High-pT particle production in p-Pb collisions with ALICE at the LHC

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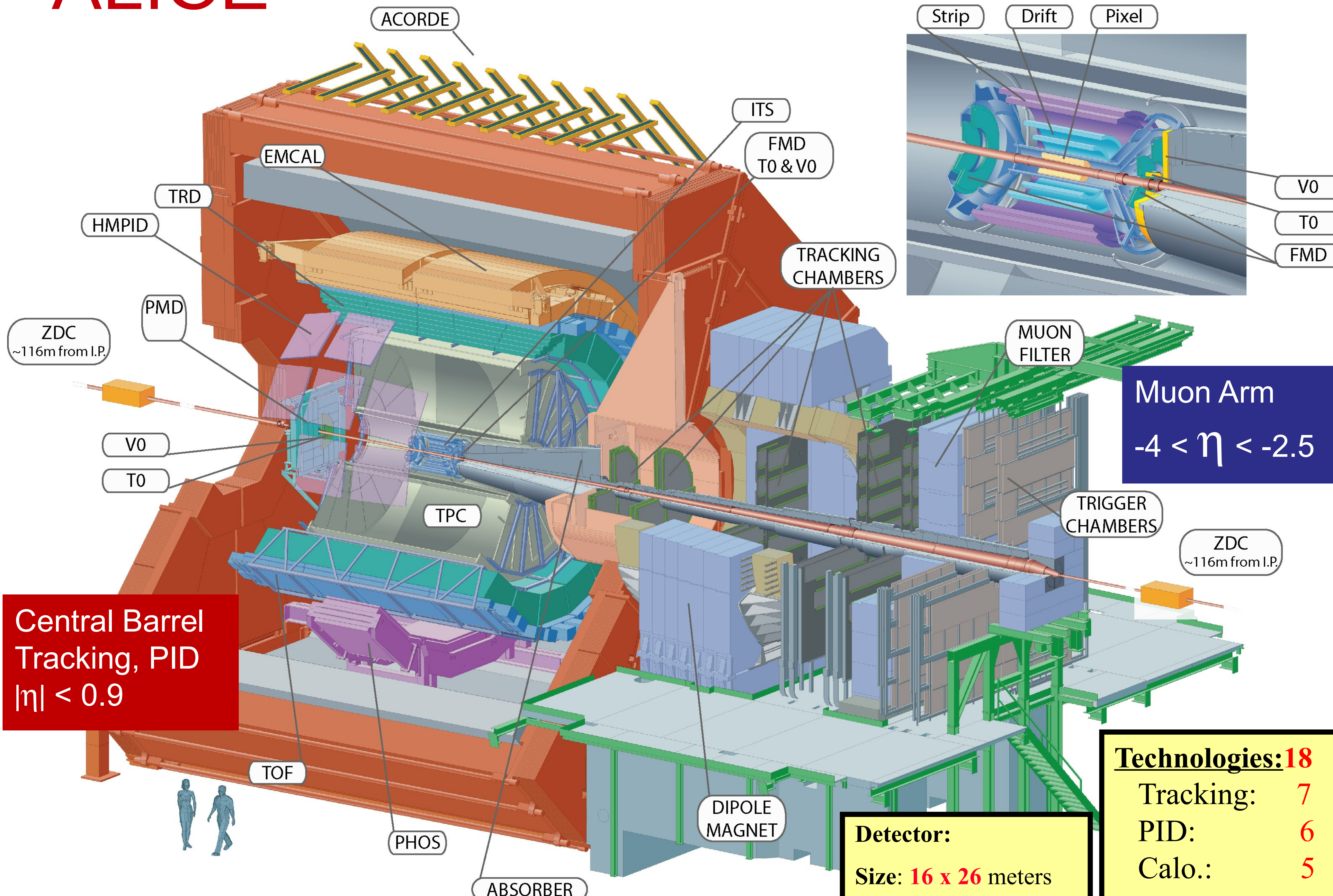
on behalf of the ALICE Collaboration

Nucleus-Nucleus 2015
Catania (Italy)

ALICE



Muon Arm

$-4 < \eta < -2.5$

Central Barrel
Tracking, PID
$|\eta| < 0.9$

Detector:

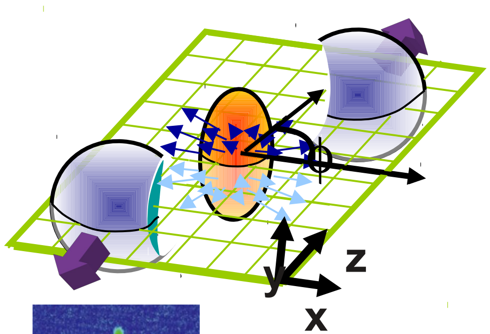
Size: 16 x 26 meters

Weight: 10,000 tons

Technologies: 18

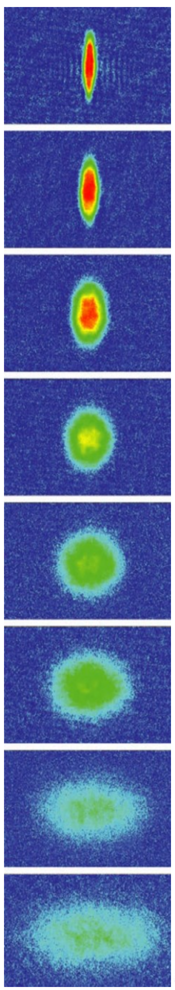
Tracking: 7
PID: 6
Calo.: 5

Pb-Pb: Signs of Collectivity

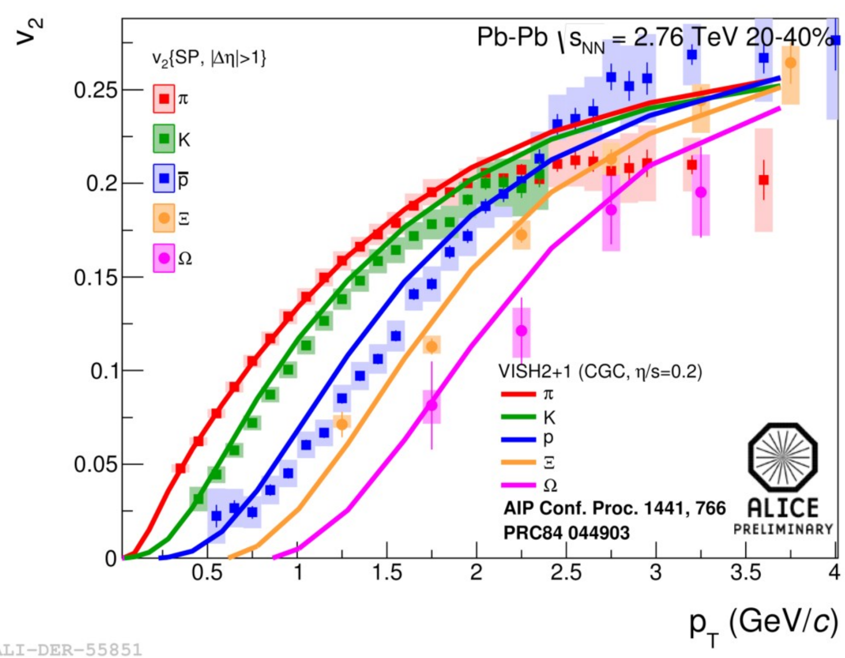


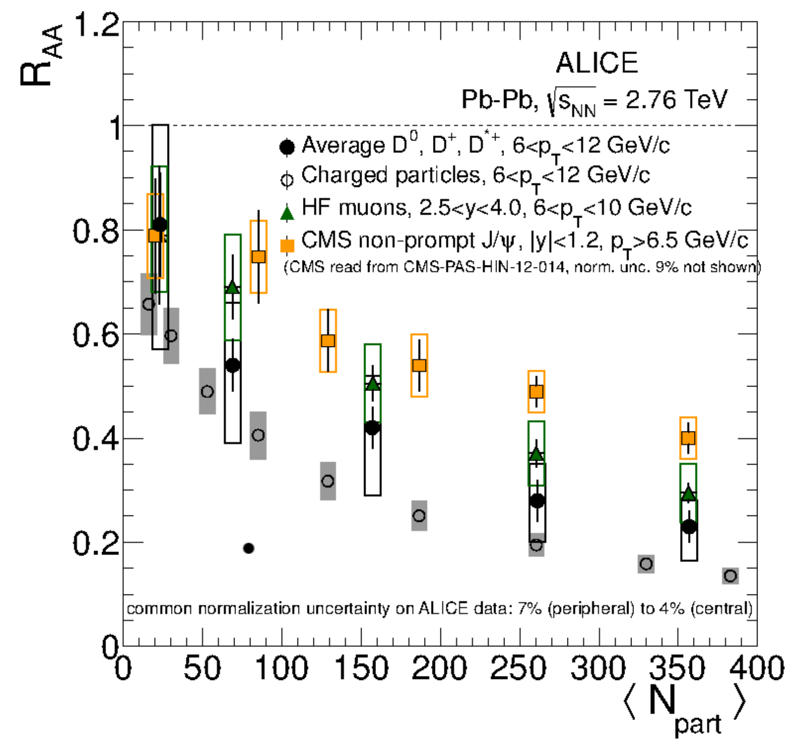
Search for medium effects with
- nuclear modification factors
- strength of collective phenomena *(mean free path)*

$$R_{AA} = \frac{Yield\ in\ A+A}{N_{binary} \times Yield\ in\ p+p}$$



Collective behavior close to ideal fluid behavior described by hydrodynamics

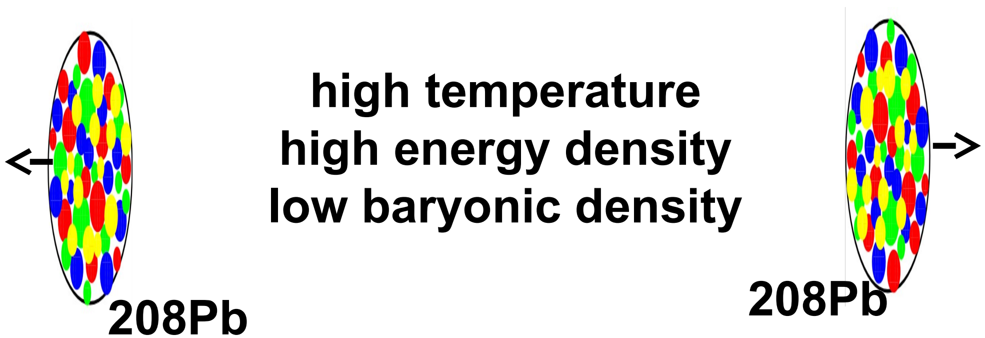




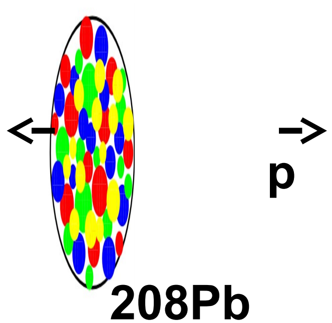
Large radiative energy loss in the medium
Hints of mass hierarchy

Proton-Nucleus Collisions

- In high-energy nucleus-nucleus collisions, large energy density (ε >> 1 GeV/fm^3) over large volume (>> 1000 fm^3)



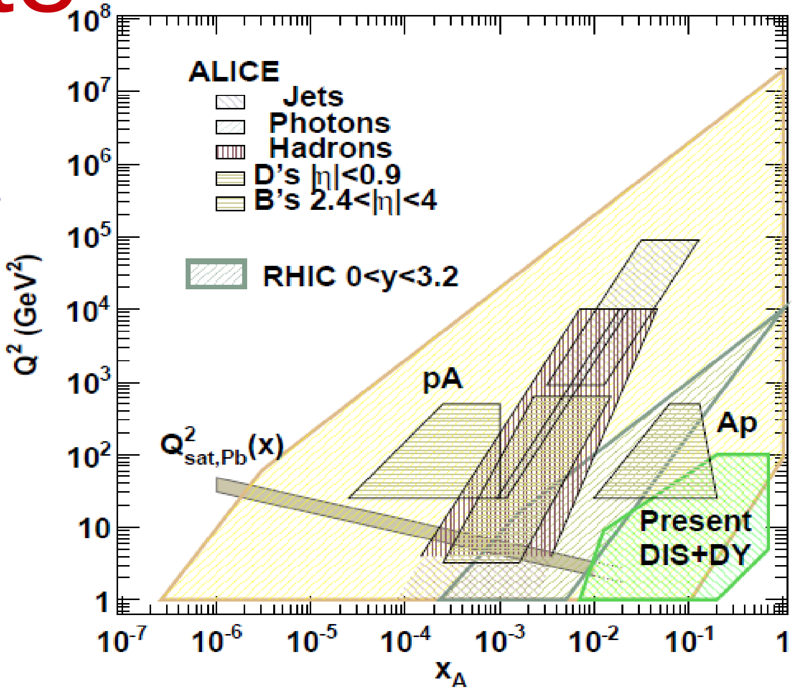
- In high-energy proton-nucleus collisions, large energy densities (?) in a <u>small volume</u>

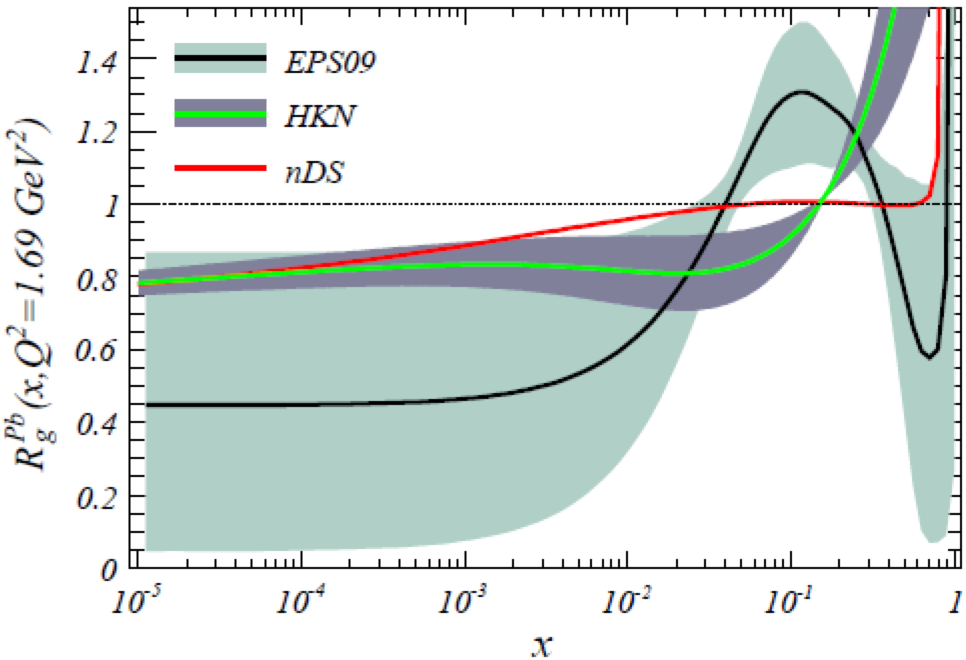


- **Control experiment**:
  - calibrate the initial-modification of hard probes (jets, heavy quarks, quarkonia),
  - single-out final-state effects (hot medium) in Pb-Pb
- Explore **new territory in QCD** (low-x):
  - high gluon density in the initial state (CGC, gluon-shadowing?)
  - potentially, high energy density in the final state, but in a small volume → surprises?

Initial State

Explore new territory in QCD (low-x):
- No data in the (x,Q^2) region of LHC
→ Parton Distribution Functions: large uncertainties
- Large gluon density for p and even more for Pb
GLUON SHADOWING
Ratio nuclear-nucleon PDF:
shadowing/anti-shadowing from constructive/destructive interference of the amplitudes due to multiple scattering



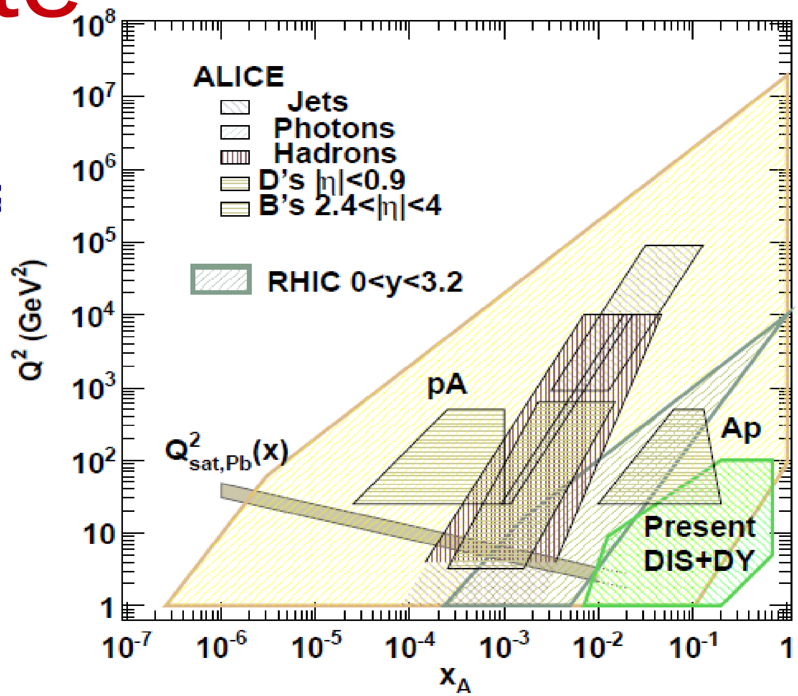


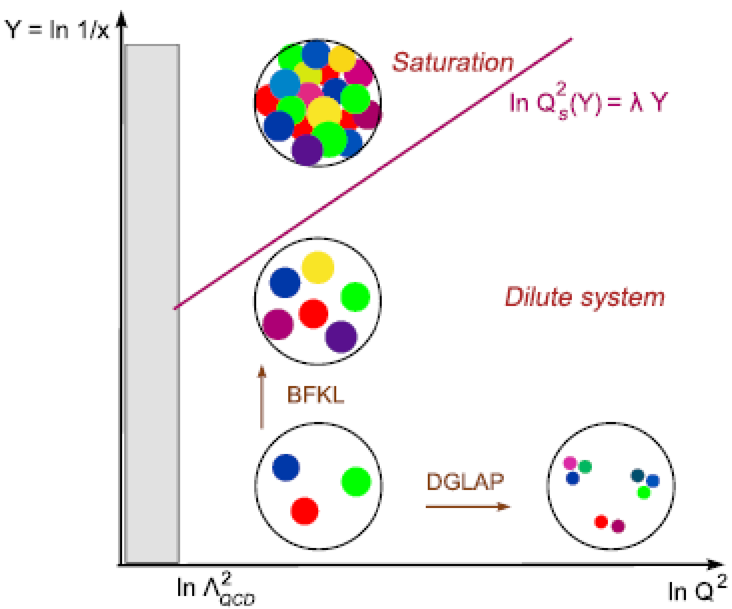
Gluon Shadowing
increases with decreasing x and Q^2
some of the partons are obscured by others in front of them
→ decrease of the scattering amplitude relative to what is expected from incoherent independent scattering

Salgado et al, arxiv: 1105.3919
Helenius et al., JHEP 1207 (2012) 073

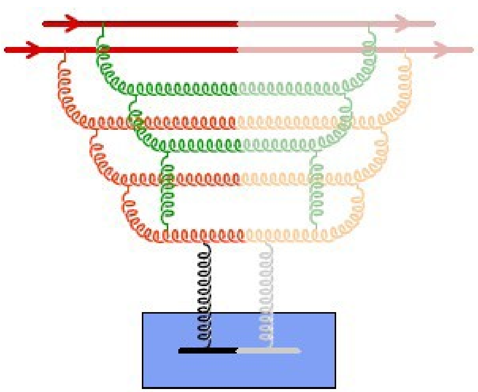
Initial State

Explore new territory in QCD (low-x):
- No data in the (x,Q^2) region of LHC
→ Parton Distribution Functions: large uncertainties
- Large gluon density for p and even more for Pb
COLOR GLASS CONDENSATE
parton evolution proceeds via soft collinear gluon emission



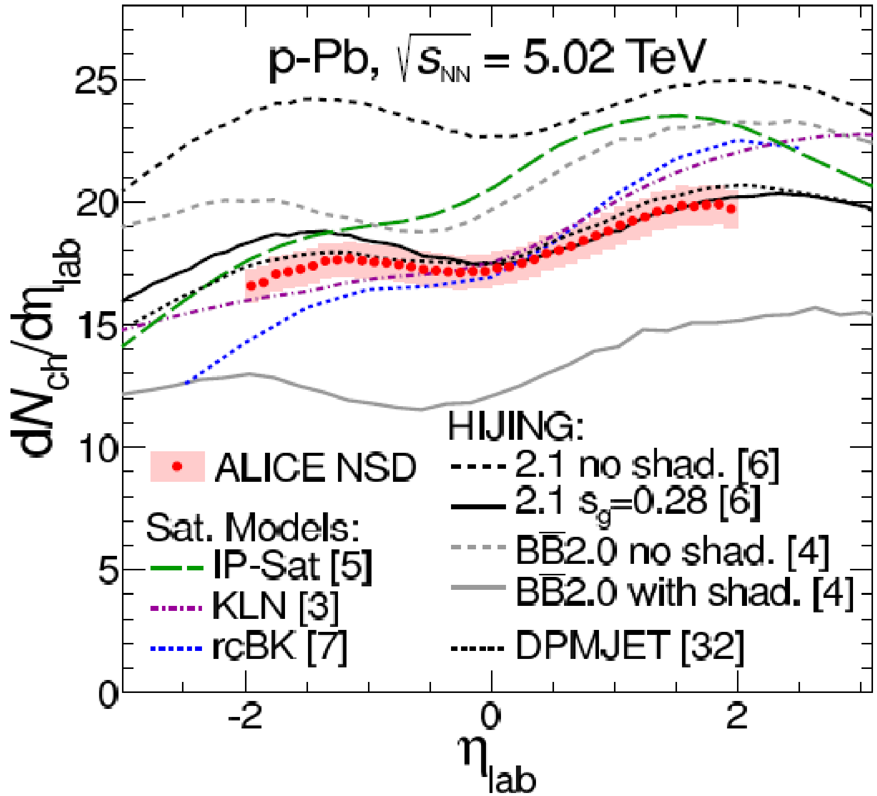


At a characteristic momentum scale (saturation scale) gluon density is large enough that parton evolution becomes non-linear → parton recombination.
Gluons act as frozen color sources (CGC)
Scale depends on x and A
→ geometric scaling



$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

Multiplicity in pA

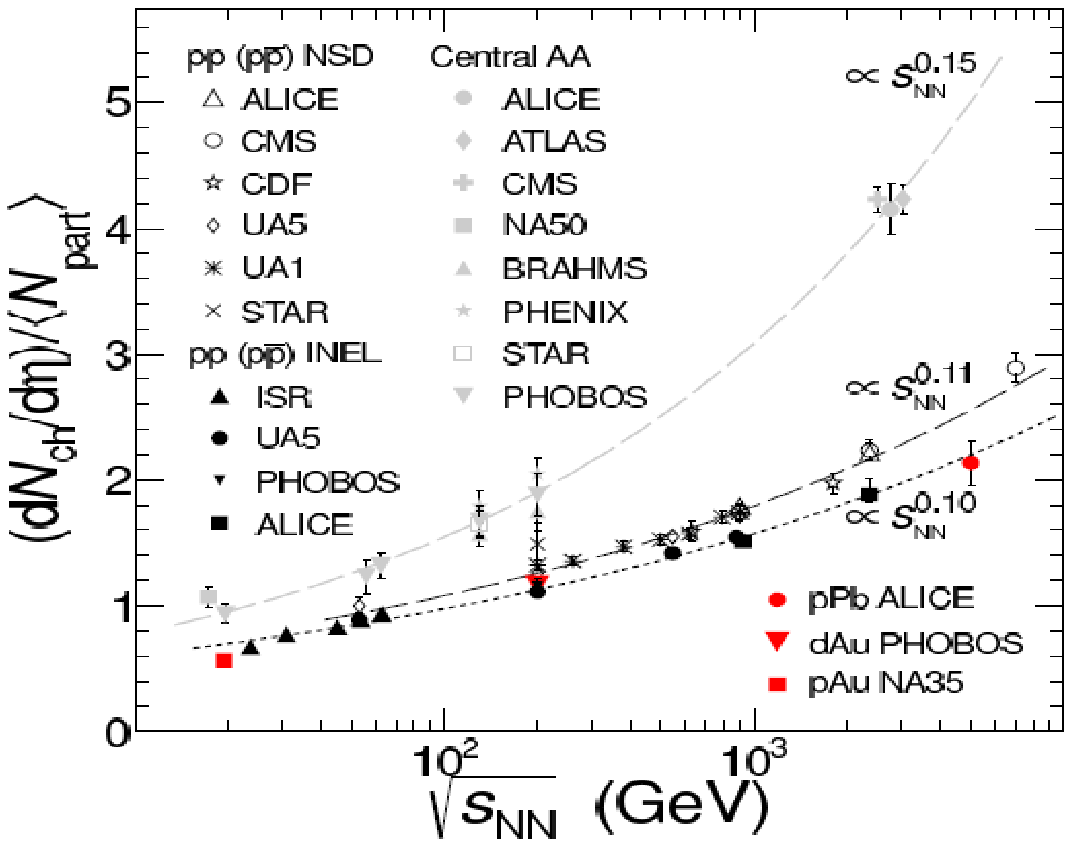


RAPIDITY DISTRIBUTION

- Data favors models that incorporate shadowing
- Saturation models predict much steeper η-dependence which is no seen in the data

ENERGY DEPENDENCE

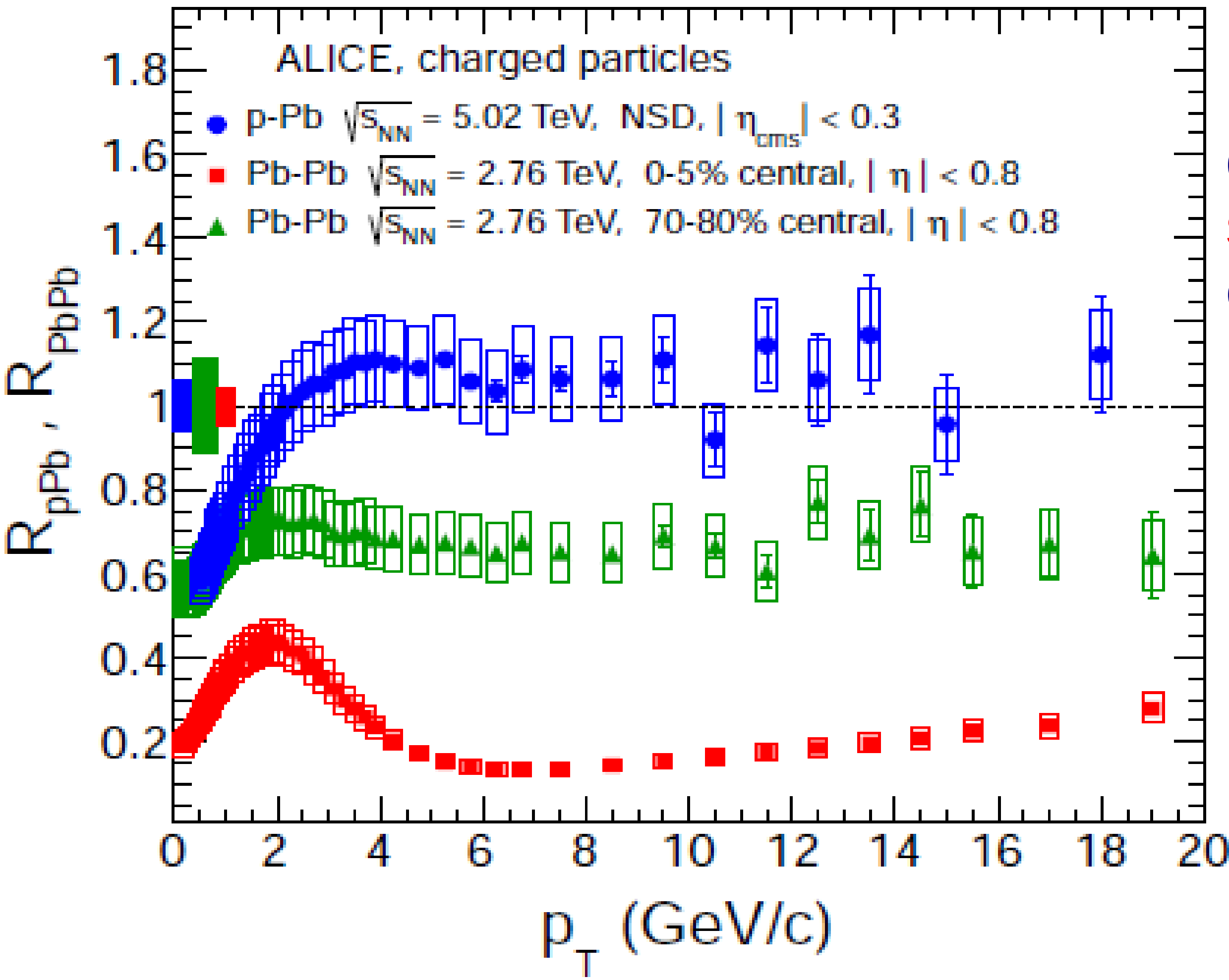
- ~15%below NSD pp collisions
- Similar to inelastic pp collisions
- 84% higher than in d–Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV.



ALICE Coll. Phys. Rev. Lett. 110, 032301 (2013)

R_{pA}

$$R_{AA} = \frac{Yield\ in\ A+A}{N_{binary} \times Yield\ in\ p+p}$$



R_{AA} (R_{pA}): test if AA (pA) can be described by incoherent superposition of Ncoll binary collisions

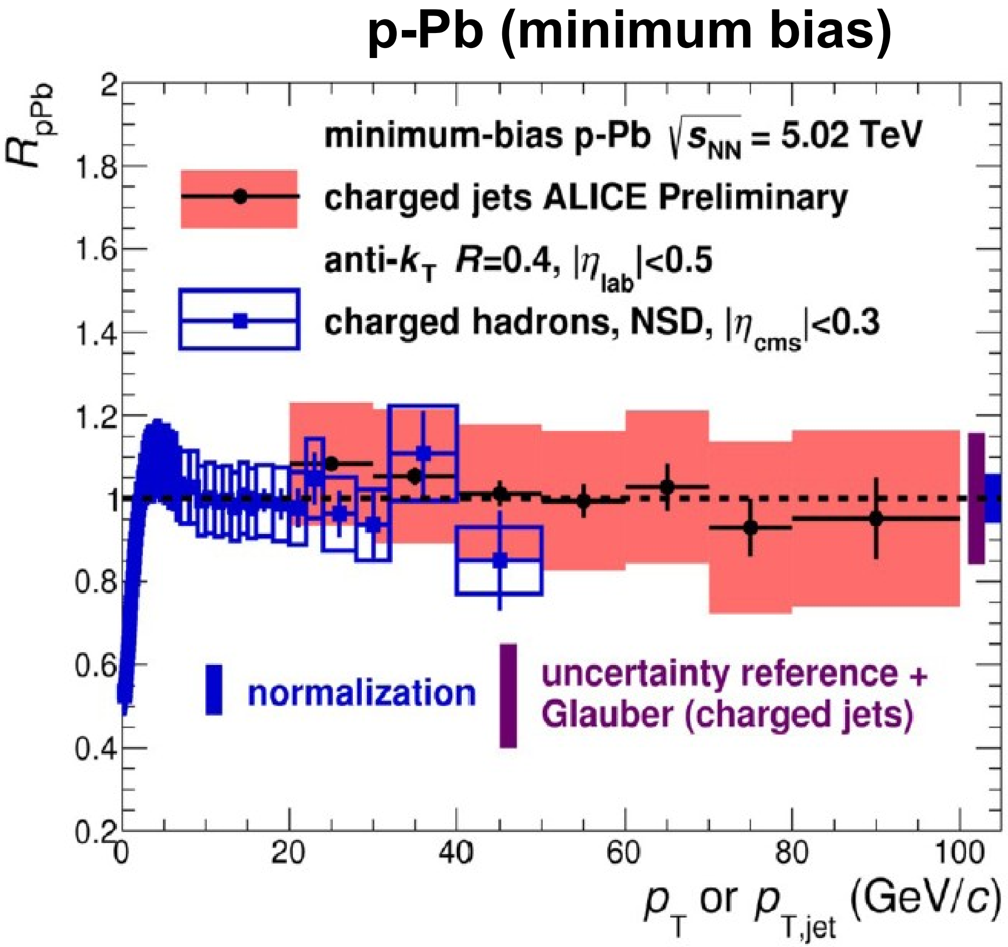
- RAA ~ 1 → No nuclear effect,
- RAA < 1 → suppression
- RAA > 1 → Cronin effect Observed at RHIC (Multiple initial/final state parton interactions)

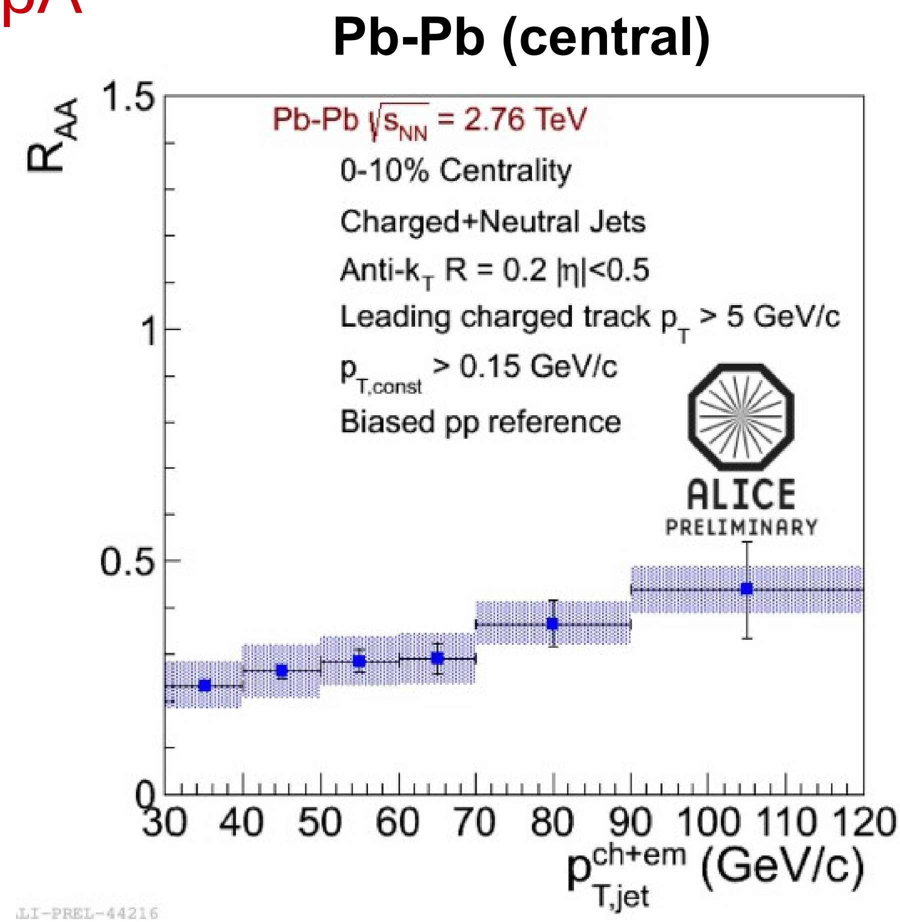
- **R_{pPb} ~1** → no nuclear effects in pPb

→ suppression in PbPb is a final state effect

ALICE Coll. Phys. Rev. Lett. 110, 082302 (2013)

Jets R_{pA}



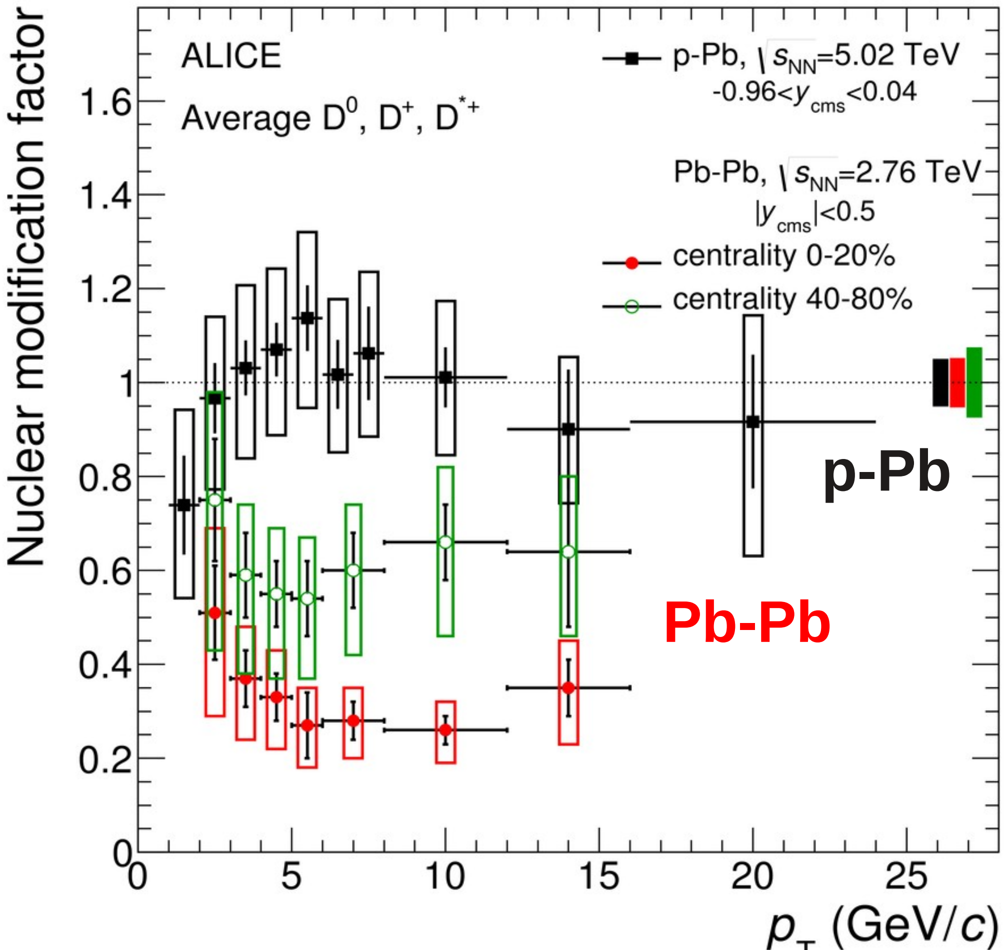


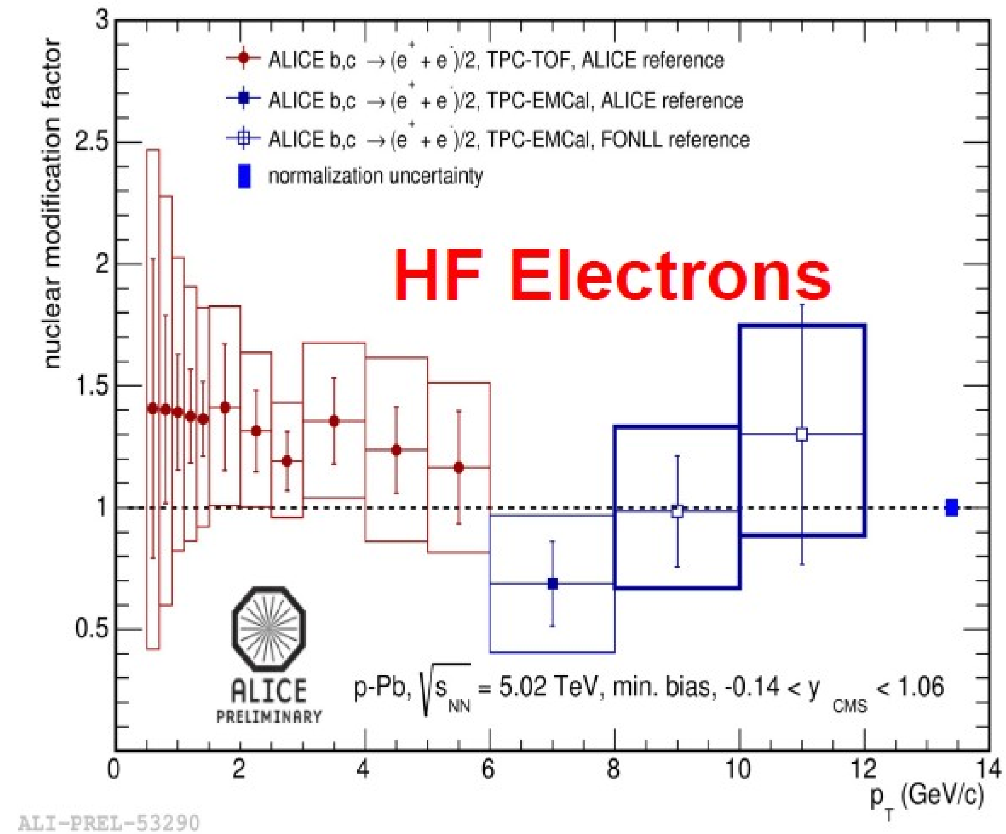
- **R_{pPb} ~1** → no nuclear effects in pPb

→ suppression in PbPb is a final state effect

ALICECoII. Phys. Lett. B 741 (2015) 38-50

Heavy Flavor R_{pA}



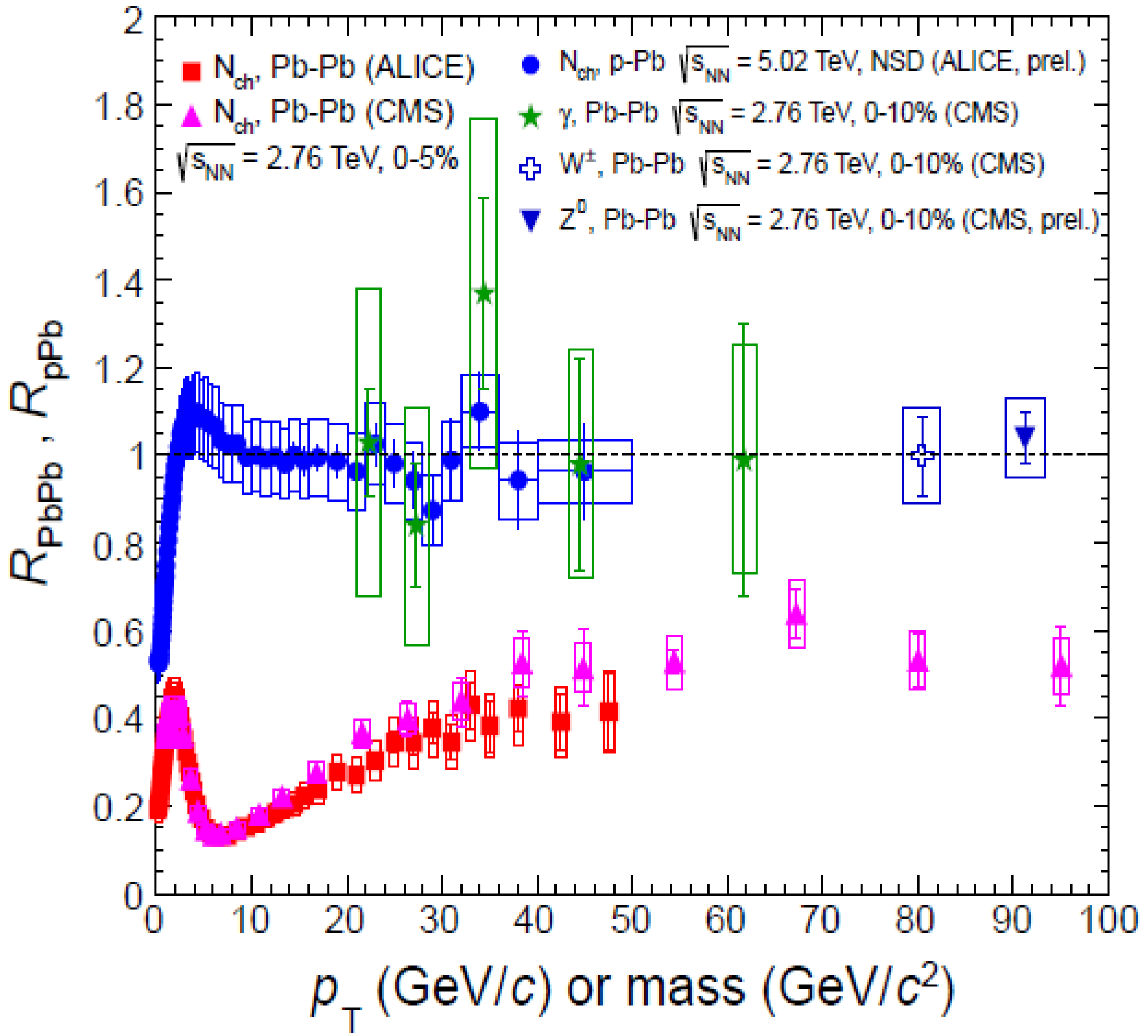


- **R_{pPb} ~1** → no nuclear effects in pPb

→ suppression in PbPb is a final state effect

ALICE Coll. Phys. Rev. Lett. 113 (2014) 232301

Jet quenching vs. “cold” matter / EW observables



“cold” nuclei (p–Pb):
shadowing / saturation
(gluon distr. func.)

binary coll. scaling, pT > 2 GeV/c

exhibited by various observables

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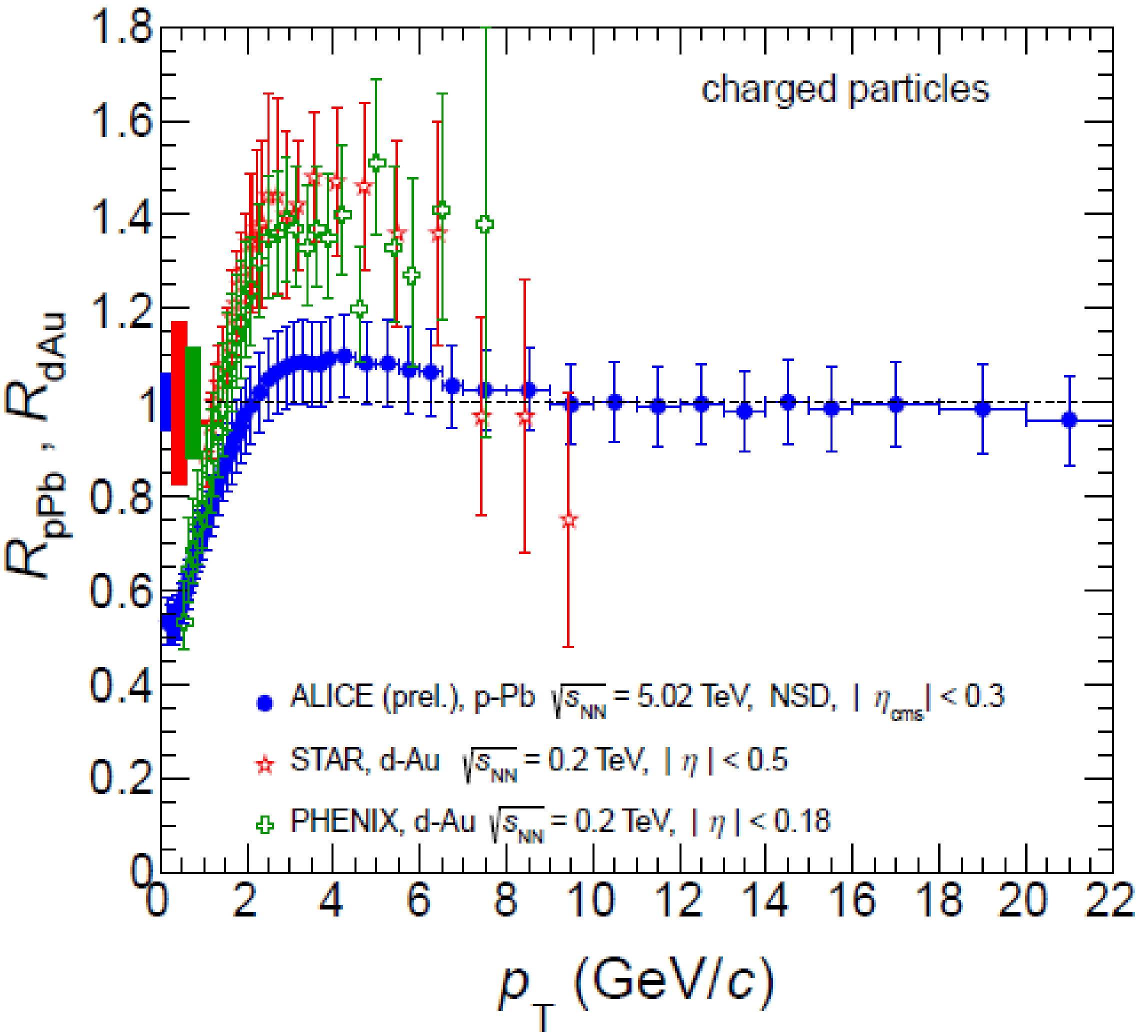
- Nch, EPJC 74 (2014) 3054
- heavy flavor, PRL 113 (2014) 232301
- Jets, arXiv:1503.00681

CMS

- γ, PLB 710 (2012) 256
- W±, PLB 715 (2012) 66
- Z0, PRL 106 (2011) 212301, CMS-PAS-HIN-13-004

...provide experimental demonstration
that suppression = parton energy loss

Flow, Cronin or saturation?



LHC vs. RHIC data

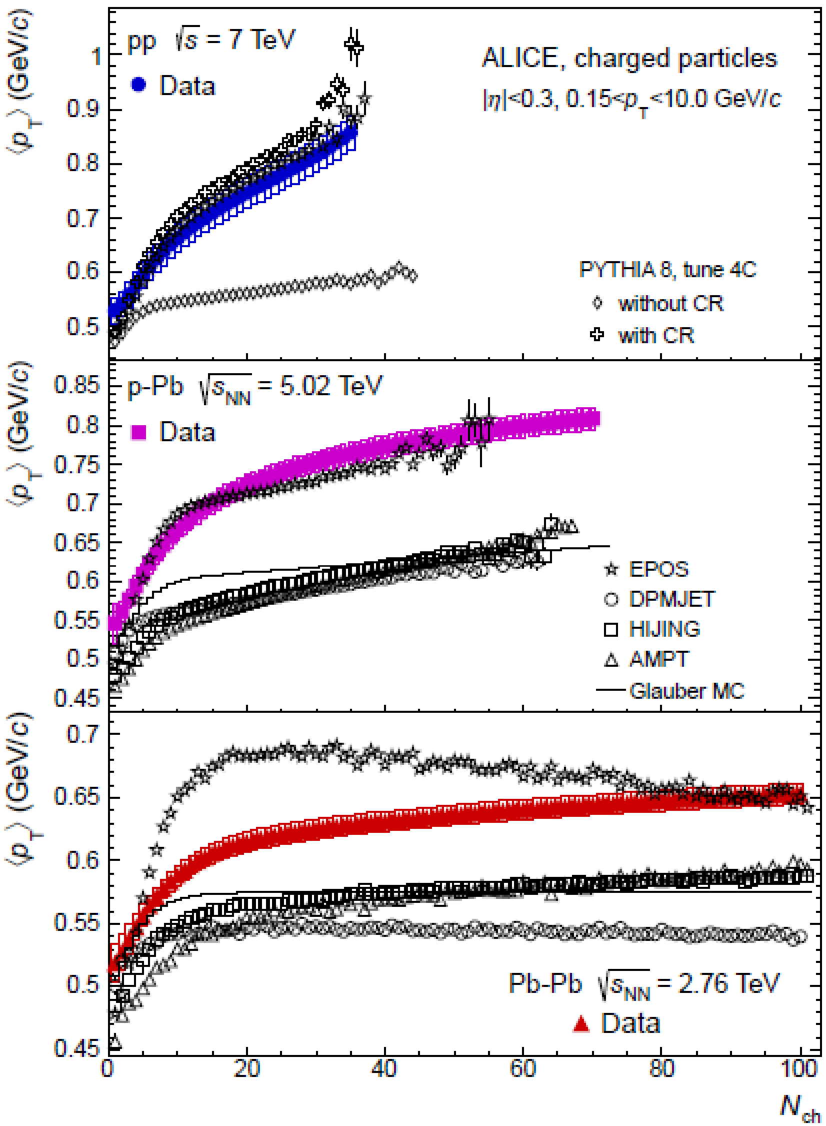
- Cronin effect: "re-distribution" of low-pT hadrons at higher pT due to multiple (parton) scattering larger at RHIC
First observed by Cronin in PRD 11 (1975) 3105
→ Multiple soft scatterings in IS prior to hard scatter (arXiv:hep-ph/0212148)

- flow: blue-shift of spectra larger at LHC

- saturation: depletion of spectra at low pT
larger at LHC

To distinguish scenarios
look differentially!

Mean p_T

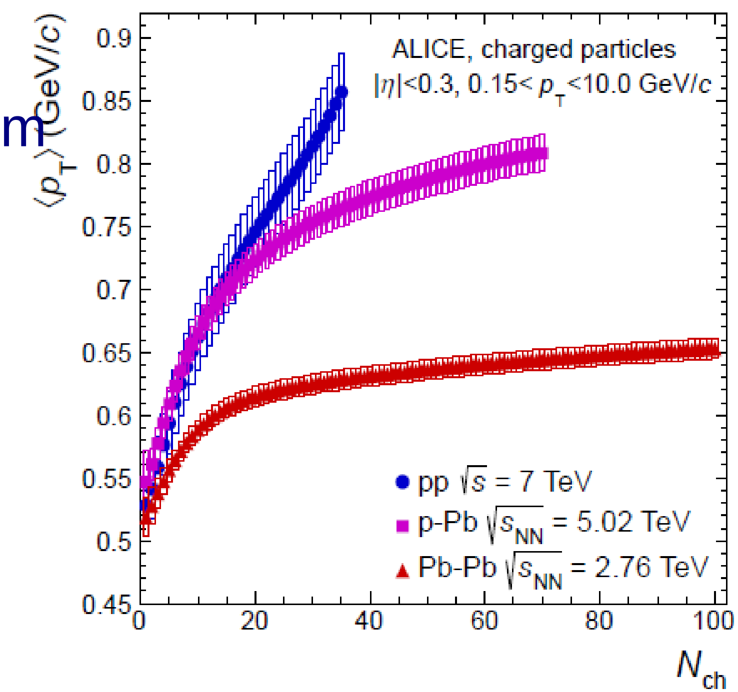


ALICE Coll. PLB 727 (2013) 371

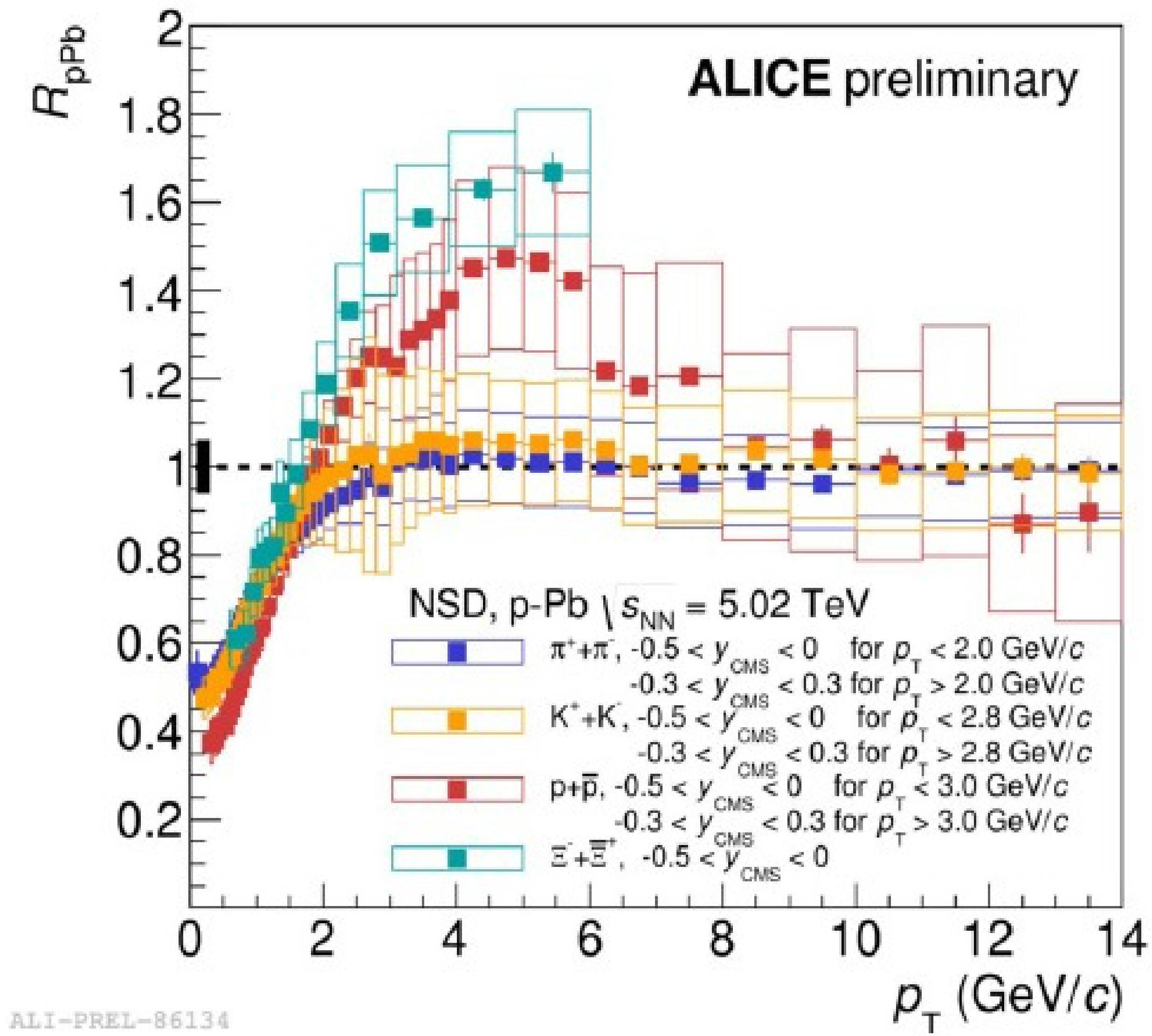
pp: high-mult through multiple parton interactions
BUT incoherent production → same <pt>
→ Color reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization
→ fewer, but more energetic, hadrons
Sign of collectivity?

pPb: features of both
less saturation than in PbPb → higher <pt>
Sign of collectivity?

PbPb: high-mult from superposition of parton interactions, collective flow
→ moderate increase of <pt>



R_{pA} for particle species



At intermediate pT (Cronin region): Indication of mass ordering

– No enhancement for pions and kaons

– **Pronounced peak for protons**

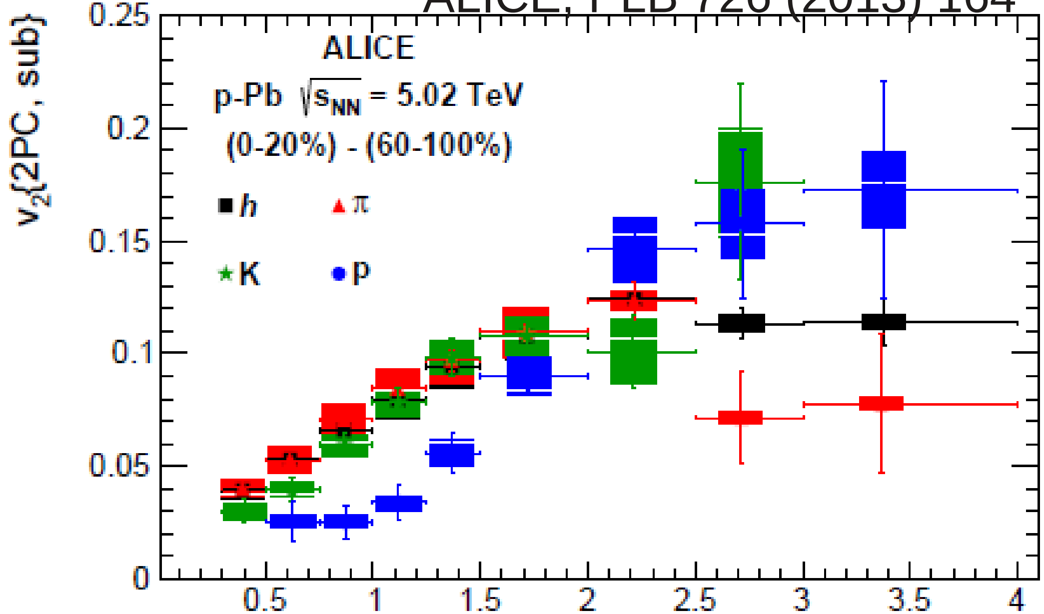
– Even stronger for cascades

Particle species dependence points to relevance of final state effects

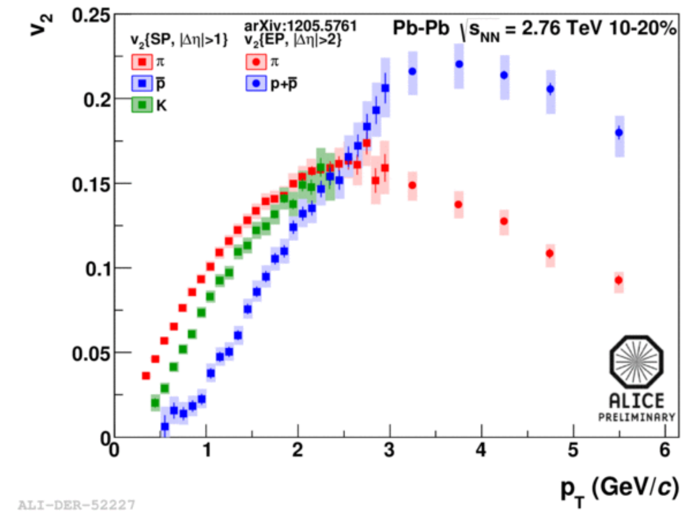
Flow of Particles

Quantify the azimuthal modulation in terms of second order Fourier harmonics v2

p-Pb ALICE, PLB 726 (2013) 164



Pb-Pb



Mass ordering of v2

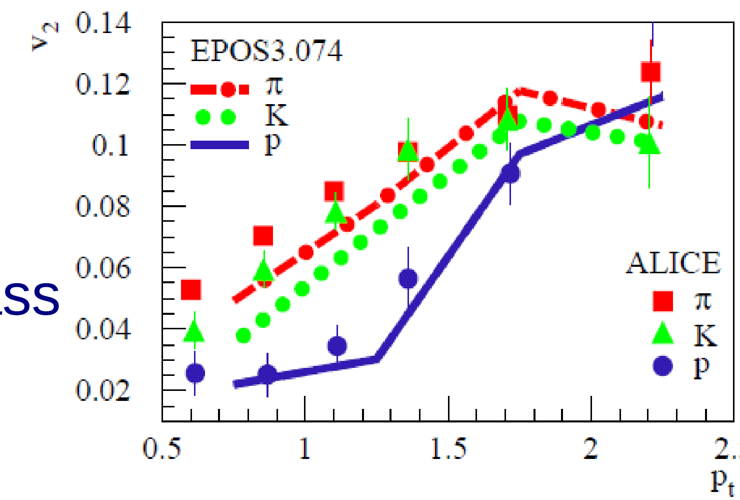
Pb-Pb interpretation:

- v2 arises from initial anisotropy of local energy density
- Mass ordering arises from the interactions with the medium and their dependence on the mass of the hadrons

→ signs of collectivity? Radial and elliptic flow?

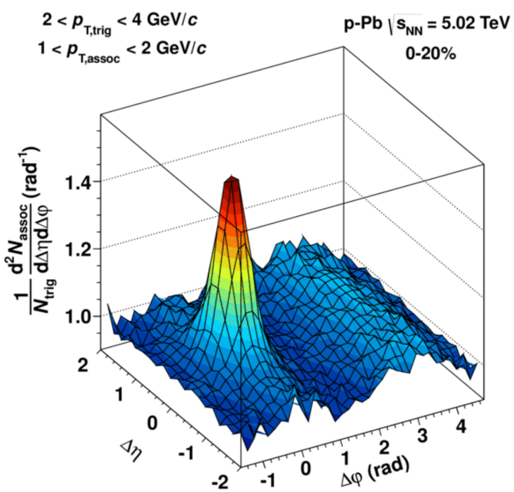
EPOS 3.074: full hydrodynamics

Werner et al., arXiv:1307.4379



Double Ridge

0-20% **60-100%**



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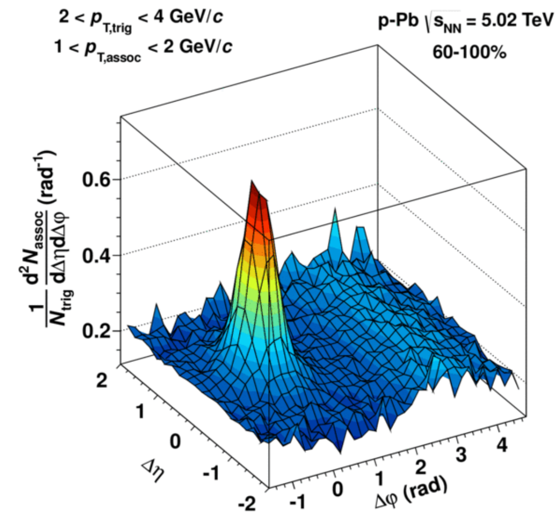

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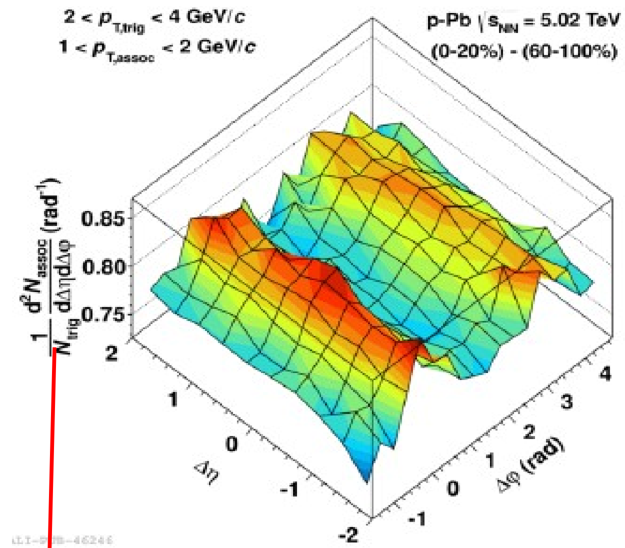
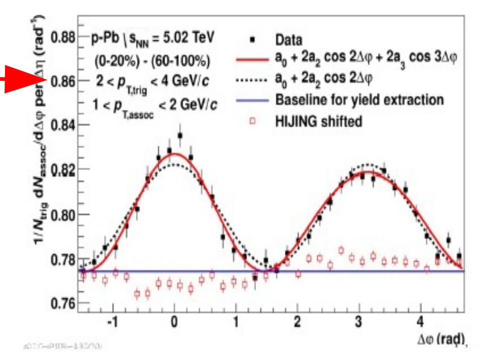


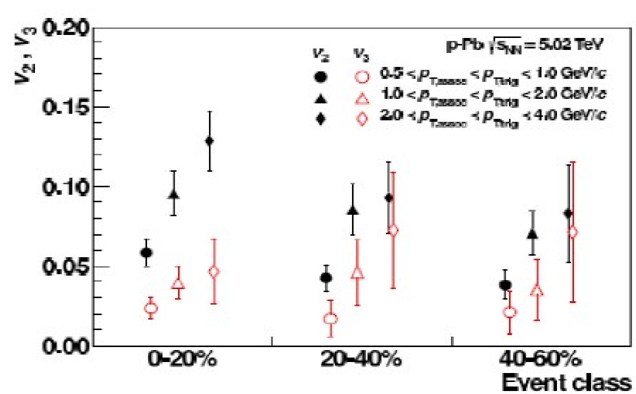
PLB 719 (2013),29-41

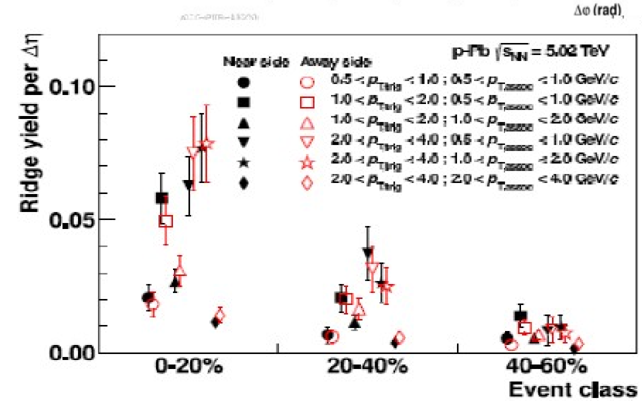


long range correlation:

Double (near+away side) ridge structure emerging when subtracting per-trigger yield of low (60-100%) from high-multiplicity (0-20%) events.

Near and away side nearly identical independent of mult.
→ common underlying physics?

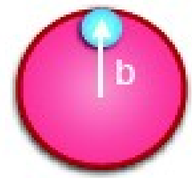


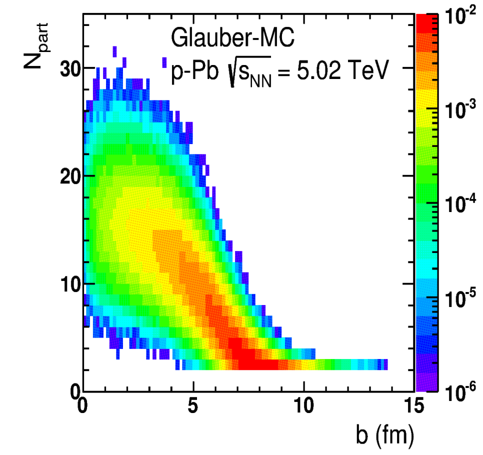


ALICEColl. PLB 719 (2013), pp. 29-41

Geometry dependence: Centrality

- Centrality: classification of collision geometry based on a measured observable
- Impact parameter b controls <Ncoll>
  - for small systems b weakly correlated with Npart

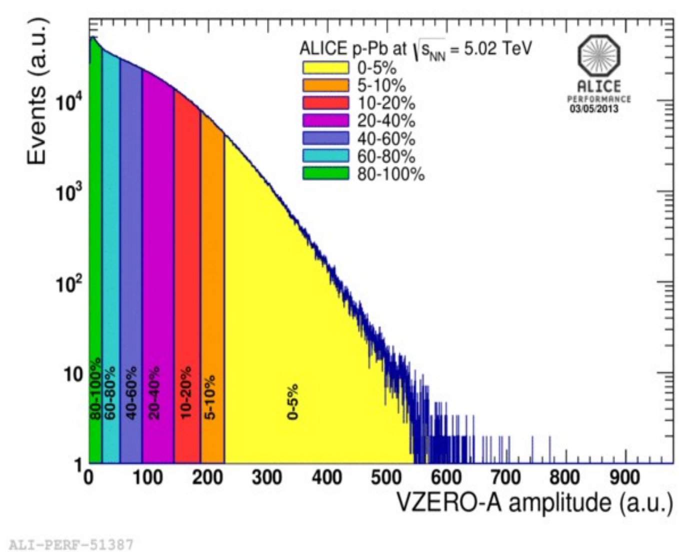




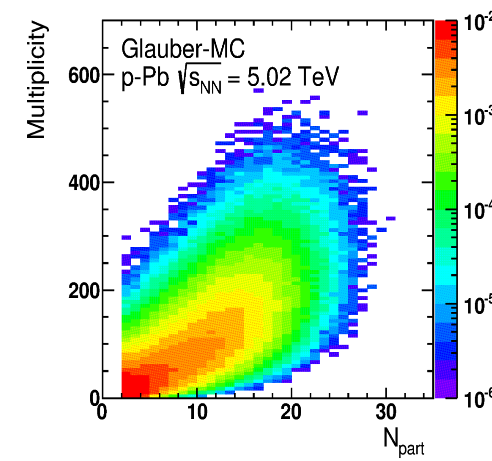
STANDARD CENTRALITY

Centrality estimator related via a Glauber model to Ncoll
- description of the observable through a model
- conditional probability P(M | Ncoll)
- classify events as % of cross-section
- <Ncoll> in each centrality bin

1) Verify the connection of the measurement to collision geometry:
- correlating observables from kinematic regions that are casually disconnected after collision
- comparing Glauber MC and data for a known process



2) Demonstrate the consistency of the approach:
- check if the centrality selection could induce a bias in the geometry parameters
  - selection in a system with large relative fluctuations can induce a bias
- need to identify the physics origin of the bias to correct centrality dependent measurements



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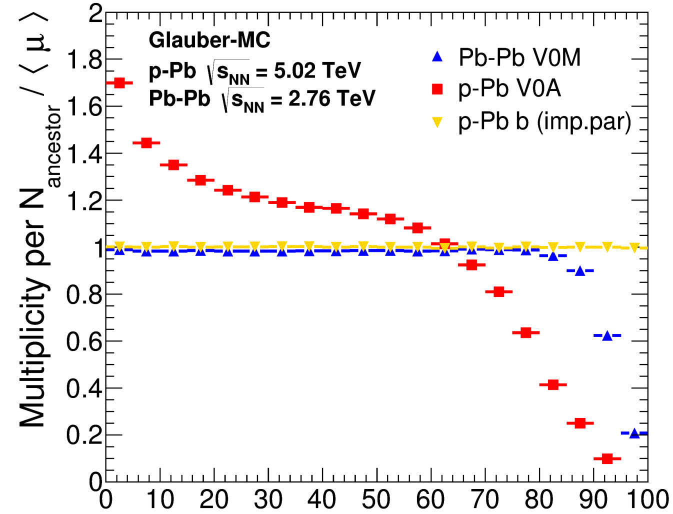
Biases in pA

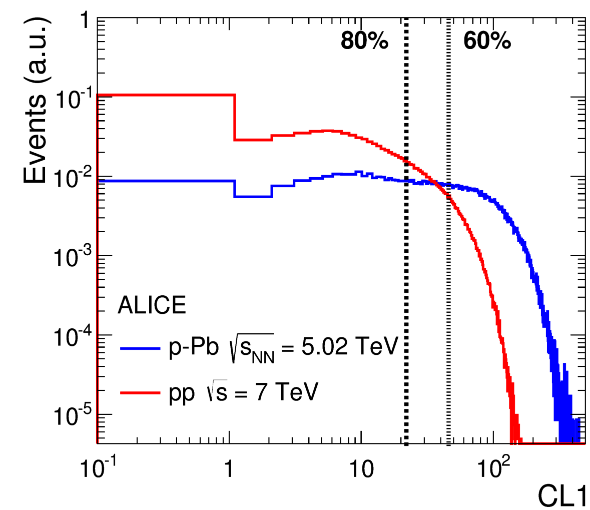
- **Multiplicity bias**: fluctuations sizable
  → centrality selection based on multiplicity may select a sample on NN collisions biased w.r.t. a sample defined by cuts on b

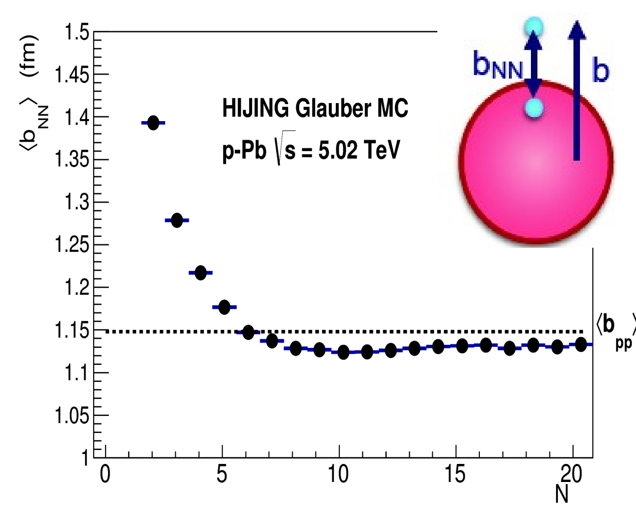
- MC generators: multiplicity fluctuations are due to fluctuations in MPIs
  → number of hard scatterings per NN collision
  $\langle n_{hard} \rangle = \sigma_{hard} * T_{NN}(b_{NN})$
  → bias in mult ~ bias in hard scattering

- **Jet-veto**: multiplicity range in peripheral events represent an effective veto on hard processes

- **Geometry bias**:
  Mean nucleon-nucleon impact parameter (b_{NN}) increases in peripheral collisions
  → reduced number of MPI for peripheral events







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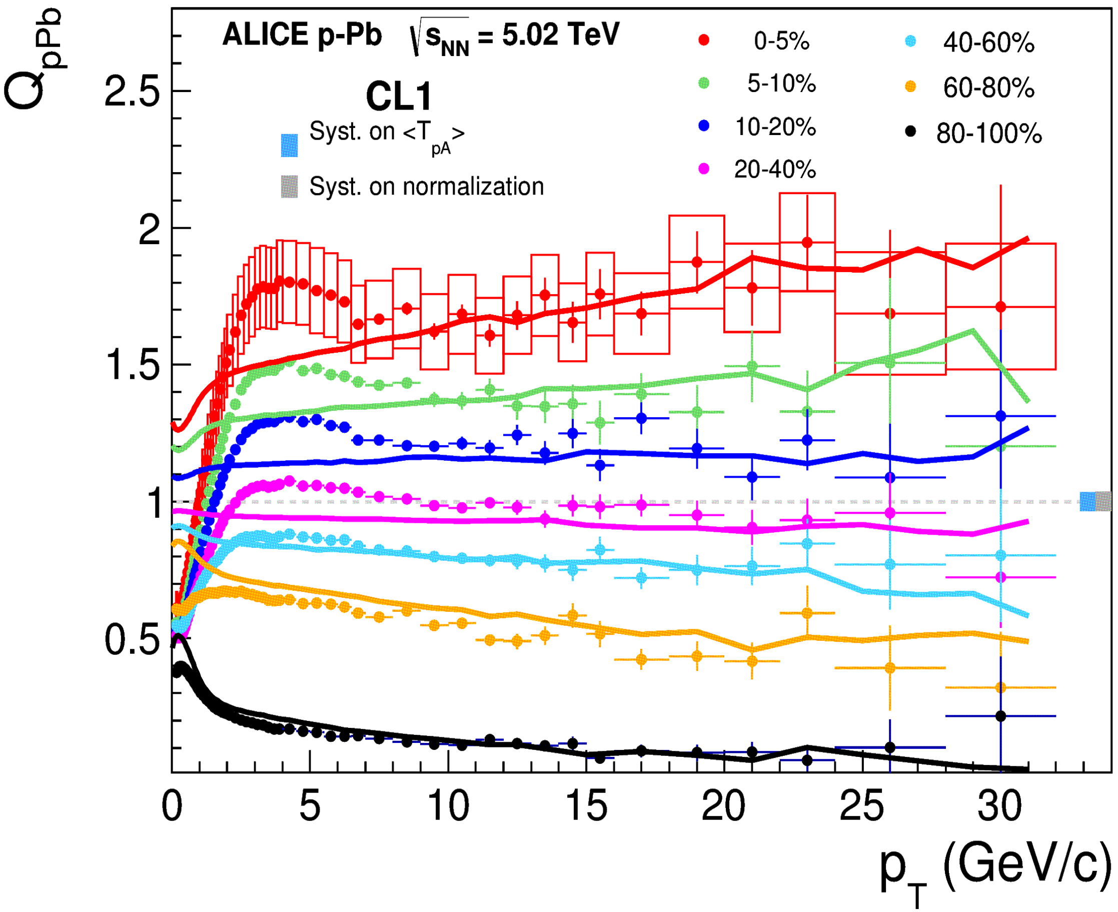
Deviations from binary scaling

Selecting events according to **multiplicity leads to a bias**
→ Expected deviations from binary scaling at high pT



higher (lower) <mult/source> in central (peripheral) events

- Central: enhanced yield → RpA>1
- Peripheral (lower yield → RpA<1)

→ large spread **NOT** related to nuclear effects!

The bias decreases increasing Δy between the measurement and centrality estimator

Jet-veto effect in most peripheral bin with a significant negative slope vs pT

G-PYTHIA: Incoherent superposition of N-N PYTHIA collisions coupled to Glauber MC reproduces main features

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The ALICE approach

1) assumption: an event selection based on ZN energy does not induce any bias on bulk particle production at midrapidity

2) assumption:

a) Mid-rap dN/dη scales with N_{part}

b) Yield at high-p_T scales with N_{coll}

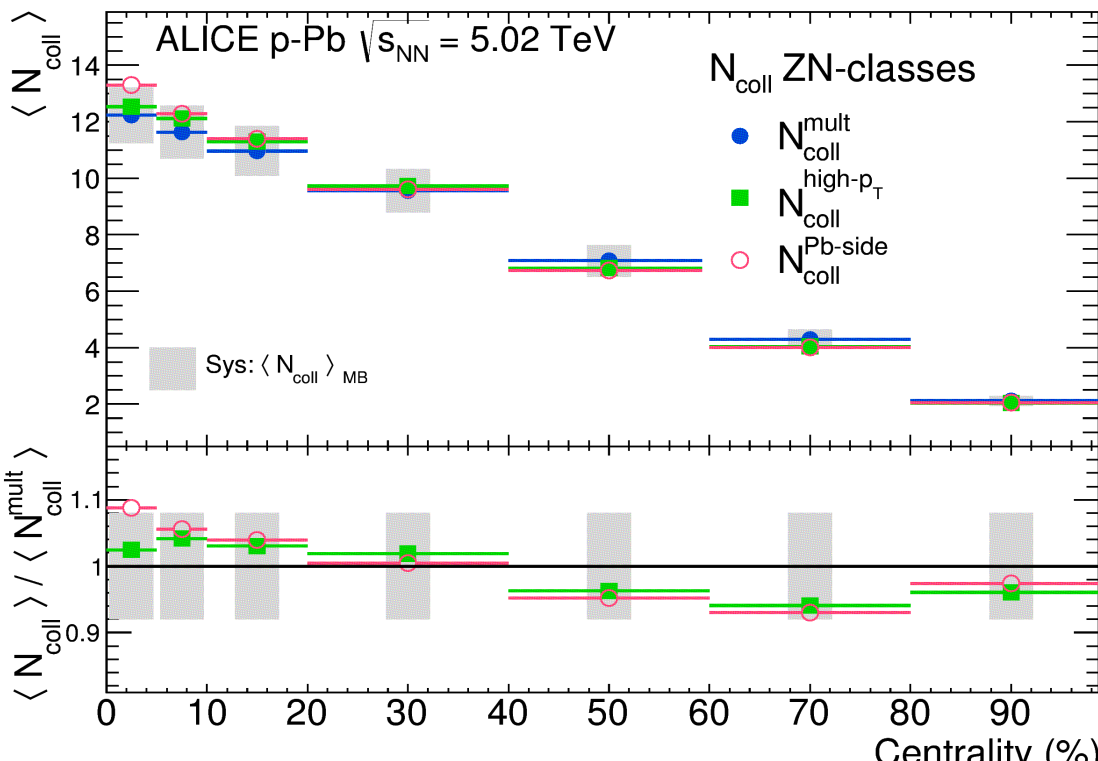
c) Pb-side dN/dη scales with N_{part}^{target} (= N_{coll} in pA)

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

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

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

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



Γoia

- All values within at most 10% → consistency of assumptions
- This does not yet prove the validity of any (or all) of these assumptions 2a),b),c)

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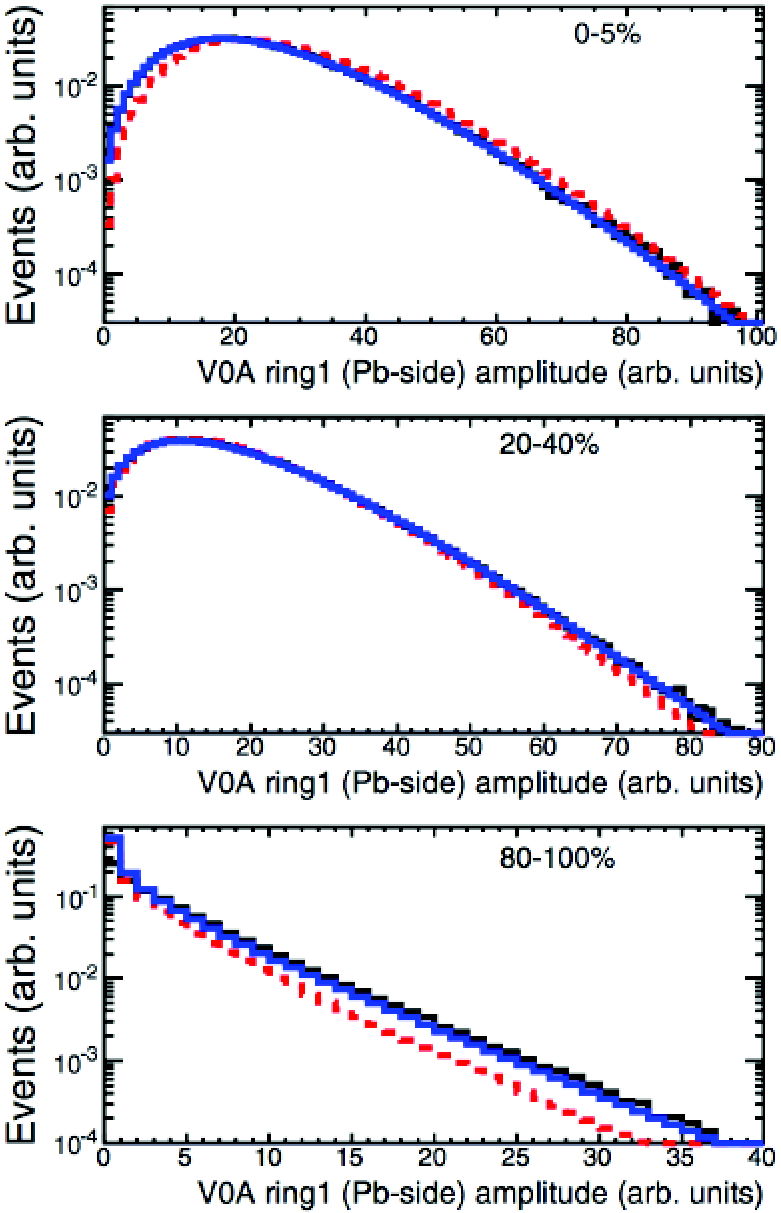
Consistency Check

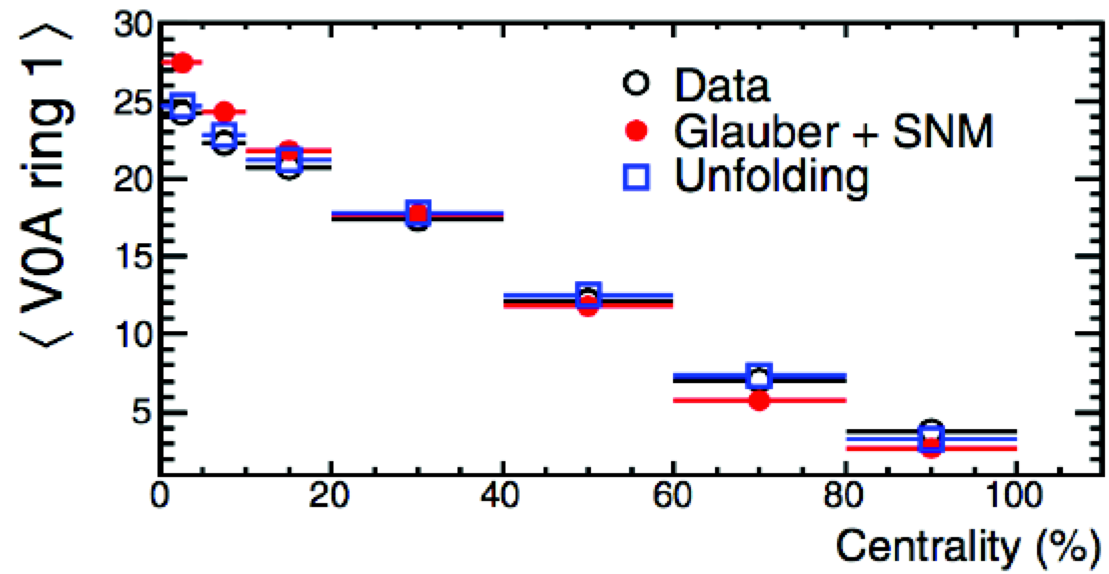


ALICE Coll., PRC 91 (2015) 064905

• Measurement of Ncoll in separated y regions to establish their relation to centrality: ZN vs. V0A

- P(Ncoll|centZNA) from SNM+Glauber fit convolved with NBD from NBD+Glauber fit to MB V0A multiplicity
- Unfolding: find the input π(Ncoll) distribution that convolved with NBD MB fits the V0A distribution from data in ZNA classes

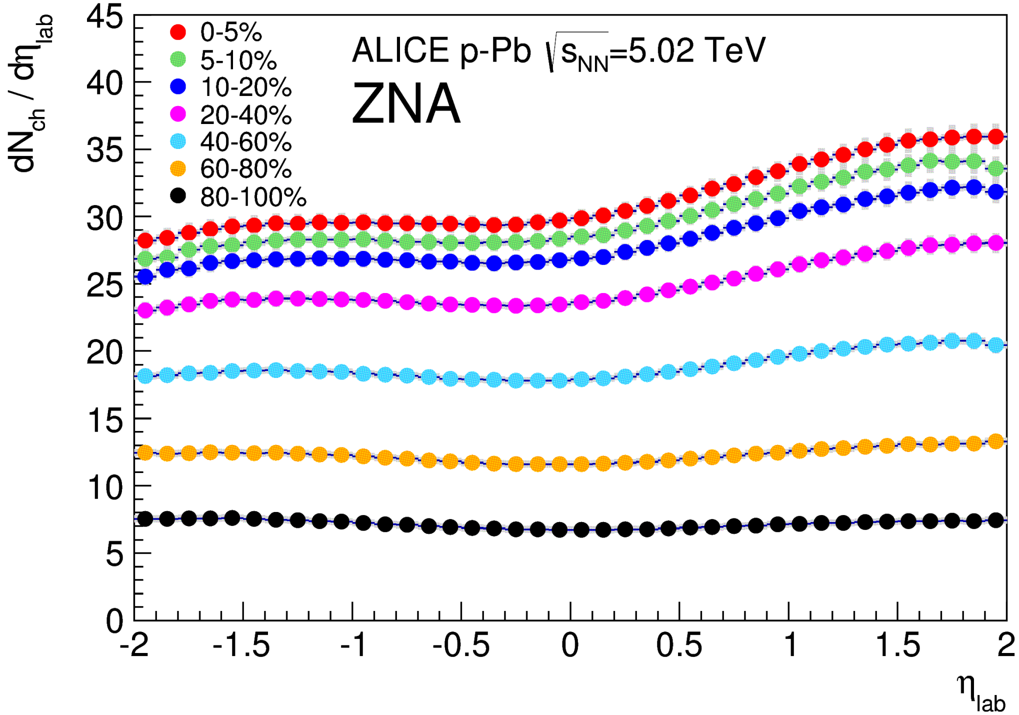
does not work for biased centrality selection (CL1)

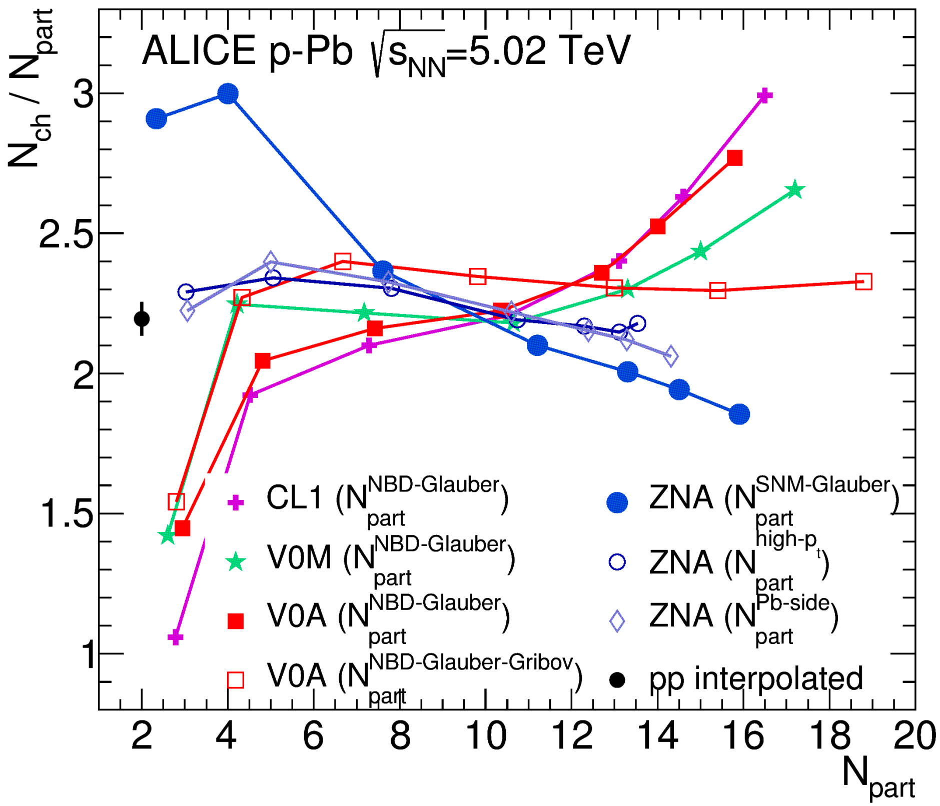


• Ncoll distribution folded with NBD agrees with measured signal distributions

→ ZNA unbiased centrality selection

dN/dη at midrapidity





- for V0A (Glauber) steeper than linear increase in Npart
- for V0A (Glauber-Gribov) linear scaling with Npart apart from the peripheral point

- ZN centrality + assumptions on scaling for high-pT and Pb-fragmentation side yields show linear scaling with Npart within 10% and the peripheral bin agrees with pp data

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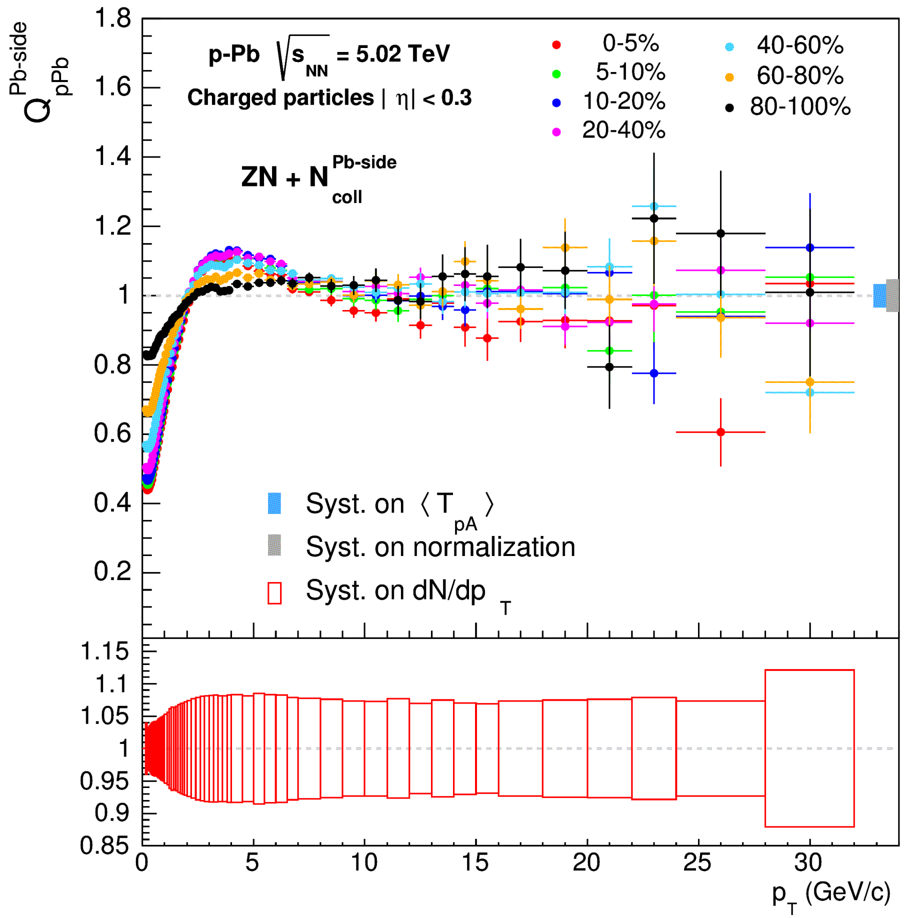
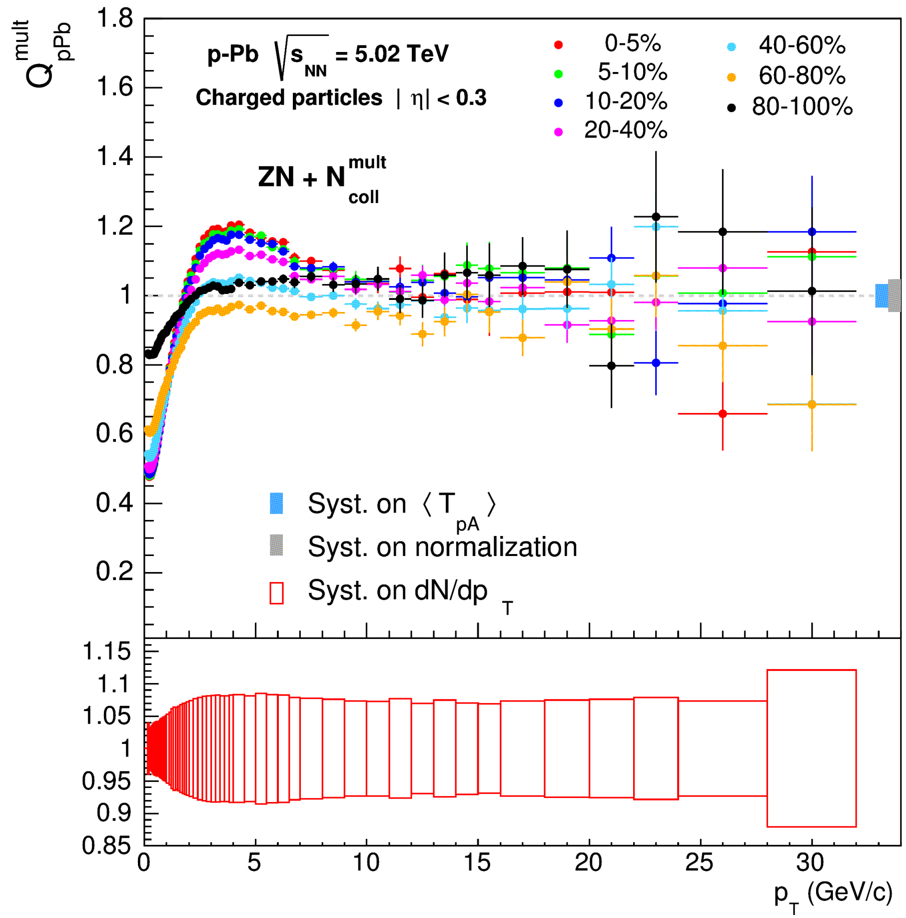
Nuclear modification factor





- Nuclear modification factors consistent with unity at high pT for whole centrality range
- intermediate-pT enhancement ("Cronin") increases with centrality
- Results from the 2 assumptions used here are in agreement within uncertainties
- The geometry bias effect is still present in the most peripheral bin

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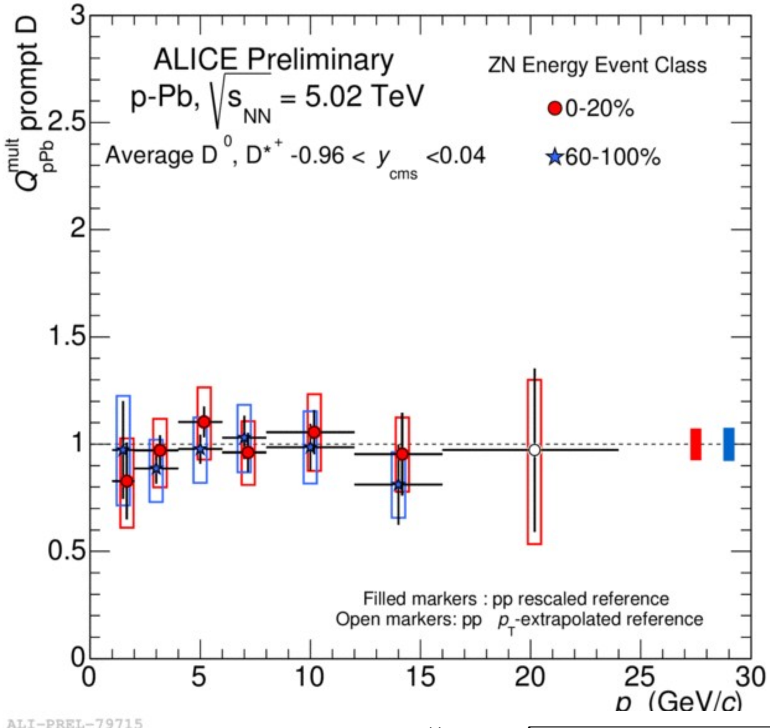
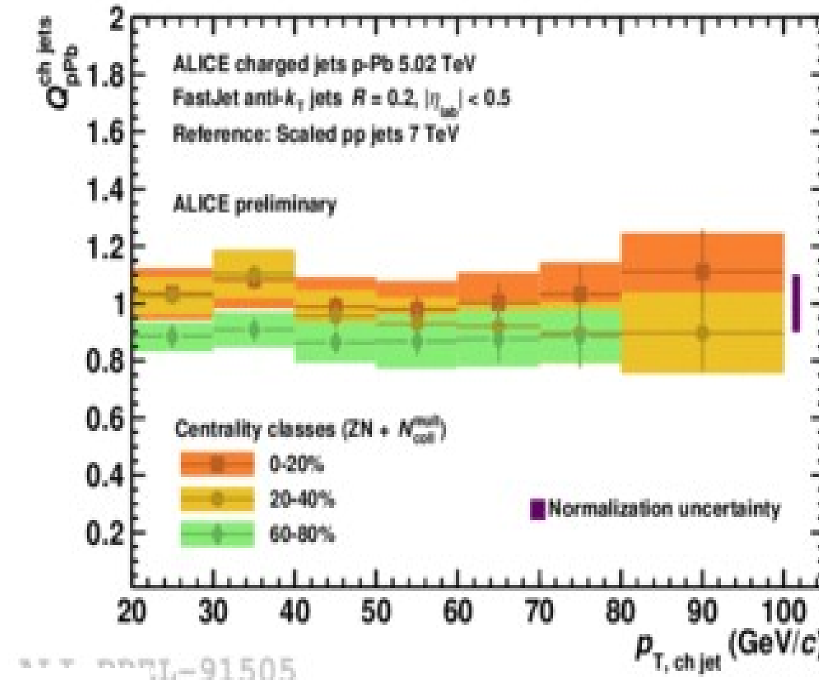
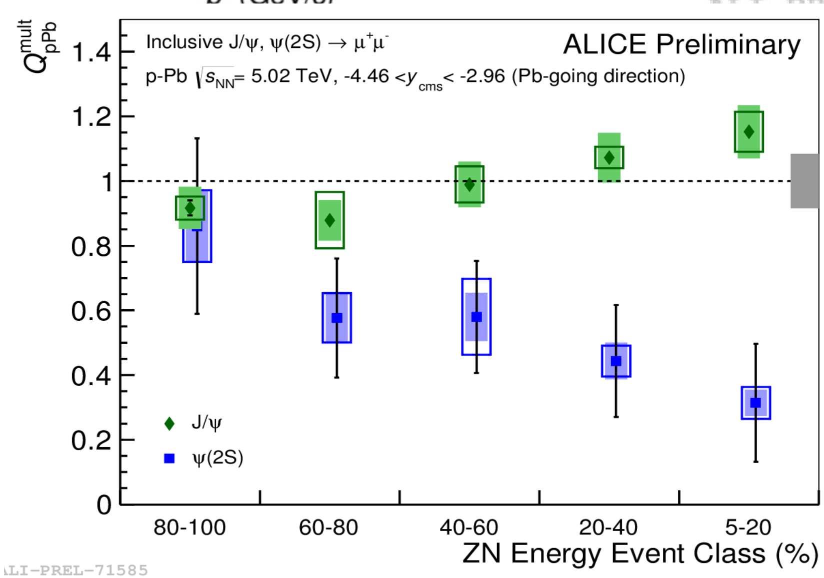
… and many more pA results vs. centrality...

D-mesons



jets





J/ψ
forward/backward

Conclusions

- pA physics program: As control experiment: baseline measurements provide clear proof that effects in Pb–Pb collisions are genuine hot deconfined QCD matter effects related to parton energy loss
- Centrality dependence of measured particle production:
  dN/dη at midrapidity scales with Npart
  high-pT particle production follows binary scaling
  - And also: Jets, Charm
- However both initial state and final state play a role
  - Hydrodynamic flow in the final state: a “medium”
    →collectivity in pA?
    - Initial energy density in p-Pb comparable to Pb-Pb
    - p-Pb small and short-lived: able to thermalize?
    - Jet quenching would need larger path length and longer time
  - Multi-gluon processes from saturated initial-state (Color Glass Condensate)

Night wraps the sky in tribute from the stars.
(Vladimir Mayakovsky, 1930)