Hadronization and Soft QCD
Interacting strings and collective behaviour

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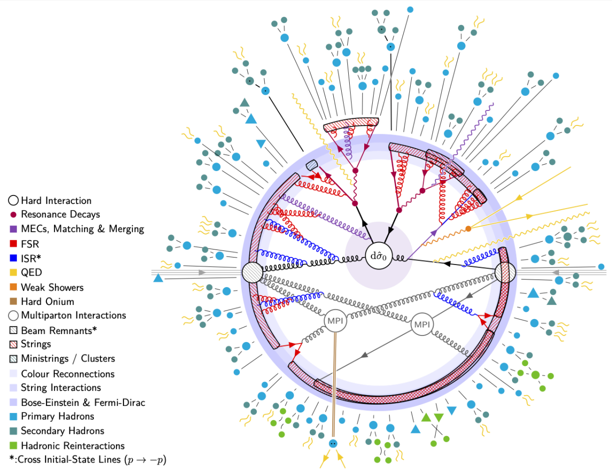
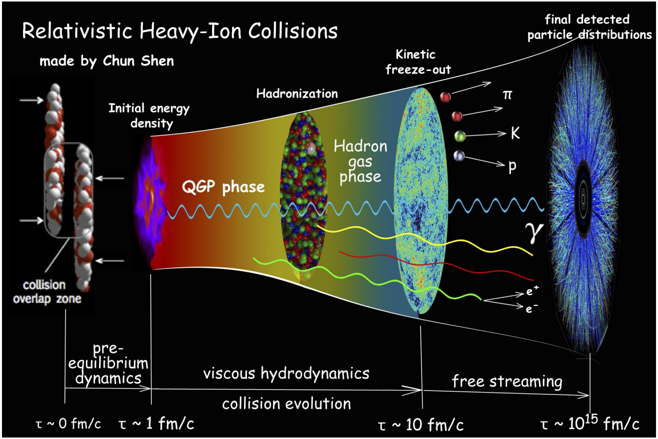
Heavy ions vs. pp (Most material: CB: arXiv:2401.07585)



- Are ion collisions different than many of these stacked together?

Standard model of heavy ion physics

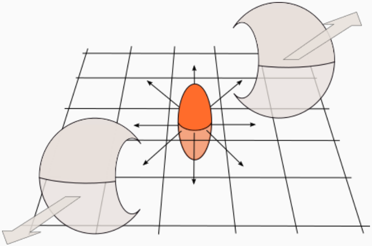
- Heavy ions traditionally viewed very differently.

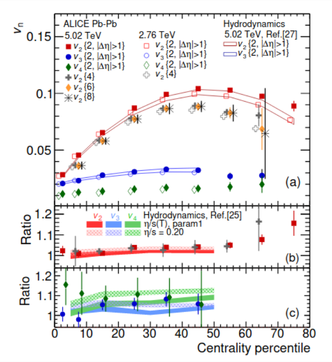


- Experimentally focused on properties of the QGP, viscosity, temperature, mean-free-path.

Flow: the collective behaviour of heavy ions

- Staple measurement: often modeled with hydrodynamics.





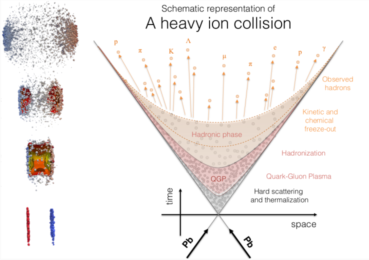
(ALICE: 1602.01119)

Fourier series decomposition of ϕ distribution:

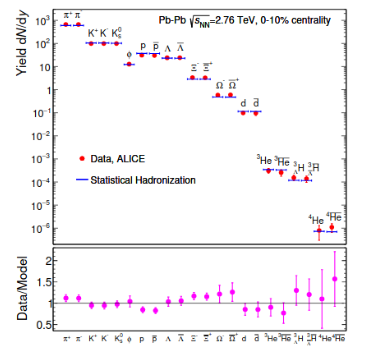
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]$$

Hadron abundances: a QGP thermometer

- The temperature when QGP ends: statistical hadronization.
- Describes yields well with few parameters.



(Figure: D. Chinellato)

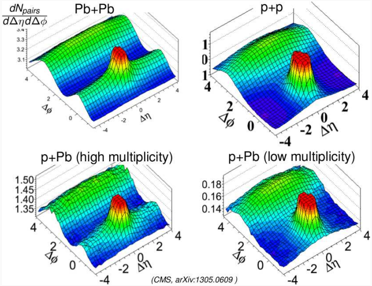


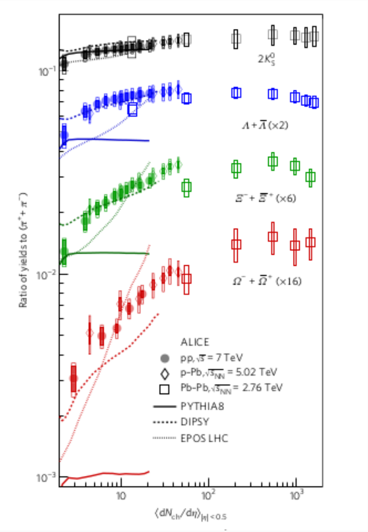
(Andronic et al: 1710.09425)

- There are other types of observables (jet quenching, HBT, quarkonia, ...). But these will be today's focus.

Not so clear division!

- LHC revealed heavy-ion like effects in pp collisions.





(ALICE: Nat. Phys.13 (2017))

- And the transition is smooth!
- Are heavy ion collisions and pp collisions then really that different?

Microscopic view on collectivity

- Can PYTHIA save itself, without introducing QGP?
- Answer: Microscopic, string interaction model.
- If this works well, can it also work in heavy ions?
- If yes, where does it leave the QGP?

Microscopic view on collectivity

- Can PYTHIA save itself, without introducing QGP?
- Answer: Microscopic, string interaction model.
- If this works well, can it also work in heavy ions?
- If yes, where does it leave the QGP?
- Answer: These are very good questions
- Rest of this lecture:
    1. Microscopic model ingredients: string shoving, colour reconnection, rope formation, hadronic rescattering.
    2. Performance against pp data.
    3. Performance against AA data.
    4. Distinguishing between string interactions and QGP.

MPIs in PYTHIA8 pp (Sjöstrand and Skands: arXiv:hep-ph/0402078)

- Several partons taken from the PDF.
- Hard subcollisions with $2 \to 2$ ME:

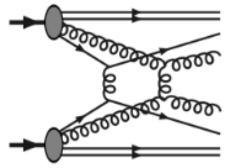


Figure T. Sjöstrand

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

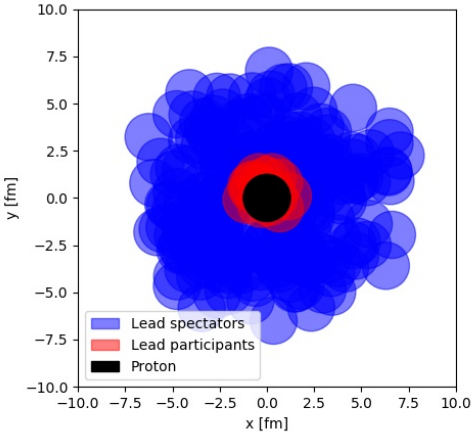
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp \right]$$

- Picture blurred by CR, but holds in general.

The Glauber model

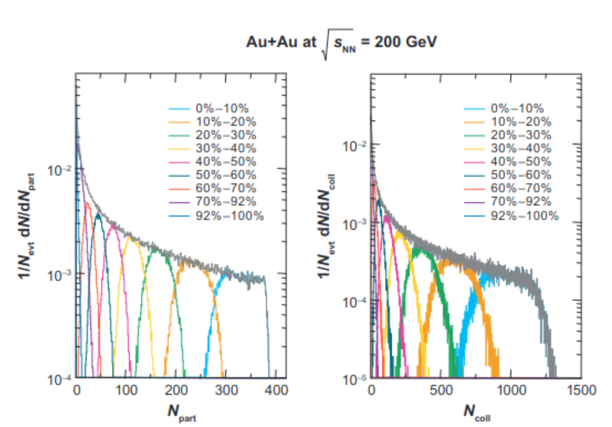
$$\text{Nucleon size: } r_p = \sqrt{\sigma^{NN}_{\text{inel}}/4\pi}$$



Participants and subcollisions

Basic geometric quantities readily available.

Not directly measurable, don't believe what they tell you!



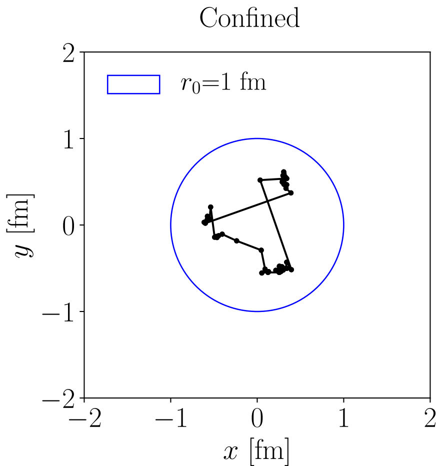
(arXiv:0701025)

Source of “centrality” binning.
Works fine in AA, ambiguous in *p*A.

Cross section fluctuations (arXiv:1907.12871, arXiv:1607.04434)

Because protons are not just static balls.

Substructure event by event → modified Glauber calculation (details in bonus material).



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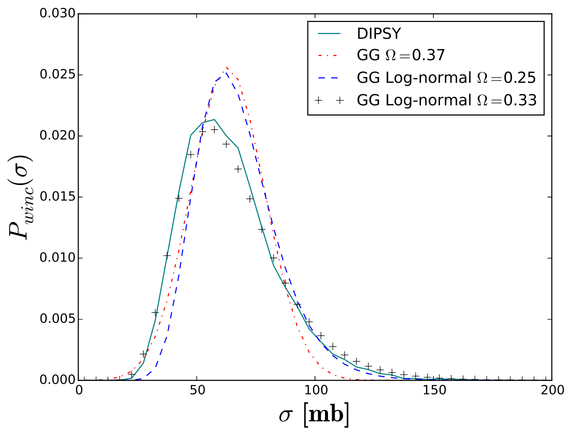

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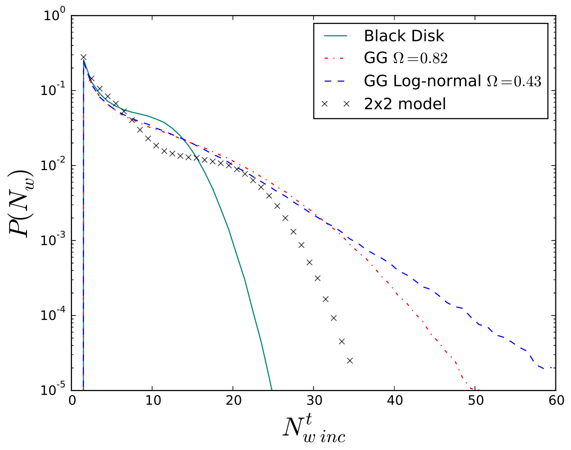


Good–Walker & cross sections

- Cross sections from $T(\vec{b})$ with normalizable particle wave functions:

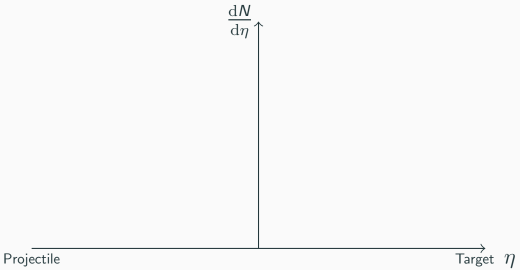
$$\sigma_{\rm tot} = 2 \int d^2\vec{b}\, \langle T(\vec{b}) \rangle_{p,t}$$

$$\sigma_{\rm el} = \int d^2\vec{b}\, \langle T(\vec{b}) \rangle_{p,t}^2$$

- Name of the game:
  1. Make spatial model for $T(\vec{b})$.
  2. Fit parameters in pp.
  3. Use model for pA or AA Glauber.

Particle production: The Angantyr model (arXiv:1806.10820)

- Emission $F(\eta)$ per wounded nucleon
$$\rightarrow \frac{\mathrm{d}N}{\mathrm{d}\eta} = n_t F(\eta) + n_p F(-\eta).$$
- $F(\eta)$ modelled with even gaps in rapidity, as diffraction.
- Tuned to reproduce pp in the $n_t = n_p = 1$ case.
- No tunable parameters for AA – though some freedom in choices along the way.



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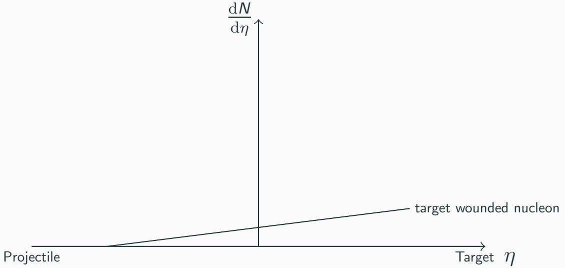

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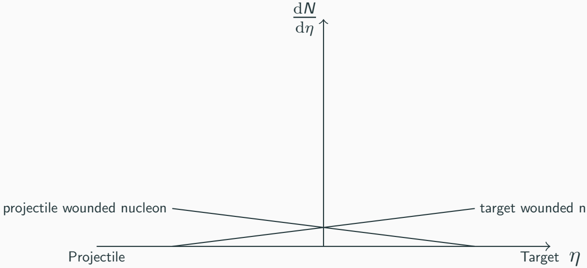

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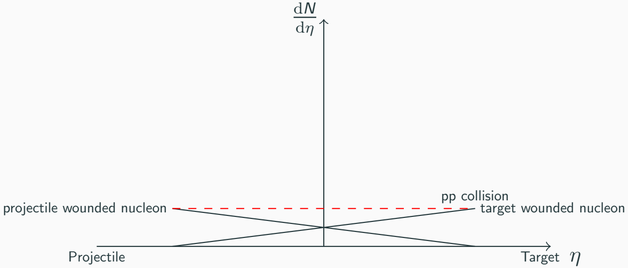

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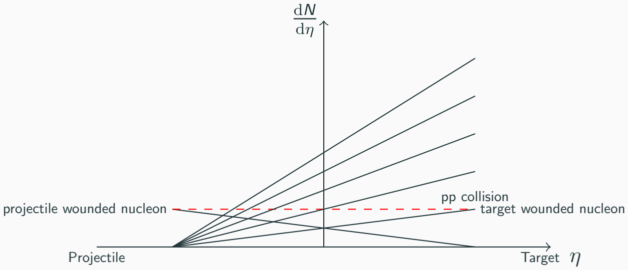

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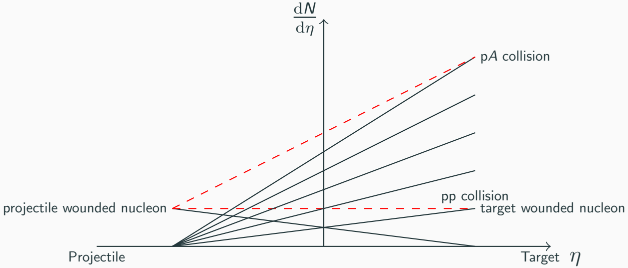

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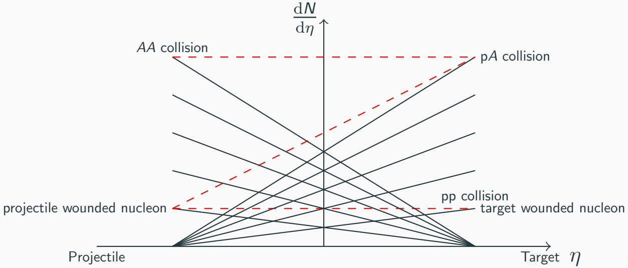
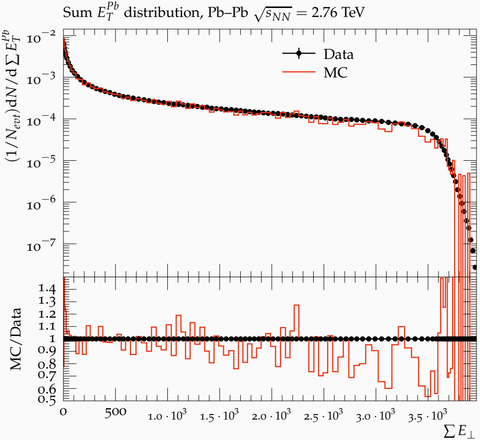


Angantyr results

- Reduces to normal Pythia in pp. In pA and AA:
  - ♠ Centrality measures & multiplicities.
  - ♣ Fluctuations more important in pA.



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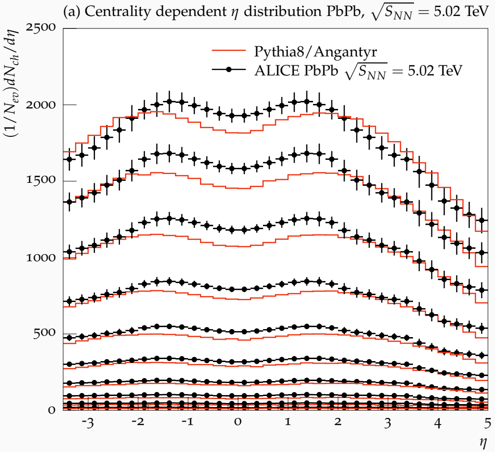

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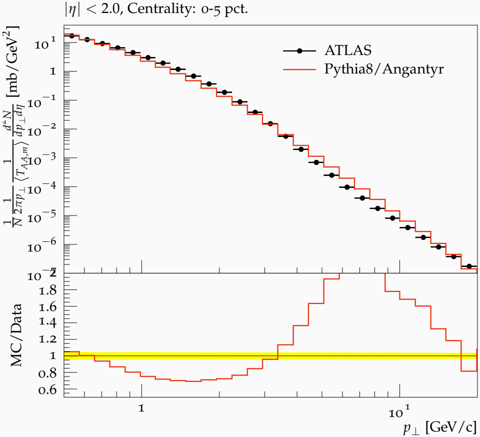

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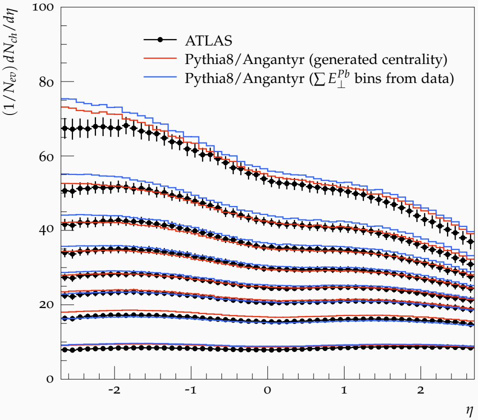
(a) Centrality-dependent η distribution, pPb, $\sqrt{S_{NN}} = 5$ TeV.



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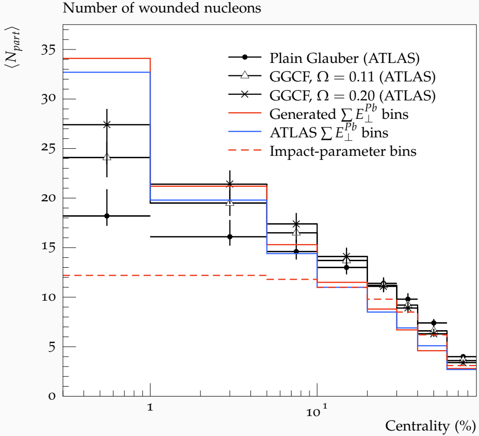
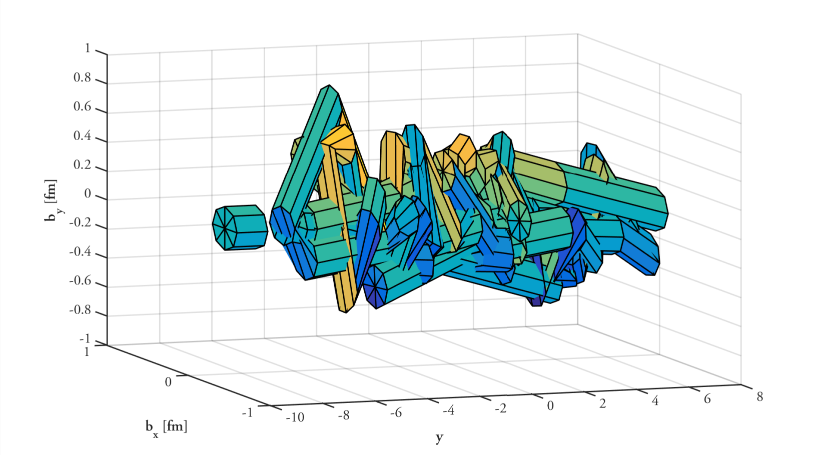


Adding collective effects

- We now have a whole bunch of strings, but no collective effects!
- Let the strings interact, starting from pp collisions.



Pythia: No QGP, just interacting strings

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$\tau \approx 0$ **fm:** Strings no transverse extension. No interactions, partons may propagate.

$\tau \approx 0.6$ **fm:** Parton shower ends. Depending on "diluteness", strings may shove each other around.

$\tau \approx 1$ **fm:** Strings at full transverse extension. Shoving effect maximal.

$\tau \approx 2$ **fm:** Strings will hadronize. Possibly as a colour rope.

$\tau > 2$ **fm:** Possibility of hadronic rescatterings.

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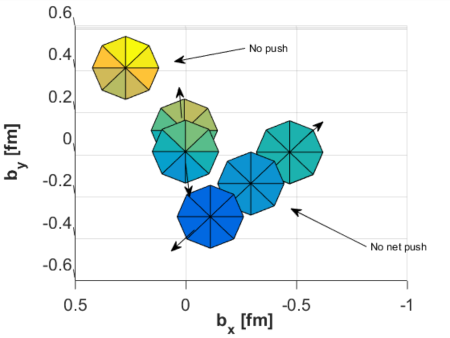
Shoving: The cartoon picture (arXiv:1710.09725,2010.07595)

- Strings push each other in transverse space.
- Colour-electric fields → classical force.



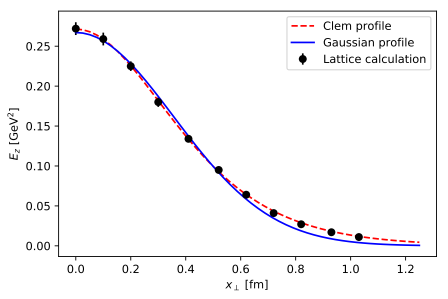
👍 Transverse-space geometry.

👍 Particle production mechanism.

?? String radius and shoving force

Shape of the field

- Easier analytic approaches, eg. bag model:
  $\kappa = \pi R^2[(\Phi/\pi R^2)^2/2 + B]$
- No consensus on R with field shape as input.
- Lattice can provide shape, but uncertain R.



- Solution: Keep shape fixed, but R ballpark-free.

The shoving force

- Energy in field, in condensate and in magnetic flux.
- Let g determine fraction in field, and normalization N is given:

$$E = N \exp(-\rho^2/2R^2)$$

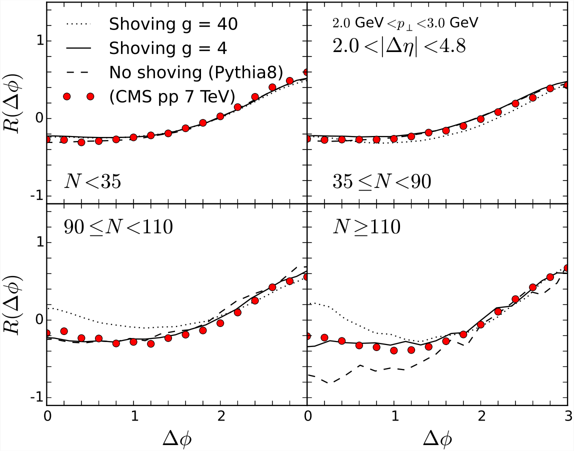
- Interaction energy calculated for transverse separation $d_\perp$, giving a force:

$$f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

- Distance calculated in "shoving frame", resolved as two-string interactions.

String shoving in pp (arXiv:1710.09725,2211.04384,1906.08290,2101.03110)

- Inclusive flow observables well reproduced.
- Add a hard probe trigger, interactions handled.
- In Pythia. Download and play around.



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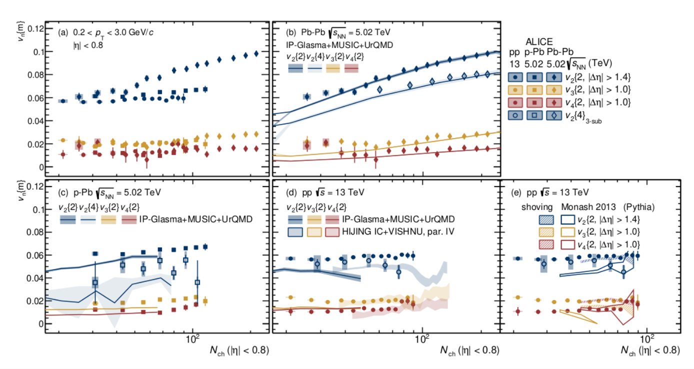

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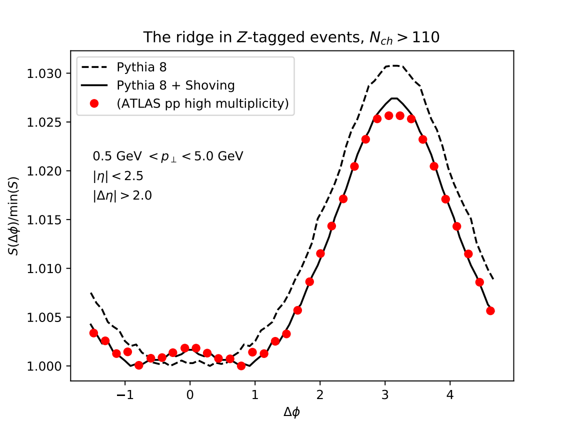

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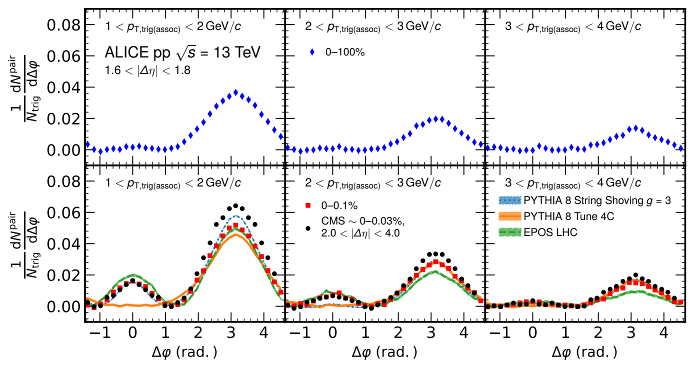

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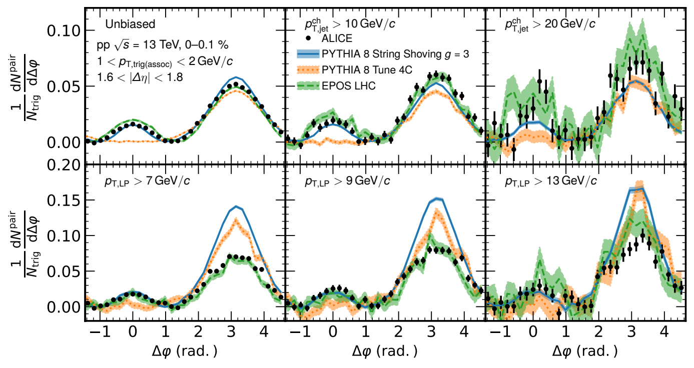

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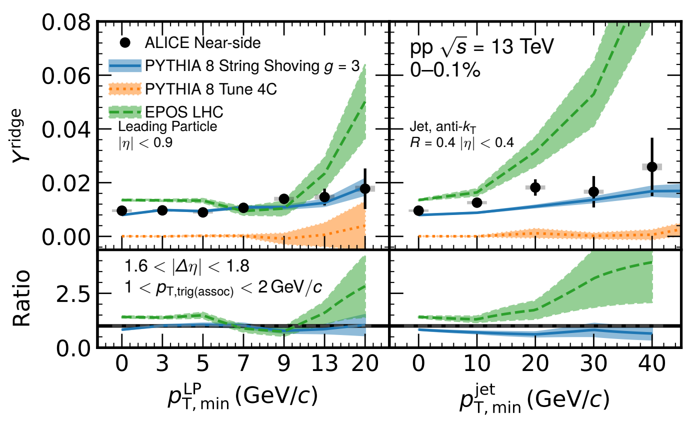

String shoving in AA (arXiv:1806.10820,2010.07595)

- Starting point: Angantyr, Pythia heavy ion model (ask...).
- Geometry difficult: Parallel frame.
- Gluon-rich environments difficult: String EOMs.
- Time evolution difficult: Parton shower formalism.
- Many pushes difficult: Cache and add to hadrons.
- N^2 scaling difficult: Buy a new computer.

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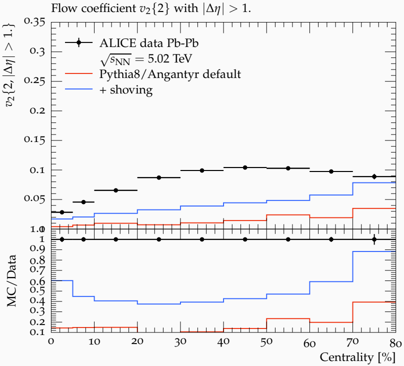

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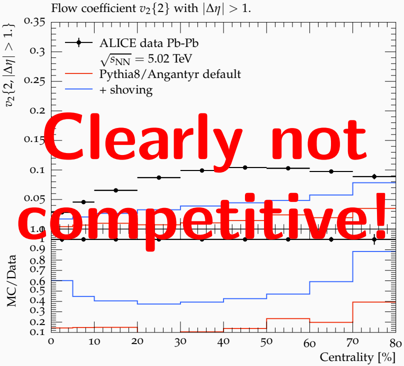

Toy initial states (arXiv:2010.07595)

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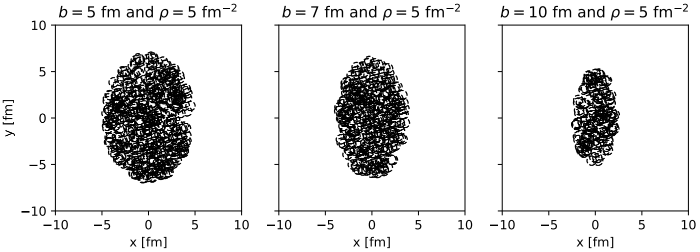
- Model behaves like hydro for such initial states.
- Work continues to fully generalize and integrate.



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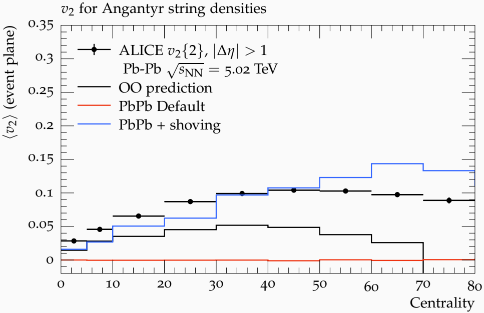

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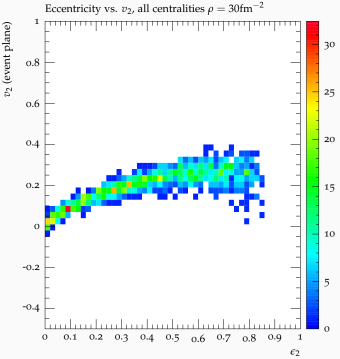
- Work continues to fully generalize and integrate.



- Better understanding of model.
- Couple with hadronic rescattering non-trivial (ask...)

Toy initial states (arXiv:2010.07595)

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- Model behaves like hydro for such initial states.
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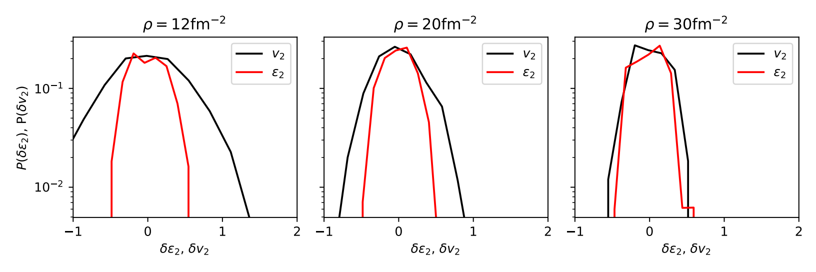
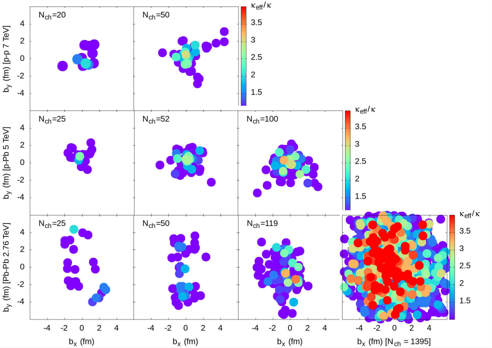


with $\delta\epsilon_2 = \frac{\epsilon_2 - \langle\epsilon_2\rangle}{\langle\epsilon_2\rangle}$ and $\delta v_2 = \frac{v_2 - \langle v_2\rangle}{\langle v_2\rangle}$

- Better understanding of model.
- Couple with hadronic rescattering non-trivial (ask...)

Should the strings/prehadrons not be melting? (2205.11170)

- Energy density too high, strings must be melting!
- At early times, energy primarily in partons .



- Flow signals alone cannot discriminate.

Rope Hadronization (arXiv:1412.6259 – explored heavily in 80's and 90's!)

- Overlapping strings combine into multiplet with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

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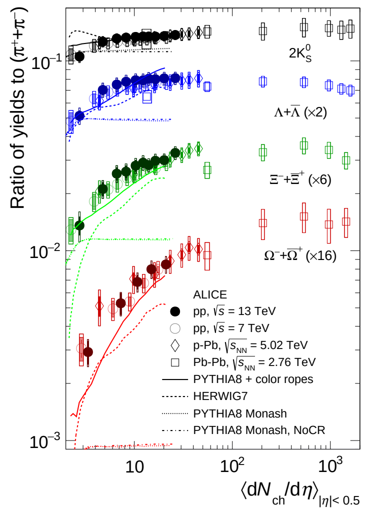
Strangeness enhanced by:

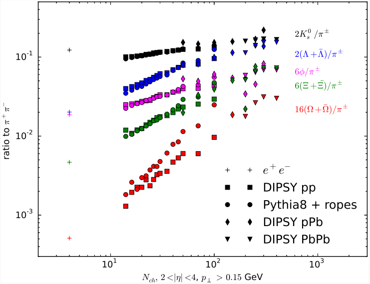
$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- QCD + geometry extrapolation from LEP.
- Can never do better than LEP initial conditions!

Rope hadronization from small to large (arXiv:2003.02394, arXiv:1807.05271)



- Rope production works in pp, download Pythia and play.
- Extension to pA and AA is still work in progress.



Summary

- Hadronization models historically important to transform parton level results.
- Developed into a field of its own.
- Lund string: rich dynamical picture, framework for calculation and model building.
- Soft QCD: Broad field – topic of interest: similarities with heavy ions.
- Both: We must rely on models! Given you an idea what those models look like.