Soft physics and the initial condition of the quark-gluon plasma

Giuliano Giacalone

Institut für Theoretische Physik (ITP)
Universität Heidelberg

October 26th 2022

OUTLINE

1 – Collective flow and the initial condition at the end of 2020. Stark inconsistencies among models.

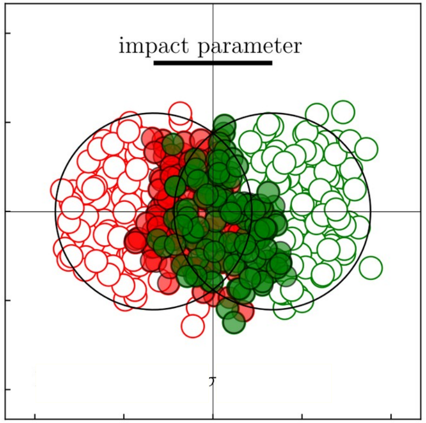
2 – Progress in 2021/2022. Observables to restore consistency and the role of the nucleon size.

3 – Future directions and prospects across systems.

1 – Collective flow and the initial condition at the end of 2020. Stark inconsistencies among models.

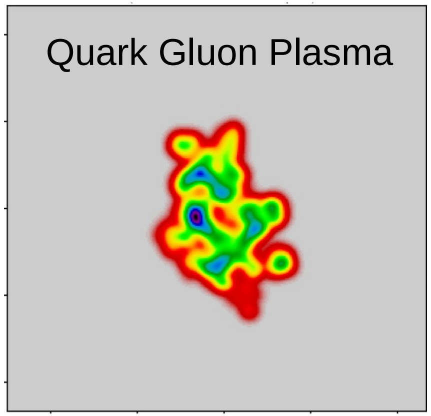
Established picture of a heavy-ion collision

COLLISION GEOMETRY AND NUCLEON SIZE



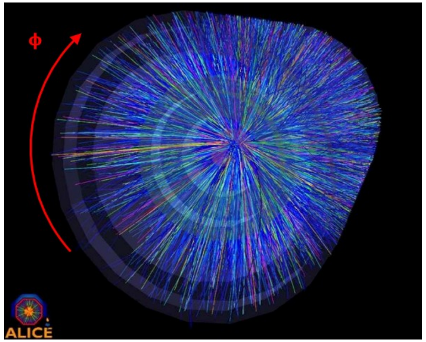
ENERGY DEPOSITION AND EQUILIBRATION ⇨

HYDRODYNAMICS, RESCATTERING



⇨

FINAL STATE



Soft physics = dynamics of the bulk of particles sitting at low transverse momenta.

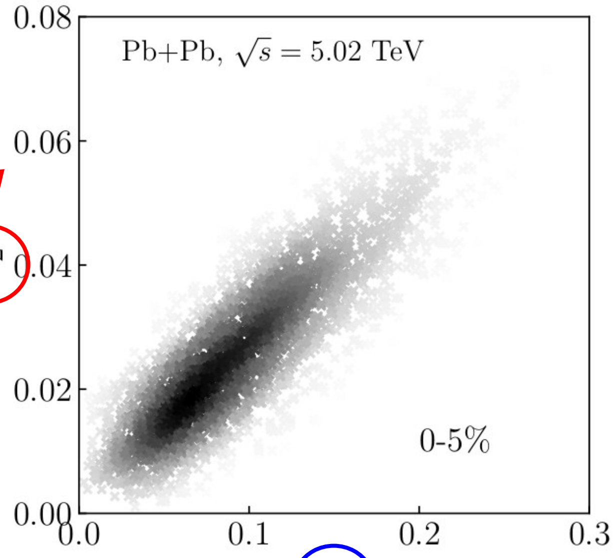
$$\frac{d^2N}{dp_{\mathrm{T}}d\phi} = \underbrace{\frac{dN}{2\pi dp_{\mathrm{T}}}}_{\text{EXPLOSIVENESS OF EXPANSION}} \underbrace{\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)}_{\text{AZIMUTHAL ANISOTROPY}}$$

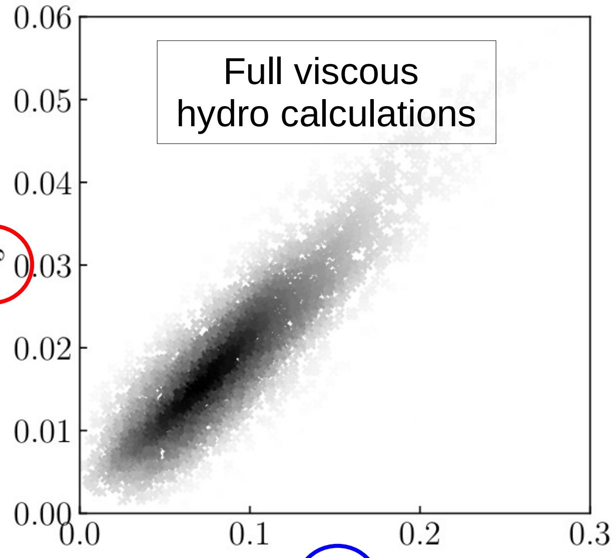
Hydrodynamic nature of expansion ensures “factorization” of the problem.

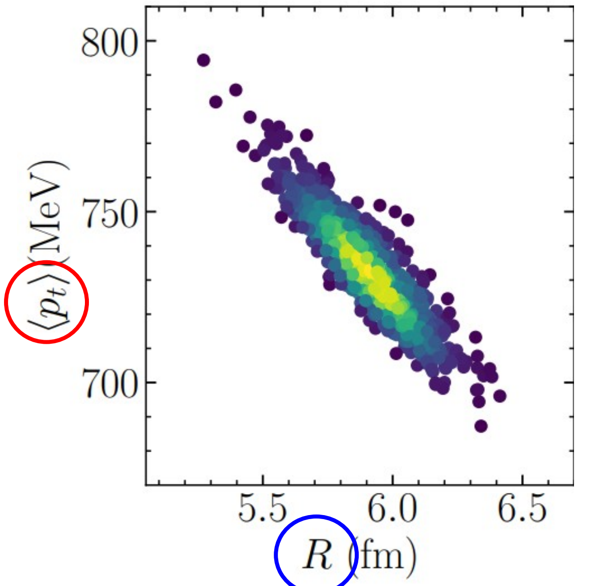
FINAL STATE = RESPONSE * INITIAL STATE

$$\frac{d^2N}{dp_T d\phi} = \underbrace{\frac{dN}{2\pi dp_T}}_{\langle p_t \rangle} \left(\underbrace{1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)}_{v_n} \right)$$

final state anisotropy and mean momentum







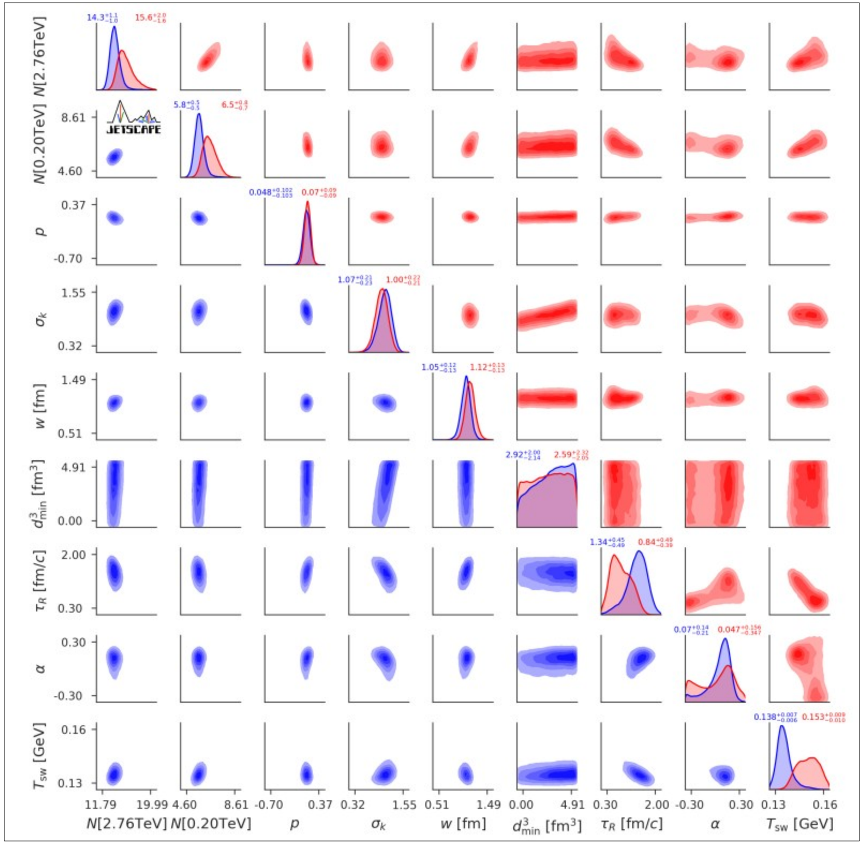
initial state anisotropy and mean transverse size

[Giacalone, arXiv:2101.00168]

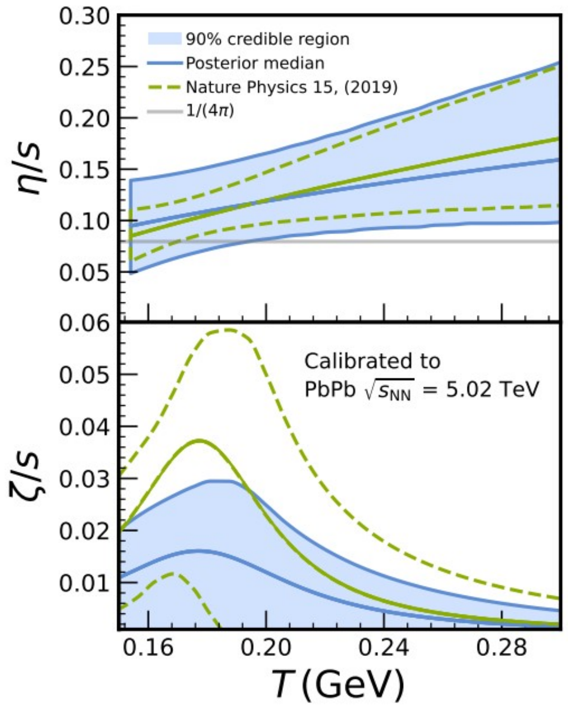
Comprehensive Bayesian analyses for determination of initial states and hydrodynamic response (transport properties).

$$\Pr(p \,\&\, D) = \Pr(p) \times \Pr(D|p) = \Pr(D) \times \Pr(p|D)$$
$$\text{prior} \times \text{likelihood} = \text{evidence} \times \text{posterior}$$

[JETSCAPE, PRC **103** (2021) 5, 054904]
[JETSCAPE, PRL **126** (2021) 24, 242301]

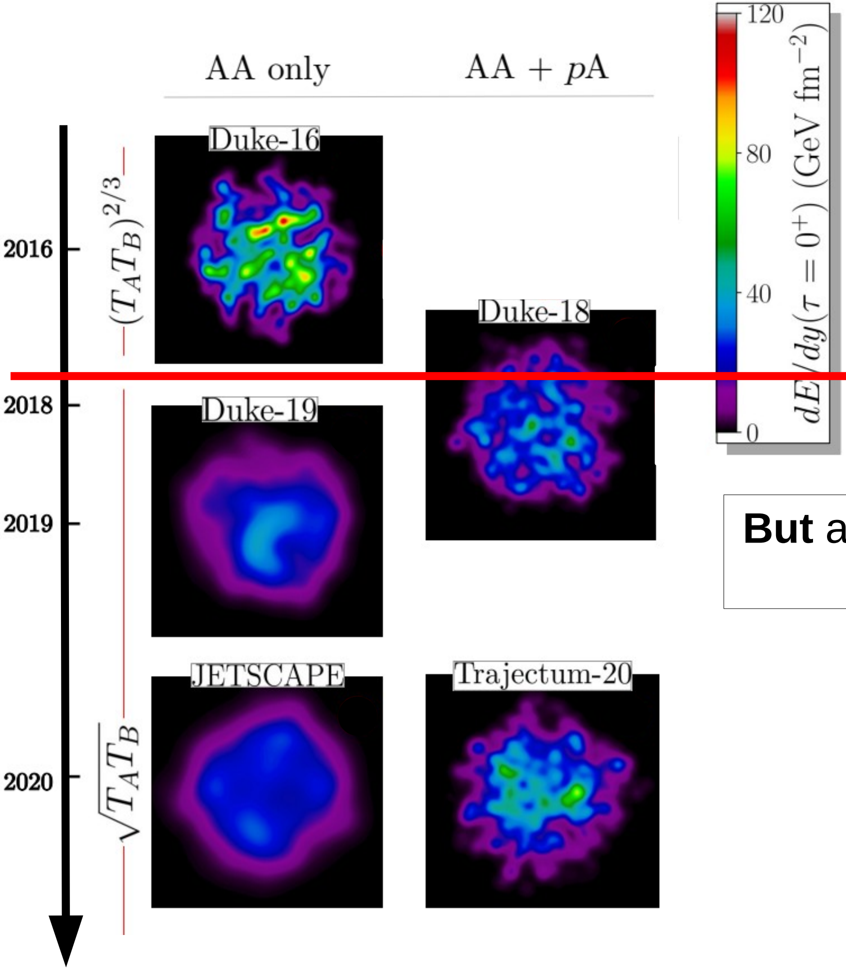


[Bernhard, Moreland, Bass, Nature Phys. **15** (2019) 11, 1113-1117]
[Parkkila, Onnerstad, Kim, PRC **104** (2021) 5, 054904]

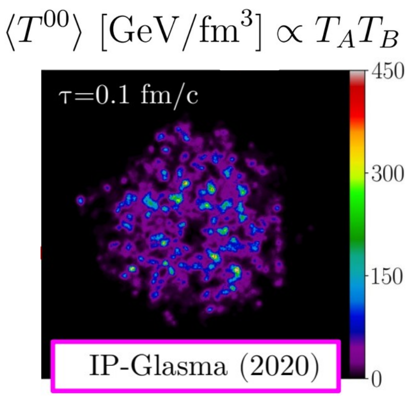


Nice agreement found between IP-Glasma model and initial state from the first Bayesian analysis (2016).

[Bernhard *et al.*, PRC **94** (2016) 2, 024907]
[Schenke, Shen, Tribedy, PRC **102** (2020) 4, 044905]

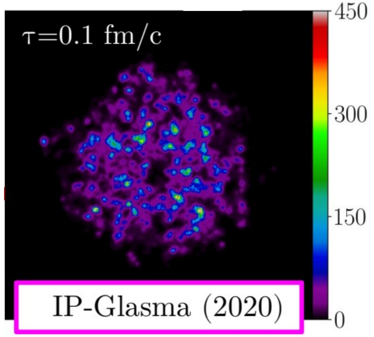


$\approx$



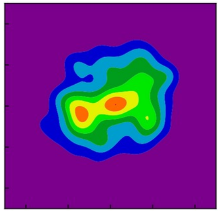
But agreement has disappeared over the years.
The QGP becomes very smooth.

$\neq$

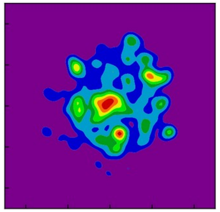


Disagreement in initial state implies disagreement in transport properties.

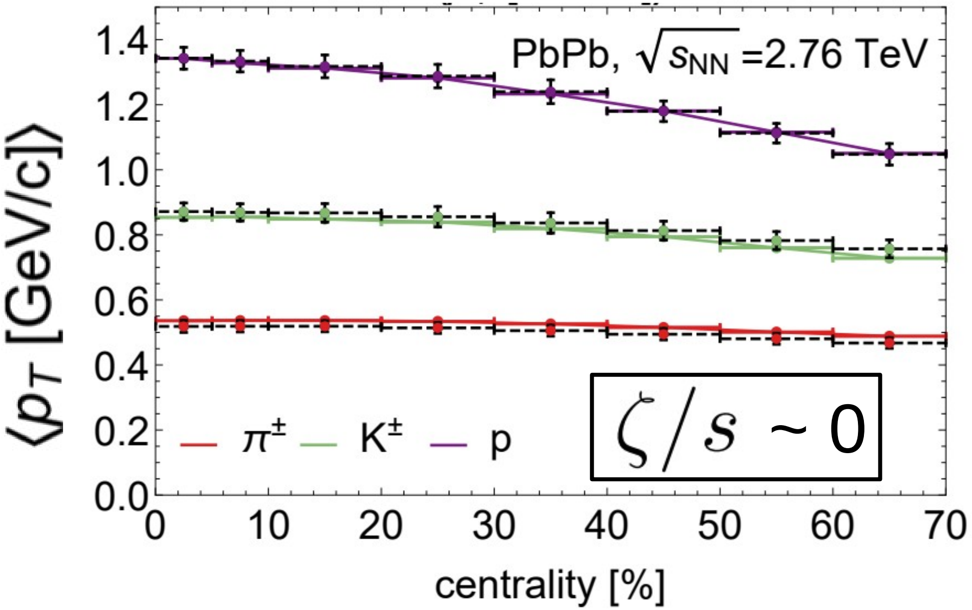
Is the bulk viscosity nonzero?
Depends on the model… smooth vs. sharp.



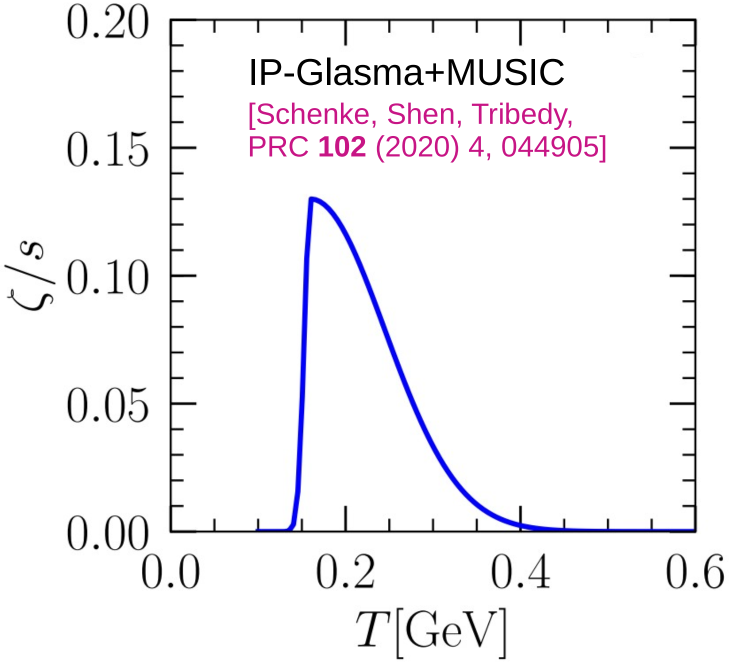
VS



[Nijs, van der Schee, Gürsoy, Snellings, PRC **103** (2021) 5, 054909]
[Nijs, van der Schee, Gürsoy, Snellings, PRL **126** (2021) 20, 202301]



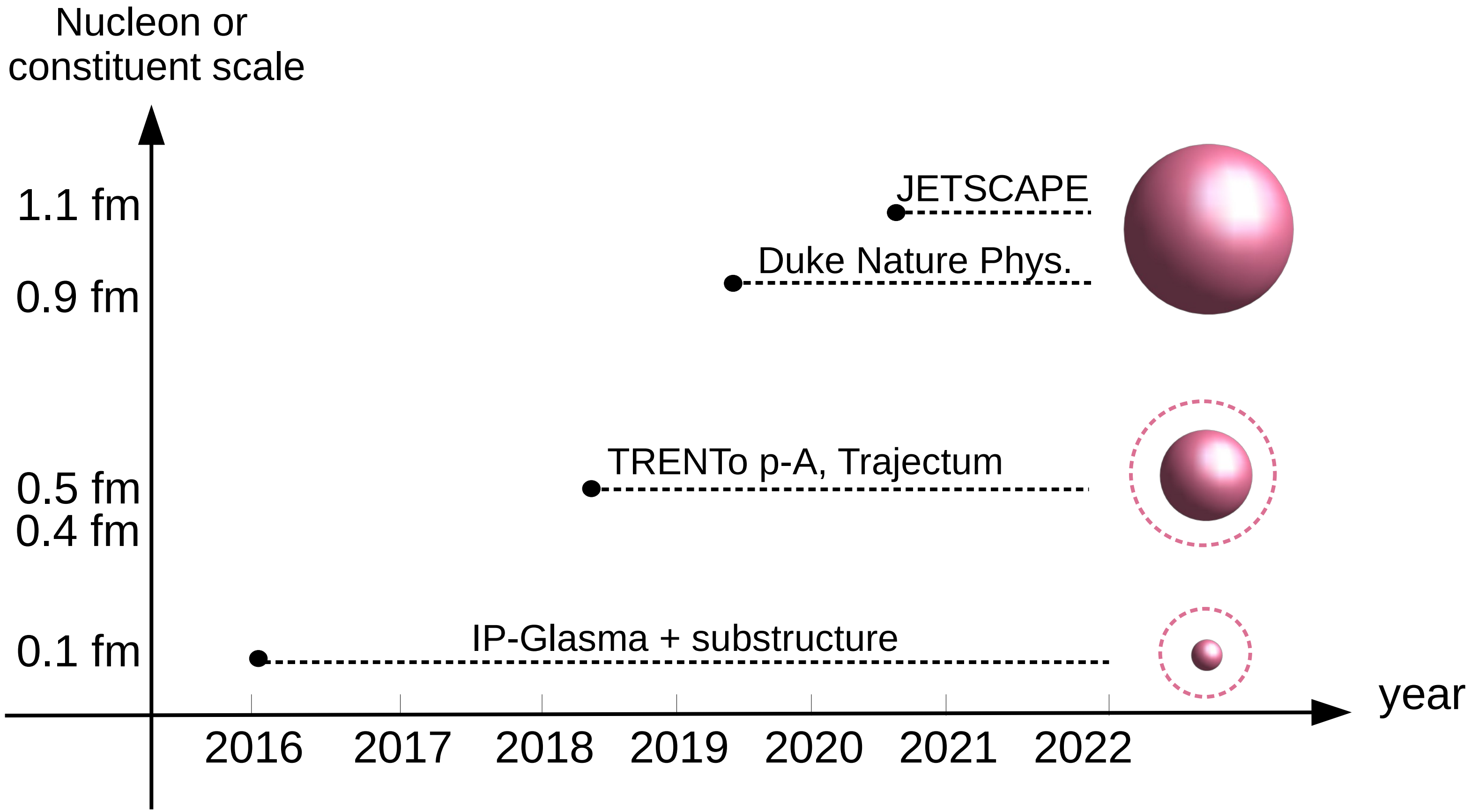
VS

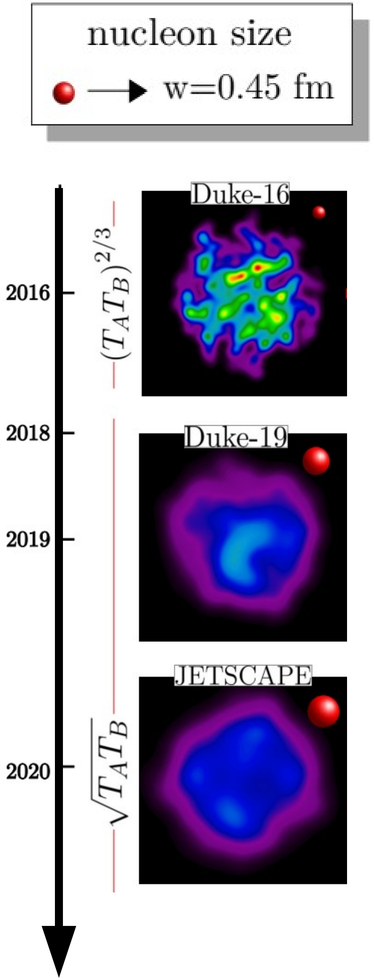


End of 2020: great confusion!

2 – Progress in 2021/2022.
Observables to restore consistency and the role of the nucleon size.

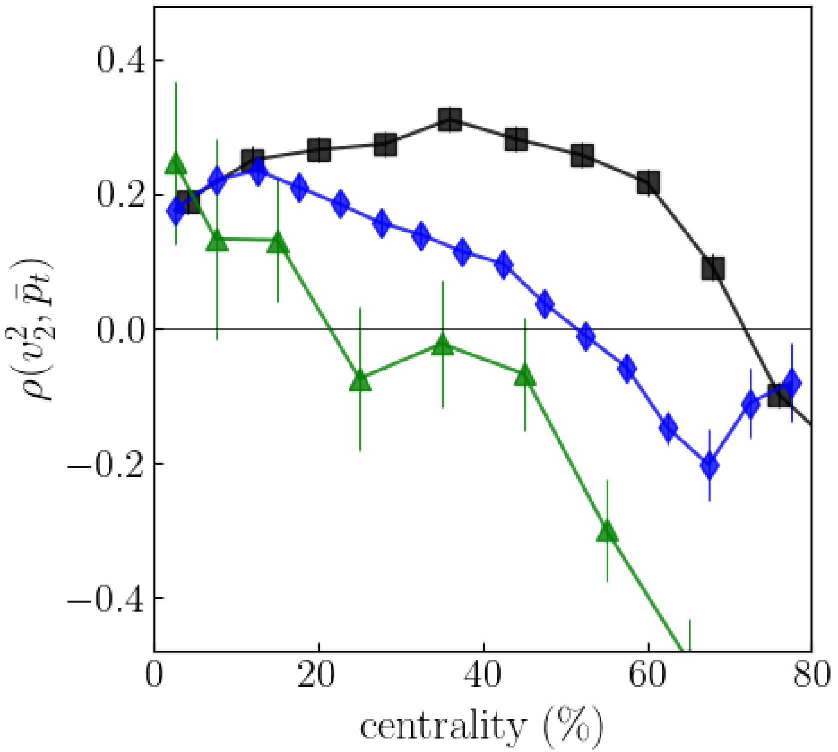
Profiles got smooth because size associated to nucleons got huge.

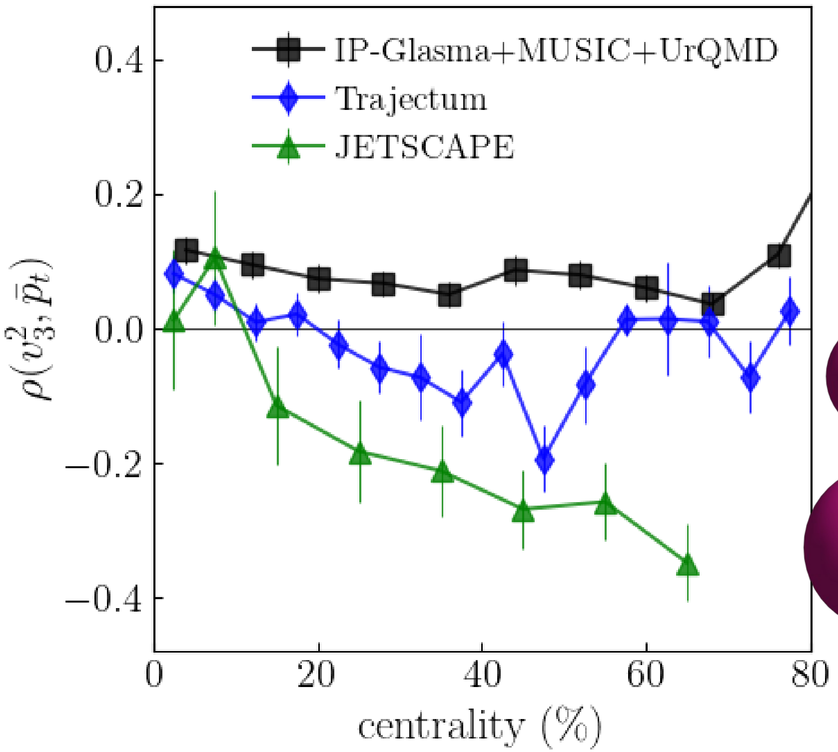


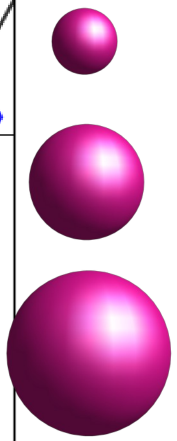


Can we discern different models presenting the same v_n?

The 2021 realization: Use mean momentum–flow correlations.

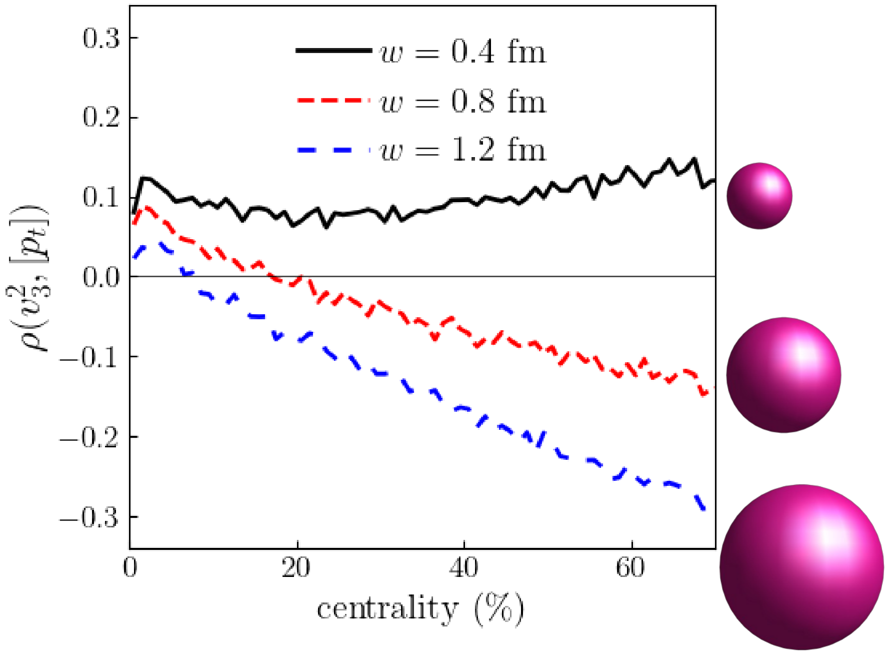




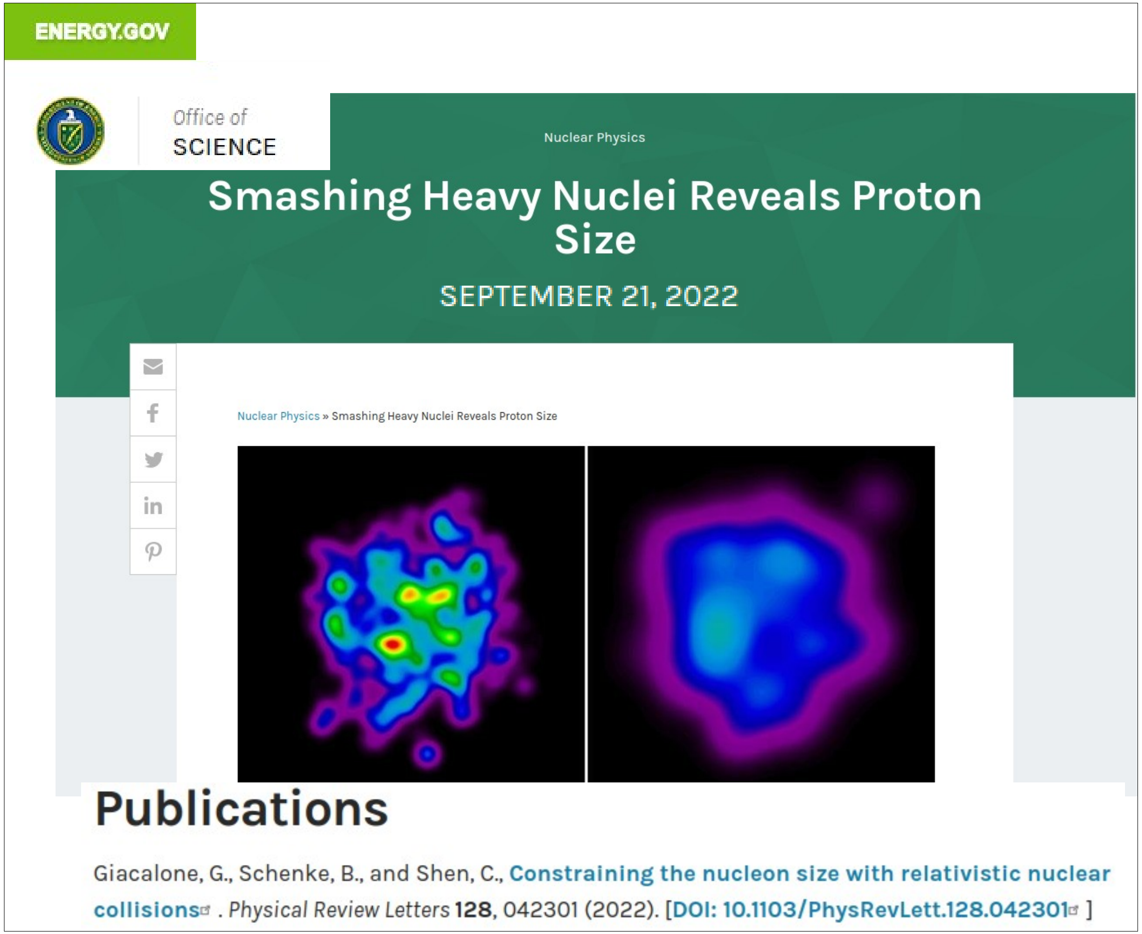


Qualitatively different results. **Same ordering as implemented nucleon sizes?**

We demonstrate the strong sensitivity to the nucleon size.



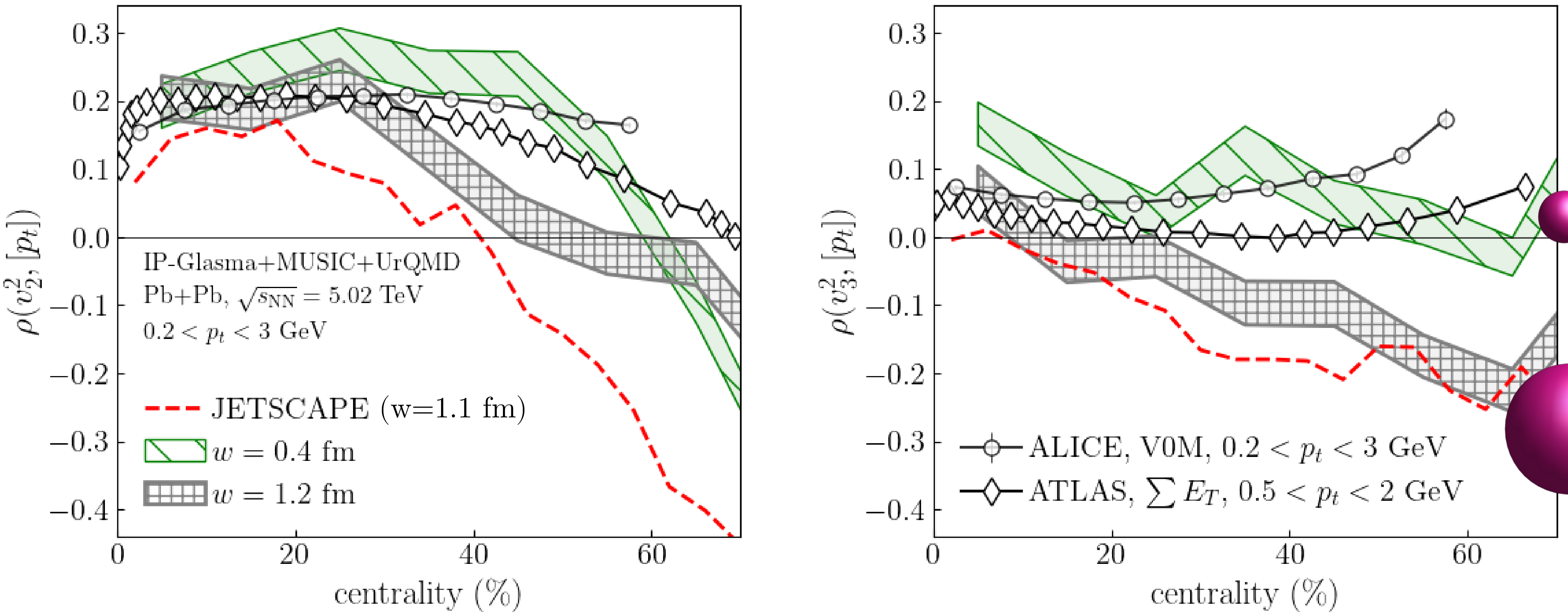
https://www.energy.gov/science/np/articles/smashing-heavy-nuclei-reveals-proton-size



Hydro results and experimental data.

[Giacalone, Schenke, Shen, PRL **128** (2022) 4, 042301]

[ATLAS collaboration, EPJC **79** (2019) 12, 985]
[ALICE collaboration, PLB **834** (2022) 137393]
[ATLAS collaboration, arXiv:2205.00039]



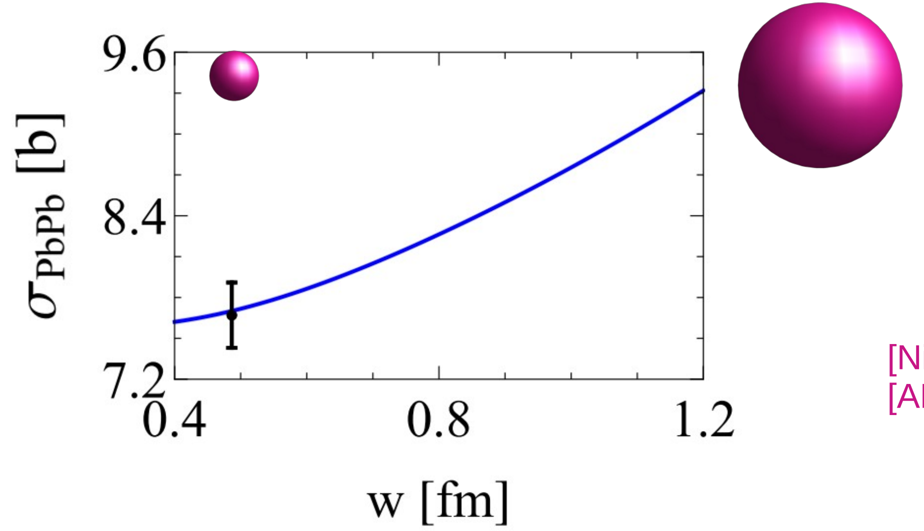
Experimental data does not support a large size, $\rho_3>0$.

Size estimates in Bayesian analyses are not OK. Fitted data is not enough.

More instances?

One way to fix this issue is to look at the total inelastic nucleus-nucleus cross section, σ_{AA}. In TRENTo and IP-Glasma, the nucleon size determines the probability of interaction between two ions at a given impact parameter. As the total cross section is constrained fairly well by Glauber fits of multiplicity distributions, it provides an experimental handle on w. The latest

Large nucleons are not compatible with the quasi-measured nucleus-nucleus cross section.



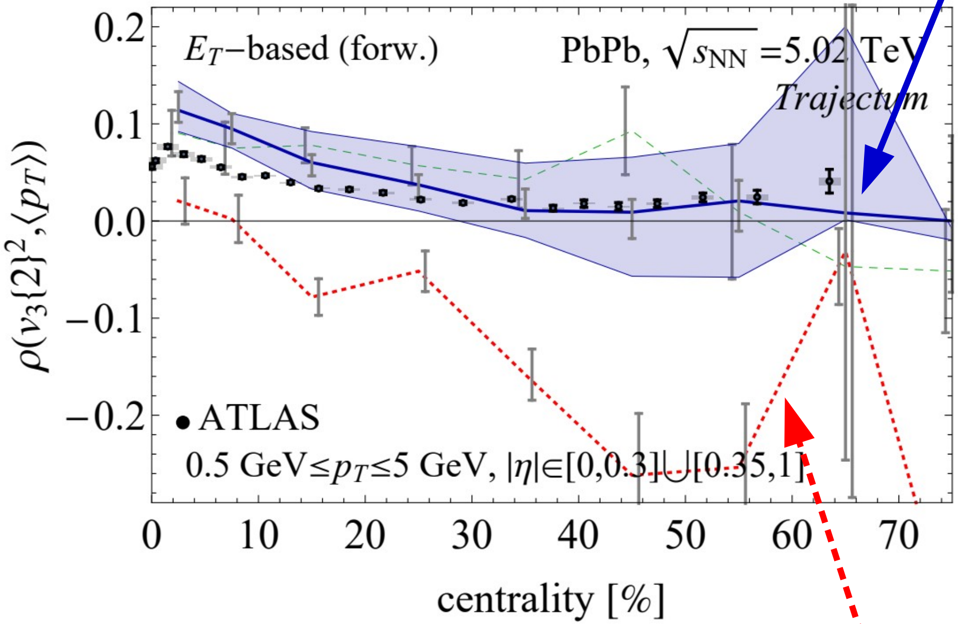
[Nijs, van der Schee, arXiv:2206.13522]
[ALICE Collaboration, arXiv:2204.10148]

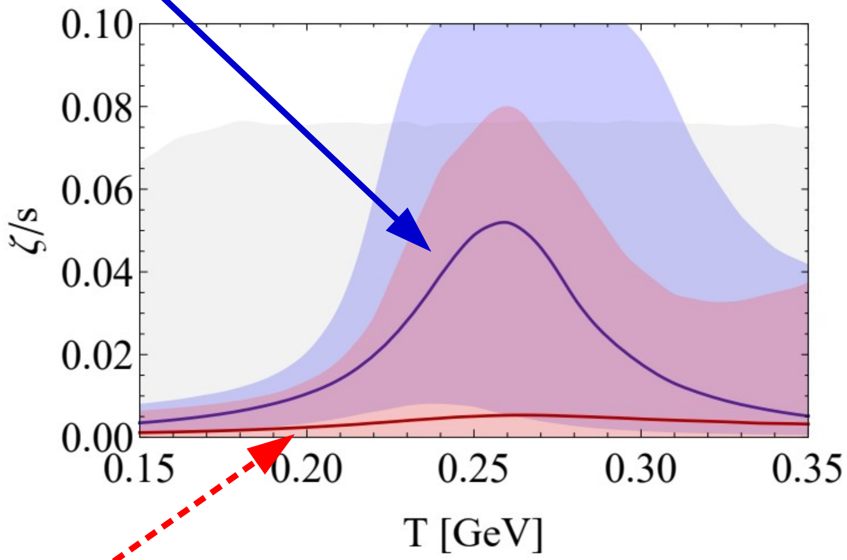
Re-analysis of data with constraint from cross section.

Nucleons shrink and bulk viscosity is no longer zero!

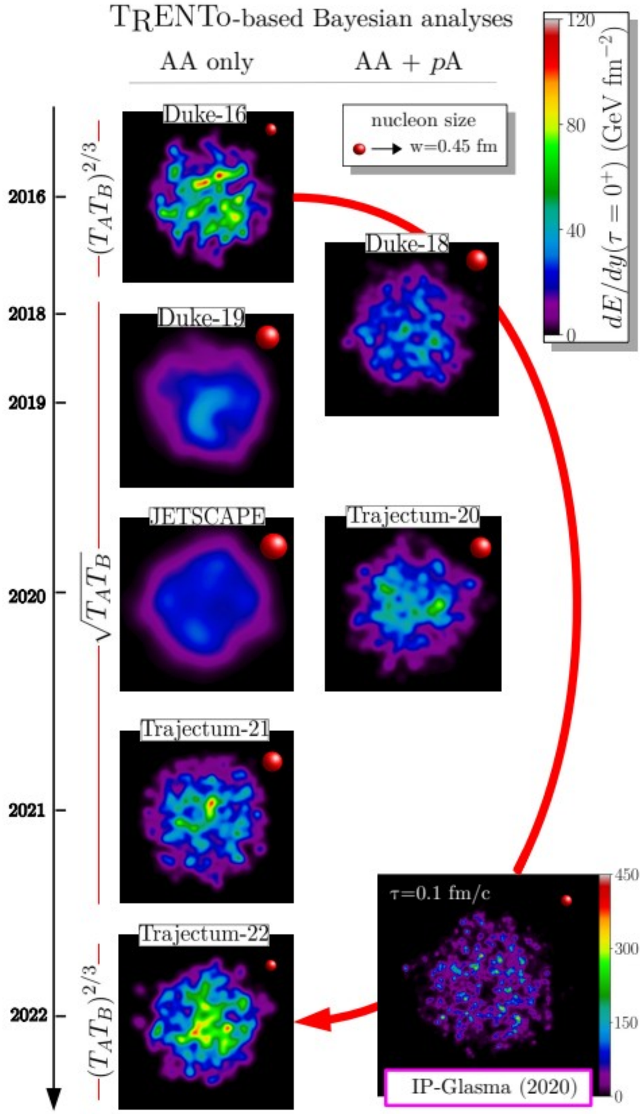
Nucleon size ~ 0.5 fm.
Right AA cross section.

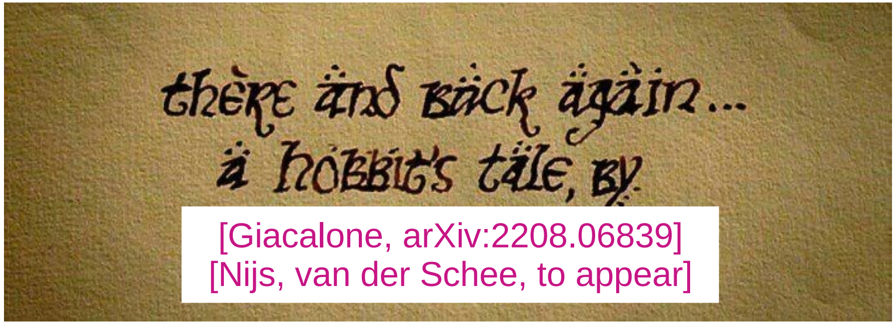
[Nijs, van der Schee, arXiv:2206.13522]





Nucleon size ~ 1 fm.
Wrong AA cross section.





[Giacalone, arXiv:2208.06839]
[Nijs, van der Schee, to appear]

VERY IMPORTANT:

$$\frac{dE}{dy}(\tau = 0^+) \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$

Only viable p value is p=0:

$$\left(T_A T_B\right)^{q/2}$$

Data prefers q=4/3

This result seems now very robust.

What does it imply?
Relation with color glass condensate?

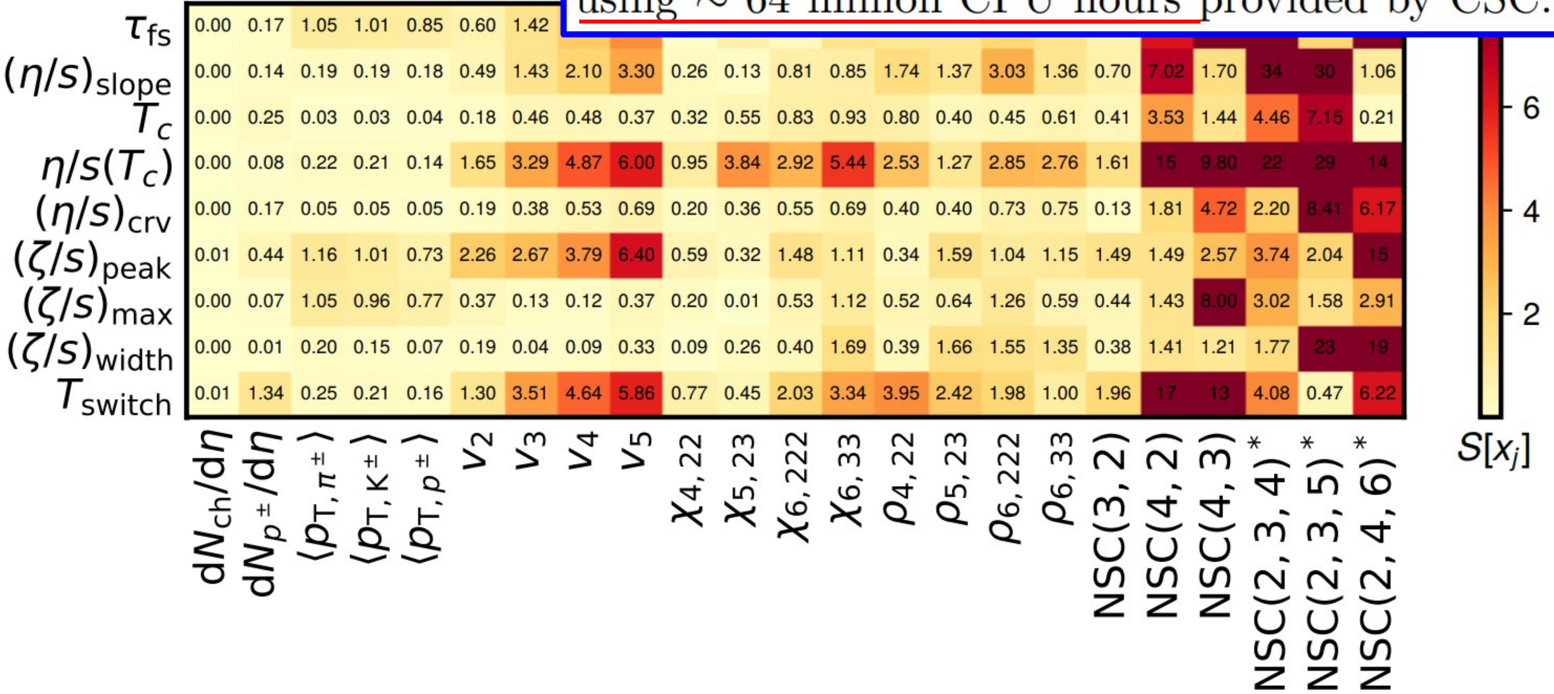
3 – Future directions and prospects across systems.

OUTLOOK #1. **“Fixing” Bayesian analyses with observables that target the initial state.**

Huge computational efforts to include more observables, but missing ρ_n correlations.

[Parkkila *et al.*, **PLB** 835 (2022) 137485]

computational resources. This research was completed using ∼ 64 million CPU hours provided by CSC. Three



OUTLOOK #2. Supplementing Bayesian analyses with field theoretical studies.

$\rho(z) \longrightarrow$ energy density

[Blaizot, Broniowski, Ollitrault, PLB **738** (2014) 166-171]

$$S(z_1, z_2) \equiv \langle \rho(z_1)\rho(z_2)\rangle - \langle \rho(z_1)\rangle\langle \rho(z_2)\rangle$$

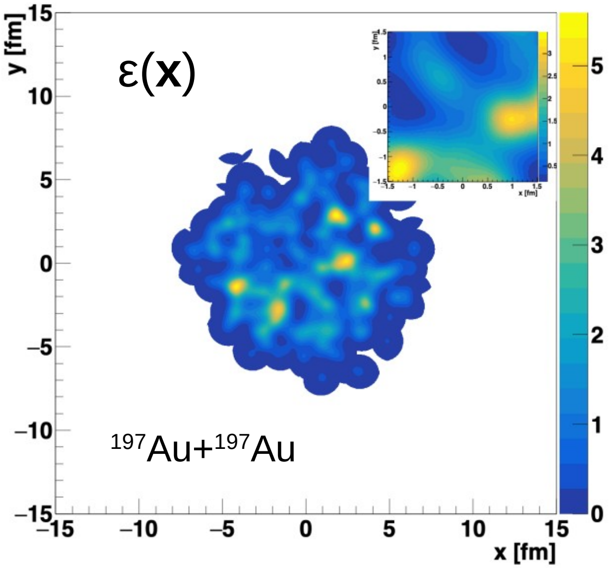
average

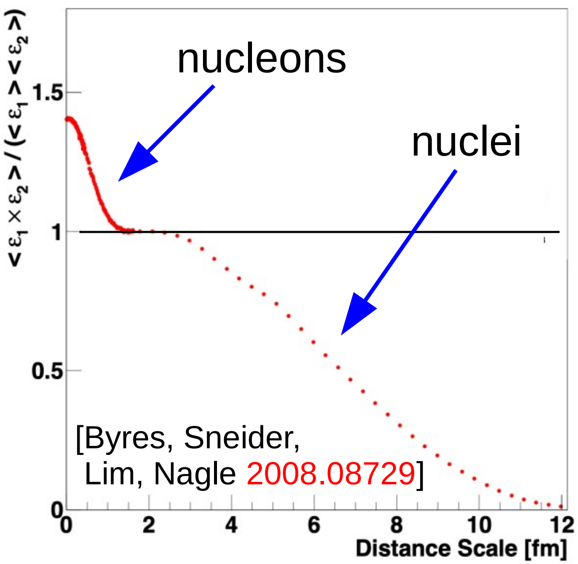
$$S(z_1, z_2) = A(z)h(s), \qquad z \equiv \frac{z_1 + z_2}{2}, \quad s \equiv z_1 - z_2$$

fluctuation amplitude

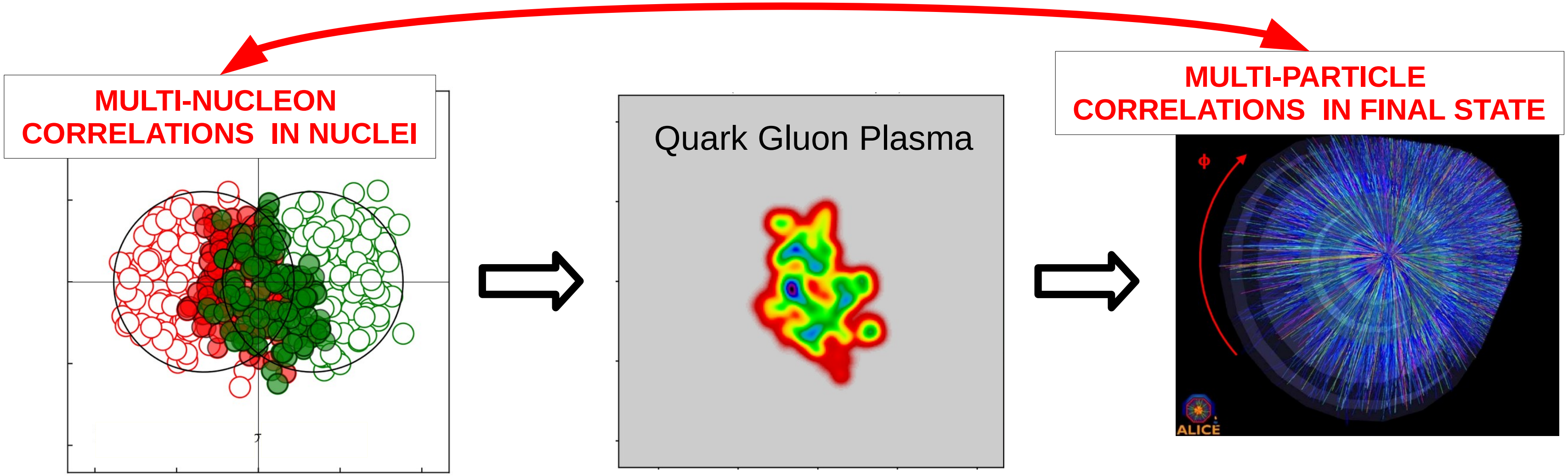
correlation length

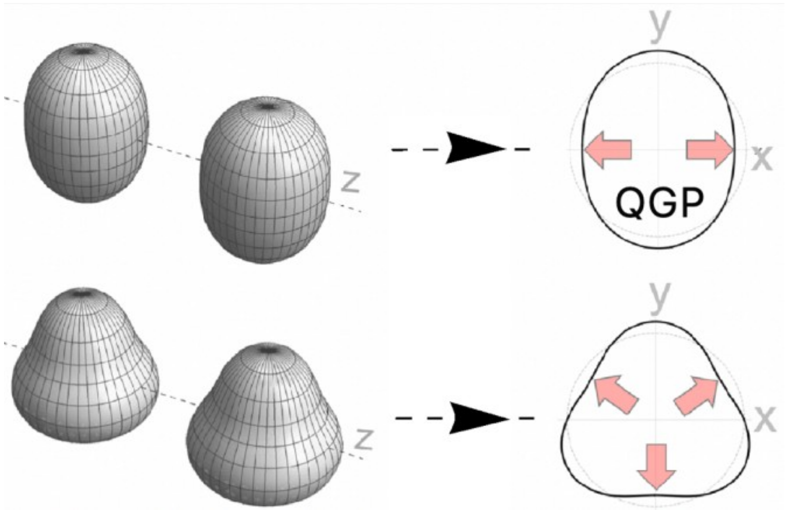
[Snyder *et al.*, PRC **103** (2021) 2, 024906]





OUTLOOK #3. **Improving input at the level of the colliding ions.**





See my talk on Friday

CONCLUSION

- **Goal of soft sector:** characterizing initial condition and hydrodynamic response.

- Bayesian analyses allow us to do that, but they have lead us through a weird path… **End of 2020:** Smooth QGP and zero bulk viscosity. Incompatible with IP-Glasma.

- Progress in 2021. Smooth QGP due to huge nucleon size. v_n-<p_t> correlations and cross section measurements have a strong sensitivity to the nucleon size.

- Bayesian analysis with cross section constraint. Nucleon size back to ≈ 0.5fm. Scaling of dE/dy ~ $(T_A T_B)^{2/3}$. Bulk viscosity is nonzero.

- **End of 2022:** Initial state of the collisions seems now robustly understood from data. **2023 and beyond: sharpen the details, improve extractions, test CGC.**

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

https://www.int.washington.edu/programs-and-workshops/23-1a

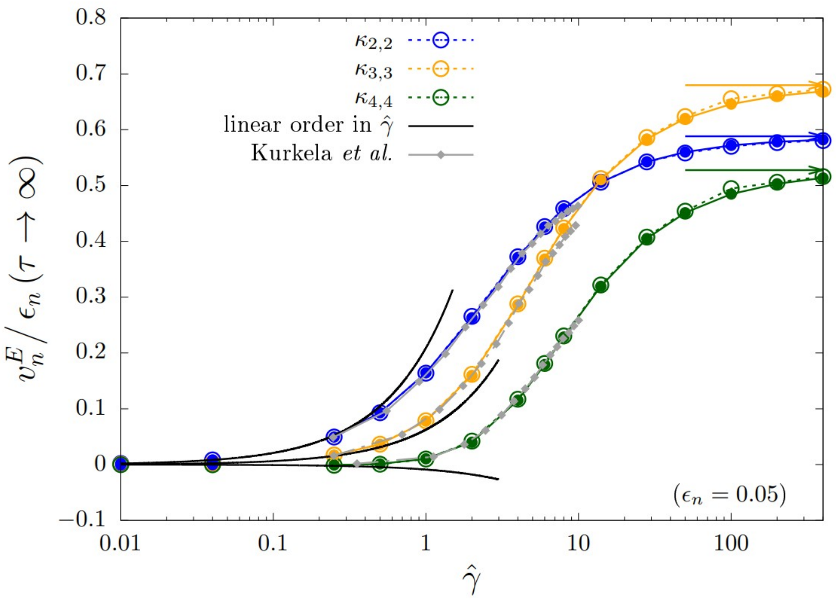
Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

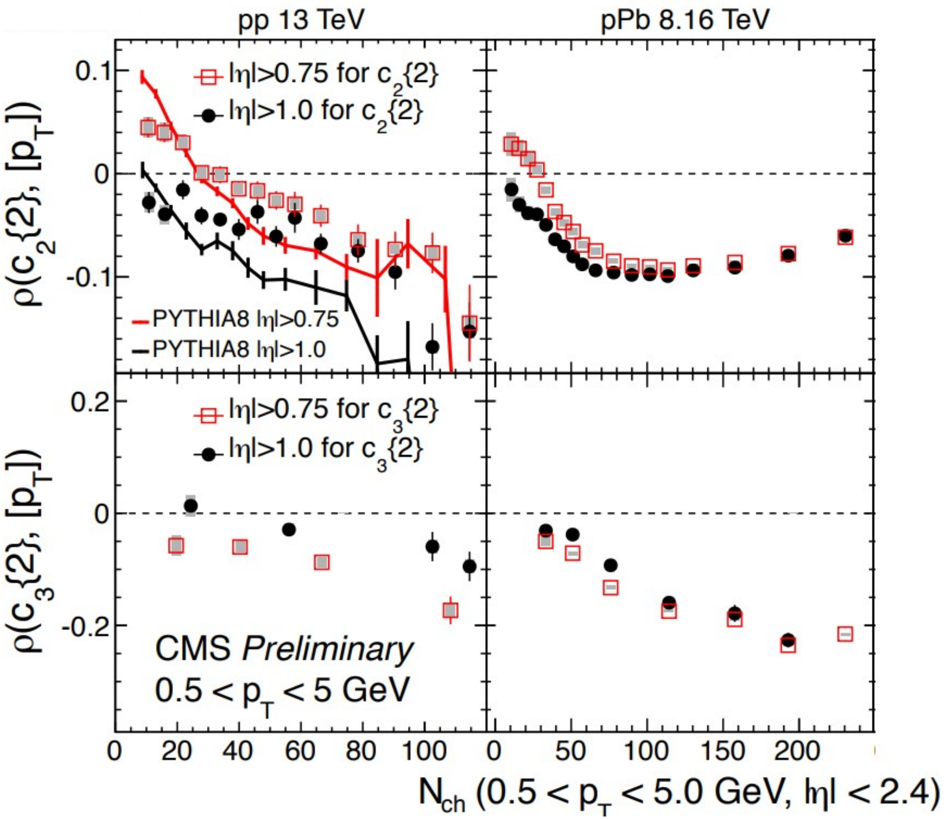
Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jaki Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

Small systems?

$$v_n = \kappa_n \varepsilon_n$$



[Ambrus, Schlichting, Werthmann, PRD **105** (2022) 1, 014031]



[Shengquan Tuo, Quark Matter 2022]