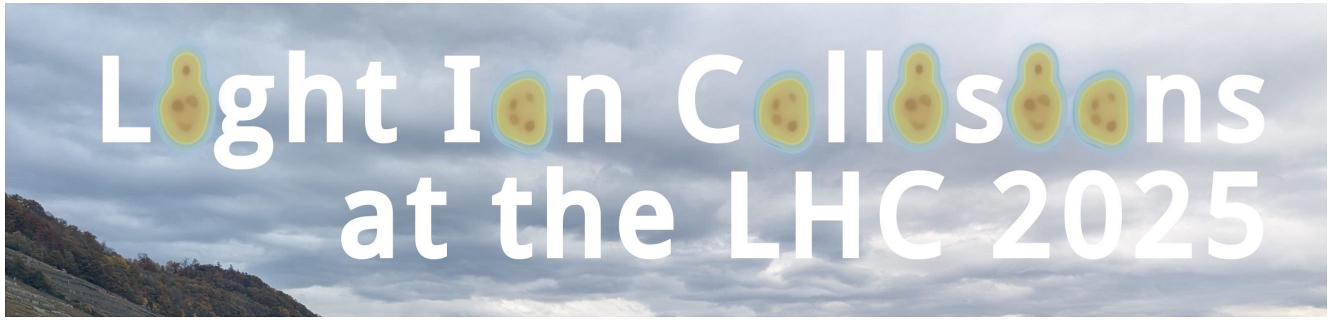
Light-Ion Suppression from pQCD Energy Loss with Small-System Corrections



Coleridge Faraday

University of Cape Town, South Africa

Based on CF and W. A. Horowitz, JHEP **11**, 019 (2025) and CF and W. A. Horowitz, Phys. Lett. B **864**, 139437 (2025).

National Institute for Theoretical and Computational Sciences

National Research Foundation

Big questions in small systems

- **Does a quark-gluon plasma form in small systems?**

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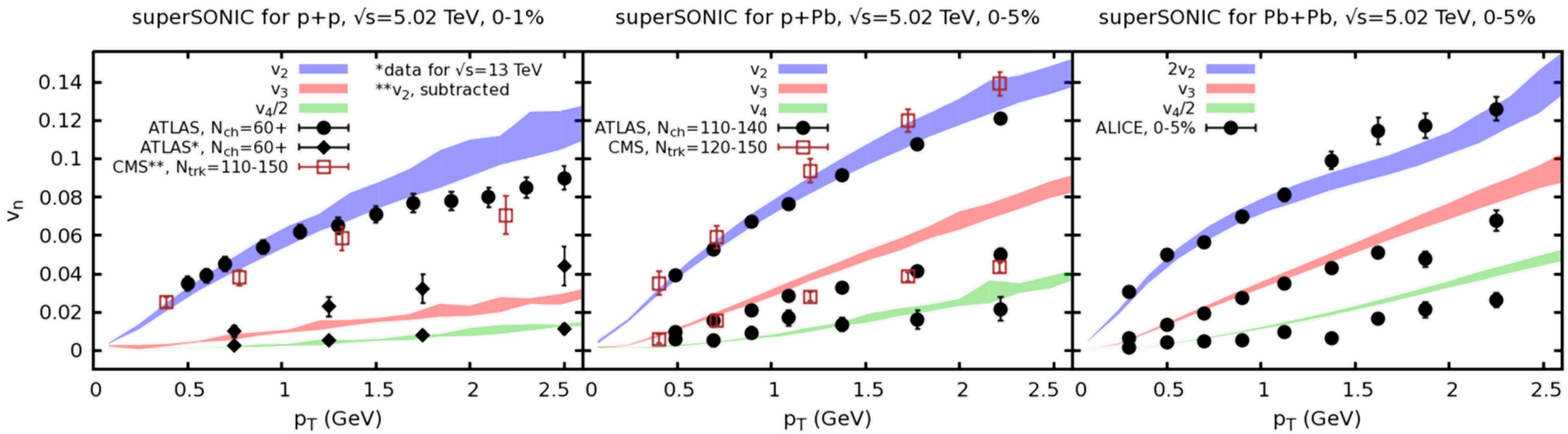
Soft observables say… **YES**
… as long as you're at high enough multiplicity



Weller et al., PLB 774 (2017) 351-356

Big questions in small systems

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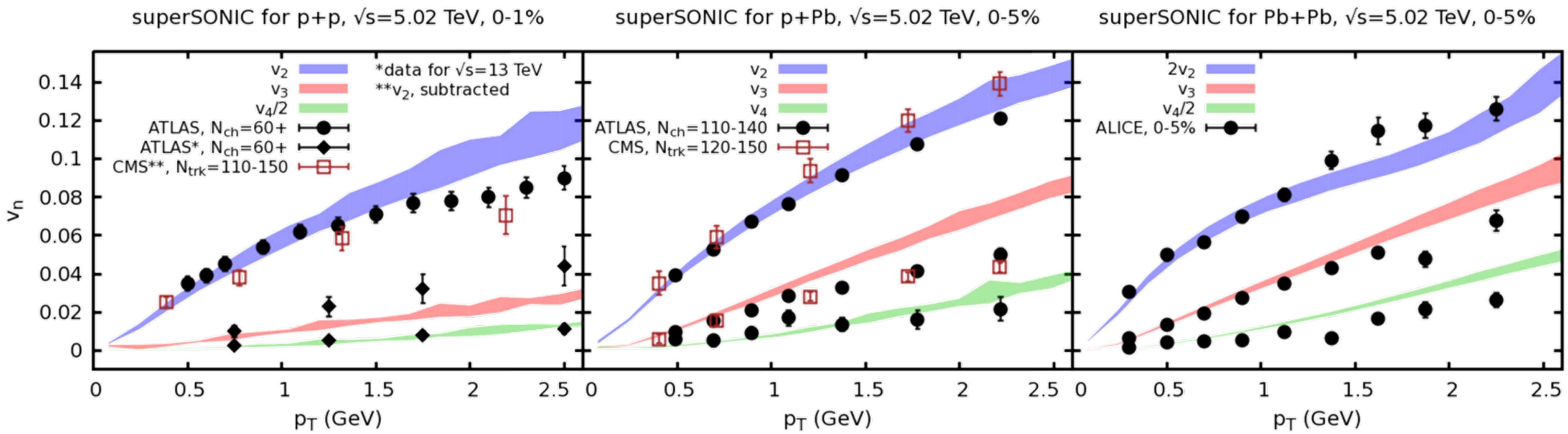

- **How does this QGP differ from that formed in large systems?**

Weller et al., PLB 774 (2017) 351-356

Energy loss in small systems

From large systems, we expect that QGP => partonic energy loss; however, …

There are mixed signals for energy loss in *p* / *d* + A

ATLAS *JHEP* 07, 074 (2023)

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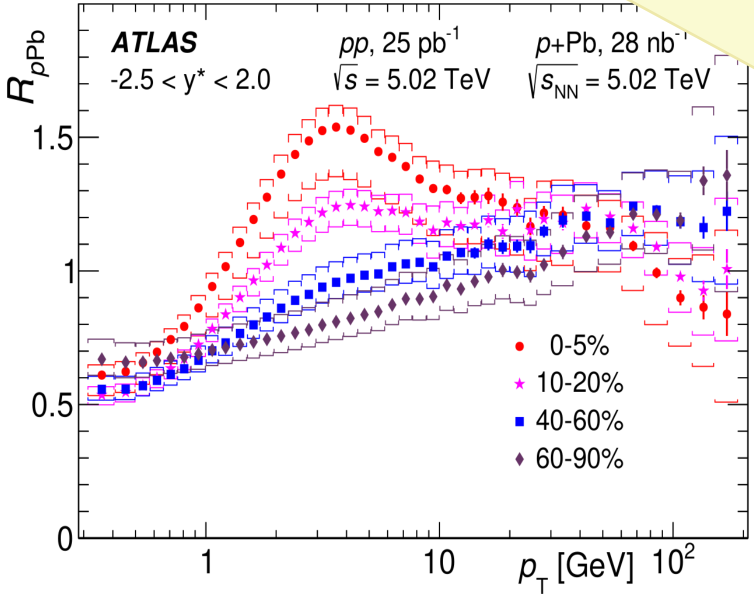

Glauber

No energy loss?

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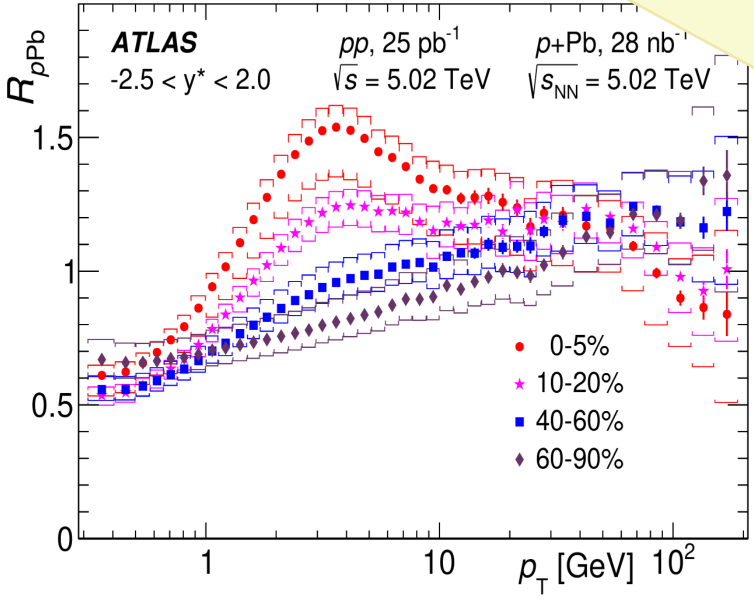

No energy loss?

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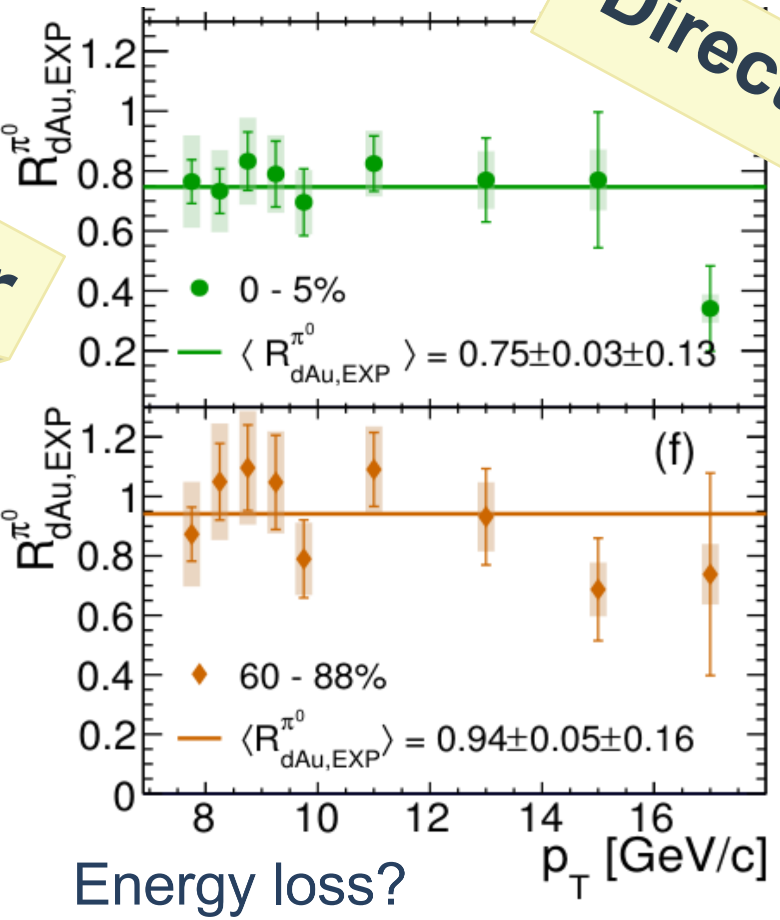
Direct γ



Energy loss?

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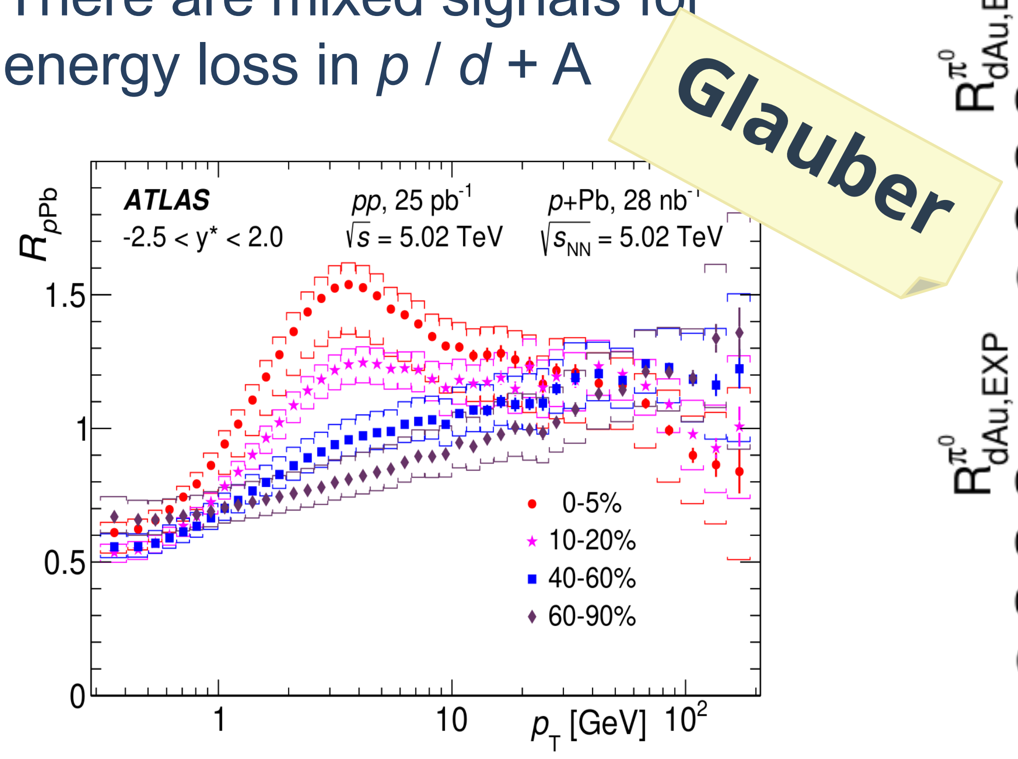

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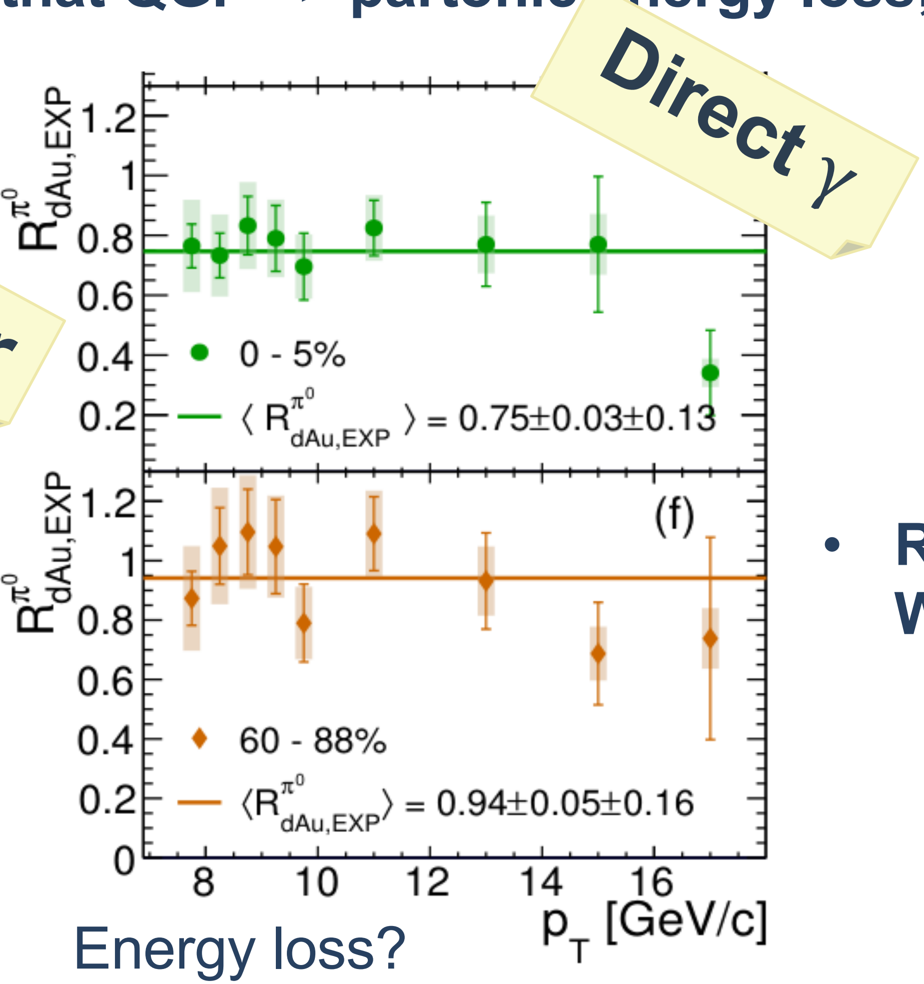

Energy loss?

- **Results are unclear! What to do?**

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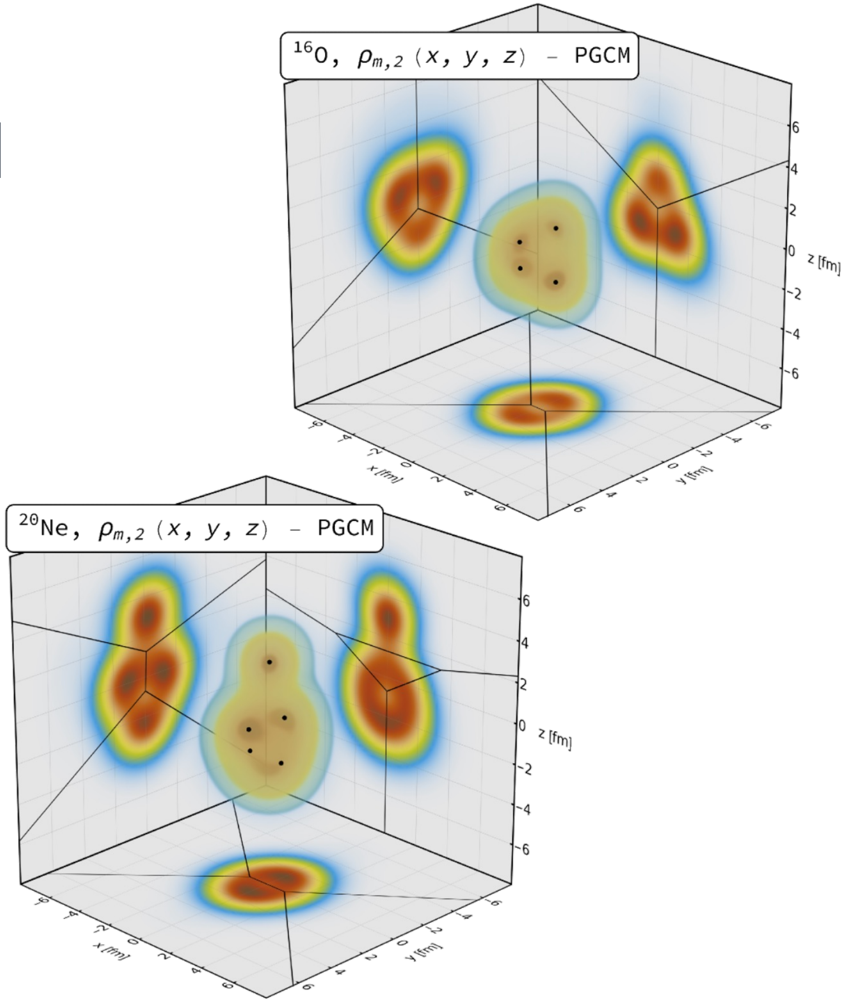
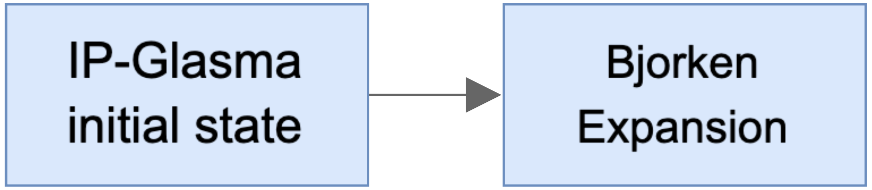
Light-ion collisions!

- Collisions of **oxygen** and **neon** are an ideal testing ground for small system energy loss
  - Symmetric, meaning 3D hydro not mandatory
  - No centrality-cuts needed
  - Large enough to expect non-trivial energy loss signal
  - Large enough to expect hydro to apply



Giacalone, G. *et al. Phys. Rev. Lett.* 135, 012302 (2025)

Physics model



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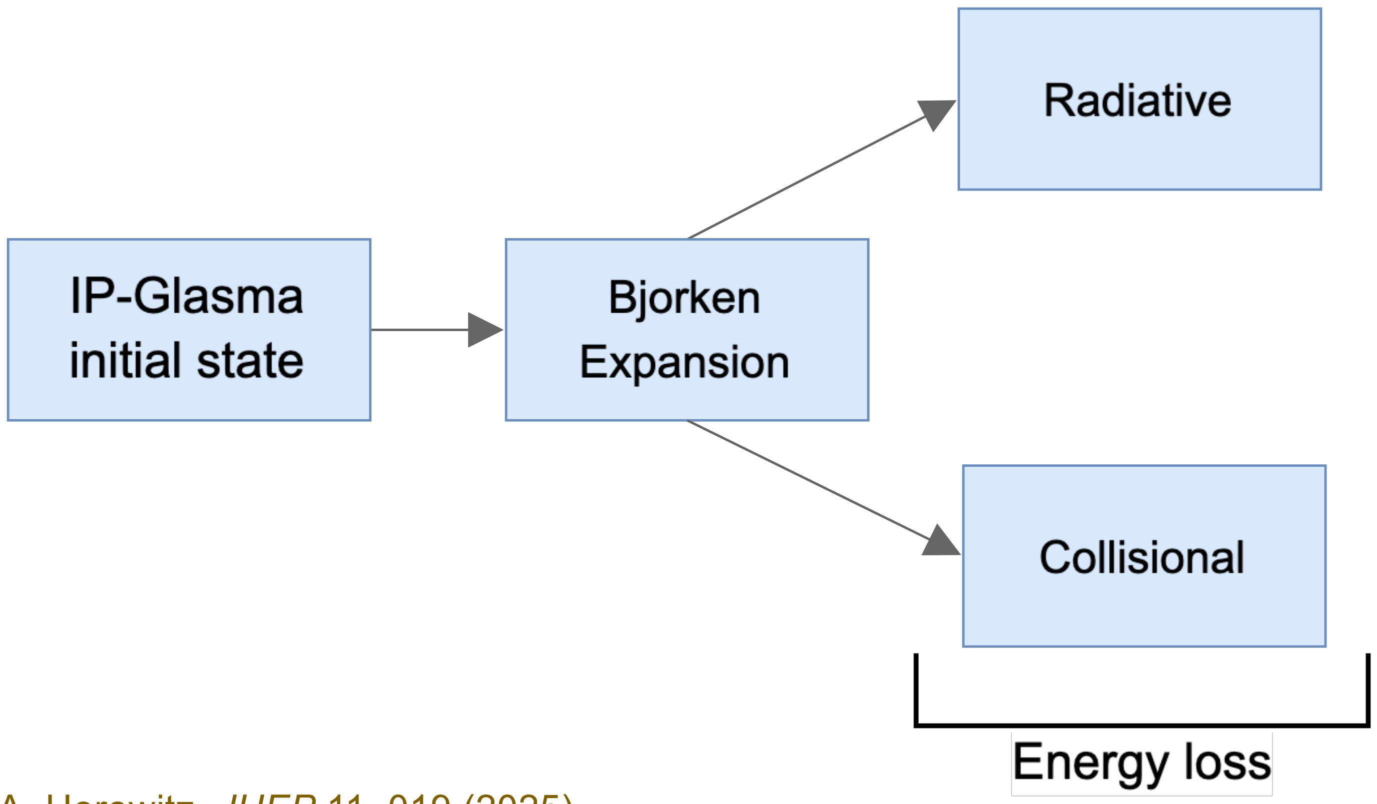

CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

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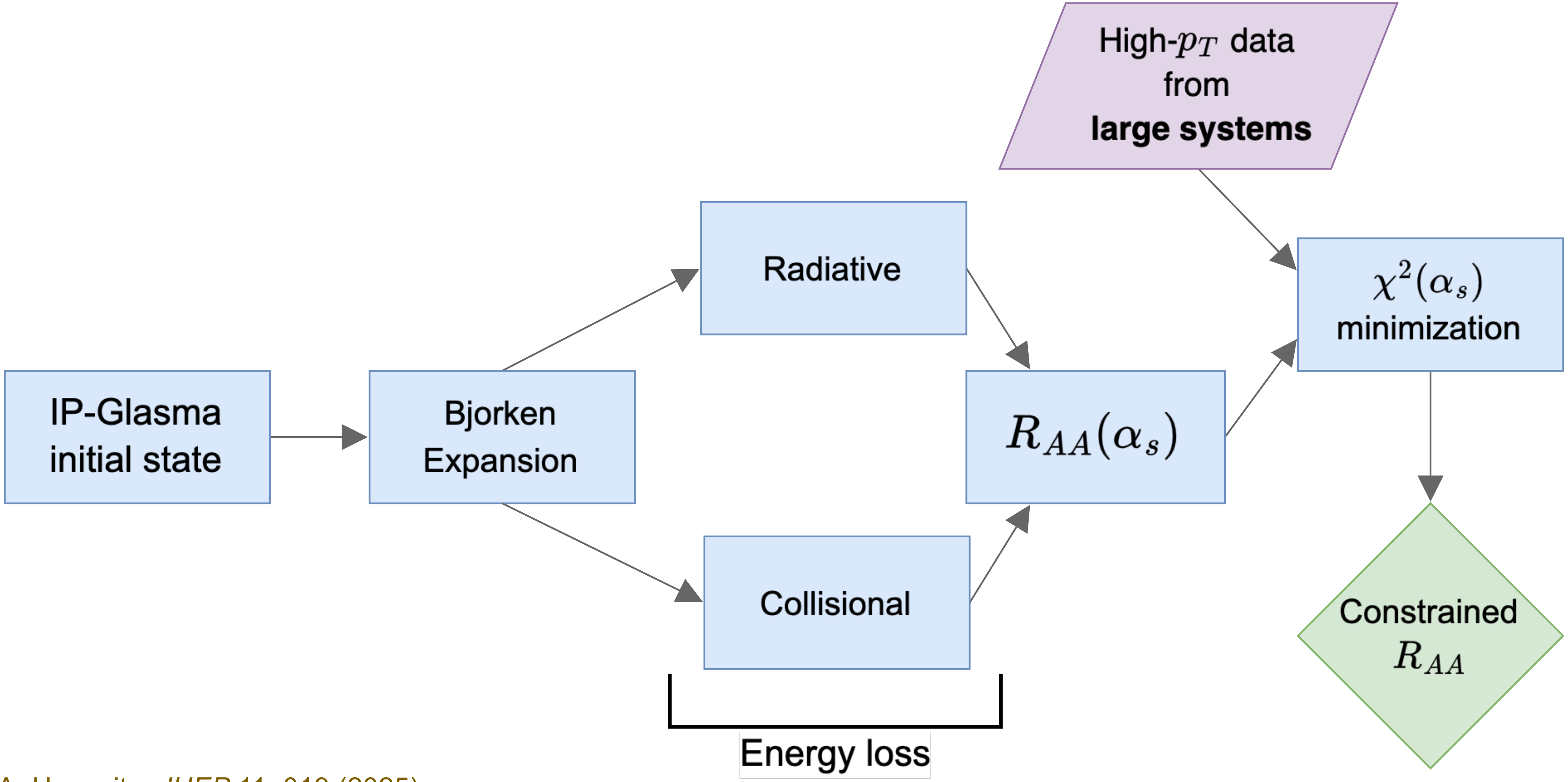

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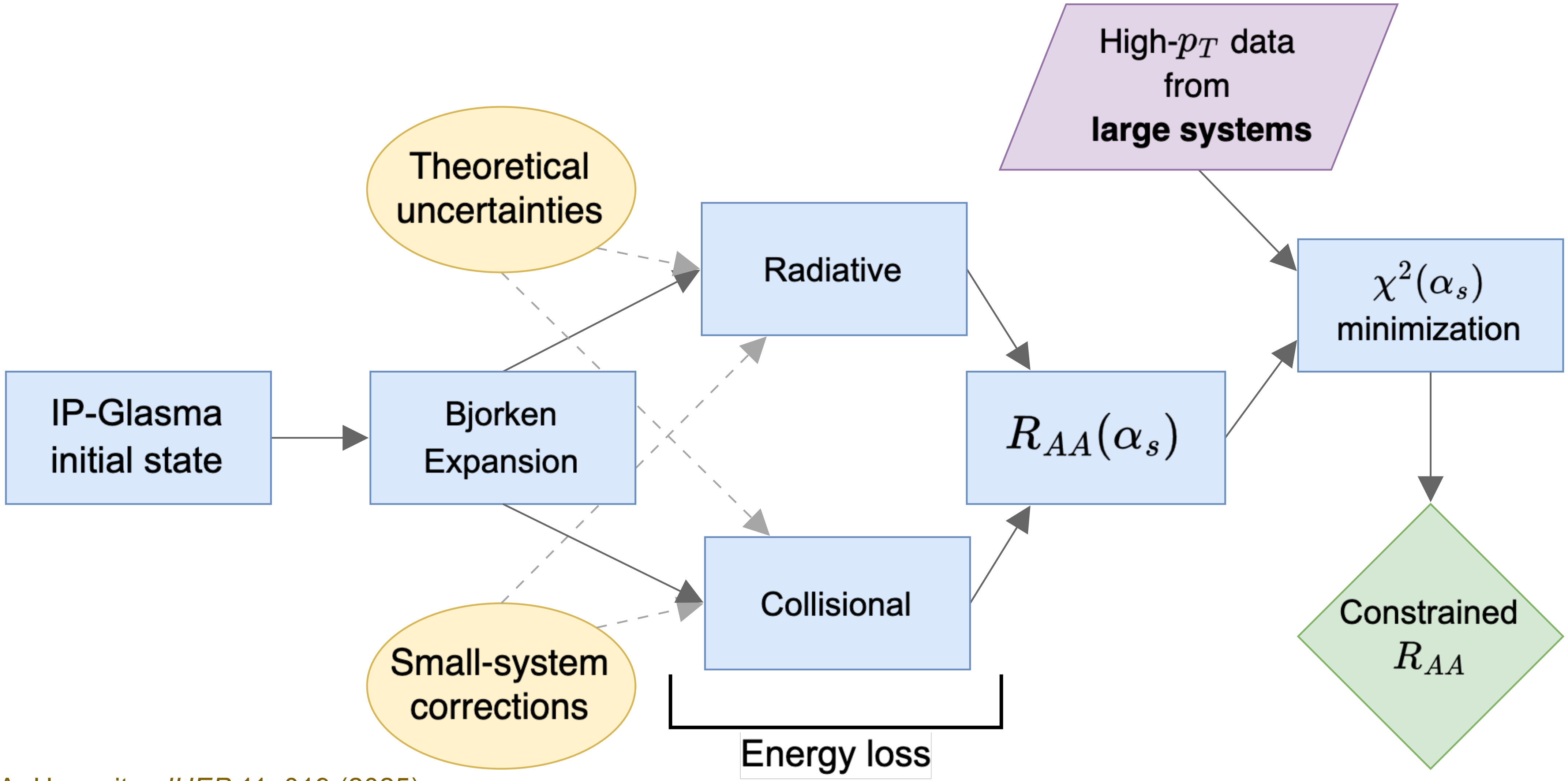


CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

Theoretical uncertainties

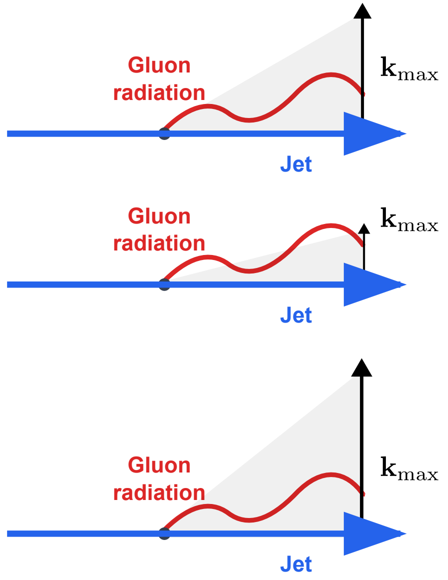
Theoretical uncertainties are usually not treated in energy loss models,
But we know that they can be significant.

Collisional

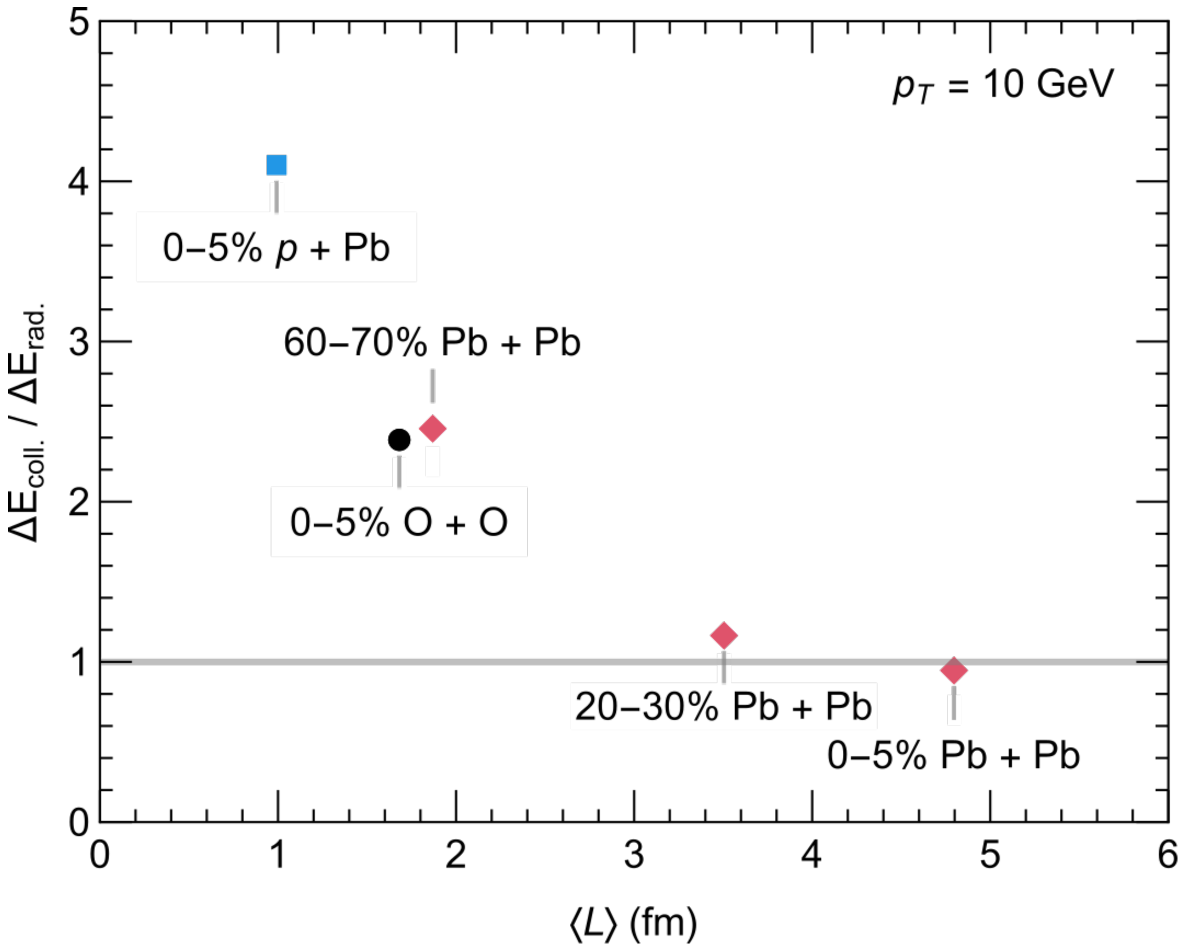
- We implement two limiting assumptions on the **transition between HTL and vacuum propagators** in the **collisional** energy loss

Radiative

- We use DGLV + $\mathcal{O}(e^{-\mu L})$ terms
- We vary the cutoff on the **transverse radiated gluon momentum**



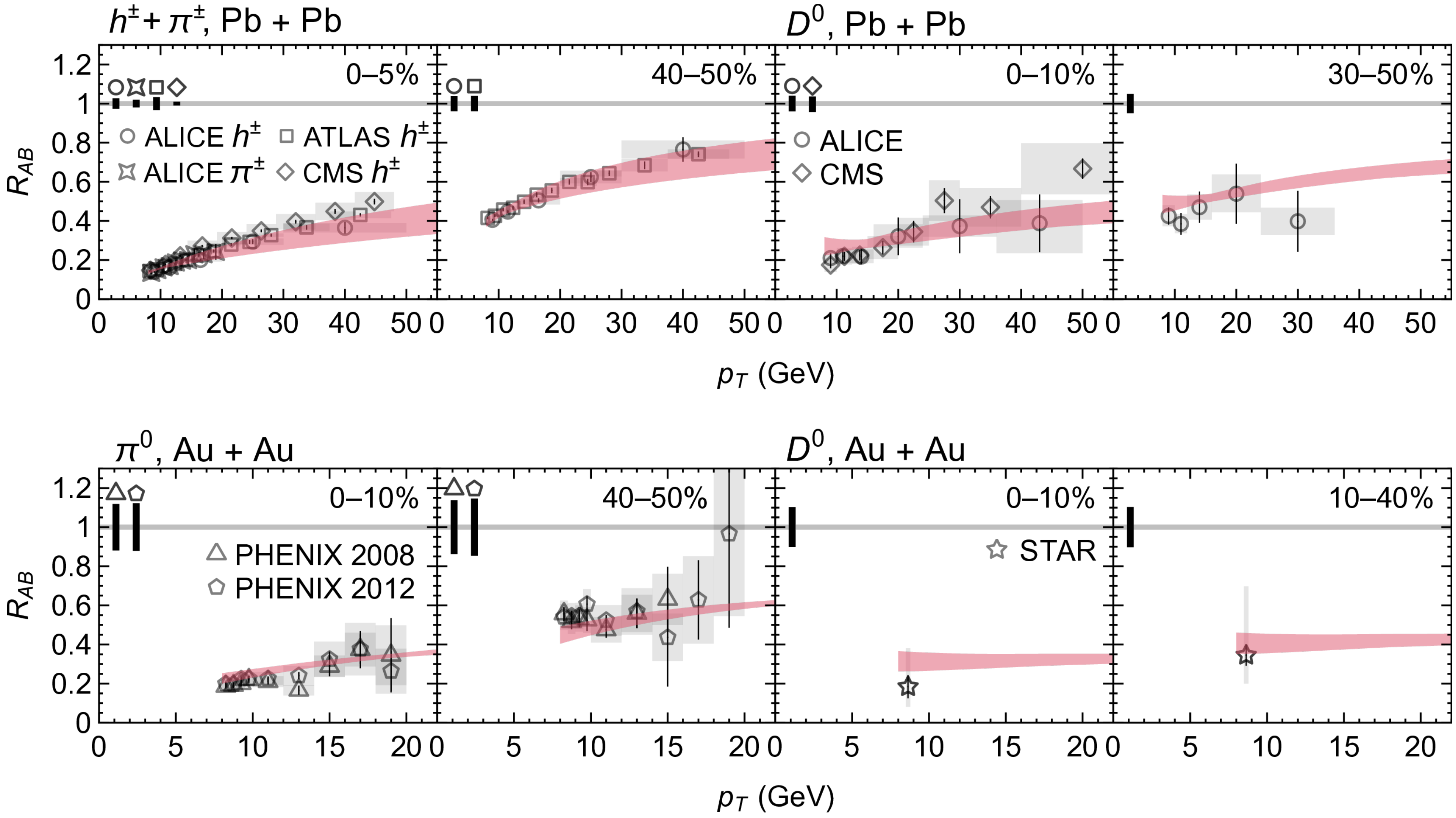
Collisional energy loss is important!



CF and W. A. Horowitz *Phys. Rev. C* 111, 054911 (2025)

- Collisional energy loss is often assumed to be negligible in energy loss models
- However, since collisional E-loss $\sim$ L and radiative E-loss $\sim L^2$, collisional dominates in small systems
- Must be included!

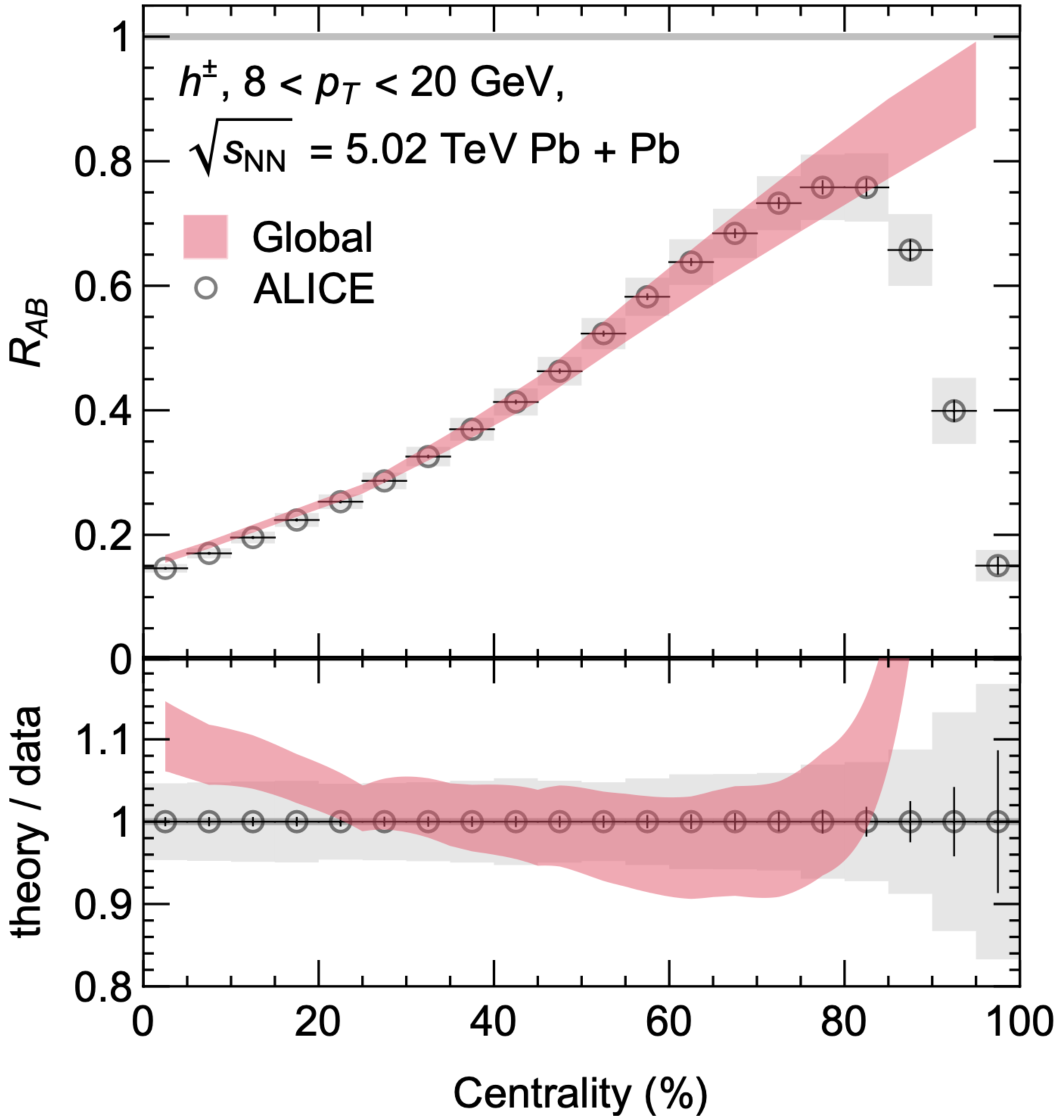
Sample of results post-fitting



Total of 295 data points used in fit

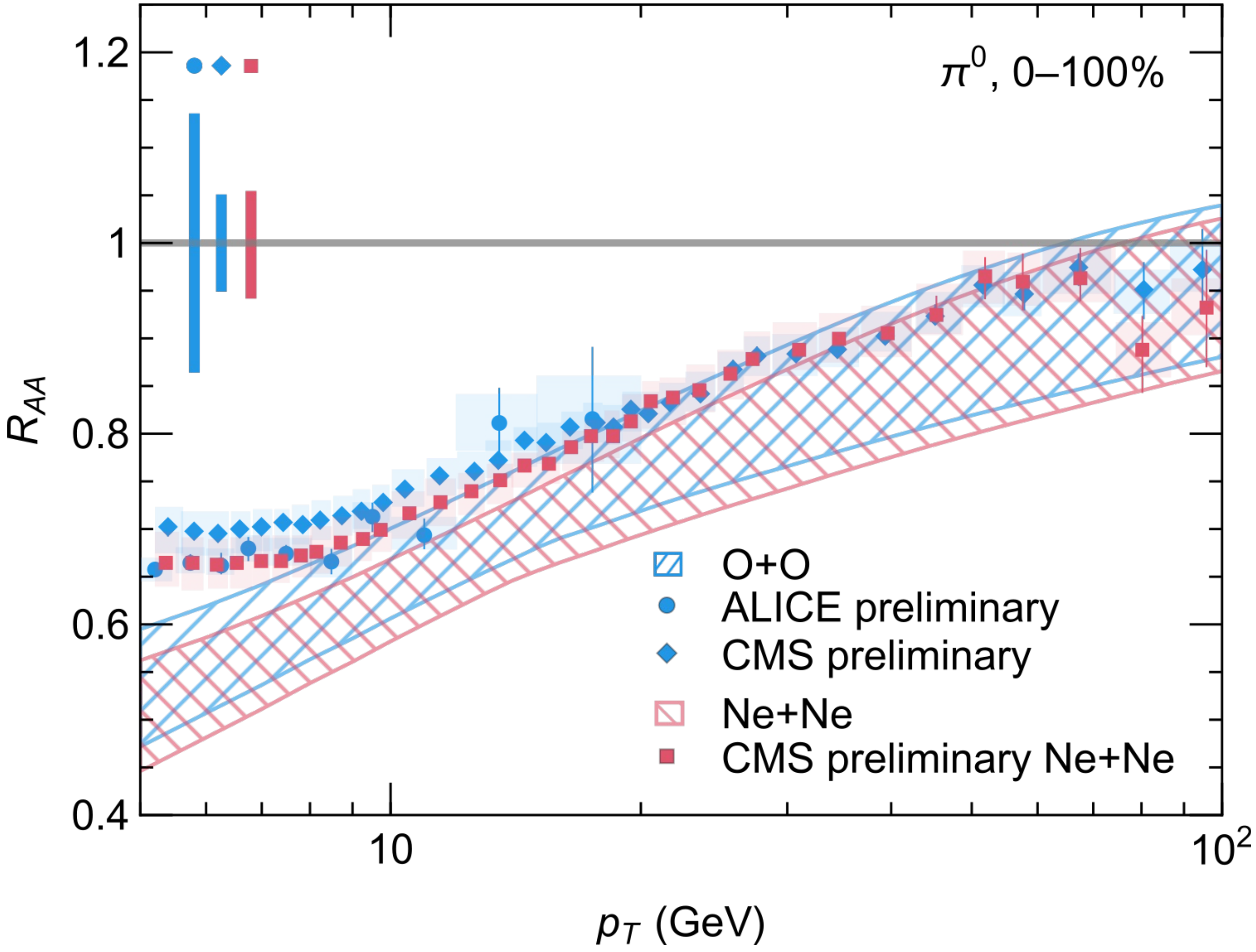
Good agreement with all available single-inclusive high-p_T data

Centrality dependence



- Very good description of centrality dependence
- Above 80%, selection biases lead to large anomalous suppression
- Gives us confidence to extrapolate to small systems

Predictions for light ions



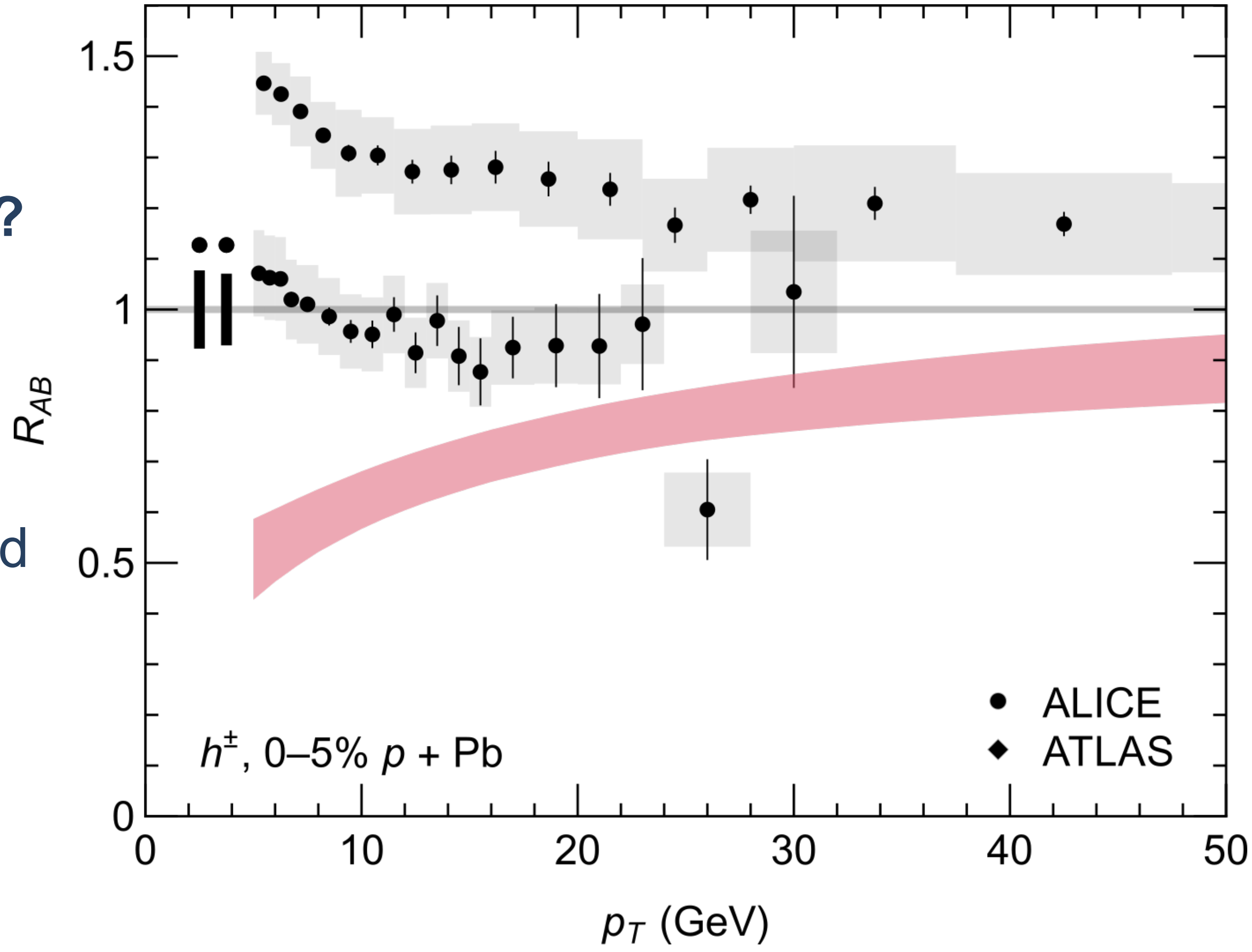
- Overall, good agreement between predictions and data!
- Slightly over-suppressed compared to data, but within theoretical uncertainties
- Missing physics for $p_T \lesssim 10\ \mathrm{GeV}$
  - Medium-modified hadronization
  - Unclear what should happen pre-thermalization

Can we go smaller? *p*Pb

Model is significantly over-suppressed compared to data

Is there still room for energy loss in pA?
Maybe. Need:

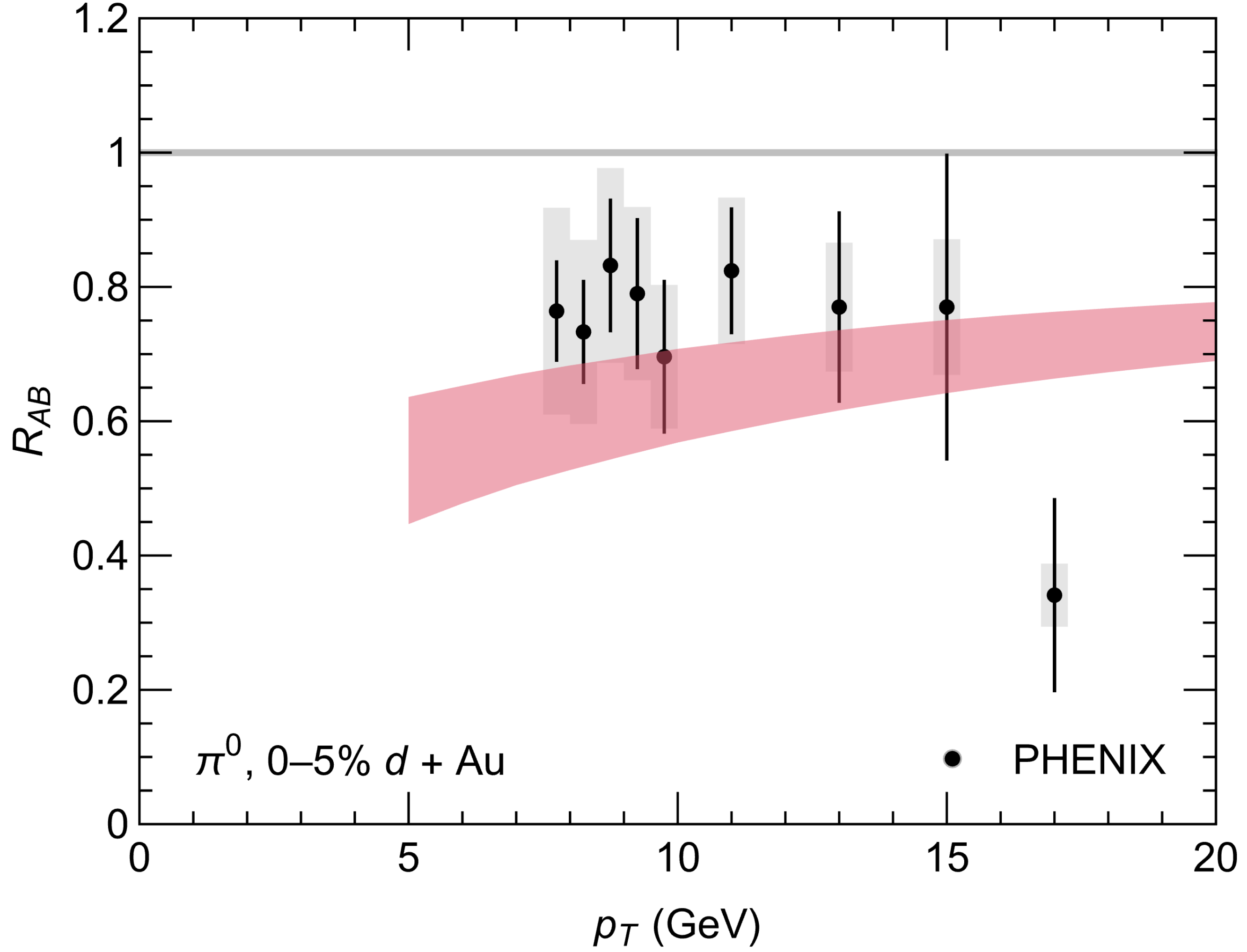
- Inclusion of hard-soft correlations in energy loss models
- 3D initial state + 3D hydro backgrounds
- Same centrality determination as is used by experiments (forward are even zero-degree multiplicity)



ATLAS *JHEP* 07, 074 (2023)

ALICE *Phys. Rev. C* 91, 064905 (2015)

Can we go smaller? *d*Au



- Good agreement with *d*Au data
- Shows that self-normalized observables are a promising probe for energy loss in small systems
- More measurements needed for concrete conclusions.
- Need cohesive understanding of *both* *p*Pb and *d*Au

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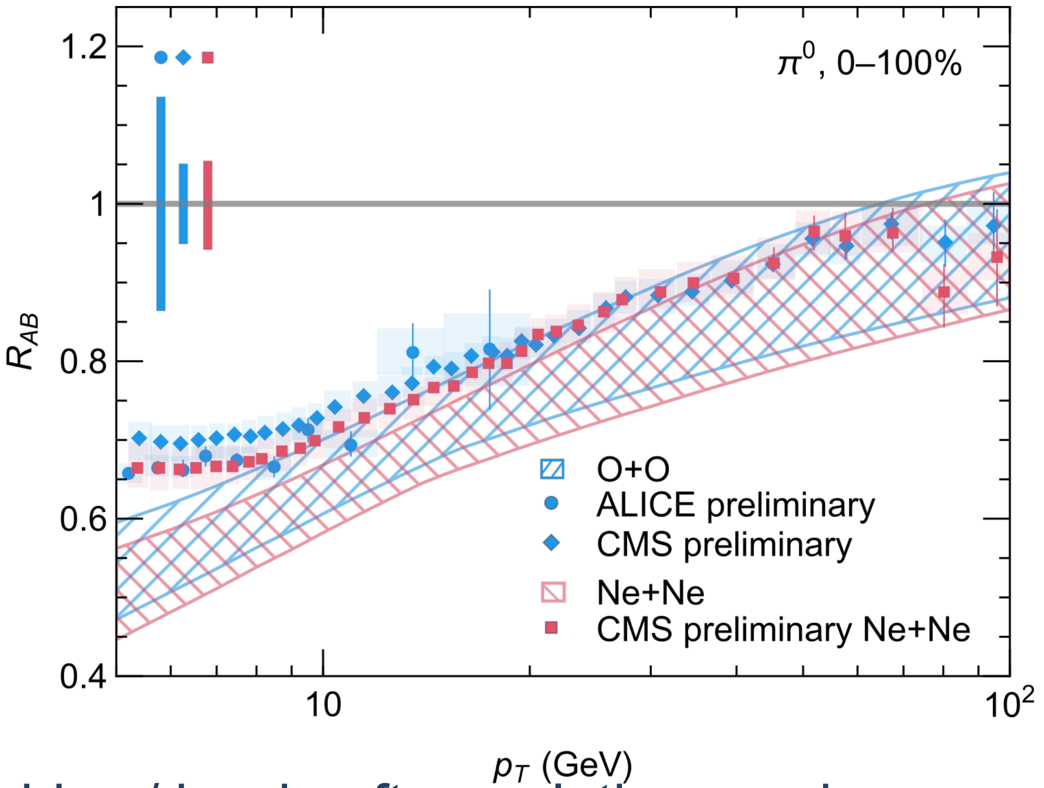
Conclusions and outlook

Summary

- Energy loss in small systems is **key** to understanding whether QGP forms.
- OO + NeNe form a crucial stepping stone towards even smaller systems
- We found good agreement with large-system constrained predictions; however room for improvement at lower-p_T

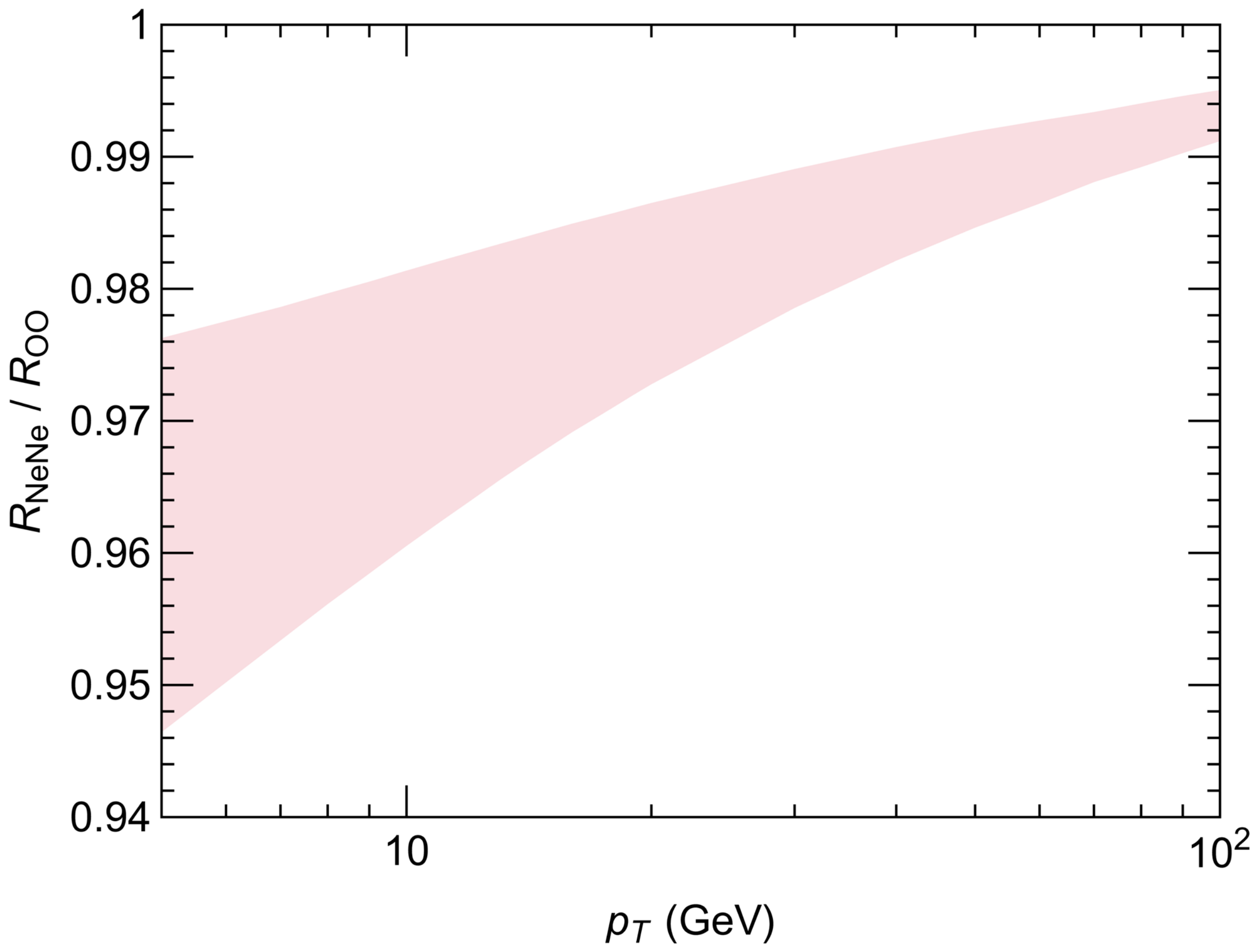


Outlook

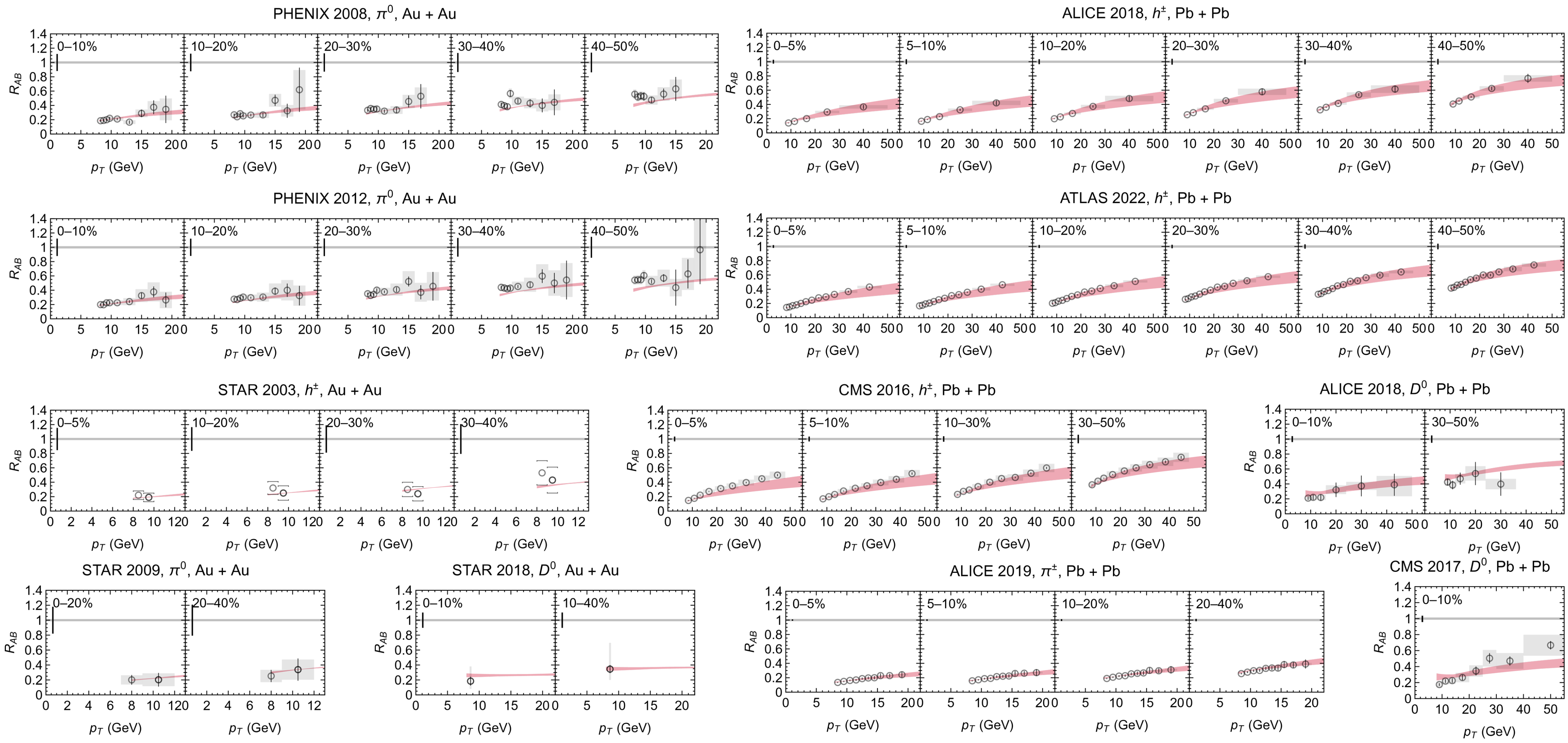
- **Central OO** is likely a system where *both* centrality bias / hard-soft correlations and energy loss are important; teaching us how to move to pA, pp, where centrality cuts are mandatory
- Smaller, but still symmetric, systems like **HeHe** will test the system-size dependence of energy loss models even more

Backup

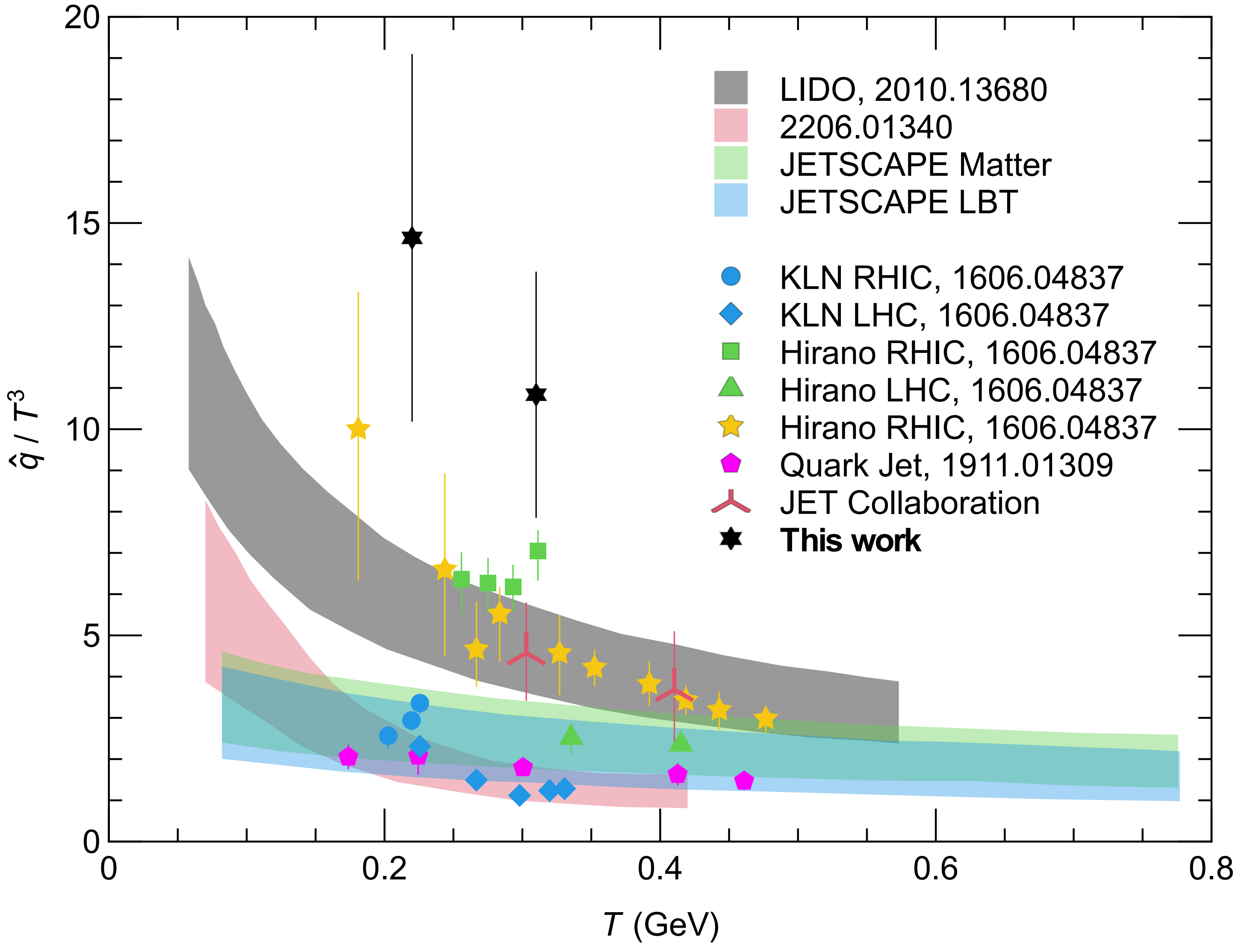
Ratio NeNe / OO



All results post-fitting, 295 data points



Extraction of $\hat{q}$



- **NB**: almost all uncertainty is due to theoretical uncertainties and **not** from the extraction procedure
- Wide range of extracted $\hat{q}$ from different models

Geometry

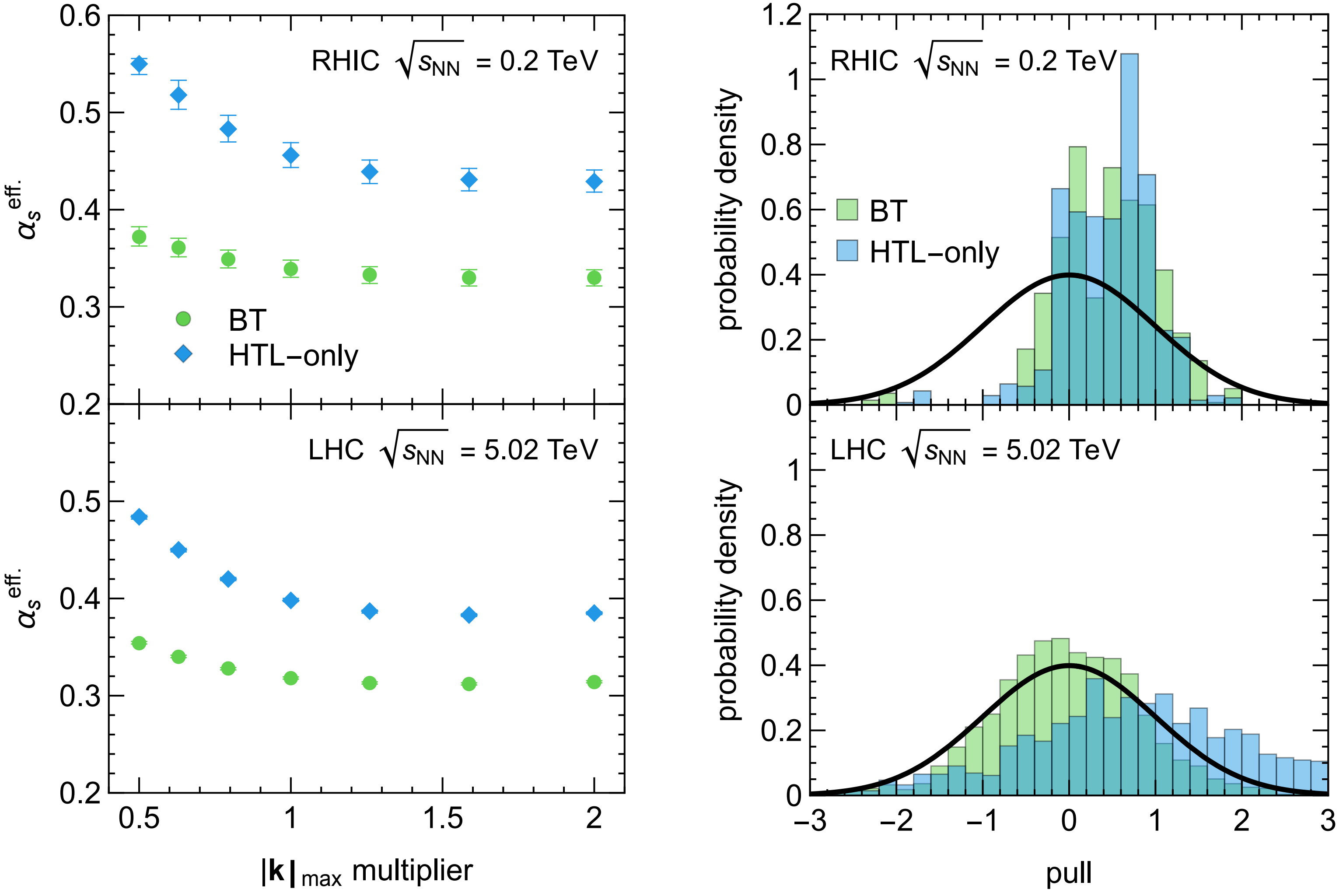
We assume longitudinal Bjorken expansion

$$T_{\text{eff}}(\tau) \approx T_{\text{eff}}(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1/3} \approx T_{\text{eff}}(\tau_0)\left(\frac{2\tau_0}{L_{\text{eff}}}\right)^{1/3}$$

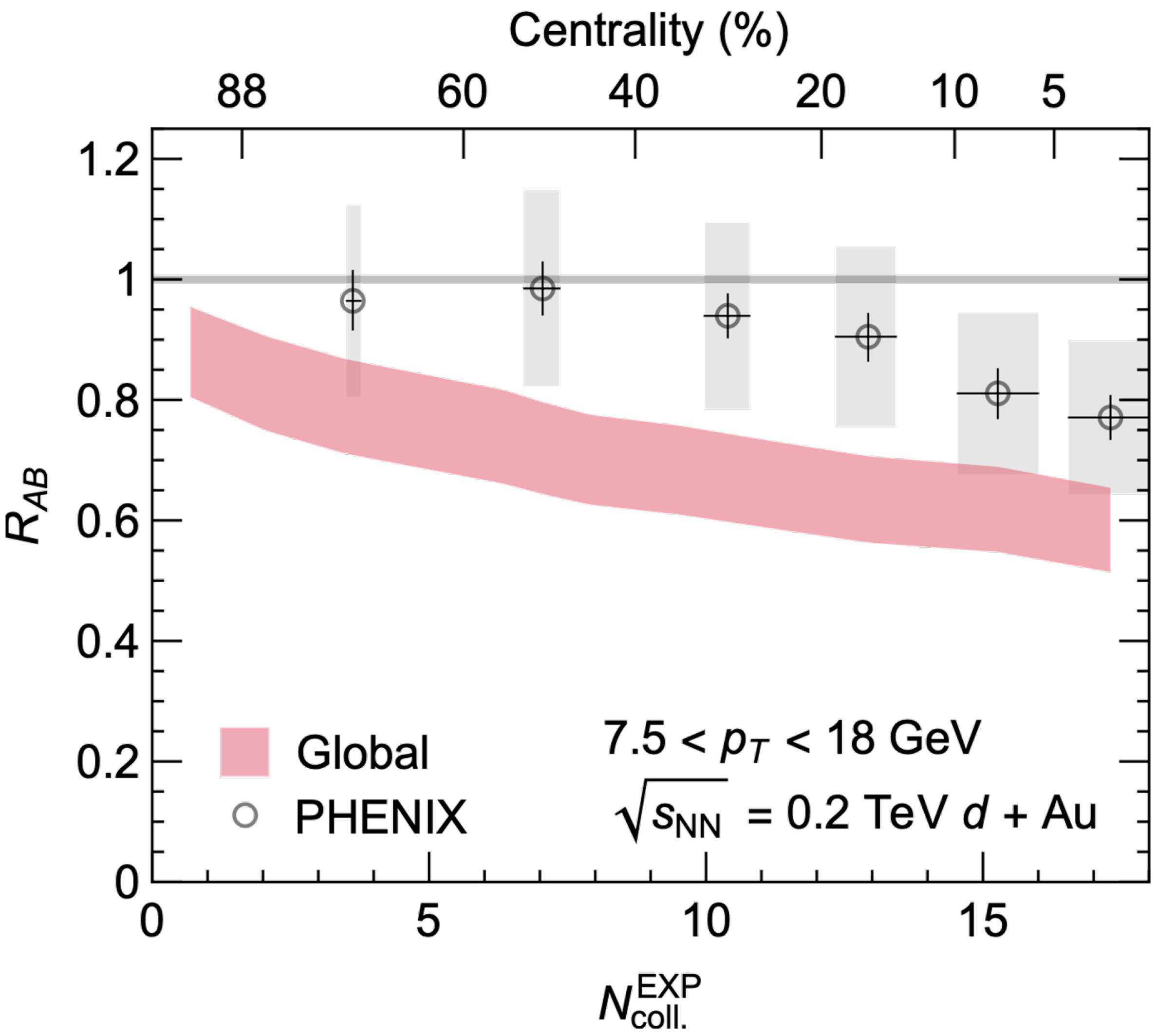
And use the initial collision geometry to generate effective temperatures and lengths (but energy loss with full event-by-event hydrodynamic evolution is in the works!)

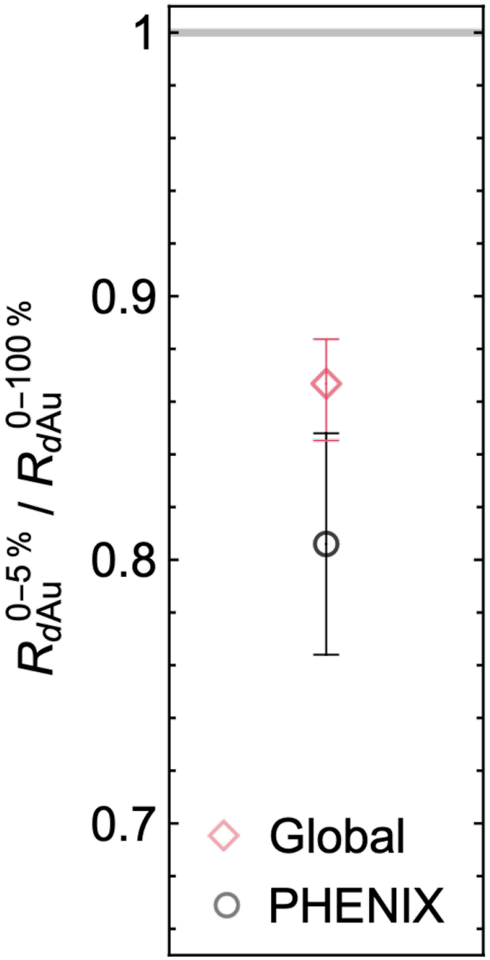
$$\rho_{\text{eff}} \equiv \frac{\int d^2\mathbf{x}\ \rho^2(x,\ \tau_0)}{\int d^2\mathbf{x}\ \rho(x,\ \tau_0)} \Leftrightarrow T^3_{\text{eff}} \equiv \frac{\int d^2\mathbf{x}\ T^6(x,\ \tau_0)}{\int d^2\mathbf{x}\ T^3(x,\ \tau_0)} \qquad L_{\text{eff}}(x_i, \hat{\phi}) = \frac{1}{\rho_{\text{eff}}}\int_0^\infty d\,z\rho(x_i + z\hat{\phi}, \tau_0)$$

Results of extraction



Small system suppression at RHIC





- Agree within one-sigma with PHENIX centrality dependence
- Note: all grey boxes are fully correlated systematic uncertainties
- Moderately oversuppressed: no energy loss in the initial stage, soft / hard correlations, QGP formation turns off at some event-activity?

PHENIX, Phys. Rev. Lett. 134, 022302 (2025).