

From Lead to Helium: Partonic Energy Loss in Very Light Ion Collisions

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Based on **CF**, W. A. Horowitz, B. Schenke [arXiv:26xx.xxxxx](#),
B. Bert, **CF**, and W. A. Horowitz, [arXiv:2603.21861](#),
CF, B. Bert, J. Brand, W. Vogelsang, and W. A. Horowitz, [arXiv:2512.17832](#)
and **CF** and W. A. Horowitz, [JHEP 11, 019 \(2025\)](#)

> The *Cape Town* Model

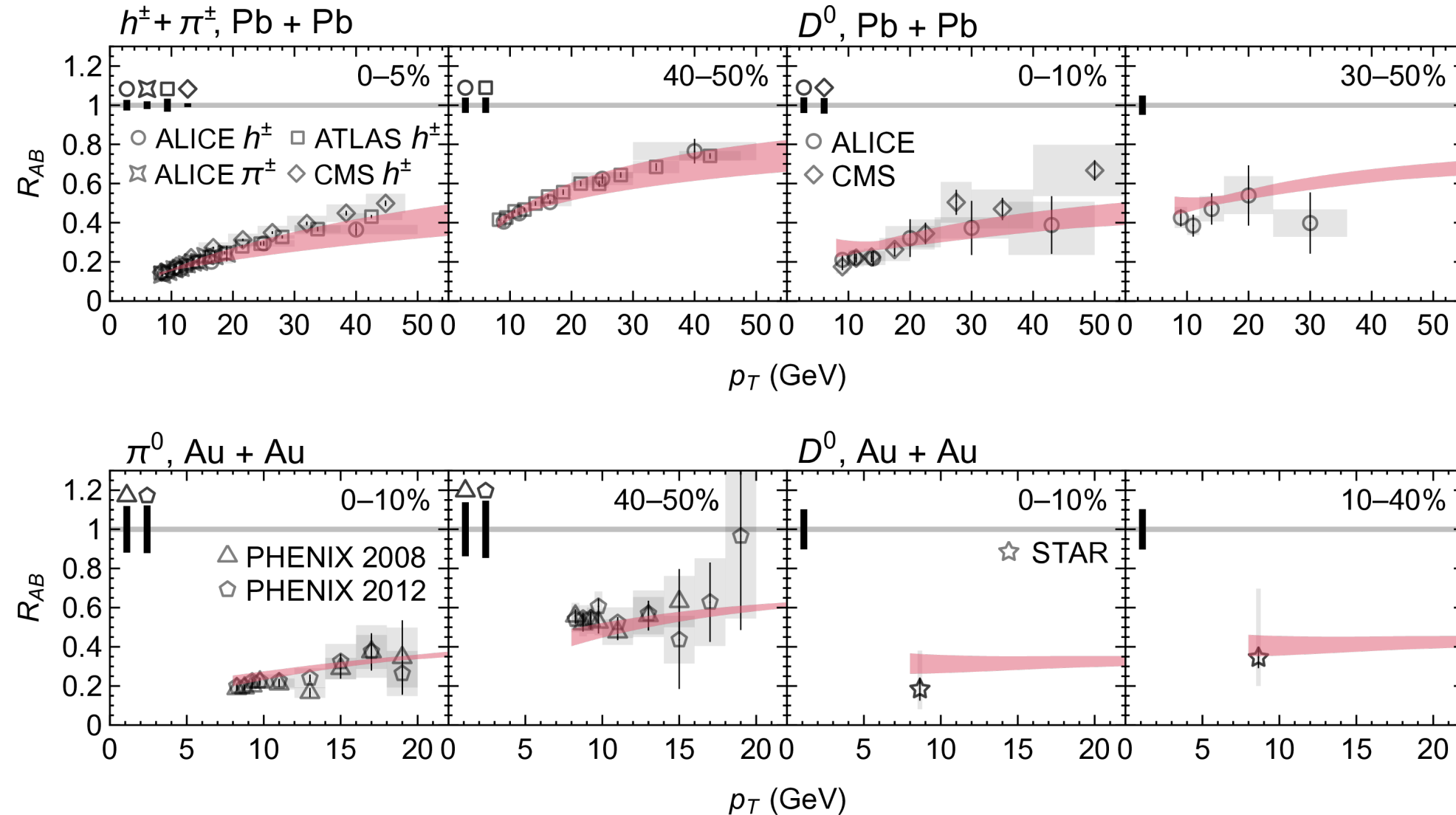
The *Cape Town* model is a pQCD-based, partonic energy loss model

- Includes **elastic** and **radiative** energy loss
 - NB: elastic very important in small systems, cannot be neglected!
- Includes **analytic corrections** to calculation relevant for **small systems**
- Realistic 2+1D hydrodynamic event-by-event and path-by-path fluctuations
- **Single free parameter** (α_s) tuned to large-system data



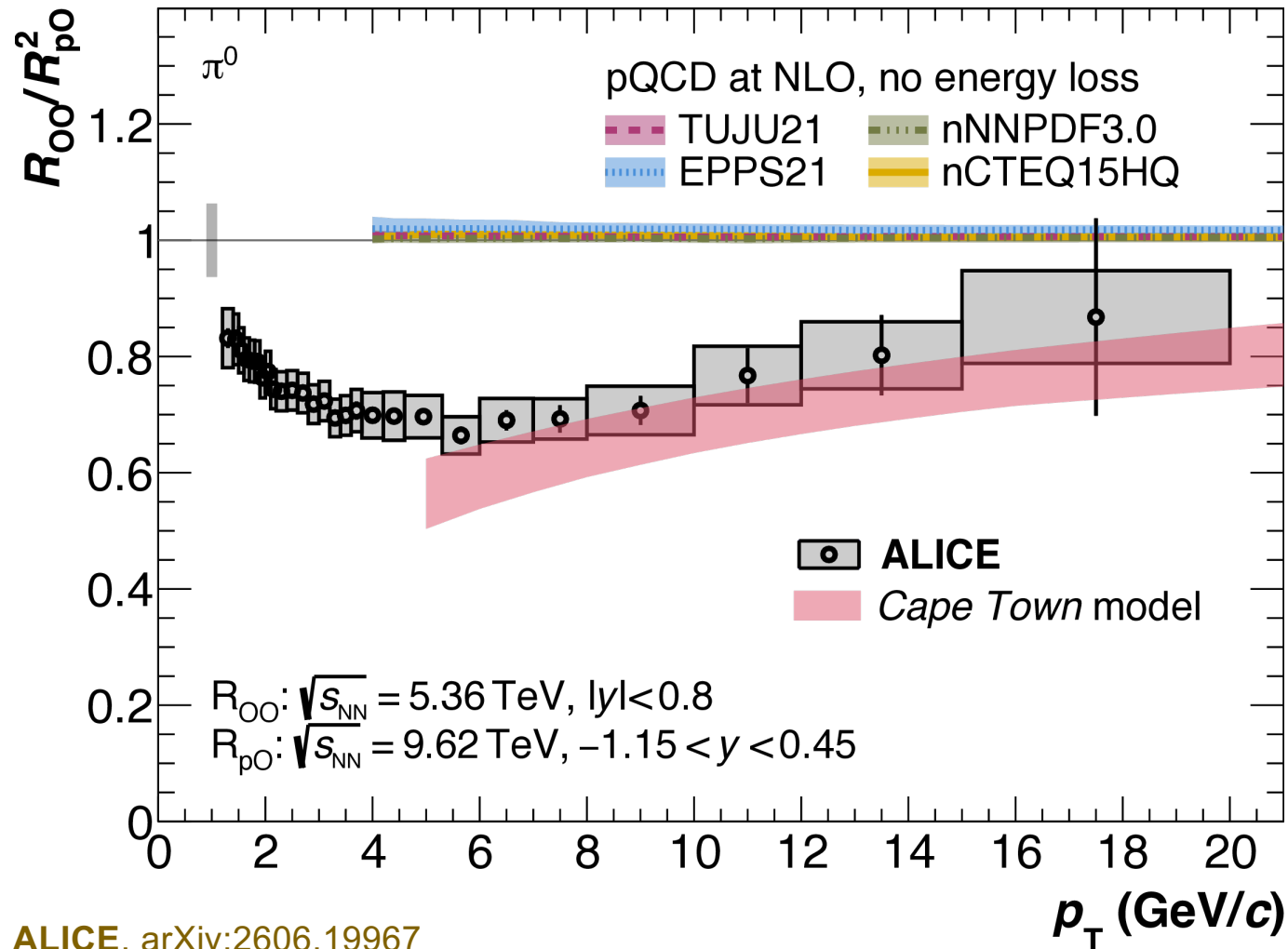
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Sample of results post-fitting



- Fit α_s separately at RHIC and LHC
- Good agreement with all available single-inclusive high- p_T data
- Band width indicates theoretical uncertainty

Predictions for oxygen

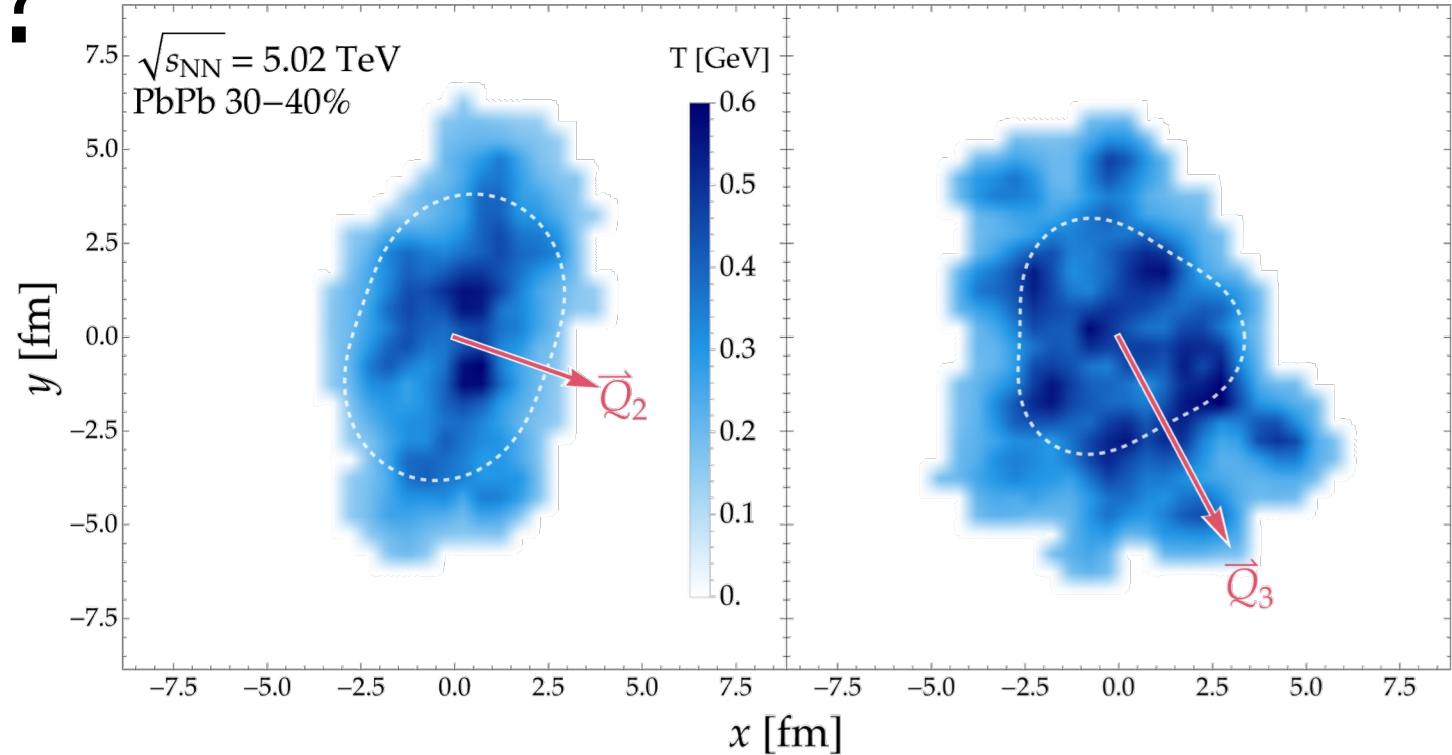


- Good agreement between (blind) predictions and data!
- Missing physics for $p_T \lesssim 10 \text{ GeV}$
 - Likely medium-modified hadronization

ALICE, arXiv:2606.19967

CF, W. A. Horowitz, *JHEP* 11, 019 (2025), arXiv: 2505.14568

What about v_2 ?



- Compute v_2 using experimental definition:

$$\frac{R_{AB}(p_T, \phi)}{R_{AB}(p_T)} = 1 + 2 \sum_{n=1}^{\infty} v_n^{\text{hard}}(p_T) \cos \left[n \left(\phi - \psi_n^{\text{hard}}(p_T) \right) \right]$$
$$v_n^{\{\text{SP}\}}(p_T) \propto \cos \left[n \left(\psi_n^{\text{hard}}(p_T) - \psi_n^{\text{soft}} \right) \right] v_n^{\text{hard}}(p_T)$$

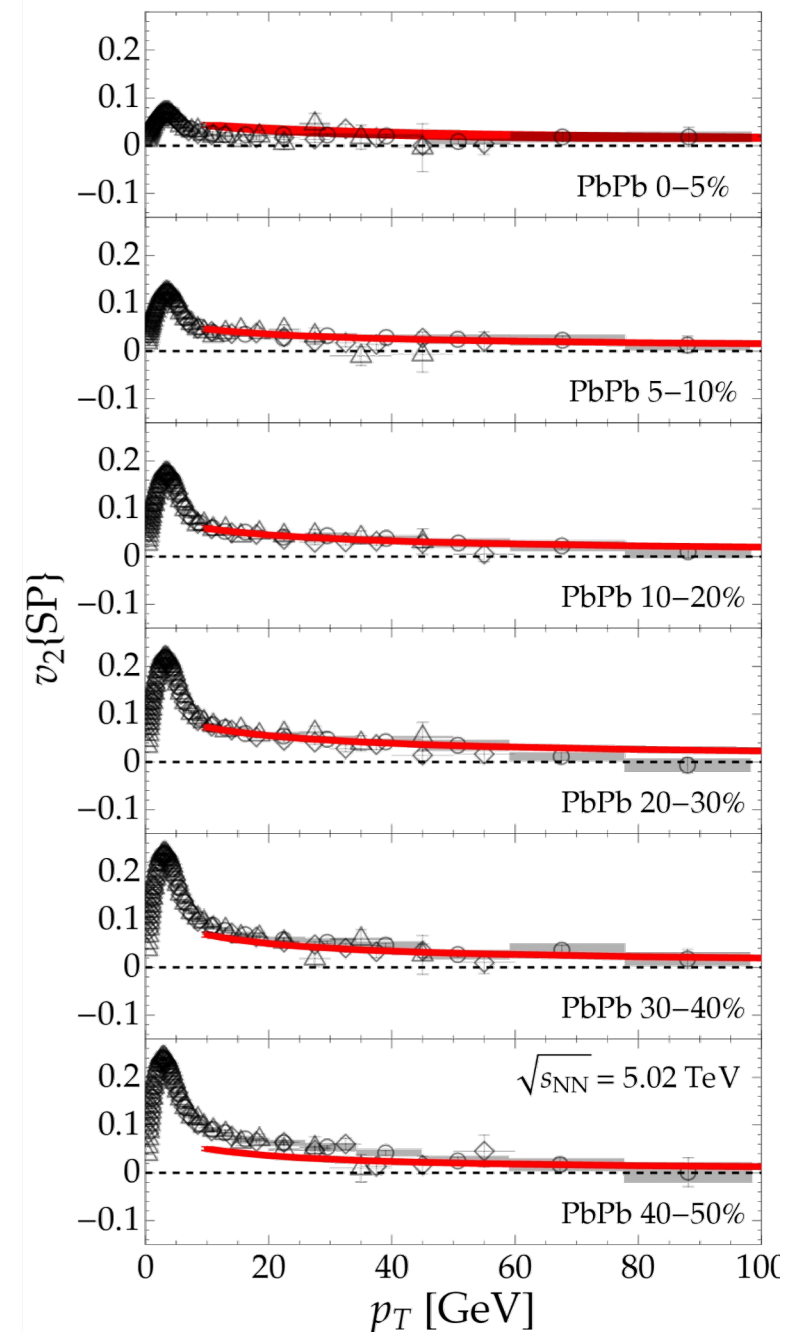
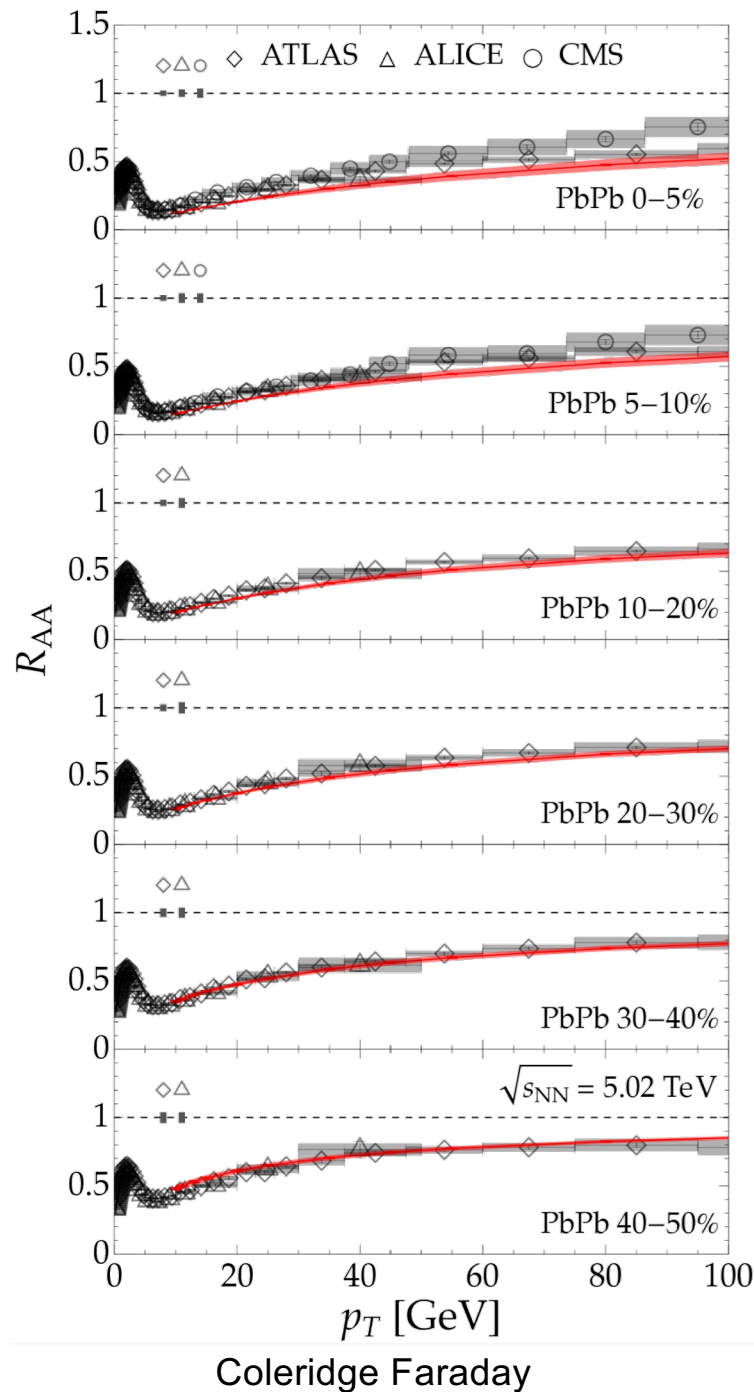
B. Bert, **CF**, and W. A. Horowitz, [arXiv:2603.21861 \[hep-ph\]](https://arxiv.org/abs/2603.21861) (2026)

v_2 in large systems

- Good description of v_2 in PbPb for $p_T \gtrsim 10 - 15$ GeV
- At lower p_T , missing coalescence

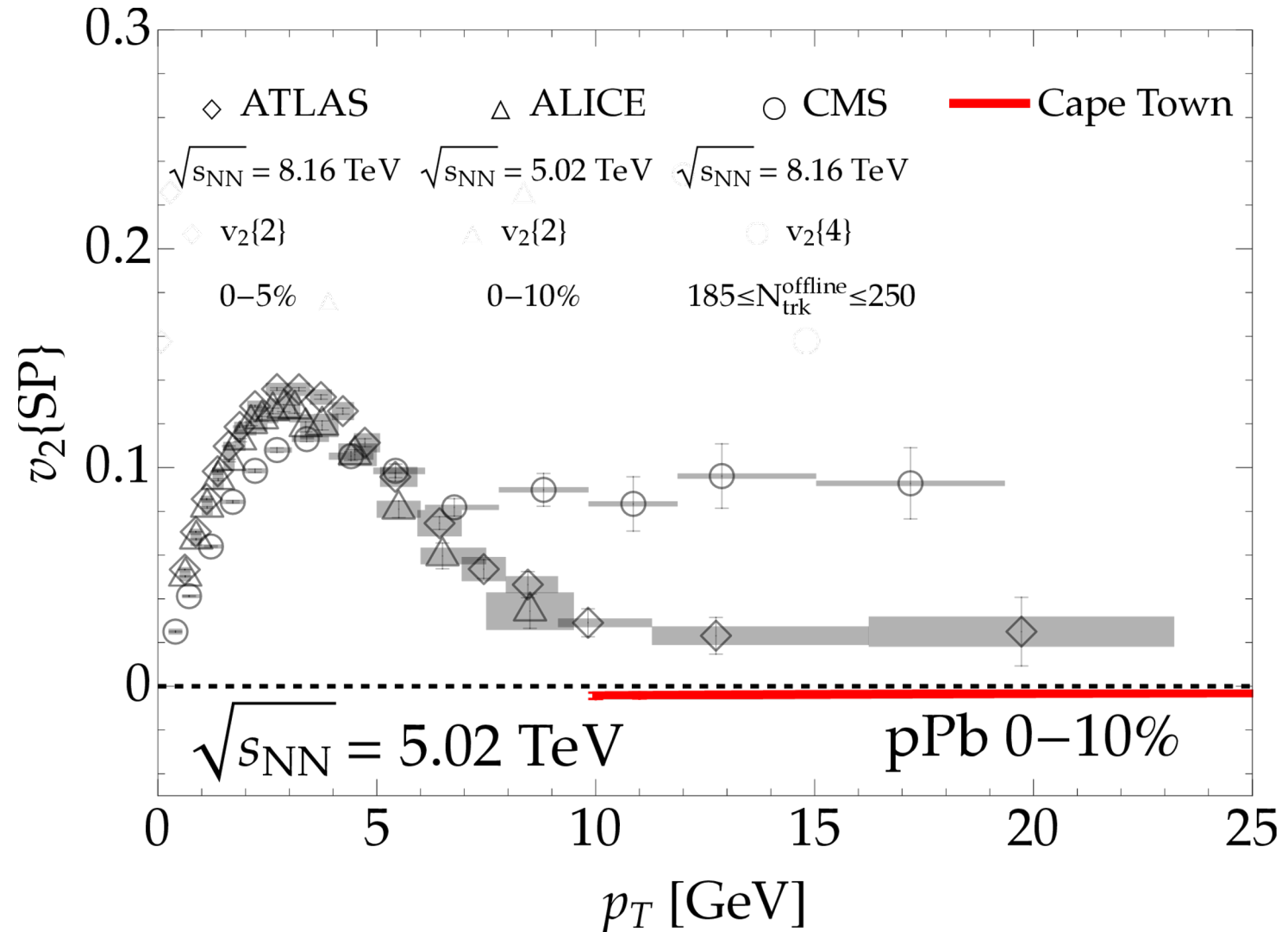
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v_2 in pA collisions

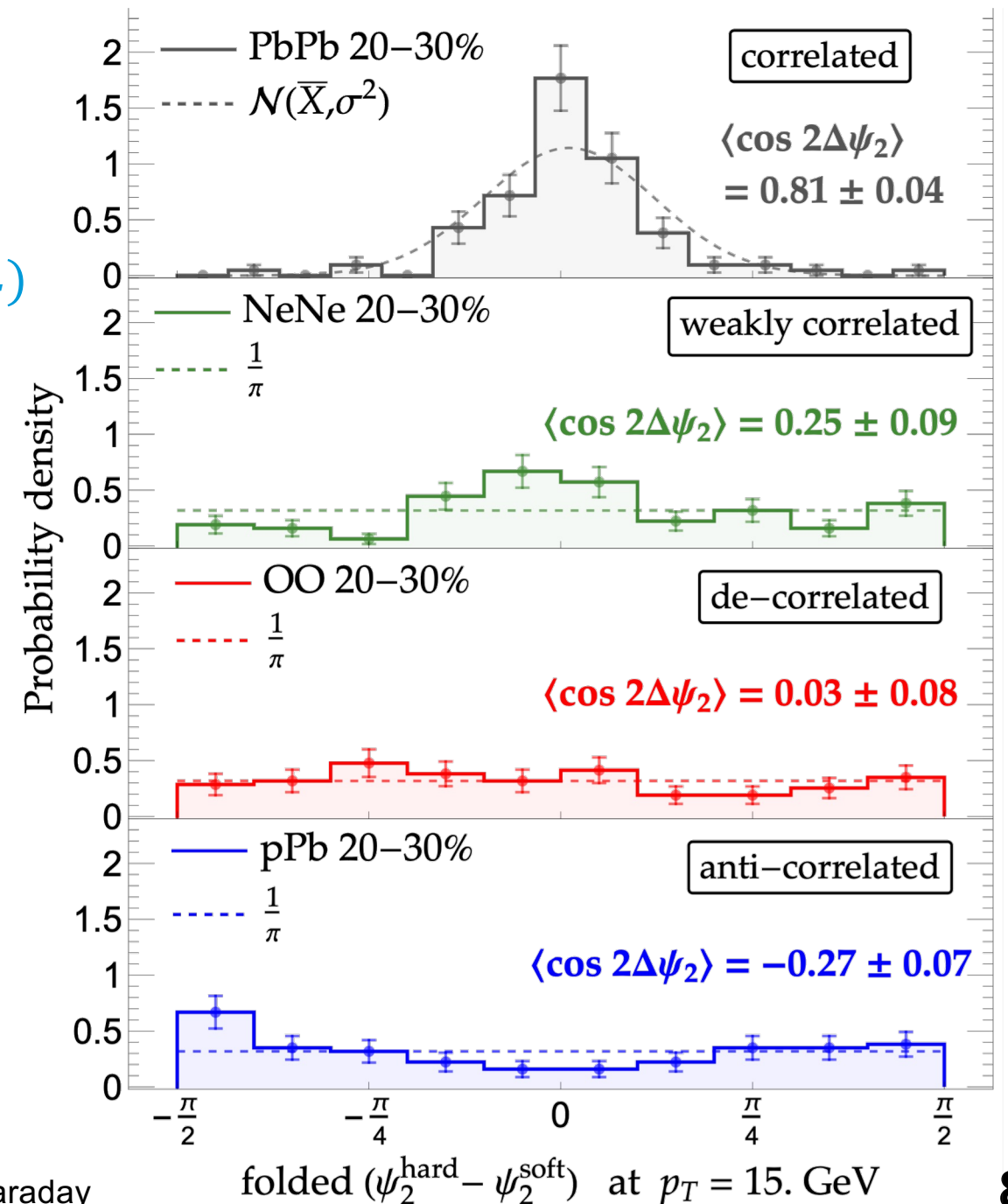
- v_2 in pPb is very confusing
- Experimentally, disagreement with $v_2\{2\}$ and $v_2\{2\}$
- Theoretically, $v_2\{2\} \sim 0$ predicted



Why is $v_2 \approx 0$?

$$v_n\{\text{SP}\}(p_T) \propto \cos \left[n \left(\psi_n^{\text{hard}}(p_T) - \psi_n^{\text{soft}} \right) \right] v_n^{\text{hard}}(p_T)$$

- ψ_2^{hard} and ψ_2^{soft} correlated in Pb + Pb
 - Uncorrelated or even anti-correlated in small systems (!)

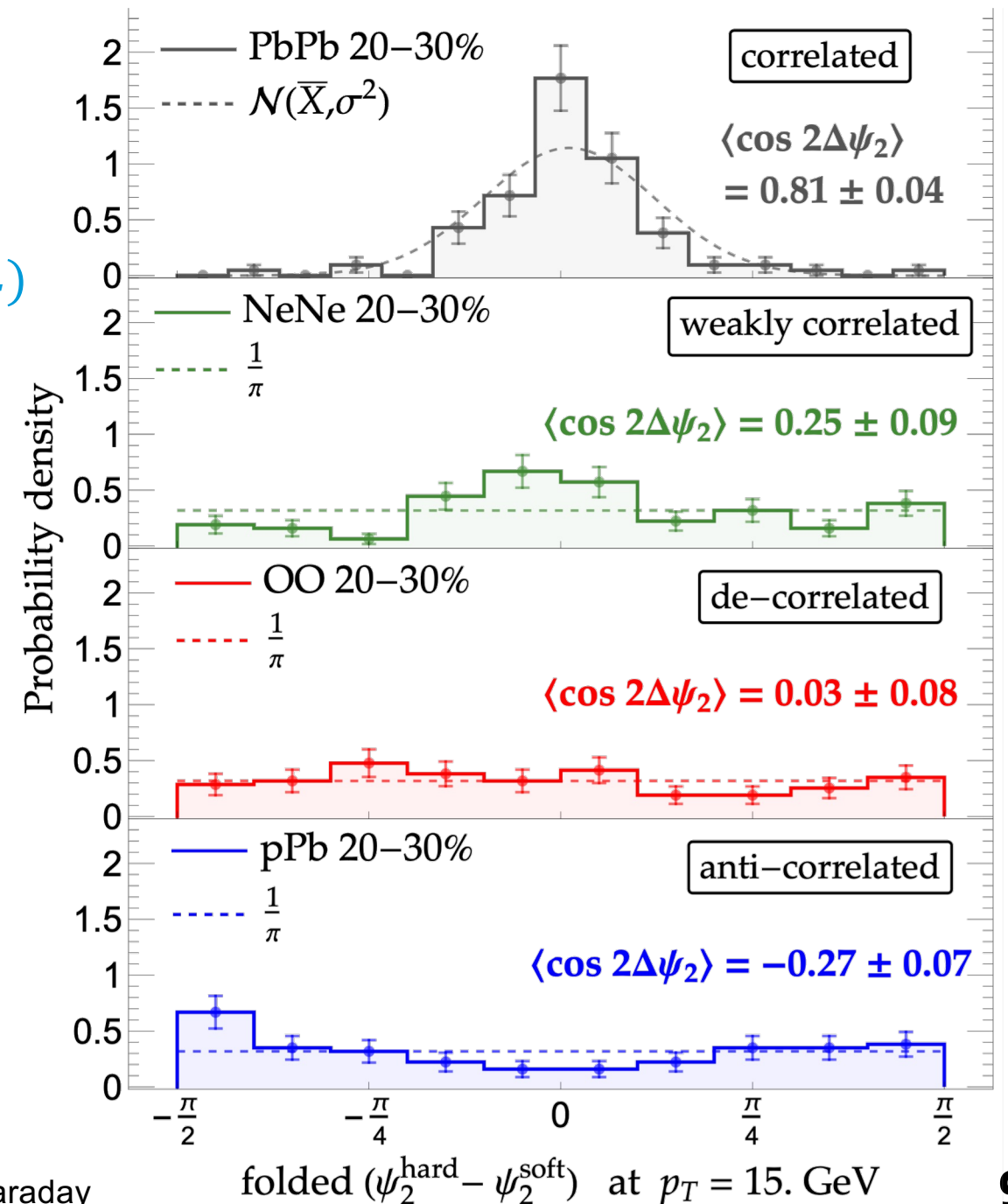


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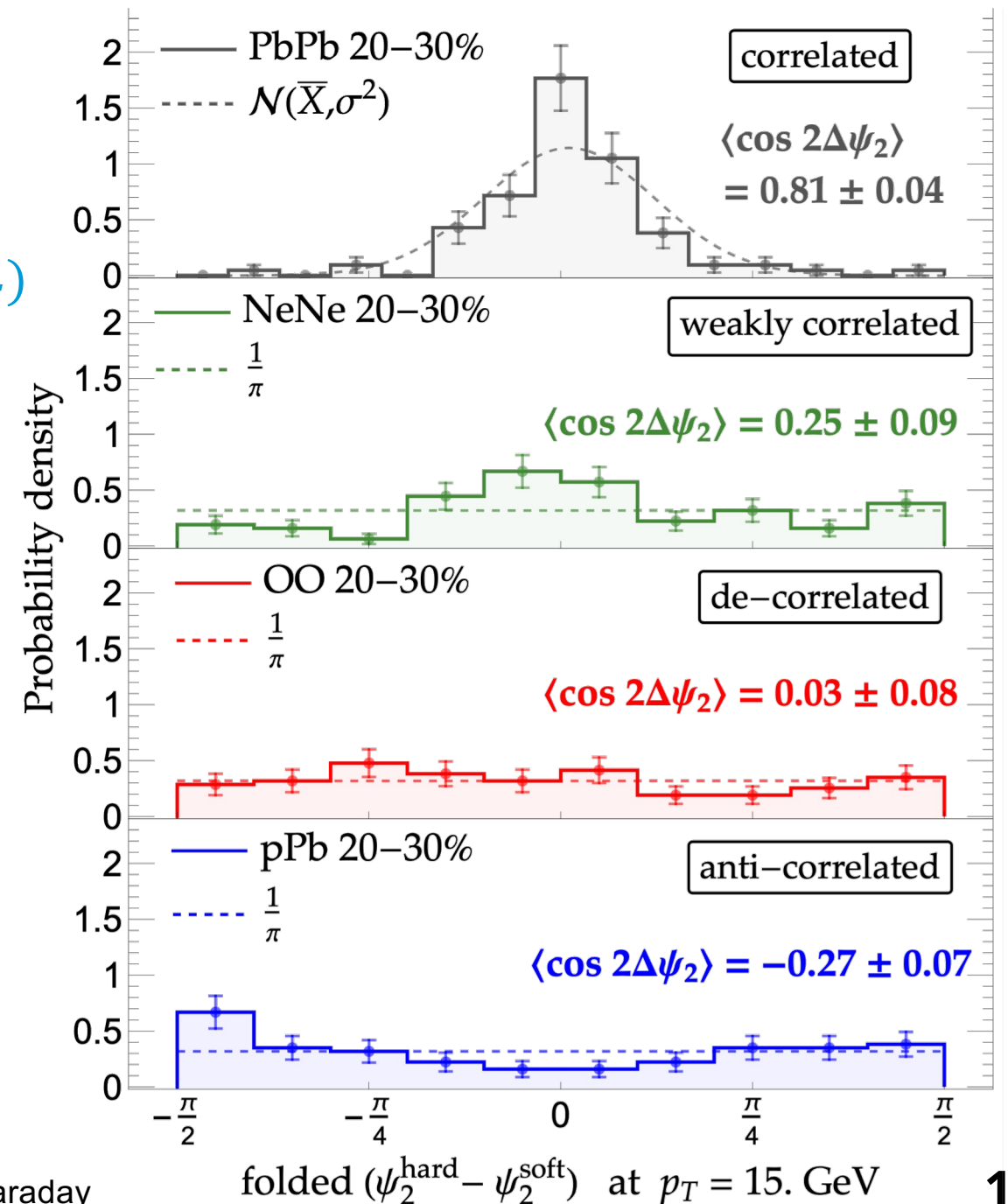


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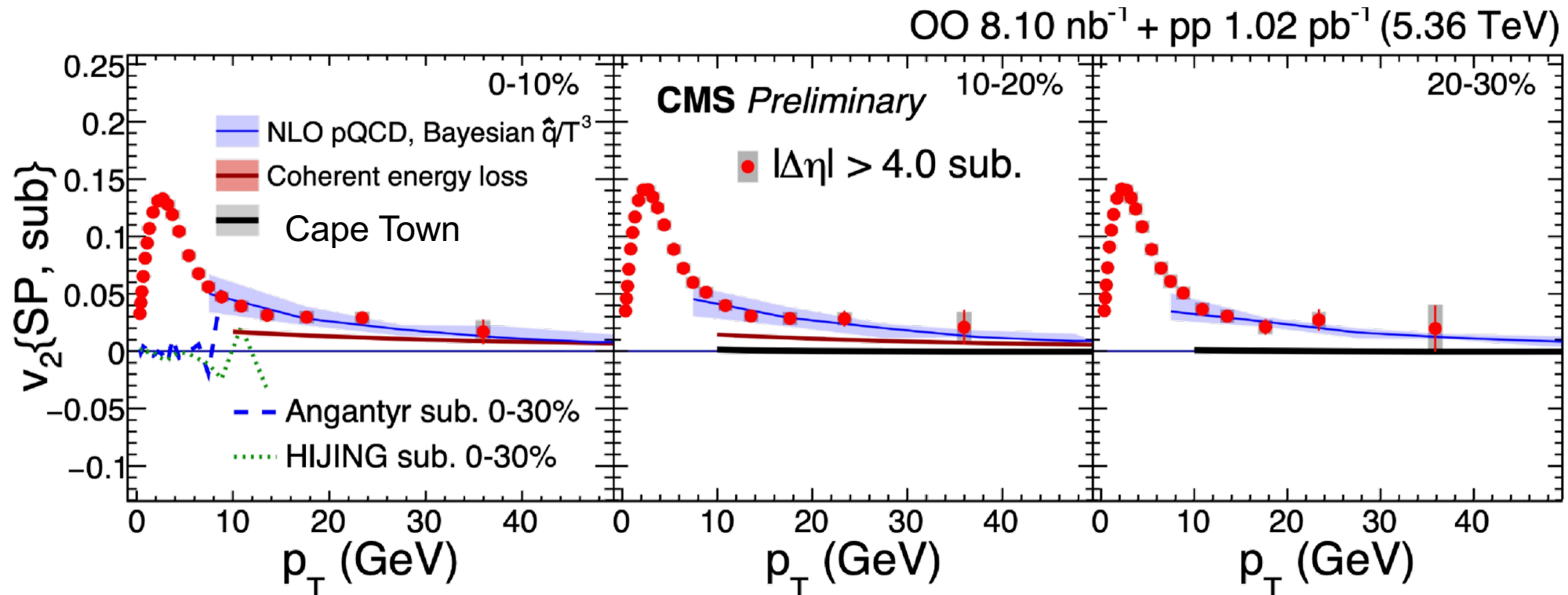
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- Likely culprit: initial state effects, experimental issues?



B. Bert, CF, and W. A. Horowitz, arXiv:2603.21861 [hep-ph] (2026).

v_2 in 00 collisions

- 00 $v_2 \sim 0.05$ at high- p_T was measured just a few months ago; **we predict 0**
- Issues in energy loss model / hydro model?
- Contribution of initial state effects / biases (similar to pPb)?
- **NB:** both other theory predictions do v_2^{hard} *not* v_2^{SP} ; potential open puzzle in 00?



Can we go smaller?

Two paths:

- Can we better model the physics of centrality-selected $p\text{Pb}$?
- What future light-ion runs in LHC run 4 / 5 would help us answer these questions?

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Tackling hard-soft correlations

- IP-Glasma is built on the color glass condensate (CGC), valid at small Bjorken x
- Solves classical Yang-Mills equations event-by-event, including geometric, subnucleonic color-charge, and saturation-scale fluctuations
- Use the IP-Glasma framework to model *both* soft and semi-hard particles
 - Naturally includes hard-soft correlations
 - p_T relevant for energy loss: 5-20 GeV
→ Bjorken x of $\mathcal{O}(0.001)$

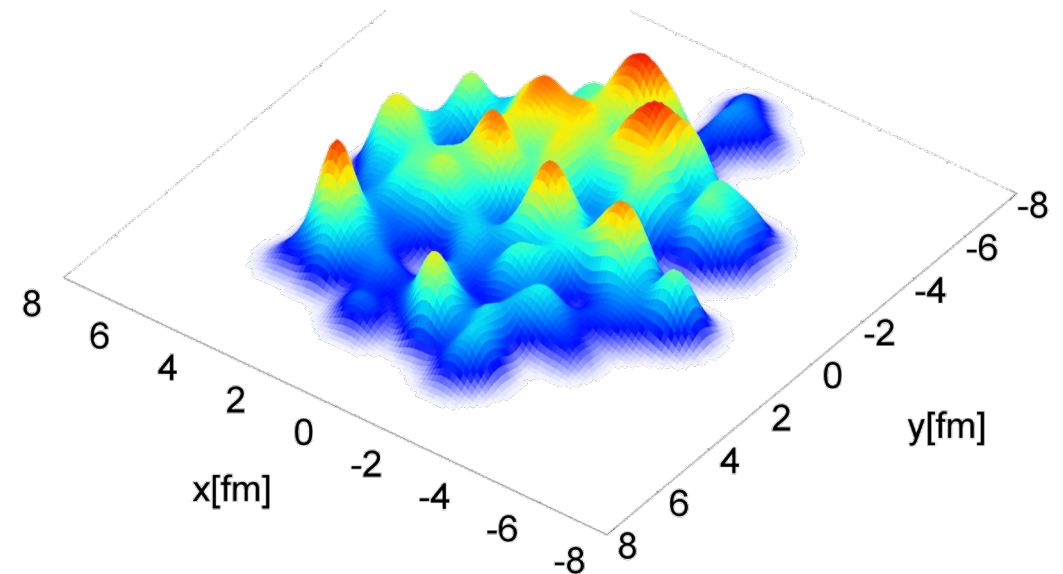
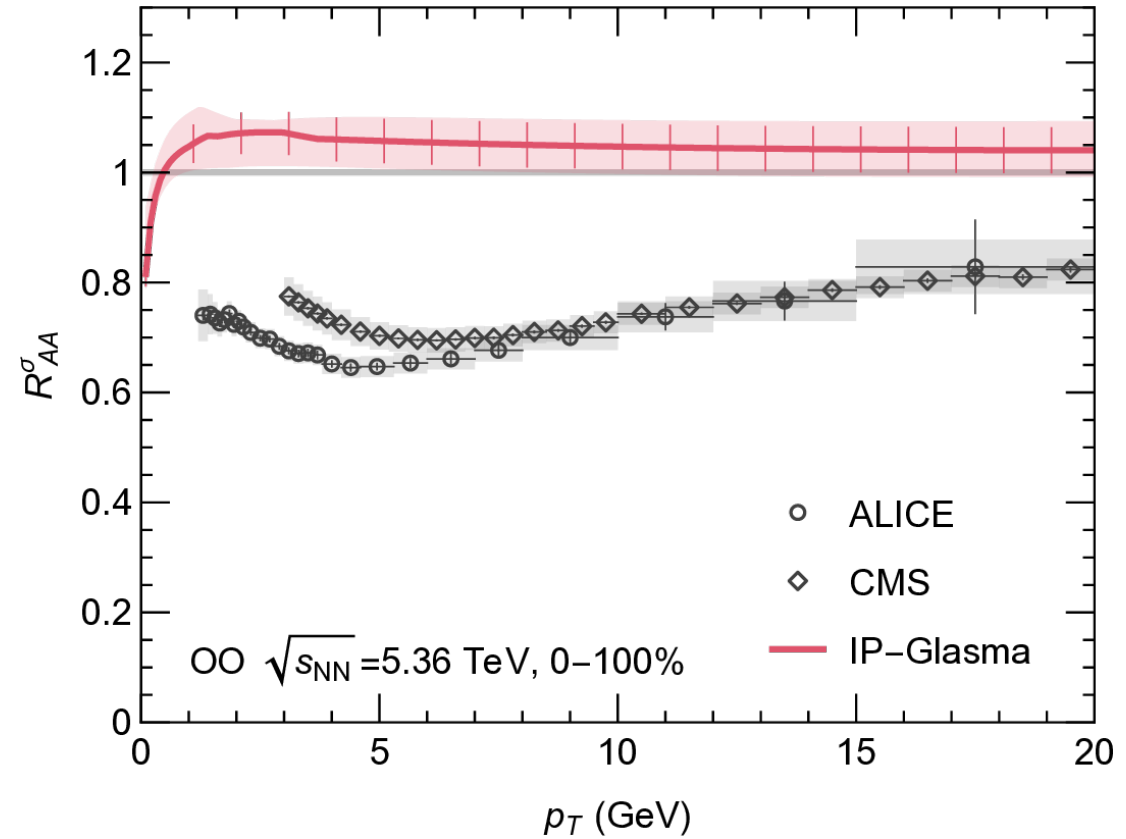
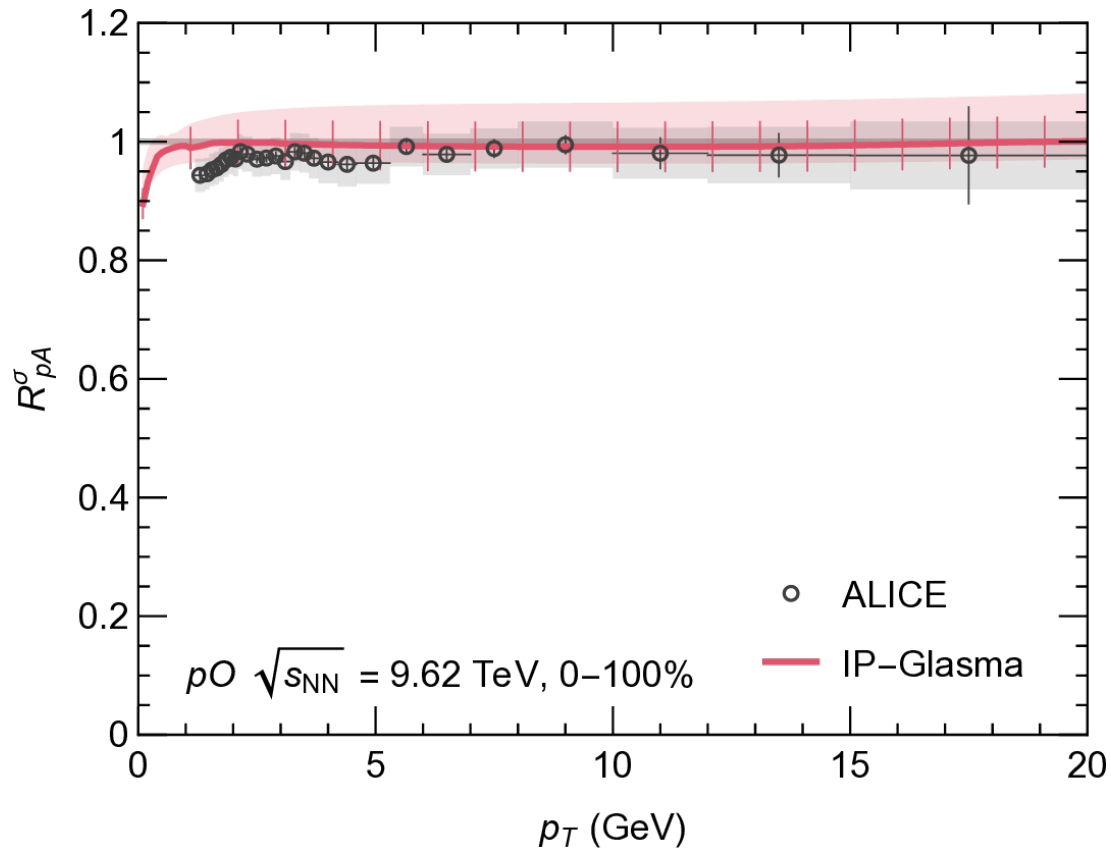


Figure from B. Schenke, P. Tribedy, and R. Venugopalan, PRL **108**, 252301 (2012).

Oxygen baseline

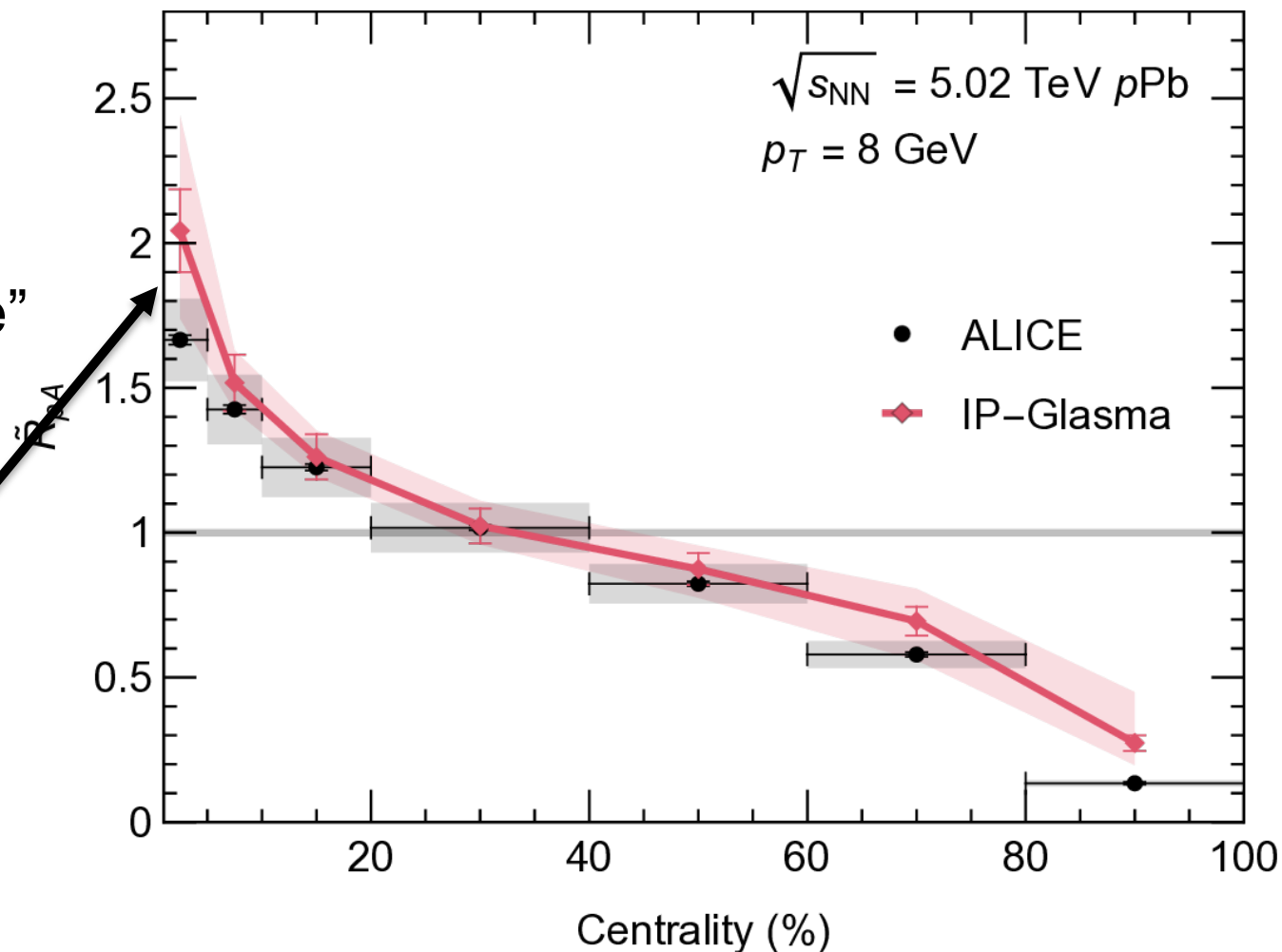


Initial-state only agrees with pO but not with OO -> supports partonic energy loss

CF, W. A. Horowitz, B. Schenke arXiv:26xx.xxxxx

Centrality cut R_{pA}

- Centrality determined by (soft) multiplicity at midrapidity
- IP-Glasma reproduces the “strange” data very well!
- Room for partonic energy loss?



CF, W. A. Horowitz, B. Schenke arXiv:26xx.xxxxx

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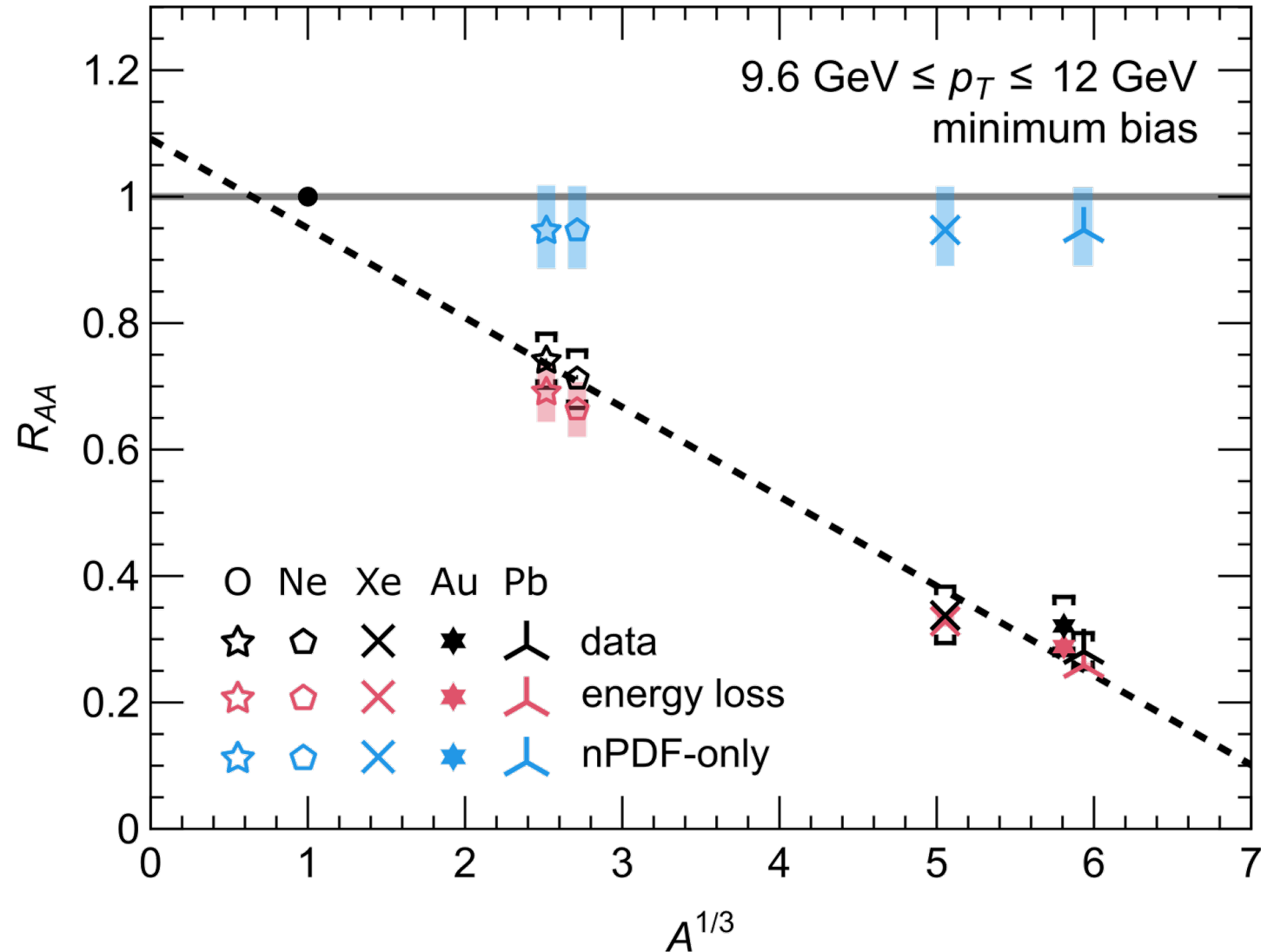
Two paths:

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- **What future light-ion runs in LHC run 4 / 5 would help us answer these questions?**

Current systems

- This is the current status of nuclear modification measured in symmetric ion collisions (and our model predictions)
- We see the same $R_{AA} \simeq A^{1/3}$ approximate scaling as is seen in the data

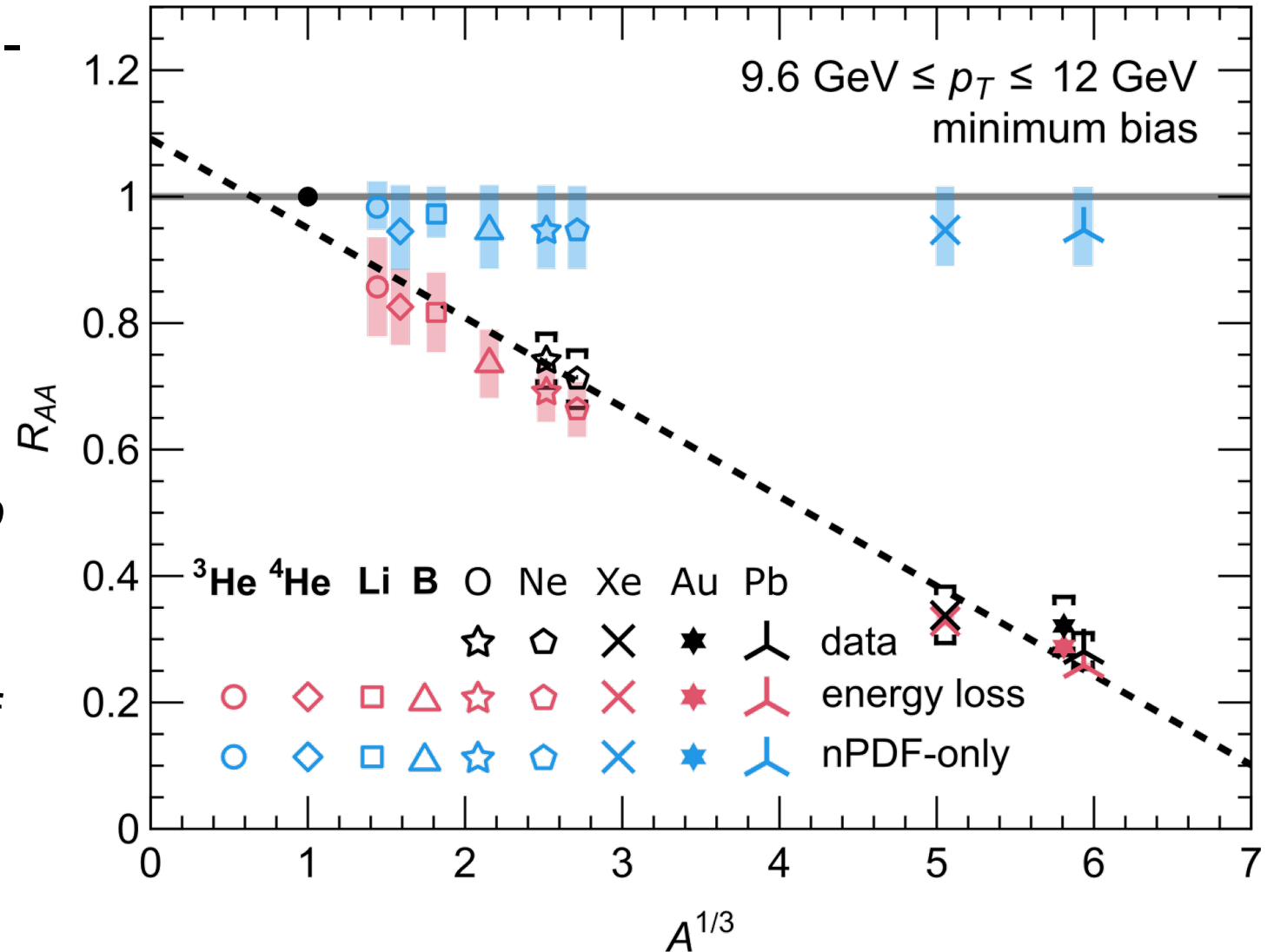
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Can we go smaller? – min. bias

- ^3He and ^6Li offer the most “bang-for-buck” in terms of discovering energy loss in very small systems
- ^6Li and ^{10}B offer ability to clearly differentiate between energy loss and initial state effects
- Helium would require baseline p + He to cancel initial state effects
- Systems require only $\lesssim 1$ day of runtime for sufficient statistics

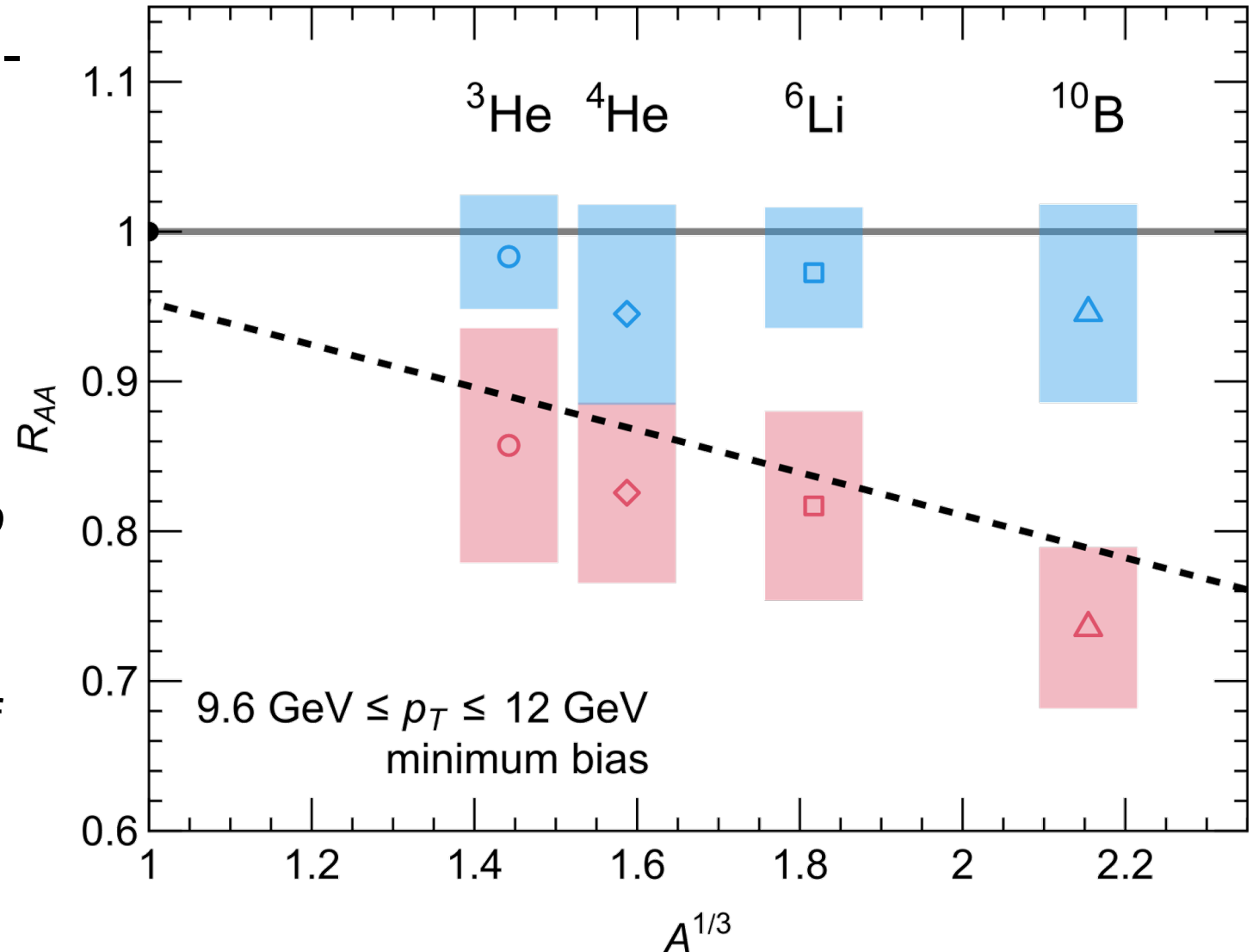
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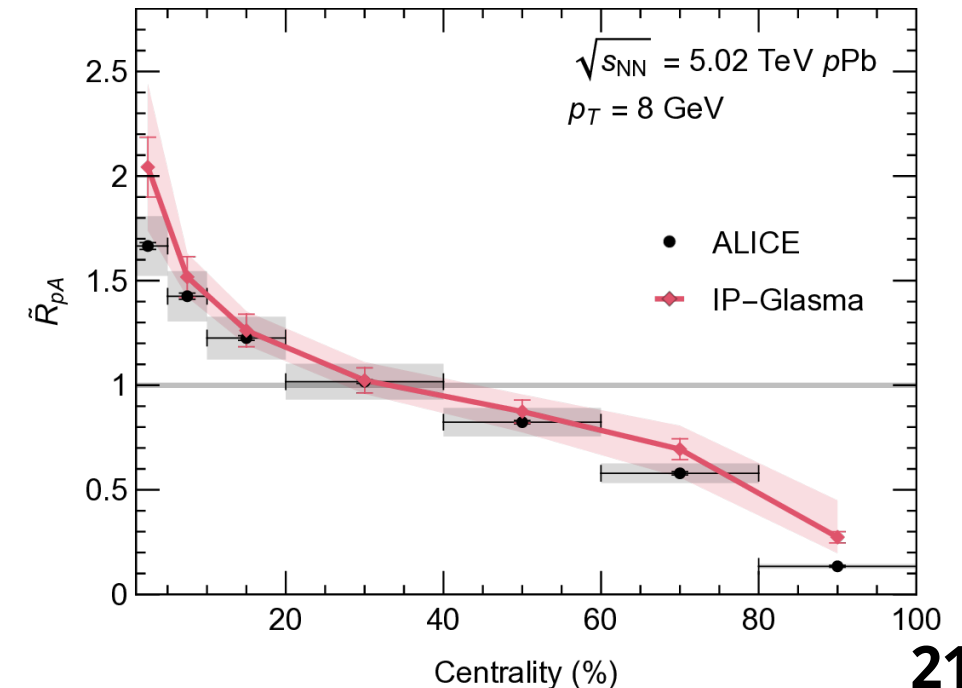
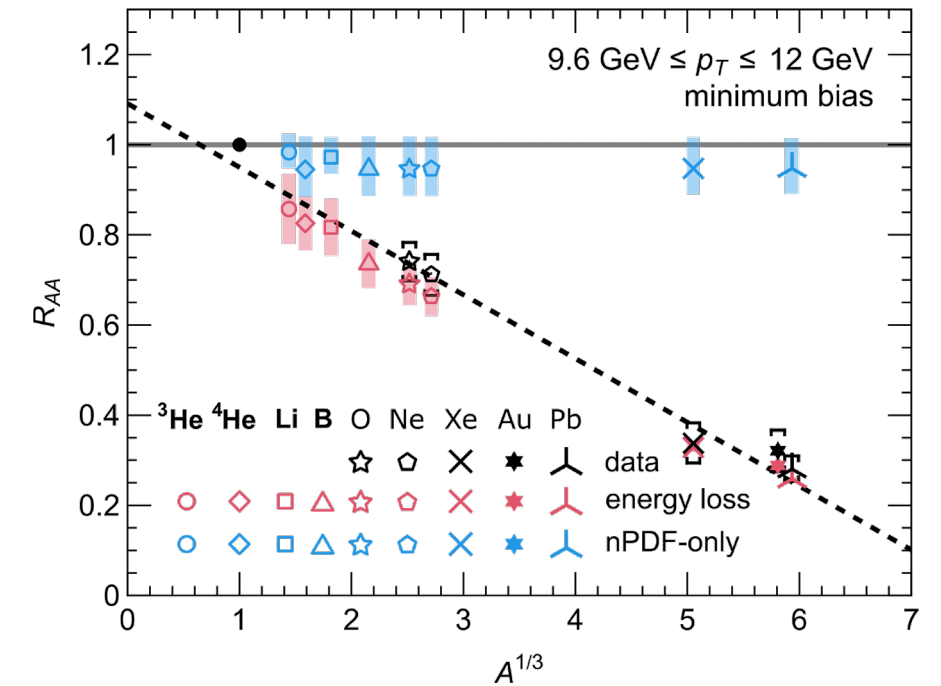
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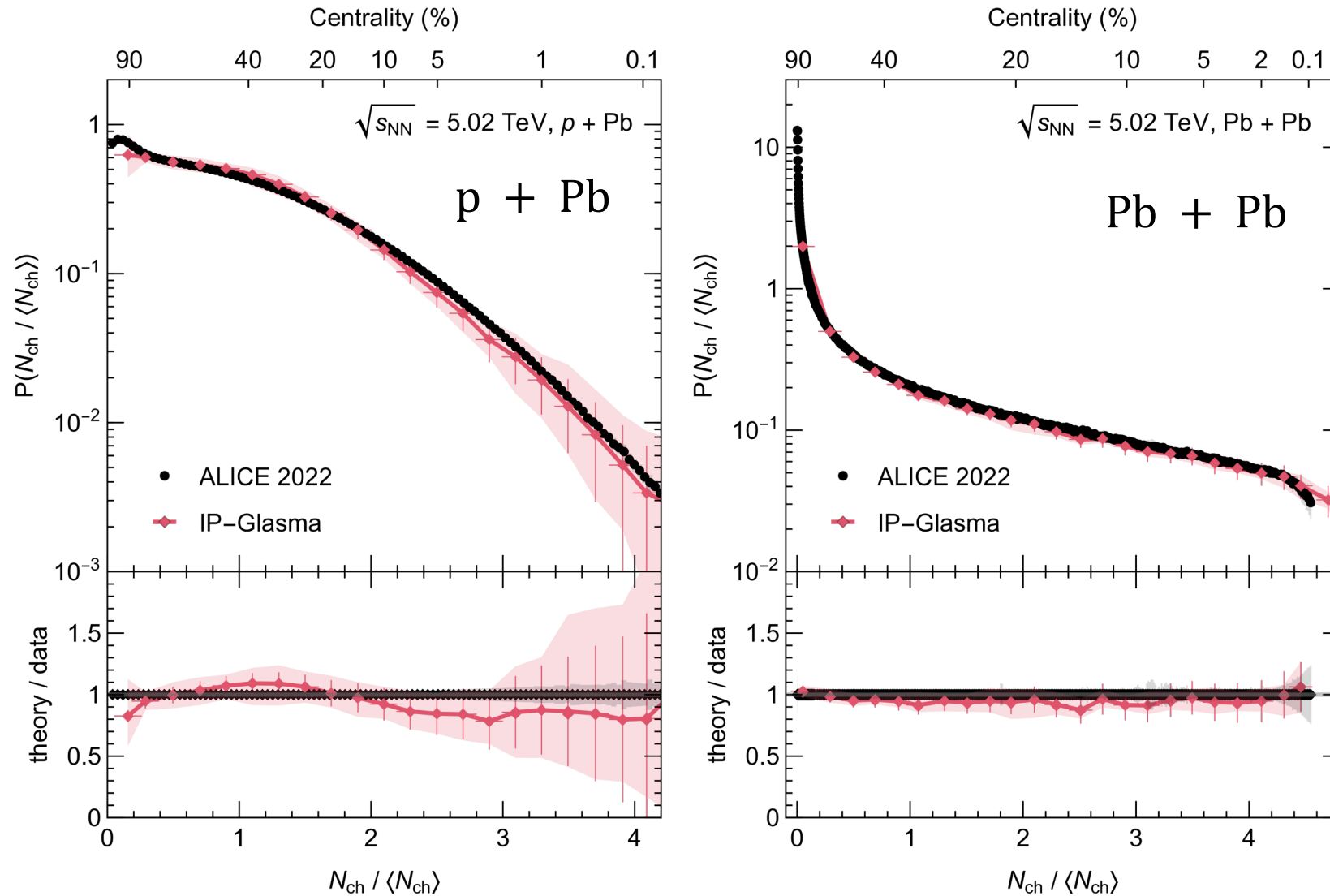
Summary

- Presented results from the *Cape Town* model
- Hard-soft decorrelations lead to $v_2 \sim 0$ from energy loss
 - other energy loss models need to compute v_2 as is done experimentally
- Asymmetric systems are particularly complicated. Either:
 - Go to smaller symmetric systems
 - Model hard-soft correlations in pA
- Lithium collisions form a “sweet spot” for distinguishable energy loss
 - Helium would likely require dedicated $p + \text{He}$ run
- Using IP-Glasma for all soft and hard particles accurately describes R_{pPb} as a function of centrality
 - Tantalizing room for energy loss in most central collisions
 - Ongoing work to include energy loss



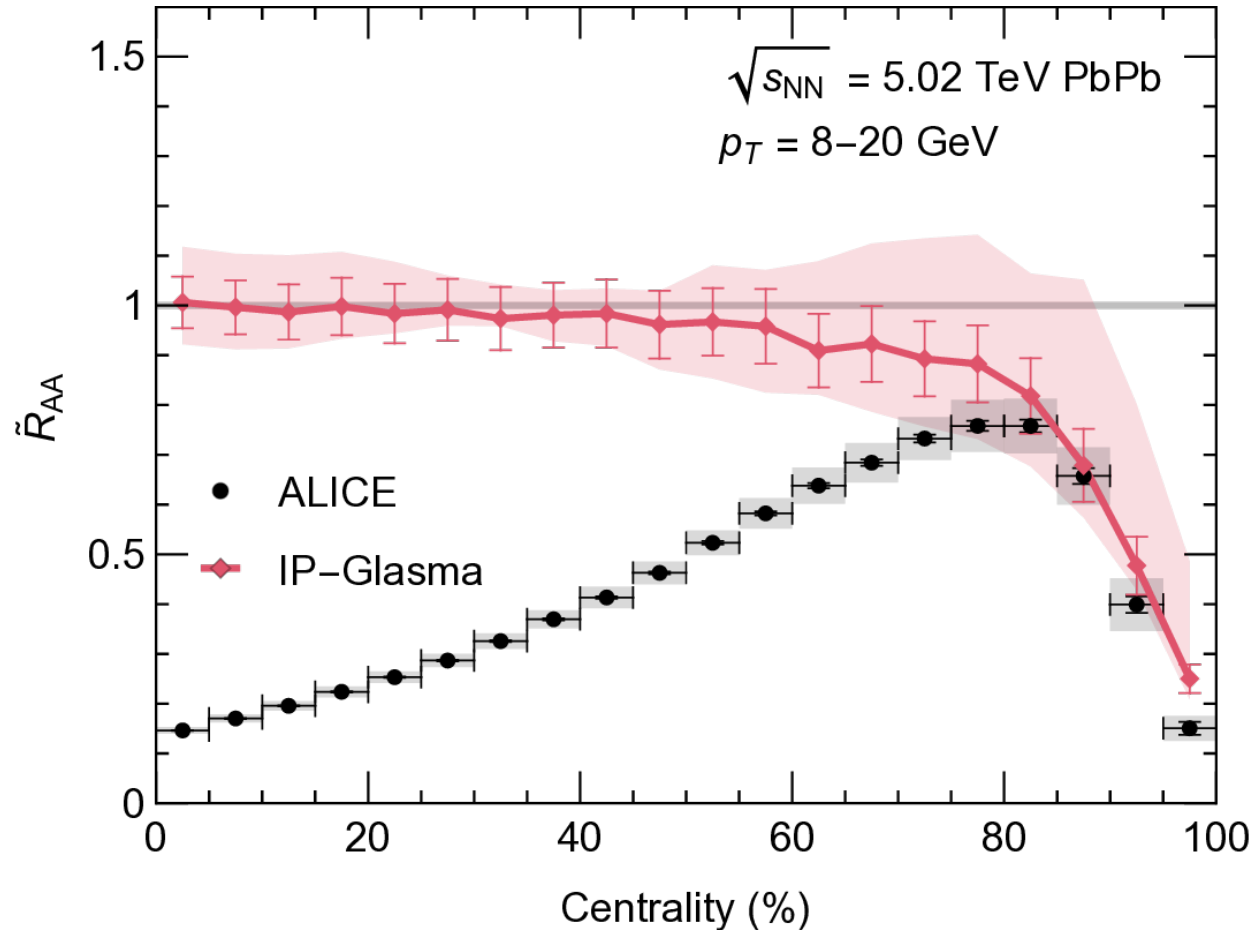
Backup

Multiplicity distributions



- Multiplicity distributions are largely unchanged by the (missing) hydro evolution
- Excellent agreement with multiplicity distributions from 0.1 – 100% centrality
→ centrality classification is reliable

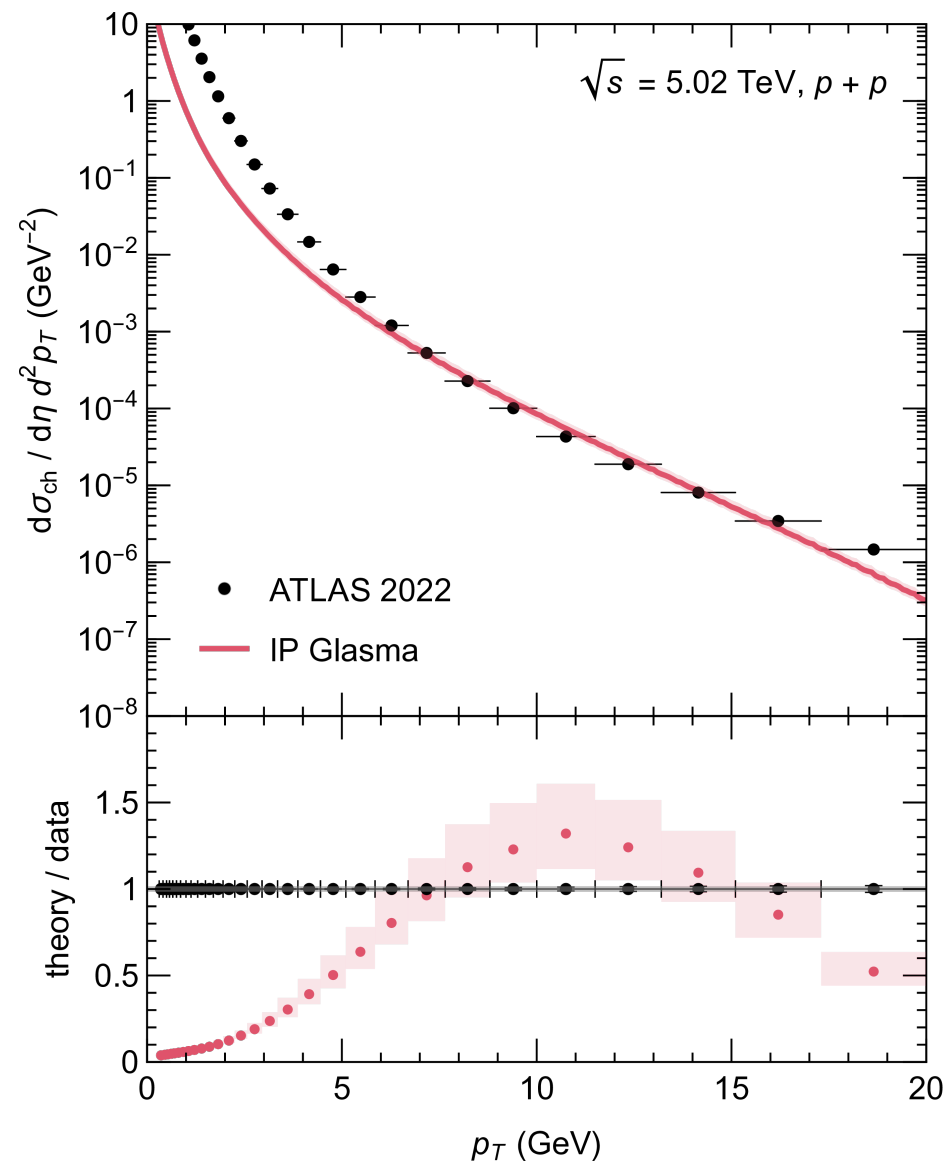
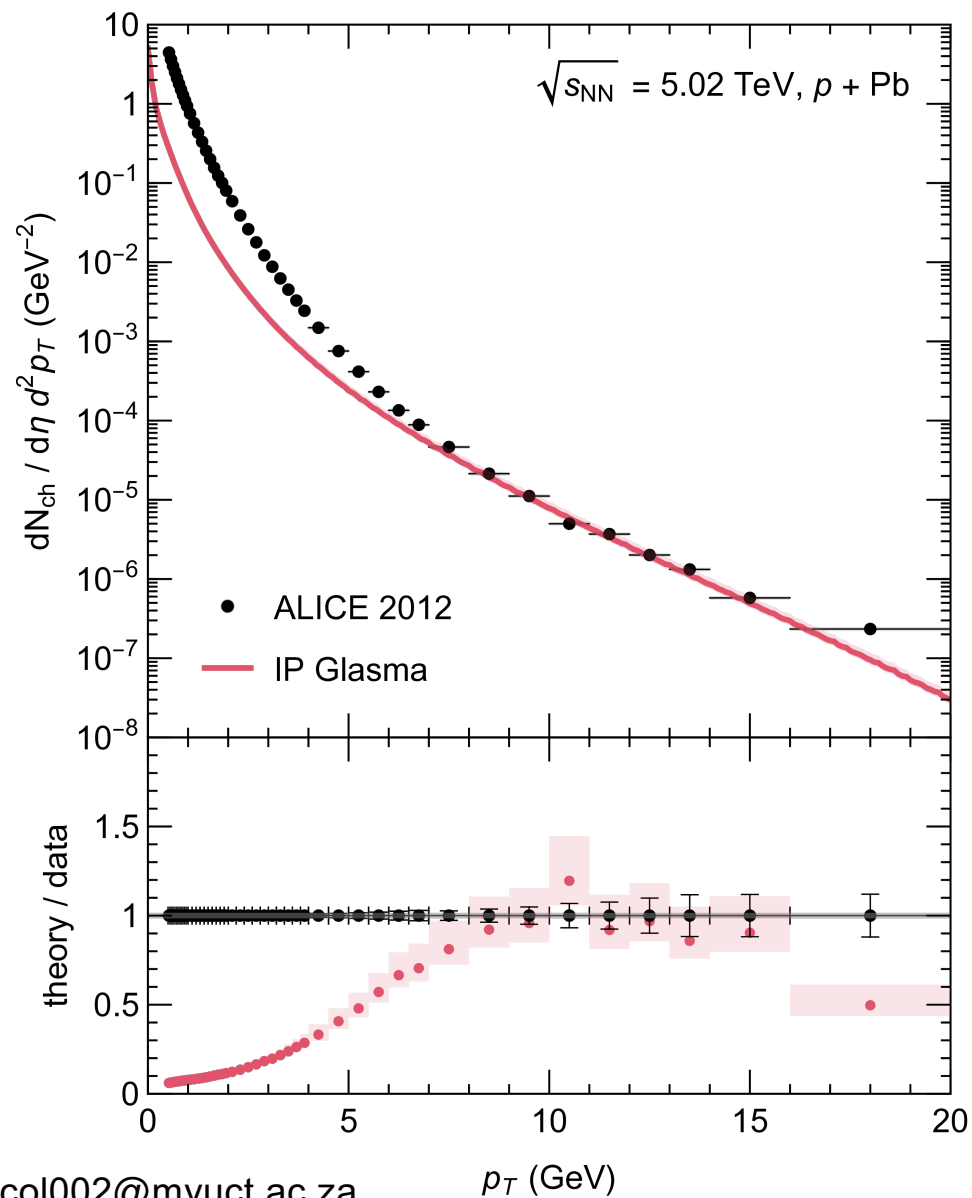
Centrality cut R_{AA}



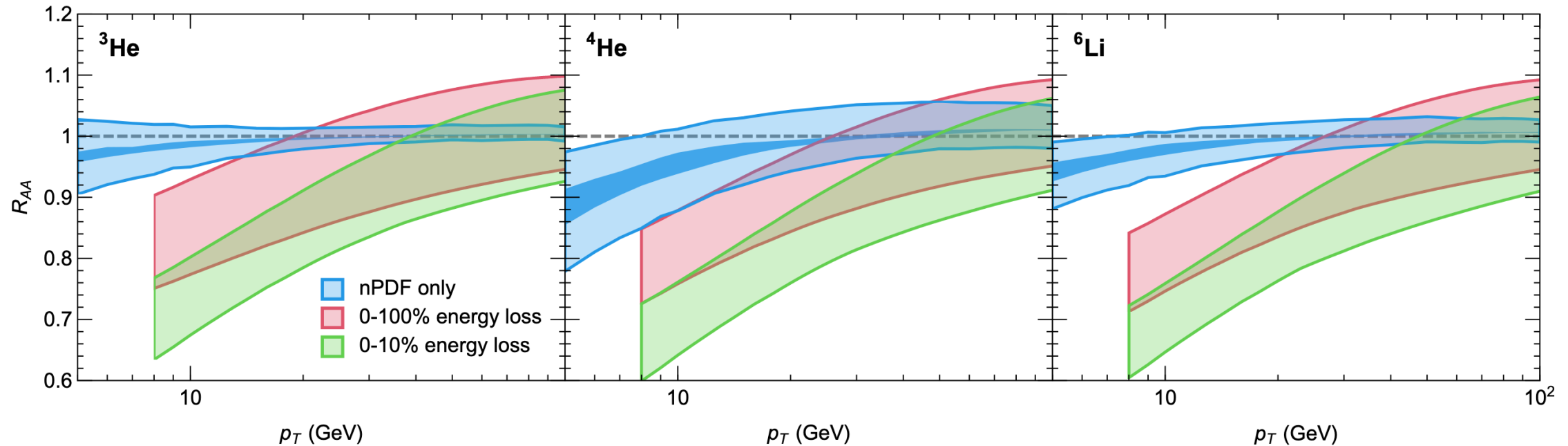
CF, W. A. Horowitz, B. Schenke arXiv:2606.xxxxx

- In central collisions, we're missing energy loss
- IP-Glasma reproduces the most peripheral data qualitatively very well!
- Quantitative disagreement in peripheral classes likely due to missing jet veto bias or residual energy loss

IP-Glasma spectrum



> Can we go smaller? – centrality cut



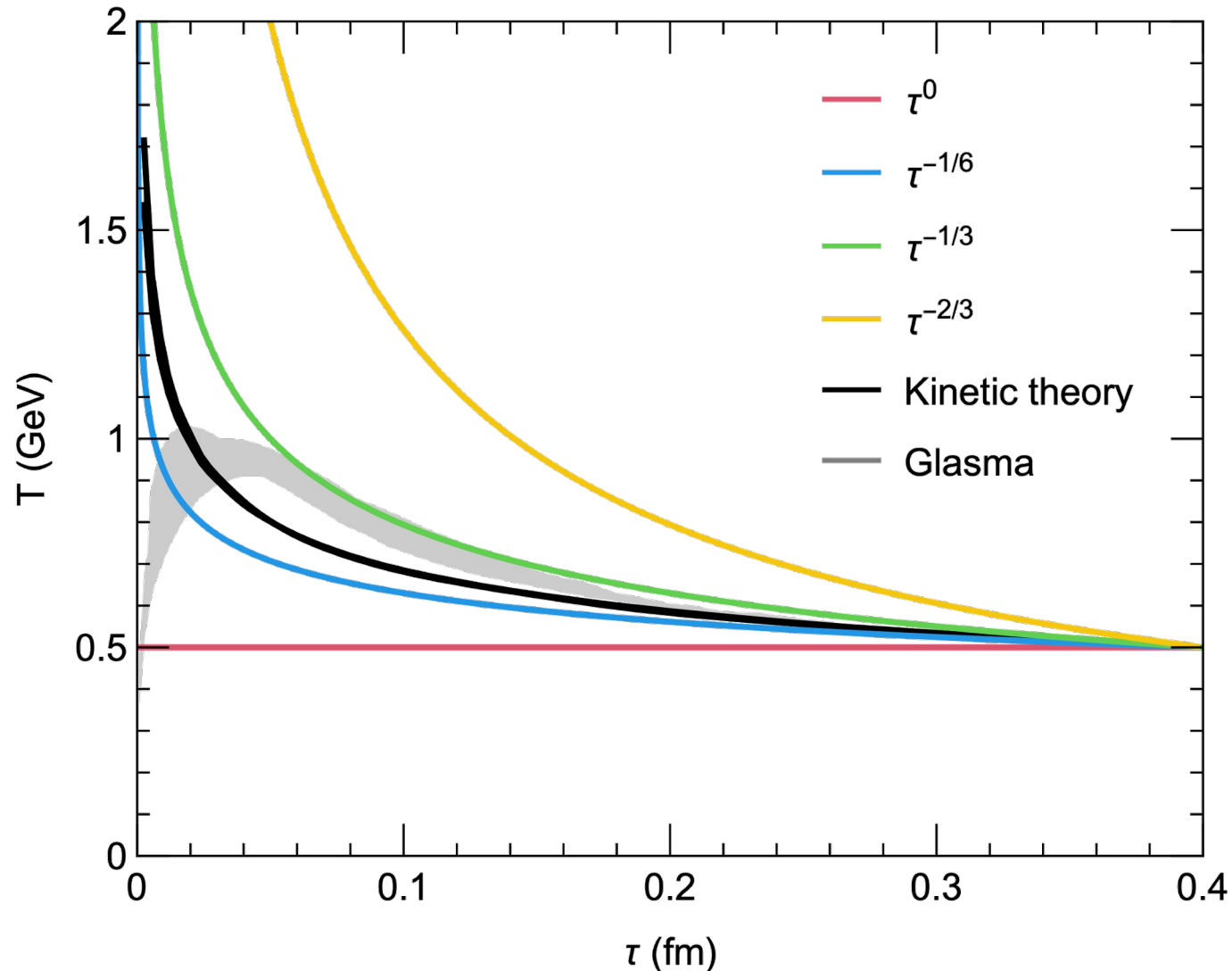
- Small window around ~8-20 GeV where energy loss should be measurable in min. bias
- If we can tackle centrality cuts in small systems, then any of these systems would have measurable energy loss

CF, B. Bert, J. Brand, W. Vogelsang, and W. A. Horowitz, arXiv:2512.17832 [hep-ph] (2025).

How robust are these predictions?

- While not included in the uncertainty bands shown, also investigated uncertainties due to:
 - Pre-thermalization time energy loss
 - Initial nuclear structure
 - Running coupling
 - Minimum bias trigger efficiency

Pre-thermalization time energy loss



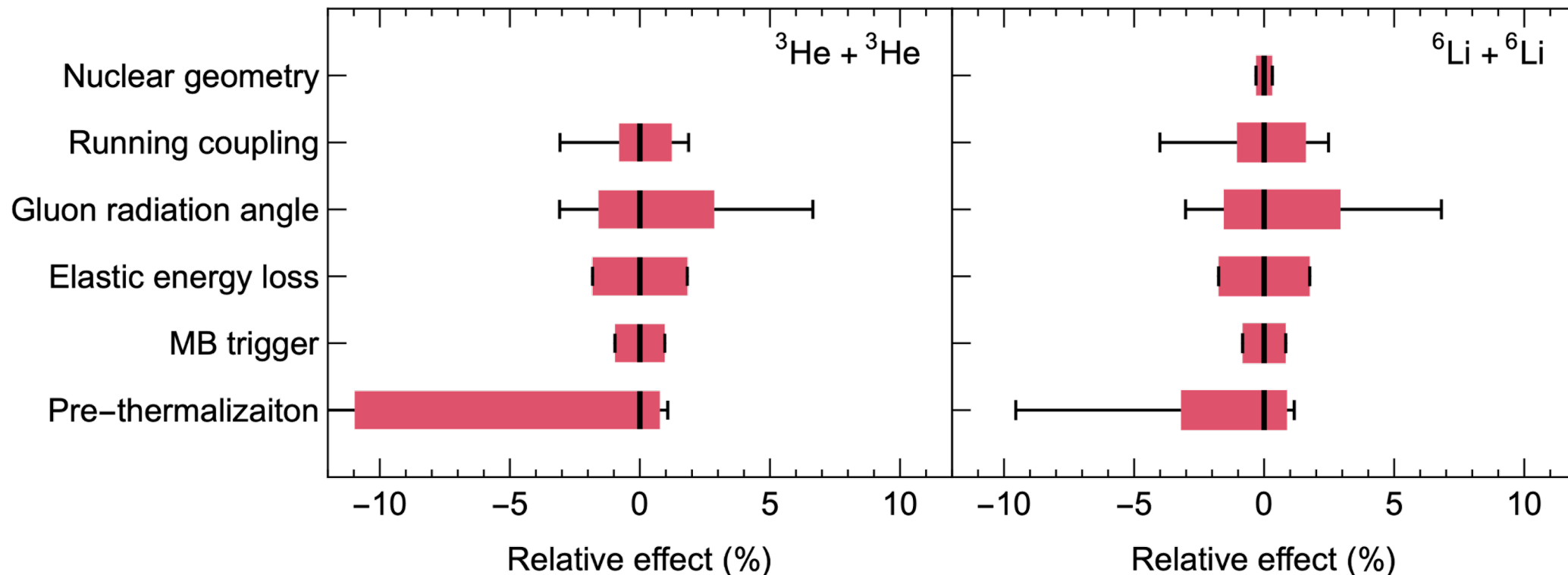
- Not clear how partons lose energy before thermalization
- We use a variety of assumptions as an estimate for the uncertainty
- Assumptions cover the estimates from pre-equilibrium calculations

Kinetic Theory: K. Boguslavski and F. Lindenbauer, Phys. Re **110**, 074017 (2024).

Glasma: A. Ipp, D. I. Müller, and D. Schuh, Phys. Lett. B **810**, 135810 (2020).

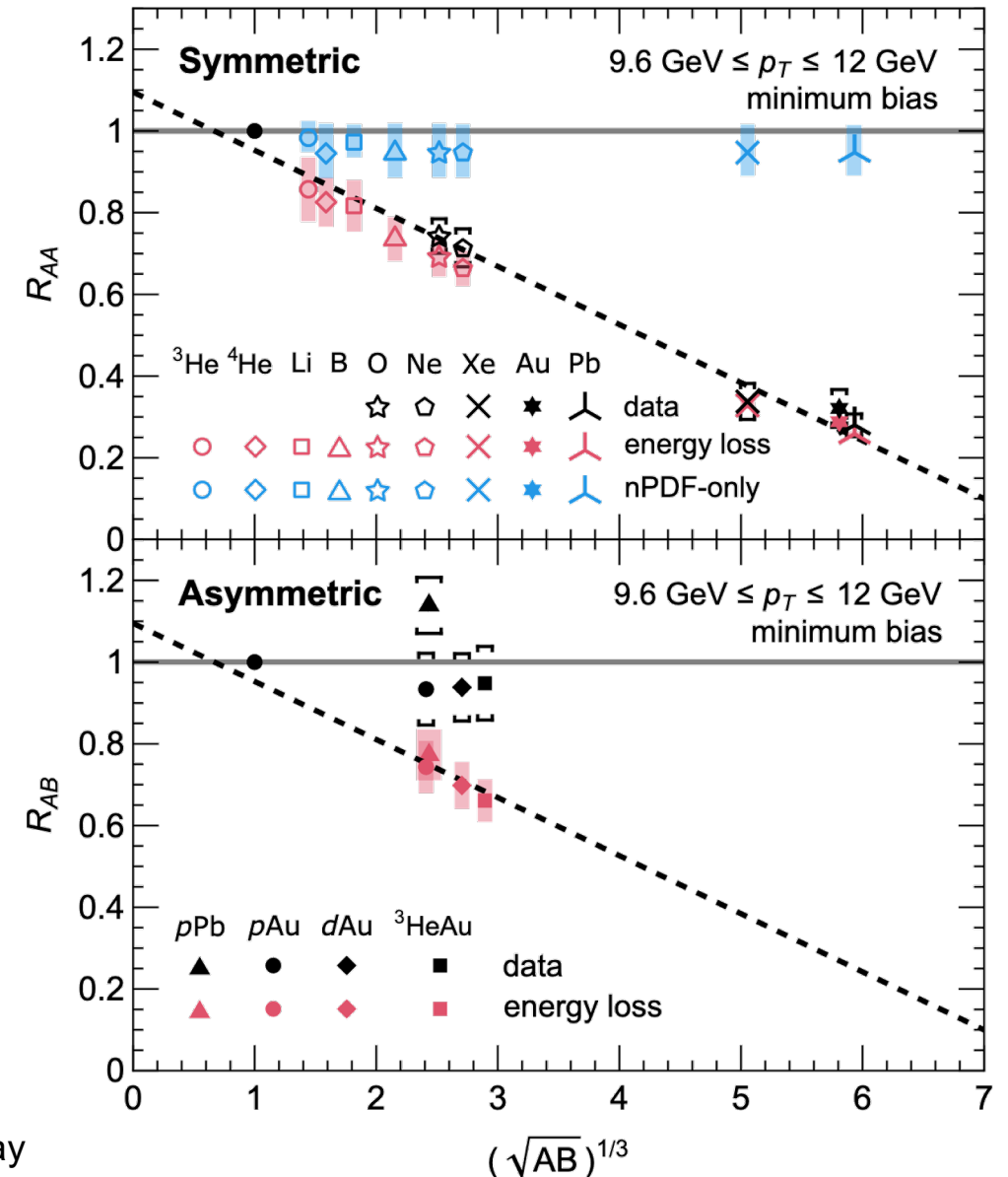
Uncertainty analysis

- Our original estimate is still the upper bound for RAA
- Pre-thermalization can lead to significantly more suppression, but high pre-therm. temp. likely ruled out by OO data (for example)



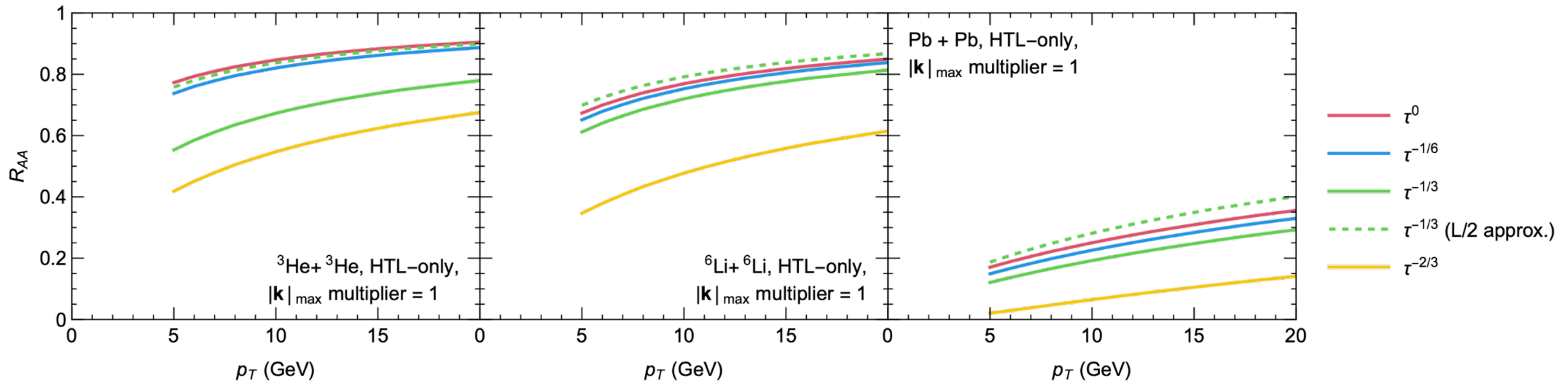
Asymmetric systems

- Further, our model predicts $R_{AB} \simeq (\sqrt{AB})^{1/3}$ in disagreement with asymmetric experimental data (but good agreement with symmetric data)
- However, asymmetric systems are in significant tension with data
 - Difficulty in interpreting measurements
 - Self-normalized probes
 - Centrality bias
 - Applicability of theory?
 - Better understanding of hard soft-correlations
 - 3+1D hydro models needed
- Symmetric, very light ions will help us learn about which of the above cause problems in pA



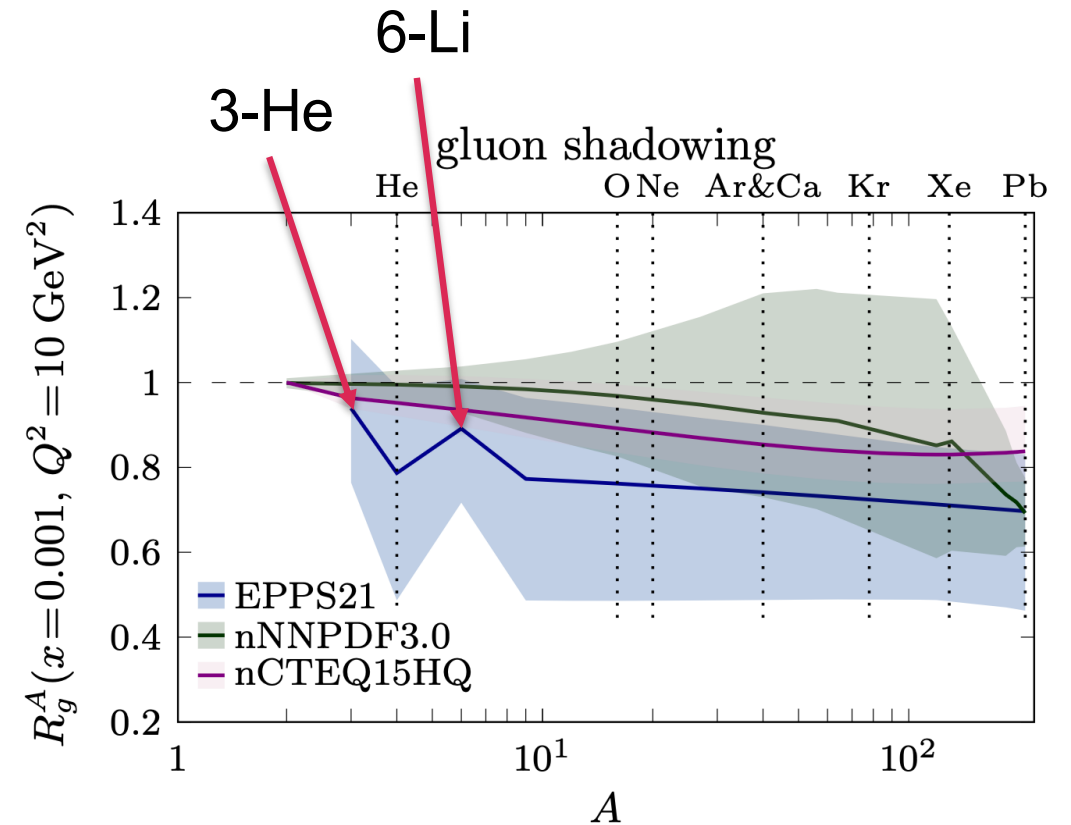
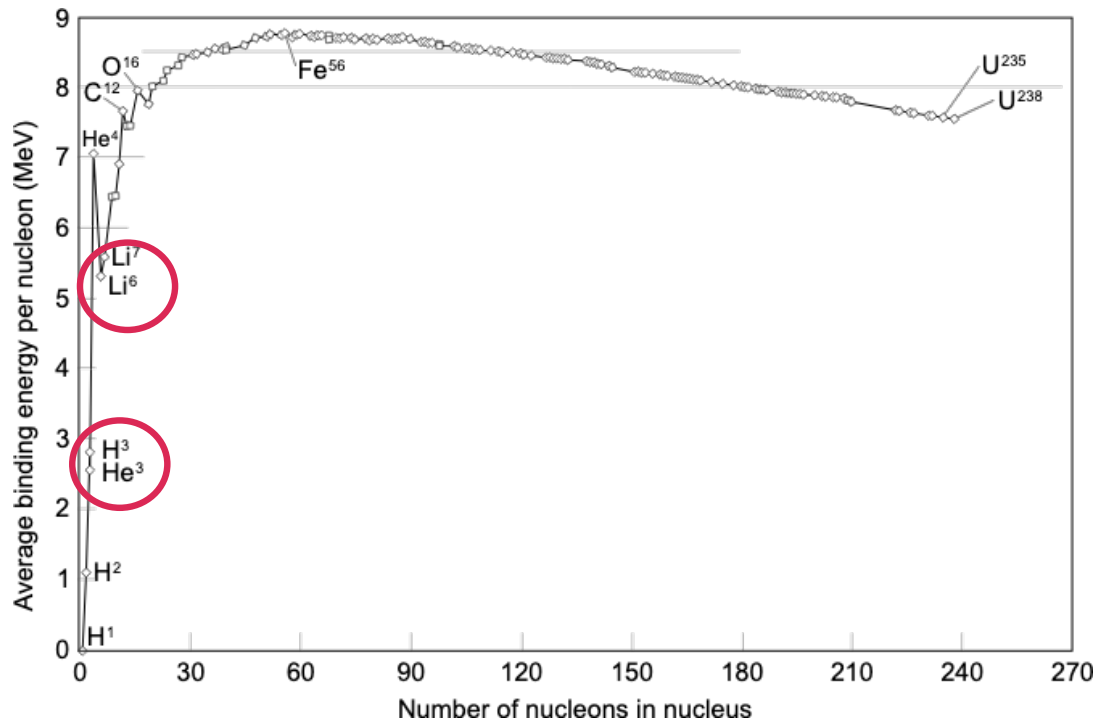
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Effect of pre-thermalization e-loss



3-He and 6-Li

- Why do 6-Li and 3-He have significantly smaller nPDF suppression and uncertainties than their neighbors?



Baseline predictions

- We use an NLO pQCD code to produce baseline predictions for R_{AA} modified only by nuclear PDFs (we use EPPS21)

$$d\sigma_{AB \rightarrow hX} = \sum_{a,b,c} f_{a/A}(x_a, \mu_F) \otimes f_{b/B}(x_b, \mu_F) \quad (3)$$
$$\otimes d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h/z, \mu_R, \mu_F, \mu'_F) \otimes D_{c \rightarrow h}(z, \mu'_F),$$

$$R_{AB}^{h,\text{nPDF}}(p_T, y) = \frac{1}{AB} \frac{d\sigma_{AB}^{h+X}/dp_T dy}{d\sigma_{pp}^{h+X}/dp_T dy}, \quad (4)$$

- Uncertainties are estimated from:
 - (n)PDF error sets
 - Varying the PDF, fragmentation, and renormalization scales