Jet quenching in the smallest quark-gluon plasma droplet

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Based on **CF**, B. Bert, J. Brand, W. Vogelsang, and W. A. Horowitz, arXiv:2512.17832
and **CF** and W. A. Horowitz, JHEP **11**, 019 (2025)

NITheCS National Institute for Theoretical and Computational Sciences

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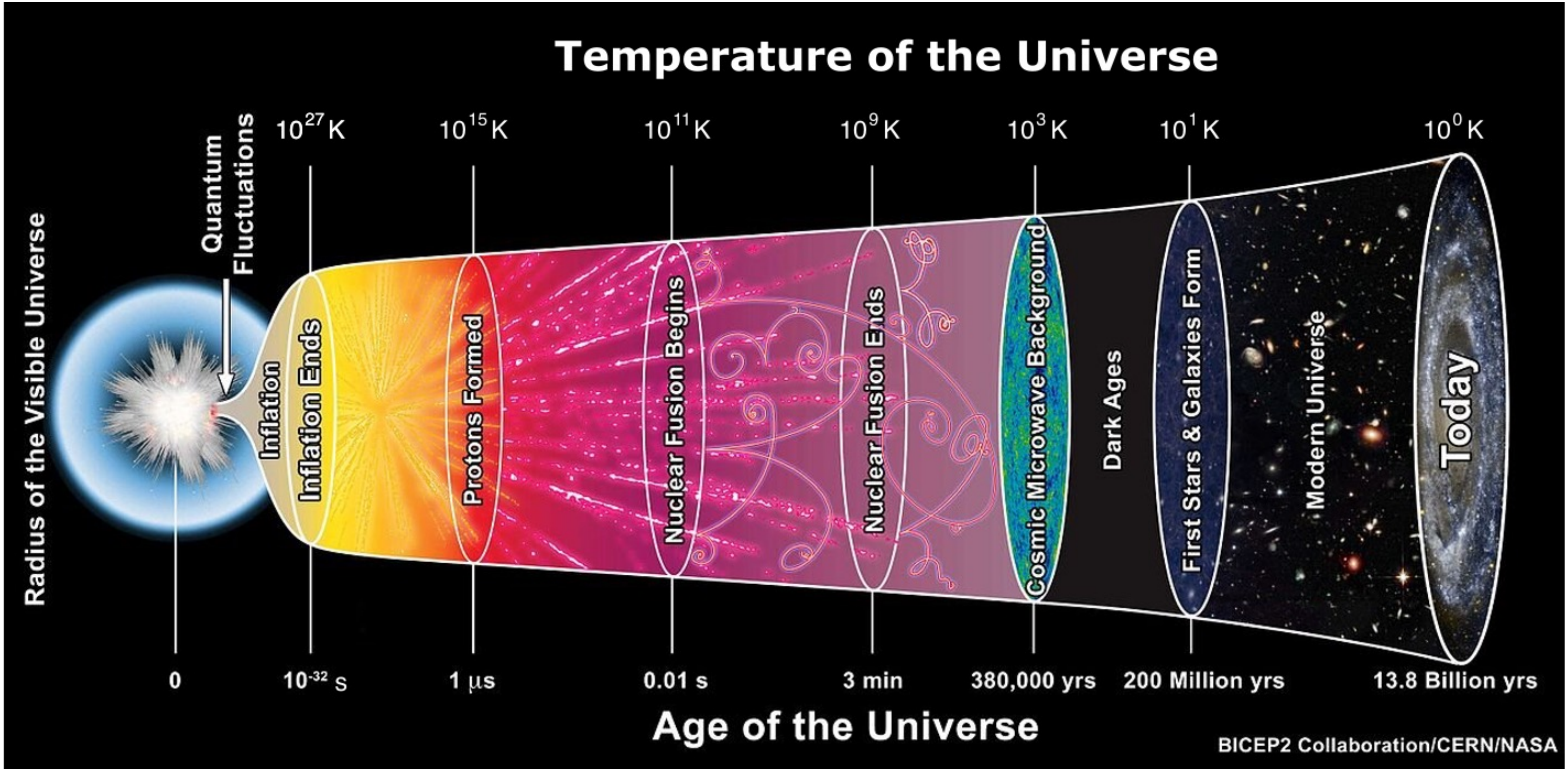
CERN

NRF National Research Foundation

Matter under extreme conditions



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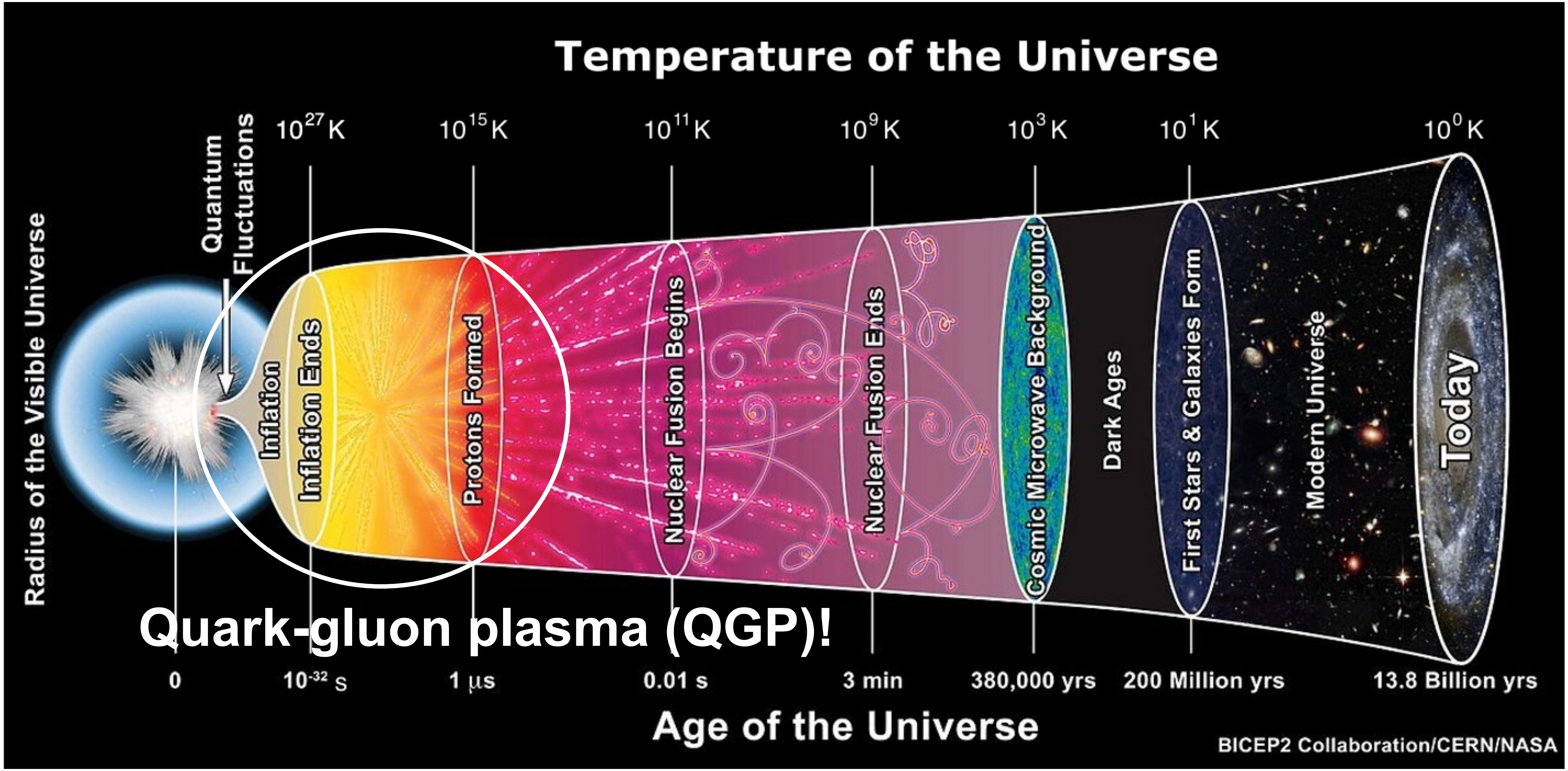
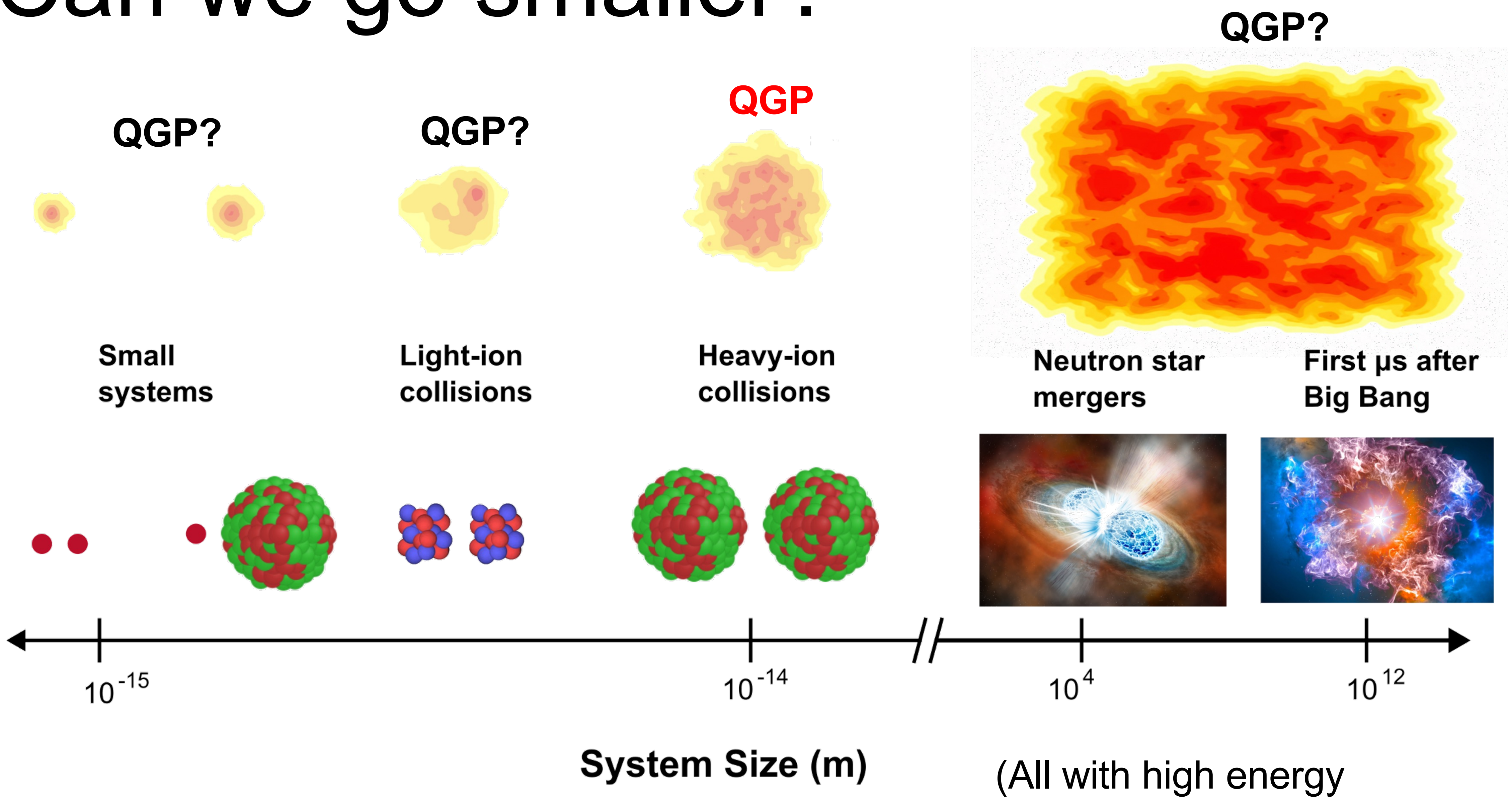


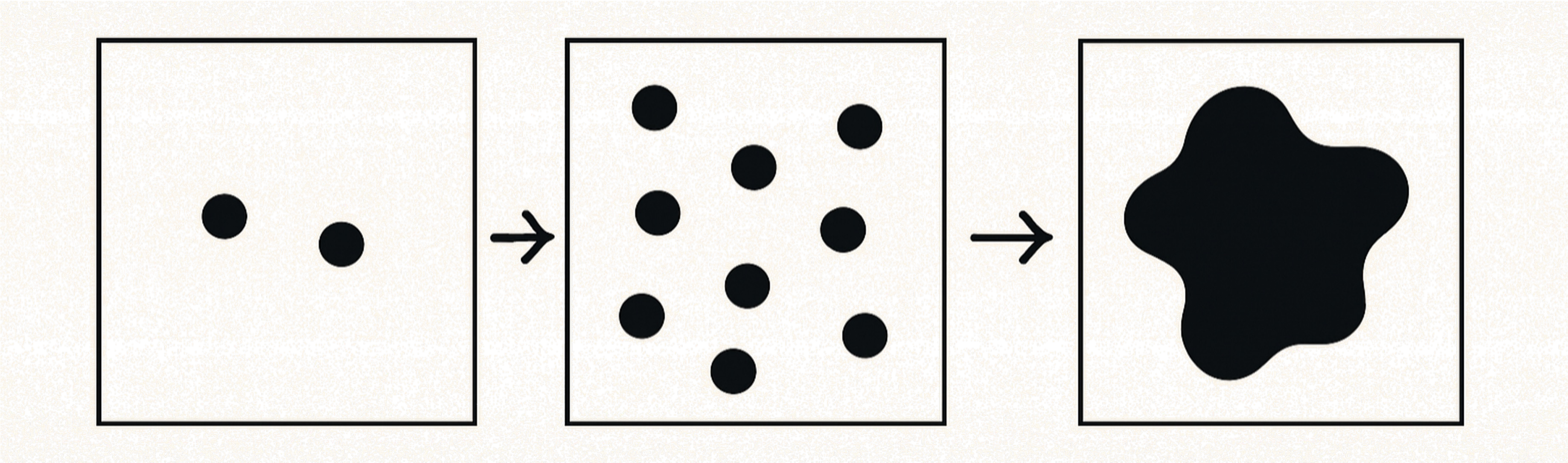
Can we go smaller?



(All with high energy density / ”temperature”)

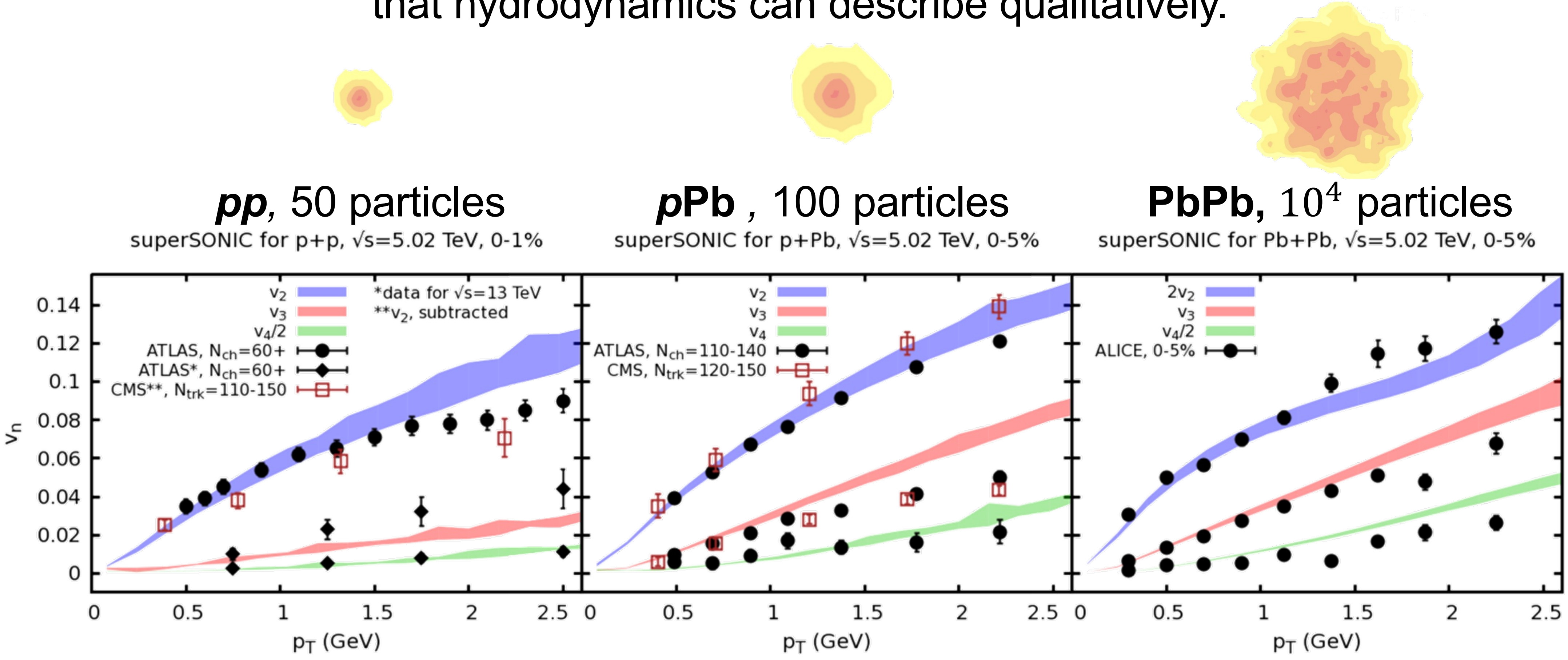
How many particles for collectivity?

From statistical mechanics, you might say ~ 1 mole ~ 10^{23} particles



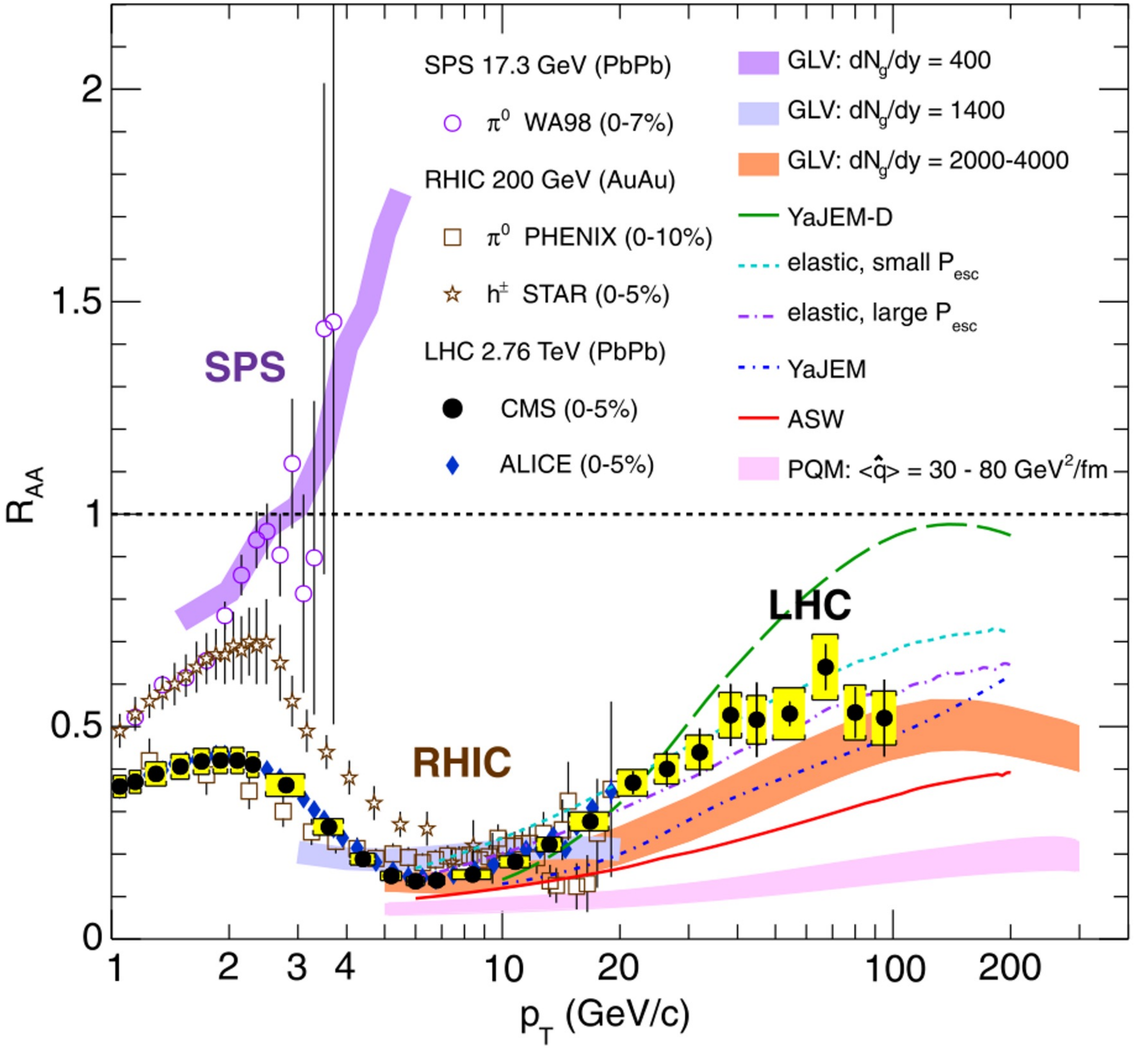
Collective phenomena in small systems

High-multiplicity events in **all collision systems** show **collective phenomena** that hydrodynamics can describe qualitatively.



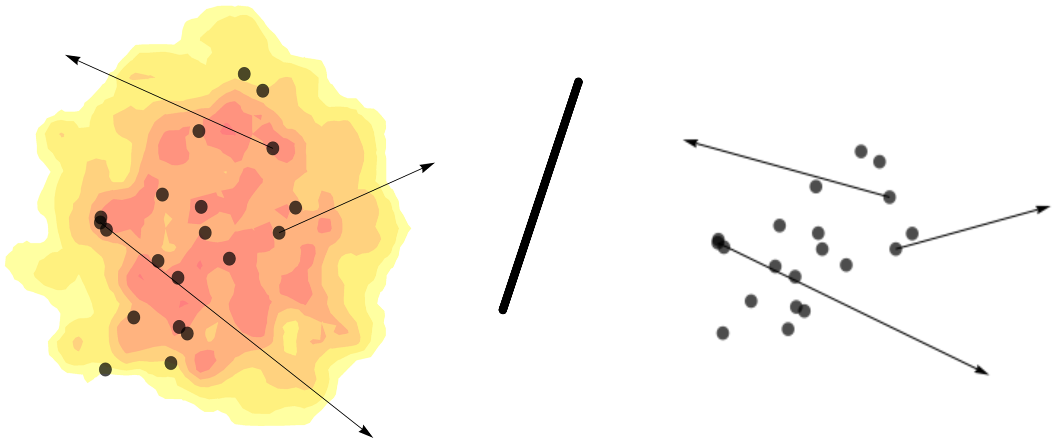
Weller et al., PLB 774 (2017) 351-356

High momentum probes of the QGP



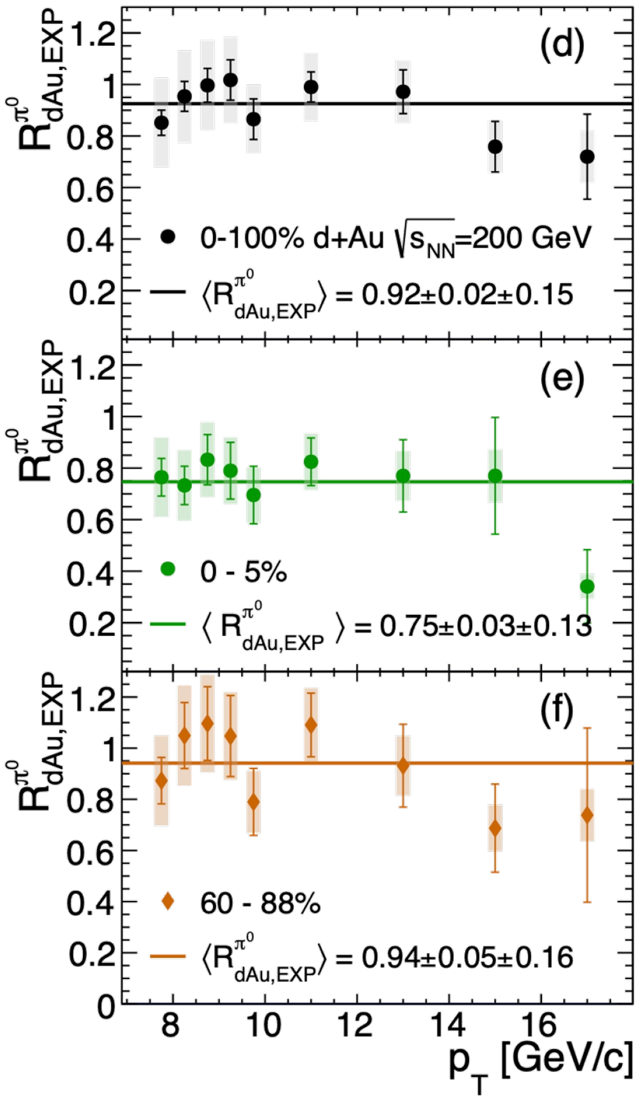
$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

=



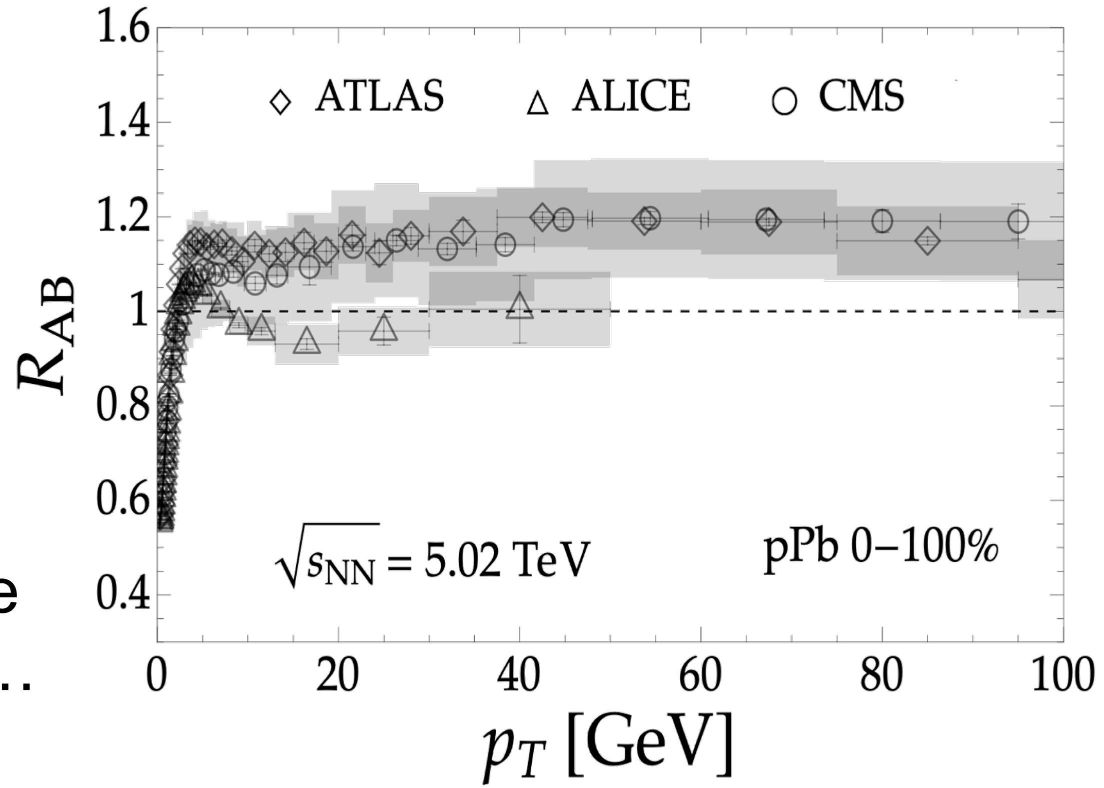
Quantifies how much **energy is lost** by high momentum particles

High momentum probes in small systems



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

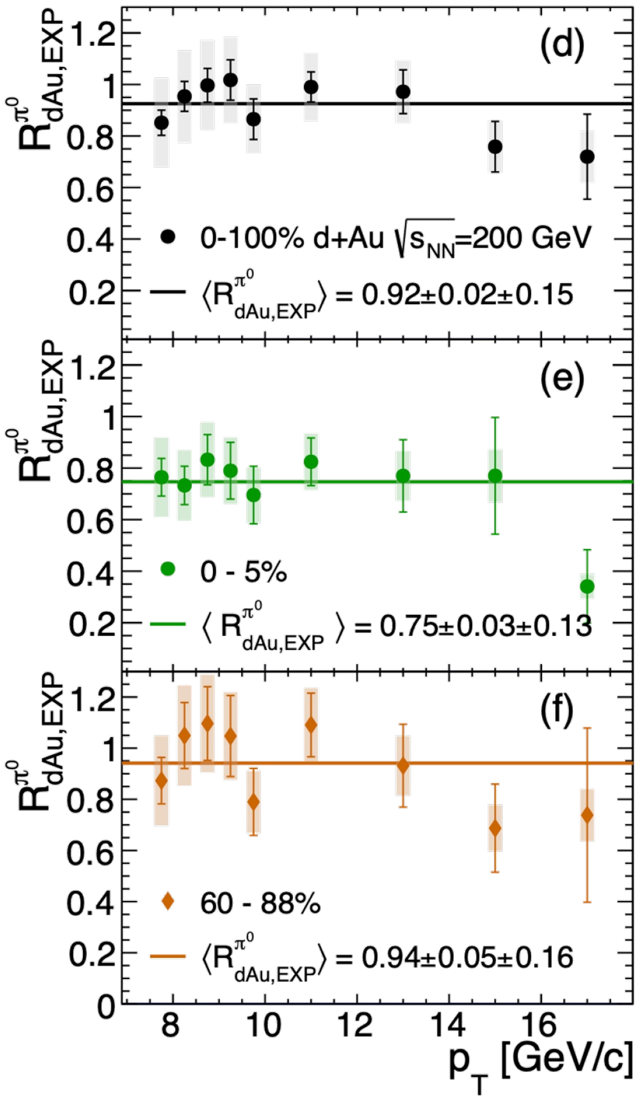
And many more measurements…



Bert, CF, and Horowitz, arXiv:2603.21861

Small system suppression pattern is not clear

High momentum probes in small systems



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

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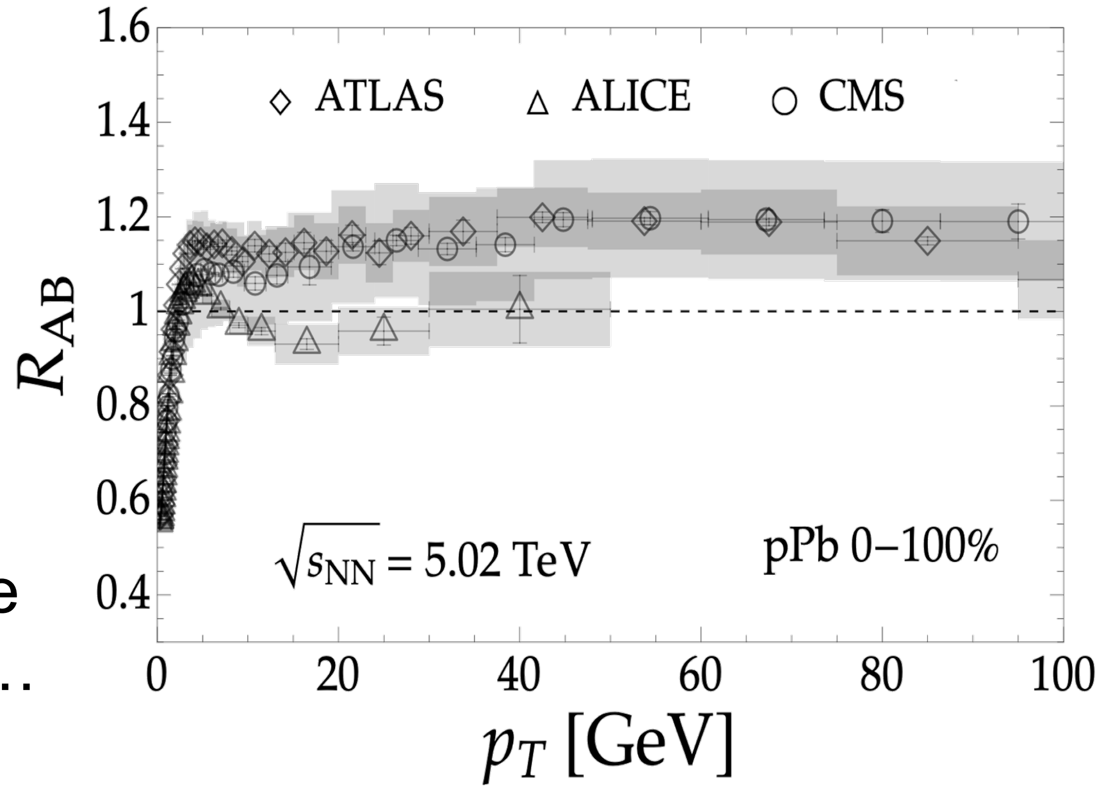


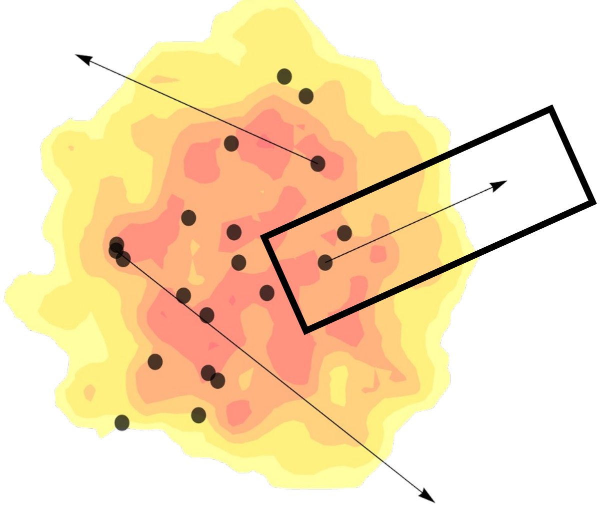
Bert, CF, and Horowitz, arXiv:2603.21861

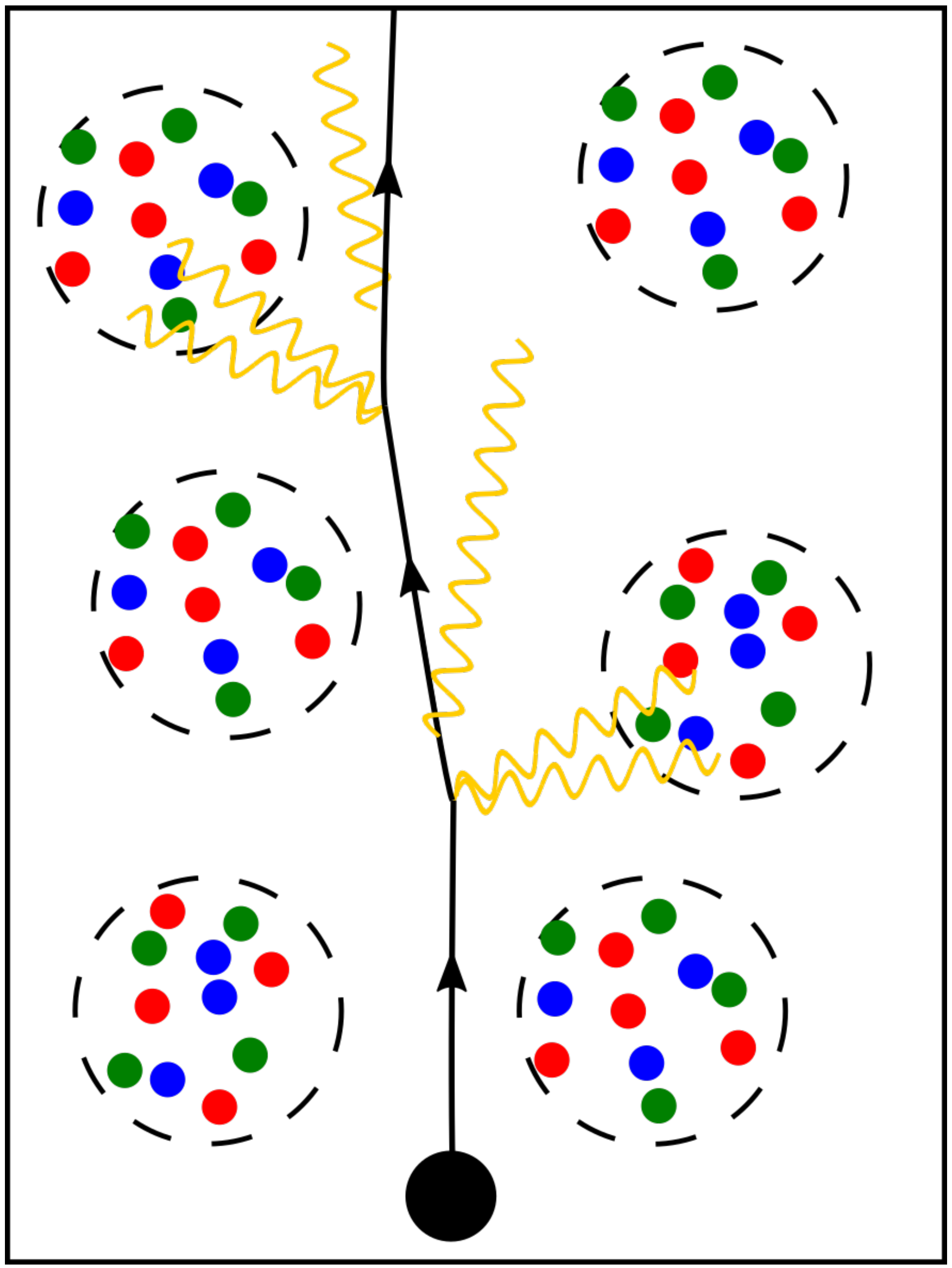
Small system suppression pattern is not clear

→ High energy particles are ***the missing link*** to discovering QGP in small systems

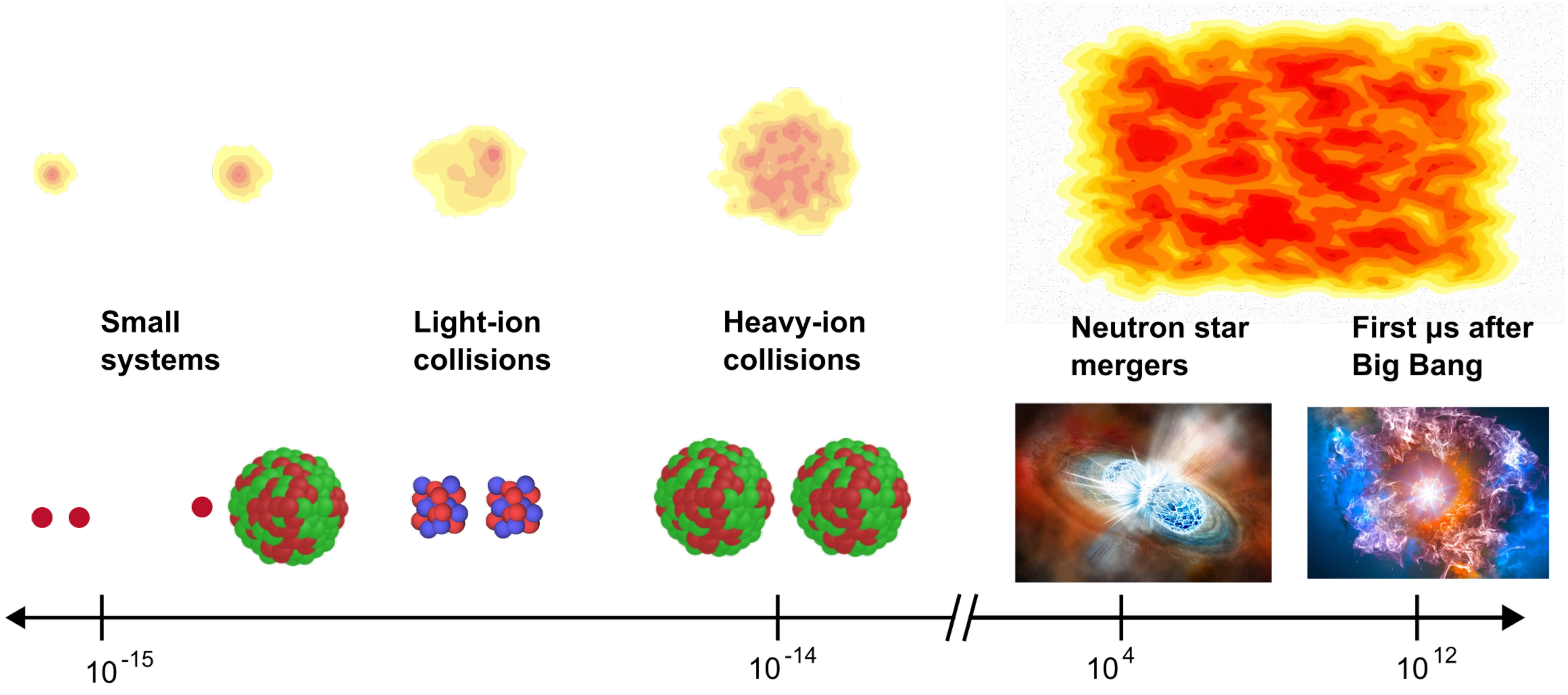
Physics model

- The plasma is modeled as a collection of "scattering centers"
- Plasma properties (temperature, shape, size) are taken from realistic hydrodynamic simulations
- High energy partons lose energy through **elastic** scatters and induced **radiative** emission
- Single free parameter, strong coupling, that we fit to high momentum data from large systems





Reminder: the goal

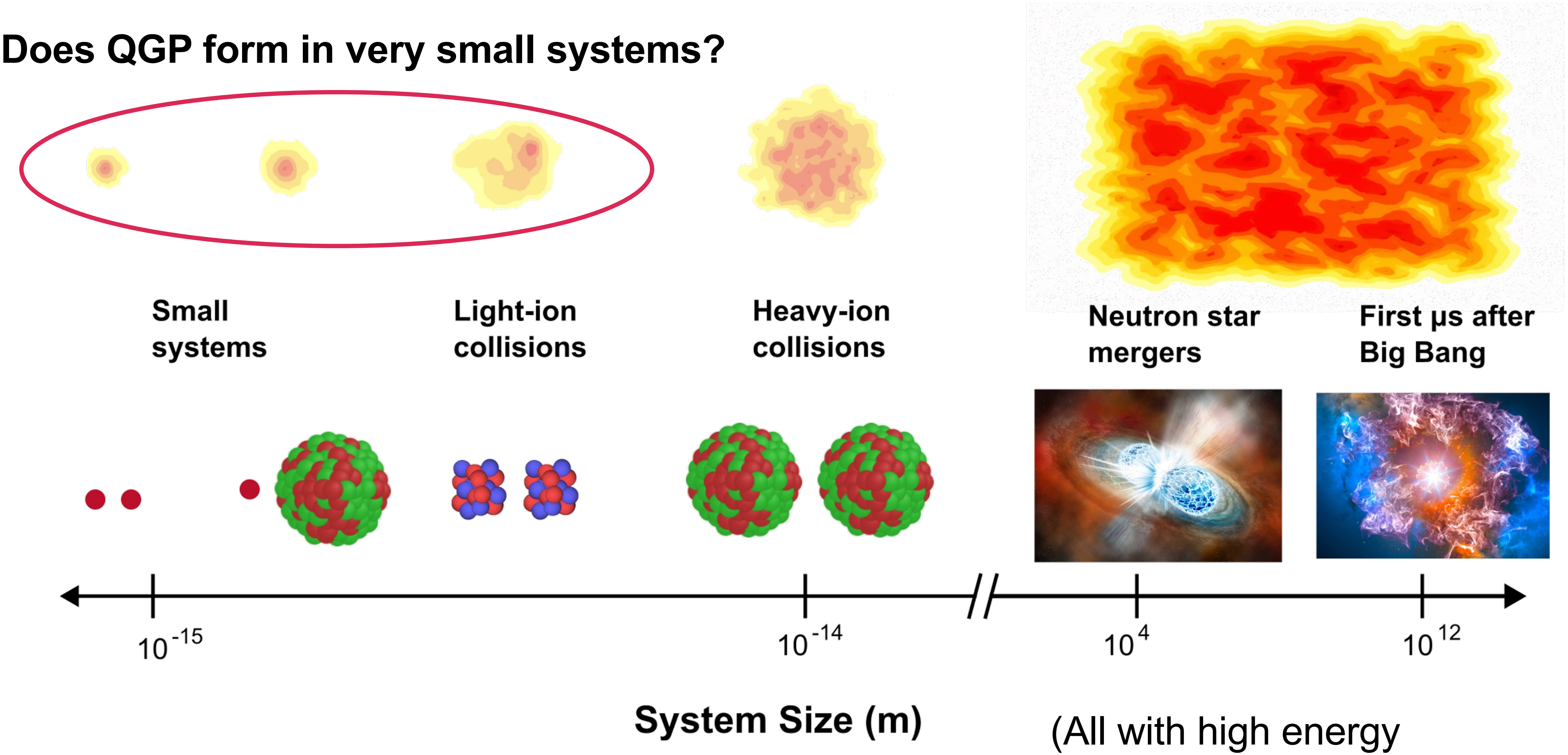


(All with high energy density / ”temperature”)

frdcol002@myuct.ac.za

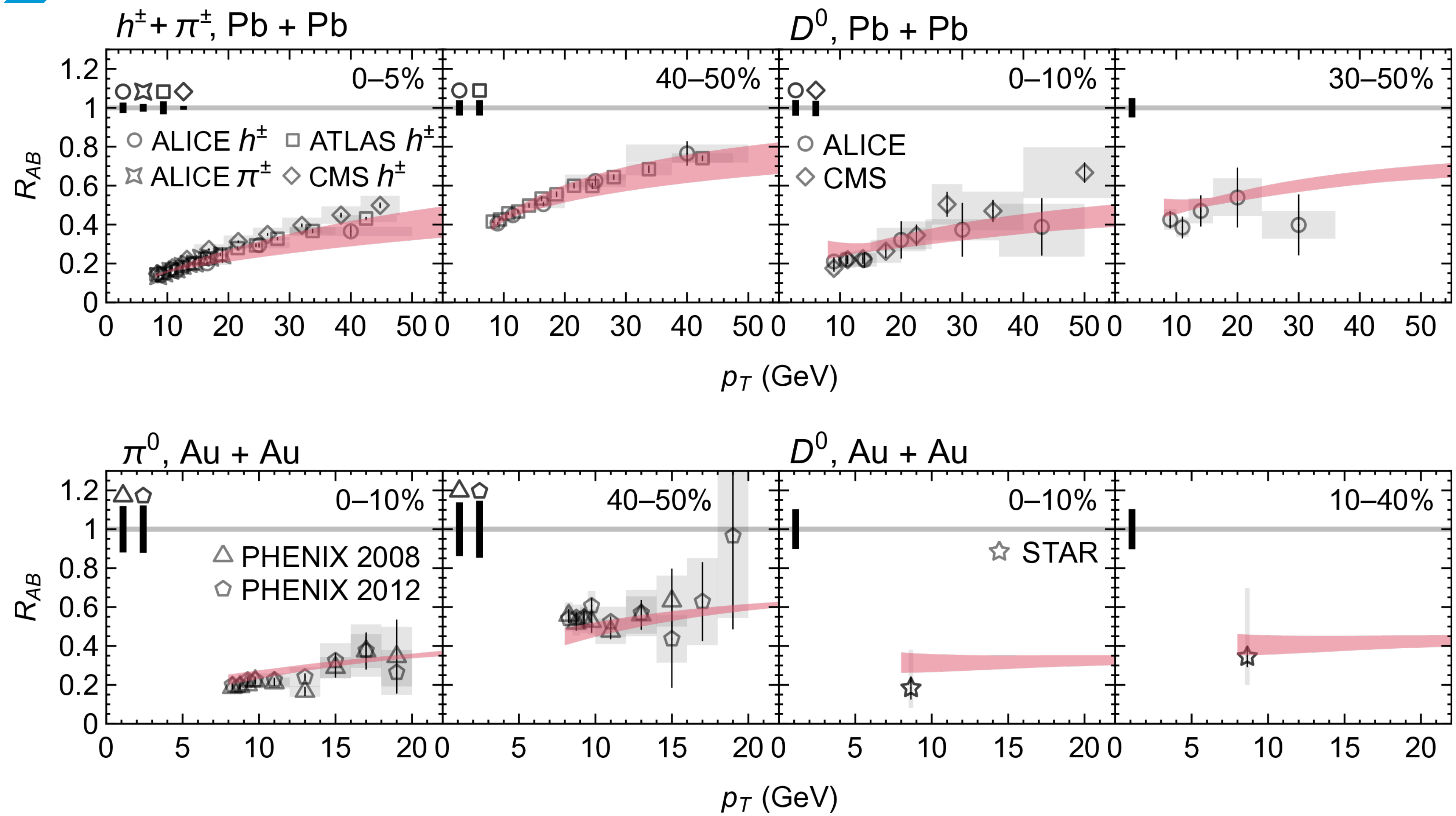
Reminder: the goal

Does QGP form in very small systems?



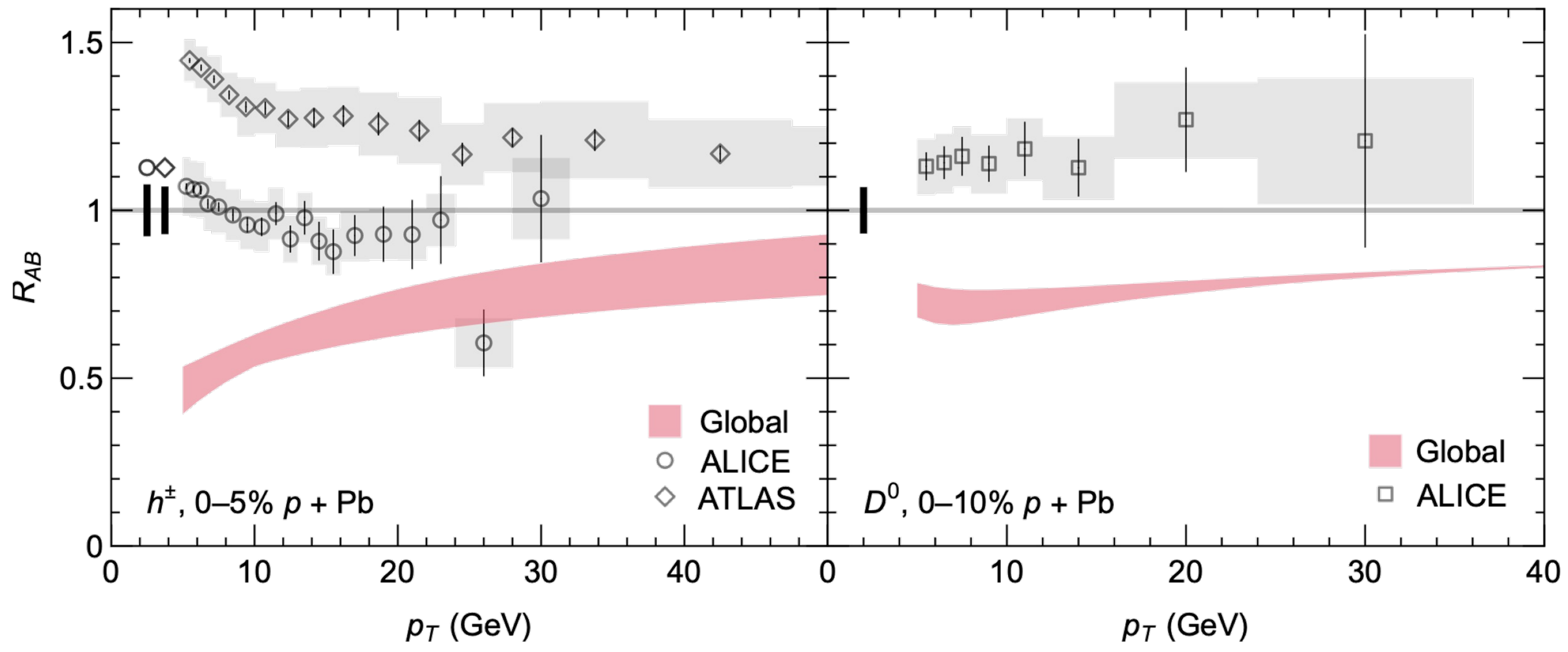
(All with high energy density / ”temperature”)

Sample of results post-fitting



- Good agreement with all available single-inclusive high-p_T data
- Band width indicates theoretical uncertainty

Small system suppression at LHC



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

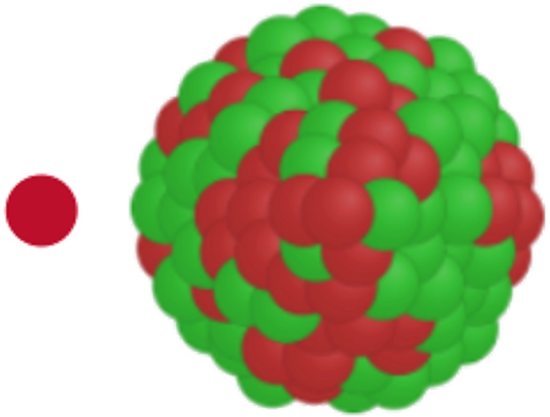
ATLAS, JHEP **07**, 074 (2023).

ALICE, JHEP **12**, 092 (2019).

- Disagree with *p*Pb results. Why?
  - No plasma?
  - No energy loss?

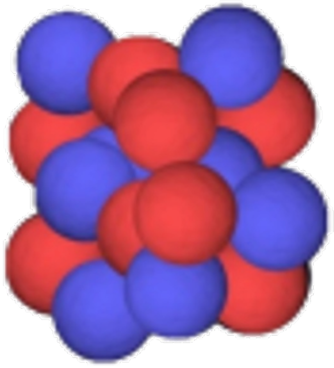
Difficulties with *pA*

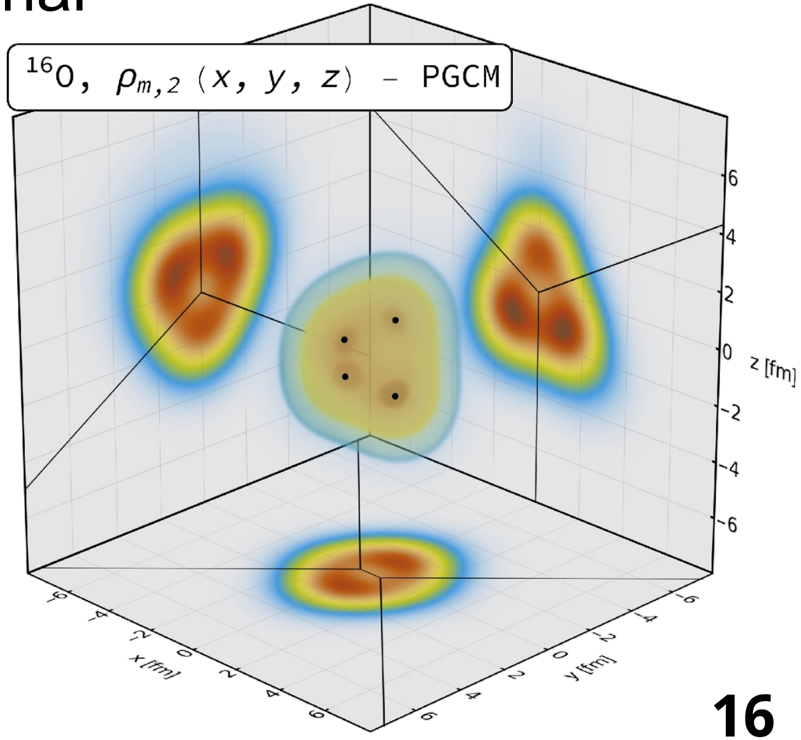
- Hydro medium depends in detail on uncertainties in the proton structure
- Correlations between hard and soft particles (one proton produces the medium + the jet)
- Centrality classification is very difficult without significant biases
- Breakdown of boost invariance due to asymmetry



Light-ion collisions

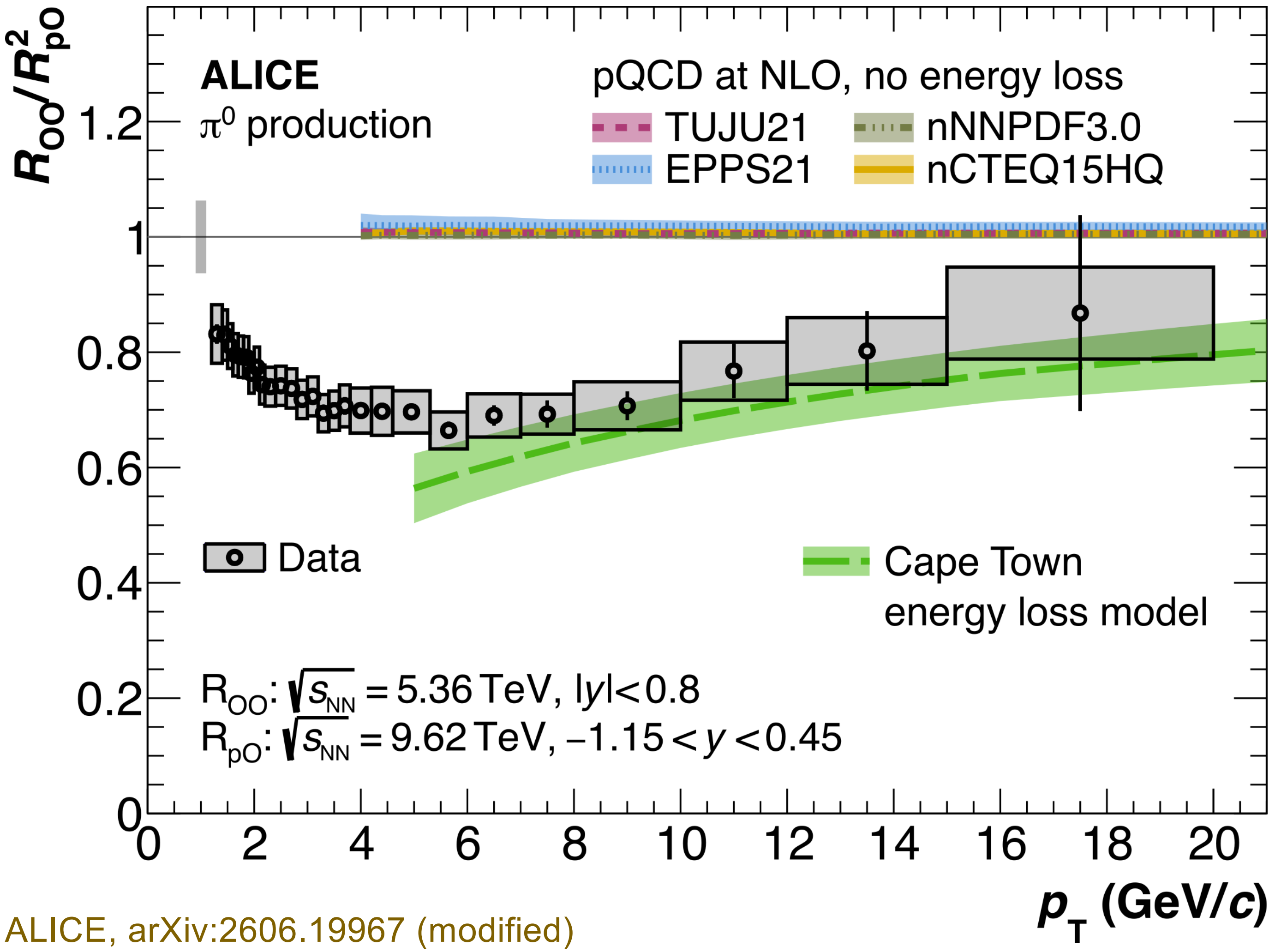
- Collisions of **oxygen** is an ideal testing ground for small system energy loss
  - Symmetric, meaning 3D hydro not mandatory
  - No centrality-cuts needed
  - Large enough to expect non-trivial energy loss signal
  - Large enough to expect hydro to apply





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

Predictions for oxygen-oxygen

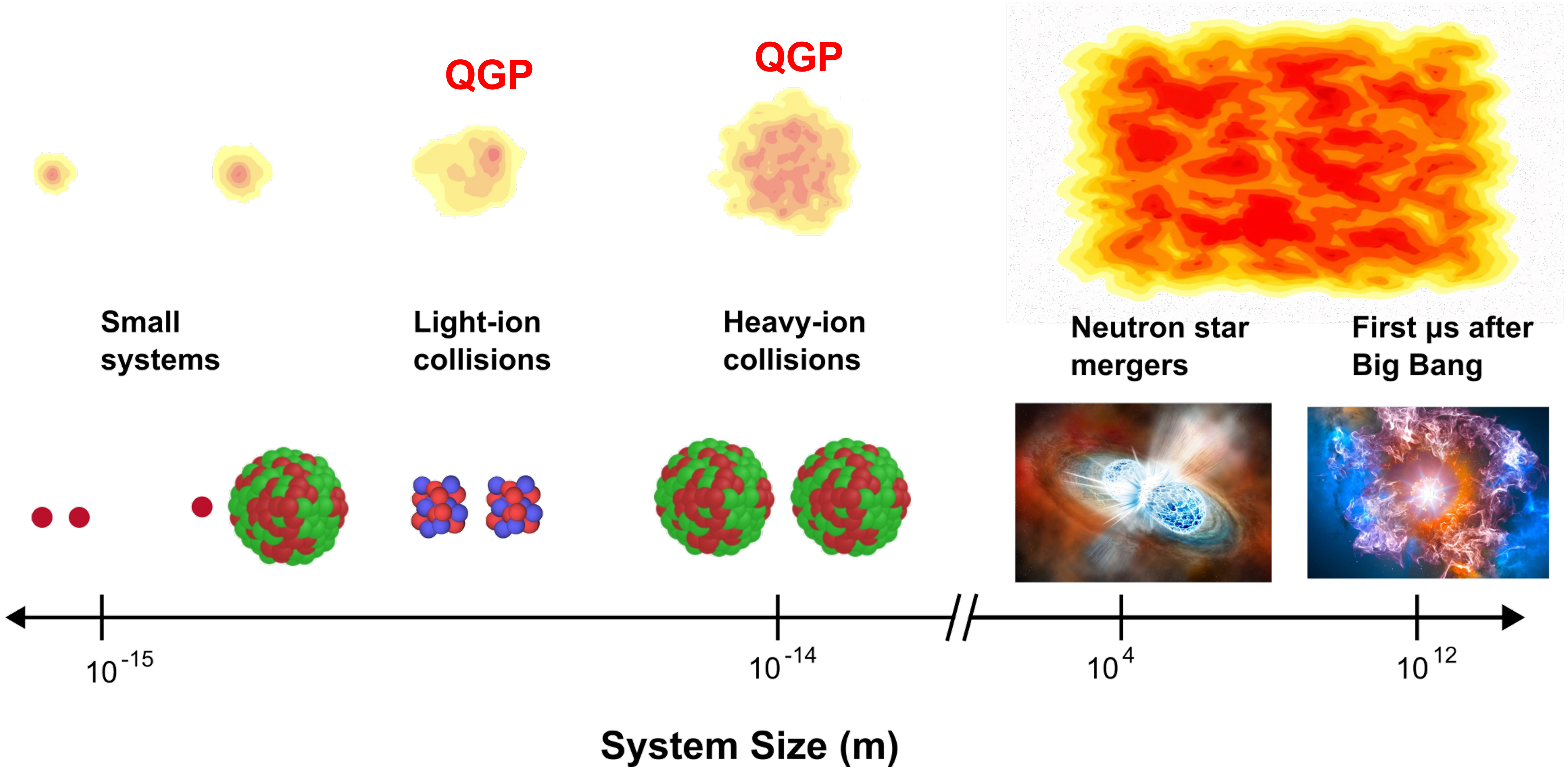


ALICE, arXiv:2606.19967 (modified)

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

- Good agreement between (blind) predictions and data!
- Missing physics for $p_T \lesssim 10$ GeV
  - Likely medium-modified hadronization
- Clear that energy loss causes $R_{AA} < 1$ for oxygen-oxygen (cf initial-state effects)
- Strong evidence for plasma formation in oxygen-oxygen

Can we go smaller?



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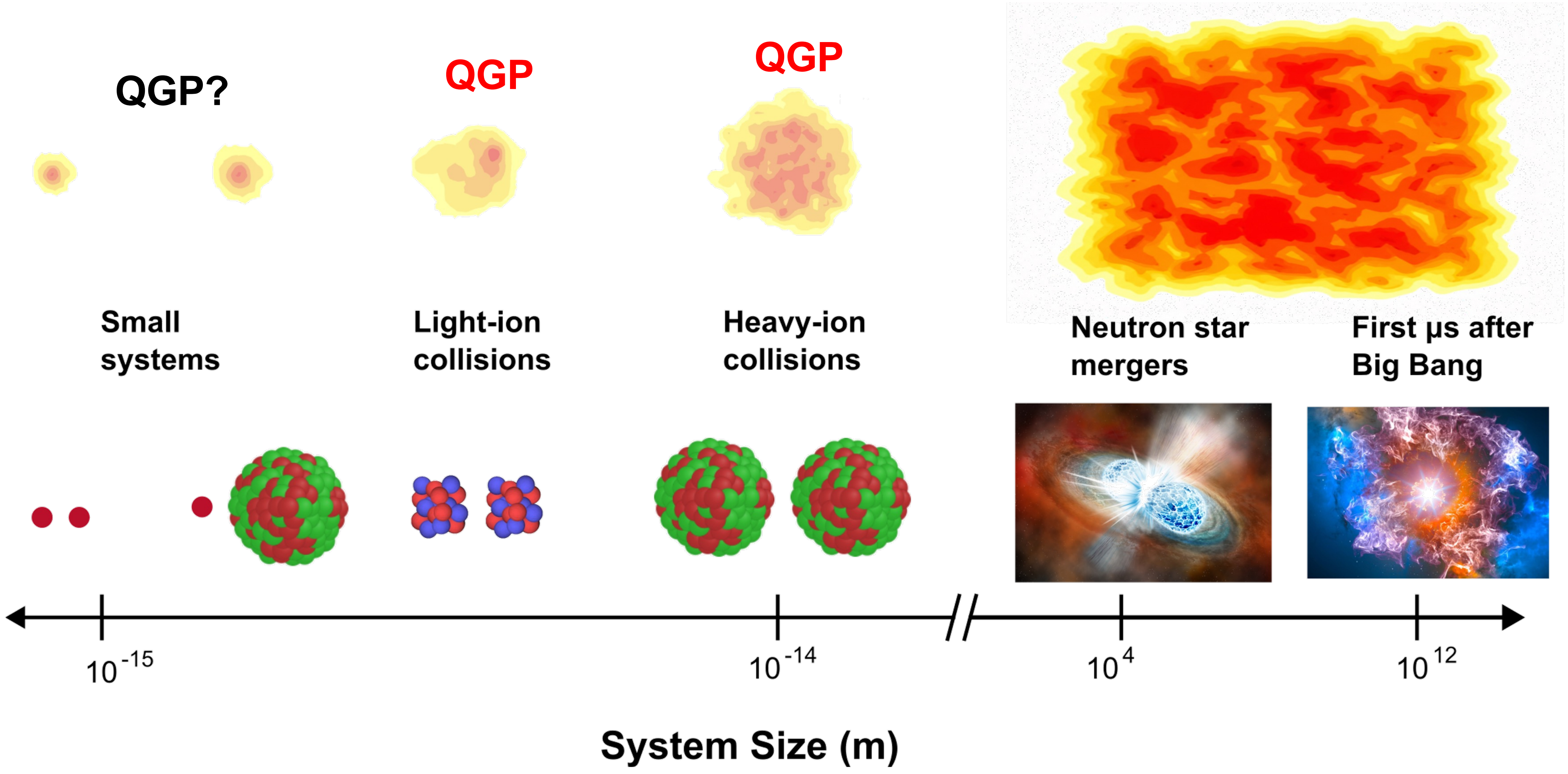
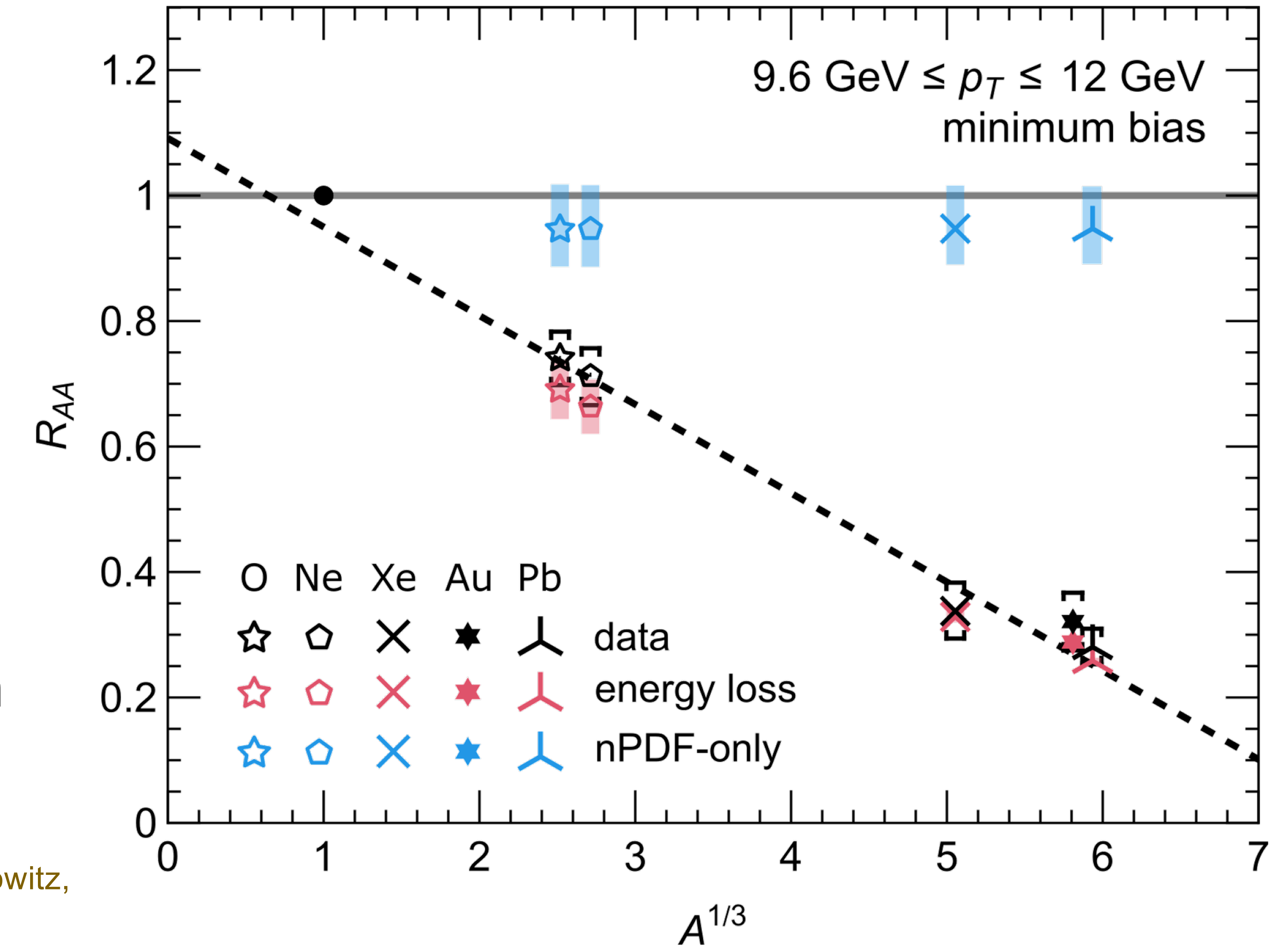


Current systems

- Current status of nuclear modification measured in symmetric ion collisions (and our model predictions)
- Also shown are nPDF-only baseline, which assumes no QGP is formed
- We see the same $R_{AA} \simeq A^{1/3}$ approximate scaling as is seen in the data

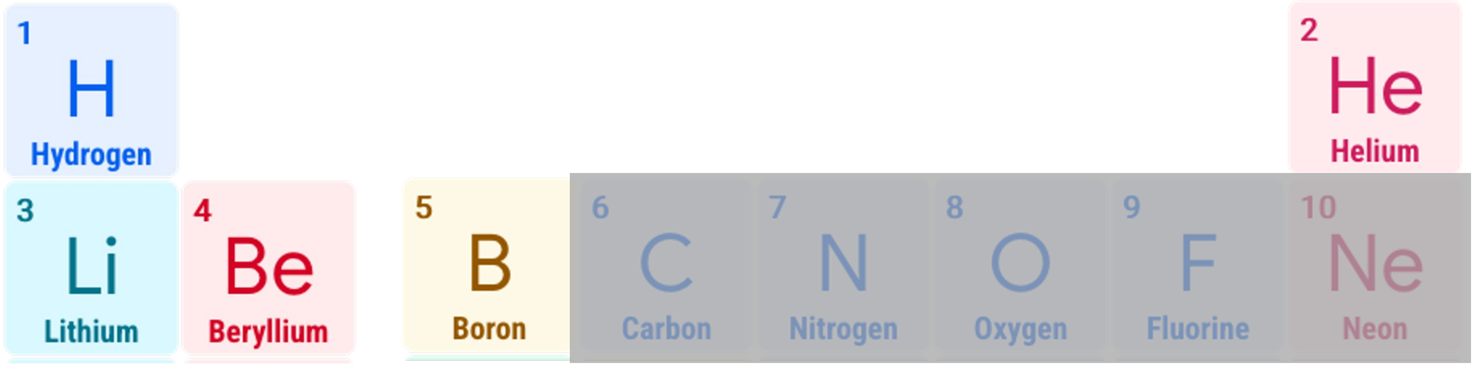
CF, B. Bert, J. Brand, W. Vogelsang, and W. A. Horowitz, arXiv:2512.17832 [hep-ph] (2025).



Candidates for $A \leq 10$ ion runs

p, Z/A = 1
2-H, Z/A = 0.5

3-He, Z/A = 0.67
4-He, Z/A = 0.5



Only $A \leq 10$ to get some distance from Oxygen and Neon

6-Li, Z/A = 0.5
7-Li, Z/A = 0.43

10-B, Z/A = 0.5
11-B, Z/A = 0.45

9-Be, Z/A = 0.44

Ideally, we want Z/A = 0.5 (easiest for magnets at LHC)

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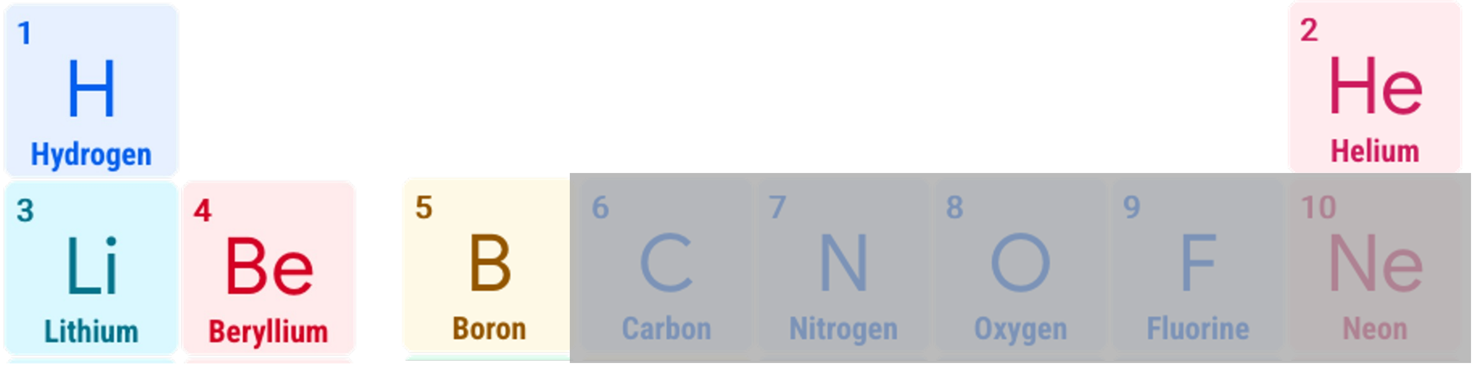

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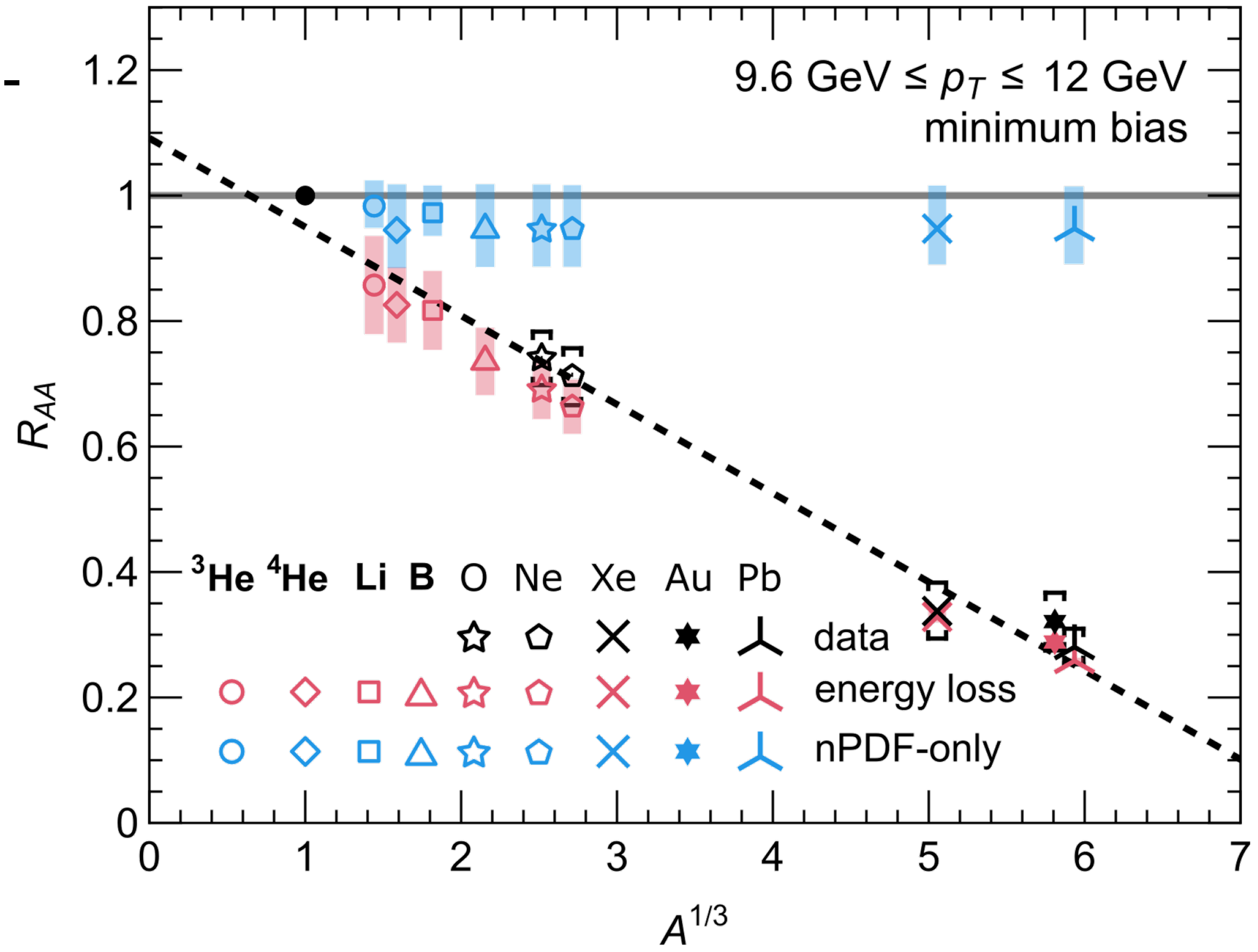
Can we go smaller?

- ^{3}He and ^{6}Li offer the most "bang-for-buck" in terms of discovering energy loss in very small systems
- ^{6}Li and ^{10}B offer ability to clearly differentiate between energy loss and initial state effects
- Such systems could be considered for future LHC runs, similar to Ne+Ne; $\lesssim$ 1 day of runtime would yield enough statistics

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



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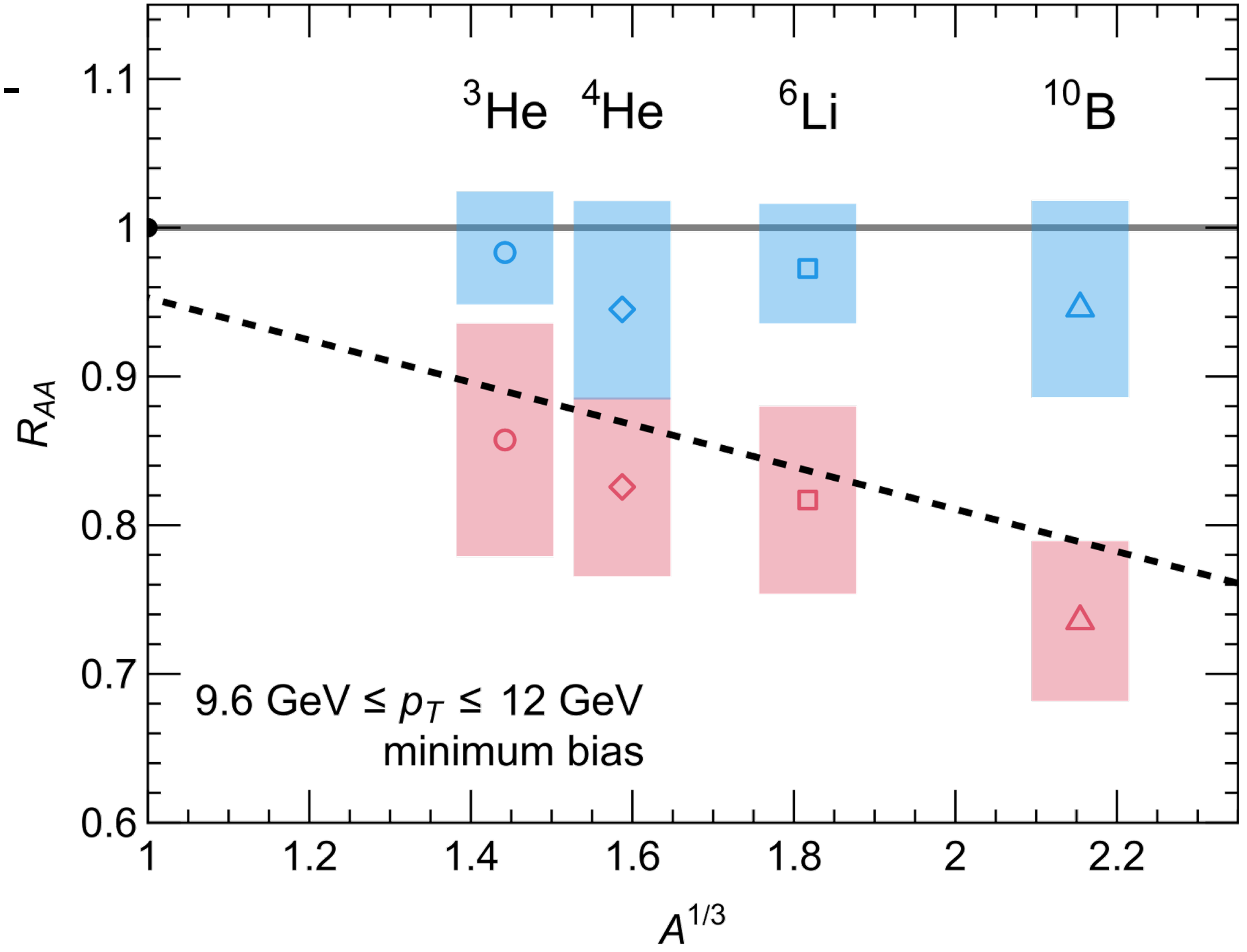
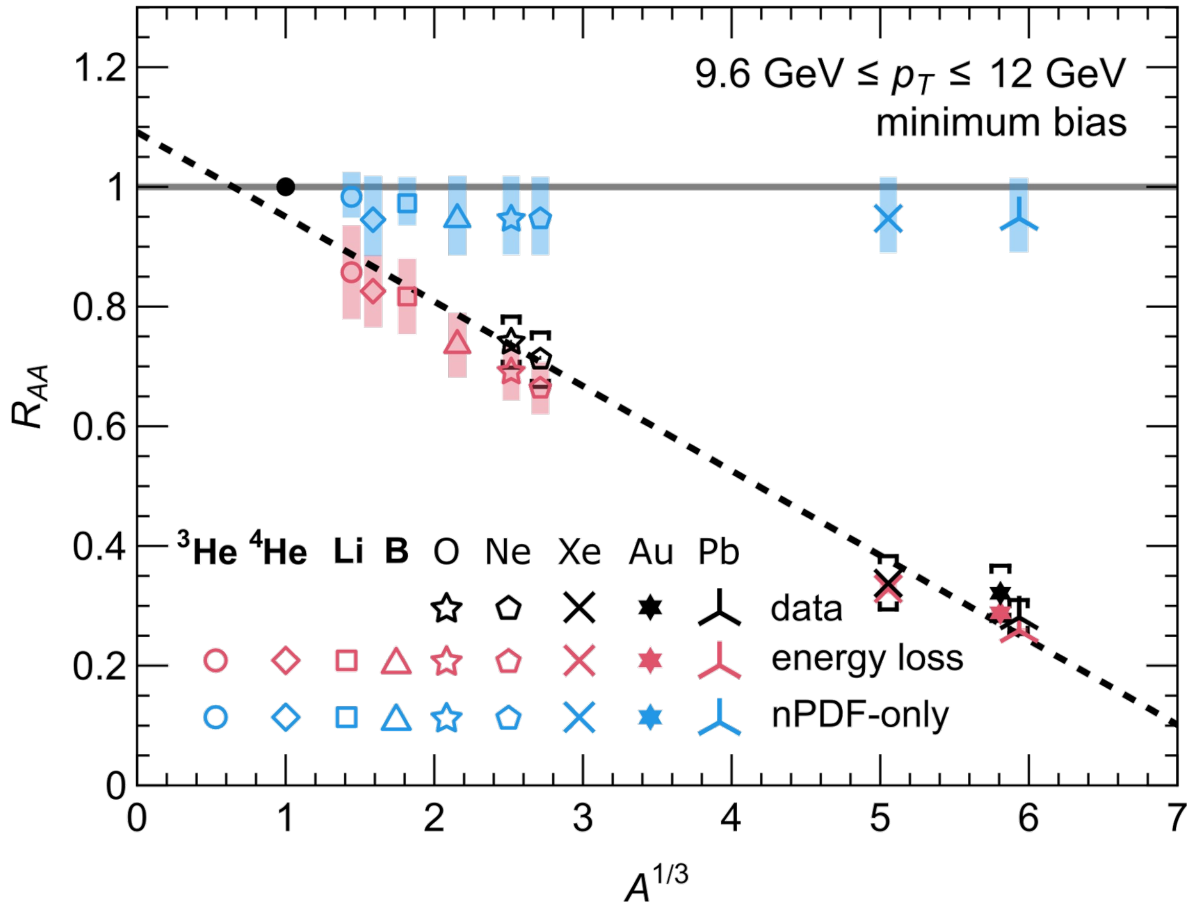


Summary



- Small hadronic collisions answer fundamental questions about collectivity
- Asymmetric systems are complicated; discovering QGP in extremely small systems is best done with **small symmetric systems**
- Lithium collisions form a “sweet spot” for distinguishable energy loss
  - But boron and helium are also possibilities!
- For LHC run 4 (~2031), a short run of new ions is being discussed
  - We argue that small symmetric light-ion collisions should be considered
  - **Future:** input from
    - Nuclear structure interests (alpha clustering in boron / lithium?)
    - Hydrodynamic calcluations (out of equilibrium evolution? Applicability of hydro in small systems?)

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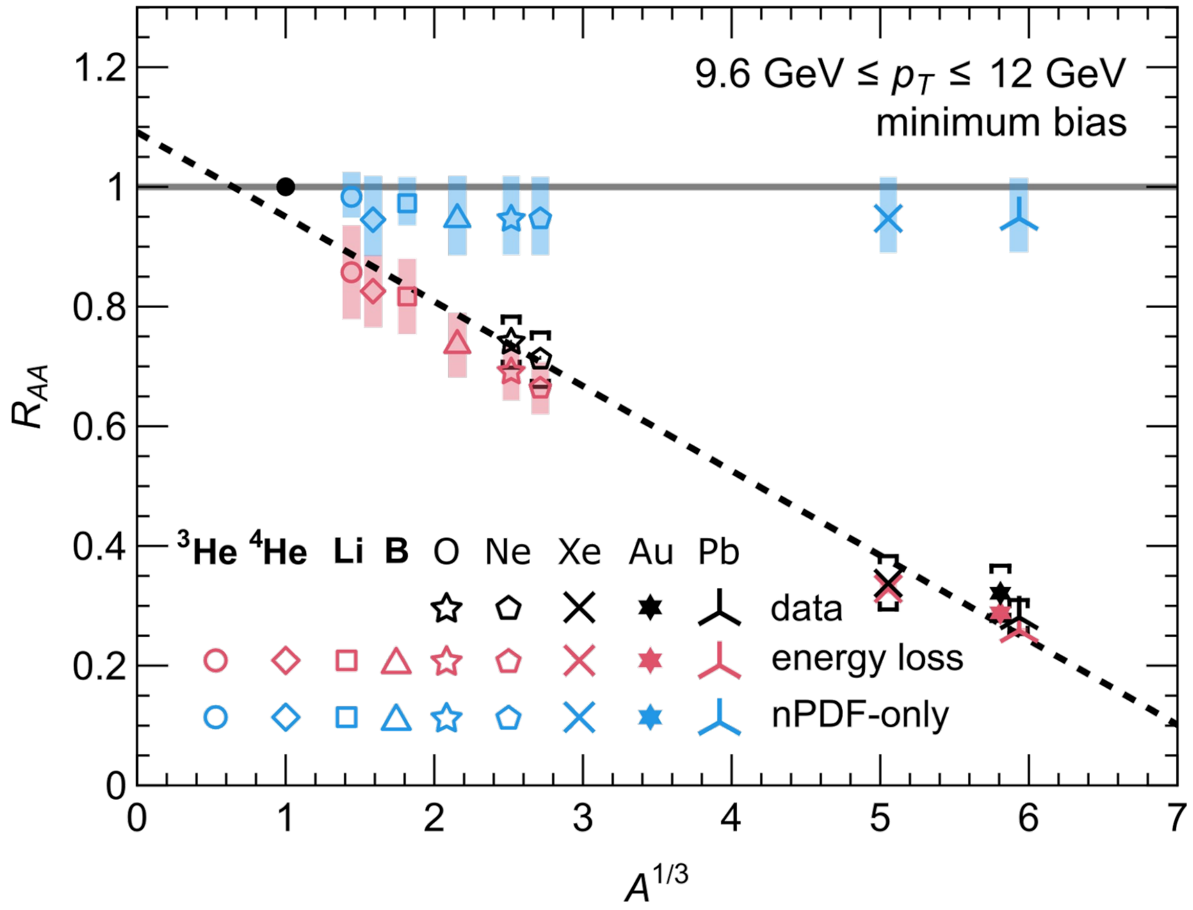

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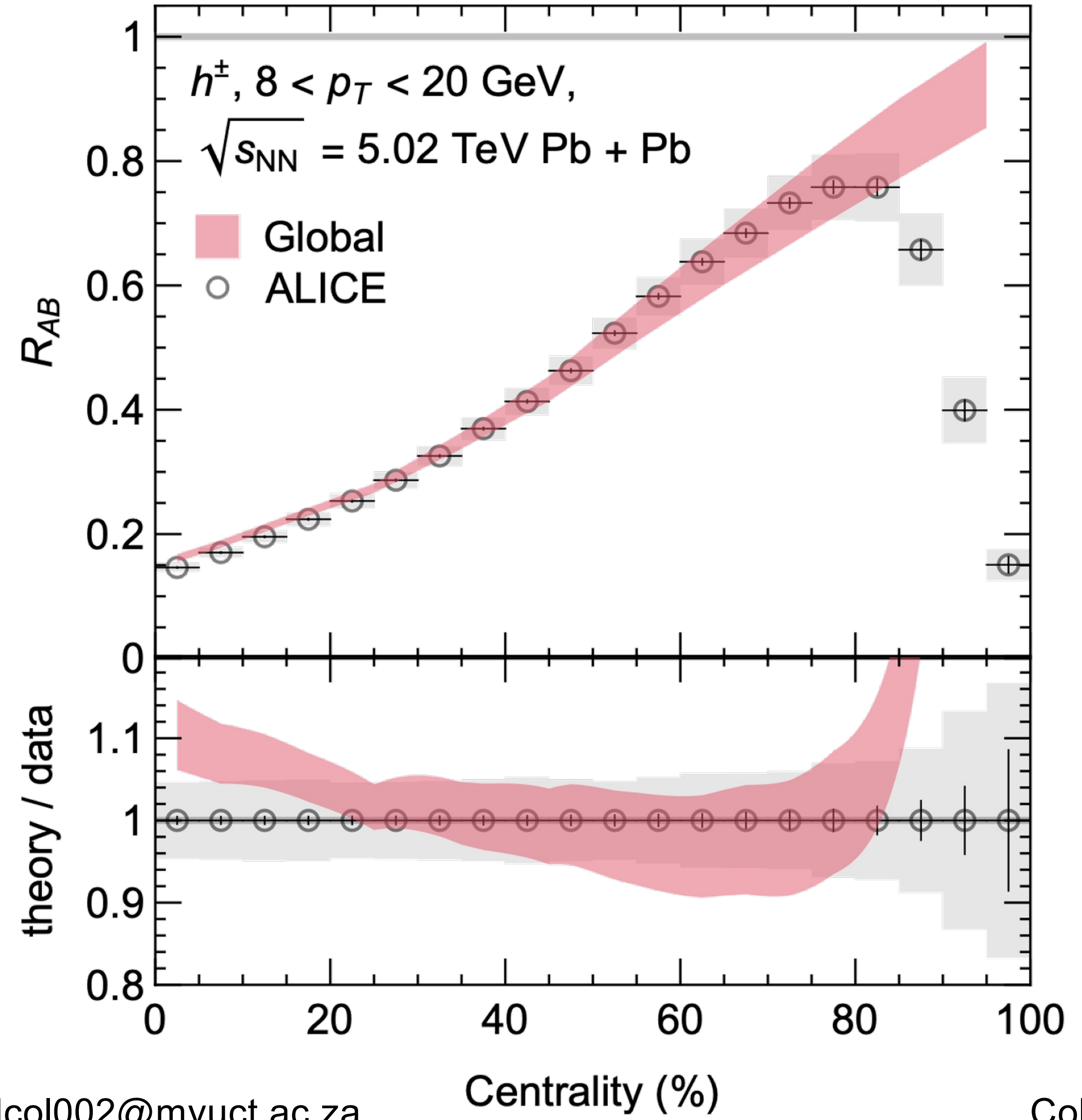
Thanks!

Backup

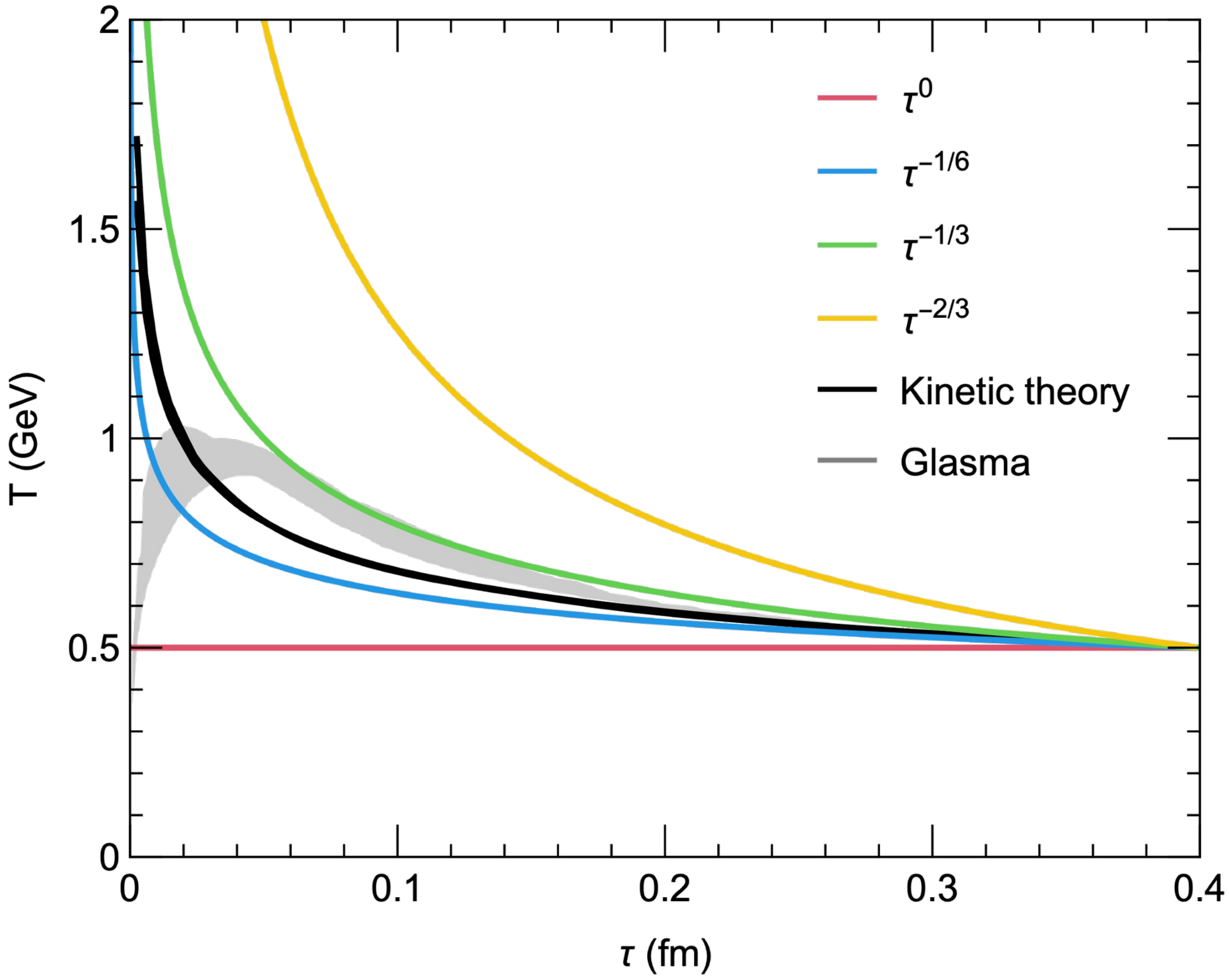
Centrality dependence



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

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

Pre-thermalization time energy loss



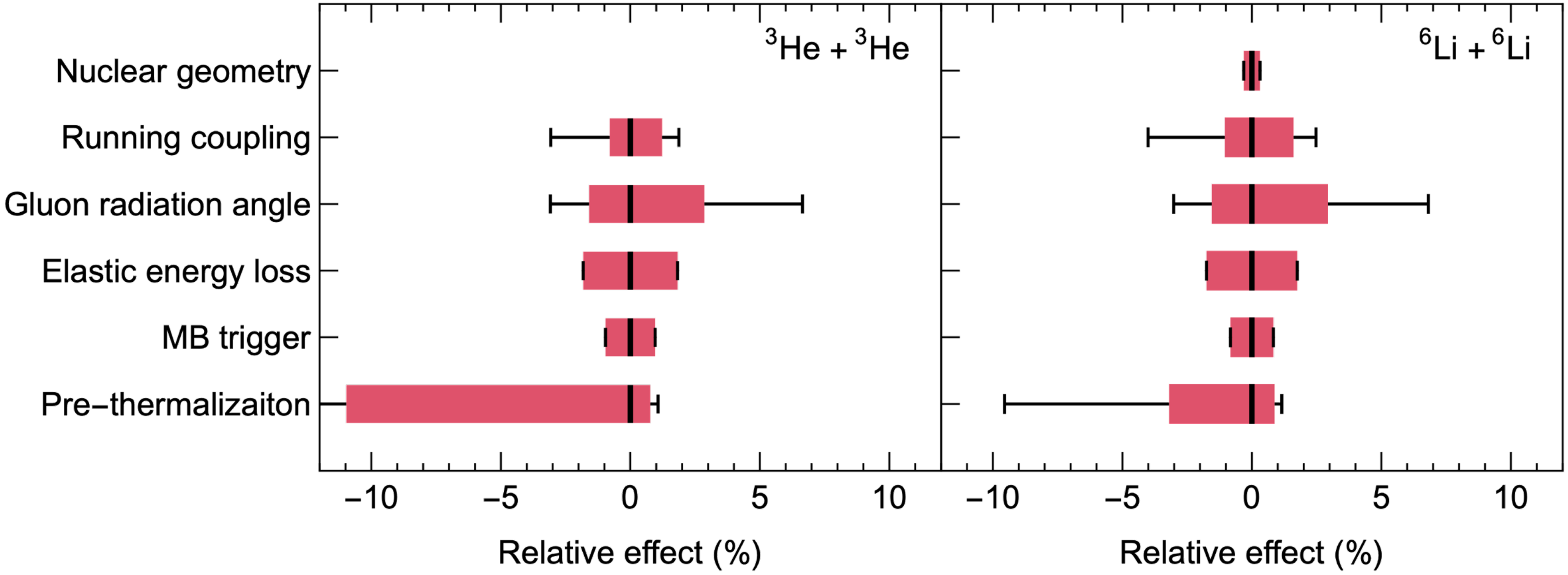
- Not clear how partons lose energy before thermalization
- We use a variety of assumptions as an estimate for the uncertainty
- Assumptions cover the estimates from pre-equilibrium calculations

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).

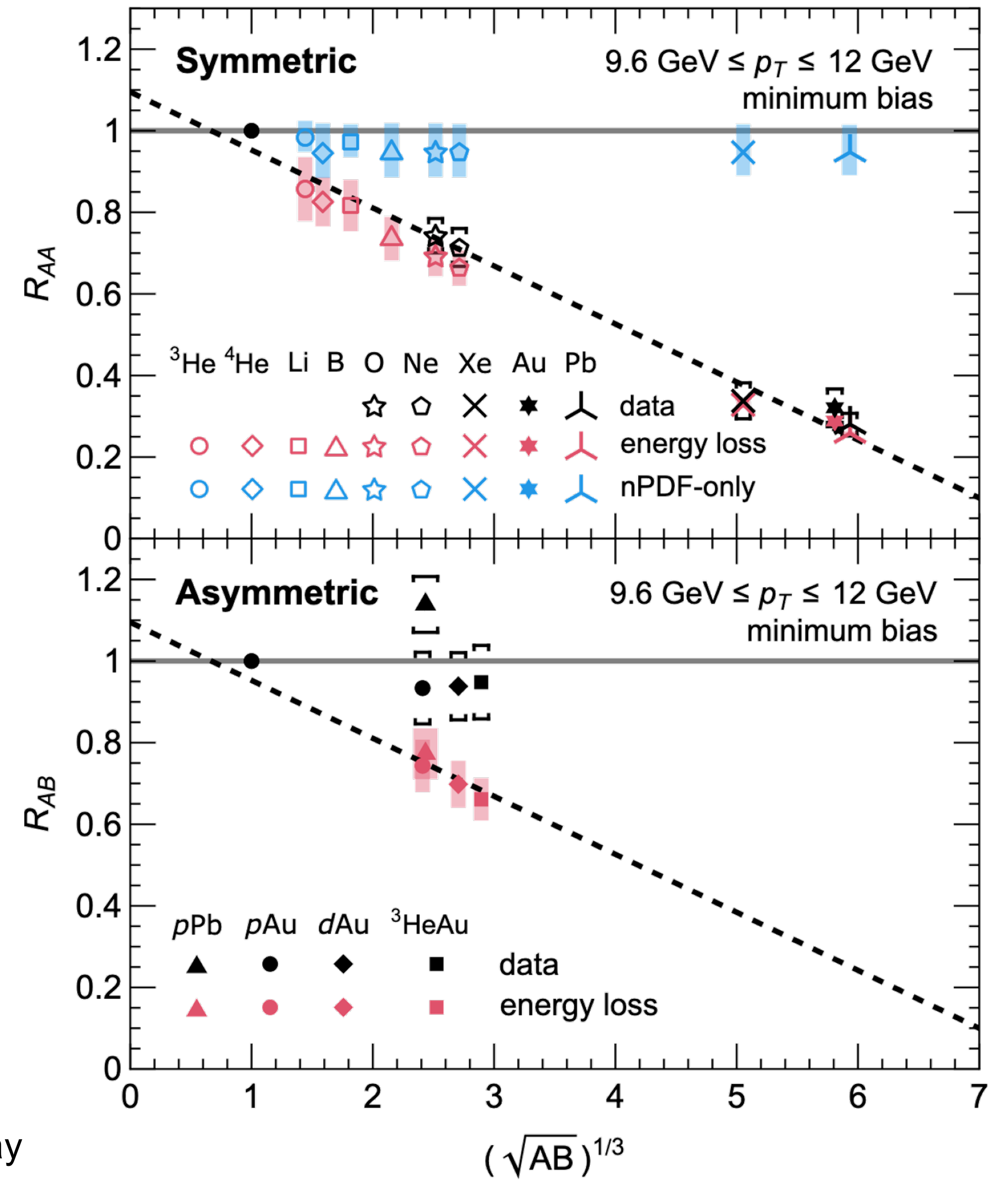
Uncertainty analysis

- 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)



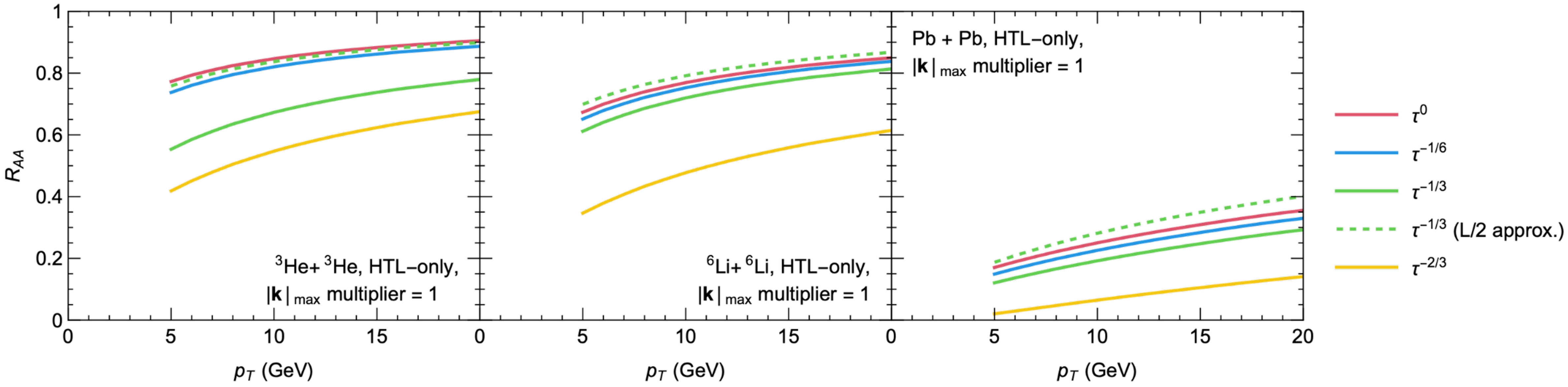
Asymmetric systems

- Further, our model predicts $R_{AB} \simeq \left(\sqrt{AB}\right)^{1/3}$ 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 *p*A



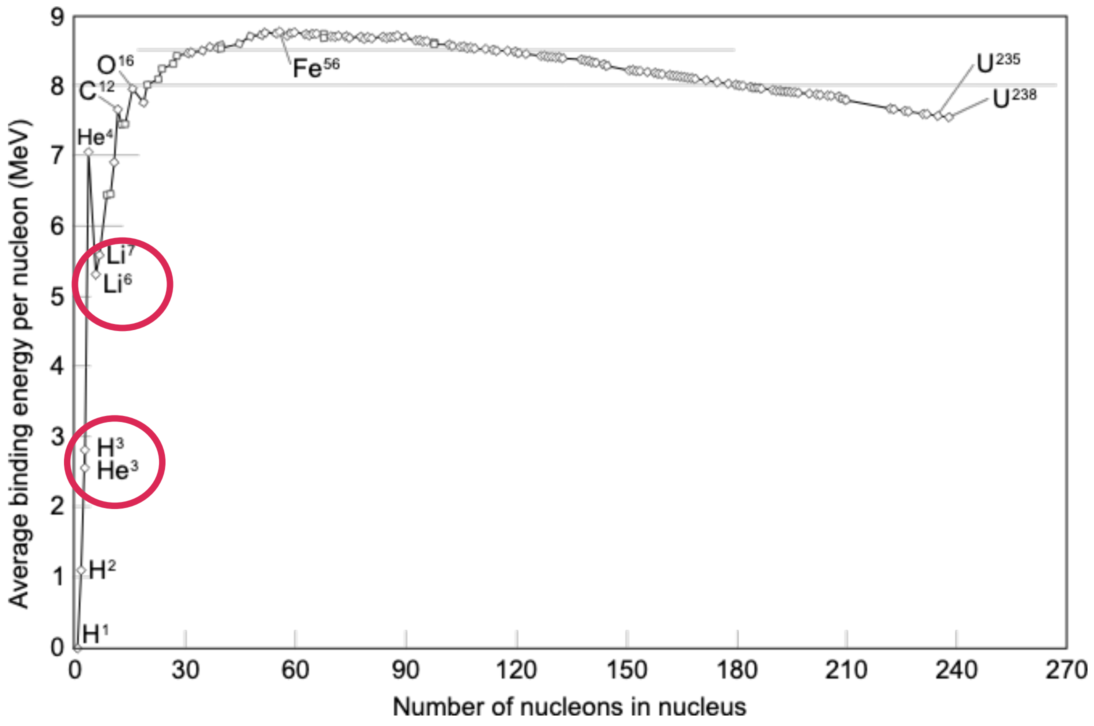
CF, B. Bert, J. Brand, W. Vogelsang, and W. A. Horowitz, arXiv:2512.17832 [hep-ph] (2025).

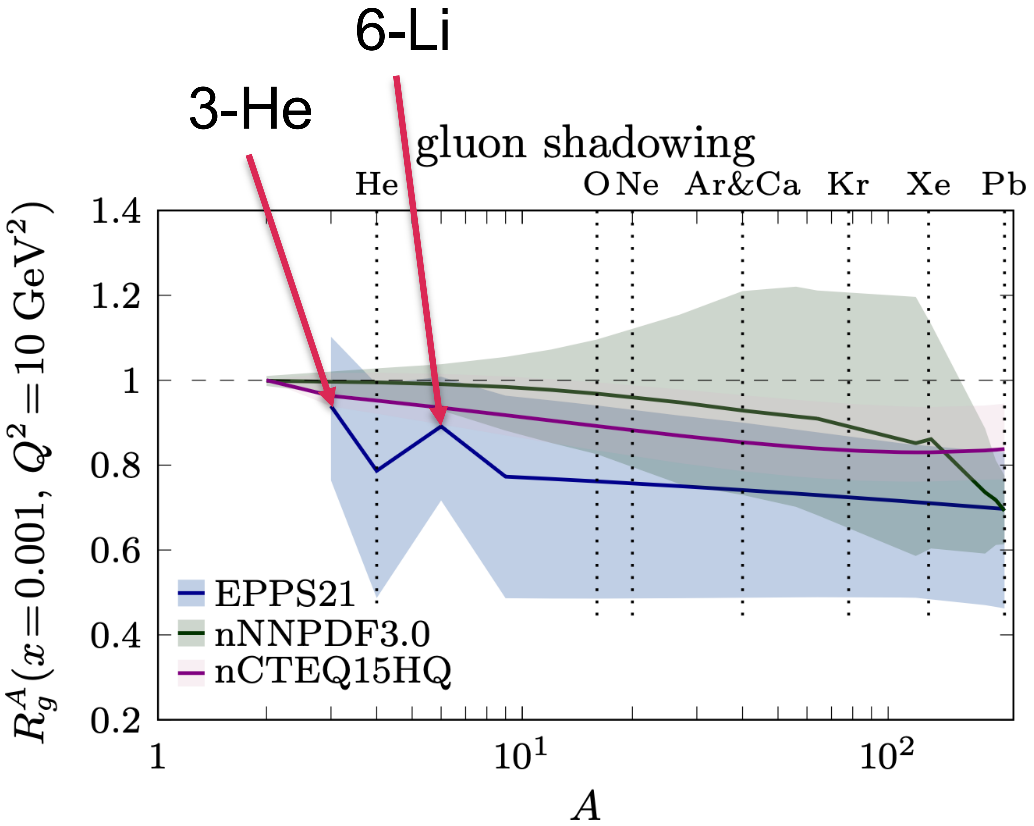
Effect of pre-thermalization e-loss



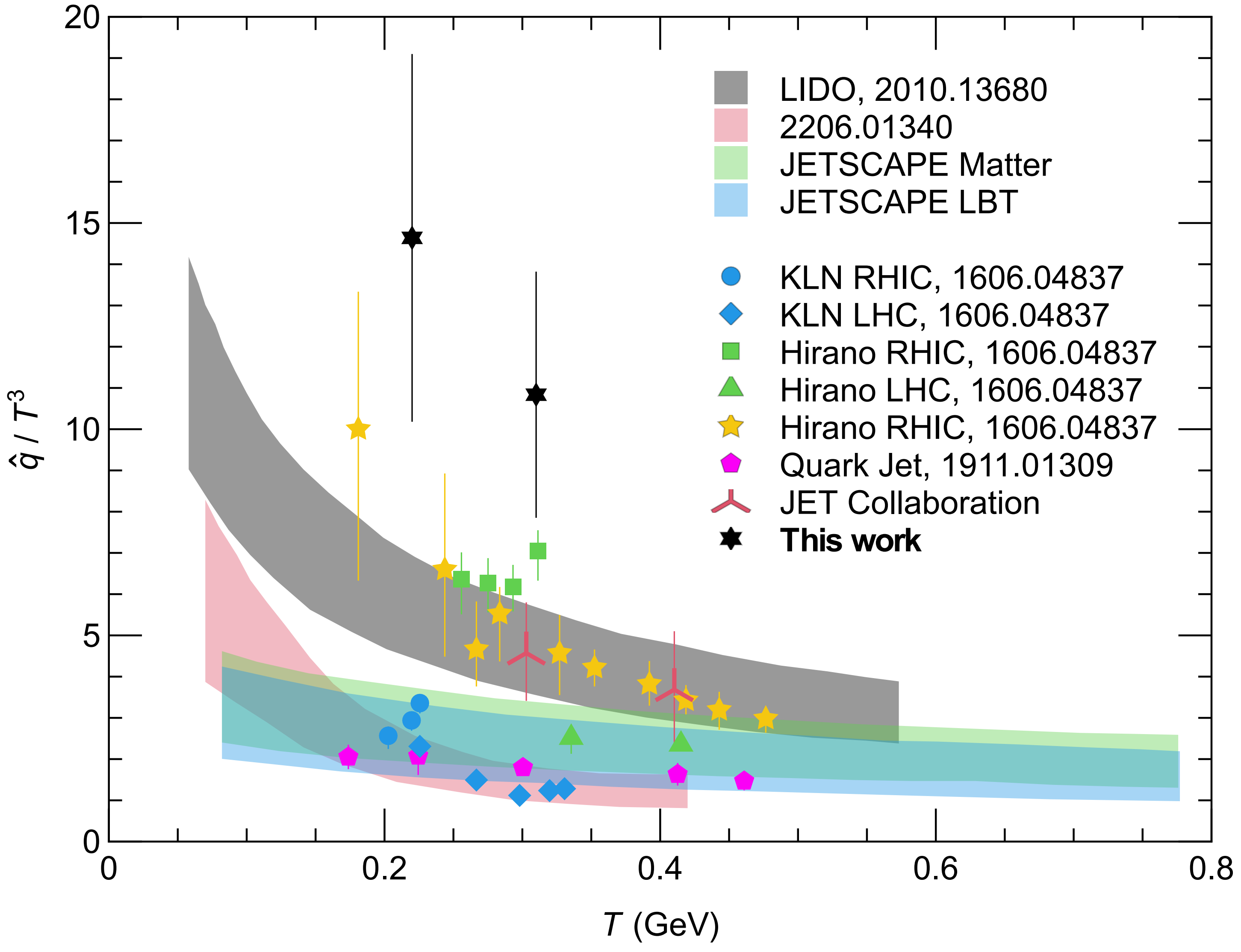
3-He and 6-Li

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





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

Statistical extraction of α_s

$$\chi^2 = \sum_{k}^{N_{\text{exp.}}} \chi_k^2 \quad \text{with} \quad \chi_k^2 \equiv \sum_{i,j}^{N_k} \left(y_{k,i} - \mu_{k,i}\right)\left(C^{-1}\right)_{k,ij}\left(y_{k,j} - \mu_{k,j}\right)$$

Where

- χ^2 is minimized as a function of α_s
- k indexes the different experimental datasets
- $y_{k,i}$ are the experimental observations for the experimental result k and the data point i
- $\mu_{k,i}$ are the corresponding predictions (as a function of α_s)
- C_k are the covariance matrix for the experimental data k

CF and W. A. Horowitz, arXiv:2505.14568 [hep-ph] (2025).

The covariance matrix C

- Captures the correlations between uncertainties
- **Fully uncorrelated** uncertainties contribute only to the diagonal (statistical & uncorrelated systematics)
- **Fully correlated** uncertainties contribute only to the off-diagonal (correlated & globally correlated systematics)
- In principle, there are
  - correlations between experiments, centrality classes, particle species, but the form is not known.
  - Contributions from theoretical uncertainties

JETSCAPE, Phys. Rev. C **109**, 064903 (2024).

R. A. Soltz, D. A. Hangal, and A. Angerami, Phys. Rev. C **111**, 034911 (2025).

CF and W. A. Horowitz, arXiv:2505.14568 [hep-ph] (2025).

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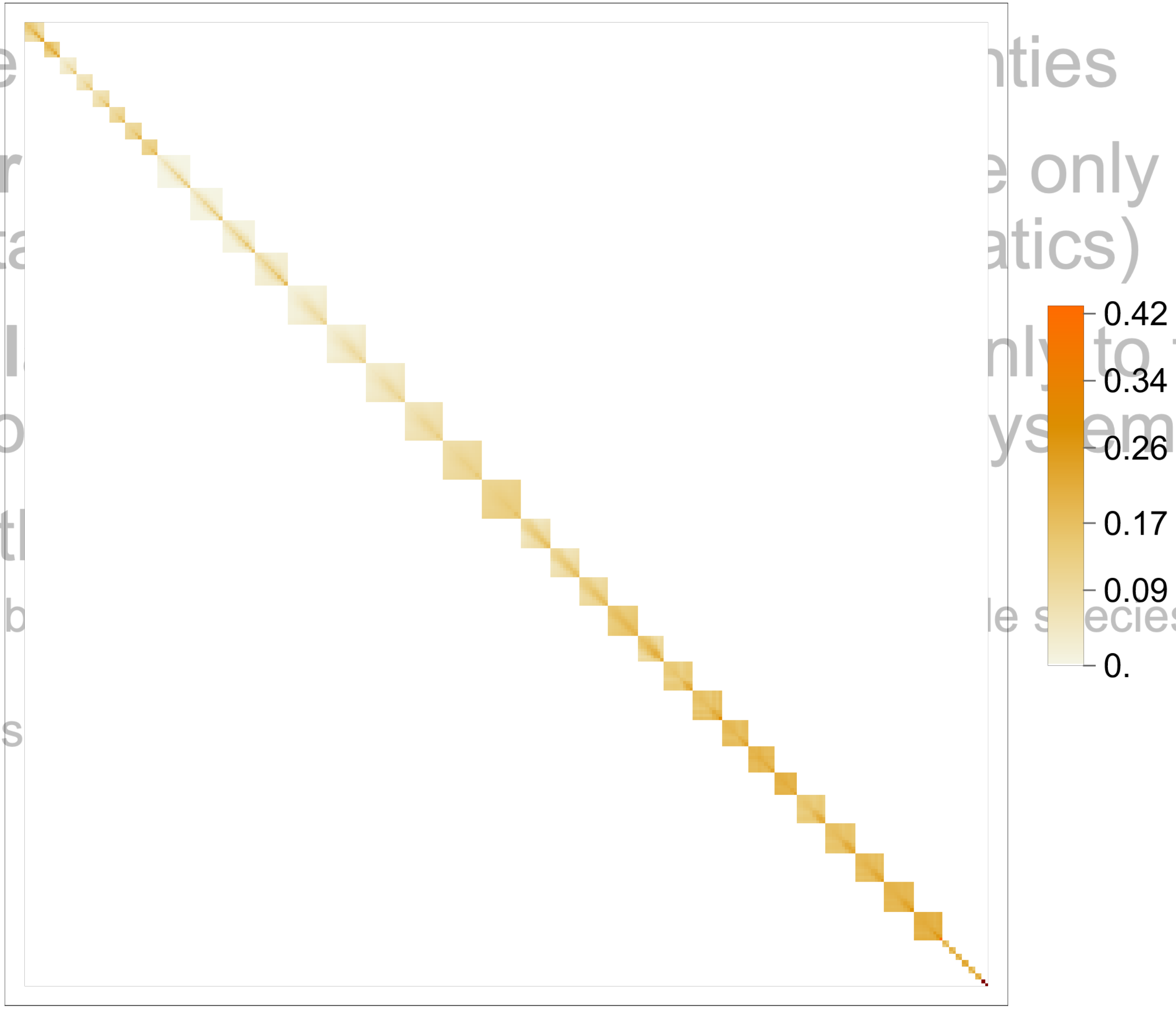

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Baseline predictions

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

$$d\sigma_{AB\to hX} = \sum_{a,b,c} f_{a/A}(x_a, \mu_F) \otimes f_{b/B}(x_b, \mu_F) \quad (3)$$

$$\otimes\, d\hat{\sigma}^c_{ab}(x_a P_A, x_b P_B, P_h/z, \mu_R, \mu_F, \mu'_F) \otimes D_{c\to h}(z, \mu'_F),$$

$$R^{h,\mathrm{nPDF}}_{AB}(p_T, y) = \frac{1}{AB} \frac{d\sigma^{h+X}_{AB}/dp_T dy}{d\sigma^{h+X}_{pp}/dp_T dy}, \quad (4)$$

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

Geometry

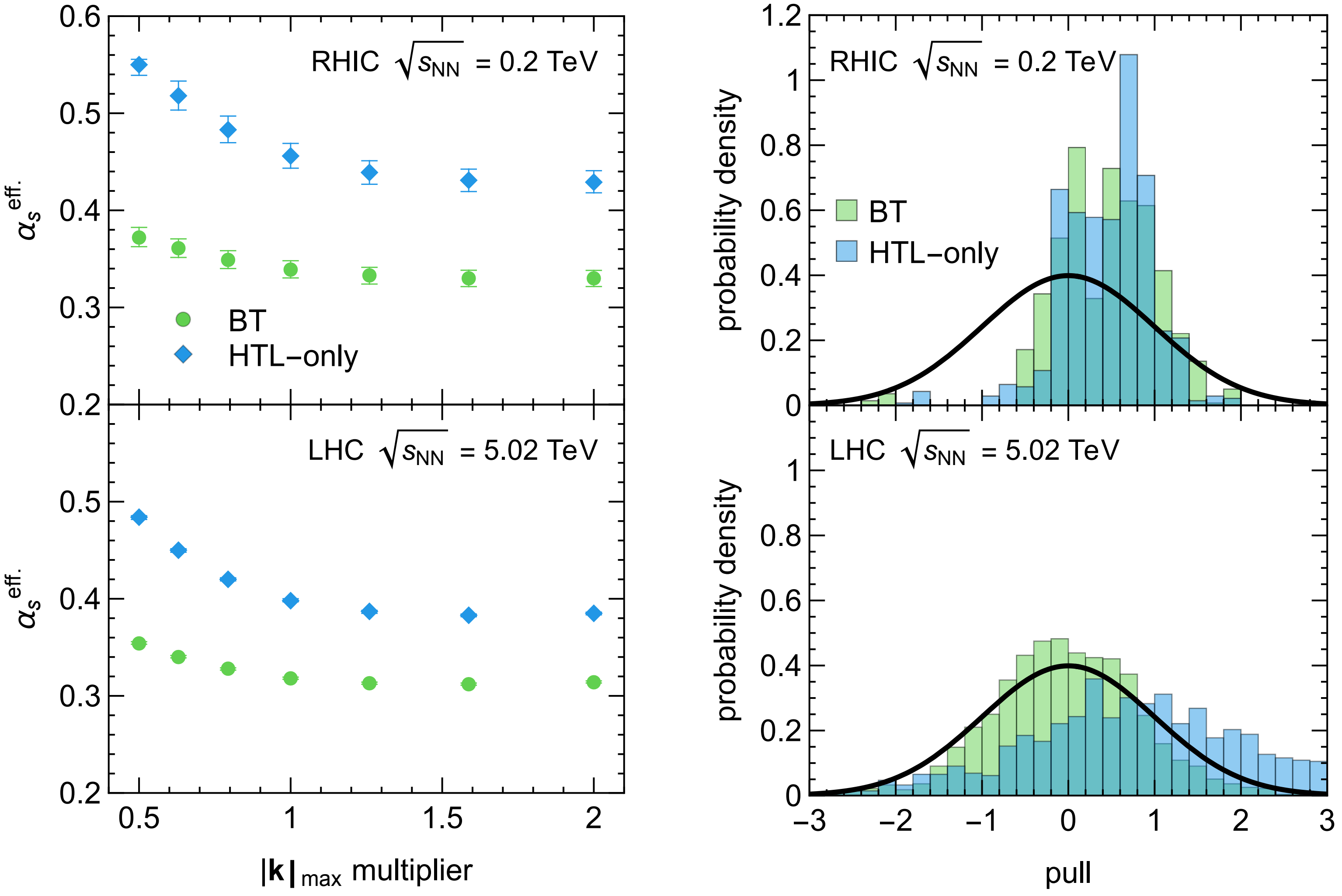
We assume longitudinal Bjorken expansion

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

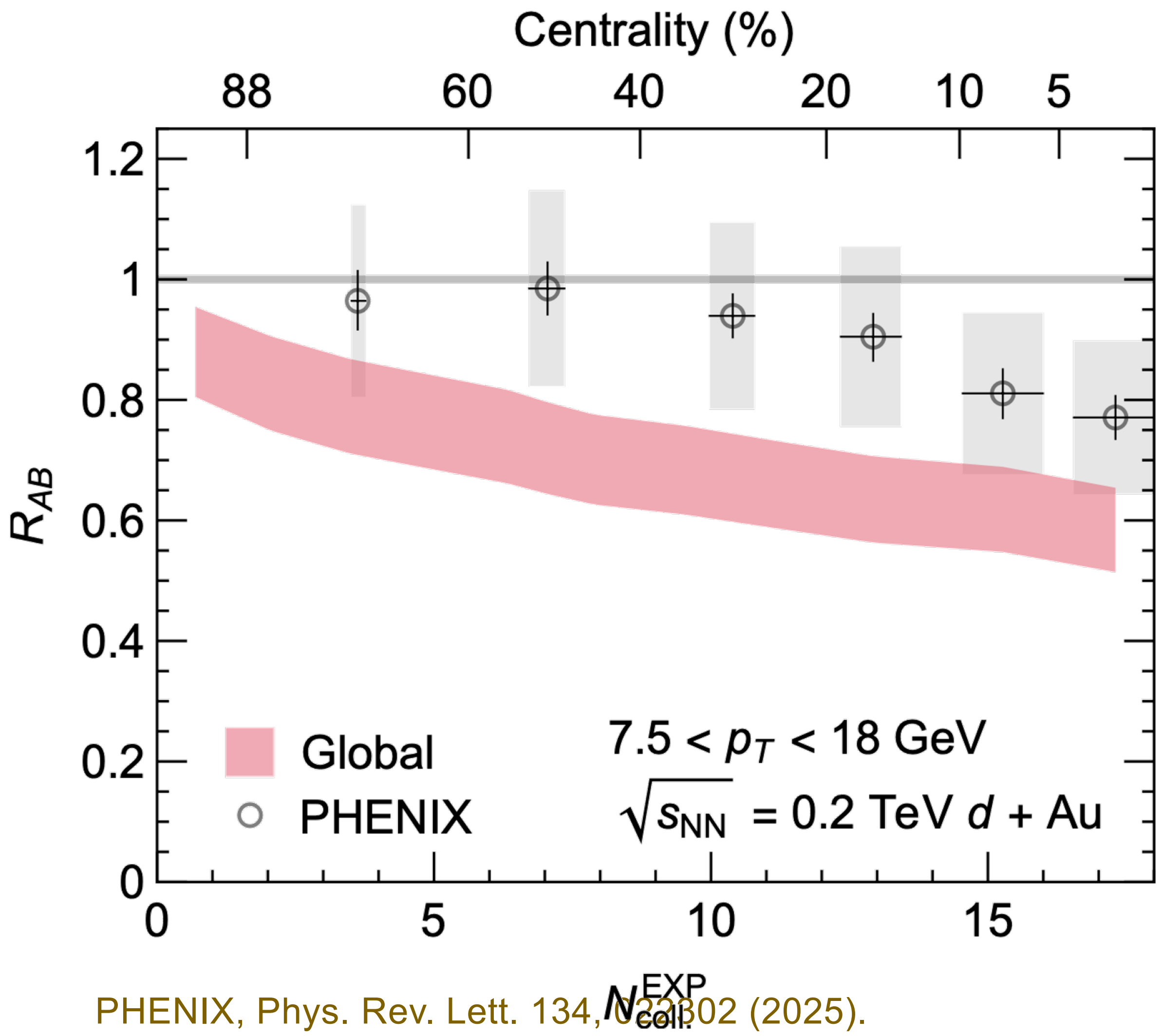
And use the initial collision geometry to generate effective temperatures and lengths (but energy loss with full event-by-event hydrodynamic evolution is in the works!)

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

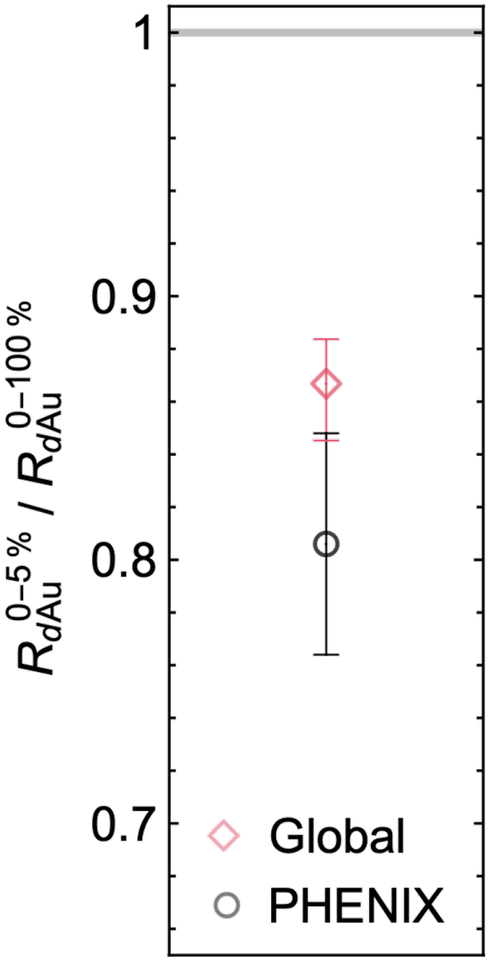
Results of extraction



Small system suppression at RHIC



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



- 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?

Radiative energy loss

We use Djordjevic-Gyulassy-Levai-Vitev (DGLV) radiative energy loss to first order in opacity:

$$\frac{\mathrm{d}N^g_{\mathrm{DGLV}}}{\mathrm{d}x} = \frac{C_R \alpha_s^{\mathrm{eff.}}}{\pi \lambda_g} \frac{1}{x} \int \frac{\mathrm{d}^2\mathbf{q}_1}{\pi} \frac{\mu^2}{\left(\mu^2 + \mathbf{q}_1^2\right)^2} \int \frac{\mathrm{d}^2\mathbf{k}}{\pi} \int \mathrm{d}\Delta z\, \bar{\rho}(\Delta z)$$

$$-\frac{2\left\{1-\cos\left[\left(\omega_1+\tilde{\omega}_m\right)\Delta z\right]\right\}}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+m_g^2+x^2M^2}\left[\frac{(\mathbf{k}-\mathbf{q}_1)\cdot\mathbf{k}}{\mathbf{k}^2+m_g^2+x^2M^2}-\frac{\left(\mathbf{k}-\mathbf{q}_1\right)^2}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+m_g^2+x^2M^2}\right]$$

$$+\frac{1}{2}e^{-\mu_1\Delta z}\left(\left(\frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+x^2M^2}\right)^2\left(1-\frac{2C_R}{C_A}\right)\left\{1-\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]\right\}\right.$$

$$\left.\left.+\frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q}_1)}{\left(\mathbf{k}^2+m_g^2+x^2M^2\right)\left(\left(\mathbf{k}-\mathbf{q}_1\right)^2+m_g^2+x^2M^2\right)}\left\{\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]-\cos\left[\left(\omega_0-\omega_1\right)\Delta z\right]\right\}\right)\right]$$

+ the short pathlength correction (SPLC)

M. Djordjevic and M. Gyulassy, Nucl. Phys. A **733**, 265 (2004).

I. Kolbé and W. A. Horowitz, Phys. Rev. C **100**, 024913 (2019).
CF, A. Grindrod, and W. A. Horowitz, Eur. Phys. J. C **83**, 1060 (2023).

Large formation time approximation

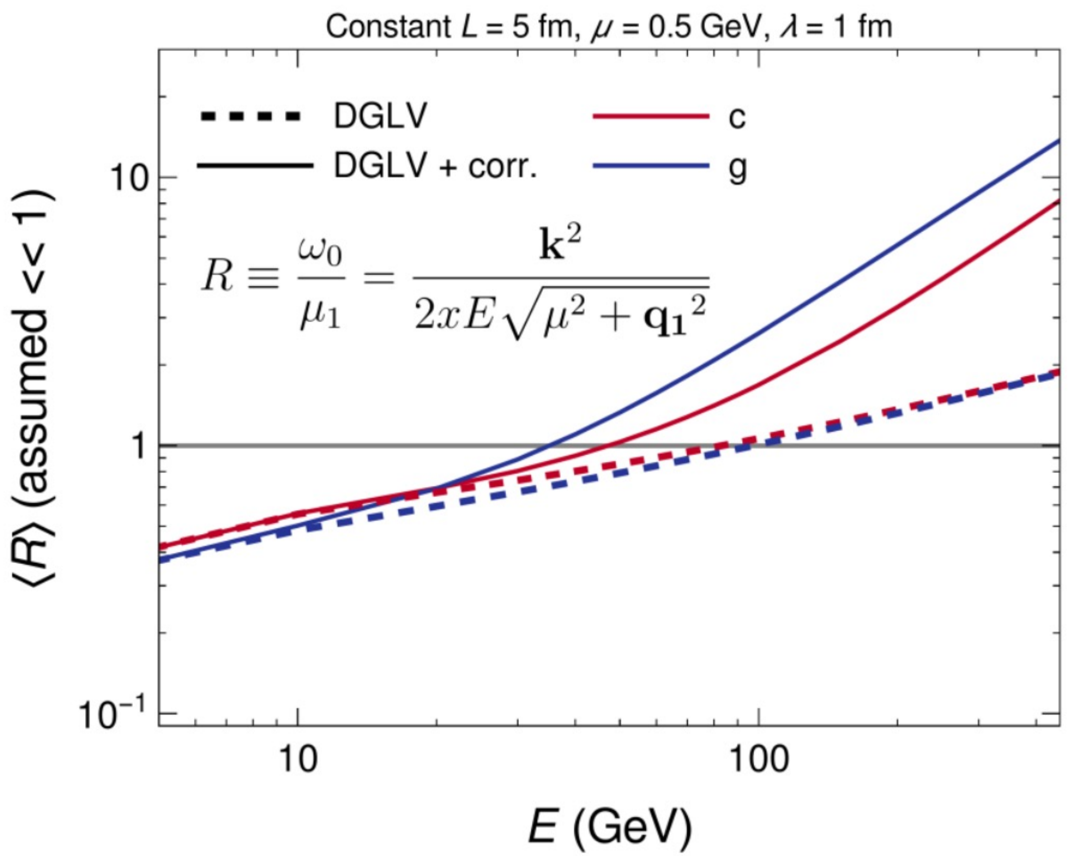
- The large formation time approximation is used in both DGLV and DGLV + SPLC, but it has a much larger impact for SPLC
- We previously showed that this assumption is **not** self-consistently satisfied in either DGLV or DGLV + SPLC, but can be tamed by restricting the phase space of the radiative gluon emission.

$$|\mathbf{k}|_{\text{max}}^{\text{LFT + coll.}} = \min\left[2xE(1-x), \sqrt{2xE}\left(\mu^2+\mathbf{q}^2\right)^{1/4}\right]$$

In this work, we vary this bound up and down by factors of two to estimate the sensitivity to this constrain.

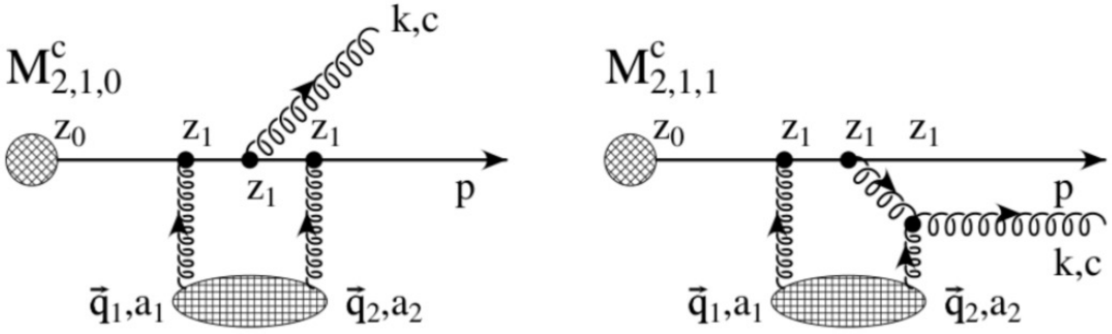
CF, A. Grindrod, and W. A. Horowitz, Eur. Phys. J. C **83**, 1060 (2023).

Large Formation Time Assumption



- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption

- Also impacts DGLV



$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

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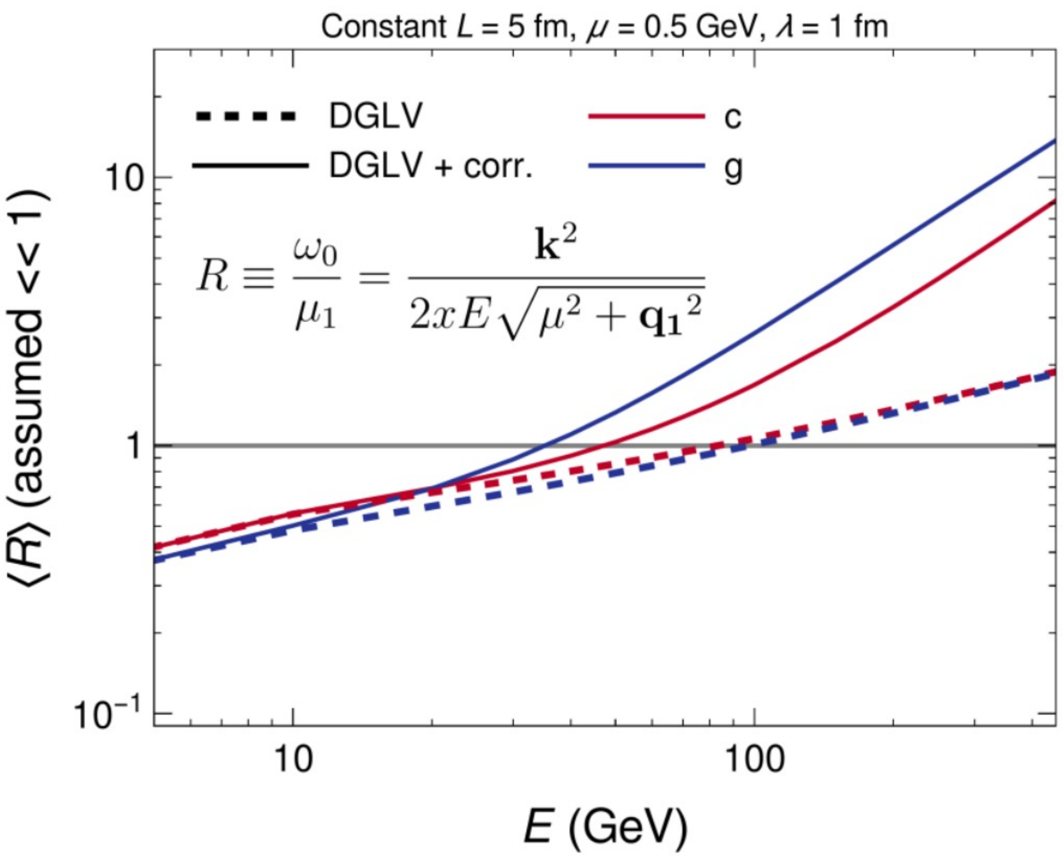
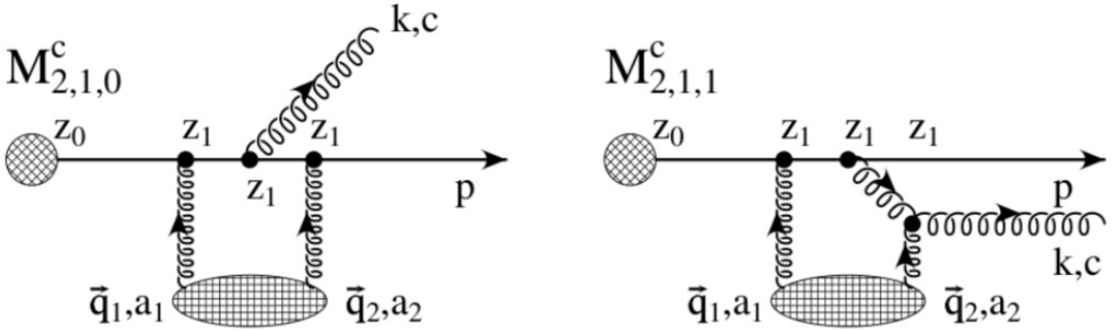
Large Formation Time Assumption



- **Large contributions** to SPL corr. at high energies from regions of phase space **not allowed** according to Large Formation Time assumption
- Also impacts DGLV
- Future work should include a full rederivation of DGLV with LFT assumption relaxed
- Can implement a phenomenological cut in the phase space as well to limit assumption-violating contributions



$$\sim \frac{\mathbf{k}_\perp^2 + m_g^2 + x^2 M^2}{2\omega} \frac{1}{\mu_1} \to 0$$

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Controlling the LFT approximation

- Collinearity can be enforced via $|\mathbf{k}_\perp|_{\mathrm{max}} = 2xE(1-x)$
- Similarly, collinearity + LFT $\Rightarrow |\mathbf{k}_\perp|_{\mathrm{max}} = \mathrm{Min}[2xE(1-x), \sqrt{2xE\mu_1}]$.