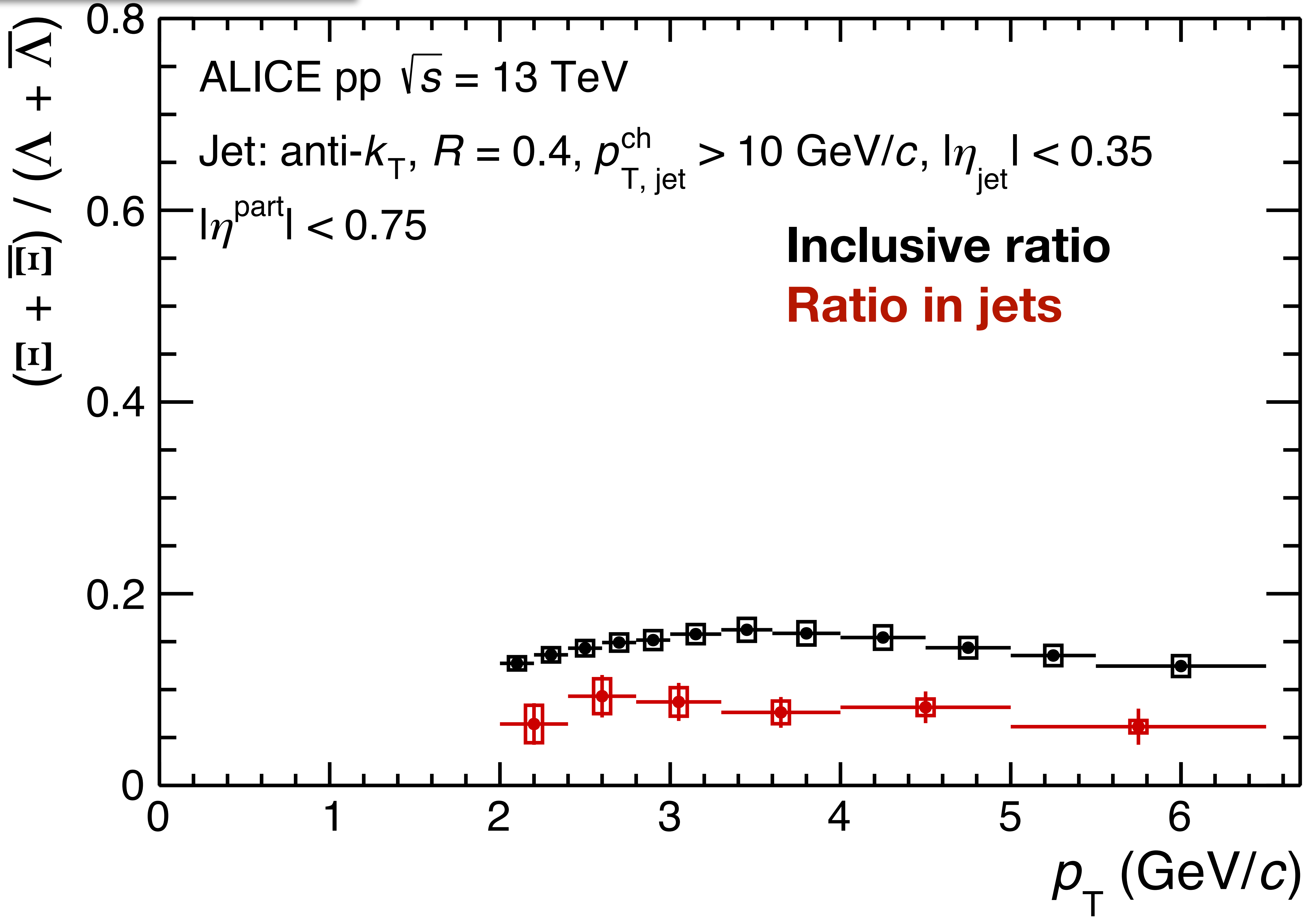
Ξ±/Λ ratio in jets

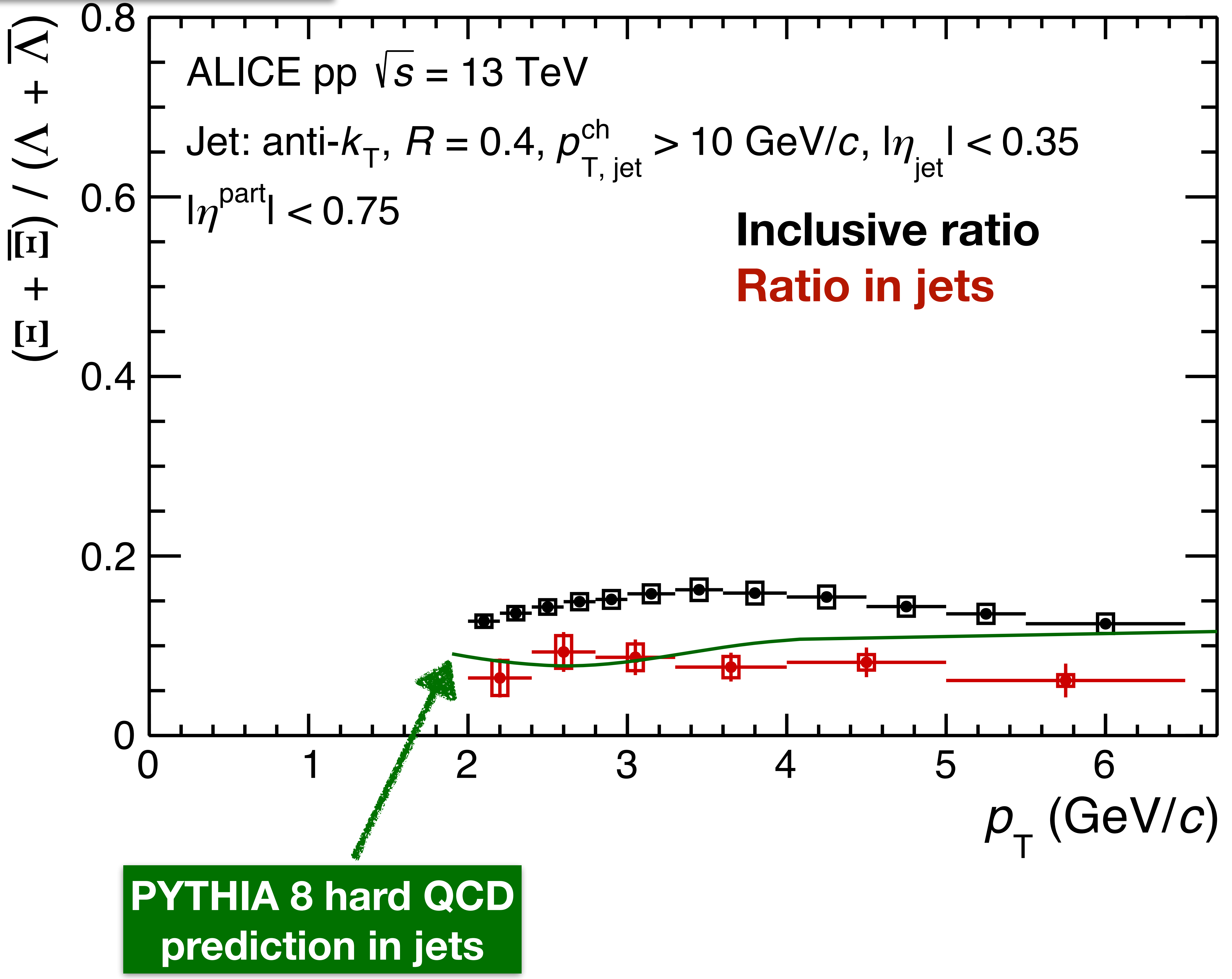
pp 13 TeV Ξ± / Λ



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

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

pp 13 TeV $\Xi^{\pm}$ / Λ

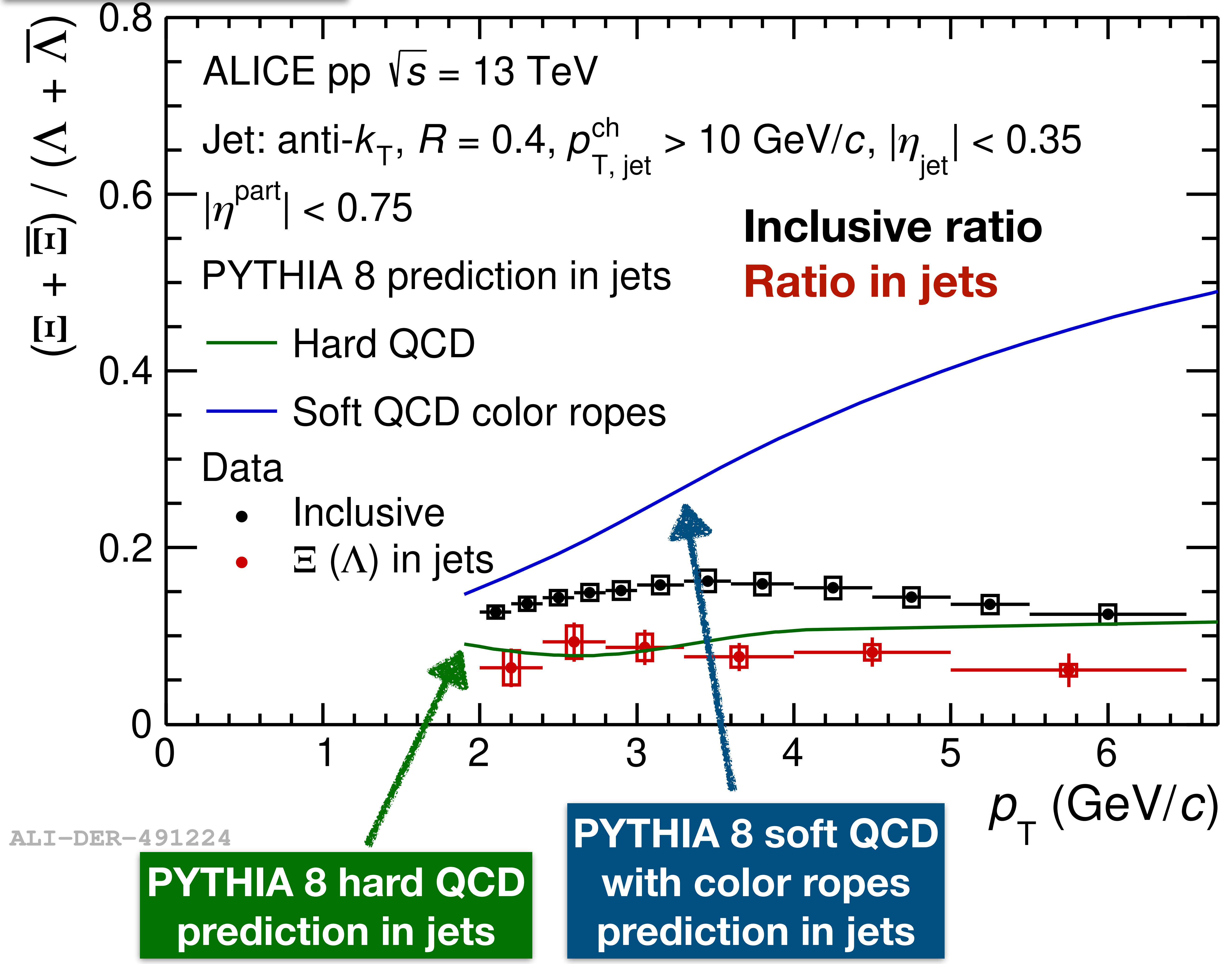


- Increase on baryon-to-baryon ($\Xi^{\pm}/\Lambda$) ratio at intermediate-p_T suppressed in jets
- PYTHIA 8 hard QCD generally reproduces ratio in jets

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

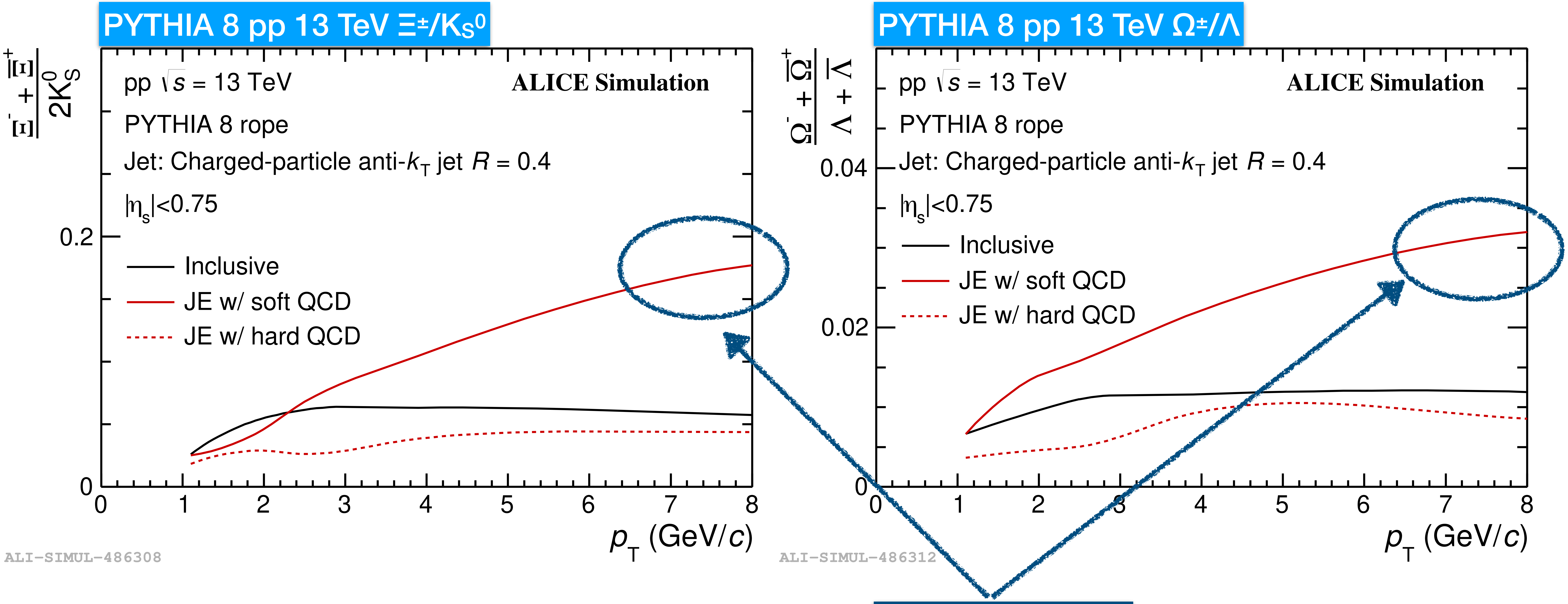
ALICE

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



Next step extend the study to Ω-baryon

PYTHIA 8 soft QCD with color ropes prediction in jets

Conclusion

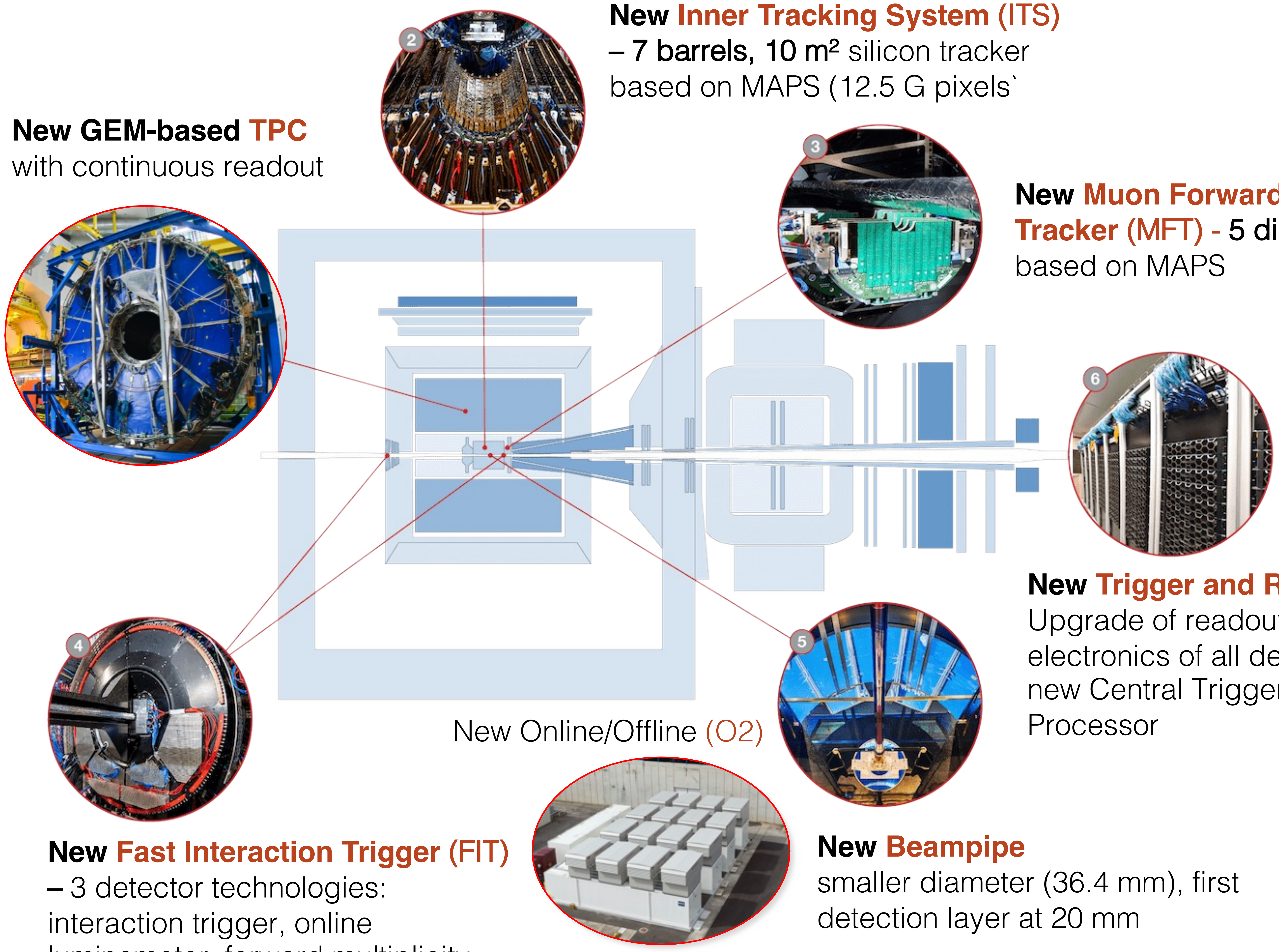
- Mass ordering of <p_T> is not observed in peripheral heavy-ion collisions as well as in pp and p–Pb collisions
- Underlying processes (transverse to leading processes) give the dominant contribution to strangeness production
- The Λ/K_S^0 increase at intermediate p_T is not present within the jets, but is related to the underlying event
- Strangeness enhancement in pp collisions: strongly correlated with effective energy (initial stage dynamics), better reproduced by color ropes
- 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

2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

ALICE 2 Upgrade

→ Tracking precision ×3

→ Pb-Pb rate ×50



New Inner Tracking System (ITS) – 7 barrels, 10 m² silicon tracker based on MAPS (12.5 G pixels`

New GEM-based TPC with continuous readout

New Muon Forward Tracker (MFT) - 5 disks based on MAPS

New Trigger and Readout Upgrade of readout electronics of all detector, new Central Trigger Processor

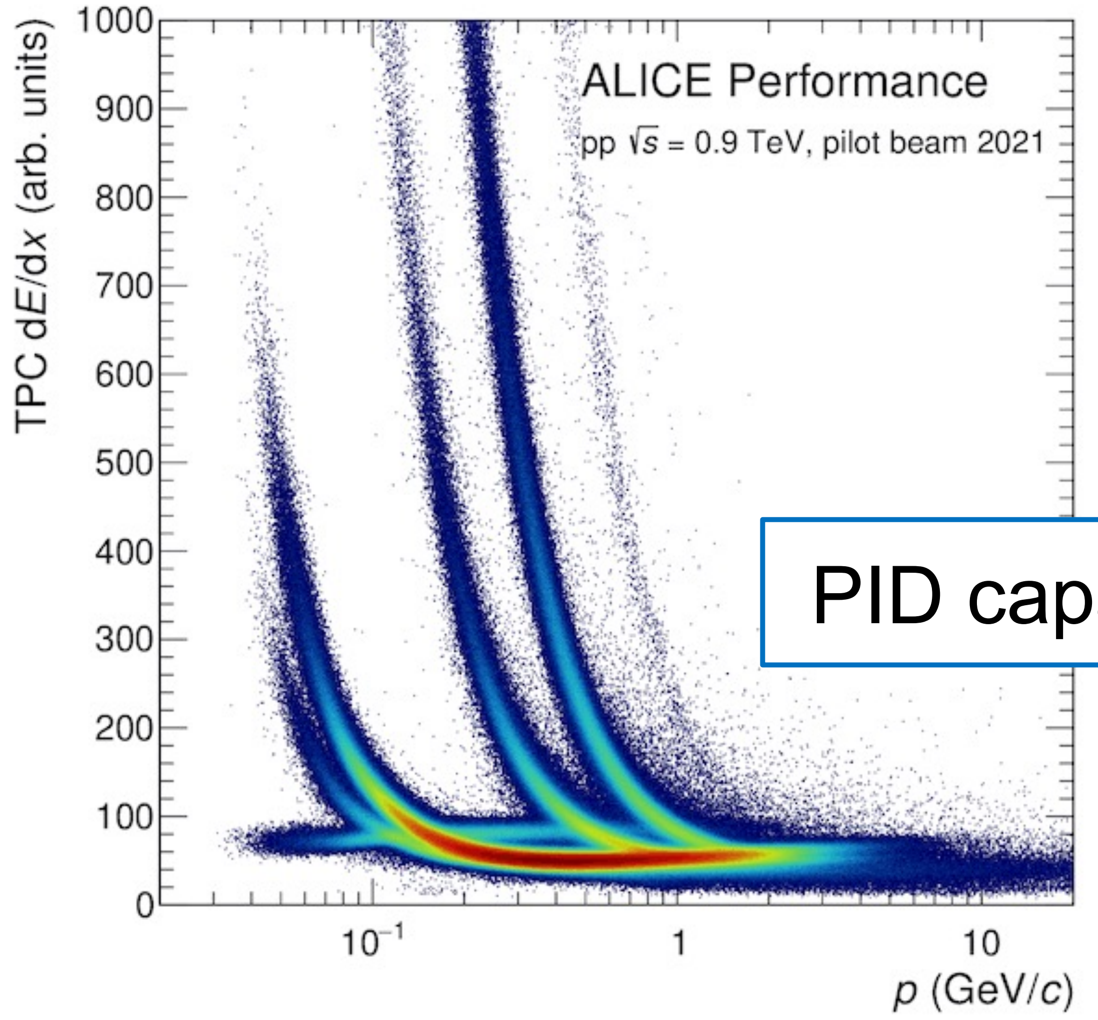
New Online/Offline (O2)

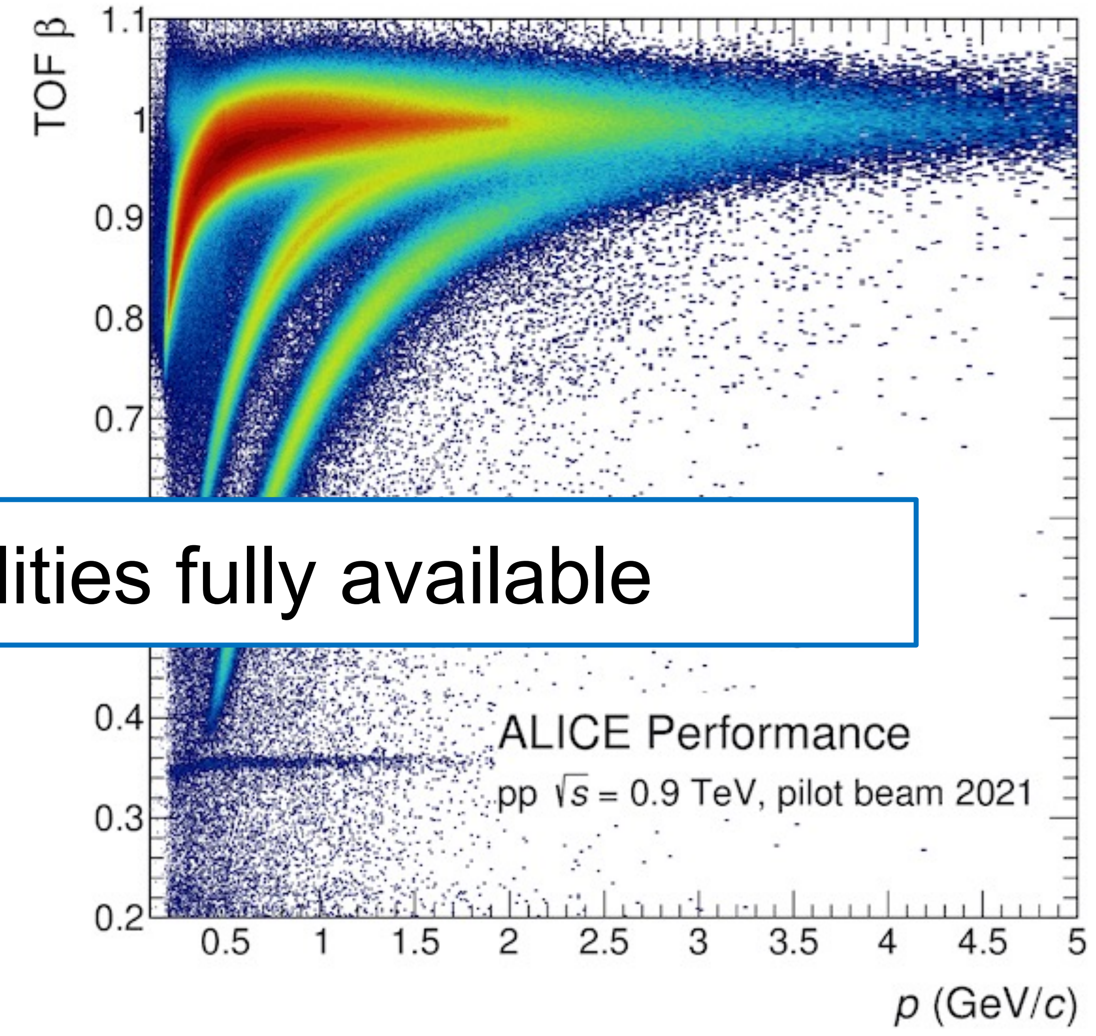
New Fast Interaction Trigger (FIT) – 3 detector technologies: interaction trigger, online luminometer, forward multiplicity

New Beampipe smaller diameter (36.4 mm), first detection layer at 20 mm

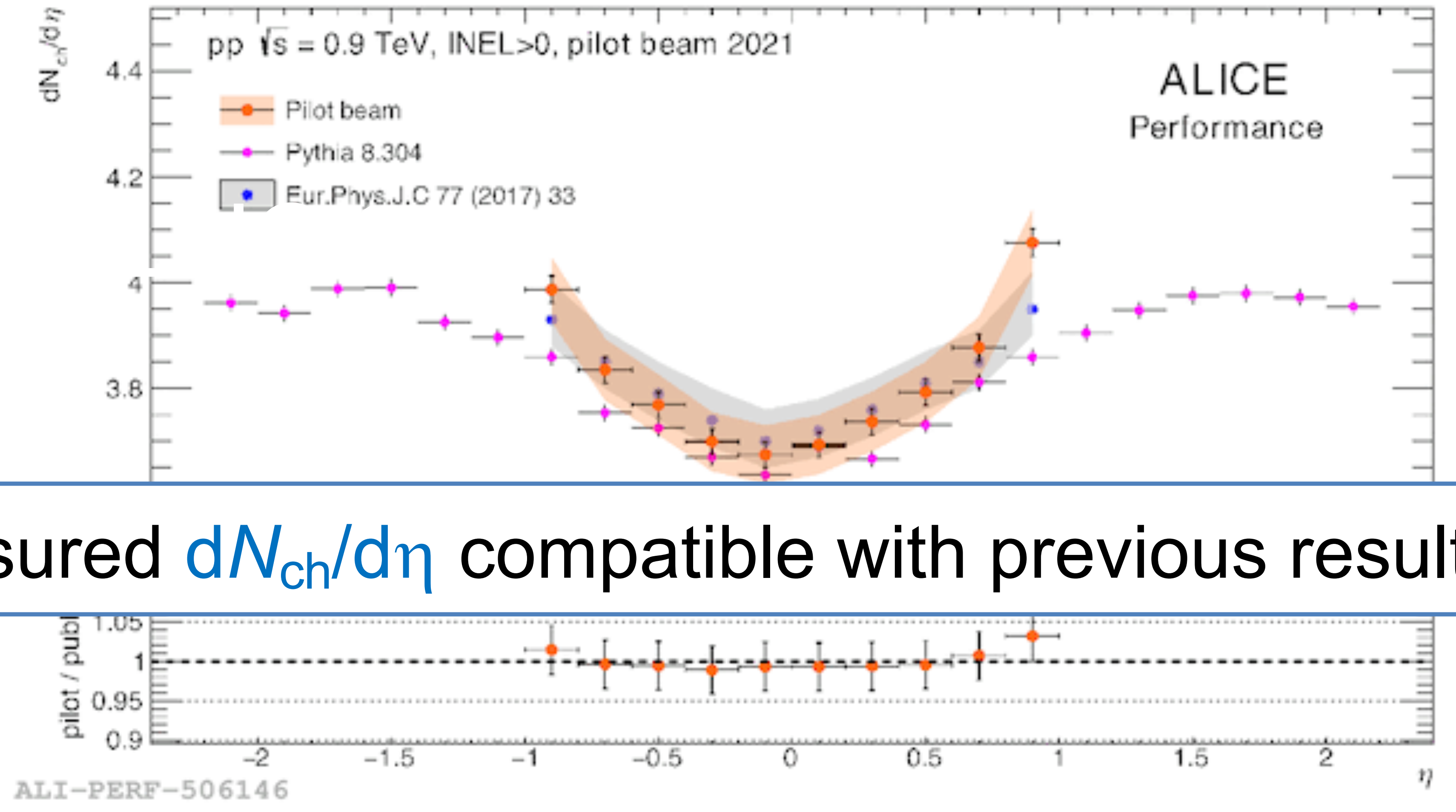
2010-2012		2015-2018		2022-2025		2029-2032	
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4

Commissioning with pilot beam and start of Run 3

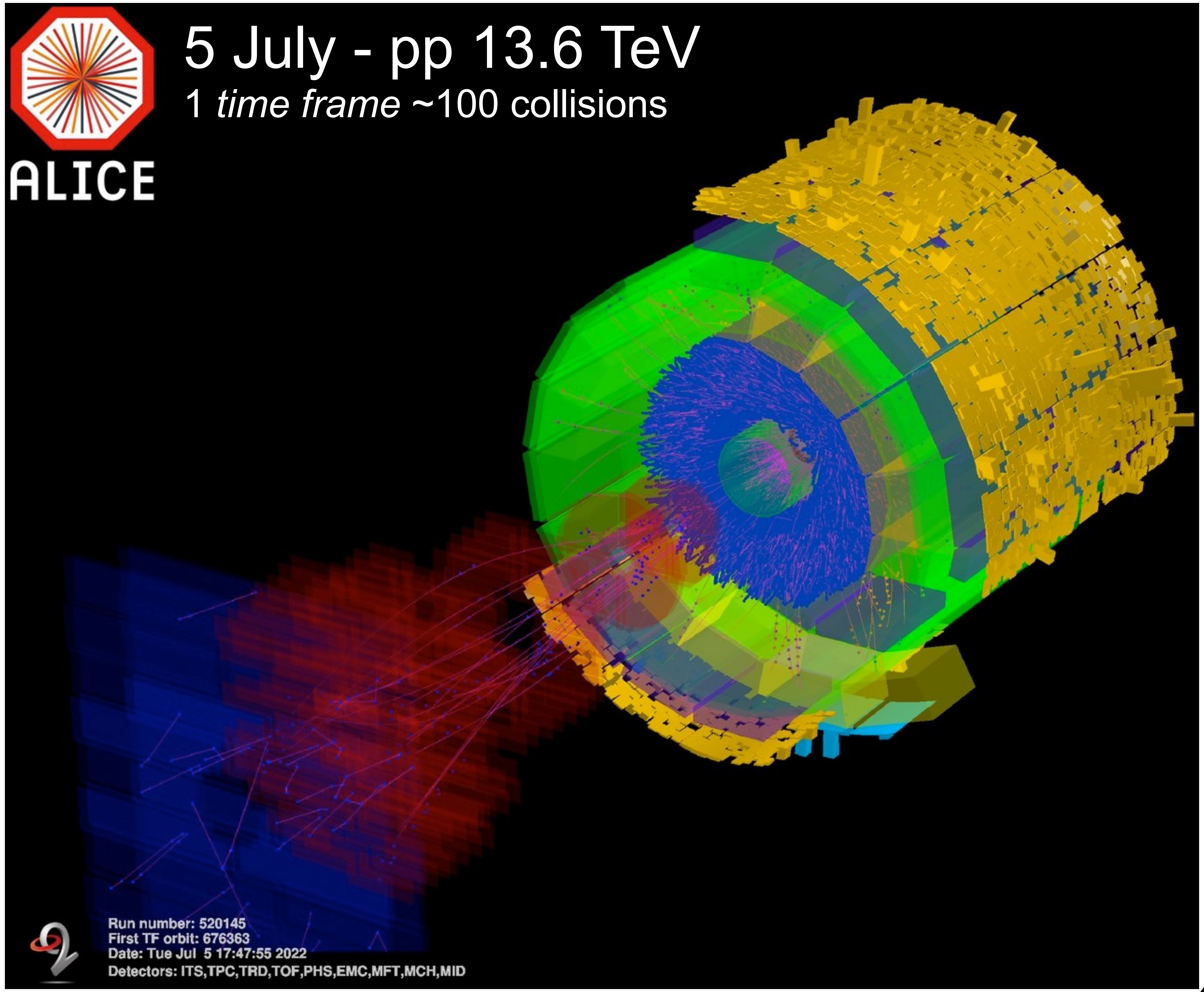




PID capabilities fully available



Measured $dN_{ch}/d\eta$ compatible with previous results

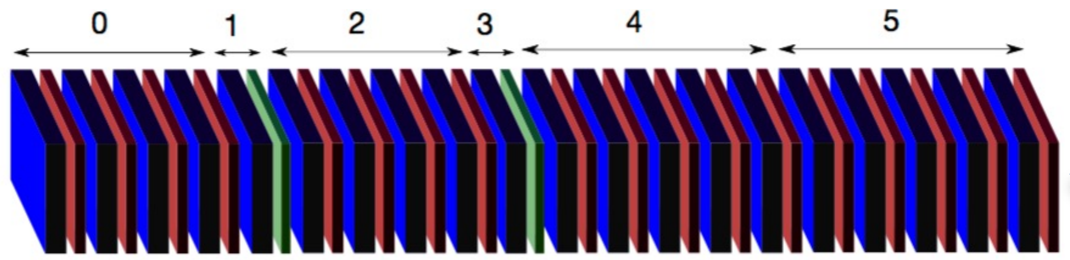


2010-2012 | 2015-2018 | 2022-2025 | 2029-2032

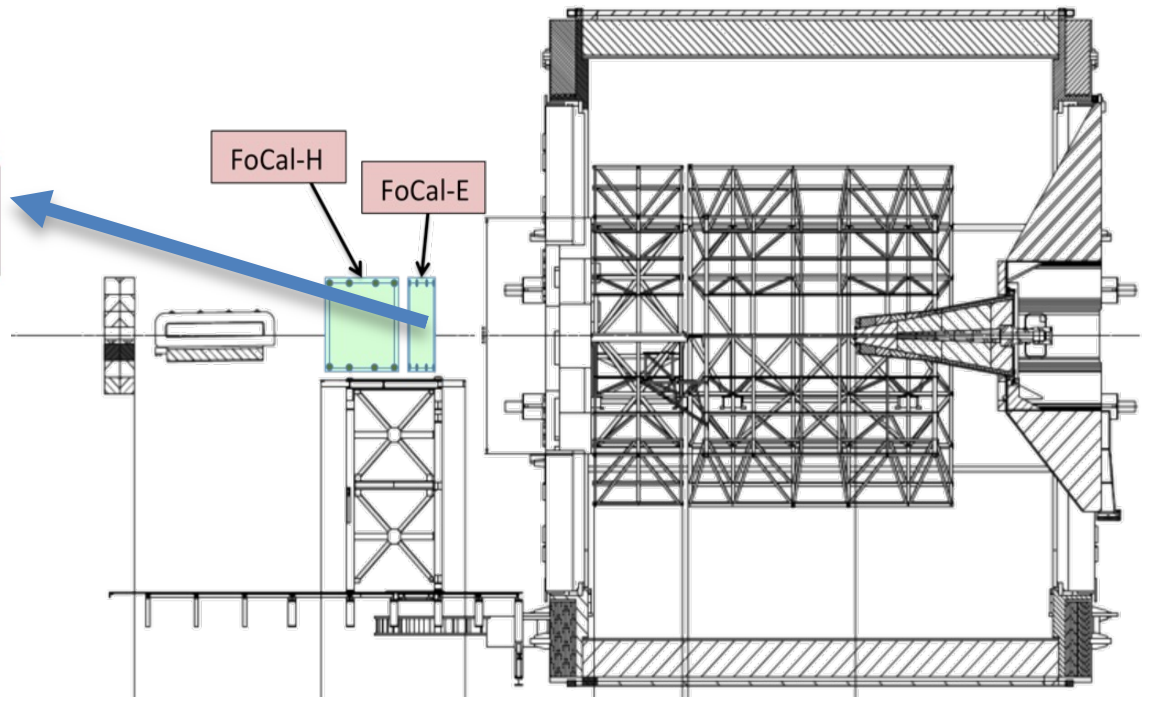
Run I | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4

LS3: forward calorimenter and ultra-thin tracker

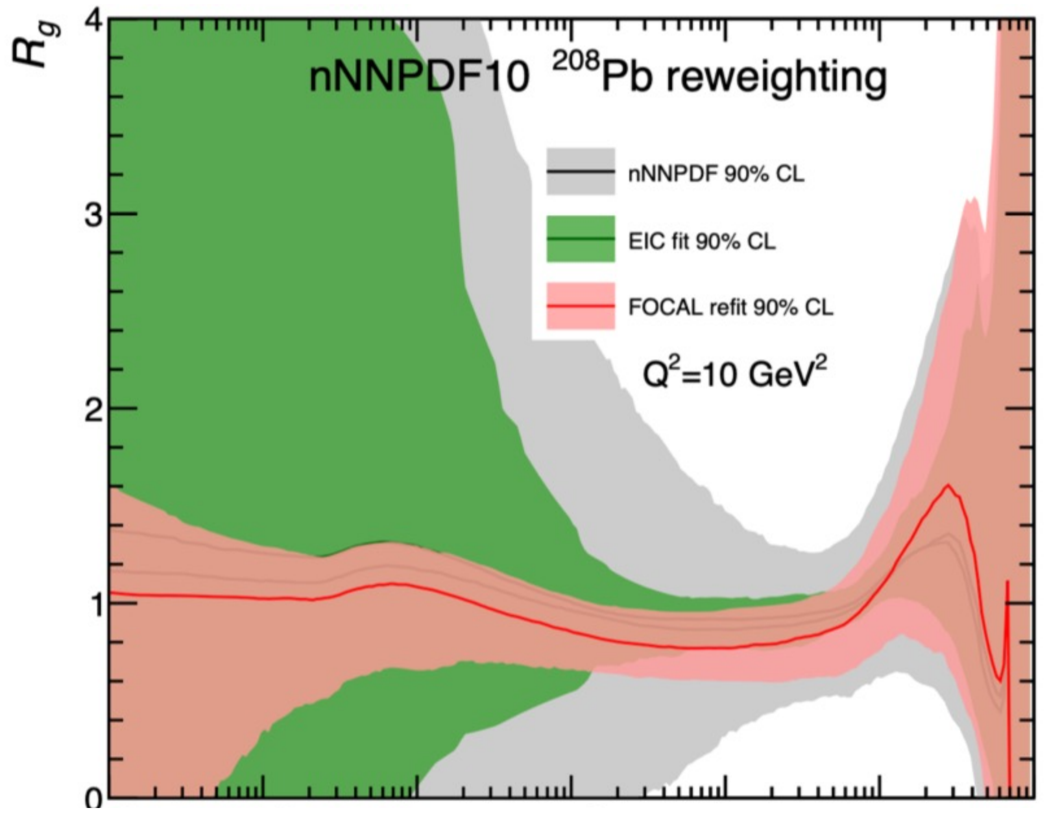
- FoCal: forward e.m. calo with Si readout for isolated γ measurements $3.2<\eta<5.8$ in p-Pb
- Constrain nuclear PDFs down to $x < 10^{-5}$
- **LoI:** CERN-LHCC-2020-009



Si pad / pixel readout

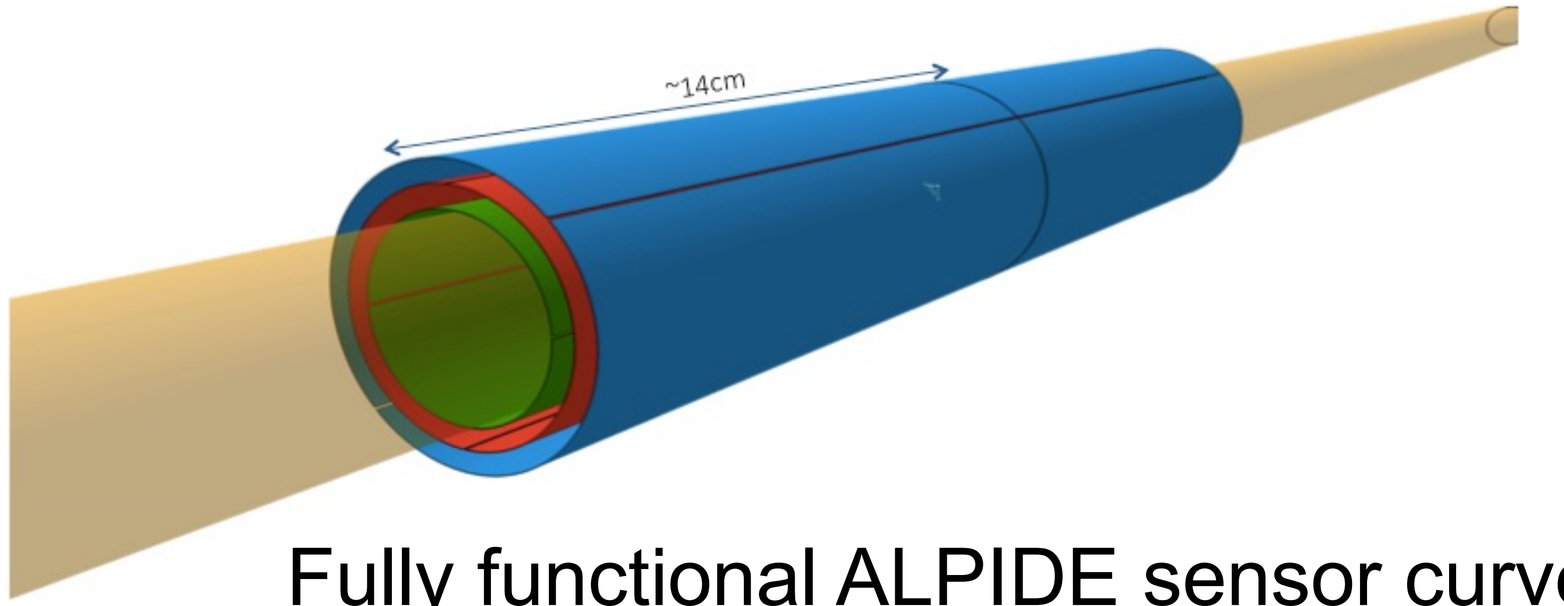


Impact on gluon nuclear PDFs:
Present nNNPDF
w/ FoCal pseudodata
w/ EIC pseudodata

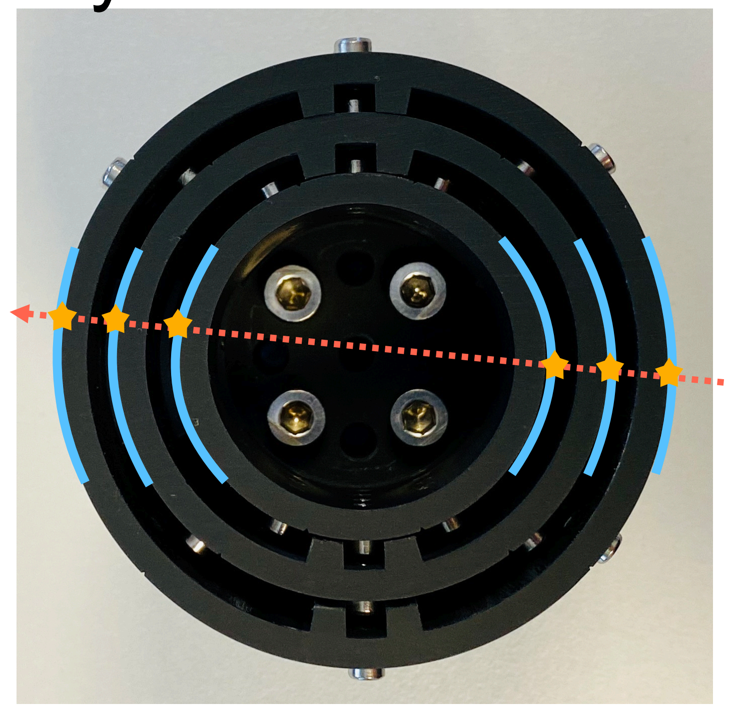


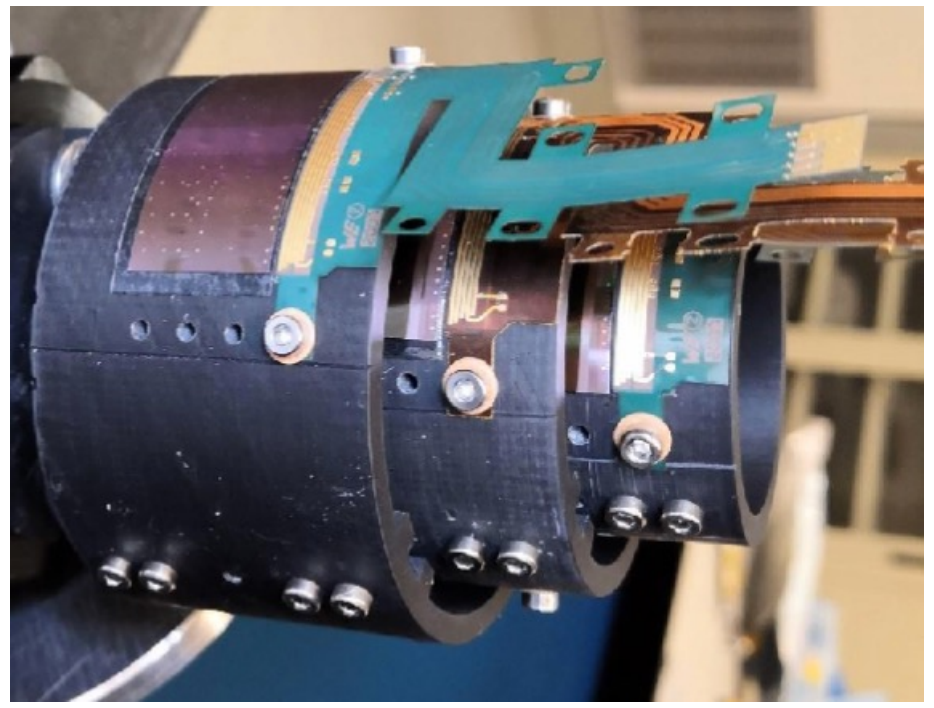
TDRs in 2023

- ITS3: new inner barrel – 3 truly cylindrical MAPS layers around smaller beam pipe
  - $\times$ 3 less material budget
  - $\times$ 2 tracking precision and effic. (low p_T)
- **LoI:** CERN-LHCC-2019-018



Fully functional ALPIDE sensor curved to R=1.8 cm





2010-2012 2015-2018 2022-2025 2029-2032 **2035-2038** **2040-2041**

Run I | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 | LS5 | Run 6

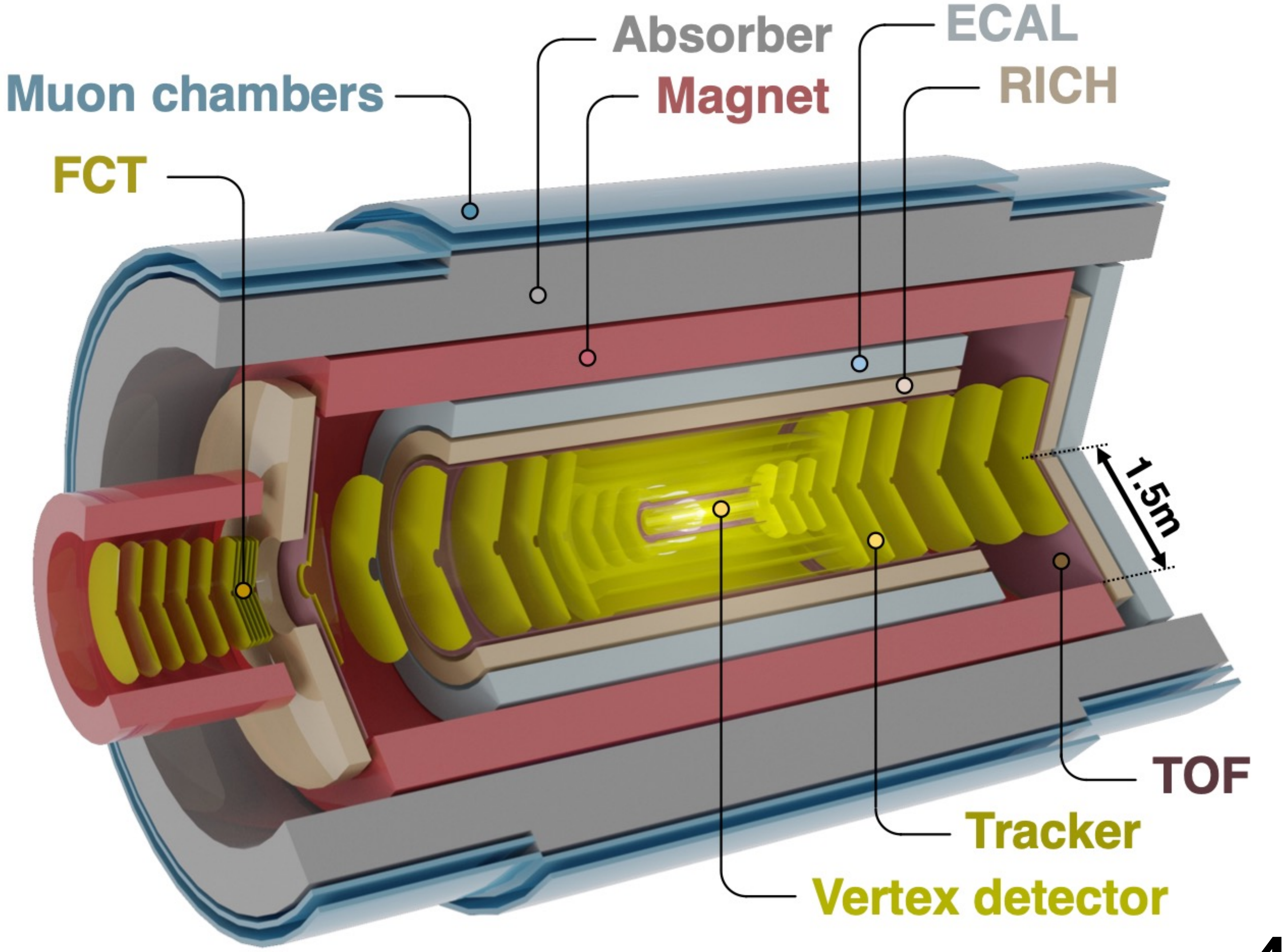
ALICE 3: next-generation heavy-ion detector

→ Tracking precision $\times$ 3: 10 μm at p_T = 0.2 GeV/c
→ Acceptance $\times$ 4.5: $|\eta|$ < 4 (with particle ID)
→ A-A rate $\times$ 5 (pp $\times$ 25)

Enables unique physics in Run 5+

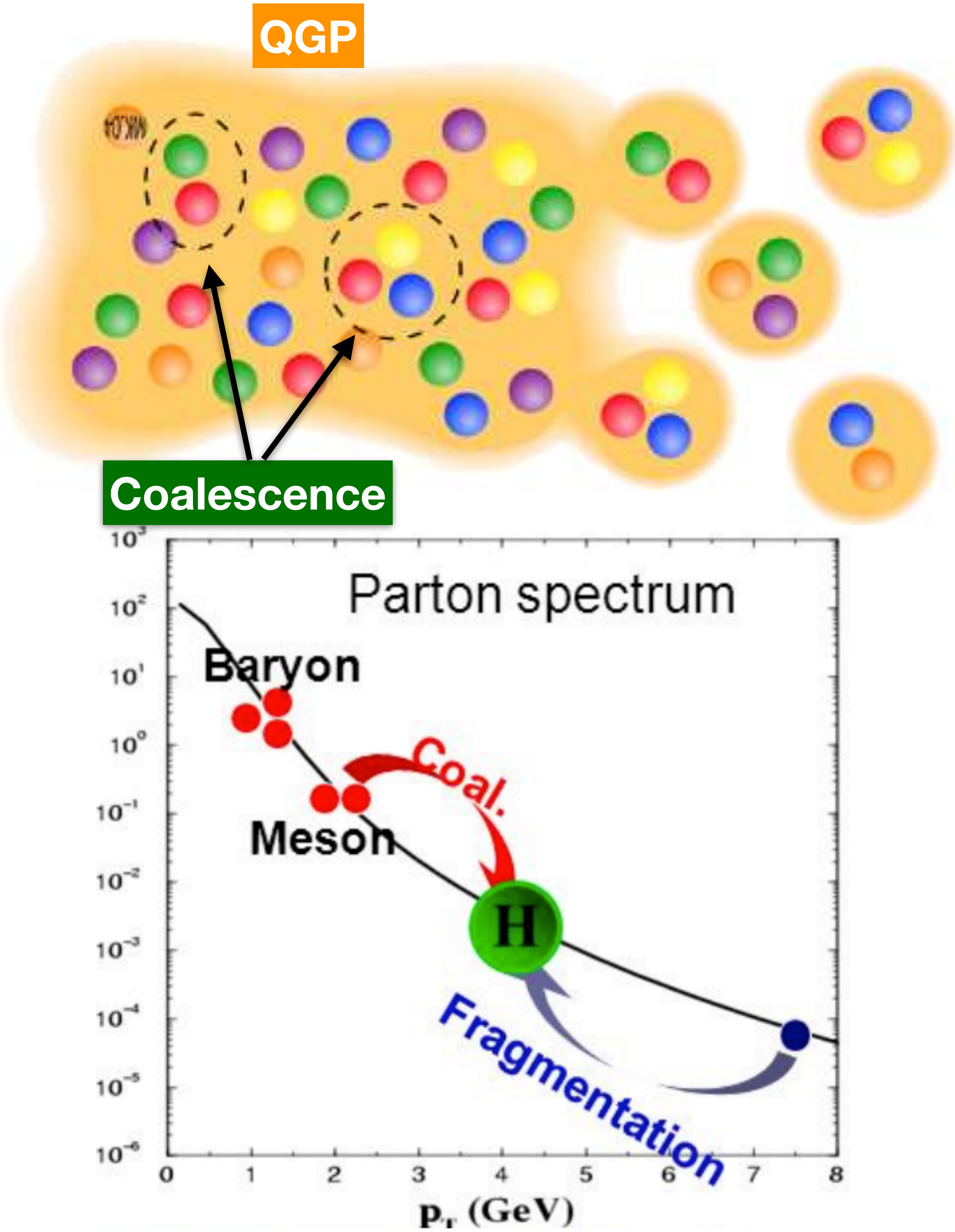
- Multi-charm hadrons
- Charm - anticharm angular (de)correlation
- Thermal radiation and its time dependence
- Chiral symmetry restoration in QGP
- Charm h-h residual interaction
- …

LoI: CERN-LHCC-2022-009



Backup

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

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

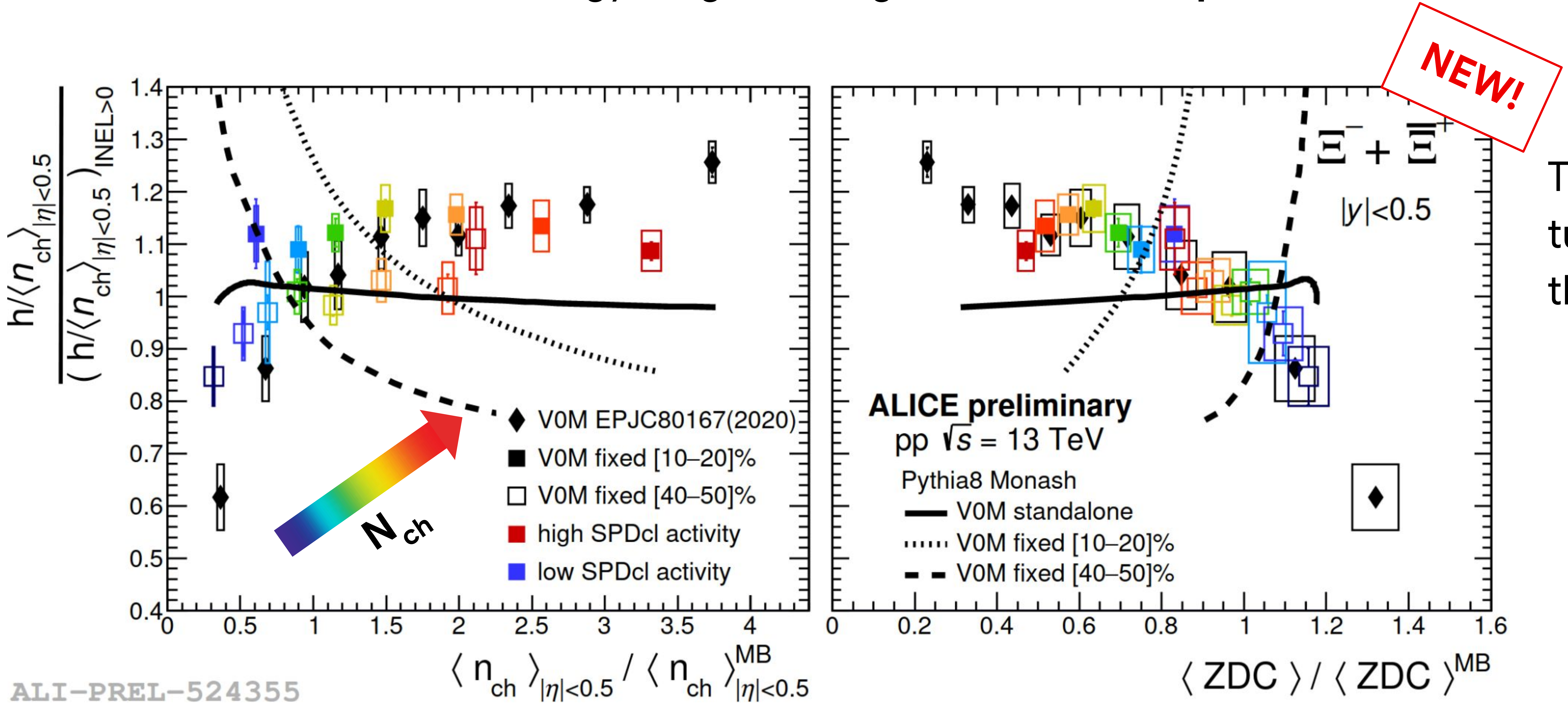
➡ Sensitive to baryon and meson species

➡ 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

In events with ZDC energy deposits fixed in a small range:

- strangeness **enhancement with multiplicity is reduced** (left)
- within the small ZDC energy range, scaling **trends** are **compatible** within uncertainties (right)



The **Pythia Monash 2013** tune **fails to reproduce** the results