Laboratory for
Nuclear Science

CTP-MITHIG discussion on future measurements: focus on light-ion measurements

Wednesday 18th, February 2026

Including inputs from the group and discussions at the Light-Ion Workshop, Initial Stages, etc

Introduction

An exciting (and critical) period for "extreme" QCD physics and heavy-ion research:

- **The RHIC physics program has officially concluded**
- In the coming months (~ June 2026), **a long shutdown will begin at the LHC** (with no new data expected until approximately 2032)
- The Electron-Ion Collider is expected to begin operations in early 2030 at BNL

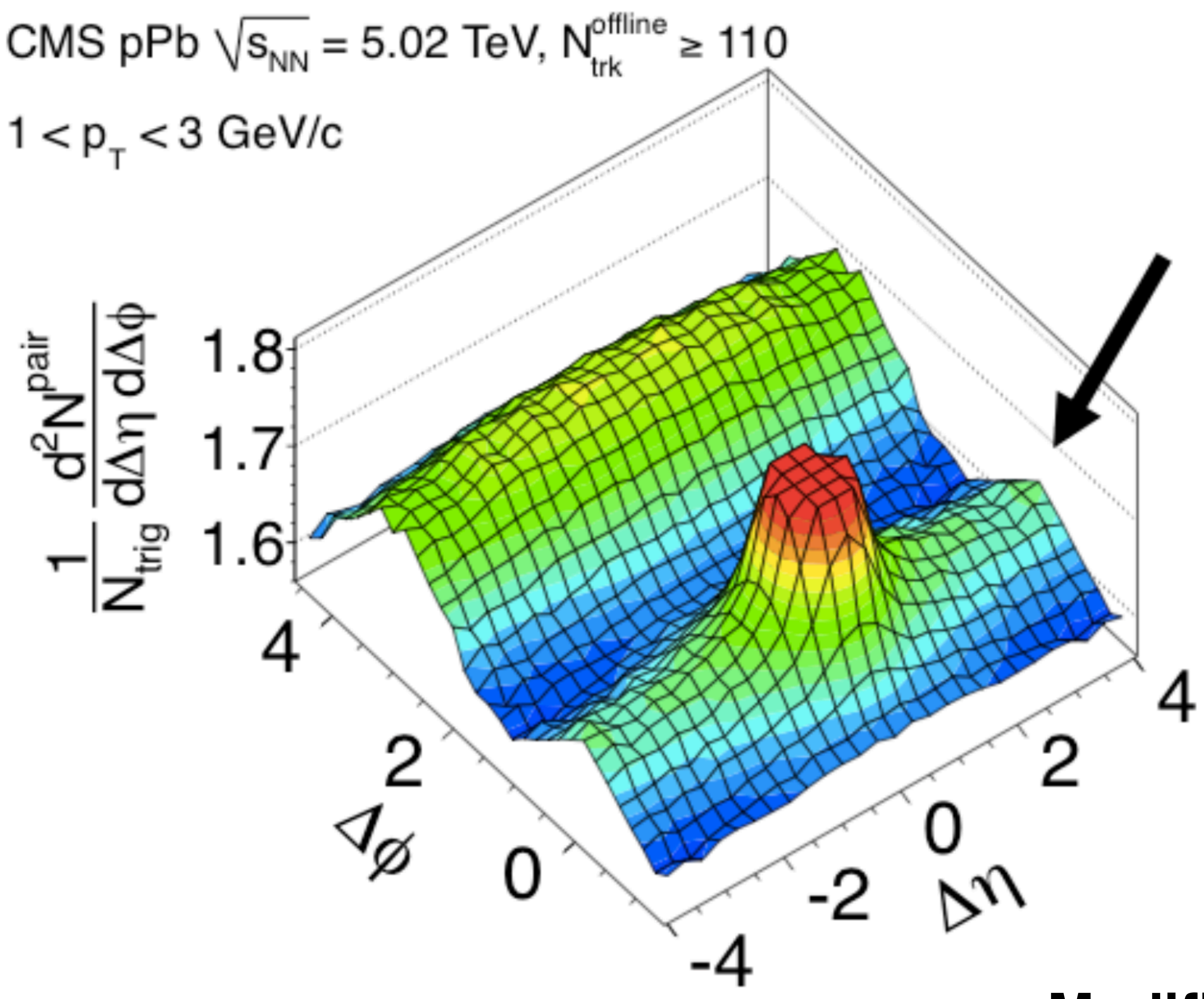
Challenges:

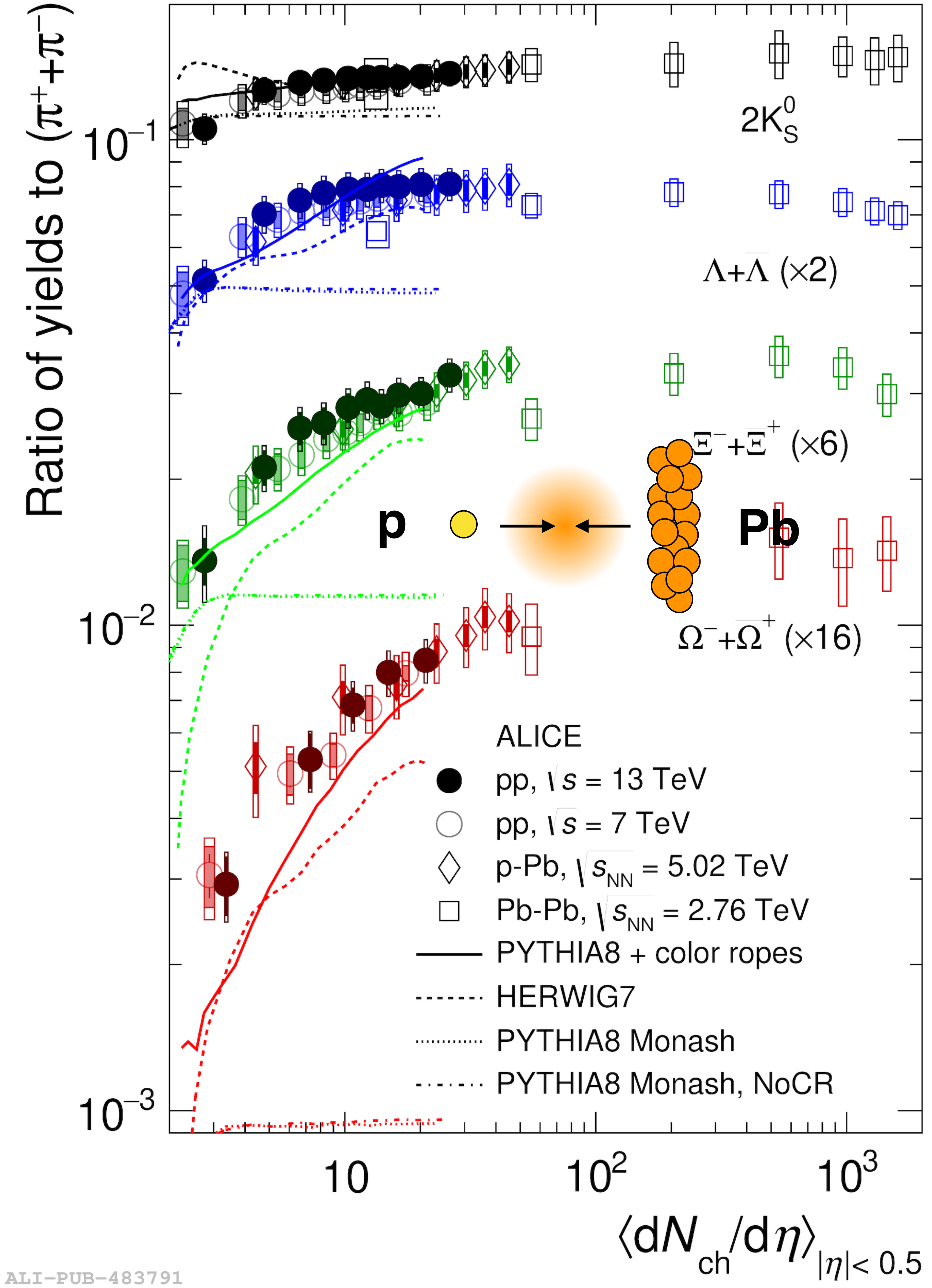
- Maximize the physics reach of the traditional heavy-ion program at RHIC and LHC
- Exploit new experimental opportunities (e.g. the LHC and RHIC light-ion program)
- Provide inputs to shape future heavy-ion runs at the LHC in Run 4 and Run 5

New opportunities with light ions with LHC and RHIC data

The “puzzle” of small systems

Long-range correlations in pp and pPb collisions
→ emergence of a strongly-interacting liquid-like medium in small systems as in PbPb or AuAu collisions

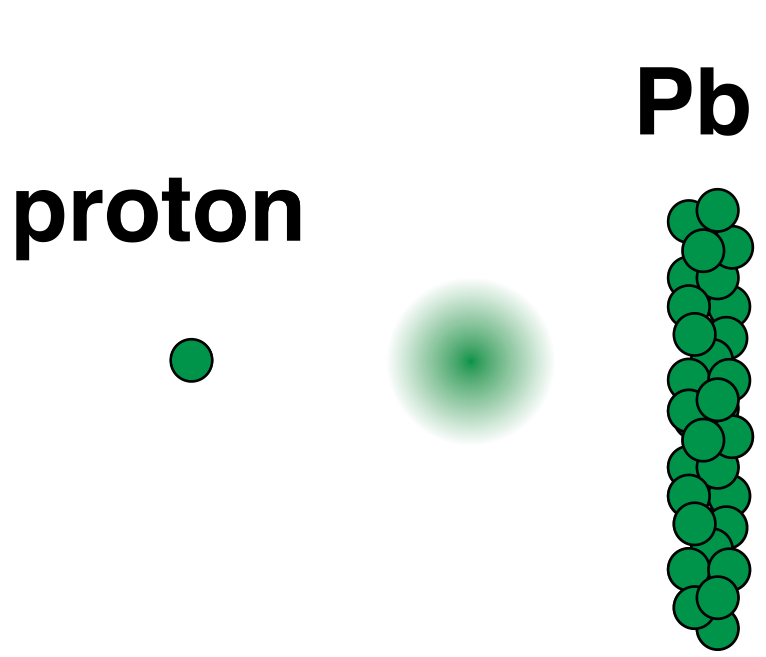


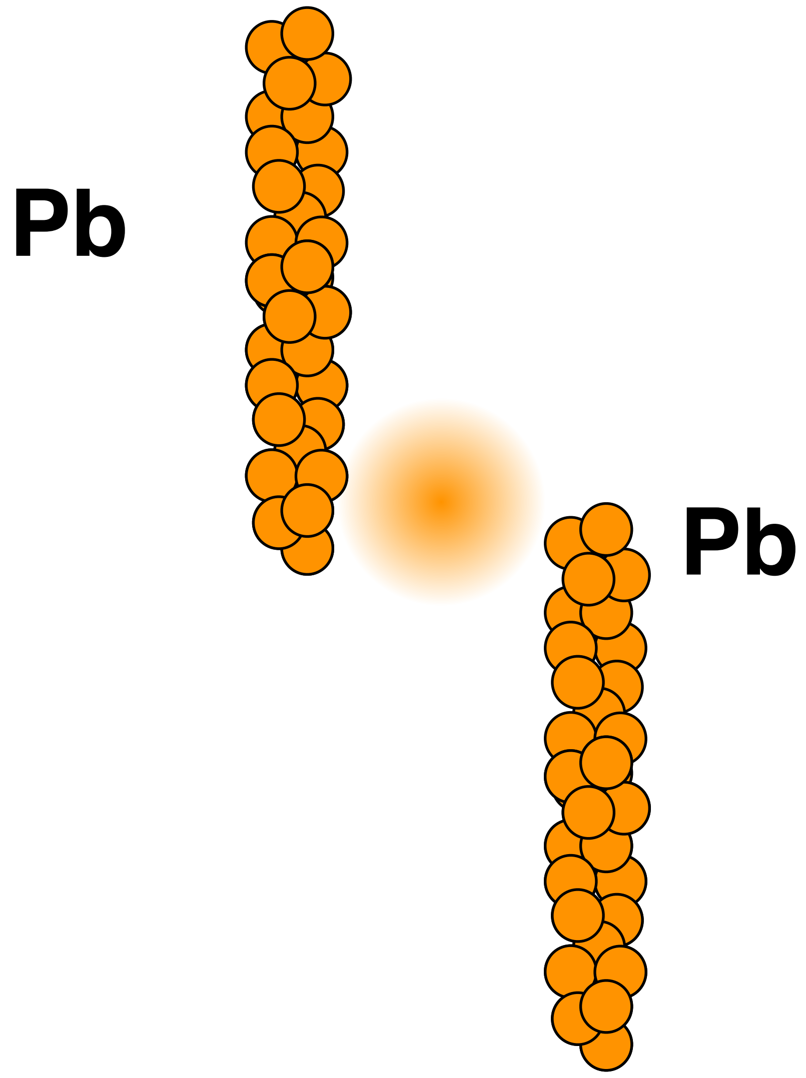


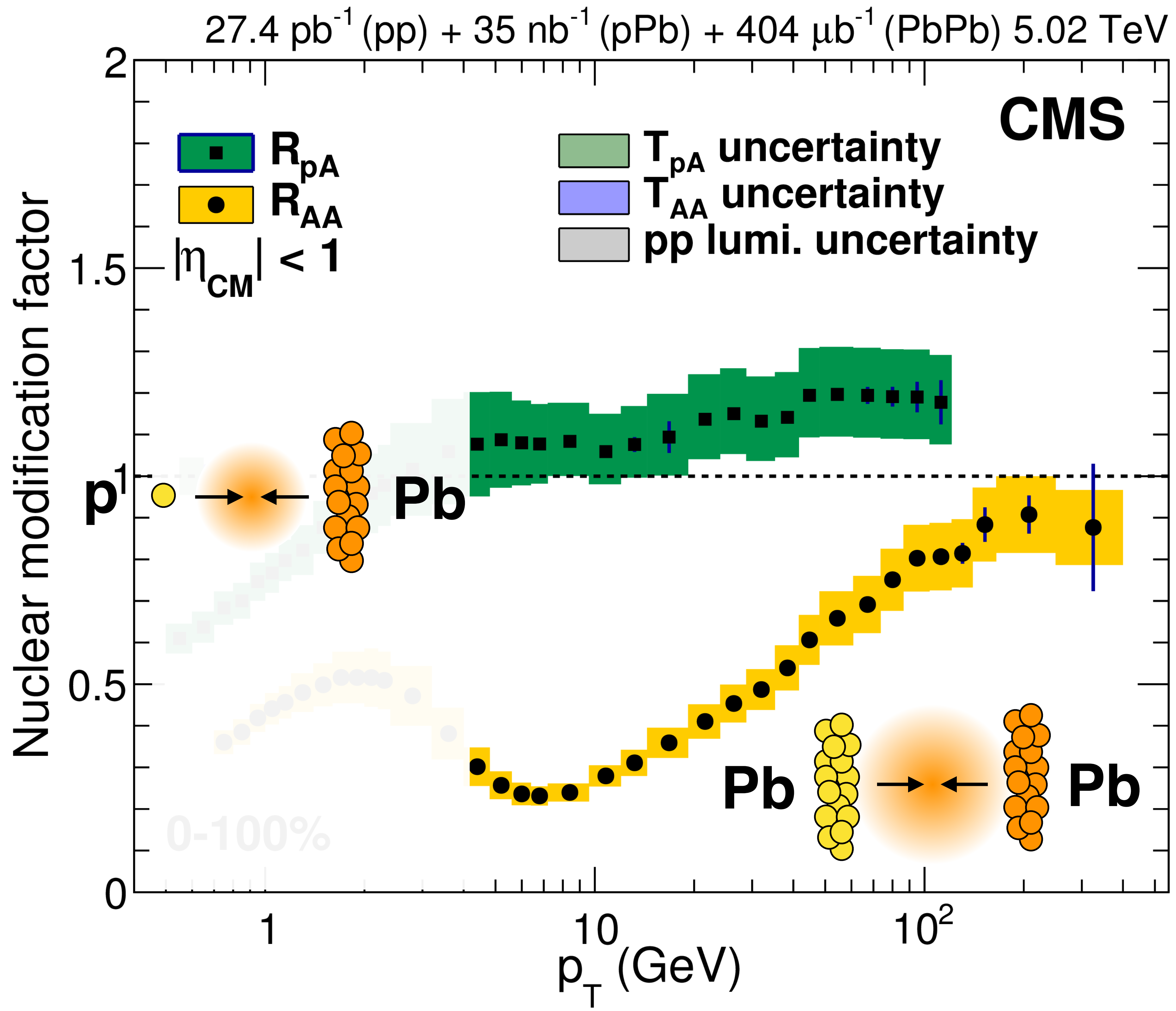
Modification of the particle abundances
as a function of the event multiplicity
→ traditionally considered a “signature” of deconfinement in AA collisions

ALICE, PLB 793 (2019) 420
CMS, JHEP 04 (2017) 039
CMS, PRL 127 (2021) 102002

Do we observe quenching in small-size collisions?



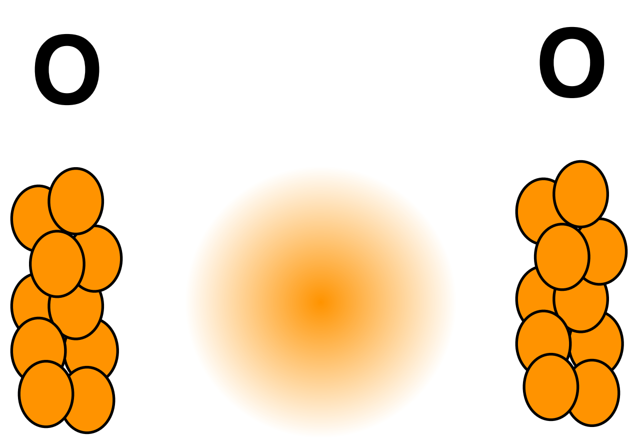


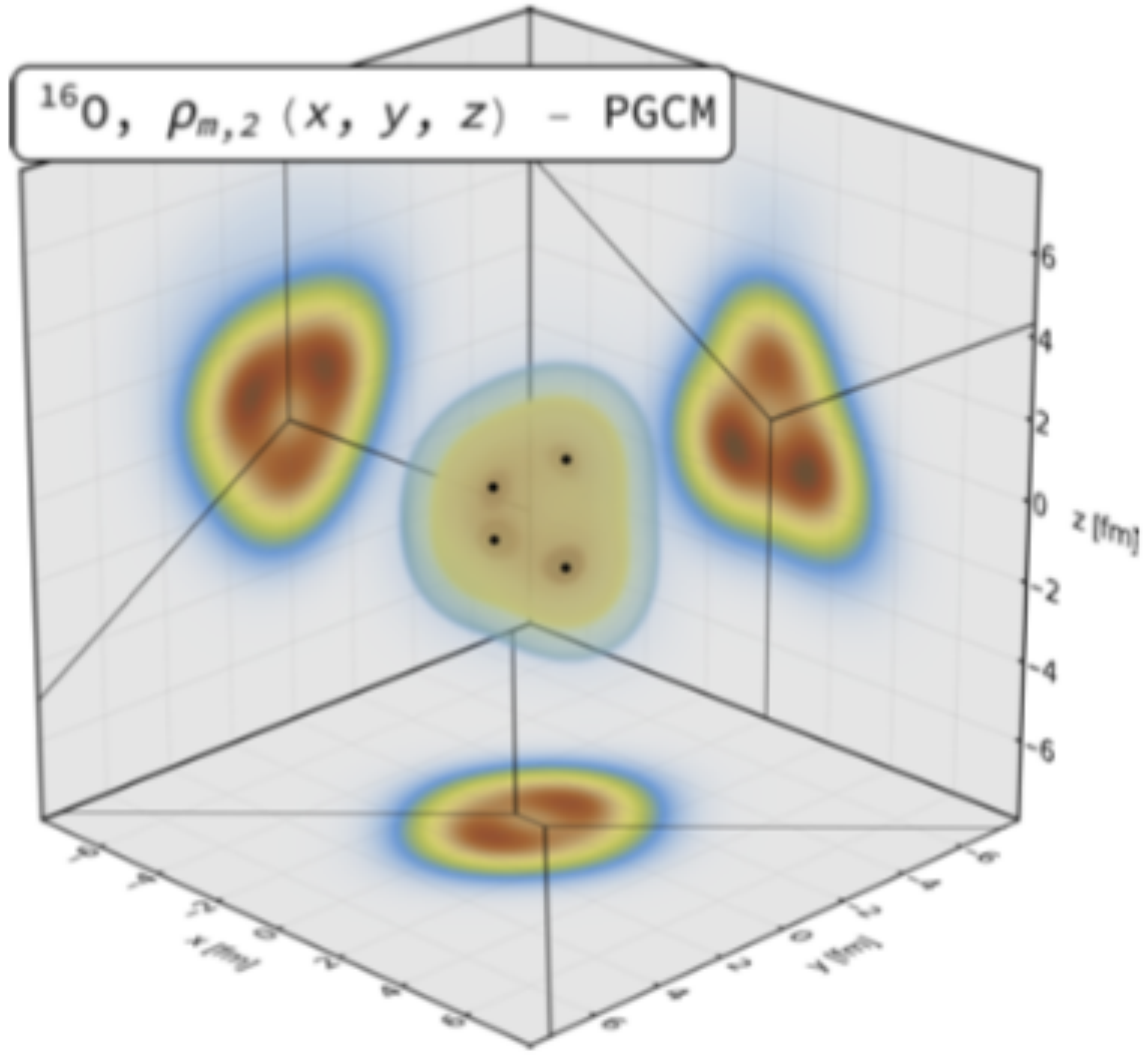


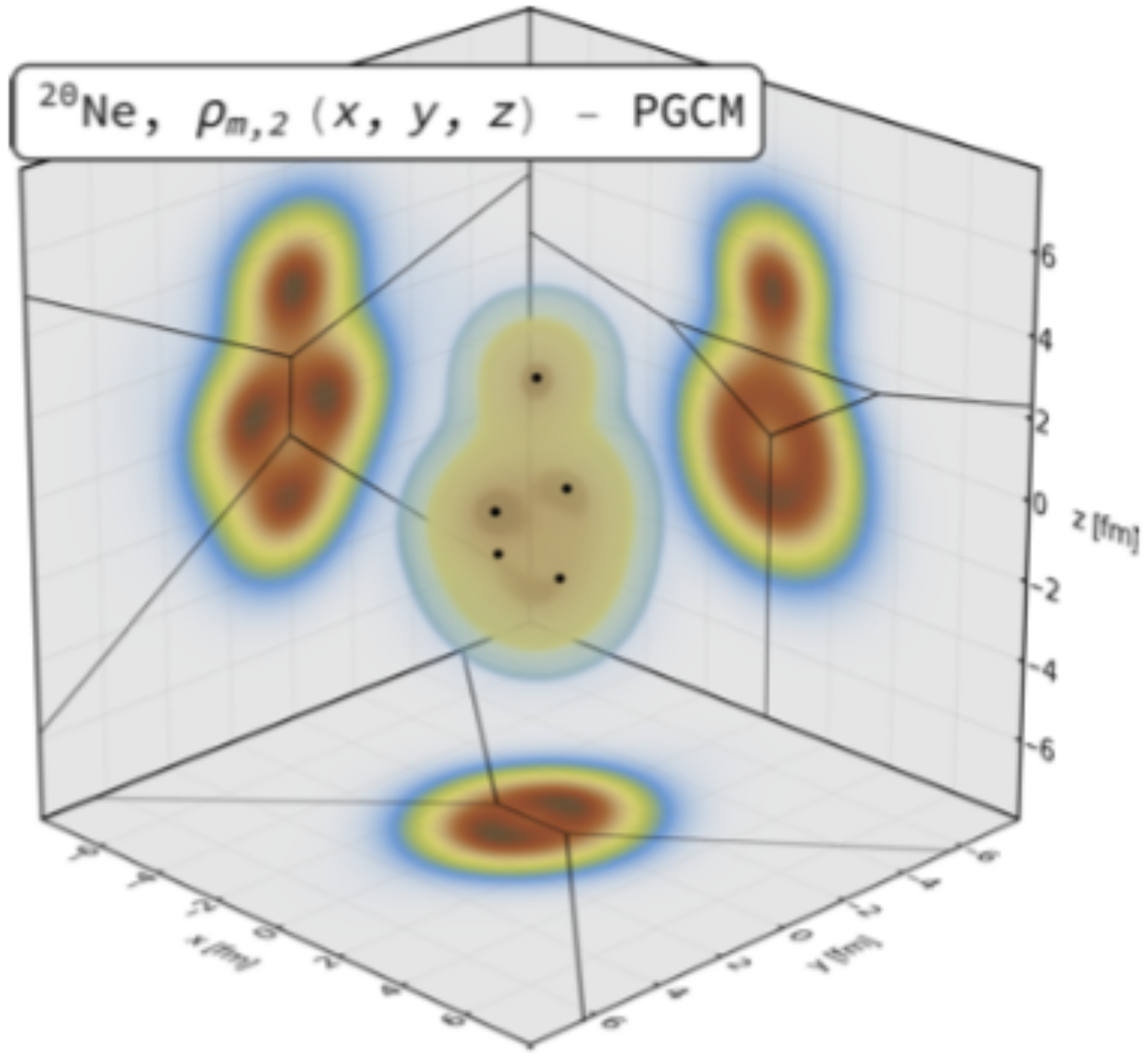
No conclusive evidence for quenching resulting from the partonic rescattering of high-p_T quarks and gluons in a deconfined medium

OO and NeNe collisions at the LHC

~ Similar multiplicity as in peripheral PbPb or pPb, but with a simpler initial geometry







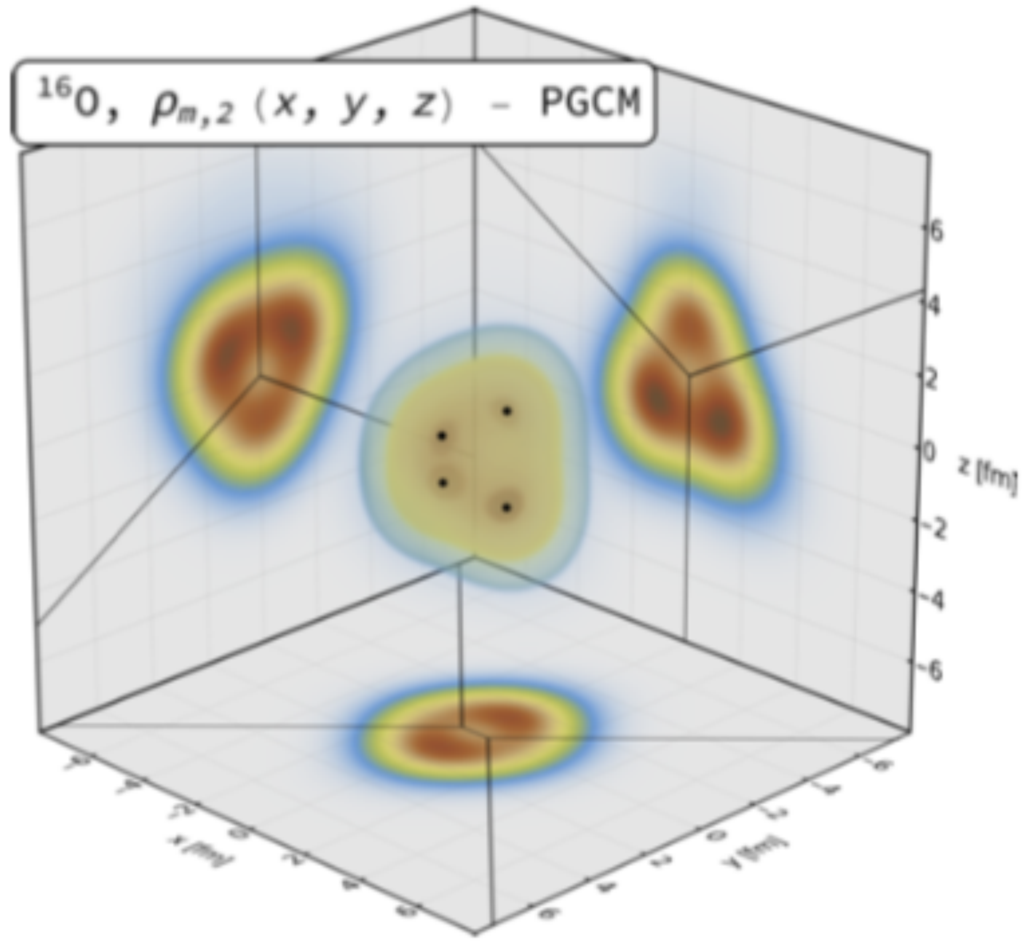
Quantify the magnitude of flow phenomena and connection with initial geometry

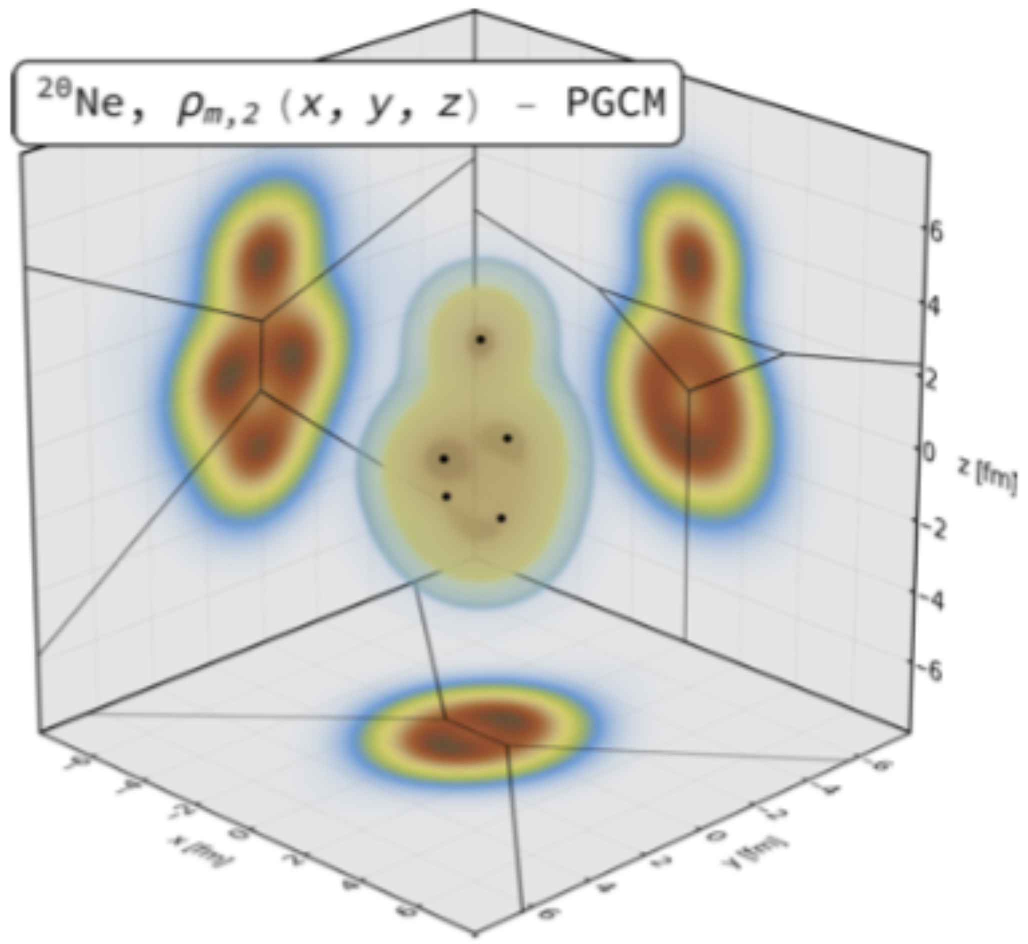
Test the emergence of quenching effects without sizable selection biases

Oxygen

Neon

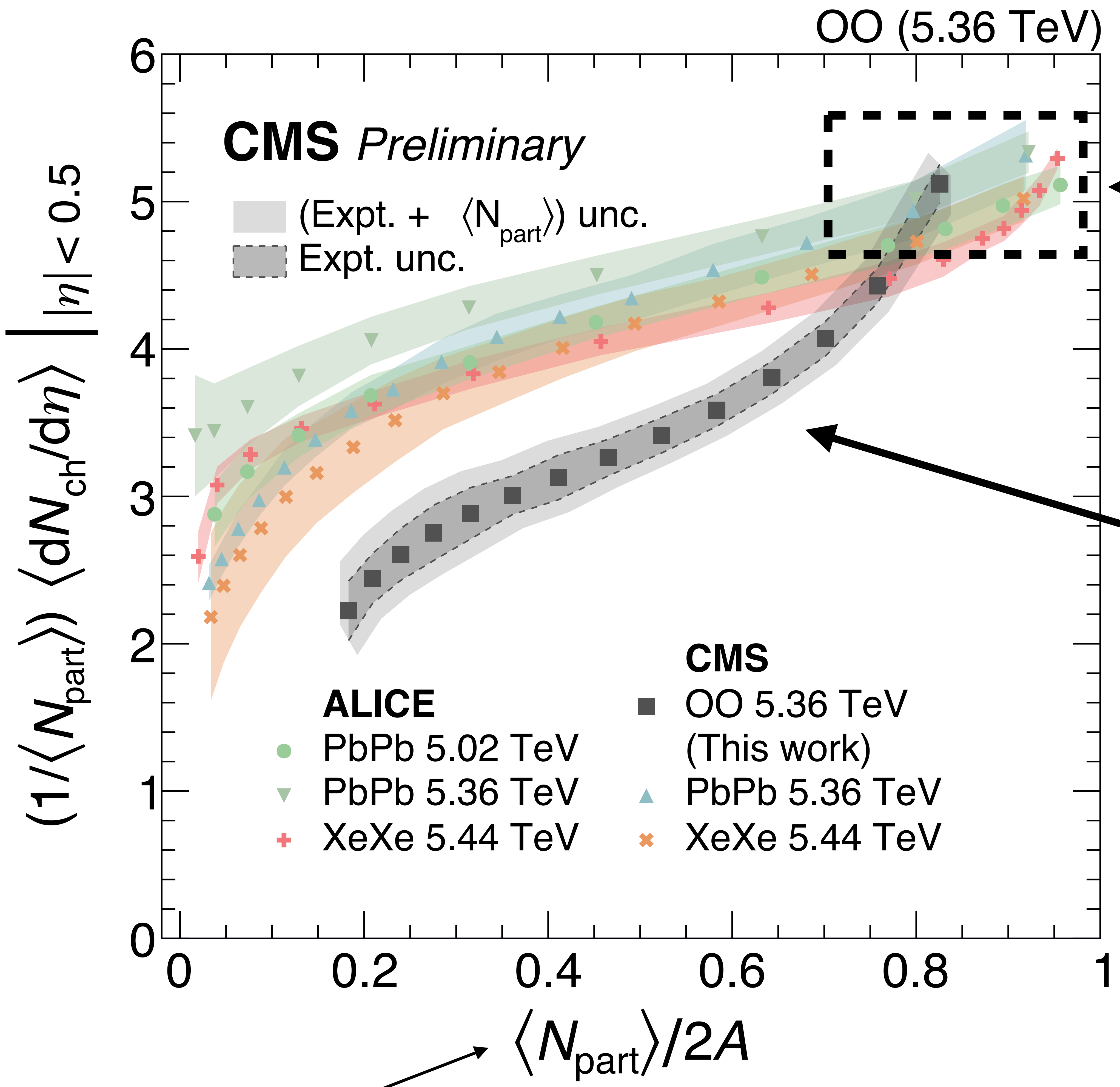
Light ions at the LHC





dN/dη per participant across systems

CMS, CMS-PAS-HIN-25-010



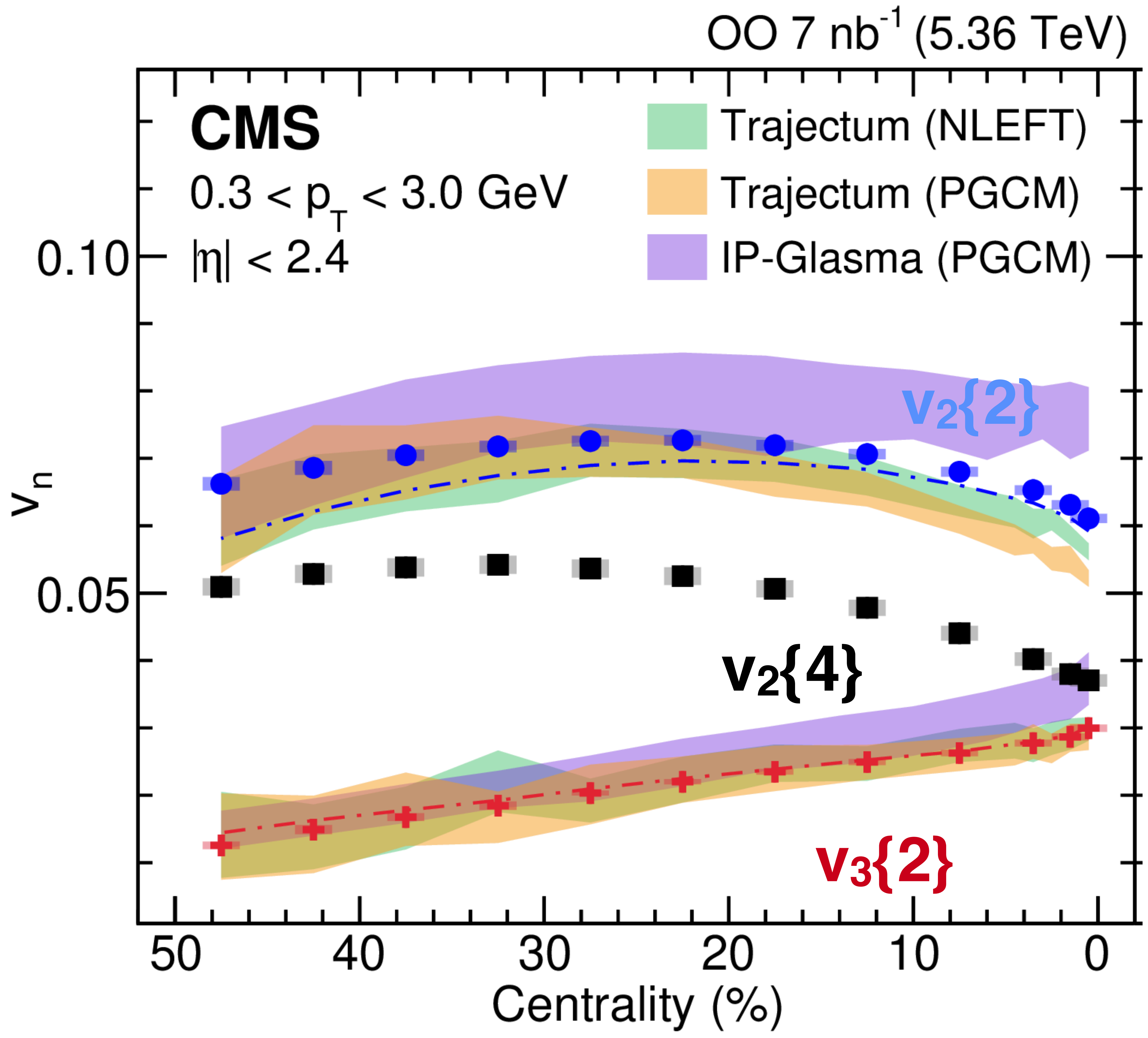
All nucleus-nucleus systems reach a similar average multiplicity per participant
→ deconfined medium in OO?

Much “steeper” increase for OO collisions
→ “faster” transition? selection bias?

average fraction of participant nucleons

CMS, arXiv:2510.02580

OO v_n compared to theory predictions

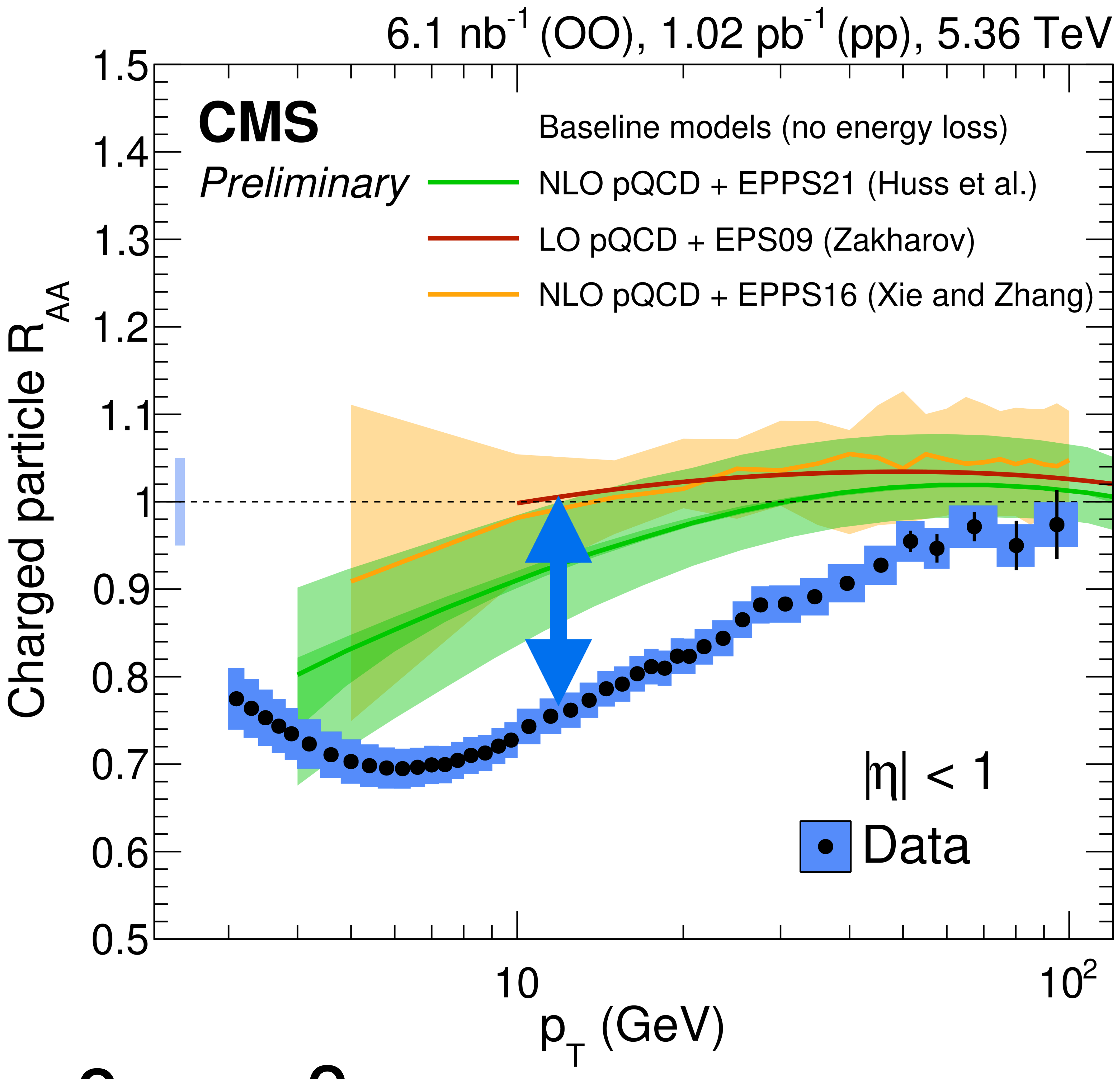


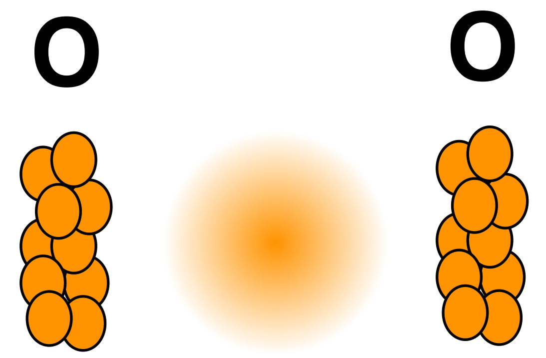
→ **Hydrodynamic models overall provide a good description**

→ **Sensitivity on the modeling of the initial conditions** (ab-initio nuclear structure)

CMS, arXiv 2510.09864

Charged-hadron R_{AA} in OO collisions at 5.36 TeV





inclusive (0-100%) OO events (A^2 normalization)

→ no selection on centrality

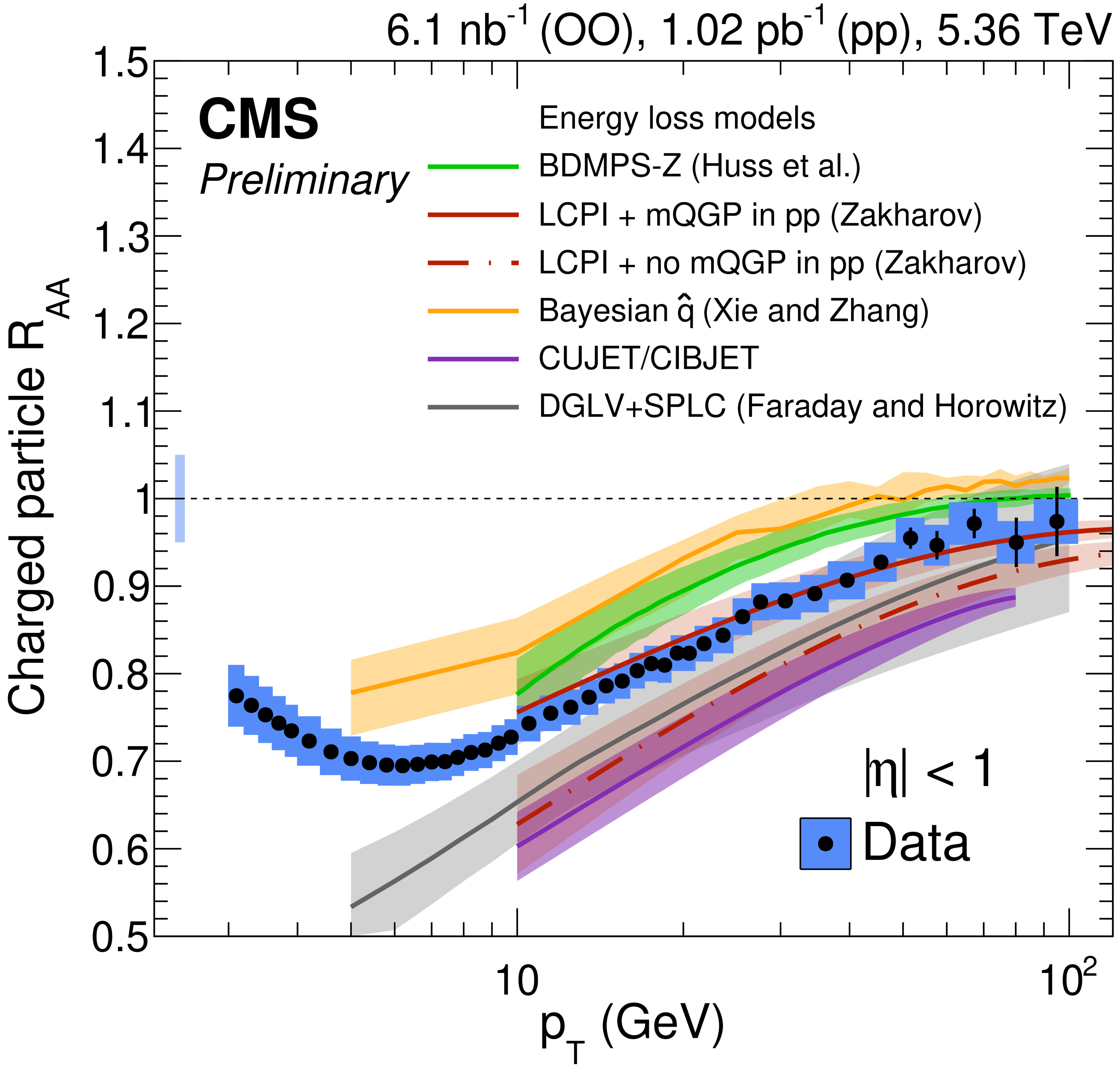
$$R_{AA} = \frac{1}{A^2}\left(\frac{d\sigma^{AA}}{dp_T}\right) \Big/ \left(\frac{d\sigma^{pp}}{dp_T}\right)$$

Predictions from pQCD LO/NLO
without energy loss

CMS shows for $R_{AA} < 1$ (>5σ, at $p_T = 6$ GeV)

- Typical p_T dependence already observed in large systems

Comparison to quenching pQCD calculations



Predictions from pQCD LO/NLO **with energy loss**

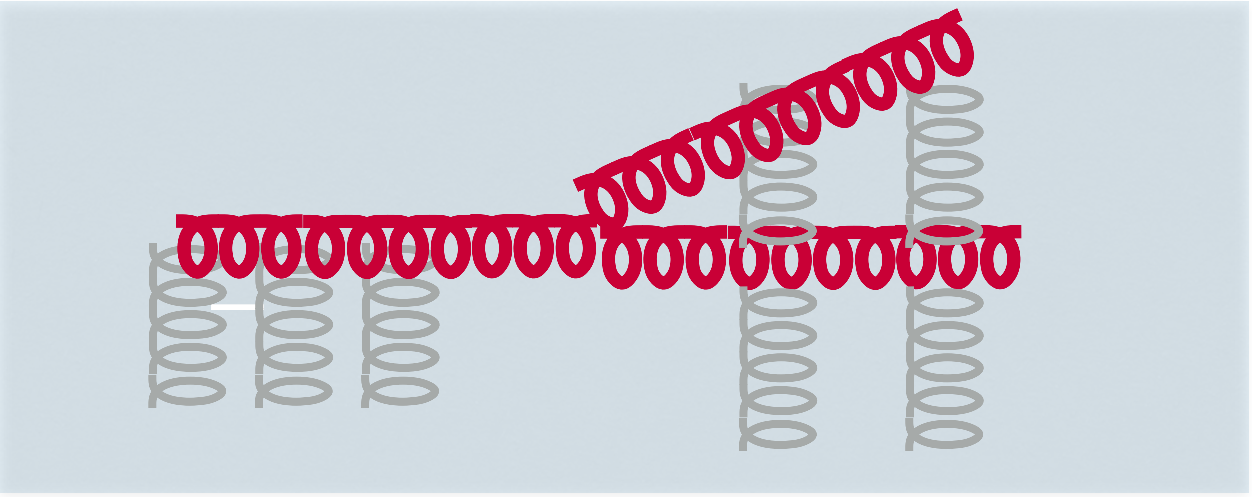
R_{AA} is much better described by calculations including in-medium parton energy loss!

→ Evidence that a QGP can be formed and detected in very small collision systems?

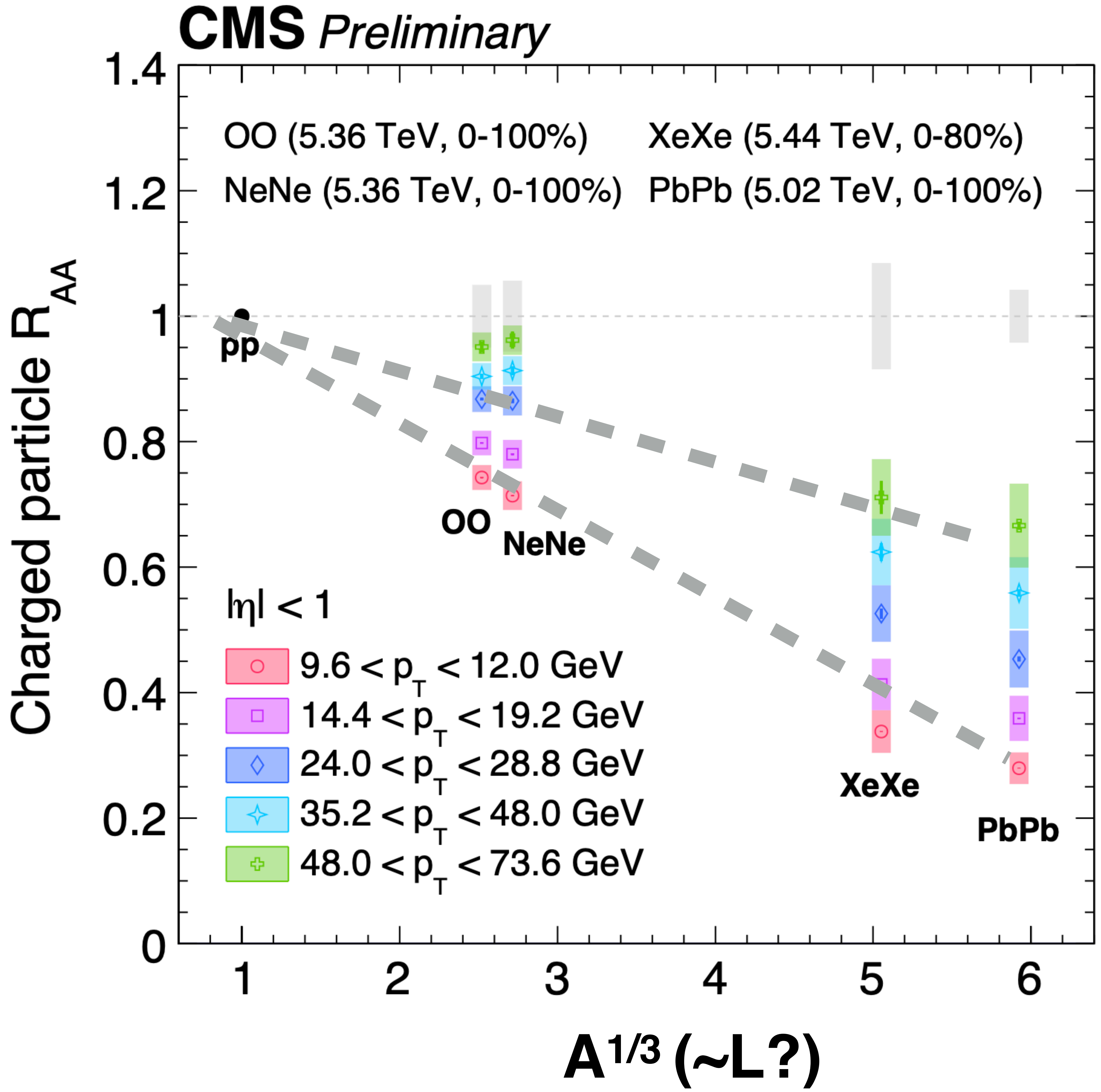
CMS, CMS-PAS-HIN-25-014

System-size (A) dependence of quenching effects

→ Is the energy-loss magnitude simply proportional to the in-medium path length?



QGP with length L

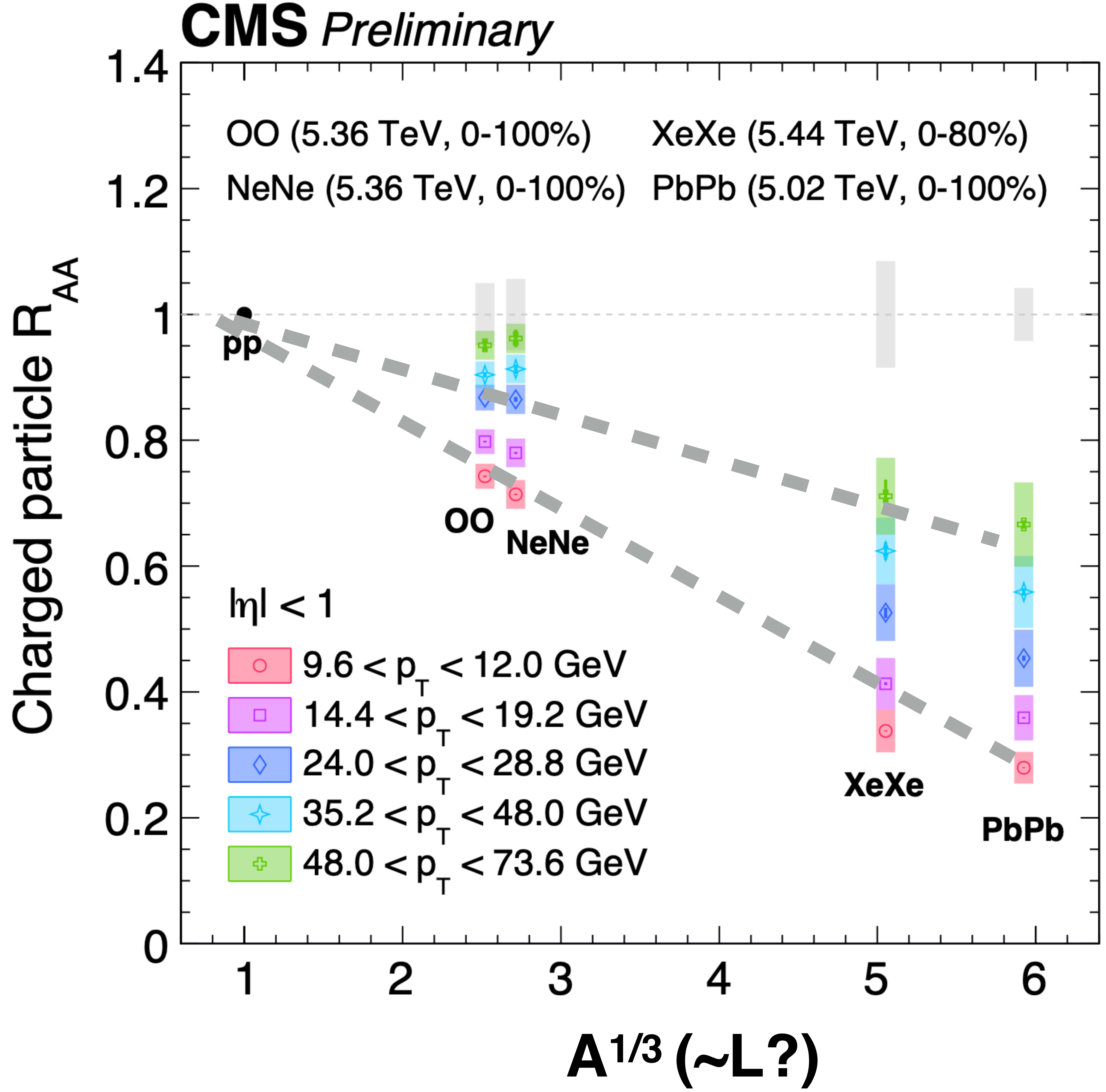


→Non-linear L dependence as predicted by pQCD calculations?

With "minimum-bias" measurements with light and heavy ions

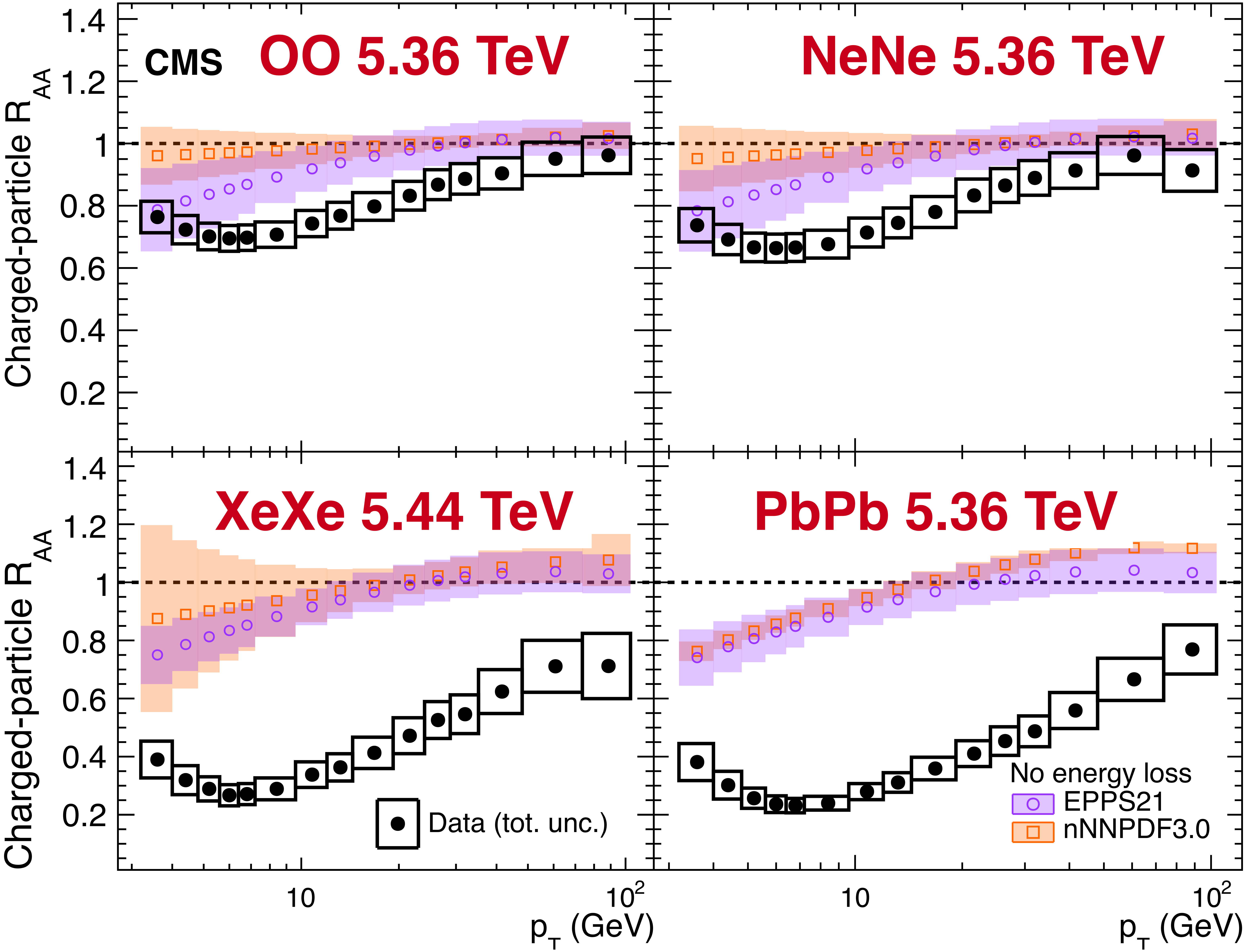
→ model-independent constraints on A dependence of quenching with no obvious selection biases induced by e.g. centrality selections

Caveats and open questions



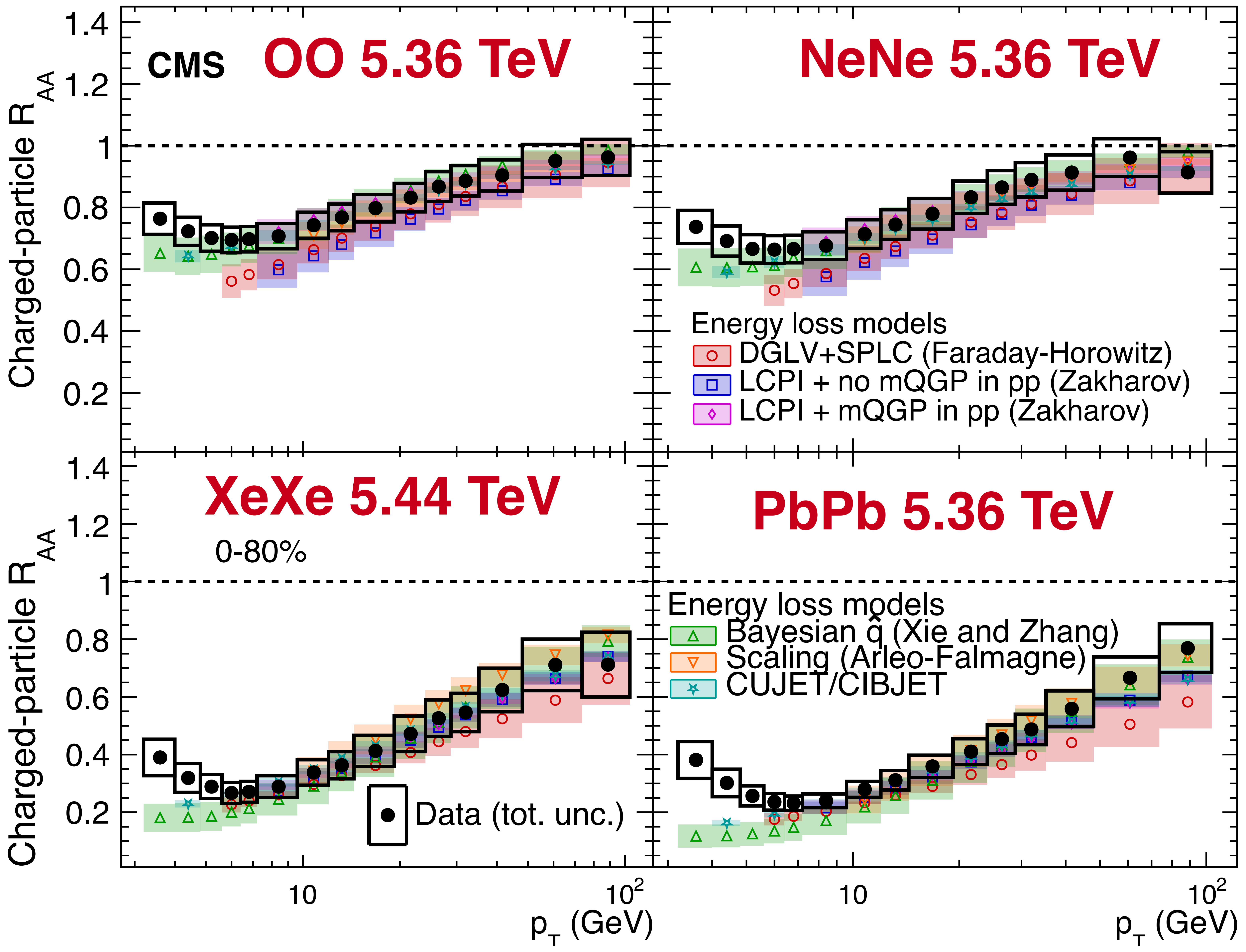
- **To what extent can we make an unambiguous statement about genuine path-length dependence?**
- Do we retain sensitivity to path-length dependence, once we account for nPDF uncertainties and the modeling of temperature and energy dependence?
- What is the smallest collision system that still exhibits quenching?

Nuclear modification factors vs nPDFs–only calculations



Systematic comparison of **nPDF-only calculations** with CMS data across different heavy-ion collision systems

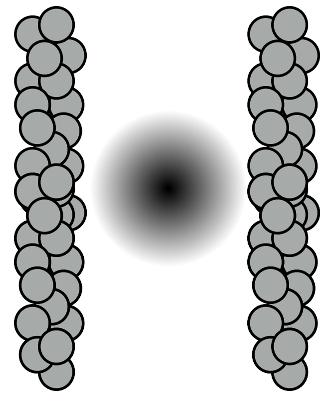
Nuclear modification factors vs jet quenching calculations

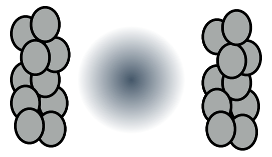


Systematic comparison of **nPDF+quenching calculations** with CMS data across different heavy-ion collision systems

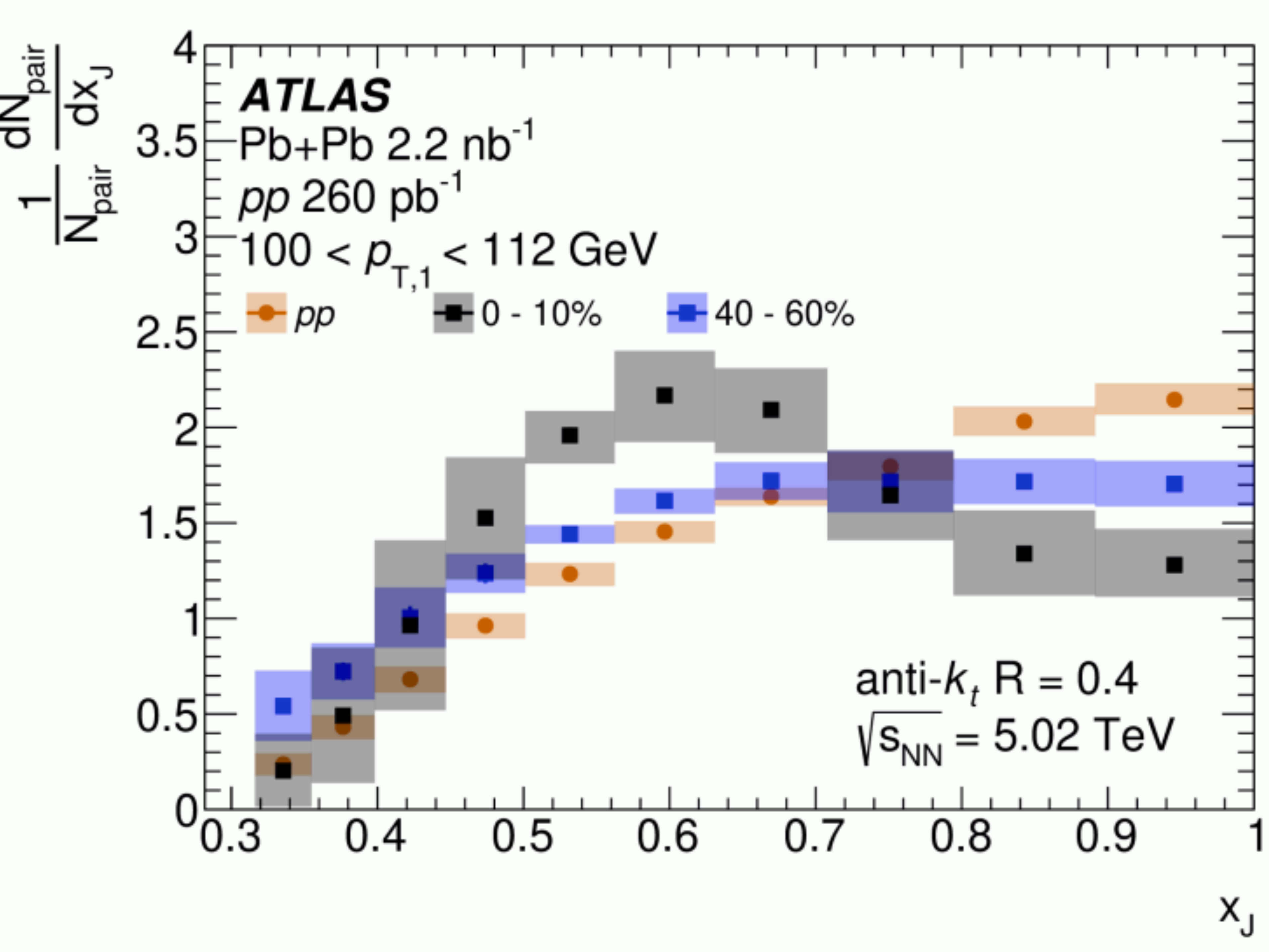
ATLAS, ATLAS-CONF-2025-010

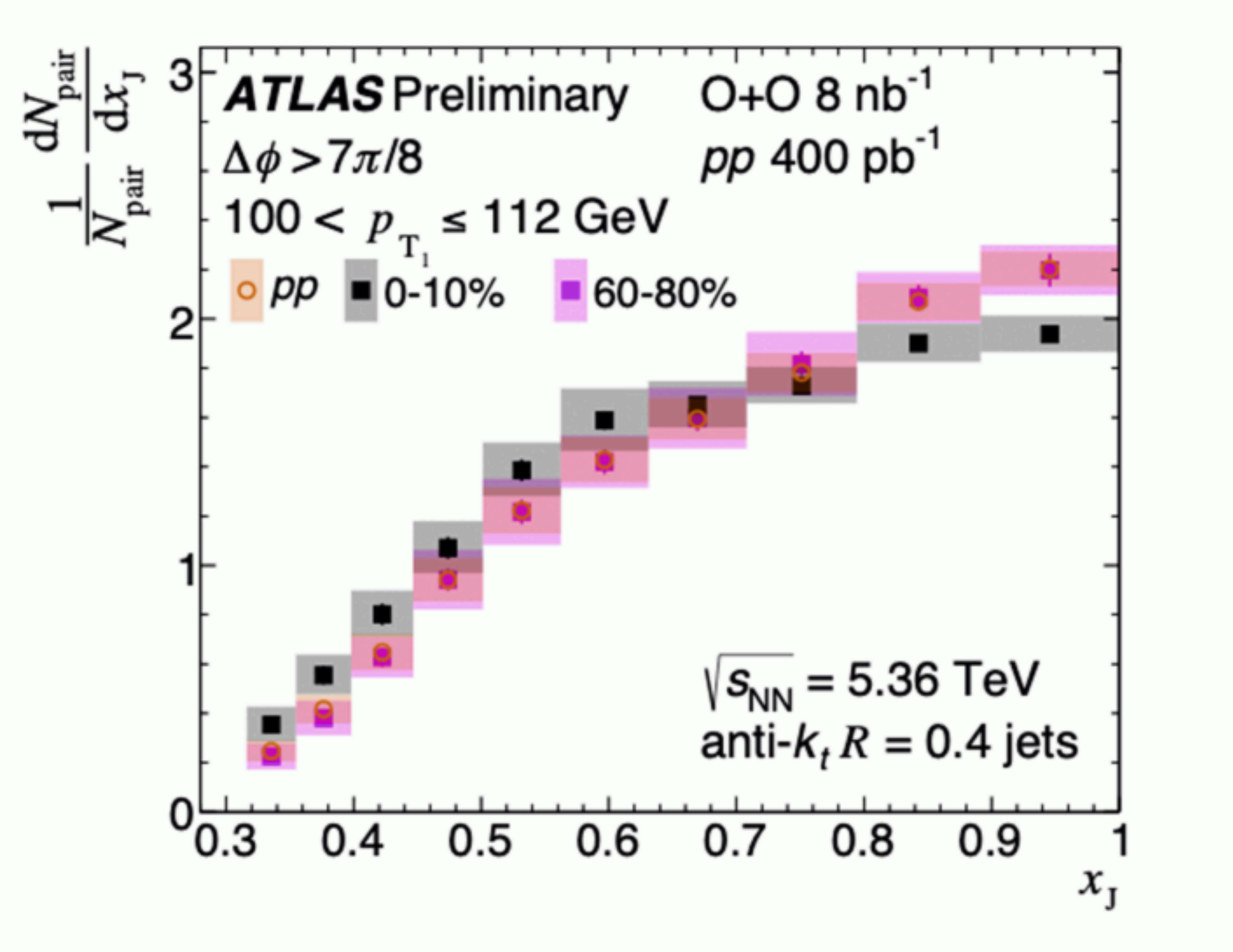
Dijet production in PbPb vs OO collisions with ATLAS

Pb  Pb

O  O

$$x_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$





Hint of a larger asymmetry in central OO collisions compared to peripheral OO and pp collisions

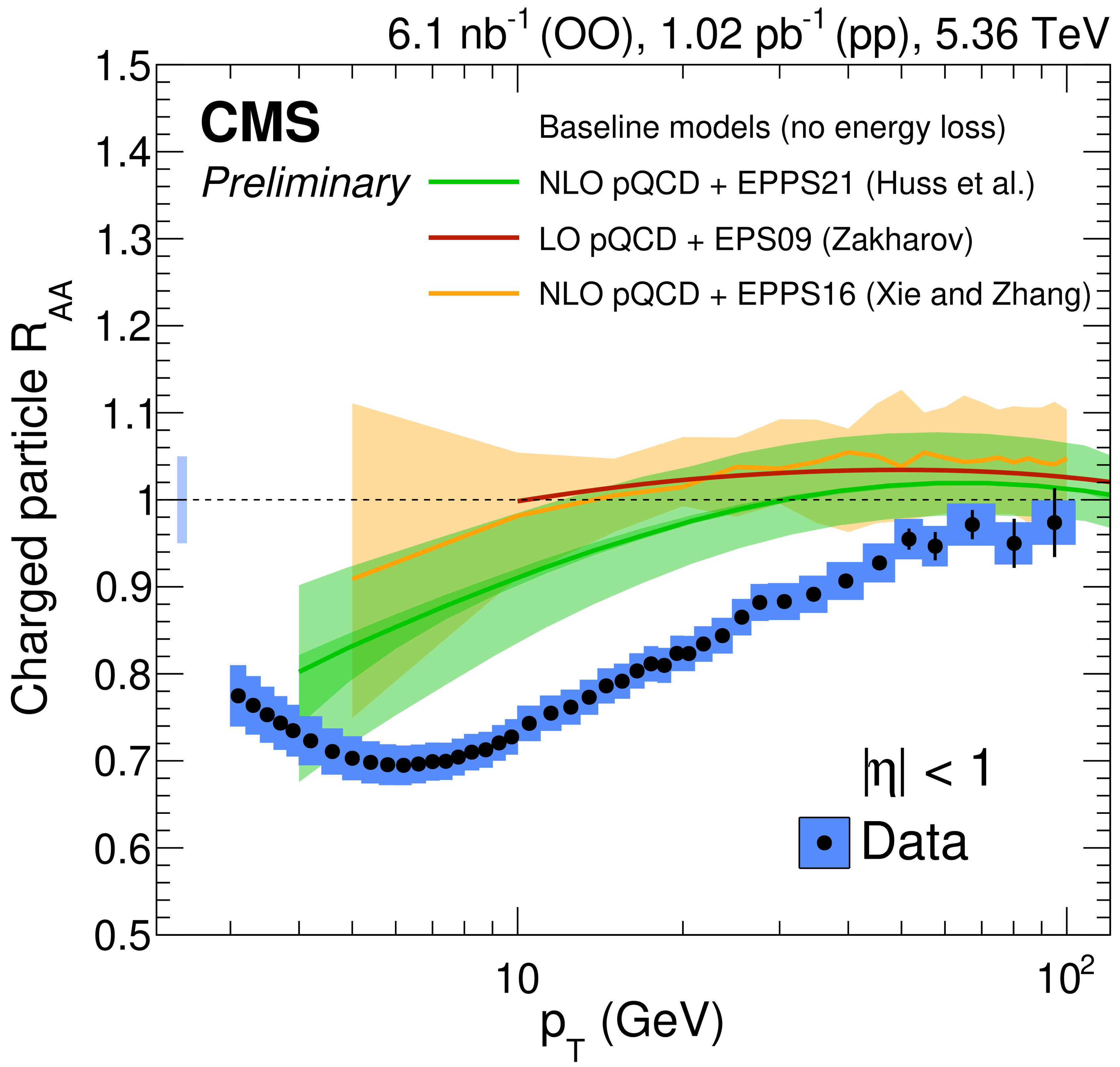
- Relevance of nPDF modifications?

Open questions and prospects for future measurements

Addressing the role of nuclear PDFs

Constraining nPDF modifications

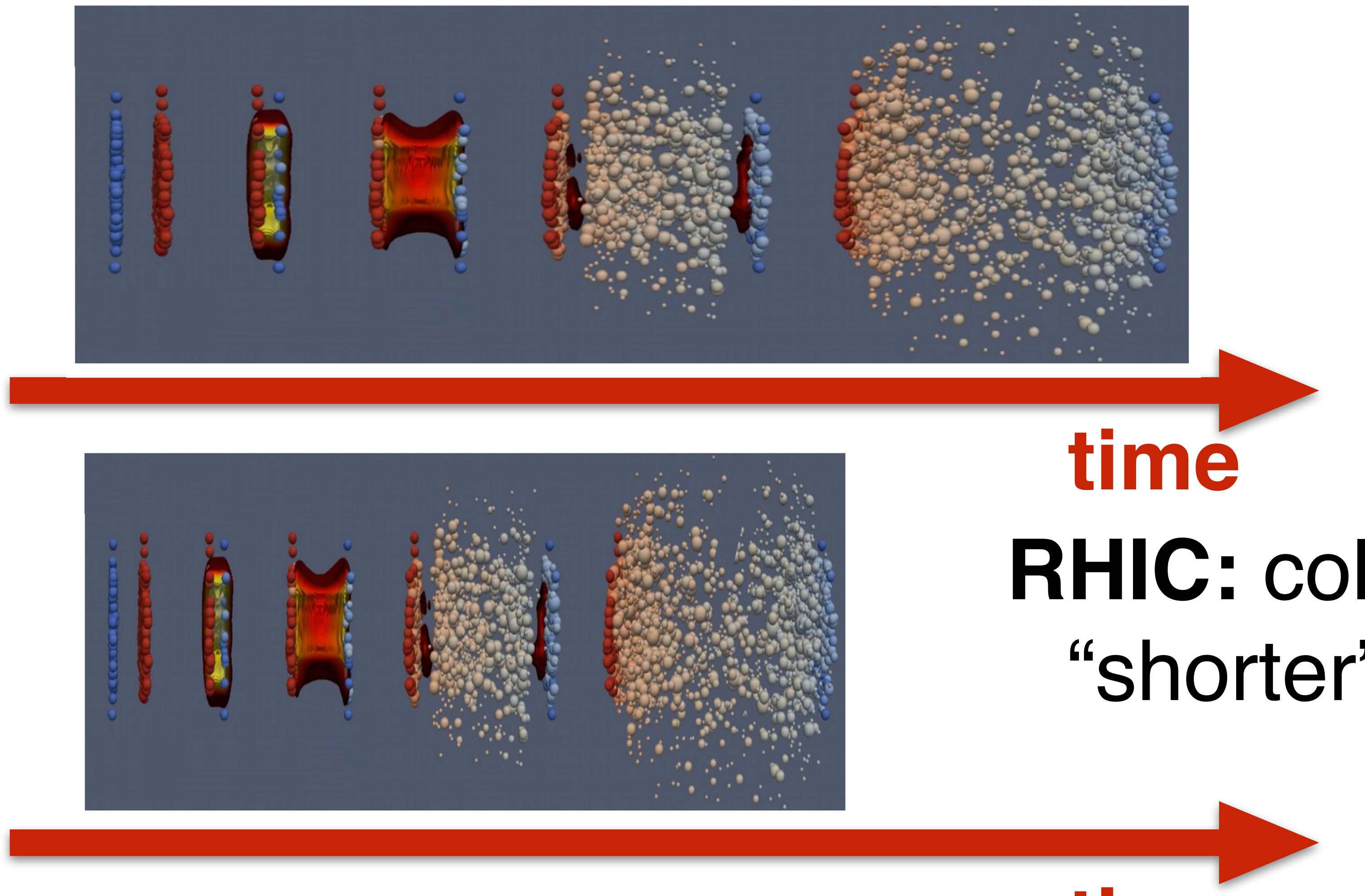
- measurements in proton-oxygen collisions to constrain gluon nPDFs (e.g. D^0 production vs rapidity)
- R_{pO} to assess the qualitative magnitude of the cold-nuclear matter effect
- UPC measurements in OO probably require larger samples



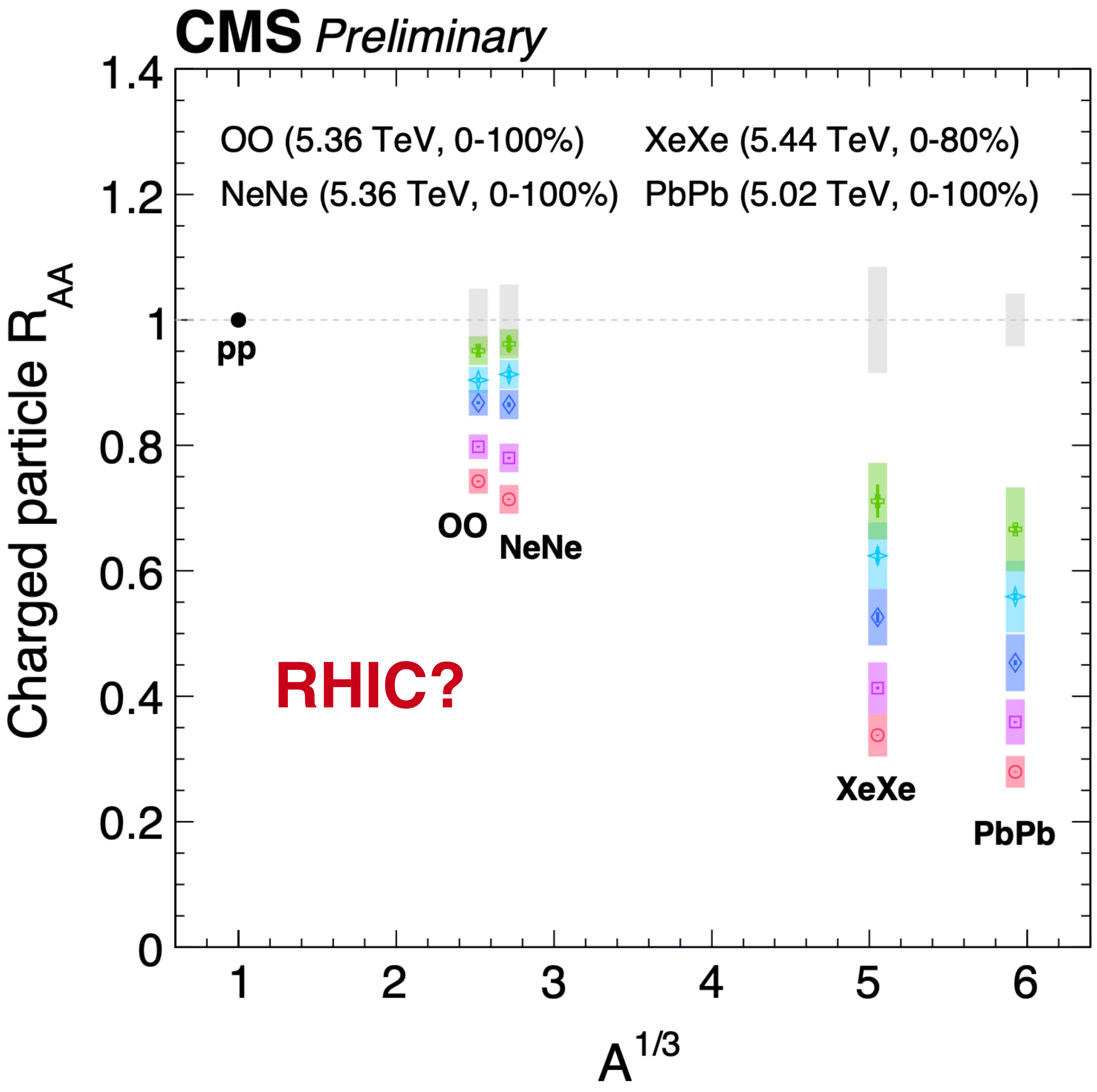
Limiting the dependence on nPDF modifications
with observables with reduced sensitivity to cold nuclear matter effects
(see next slides)

Quenching effects in light-ion collisions at RHIC and the LHC

Oxygen-oxygen collisions:
for the first time, the same nucleus-nucleus collisions at RHIC (200 GeV) and at the LHC (5.36 TeV)



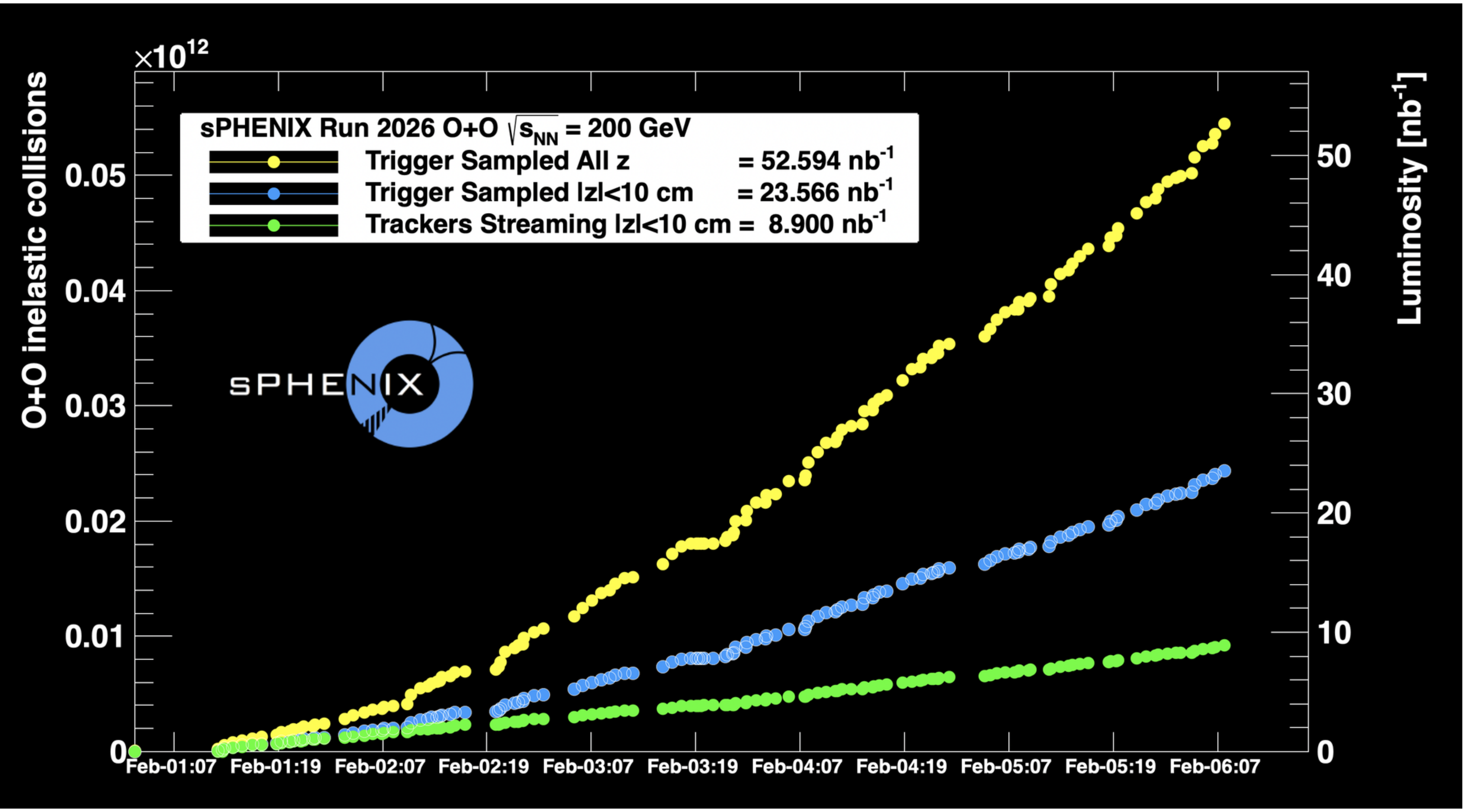
RHIC: colder and "shorter" QGP



What can we learn by comparing quenching measurements at RHIC and the LHC?
(energy density and time-scale of the medium evolution…)
→ sPHENIX OO samples enable measurements of charged-hadron R_{AA}, open heavy flavors, jets (etc) in OO collisions

First OO collisions at 200 GeV at RHIC

***At the LHC, about 7 nb^{-1} of OO collected at 5.36 TeV



σ_{inel} = 1.15 b

Collected luminosity:

~23.5 nb^{-1} of high-p_T data triggered **(27 billion events)**

~ 8.9 nb^{-1} of "minimum-bias" events **(10 billion events)**

Sizeable statistics (thanks to the high-interaction rate and readout mode)

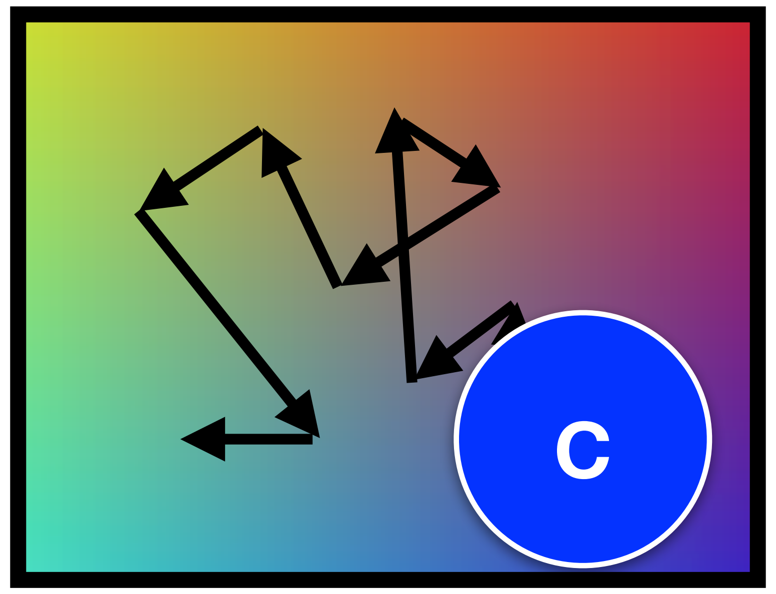
→ WIP to assess p_T reach and accuracy for the various observables (charged hadrons, HF hadrons, jets, jet substructure...

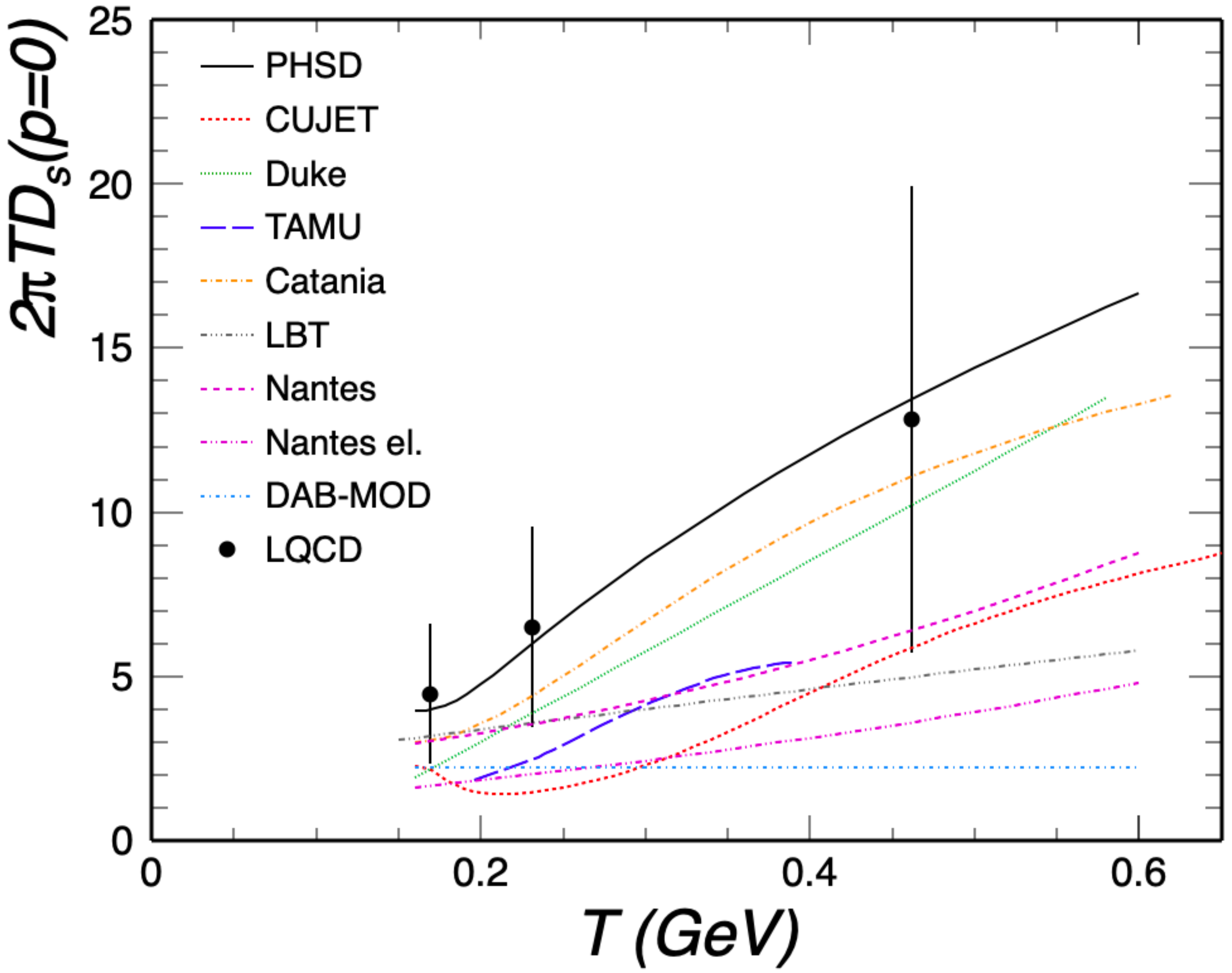
Drag and diffusion coefficients in OO at RHIC vs LHC

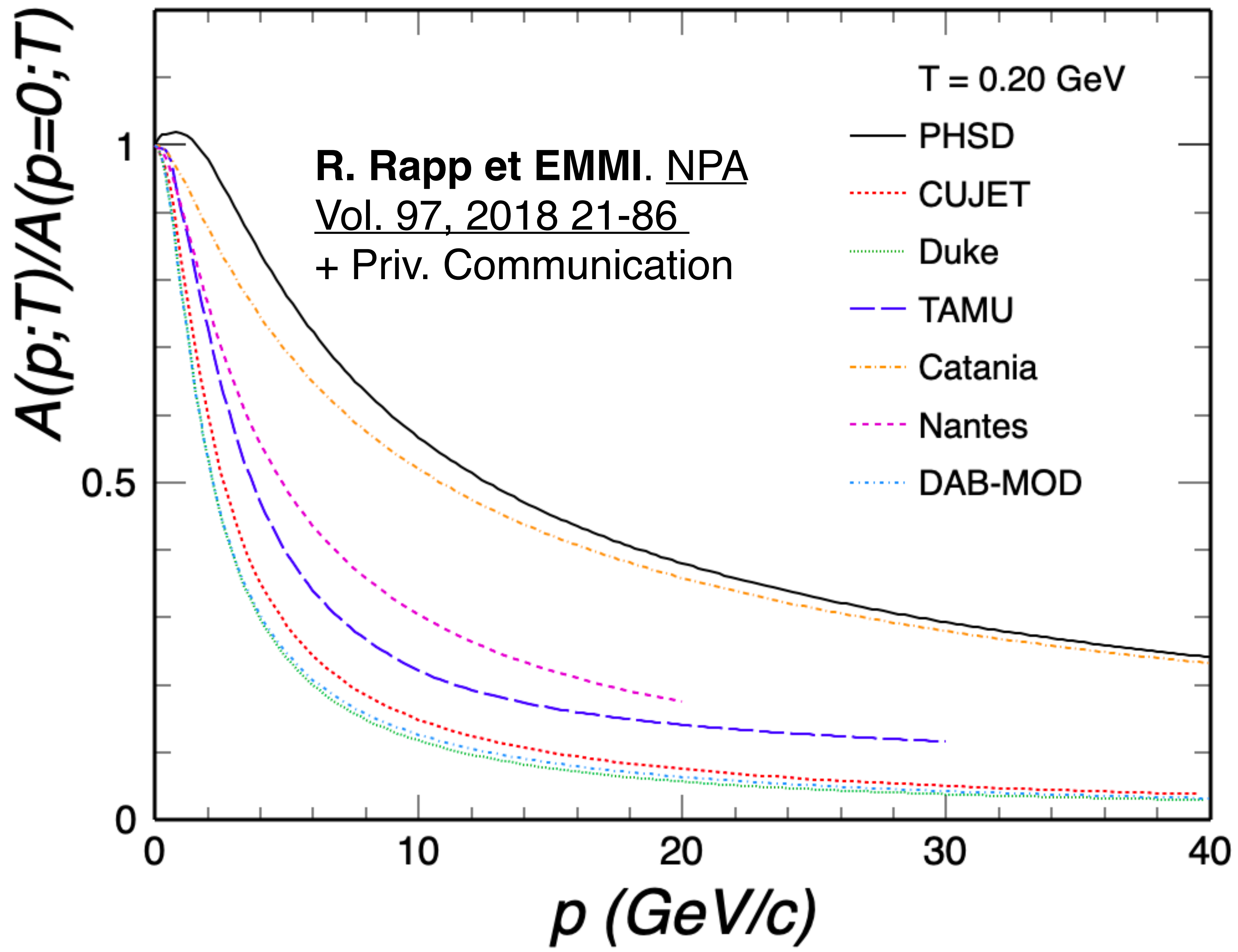
- **$m_{c,b} > m_{u,d,s}$: "Brownian regime" in the QGP**

→ sensitive to the QGP diffusion and drag properties

Temperature and momentum dependence of drag coefficients γ=f(T,p) for PbPb collisions at LHC energies







→ Constraints on the temperature and momentum dependence of the HQ drag properties by performing the same measurements at RHIC and LHC energies (e.g., charm and beauty v_2, R_{AA}..)

→ Analogous strategies can be developed for other quenching observables and parameters

Jet and substructure measurements in OO collisions

Why are OO jet measurements promising?

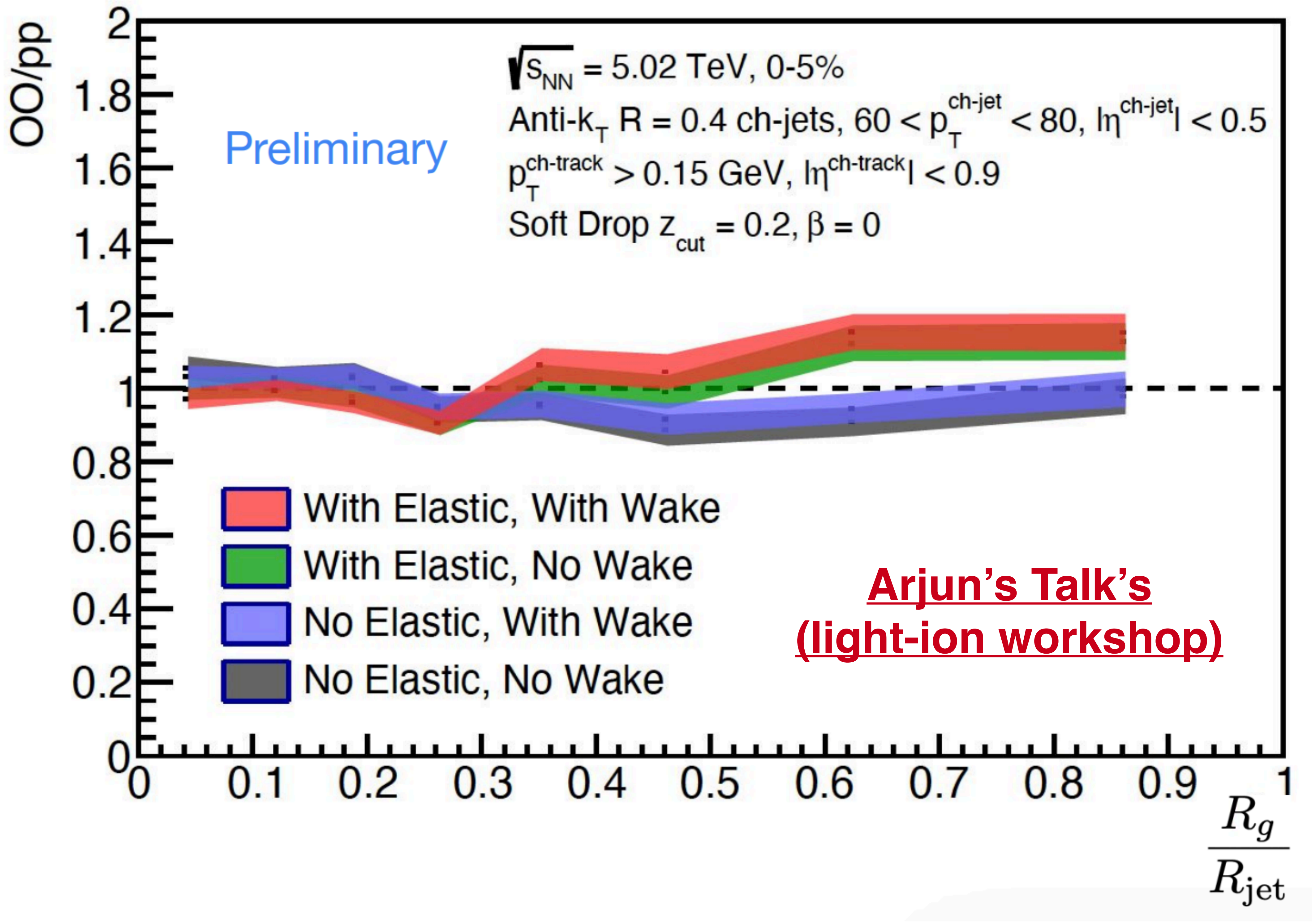
- The underlying event (UE) is substantially lower making jet and jet-substructure measurements less challenging
- Quenching effects are smaller than in PbPb, but still sizeable!

Goals and opportunities:

- Consolidate observation of quenching with observables that have lower sensitivity to nPDFs
- Search for direct evidence of quenching by detecting substructure modifications

→ characterization of splitting modifications and inner structure of the QGP at different scales

Some thoughts from the OO workshop



Jet substructure and EEC

Smaller quenching effects and selection bias in OO:

→ stronger sensitivity to elastic scatterings
and medium response

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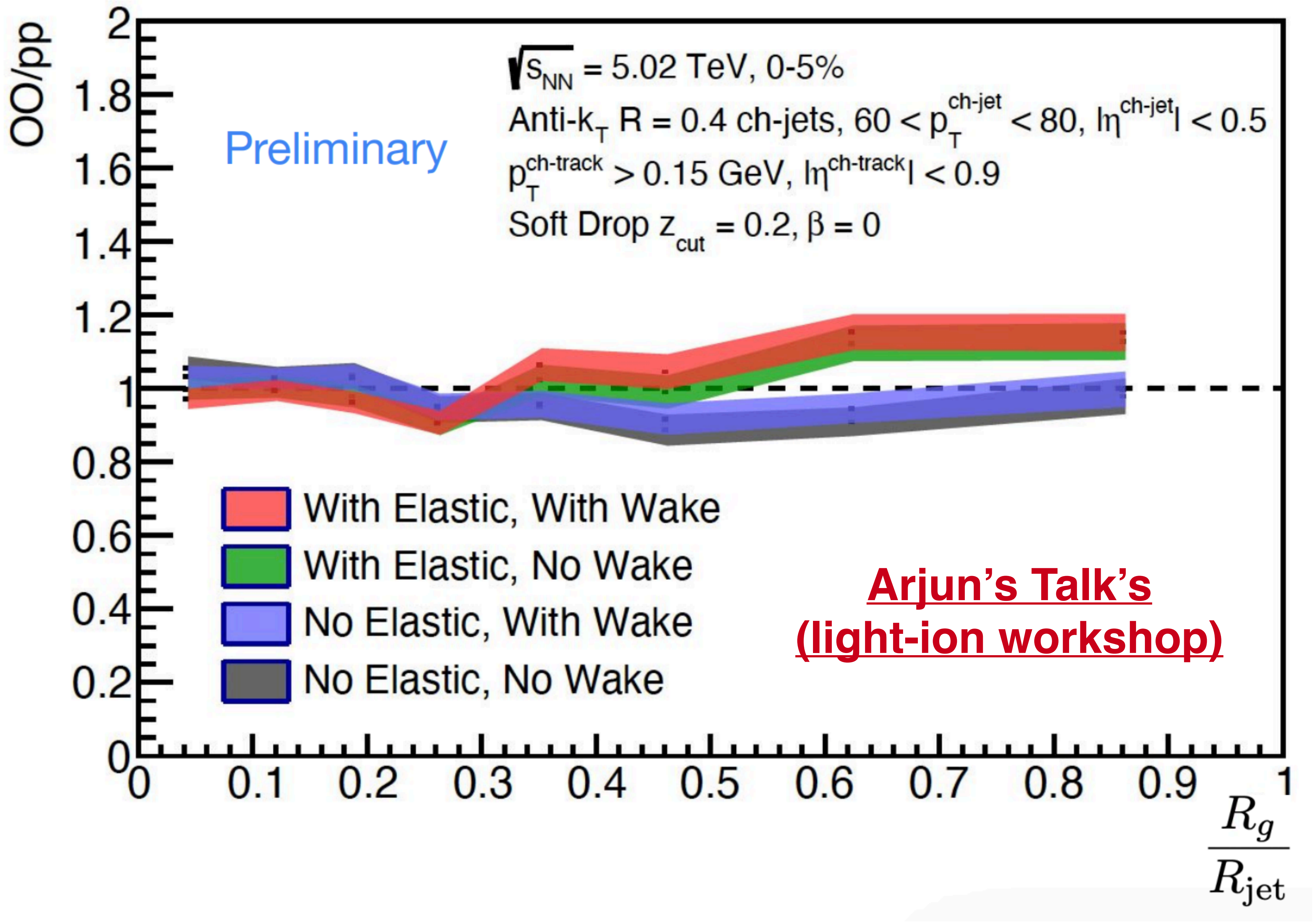
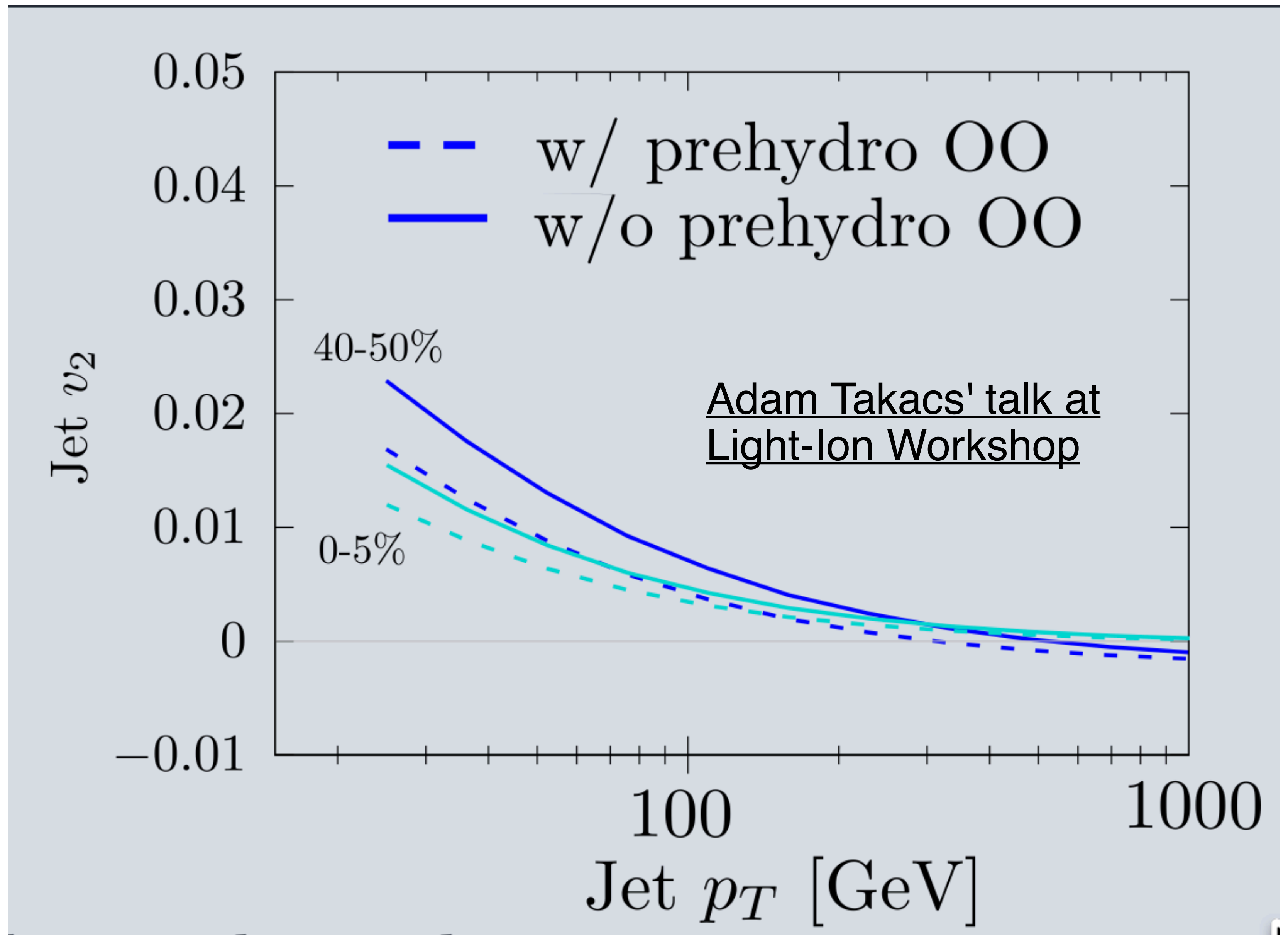
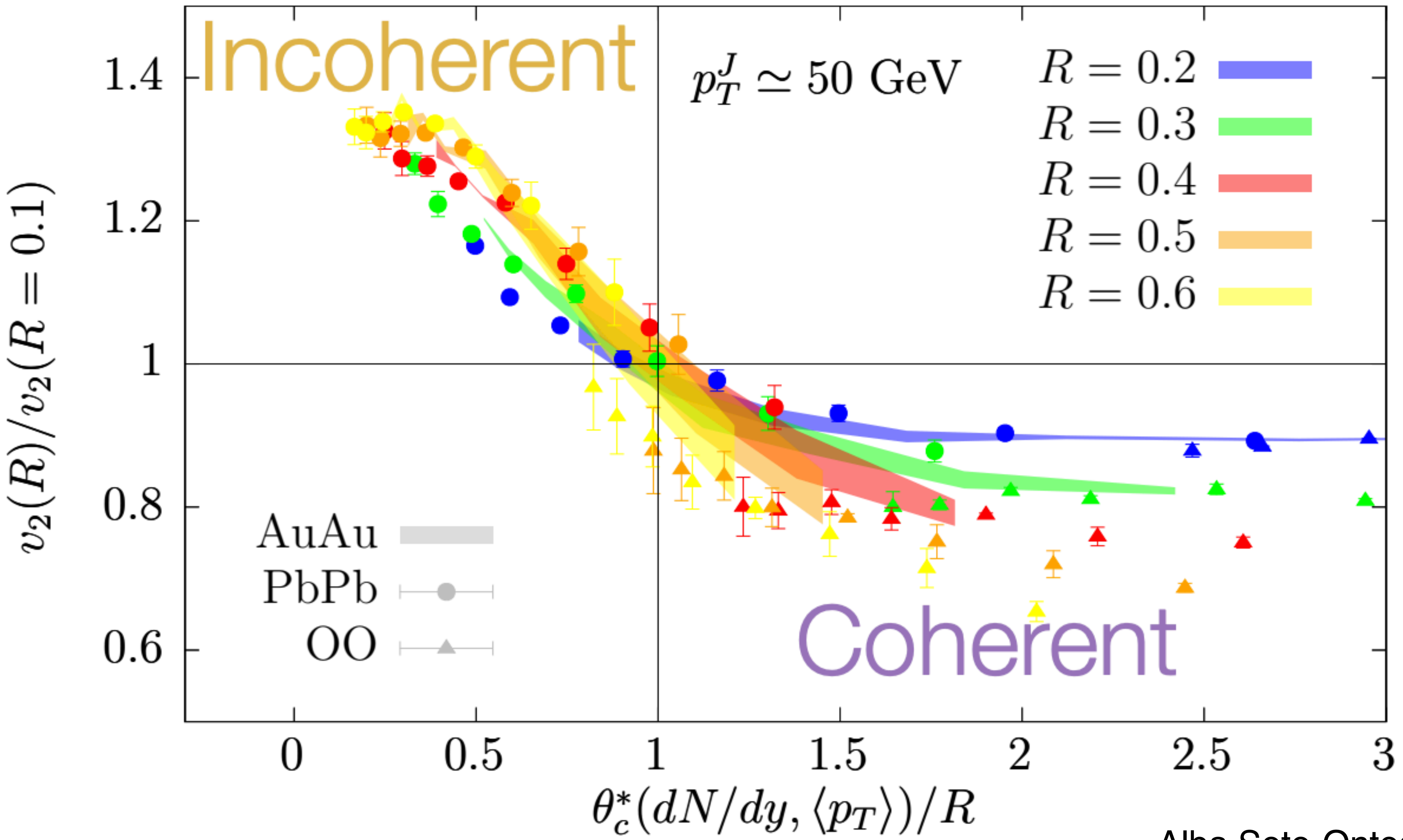






Alba Soto-Ontoso's talk
at Light-Ion Workshop

Jet substructure and EEC

Smaller quenching effects and selection bias in OO:

→ stronger sensitivity to elastic scatterings
and medium response

Jet measurements vs A and $\sqrt{s_{NN}}$ provide sensitivity to color-coherence, path length dependence and pre-equilibrium quenching

“Light-ion” series (LNS lunch seminars)

March 3rd, 2026 Lunch Seminar LNS (noon): Light-ion physics at the LHC with CMS: present and future
- **(Gian Michele** - MITHIG**)**

March 10th, 2026 Lunch Seminar LNS (noon): Prospects for light-ion operation at the HL-LHC
- **Reyes Alemany Fernandez** (responsible for the LHC HI beam operations and upgrades for Run 3 and Run 4)
- Beams Department Accelerator and Beam Physics Group

March 17th, 2026 Lunch Seminar LNS (noon): Theory developments for light-ion physics at the LHC
- **Giuliano Giacalone** (CERN TH)

BACKUP

First (O)Opportunities for jet substructure – Hannah

- Light ions feature minimal background with a measurable energy loss signal.

[CMS, arXiv:2510.09864] [ATLAS, ATLAS-CONF-2025-010] [ALICE, light ion workshop]

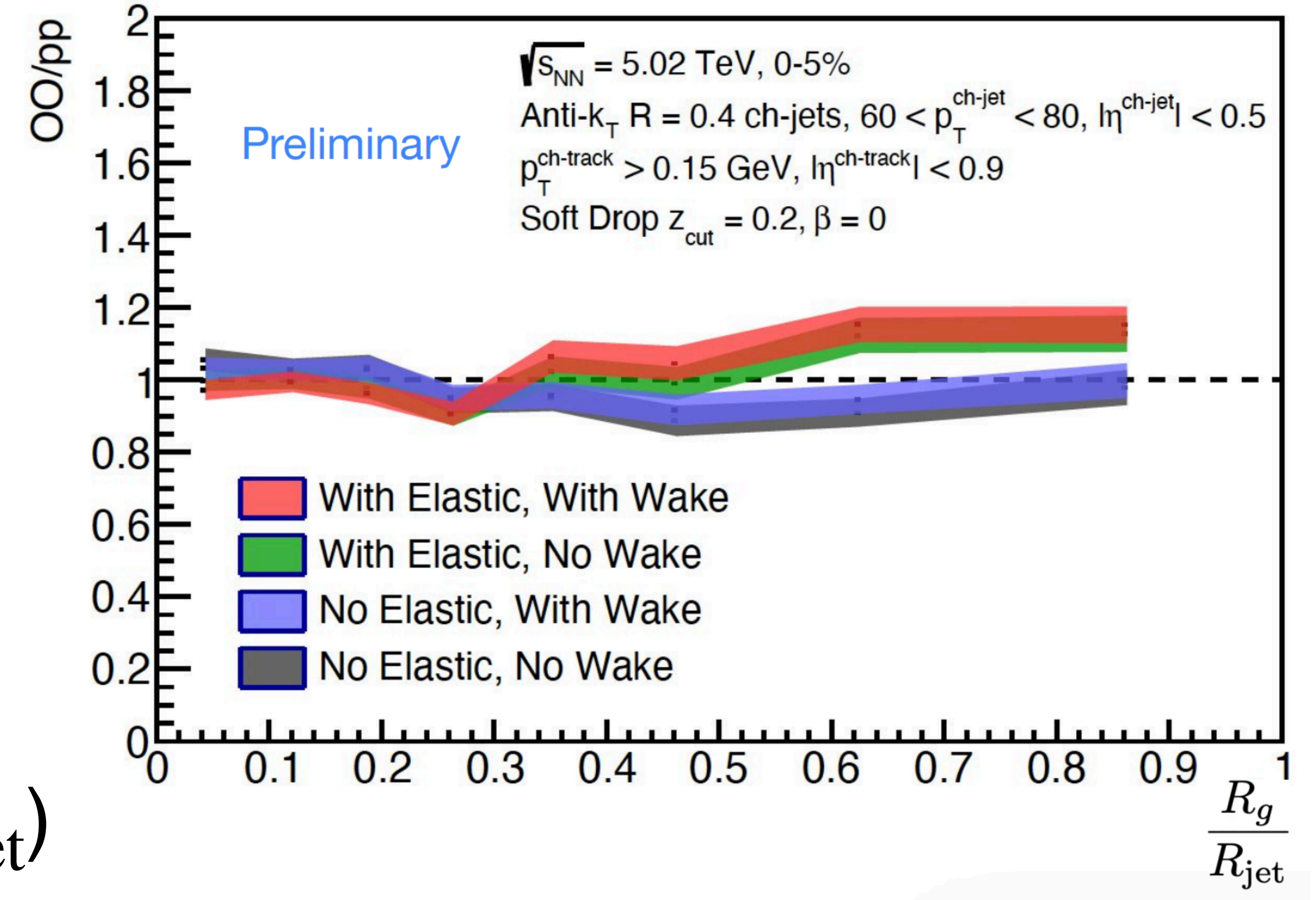
- Other pillar of jet quenching remains unexplored → is there jet (sub)structure modification?

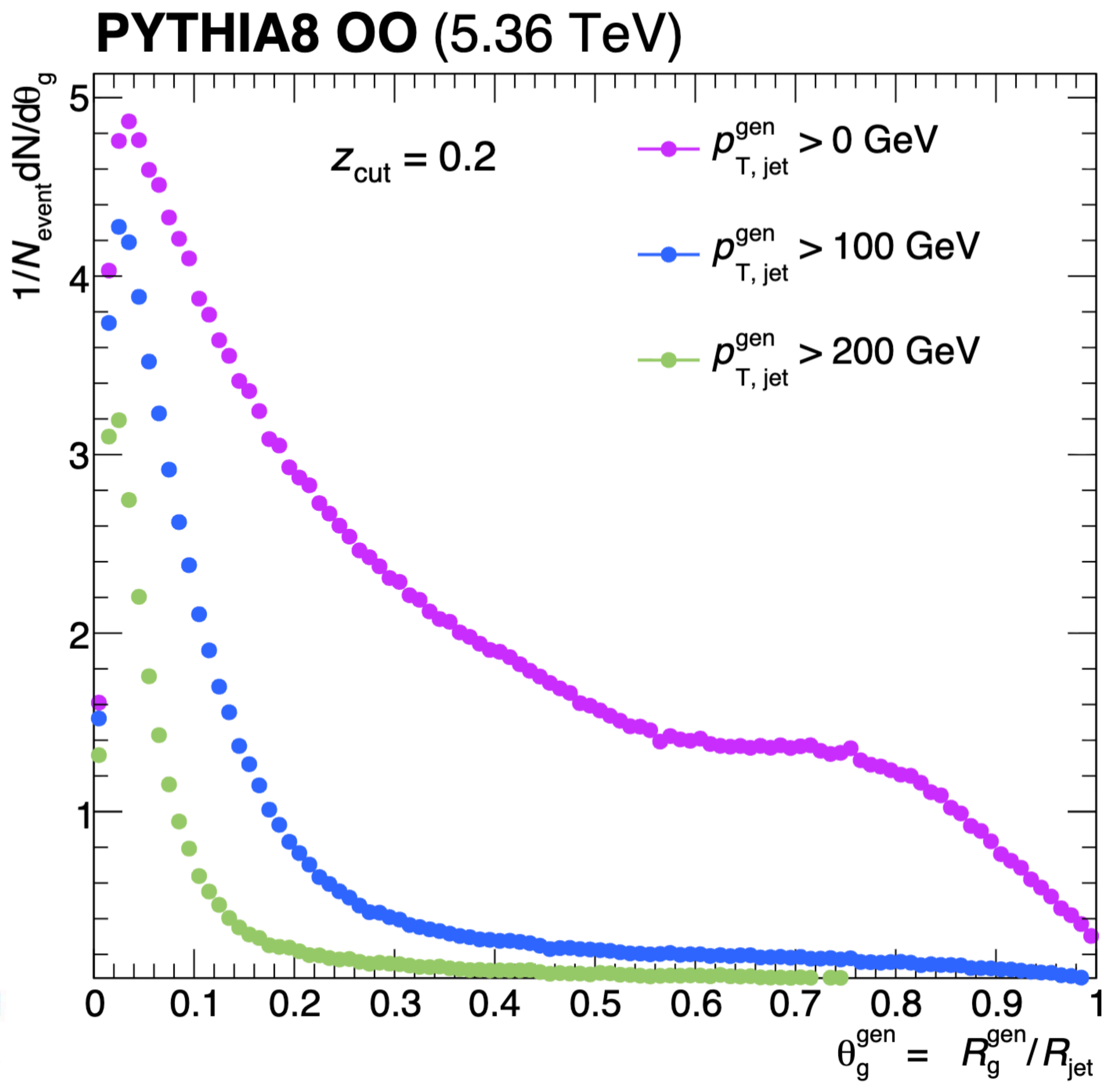
- Good candidate, groomed substructure θ_g → sensitive to coherence angle, elastic scatterings.

- Uses SD grooming, use z_{cut} (i.e. 0.2) to remove fake splittings.

- Challenge is choosing phase space to maximize sensitivity, 2D unfolding (θ_g , $p_{\mathrm{T,jet}}$)

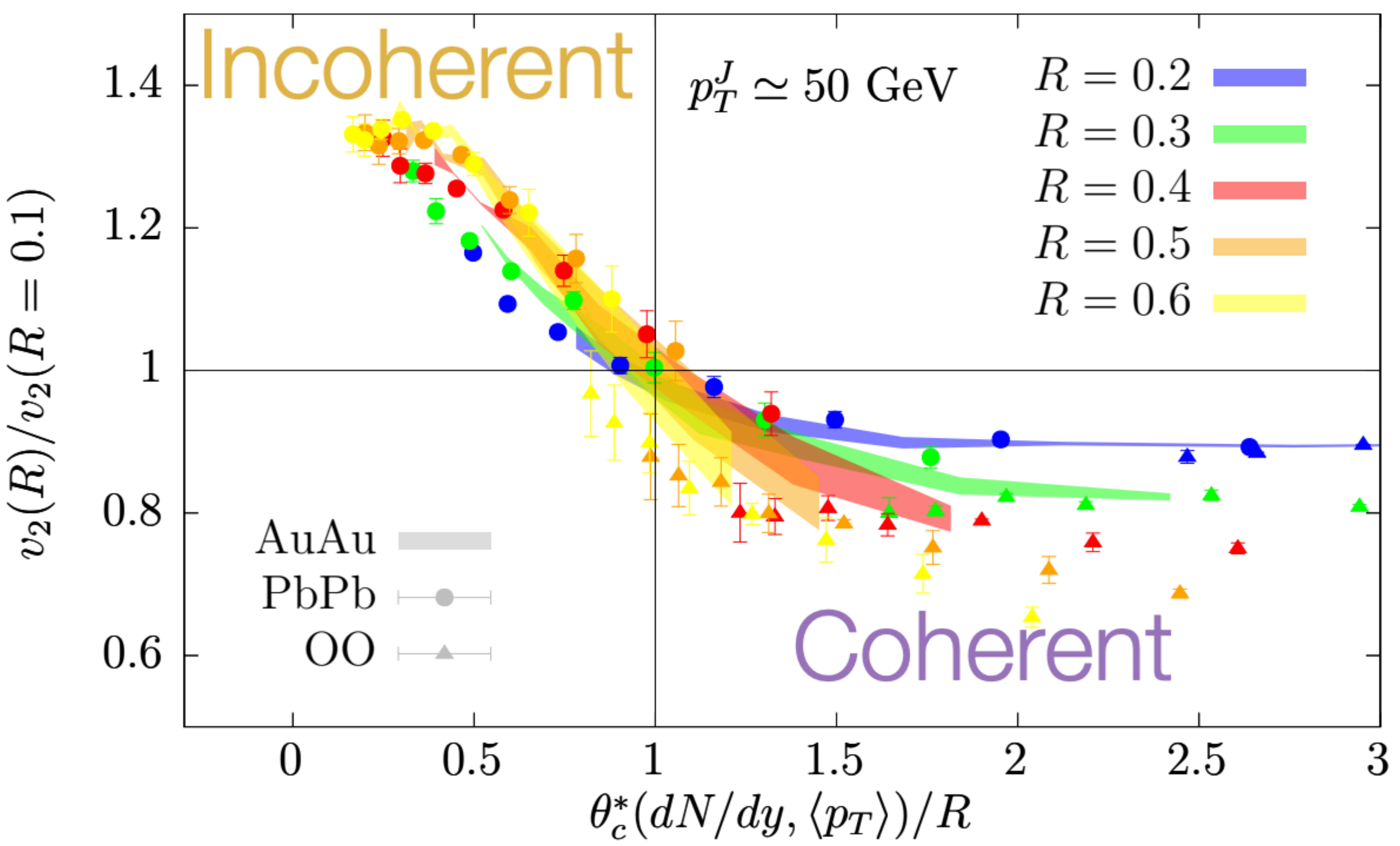
[Arjun's Talk, light ion workshop]





Future (O)Opportunities – Hannah

- Oxygen is the only species to be run at both RHIC and the LHC.
    - Unique opportunity to answer why R_{AA} and v_2 look remarkably similar despite drastically different mediums.



- Jet v_2 double ratios (wrt R = 0.1) as a function of the angle normalized by R.
- Crossing point of double ratio with unity allows for experimental extraction of coherence angle.
- Pros: Experimentally (relatively) easy (info visible without going to large R), extraction of coherence angle that is not model-dependent.

- Challenge: Need at least a few R, more reliable once baseline measurements established.

[Talk by Alba Soto-Ontoso] [Backup slide from talk by Adam Takacs]

Jets at LHC (Cristian)

related to separate discussions with Arjun, Arthur, Dani, Krishna, Yen-Jie

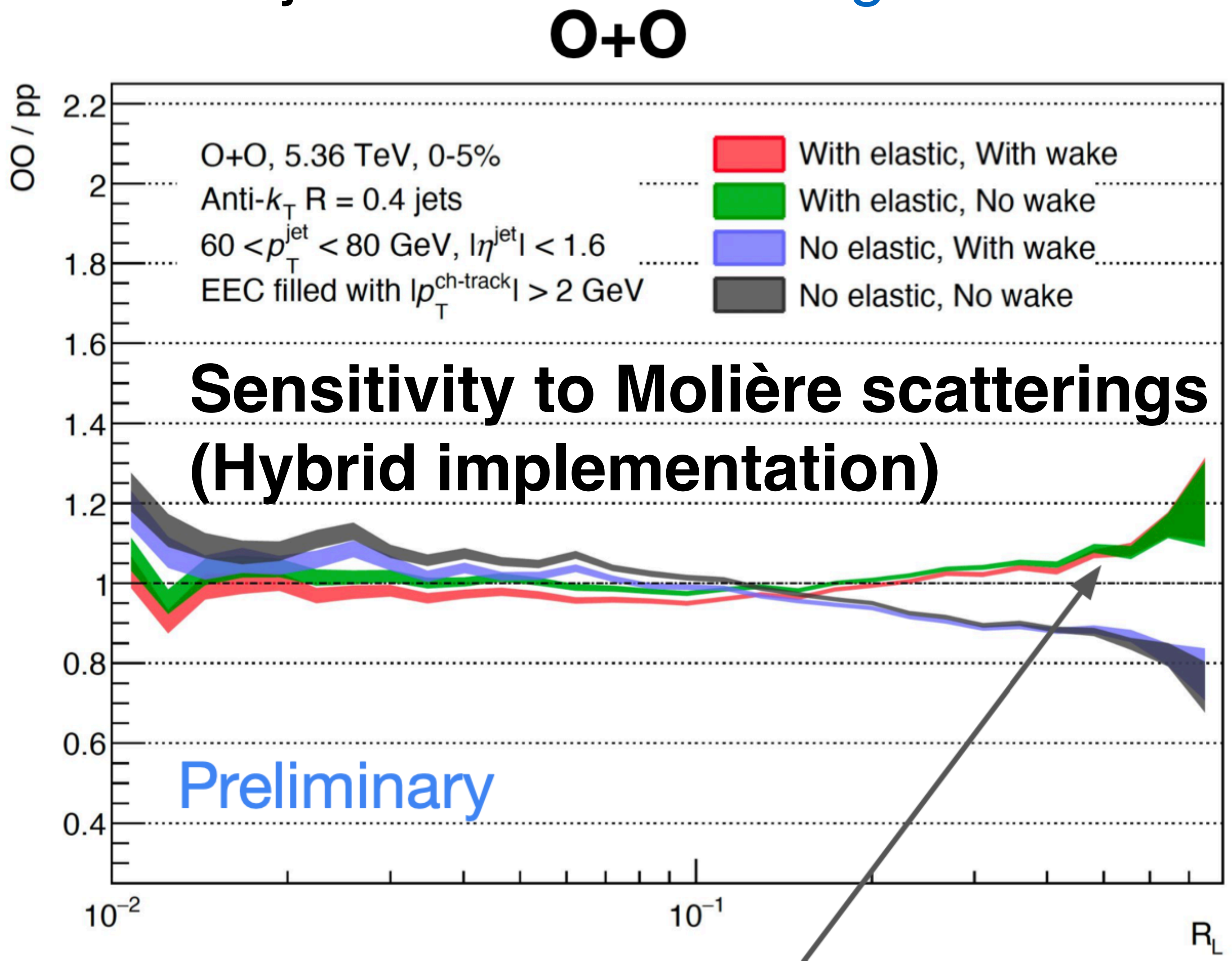
From Arjun/Arthur at [2025 light-ion workshop]

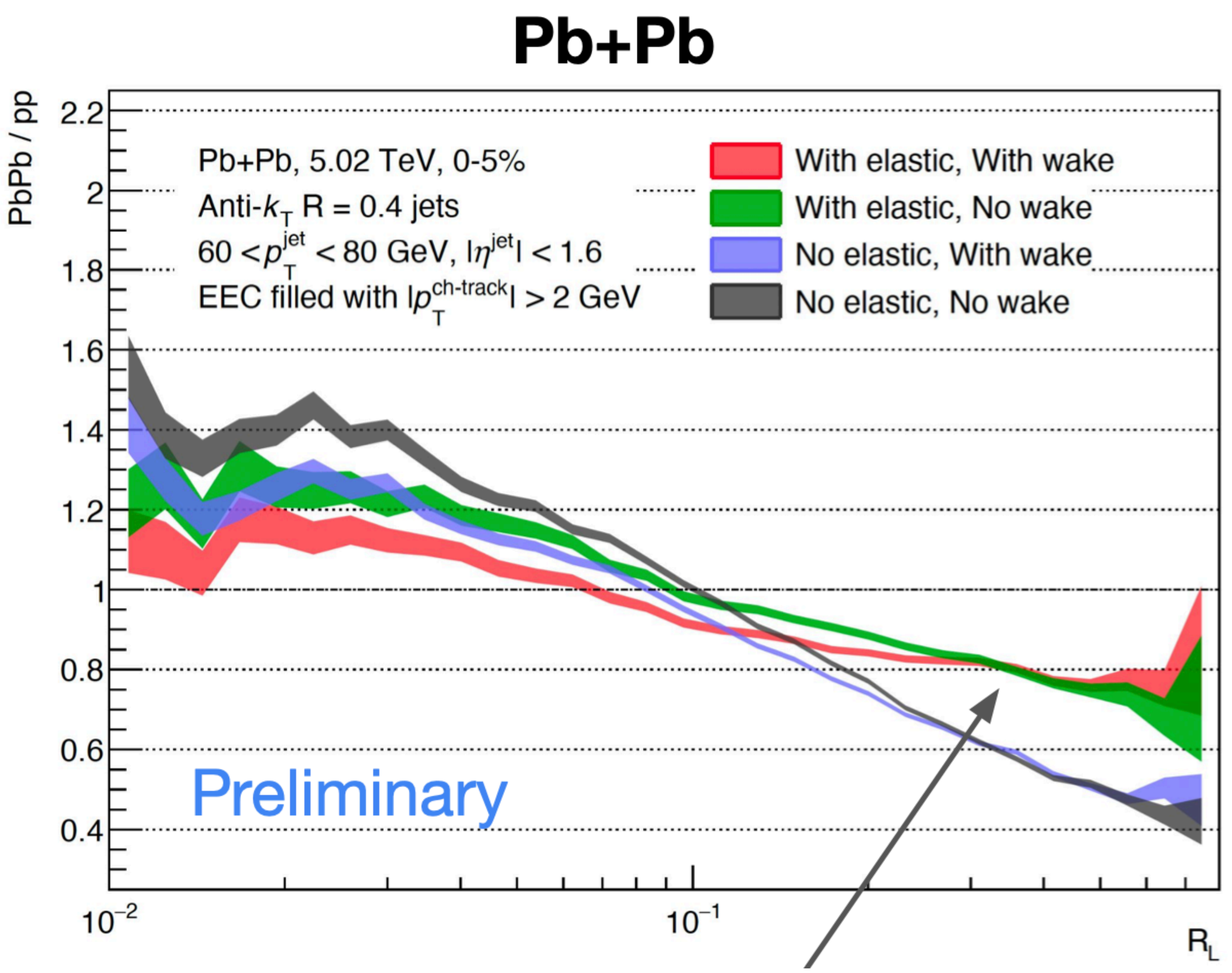
Is OO an ion species that already strikes a **reasonable trade-off for jet substructure?**

Small A (OO):
low UE
broader intrajet phase-space
pp-like exp. precision
weaker hot QCD

Large A (PbPb):
large UE
phase-space must be restricted
worse exp. precision
much stronger hot QCD

If OO is "too small", **is there an ion species that would be a better sweet-spot?**





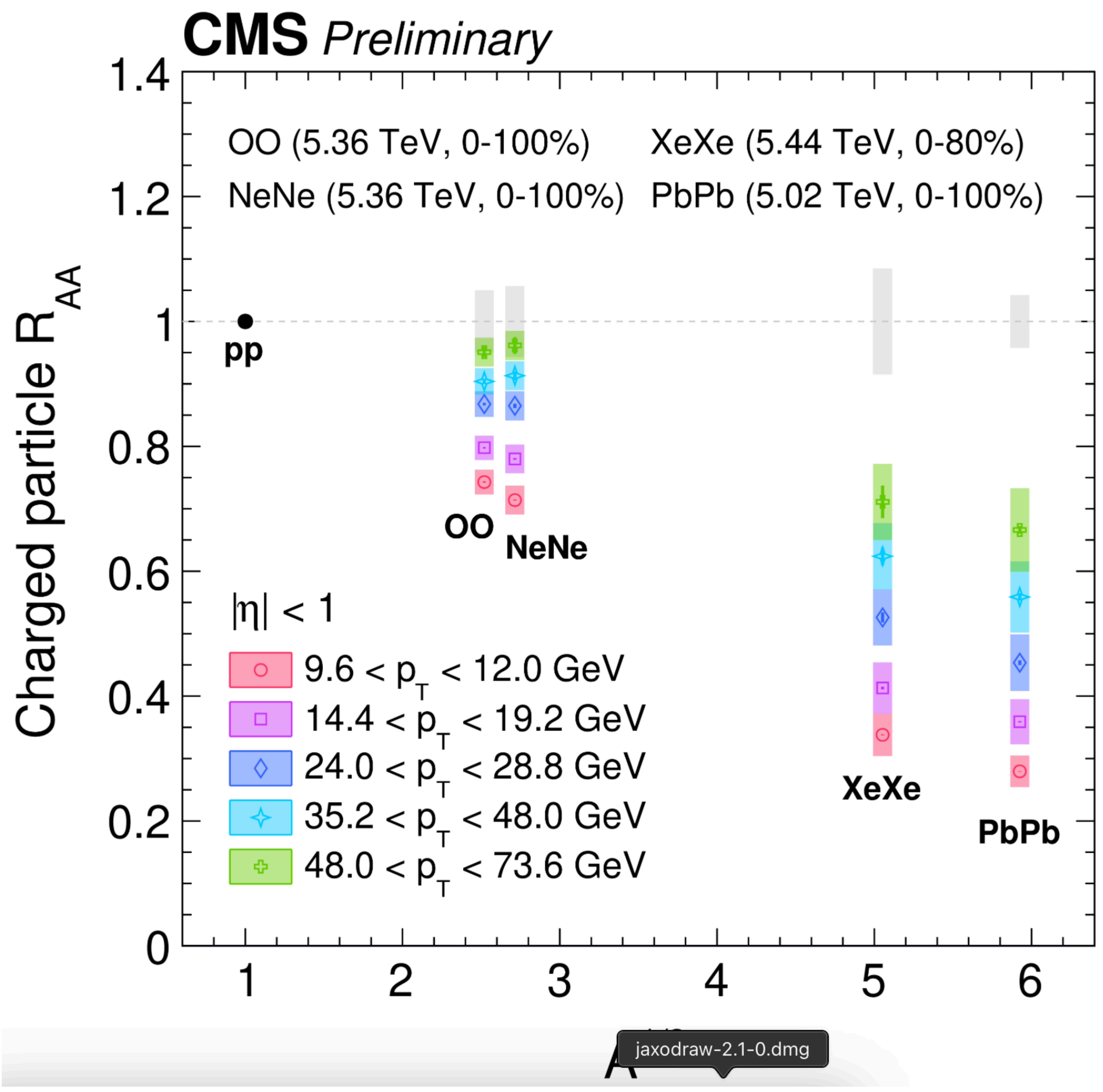
Are there observables that are typically difficult that theorists would like us to revisit? (e.g., higher-order N-point correlators, looser grooming settings, large R jet measurements, full Lund plane density, etc…)

Some open questions (Cristian)

HIN-25-014 (preliminary)

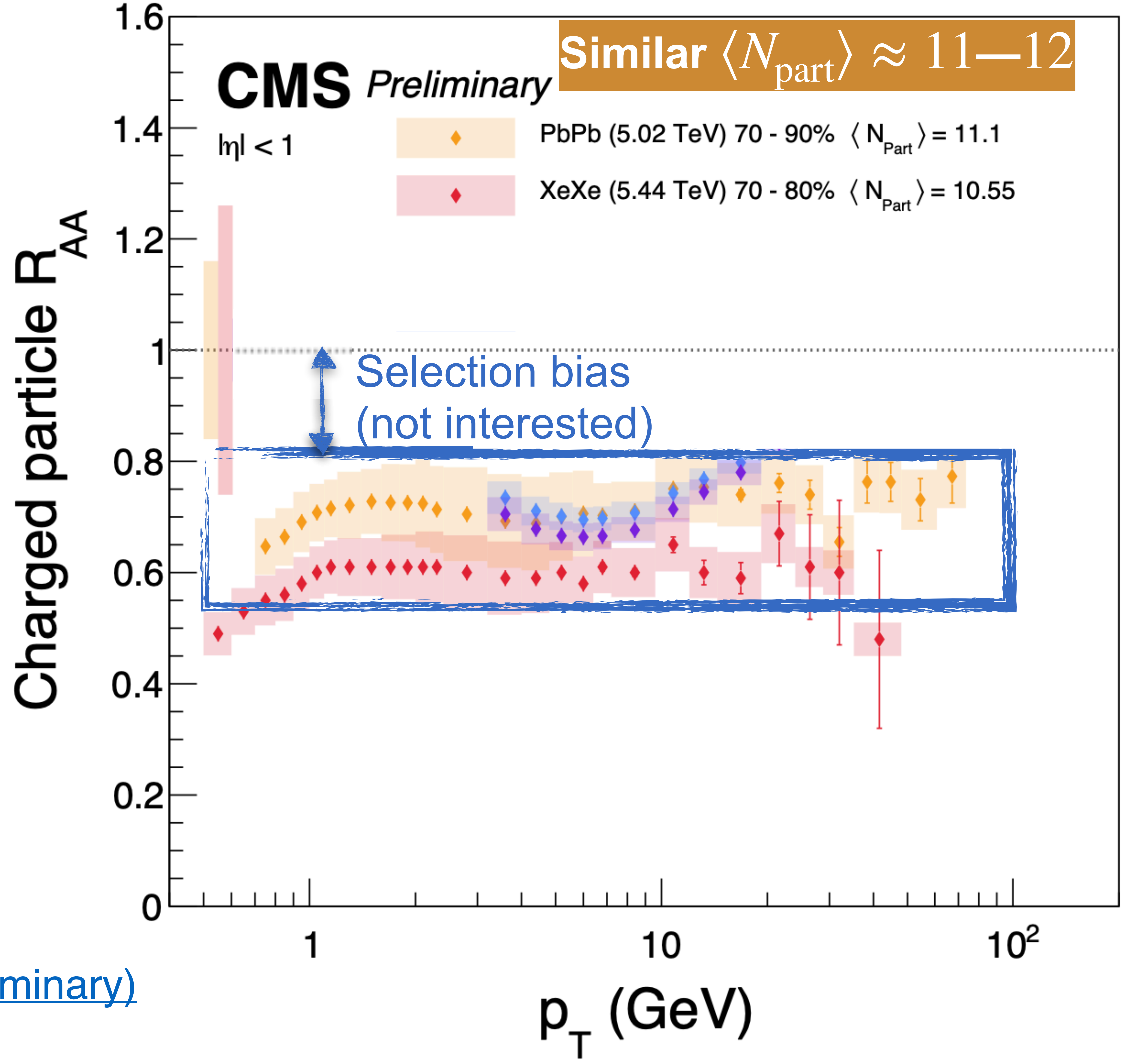
- Is it viable at all to make a quantitative statement on path length dependence from R_{AA} vs $A^{1/3}$?
  To what extent can we say something unambiguous about genuine path-length dependence here?

- **Is there any possibility of constraining the temperature-dependence of quenching?** e.g., to overconstrain $\hat{q} \propto T^3$ dependence (e.g., by comparing R_{AA} in central collisions across ¡systems)



How similar are light-ions to peripheral PbPb and XeXe?

- $R_{AA} \approx 0.8$ in peripheral PbPb/XeXe due to **selection bias effects**
- Flat-like shapes for peripheral **XeXe**/**PbPb**
- Focus should be on the **shape of R_{AA} vs p_T**



HIN-25-014 (preliminary)

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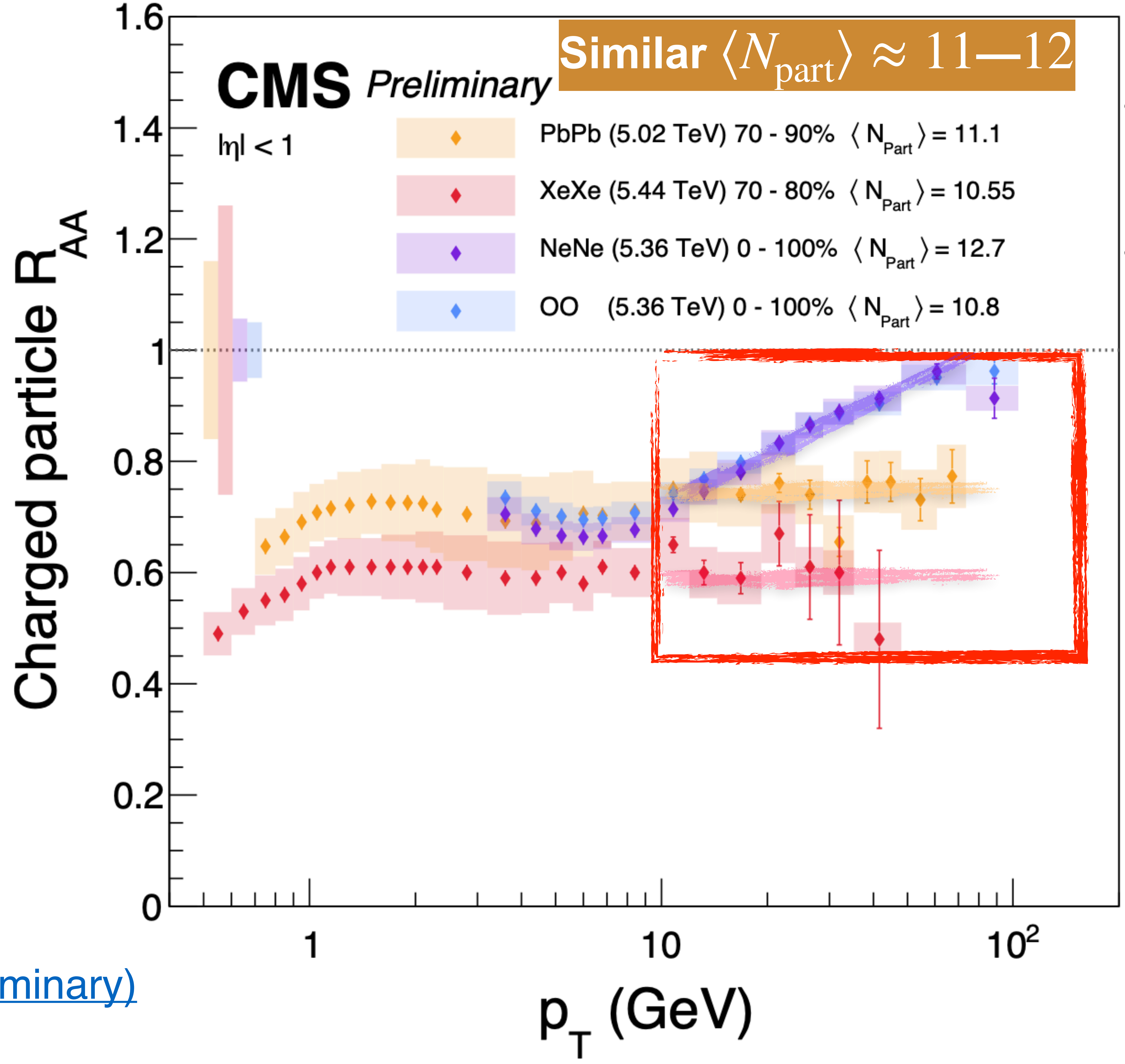

HIN-25-014 (preliminary)

- No clear "E_{loss}-slope" at high-p_T in peripheral **XeXe**/**PbPb**
- Suggests that **OO** and **NeNe** have a special combination of **path length & matter density**

(see backup for Glauber studies)

CMS-PAS-HIN-25-014