Experimental overview of p(d)-A physics

Roberto Preghenella
Istituto Nazionale di Fisica Nucleare
CERN

Hot Quarks 2014
Las Negras — Cabo de Gata Natural Park, Andalucia, Spain
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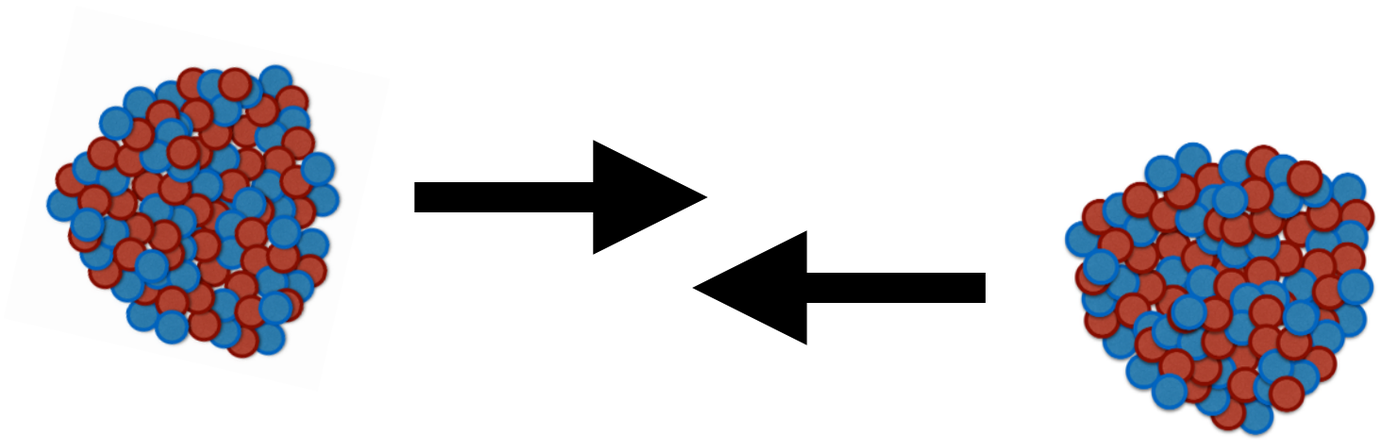
Hot and Cold Quarks



initial: nuclear
final: **hot**

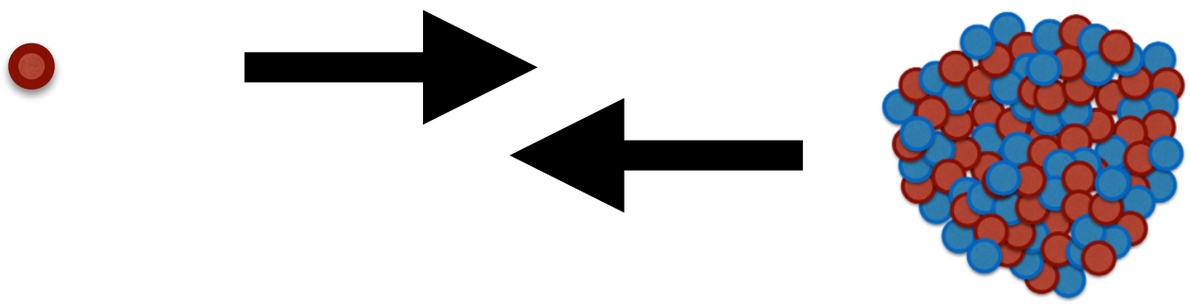
initial-state nuclear effects are present in A-A

Cronin enhancement, nuclear shadowing, parton saturation, …

but difficult to distinguish experimentally from final-state ones

a full understanding of hot QCD matter effects requires

measurements of cold nuclear matter effects with p(d)-A

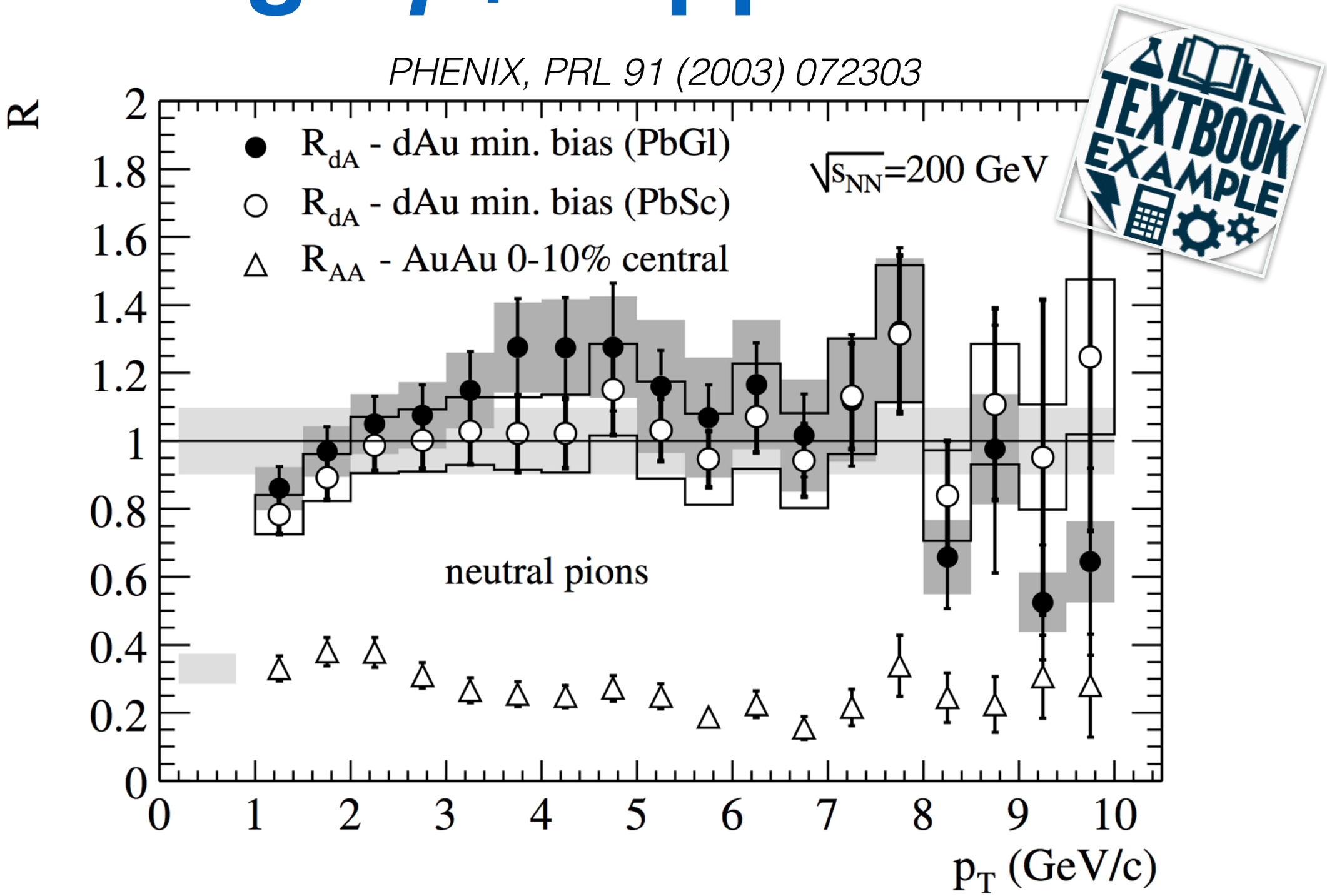


initial: nuclear
final: **cold (?)**

Main topics discussed this talk

- understanding **initial-state and CNM effects**
- hints for **collectivity** and similarities to A-A
- **quarkonia** and more hints for final state effects
- constraints on nPDFs with **vector bosons**

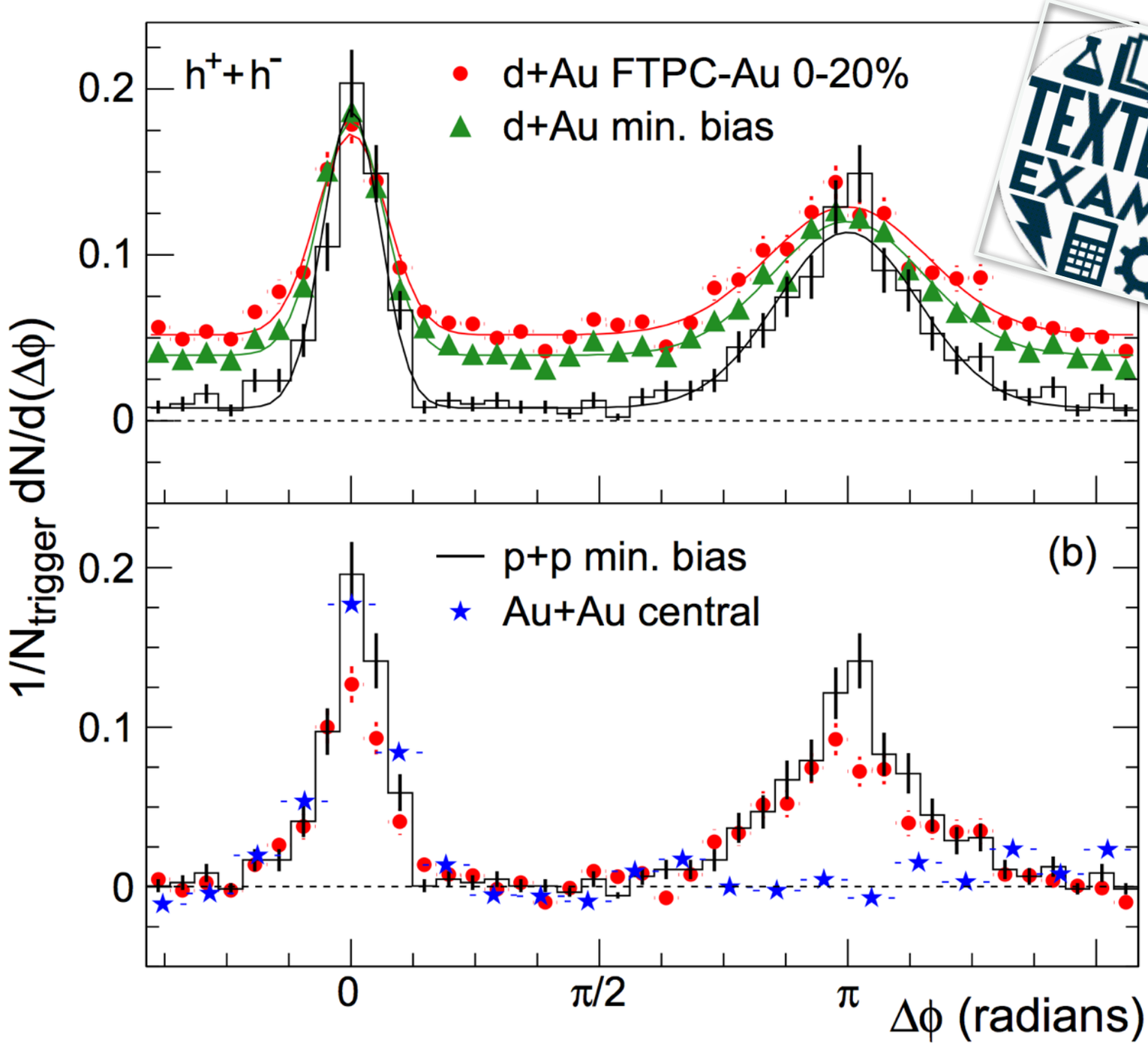
High-p_T suppression

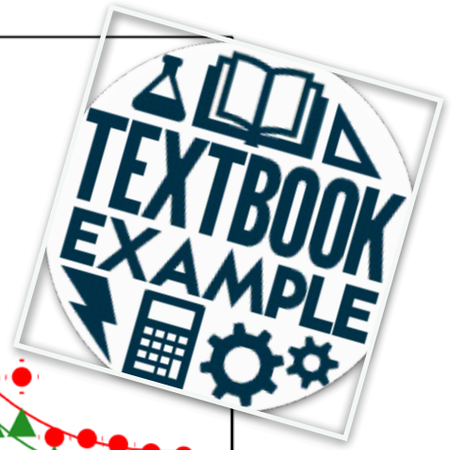


absence of suppression of high-p_T hadrons in d-Au

final-state interactions with the dense medium produced

Back-to-back correlations





d-Au two-particle azimuthal correlations **very similar to pp**

STAR, PRL 91 (2003) 072304

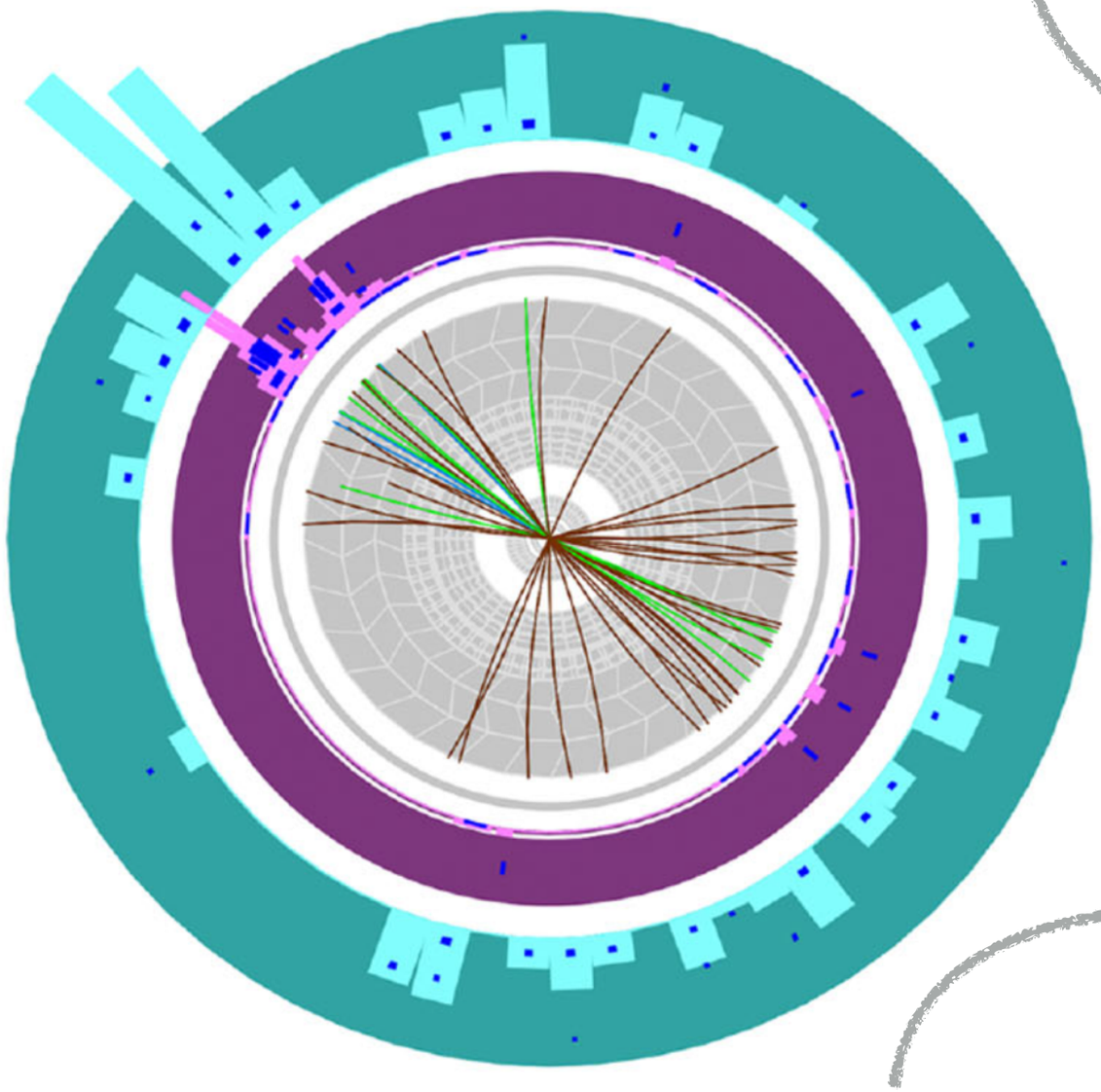
disappearance of back-to-back correlations at high p_T in central Au-Au

d-Au provides evidence of final-state interactions in Au-Au

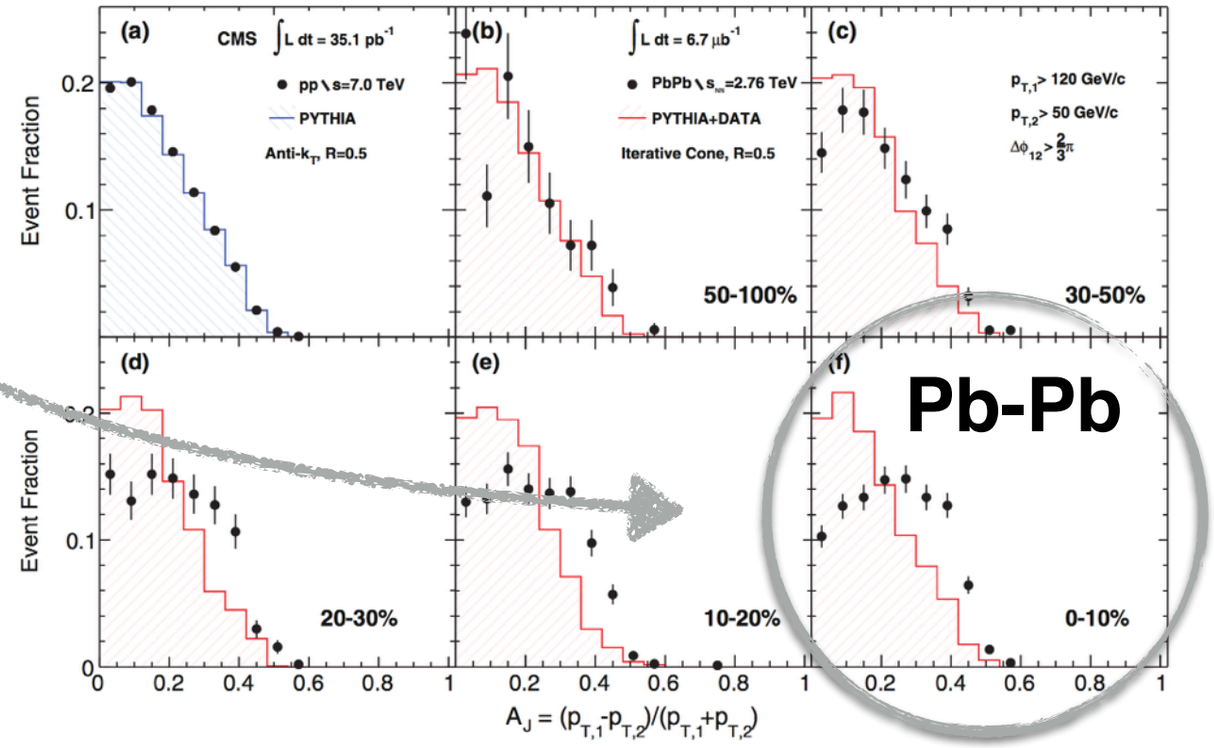
Di-jet momentum (im)balance

first observation of A-A events
with **large di-jet asymmetry**

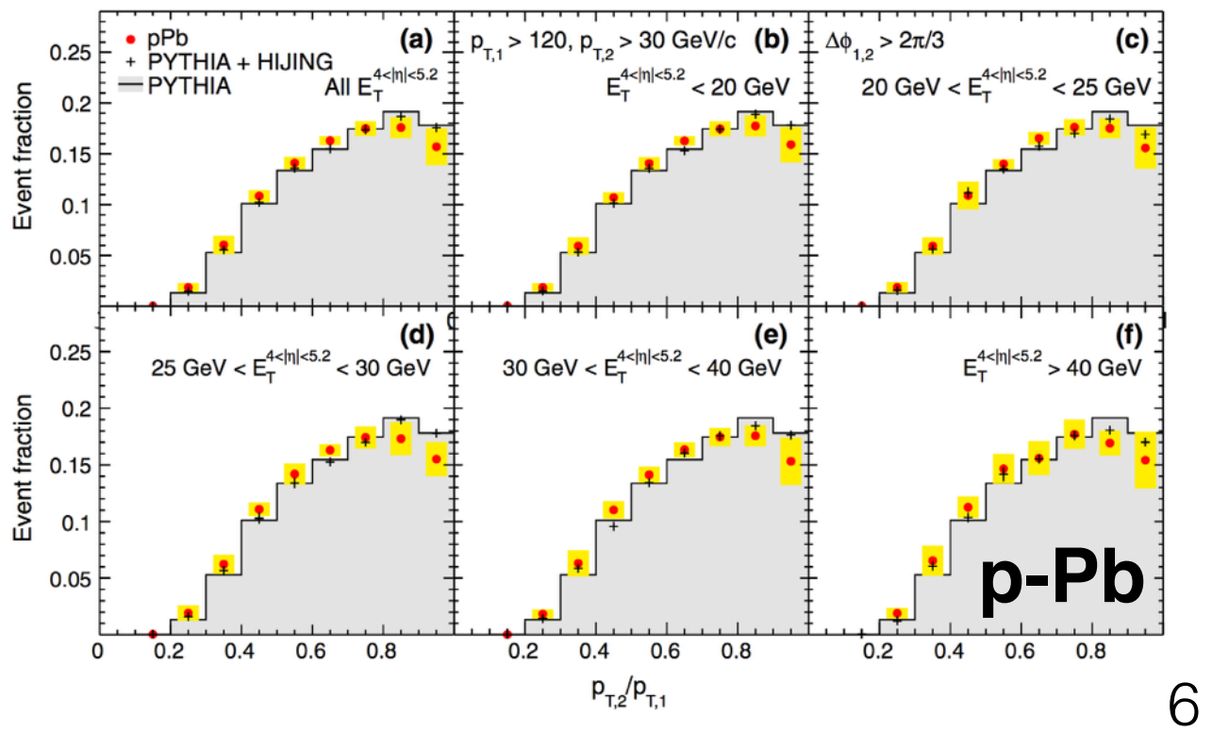
ATLAS, PRL 105 (2010) 252303



CMS, PRC 84, 024906 (2011)



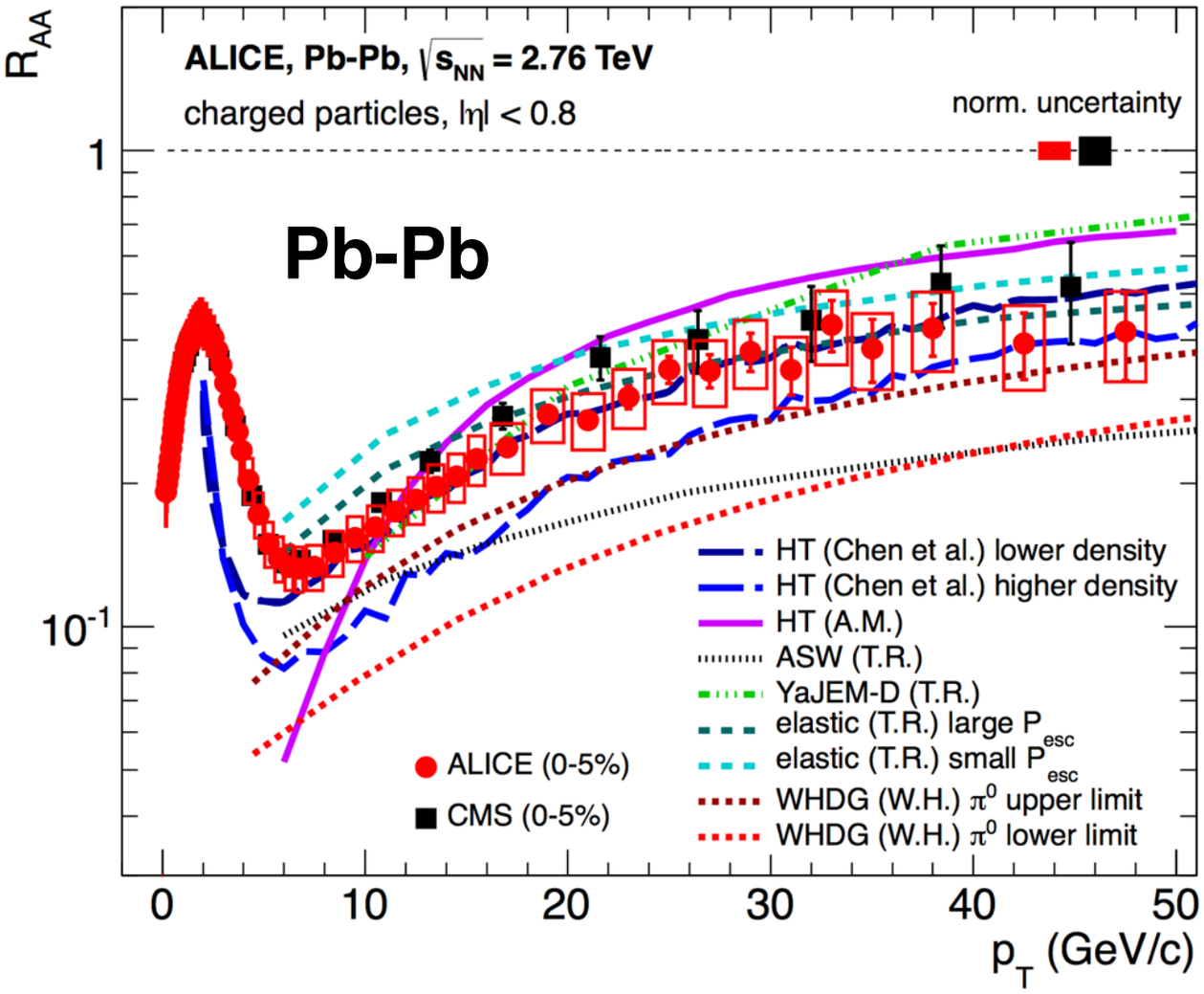
CMS, EPJC 74 (2014) 2951



di-jets are **balanced in p-Pb**

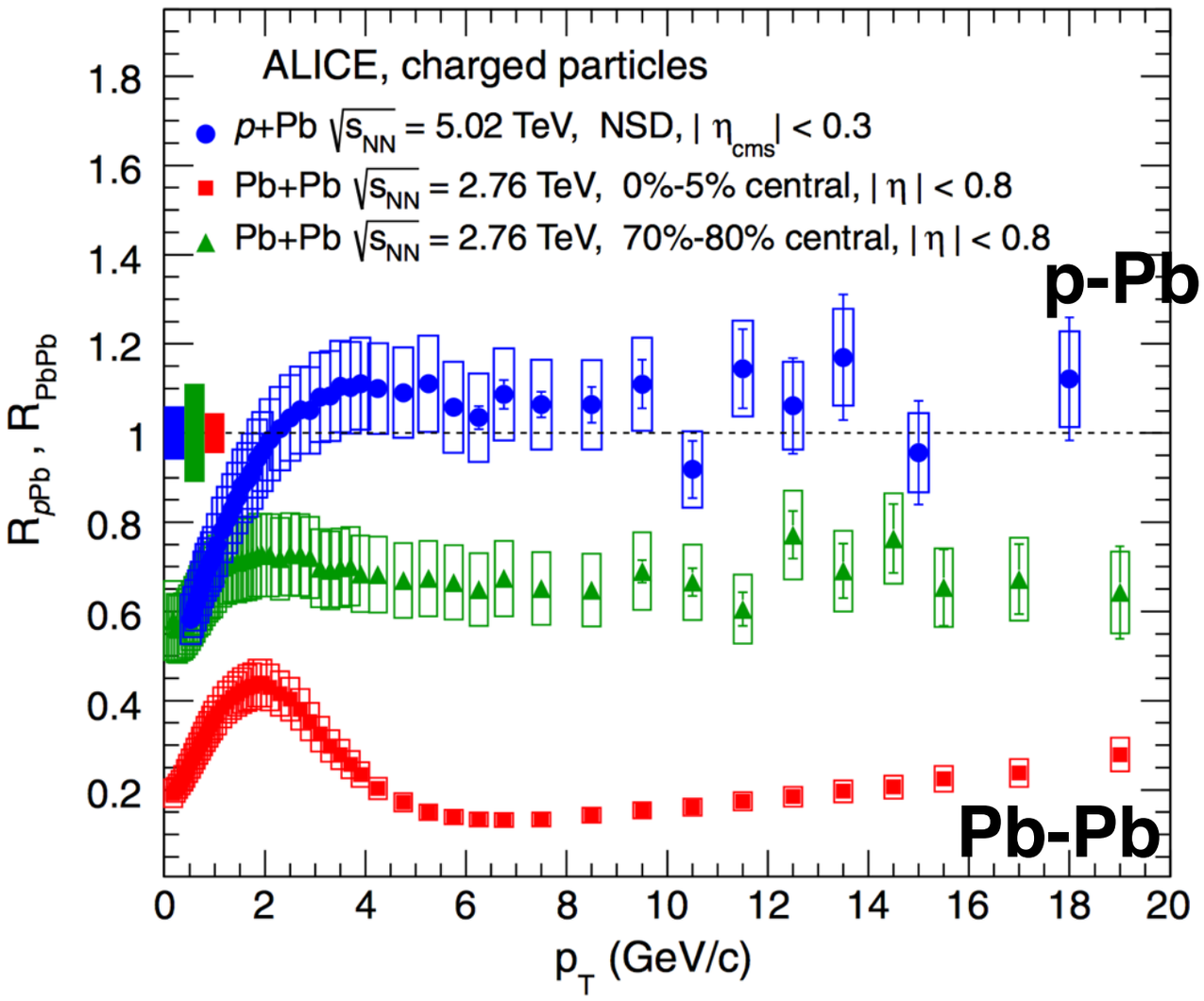
No modification in p-Pb

ALICE, PLB 720 (2013) 52



charged particle spectra
strongly modified in Pb-Pb
collisions in a wide p_T range

ALICE, PRL 110 (2013) 082302

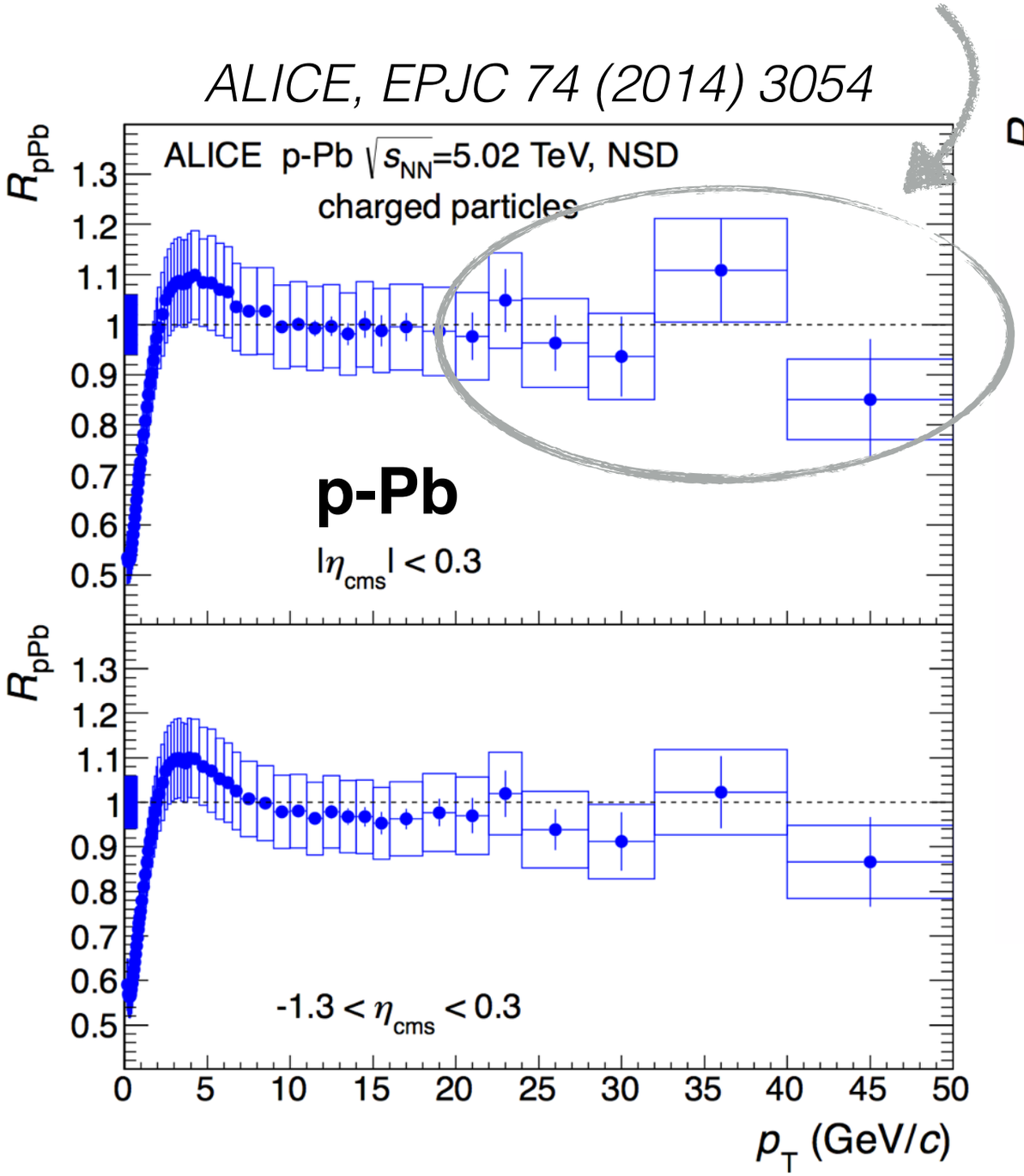


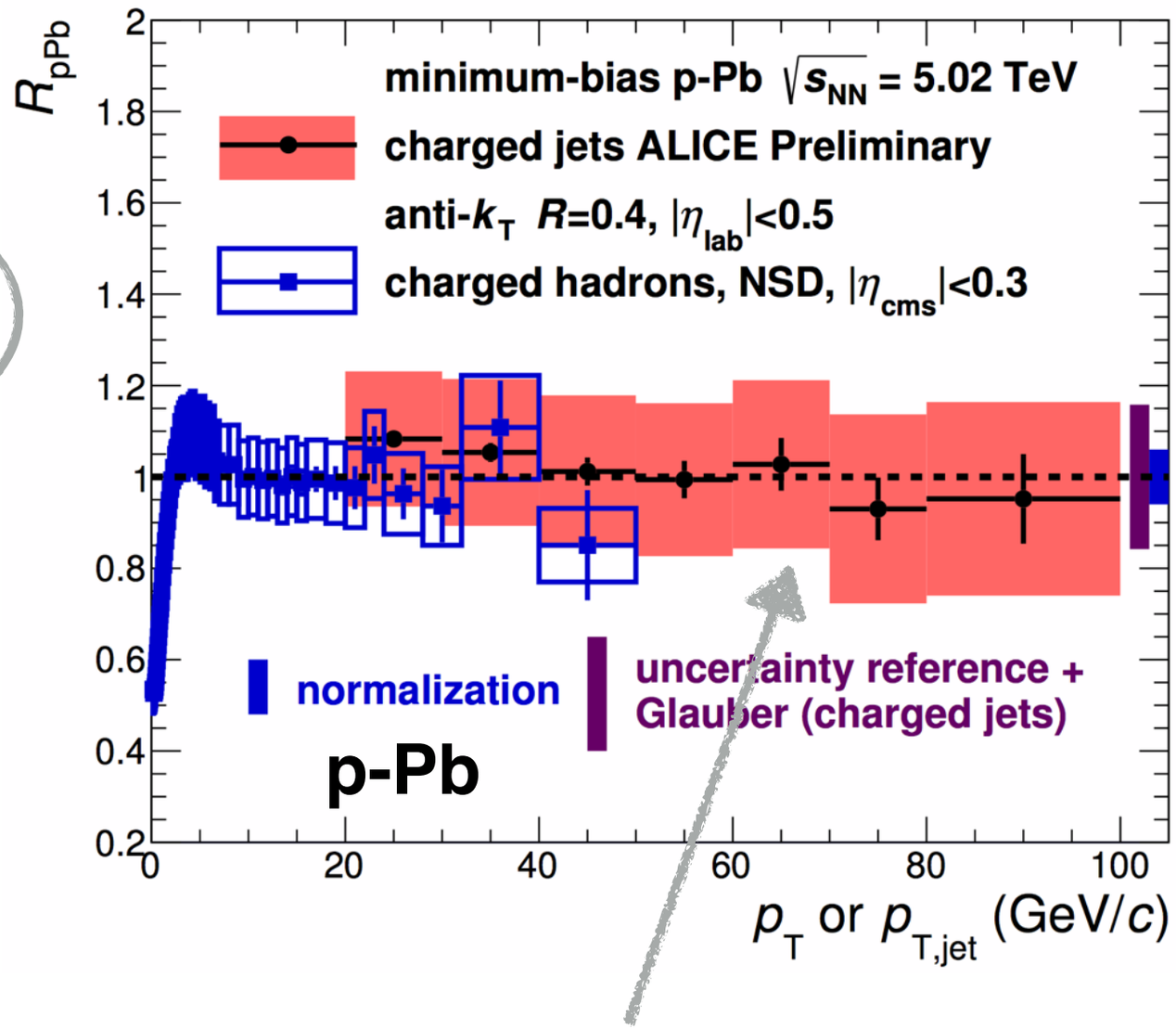
p-Pb confirms that it comes
from a **final-state effect**
parton in-medium energy loss

No modification in p-Pb

new ALICE results on charge particles
consistent with no modifications up to p_T = 50 GeV/c

ALICE, EPJC 74 (2014) 3054





same conclusion from reconstructed **jets**

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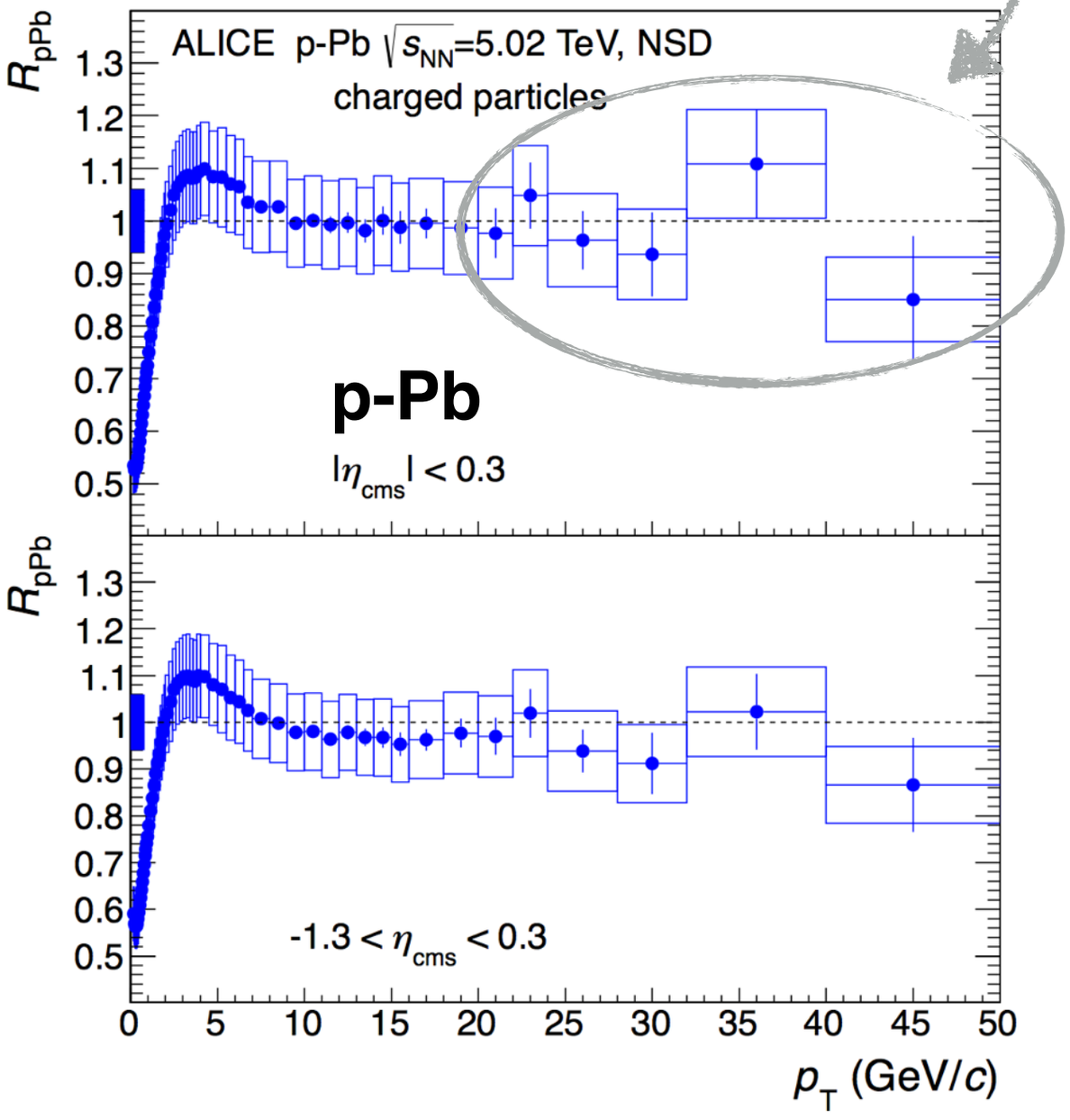
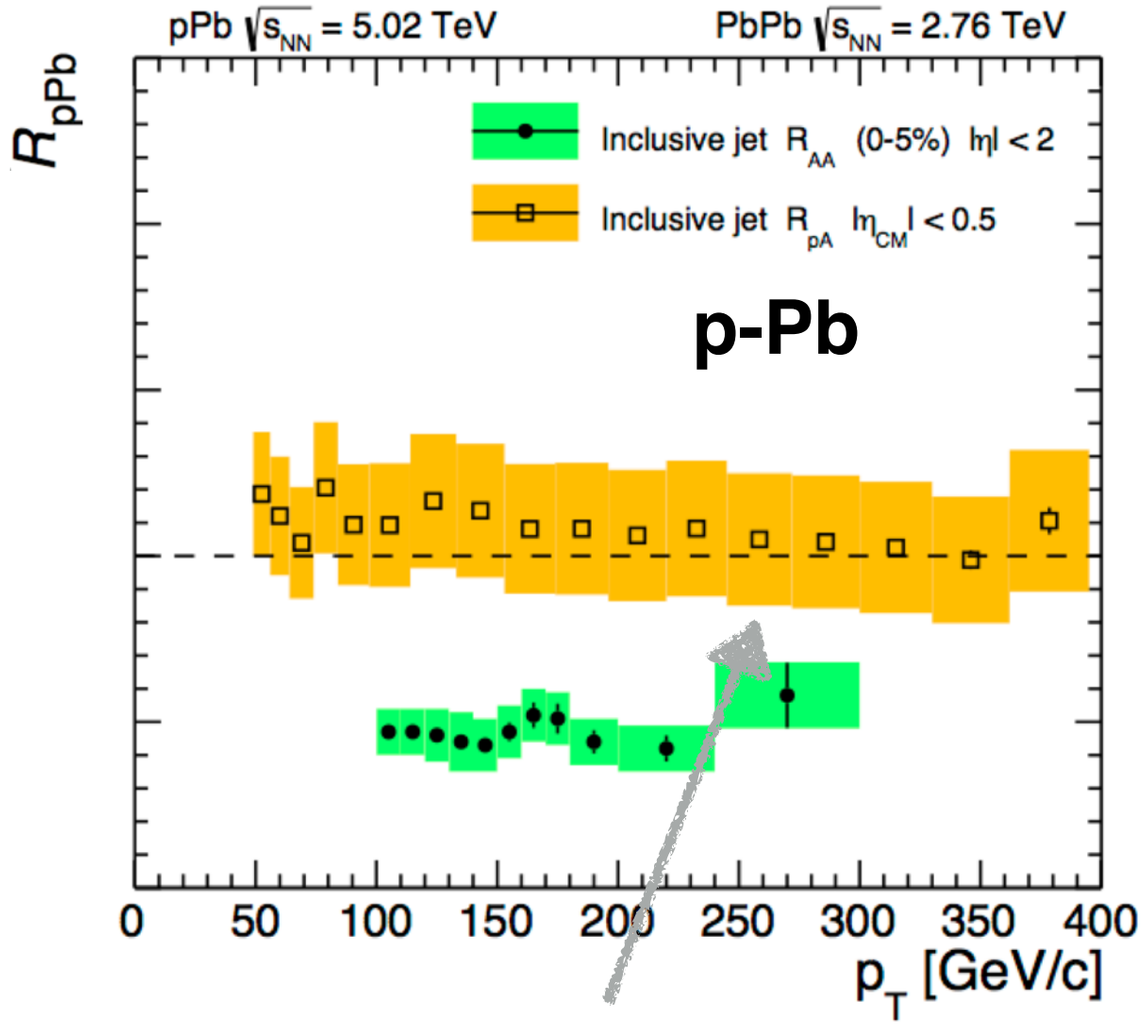
ALICE, EPJC 74 (2014) 3054



CMS, PAS HIN-14-001



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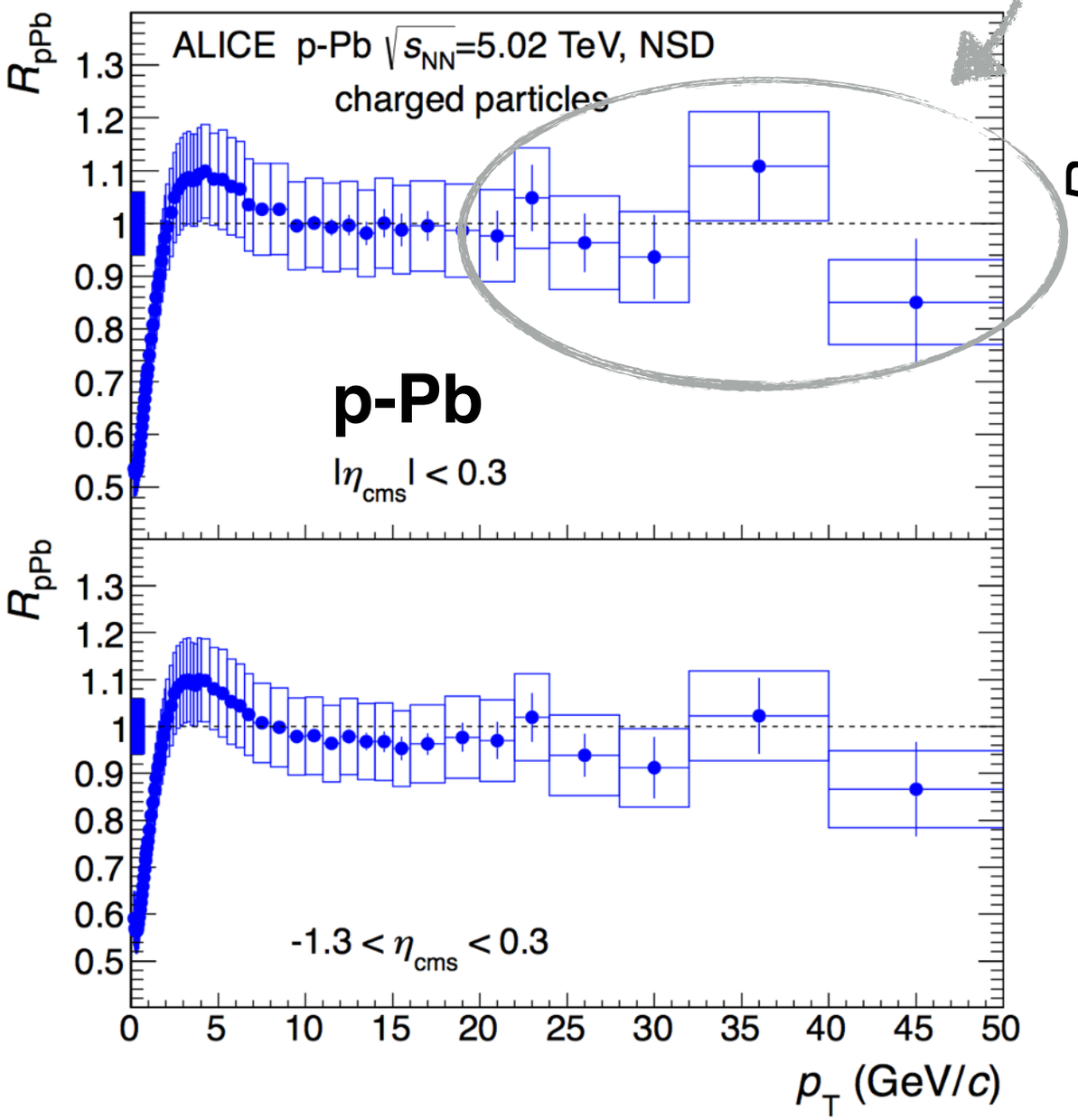
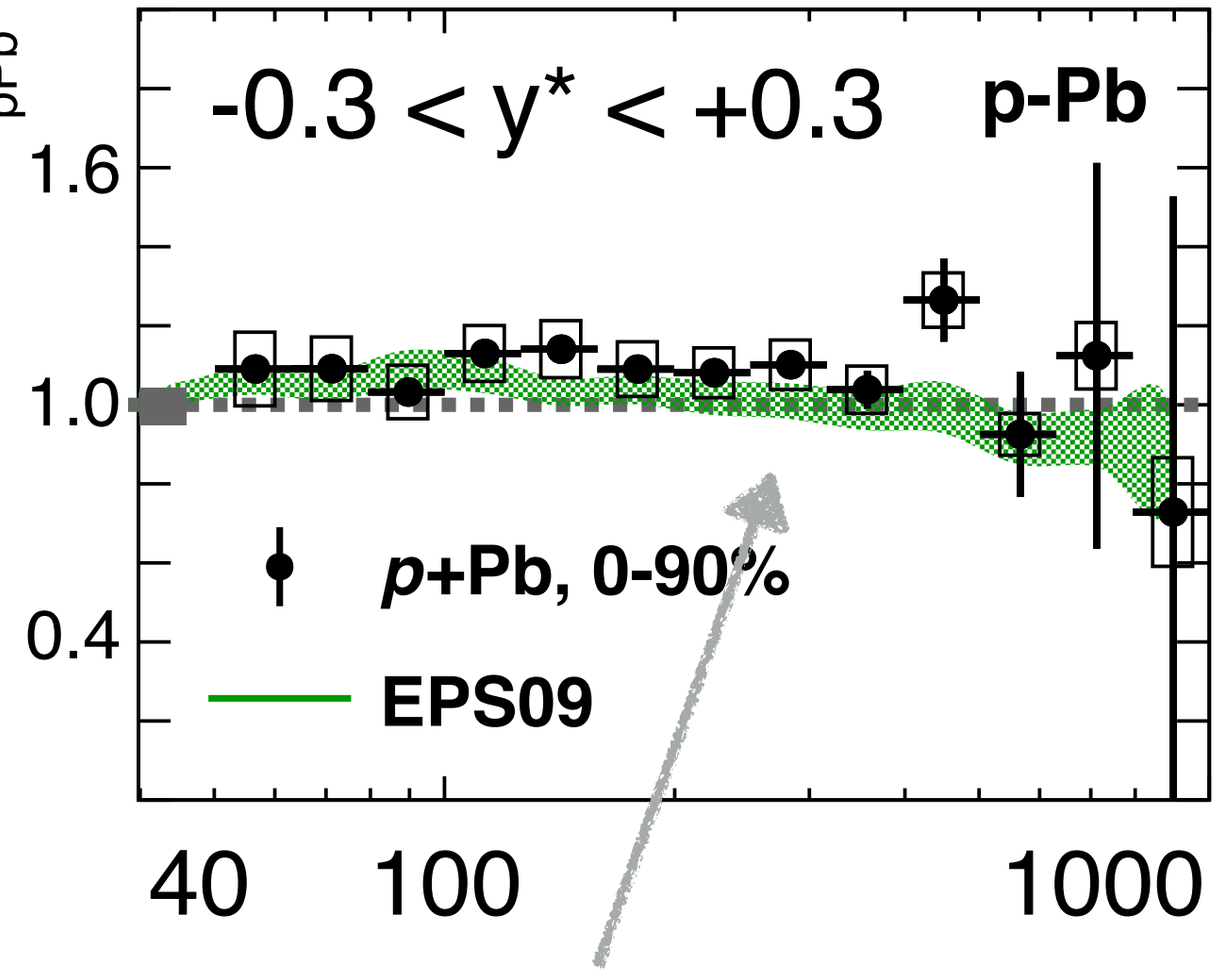
ALICE, EPJC 74 (2014) 3054



ATLAS, ATLAS-CONF-2014-024

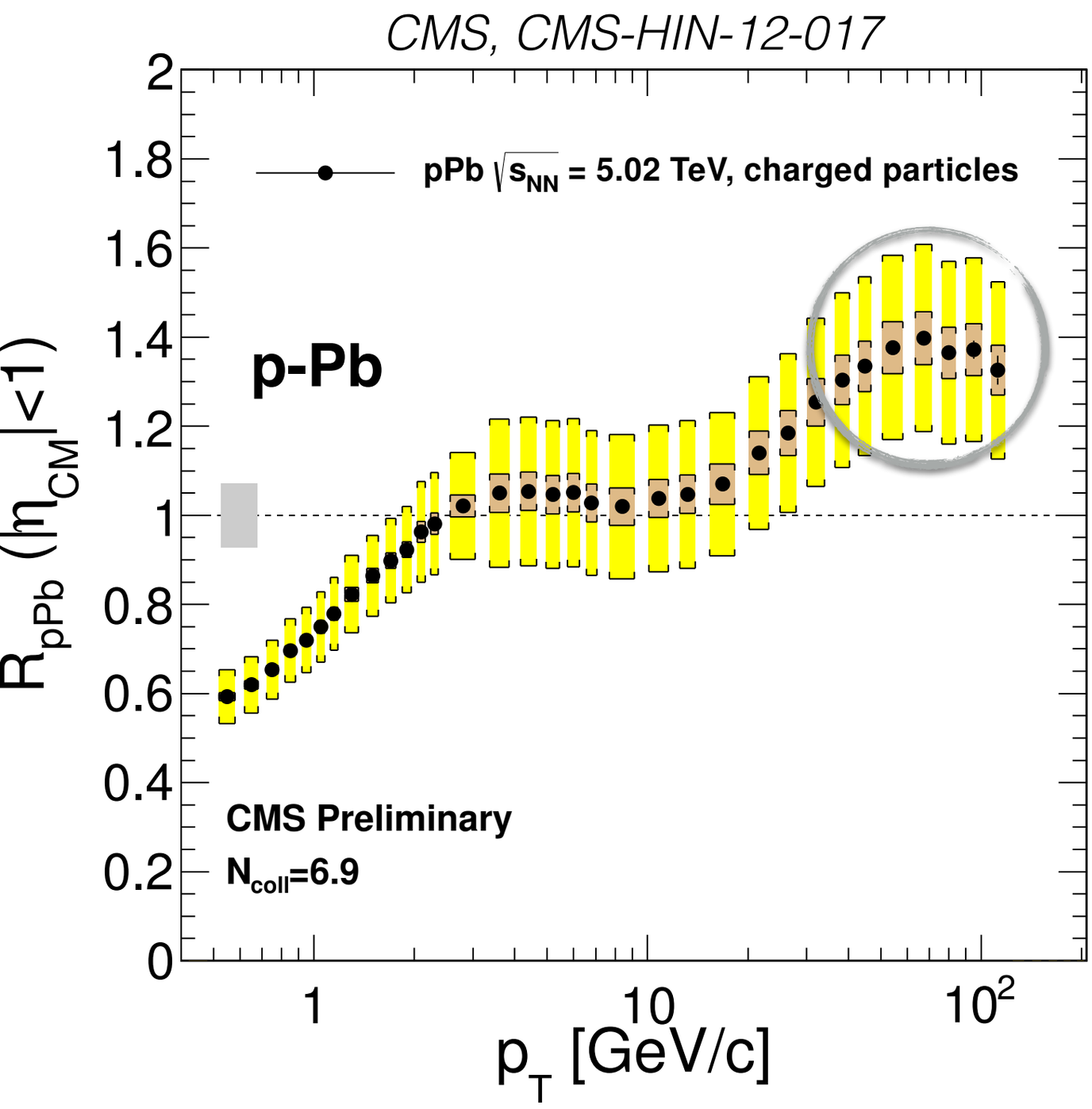


same conclusion from reconstructed **jets**

evidence that hot QCD matter exists in the final state of A-A collisions

R_{pA} does not show any surprises?

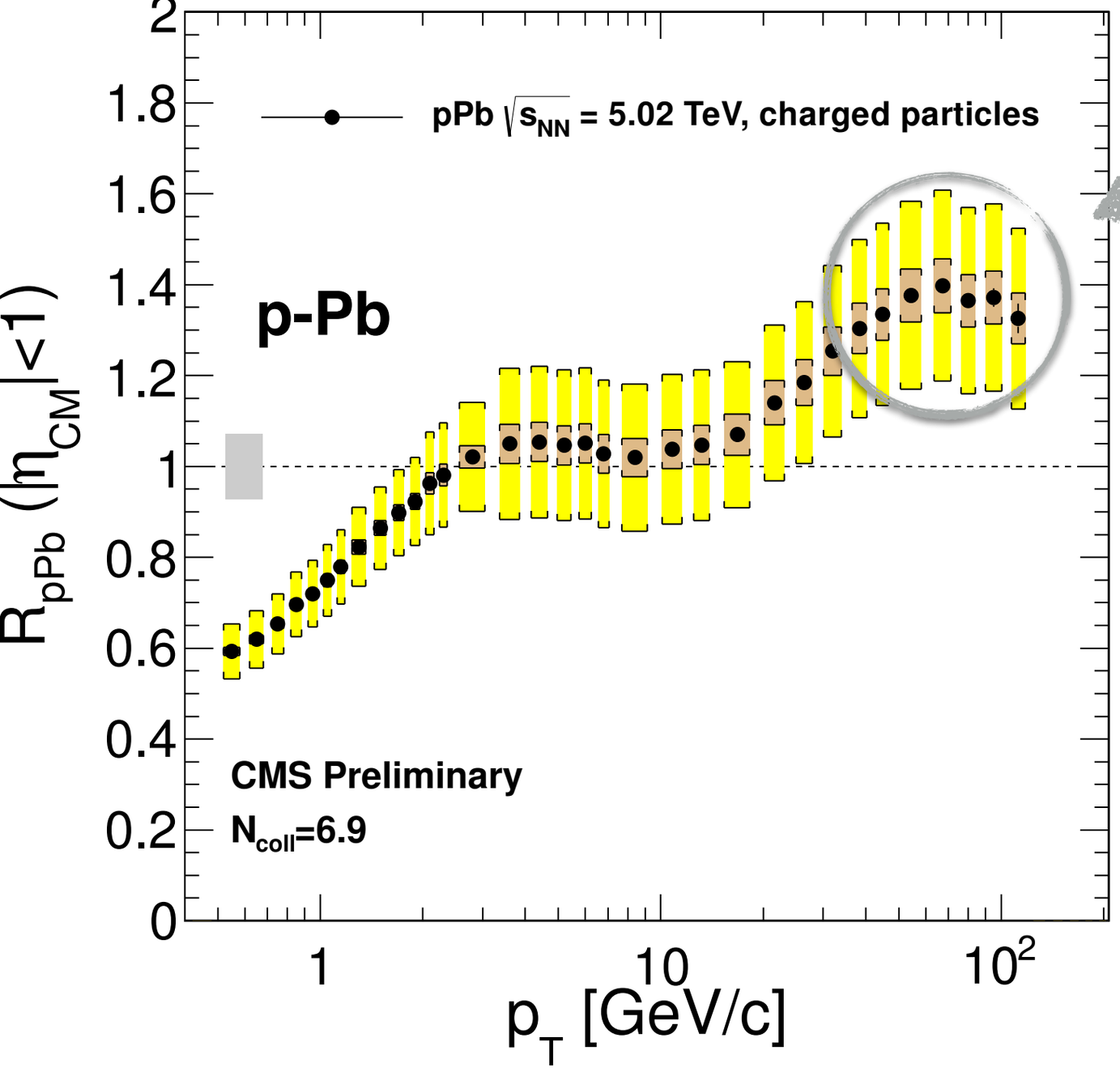
Charged-particle R_{pPb} at large p_T



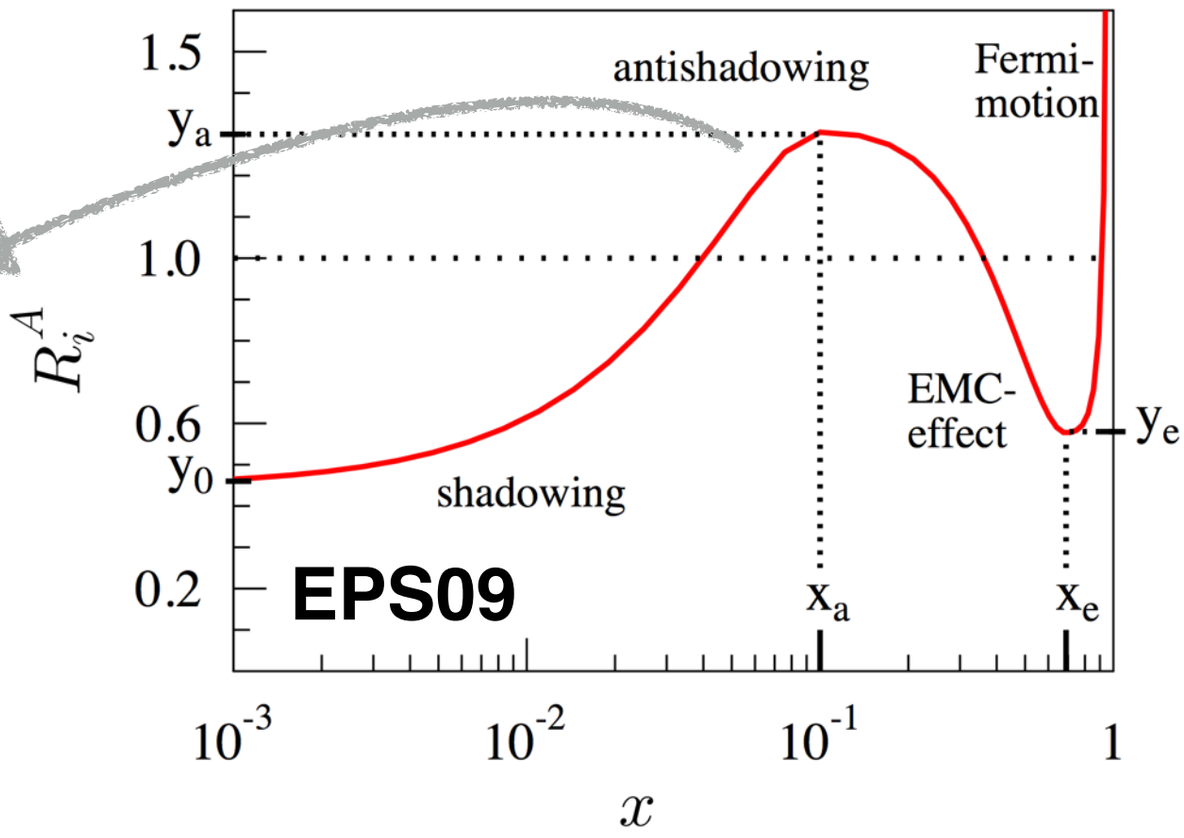
CMS observes **strong enhancement at large p_T**

Charged-particle R_{pPb} at large p_T

CMS, CMS-HIN-12-017



Eskola et al., JHEP 04 (2009) 065

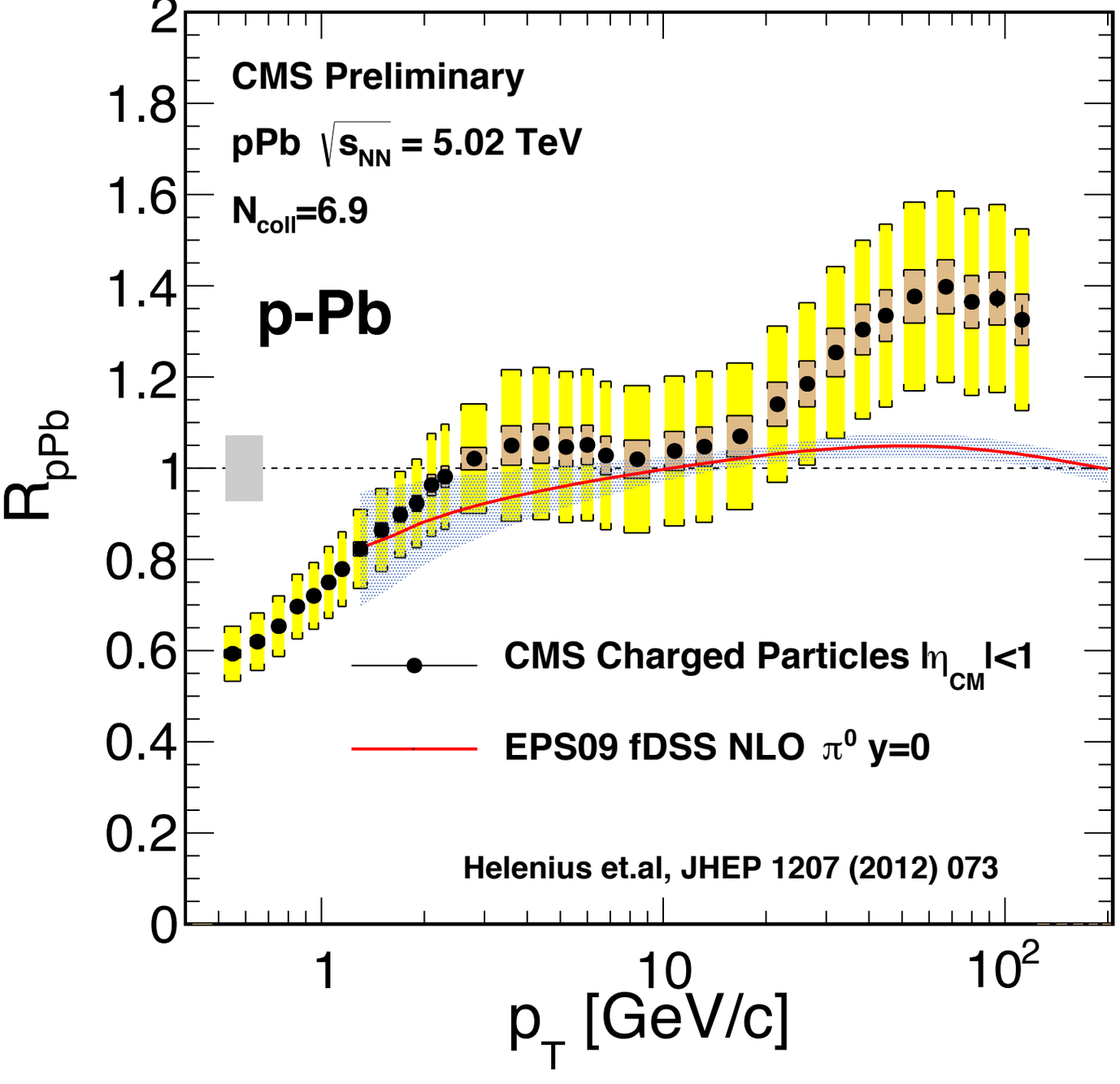


PDFs are expected to be **modified in the nucleus**

shadowing, anti-shadowing

Charged-particle R_{pPb} at large p_T

CMS, CMS-HIN-12-017



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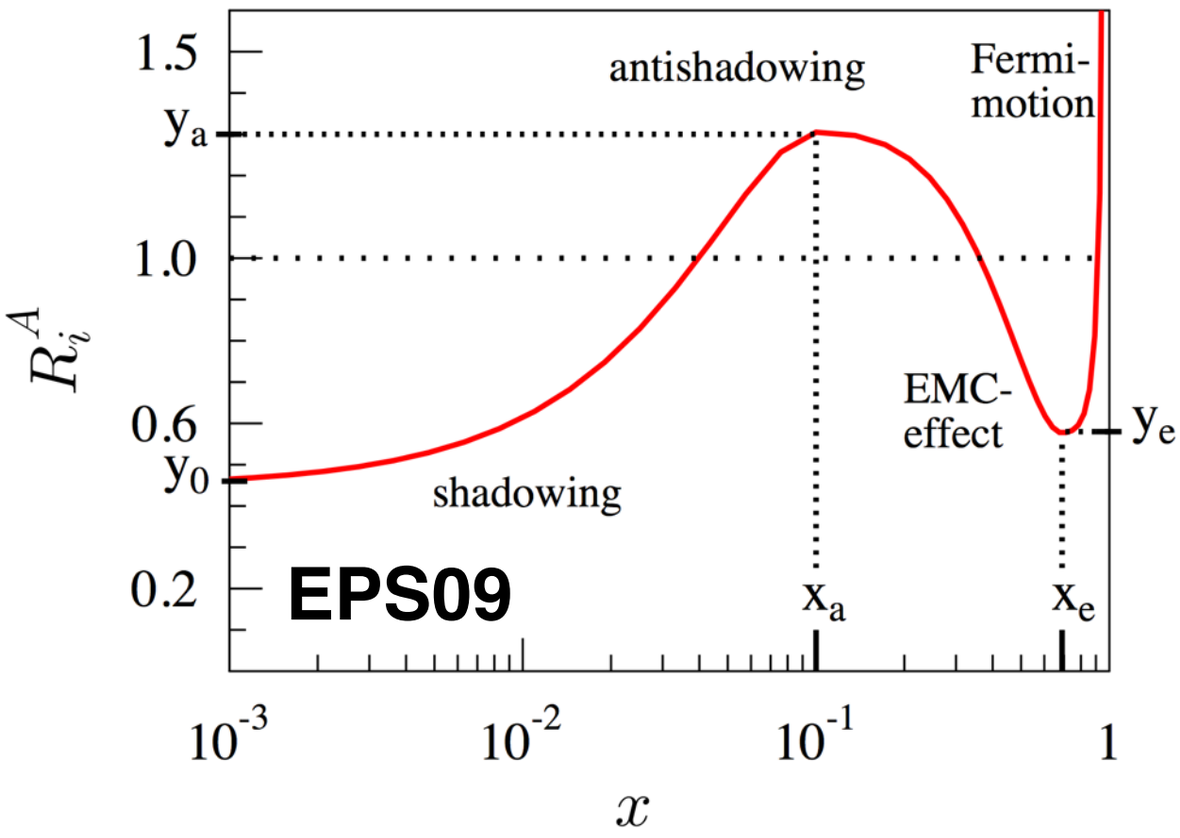
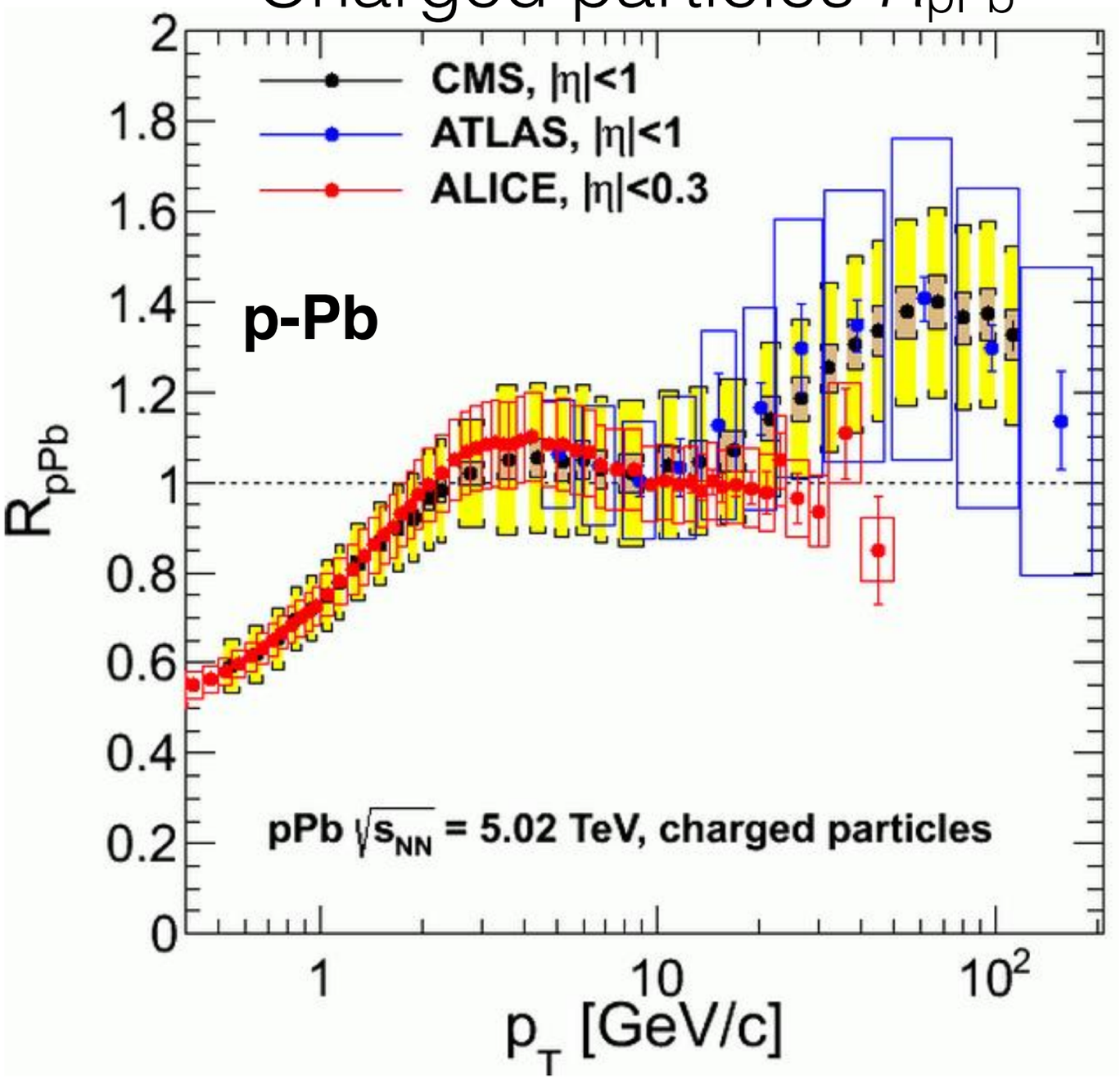


however anti-shadowing seems not to be enough

CMS charged particle R_{pPb} **cannot be described by nPDF**

Charged-particle R_{pPb} at large p_T



CMS observes strong enhancement at large p_T

confirmed by ATLAS

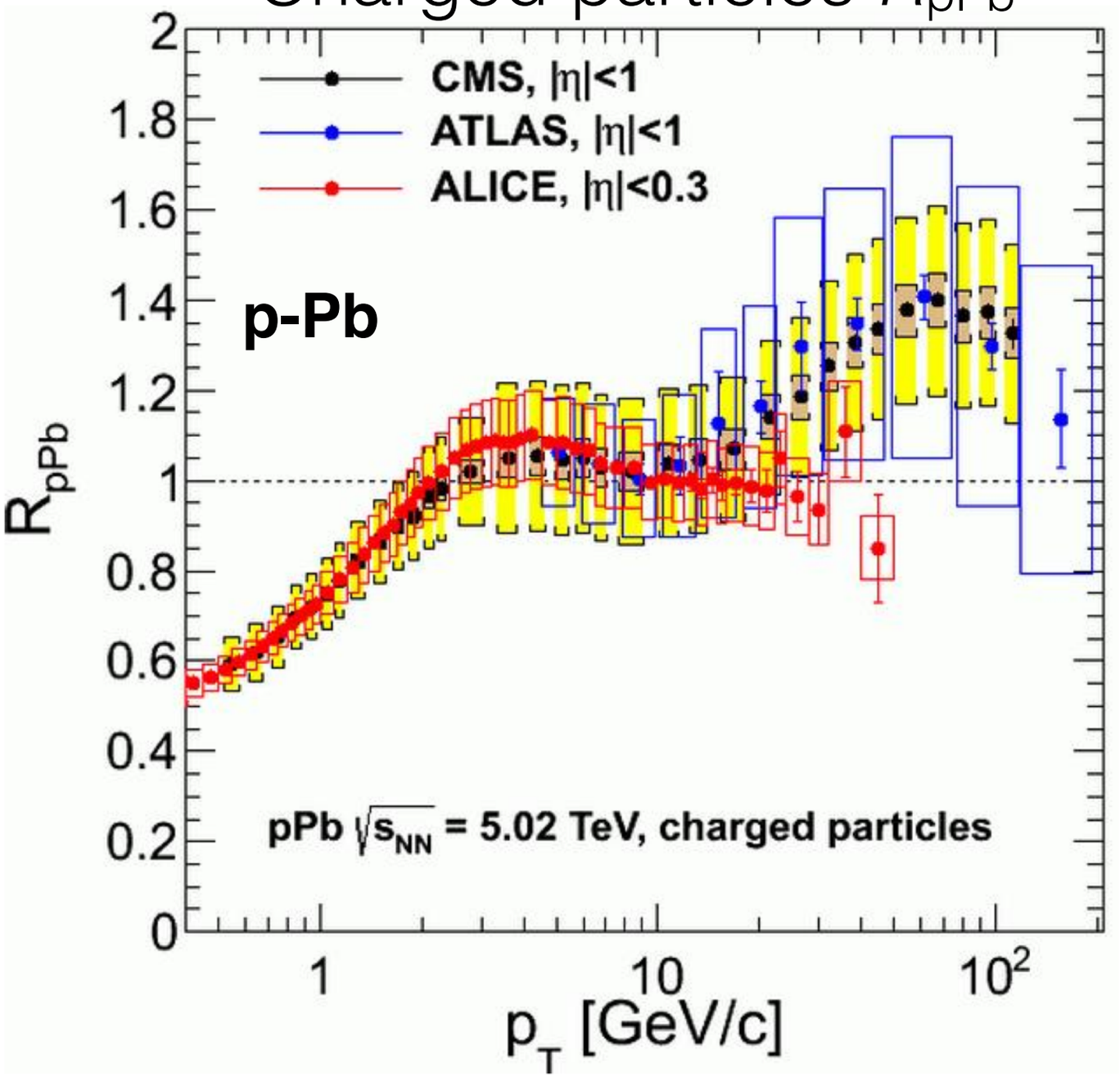
ATLAS, ATLAS-CONF-2014-029

not seen by ALICE

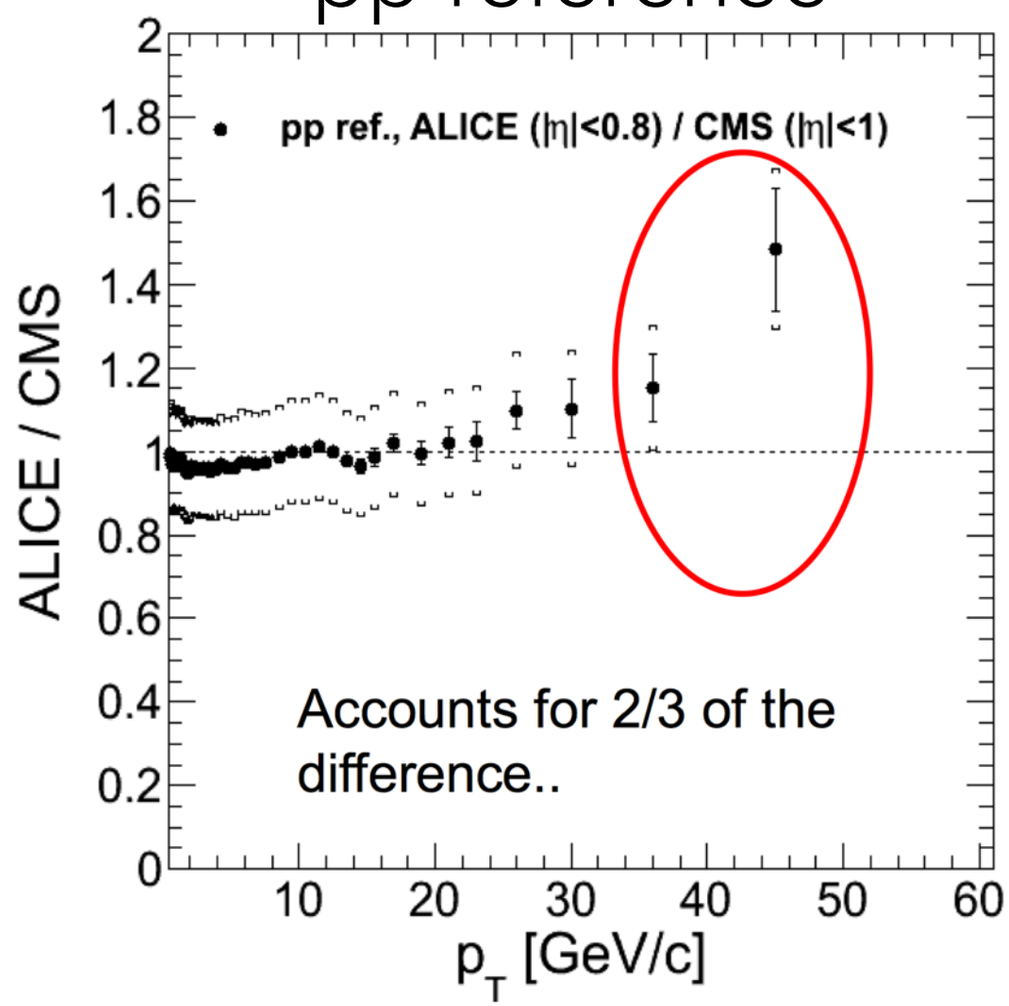
different impression when looking at ALICE points

Charged-particle R_{pPb} at large p_T

Charged particles R_{pPb}



pp reference



the discrepancy mainly comes from tension in the pp reference

urgent **need** for a **pp 5.02 TeV reference data**

R_{pPb} at intermediate p_T

the data indicate a small **enhancement at mid-p_T** where a stronger enhancement is seen at lower energies

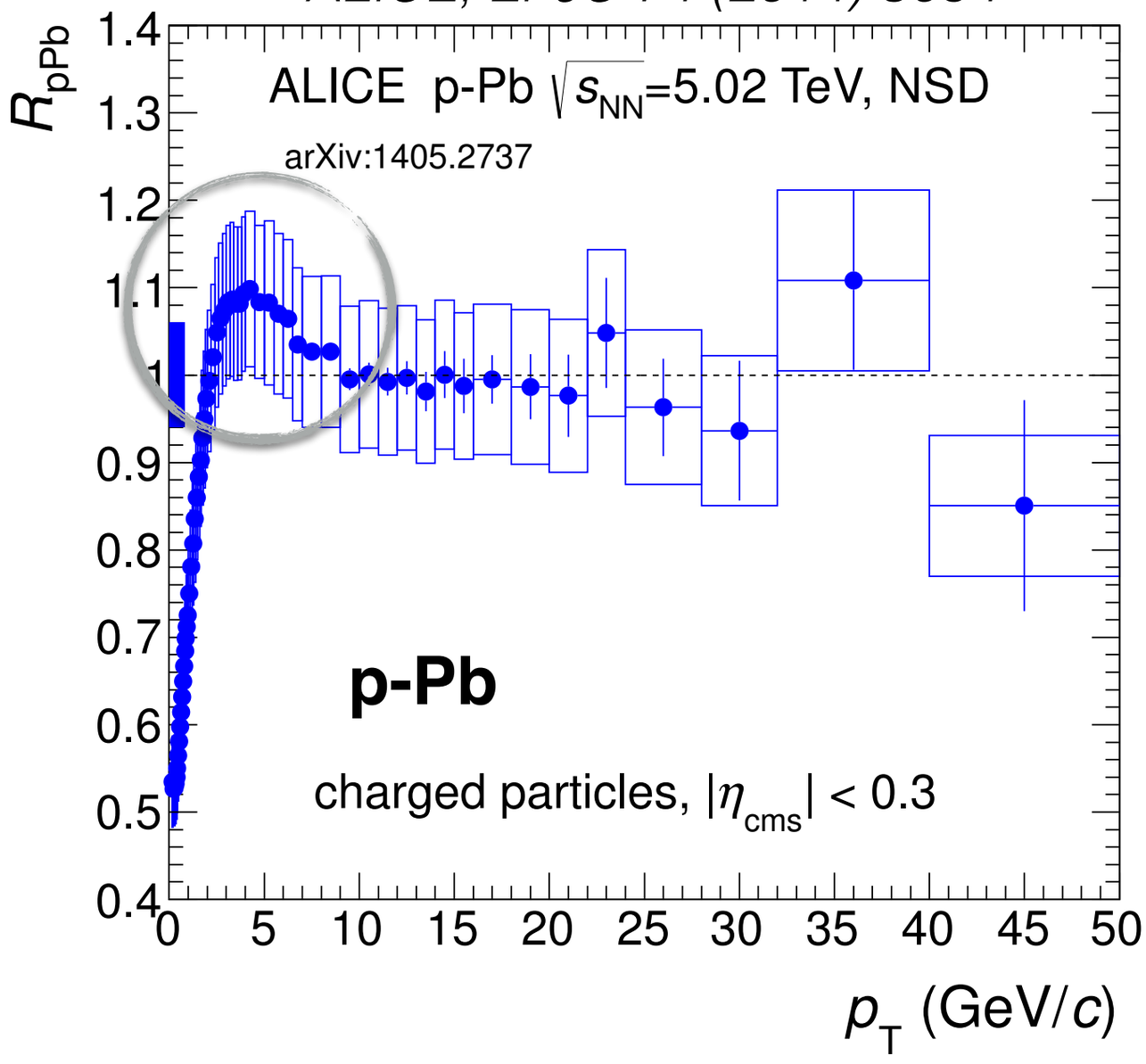
Cronin, PRD 11 (1975) 3105

traditional explanations of Cronin enhancement

multiple soft scatterings in the initial state prior to the hard scattering

Accardi, arXiv:hep-ph/0212148

ALICE, EPJC 74 (2014) 3054

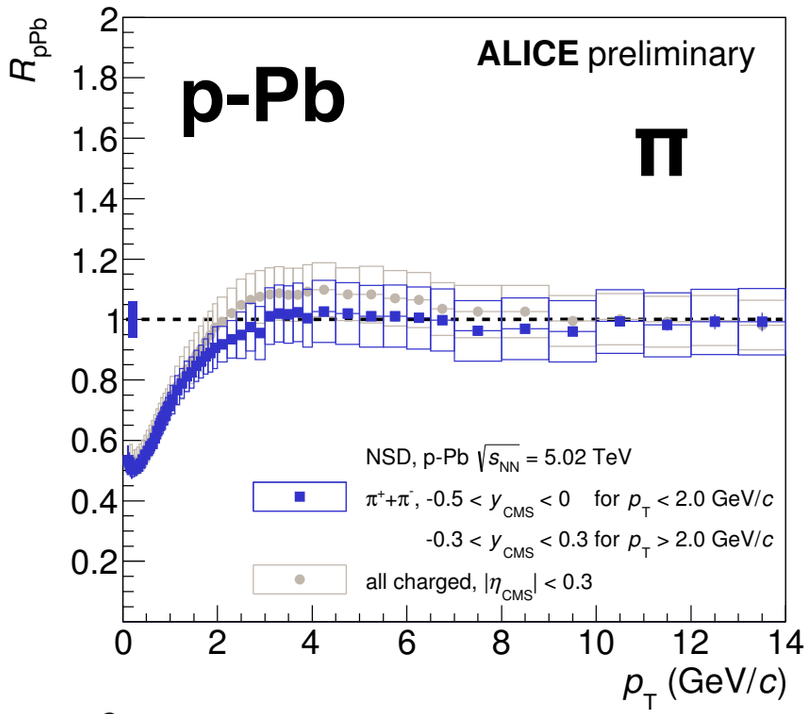


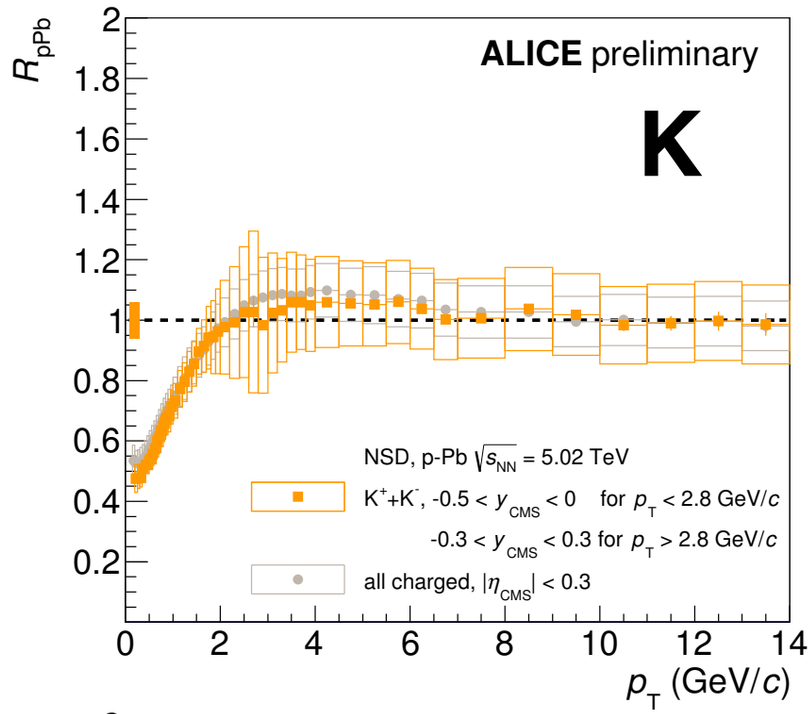
Identified particle R_{pPb}

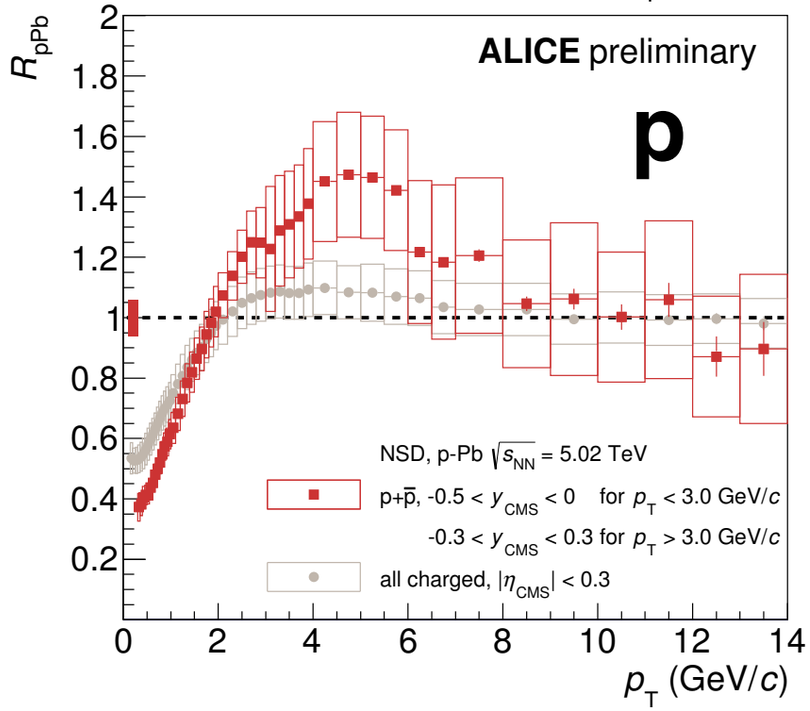
pions and **kaons** consistent with no modification at mid-p_T

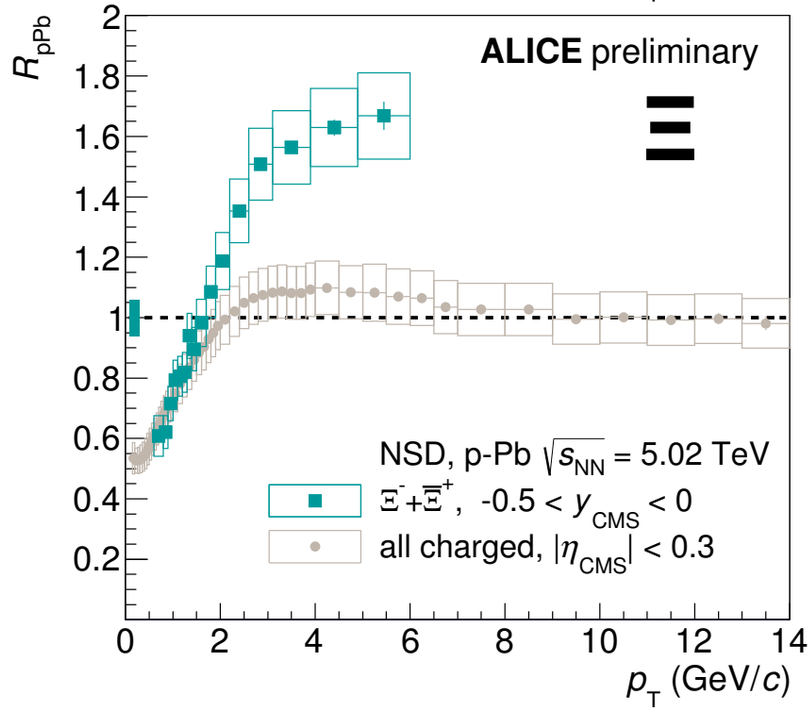
rather pronounced peak for **protons**

even stronger enhancement for **cascades**









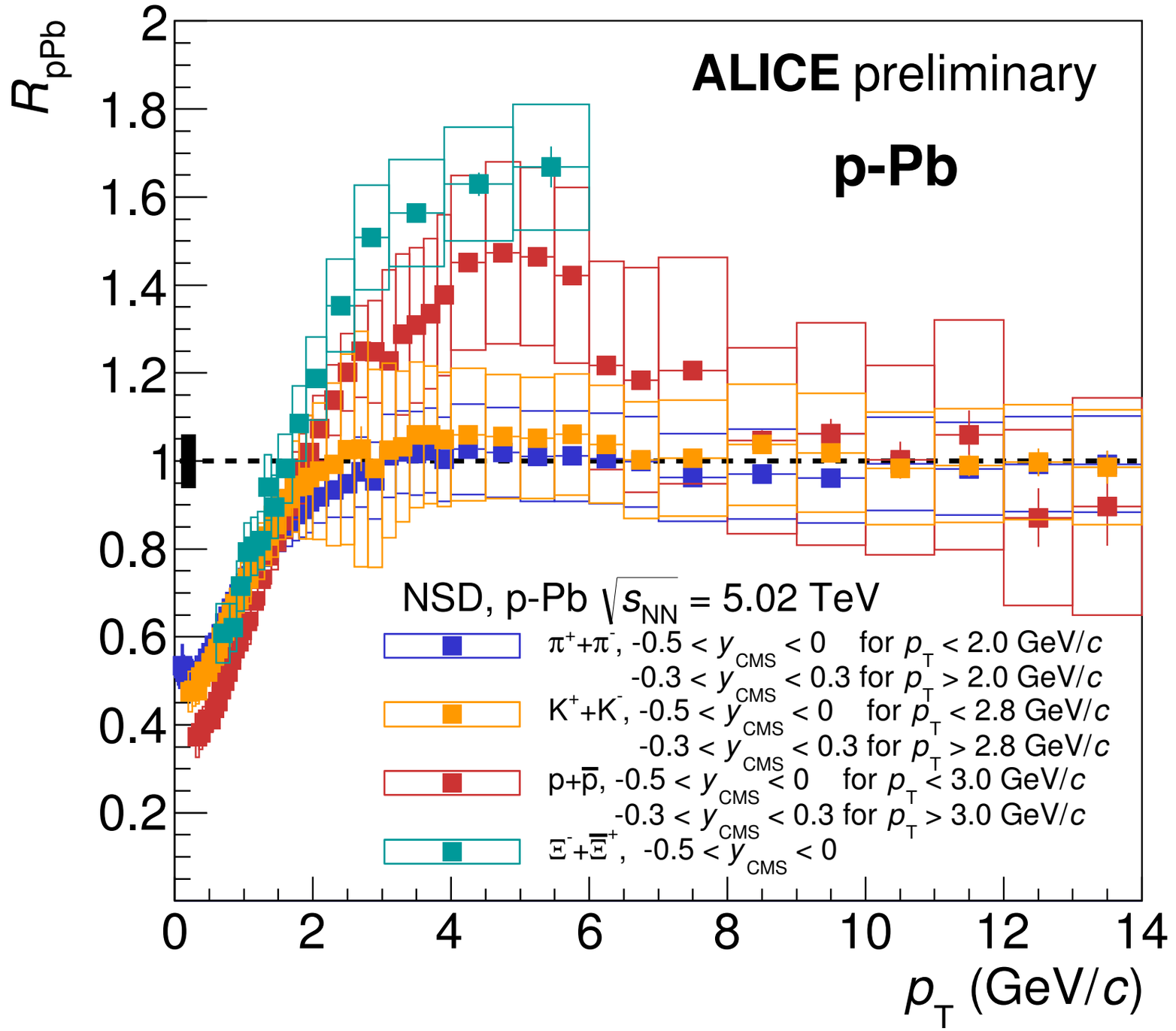
indication of **mass ordering** in the Cronin peak

Identified particle R_{pPb}

pions and **kaons** consistent with no modification at mid-p_T

rather pronounced peak for **protons**

even stronger enhancement for **cascades**

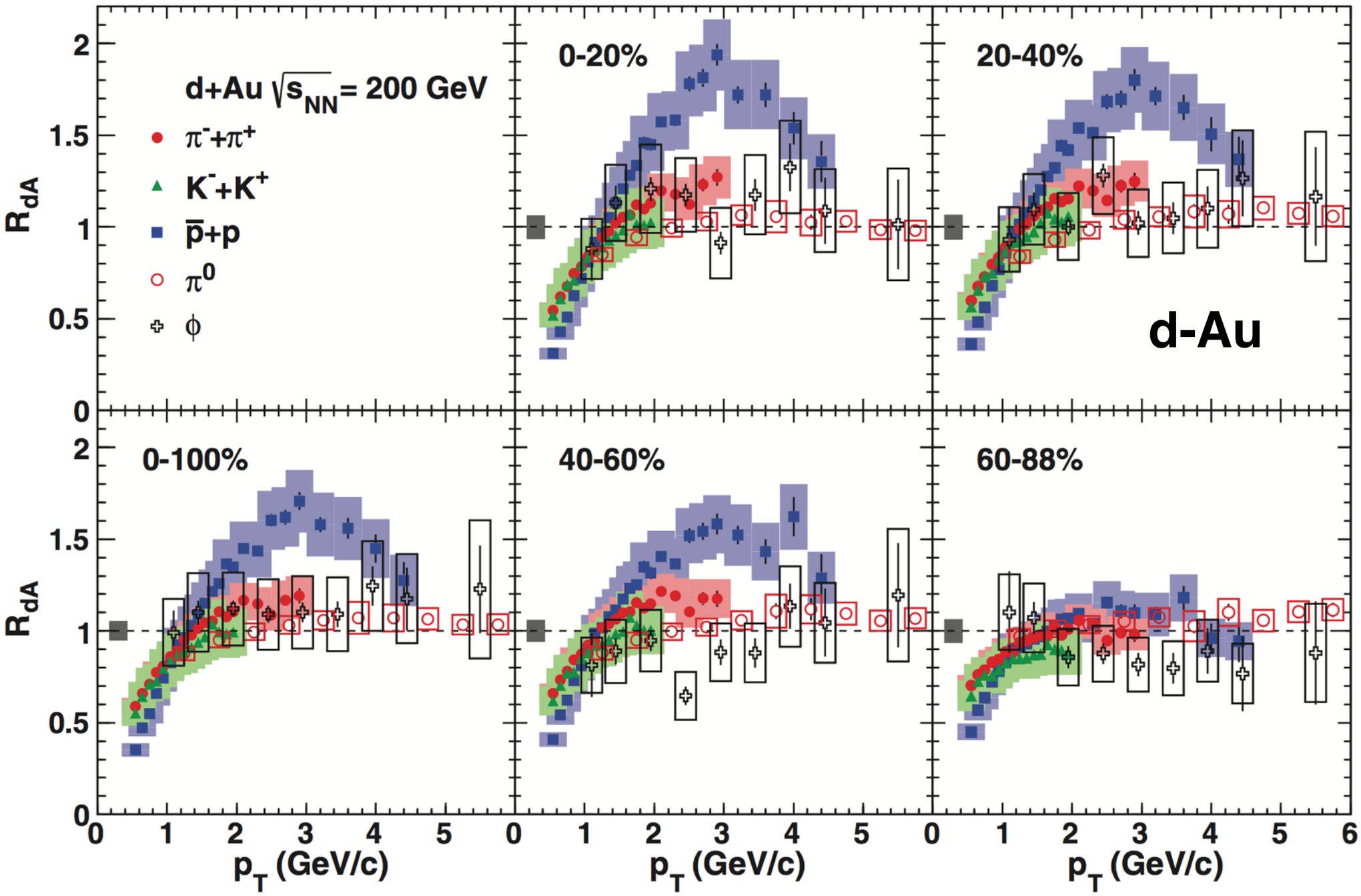


particle species dependence suggests final state effects

recombination, collective flow, …

Identified particle R_{dAu}

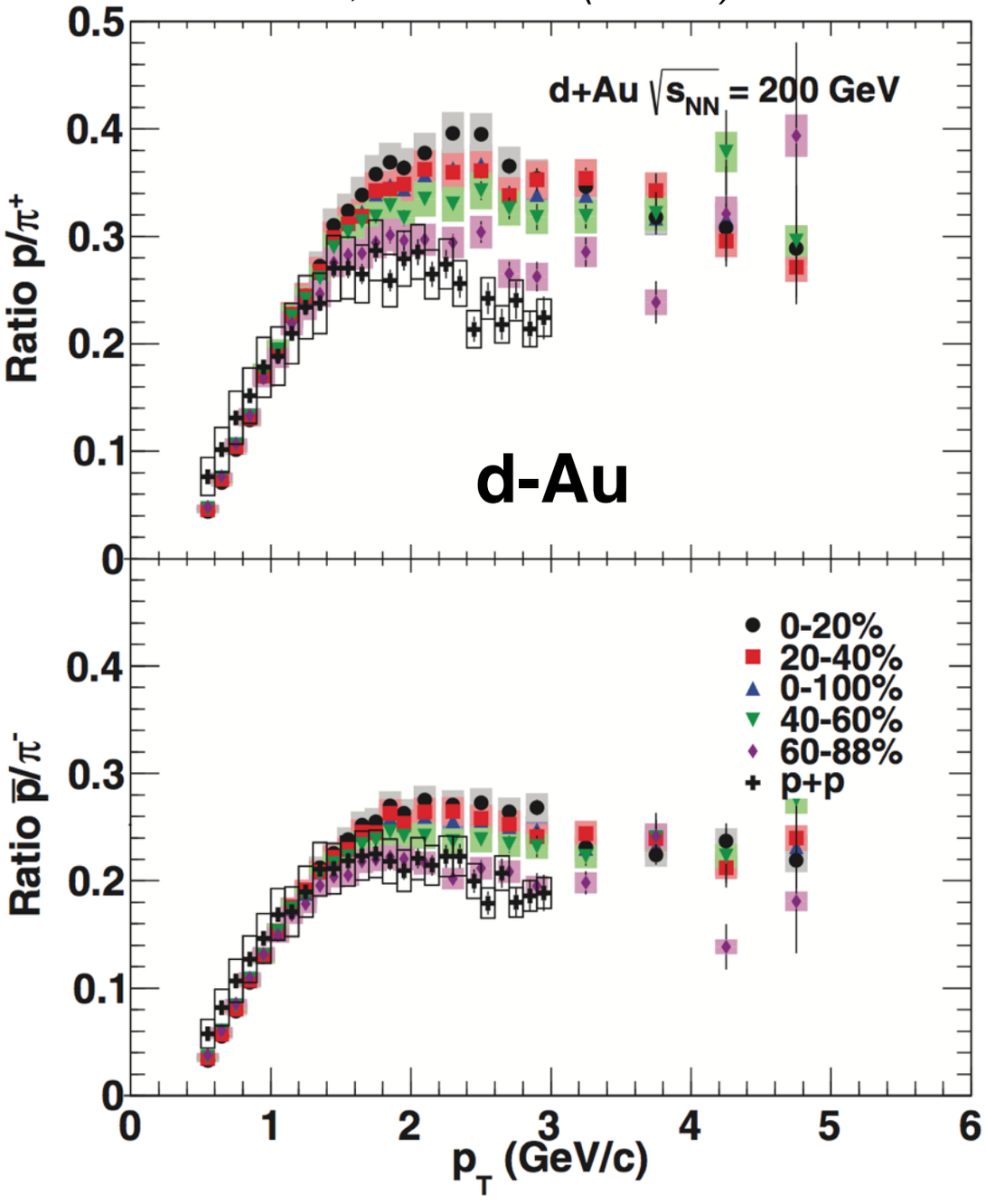
PHENIX, PRC 88 (2013) 024906

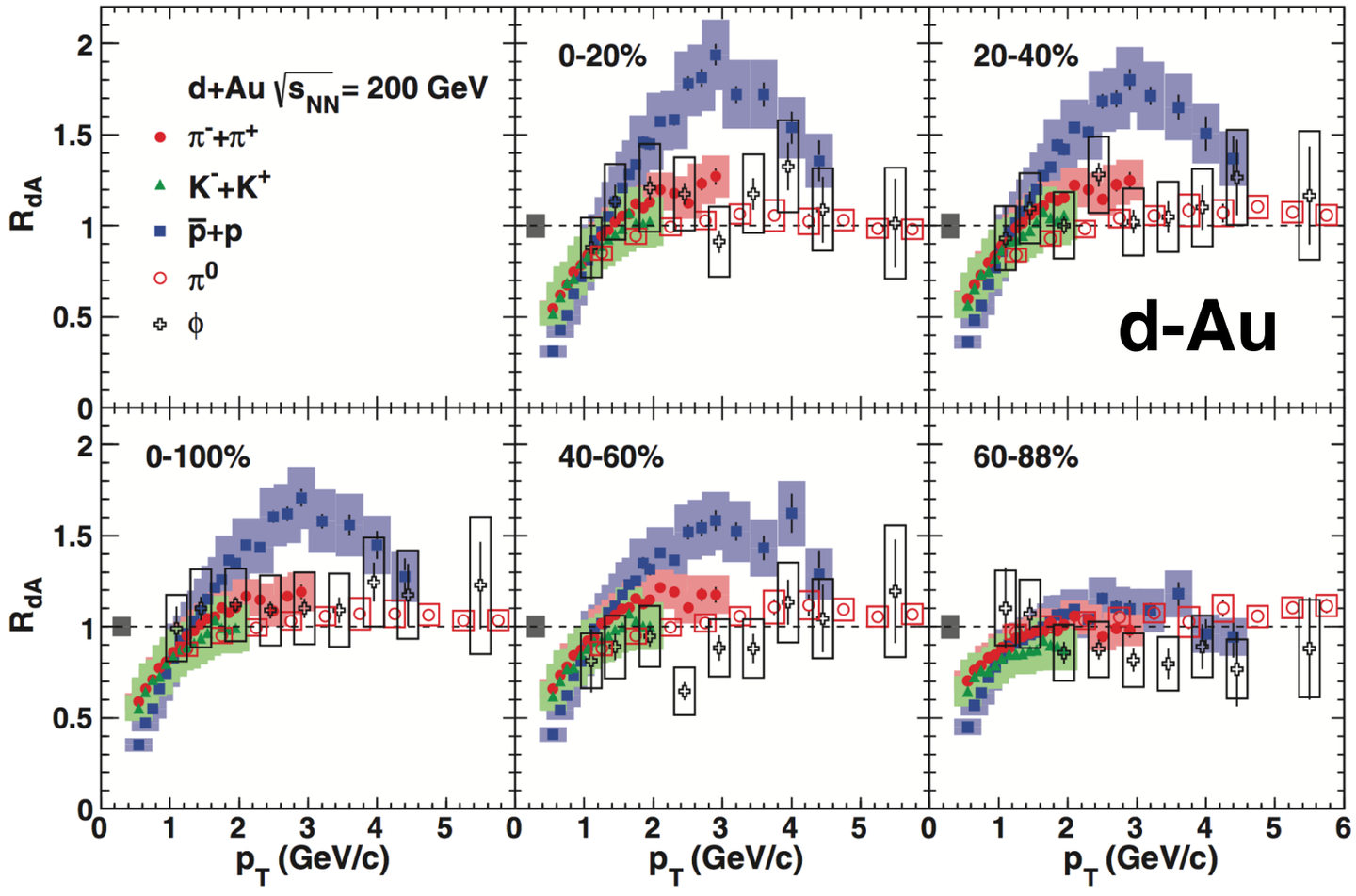


strong baryon enhancement **seen also at RHIC**

Baryon enhancement

PHENIX, PRC 88 (2013) 024906





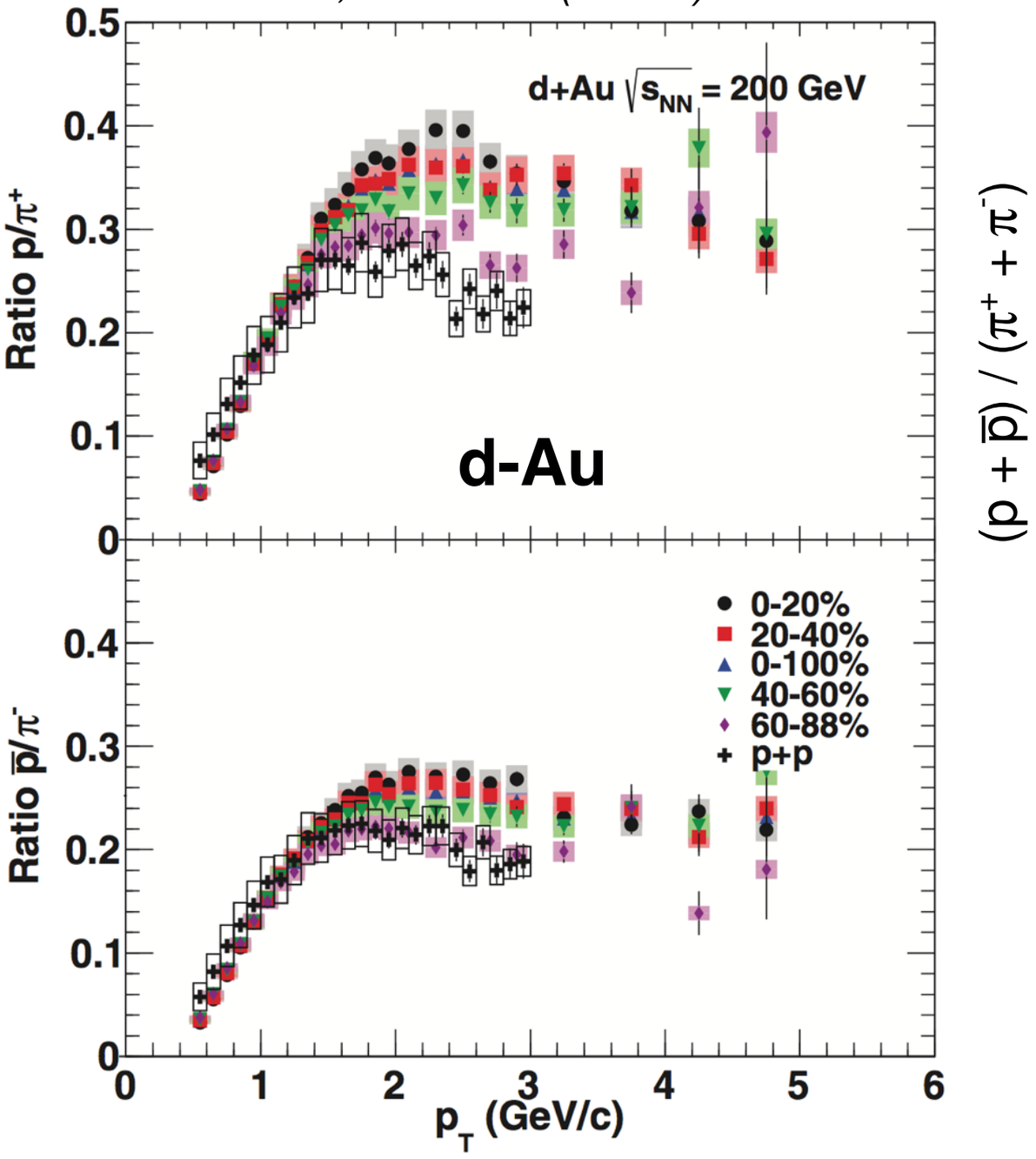
very similar to the dependence of the proton Cronin enhancement

these phenomena are likely **driven by the same mechanism**

recombination, collective flow, …

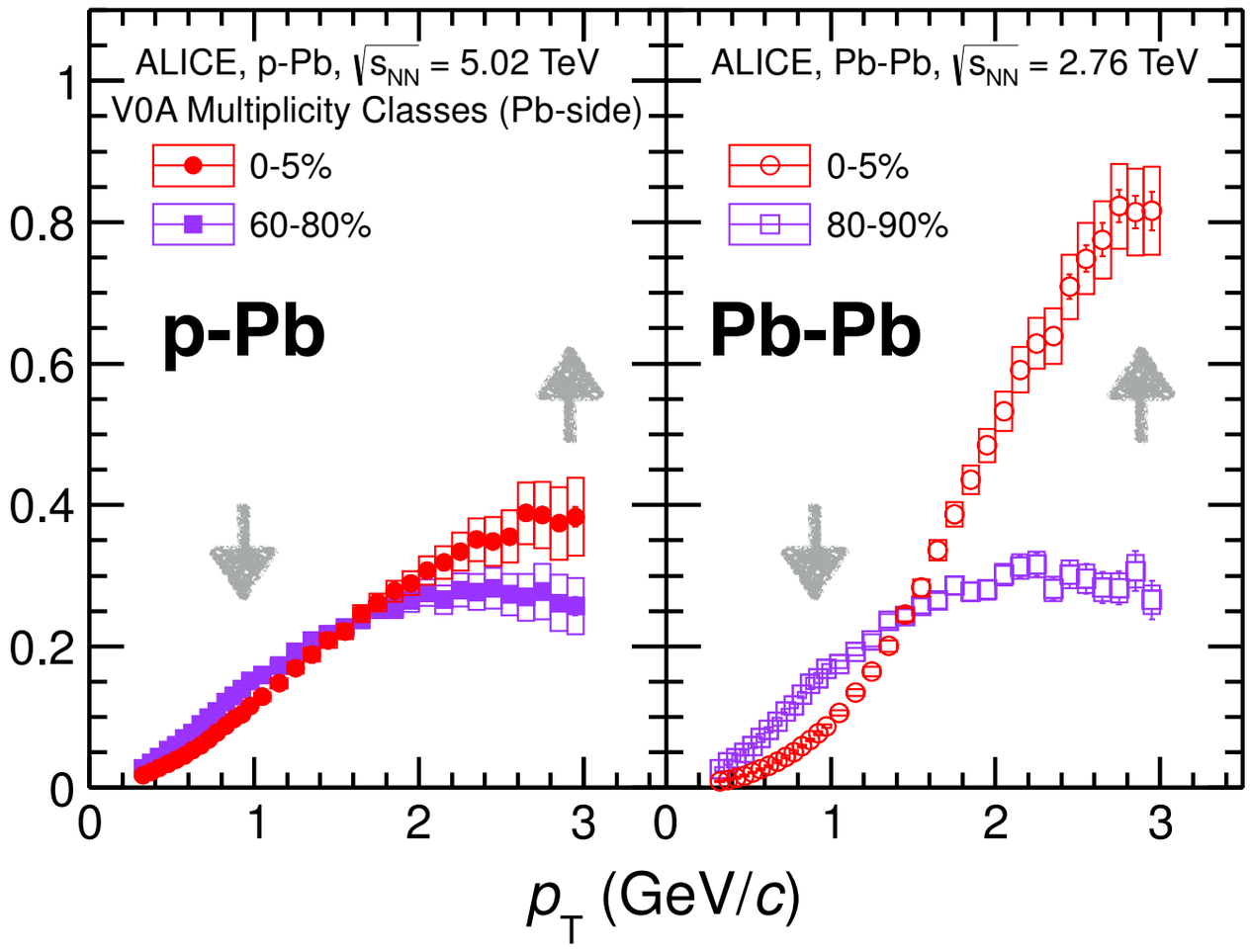
Baryon enhancement

PHENIX, PRC 88 (2013) 024906



$(p + \bar{p}) / (\pi^+ + \pi^-)$

ALICE, PLB 728 (2014) 25

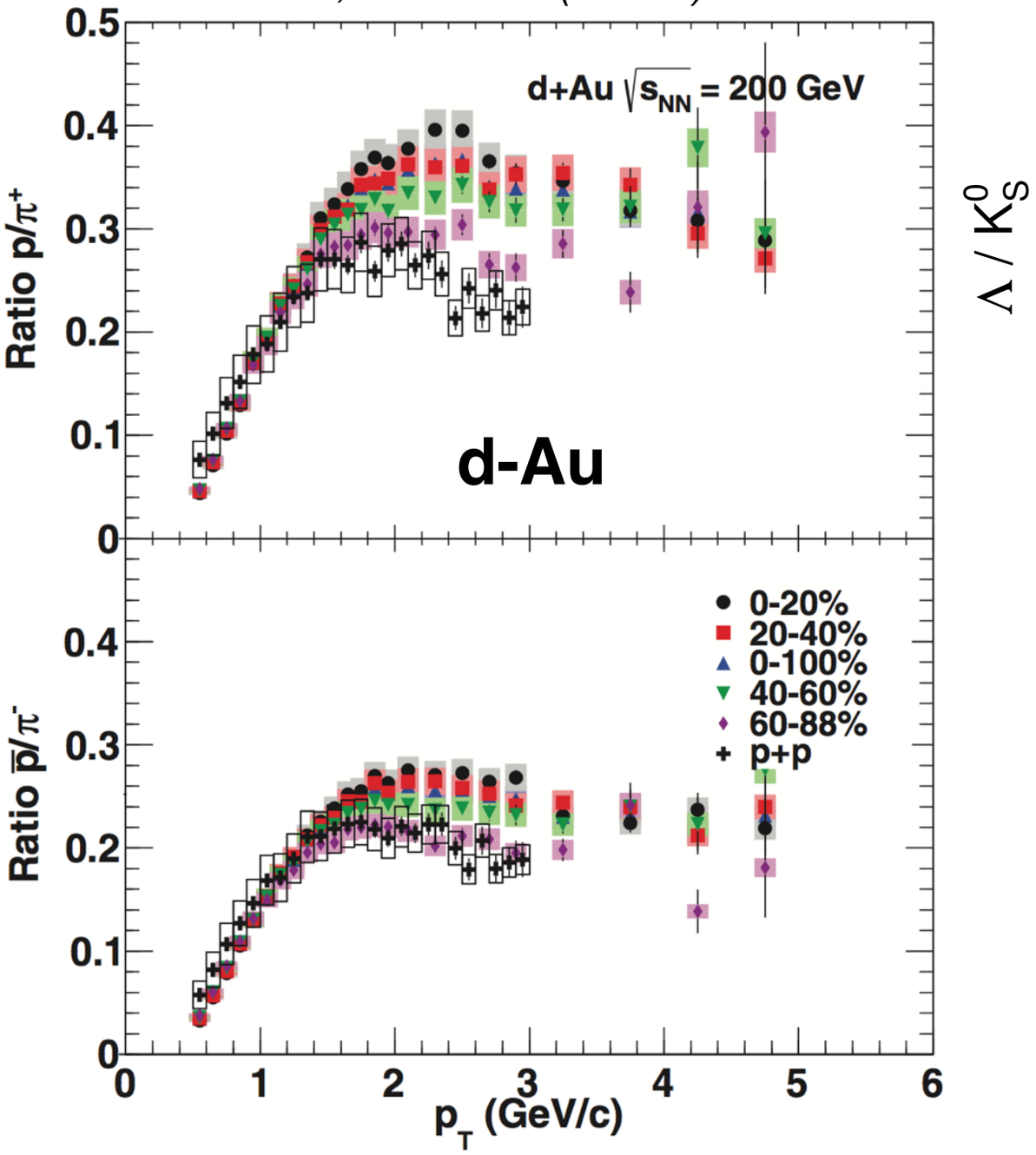


significant centrality/multiplicity dependence of p/π ratio

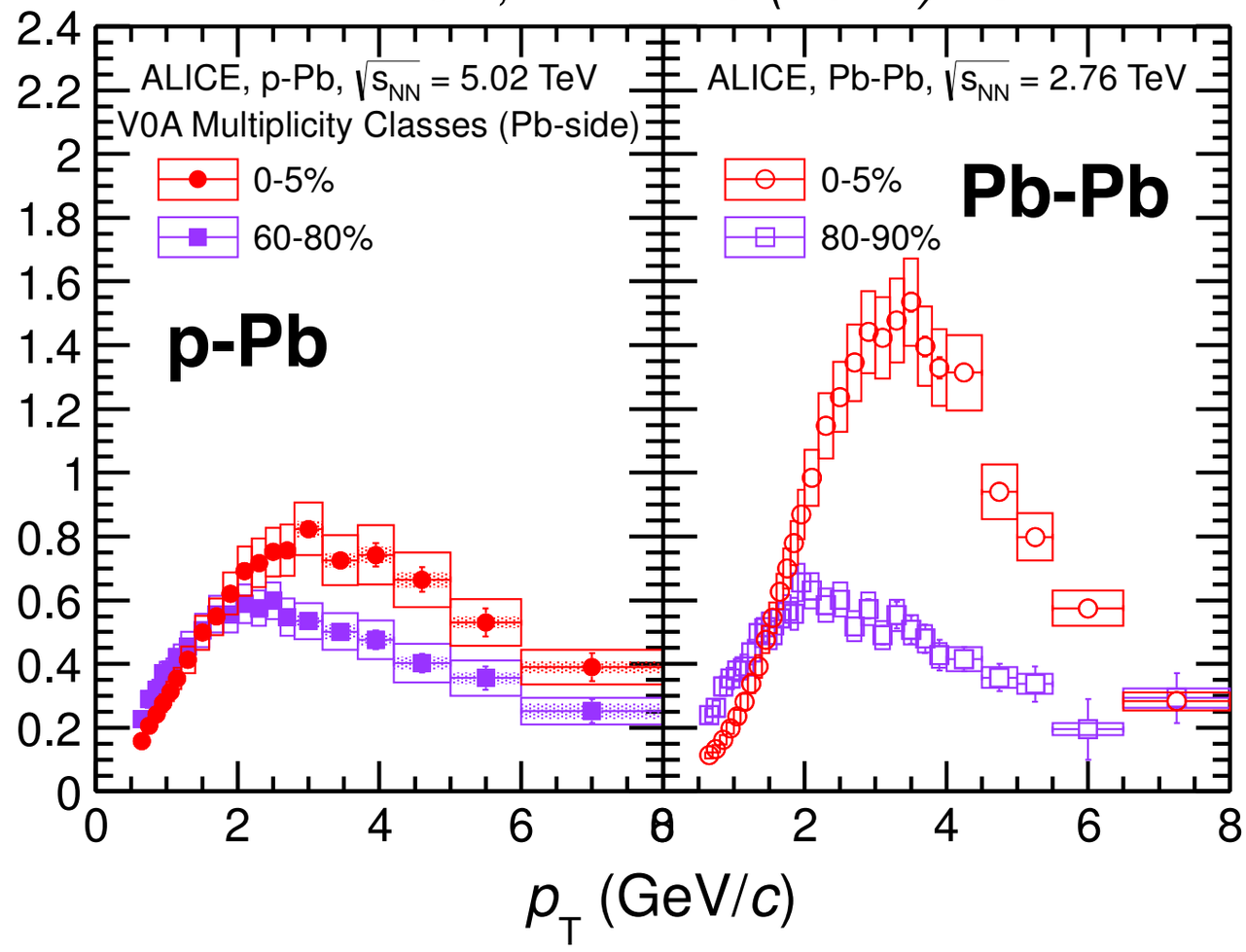
reminiscent of A-A observations

Baryon enhancement

PHENIX, PRC 88 (2013) 024906



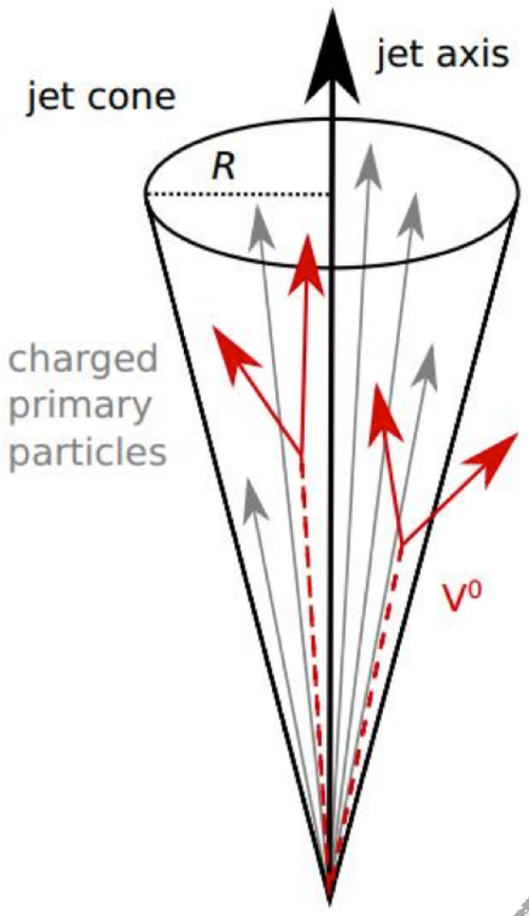
ALICE, PLB 728 (2014) 25



significant centrality/multiplicity dependence of Λ/K^0_S ratio

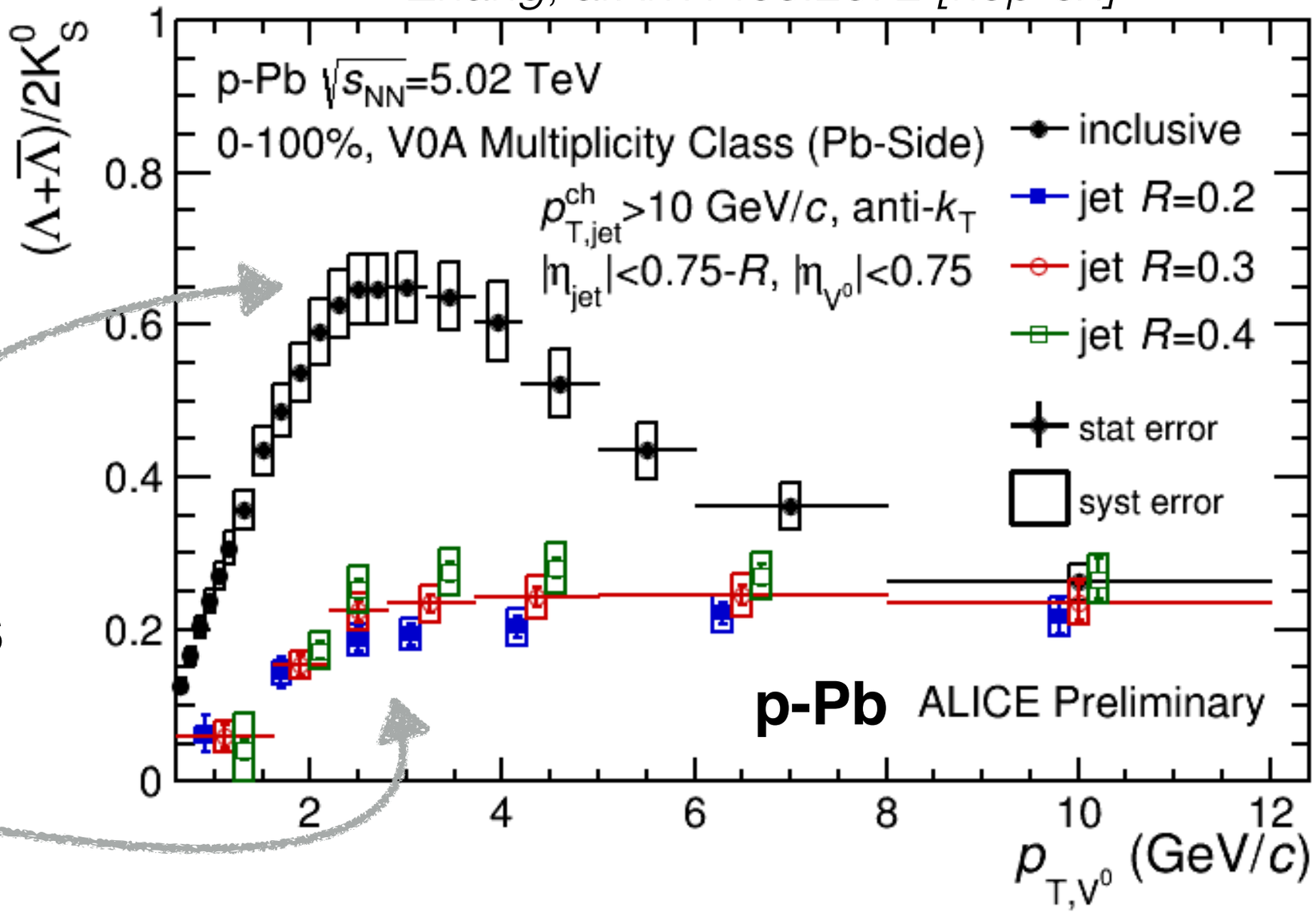
reminiscent of A-A observations

Where are the extra baryons from?



Λ/K^0_S production ratio measured in charged jets

Zhang, arXiv:1408.2672 [hep-ex]



inclusive particles

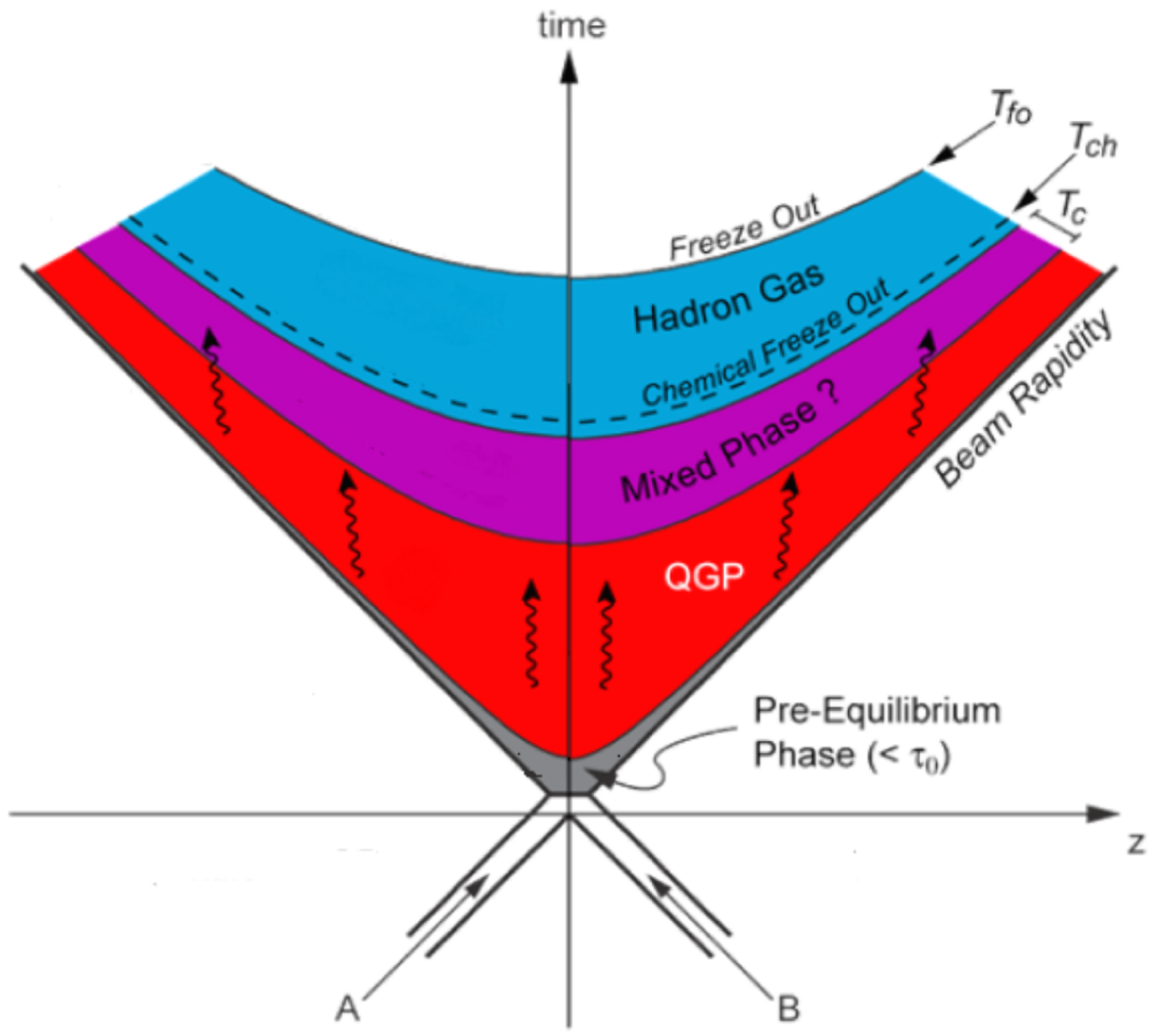
jets do not show enhancement

the extra baryons are **not coming from jets**

Collective phenomena

bulk matter created in high-energy heavy-ion collisions **can be described in terms of hydrodynamics**

- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached



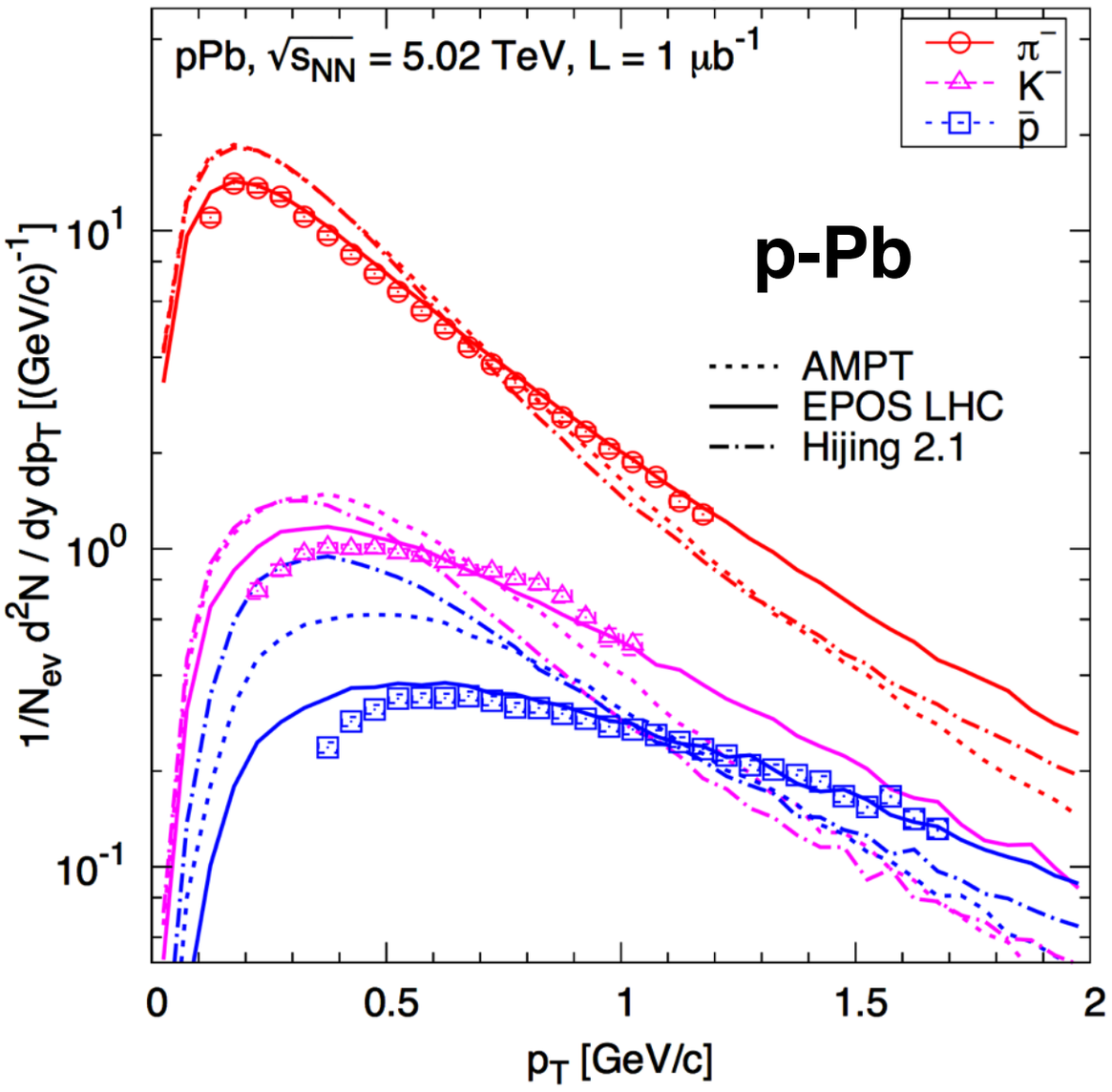
resulting in

- dependence of the shape of the p_T distribution on the particle mass
- azimuthal anisotropic flow patterns (initial spatial anisotropy)

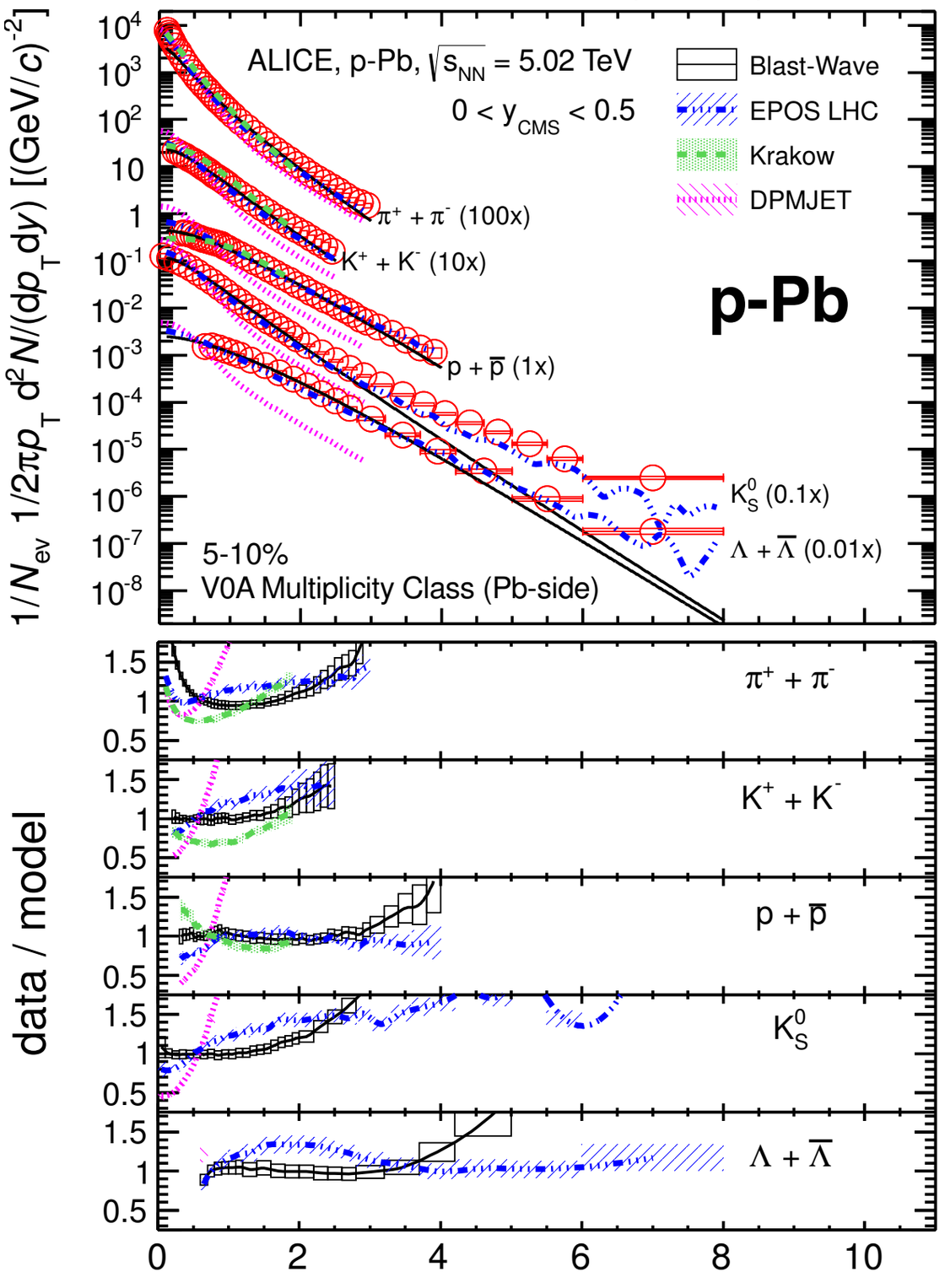
are there final state dense matter effects in p-Pb?

Identified hadron spectra

CMS, EPJC 74 (2014) 2847



ALICE, PLB 728 (2014) 25



models including hydrodynamics do a better job describing the data

Collective radial flow

Blast-Wave model

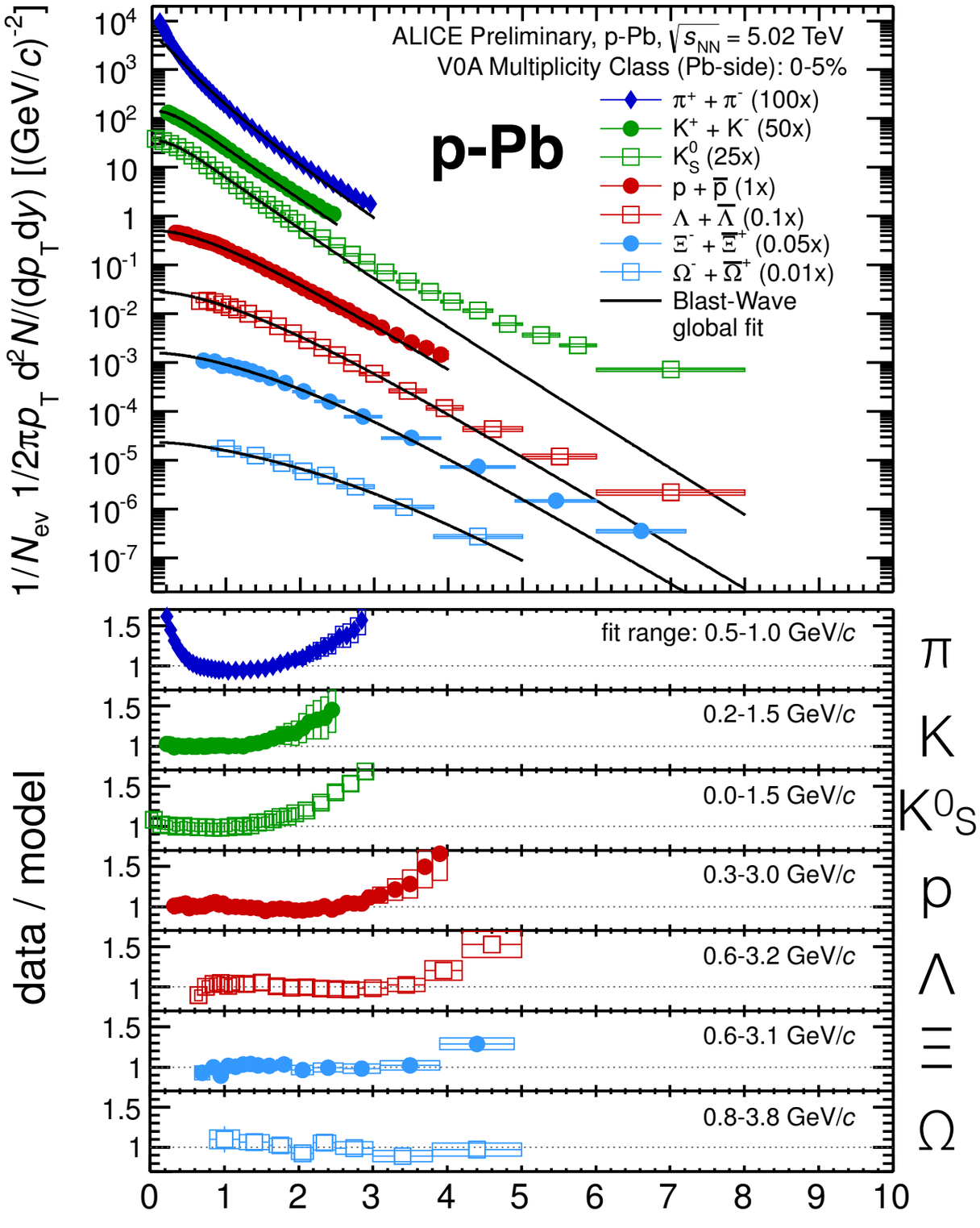
characterize spectral shapes and test collective radial flow

spectra from thermal sources T_{kin} expanding with common velocity $\langle\beta_T\rangle$

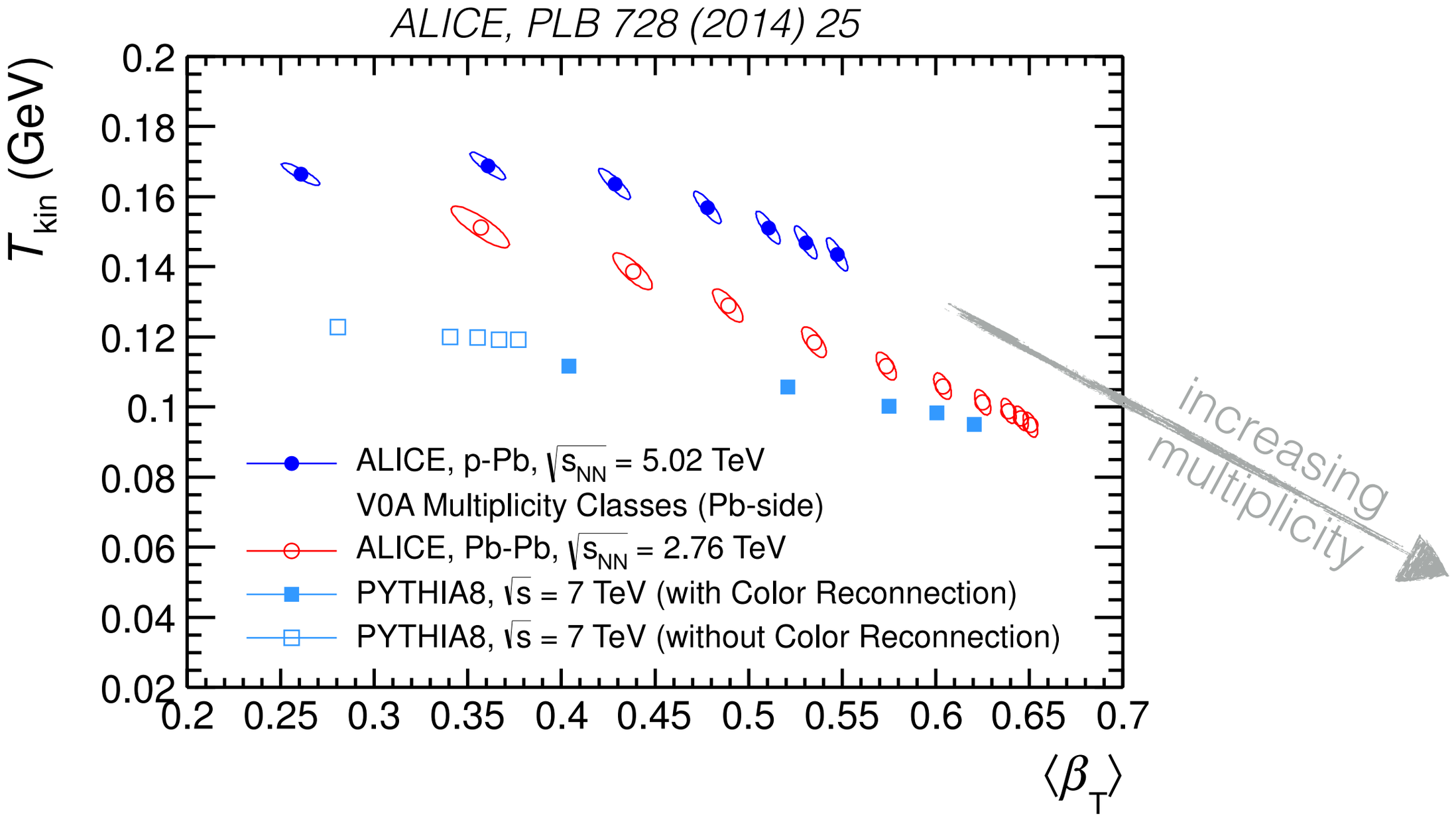
Schnedermann et al., PRC 48 (1993) 2462

coherent fit of stable hadrons
π K K^0_S p Λ Ξ Ω

reasonably **good description**
data / model agreement
extends to higher p_T for higher particle masses

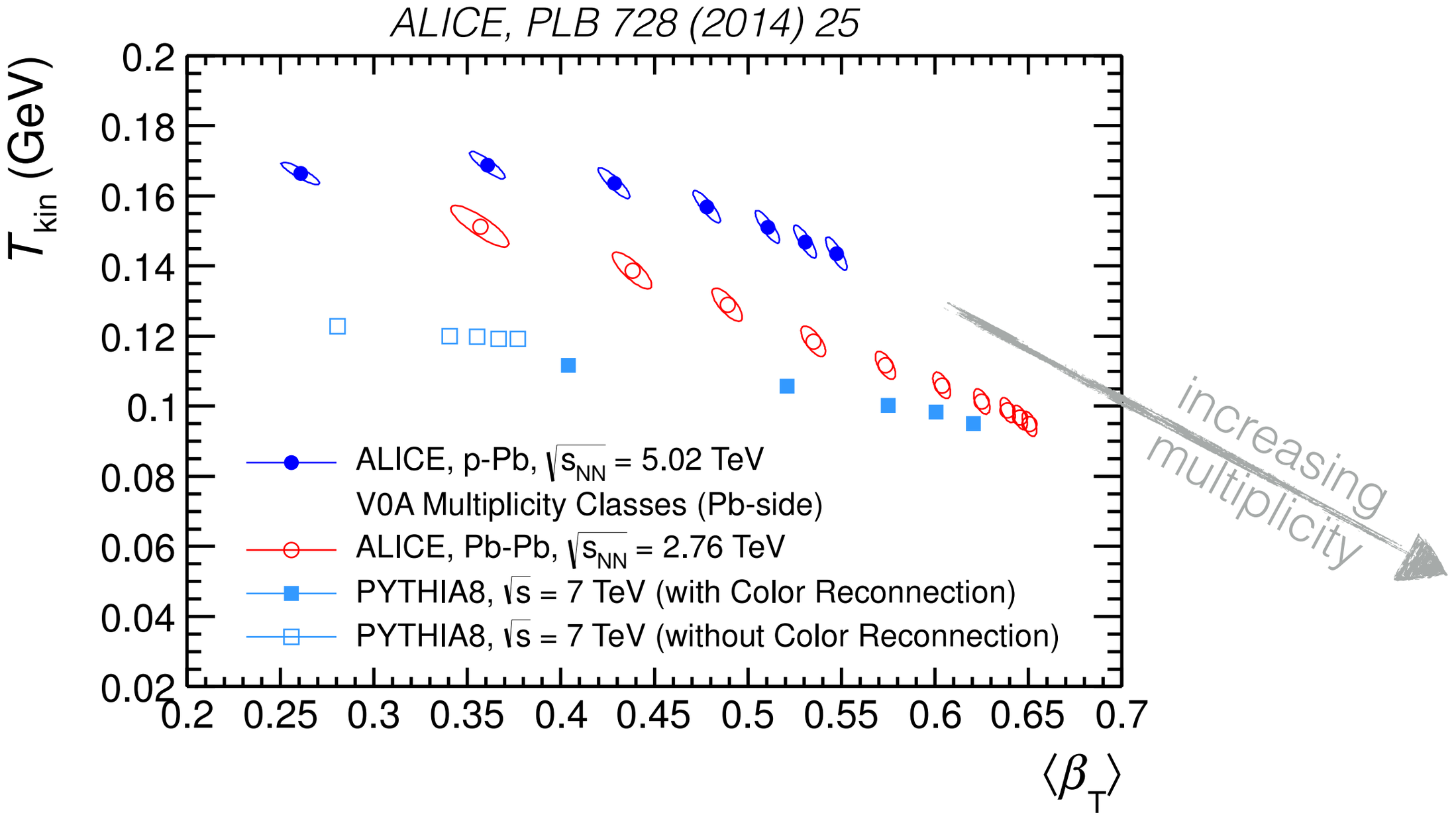


Blast-Wave fit parameters



p-Pb presents **similar features as observed in Pb-Pb**
parameters evolve with multiplicity: larger $\langle\beta_T\rangle$, smaller T_{kin}

Blast-Wave fit parameters

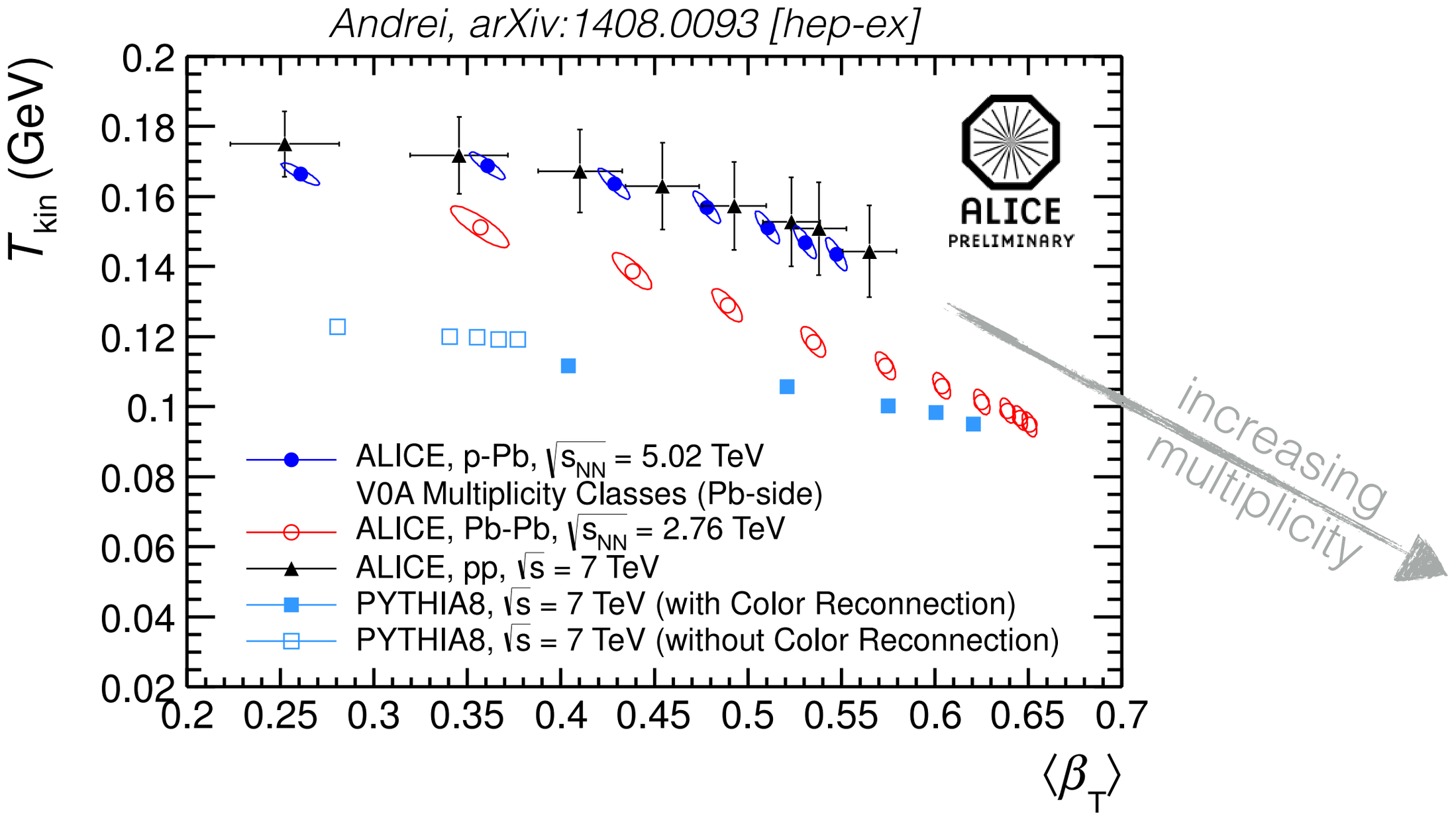


PYTHIA with Colour Reconnection shows similar features

does not include hydrodynamics collectivity, but mimics flow-like patterns

Ortiz et al., PRL 111 (2013) 042001

Blast-Wave fit parameters



also proton-proton collisions show similar features

Blast-Wave analysis not conclusive, complementary information needed

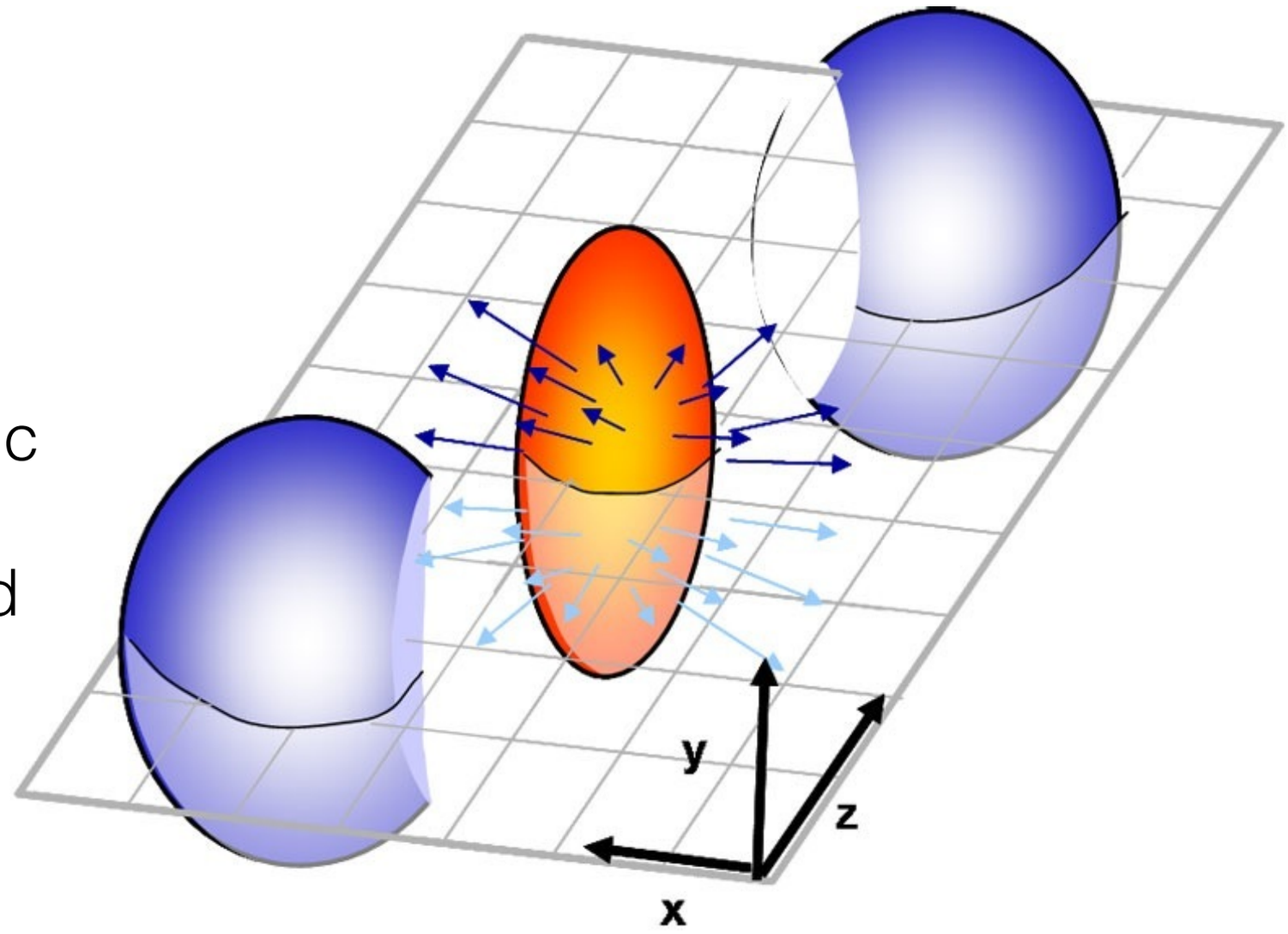
several hints for collectivity from single-particle spectra

complementary information from two-particle correlations

Collective phenomena

bulk matter created in high-energy heavy-ion collisions **can be described in terms of hydrodynamics**

- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached



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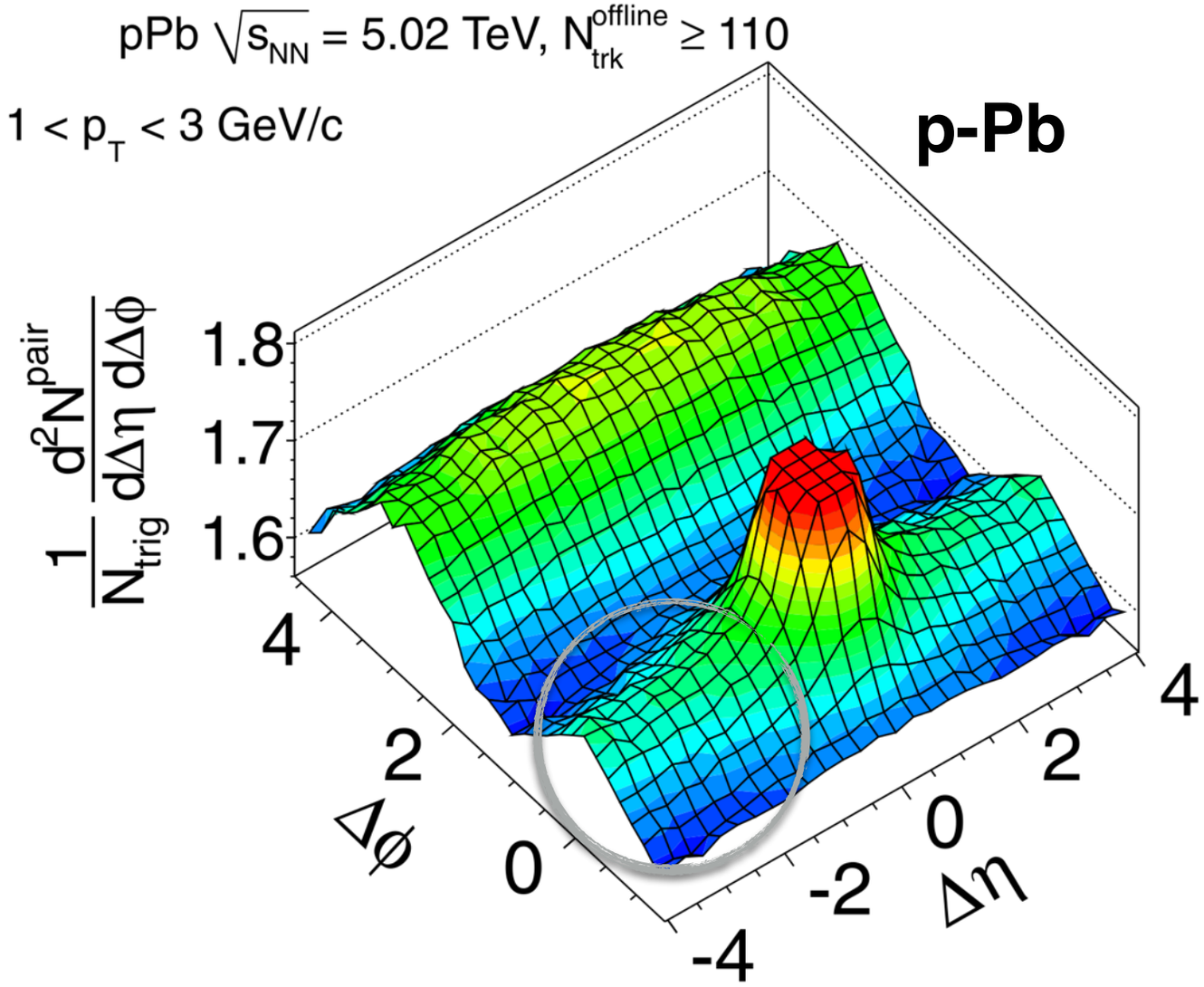
are there final state dense matter effects in p-Pb?

The ridge

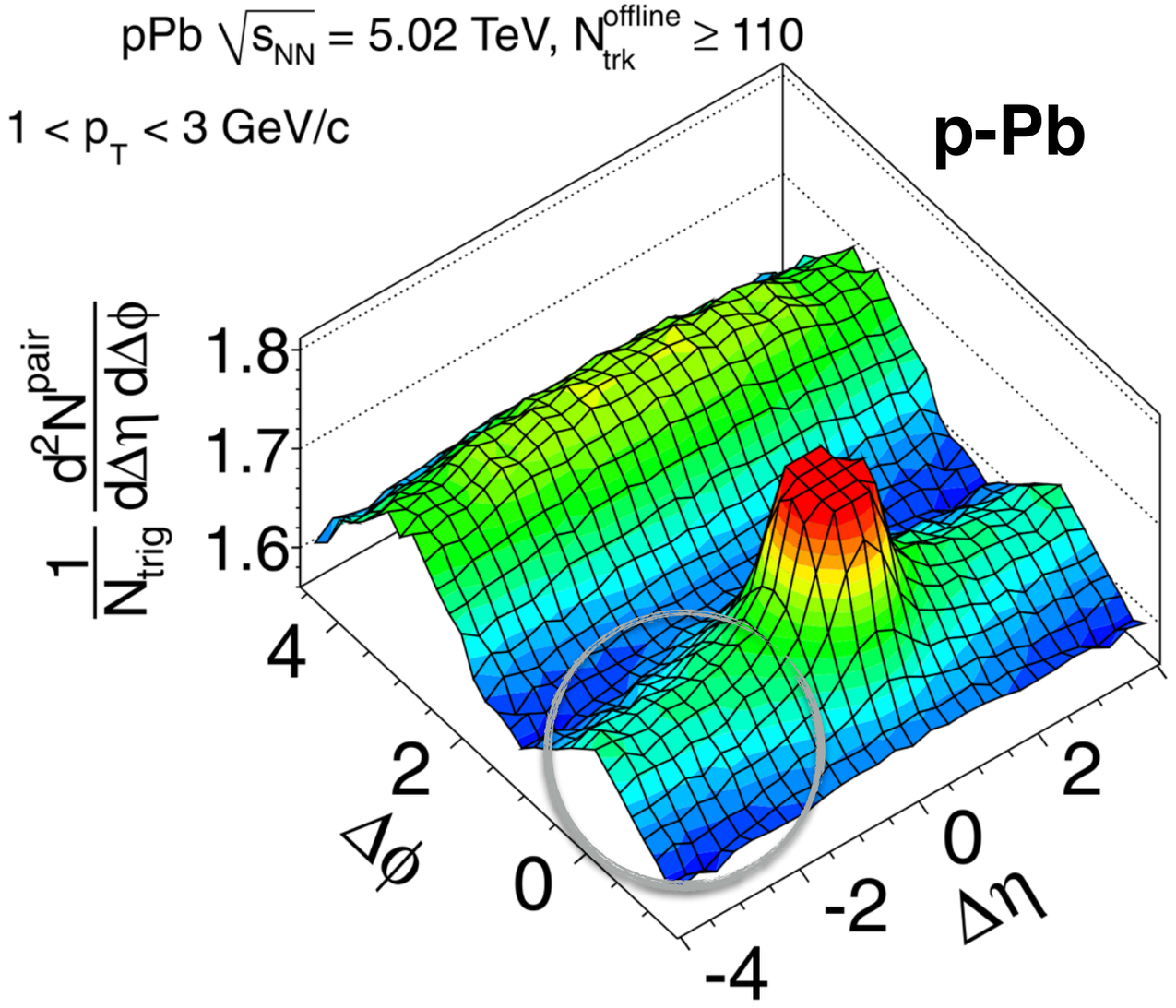
study of two-particle correlations led to the observation of **long-range** ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$) angular correlations in high-multiplicity p-Pb events



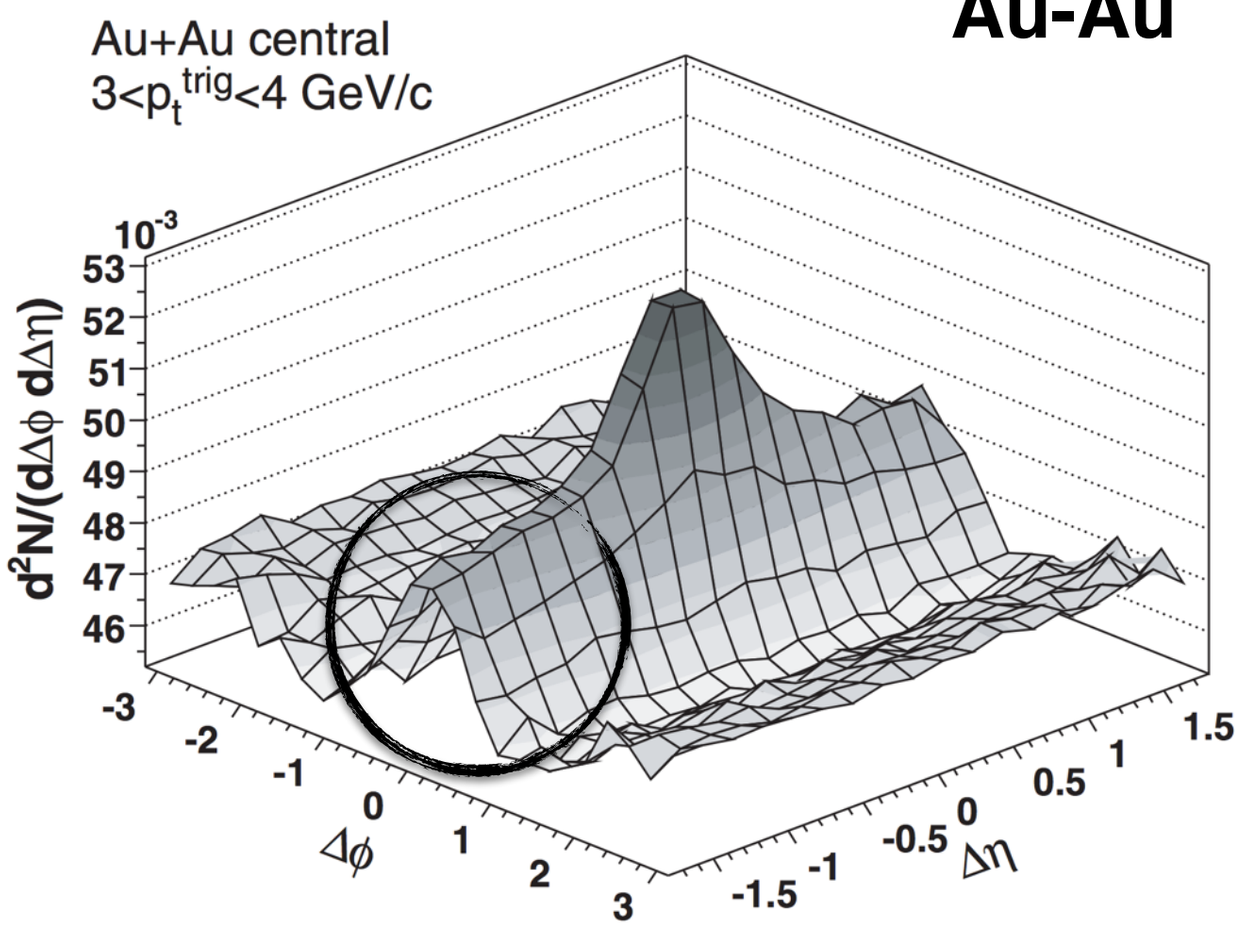
CMS, PLB 718 (2013) 795

The ridge

long-range ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$)
resembles the ridge-like correlation seen in A-A collisions
interpreted as consequence of hydrodynamic flow



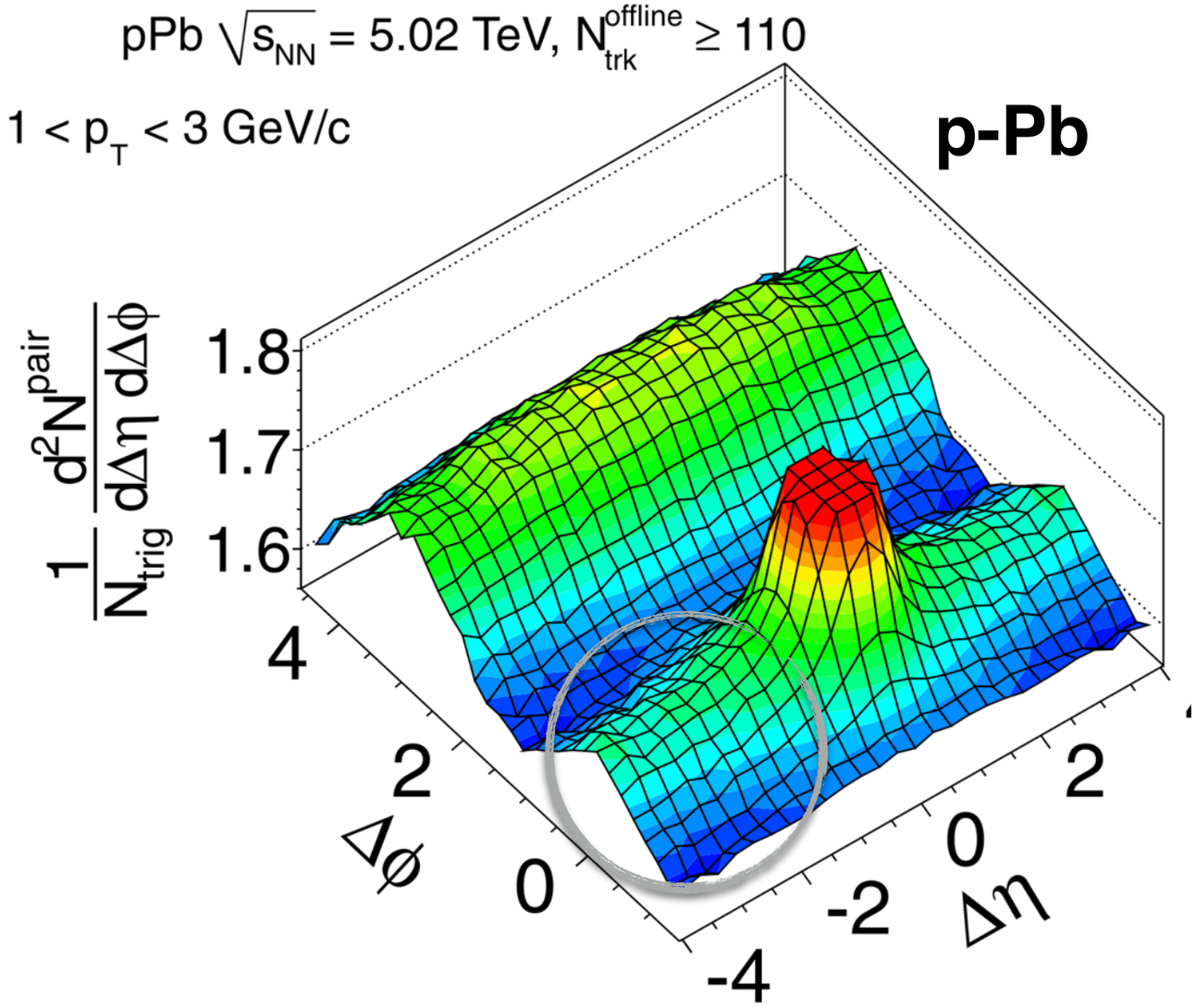
CMS, PLB 718 (2013) 795



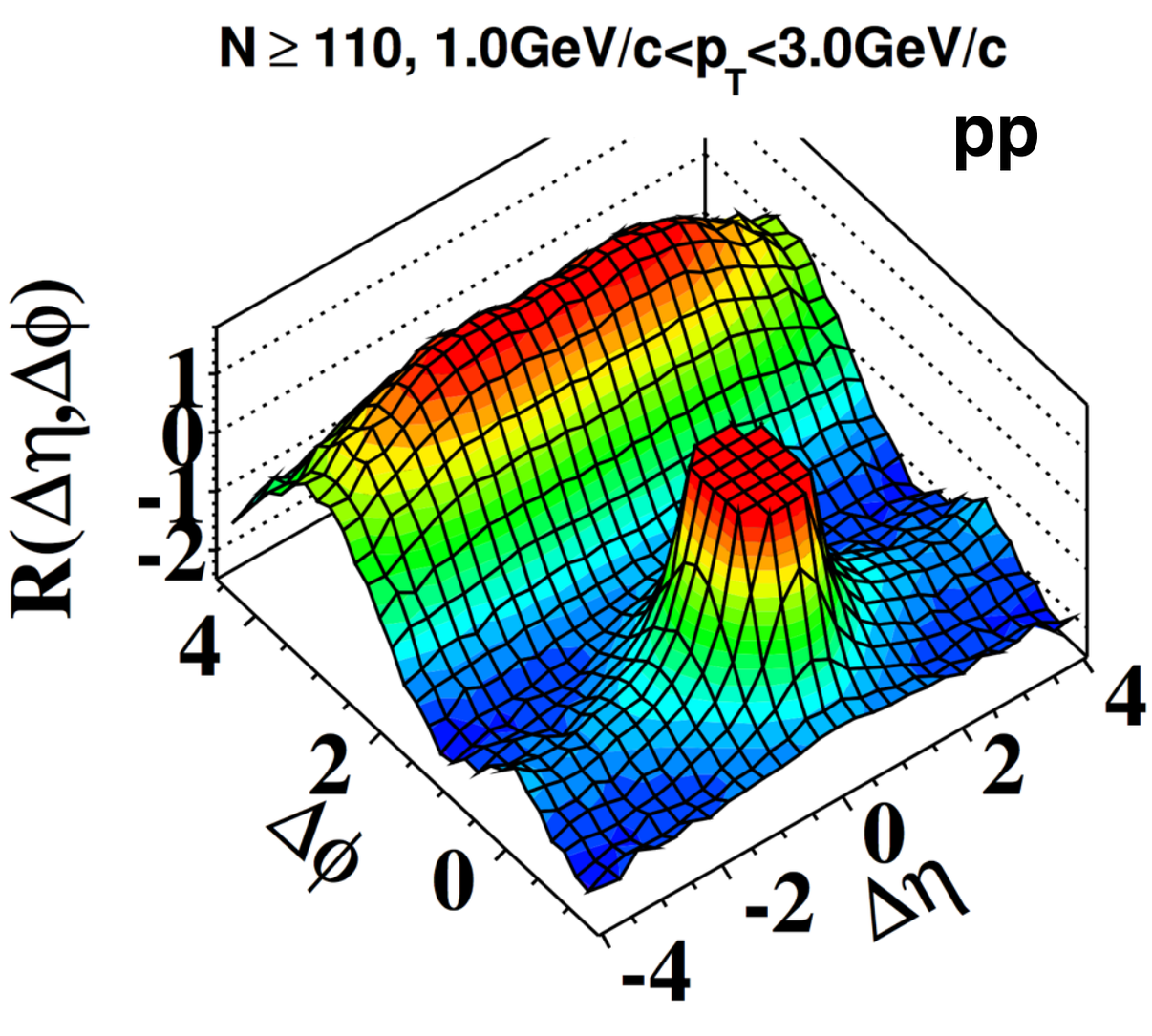
STAR, PRC 80 (2010) 064912

The ridge

long-range ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$)
was also observed in high-multiplicity proton-proton events
it was actually observed before in pp than in p-Pb



CMS, PLB 718 (2013) 795



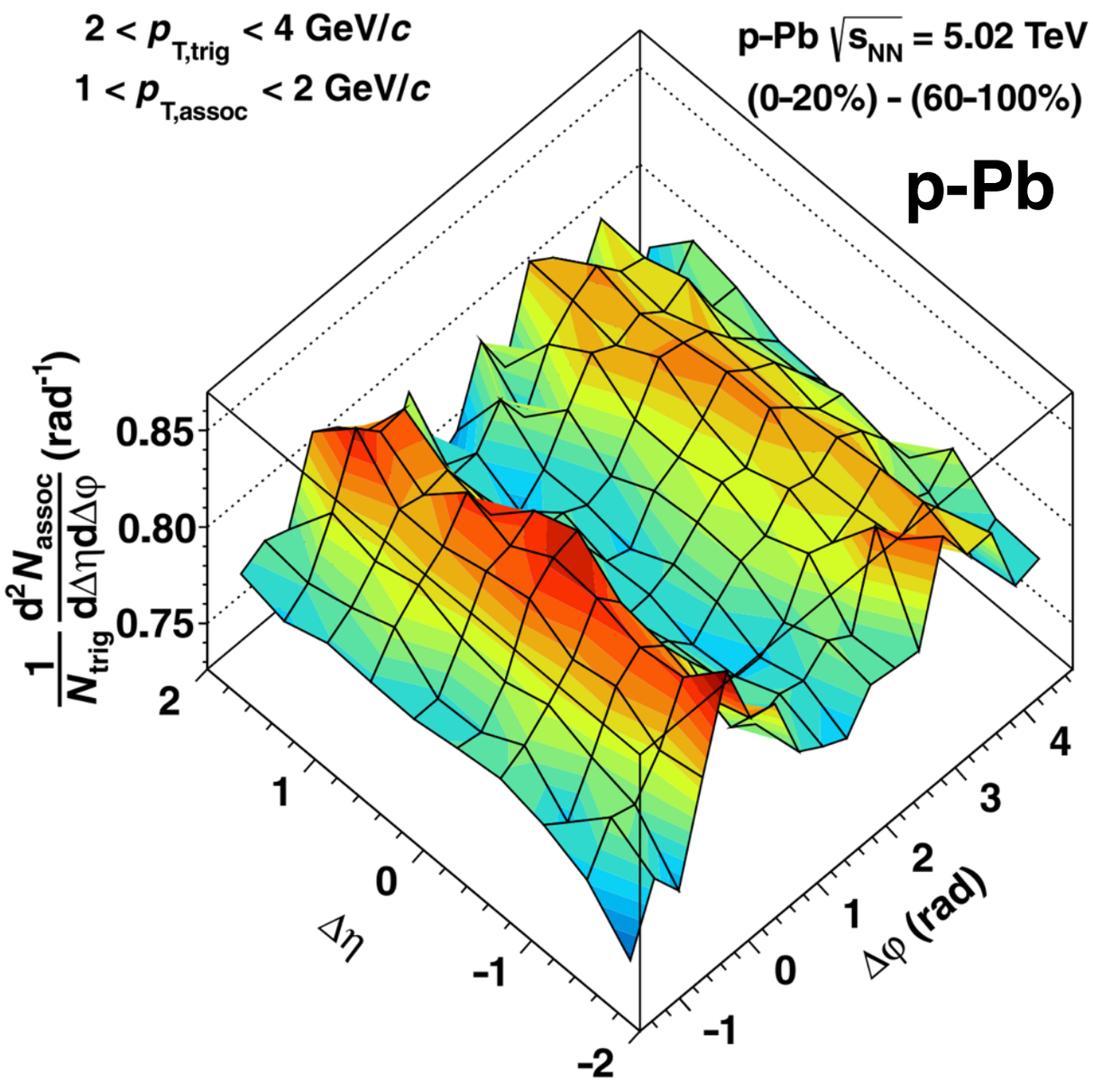
CMS, JHEP 09 (2010) 091

The double ridge

the ridge in p-Pb events triggered further investigations

jet contribution removed by subtracting low-multiplicity events

a **double ridge** structure **was revealed**



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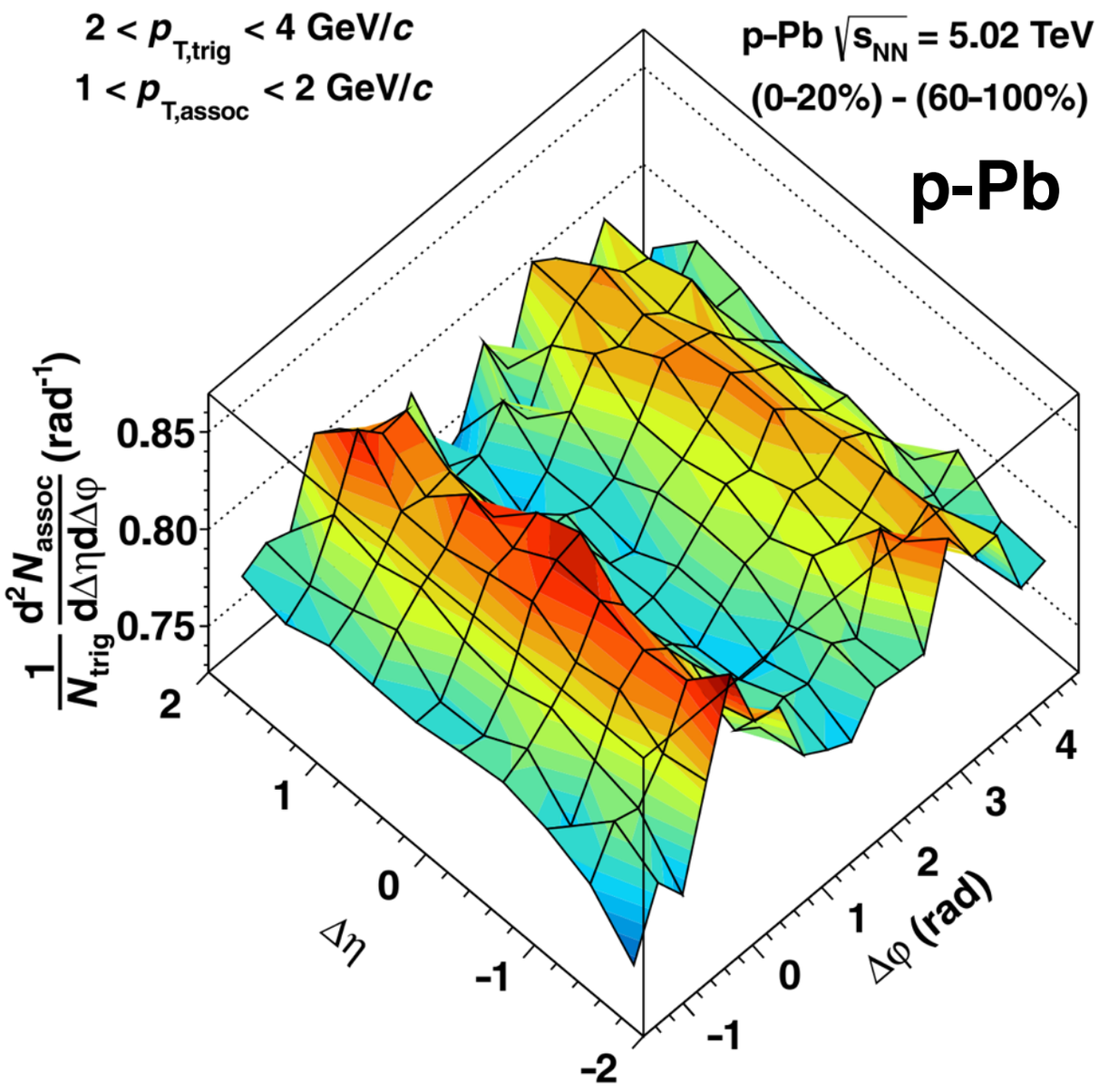
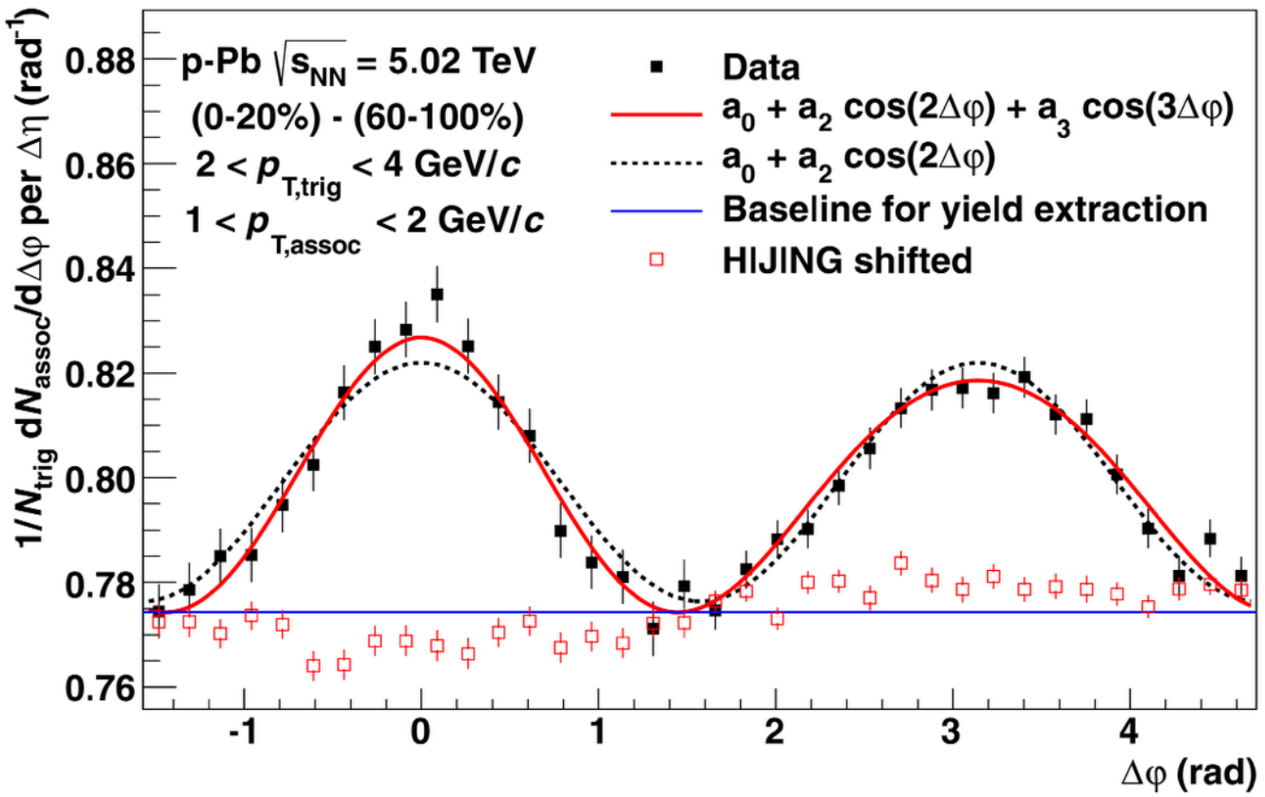


this looks so much like flow

Fourier decomposition of $\Delta\phi$: v_2, v_3, ...



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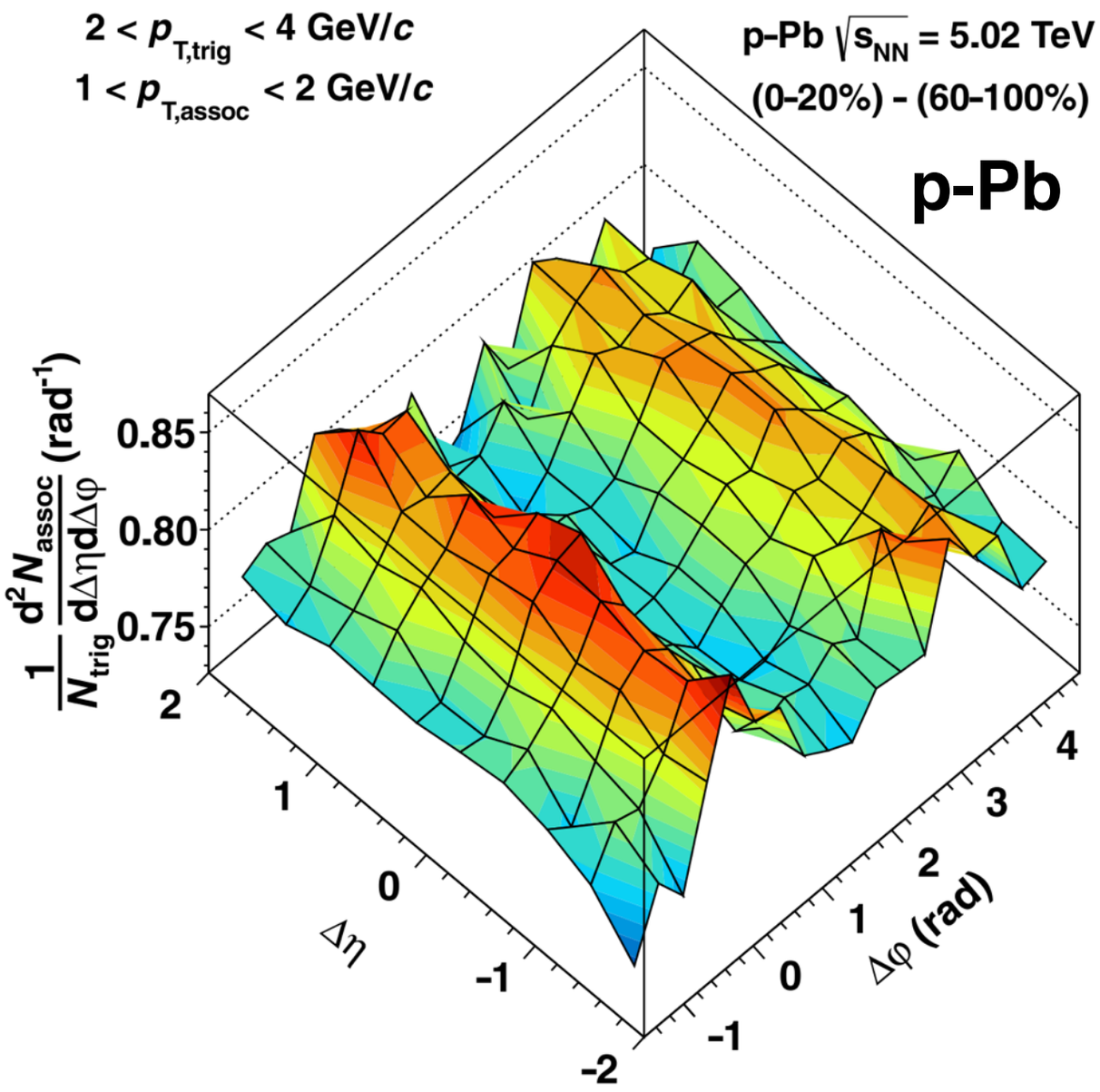
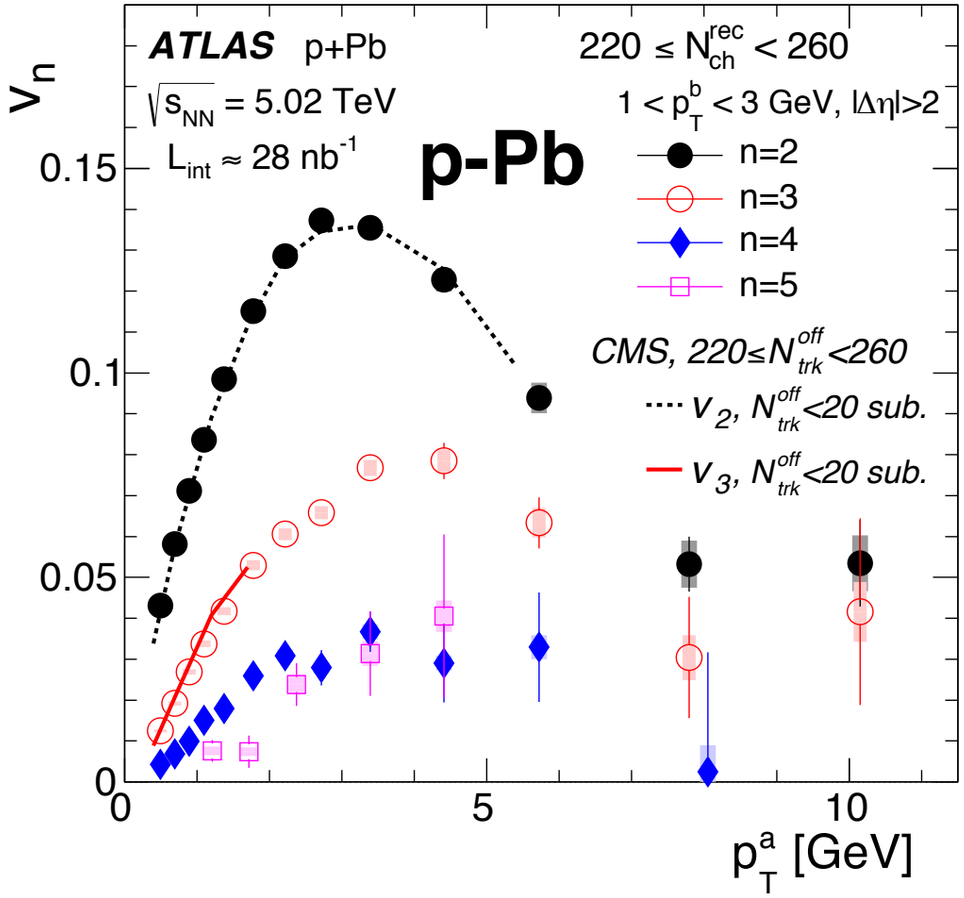


this looks so much like flow

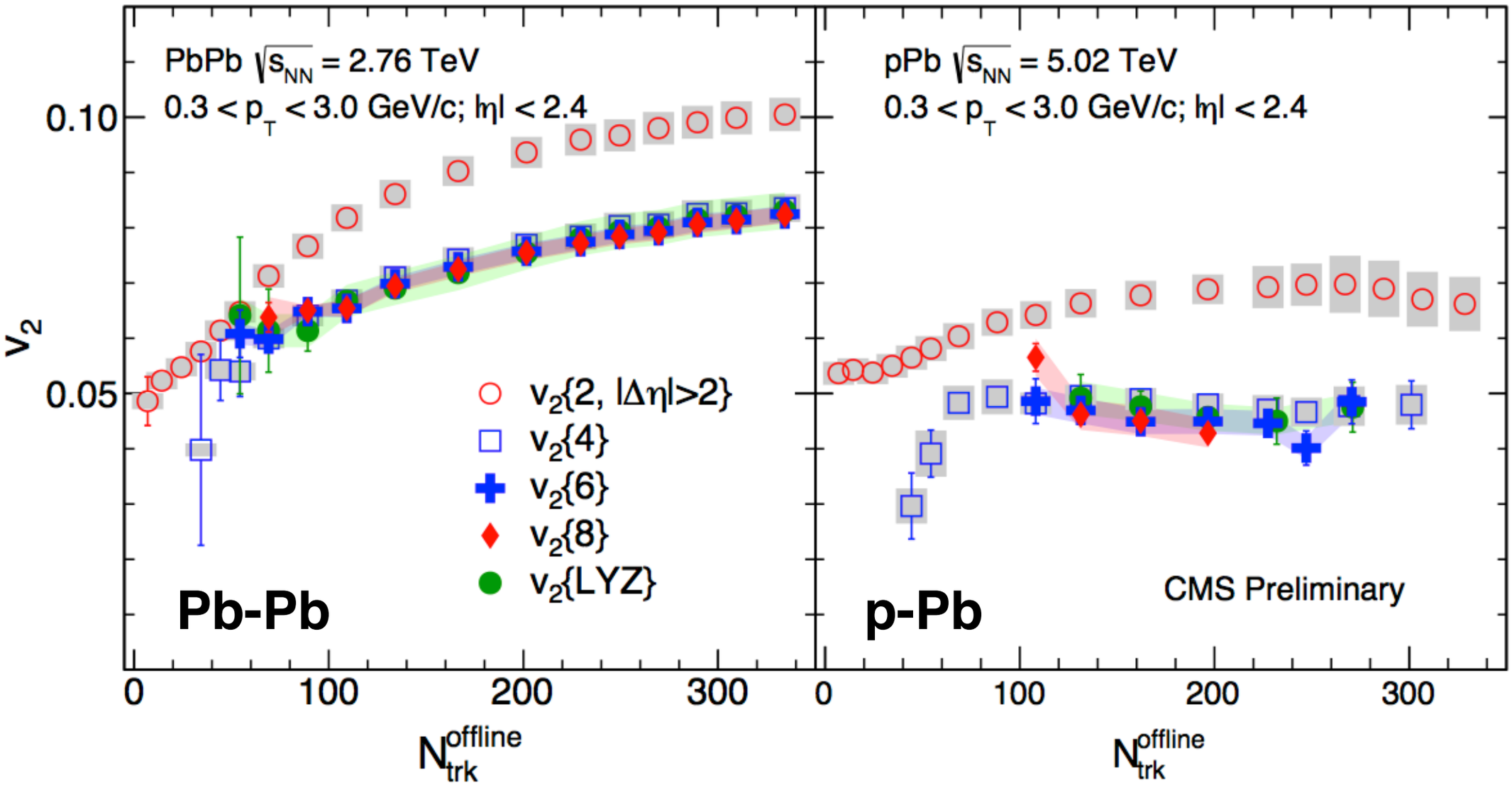
Fourier decomposition of $\Delta\phi$: v_2, v_3, ...

ATLAS, arXiv:1409.1792 [hep-ex]



True collective effect

CMS, PAS HIN-14-006



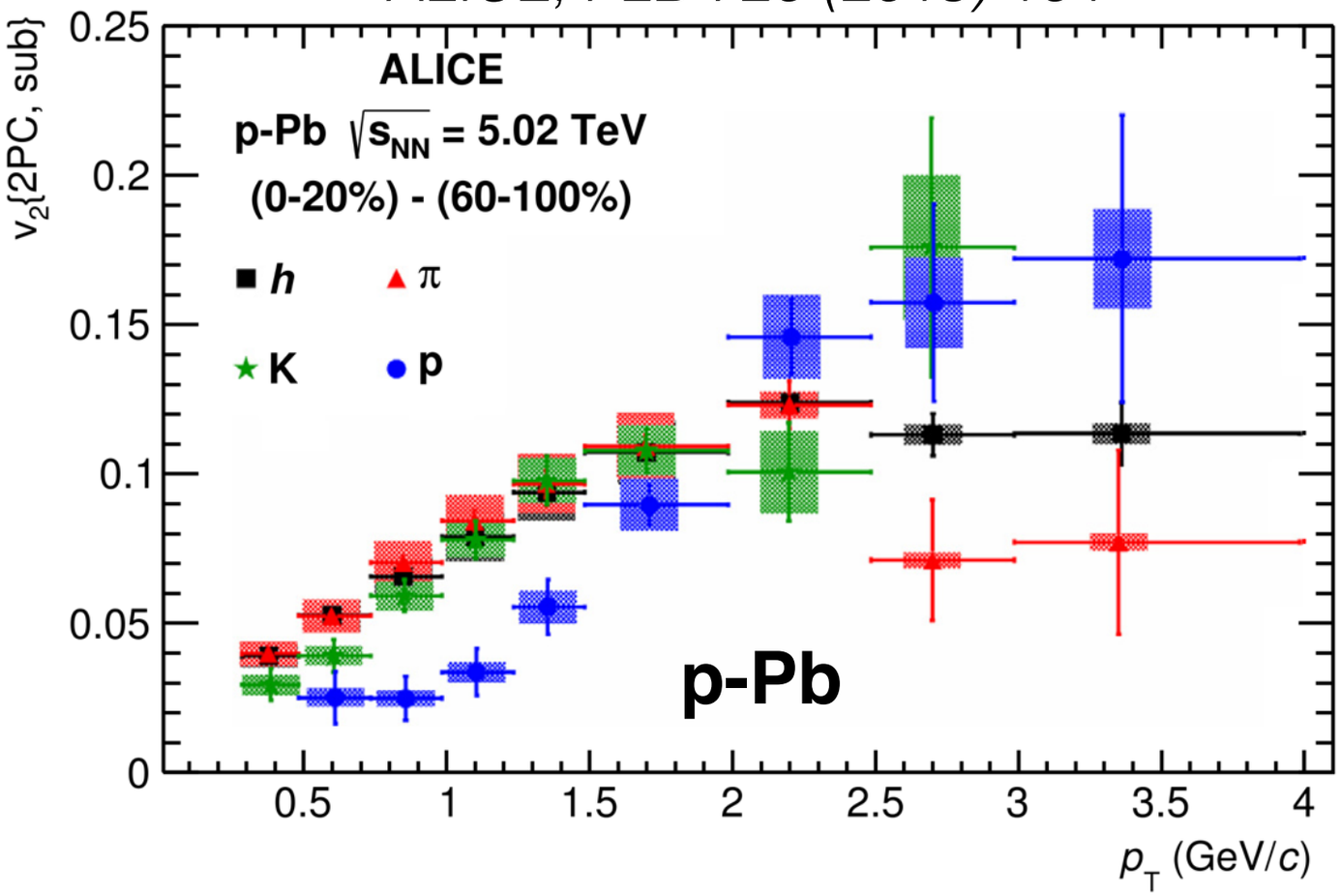
v_2 stays large when computed with multi-particles

$v_2\{4\} = v_2\{6\} = v_2\{8\} = v_2\{\text{LYZ}\}$ have different sensitivity to non-flow effects

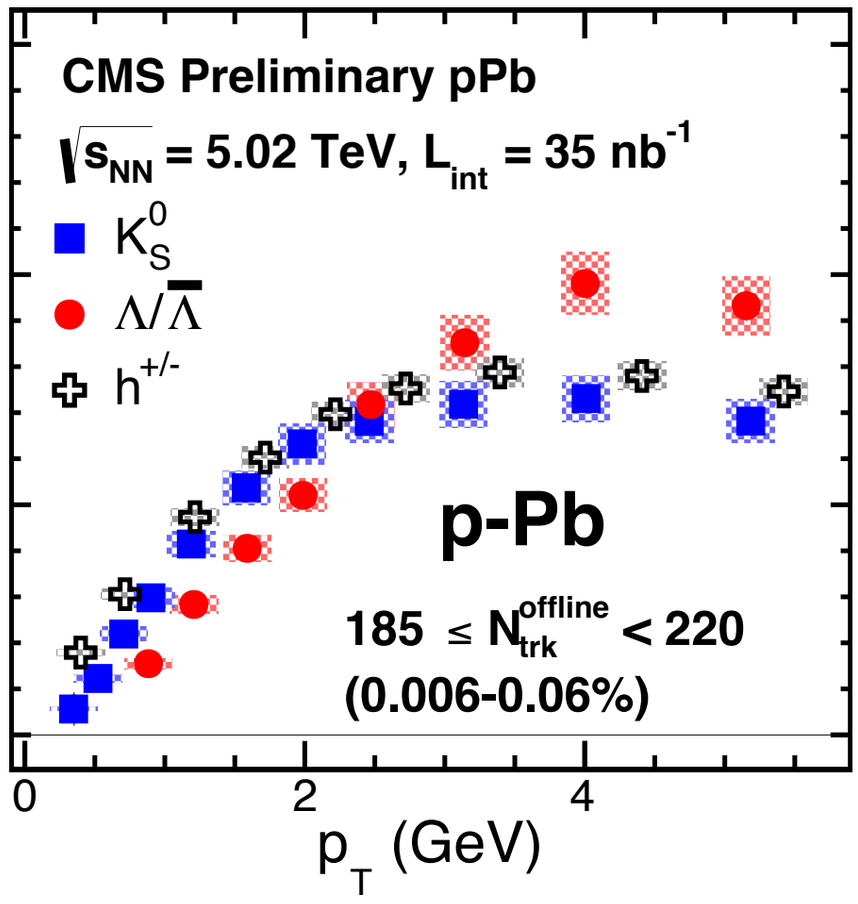
there is **true collectivity in p-Pb**

v_2 of identified particles

ALICE, PLB 726 (2013) 164



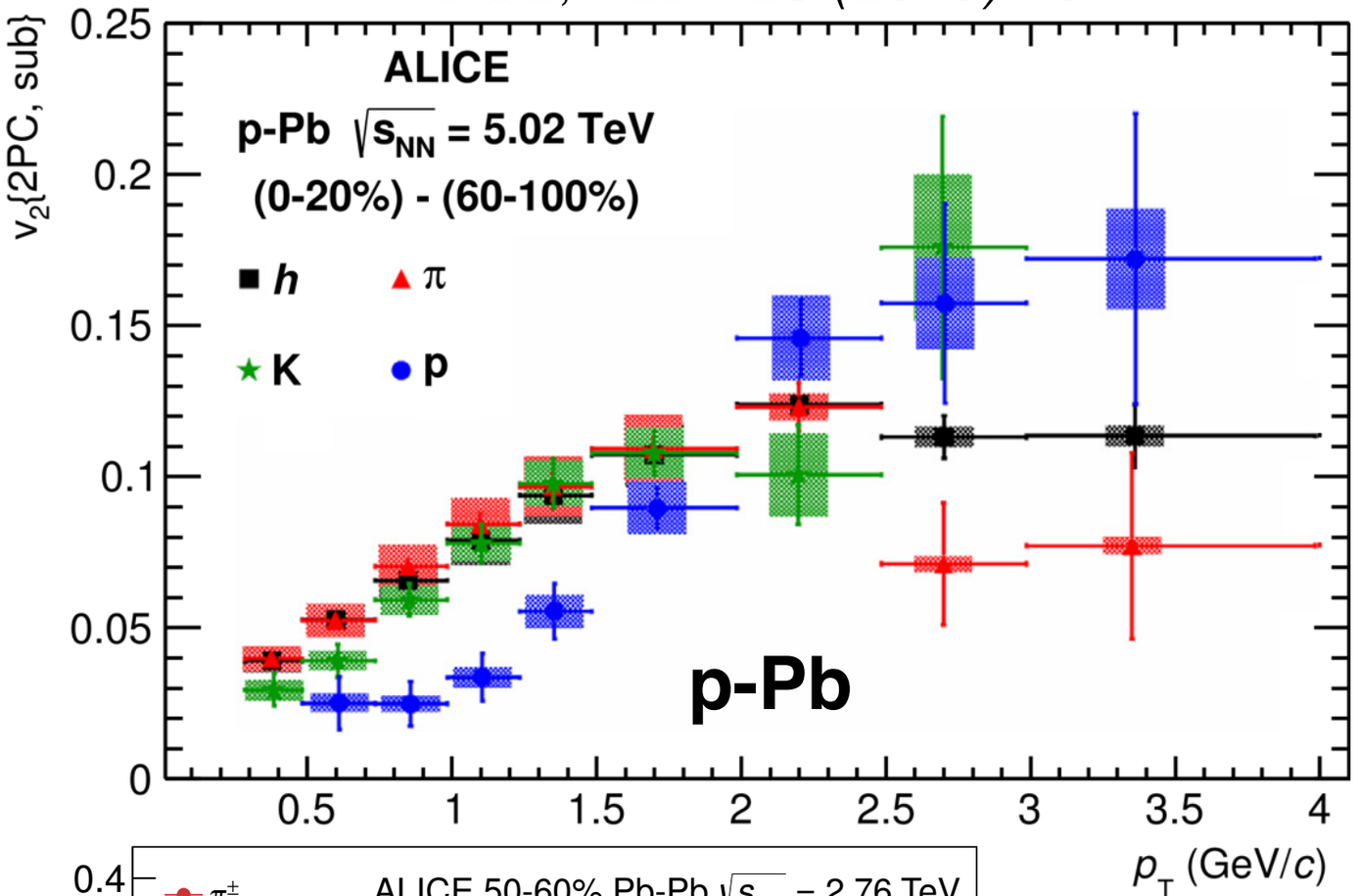
CMS, CMS-HIN-14-002



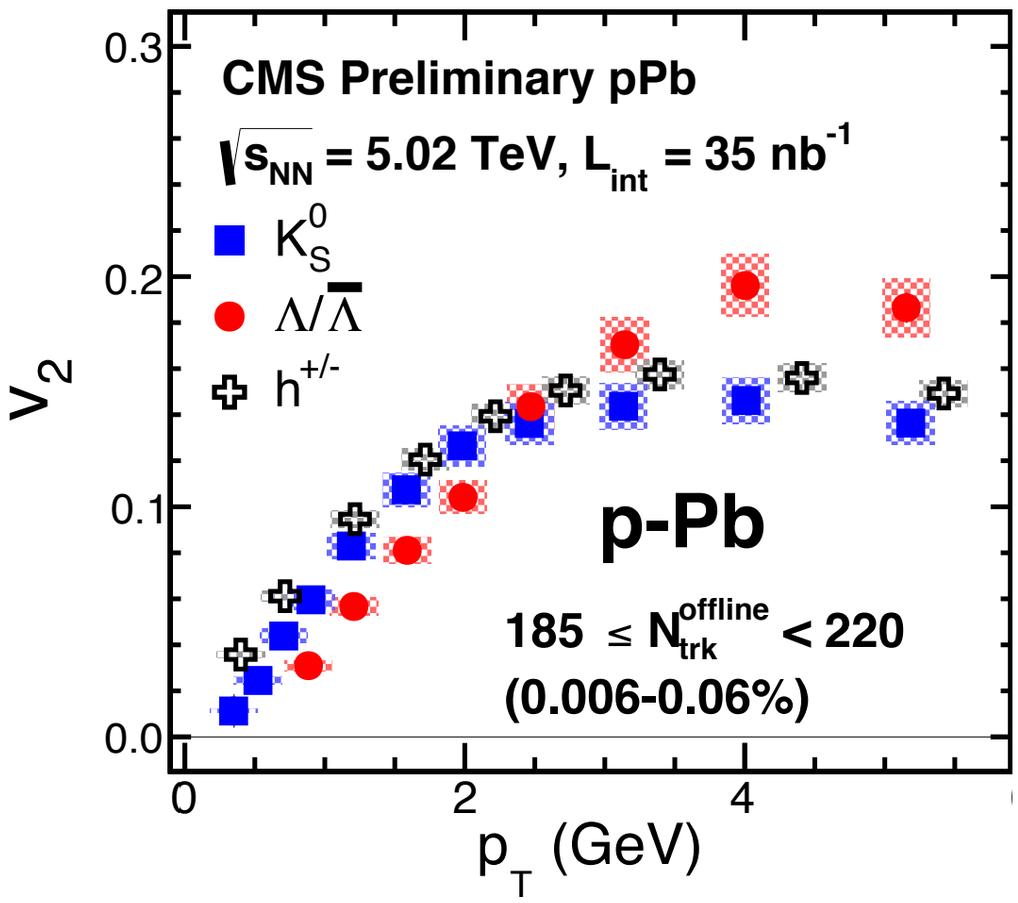
mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T

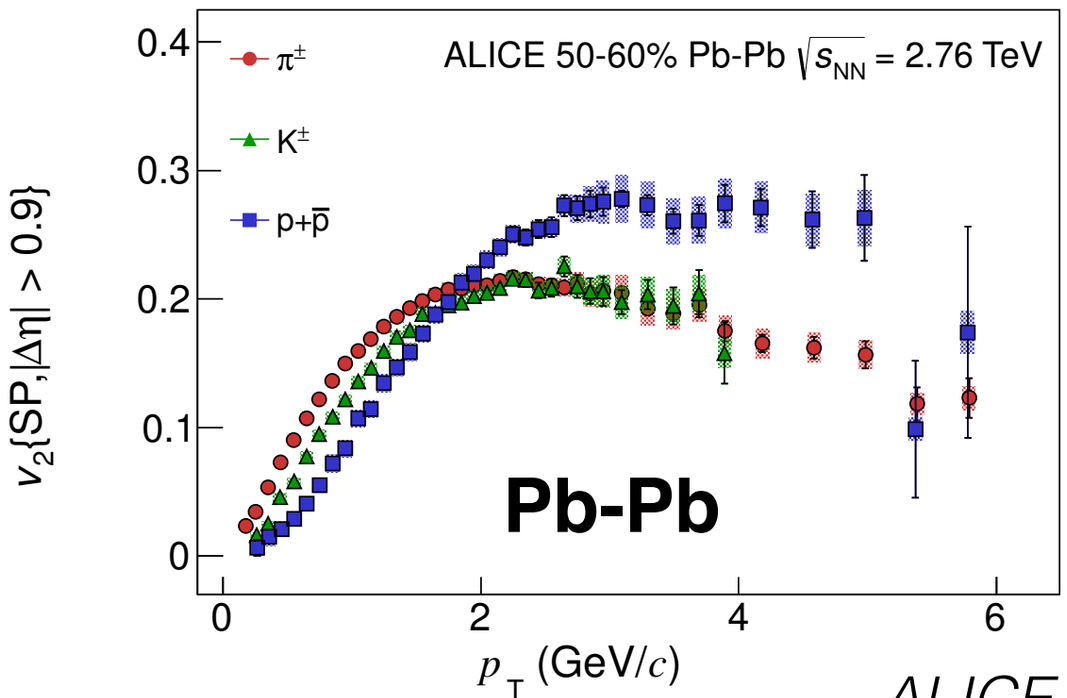
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PAS HIN-14-002



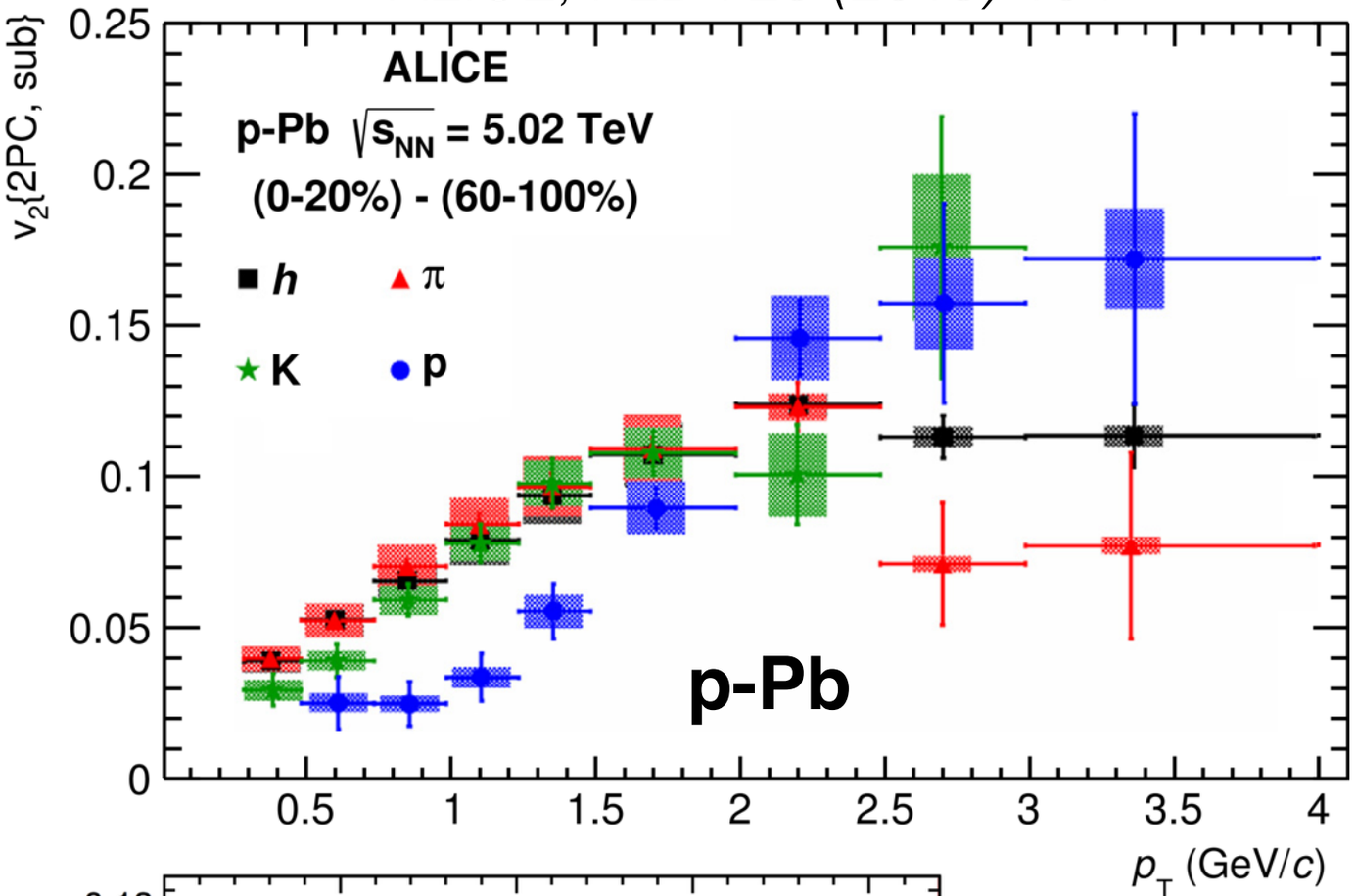


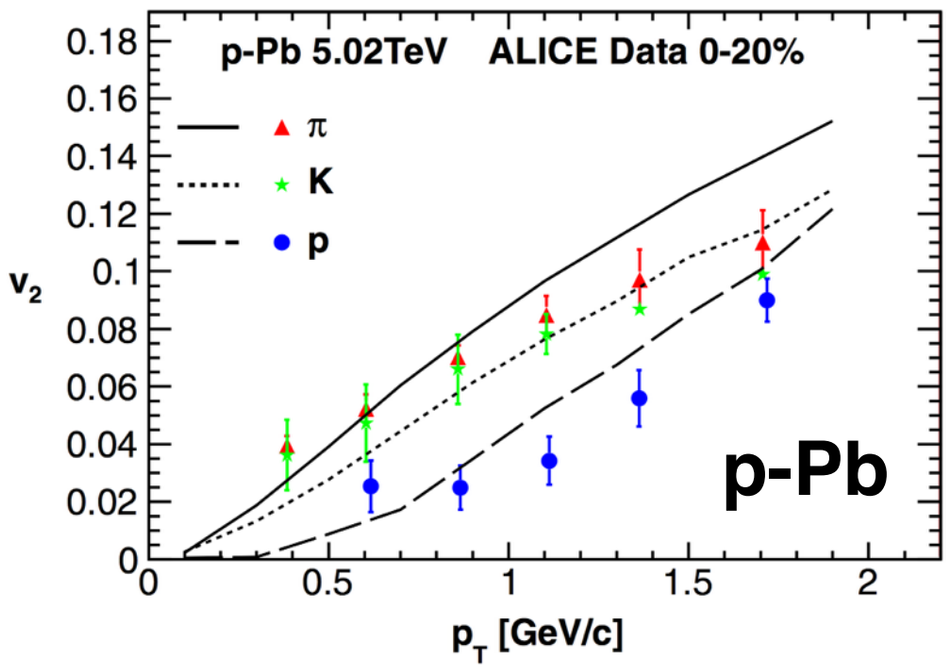
mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T
reminiscent of A-A observations

ALICE, arXiv:1405.4632 [nucl-ex]

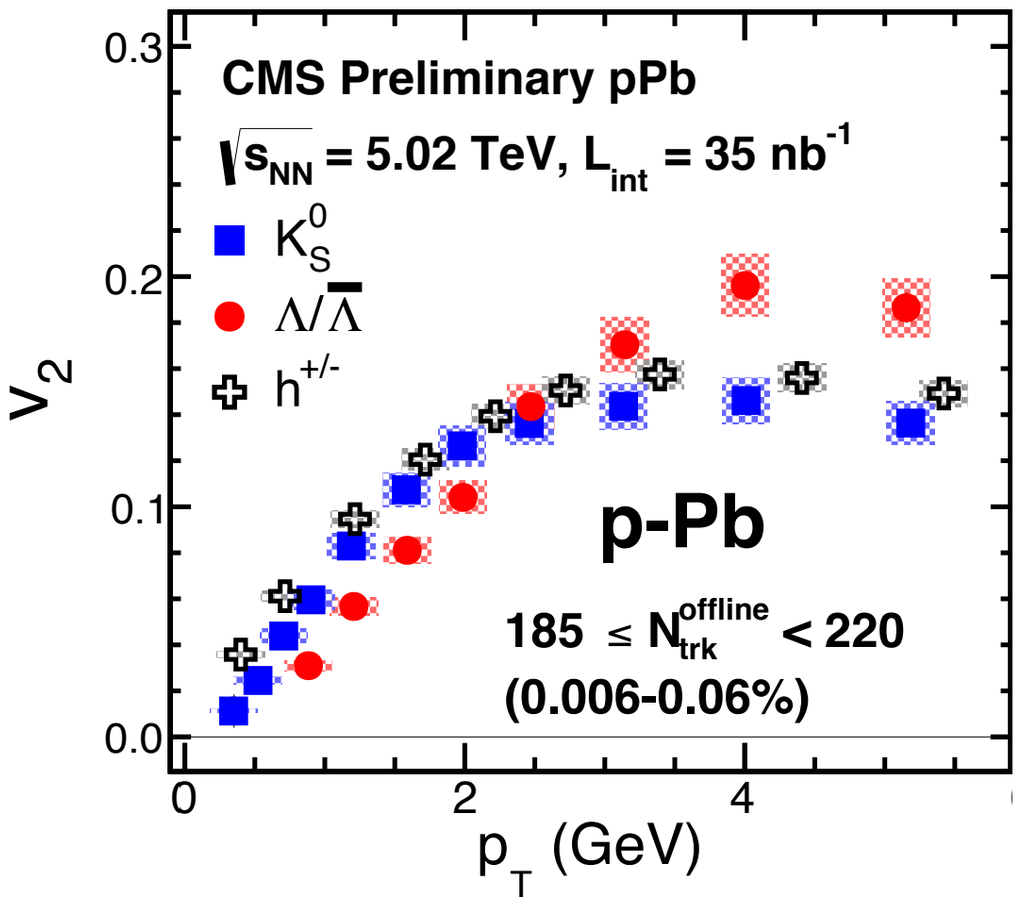
v_2 of identified particles

ALICE, PLB 726 (2013) 164





CMS, CMS-HIN-14-002

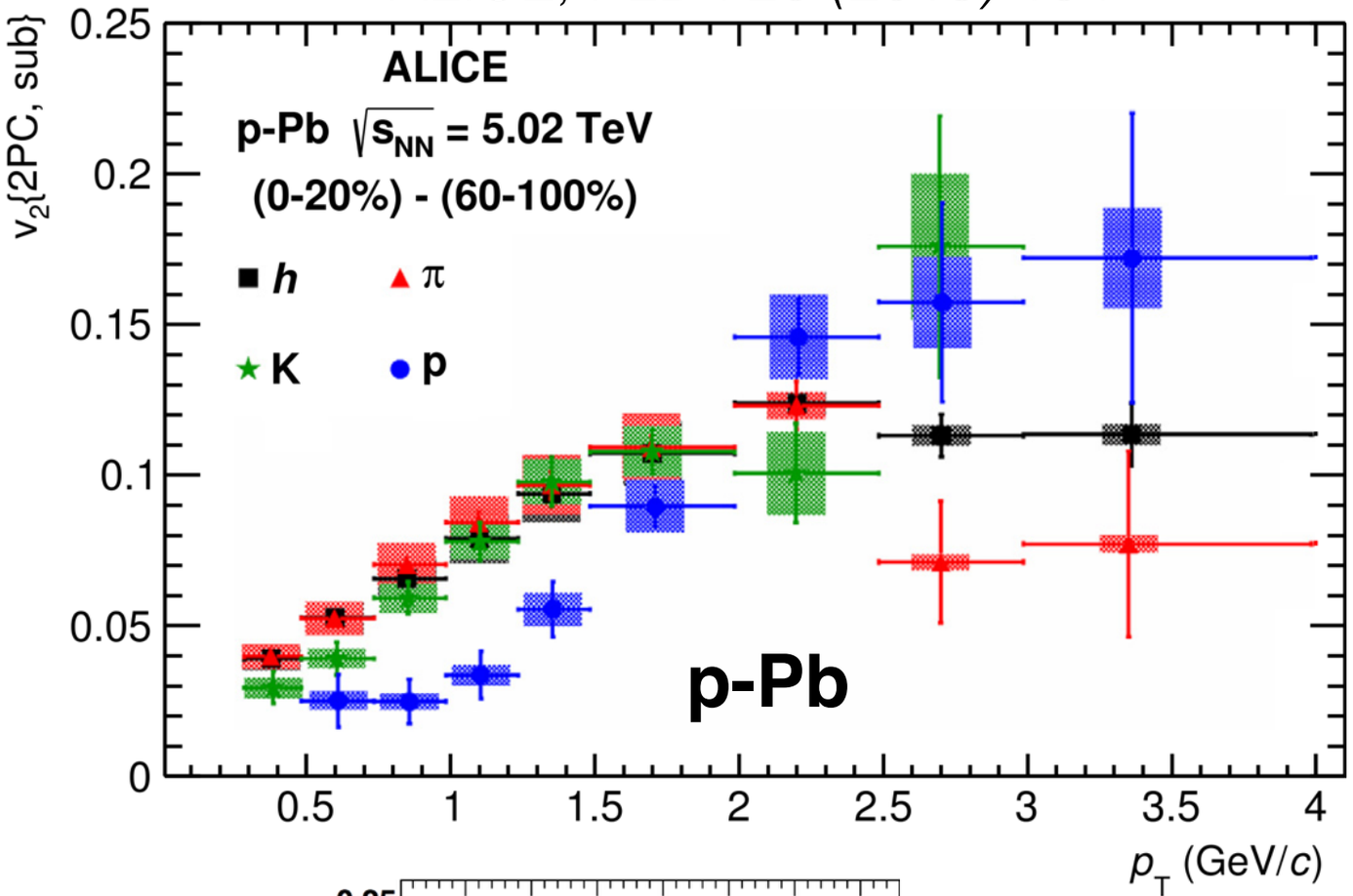


mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T
consistent with expectations from
collective hydrodynamic expansion

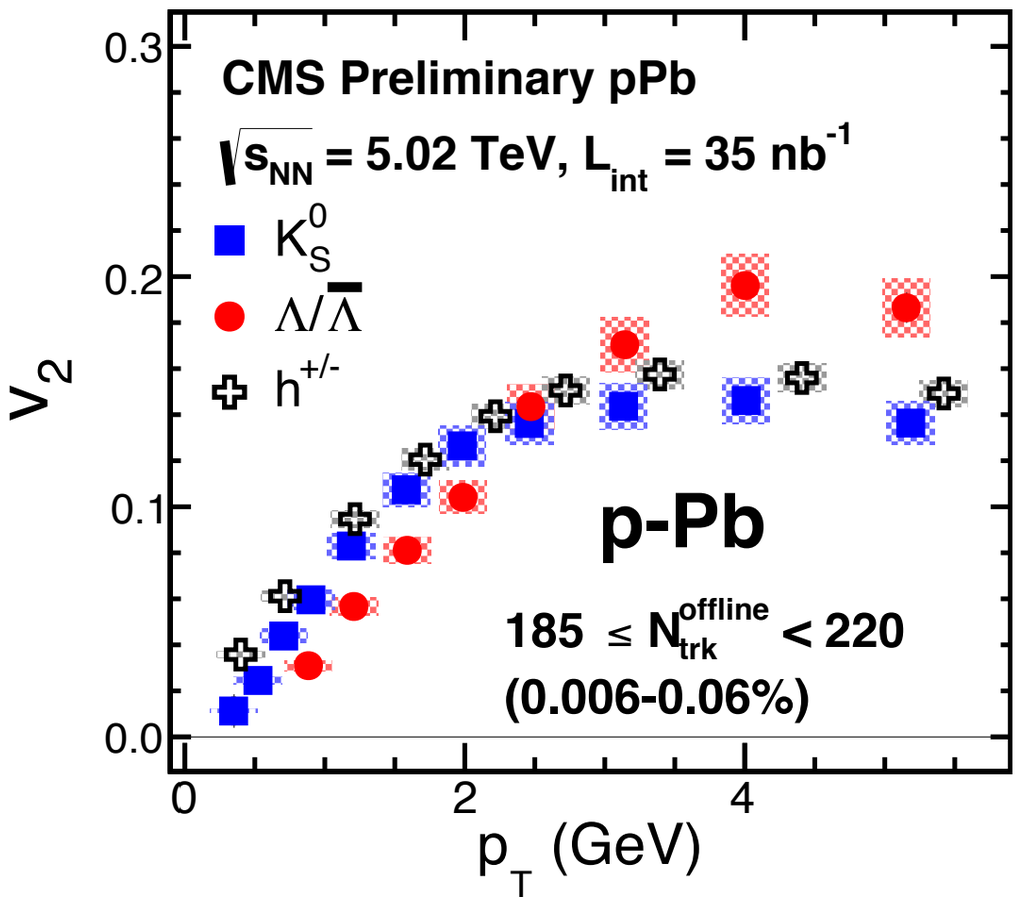
Bozek et al., PRL 111 (2013) 172303

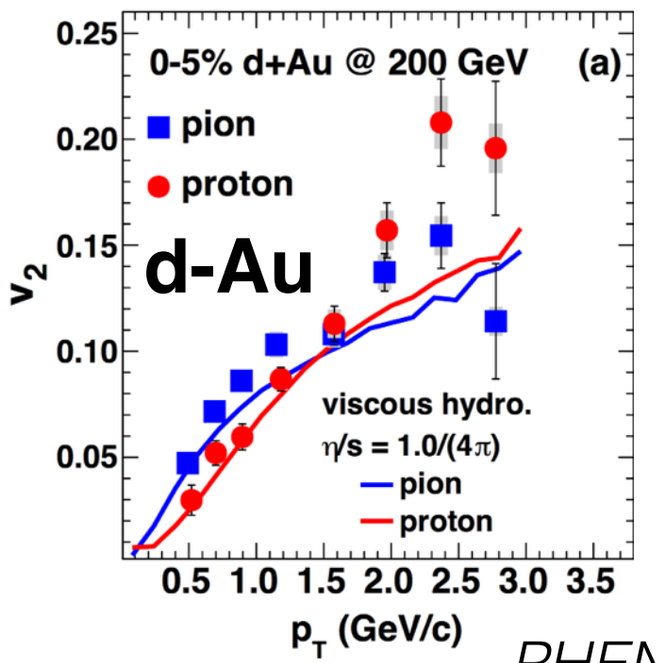
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PAS HIN-14-002



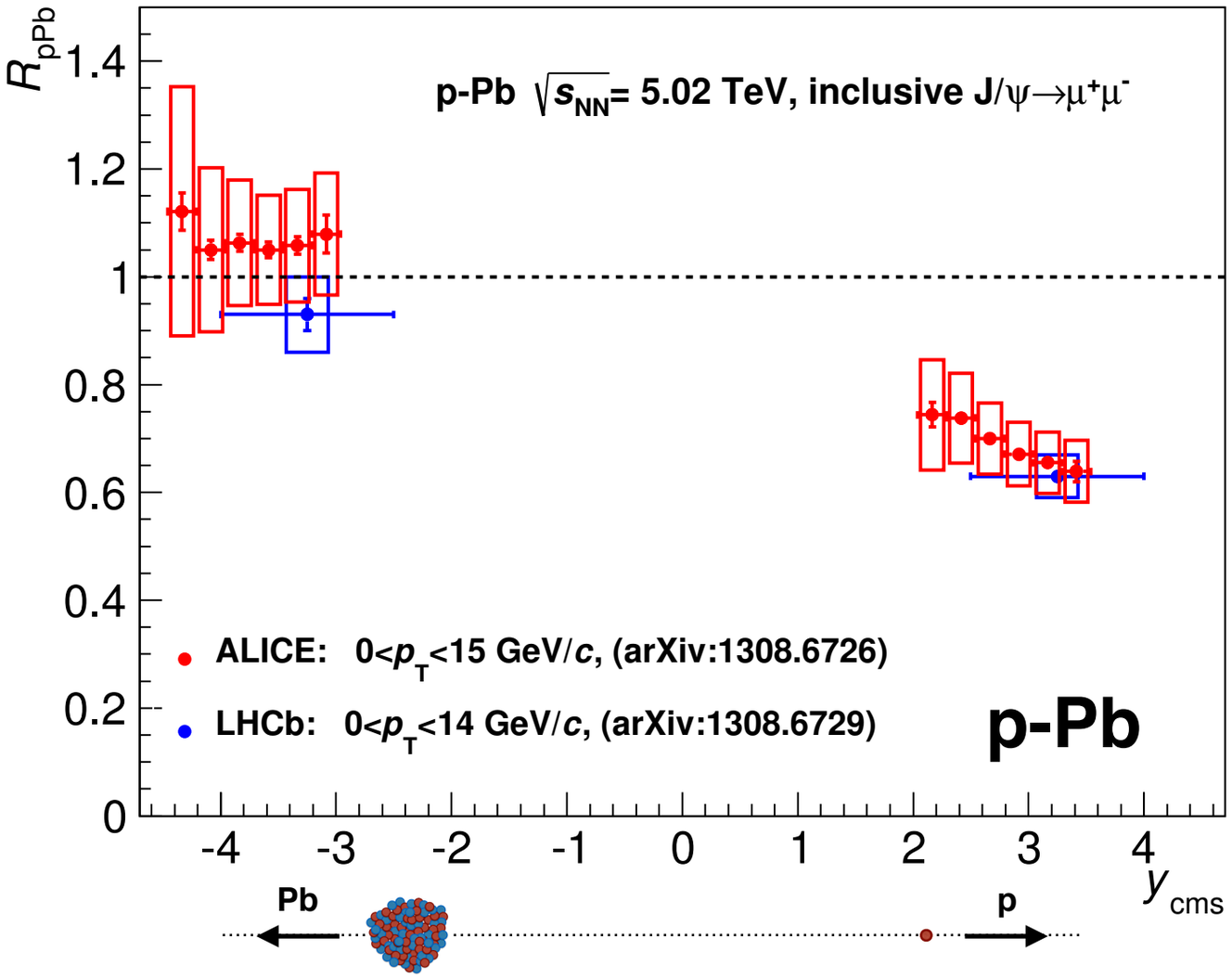


mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T
also at RHIC in d-Au collisions

PHENIX, arXiv:1404.7461 [nucl-ex]

further information on initial- and final-state effects from quarkonia

Inclusive J/ψ production



suppression at forward (and central) rapidity

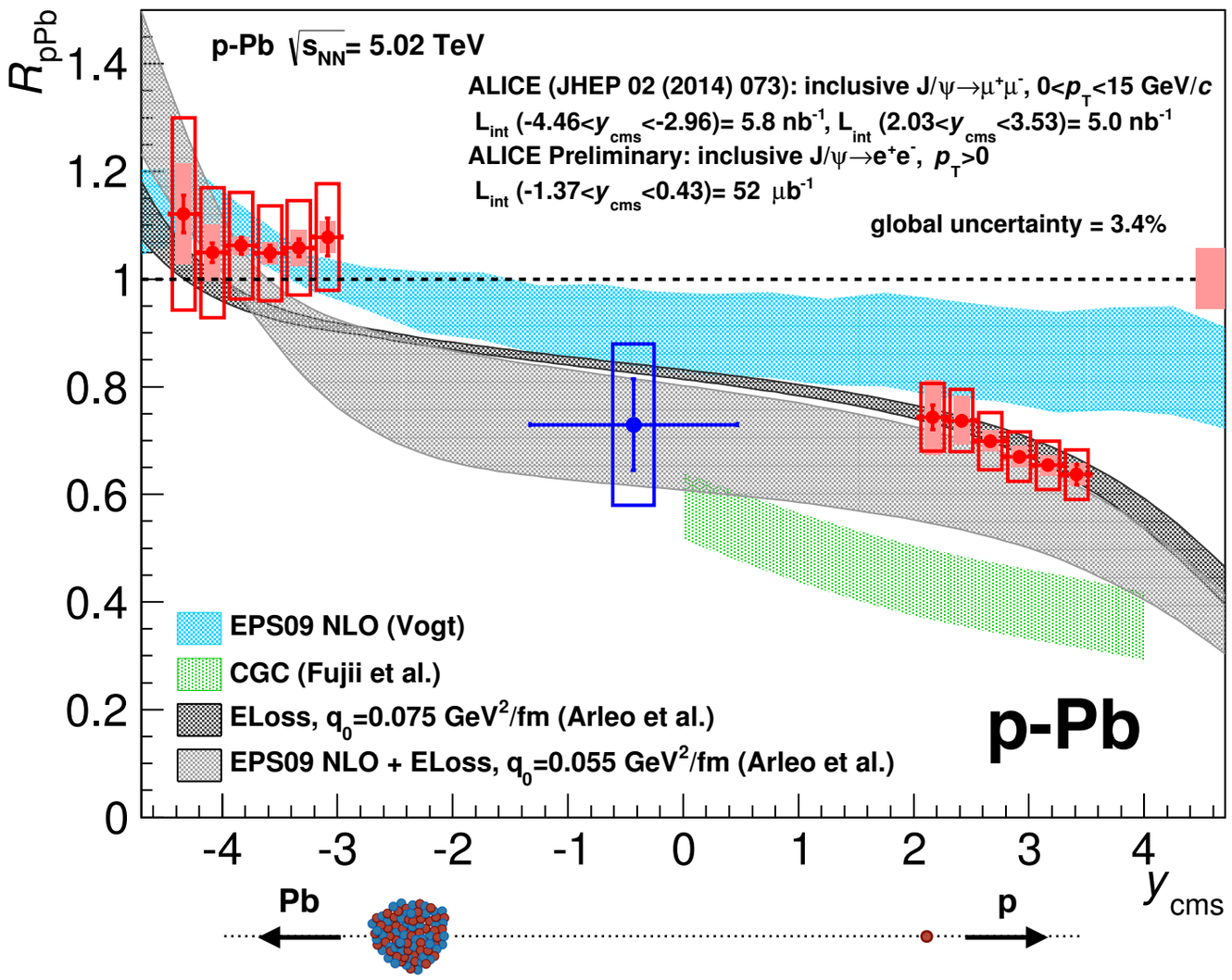
no suppression at backward rapidity

enhancement?

LHCb, JHEP 02 (2014) 072
ALICE, JHEP 02 (2014) 073

Inclusive J/ψ production

ALICE, JHEP 02 (2014) 073



suppression at forward (and central) rapidity

no suppression at backward rapidity

enhancement?

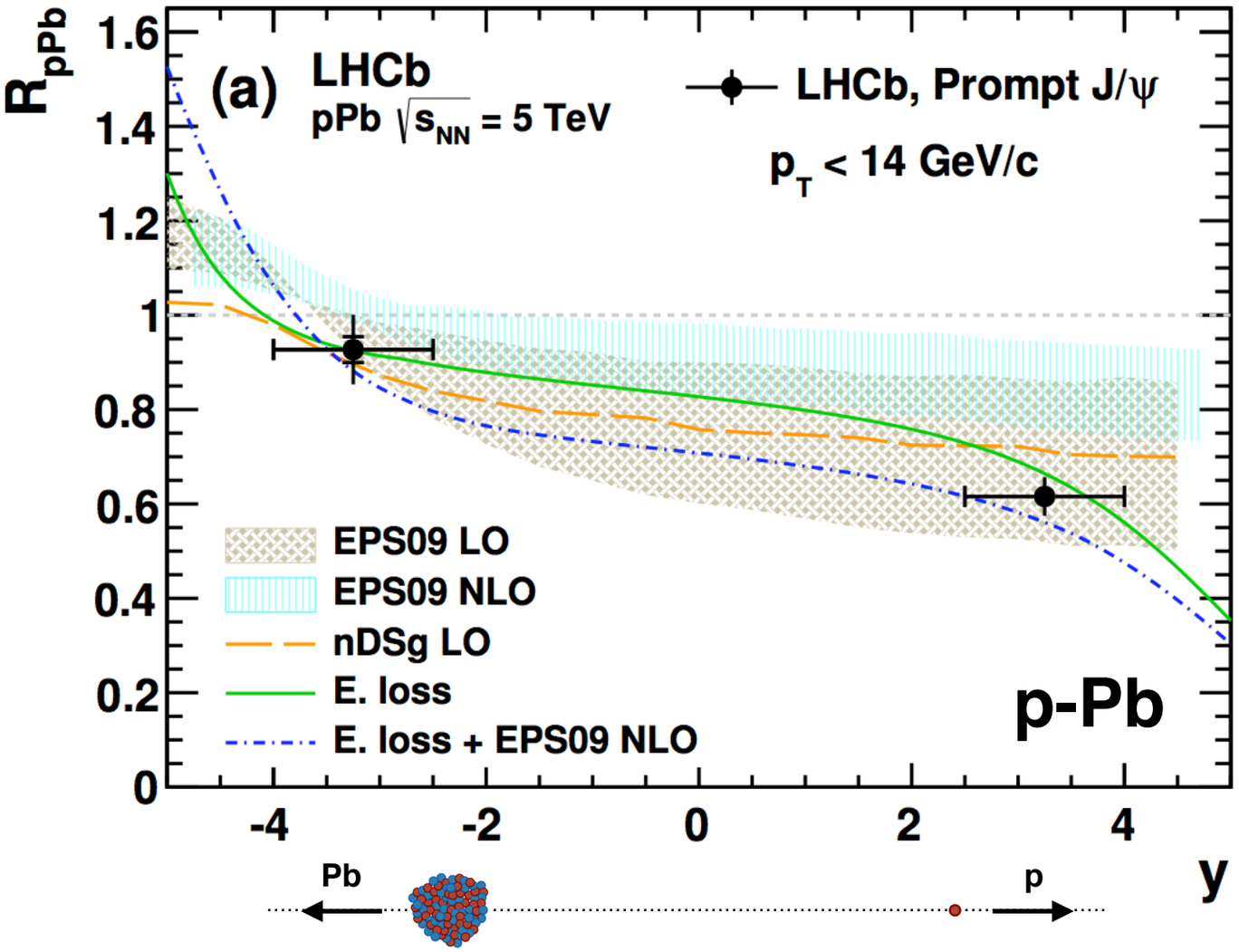
nuclear shadowing and/or partonic energy-loss models in fair agreement

saturation (CGC) models overestimate suppression

cold nuclear matter effects (**CNM**) are **not negligible**

Same picture from prompt J/ψ

LHCb, JHEP 02 (2014) 072



suppression at forward (and central) rapidity

no suppression at backward rapidity

enhancement?

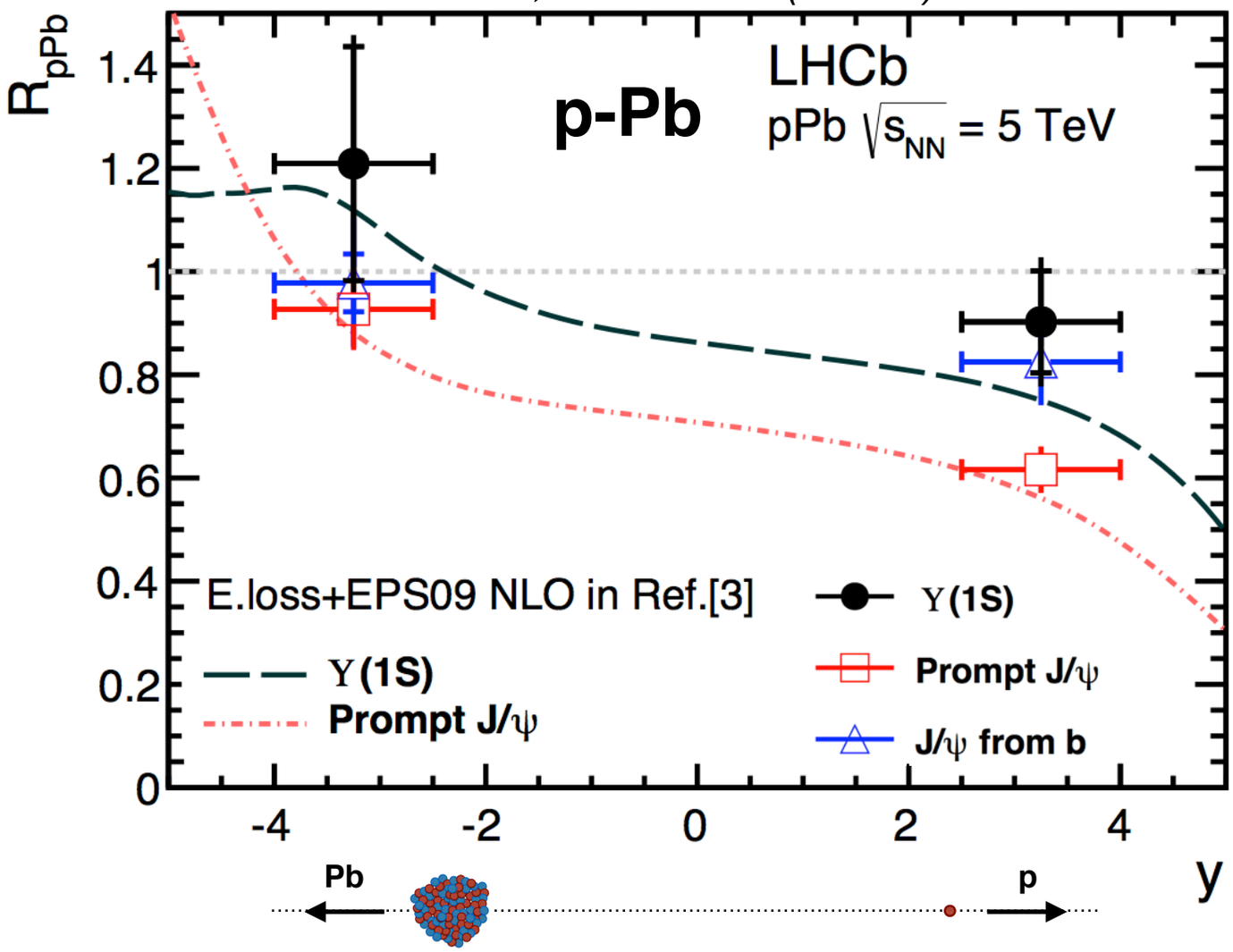
nuclear shadowing and/or partonic energy-loss models in fair agreement

saturation (CGC) models overestimate suppression

cold nuclear matter effects (**CNM**) are **not negligible**

Same picture from Υ(1S)

LHCb, JHEP 07 (2014) 094



suppression at forward rapidity

no suppression at backward rapidity

enhancement?

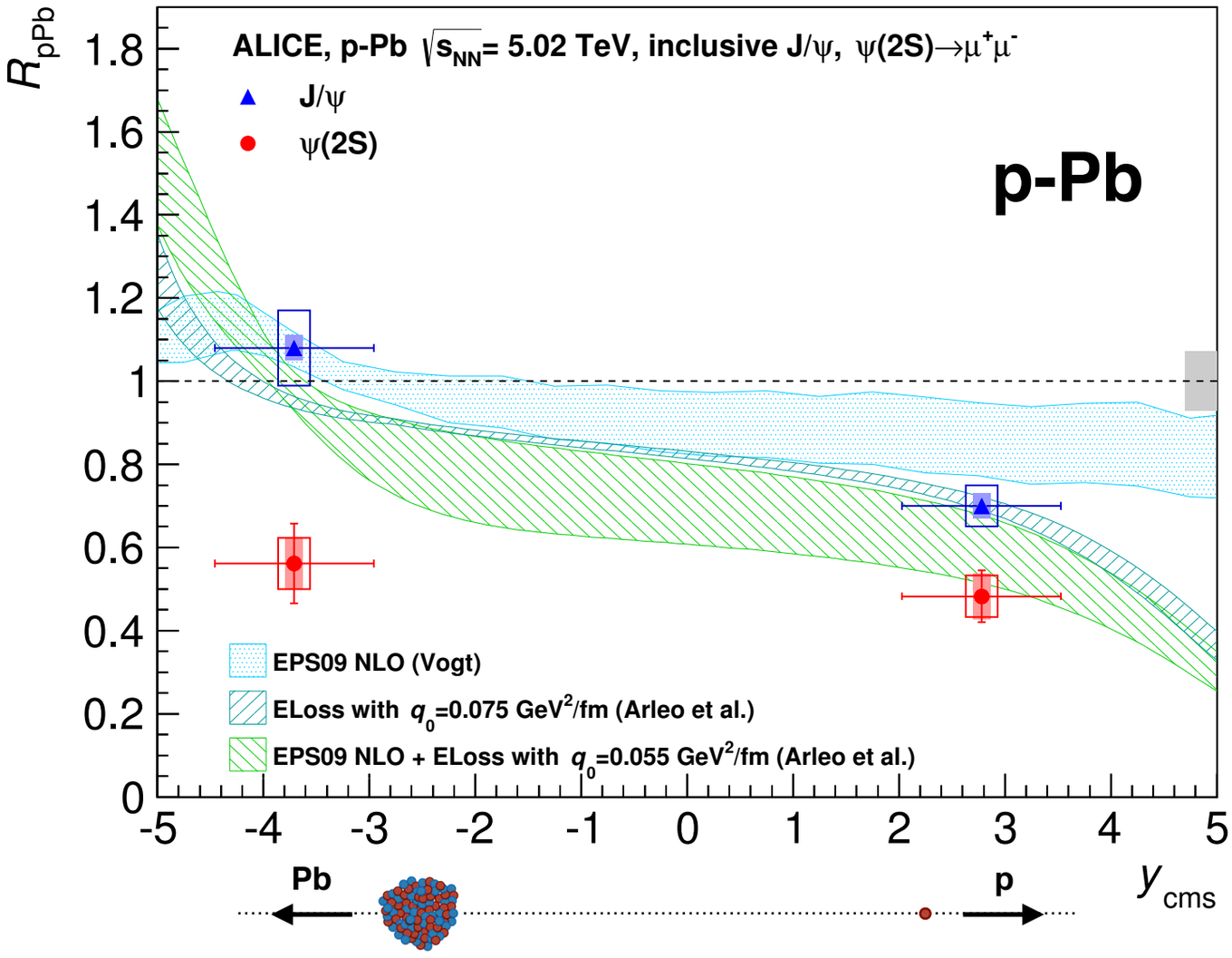
suppression smaller than prompt J/ψ

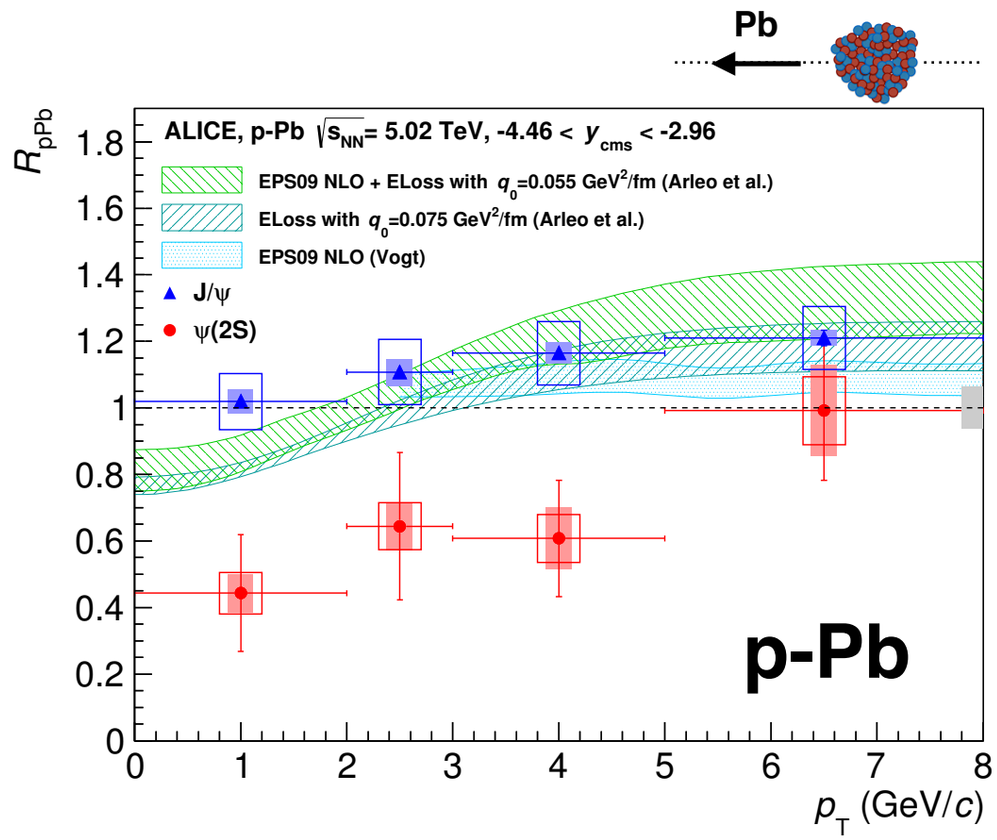
J/ψ from b

indication of suppression of b-hadron production

ψ(2S) suppression

ALICE, arXiv:1405.3796 [nucl-ex]





strong ψ(2S) suppression

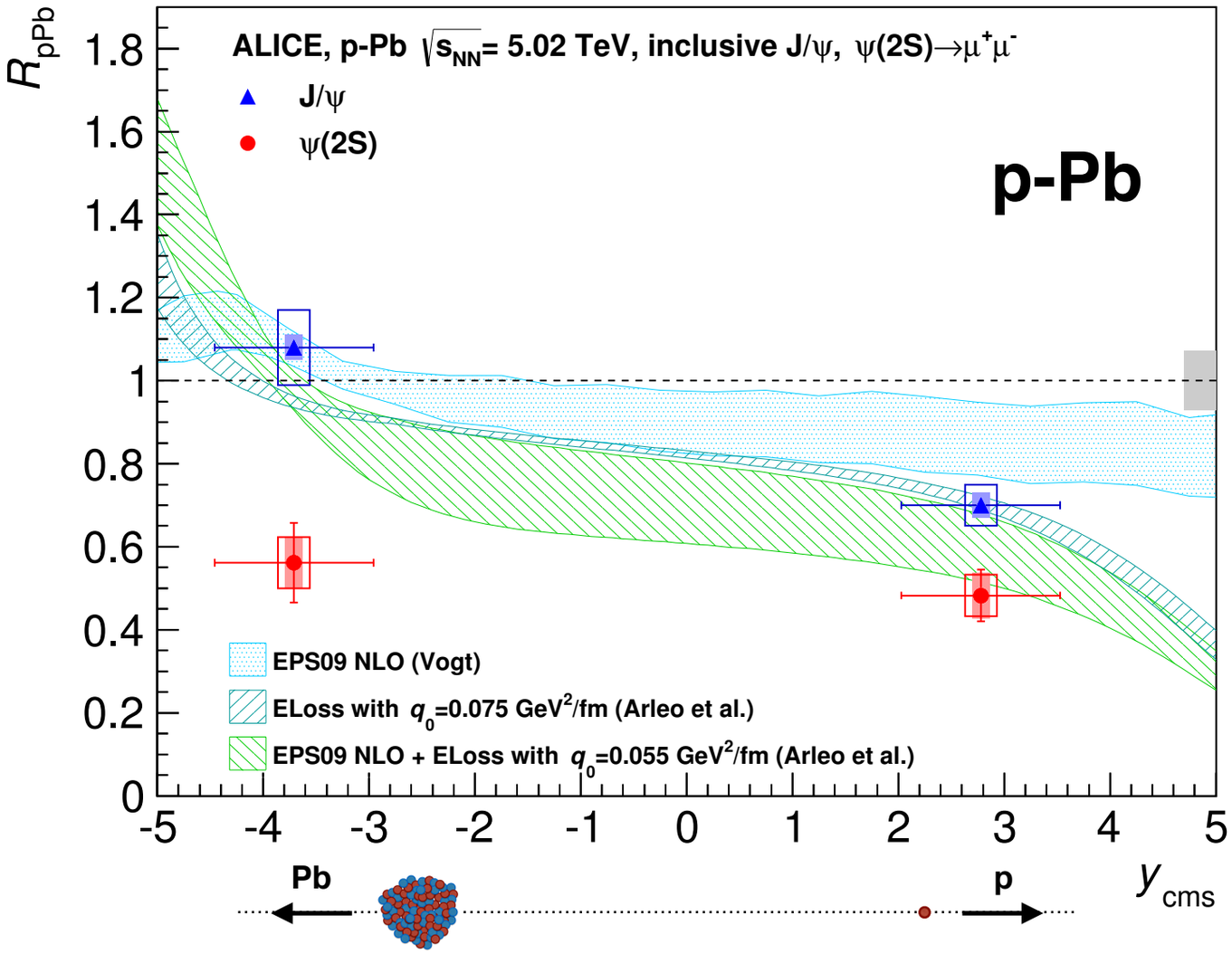
in Pb-side significantly larger than J/ψ and model predictions

initial-state effects cannot account for ψ(2s) modification

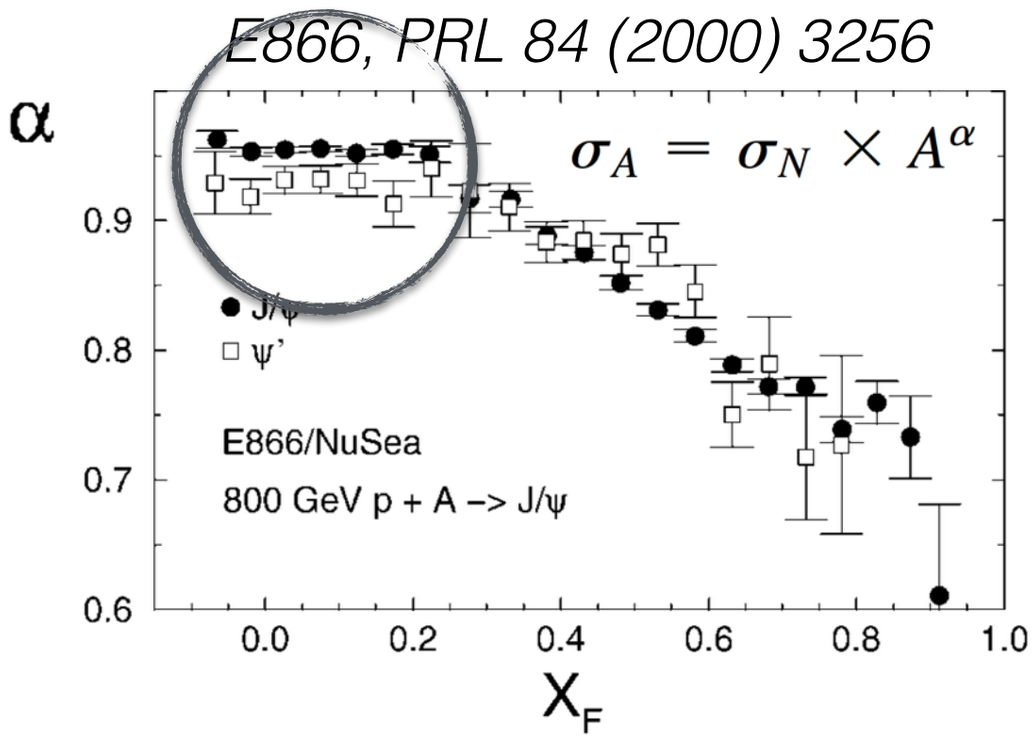
clear **indication for final state effects**

ψ(2S) suppression

ALICE, arXiv:1405.3796 [nucl-ex]



E866, PRL 84 (2000) 3256



strong ψ(2S) suppression

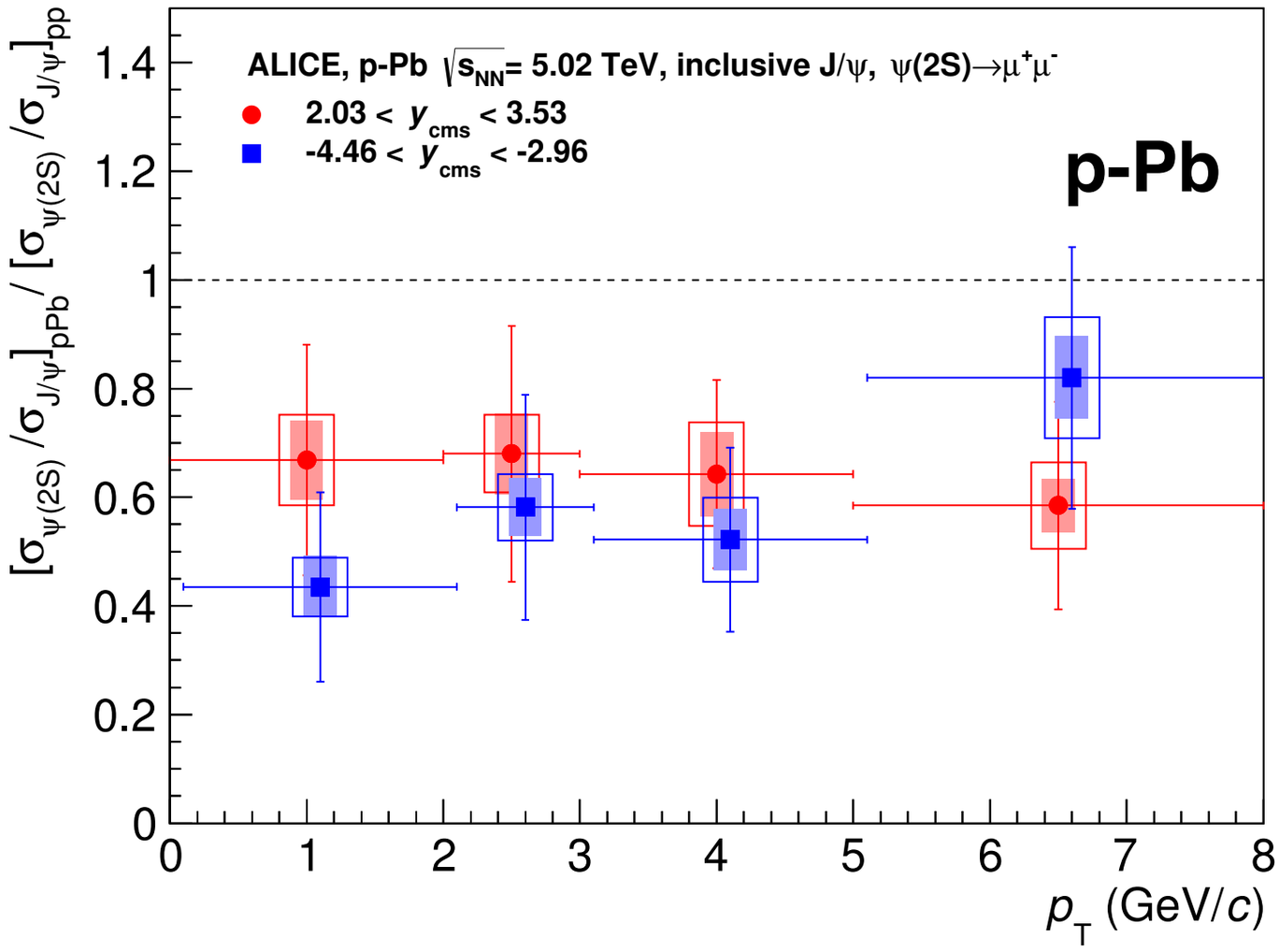
in Pb-side significantly larger than J/ψ and model predictions

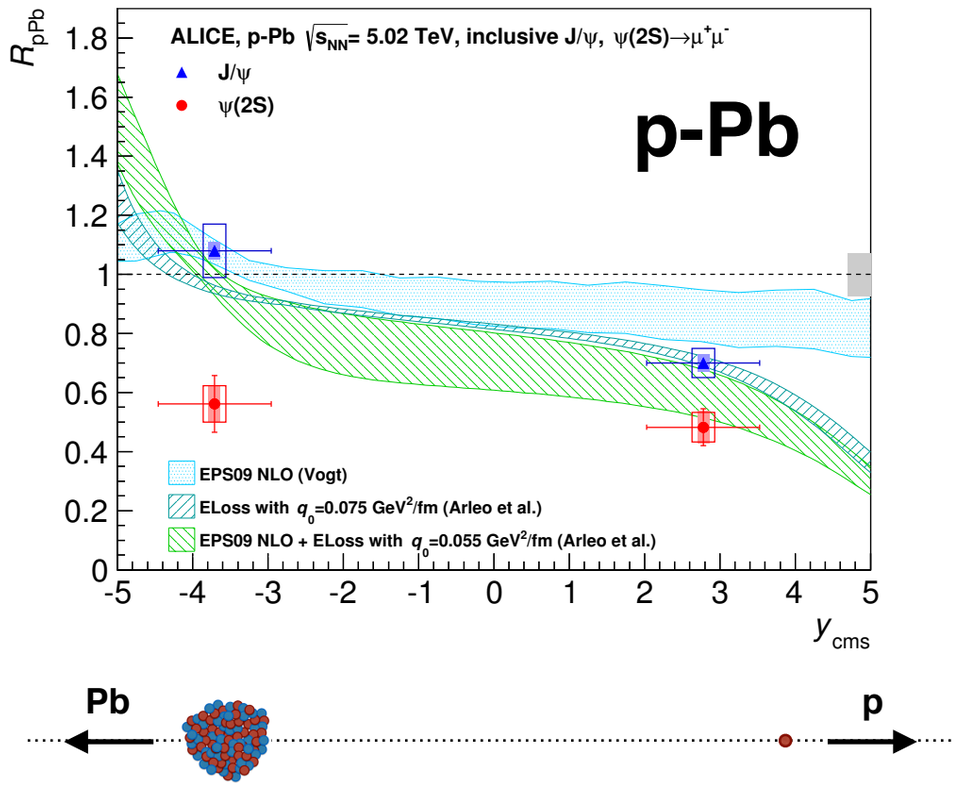
similar observation was also reported by fixed-target experiments

HERA-B, EPJC 49 (2007) 545

ψ(2S) suppression

ALICE, arXiv:1405.3796 [nucl-ex]





[ψ(2S) / J/ψ] is suppressed
in both rapidity regions

difficult to explain with $c\bar{c}$ pair break-up by interaction in CNM

extremely short crossing time in the forward region

other final state effects should be considered

interaction of $c\bar{c}$ pair with the (hot) system created in collision

Constraints from vector bosons on nPDF

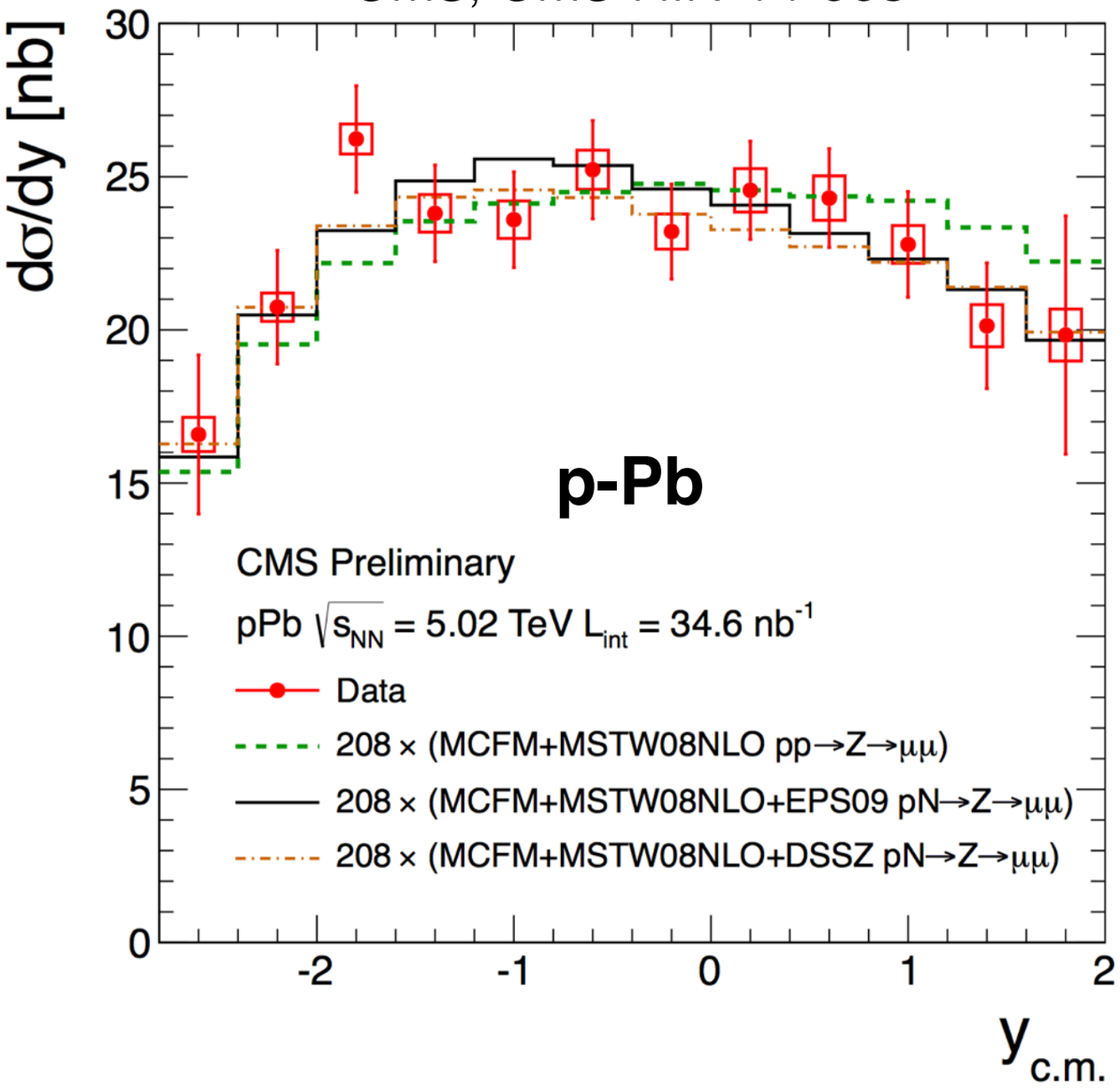
Z^0 production in p-Pb

nPDFs in (Q^2, x) phase-space region never studied before

high Q^2 (M_Z^2)

low x ($10^{-3} \div 10^{-1}$) in CMS acceptance

CMS, CMS-HIN-14-003



σ_Z versus rapidity

sensitive to parton content of interacting nucleons

symmetric in pp collisions, modified by nuclear effects

quantified by forward-backward ratio

$$R_{\mathrm{FB}}(y) = \frac{d\sigma(+y)/dy}{d\sigma(-y)/dy}$$

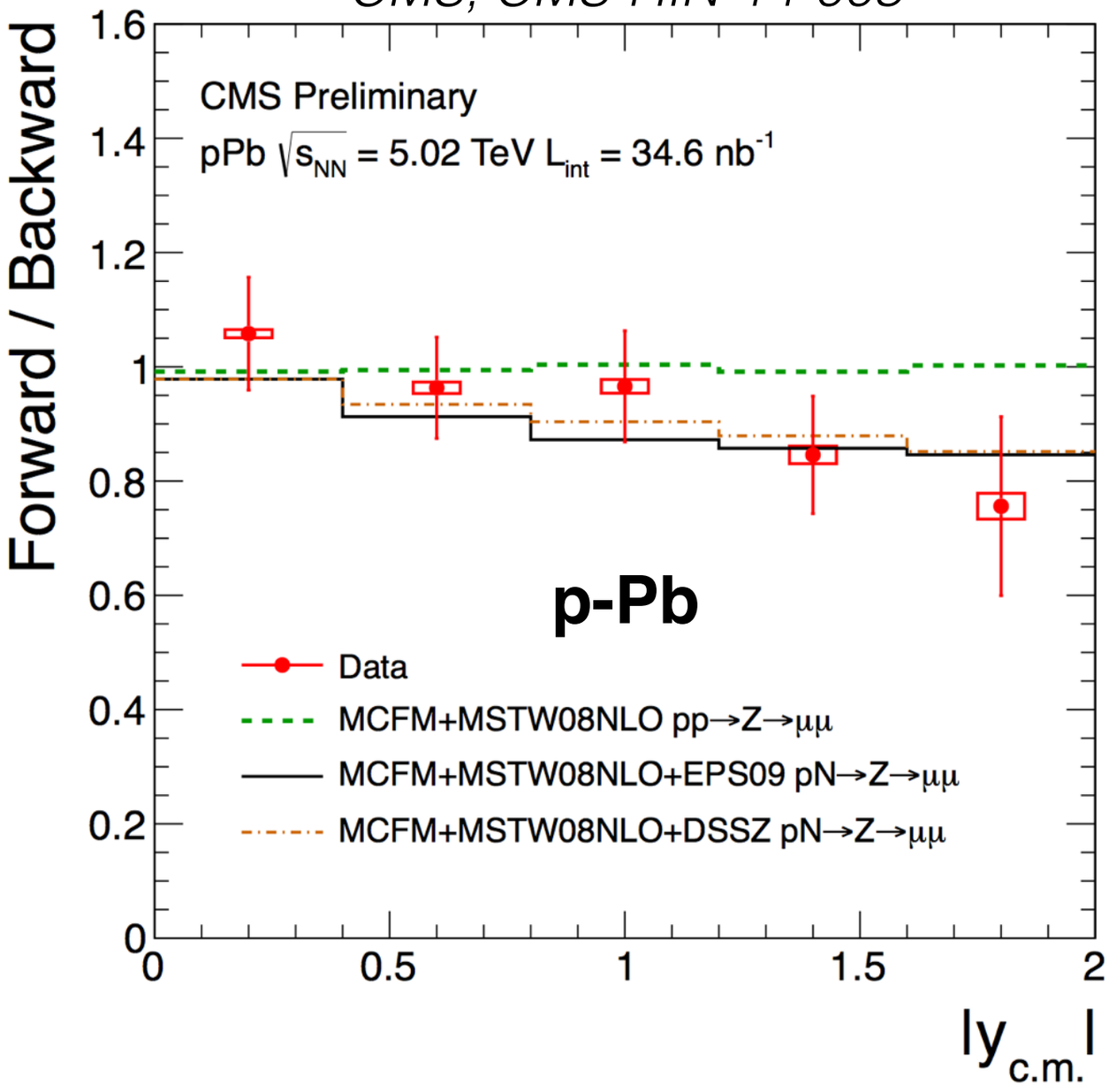
Z^0 production in p-Pb

nPDFs in (Q^2, x) phase-space region never studied before

high Q^2 (M_Z^2)

low x ($10^{-3} \div 10^{-1}$) in CMS acceptance

CMS, CMS-HIN-14-003



σ_Z versus rapidity

sensitive to parton content of interacting nucleons

symmetric in pp collisions, modified by nuclear effects

quantified by forward-backward ratio

hint of F/B asymmetry

large statistical uncertainties

not able to distinguish between different nuclear PDFs

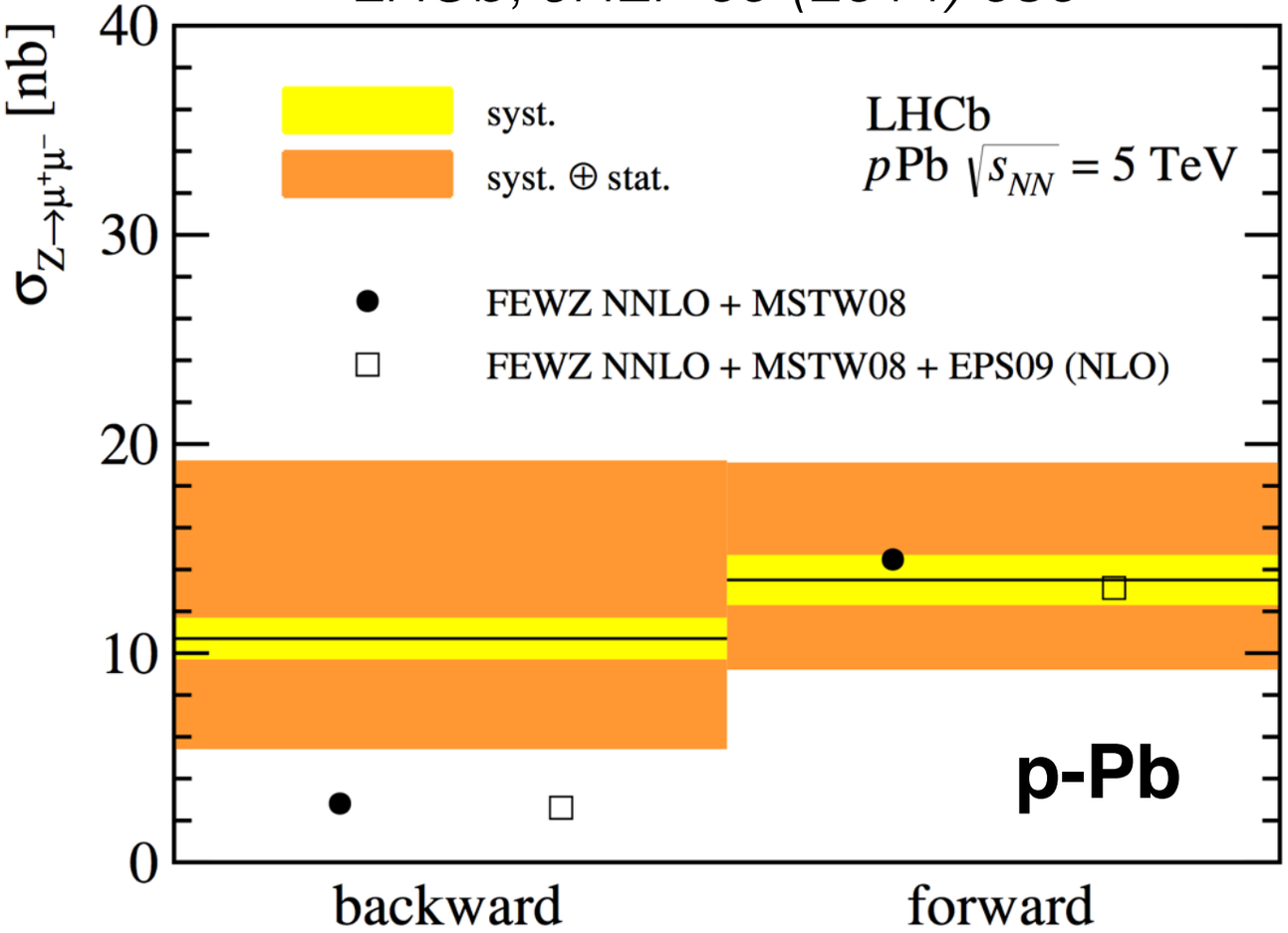
Z^0 production in p-Pb

nPDFs in (Q^2, x) phase-space region never studied before

high Q^2 (M_Z^2)

very low x ($2 \times 10^{-4} \div 3 \times 10^{-3}$) and **very high x** ($0.2 \div 1.0$) in LHCb

LHCb, JHEP 09 (2014) 030



large statistical uncertainties

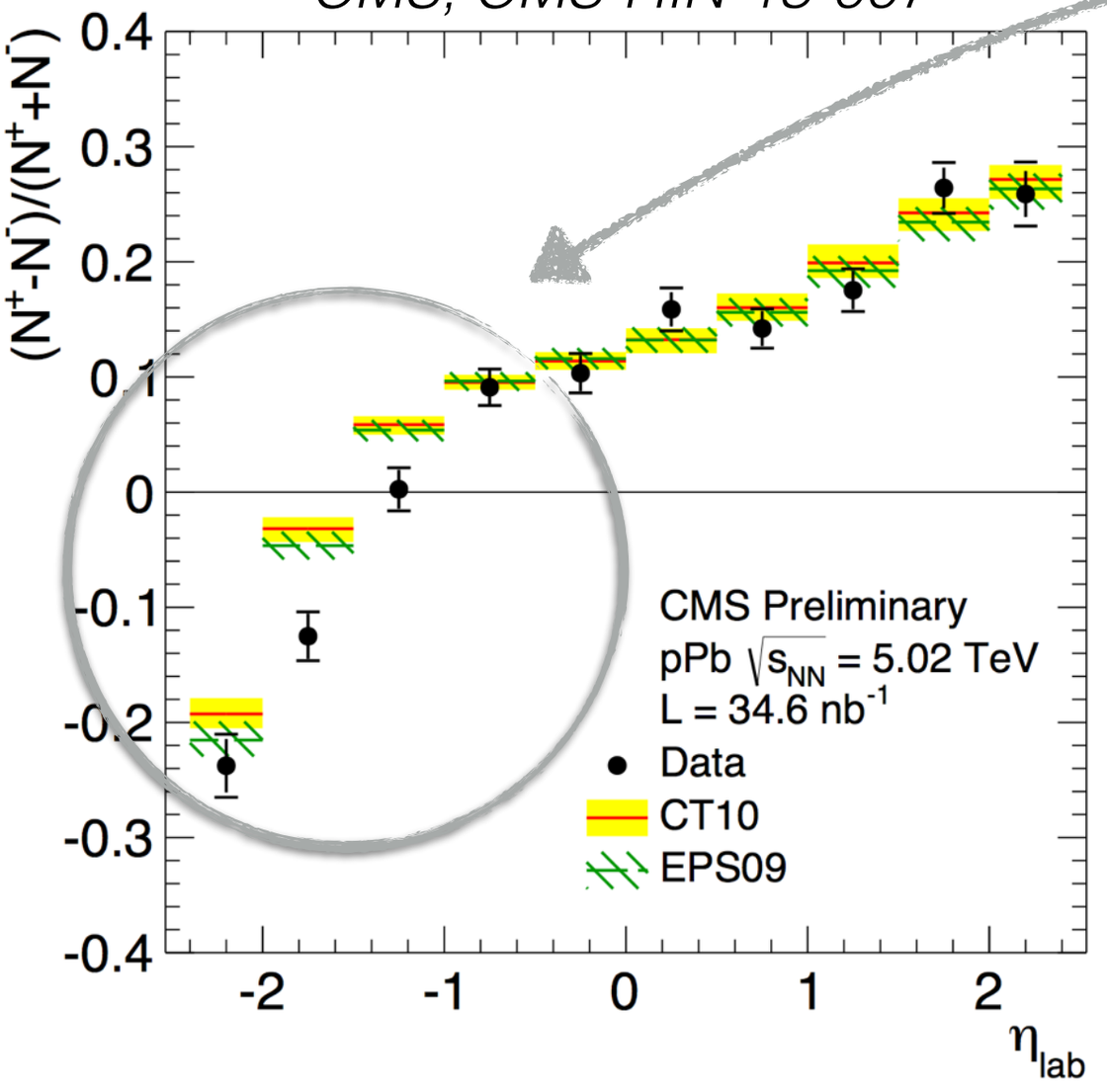
precision not enough to make any conclusions about nuclear effects

these measurements provide important constraints for nPDF fits

W± production in p-Pb

W charge asymmetry
sensitive probe of the **d/*u* quark PDF ratio**

CMS, CMS-HIN-13-007



models deviate from data
Pb-fragmentation region
probes quark densities in nucleus

hint of different *u*/*d* modification

most nPDF fits assume same modification for *u* and *d* (isospin)

u and *d* PDFs in free proton are different, therefore
they can be modified differently in nucleus

Other topics I did not discuss

- collision **centrality**
- **jets** and their modification
- **strangeness** and light-**nuclei** production
- open **heavy-flavour** observables
- exclusive vector-meson **photo-production**
- … and many more

Summary

no indication of quenching of high-p_T hadrons and jets

the strong suppression in A-A is a final state hot matter effect
however, unexplained enhancement seen by CMS and ATLAS

bulk production shows A-A features and collectivity

non-zero elliptic flow from multi-particle correlations (v_2 is true)
mass-dependence of p_T spectra and v_2

suppression of quarkonia ground states

in line with shadowing / initial-state E-loss expectations
data do not support saturation

suppression of quarkonia excited states

evidence for exotic final state $c\bar{c}$ pair break-up

vector boson production

significant constraints for nPDF fits