High-density QCD:
Exploring high-density effects in pp and p-Pb collisions

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Disclaimers/apologies:
- Focus on highlighting important concepts; not on showing the latest results
- Results shows are biased towards ALICE for practical reasons

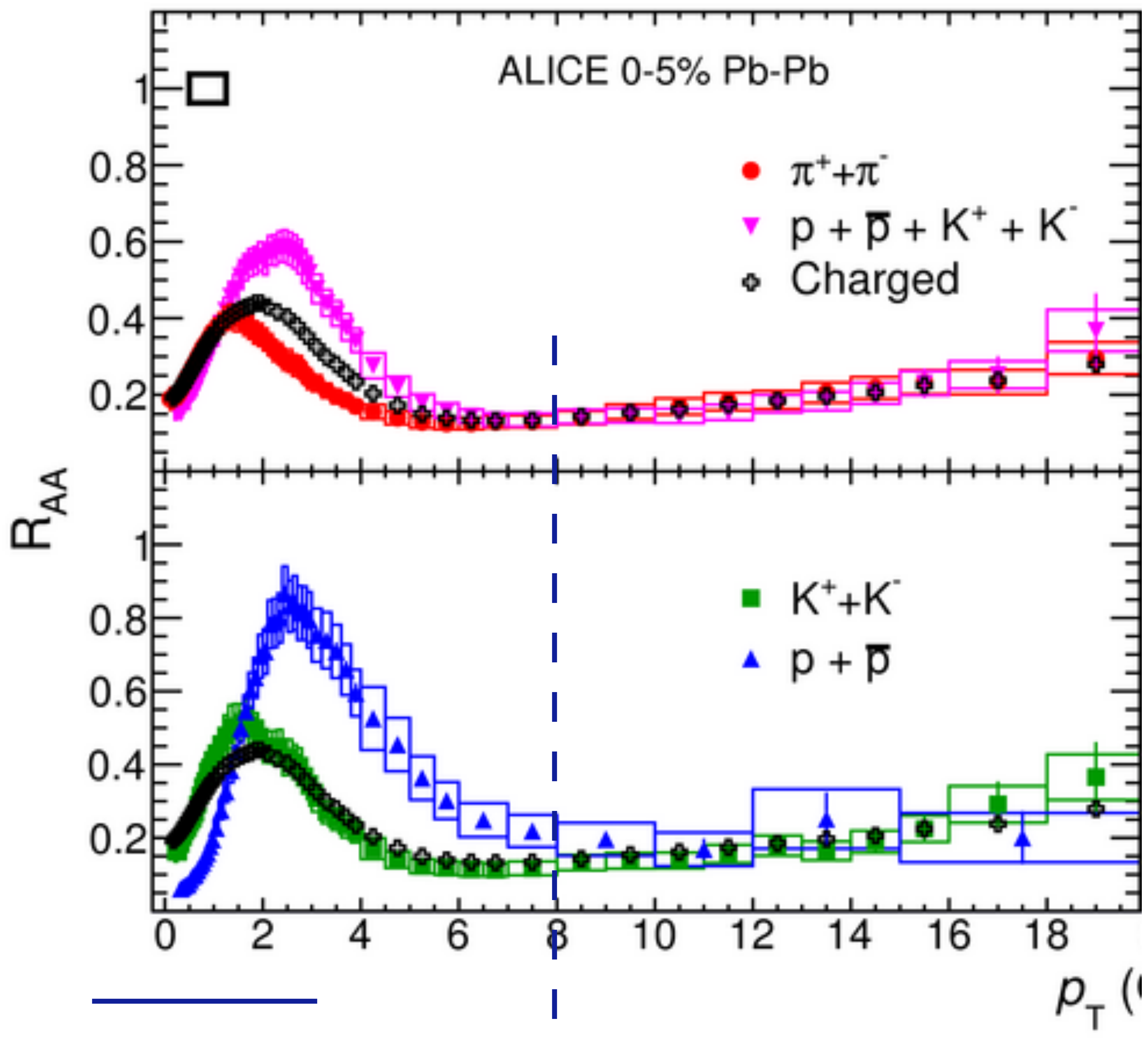
CERN-Fermilab Hadron Collider Physics Summer School
28 Aug - 6 Sep 2019

Nikhef

Physics Utrecht
EMMEΦ

Single particle R_{AA} revisited: particle type dependence

ALICE, arXiv:1506.07287



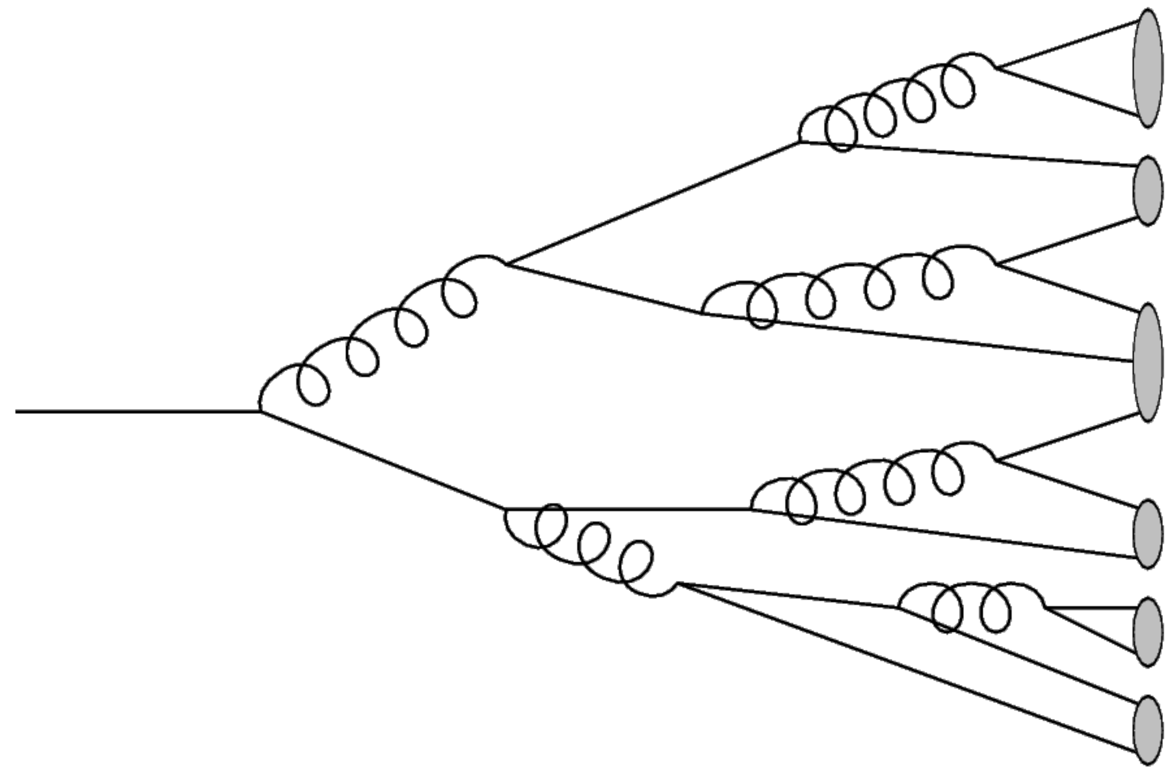
Low p_T: increase of baryon production
Mass dependence of radial flow

$p_T > 8$ GeV: baryon, meson R_{AA} similar
as expected from parton energy loss

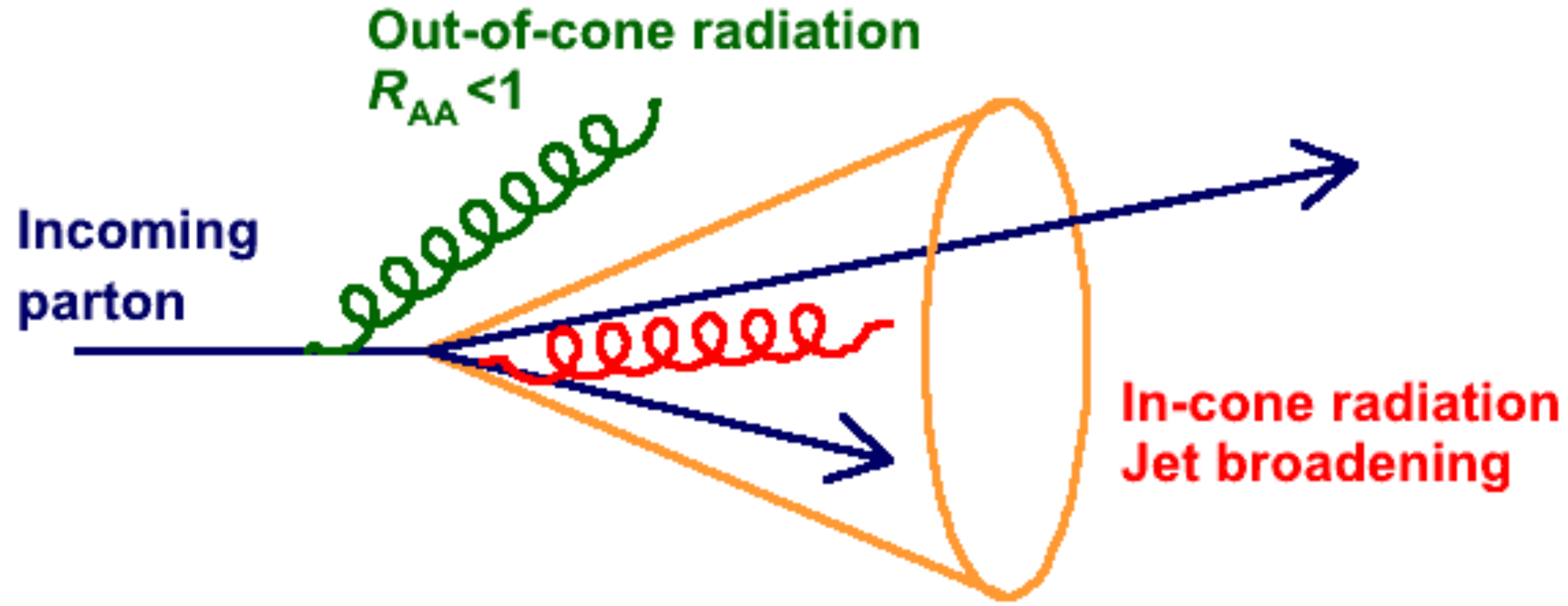
Jets and parton energy loss

Two new aspects to pursue

Jets: parton showers
+ hadronisation



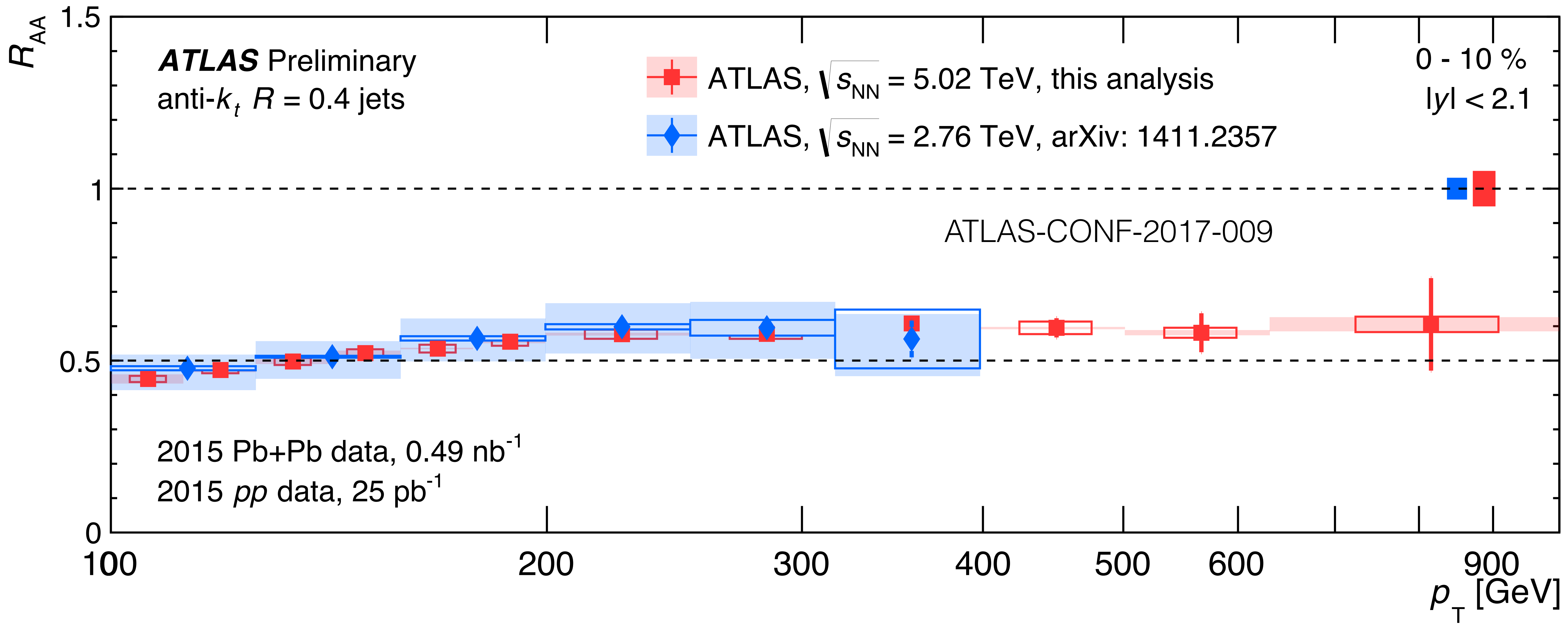
Explore energy loss of multi-parton states:
Interference effects, distance dependence?



Angular distribution of photon radiation:

1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

Nuclear modification factor for jets



$R_{AA} < 1$ out to high $p_T \approx 800$ GeV

No strong p_T-dependence: suggests increase of ΔE vs E

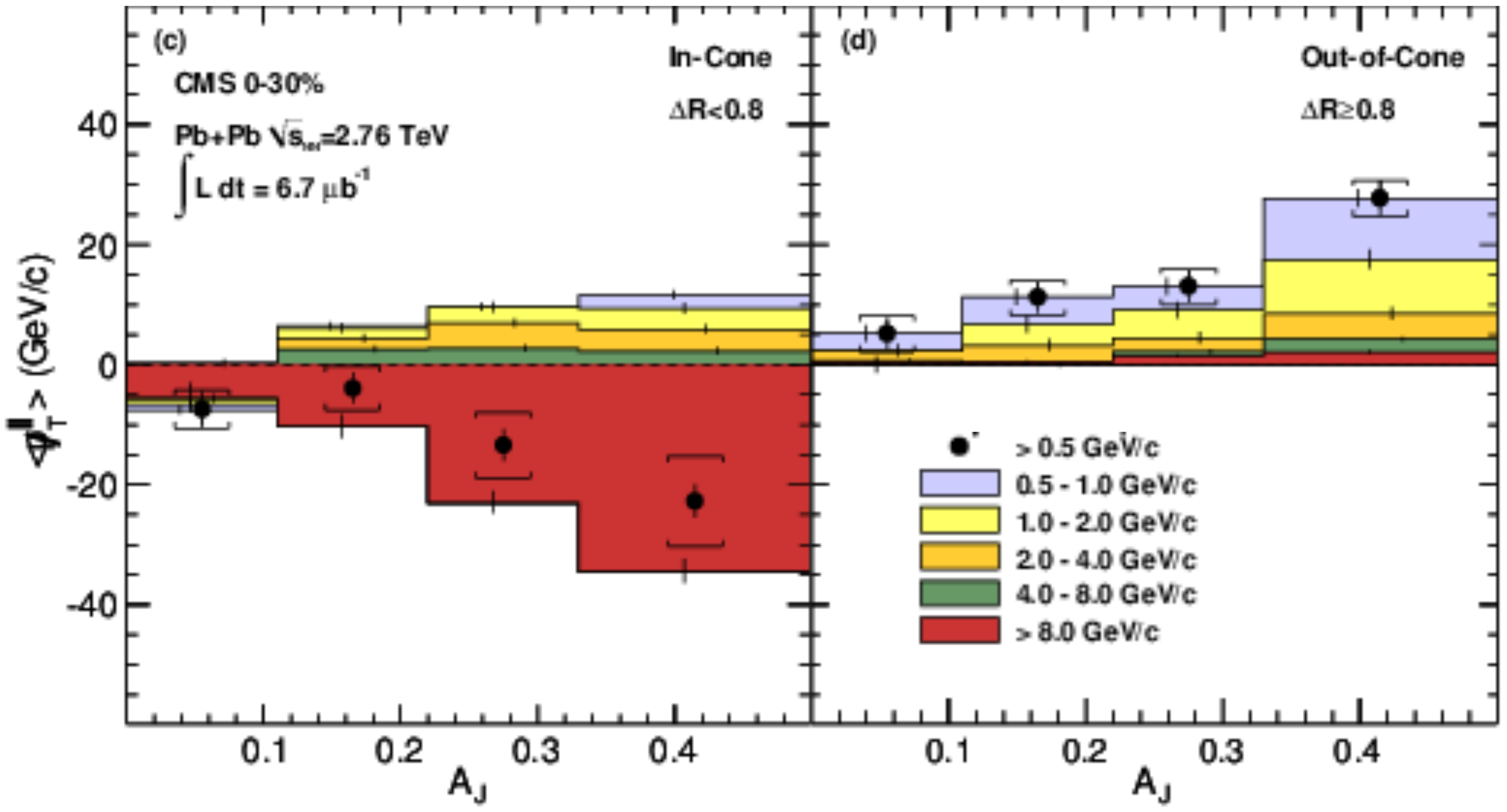
Note: 10% energy loss for a 800 GeV jet is 80 GeV !

Where is the 'lost energy': Looking outside the jet cone

Momentum balance variable:

$$p_{T,miss}^{//} = \sum_{tracks} p_T \cos(\varphi - \varphi_{jet})$$

In Cone R<0.8 Out of Cone R>0.8



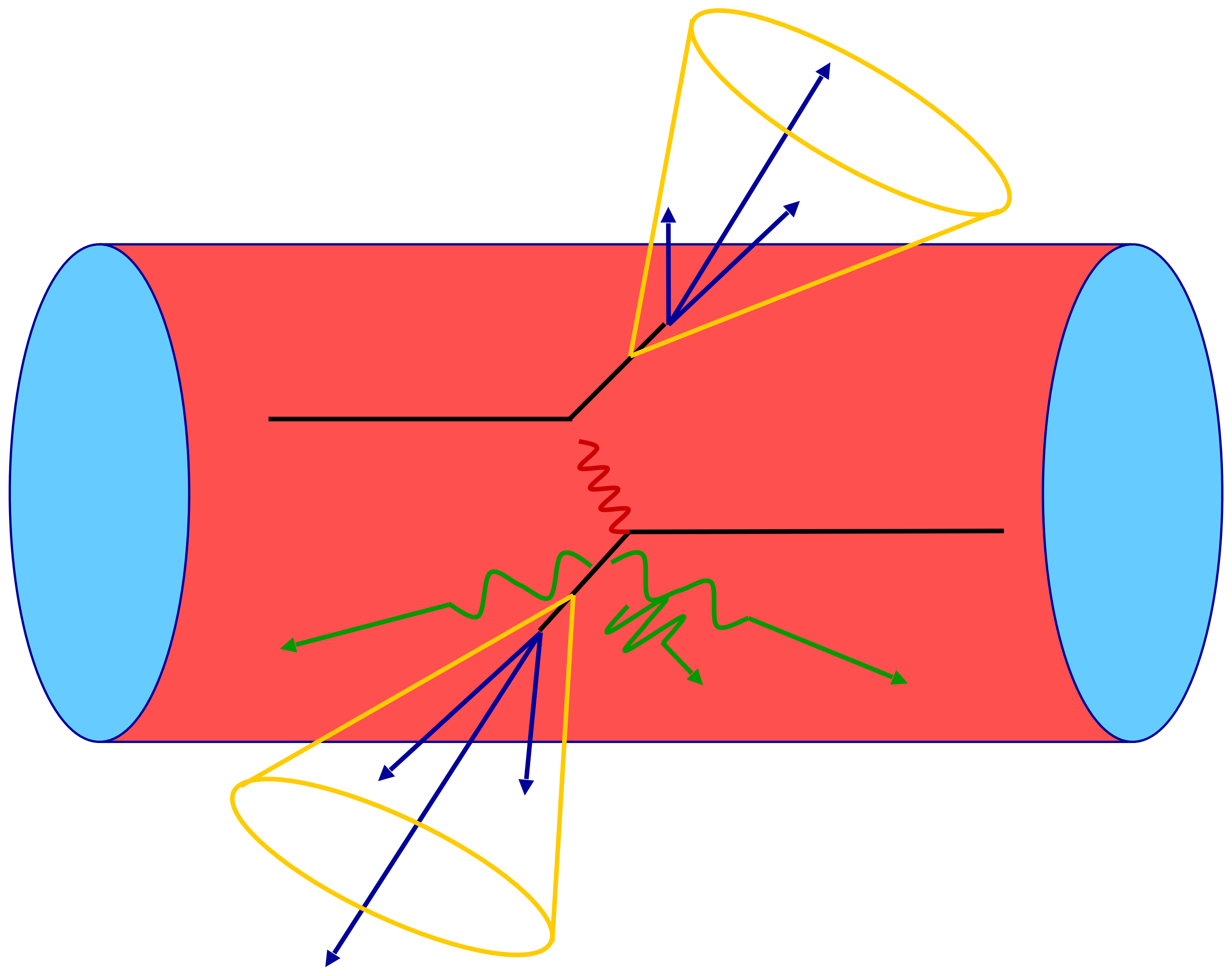
CMS, Phys. Rev. C 84 (2011) 024906

Momentum imbalance restored by hadrons at:
- large angle R > 0.8
- small p_T < 2 GeV/*c*

Jet energy loss is a dramatic effect, not a minor reshuffling of particles

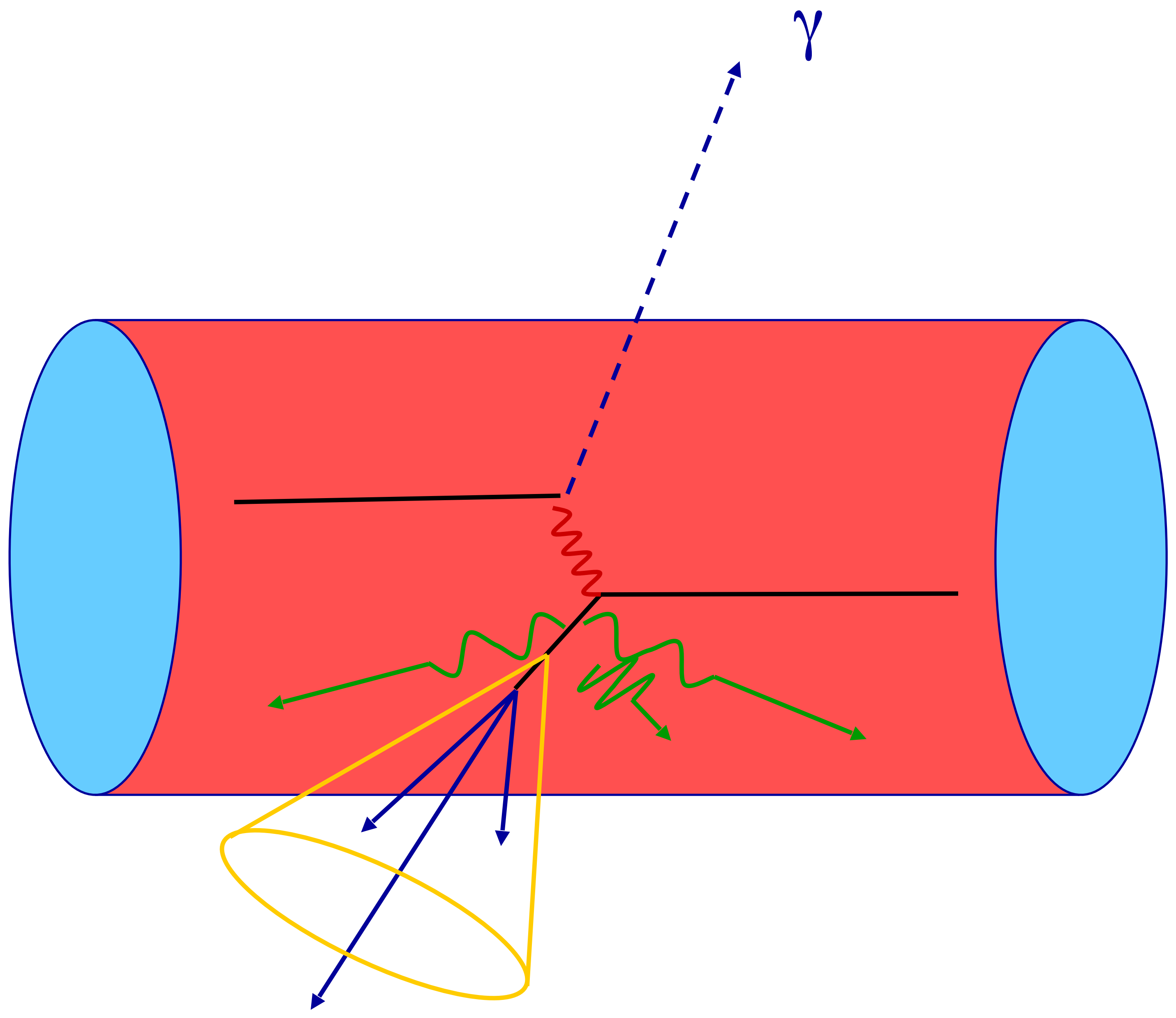
Gamma-jet vs jet-jet

Di-jet



Both jets can lose energy
Initial kinematics not well controlled
Asymmetry due to energy loss differences

γ-jet

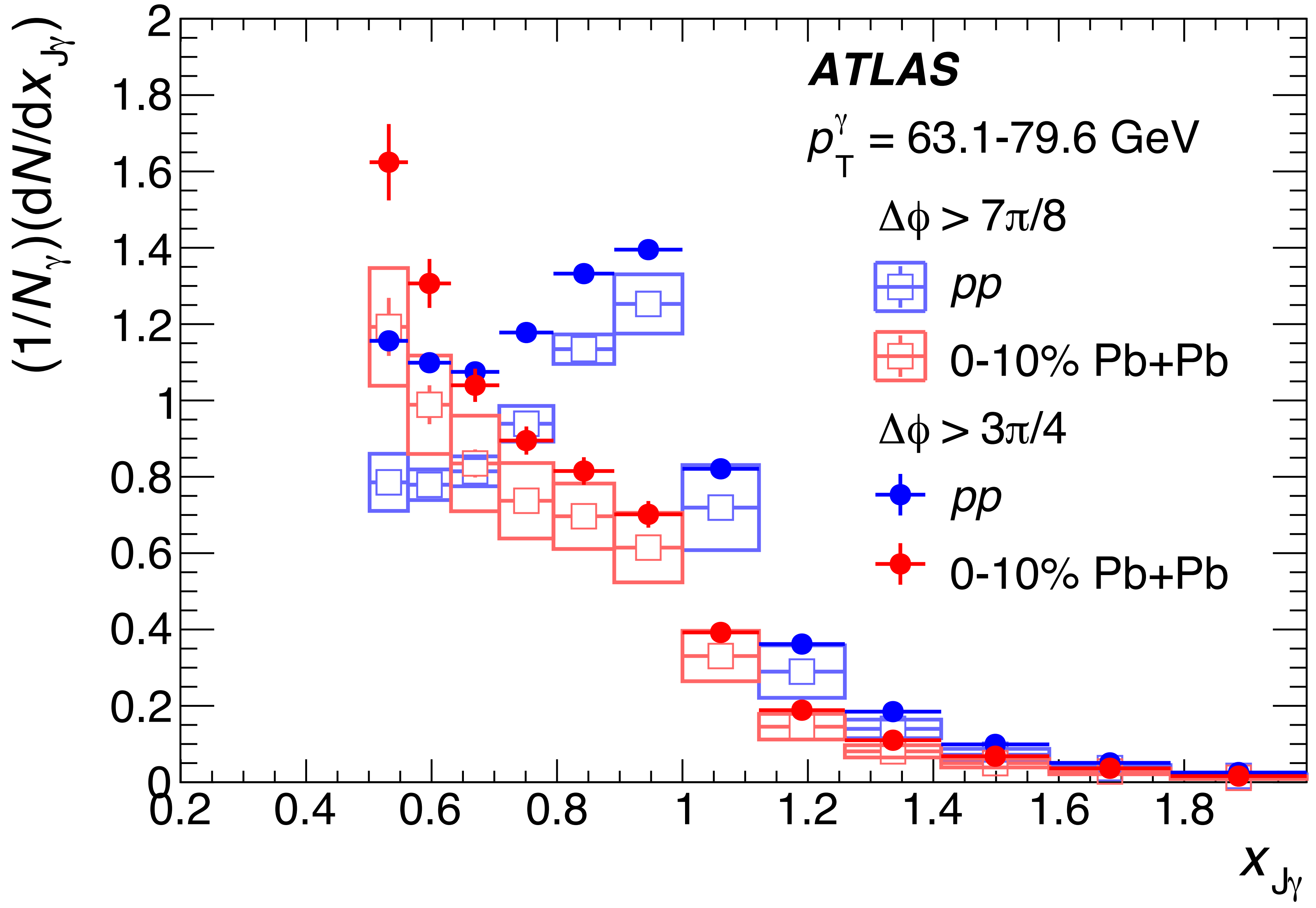


Photon does not lose energy
Clean selection of initial p_T

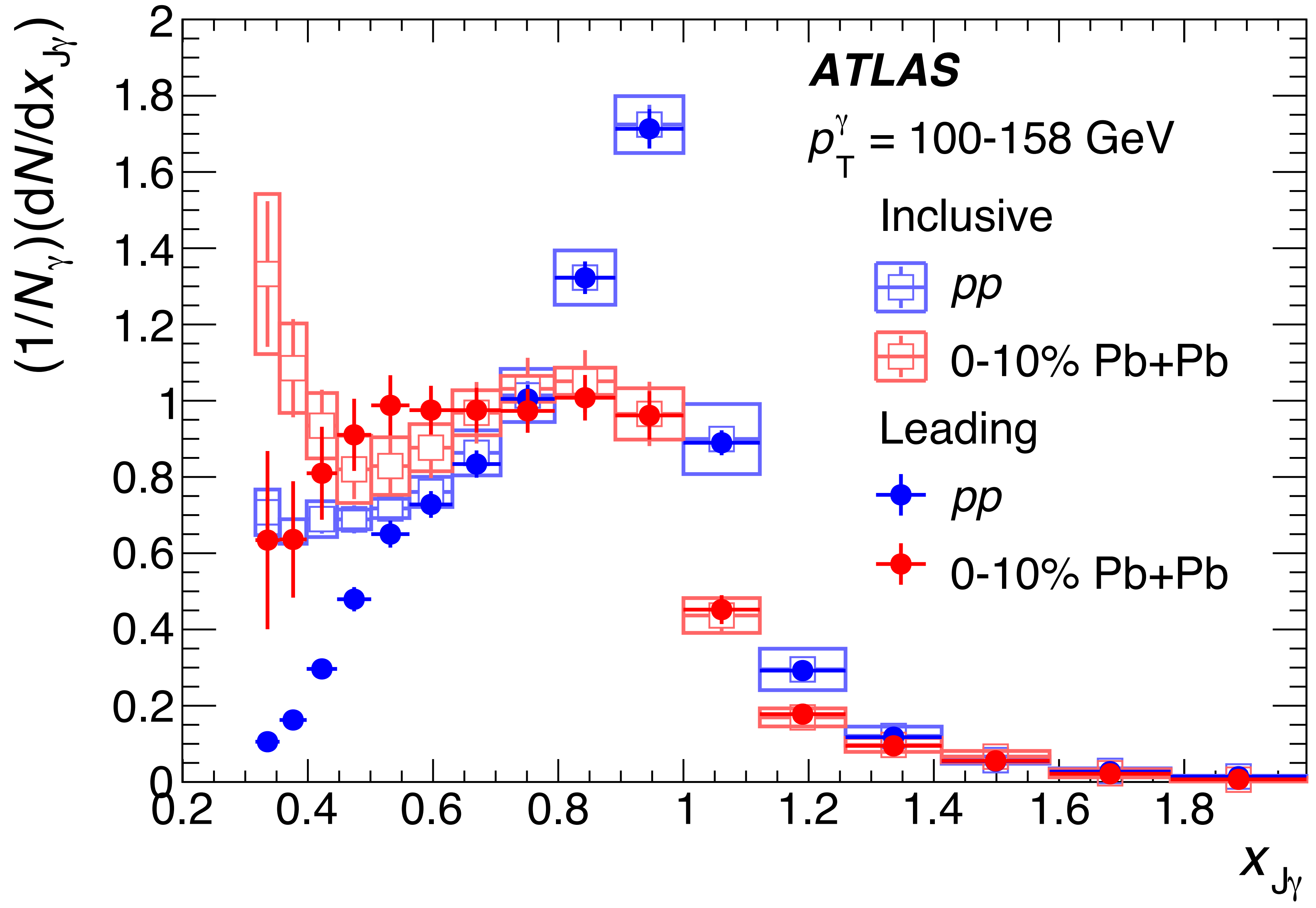
(same can be done with Z-jet)

Gamma-jet momentum balance

60 GeV trigger photon



100 GeV trigger photon



ATLAS, Phys.Lett. B789 (2019) 167-190

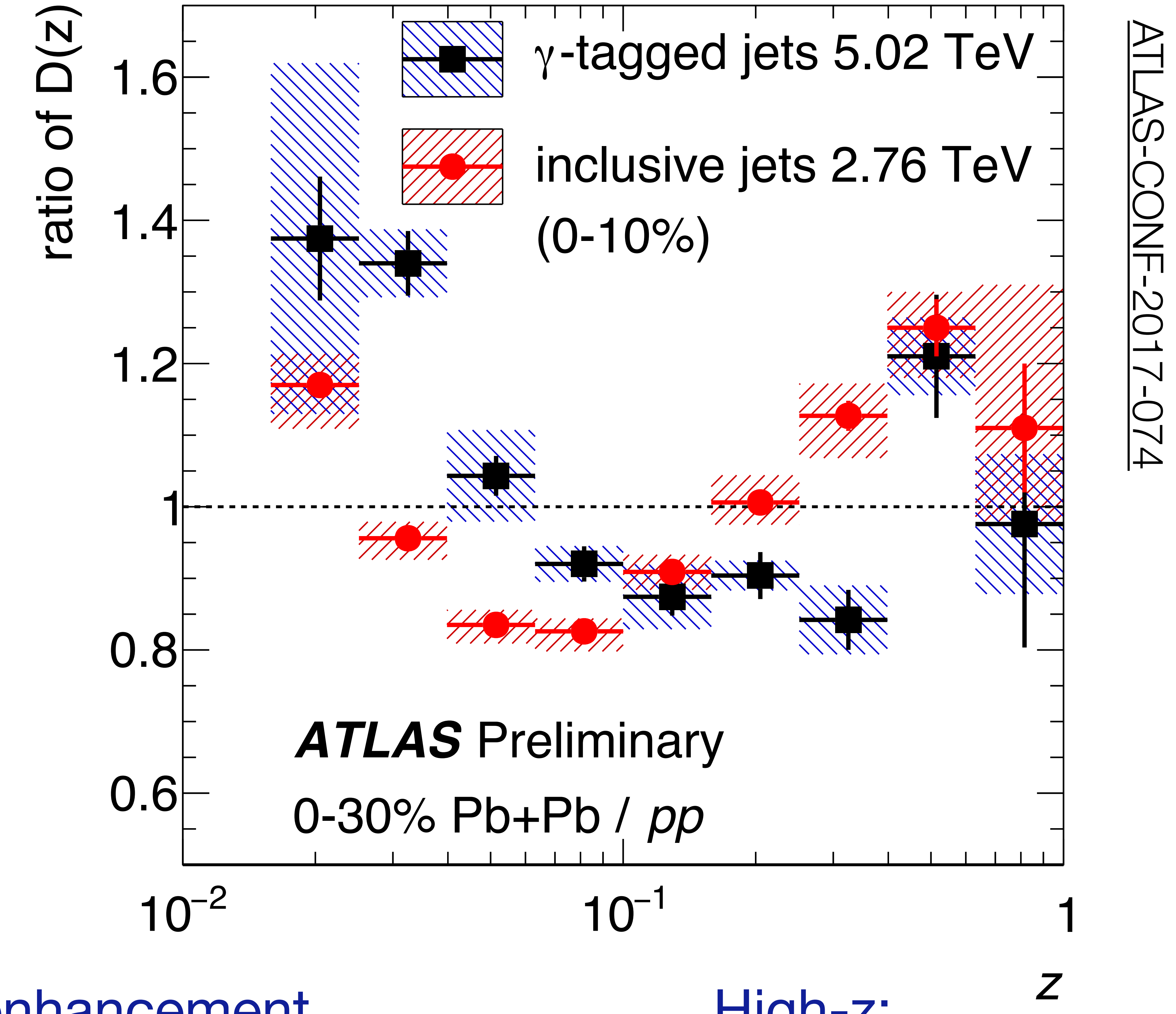
(peak at low x_{Jg}
from additional jets)

Also allows to explore energy dependence of lost energy

Looking inside jets: recoil fragment distributions

CMS, arXiv:1801.04895

Recoil fragment distributions: γ-jet and di-jet



Low-z: enhancement of soft fragments

High-z:
di-jets: increase of hard fragments
y-jet: suppresion of hard fragments

Different energy loss bias; selection quark vs gluon jets

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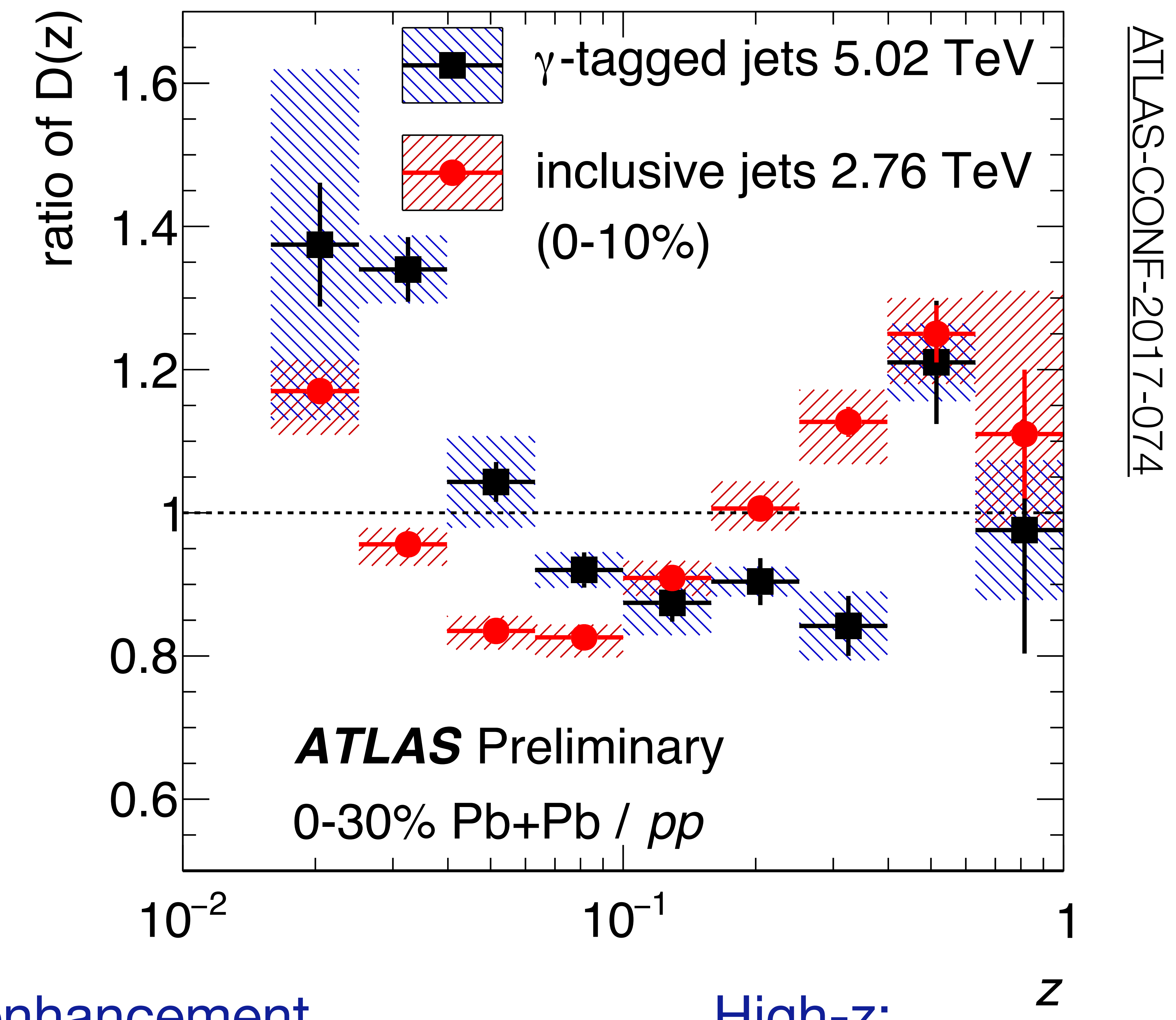
γ-jet, $p_{T\gamma}$ > 60 GeV



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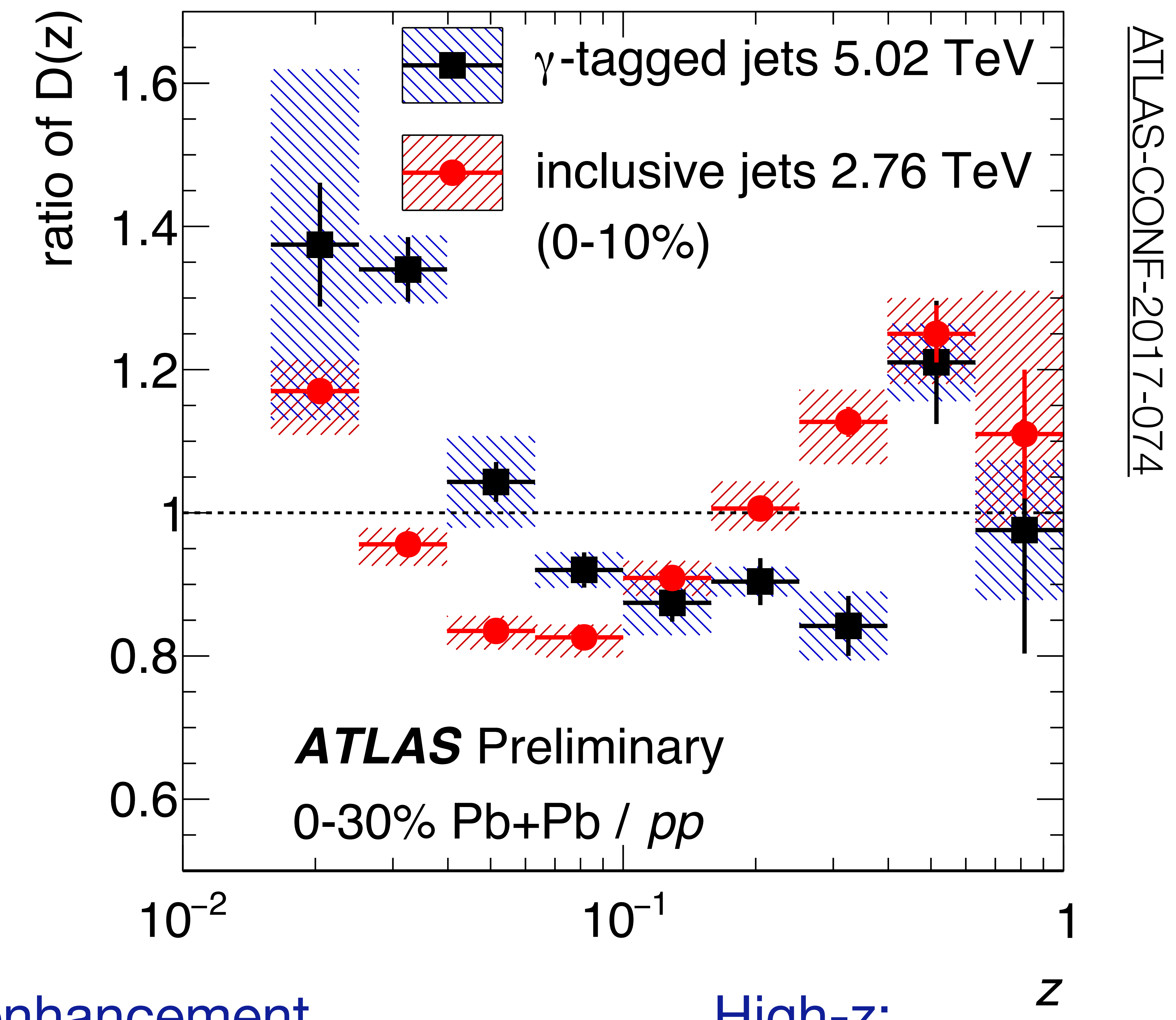

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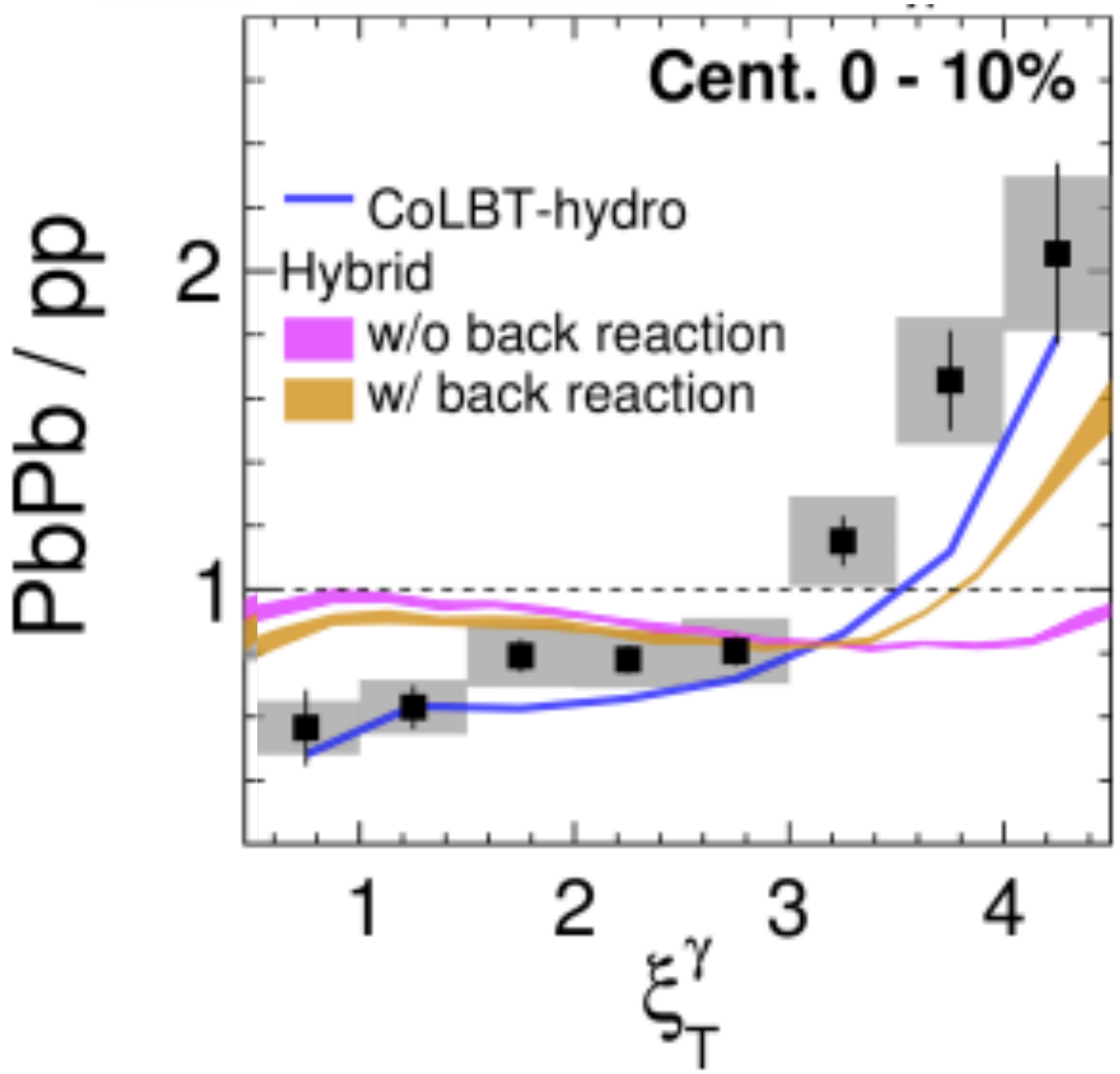

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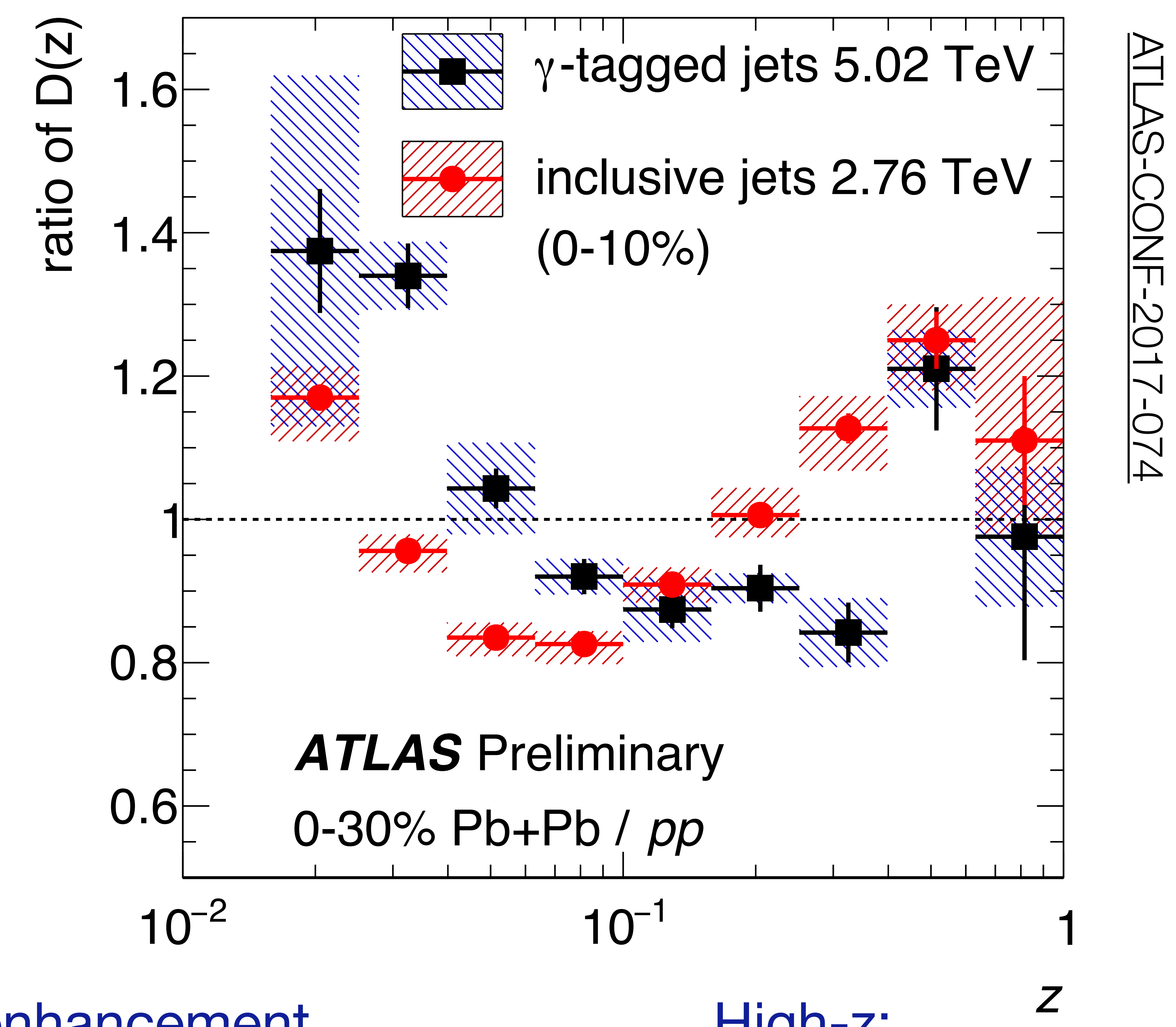

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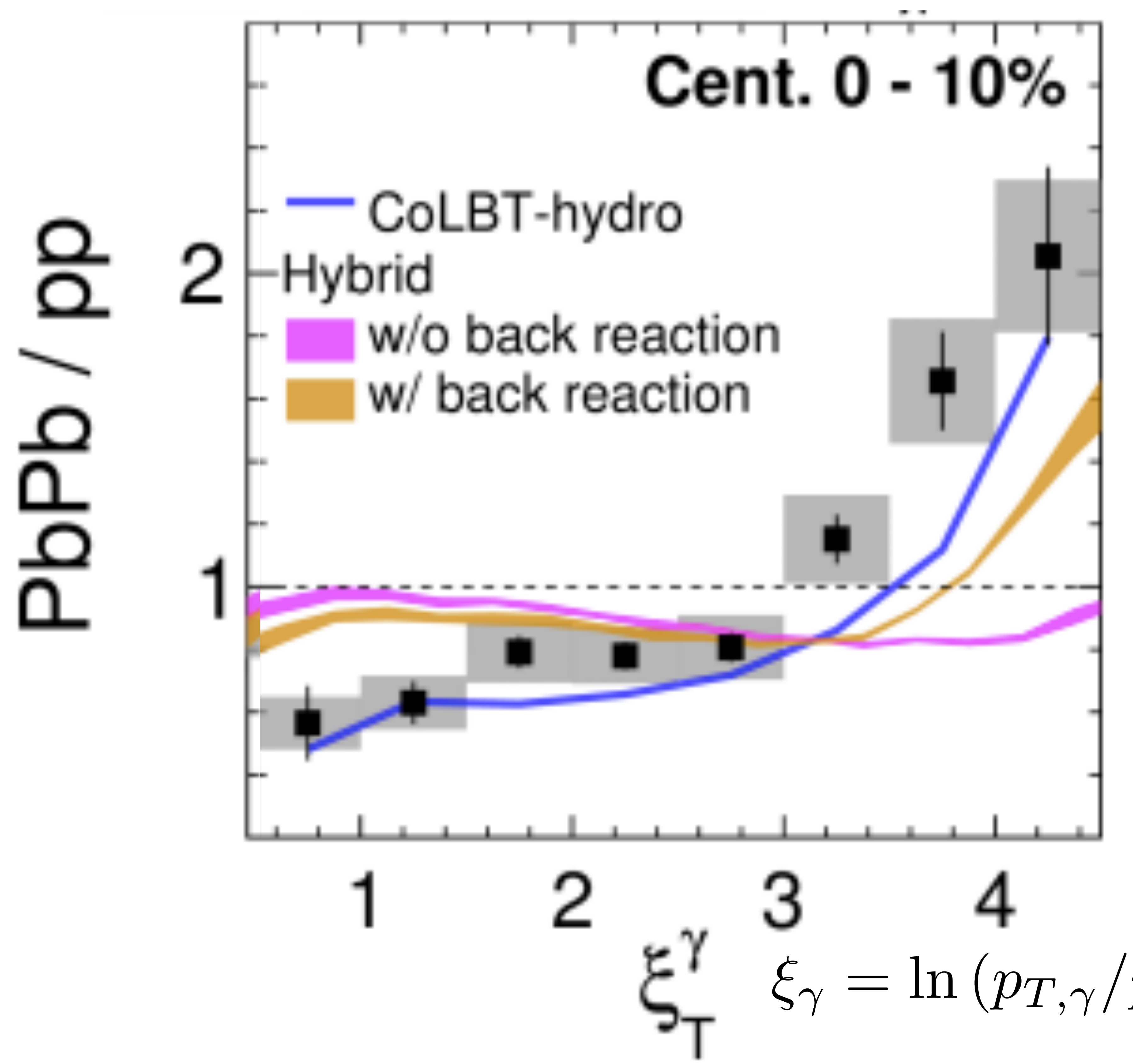

$\xi_\gamma = \ln\left(p_{T,\gamma}/p_{T,h}\right)$

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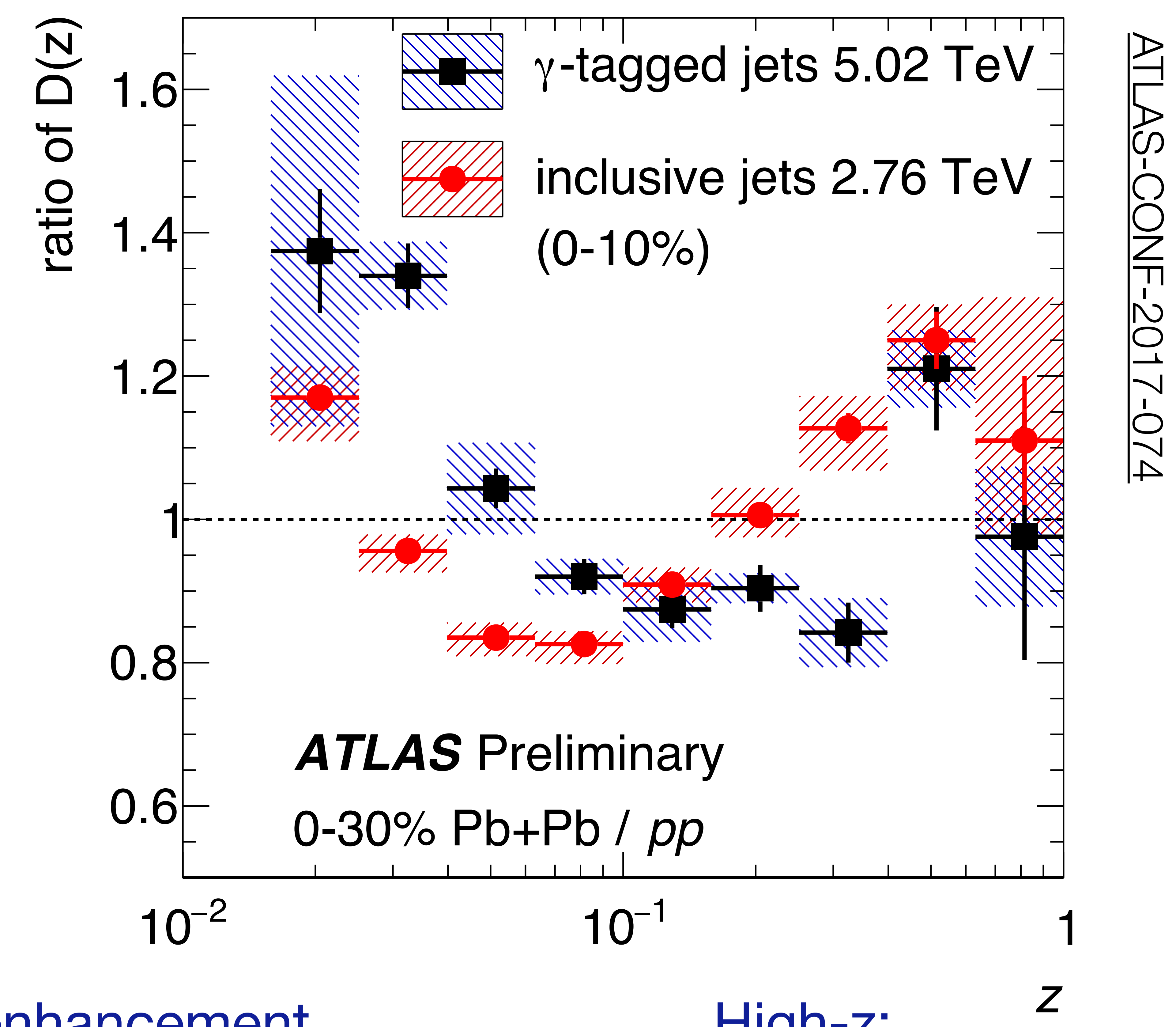

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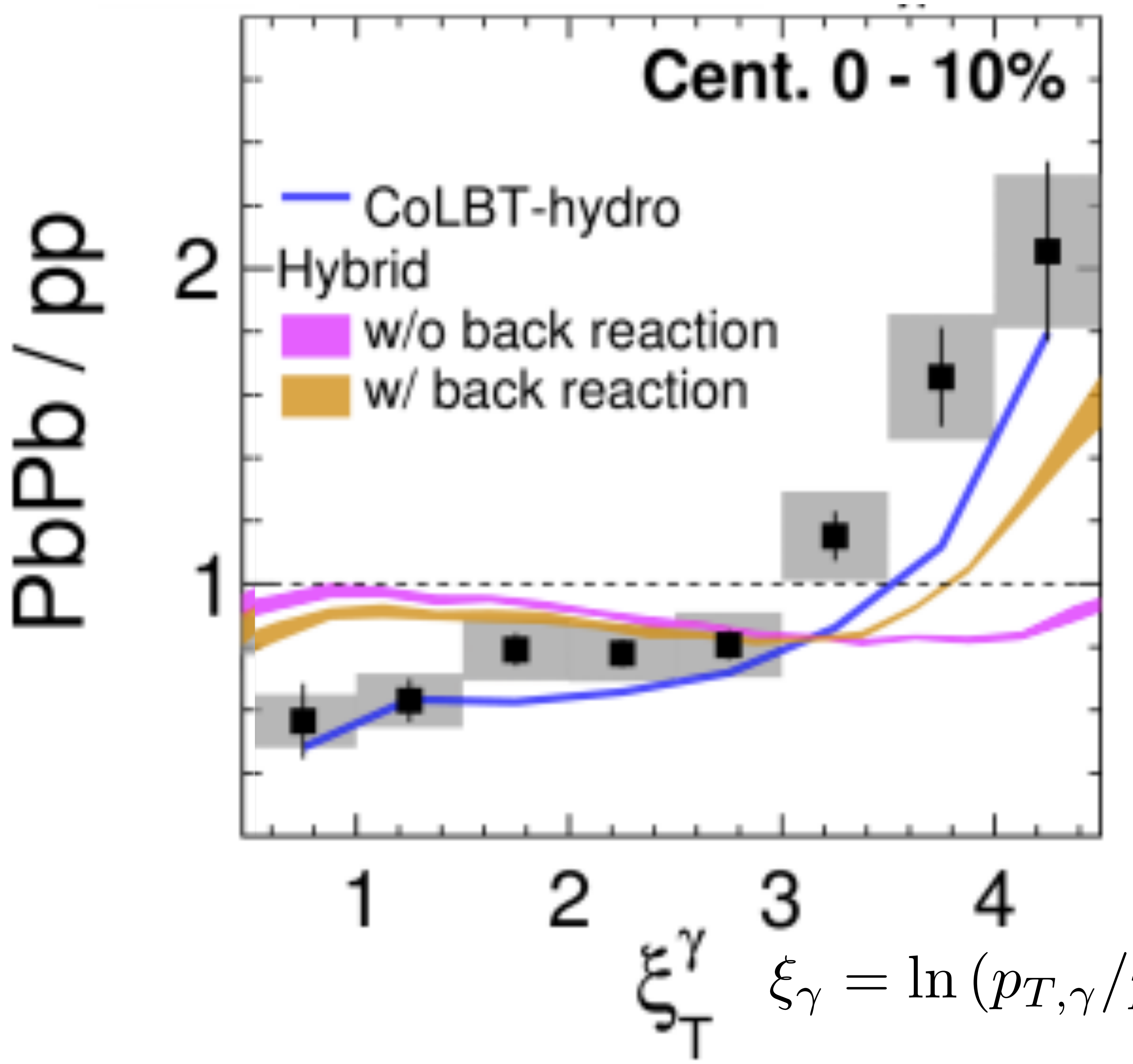

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Low-z: enhancement of soft fragments

High-z:
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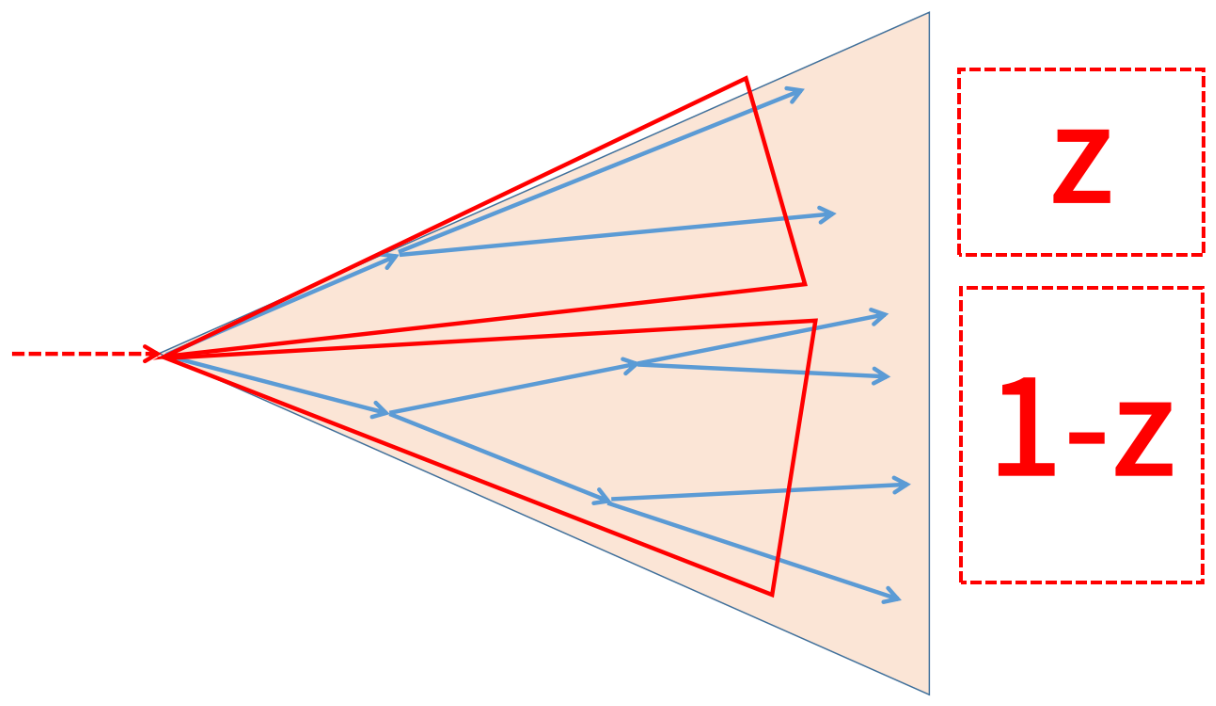
Models capture trends when soft fragments are included

Different energy loss bias; selection quark vs gluon jets

Jet substructure: Exploring the parton shower

ALICE, arXiv:1905.02512

Jet structure studied by declustering:



Momentum fraction

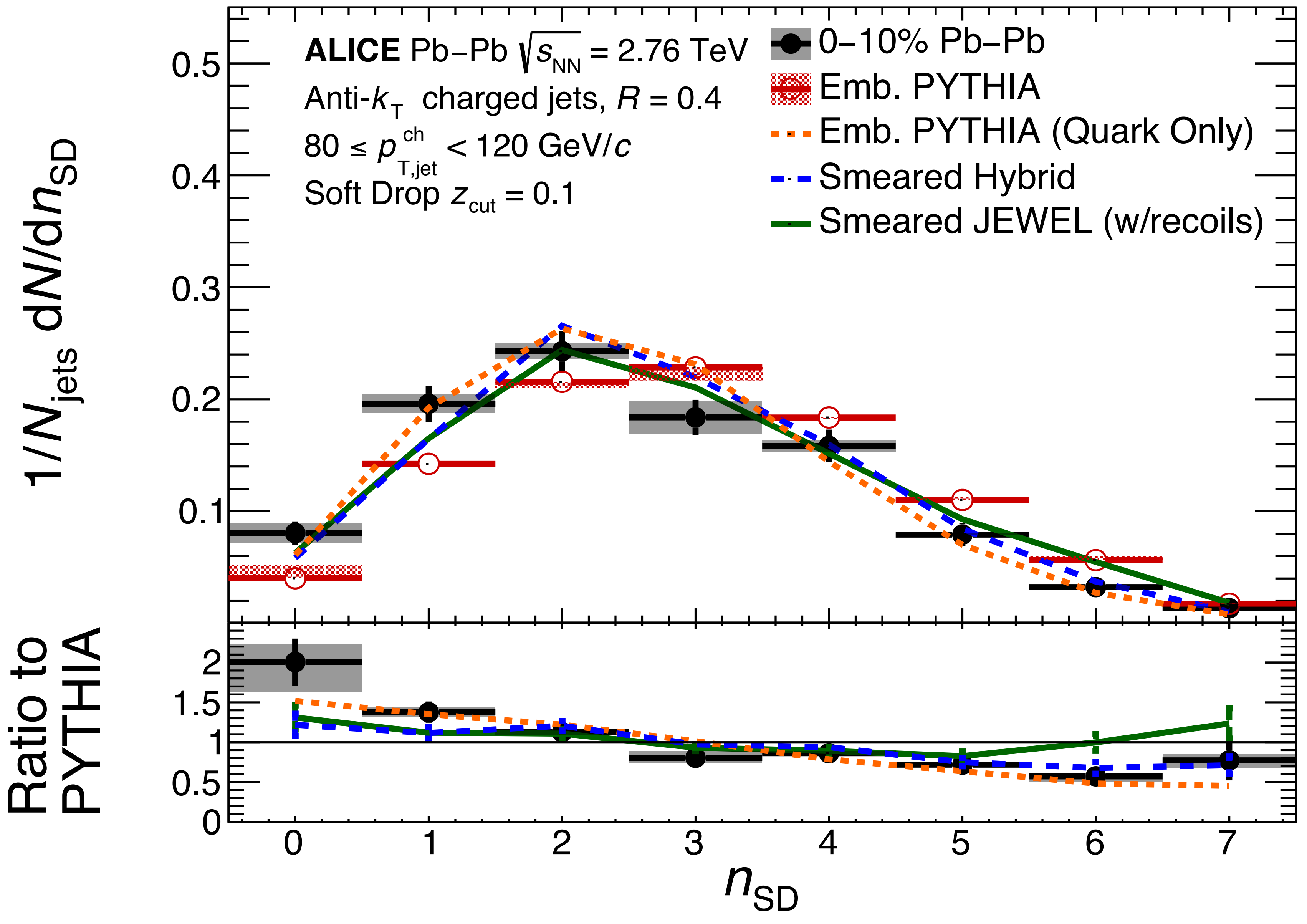
$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

$$z > z_{cut}$$

Larkoski et al, PRD 91, 111501

Re-wind clustering;
- remove soft splittings 'grooming'
- select (semi-)hard splittings

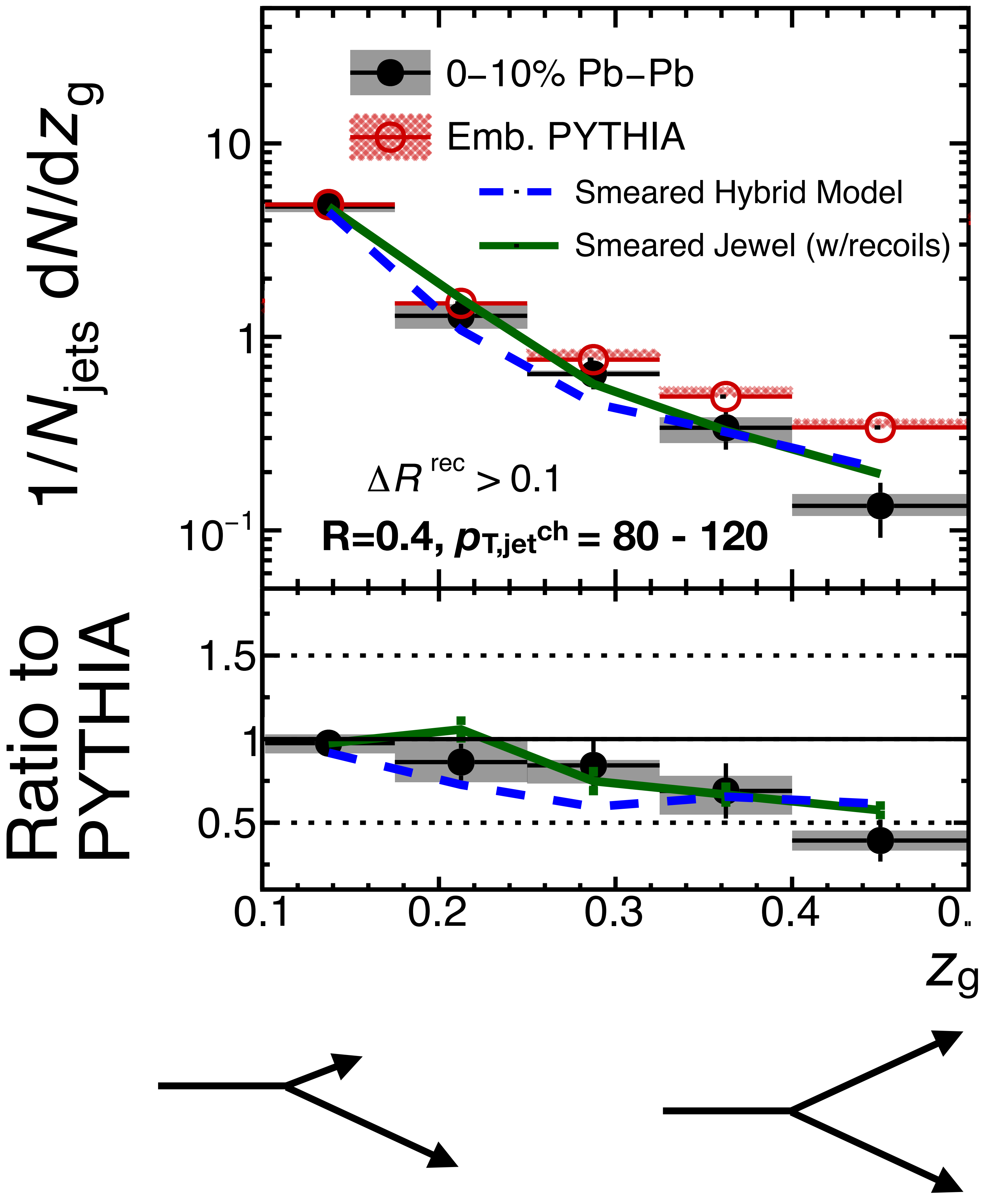
n_{SD}: number of splittings



n_{SD} similar in pp and PbPb

No extra splittings visible

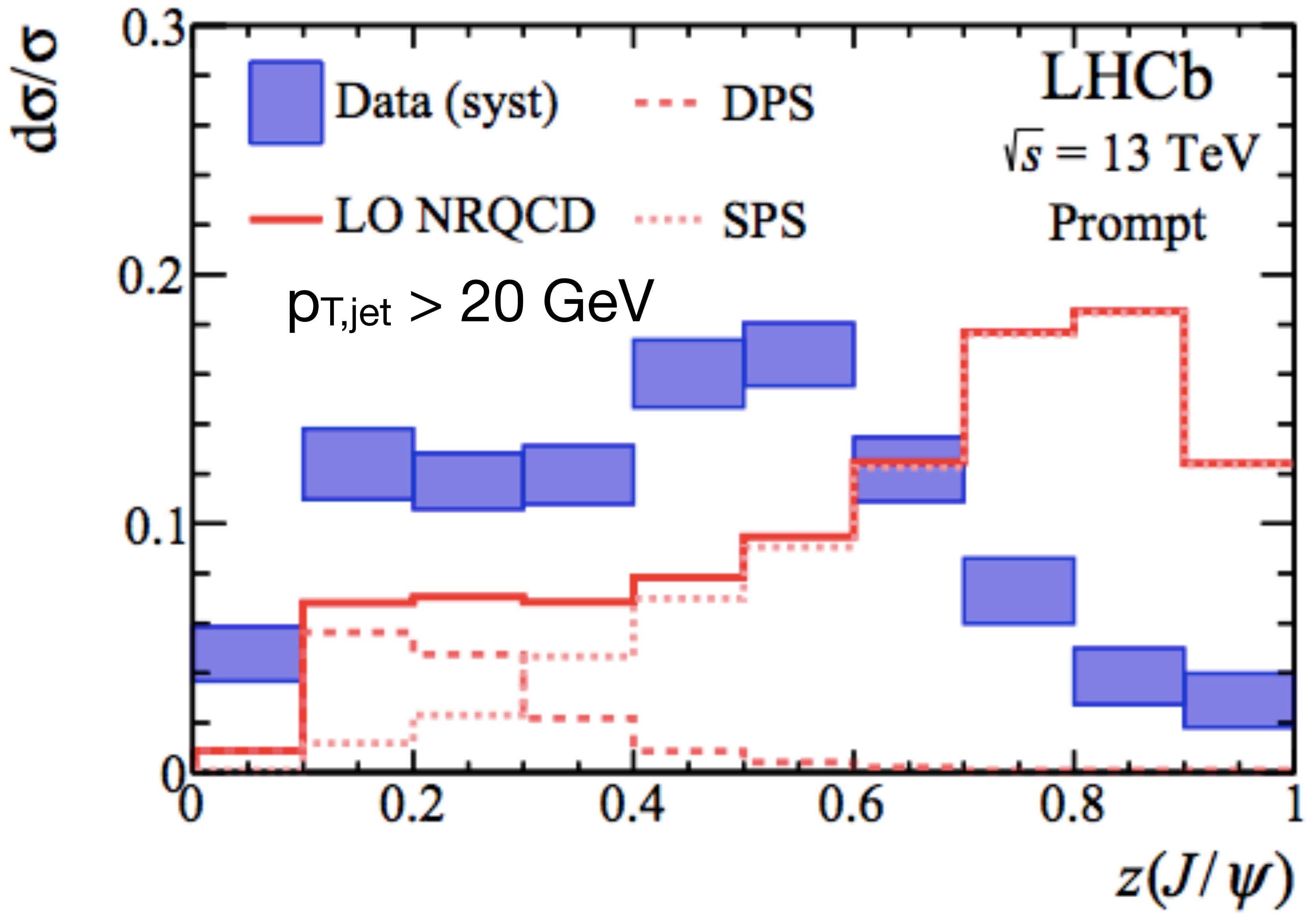
Softdrop momentum fraction



Symmetric splittings reduced:
Formation time effect?

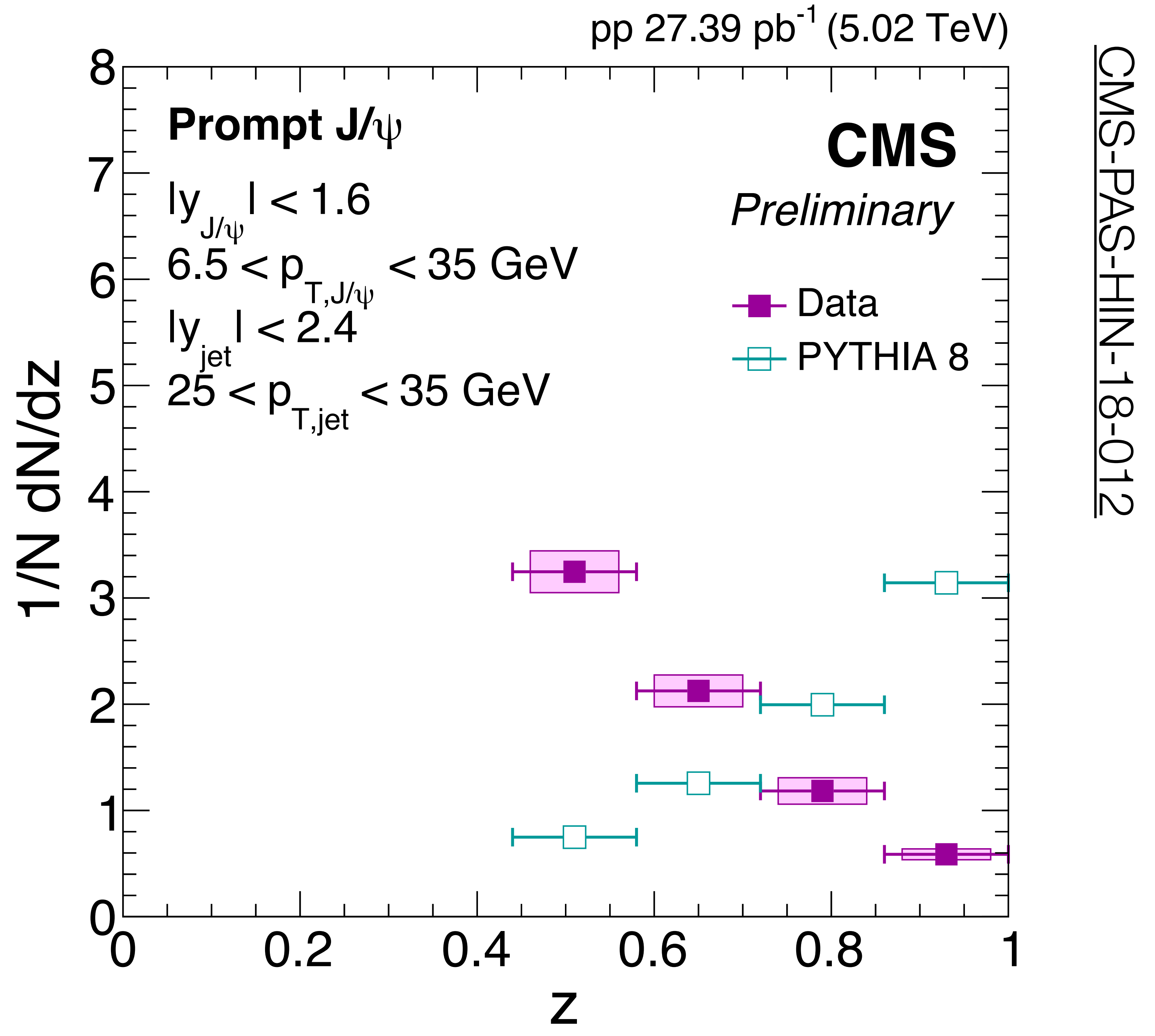
Production mechanism: Heavy flavour in in jets

J/ψ in jets (pp collisions)



LHCb, PRL 118, 192001 (2017)

J/ψ in jets (pp collisions)



Initial expectation: color-singlet J/ψ could be produced without accompanying fragments
New insight: high-p_T J/ψ produced in jets

Similar studies ongoing with open heavy flavour

Small systems: pp and p-Pb

Exploring the limits of fluid/collective behaviour

Multiplicity production in pp

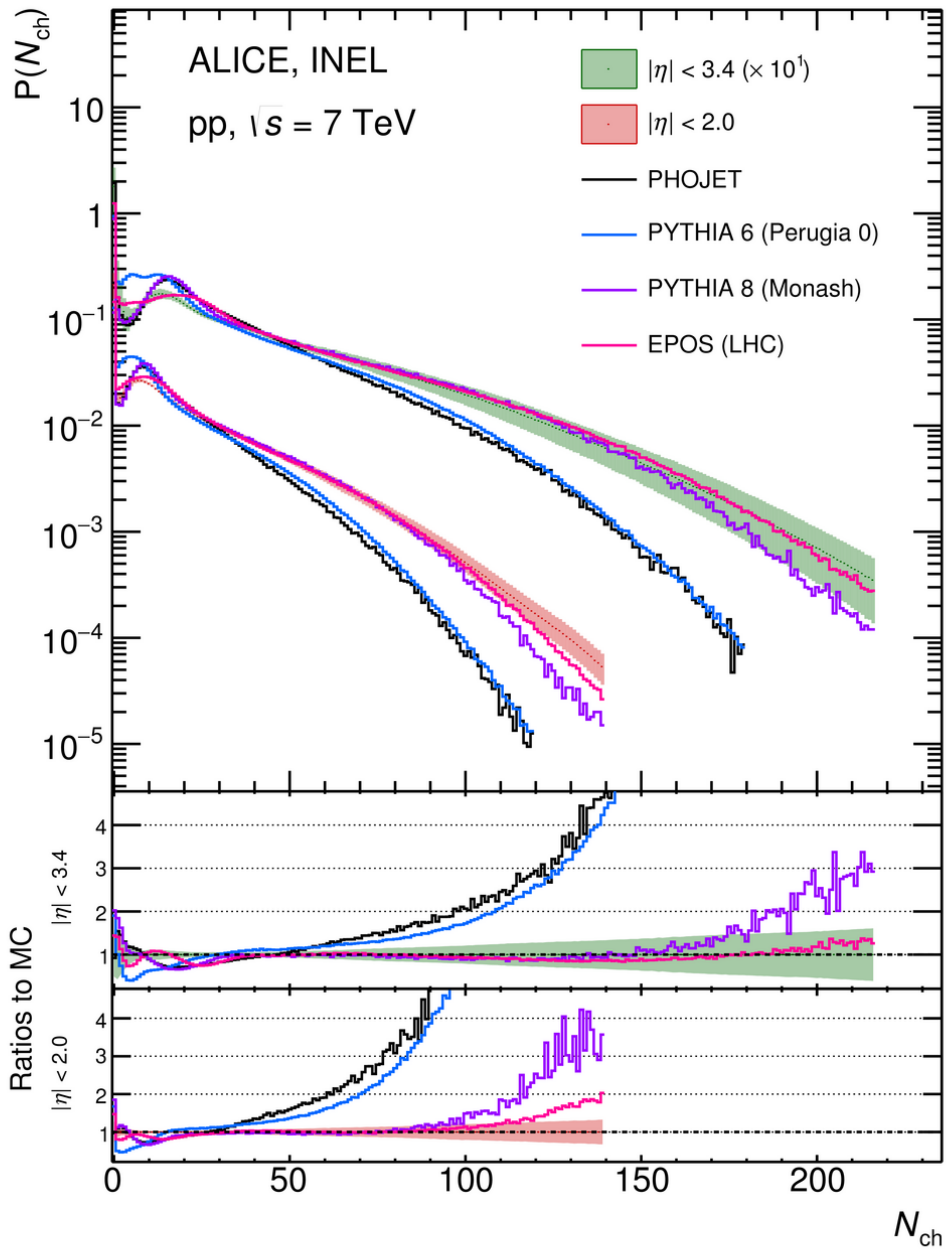
Multiplicity distribution is very broad:

- Average multiplicity small: 5-10 particles at mid rap
- Some events have > 100 particles

Very large densities also in pp!

What is the mechanism?

Single hard scattering + underlying event?
Multiple parton interactions?
Underlying even fluctuations?

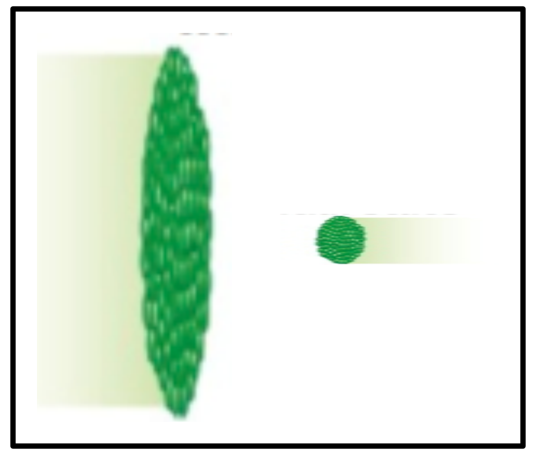


Physics of small and large colliding systems

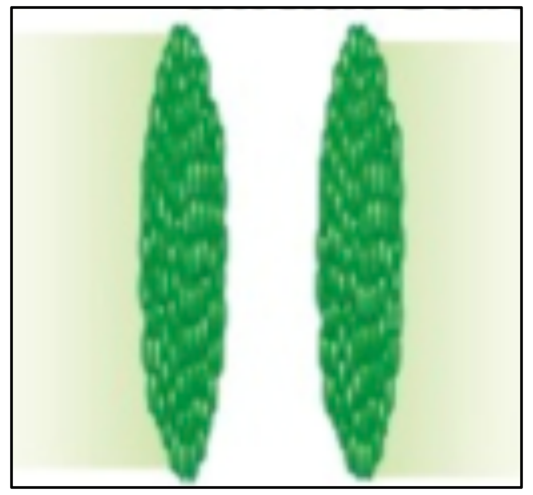
"AA" models
Hydrodynamic models
Statistical models
…

pp

p-Pb

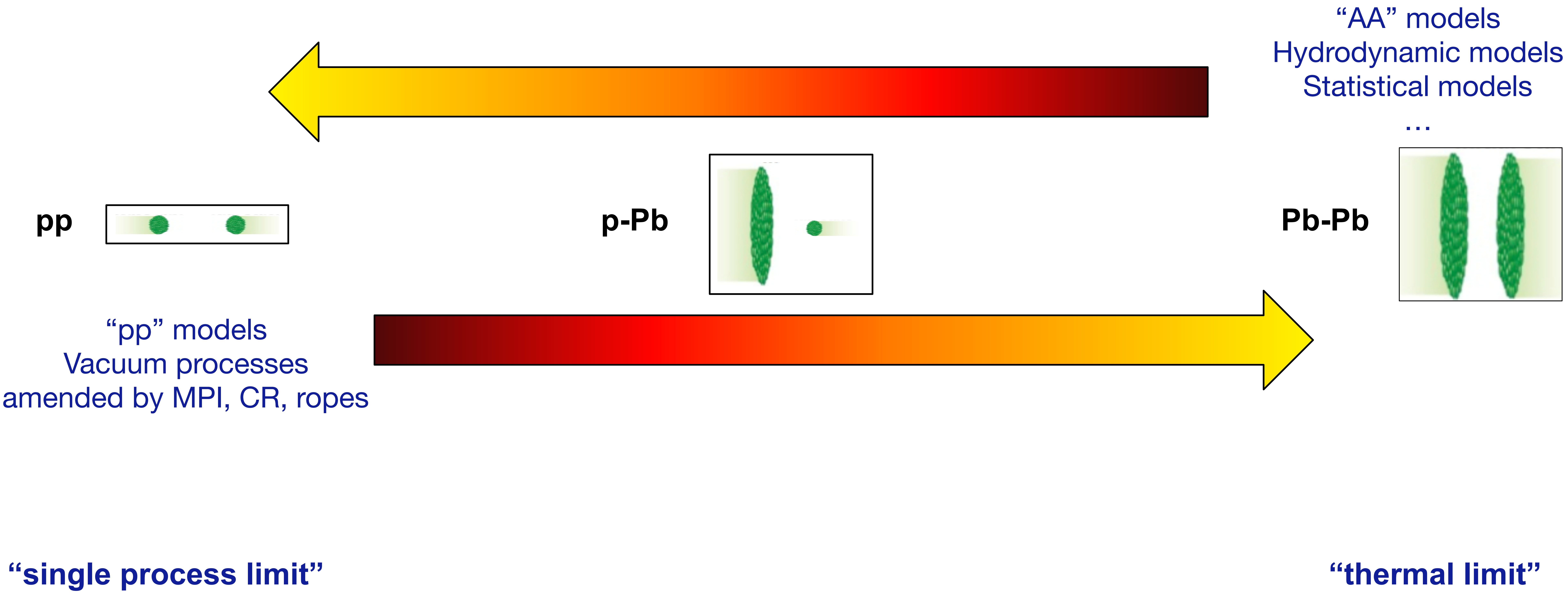


Pb-Pb



"pp" models
Vacuum processes
amended by MPI, CR, ropes

Physics of small and large colliding systems



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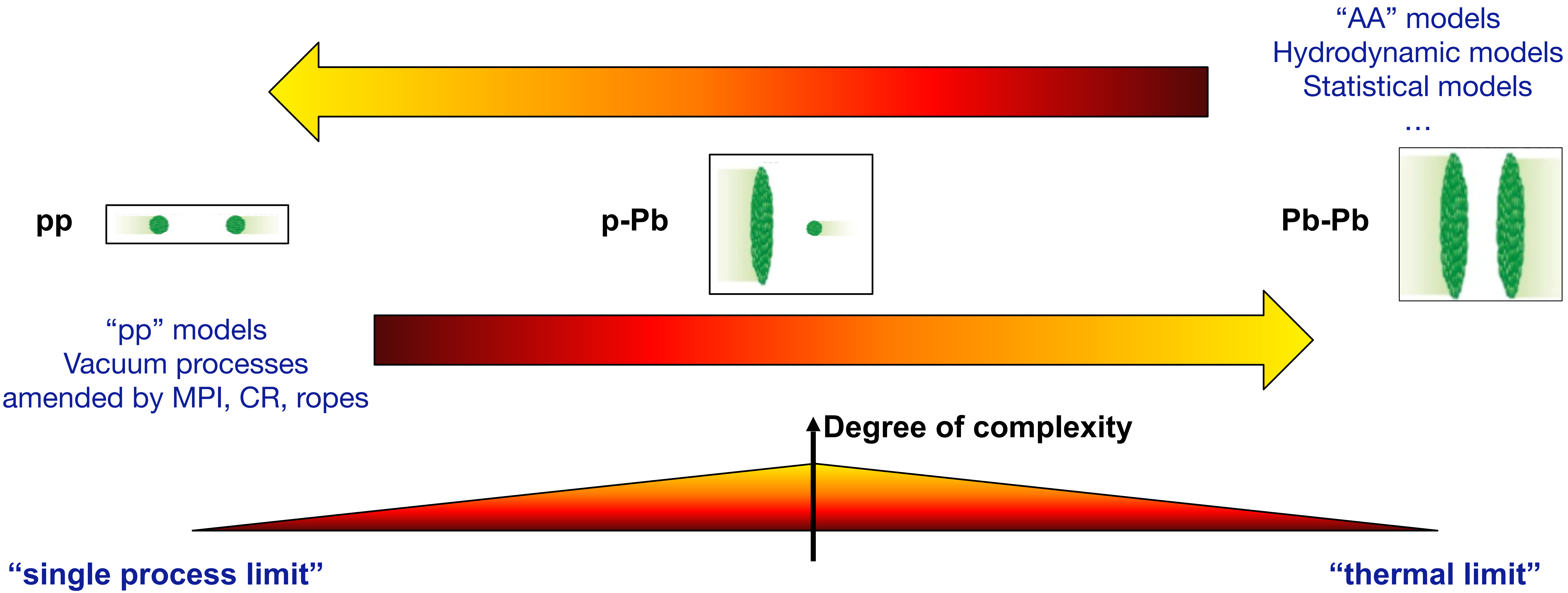

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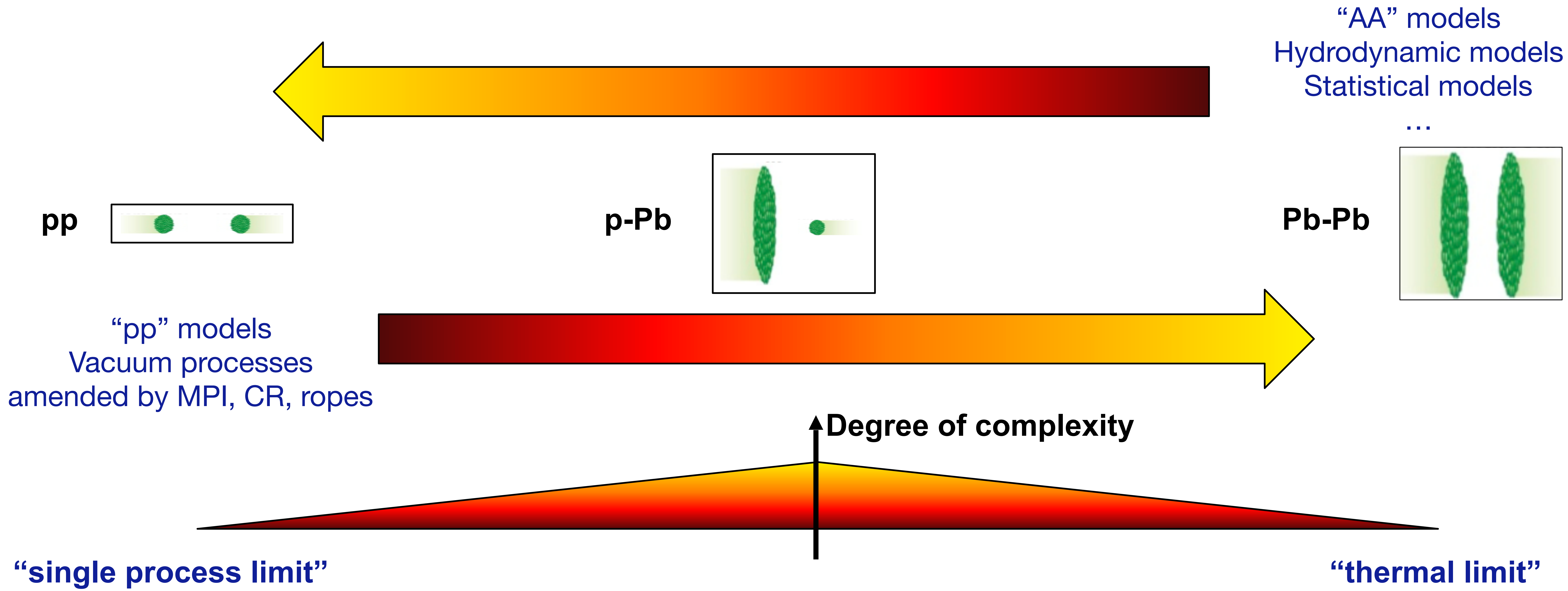
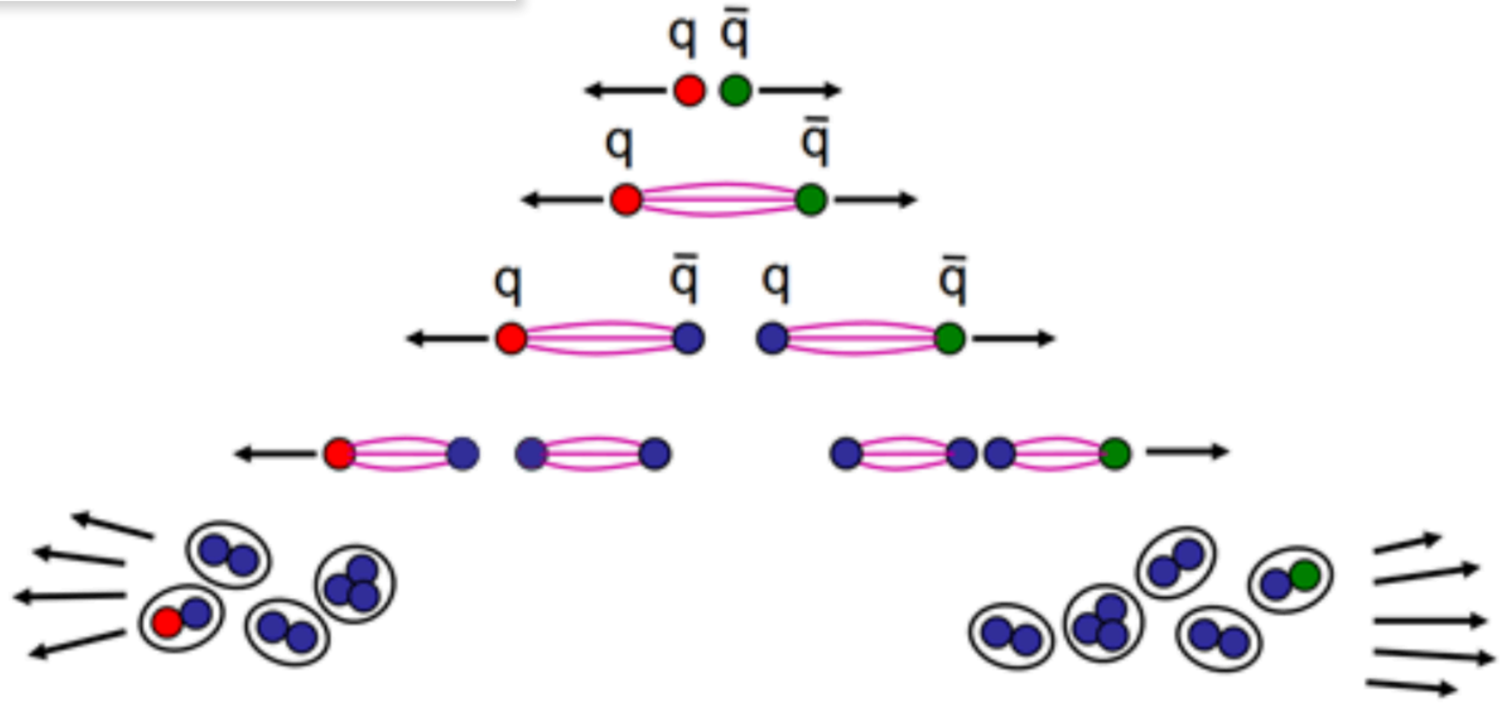


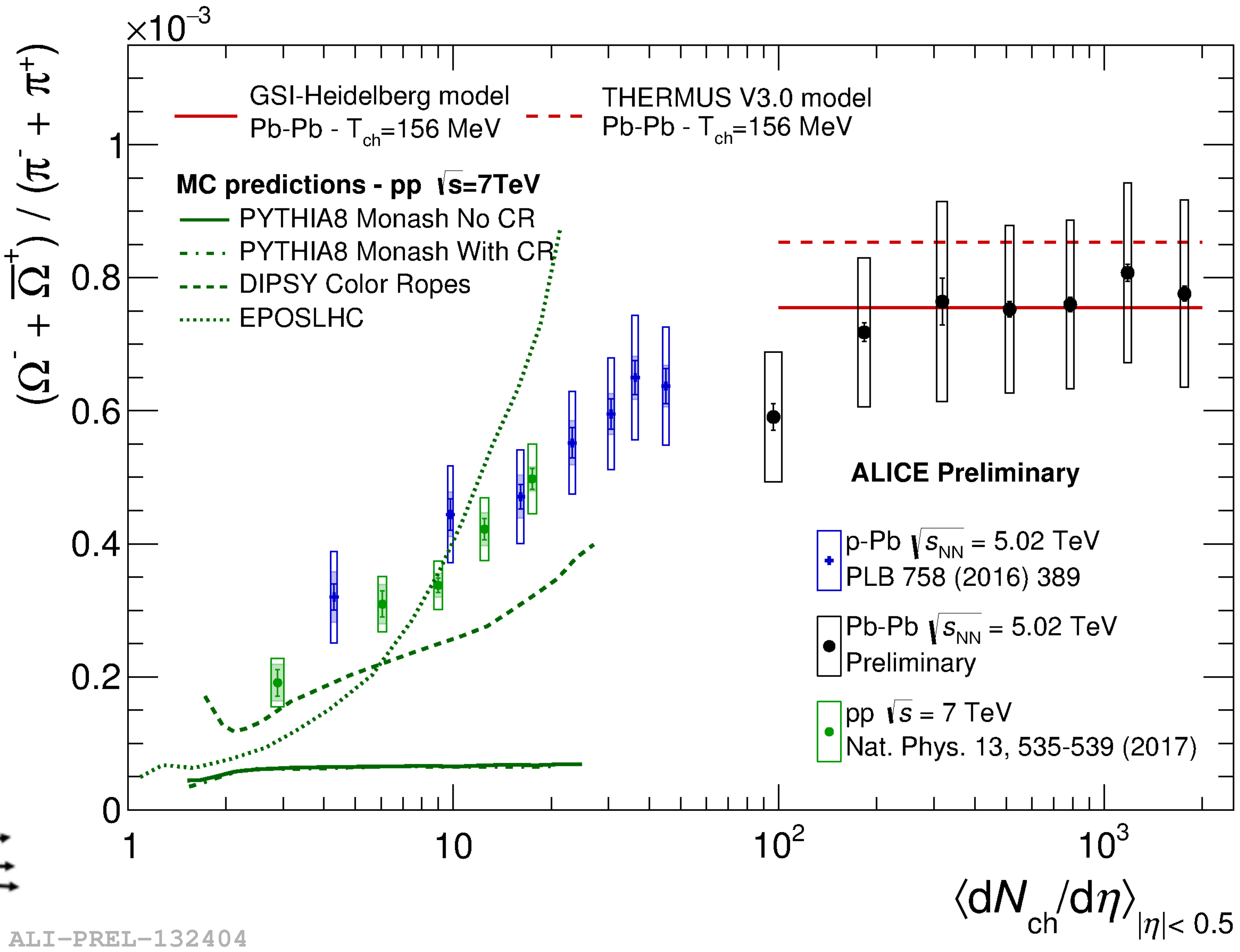
Underlying QCD is the same – different limits
Opportunity: stress test models/understanding

Example: strangeness enhancement

pp, p-Pb:
strong dependence of
strange baryon content
on multiplicity
What is the mechanism?

$$P \propto \exp\left(-\frac{\pi m_T^2}{\kappa}\right)$$





Large systems:
Yields described by
thermal model
'phase space dominance'

Baseline Pythia: no change in strange baryon content
Driven by hadronisation probability/string breaking
No final state interactions

Color Ropes, EPOS LHC:
Increasing density leads to larger strangeness content

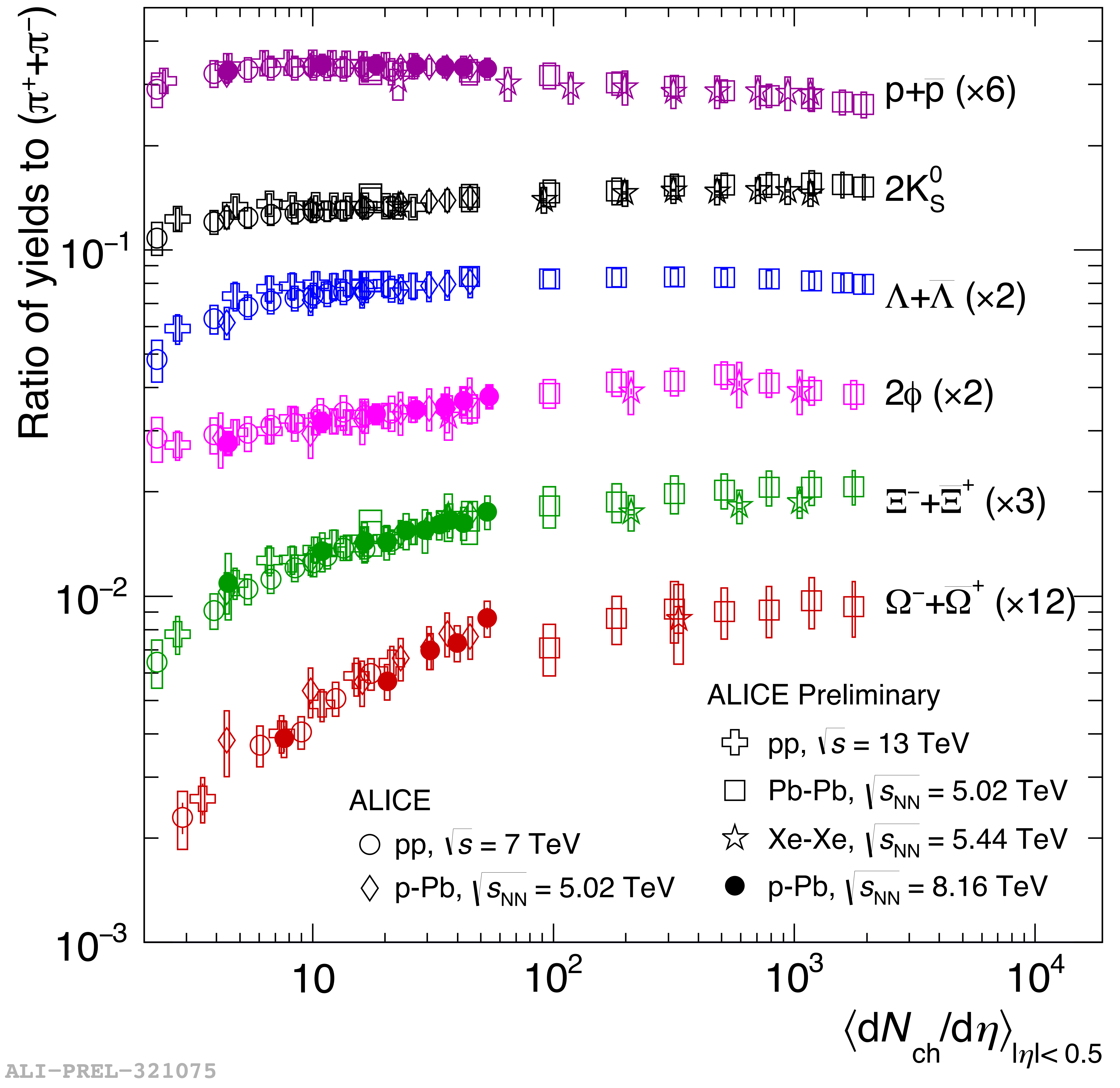
Strangeness production vs multiplicity

Is the increase driven by strangeness or baryon content?

Effect increases with strangeness content:
Ω > Ξ > ϕ

Very weak/no effect for single strange particles
K, Λ

No increase of p/π: not a pure ‘baryon effect’



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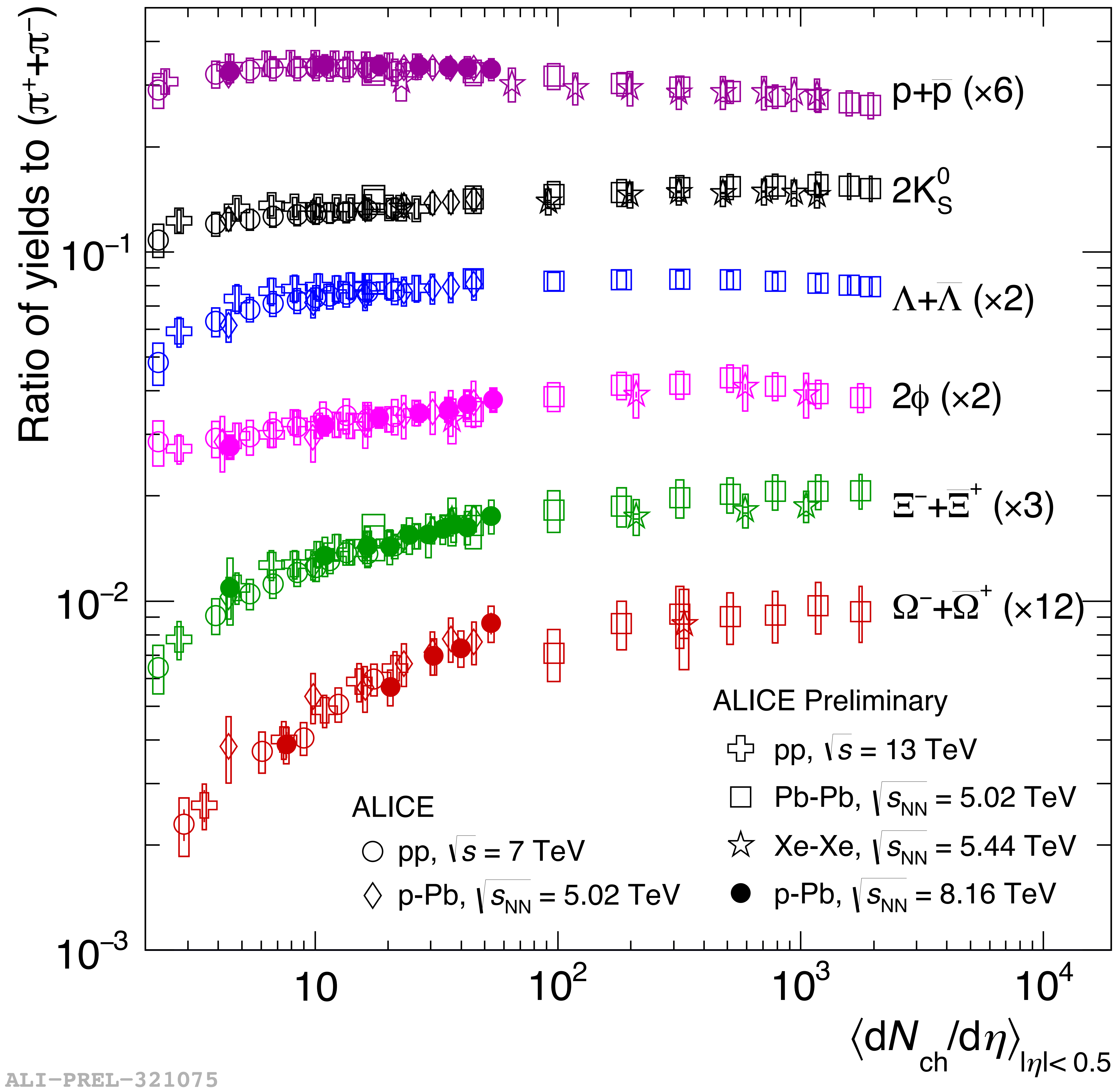
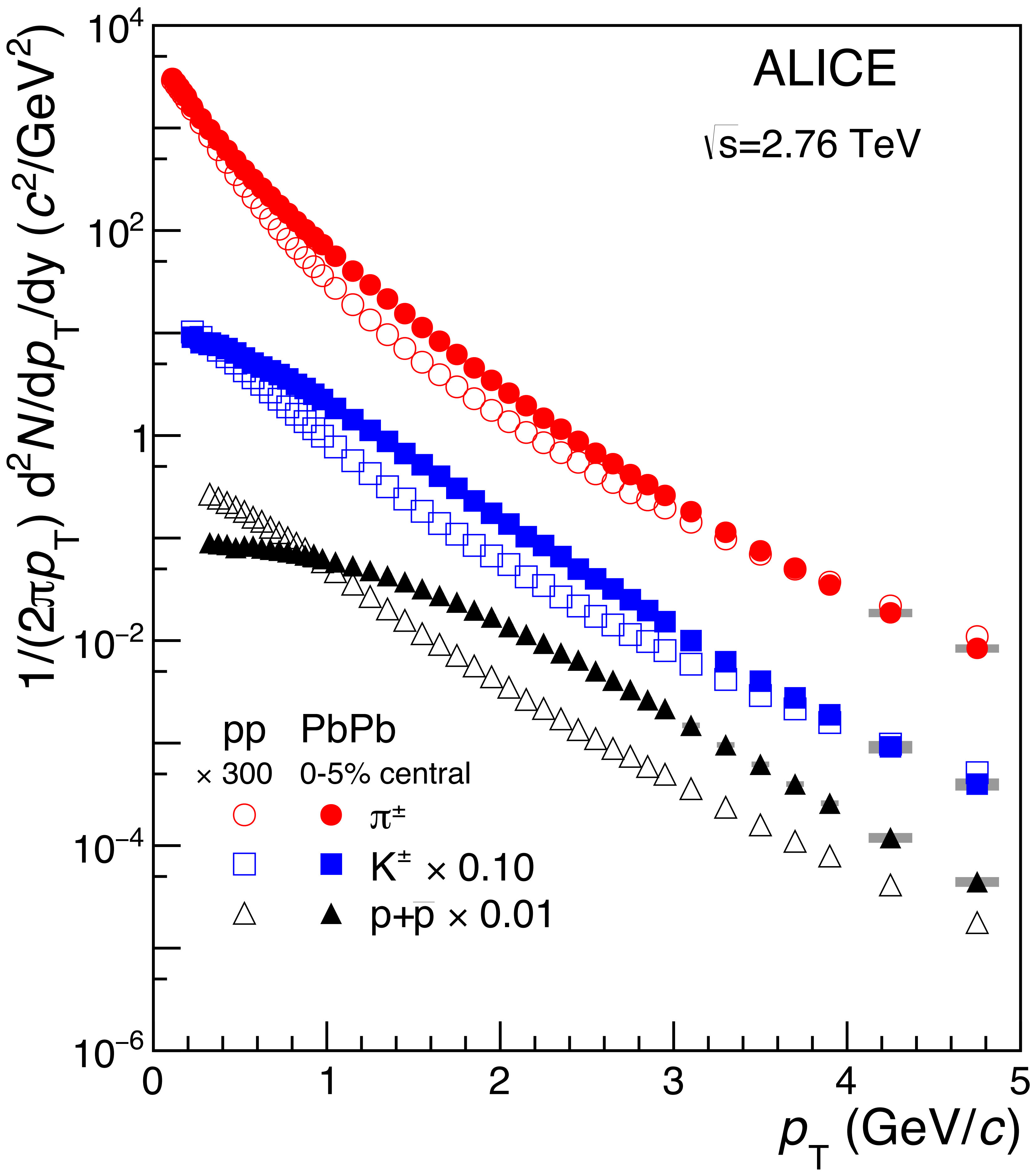
Puzzling situation: a new insight
in baryon and strangeness production/hadronisation
may emerge!



Reminder: Radial flow

ALICE, PLB 736, 196

Spectra change from pp to Pb+Pb:
- Increase in mean p_T
- Larger effect for larger mass



First indication of collective behaviour

Pressure leads to radial flow

Same Lorentz boost (β) gives larger momentum for heavier particles

$(m_p > m_K > m_\pi)$

Multiplicity dependence of spectra

Shapes of the spectra change!

Selection of larger multiplicity (mostly low p_T)

Gives strong increase at high p_T

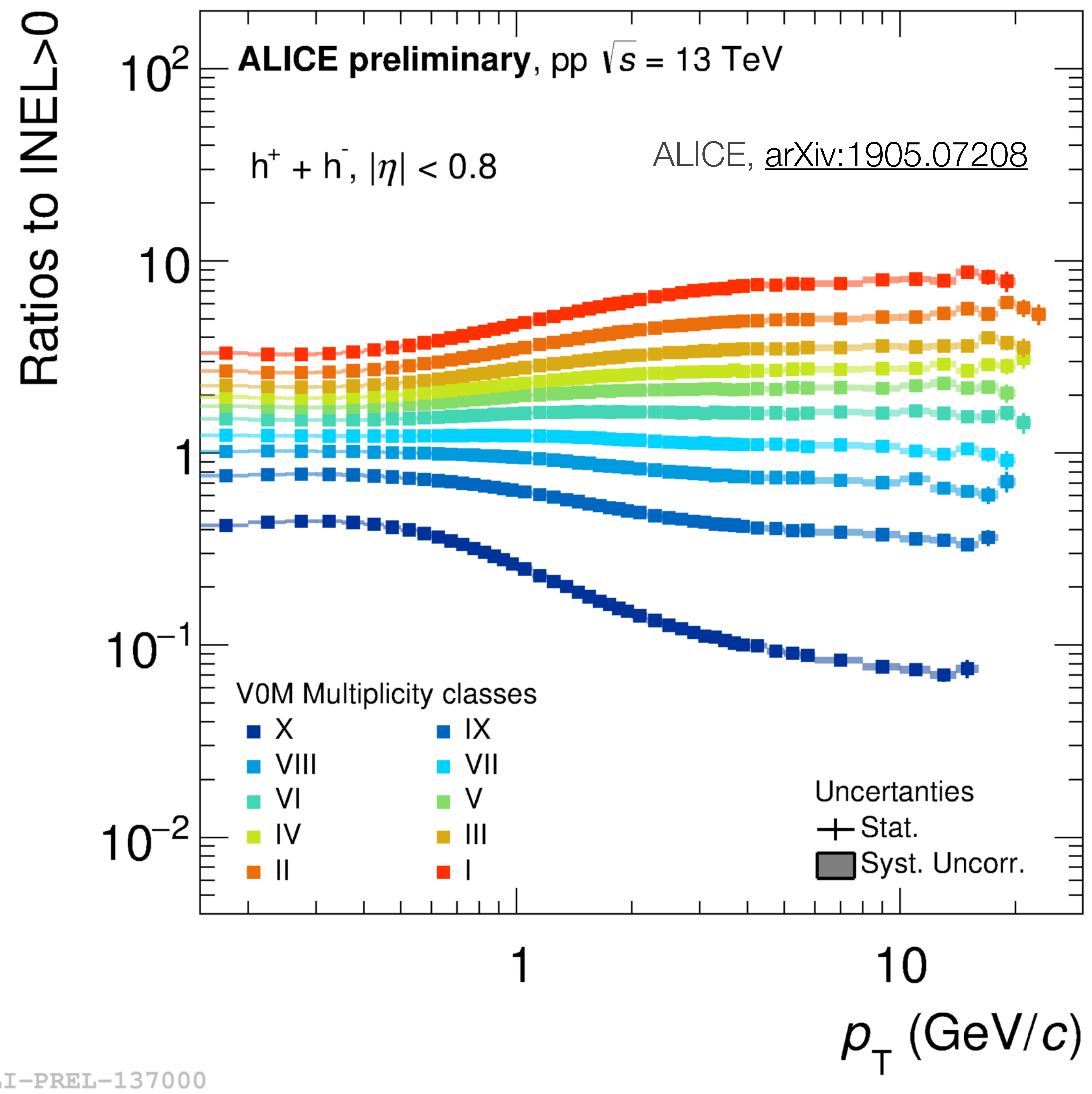
Correlation between

soft processes: multiplicity

and

hard processes: high p_T

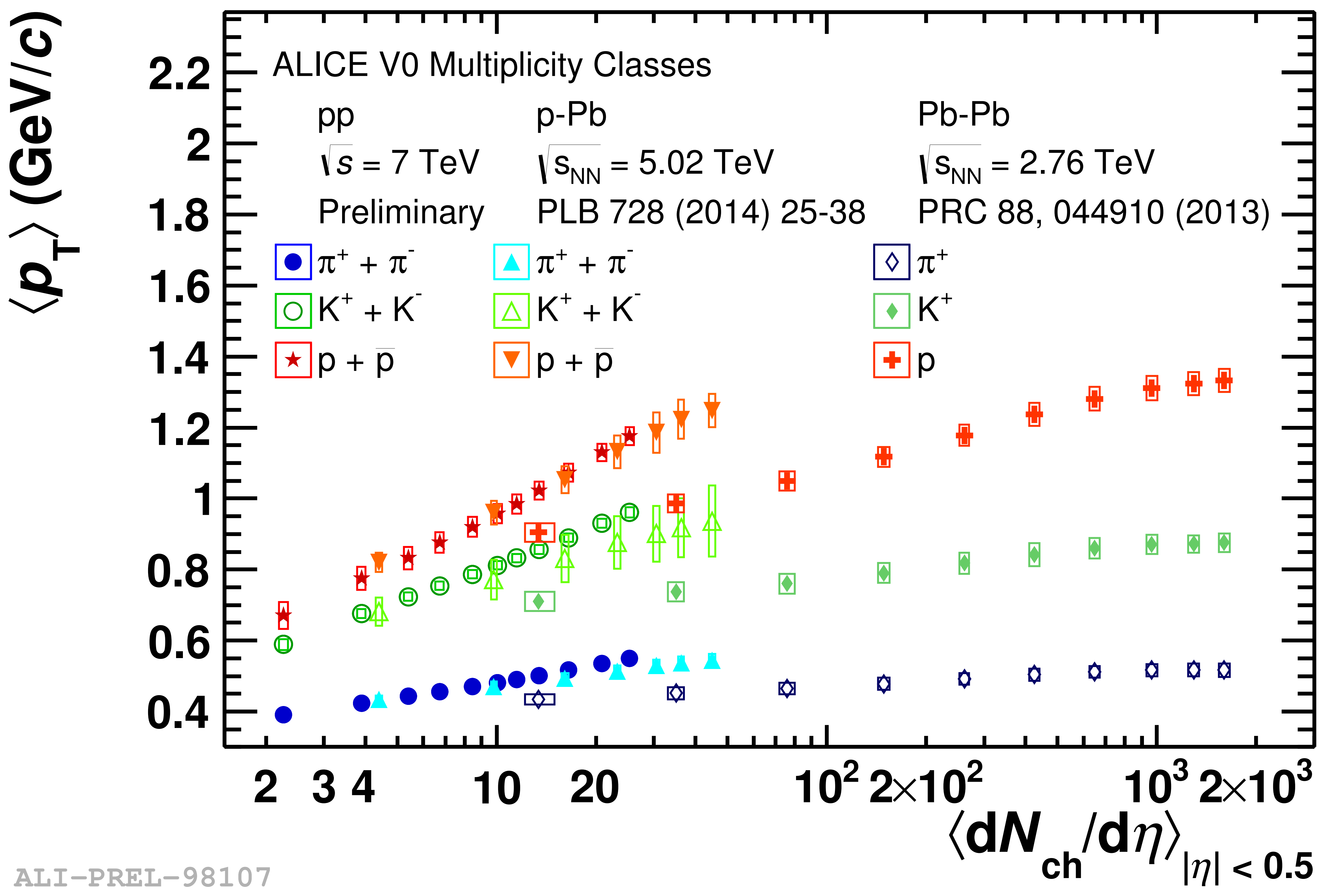
Ratio to MB spectra: ‘modulation of p_T spectra’



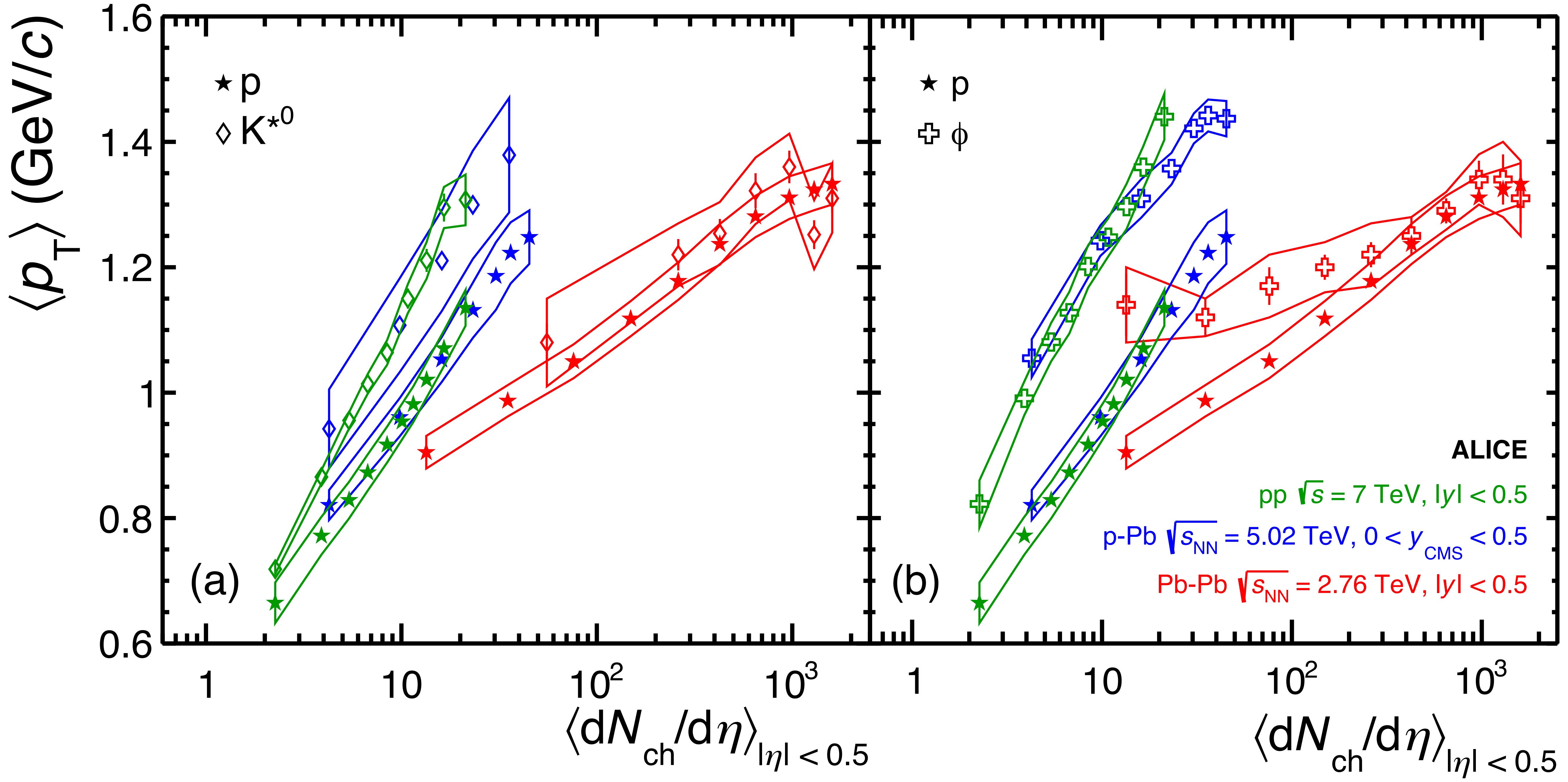
Mean p_T vs multiplicity — mass dependence

ALICE, Phys. Rev. C 99, 024906

pions, kaons, protons



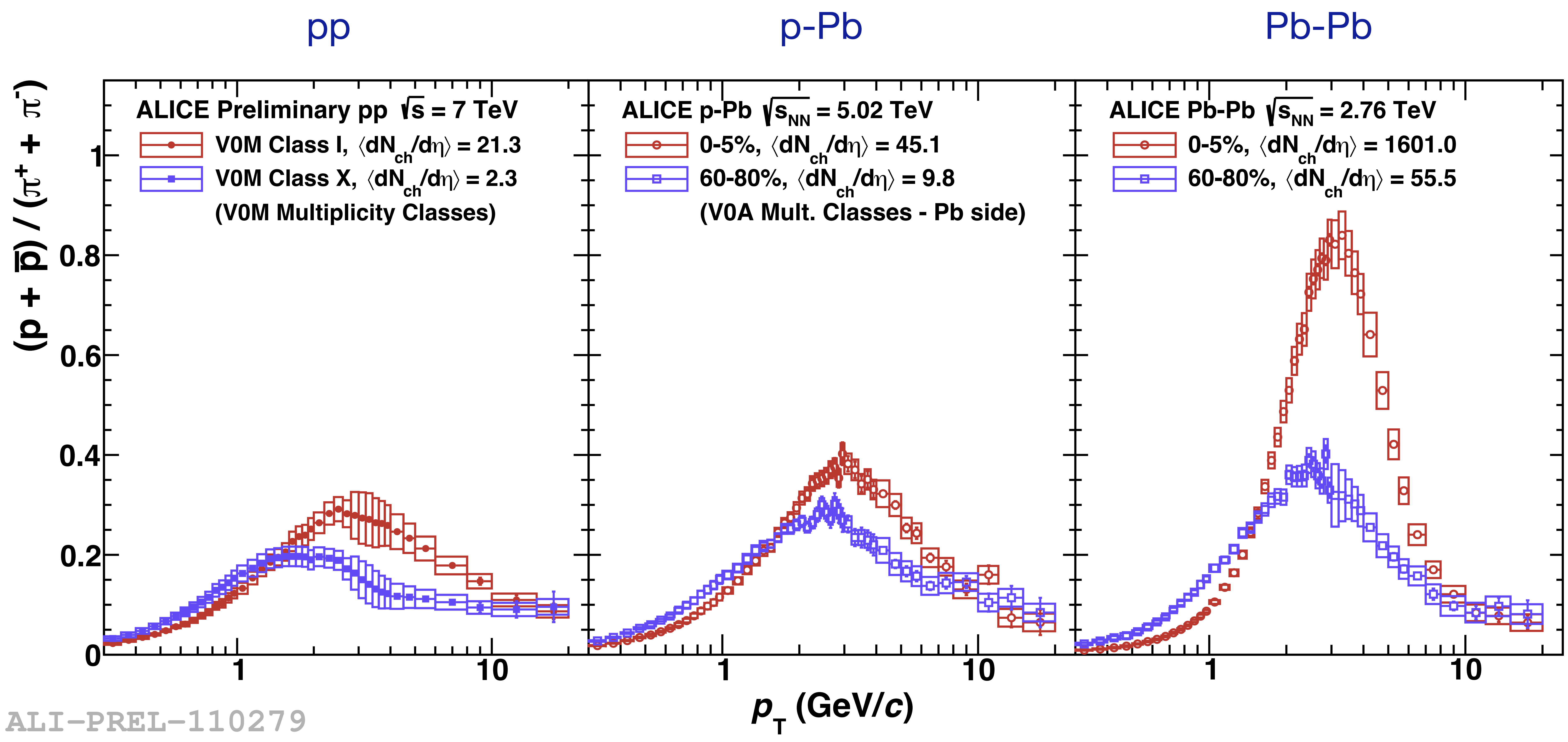
protons, ϕ, K*



Increase of the mean p_T depends on mass — suggests radial flow?

Trends similar to Pb-Pb, but do not match smoothly…
Different mechanism?

Baryon to meson ratios vs p_T

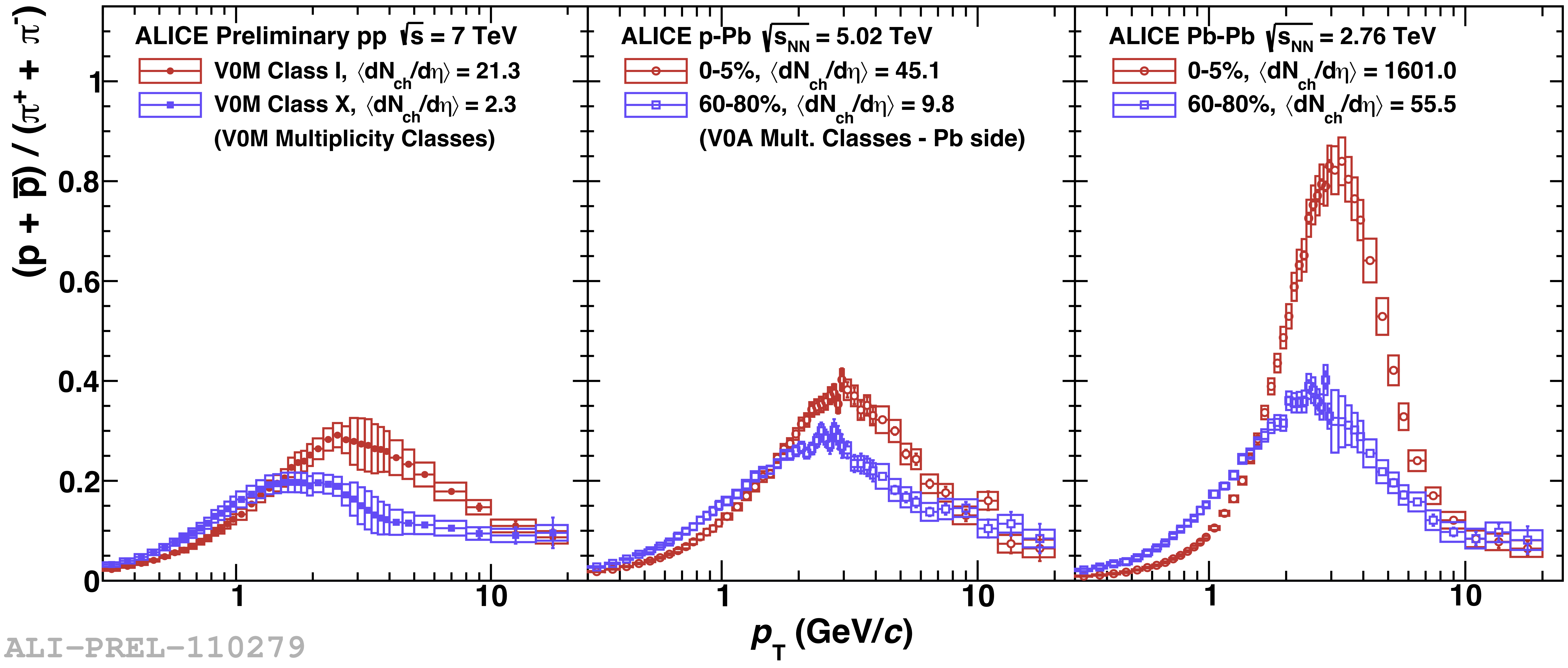


Pb-Pb: increase driven by radial flow

pp, p-Pb:
baryon/meson ratio at intermediate p_T depends on multiplicity

Baryon to meson ratios vs p_T

pp p-Pb Pb-Pb



Pb-Pb: increase driven by radial flow

pp, p-Pb:

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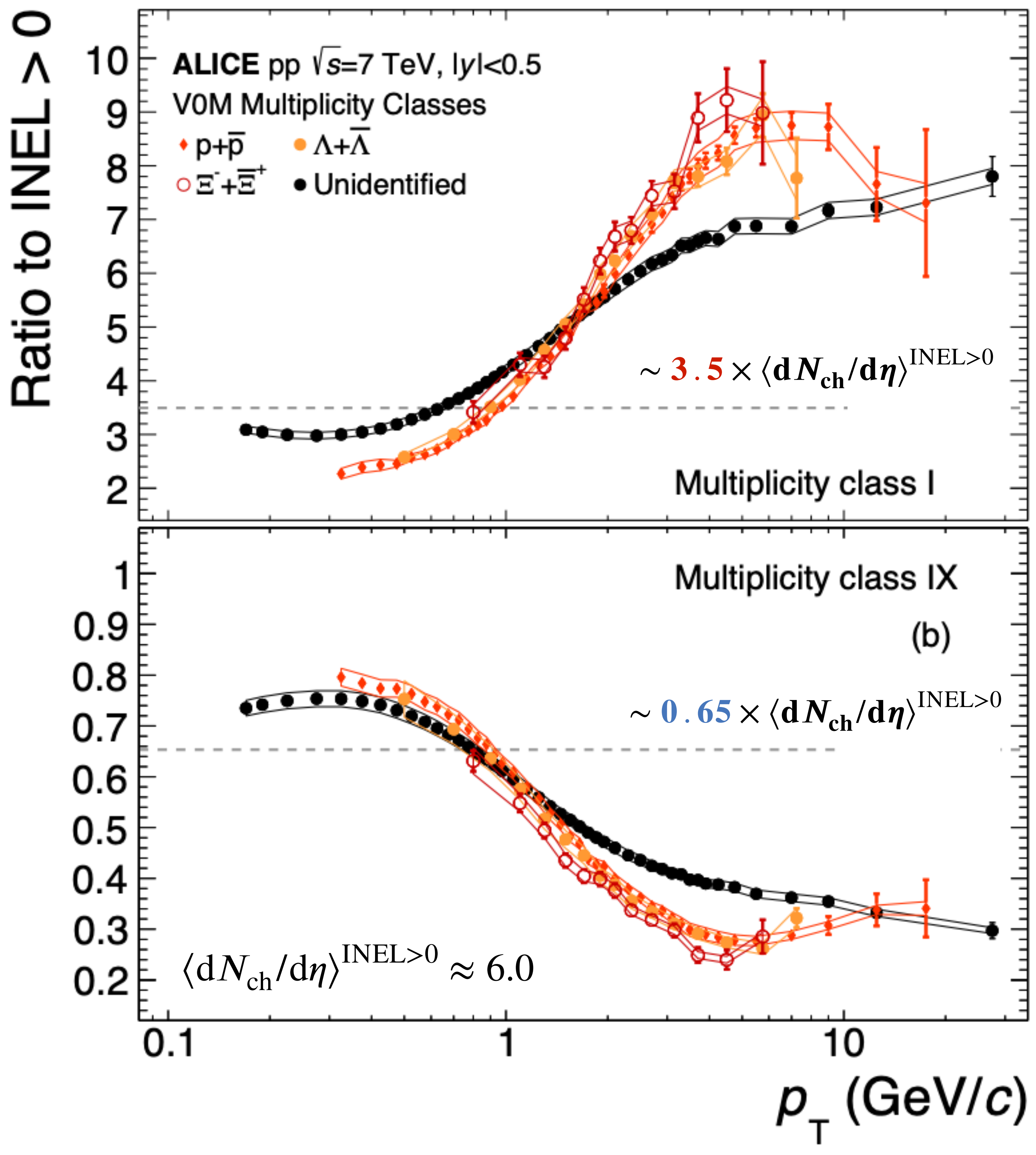
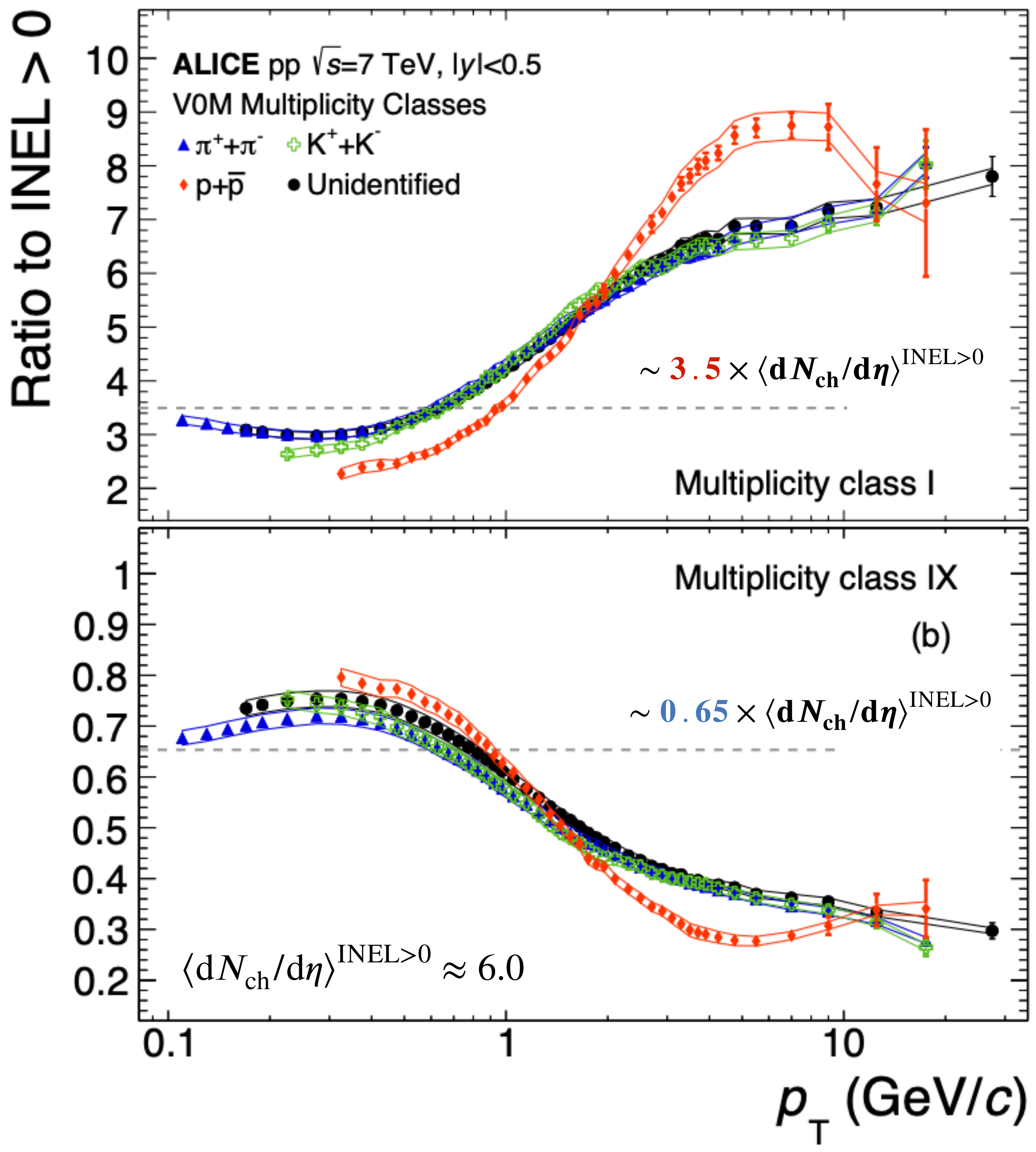
Are these effects related?

Try a different ordering: spectra ratios by particle type

ALICE, PRC 99, 024906

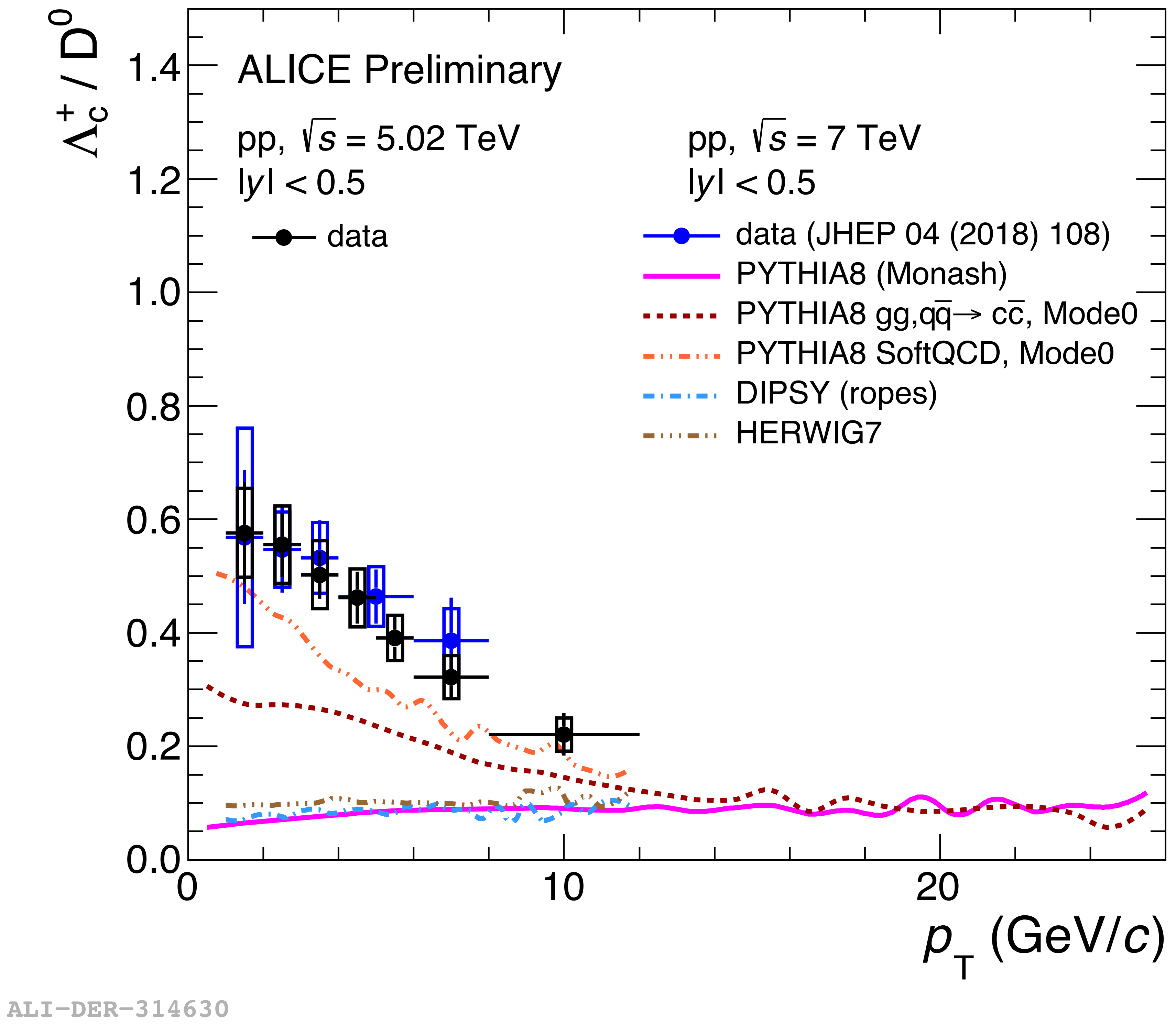


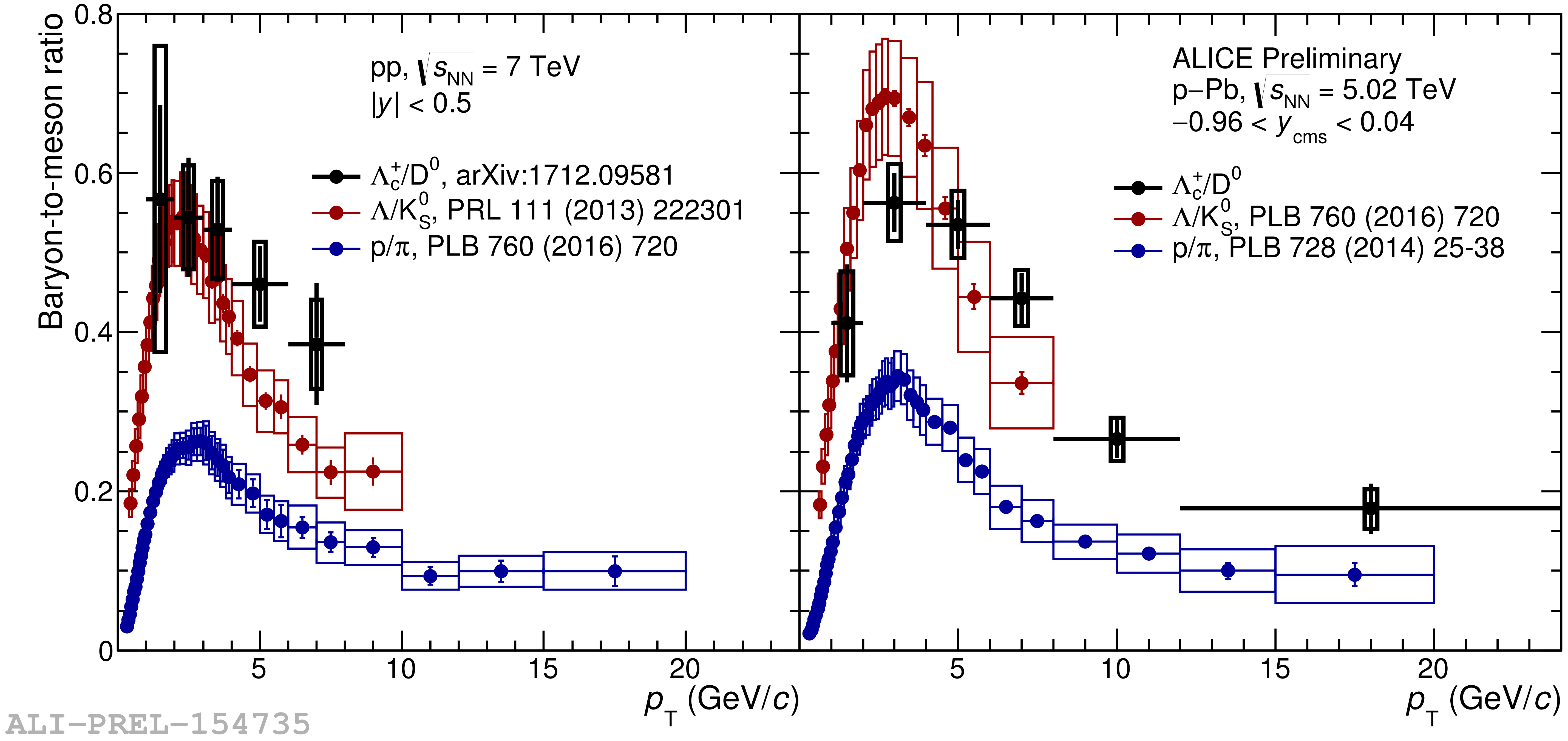


Interesting pattern: baryon-meson difference. No mass dependence?

NB: this divides out the mass dependence of mean-p_T in minbias spectra

A propos baryon production: Λ_c also?





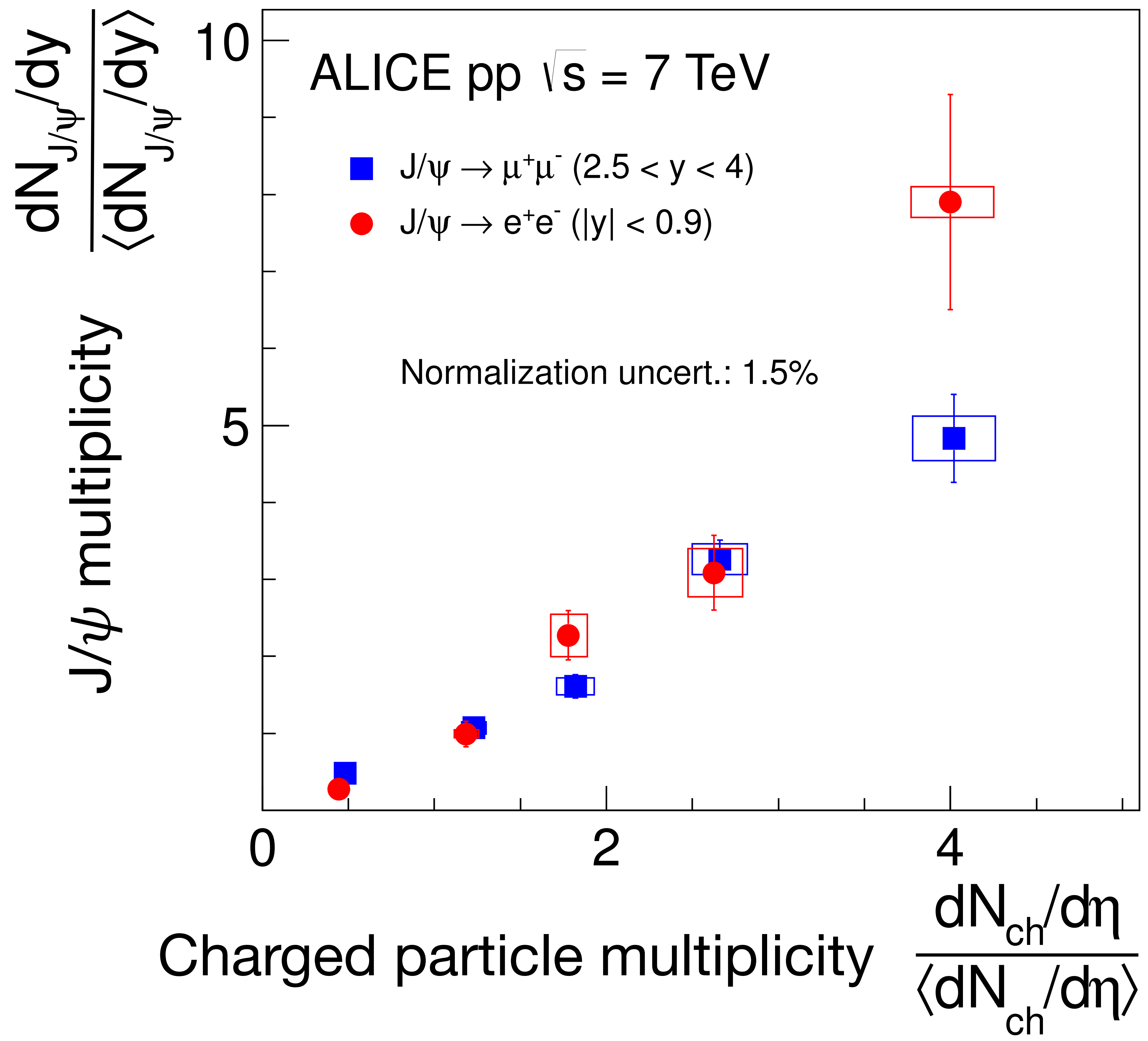
Λ_c/D in pp much larger than expected from fragmentation, e^+e^-

Λ_c/D similar to Λ/K: Specific mechanism for low p_T baryon production in pp?

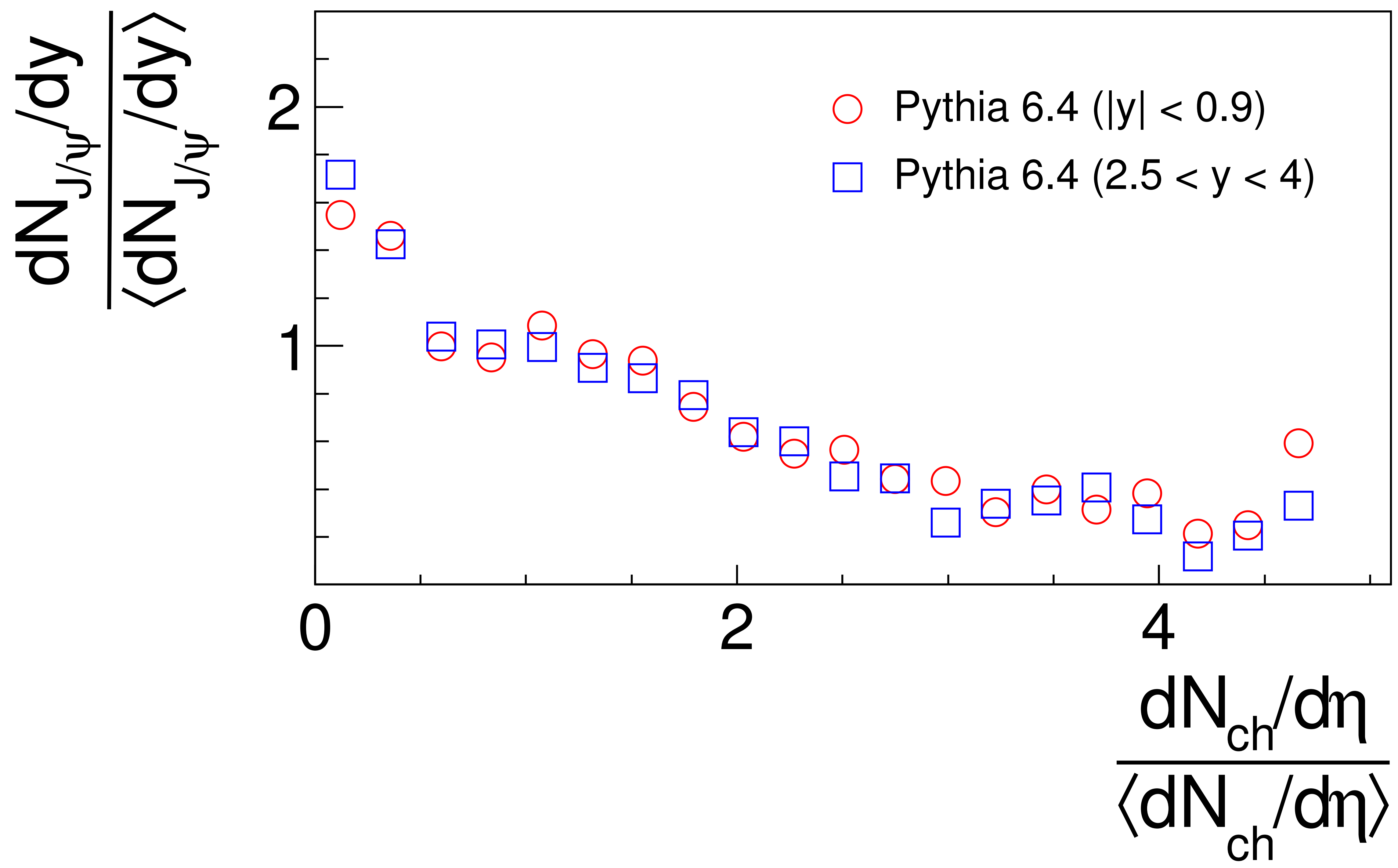
Charm production and Multiple Parton Interactions

Phys.Lett. B712 (2012) 165-175

J/ψ vs multiplicity: measured



J/ψ vs multiplicity: PYTHIA 6.4

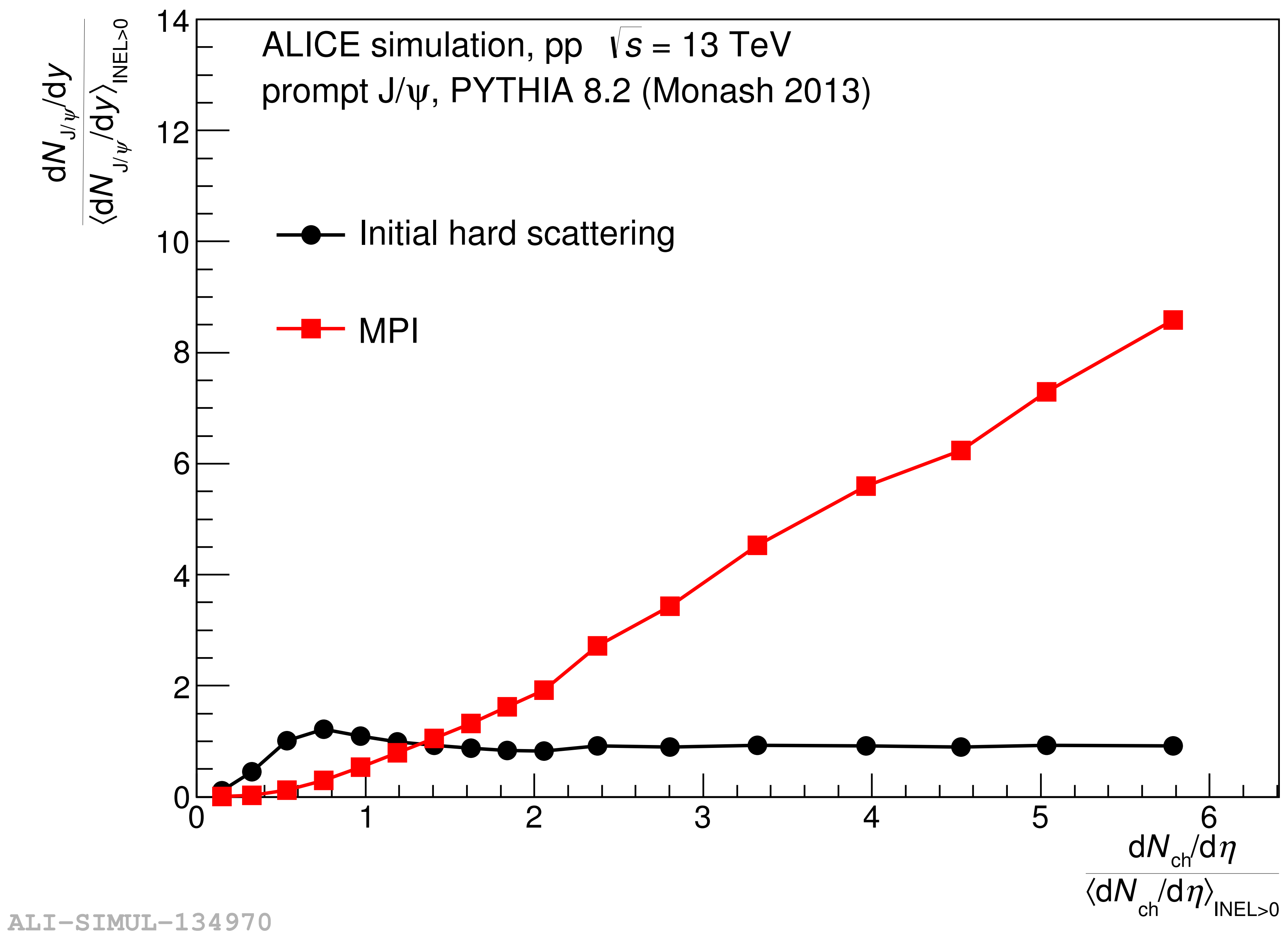


Pythia 6.4: single hard scattering + underlying event

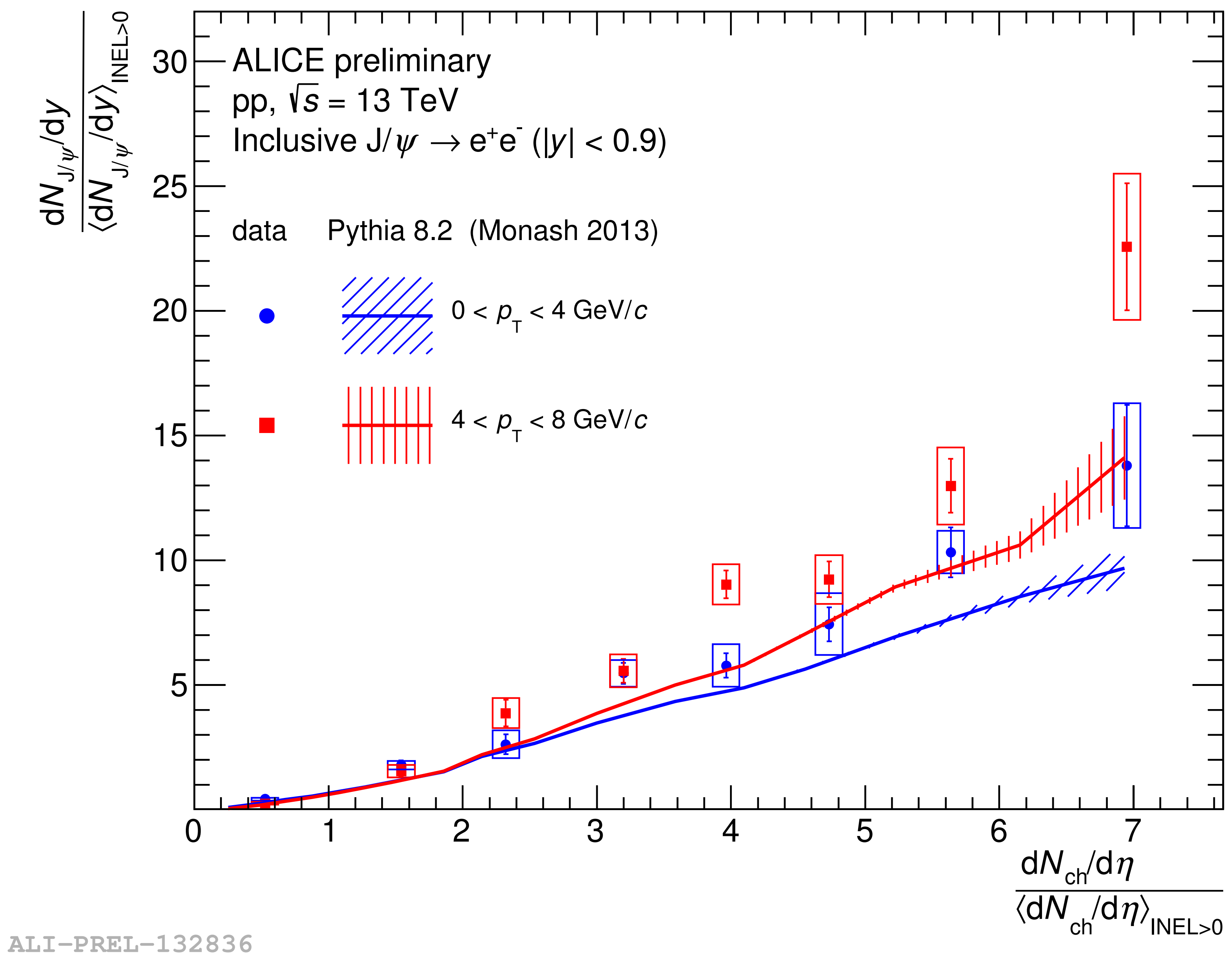
Multiple parton interactions produce multiple c-cbar pairs

J/ψ vs multiplicity — recent results

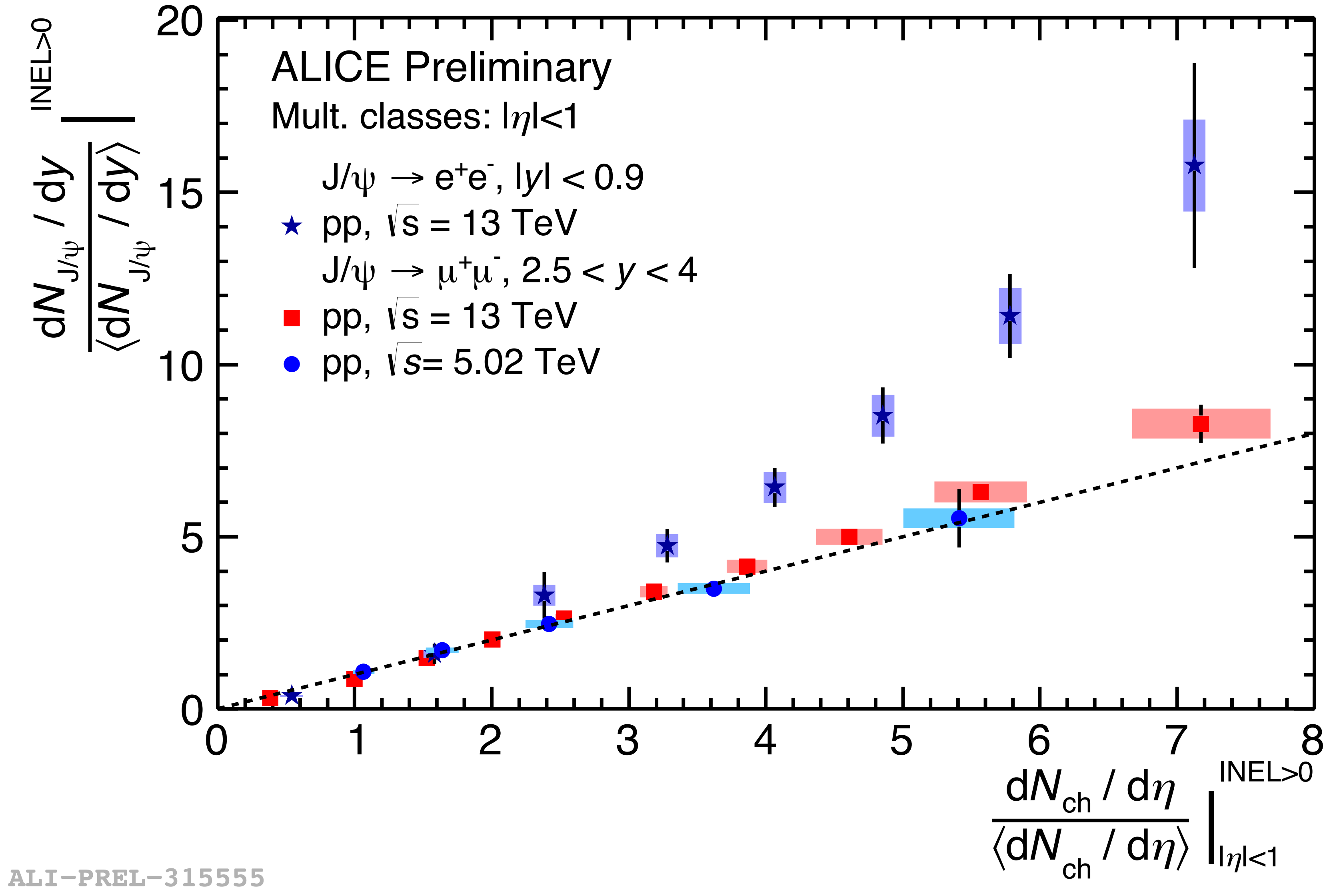
Multiple parton interactions in Pythia



Comparison to data



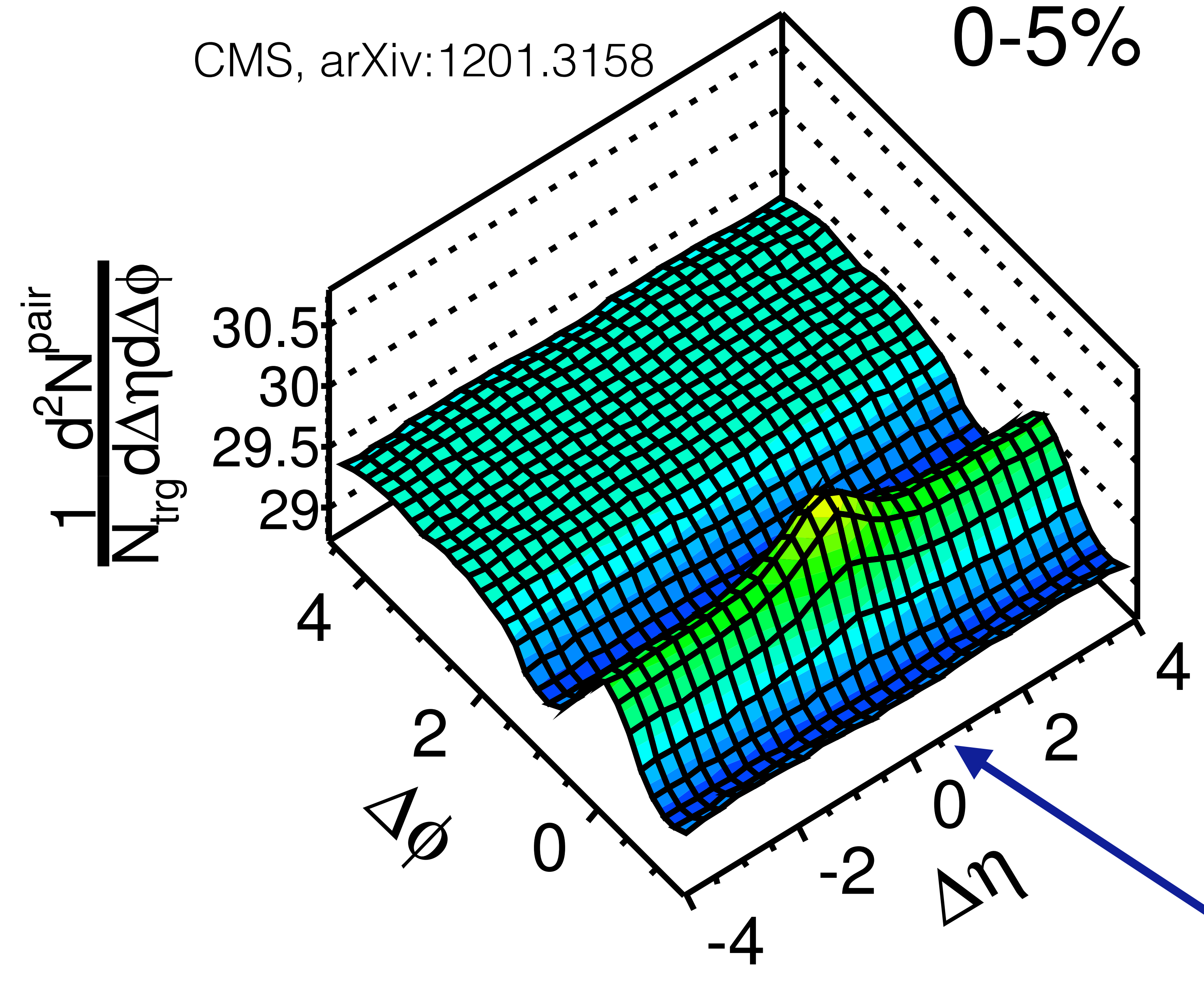
Forward vs mid-rapidity



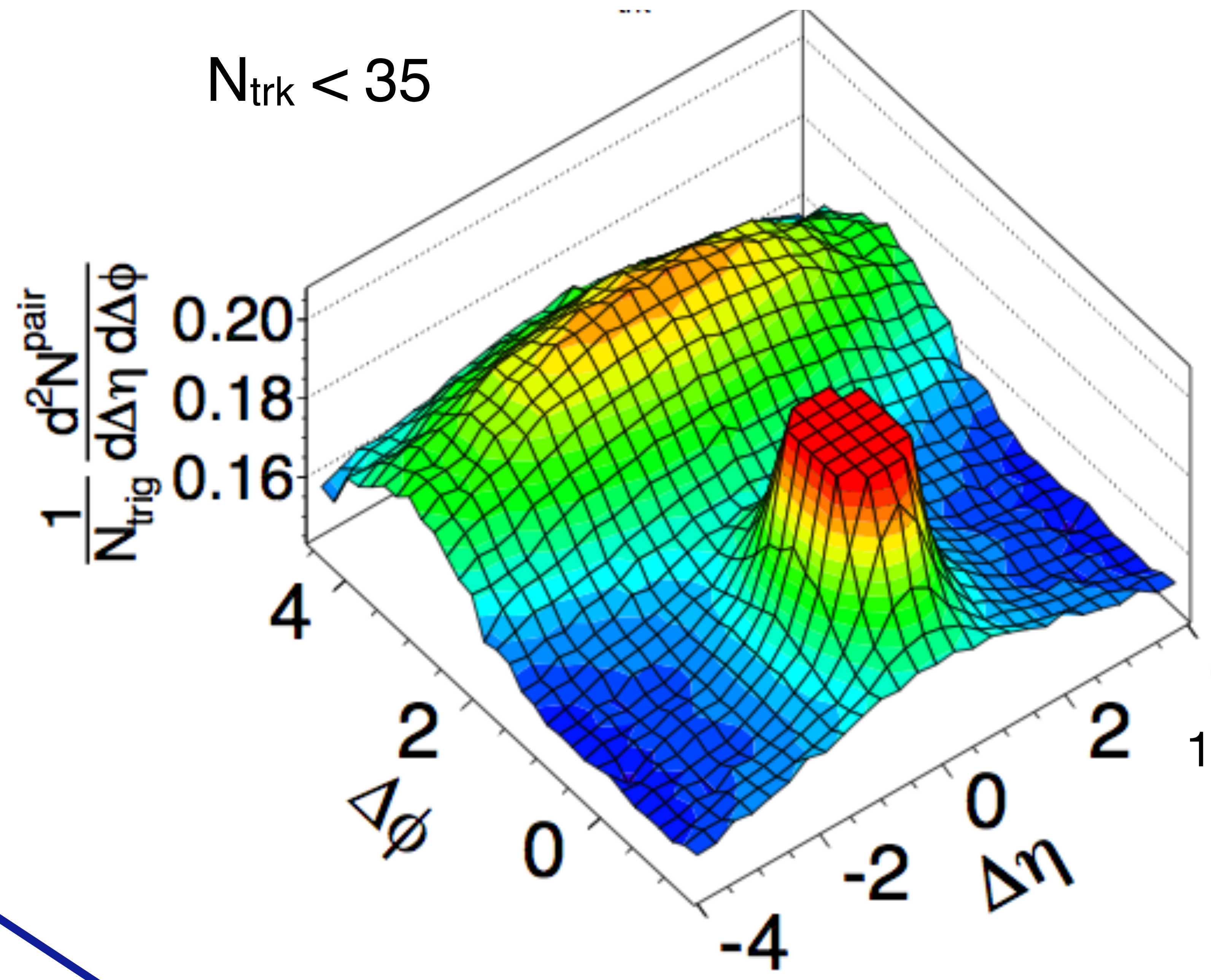
Models with MPIs reproduce the observed trends

Two-particle correlations in pp and Pb+Pb

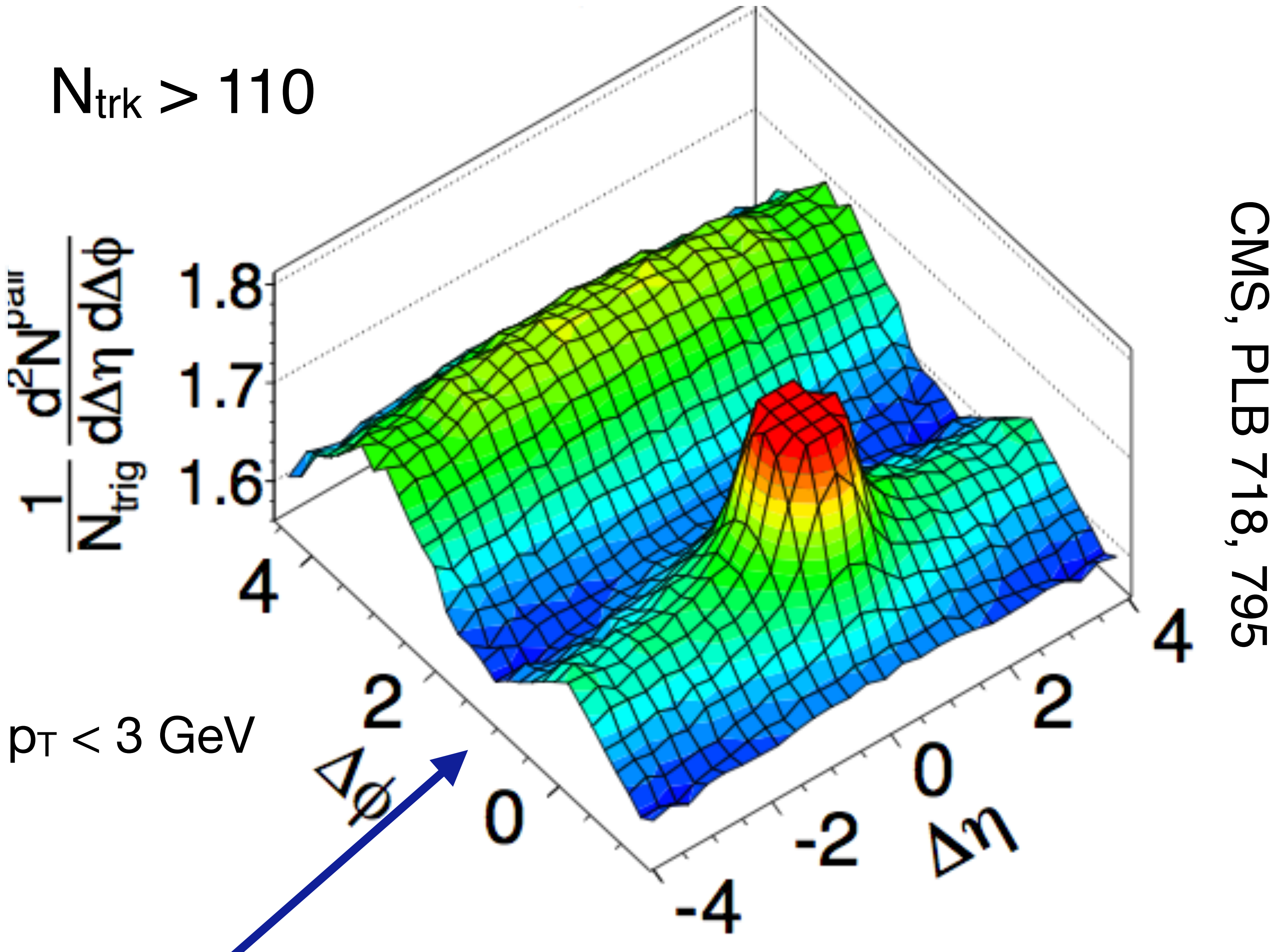
Central Pb+Pb

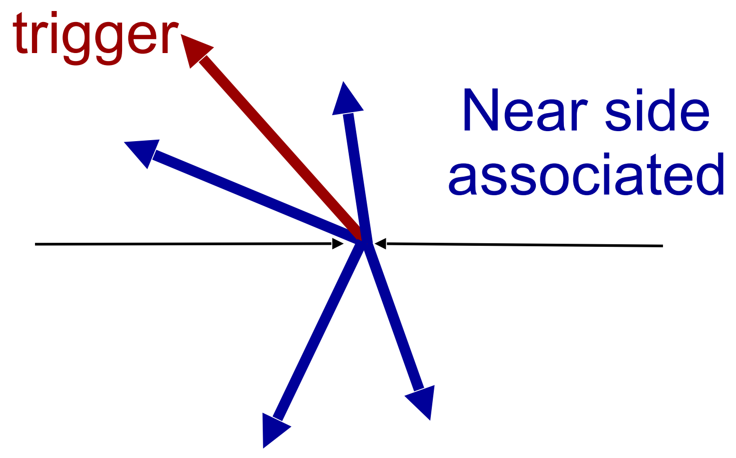


p+p low multiplicity



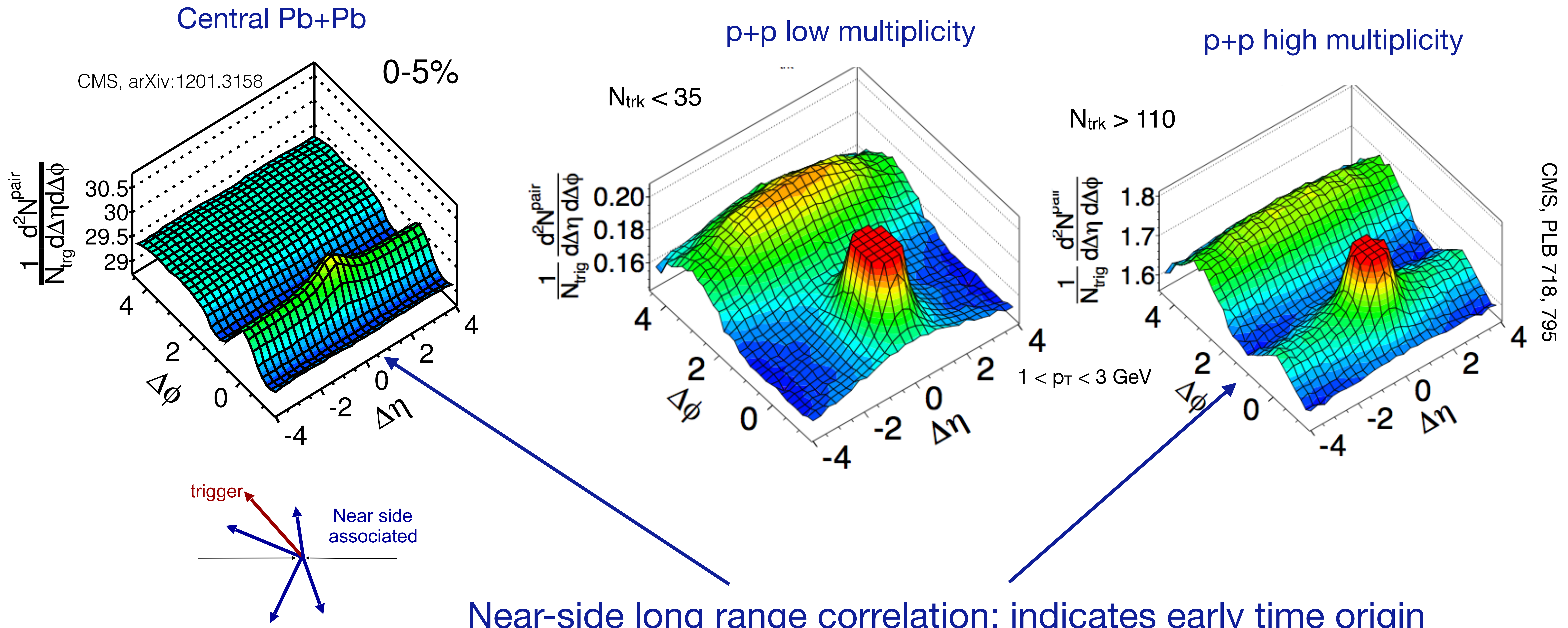
p+p high multiplicity



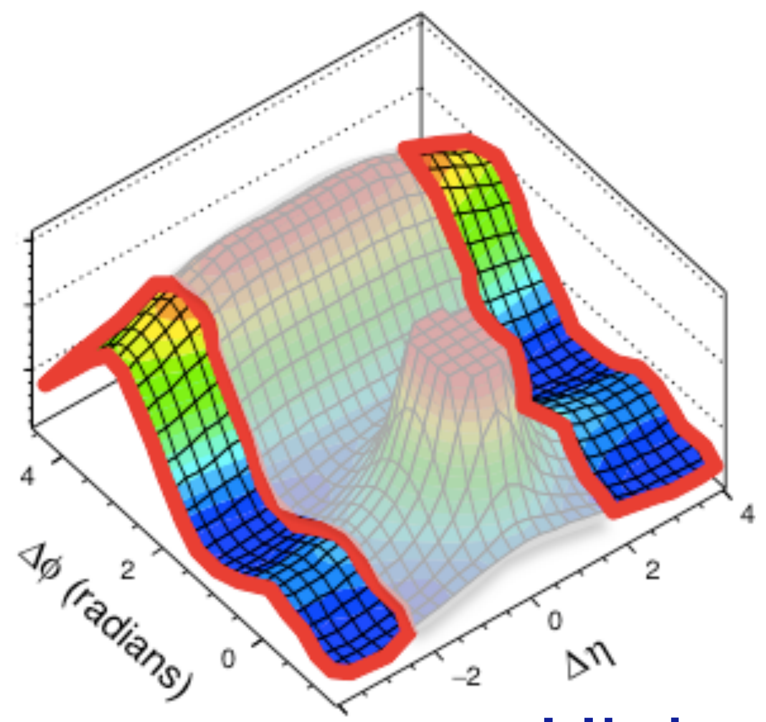


Near-side long range correlation: indicates early time origin

Two-particle correlations in pp and Pb+Pb



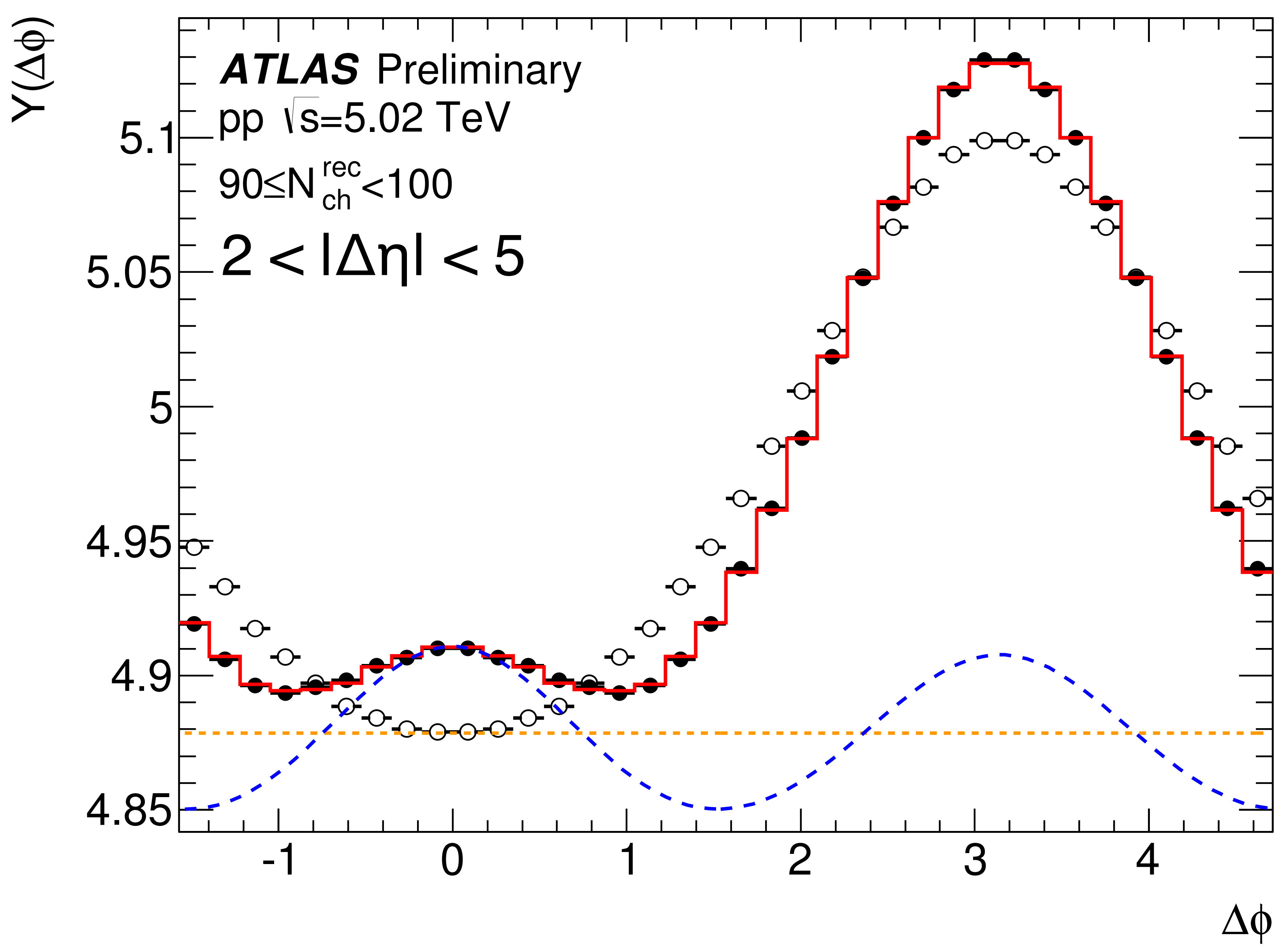
Near-side long range correlation: indicates early time origin
Seen in high-multiplicity pp and p+Pb events



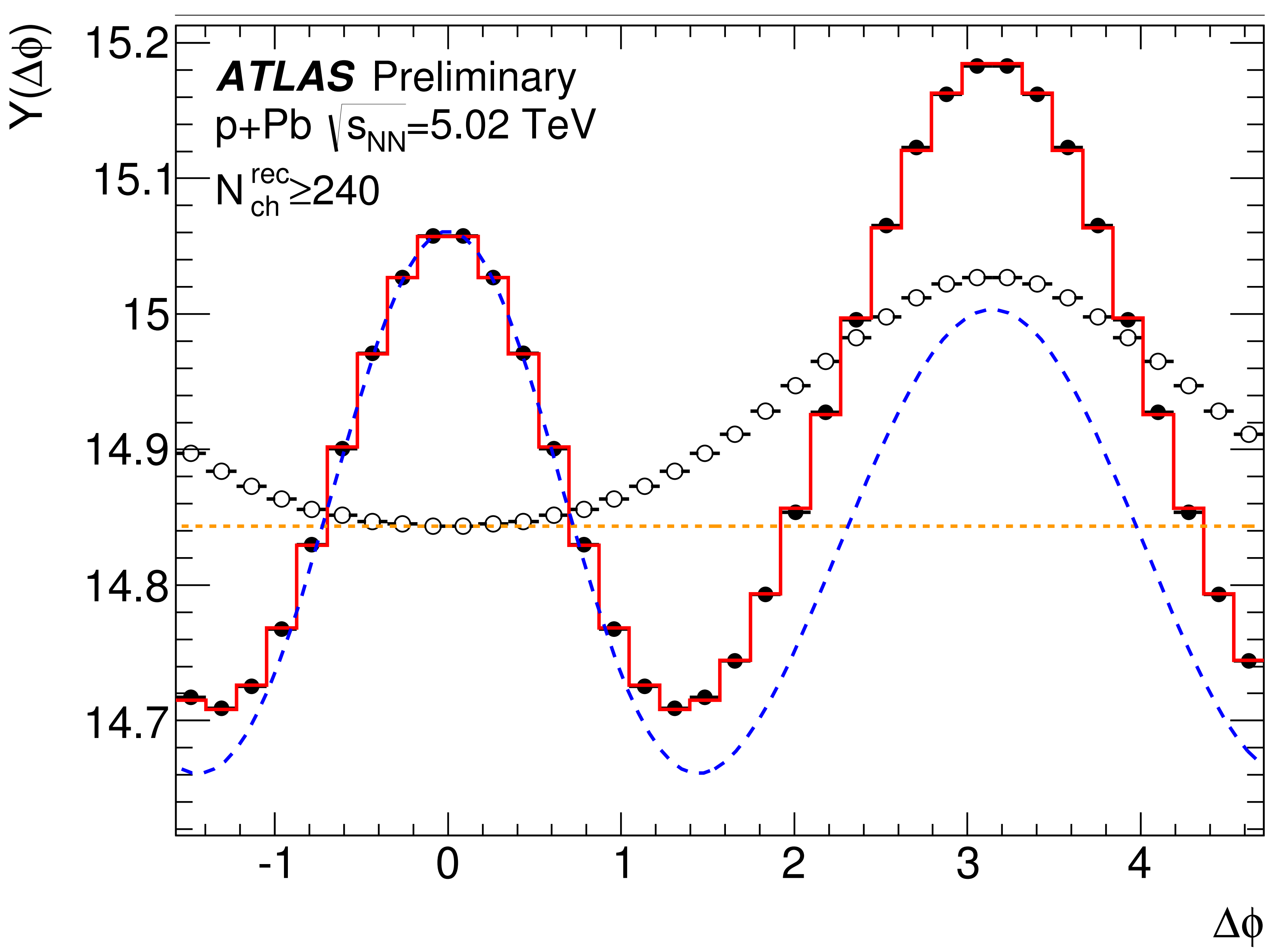
Two-particle correlations

ATLAS-CONF-2016-026

High-multiplicity p+p



High-multiplicity p+Pb



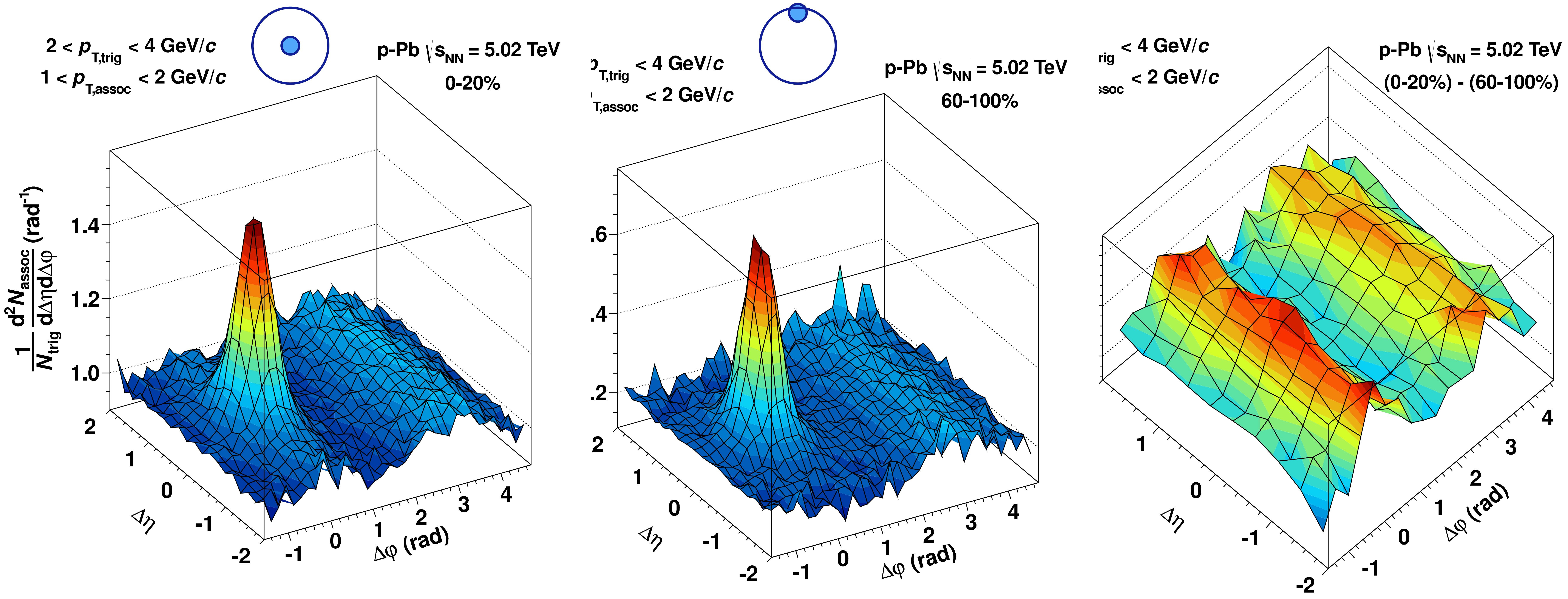
Clear change in shape from low multiplicity to high multiplicity:
no near-side peak in low multiplicity events

Away-side also affected: well described by dipole term (cos (2 Δφ))

Smooth evolution from pp to p+Pb: effect stronger in p+Pb

Extracting the double-ridge/flow

Central - Peripheral = Double ridge



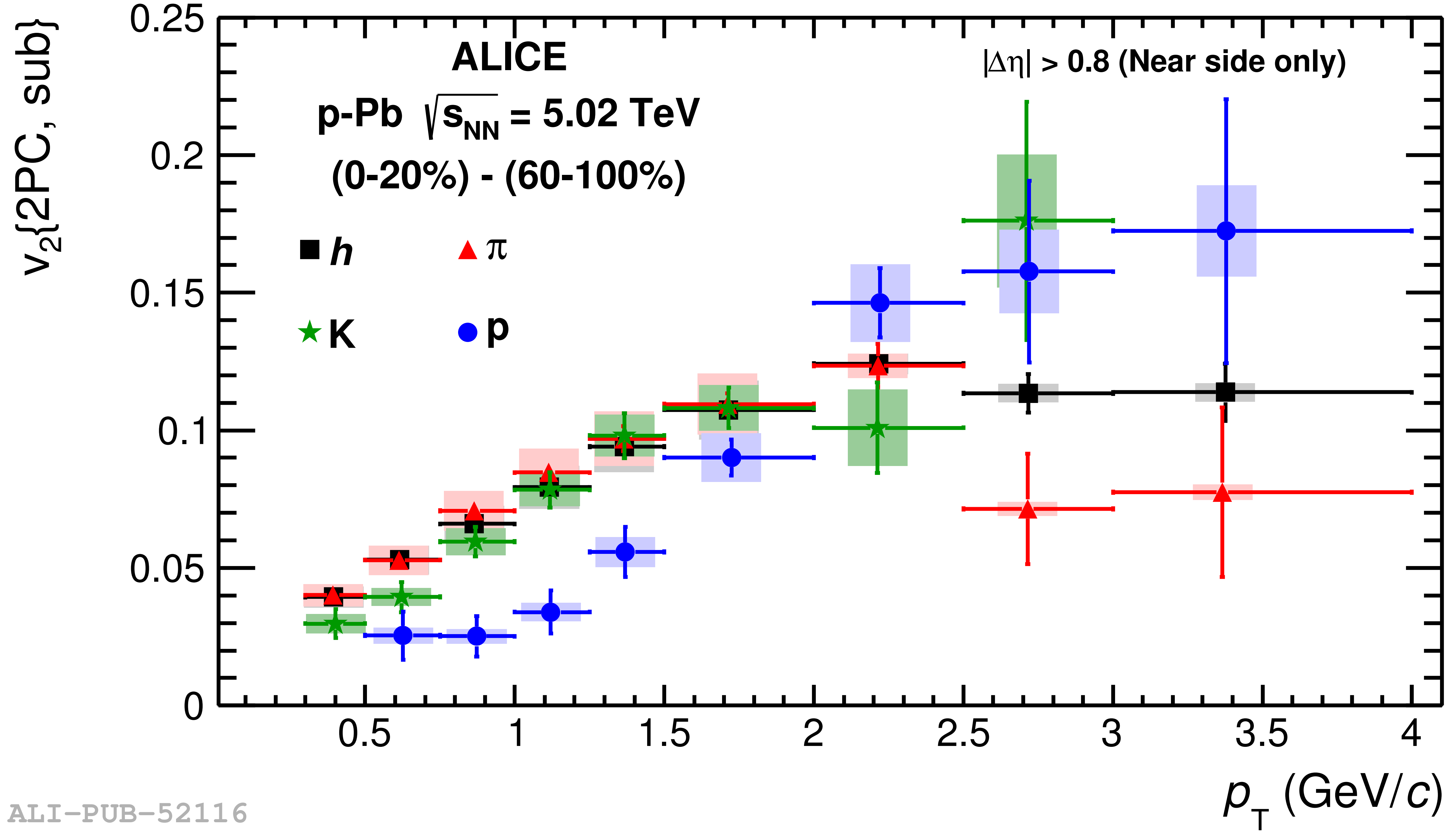
ALICE, arXiv:1212.2001, PLB 719, 29

Use peripheral to subtract jet contribution from central

Remaining signal almost symmetric between near- and away-side:
looks like v_2 (+ smaller contributions from higher harmonics)

v_2 from di-hadron correlations in p+Pb

PLB 726,164



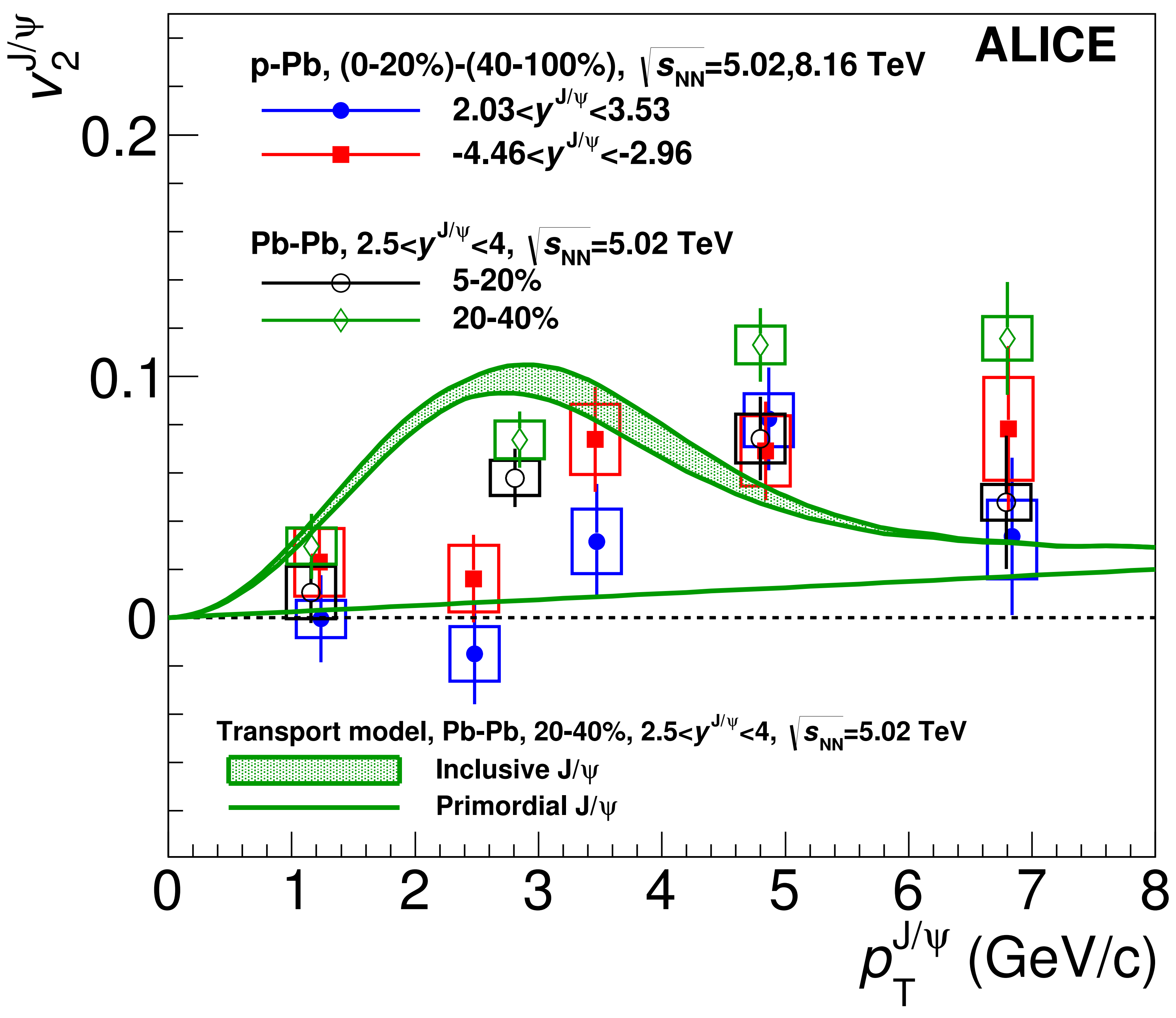
Similar 'mass ordering' observed for v_2 from two-particle correlations in p+Pb

Is this also pressure-driven?

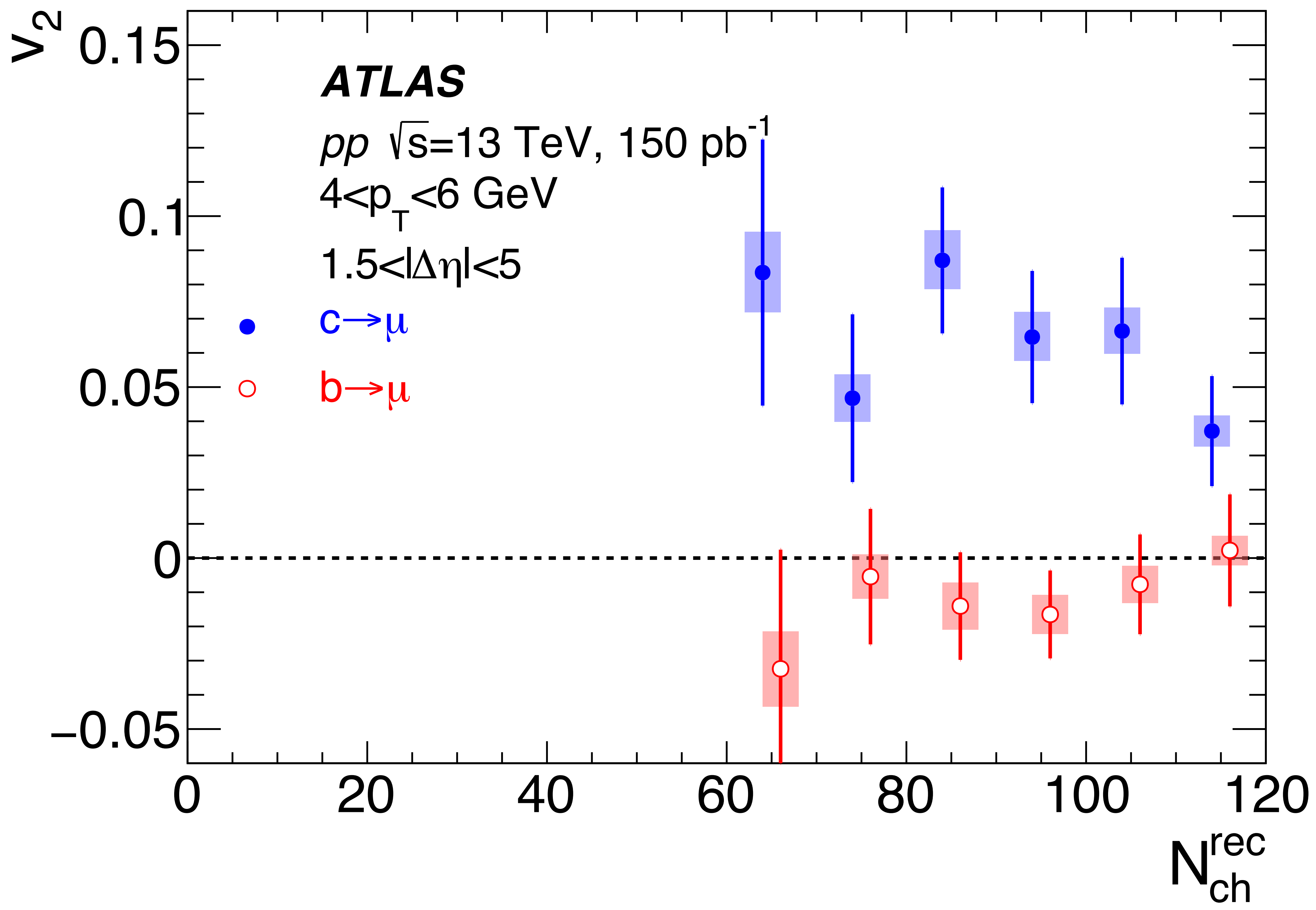
Elliptic flow in p-Pb: heavy flavours

ATLAS, arXiv:1909.01650

J/ψ v_2 in p-Pb and Pb-Pb



Heavy flavour decay muons: charm and beauty



Charmed particle also carry azimuthal asymmetries: not a soft underlying event effect

No v_2 for beauty?

Limits on hydrodynamic behaviour

Naive expectation: need at least a few collisions for each parton to reach thermal equilibrium and apply hydrodynamic

1) System size: $R > \lambda$

Would not expect azimuthal asymmetries in pp and p-Pb

Heiselberg and Levy, nucl-th/9812034,
W Lin et al,

2) Thermalisation time: $\tau > \dfrac{\lambda}{v}$

Fits to data: thermalisation times $\tau \approx$ 0.1-1 fm/c

pQCD calculation: $\tau \gtrsim$ 6.9 fm/c

Baier et al, PLB 502, 51, PLB 539, 46

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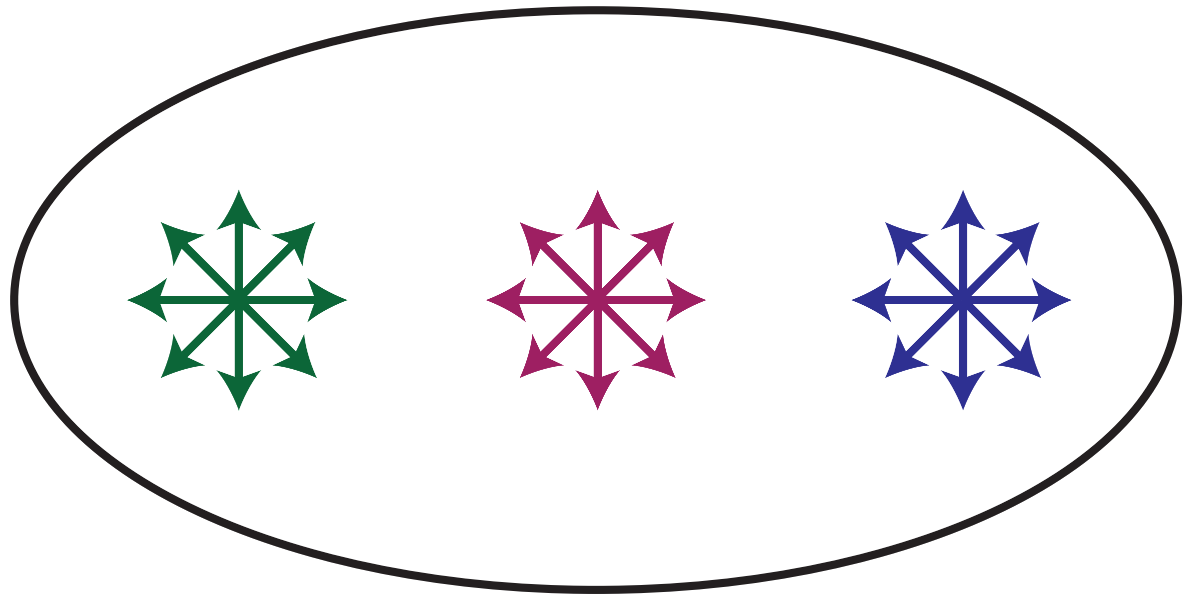
Naive expectations can be bypassed in nature…

Active field of research — brings together
foundations of hydrodynamics, transport theory, and even string theory

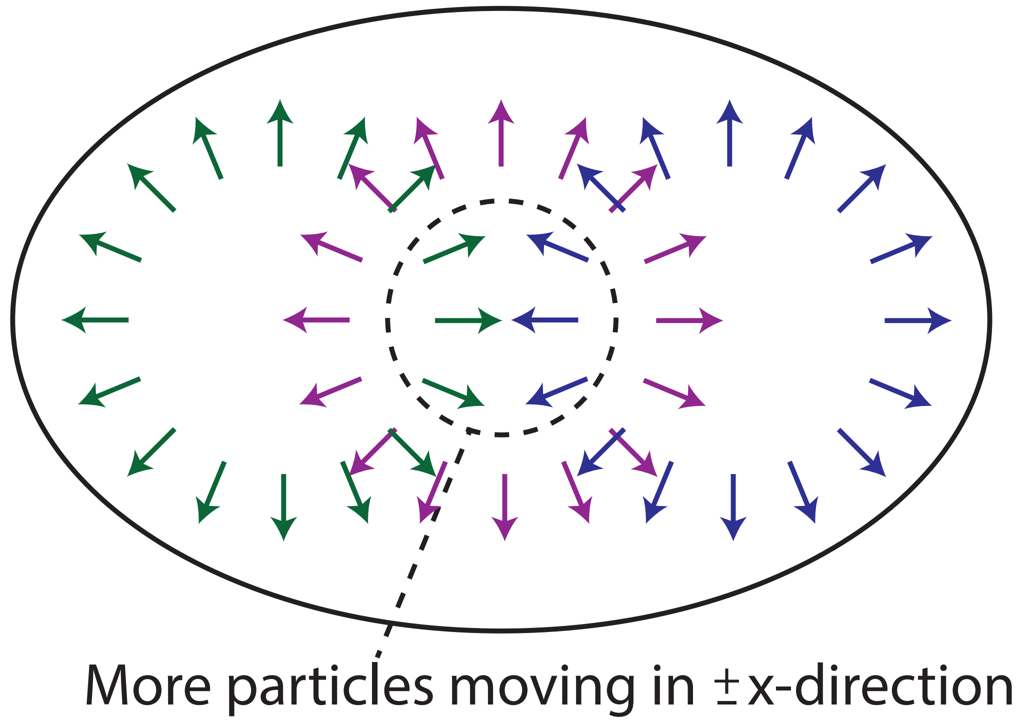
Flow without a liquid

Can you have flow with a few scatterings?
'anisotropic escape' mechanism

Kurkela, Wiedemann, Wu, arXiv:1805.04031



Initially isotropic
momentum distribution



Kurkela, Wiedemann, Wu, arXiv:1803.02072

Scattering randomises directions; more scatterings to 'out-of-plane'

Anisotropic density converted
into anisotropic momentum distribution by few scatterings

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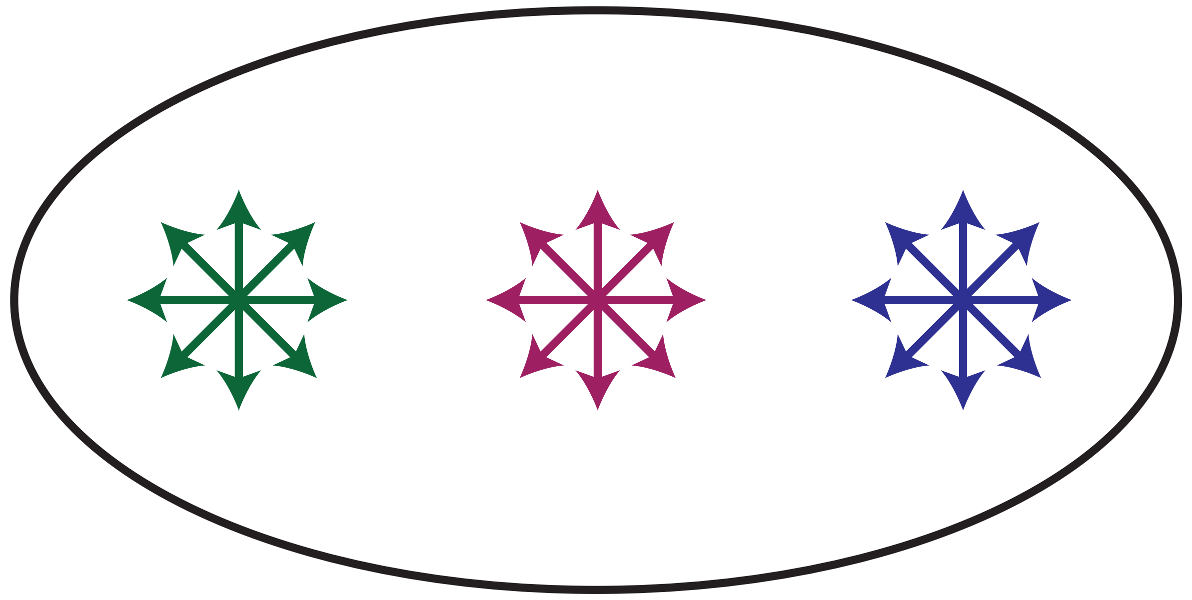

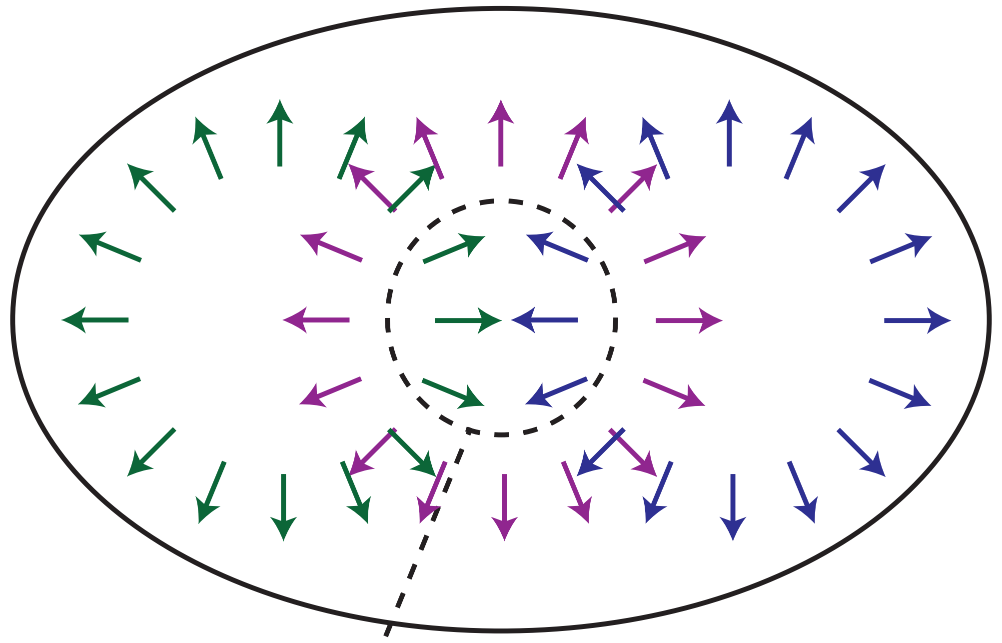

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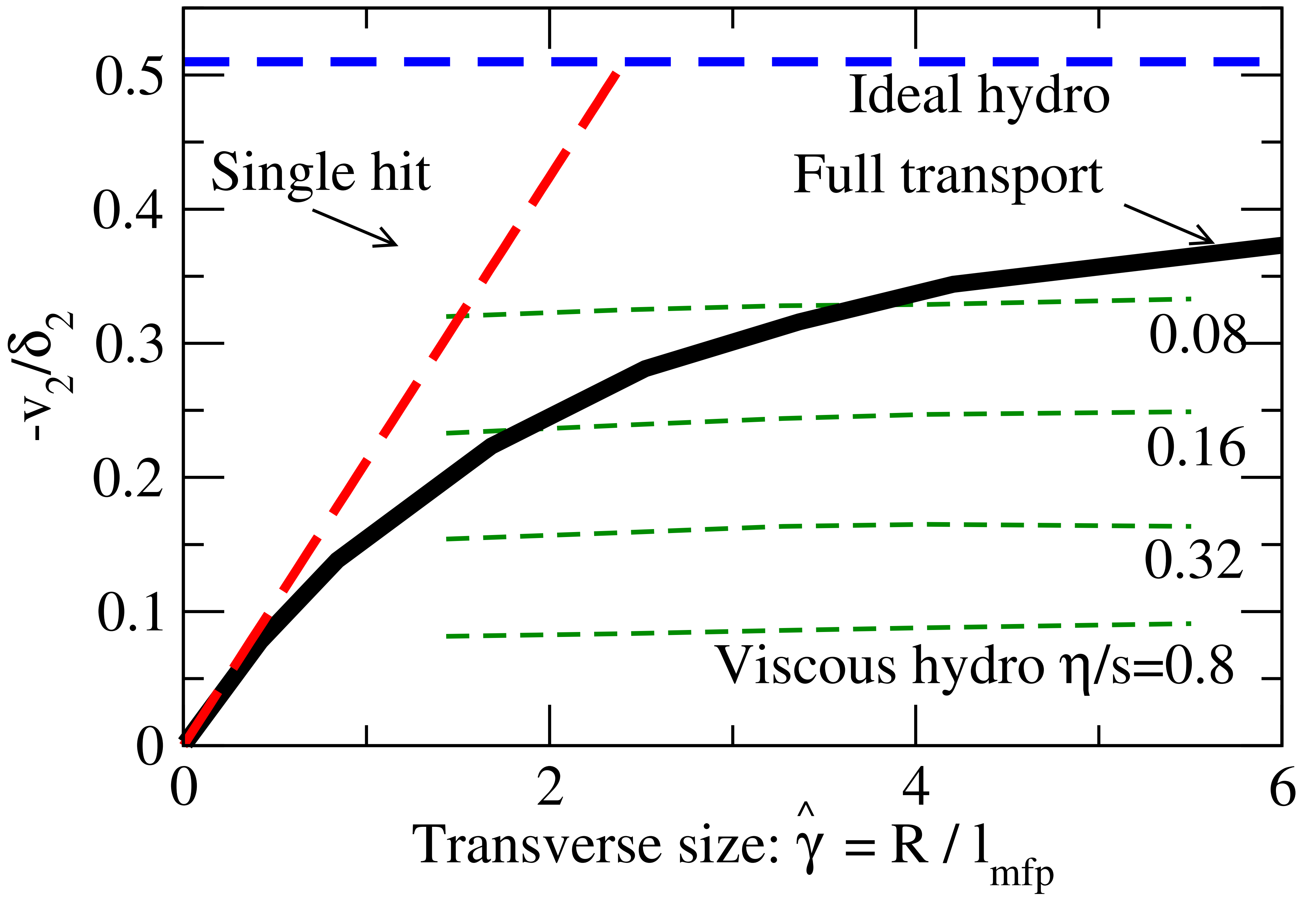

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Small systems: kinetic transport,
equal to viscous hydro

Flow without a liquid

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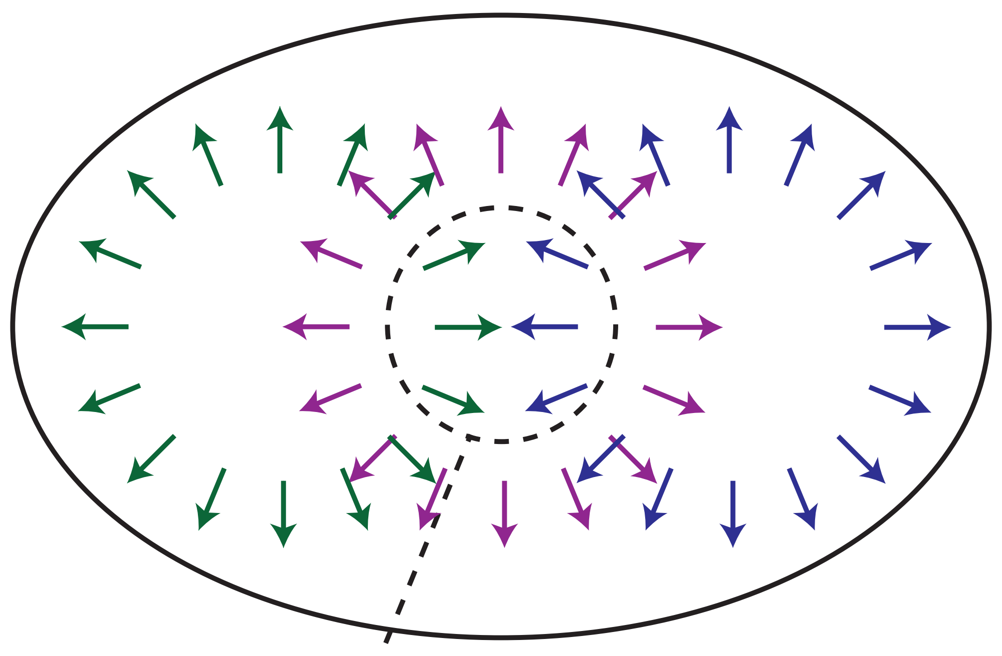
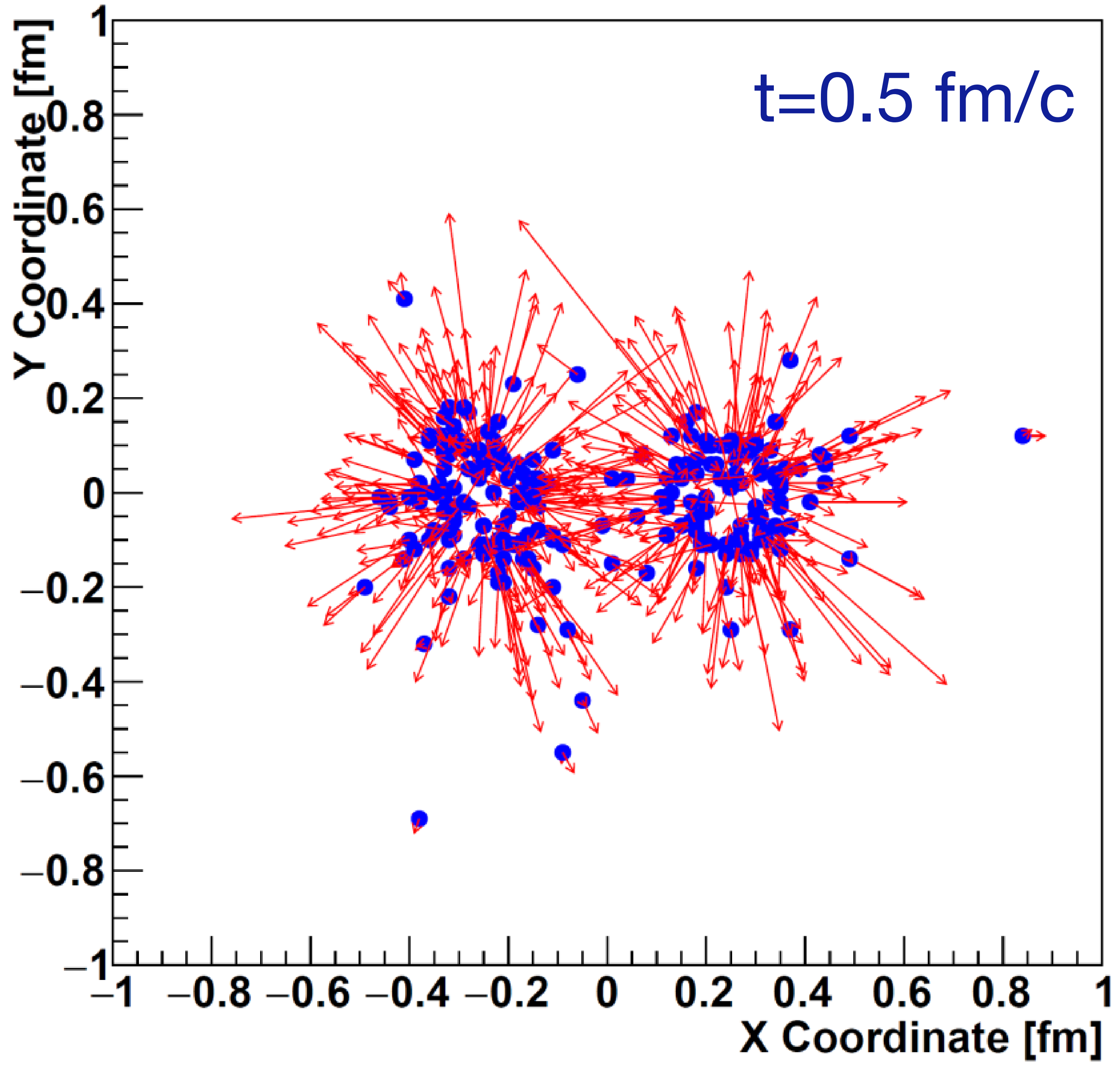


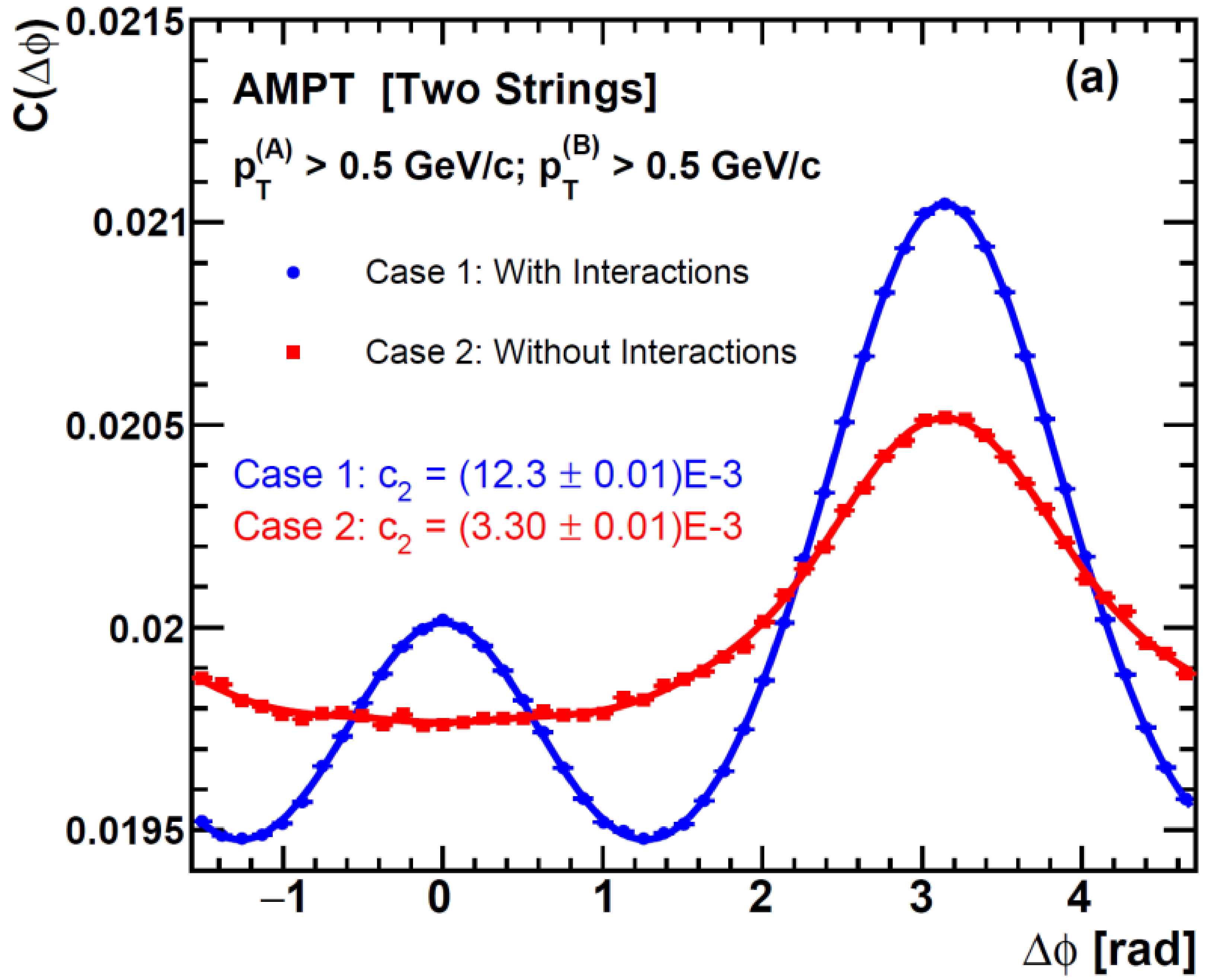
Kurkela, Wiedemann, Wu, arXiv:1803.02072

Two parallel strings in AMPT



Formation time is important

Two-particle correlations



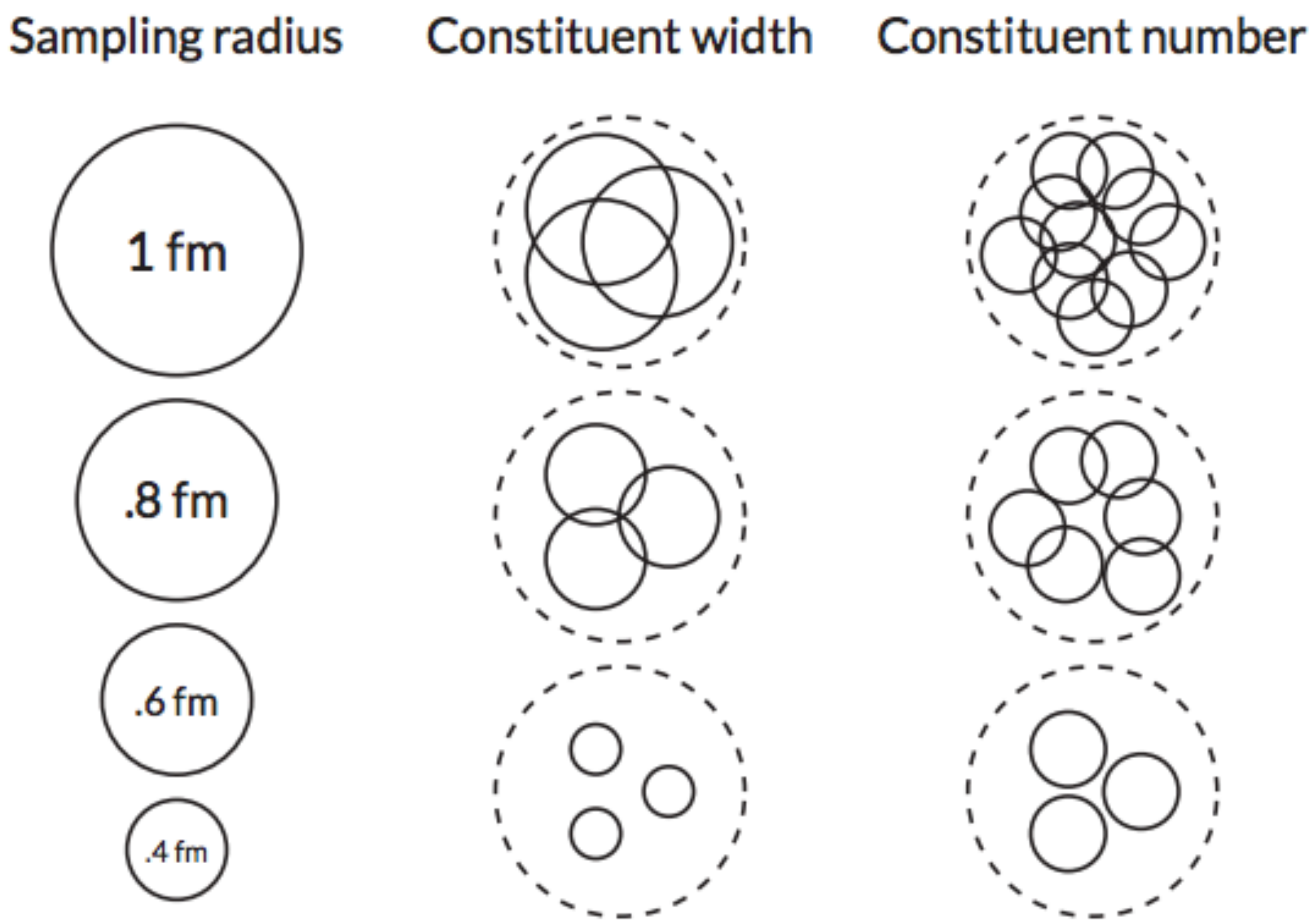
Shows a clear signal
in a transport calculation

Other mechanisms/pictures being discussed: string shoving, CGC
⇒ more field-based; to some extent just a different language?

Deriving proton substructure

J.S. Moreland, N Phys. A982, 503

Flow-like effects in pp require substructure
'constituents', strings, etc



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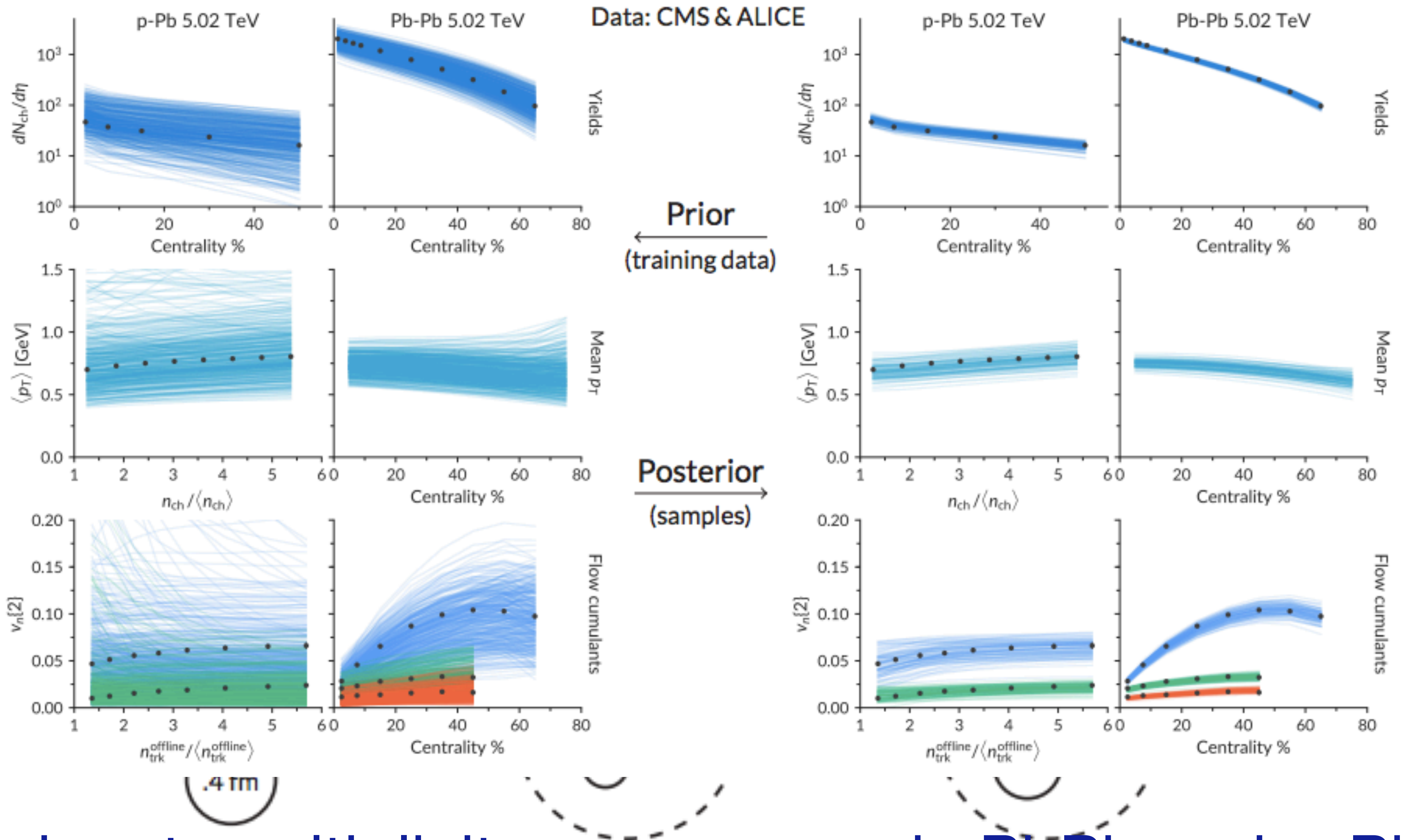

input: multiplicity, mean p_T, v_n in PbPb and p-Pb

Bayesian fit + gaussian emulator: probe large parameter space
Output: full covariance matrix 15 parameters

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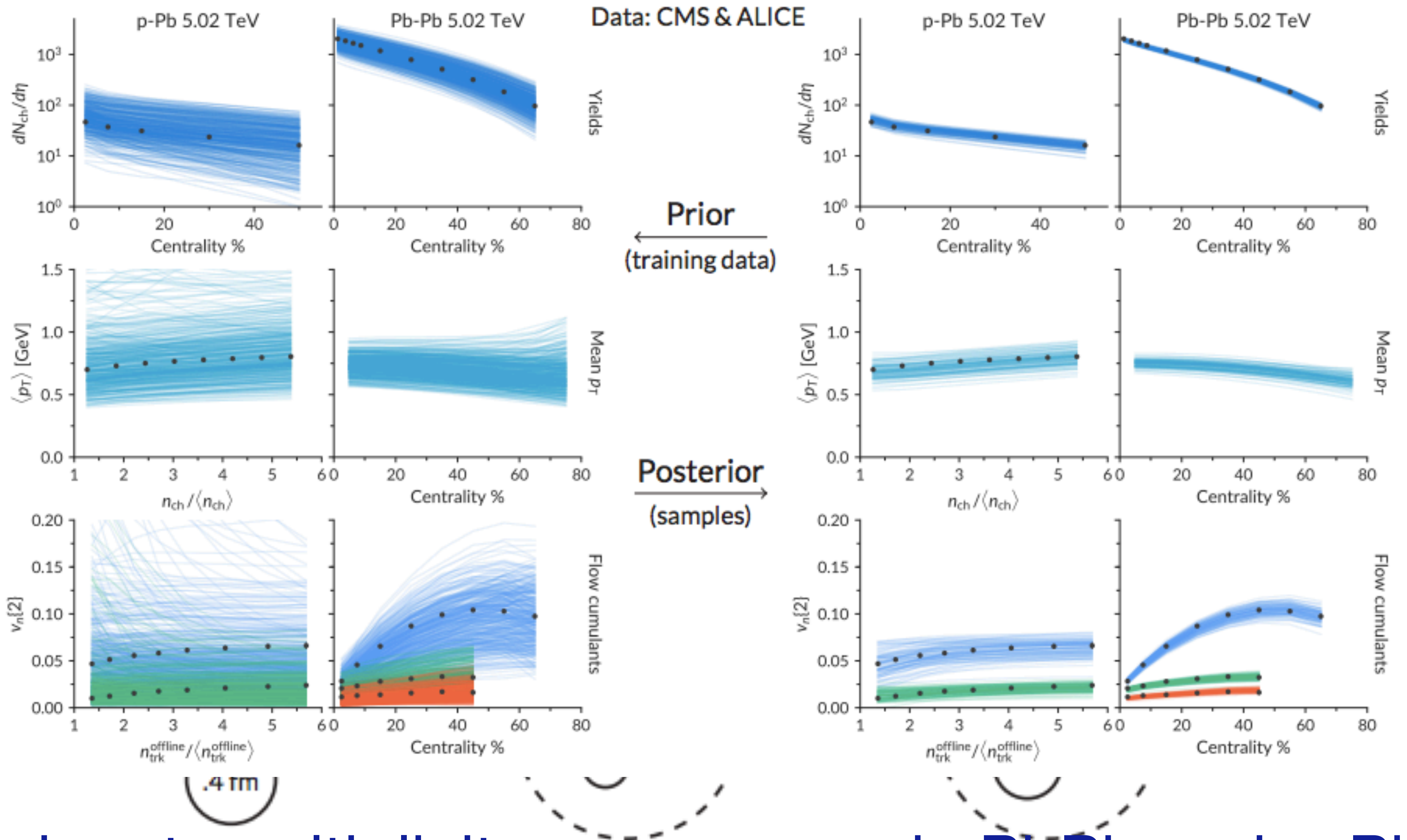

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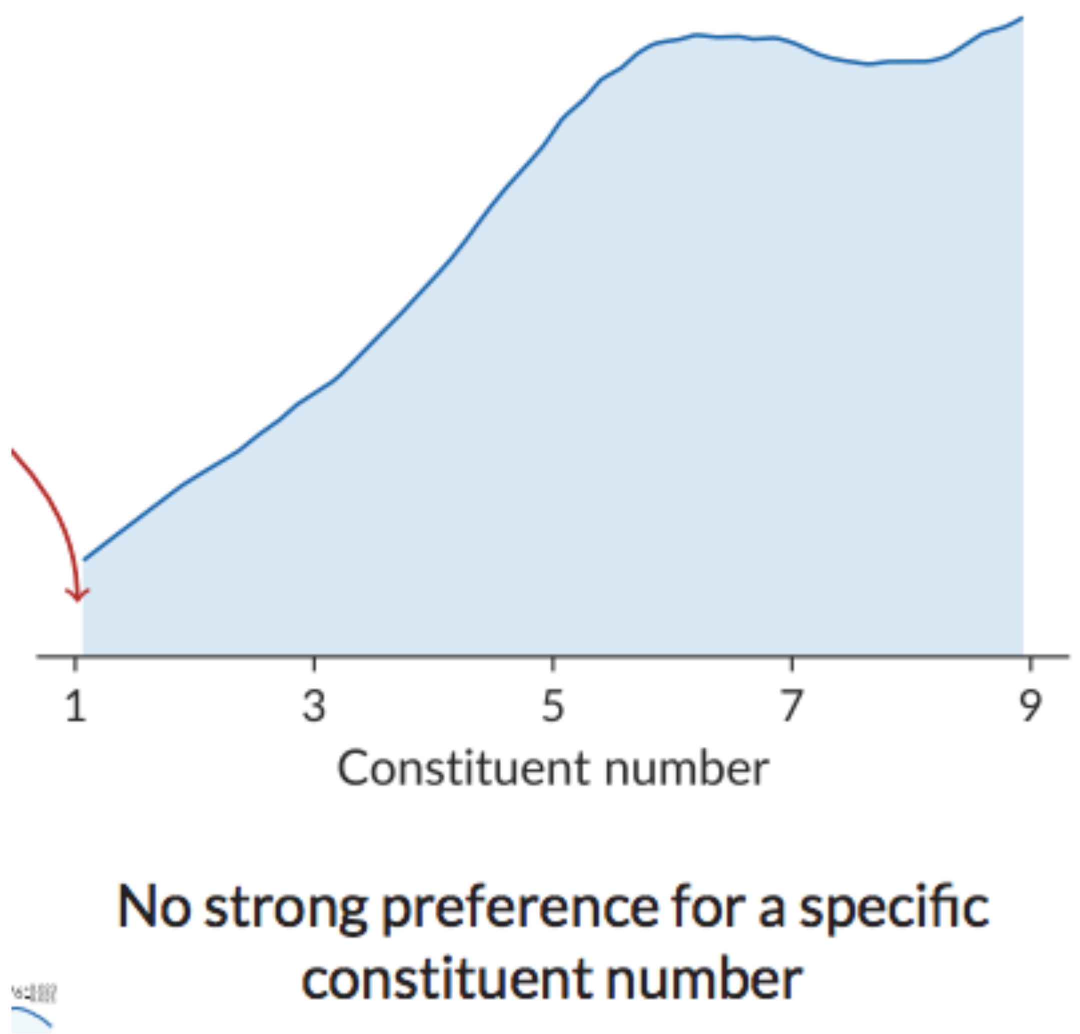
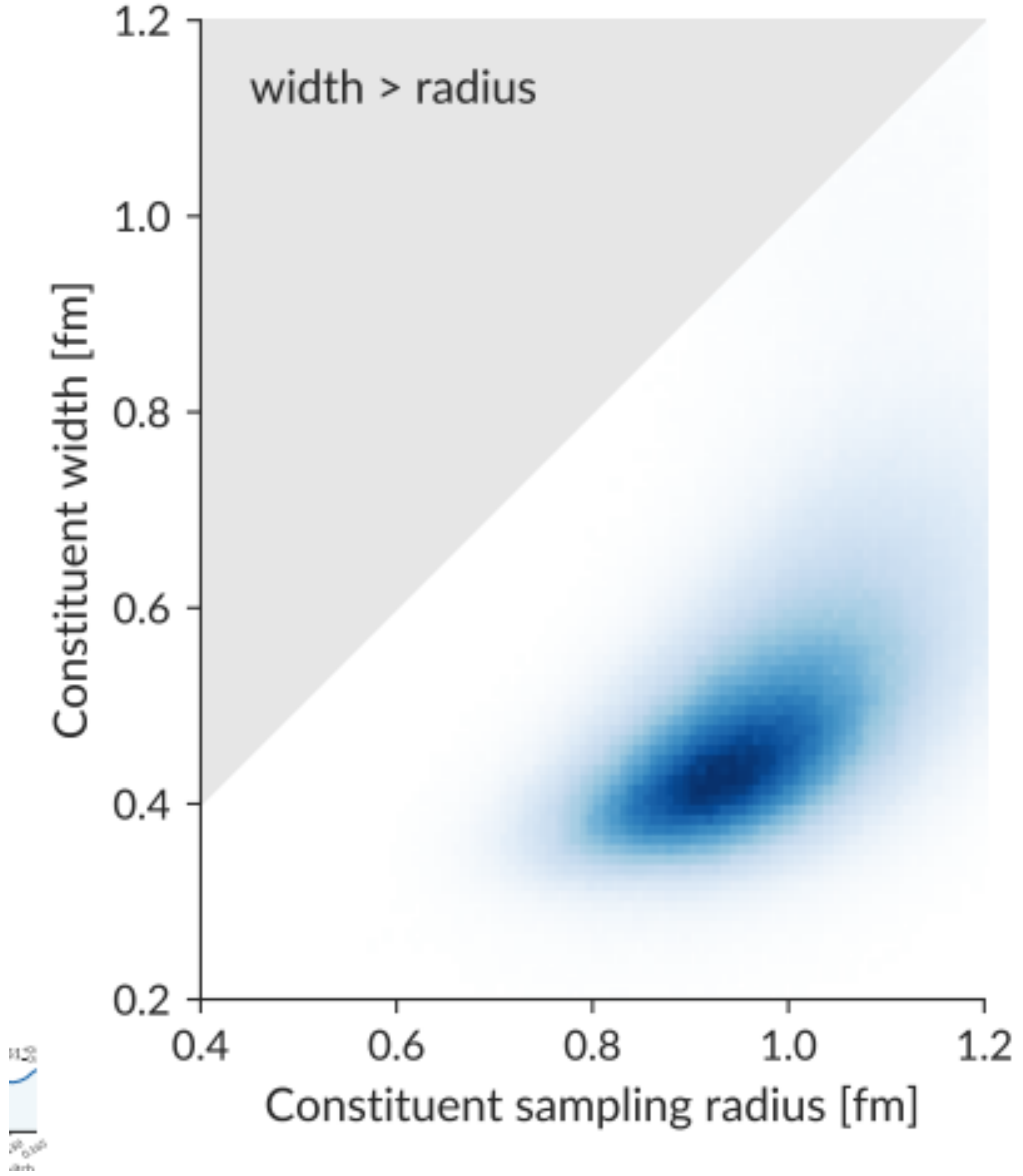
Number of constituents



Constituent width, radius



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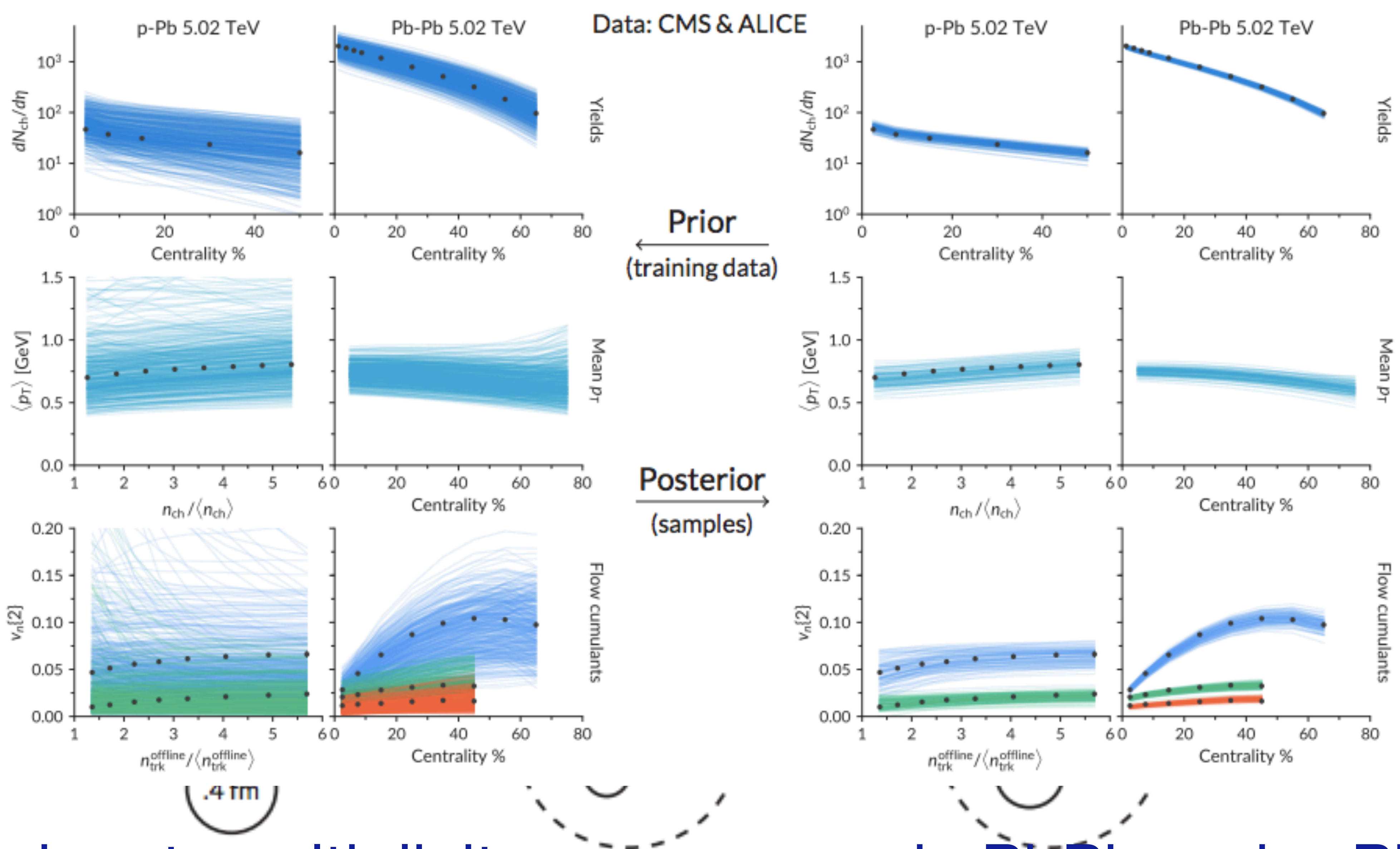

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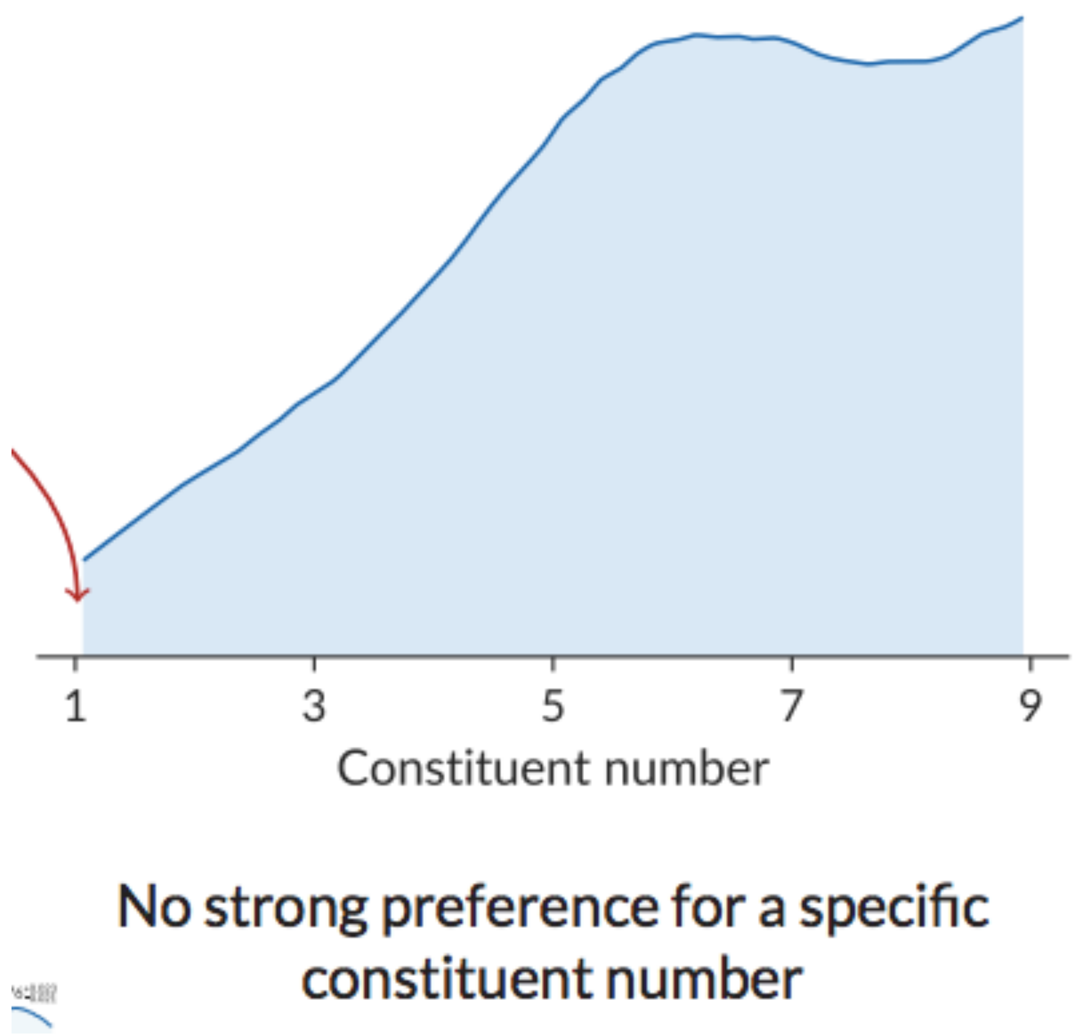

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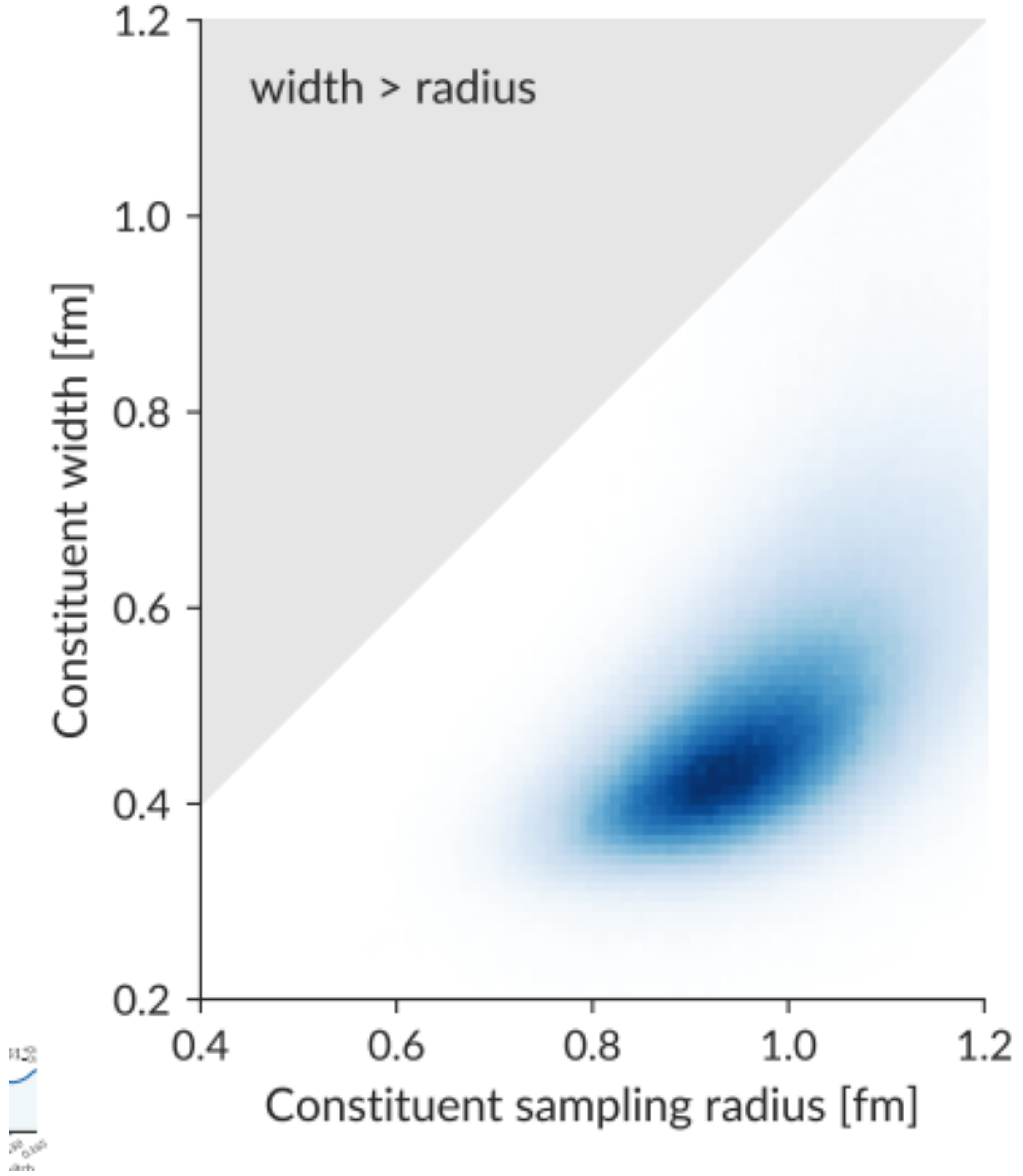
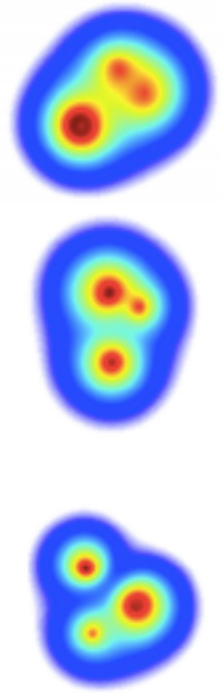


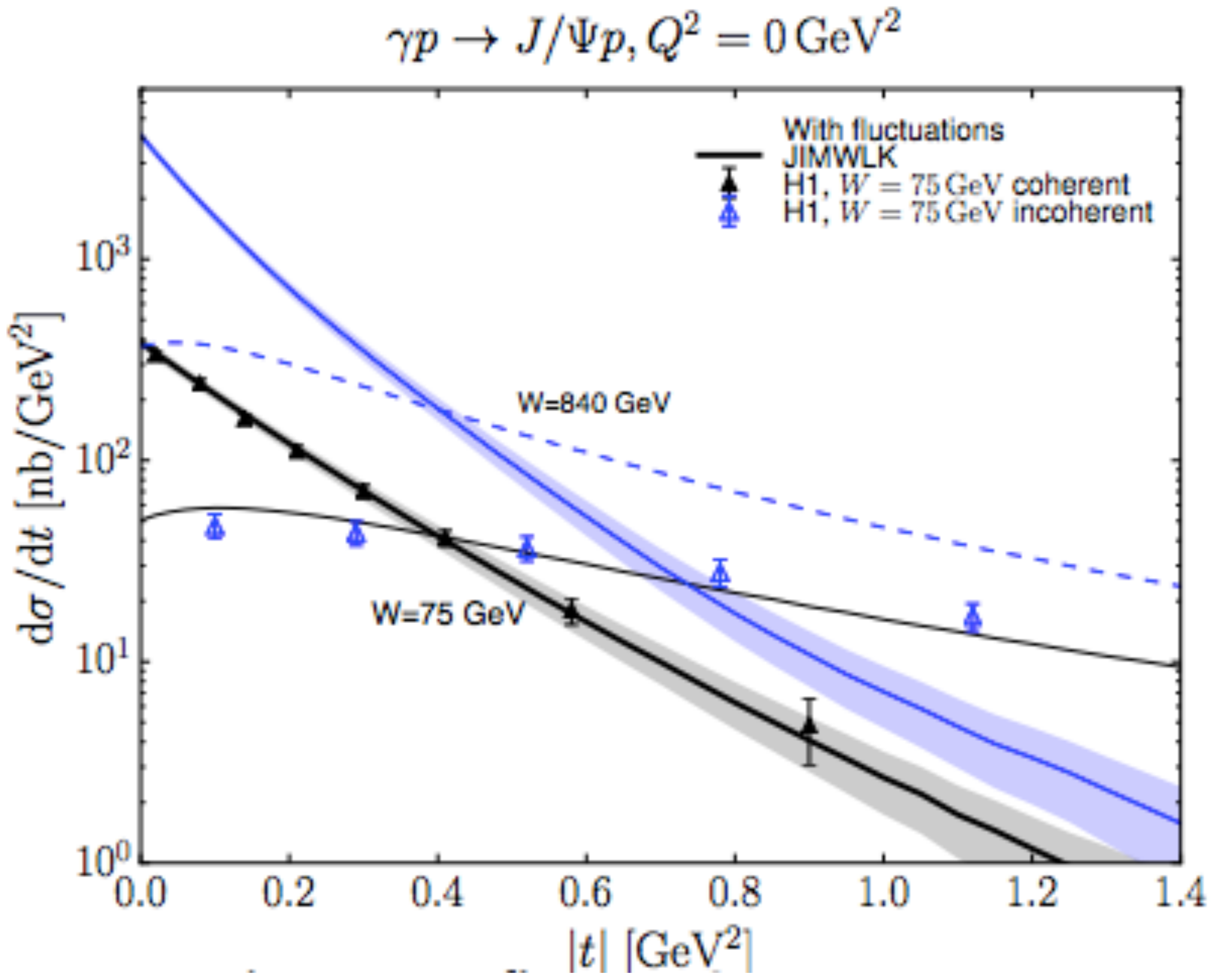
Shows that we are sensitive to nucleon substructure
'configuration space picture of the proton'

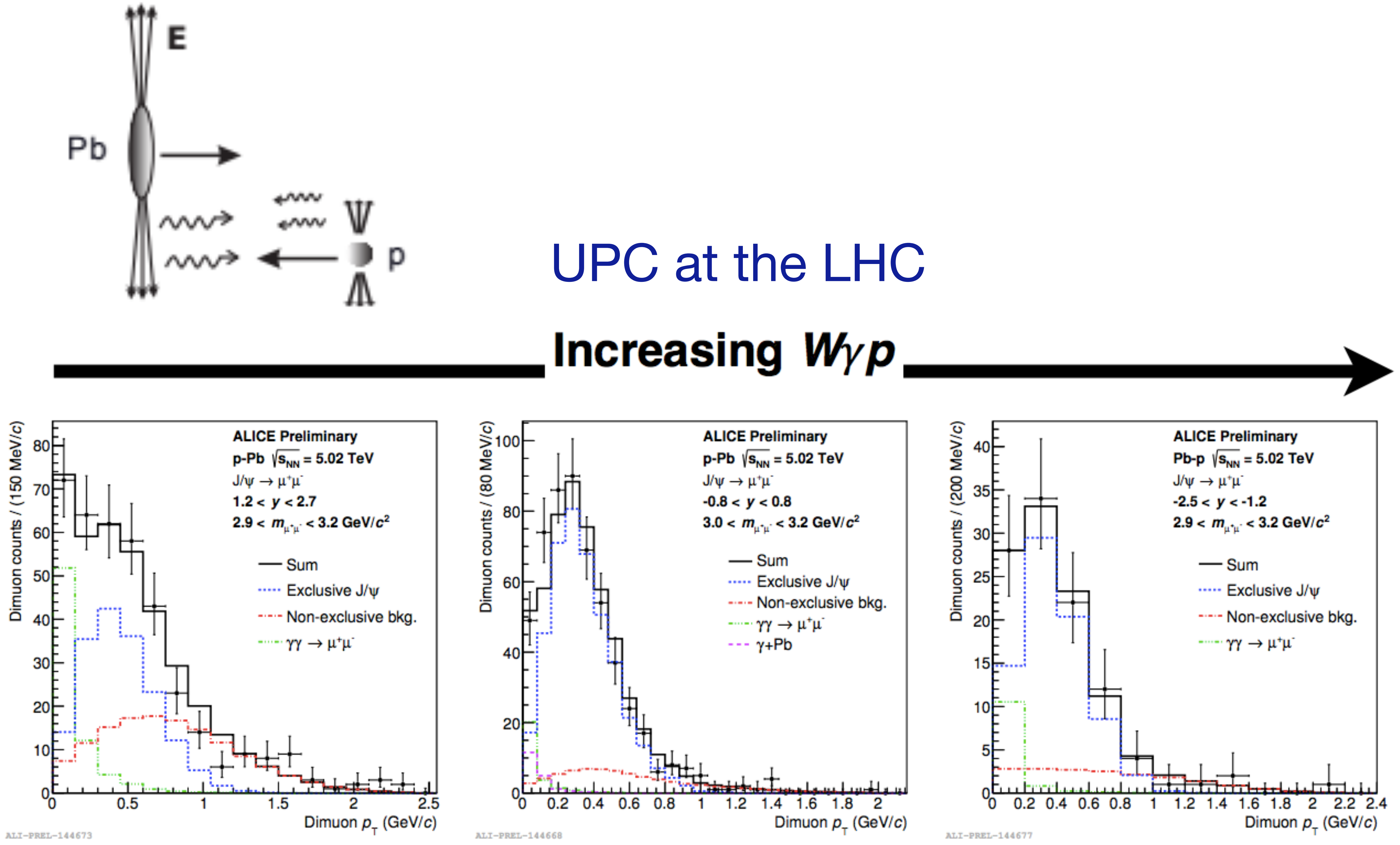
Proton substructure from UPCs

$W = 75$ GeV:



Coherent and incoherent exclusive J/ψ in ep





ALICE: 1406.7819

Coherent: average

$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Incoherent: RMS

$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

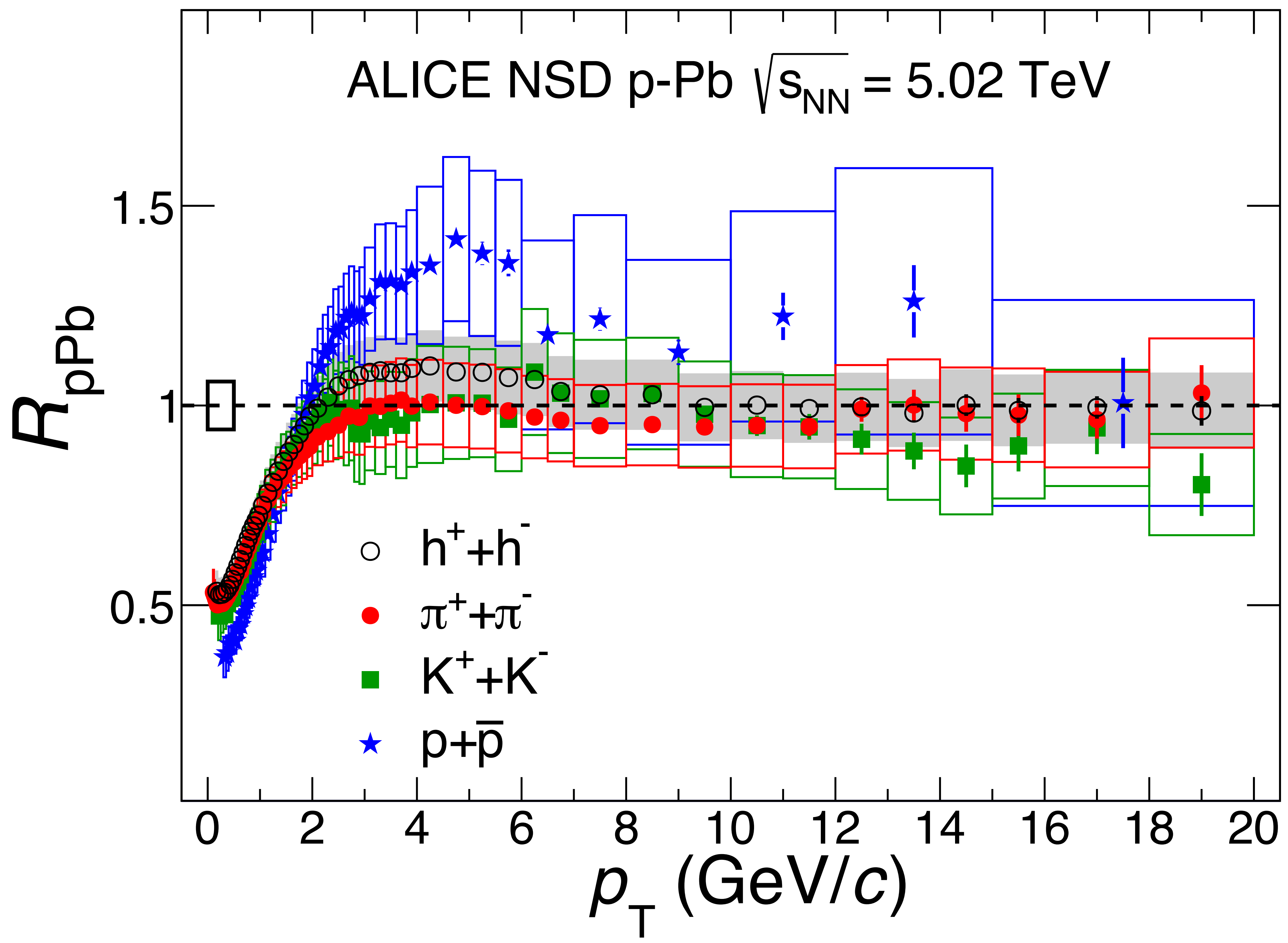
Dissociative increase more slowly than elastic consistent with HERA data

Different angle: Spatial size, fluctuations measured by coherent/incoherent interactions

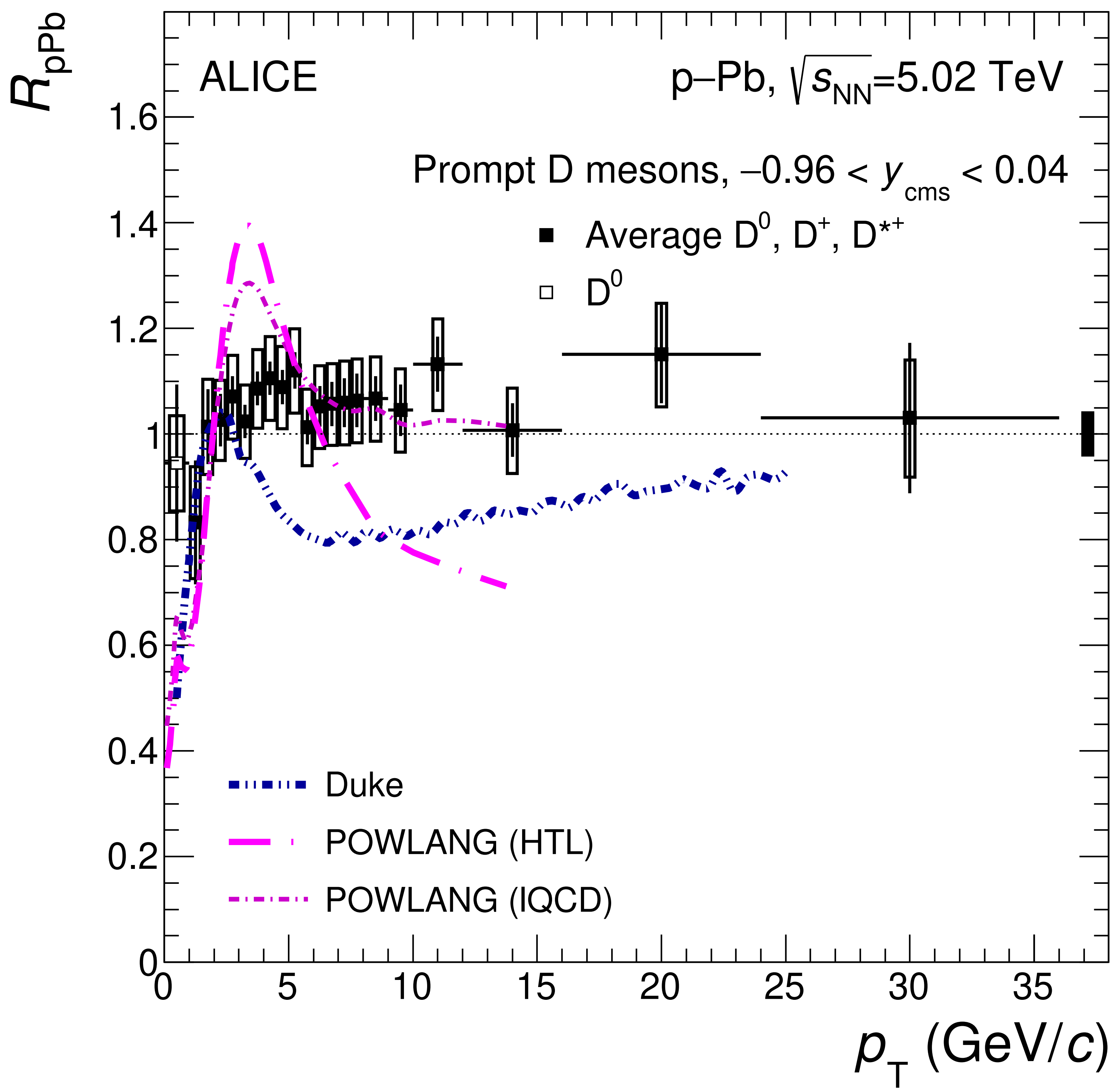
Should compare and contrast conclusions from flow/final state and EM interactions

Final state interactions, but no energy loss?

Light flavor hadrons



Heavy flavour: D meson



For all particle types: R_{pPb} = 1, no (large) energy loss

Model curves: effect of parton energy loss

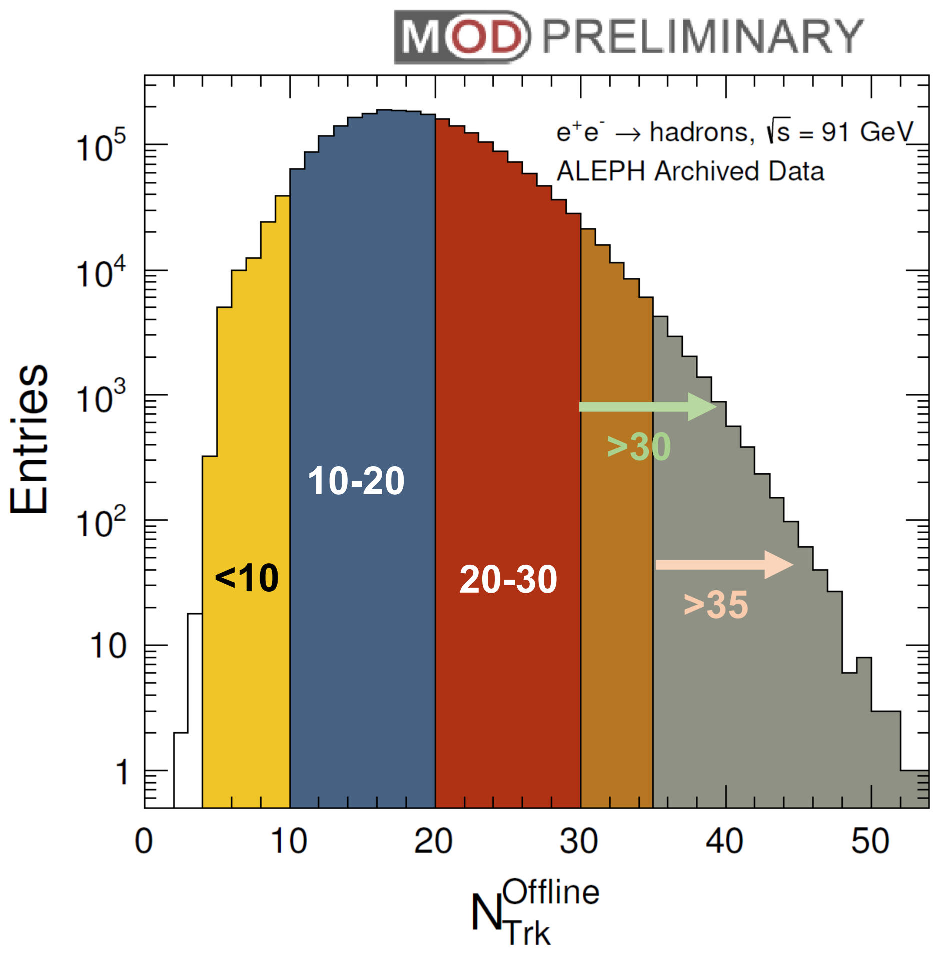
However: spectra shapes change at low to intermediate p_T in high multiplicity collisions

Summary/conclusions

- Jets: tool to study angular distributions of radiated energy
  - Access to underlying dynamics
- High-multiplicity pp and p-Pb show features similar to Pb-Pb collisions:
  - Elliptic flow
  - Increased strange baryon production
- Mechanisms:
  - Multiple parton interactions
  - Final state effects in pp: approach QGP formation?
  - Flow generation more effective than expected with $R \sim \lambda$

Switching off the flow: e^+e^-

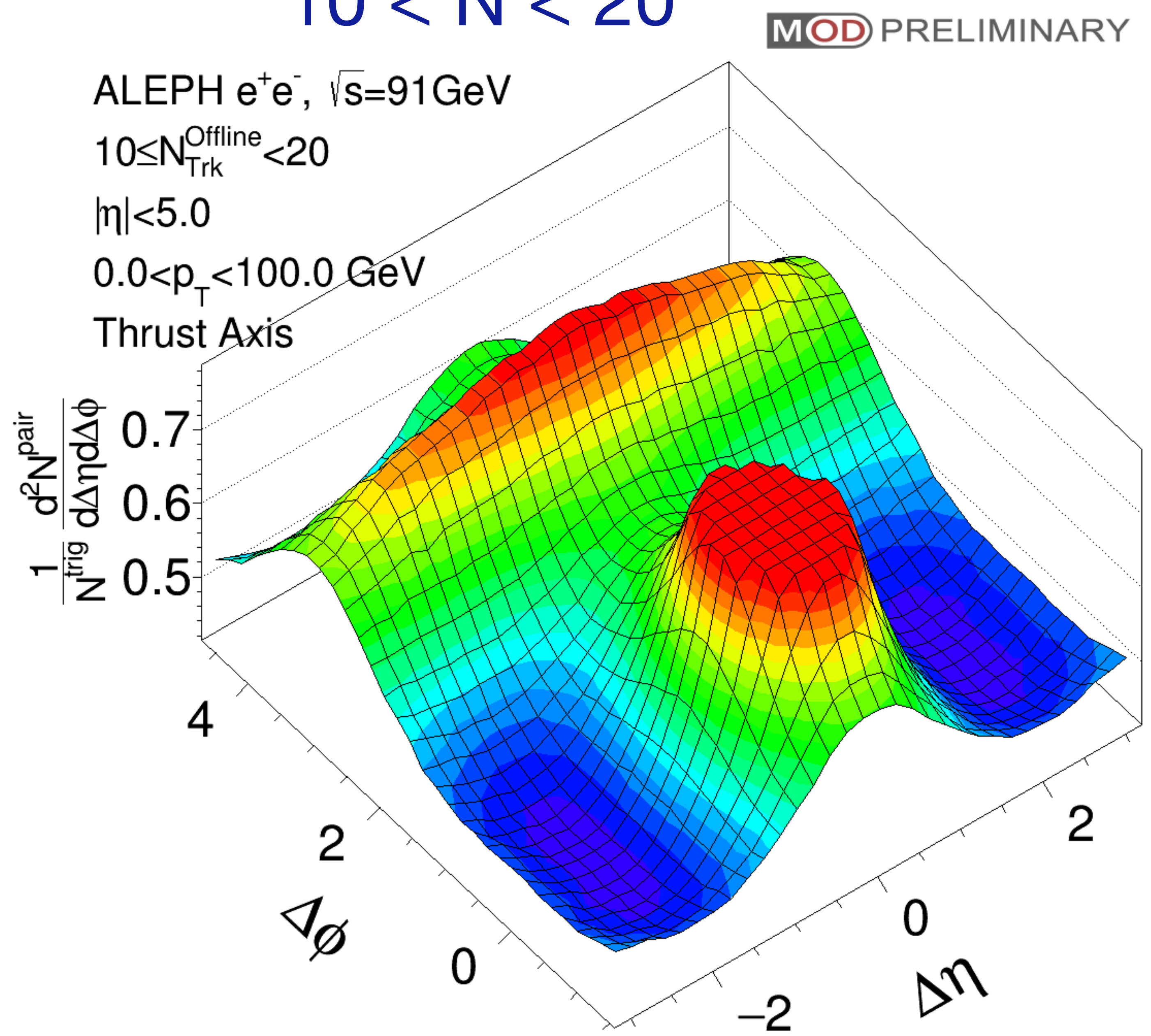
J-Y Lee



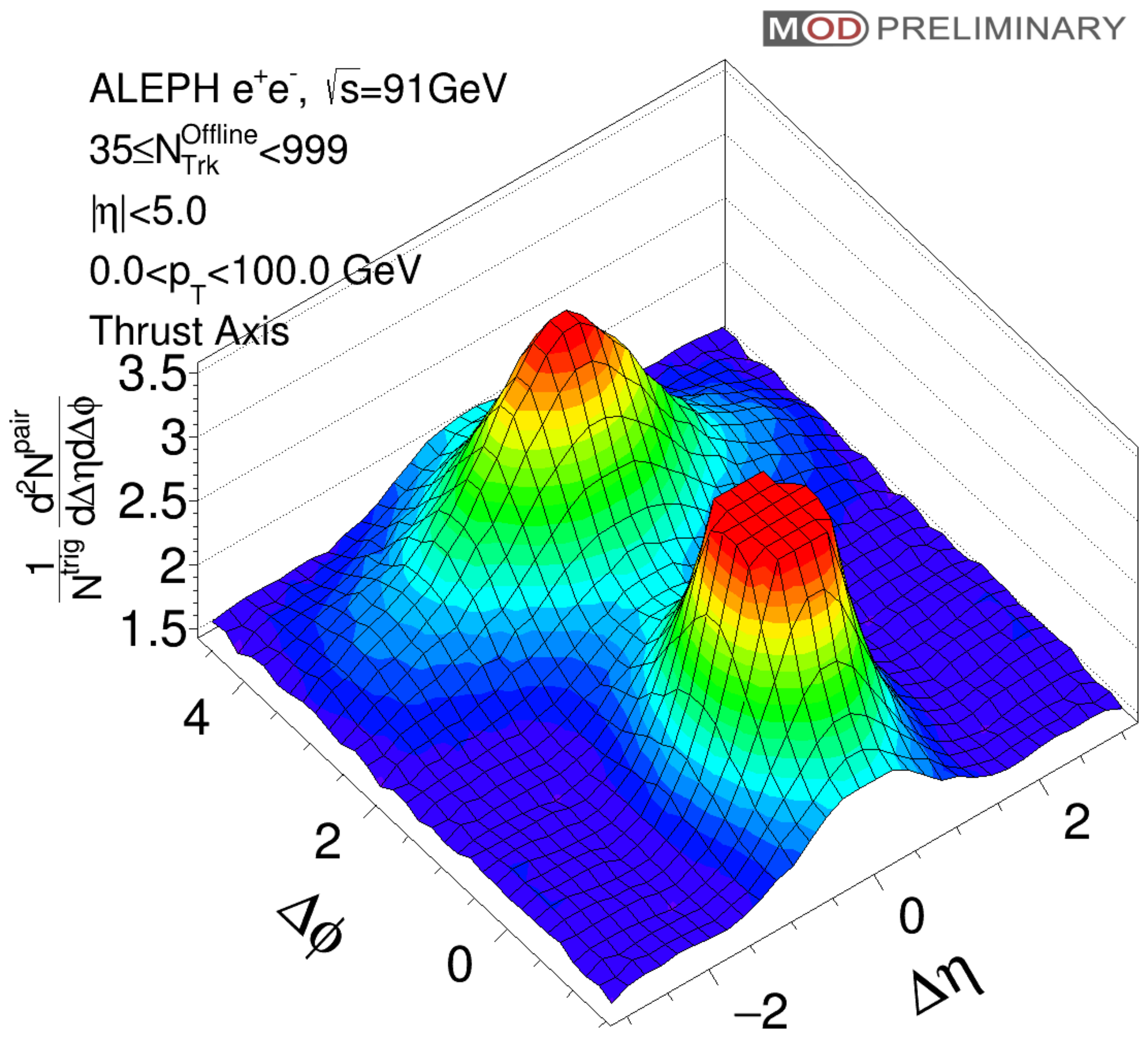
High-multiplicity events

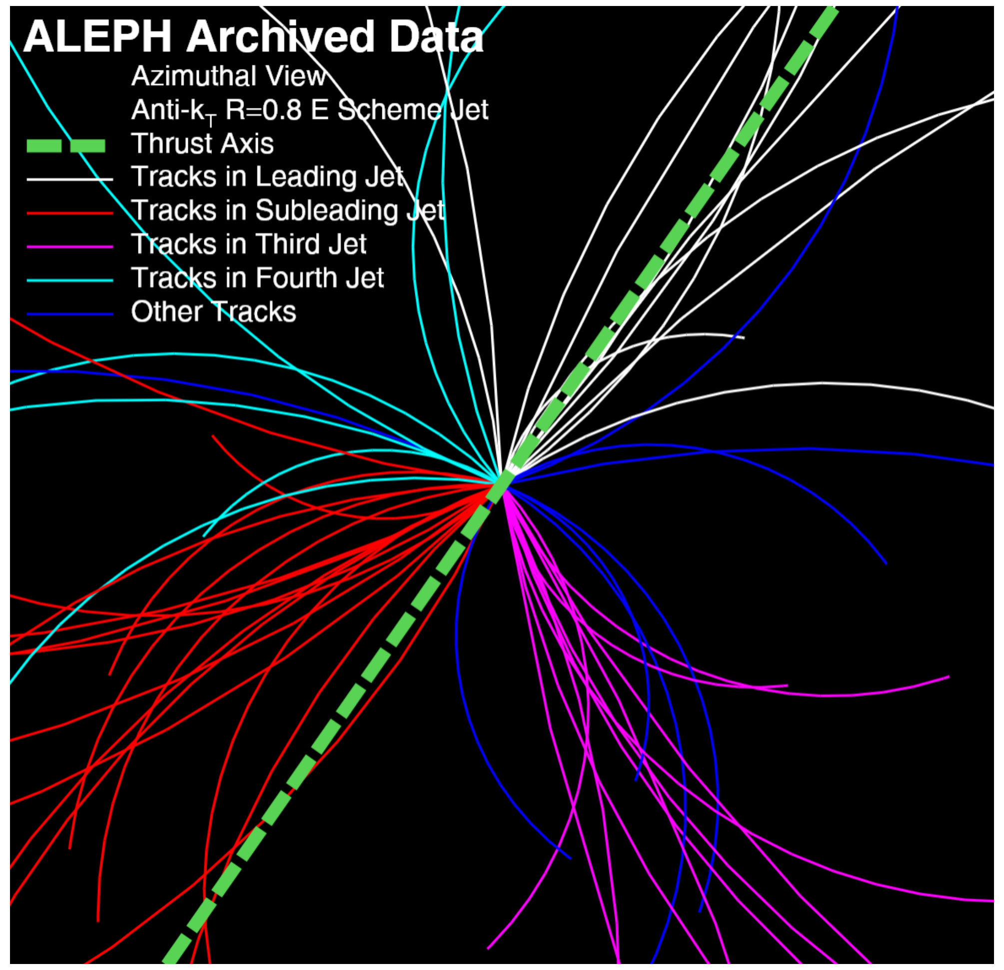
ALEPH e^+e^- thrust axis

10 < N < 20

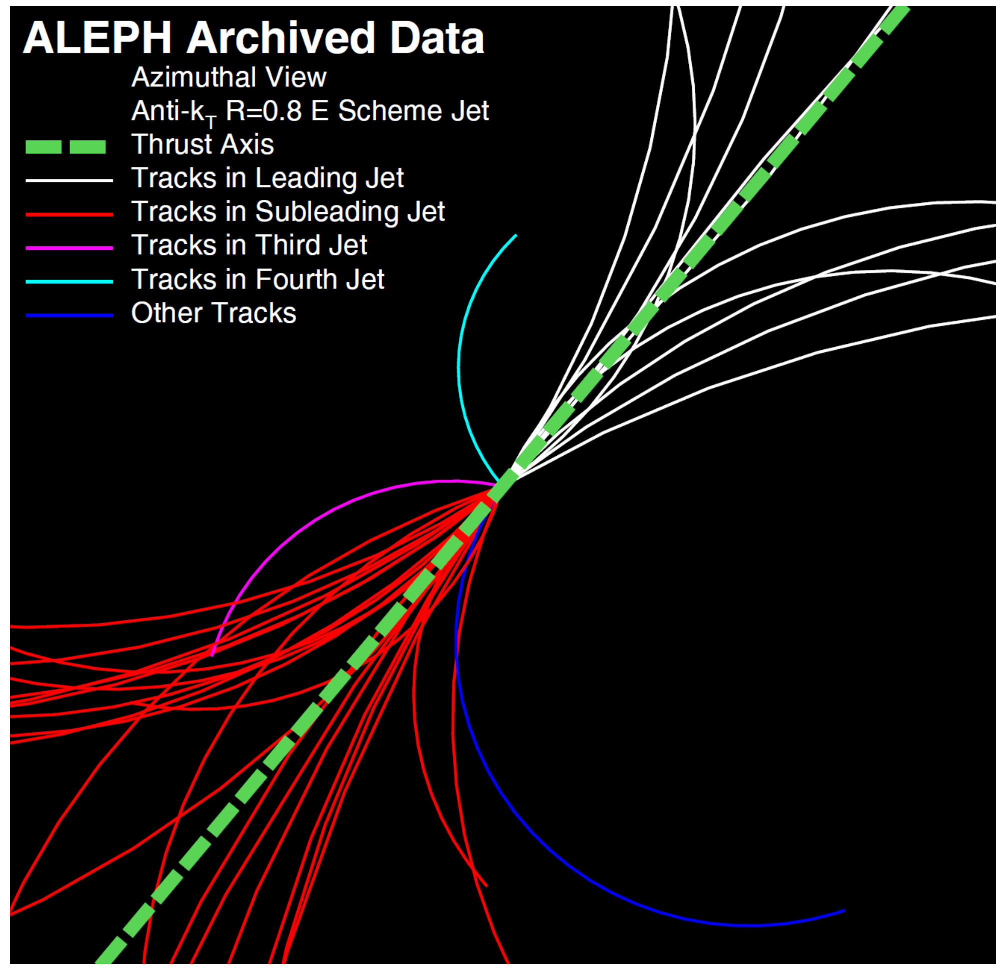


N ≥ 35





Low T; 'multi-jet'



High T; 'di-jet'

No evidence of long-range correlations beyond Pythia expectation