Sources of multiparticle correlations – a microscopic perspective

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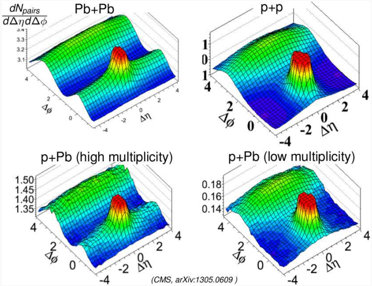
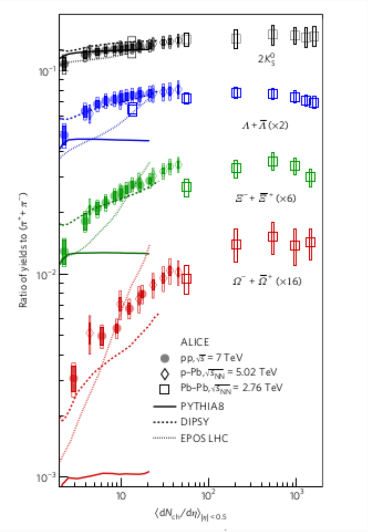
Thank you for the invitation! (DALL-E 3)

Collectivity in small systems: is it still interesting?

- Needs no introduction: more than 10 years old now.



(CMS: arXiv:1009.4122)

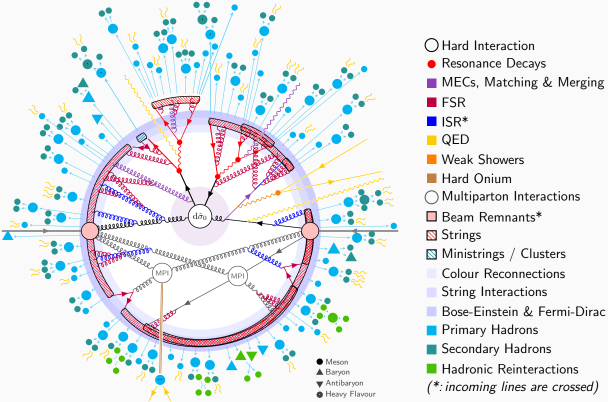


(ALICE: arXiv:1606.07424)

- Still most surprising discovery at LHC !
- Not a high multiplicity phenomennon!

The PYTHIA perspective (arXiv:2203.11601)

- General purpose Monte Carlo based on jet universality and factorization theorem(s) .



- Complex beasts even without QGP.
- And QGP breaks the fundamental assumptions.

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?

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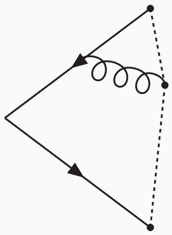
- Can PYTHIA save itself, without introducing QGP?
- Answer: Microscopic, string interaction model.
- If this works well, can it also work in heavy ions?
- If yes, where does it leave the QGP?
- Answer: These are very good questions
- Rest of this talk:
  1. Microscopic model ingredients: string shoving,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

Fragmentation of a single string (Phys.Rept. 97 (1983) 31-145)

- Non-perturbative fragmentation, Lund strings, $\kappa \approx 1$ GeV/fm.



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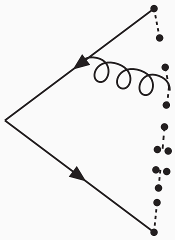
Flavour by tunnelling

$\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$, where m is the quark mass → parameter.



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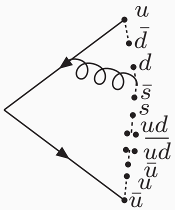
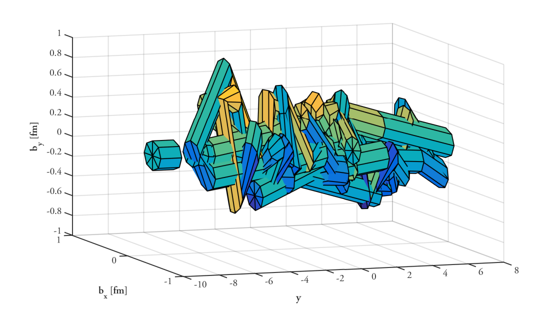
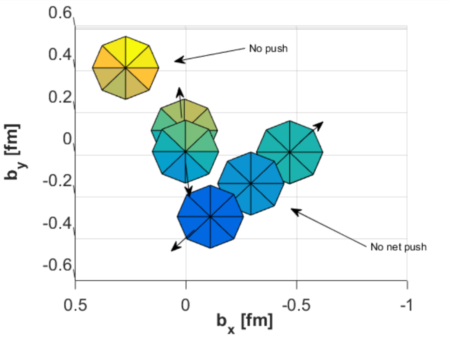




But many strings overlap in pp collisions!

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

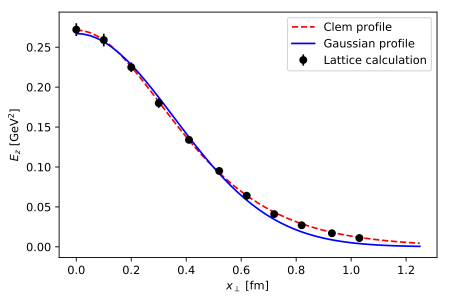
- Strings push each other in transverse space.
- Colour-electric fields → classical force.



👍 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:

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

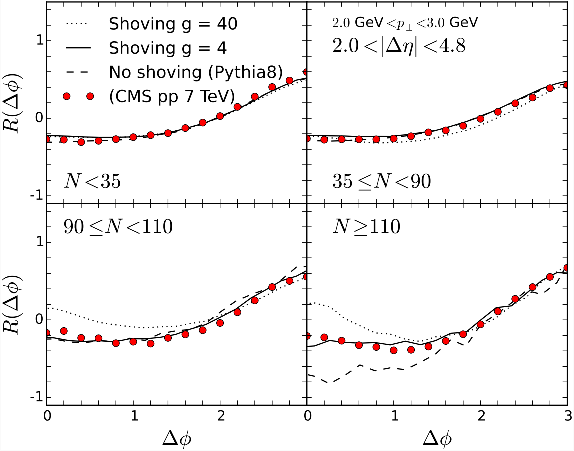
- Interaction energy calculated for transverse separation $d_\perp$, giving a force:

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

- 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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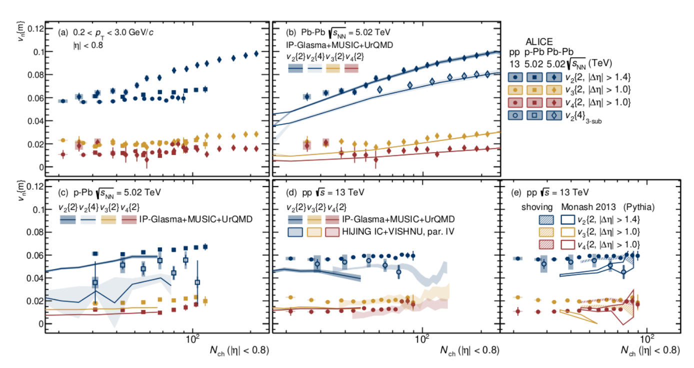

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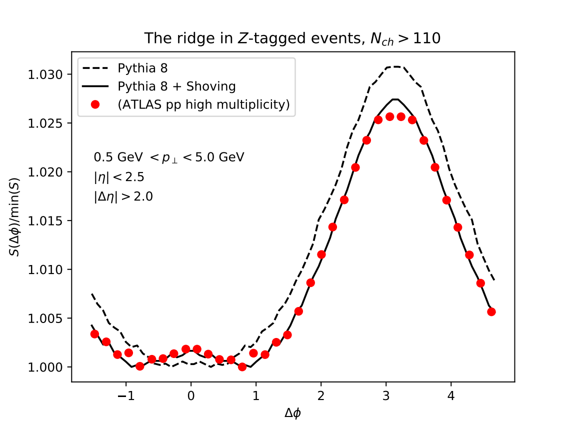

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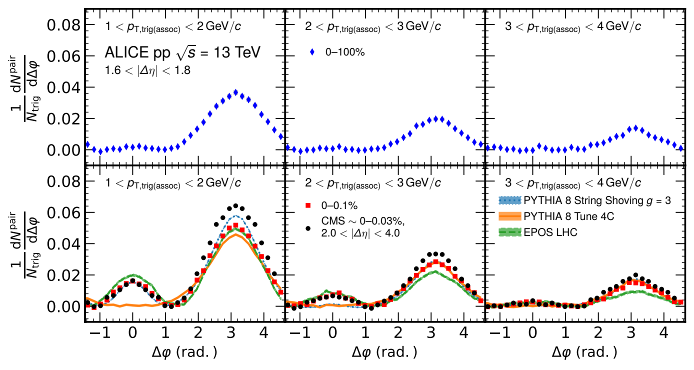

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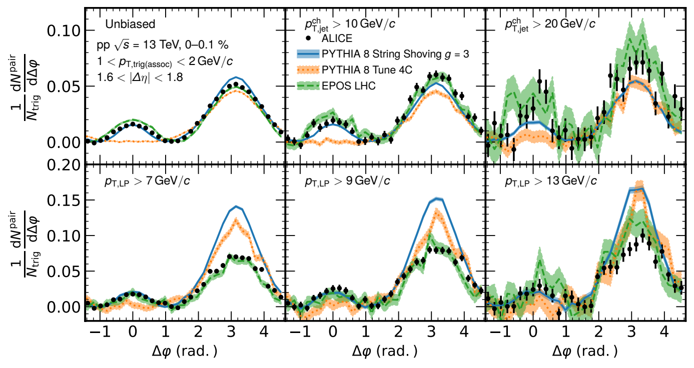

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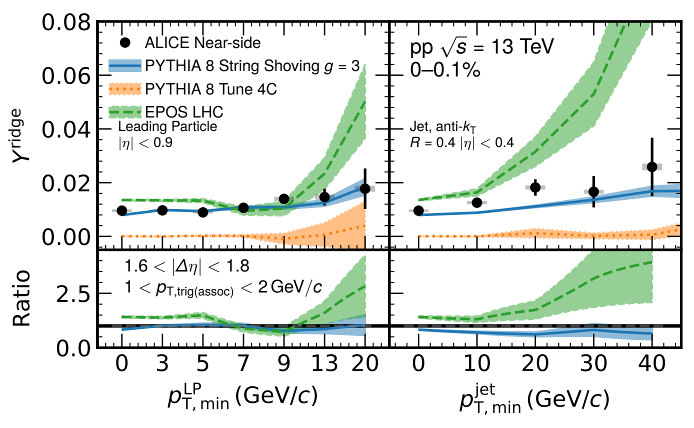

String shoving in AA (arXiv:1806.10820,2010.07595)

- 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.
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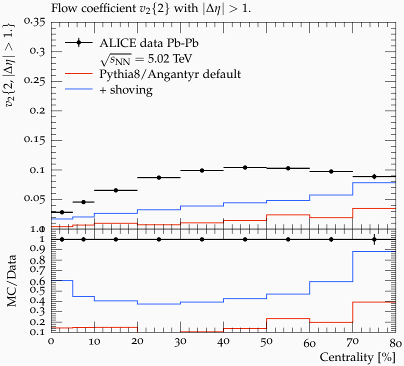

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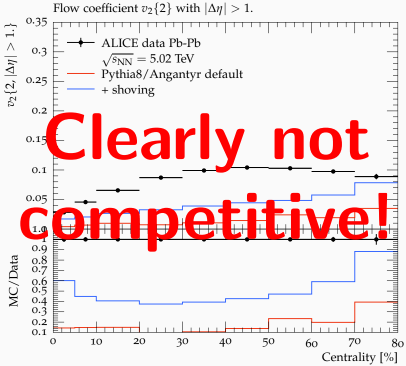
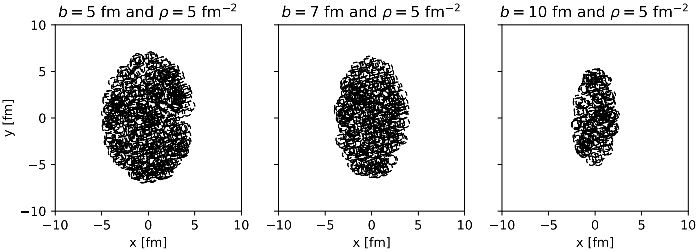


Toy initial states (arXiv:2010.07595)

- Remove the gluons + elliptic initial geometry.
- Model behaves like hydro for such initial states.
- Work continues to fully generalize and integrate.



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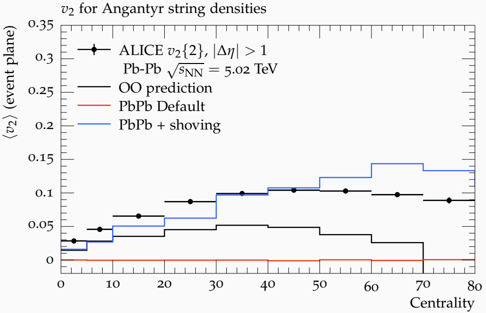

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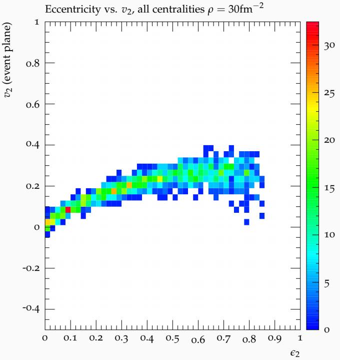

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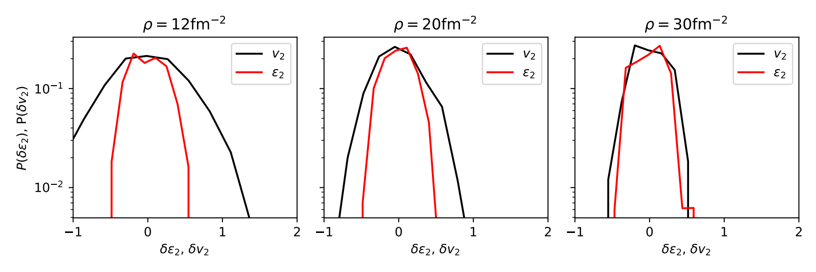

with $\delta\epsilon_2 = \frac{\epsilon_2 - \langle\epsilon_2\rangle}{\langle\epsilon_2\rangle}$ and $\delta v_2 = \frac{v_2 - \langle v_2\rangle}{\langle v_2\rangle}$

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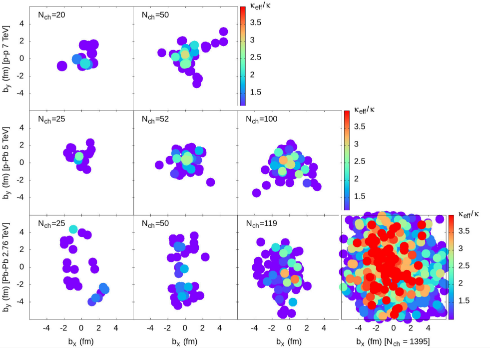
Should the strings/prehadrons not be melting? (2205.11170)

- Energy density too high, strings must be melting (PHSD, CGC energy densities, ...)
- 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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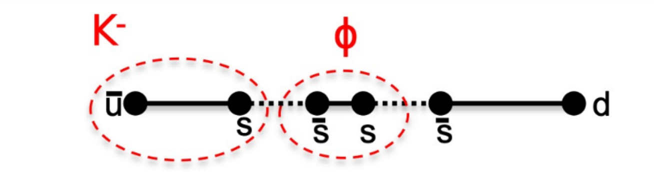
Strangeness enhanced by:

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

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

A question for data! (in preparation)

- If string melts, it's correlations should vanish.
- Special role of ϕ meson in Lund string model.

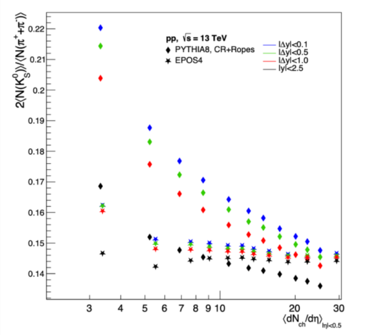


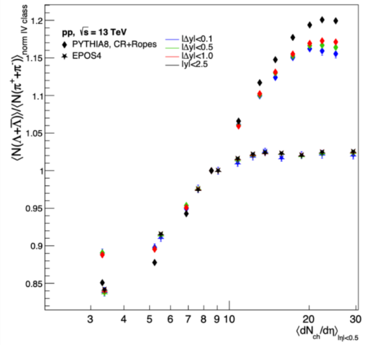
(Figure credit: David Chinellato)

- Use the ϕ as a trigger, and look for correlations along the string (rapidity).
- Work in progress with Stefano Cannito and Valentina Zaccolo (ALICE, Trieste).

Reveals difference between models (in preparation)

- Case study: EPOS-4 vs. Pythia with strings.
- Reveals differences at both small and large multiplicities.





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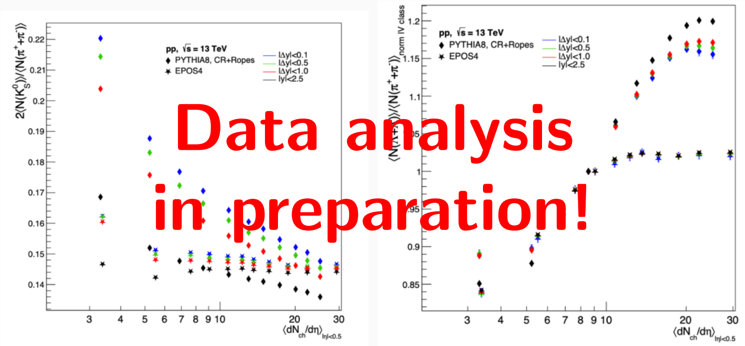

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Summary and road ahead

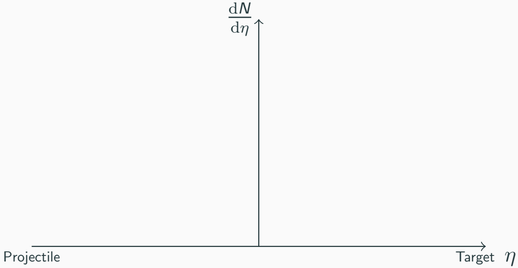
- Small system collectivity as relevant a puzzle as ever.
- Microscopic models for string interactions to solve the puzzle.
- Performance in pp remarkable, better than hydro in several cases.
- Work ongoing for AA collisions, challenging but encouraging results.
- Work ongoing for isolating discriminating signals, focus on pp.

Bonus material

1. The Angantyr model.
2. Some Angantyr results.
3. The PYTHIA hadronic cascade.
4. Some hadronic cascade results.

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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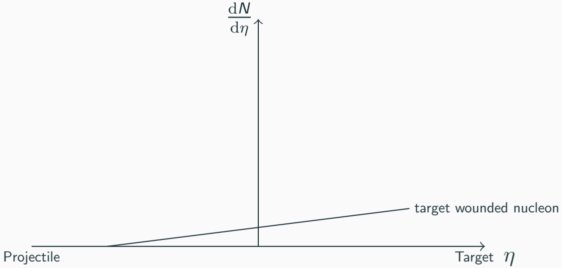

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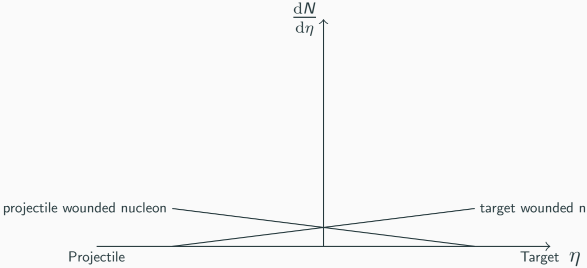

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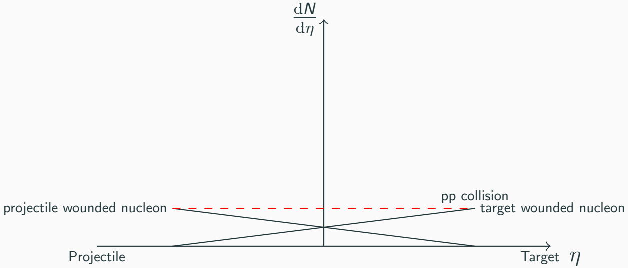

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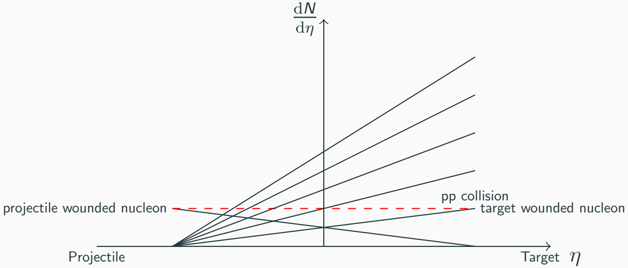

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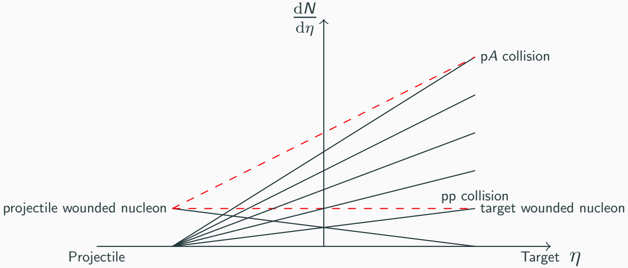

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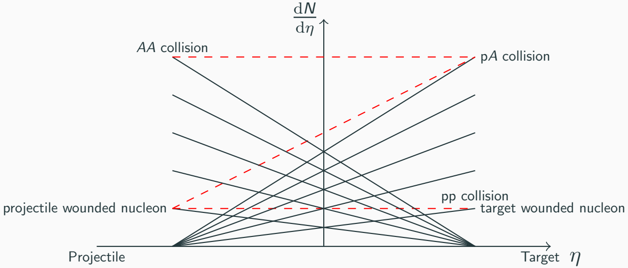
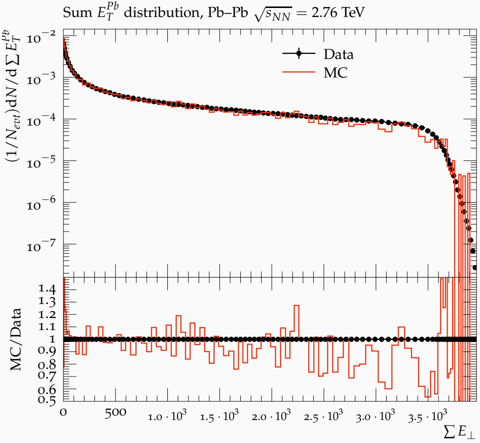


Angantyr results

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



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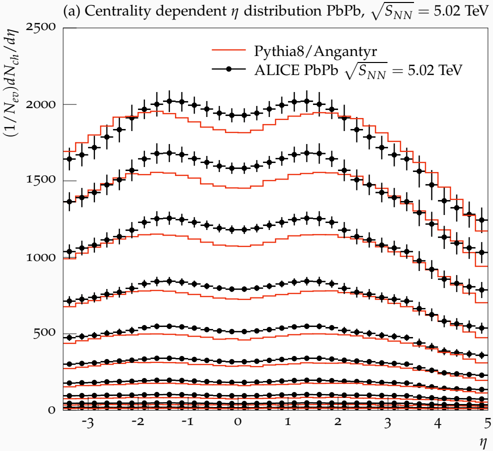

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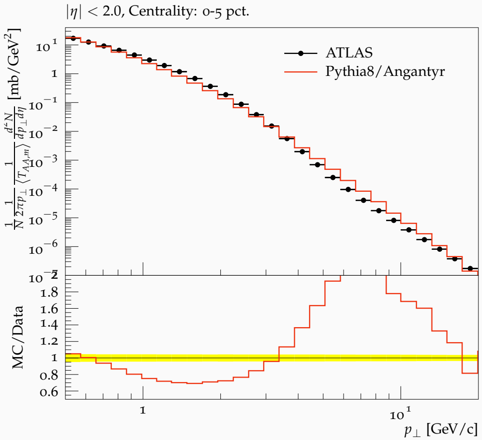

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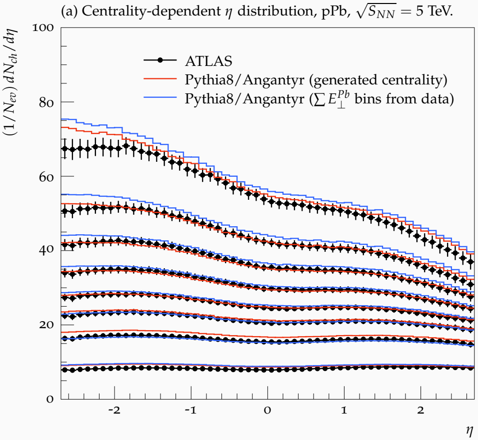

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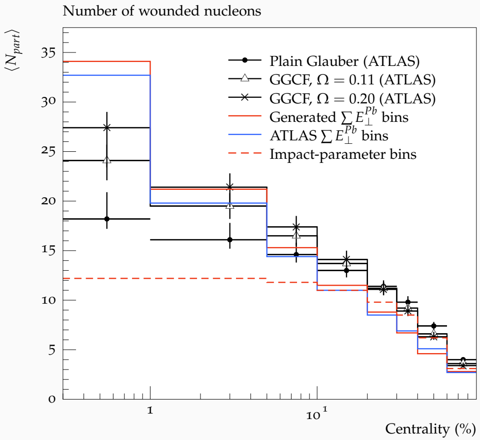
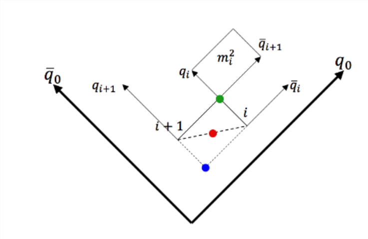


Hadronic Rescattering (arXiv:2103.09665, arXiv:2005.05658, arXiv:1808.04619)

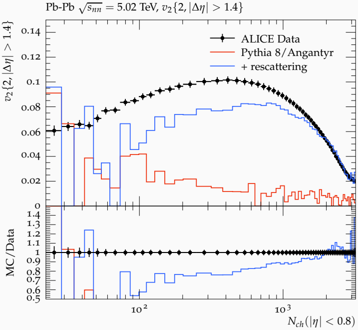
- Pythias own implementation, some difference to others.
- Hadron production vertices from strings: Earlier hadronization $\tau \approx 2$ fm.
- Momentum-space to space-time breakup vertices through string EOM: $v_i = \frac{\hat{x}_i^+ p^+ + \hat{x}_i^- p^-}{\kappa}$
- Hadron located between vertices: $v_i^h = \frac{v_i + v_{i+1}}{2} \left(\pm \frac{p_h}{2\kappa} \right)$

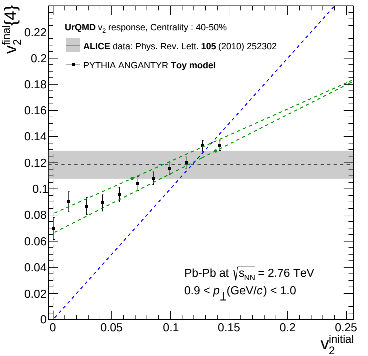


- Formalism also handles complex topologies.
- Hadron cross sections from Regge theory or data, AQM for heavy quarks.

Hadronic rescattering (arXiv:2002.10236, arXiv:2103.09665)

- Crucial for large systems, very sensitive to system lifetime.





- Not trivial to combine effects!

Hadronic rescattering and flavour (arXiv:2103.09665)

- Crucial for large systems, very sensitive to system lifetime.
- AQM the best we can do for HF, many interesting prospects.