QGP Results from CMS

Austin Baty
University of Illinois Chicago

On behalf of the CMS Collaboration

July 9, 2026

EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC
Darmstadt, Germany

The UIC group is supported by the DoE Office of Science

Introduction

- Heavy ion collisions
  - Produce QGP and jet quenching
    - Modify jet production
    - Medium response to jet propagation
- Intermediate systems studies (OO/NeNe)
  - Explore to what extent ‘large’ ions are needed to study QGP

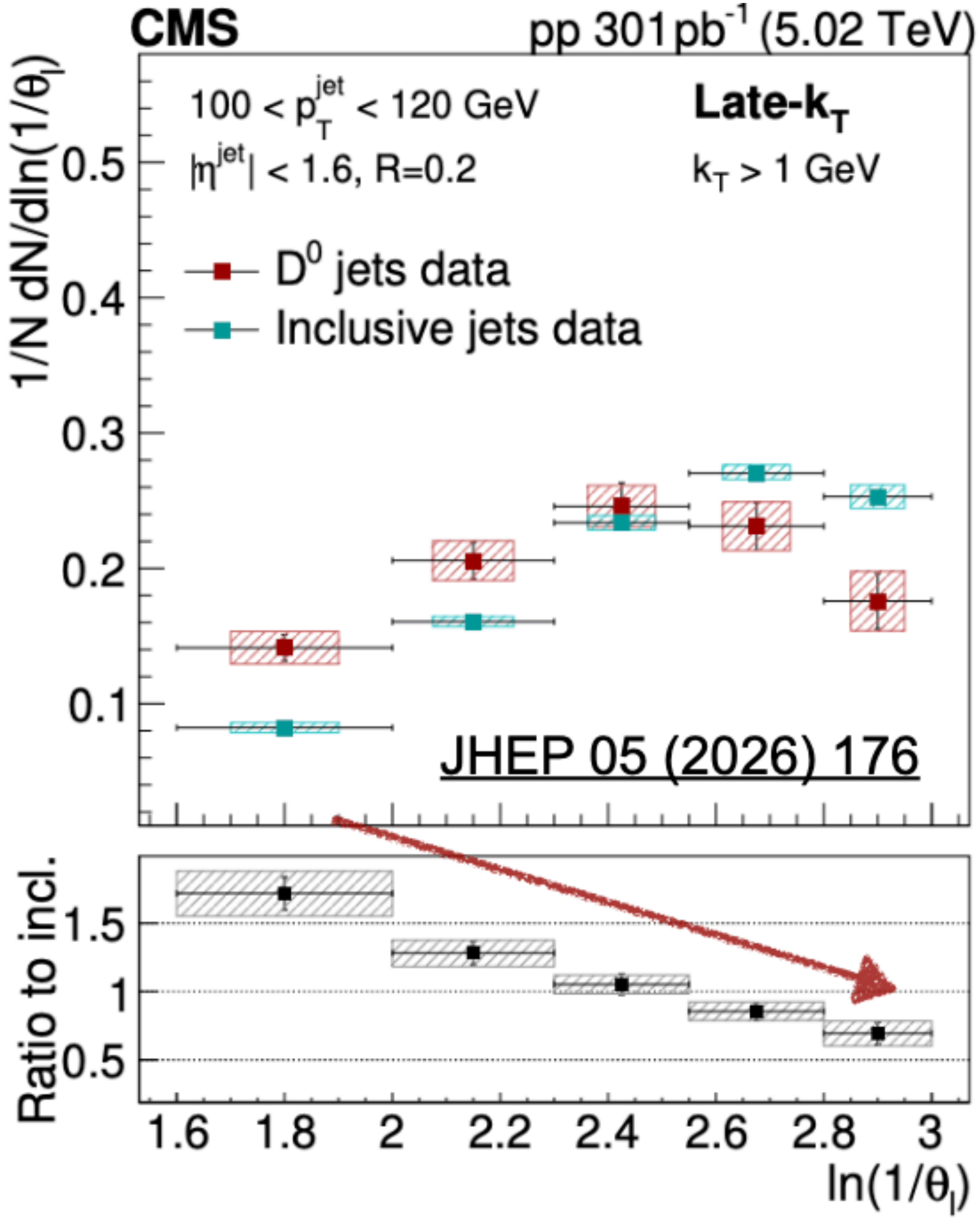
Dead cone effect in D-tagged jets (pp)

- **Gluon radiation predicted to be suppressed at small angles for heavy quarks**
  - **“Dead cone effect”**

- **Systematic exploration of emissions using jet grooming techniques**

- **Suppression confirmed for D-tagged jets compared to inclusive jets at small angles**

$$\theta_{dc} \propto \frac{m_q}{E}$$



Dead cone effect in b-tagged jets (pp)

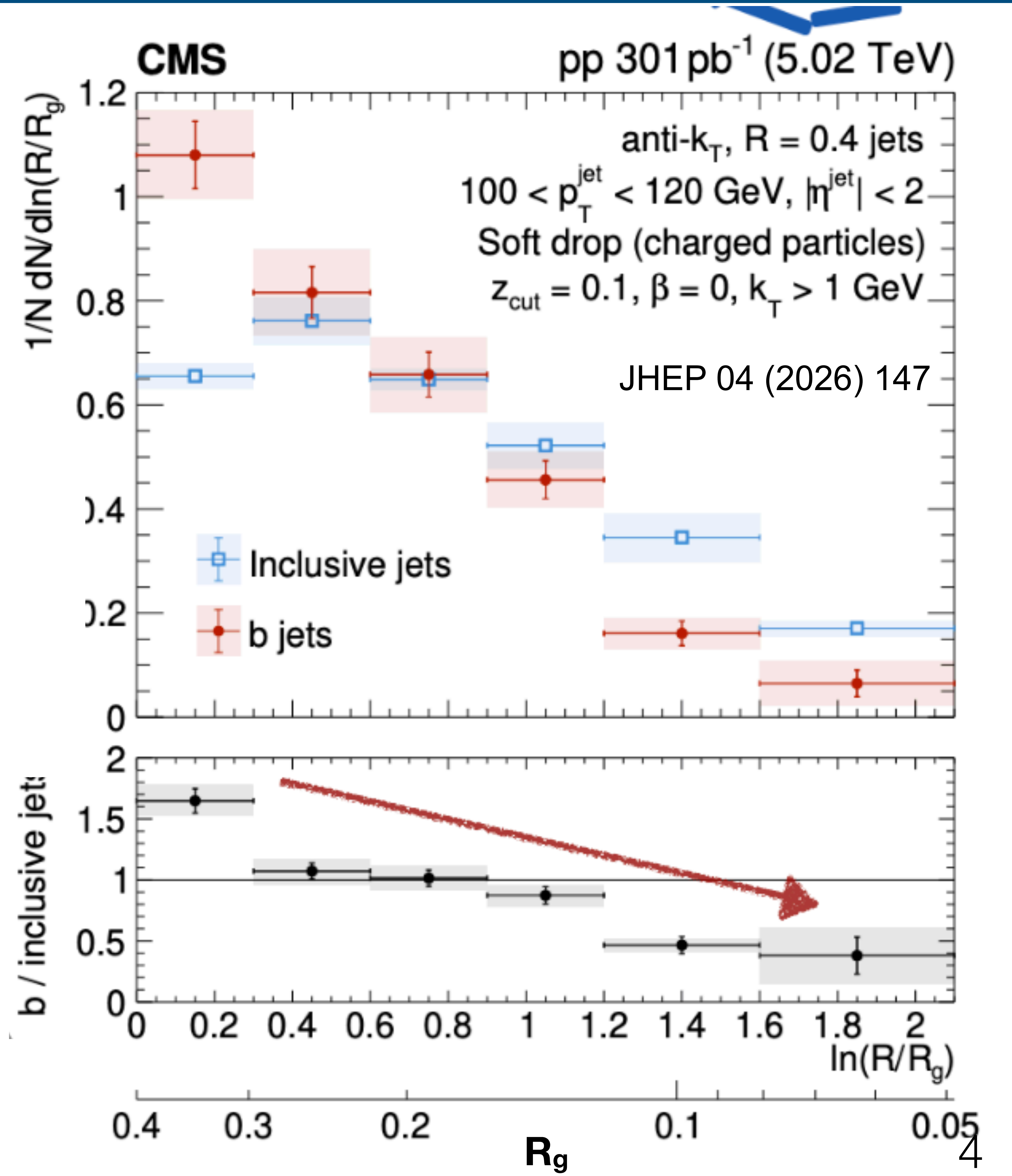
- **Gluon radiation predicted to be suppressed at small angles for heavy quarks**
  - **“Dead cone effect”**

- **Systematic exploration of emissions using jet grooming techniques**

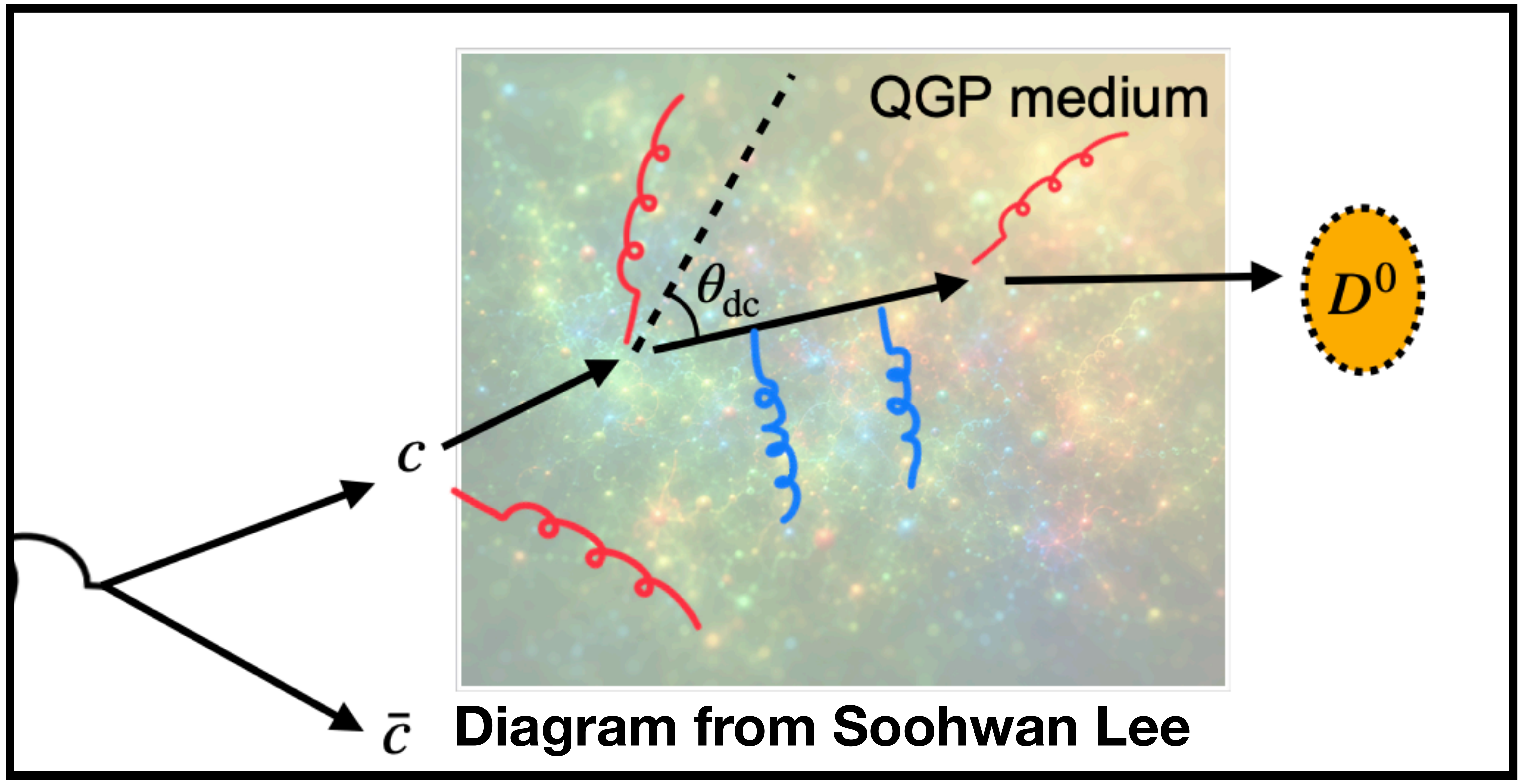
- **Suppression confirmed for D-tagged jets compared to inclusive jets at small angles**

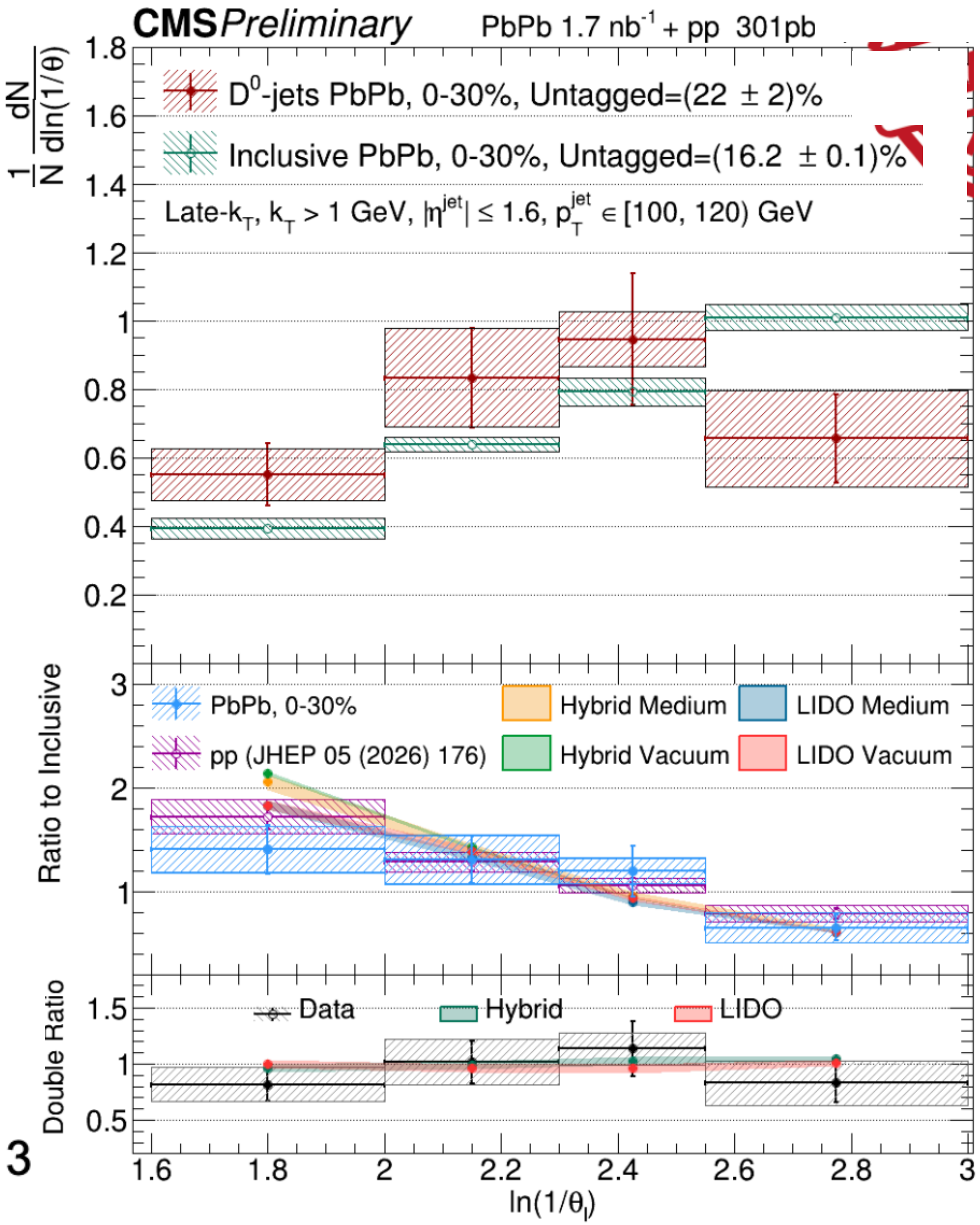
- **Effect also seen for b jets!**

$$\theta_{dc} \propto \frac{m_q}{E}$$



What happens in a QGP?





- **Medium-induced gluon radiation predicted to fill the dead cone**
- **D-tagged study repeated in PbPb**
- **First measurement of dead-cone in PbPb!**
- **No indication of 'filling' effect**

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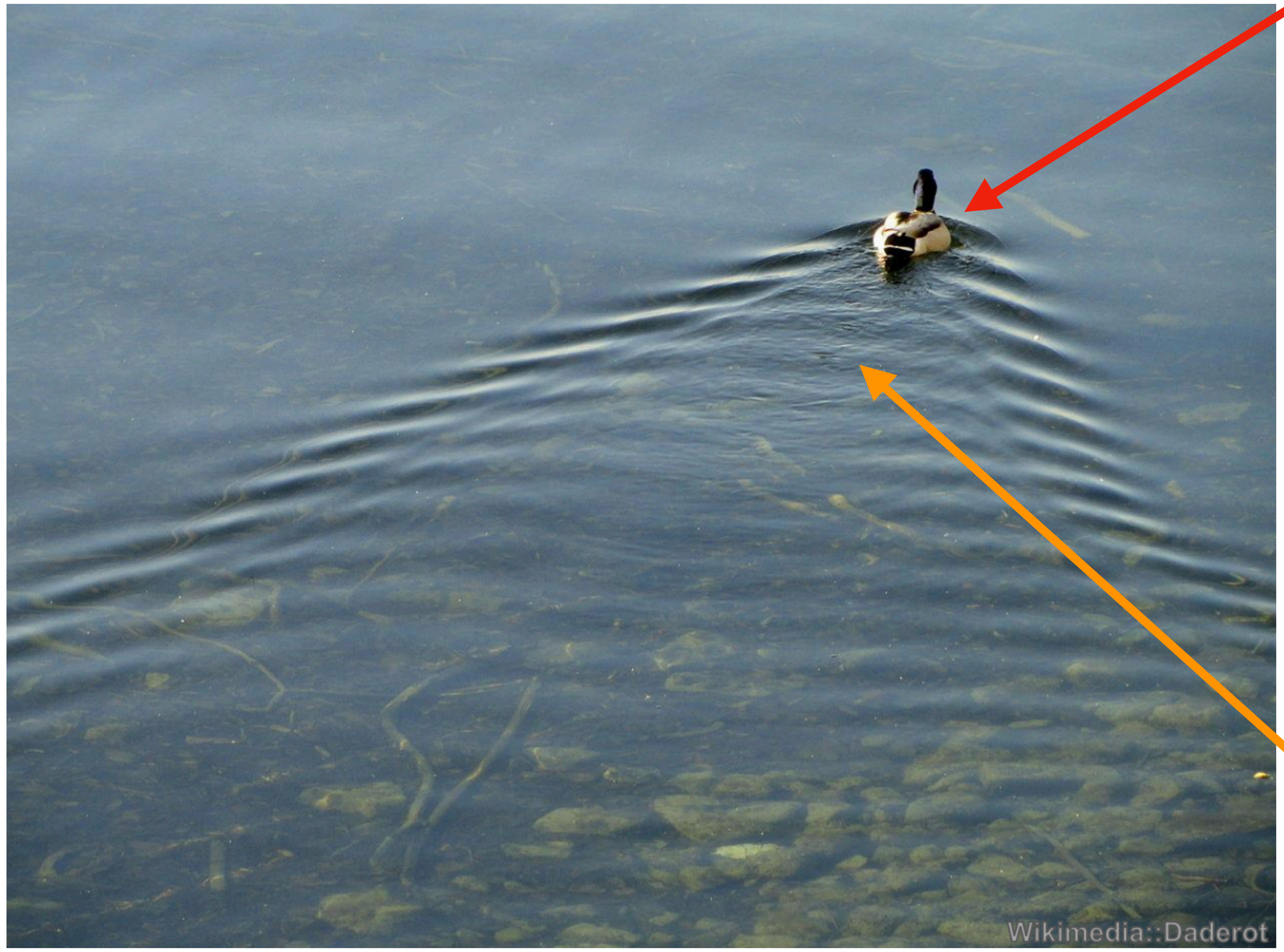
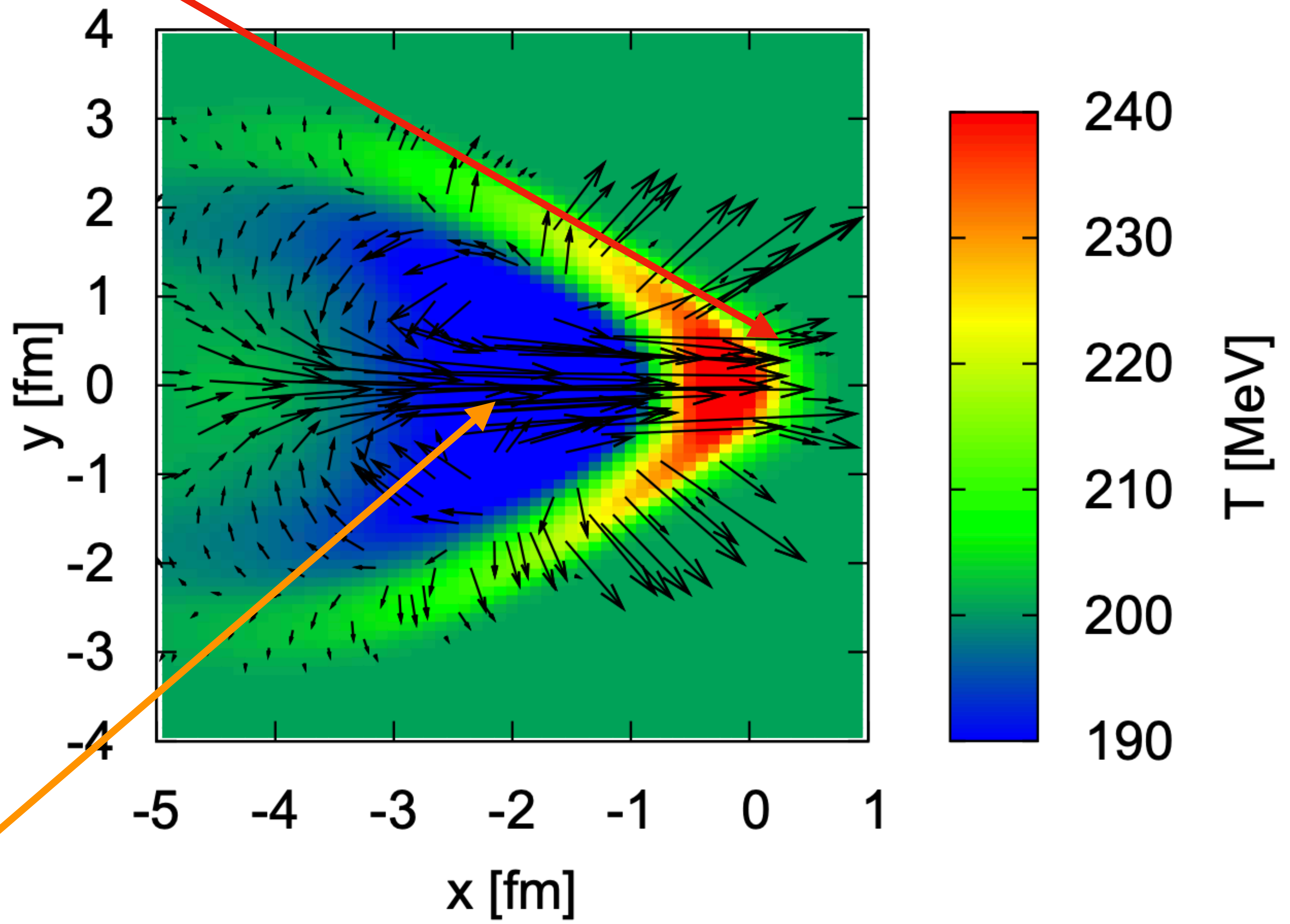
Wakes in the QGP

- If an energetic quark goes through QGP, can it leave a wake?
  - How does QGP respond to perturbations?

More water/QGP in the direction of the duck/quark (positive wake)

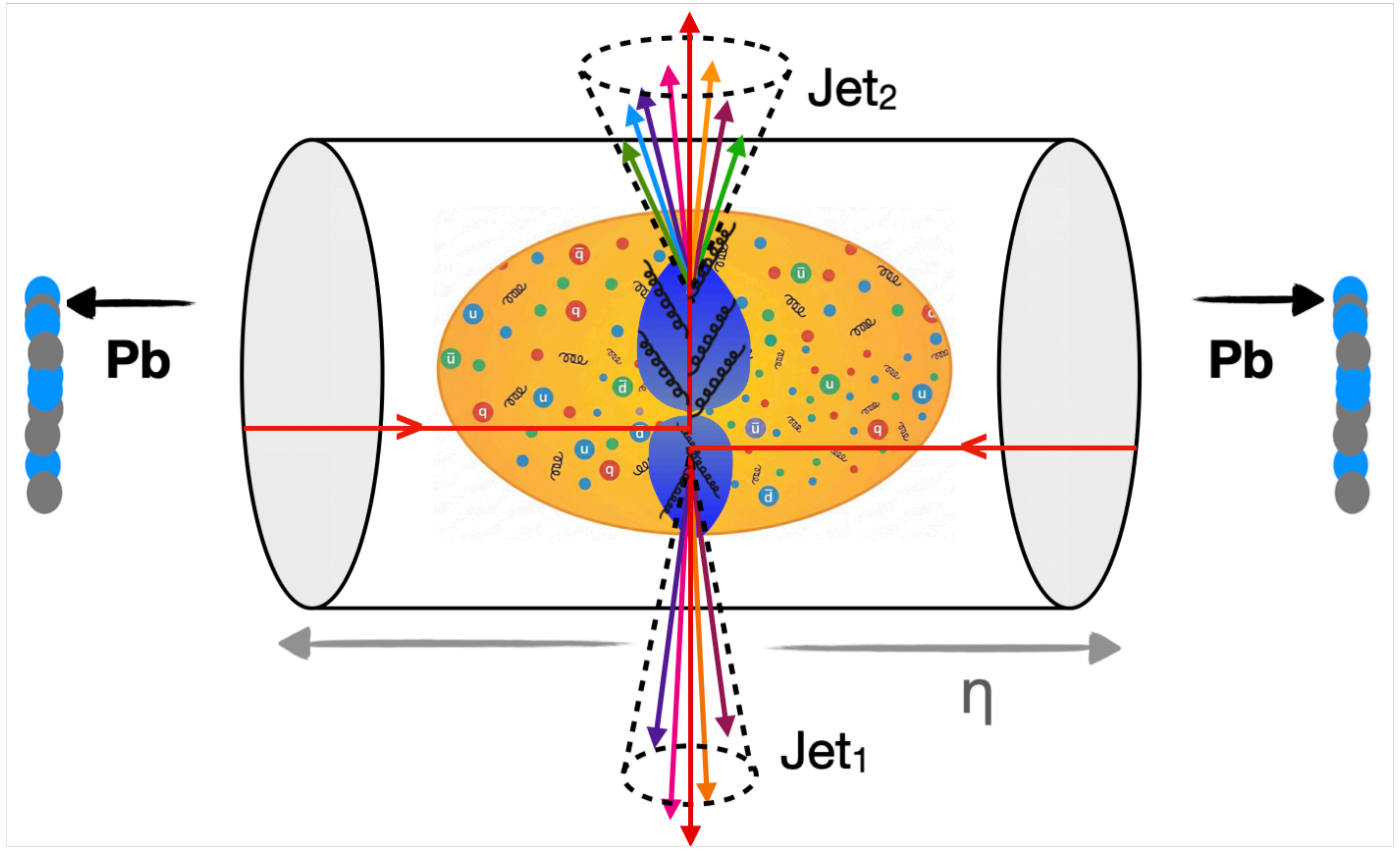




Less water/QGP behind the duck/quark (diffusion wake)

Searching for a jet wake

- **Proposed to use eta-separated dijets to search for the wake**
- **Compare large/small eta gap selections to isolate wake from jet modifications**



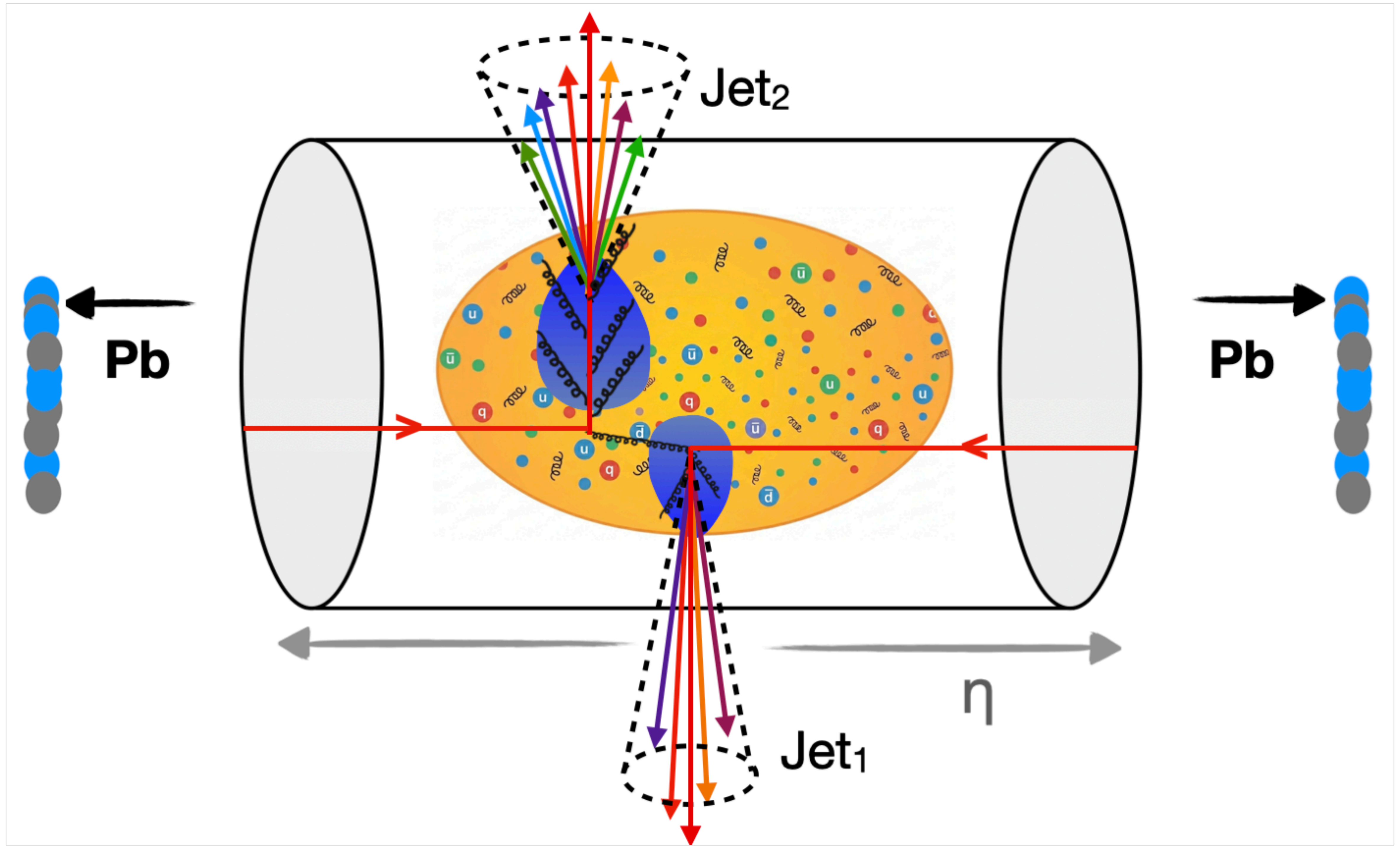
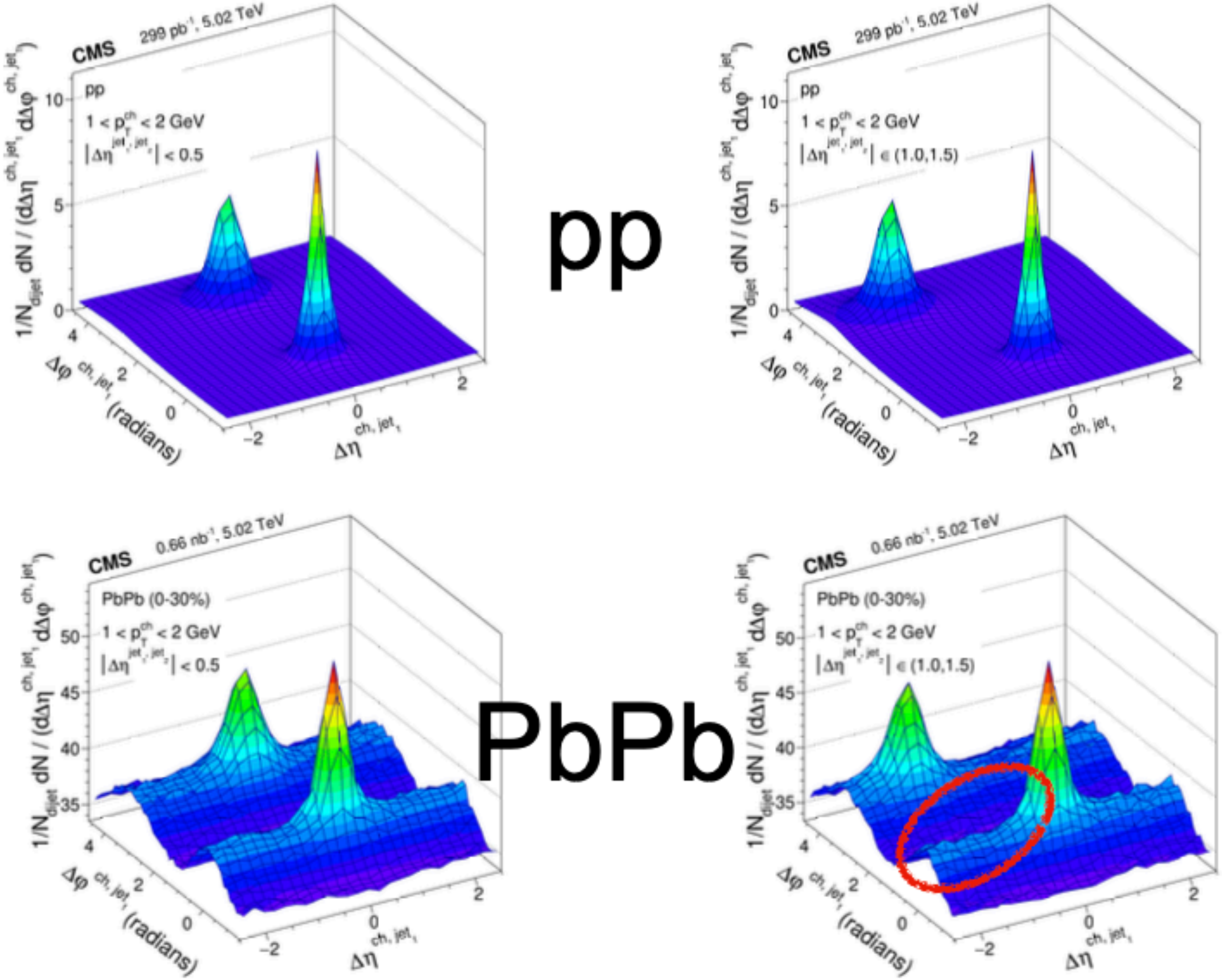


Diagram from Raghunath Pradhan

Analysis method

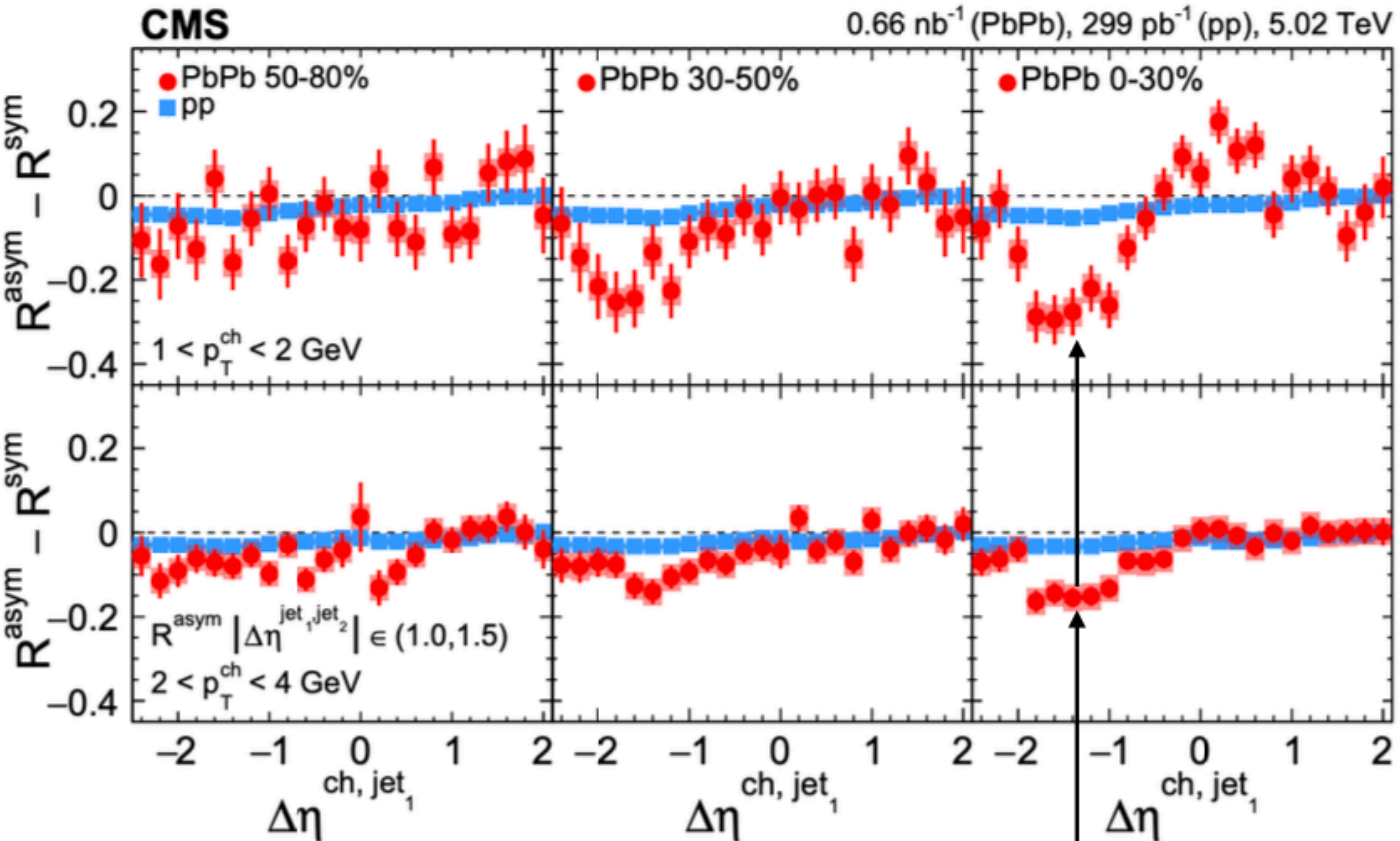
arXiv:2602.19431, Accepted by PRL as editors' suggestion

- **Examine distribution of particles with respect to dijets**
- **Compare symmetric and asymmetric cases**
- **Use pp baseline to remove vacuum effects**



Projections

arXiv:2602.19431, Accepted by PRL as editors' suggestion



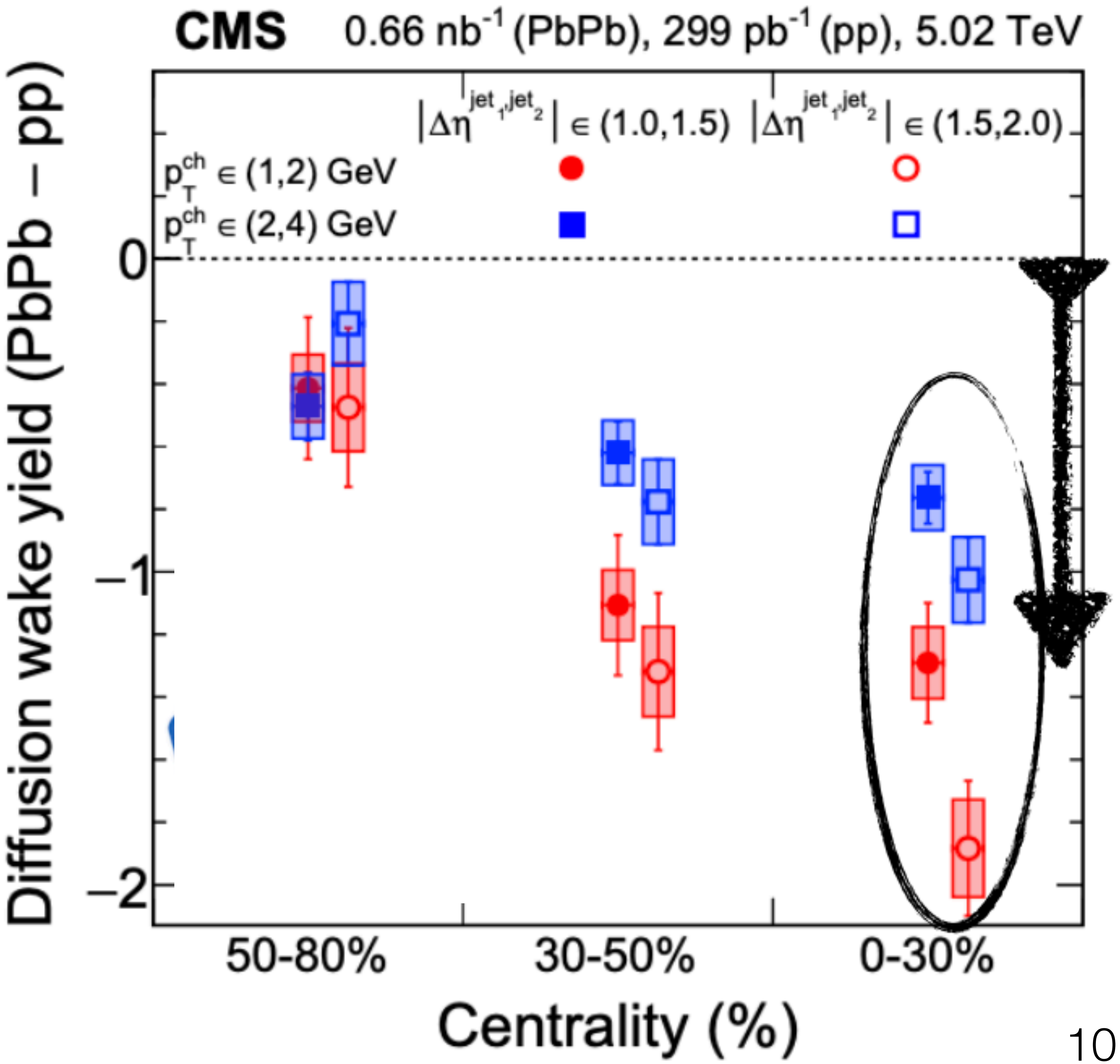
- **Take 1-d projections to quantify the effect**
- **Clear centrality-dependent depletion seen in expected region**
- **No large effect in pp**

Observation of diffusion wake

arXiv:2602.19431, Accepted by PRL as editors' suggestion

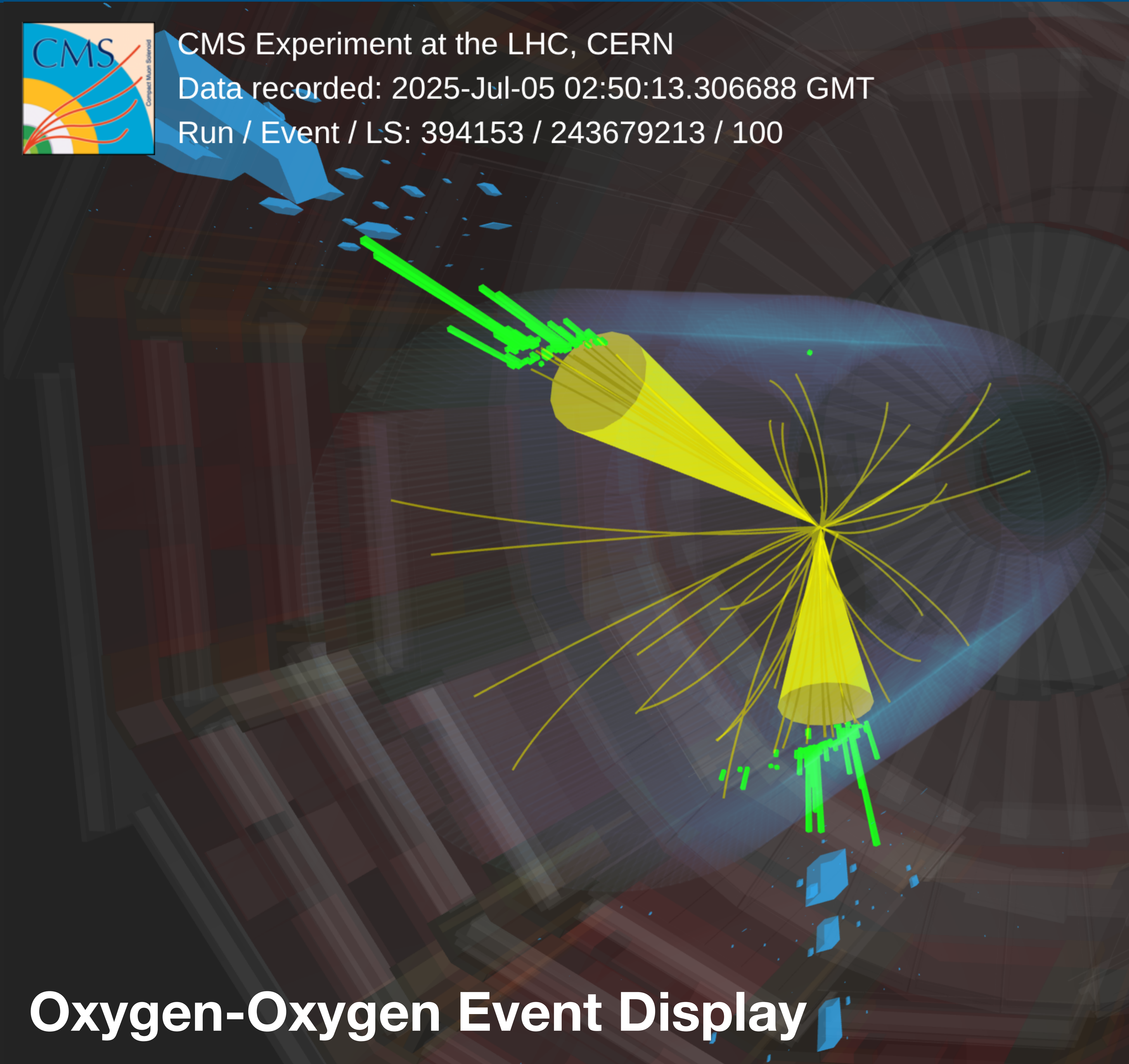
- Integrating region where depletion is seen summarizes the effect
  - >5σ observation
  - Increases with centrality
  - More pronounced at lower particle p_T
  - Depletion moves as you move the subleading jet

- All consistent with diffusion wake effect!



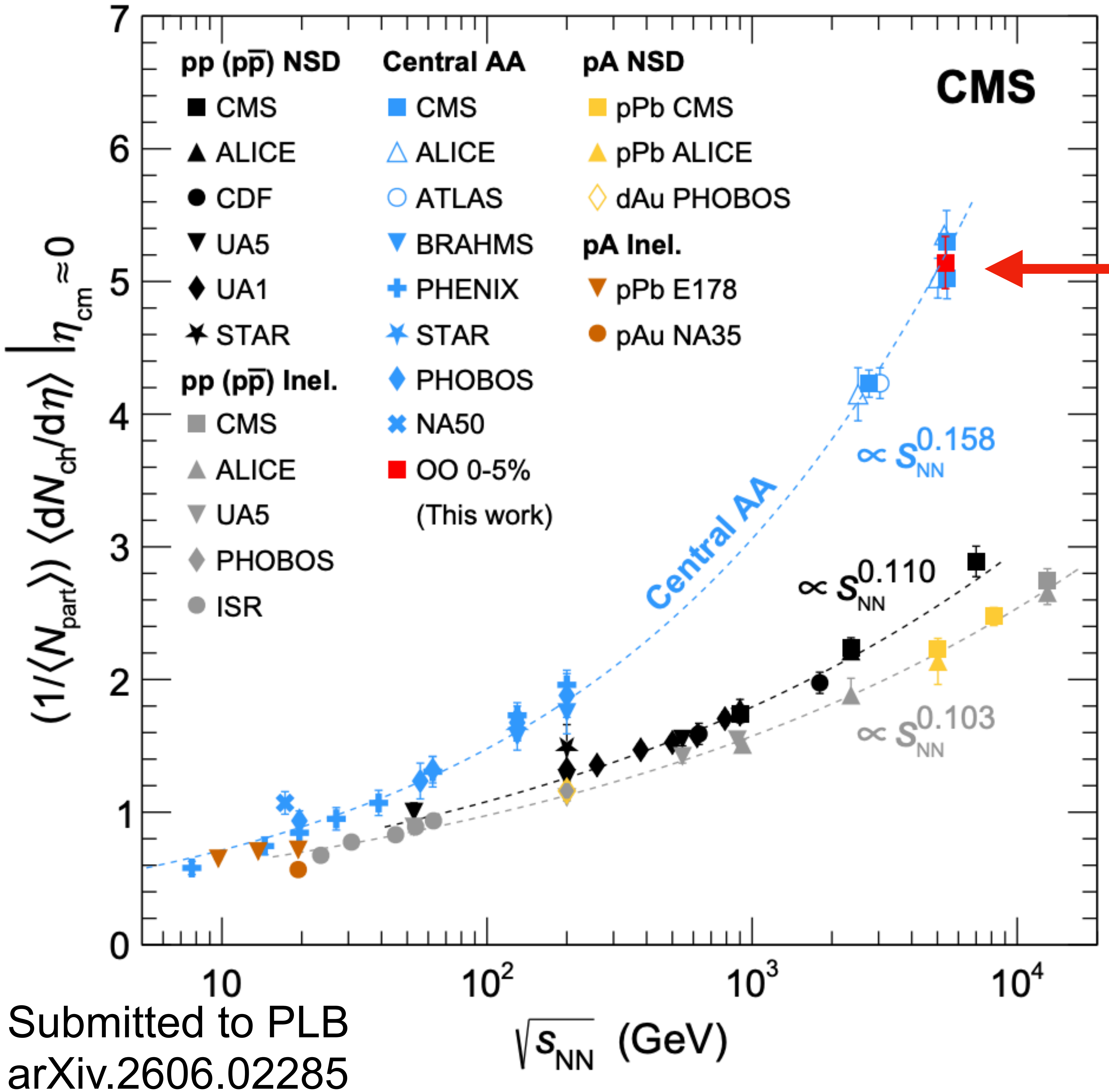
What about OO and NeNe?

- OO/NeNe provide alternative way to probe a similar multiplicity region
- Initial state more well-defined as compared to pPb
- Less chance for selection biases
- More likely to create a QGP?



Oxygen-Oxygen Event Display

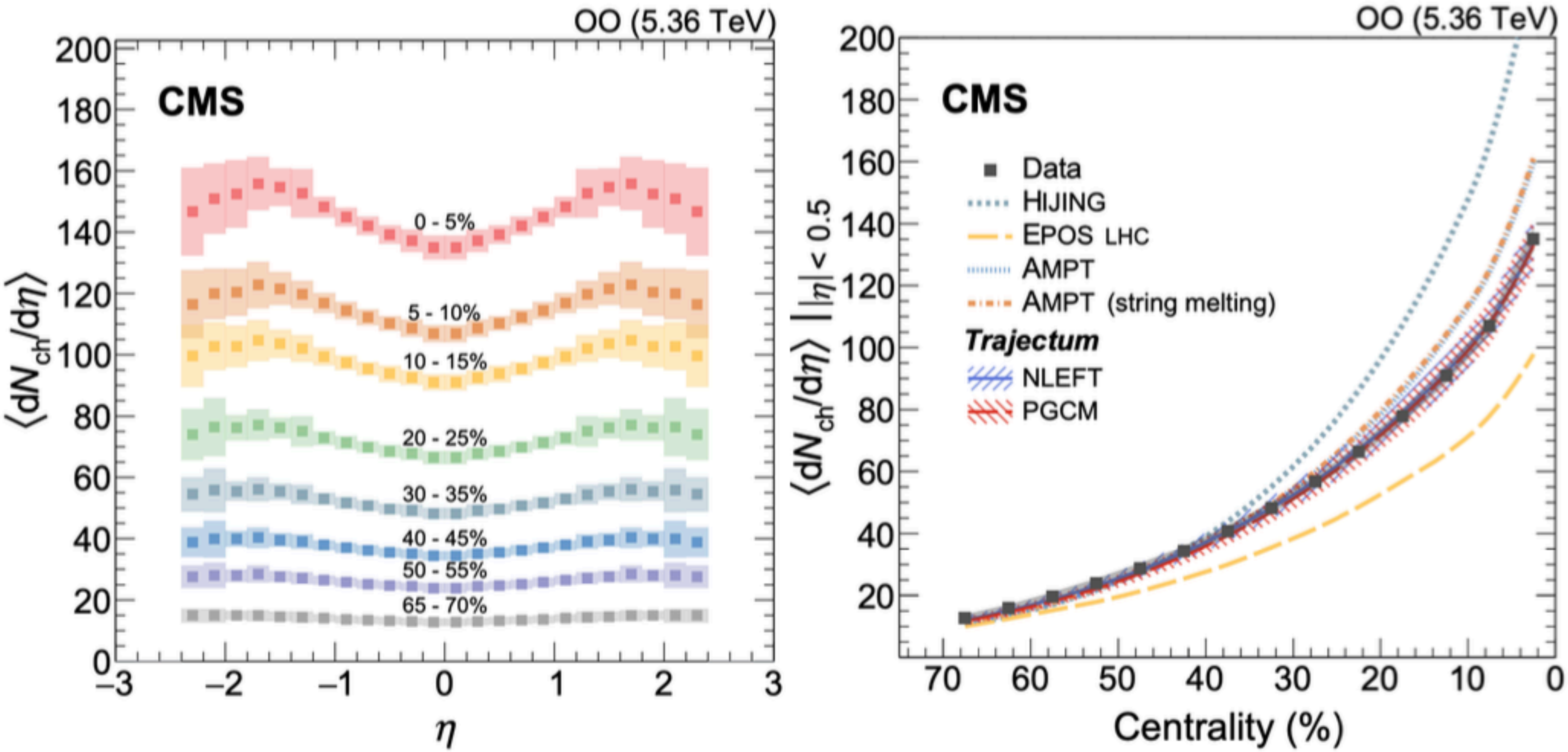
Particle production in OO



Submitted to PLB
arXiv.2606.02285

- **0-5% OO on AA power law vs. $\sqrt{s_{NN}}$**
  - **Similar translation of energy to entropy**
- **Not a superposition of pp collisions!**
- **What about full centrality-dependence?**

Centrality dependence

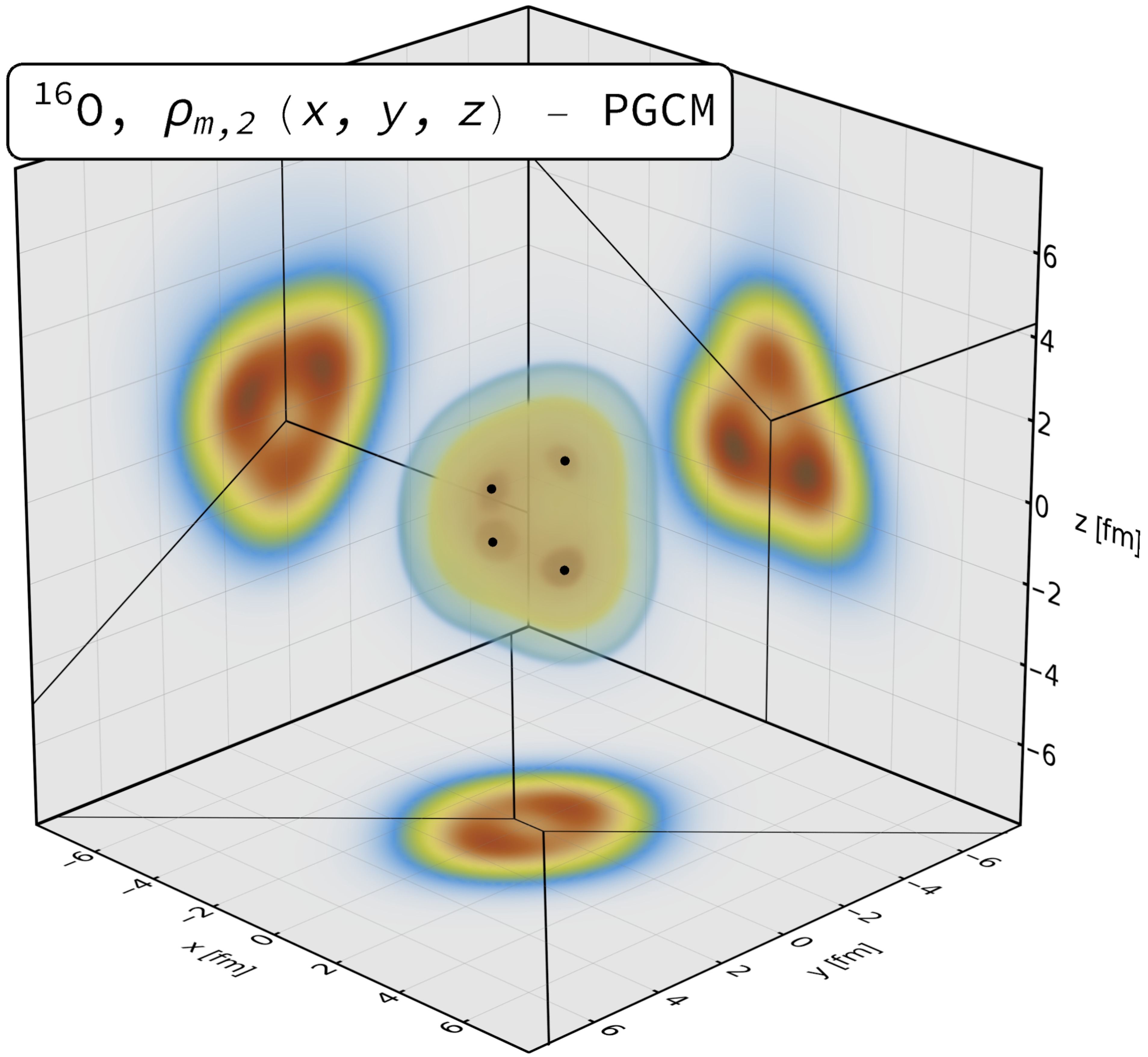


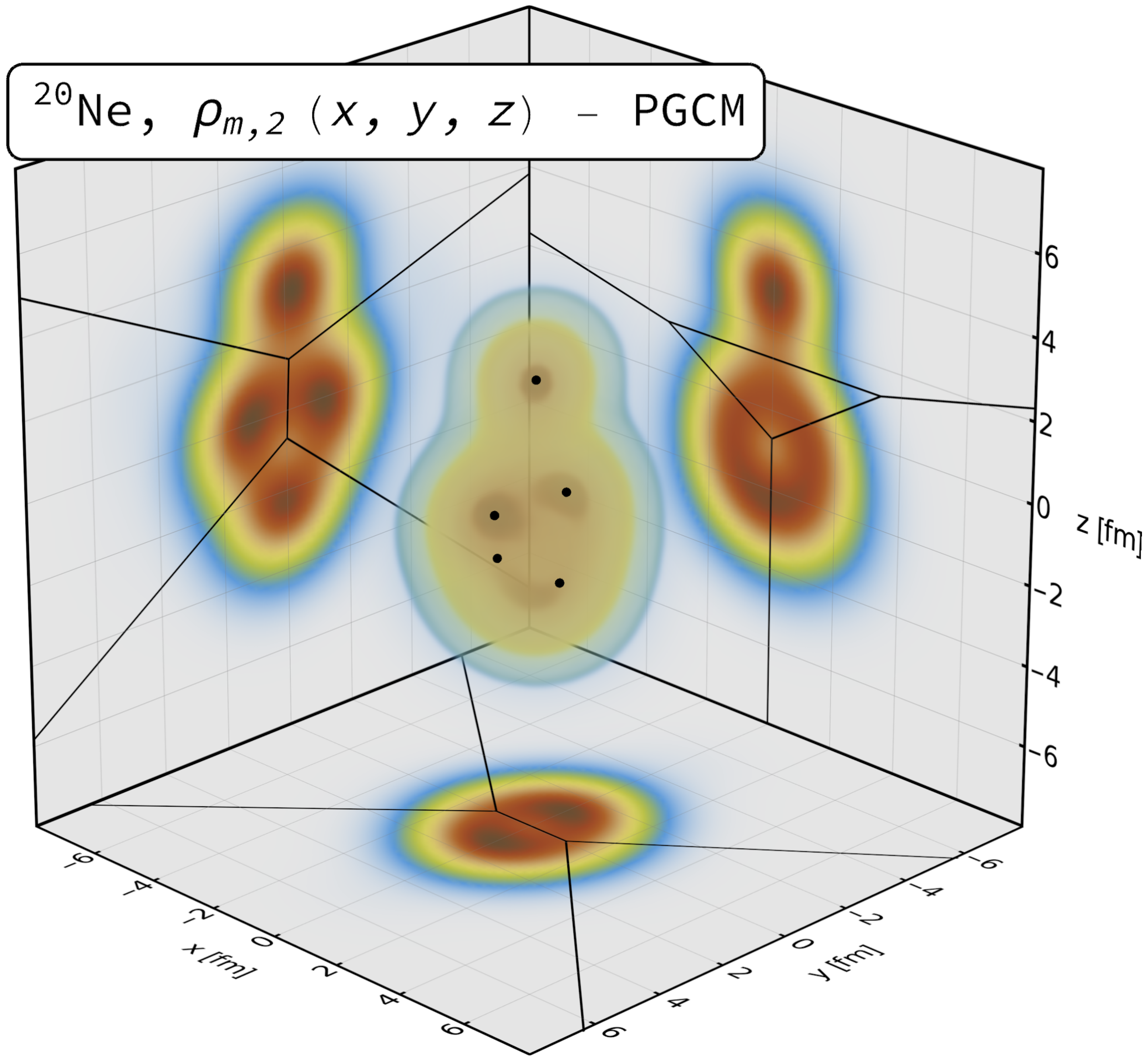
- **Characterize the geometry and entropy density of OO collisions**
- **Centrality-dependence can be used to tune MC models**

Submitted to PLB
arXiv.2606.02285

Azimuthal anisotropies in OO and NeNe

- **Collectivity effects hypothesized to be present in OO/NeNe**
- **Proposed as a way to explore nuclear structure (i.e., bowling pin Ne)**

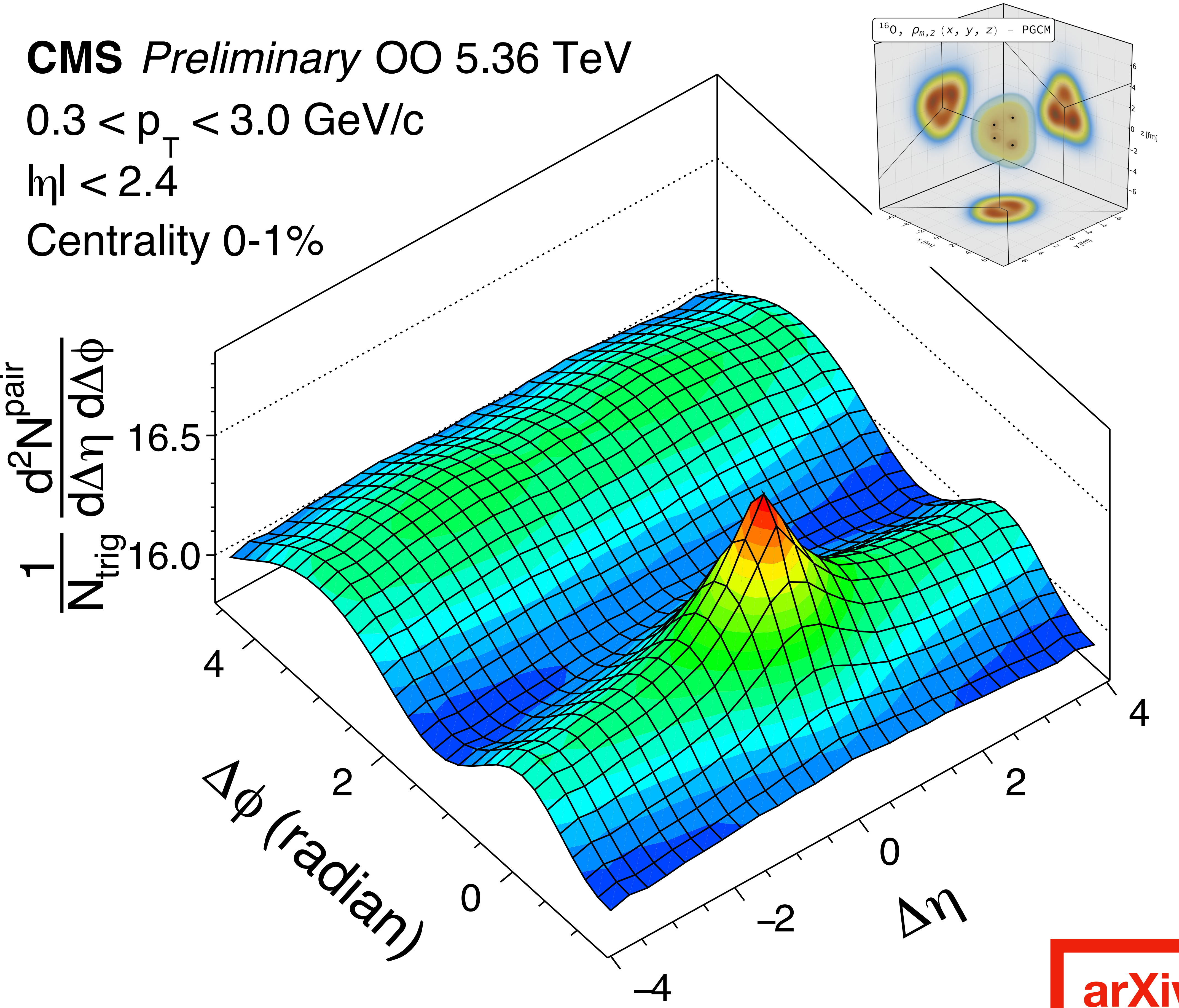


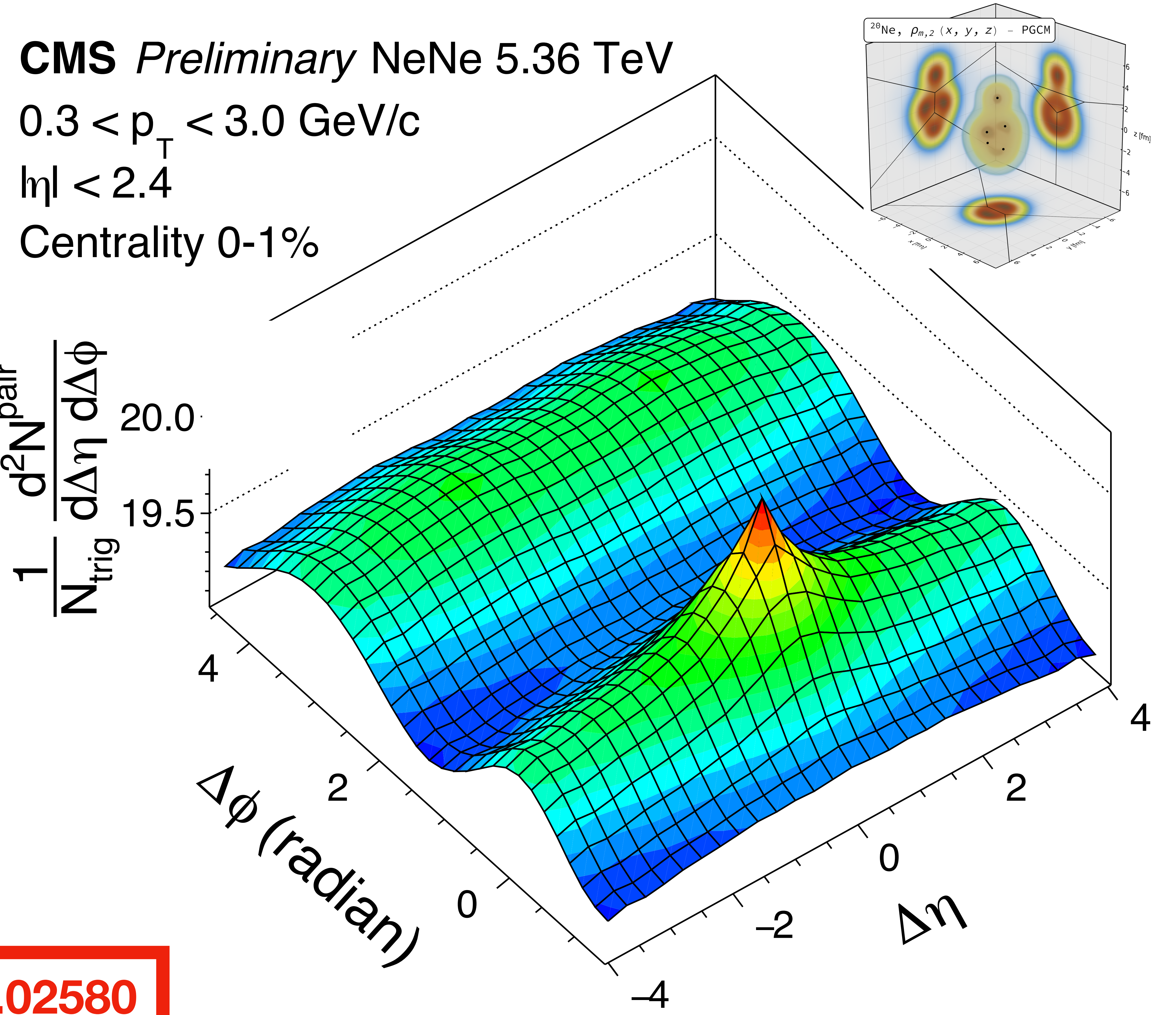


PRL 135 (2025) 012302

Azimuthal anisotropies in OO and NeNe

- **Clear ridge structures seen in OO and NeNe collisions!**

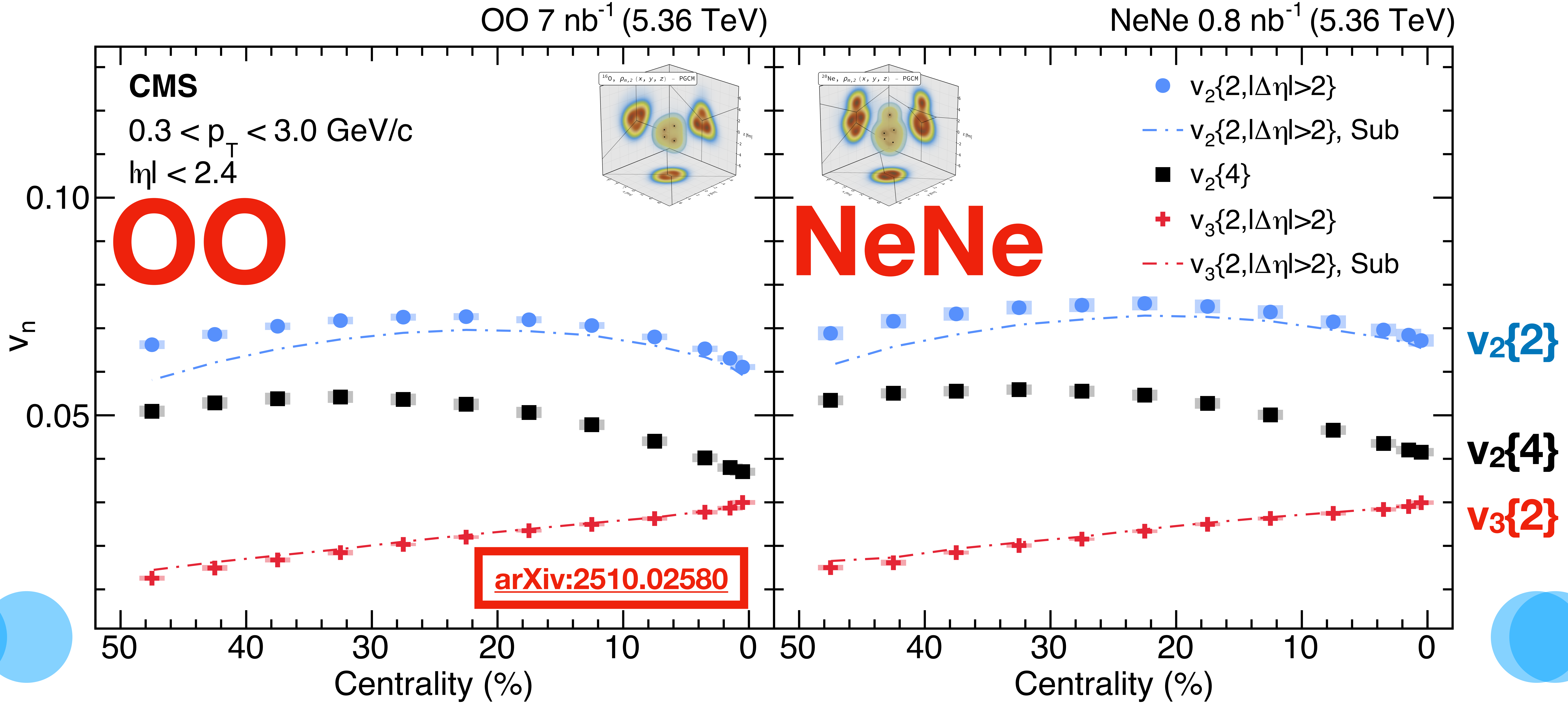




arXiv:2510.02580

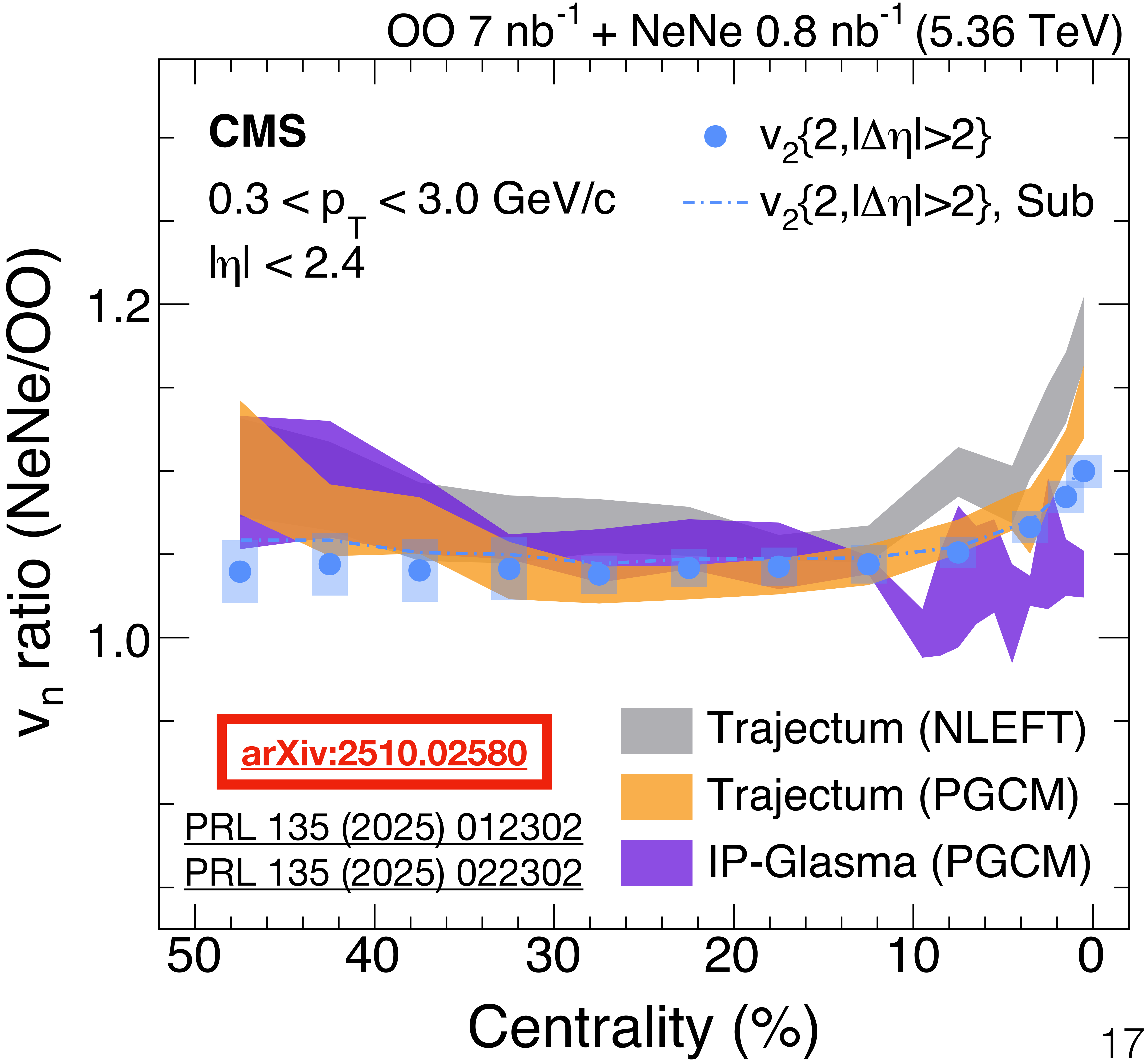
Azimuthal anisotropies in OO and NeNe

- **Measured $v_2\{2\}$, $v_3\{2\}$, $v_2\{4\}$ in OO and NeNe collisions**
- **v_2 dips towards central events - geometry changes with impact parameter**
- **v_3 increases - fluctuations important!**



NeNe/OO v_2 ratios

- **Ratio cancels hydrodynamic response: sensitive to geometry**
- **Clear uptick for central events**
- **Model differences from treatment of deformed nuclear geometry**
- **Having both NeNe and OO data valuable for nuclear structure**



Charged particle R_{AA}

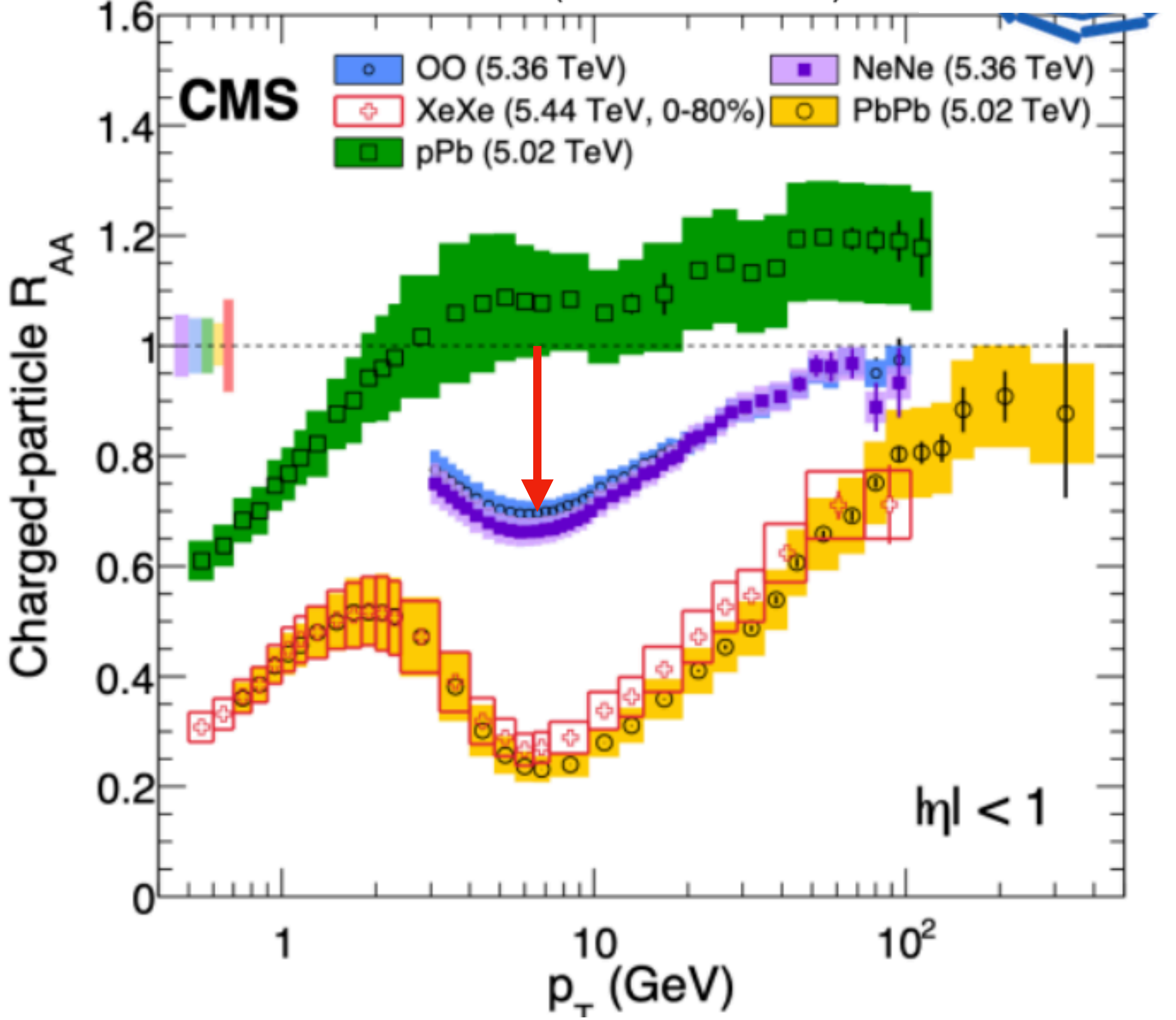
$$R_{AA} = \frac{1}{A^2} \frac{d\sigma_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- **Observation of suppressed high-p_T particle production in OO/NeNe**

- **Clear hierarchy with system size**

- **Likely from parton energy loss, but nPDFs also important**

OO: PRL 136 (2026), 162301
NeNe: arXiv:2602.21325 (Submitted to PLB)



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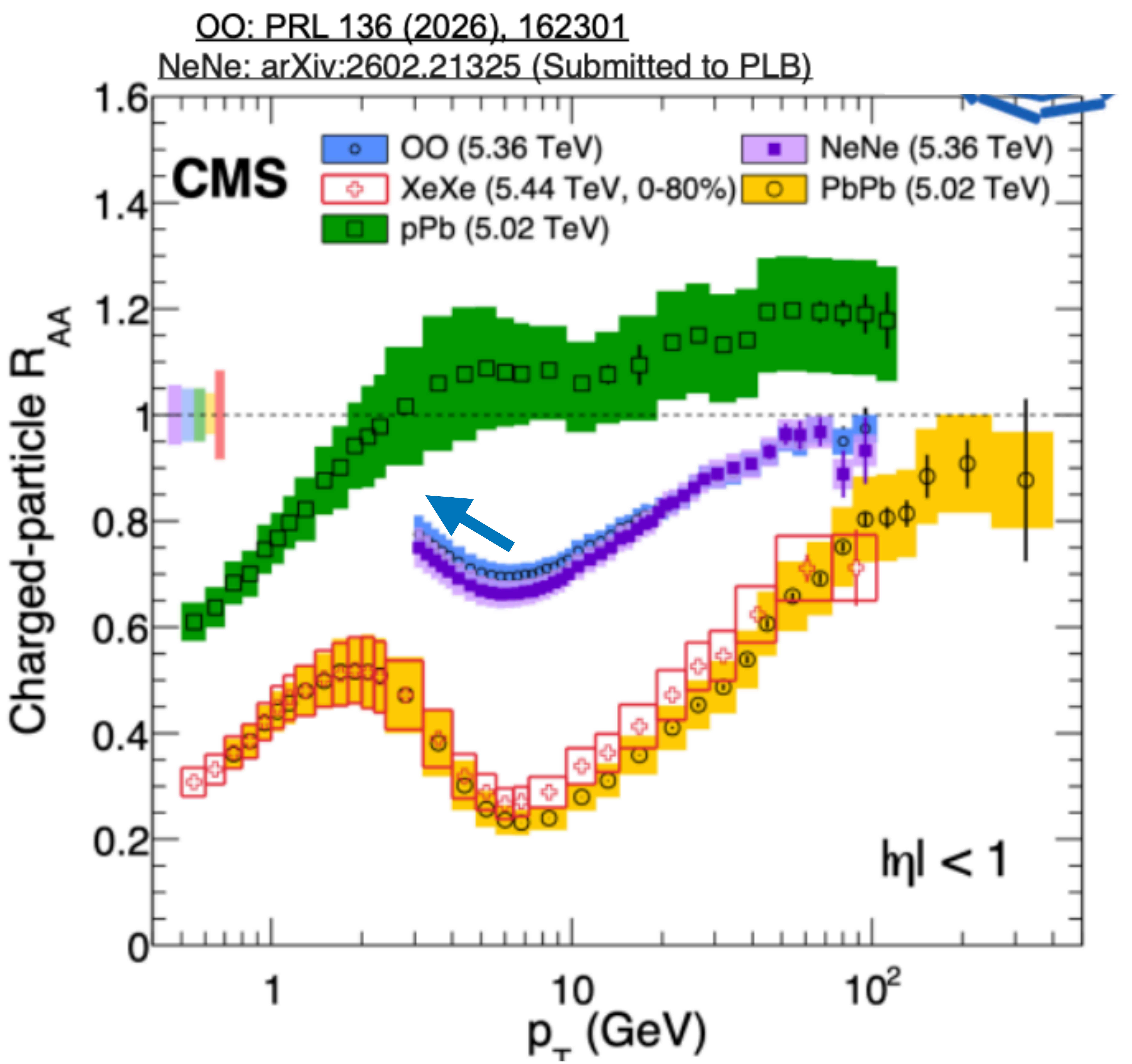
- **Observation of suppressed high-p_T particle production in OO/NeNe**
- **Clear hierarchy with system size**
- **Likely from parton energy loss, but nPDFs also important**
- **Radial flow bump also visible**

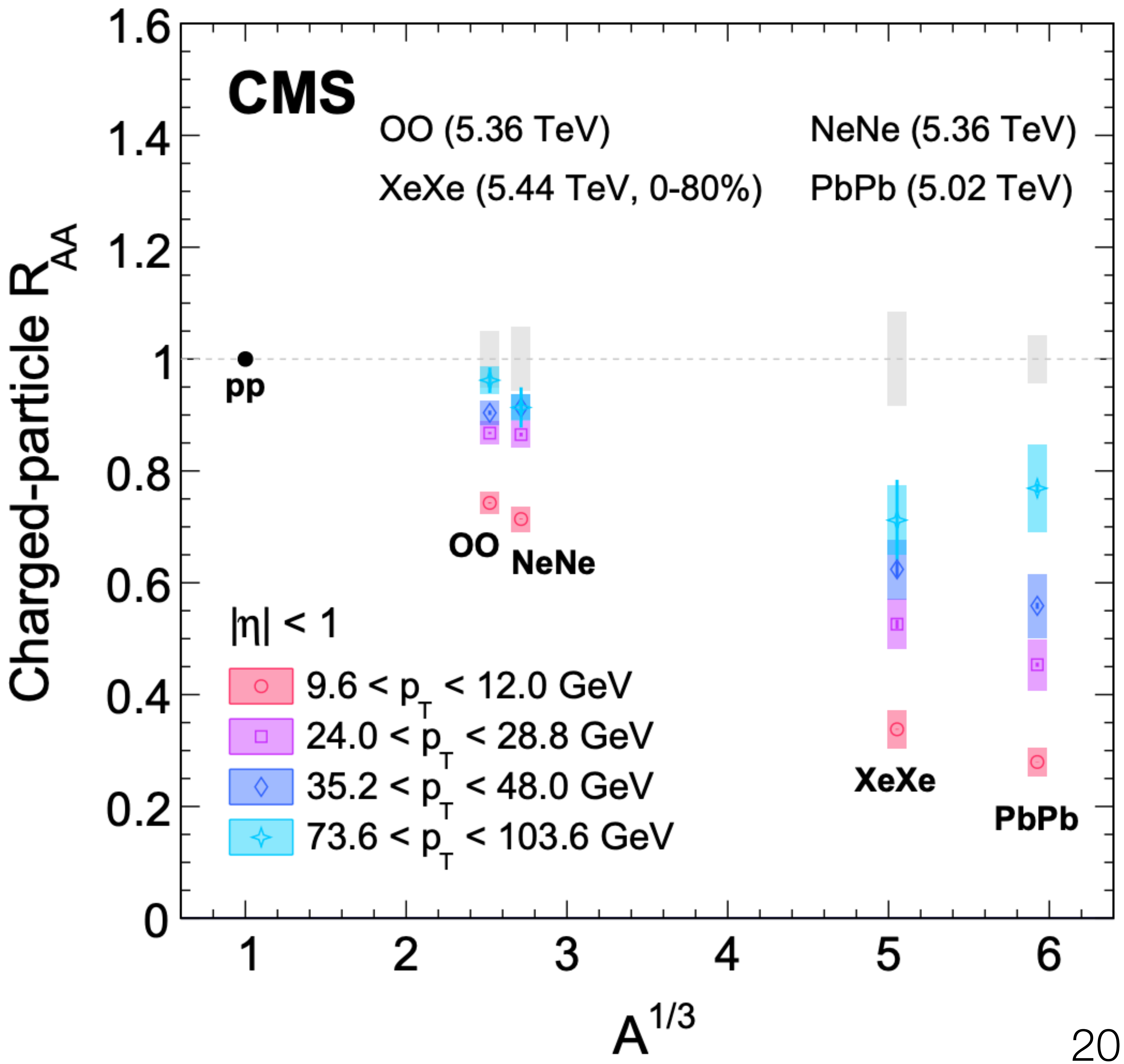


Comparing different systems

Accepted by PLB: arXiv:2602.21425

$$R_{AA} = \frac{1}{A^2} \frac{\mathrm{d}\sigma_{AA}/\mathrm{d}p_T}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_T}$$

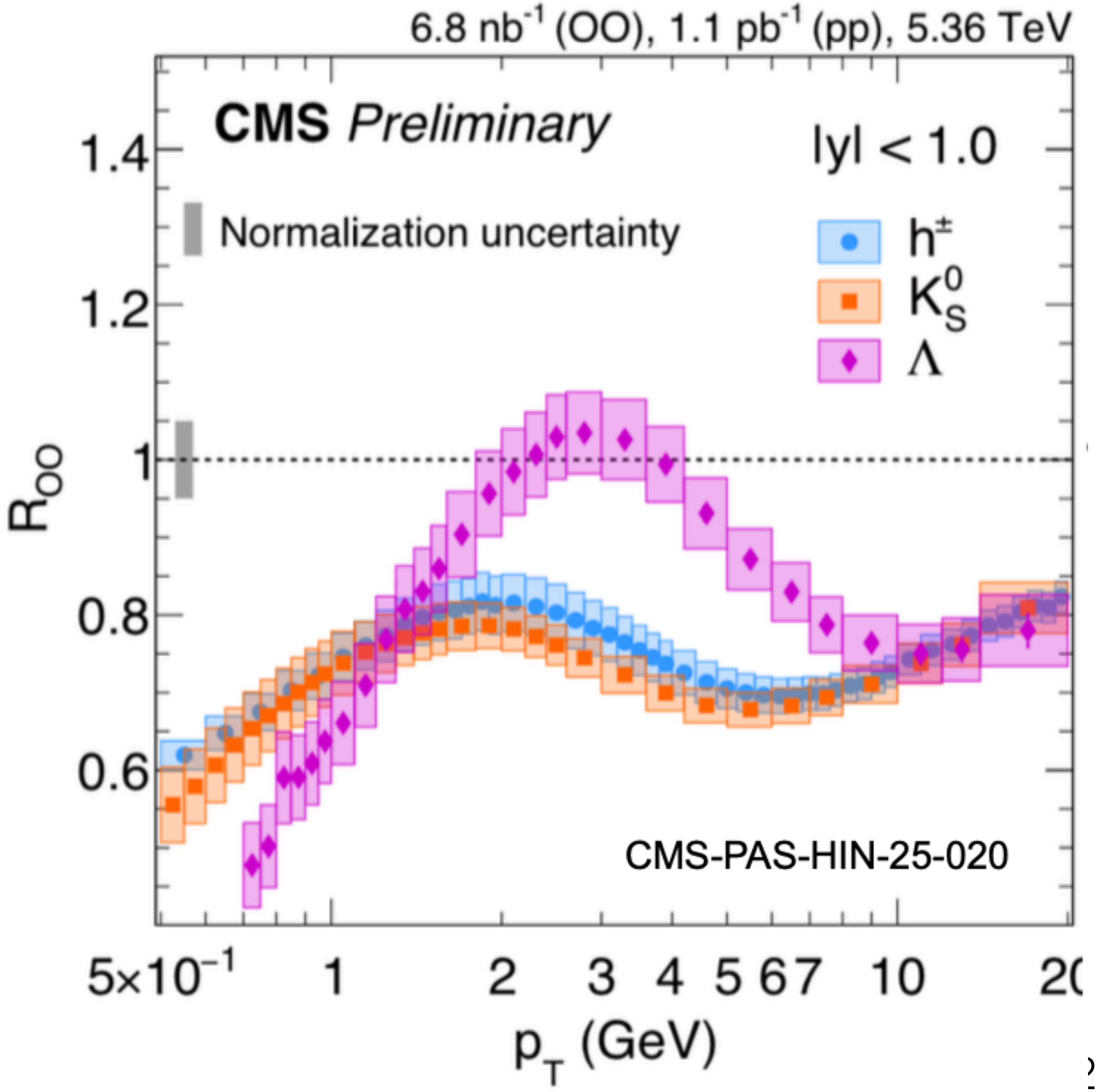
- **Using $A^{1/3}$ as proxy for nuclear radius**
- **Clear evolution see with size**
- **Provides an unbiased method to evaluate particle suppression vs. system size**
- **Greatly constraining on models of energy loss**



Identified neutral hadron R_{AA}

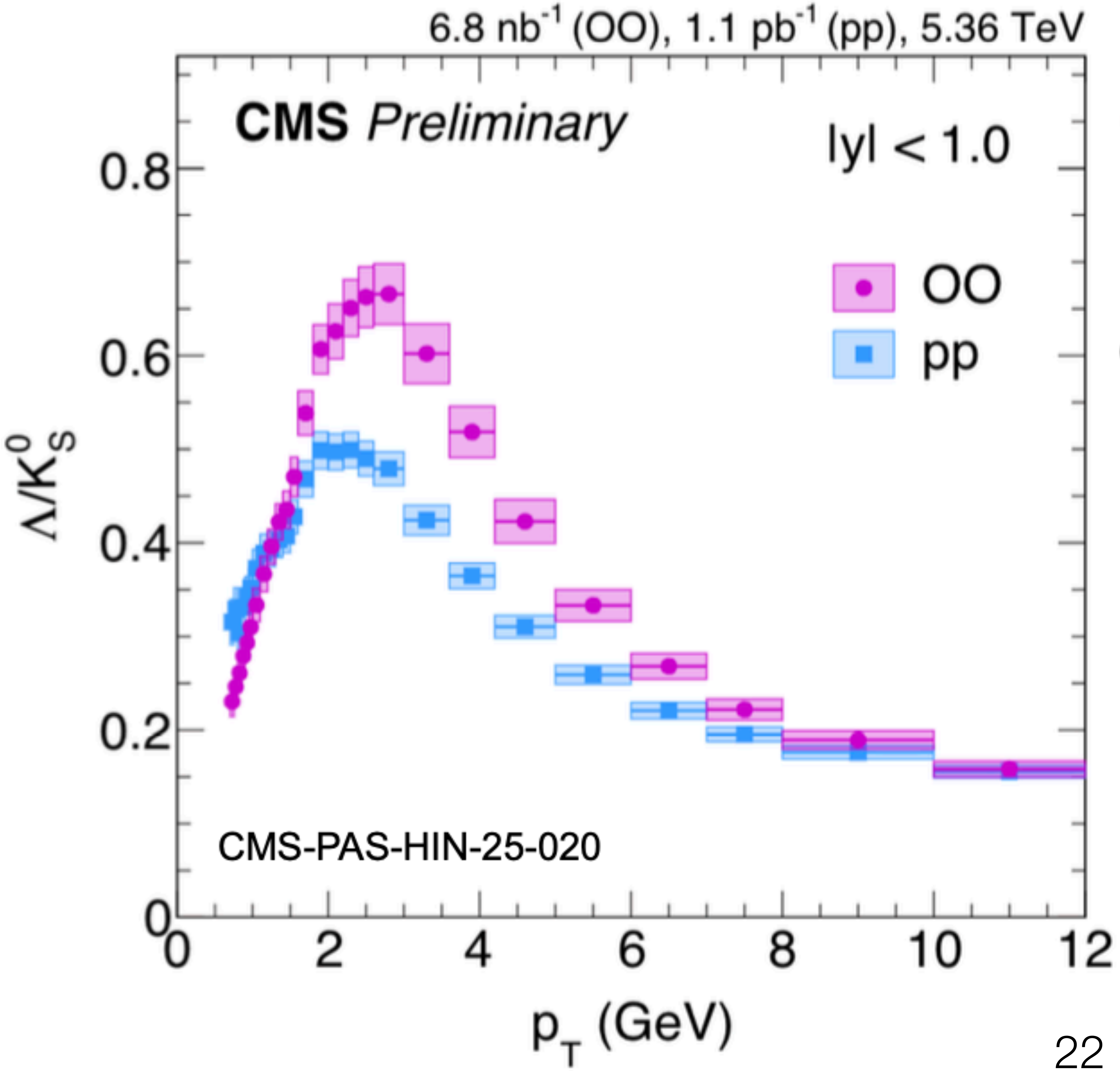
$$R_{AA} = \frac{1}{A^2}\frac{d\sigma_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- Charged hadrons extended down to 500 MeV
  - Clear radial flow bump
- K_s^0 similar to charged hadrons
- Λ less suppressed for 2-5 GeV
- All particles merge at p_T>10 GeV
  - From energy loss + nPDFs

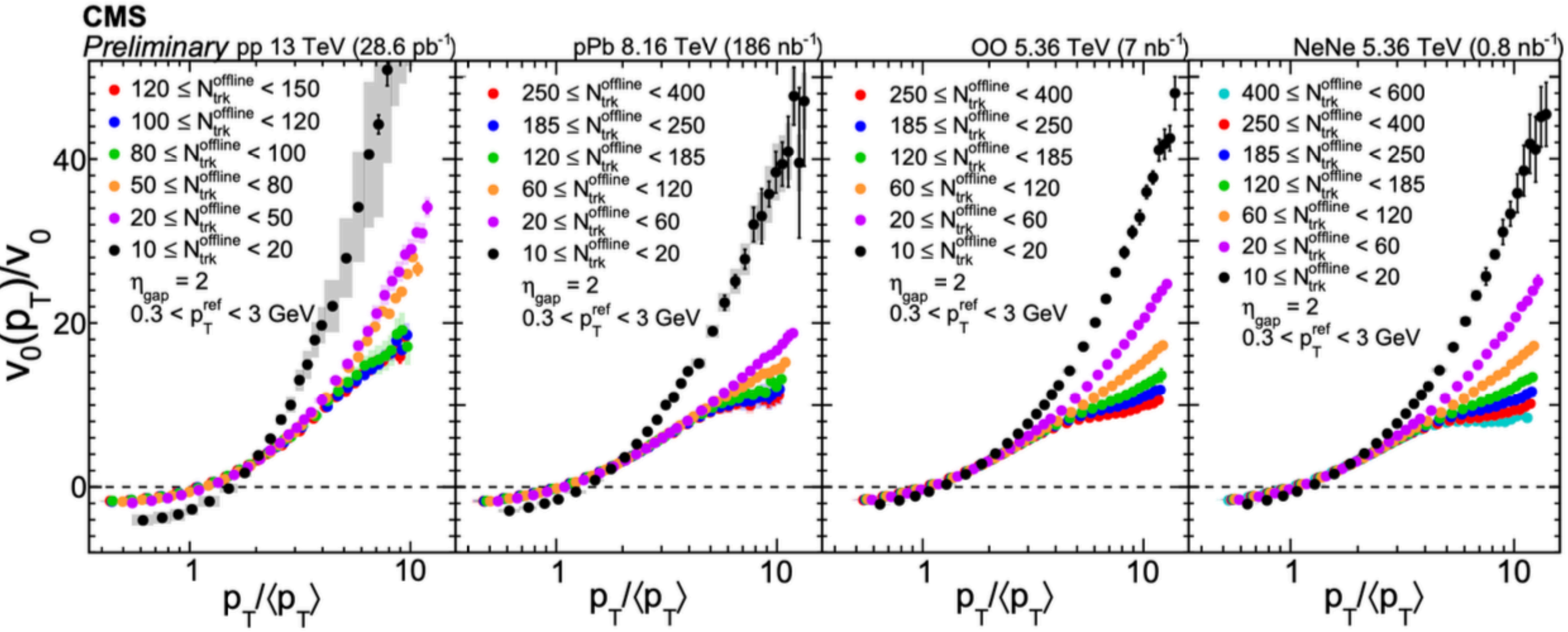


Identified neutral hadron R_{AA}

- Λ/K_s^0 ratio greatly enhanced in OO relative to pp
- Baryon anomoly likely related to radial flow + quark coalescence
- Roughly comparable to peripheral PbPb in nature



$v_0(p_T)$ in small systems



$$v_0(p_T) = \frac{\langle \delta n(p_T) \cdot \delta[p_T] \rangle}{\langle n(p_T) \rangle \cdot \sigma_{[p_T]}}$$

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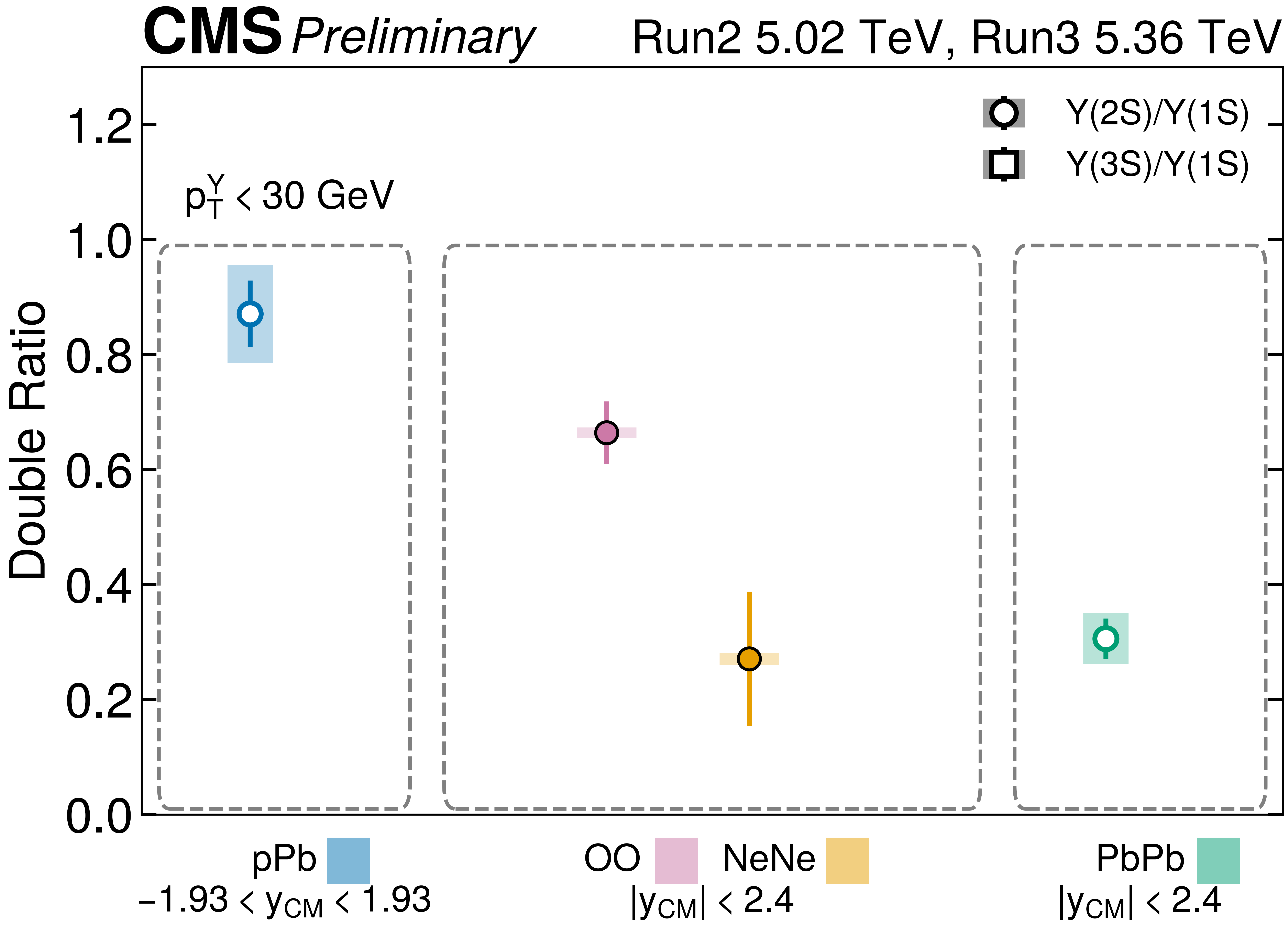
- **Quantifying event-by-event radial flow fluctuations**
- **Comprehensive evaluation of $v_0(p_T)$ in small systems over large N_{trk} range**
- **Similar behavior across systems for N^{trk}>20 and $p_T/<p_T>$ < 2**
  - **Potential signature of collective behavior, but to be discussed further**

Upsilon Invariant Mass Peaks

- **Clear $\Upsilon(3S)$ peak in OO collisions, but not visible for NeNe**
- **5.36 TeV pp reference also analyzed**

Double Ratio Results - 2S/1S



$$\left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{AA} \Big/ \left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{pp}$$

- **2S/1S:**
  - **OO between pPb and PbPb**
  - **NeNe lower, with large uncertainty**

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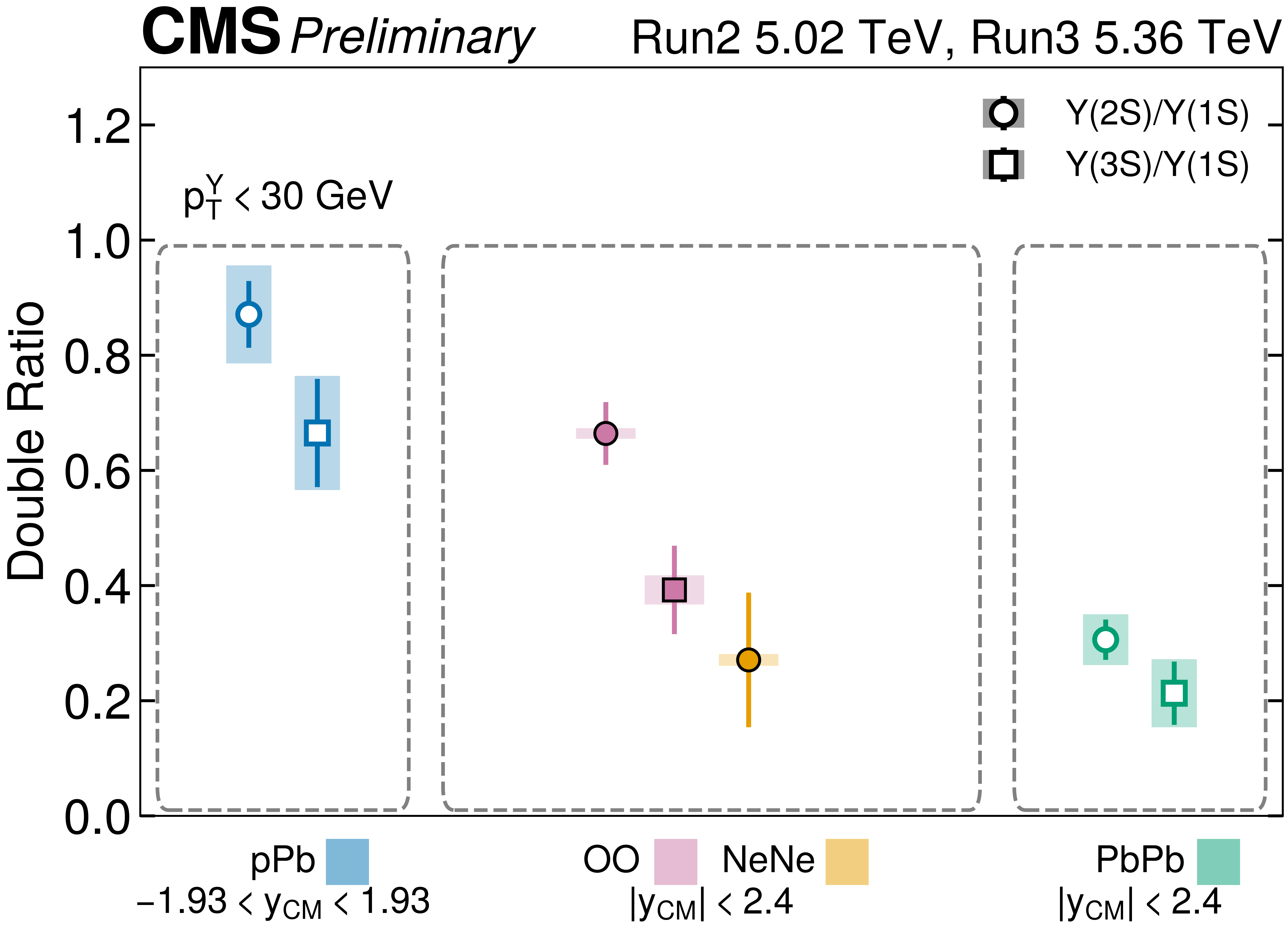
Double Ratio Results - 3S/1S



$$\left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{AA} \Big/ \left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{pp}$$

- **2S/1S:**
  - **OO between pPb and PbPb**
  - **NeNe lower, with large uncertainty**
- **3S/1S:**
  - **Clear ordering seen with system size**

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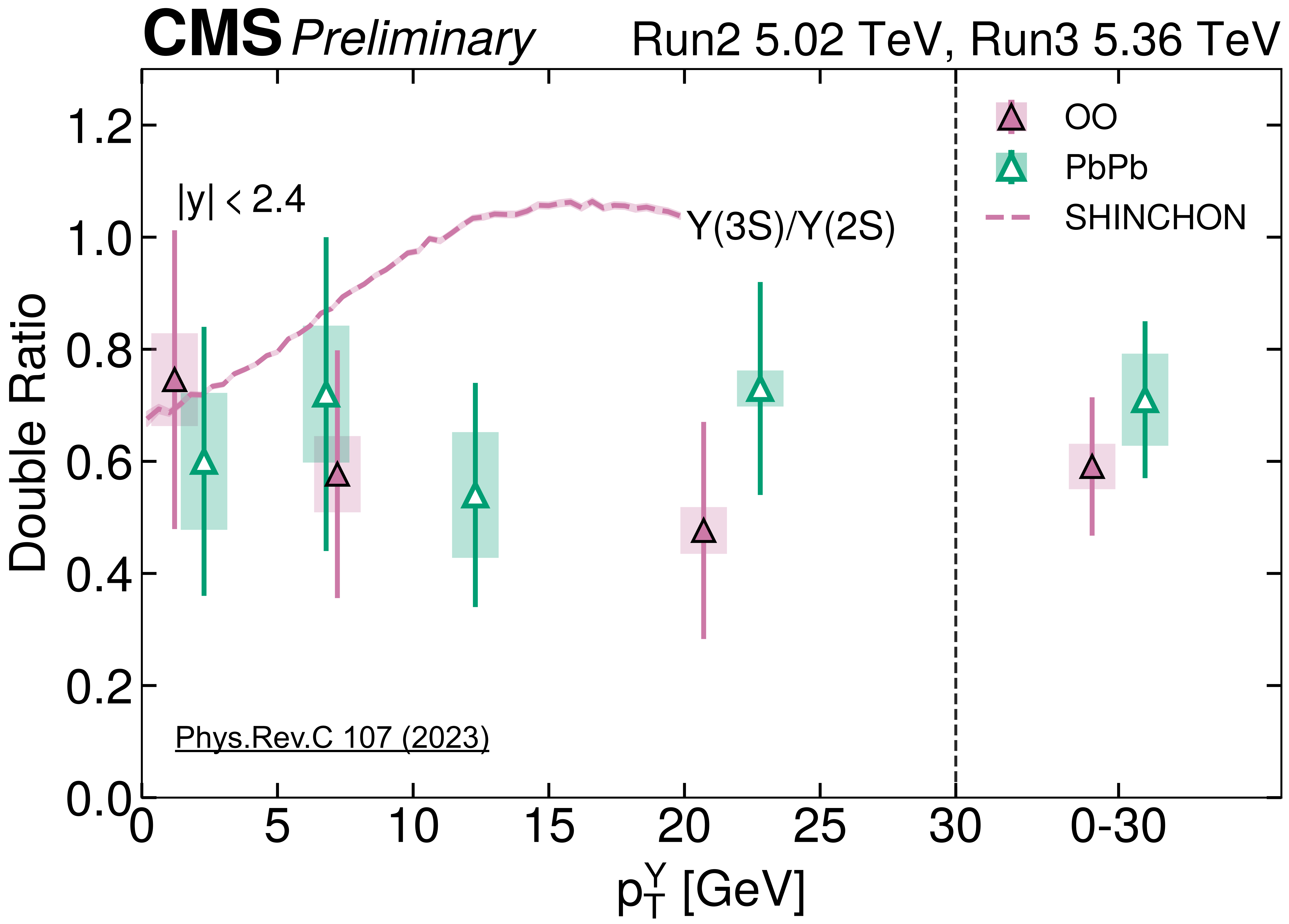
p_T dependence of 3S/2S



$$\left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{AA} \Bigg/ \left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{pp}$$

- **3S/2S double ratio suppressed significantly**
- **Evidence for sequential suppression of Υ in OO**
- **No significant p_T dependence of 3S/2S seen**
- **Trend not captured by SHINCHON at high-p_T**

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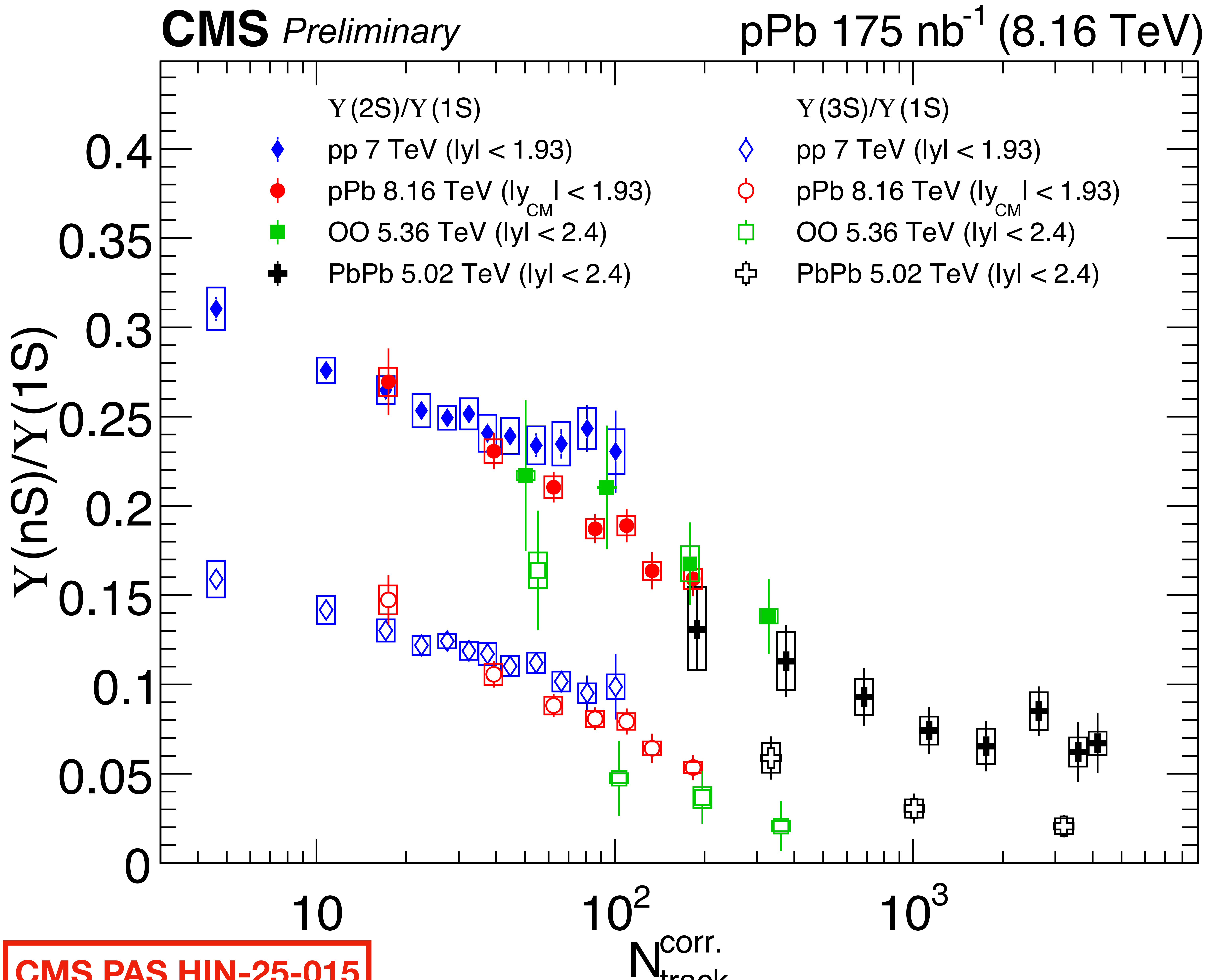
Compilation of N_{trk}-dependent results



$$\left(\frac{N^{\Upsilon(nS)}}{N^{\Upsilon(mS)}}\right)_{AA}$$

- **OO 2S/1S single ratio follows pPb, PbPb trend**
- **OO 3S/1S tends to be lower than pPb, PbPb at higher N_{trk}**
- **Potentially creating a denser QGP for a fixed N_{trk}?**
- **But different volumes, temperature, lifetimes, etc.**
  - **Need model guidance!**

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High-p_T charged particle v_2

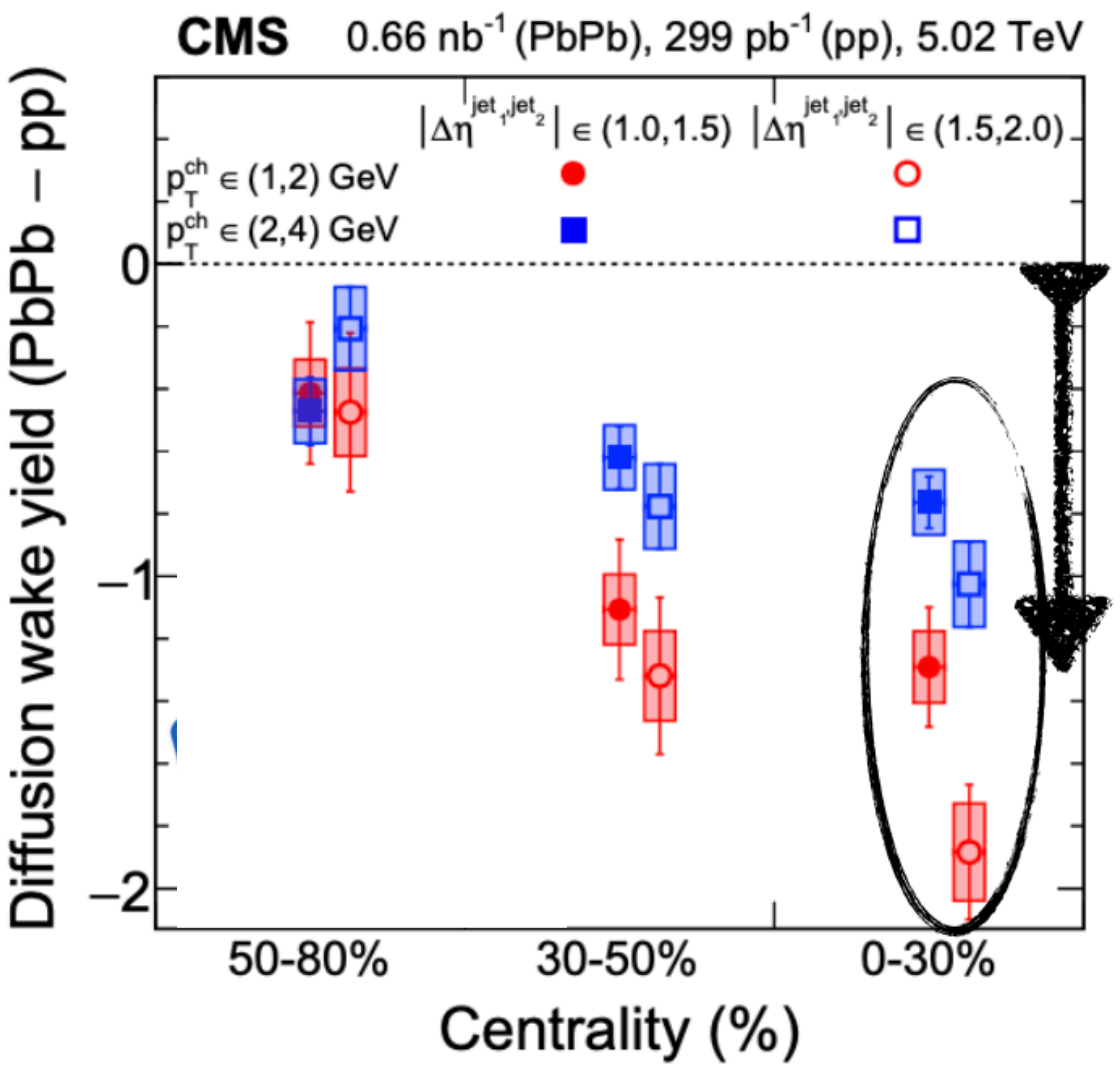
CMS-PAS-HIN-26-005

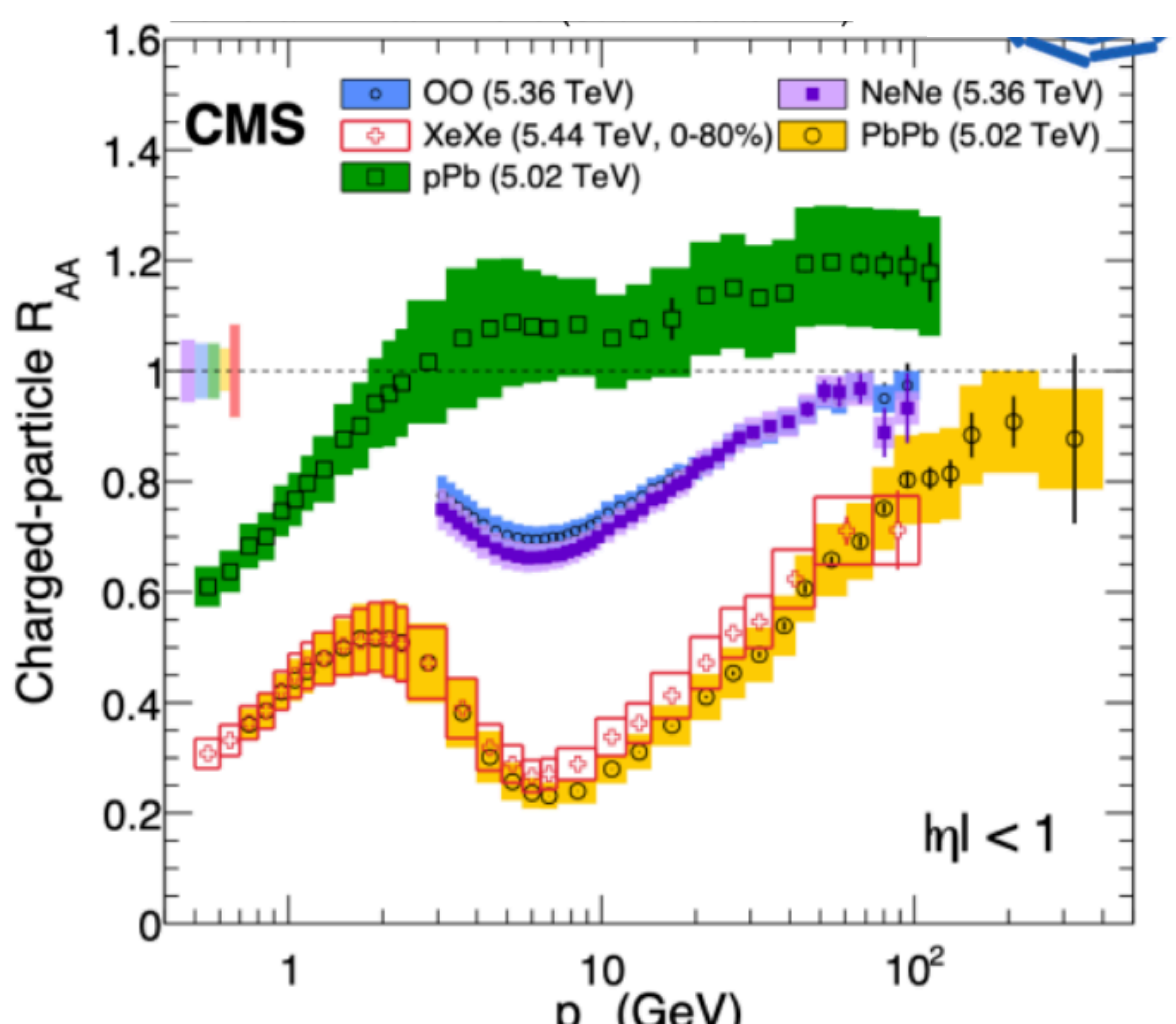
- **Nonzero v_2 observed up to 50 GeV**
- **Consistent with pQCD parton model with T constraint and radiative energy loss**

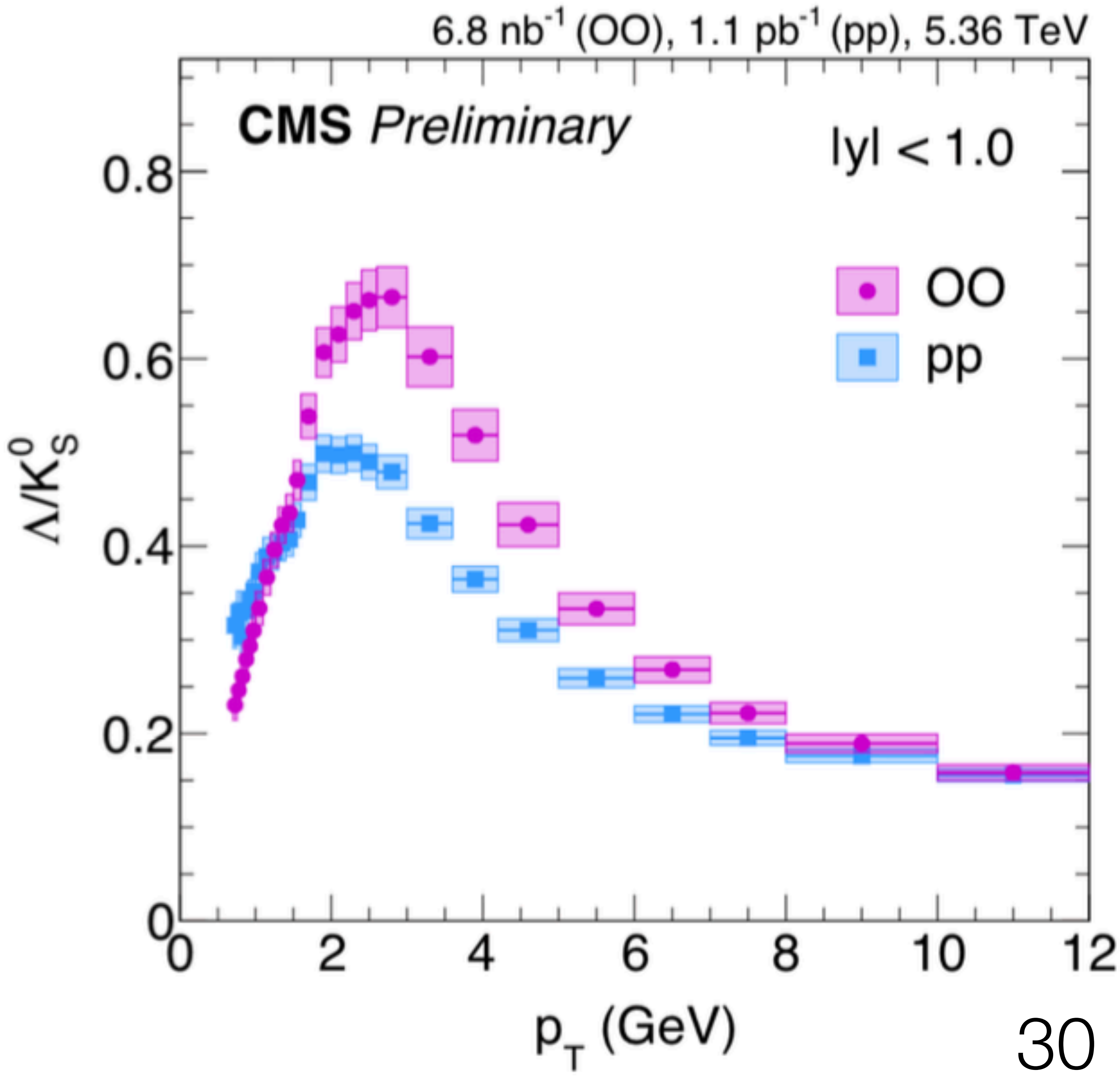
Conclusions

- **Very recent exciting new studies exploring jet quenching and medium response**
  - **No ‘dead cone filling’ and observation of ‘diffusion wake’**

- **OO and NeNe collisions display nearly all hallmark signs of QGP production**
  - **Only 1 year after taking the data, we have clear evidences for:**
  - **Particle suppression, flow, baryon anomaly, sequential quarkonia suppression**

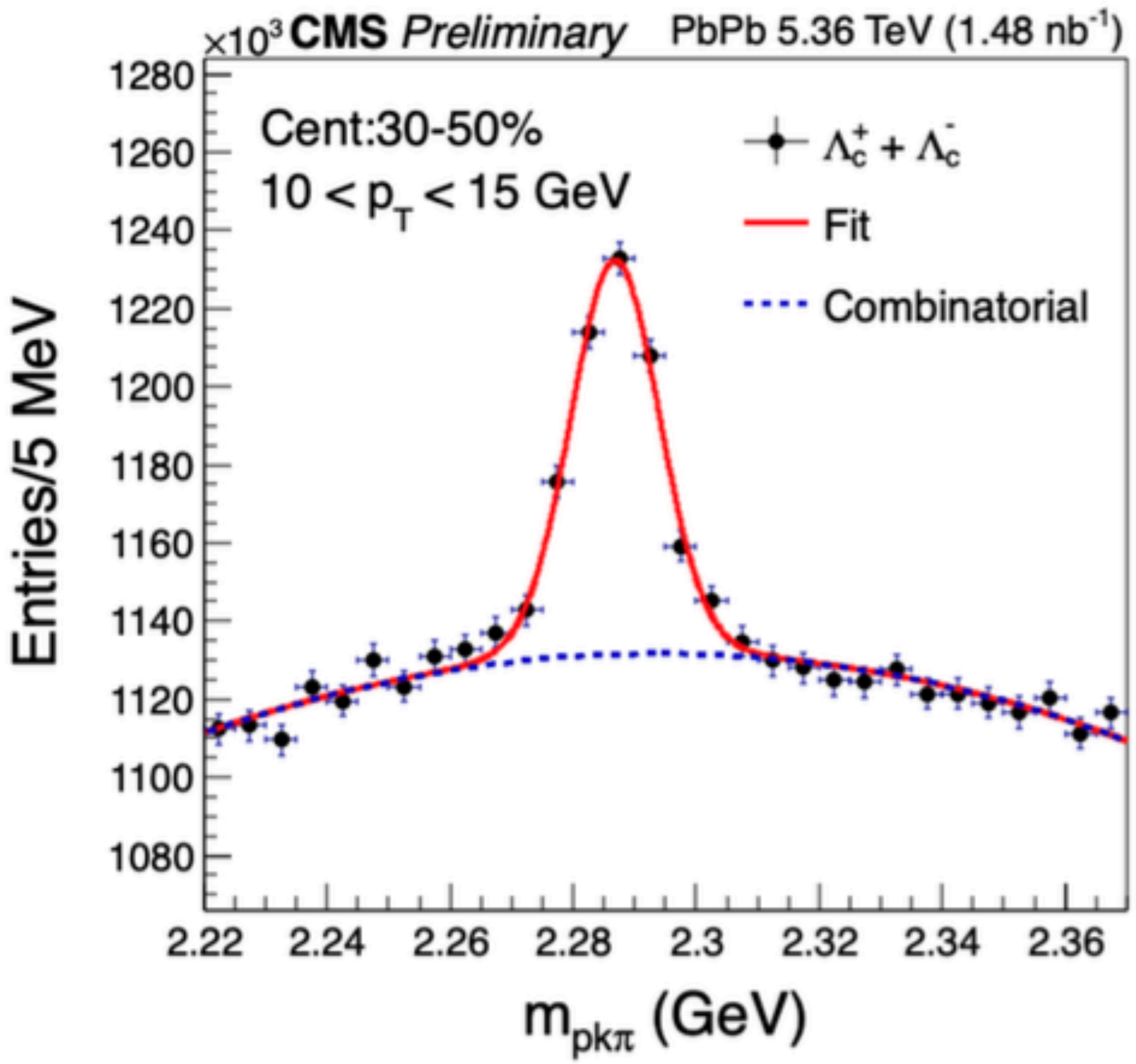


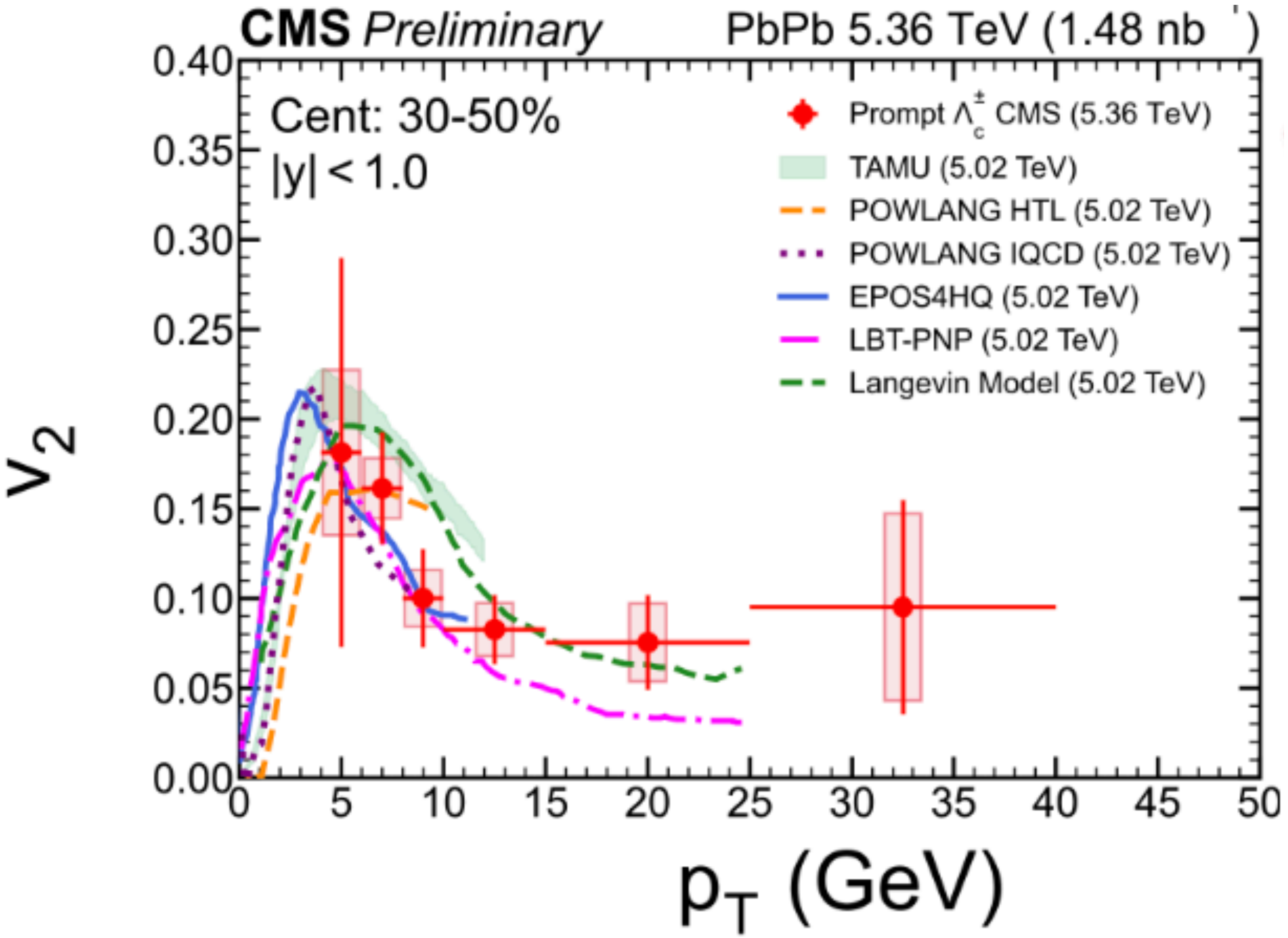




Backup

Λ_c^+ elliptic flow





- **Enhanced statistics from large Run 3 Minimum bias dataset**
- **Testing hadronization and path-length dependent energy loss at high p_T**
- **Full Run 3 dataset promising in the future!**

CMS-PAS-HIN-25-022