Recent results from p/dA collisions at RHIC and LHC

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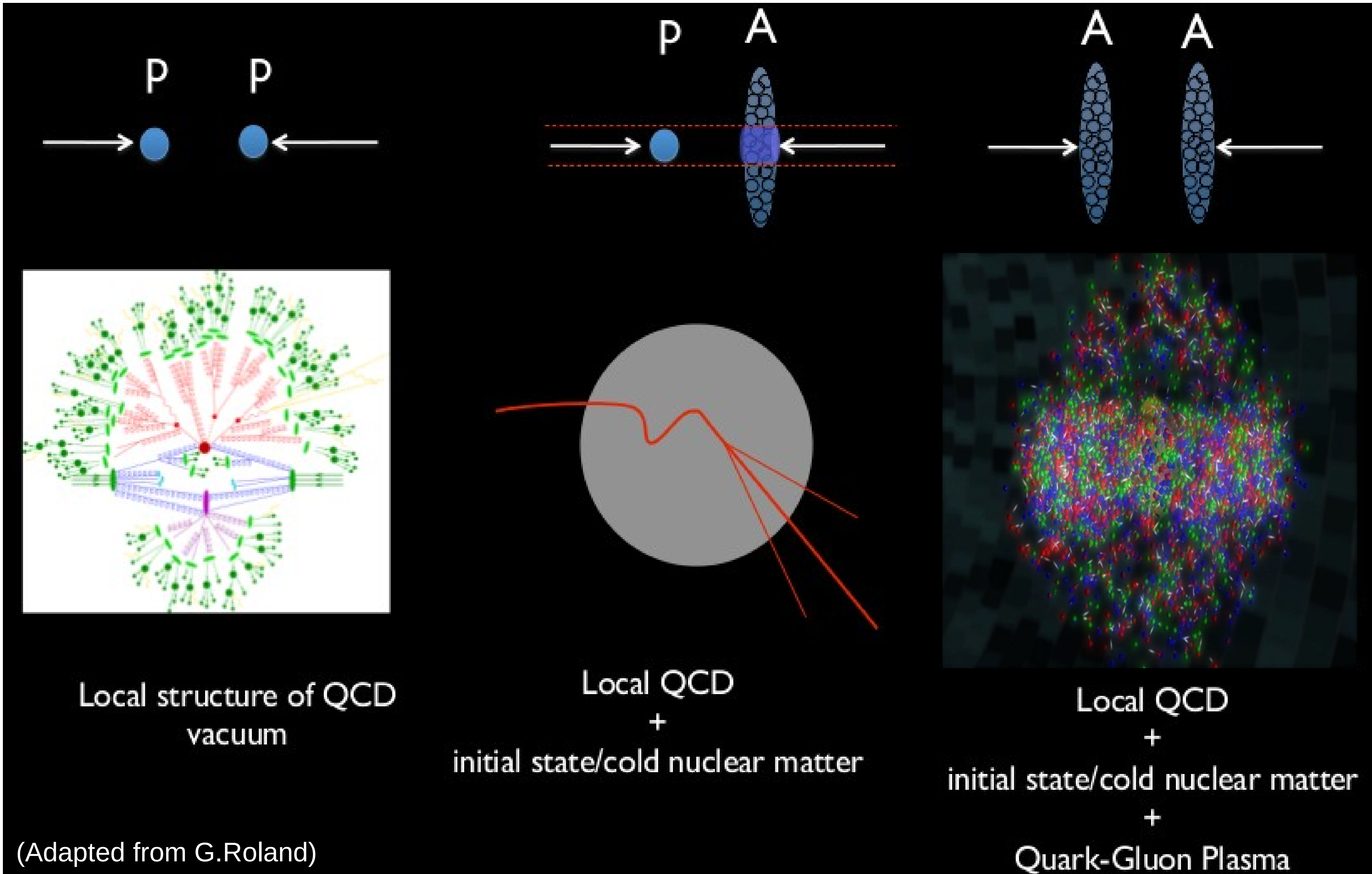
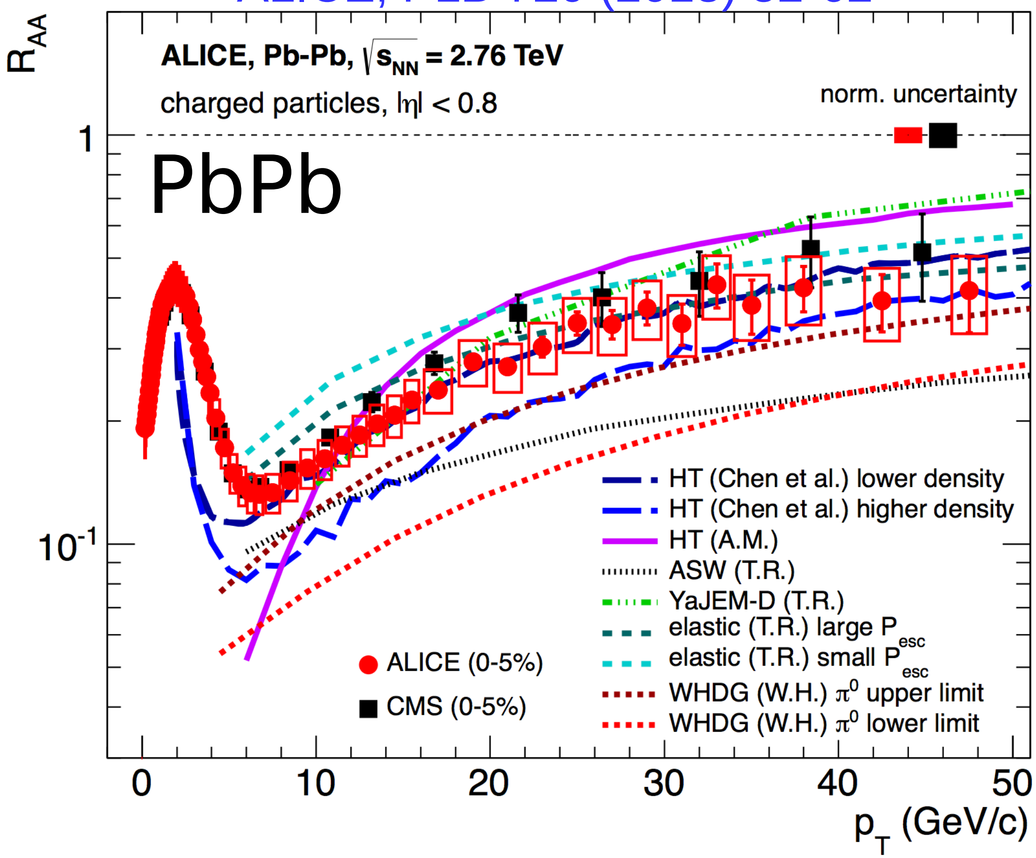
Reminder: Scientific approach



Nuclear modification factor

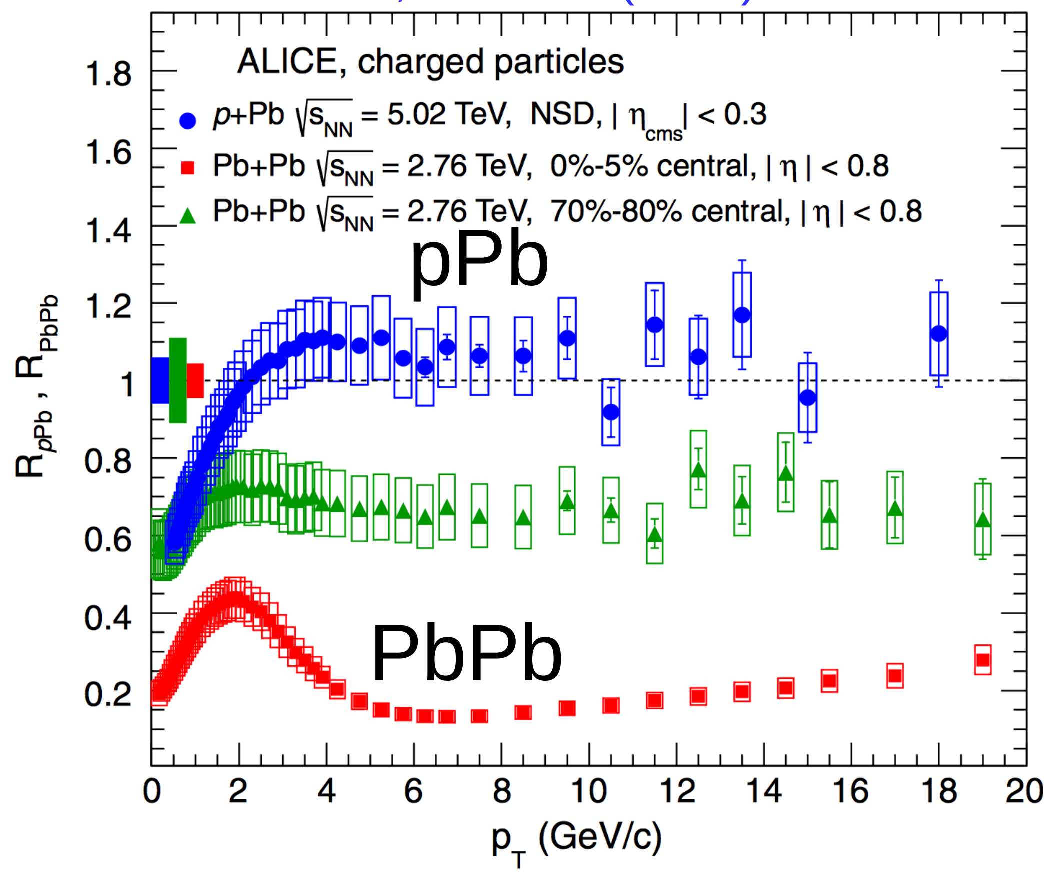
$$R_{\mathrm{AB}} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}\,\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

ALICE, PLB 720 (2013) 52-62



Charged particle spectra strongly modified in PbPb collisions

ALICE, PRL 110 (2013) 082302



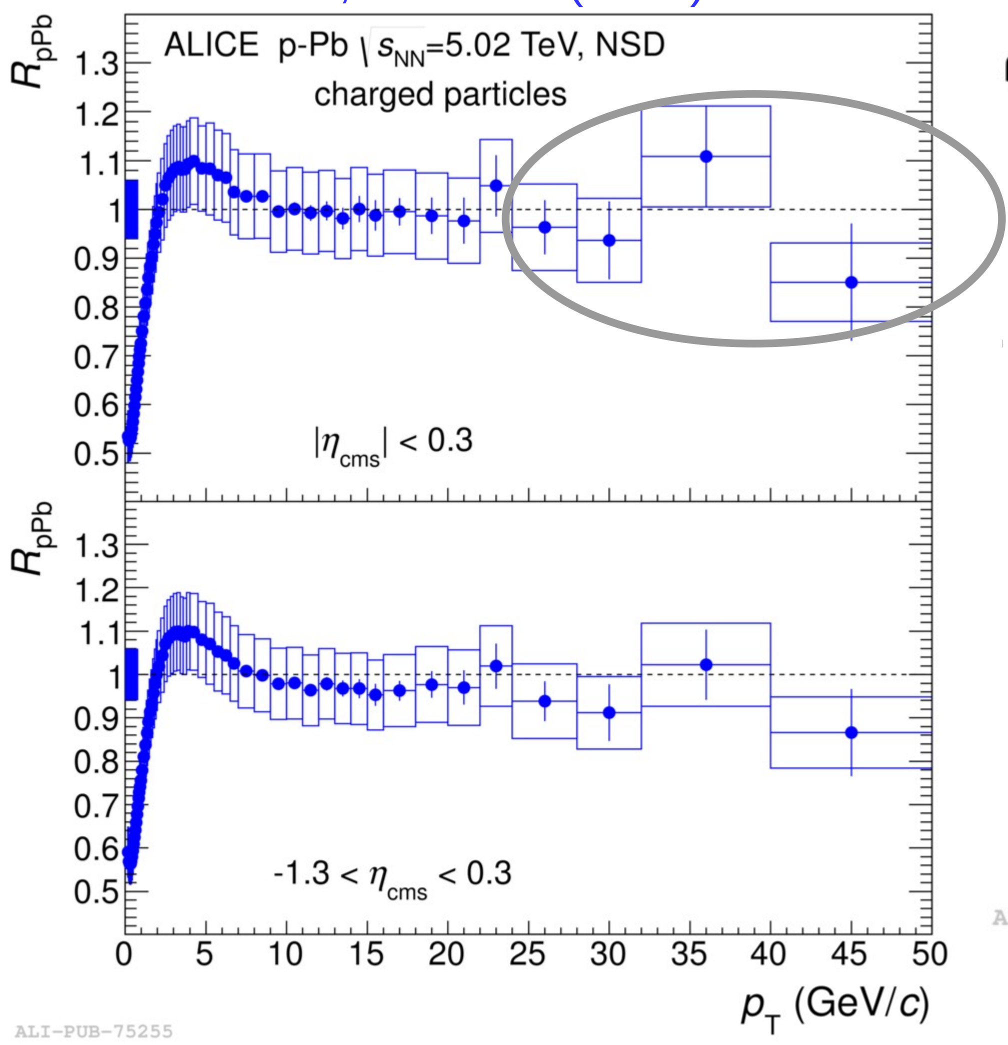
The pPb data confirm that the effect in PbPb is from the FS

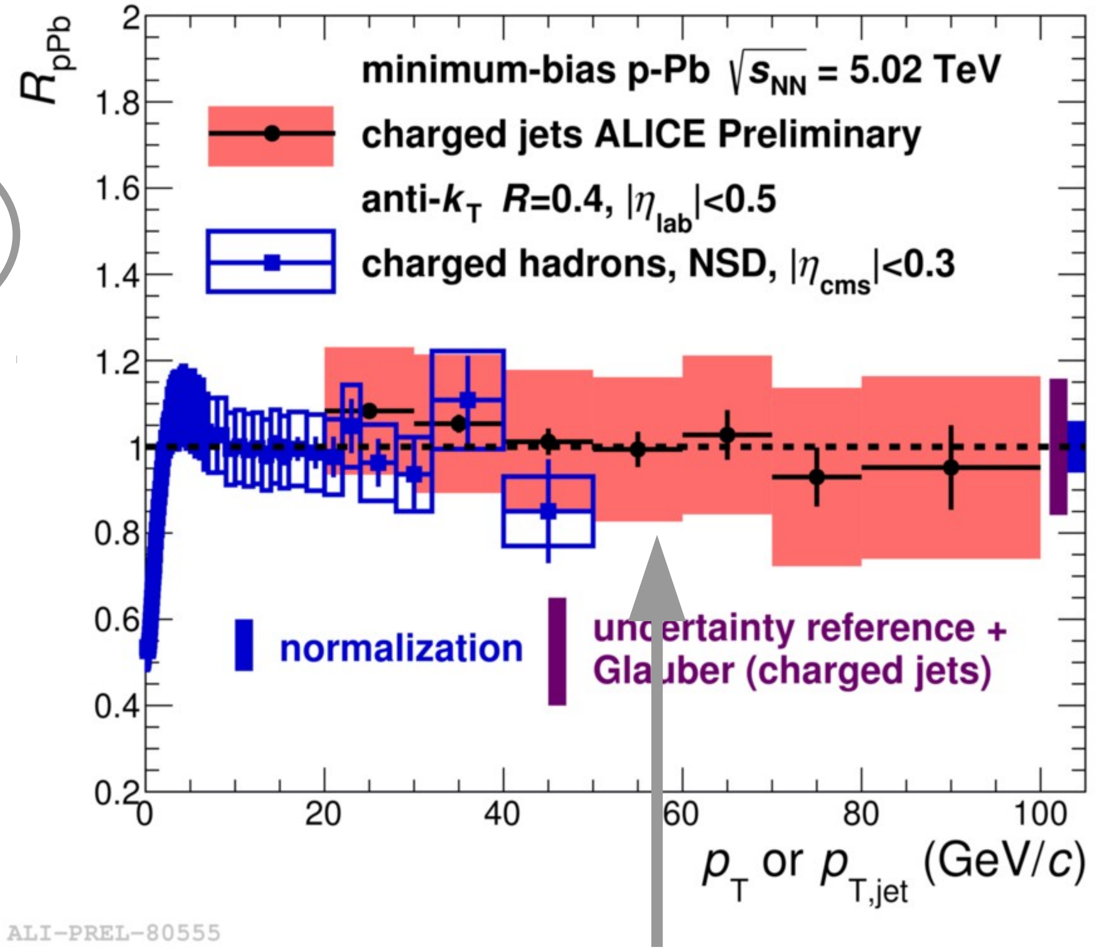
Nuclear modification factor

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{pPb}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}\,\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

New ALICE data consistent with no modification up to p_T=50 GeV/c

ALICE, EPJC 74 (2014) 3054





Same conclusion from jets

Nuclear modification factor

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{pPb}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}\,\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

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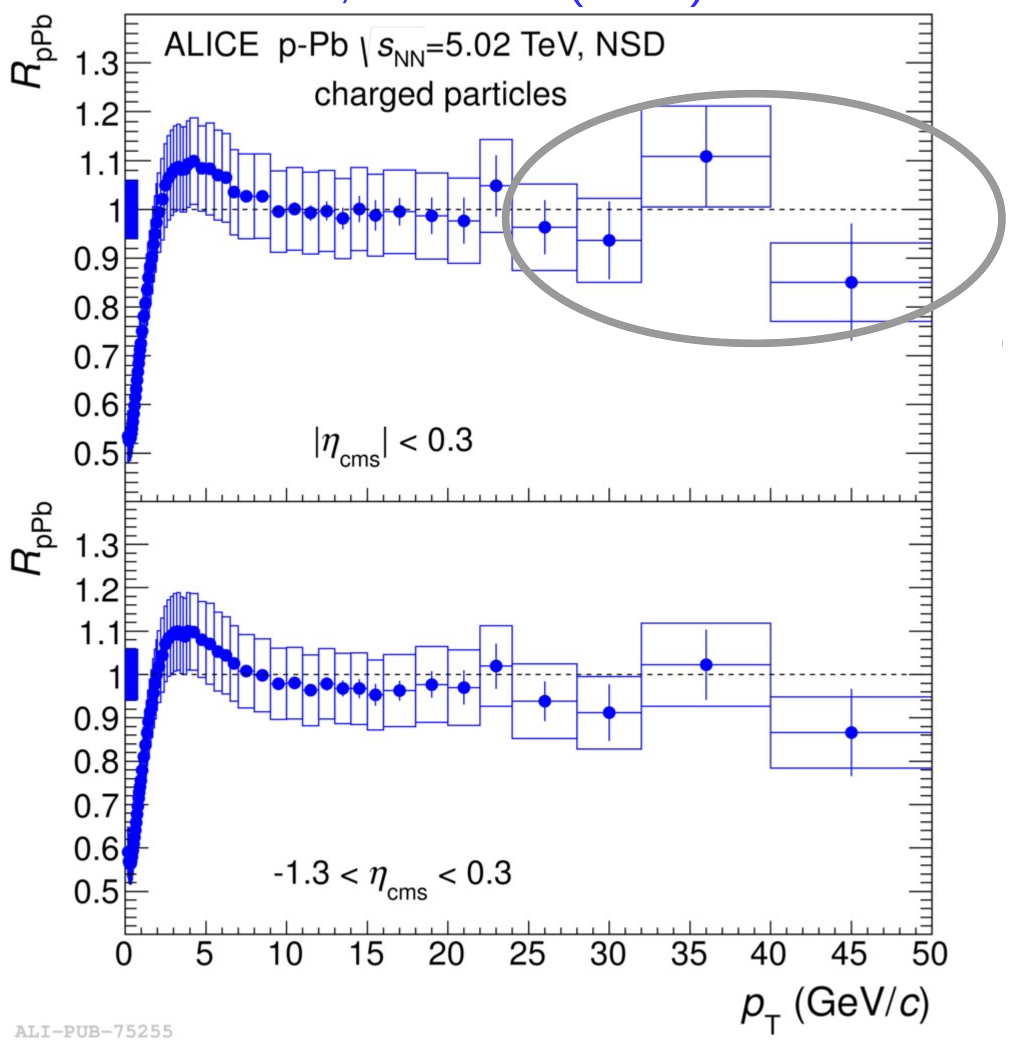
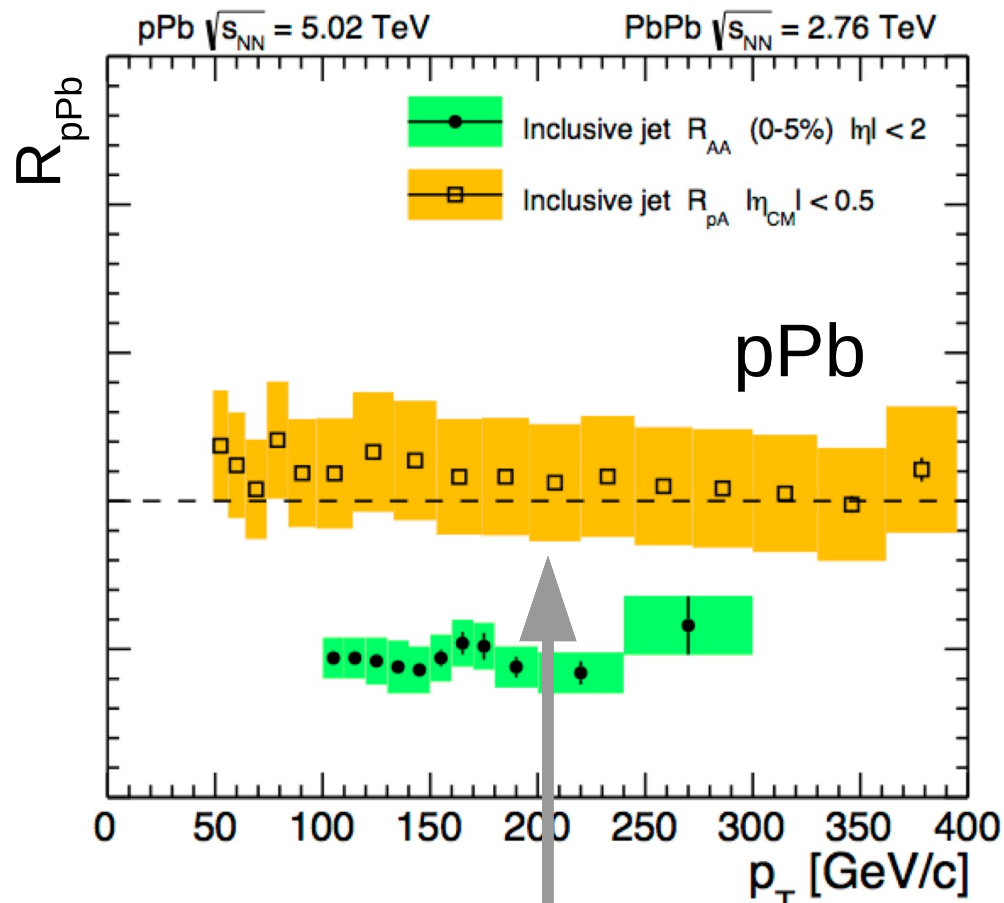


CMS-PAS-HIN-14-001



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Nuclear modification factor

$$R_{\rm pPb} = \frac{{\rm d}N_{pPb}/{\rm d}p_{\rm T}}{N_{\rm coll}\,{\rm d}N_{pp}/{\rm d}p_{\rm T}}$$

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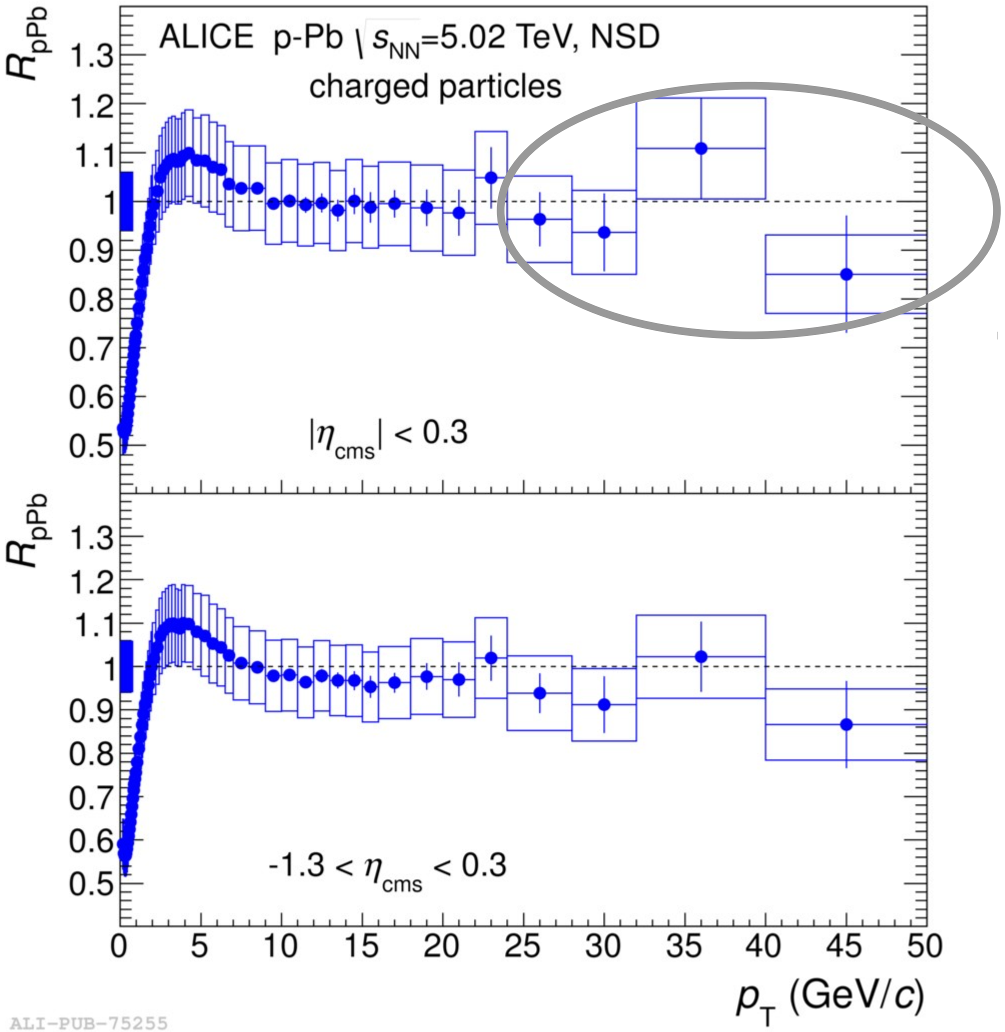
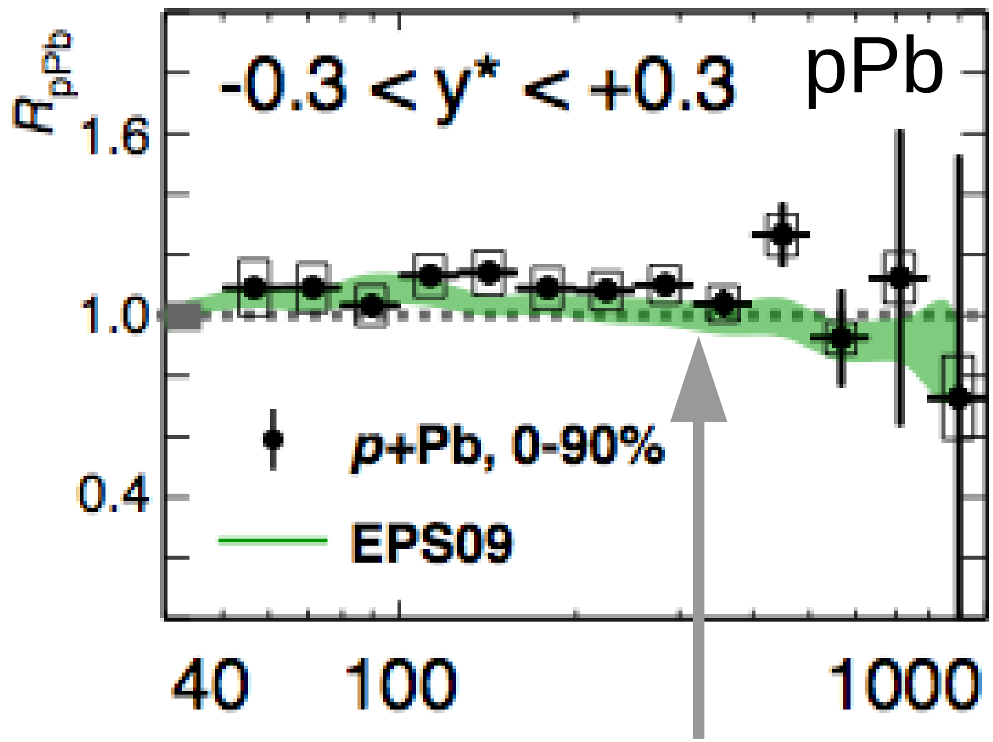
ALICE, EPJC 74 (2014) 3054



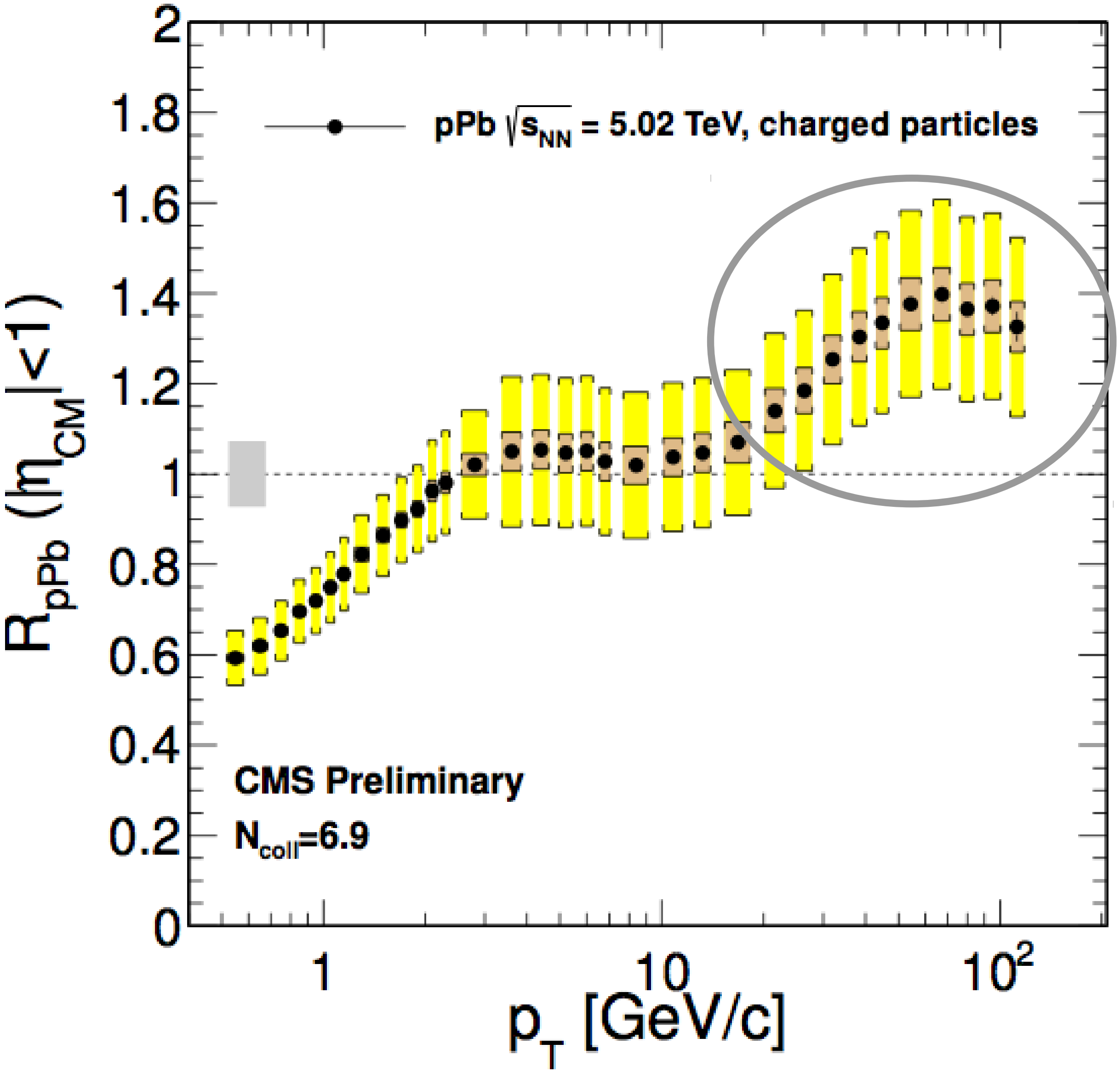
ATLAS-CONF-2014-024



Same conclusion from jets

Nuclear modification factor at high p_T

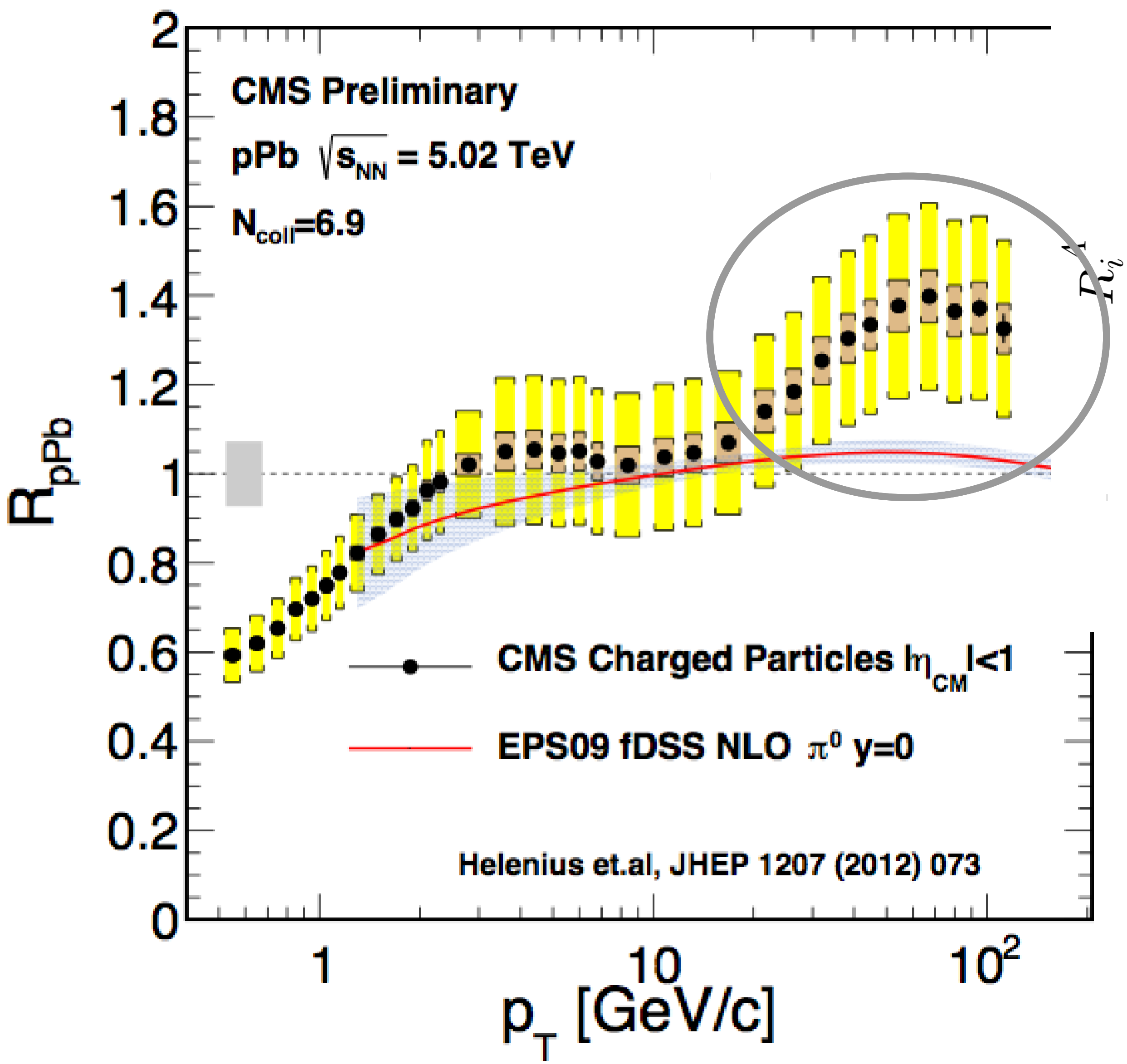
CMS-HIN-12-017



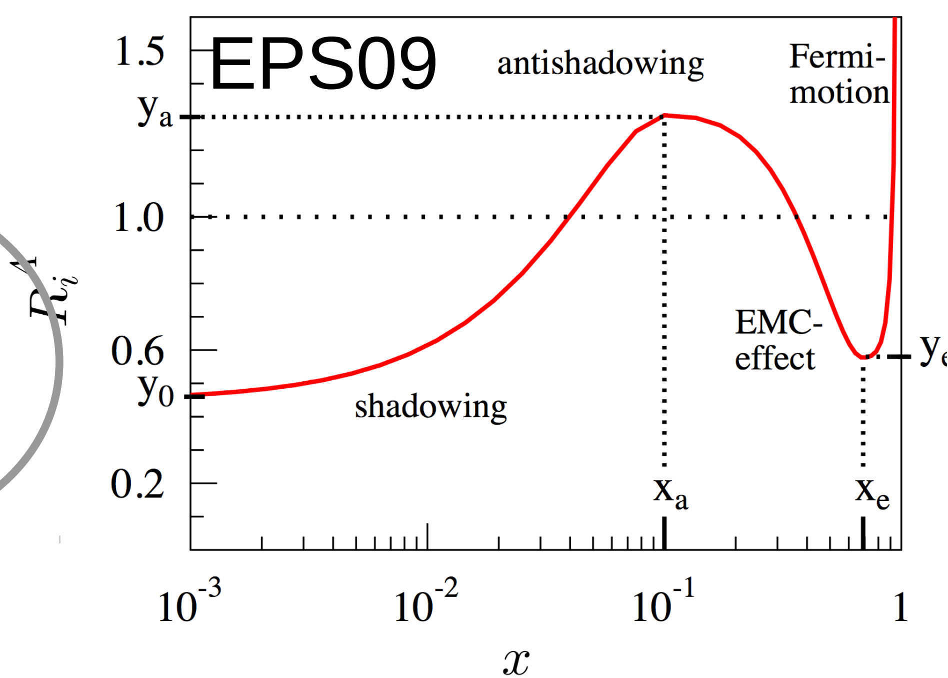
CMS observes a large enhancement at high p_T

Nuclear modification factor at high p_T

CMS-HIN-12-017

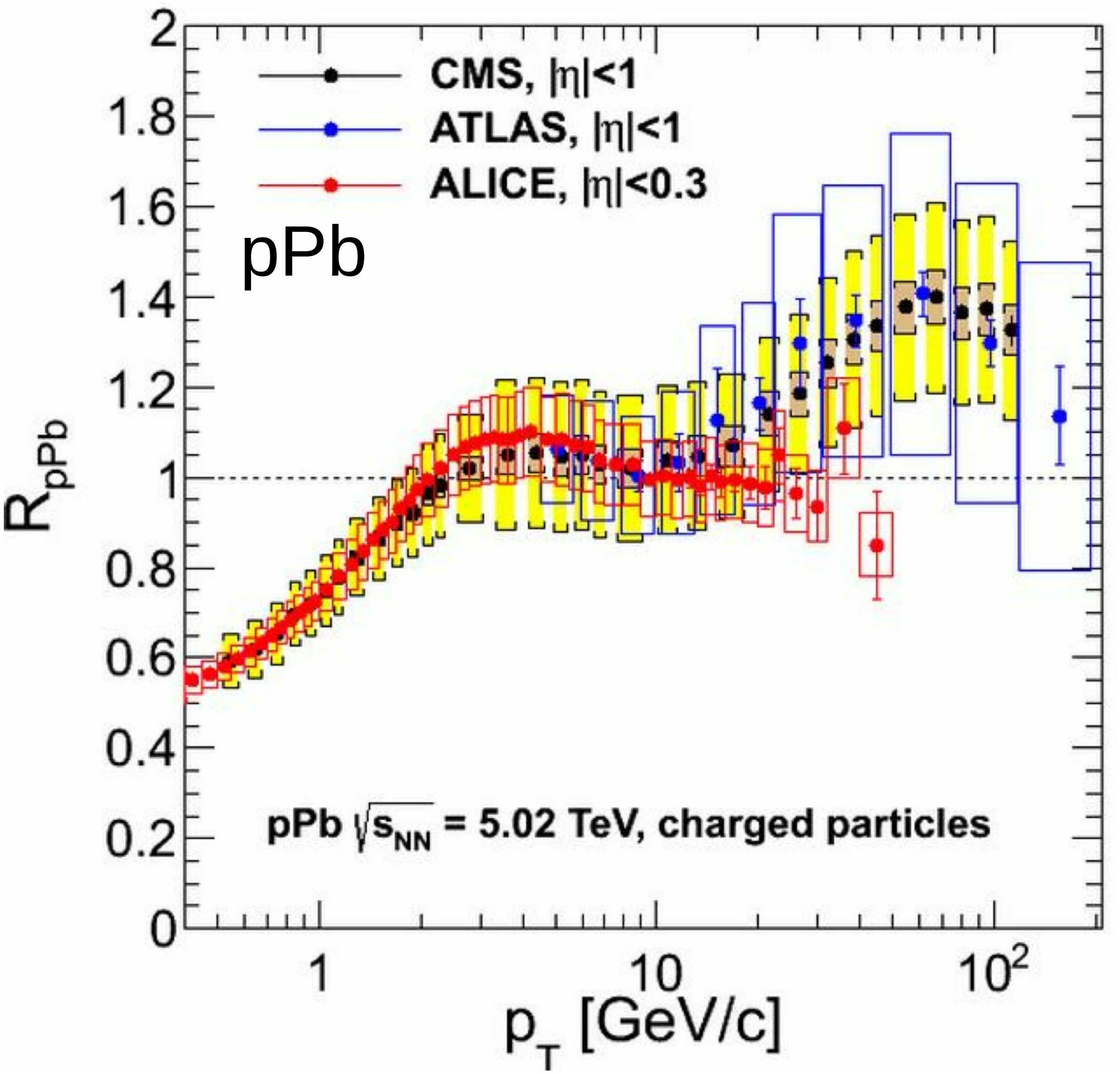


JHEP 04 (2009) 065



CMS charged particle R_{pPb} cannot be described by nPDF:
Anti-shadowing seems not to be large enough

Nuclear modification factor at high p_T

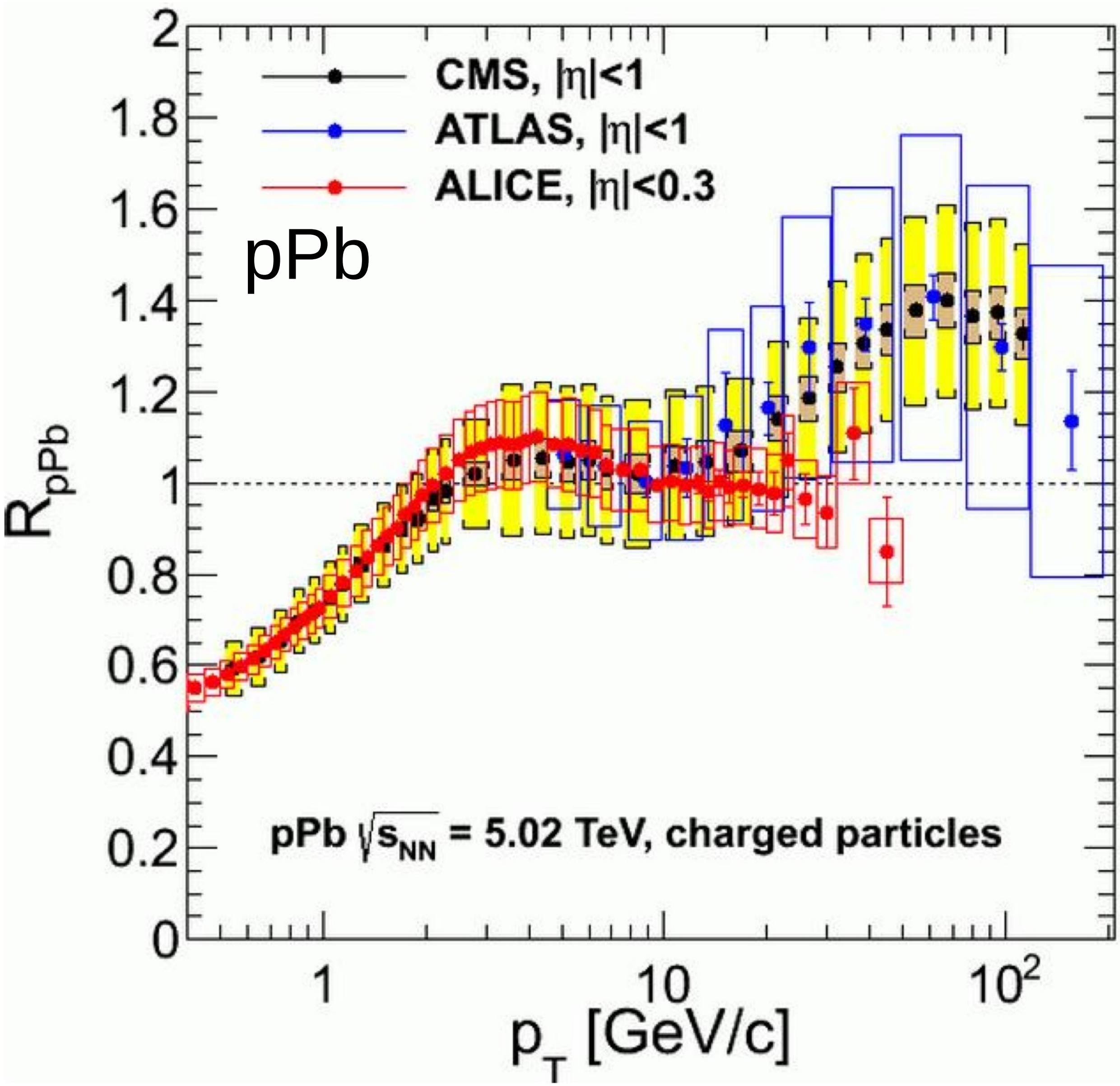


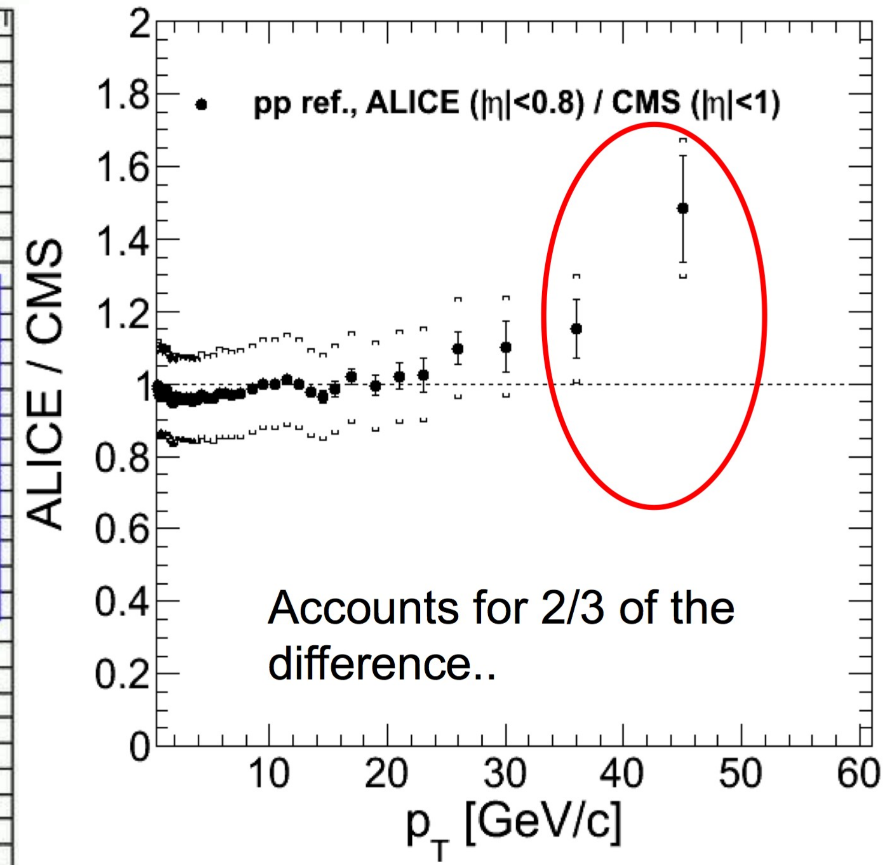
CMS observes a large enhancement at high p_T

Confirmed by ATLAS
ATLAS-CONF-2014-029

Different impression when looking at the ALICE points

Nuclear modification factor at high p_T



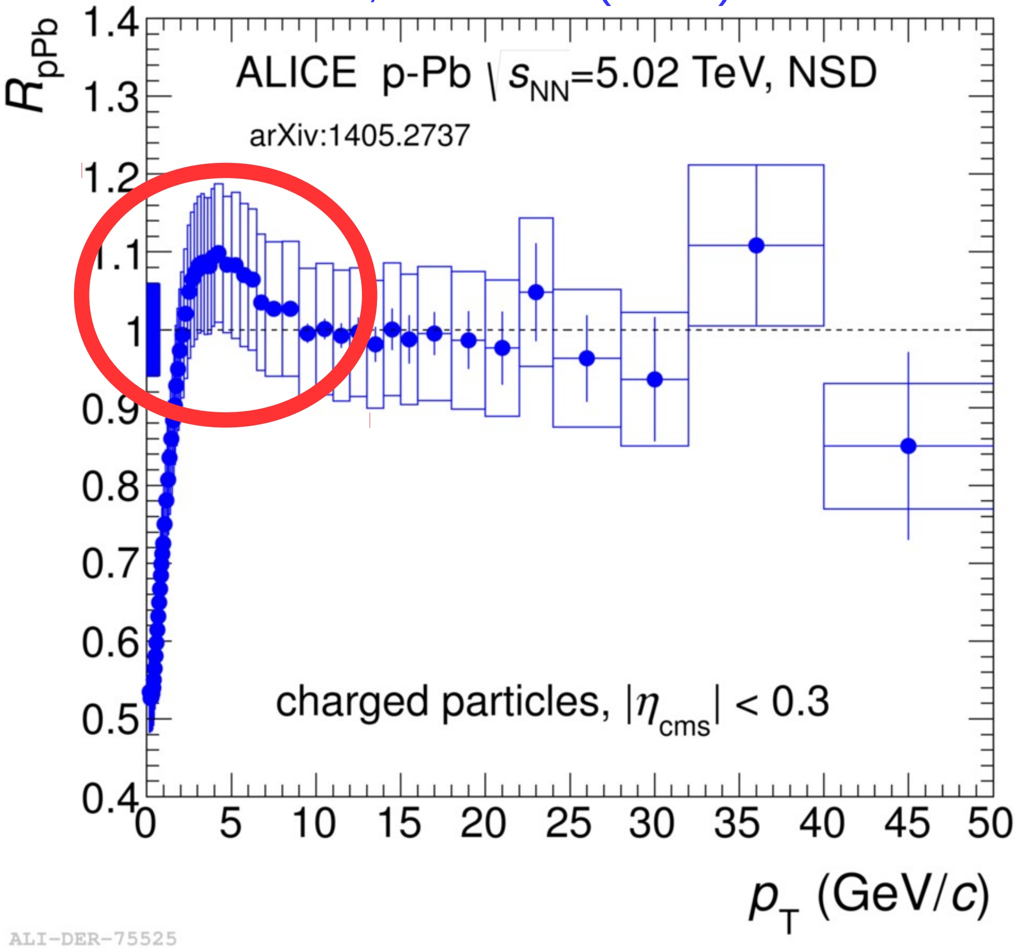


The discrepancy mainly comes from tension in the interpolated pp reference

Nuclear modification factor

$$R_{\rm pPb} = \frac{{\rm d}N_{pPb}/{\rm d}p_{\rm T}}{N_{\rm coll}\,{\rm d}N_{pp}/{\rm d}p_{\rm T}}$$

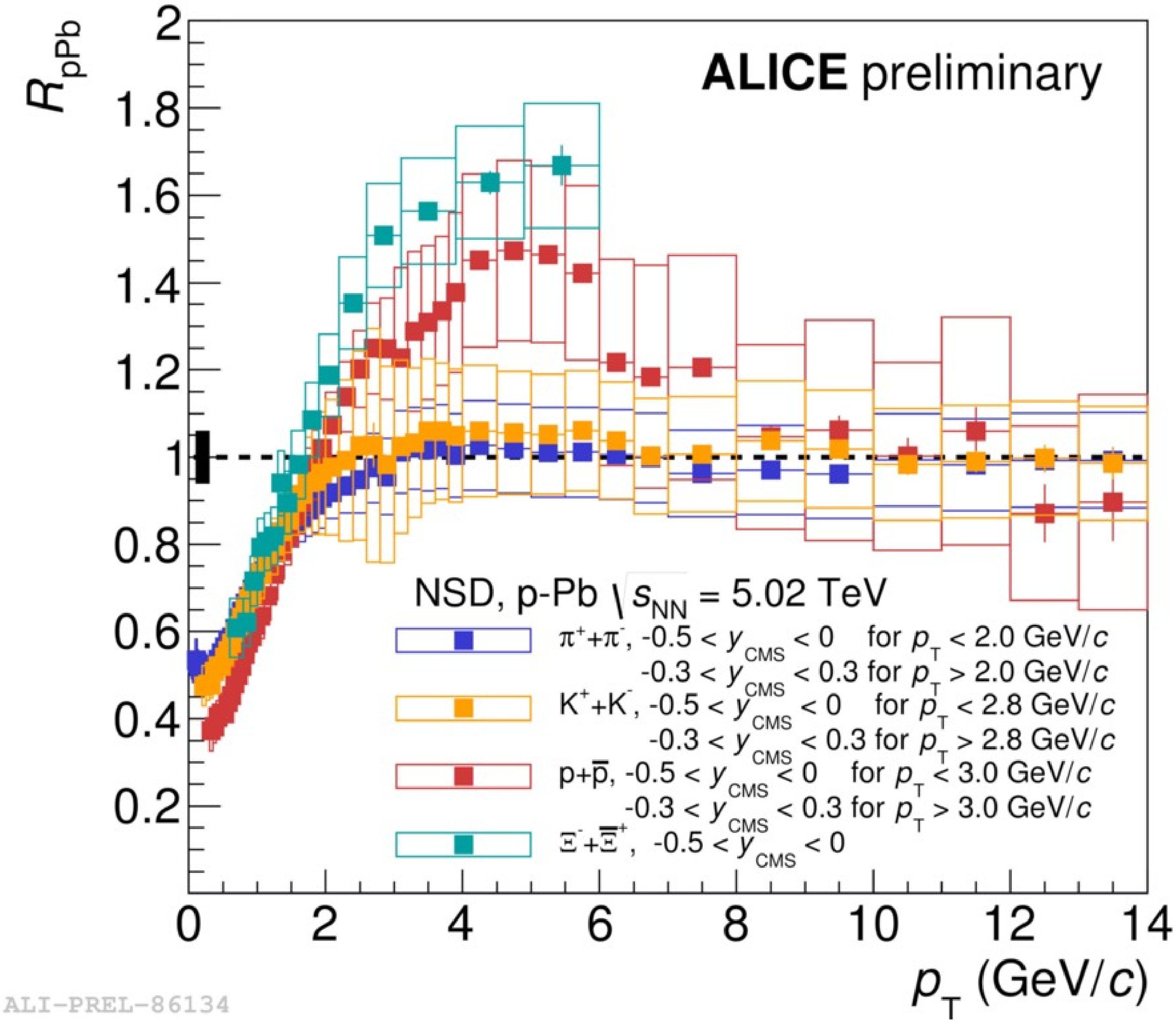
ALICE, EPJC 74 (2014) 3054



- "Cronin" enhancement
  - First observed by Cronin in PRD 11 (1975) 3105
- Traditional explanation
  - Multiple soft scatterings in IS prior to hard scatter (arXiv:hep-ph/0212148)

Enhancement at intermediate p_T

Nuclear modification factor

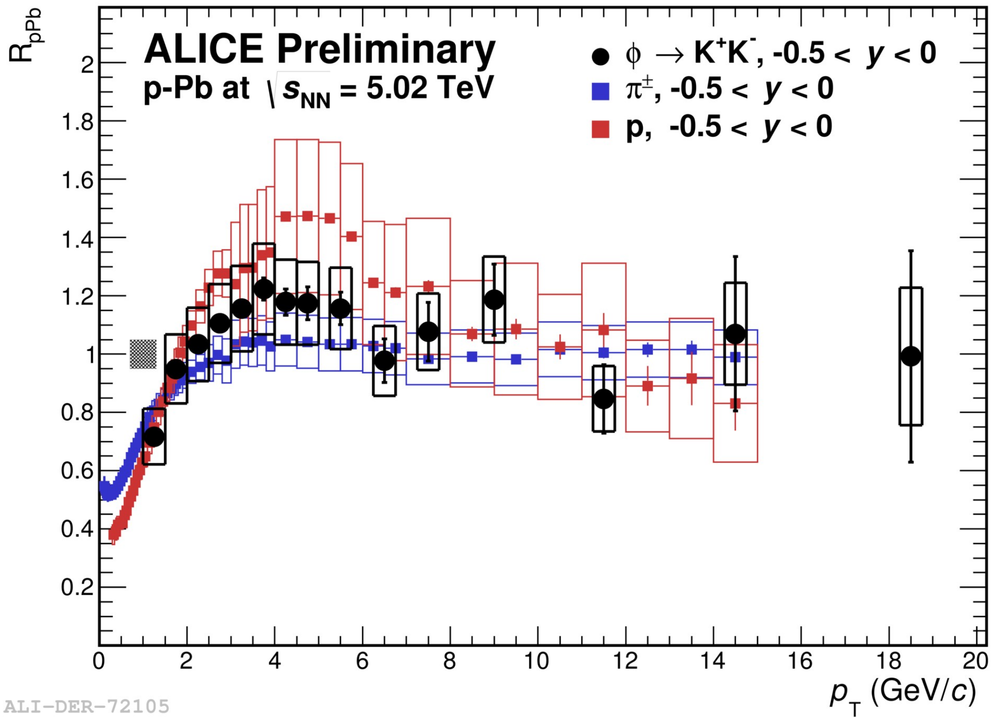


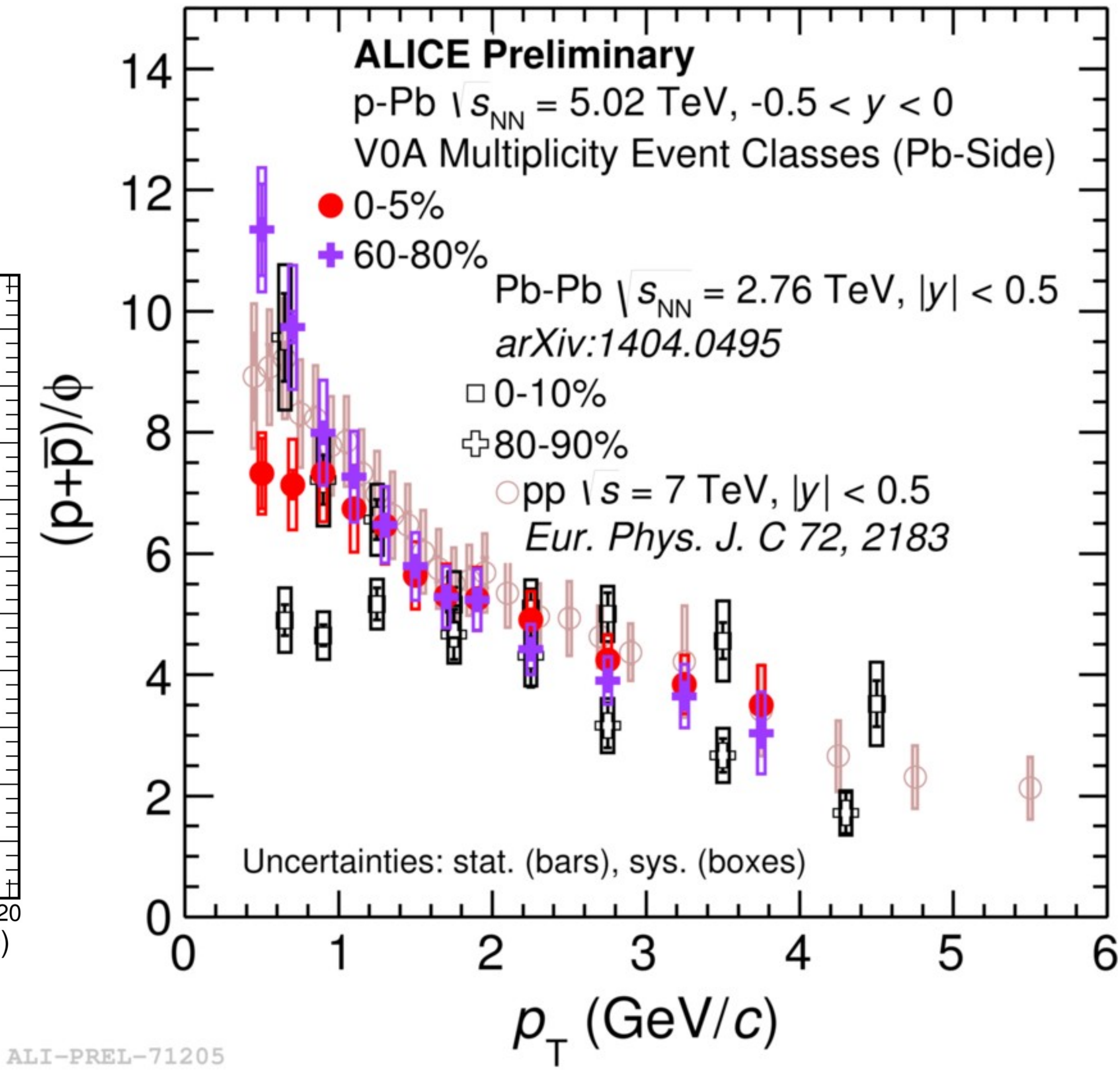
At intermediate p_T (Cronin region):

- Indication of mass ordering
  - No enhancement for pions and kaons
  - Pronounced peak for protons
  - Even stronger for cascades

Particle species dependence points to relevance of final state effects

The Φ meson

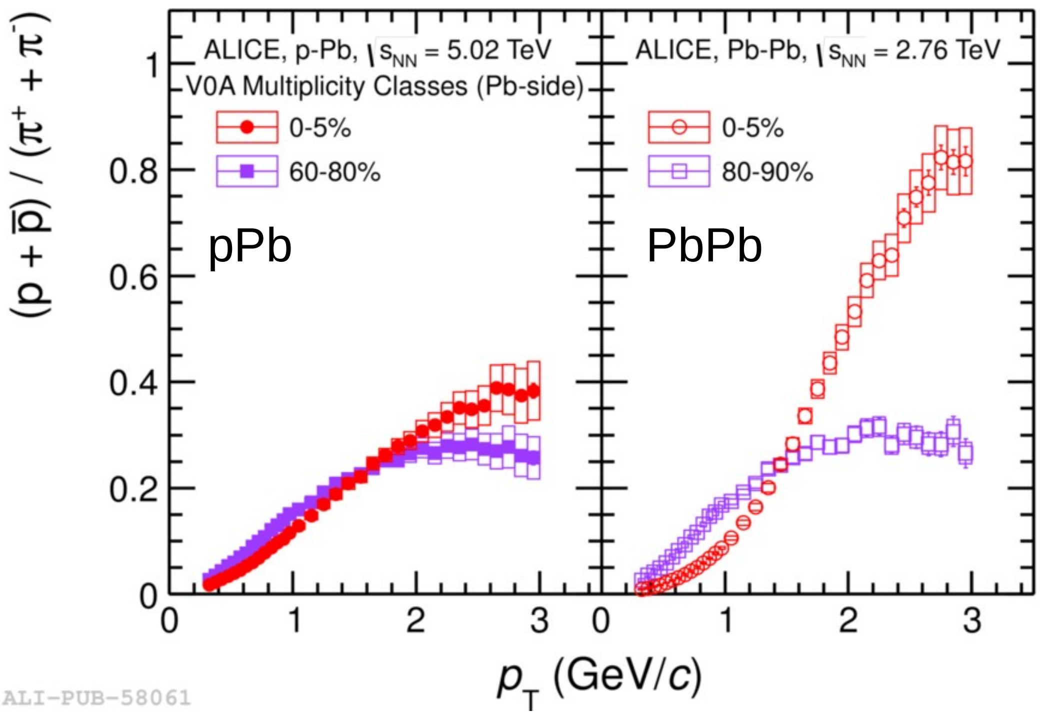




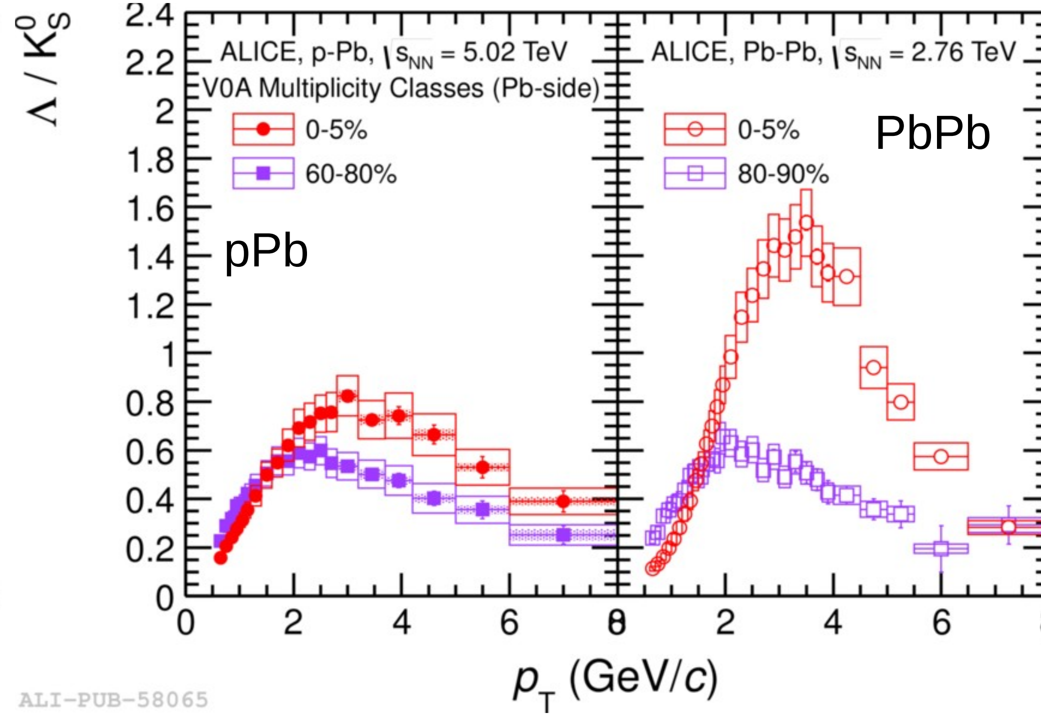
The Φ does not have the same Cronin enhancement as the proton, and also its shape in pPb does not change significantly with multiplicity

Baryon-over-meson enhancement

Proton over pion ratio



Λ over K^0_S ratio

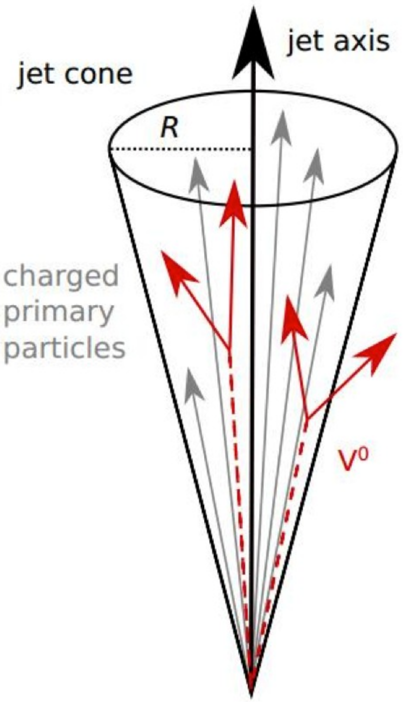


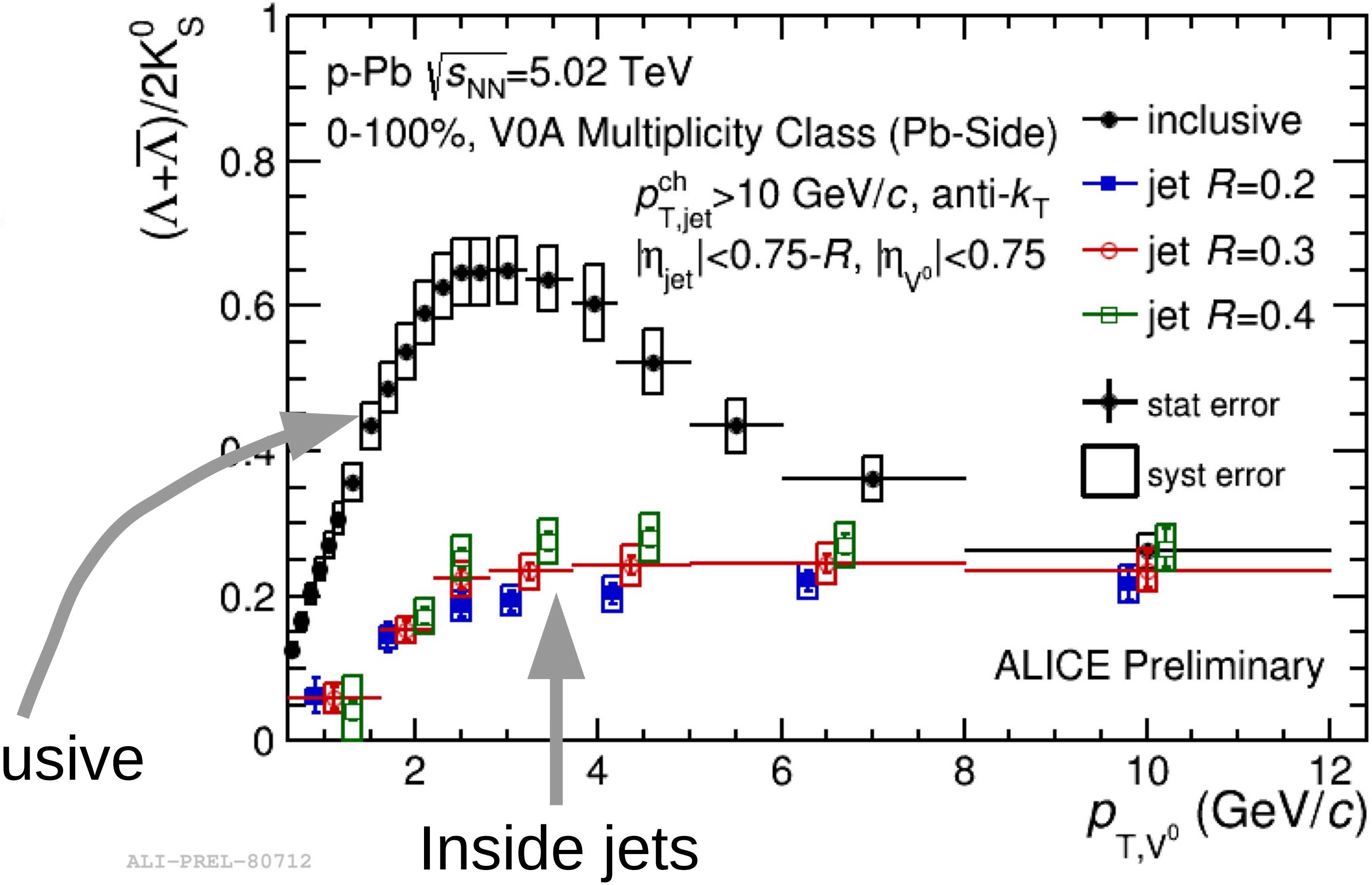
Significant multiplicity dependence of
proton over pion and Λ over K^0_S ratio:
reminiscent of observations in PbPb
(usually attributed to radial flow or recombination)

ALICE, PLB 728 (2014) 25-38

Baryon-over-meson enhancement in-/out-side of jets

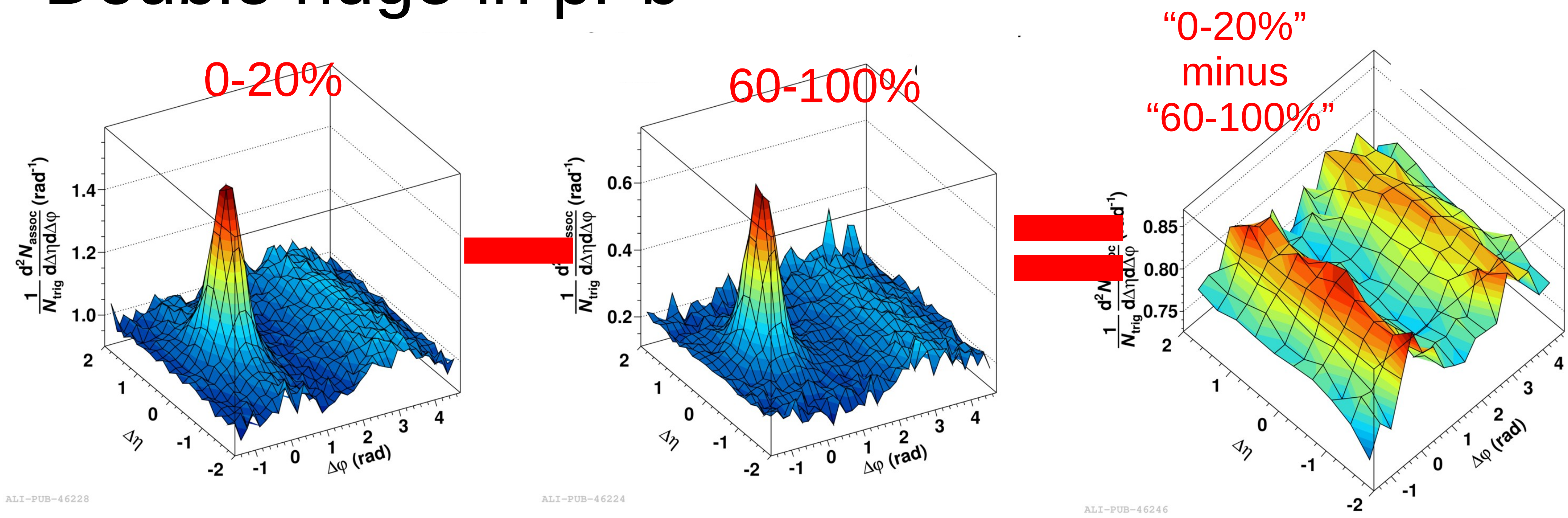
Λ over K^0_S ratio inclusive vs inside jets



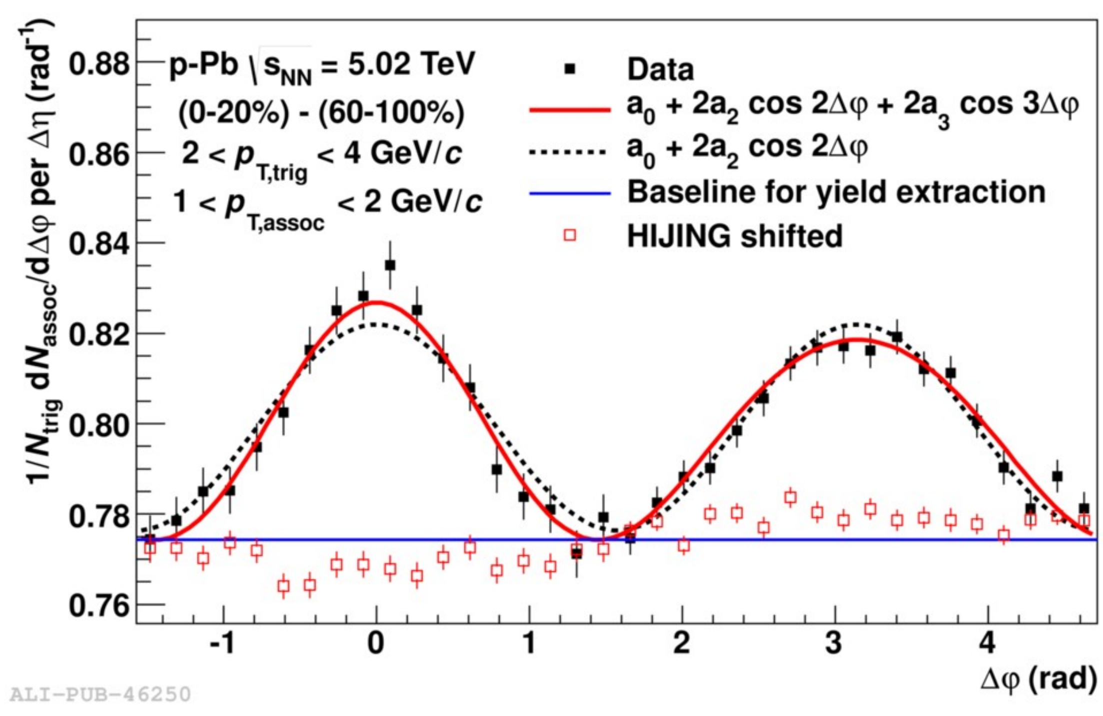


The enhancement is not coming from jets

Double ridge in pPb

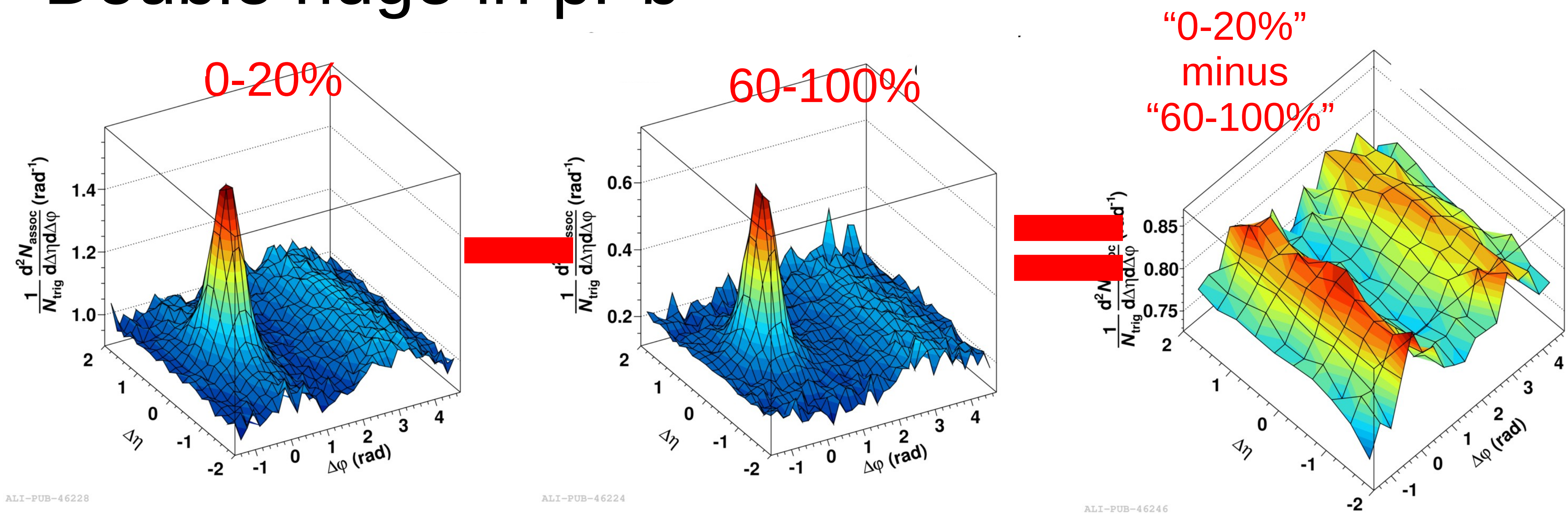


- Reveal double ridge by subtracting per-trigger yield of low from high multiplicity events
- Results looks so much like flow in AA



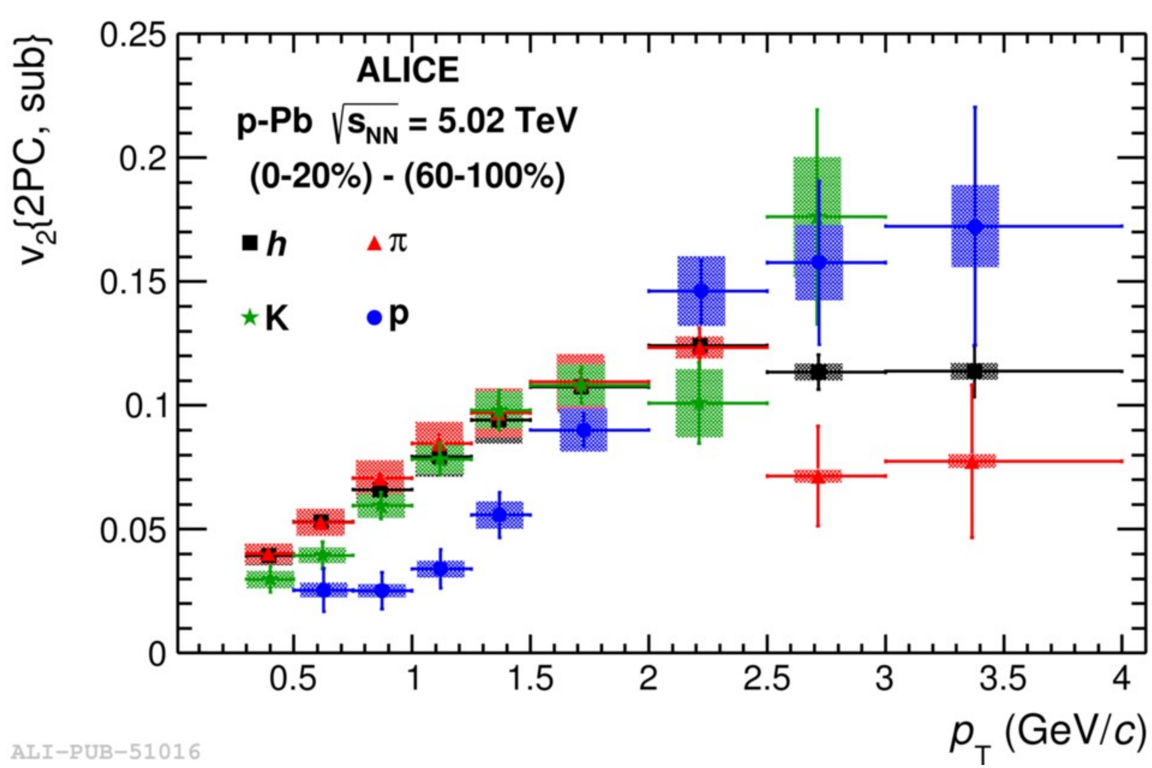
ALICE, PLB 719 (2013) 29

Double ridge in pPb

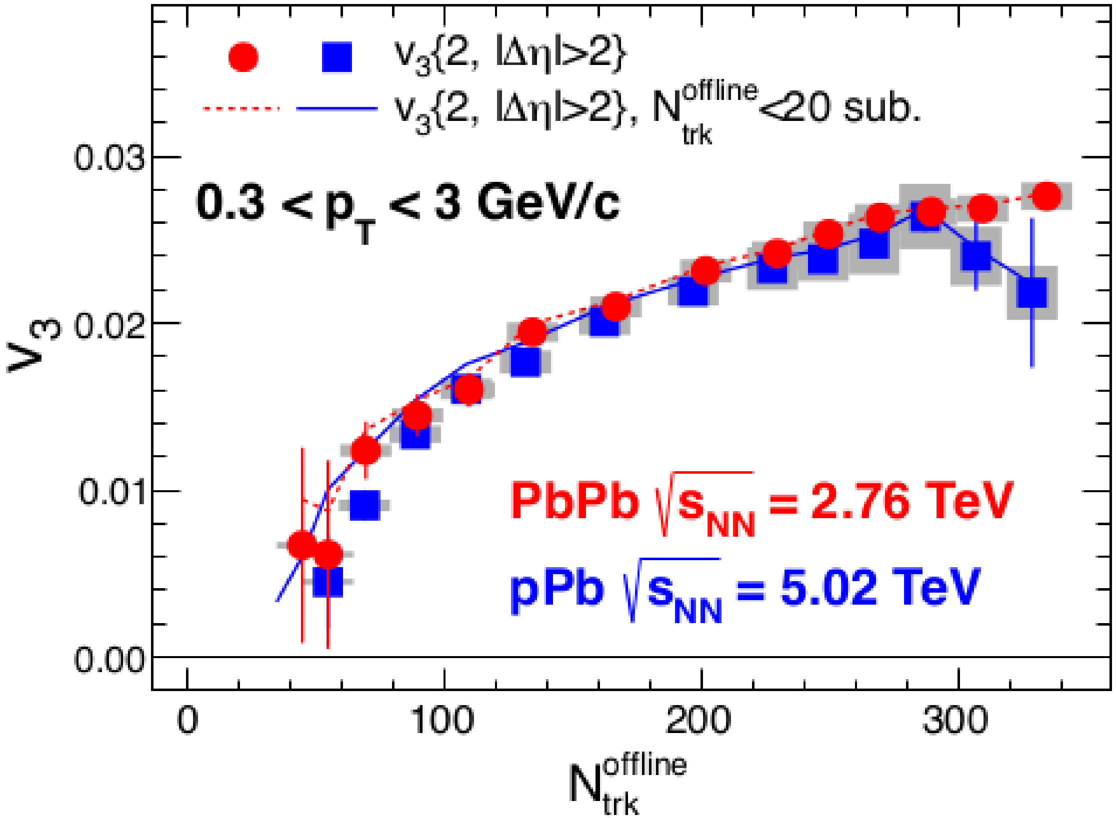


- Reveal double ridge by subtracting per-trigger yield of low from high multiplicity events
- Results looks so much like flow in AA
- Mass ordering and crossing

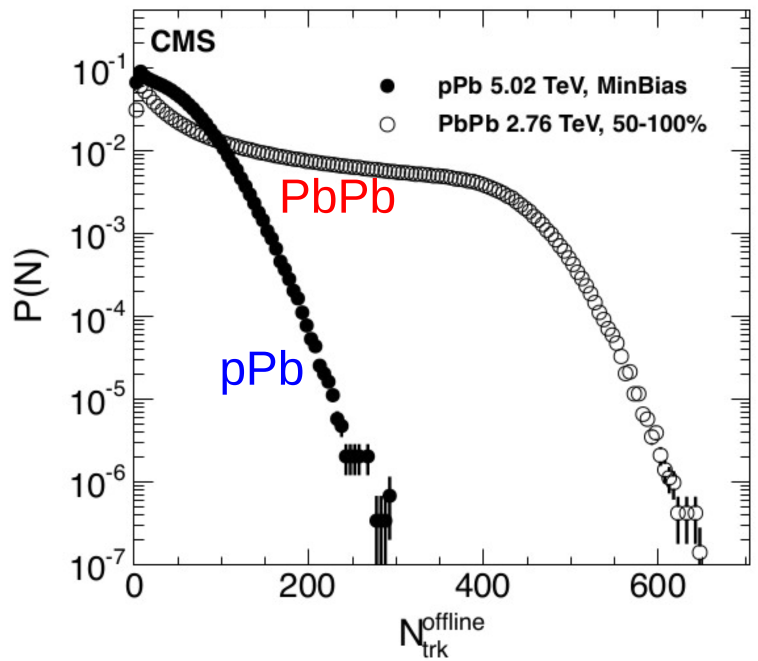
ALICE, PLB 726 (2013) 164



Integrated v_3 in PbPb and pPb



CMS, PLB 724 (2013) 213

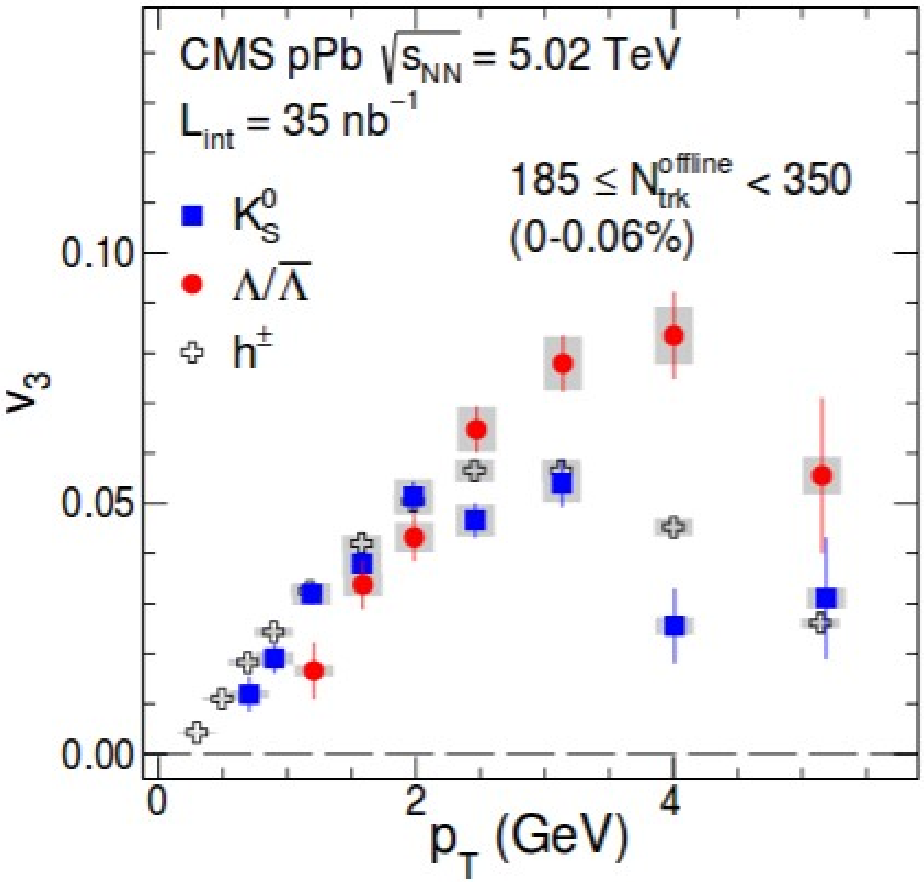


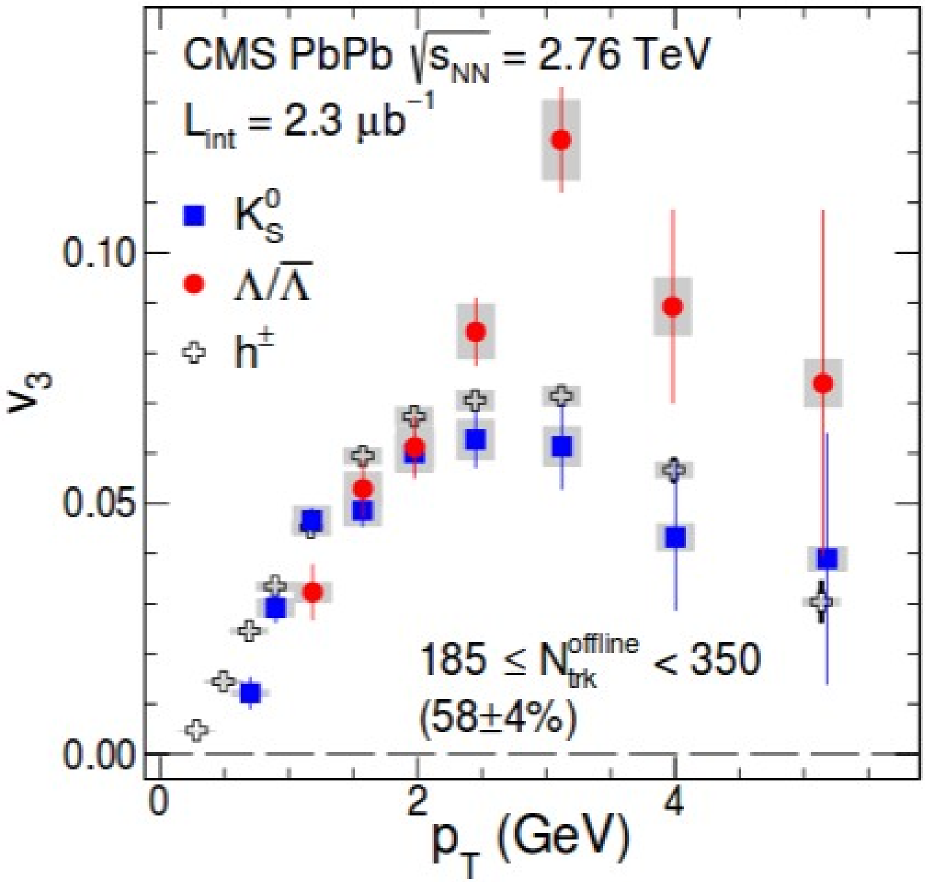
- Same v_3 in pPb as in PbPb
- Turn on at around M=50 tracks (~minbias pPb)
- Established picture in PbPb
  - Transformation of IS fluctuations into FS via interactions

- Same physics mechanism despite different underlying dynamics (+ system size)?
- Maybe we select on events in which the proton wave function fluctuated to large values (fat proton, Mueller, arXiv:1307.5911v2)

Identified particle v_3

PbPb pPb

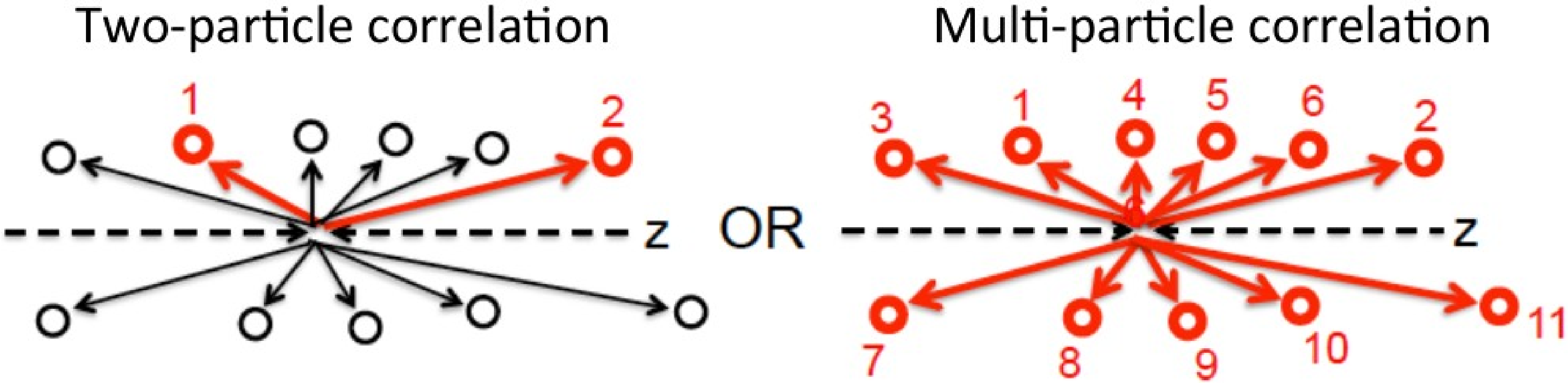




Similar for v_3, crossing at around 2 GeV/c,
points to same physics origin for v_3 in pPb as in PbPb

CMS, arXiv:1409.3392v1

Multi-particle correlations



Multi-particle (>2) cumulants:

$$\langle\langle 6\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\right\rangle$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

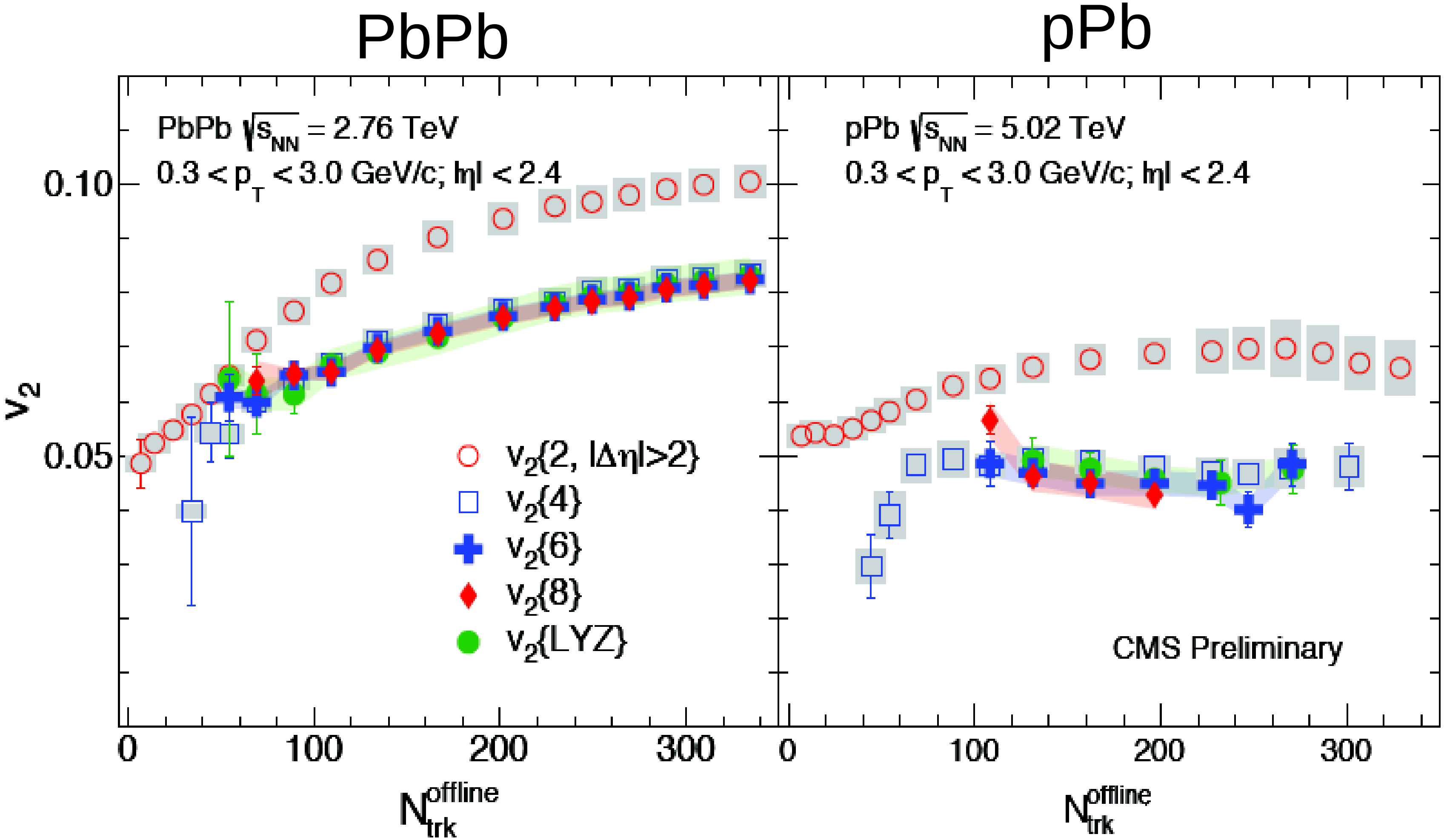
$$v_n\{8\} = \sqrt[4]{-\frac{1}{33}c_n\{8\}}$$

Insensitive to non-flow effect

Q-cumulant, PRC 83 (2011) 044913

In hydrodynamics expect: $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

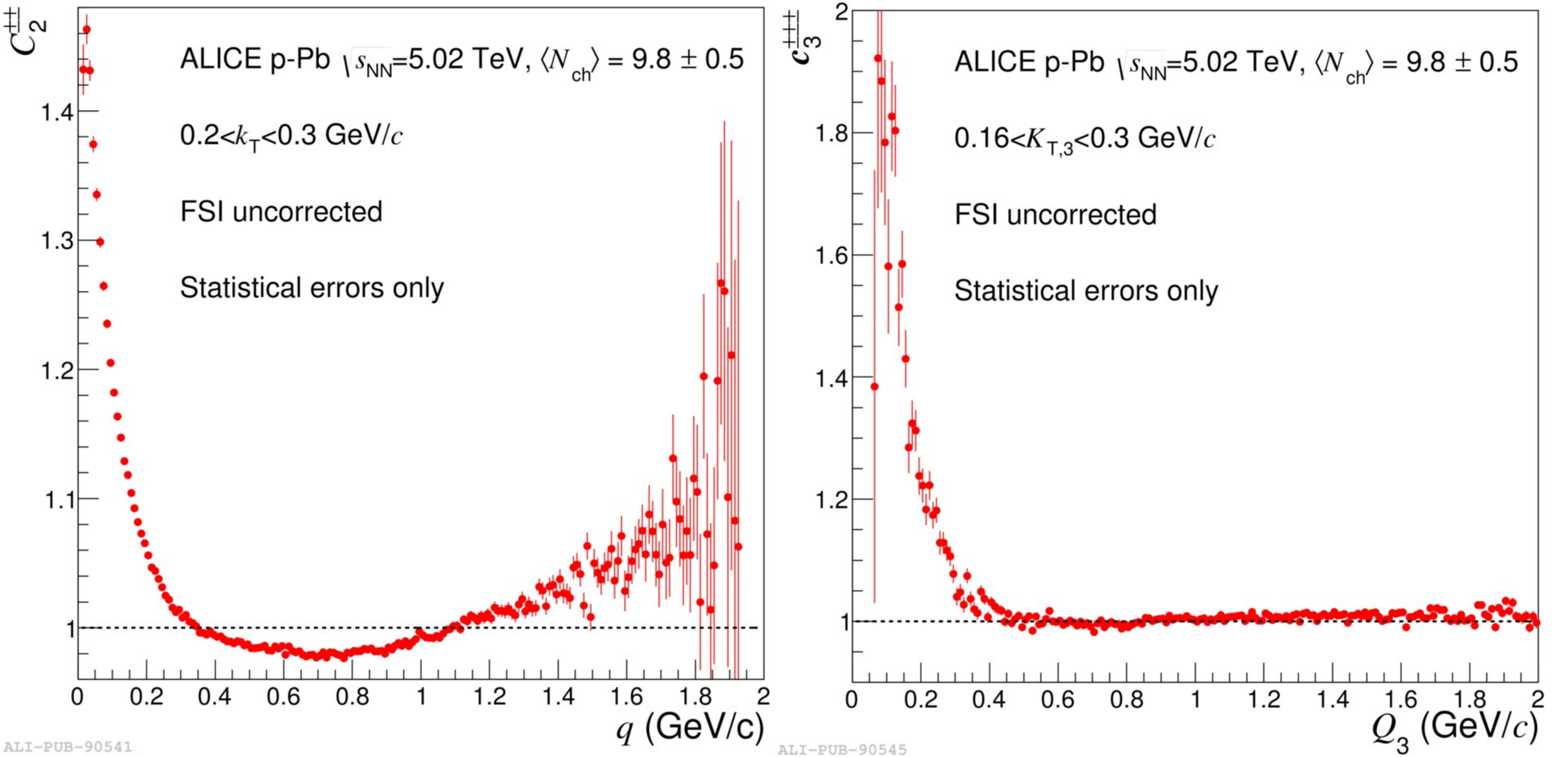
Multi-particle correlations



Multi-particle correlation results are the same within 10%.
Strong evidence of collective nature of correlations.

CMS-HIN-14-006

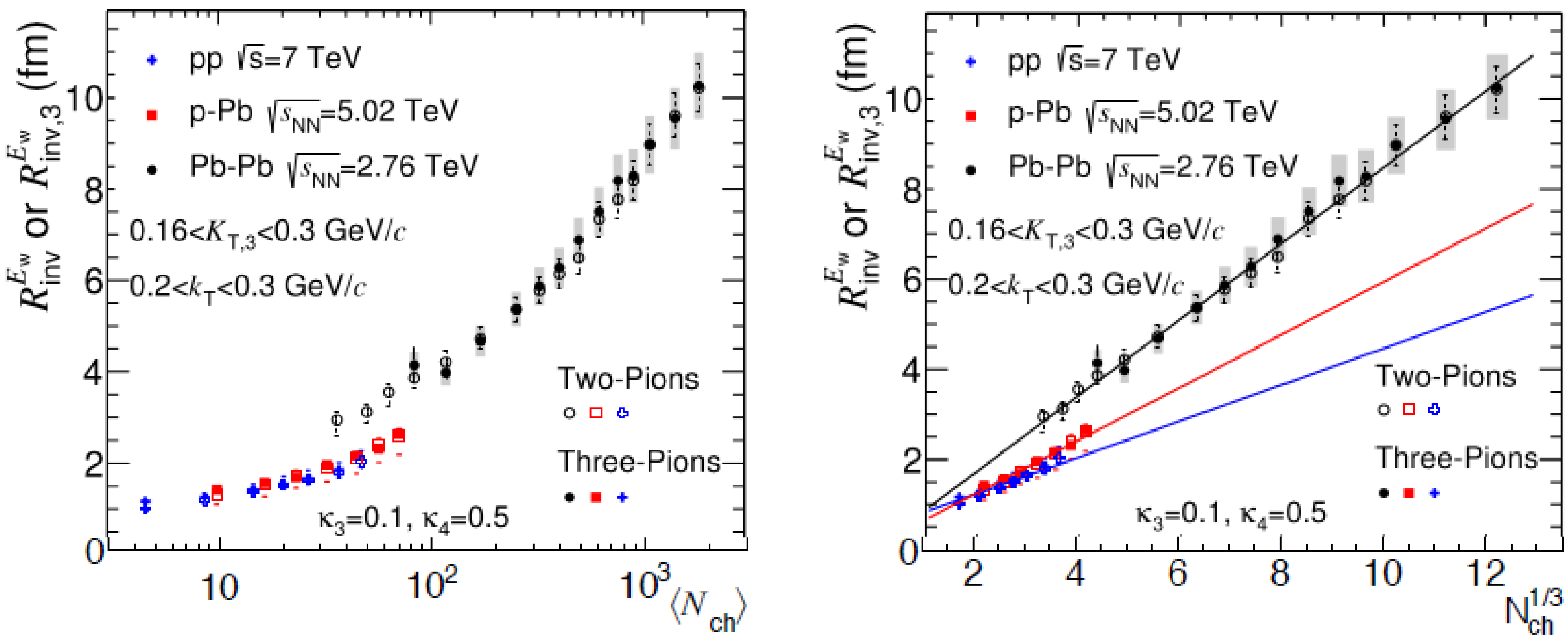
Femtoscopy using 3-pion cumulants



The baseline for the 3-pion cumulants is much more flat than for 2-pion correlations

PLB 739 (2014) 139

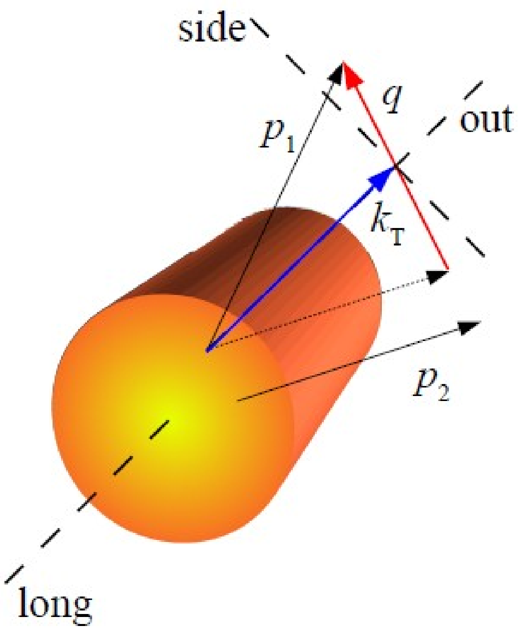
Freeze-out radii (R_{inv}) vs N_{ch}

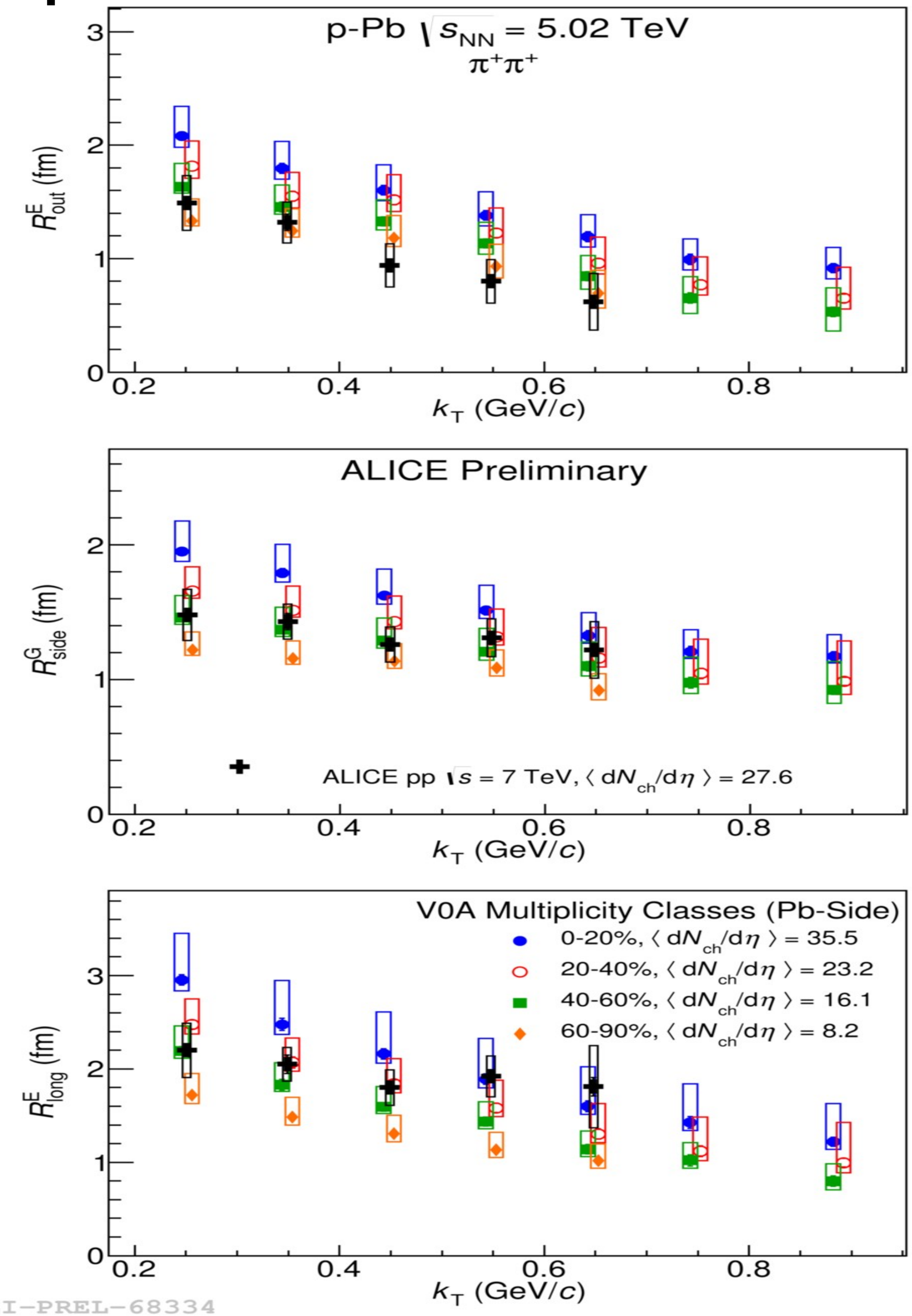


- Exhibit different trend (with linear fit over measured region)
- Radii in pp and pPb at similar measured Nch are with 5-15% while larger difference (up to 30-50%) between pPb and PbPb
- Not much room for a hydro-dynamical expansion in pPb beyond what might already be there in pp

PLB 739 (2014) 139

k_T dependence of radii in pPb

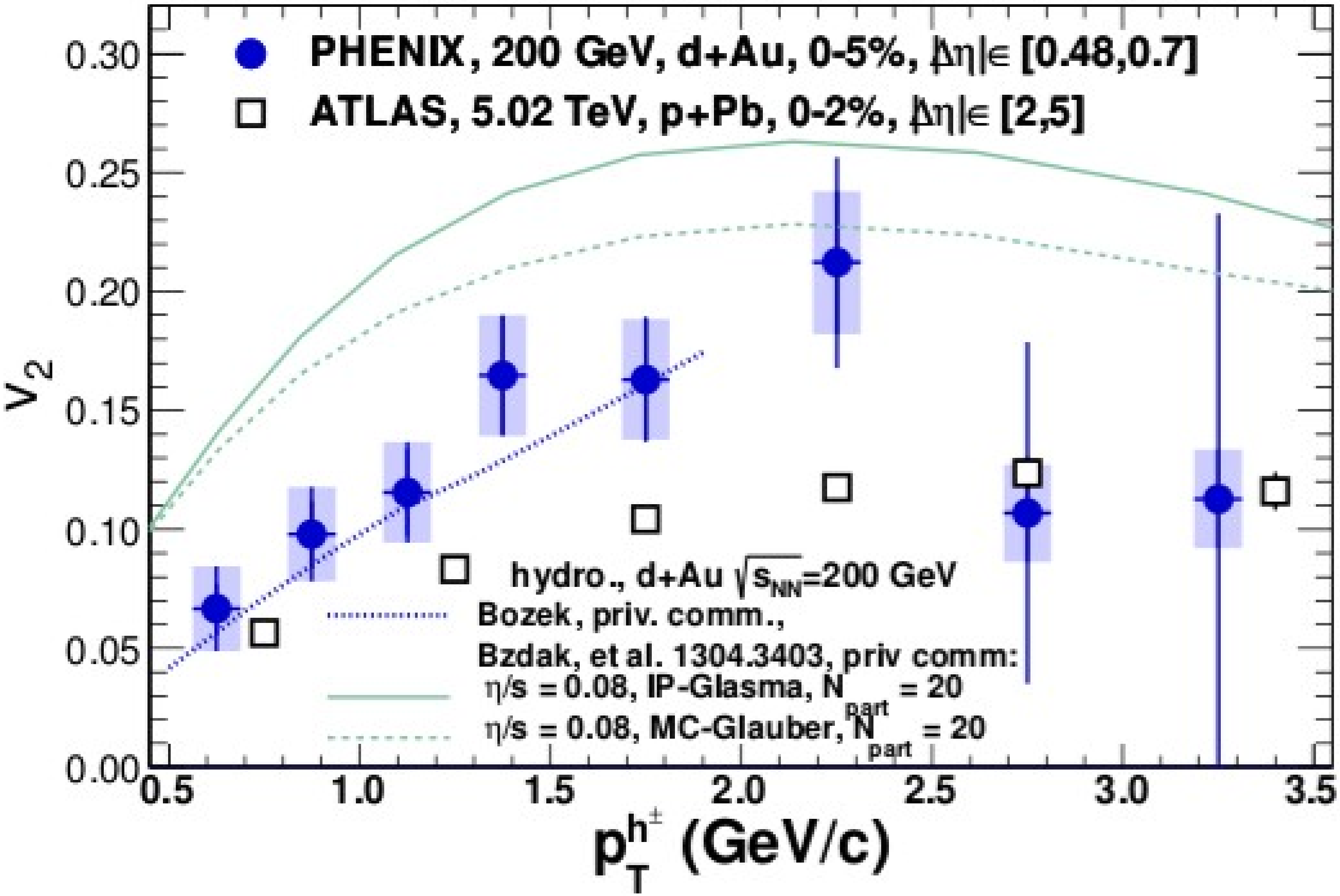




- 3d radii in LCMS from two-particle correlations
  - Needs understanding of background using MC
- Radii decrease w increasing k_T as in AA (and in hydro)
  - Similar high multiplicity pp

And v_2 in dAu at RHIC?

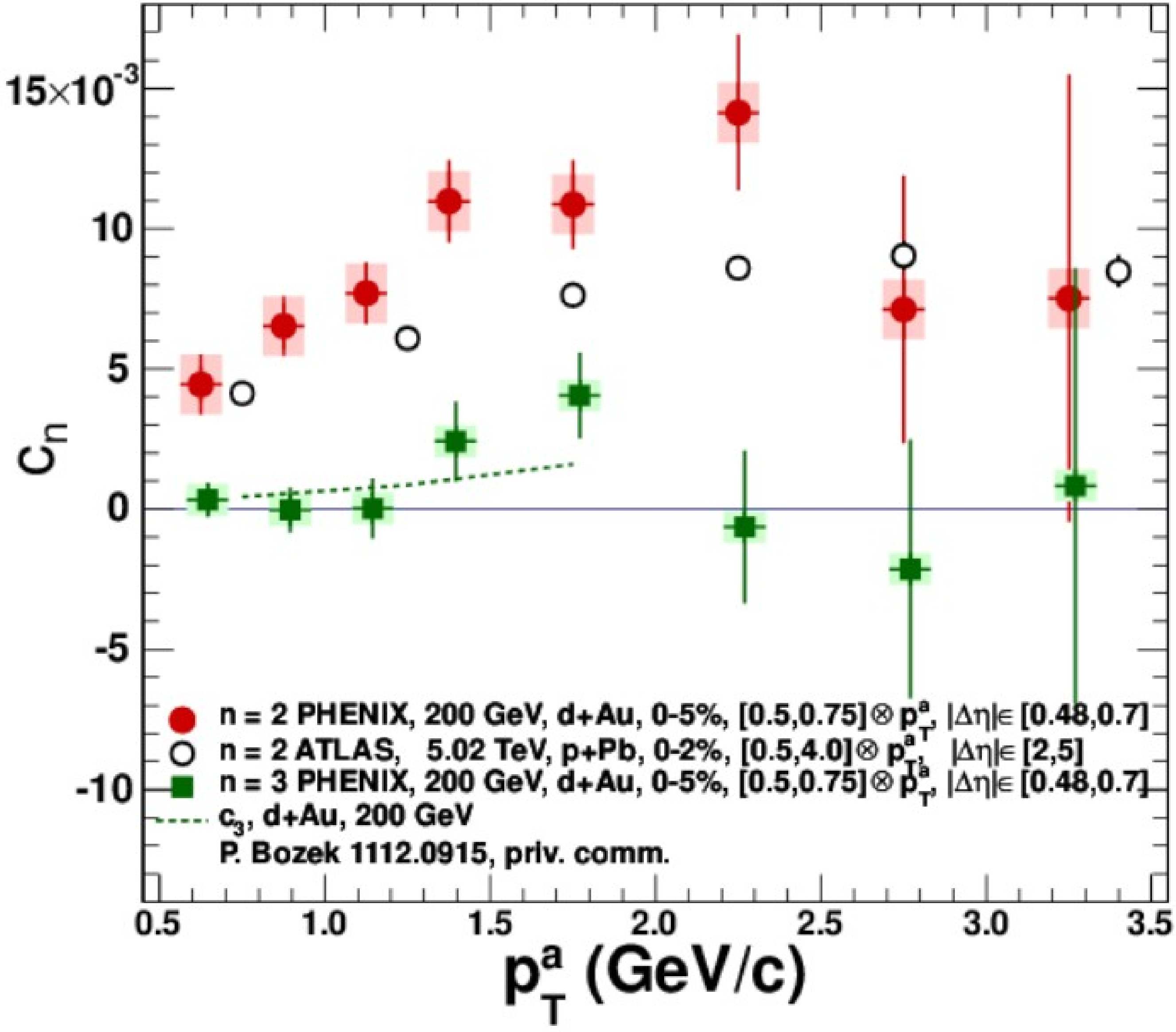
PHENIX, PRL 111 (2013) 212301



Even stronger v_2 in 0-5% d+Au at RHIC

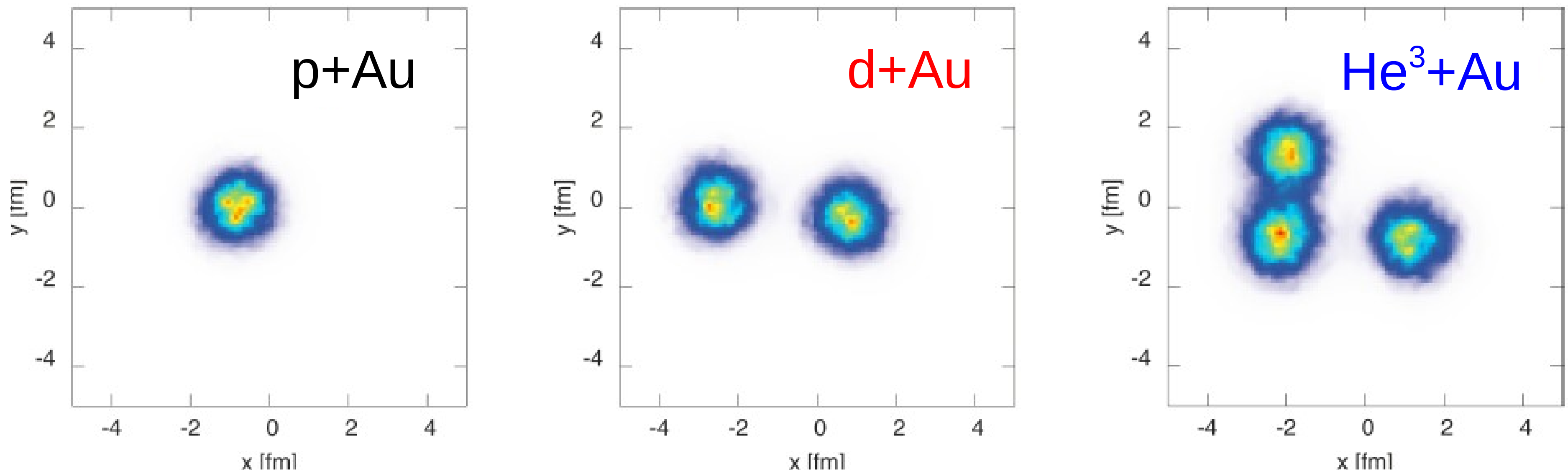
And v_3 in dAu at RHIC?

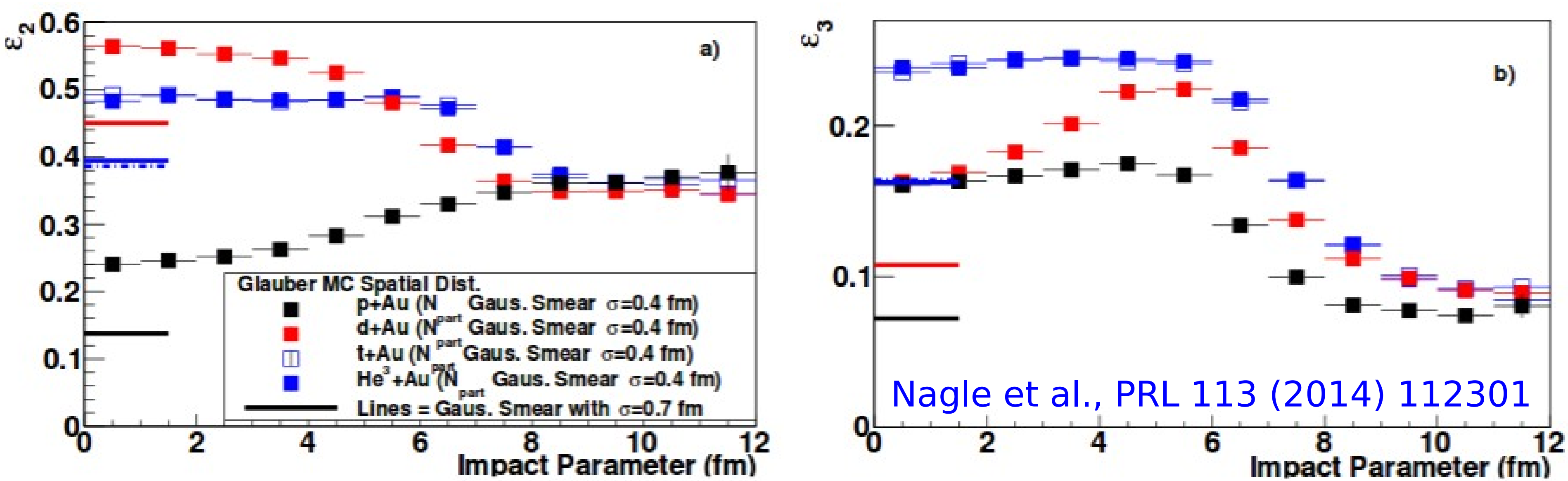
PHENIX, PRL 111 (2013) 212301



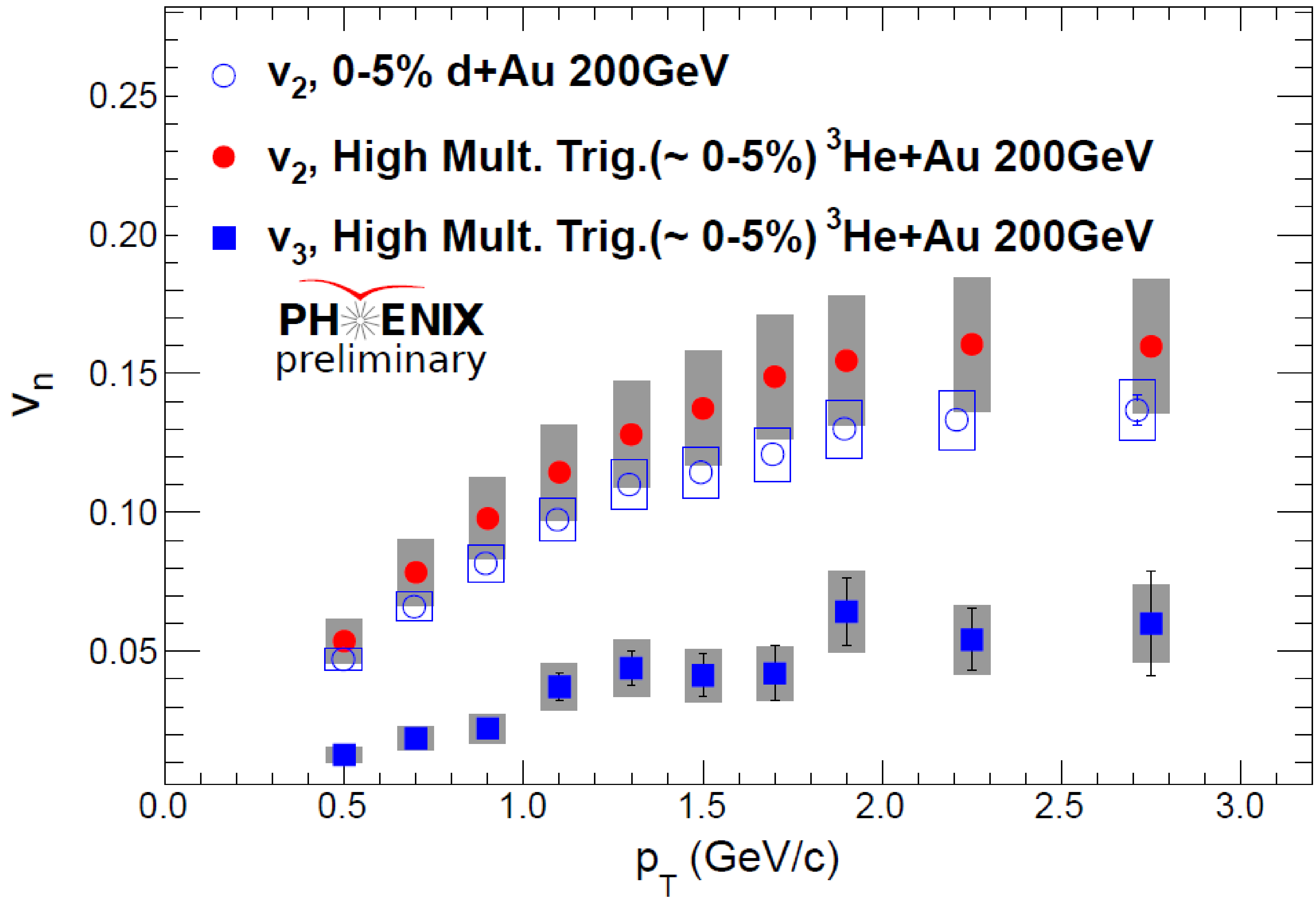
Negligible v_3 in 0-5% d+Au at RHIC

Geometry engineering



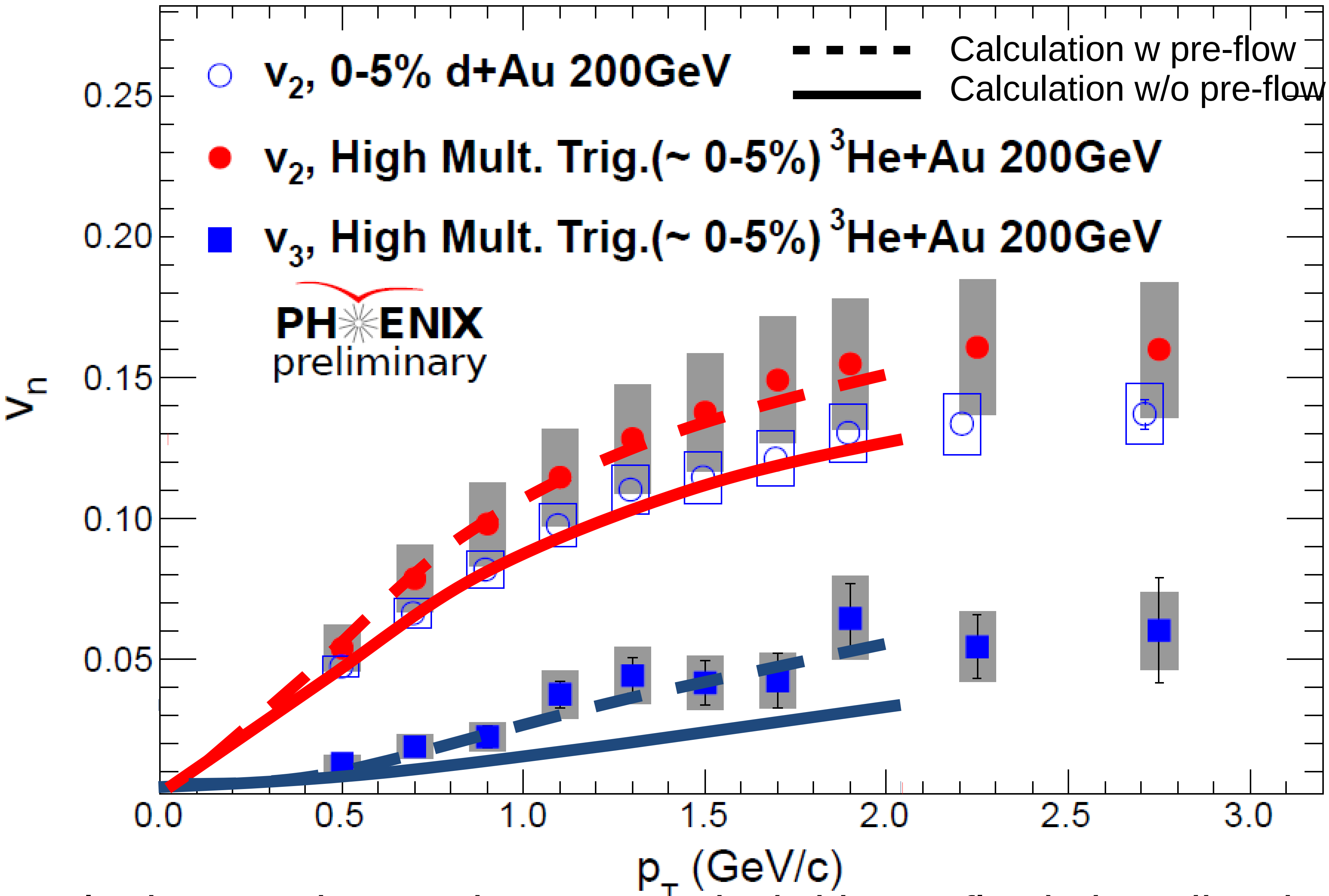


Geometry engineering: He^3-Au data



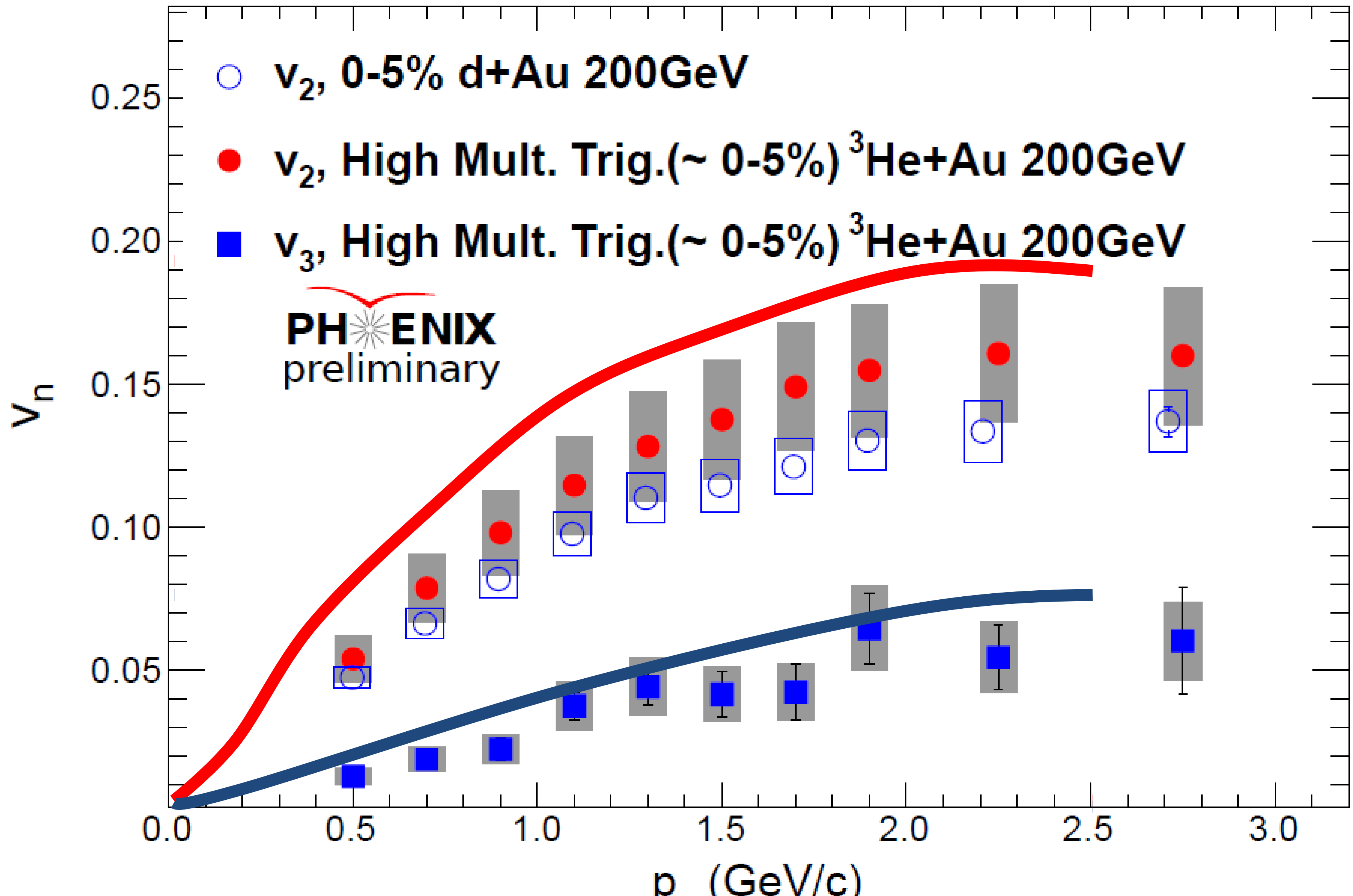
Data confirm the expectation: Significant v_3 found, and v_2 similar to dAu

Geometry engineering: He^3-Au data



Glauber+Hydro+Hadron Cascade (with pre-flow) describe data

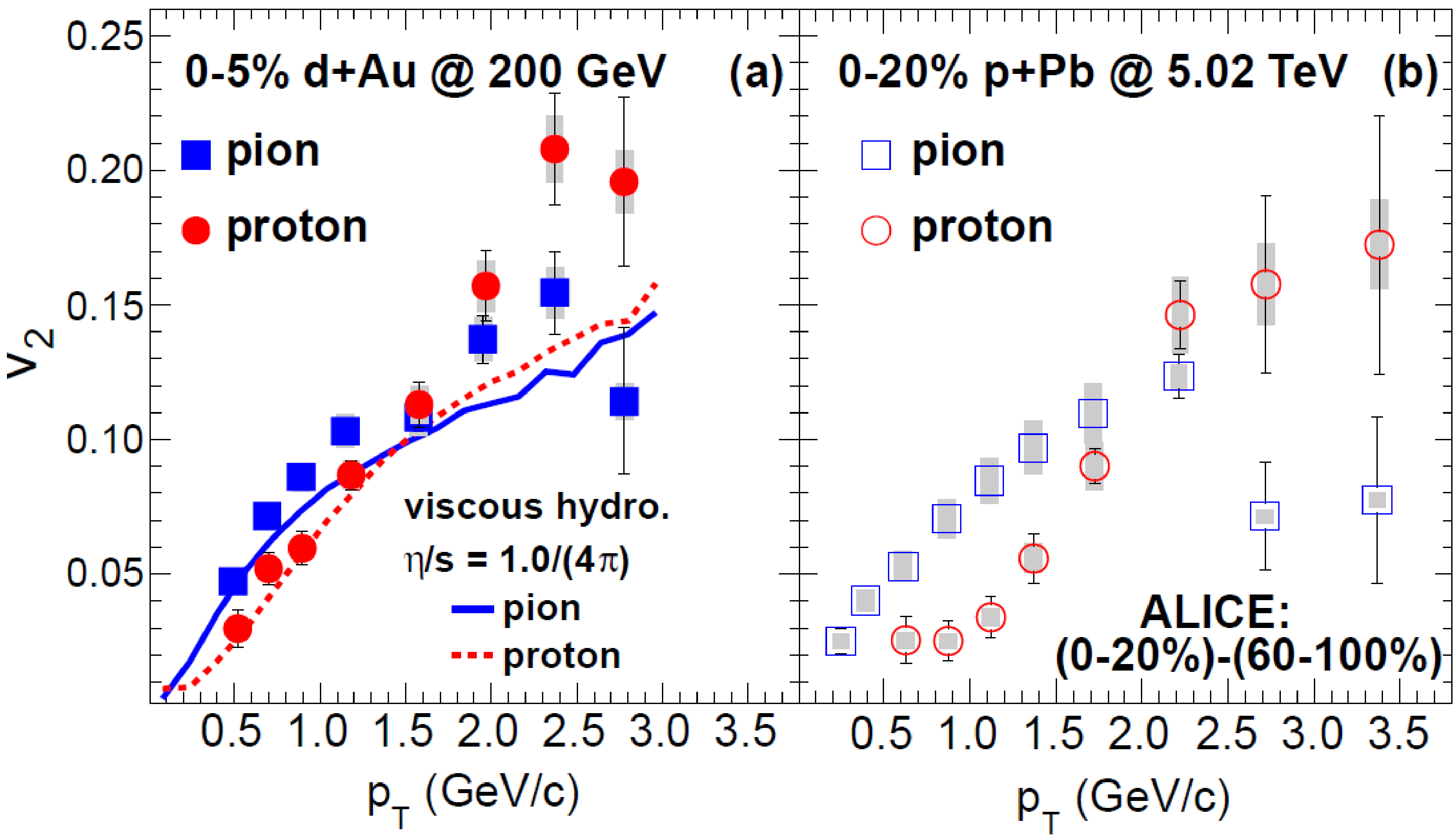
Geometry engineering: He^3-Au data



IP-GLASMA+MUSIC also reasonably well predict data

And identified v_2 in dAu at RHIC?

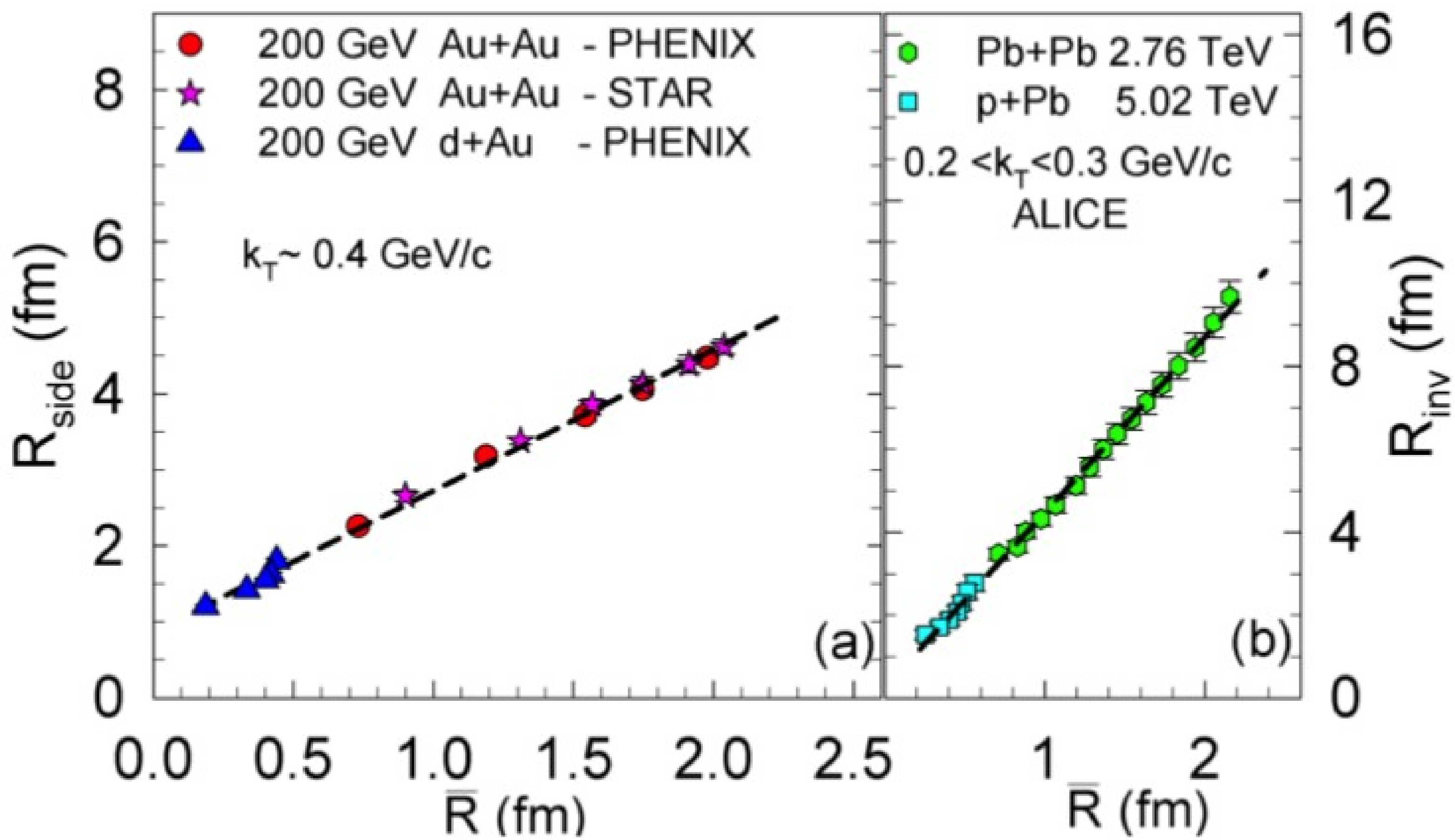
PHENIX, arXiv:1404.7461 | ALICE, PLB 726 (2013) 164

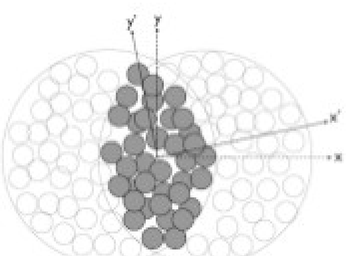


Mass ordering for identified particles observed

Initial system size scaling across systems

arXiv:1404.5291





$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

Scaling with $\overline{\text{R}}$ across systems:
Implies evidence for radial expansion

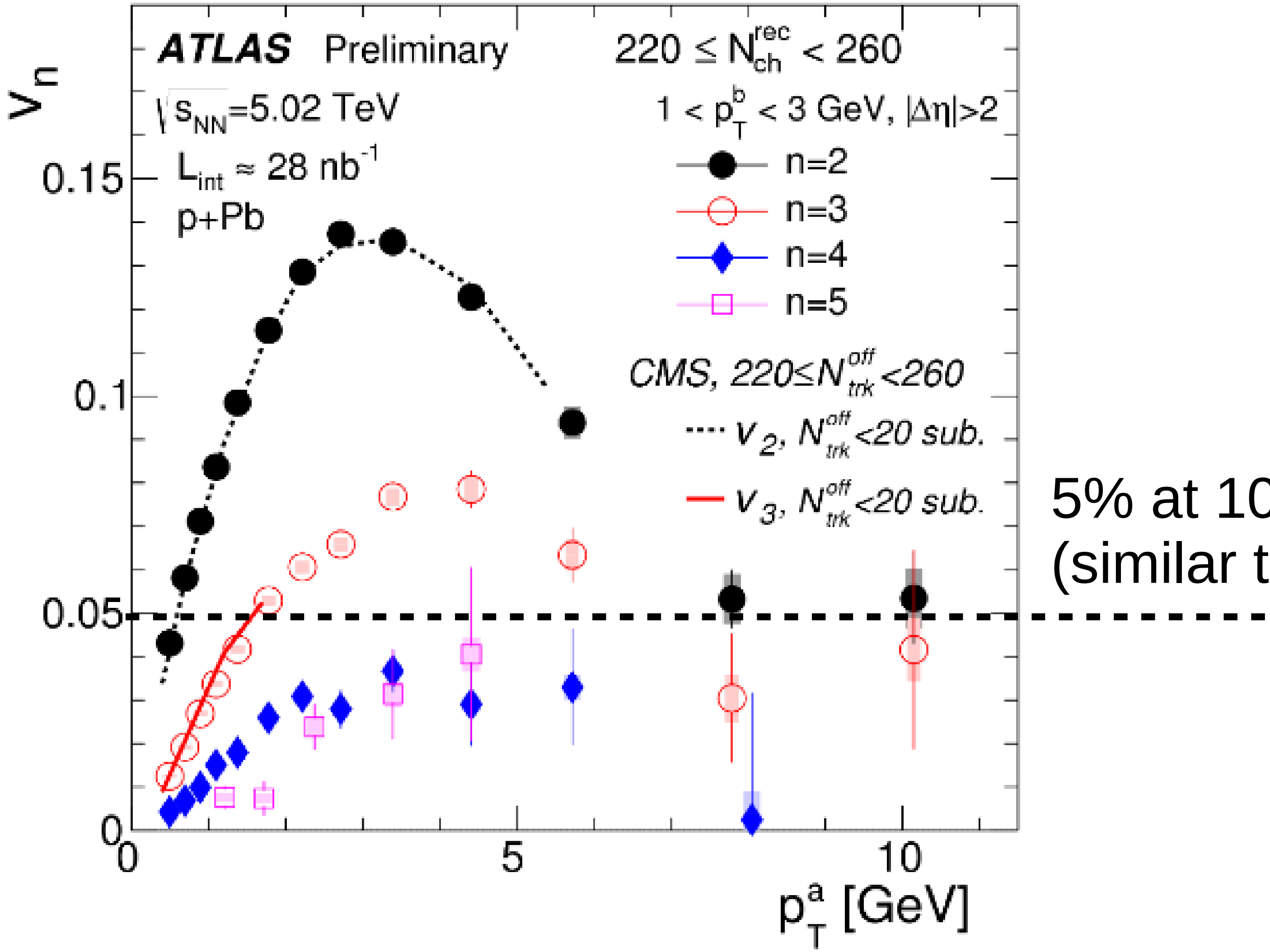
Do we indeed produce a strongly coupled liquid in “dilute-dense” collisions?

- Azimuthal anisotropies (v_n)
- Characteristic $v_n(p_T)$ shape
- Mass ordering of p_T spectra
- Mass ordering of $v_n(p_T)$
- Characteristic multiplicity dependence
- Similar size of higher order cumulants
- Weak rapidity dependence of correlations
- Characteristic η-dependence of v_2
- Breaking of factorization
- Event angle correlations (not measured in pPb)

All signatures known from PbPb also found in pPb

If it is really hydrodynamic QGP, what about parton energy loss?

Indication of parton energy loss?

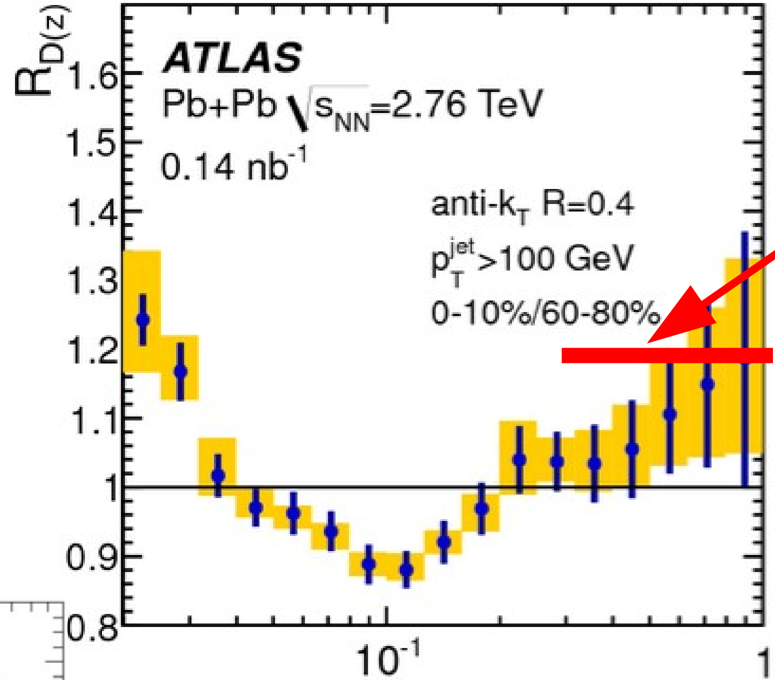


5% at 10 GeV/c
(similar to PbPb)

In PbPb at high p_T, v_2=5% thought to be from parton energy loss.
Is it crazy to speculate the same here? Need theory guidance!

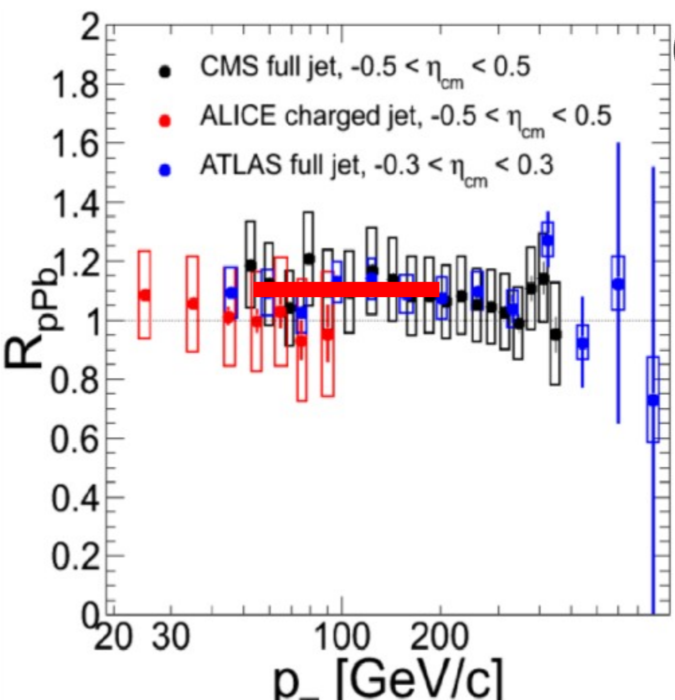
Modification of fragmentation function?

(G.Roland, IS2014)

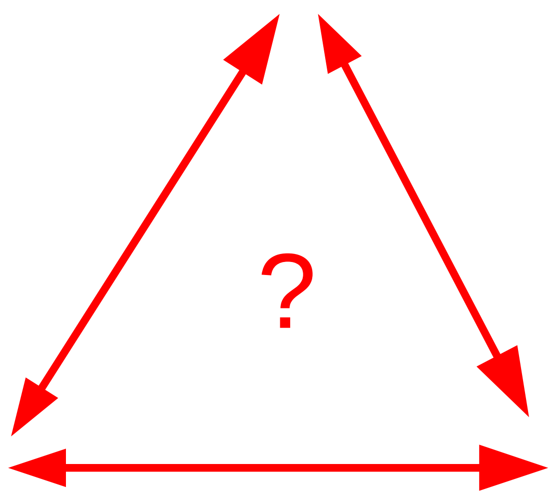


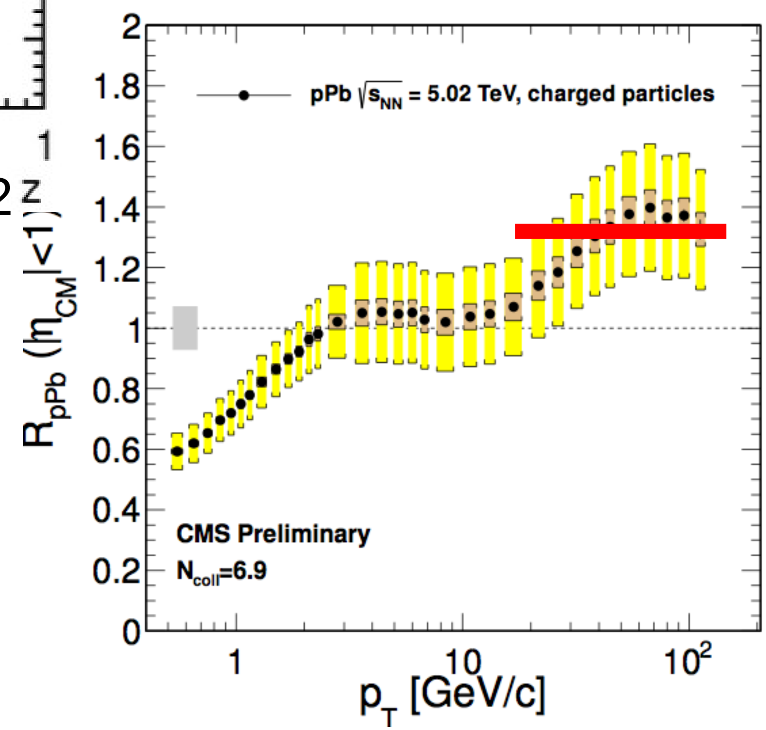
Predicted pPb/pp fragmentation function ratio

Implies $R_D(p_T=50\text{GeV})\approx1.2$



Jet $R_{pPb}(100\ \text{GeV})\approx1.1$

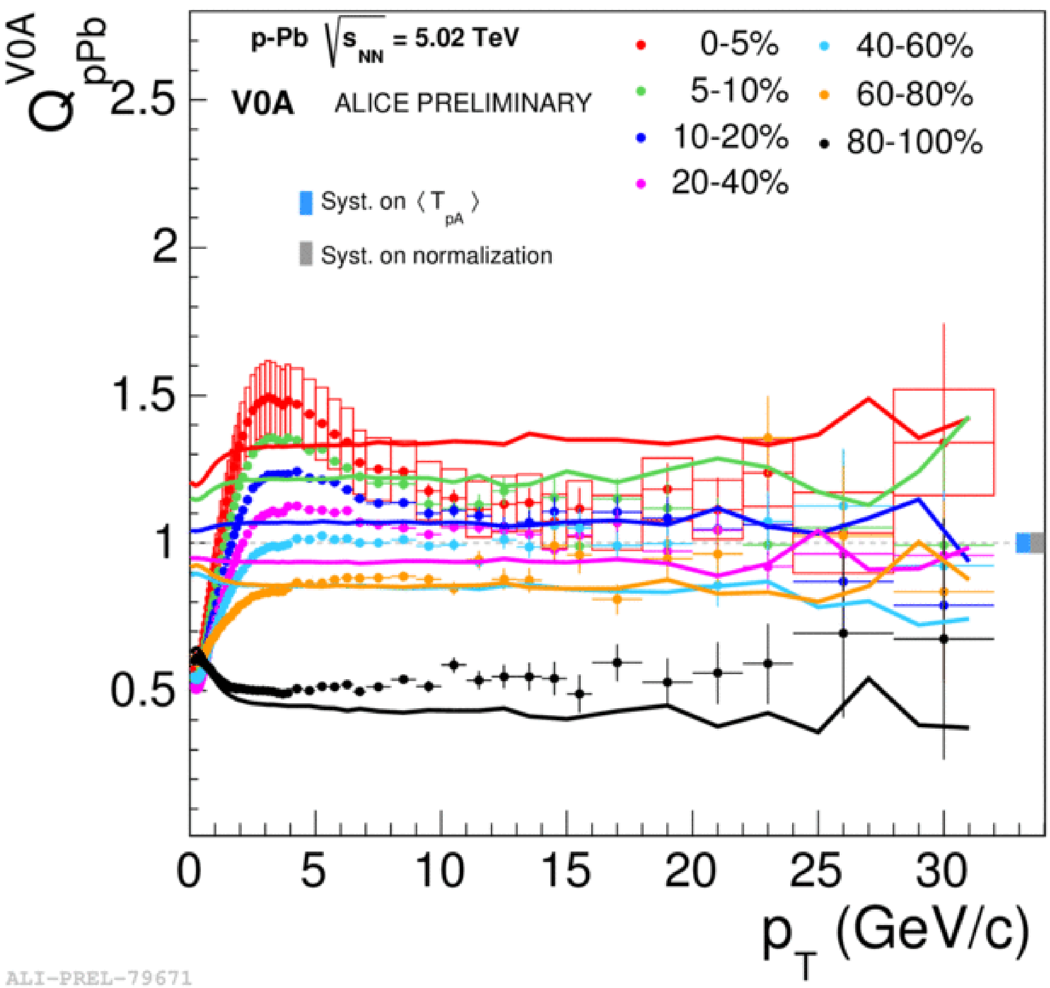




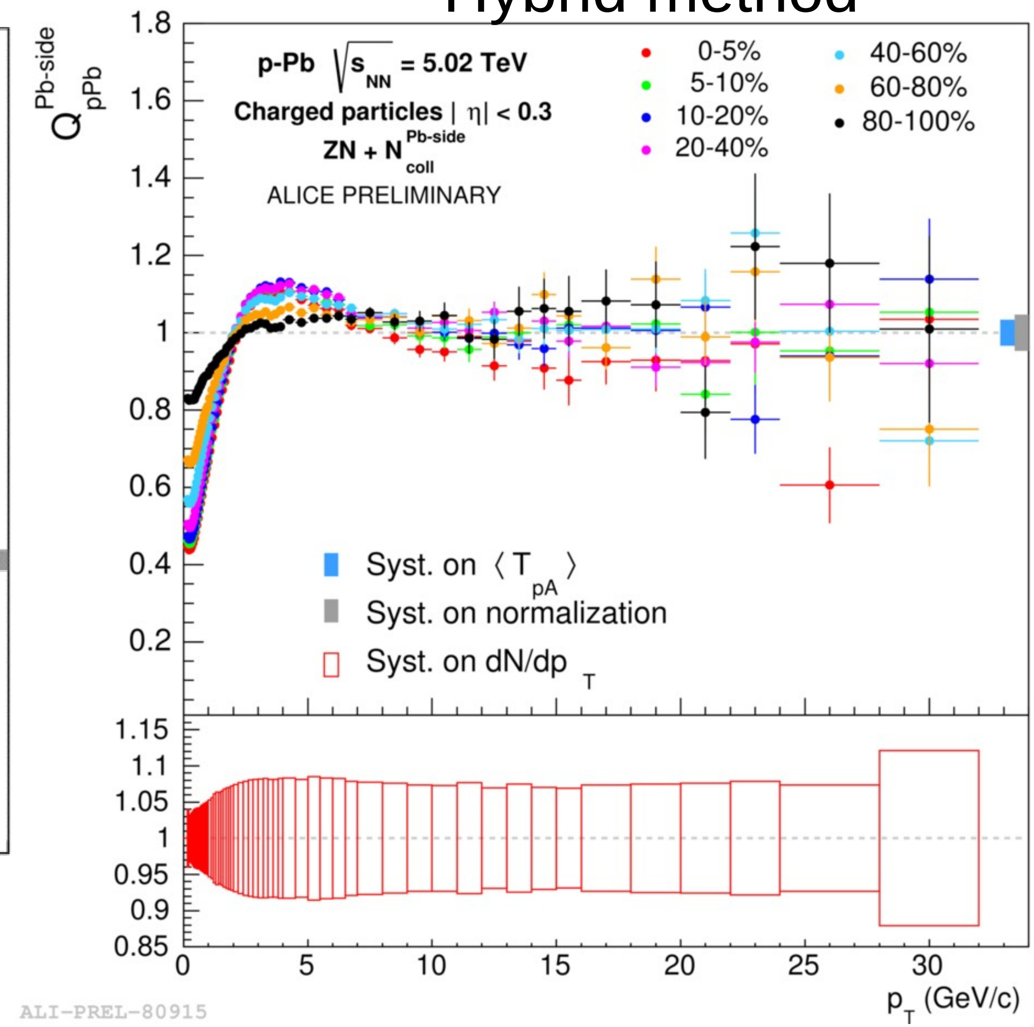
Hadron $R_{pPb}(50\ \text{GeV})\approx1.35$

Charged particle QpPb

V0A NBD



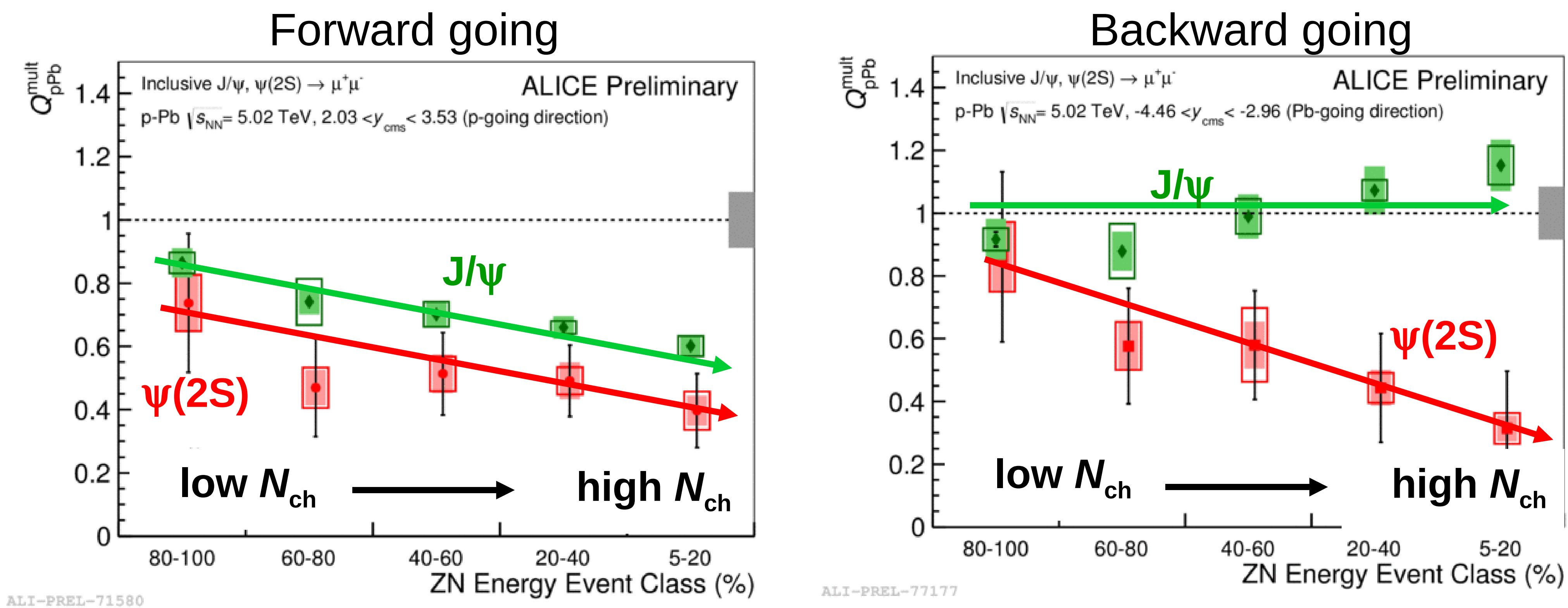
Hybrid method



Bias induced by estimator shadows small change

Hint of suppression at 10 GeV?
(Uncertainties largely correlated!)

J/Ψ and Ψ(2S) suppression



- J/ψ → μμ: Multiplicity dependent suppression in p-going direction, and no suppression in Pb-going direction
  - Consistent with shadowing
- ψ(2S) → μμ: Multiplicity dependent suppression in both directions
  - Needs additional effect (Final state?)

Summary / Outlook

- All prominent signatures of collectivity known from AA found also in “dilute+dense” collisions
  - More experimental results expected from pAu at RHIC and high mult. pp from RUN2 at LHC
- Hydrodynamical models, and other models like IP-GLASMA (+MUSIC) or AMPT, can describe the data
  - Systematic effort needed to apply models to data consistently (and across systems)
- The quest for jet quenching in “dilute-dense” collisions is open
  - Is it possible we see jet modification without (strong) jet quenching?
  - Theoretical and experimental effort needed

Only a selection of all available results shown, you find them here:

ALICE results: http://aliceinfo.cern.ch/ArtSubmission/publications

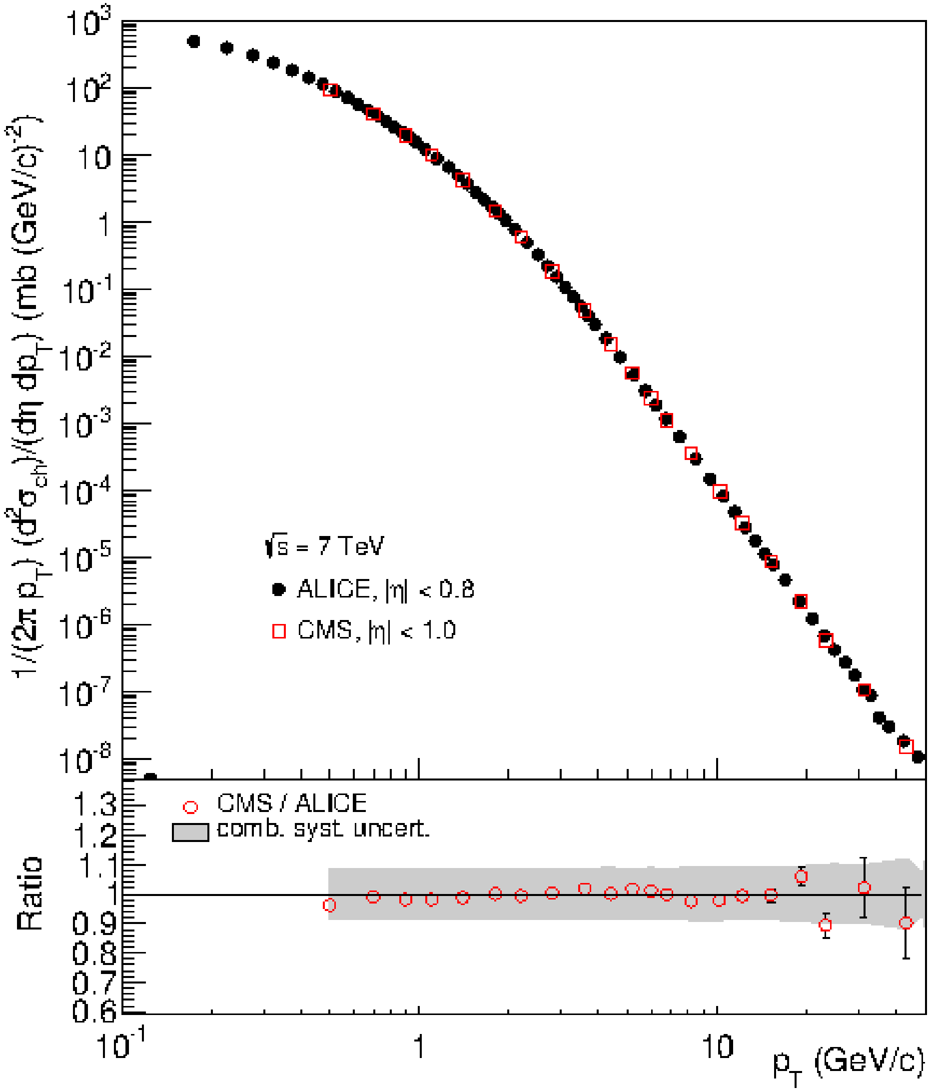
ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

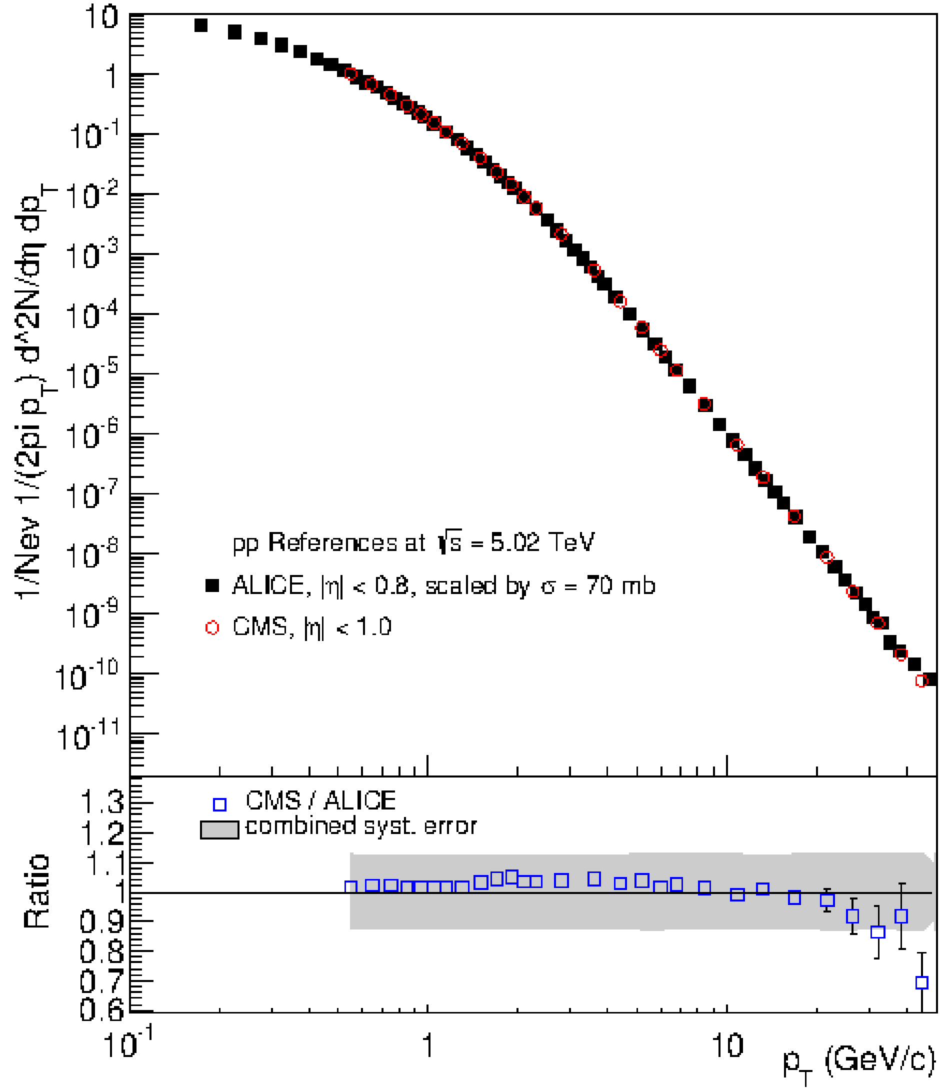
Extra

Comparison pp spectra: ALICE vs CMS

7 TeV



5 TeV (interp.)



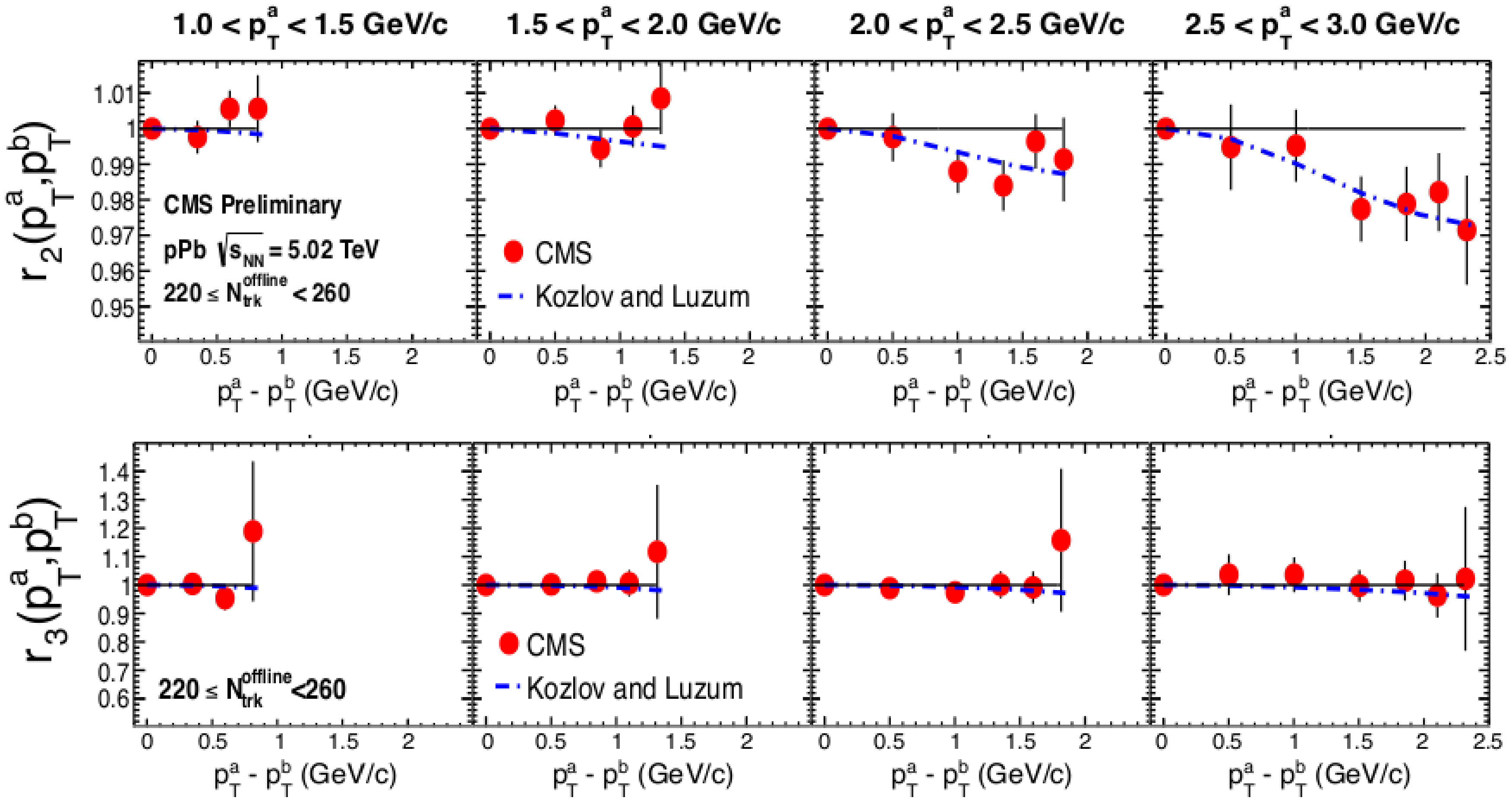
Needs a measurement of the pp reference during run 2

Breaking of factorization

$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

$220 < N_{trk} < 260$

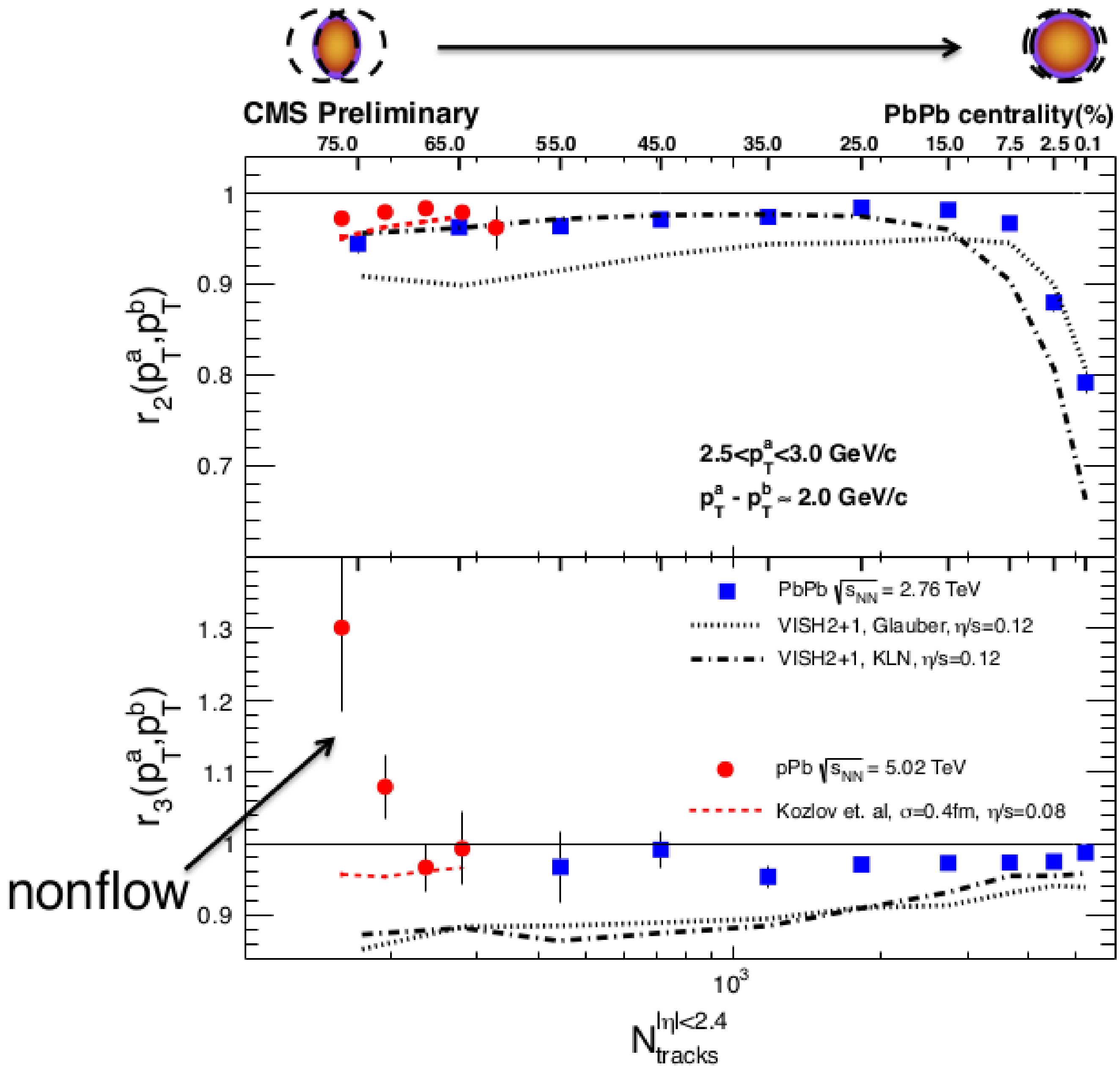
Increasing p_T^a



Only a small effect, pPb is very smooth

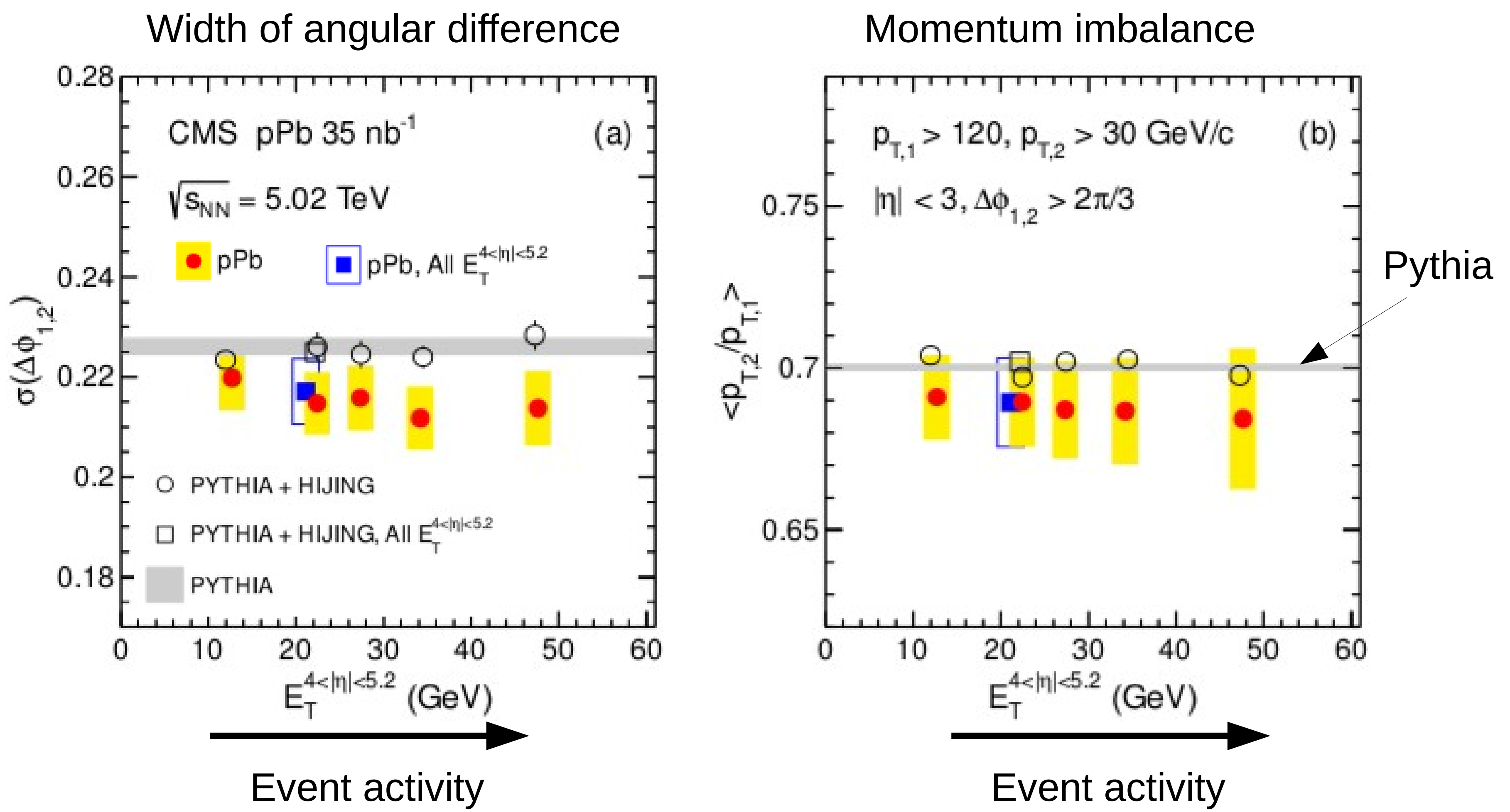
Breaking of factorization

$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}}$$



Effect in pPb is comparable to that in peripheral PbPb

Dijet imbalance: Not present in pPb



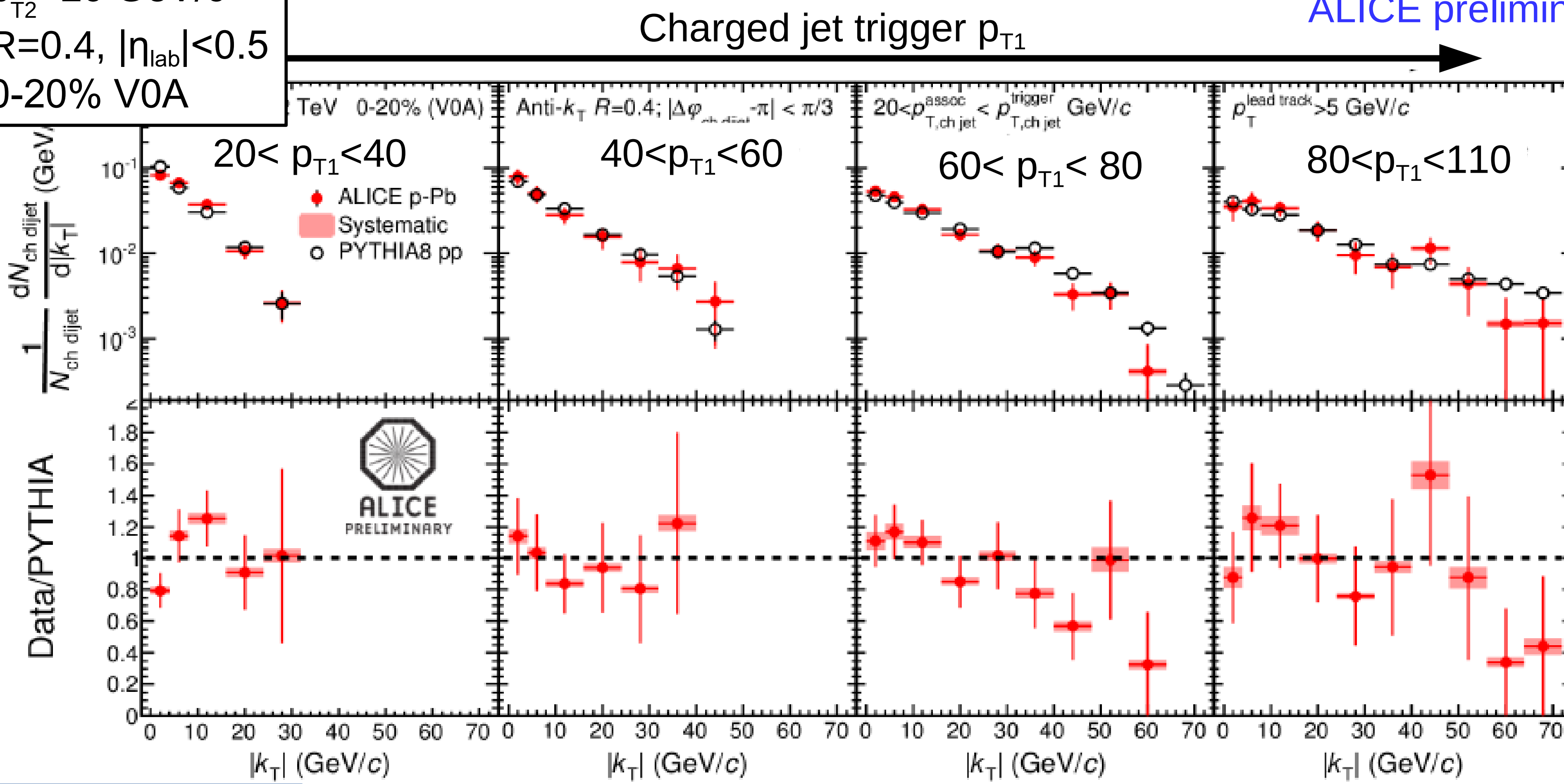
Dijet imbalance not observed in pPb collisions,
hence final state effect in PbPb

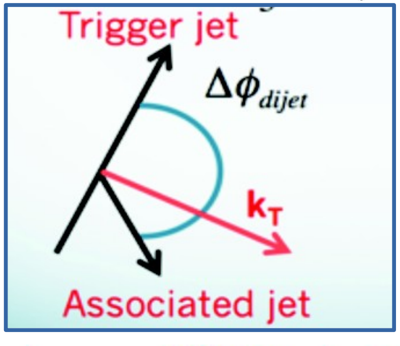
EPJC 74 (2014) 2951

Charged dijet acoplanarity

p_{T2}>20 GeV/c
R=0.4, $|\eta_{lab}|$<0.5
0-20% V0A

ALICE preliminary





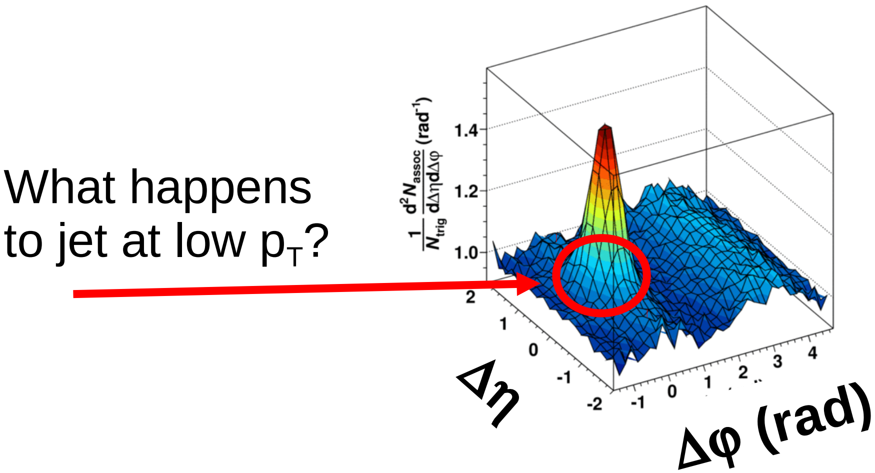
$$k_T = p^{trigger}_{T,ch\ jet}\sin(\Delta\varphi_{dijet})$$

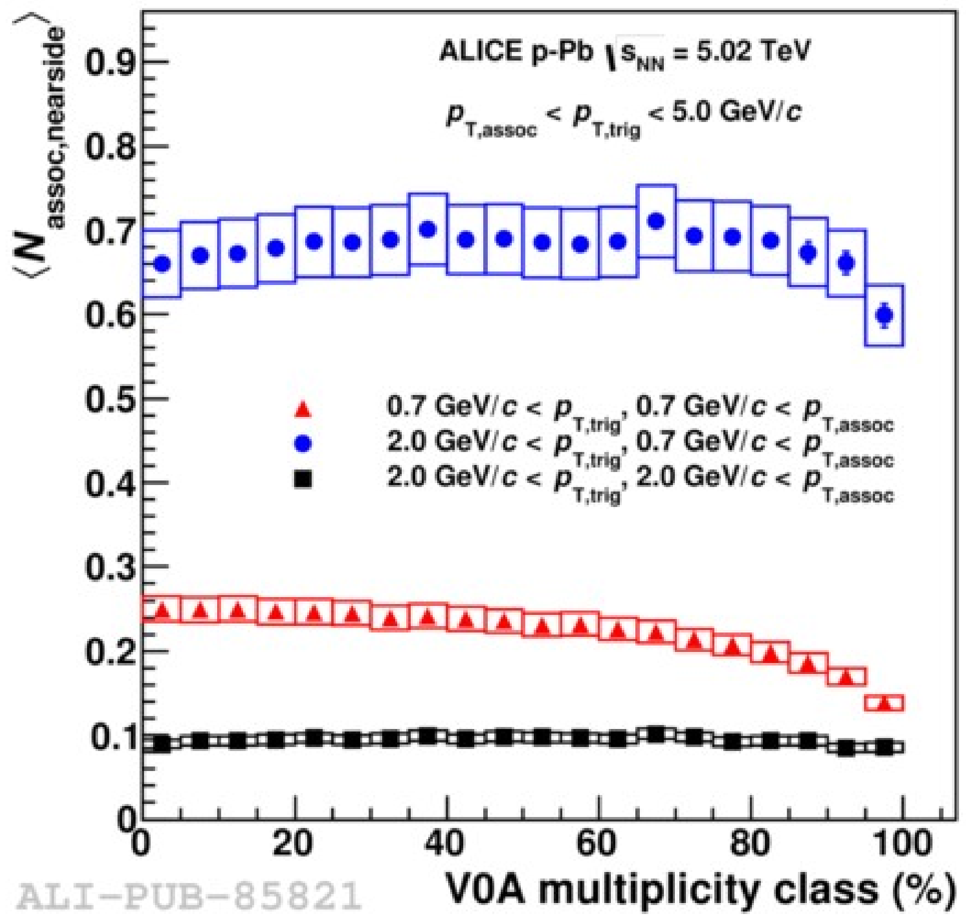
No indication for broadening even not in high-multiplicity events (relative to PYTHIA 8)

And the jet at low p_T?

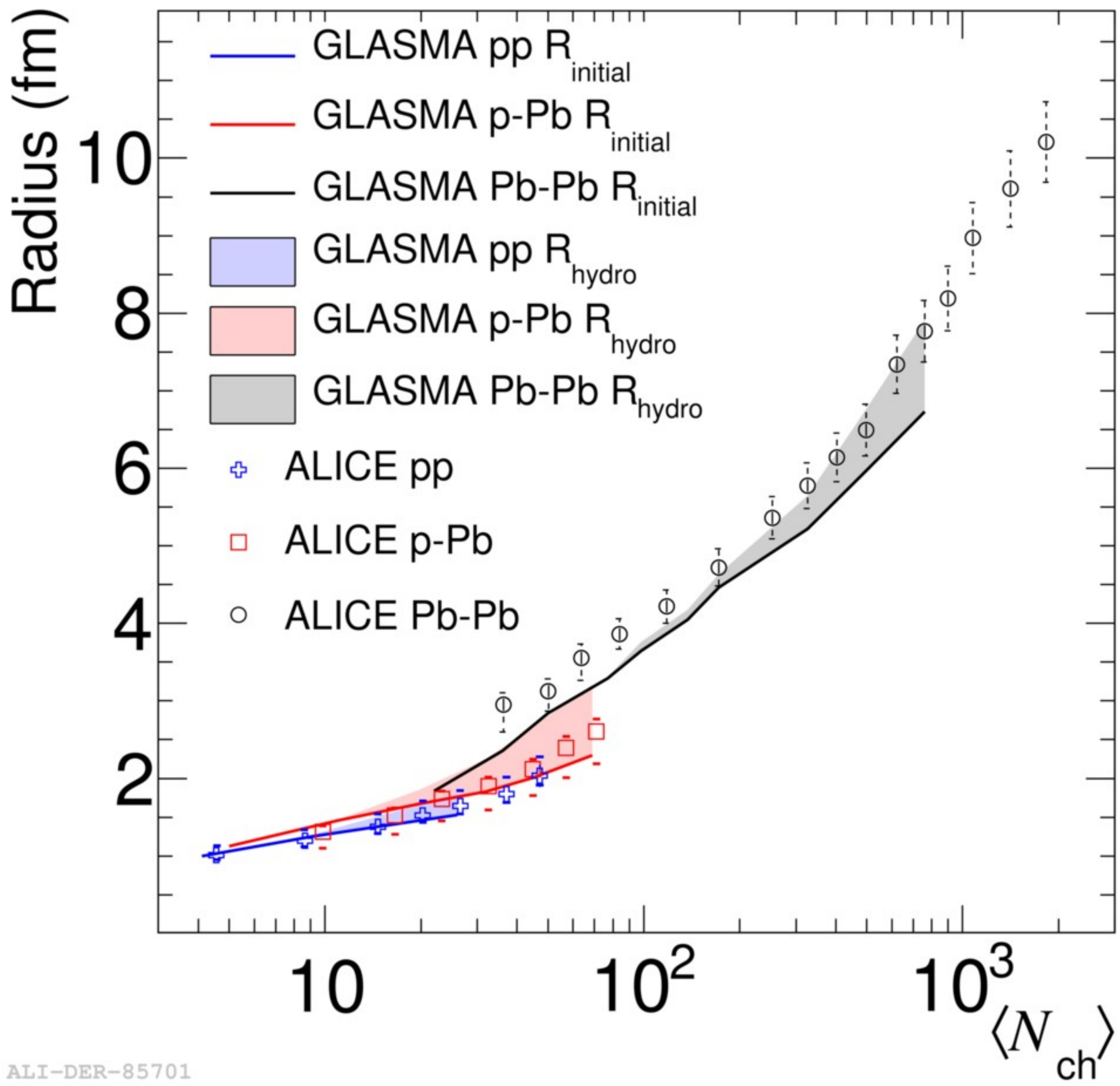
- Ridge and jet yield seem additive in 2PC
- Subtract ridge to obtain jet yields
- Resulting jet yields are constant over >60% of the pPb cross section
  - No modification even at low p_T
- Consistent with picture of minijets in pPb from independent super-positions of NN collisions with incoherent fragmentation

arXiv:1406.5463





Radii comparison with IP-Glasma model



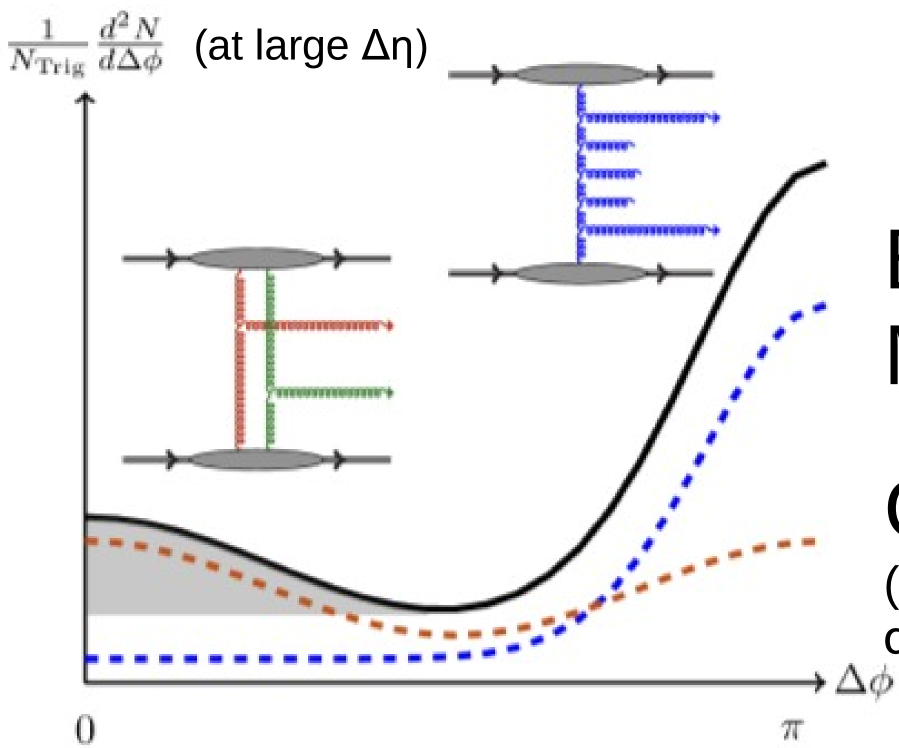
- Similarity between radii in pPb and pp can be described by Yang-Mills evolution alone
- They also can be reproduced by adding a hydrodynamic phase

GLASMA points are first scaled such that the calculations in pp match the ALICE pp data. Scale = 1.15. GLASMA calculations have uncertainty due to infrared cutoff (m=0.1 GeV).

Schenke, Venugopalan, arXiv:1405.3605

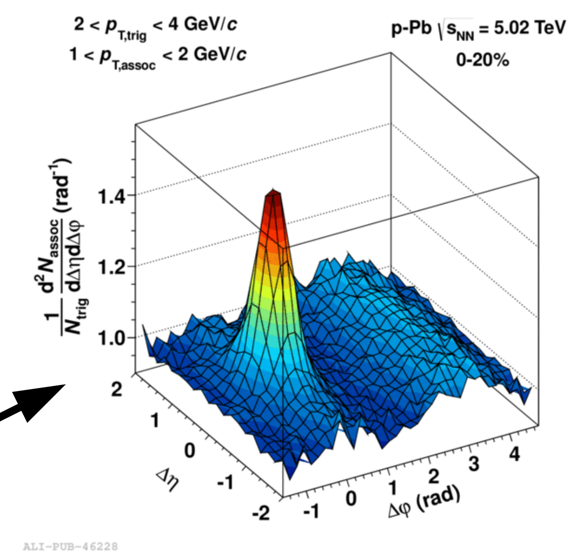
Ridge modulation v_2 and v_3 and CGC

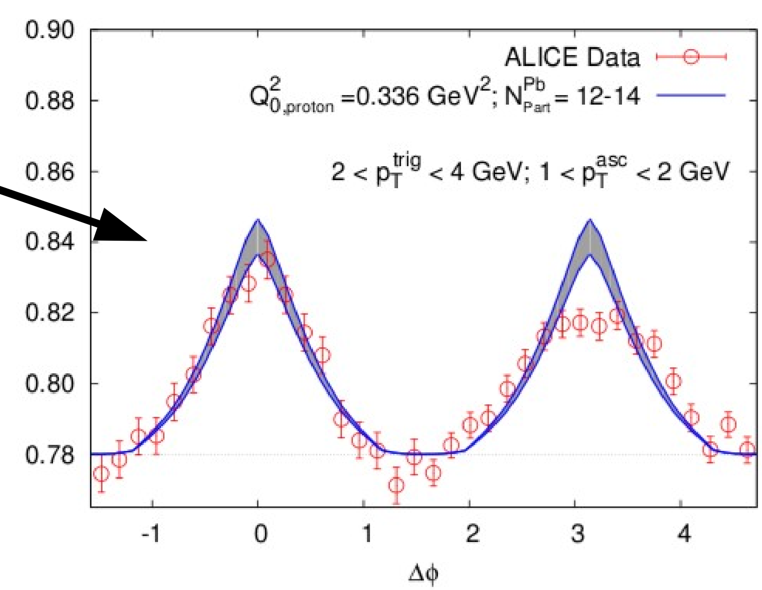
- Two symmetric ridges predicted by CGC glasma graphs found to describe the ridge yields and shape
- However, a large v_3 component would be a challenge for the model



BFKL-Minijets

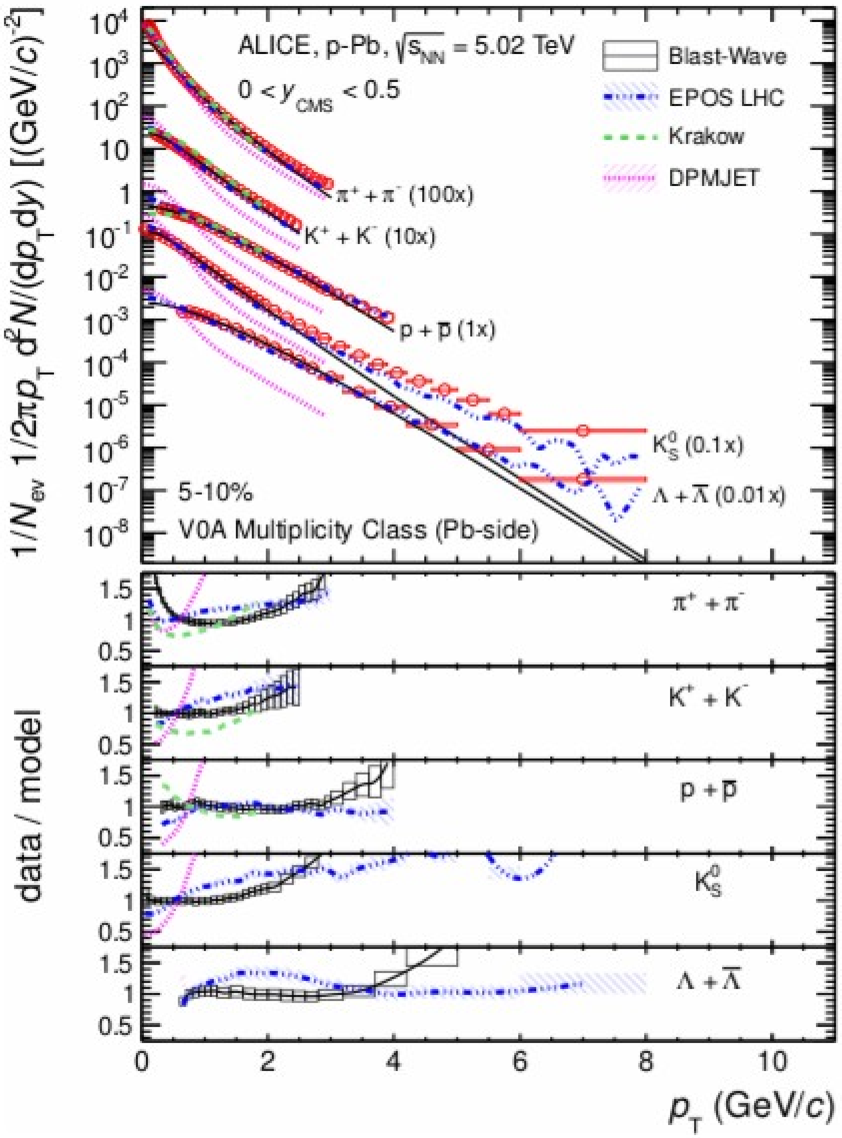
Glasma
(enhanced by α_s^{-8} for $k_T < Q_s$)



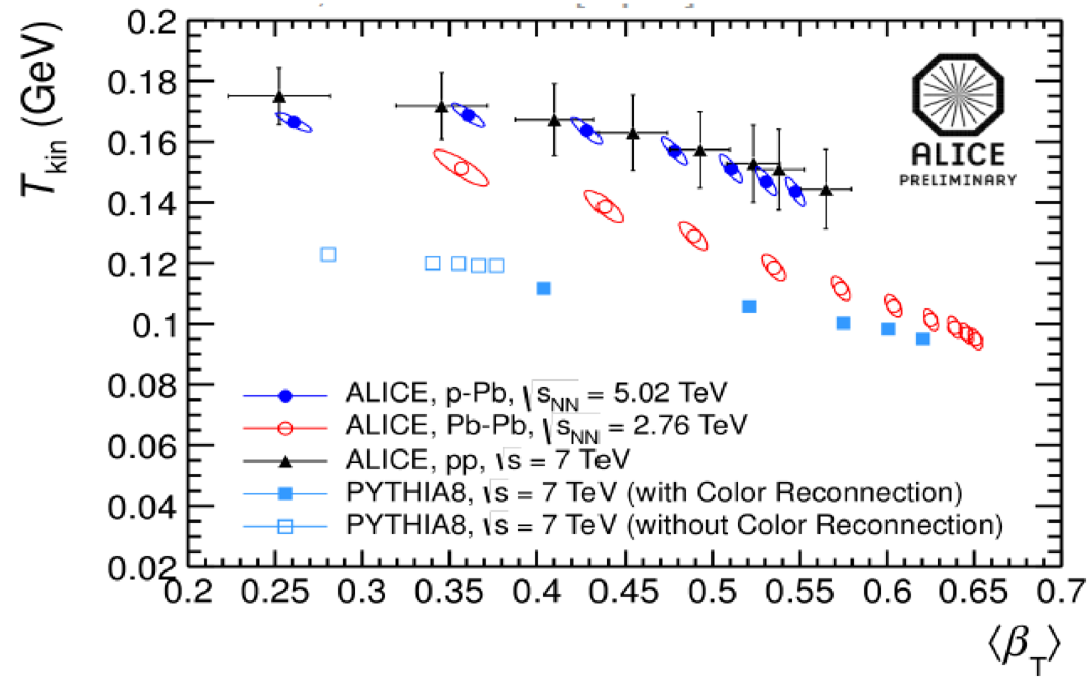


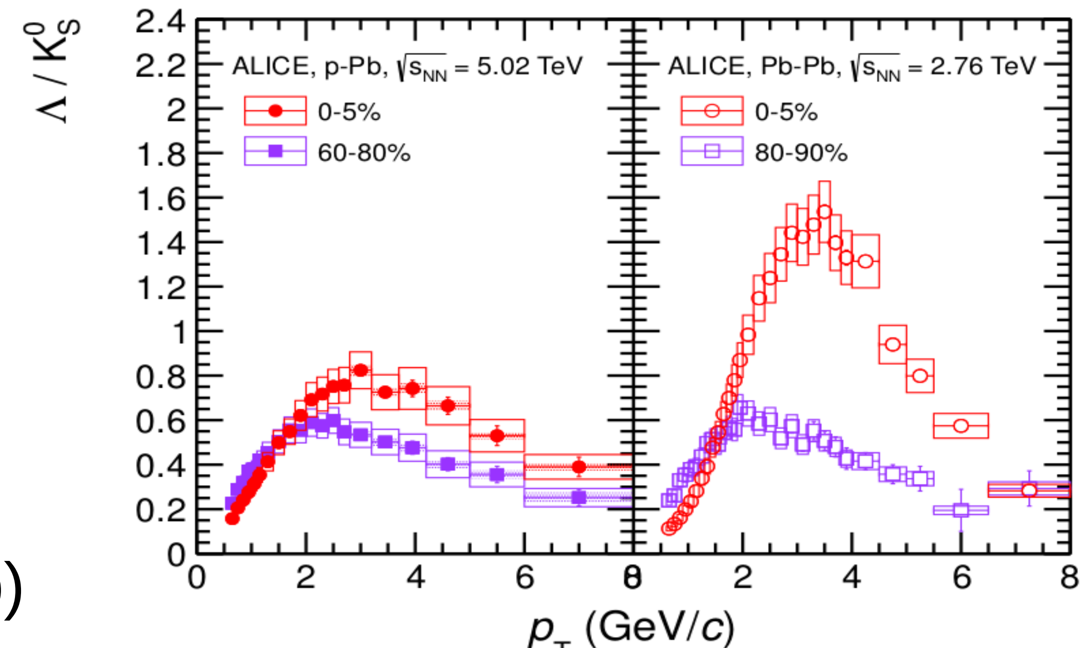
Dusling and Venugopalan, PRD 87 (2013) 094034

Identified particle spectra



ALICE, PLB 278 (2014) 25

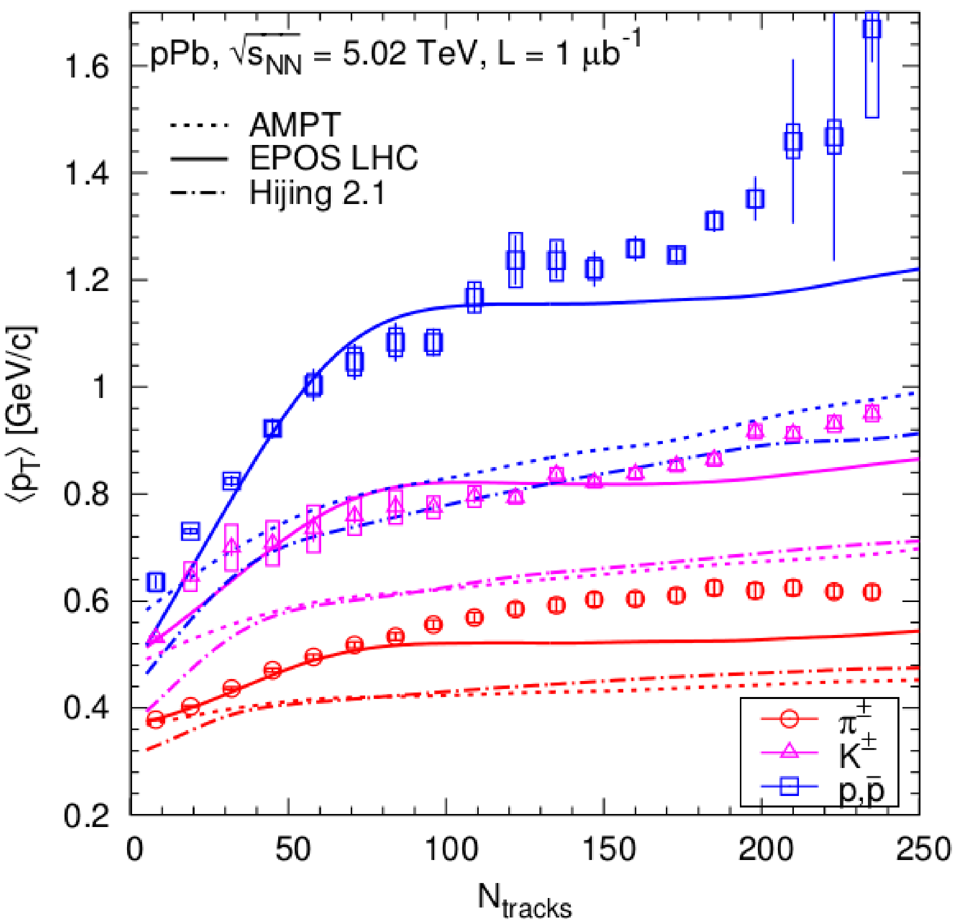




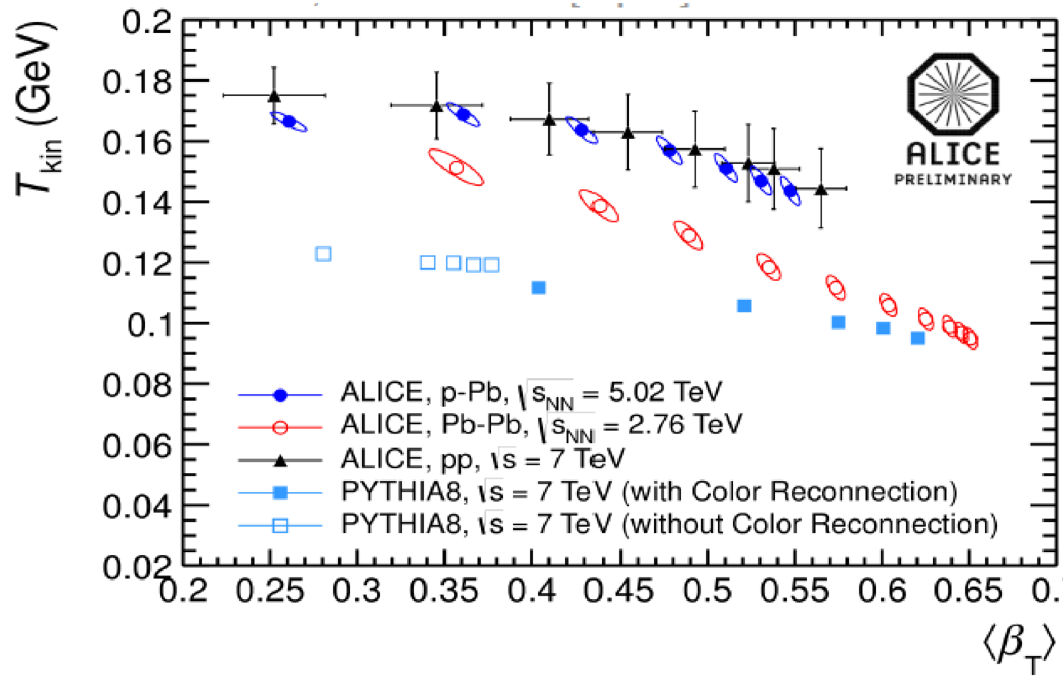
Spectra consistent with
radial flow picture (also in pp)

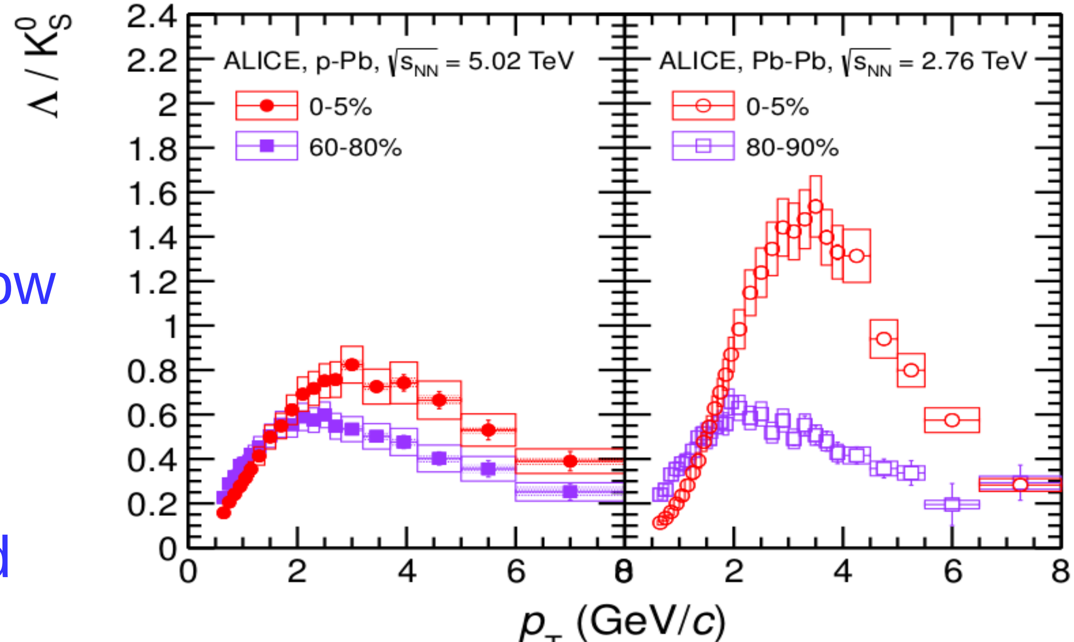
Identified particle spectra

CMS, arXiv:1307.3442



ALICE, PLB 278 (2014) 25

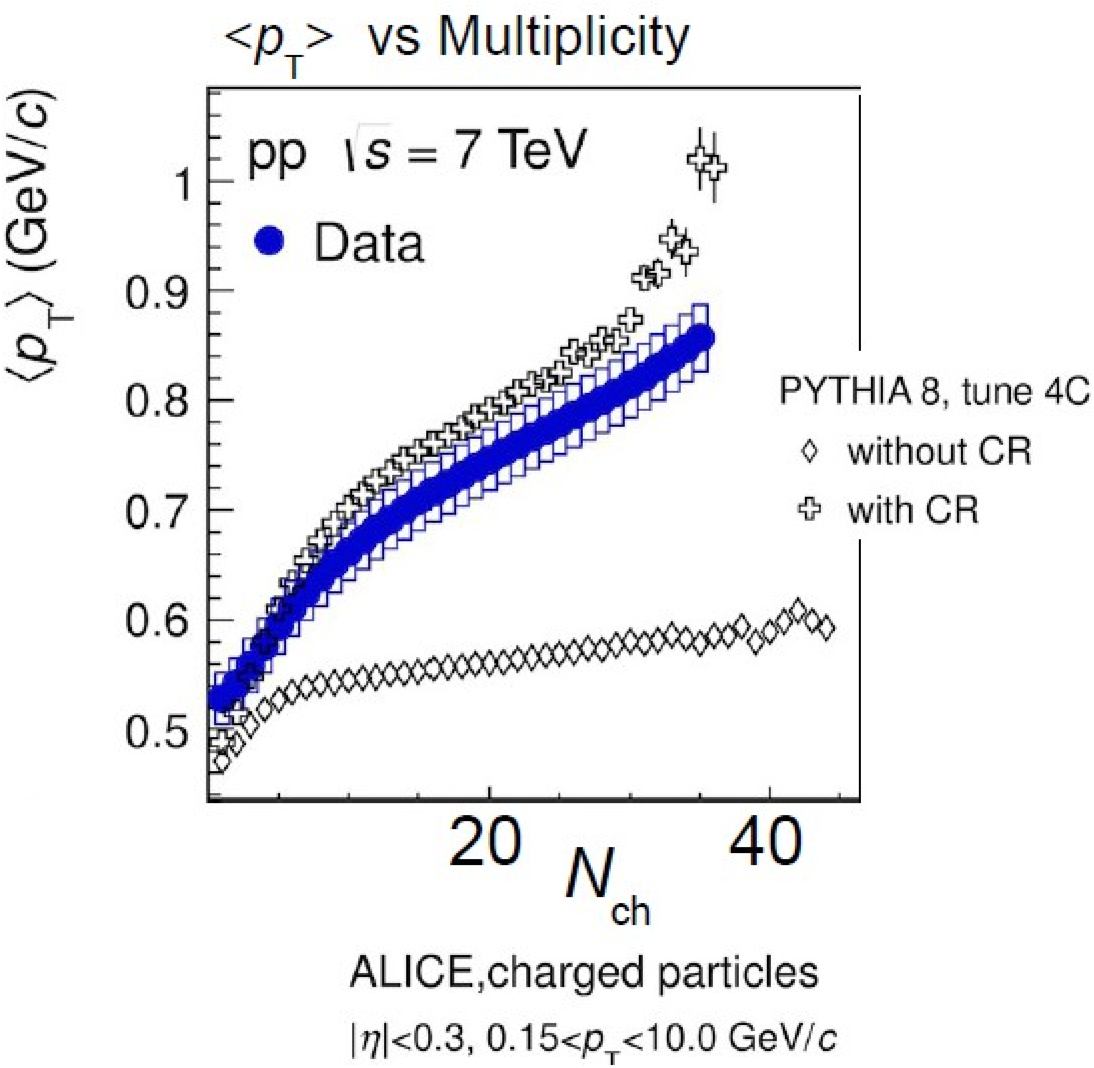


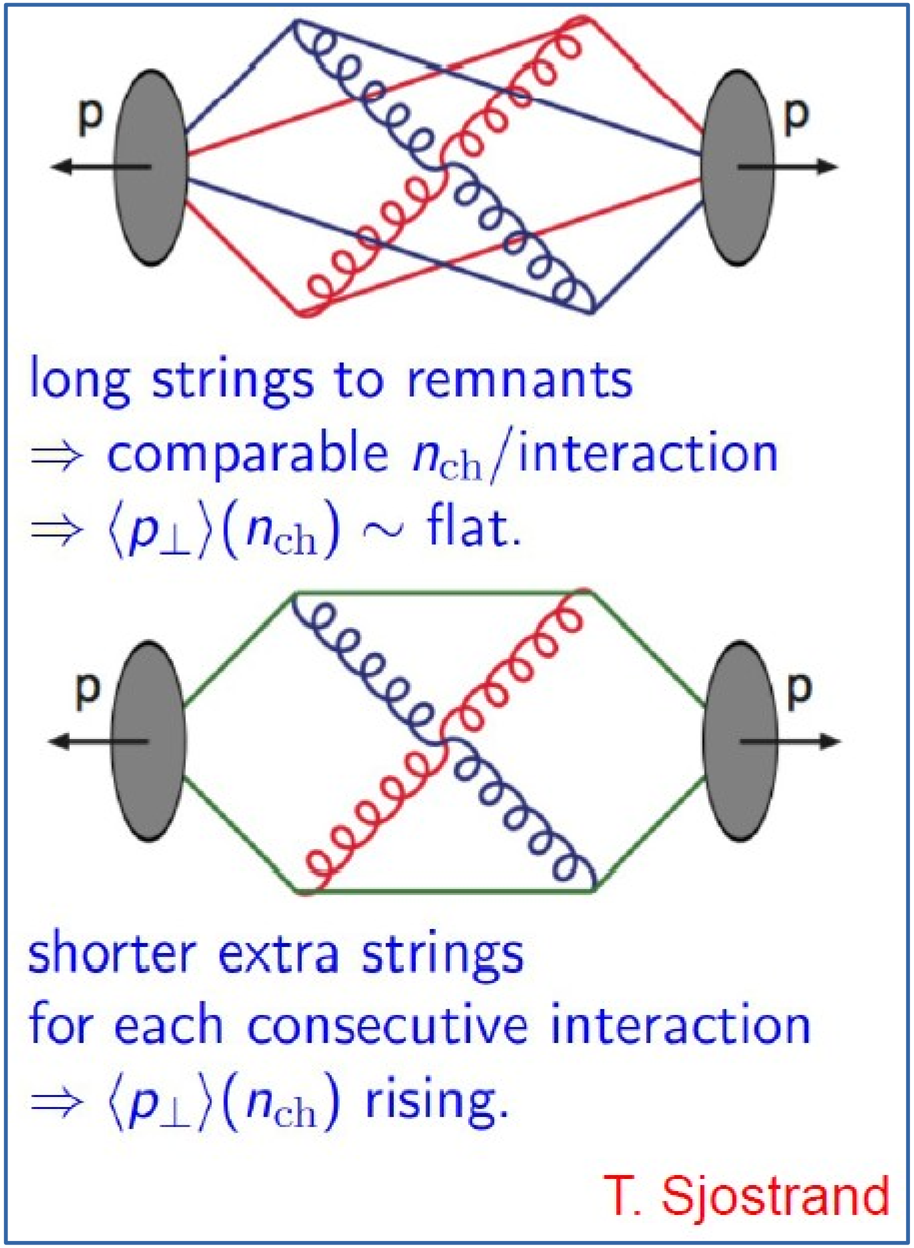


- Spectra feature effects of radial flow
- In Pythia, these can be mimicked by Color Reconnections of strings
- Data in pp and pPb can be related by geometrical scaling

Coherent MPI effects

ALICE, PLB 727 (2013) 371

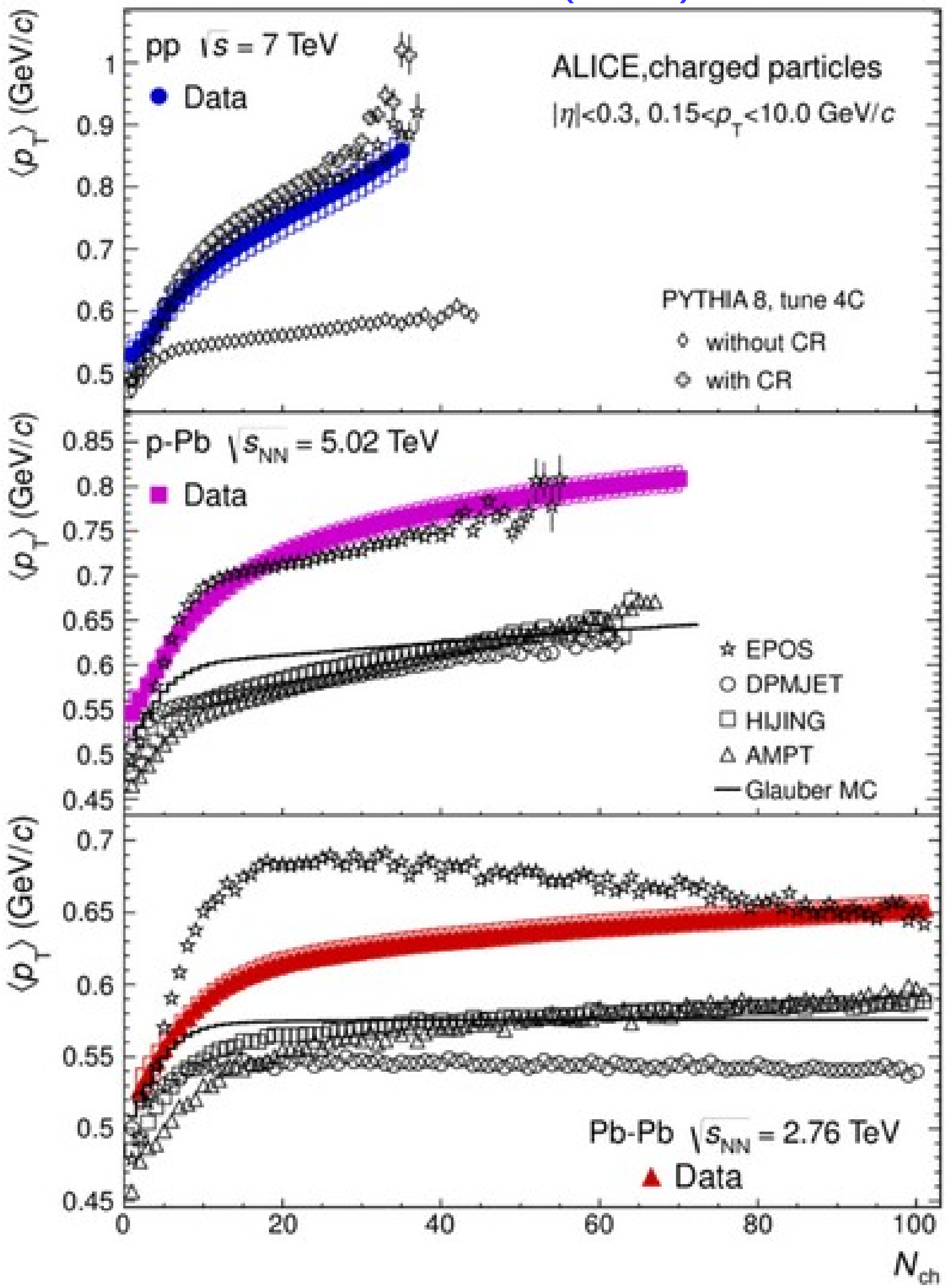




Rise of $\langle p_T \rangle$ can not be reproduced by incoherent superposition of MPI

Average p_T versus N_{ch}

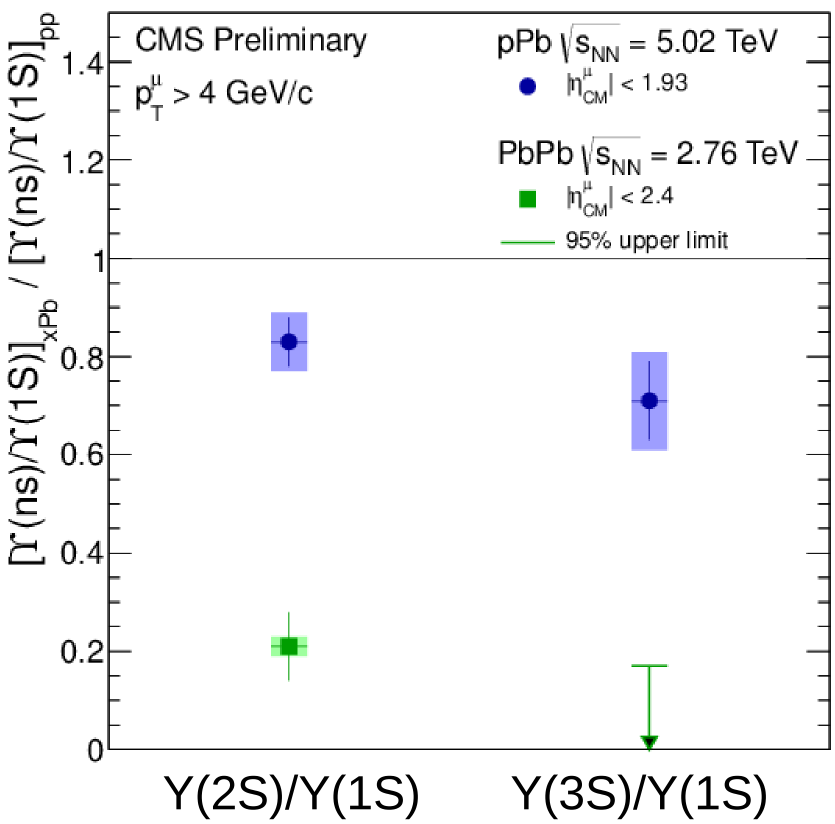
ALICE, PLB 727 (2013) 371

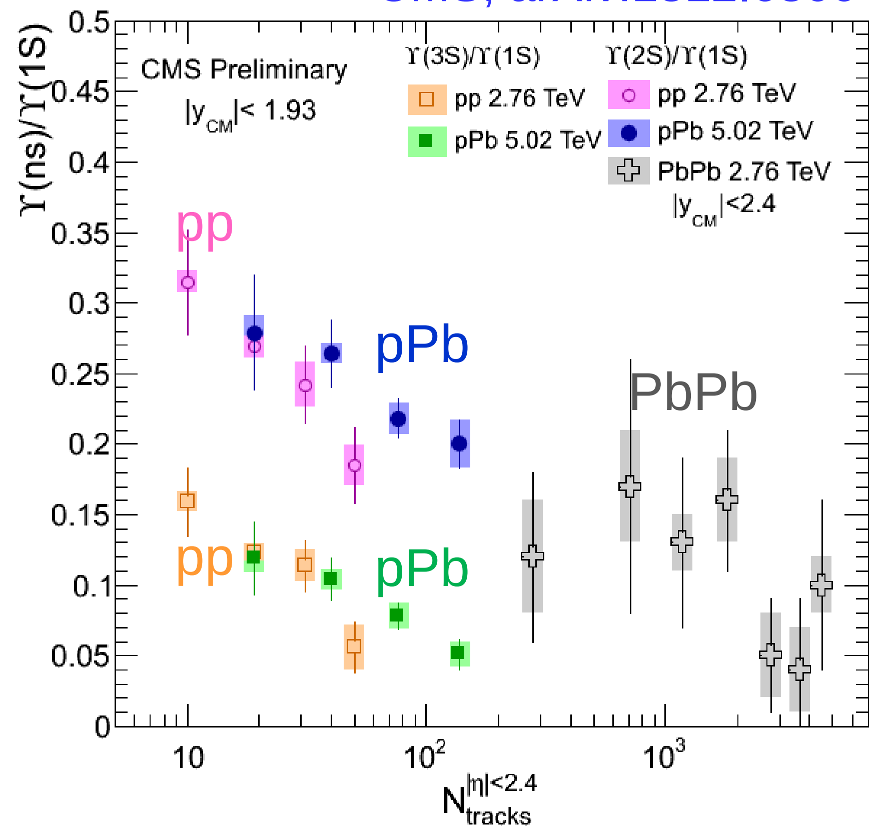


- pp
  - Within PYTHIA model increase in mean p_T can be modeled with Color Reconnections between strings
  - Can be interpreted as collective effect (e.g. Velasquez et al., arXiv:1303.6326v1)
- pPb
  - Increase follows pp up to N_{ch}~14 (90% of pp cross section, pp already biased)
  - Glauber MC (as other models based on incoherent superposition) fails
  - Like in pp: Do we need a (microscopic) concept of interacting strings?
  - EPOS LHC which includes a hydro evolution describes the data (also pp)
- PbPb
  - As expected, incoherent superposition can not describe data

Y(2S)/Y(1S) and Y(3S)/Y(1S)

CMS, arXiv:1312.6300



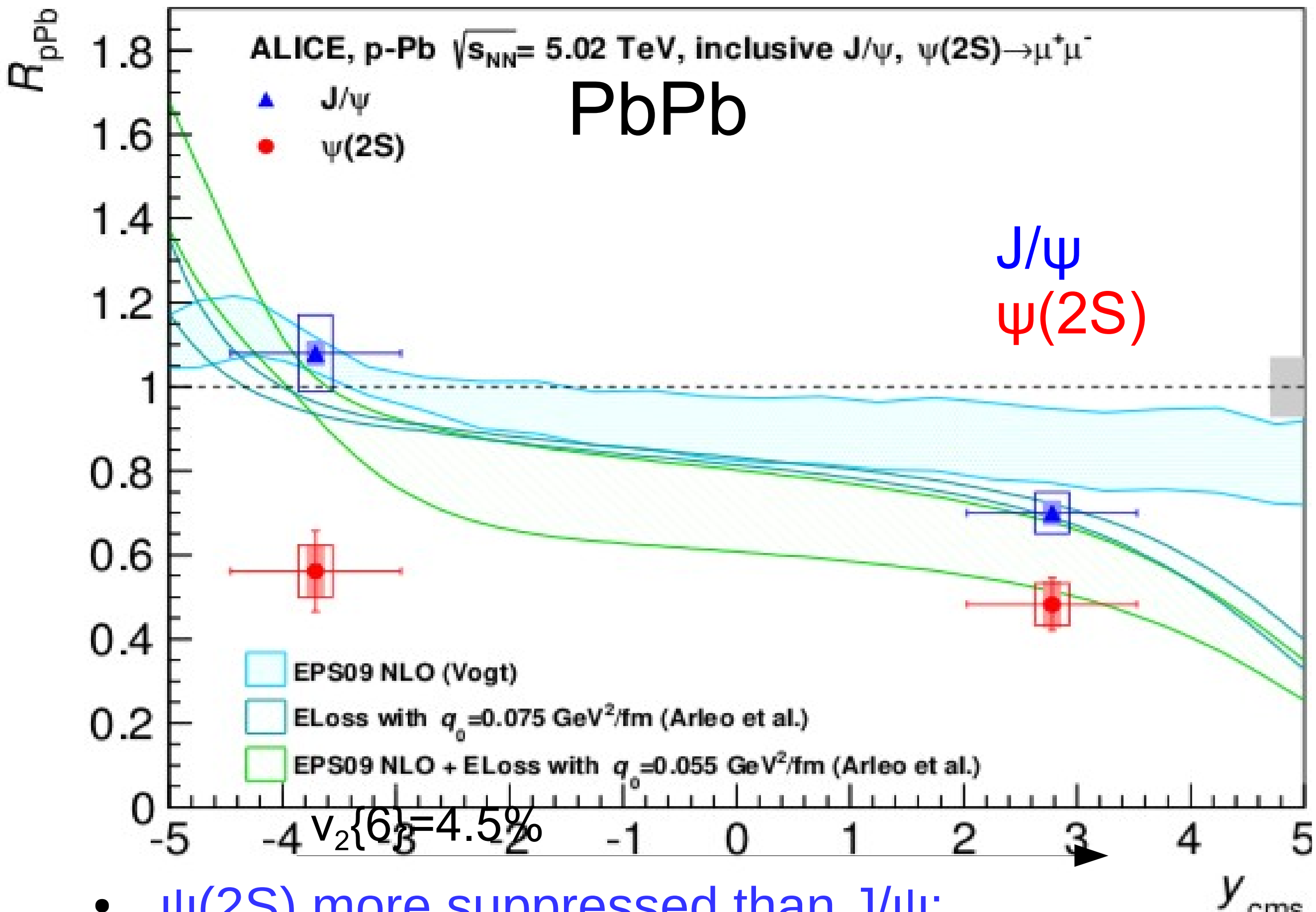


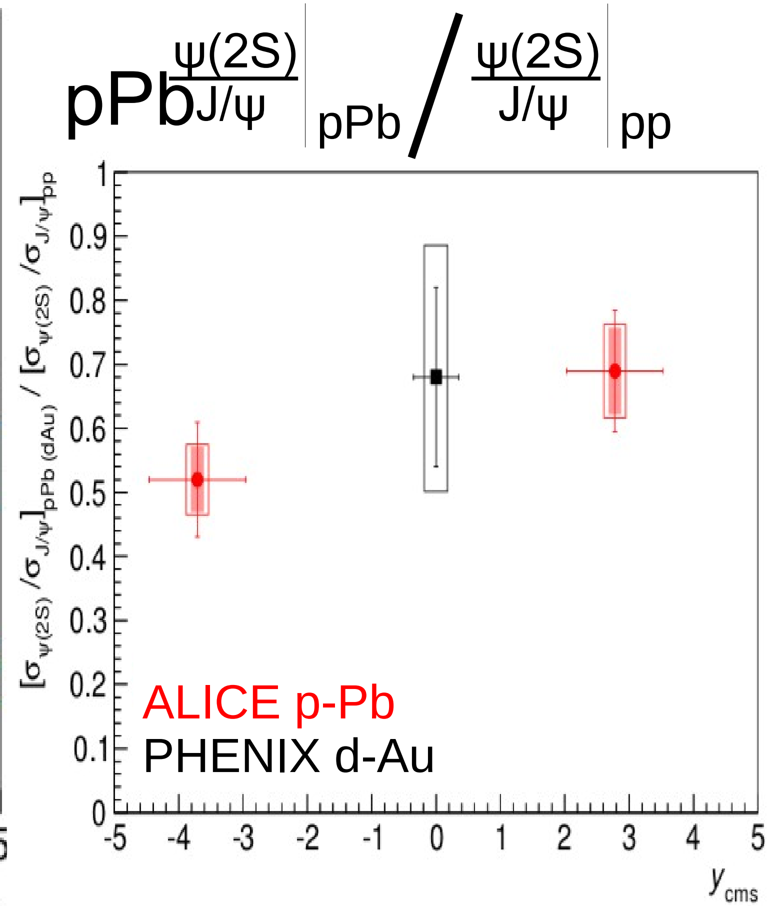
- Strong suppression (even in pPb)
  - Despite similar Q^2
- Final state effect?
  - Suppression in PbPb much stronger!

- Multiplicity scaling of suppression?
- Higher Y states affect multiplicity?
- Same mechanism as in PbPb?

ψ(2S) production in p-Pb

arXiv:1405.3796

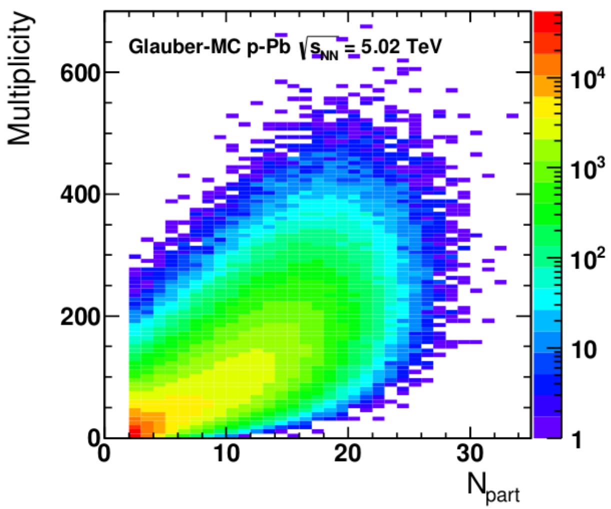


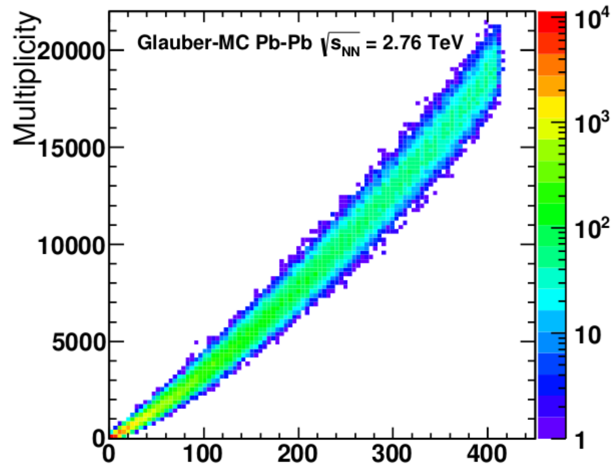


- ψ(2S) more suppressed than J/ψ:
  Not expected by initial state + CNM effects and coherent energy loss
- Stronger relative suppression in backward direction:
  Qualitatively expected from break-up due to comoving system
- But also strong s[illegible] in forward direction
  - Final state effects?

Extra slides about centrality

Centrality from multiplicity in pPb



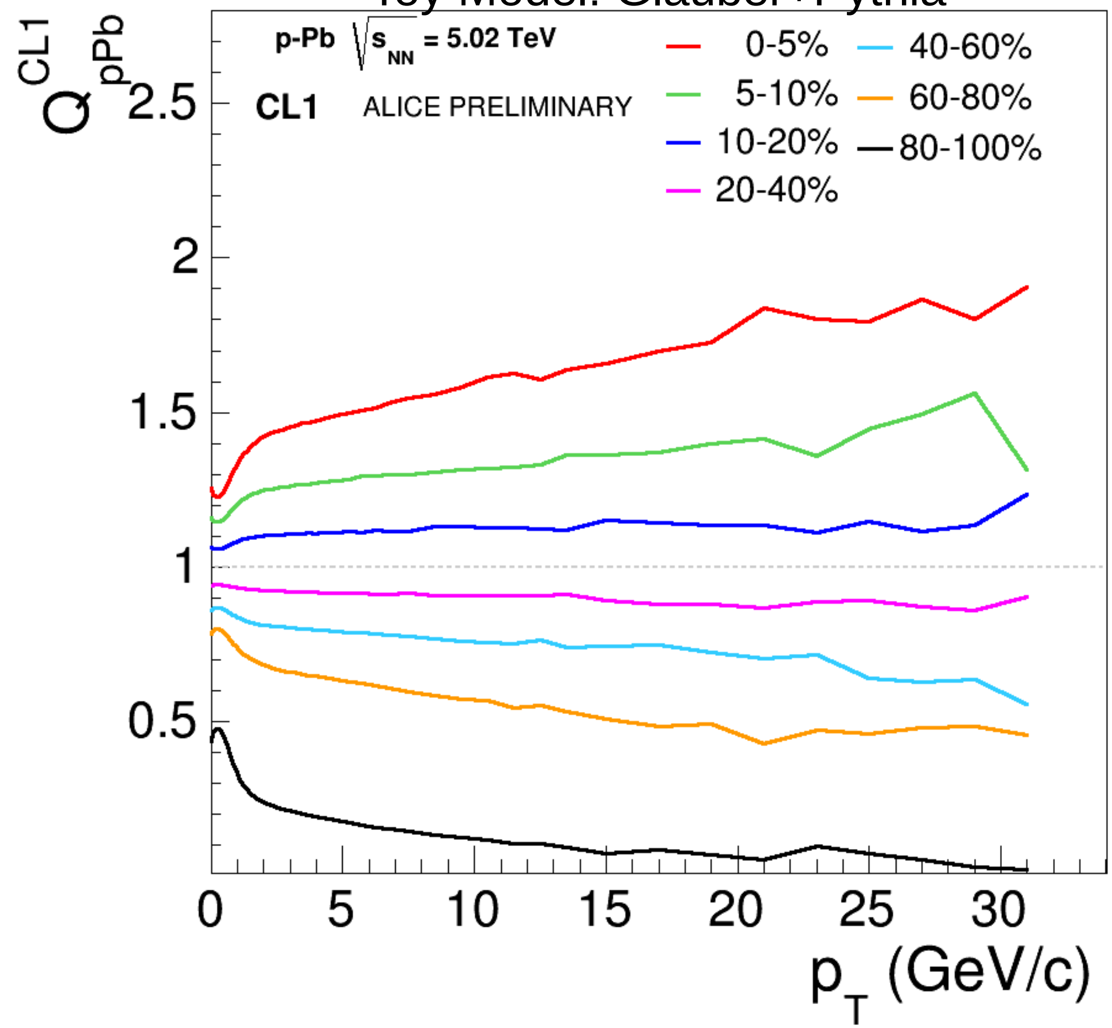


- Small dynamic range
- Several biases are present
  - Multiplicity bias
  - Jet veto bias
  - Geometrical bias
- Include (and indicate) bias in the definition

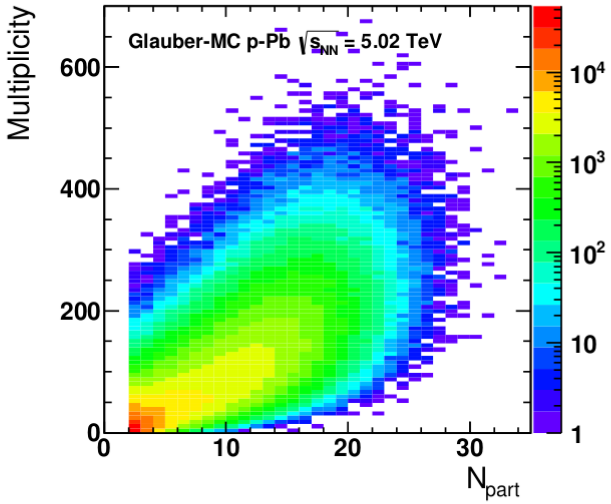
$$Q_{pPb,cent} = \langle N^{Glauber}_{cent} \rangle \frac{\langle dN^{pPb}/dp_T \rangle_{cent}}{dN^{pp}/dp_T}$$

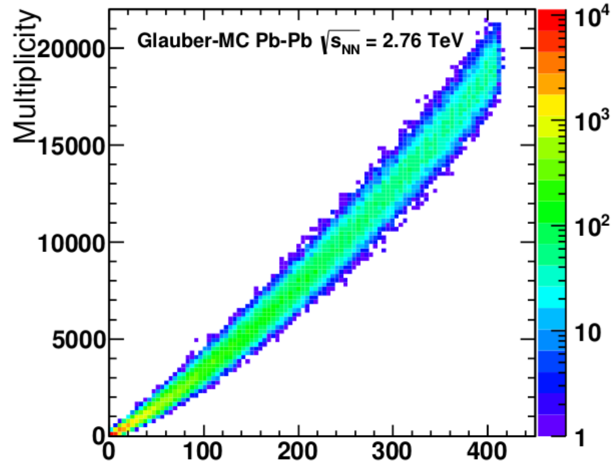
- Note Q_{pPb} is not 1 in absence of nuclear effects

Toy Model: Glauber+Pythia



Centrality from multiplicity in pPb



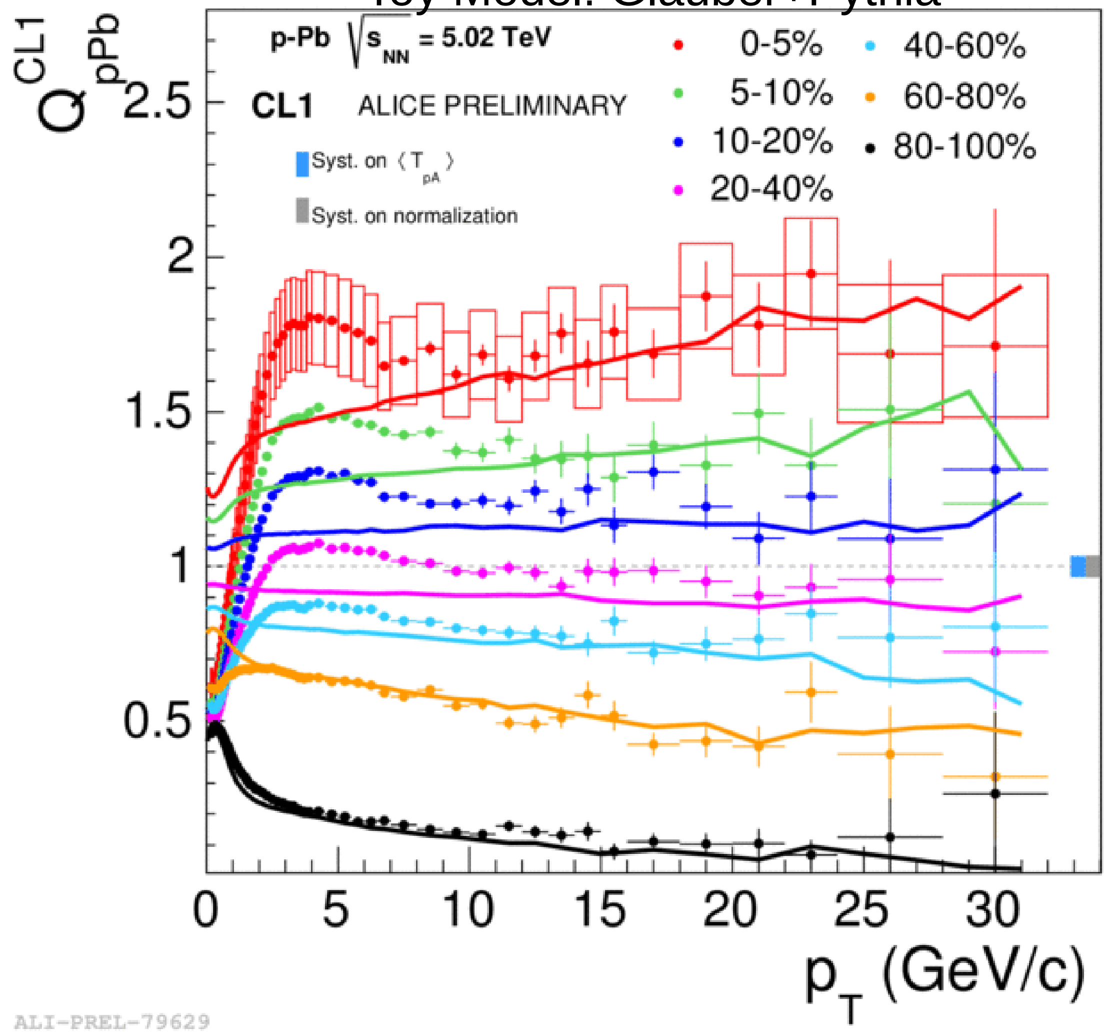


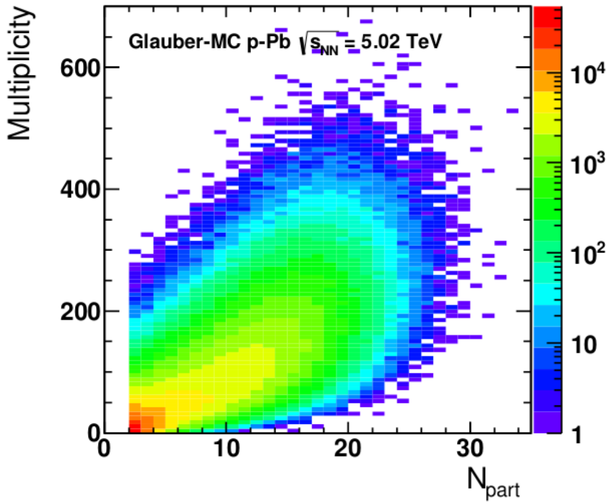
Using hits
at mid-rapidty (CL1)
Toy Model: Glauber+Pythia

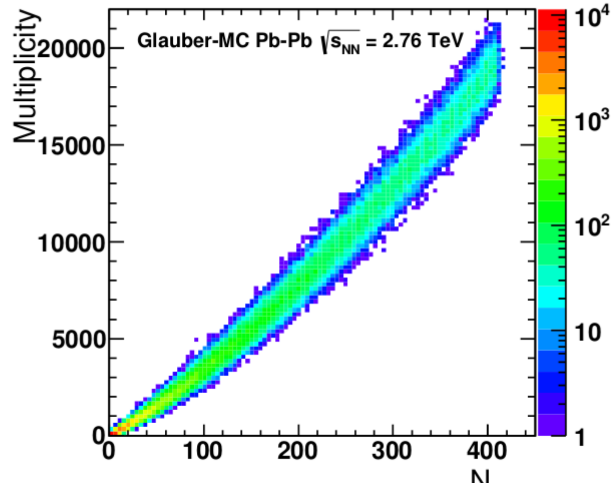
- Small dynamic range
- Several biases are present
  - Multiplicity bias
  - Jet veto bias
  - Geometrical bias
- Include (and indicate) bias in the definition

$$Q_{pPb,cent} = \langle N^{Glauber}_{cent} \rangle \frac{\langle dN^{pPb}/dp_T \rangle_{cent}}{dN^{pp}/dp_T}$$

- Note Q_{pPb} is not 1 in absence of nuclear effects



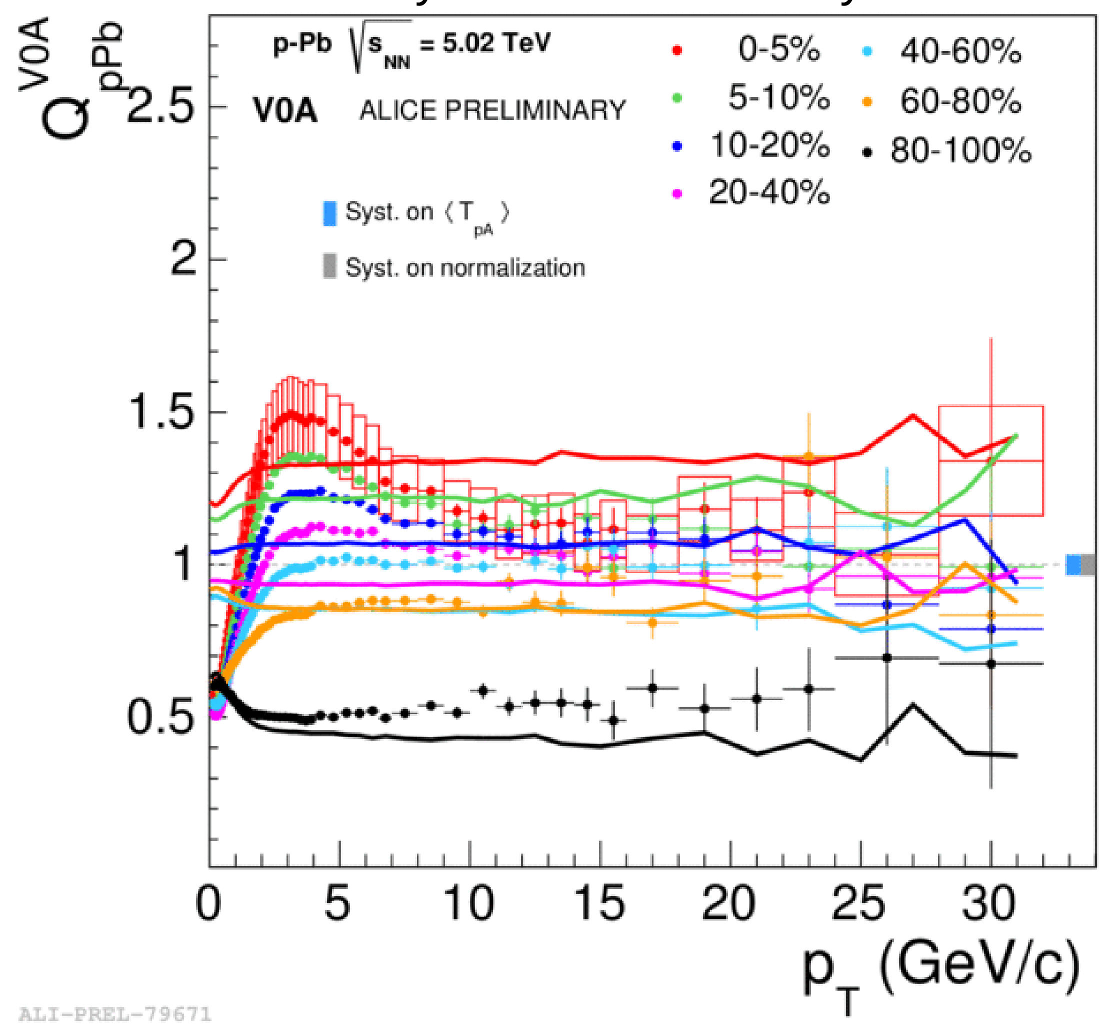




Centrality from multiplicity in pPb

Using V0A amplitudes at forward rapidity

Toy Model: Glauber+Pythia



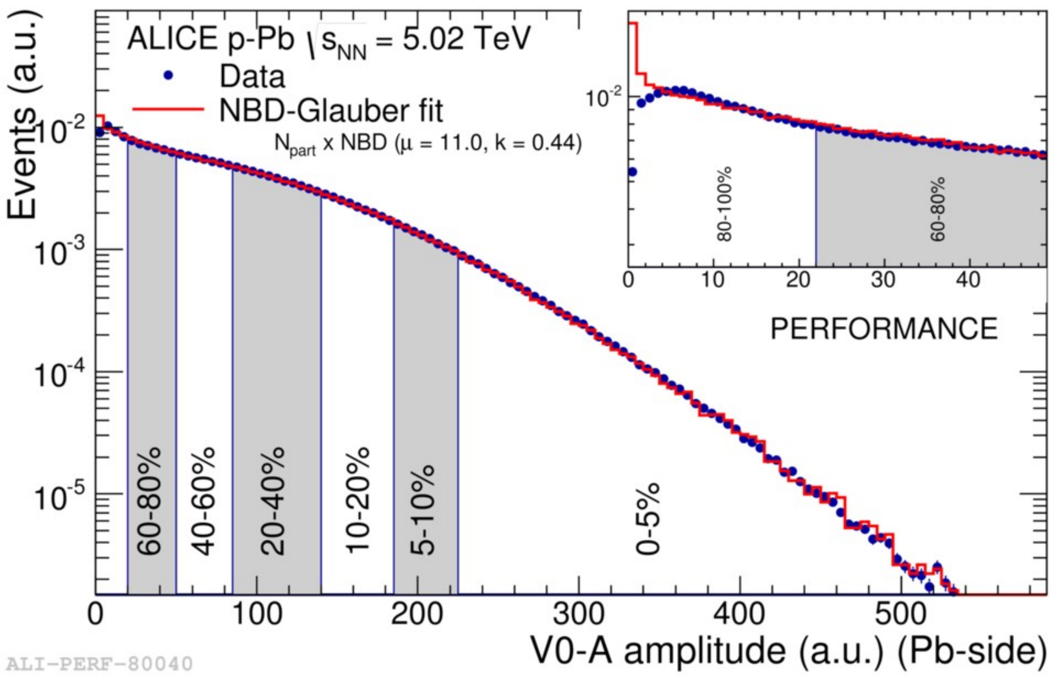
- Small dynamic range
- Several biases are present
  - Multiplicity bias
  - Jet veto bias
  - Geometrical bias
- Include (and indicate) bias in the definition

$$Q_{pPb,cent} = \langle N_{cent}^{Glauber} \rangle \frac{\langle dN^{pPb}/dp_T \rangle_{cent}}{dN^{pp}/dp_T}$$

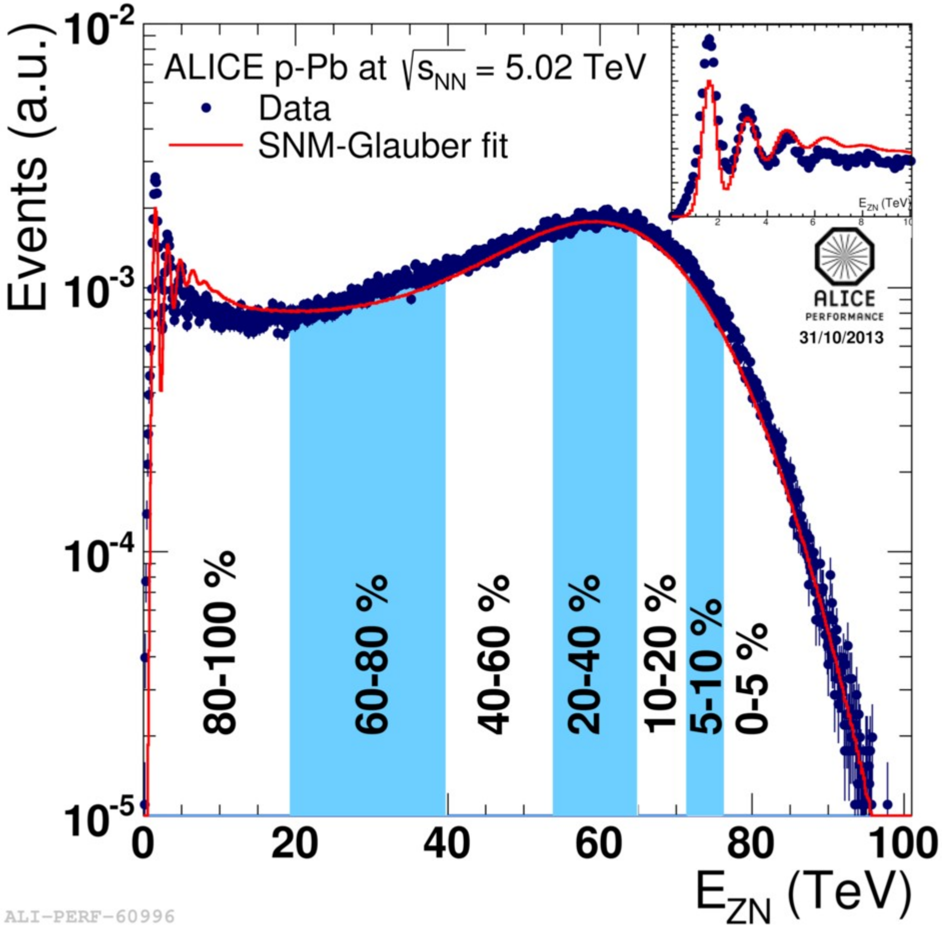
- Note Q_{pPb} is not 1 in absence of nuclear effects

Forward neutron energy vs multiplicity

NBD method

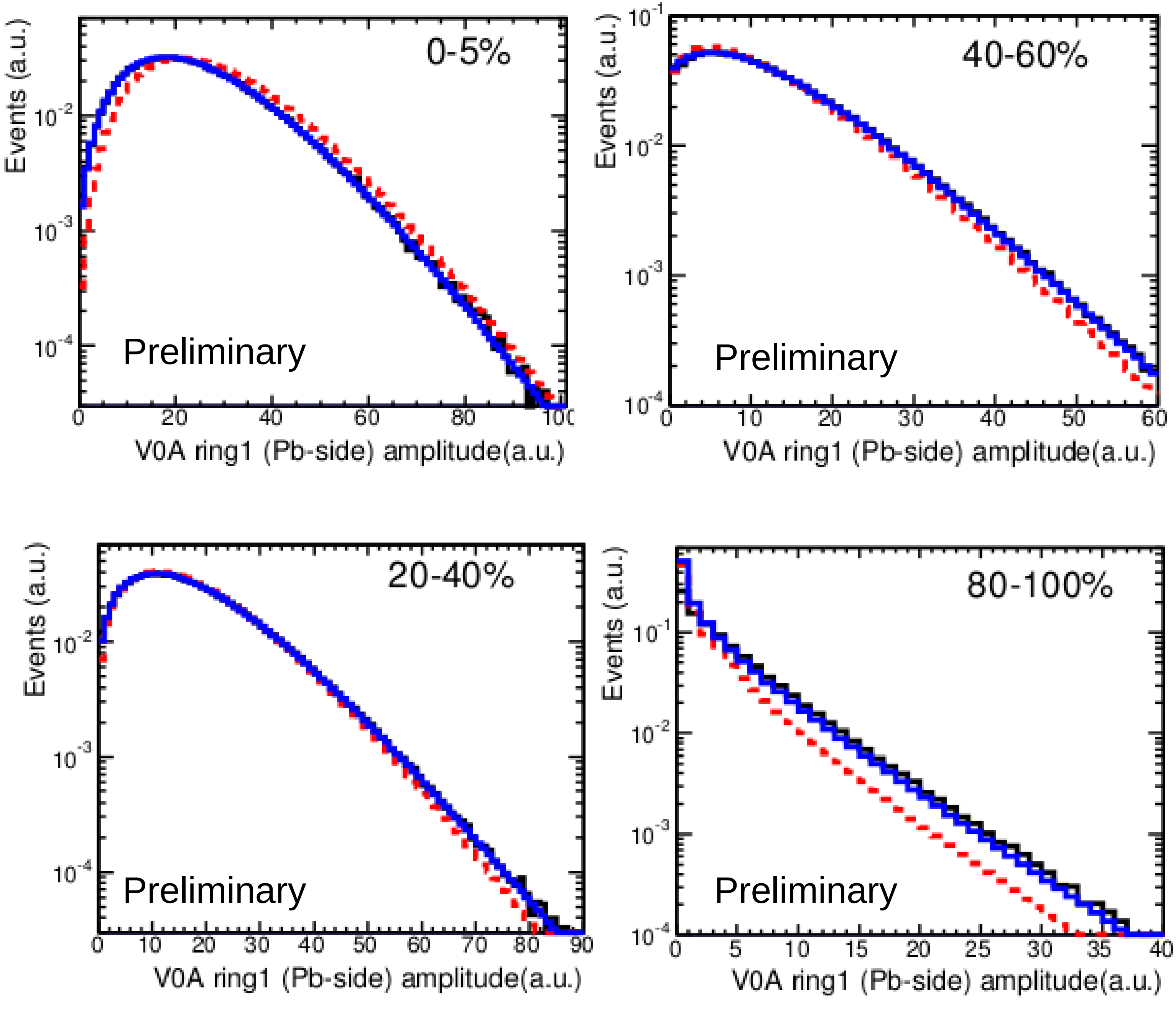


SNM method



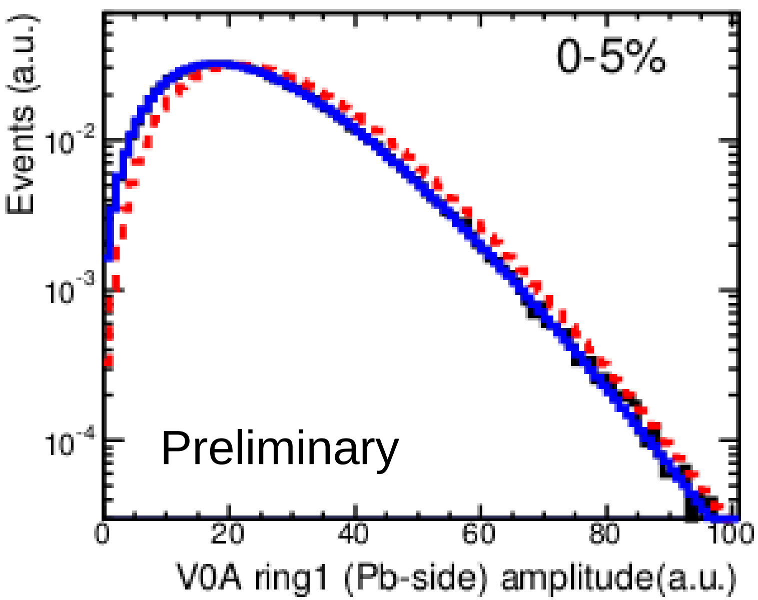
Correlation between forward neutron energy and multiplicity?

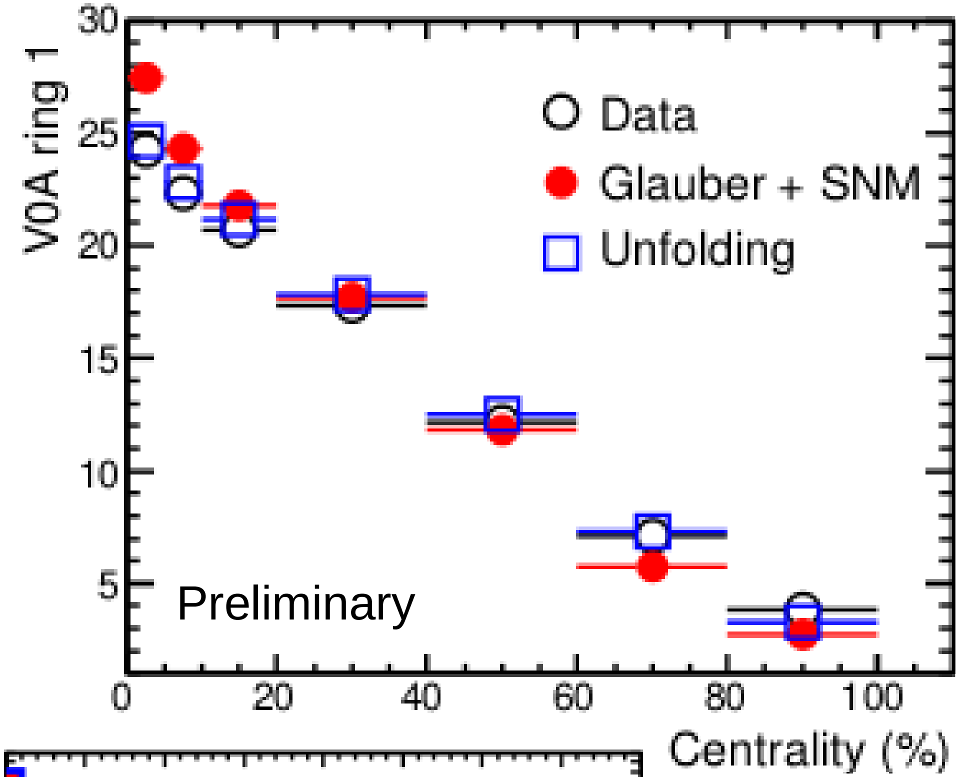
Correlation of V0A and ZNA

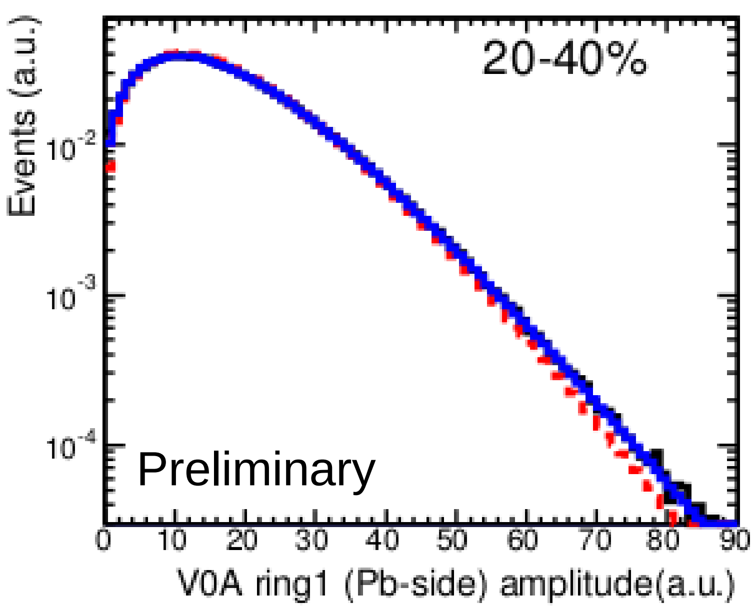


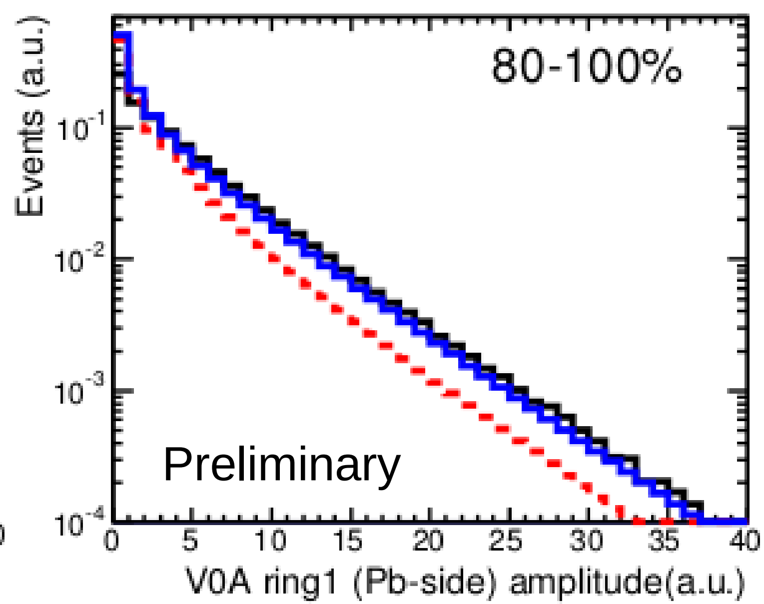
V0A in ZNA slices
Convolution of P(ZNA) x NBD(V0A)
Unfolded

Correlation of V0A and ZNA









V0A in ZNA slices
Convolution of P(ZNA) x NBD(V0A)
Unfolded

ZN slicing +scaling of data (Hybrid Method)

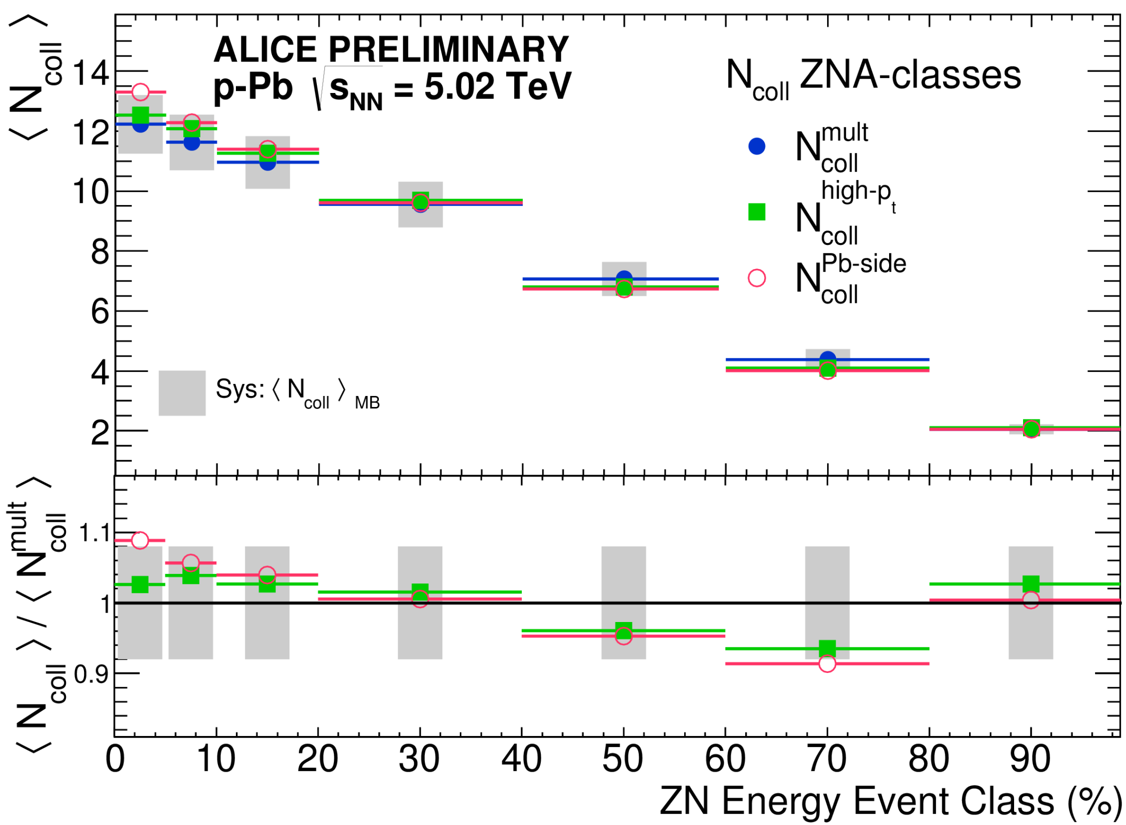
1) Assume: ZN insensitive to dynamical biases → slice events in ZN
2) Assume scaling
   a) Mid-rap dN/dη scales with N_{part}
   b) Pb-side dN/dη scales with N_{part}^{target} (= N_{coll} in pA)
   c) Yield at high-p_T scales with N_{coll}

$$\langle N_{part}\rangle_i^{mult} = \langle N_{part}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$

$$\langle N_{coll}\rangle_i^{mult} = \langle N_{part}\rangle_i^{mult} - 1$$

$$\langle N_{coll}\rangle_i^{Pb-side} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$

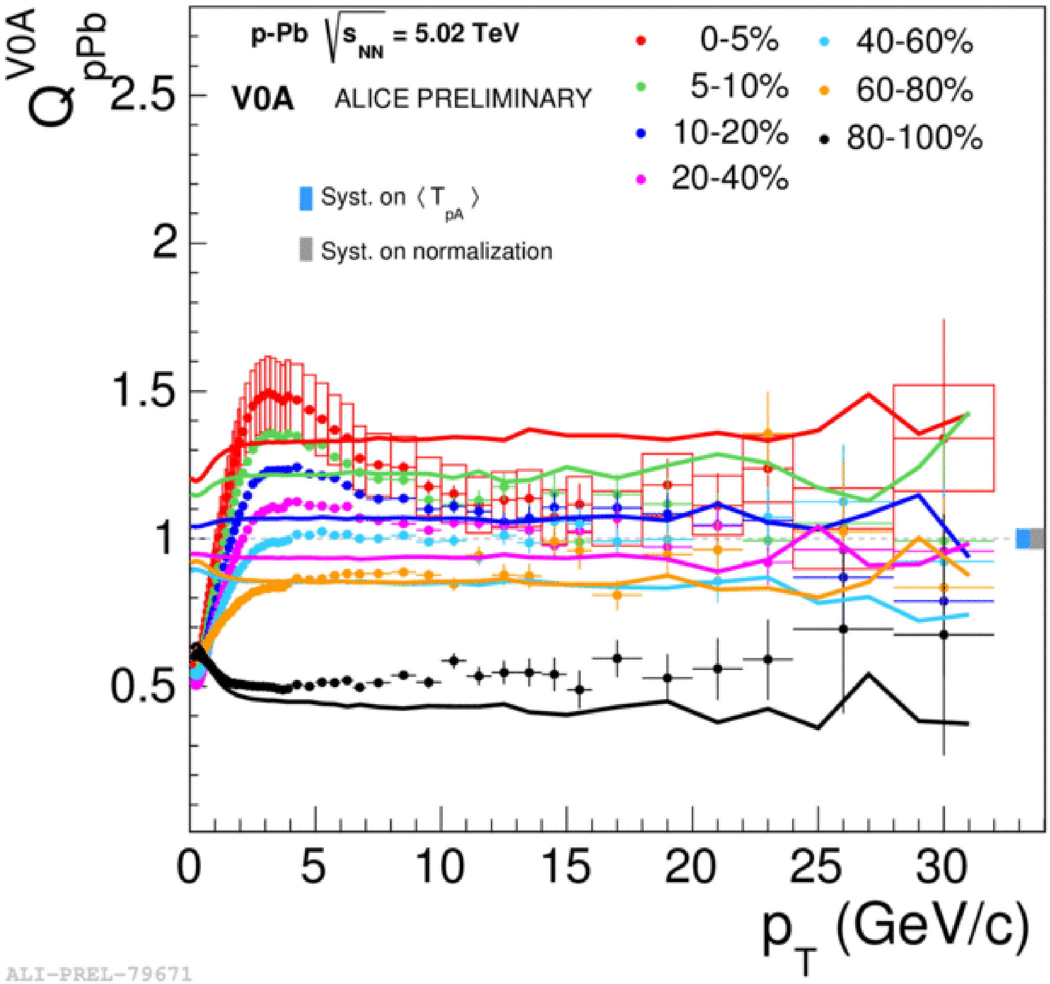
$$\langle N_{coll}\rangle_i^{high-p_T} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S\rangle_i}{\langle S\rangle_{MB}}$$



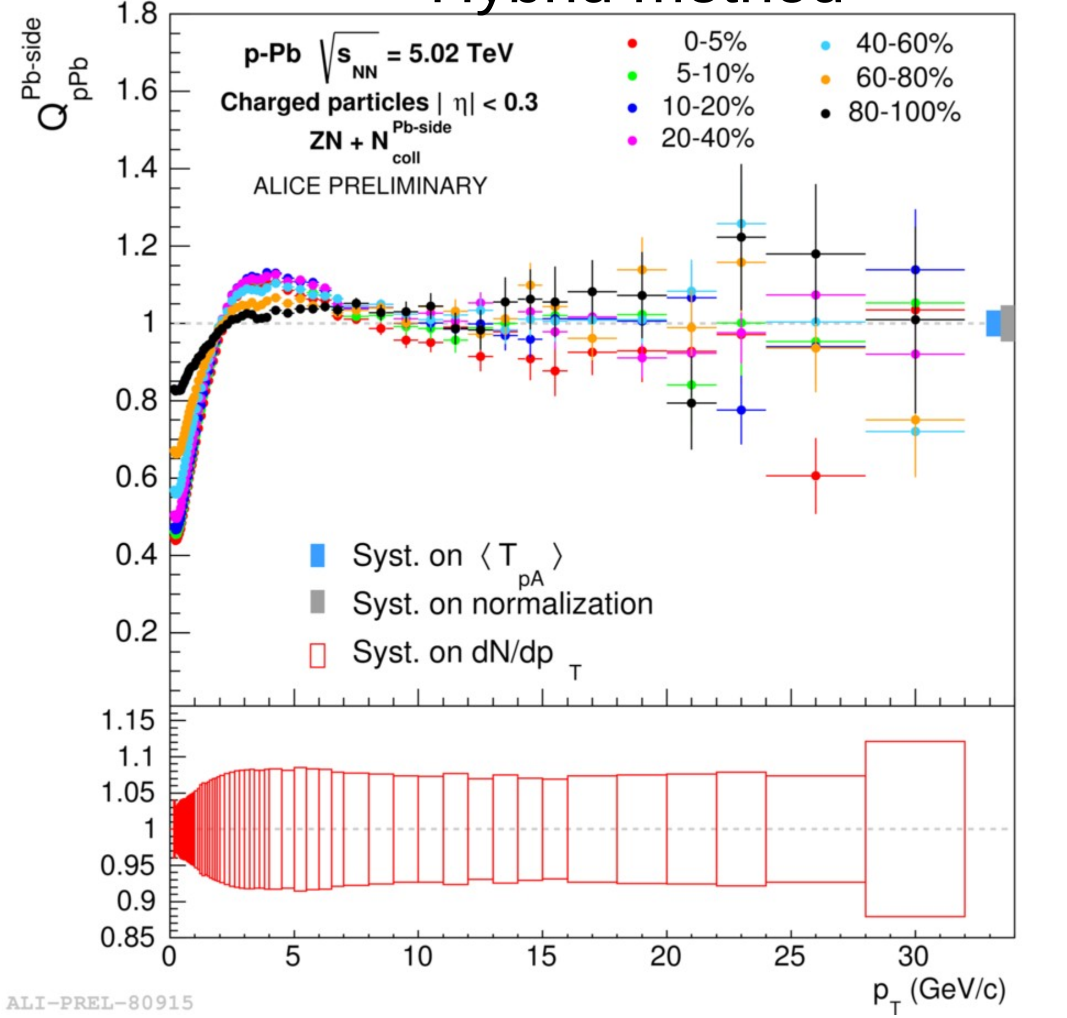
- All values within at most 10% → consistency of assumptions
- This does not yet prove the validity of any (or all) of these assumptions

Charged particle QpPb

V0A NBD



Hybrid method



Hybrid method:

- Charged particle Q_{pPb} consistent with unity at high p_T
- Cronin peak develops with multiplicity