Simulating heavy ion collisions without a Quark-Gluon Plasma

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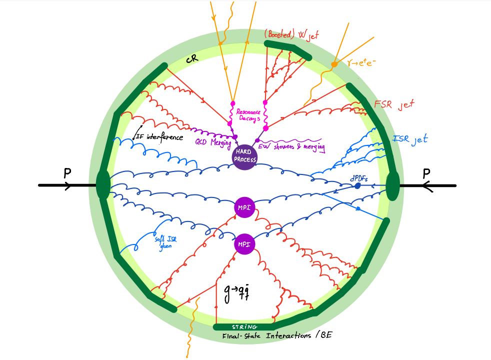
Introduction... to heavy ions vs. proton collisions

- General purpose event generator for pp collision physics and more.

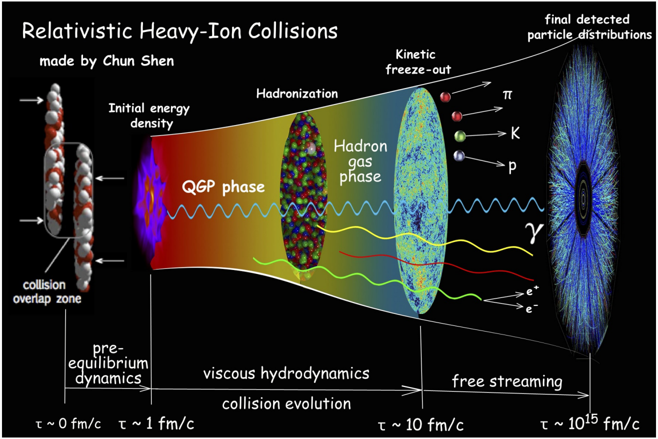


(Figure: Peter Skands)

- Experimentally focused on hard processes (+ jets), QCD resummation by parton showers, MPIs a sideshow, hadronization a necessity.

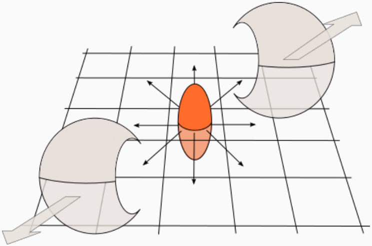
Standard model of heavy ion physics

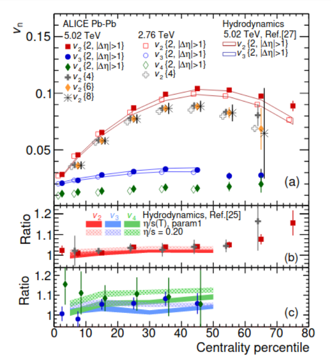
- Heavy ions traditionally viewed very differently.



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

- Staple measurement: often modeled with hydrodynamics.





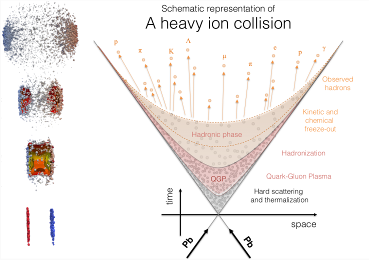
(ALICE: 1602.01119)

Fourier series decomposition of ϕ distribution:

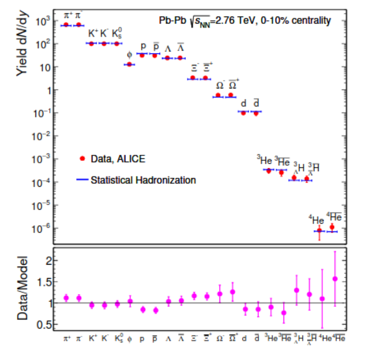
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]$$

Hadron abundances: a QGP thermometer

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



(Figure: D. Chinellato)

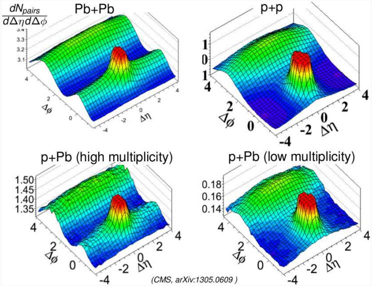


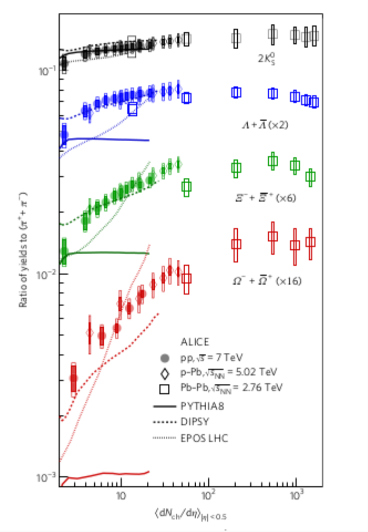
(Andronic et al: 1710.09425)

- 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?

This seminar: an overview

- Pythia soft physics: MPIs and Lund strings.
    - So what is really the big deal about pp collectivity?
- Generalization to heavy ions: The Angantyr model.
- Switching geometries, OO collisions.
- Generating flow: string shoving.
- Rope hadronization and strangeness.
- Hadronic rescatterings (and when it becomes important).
- Conclusion and next steps.

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

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

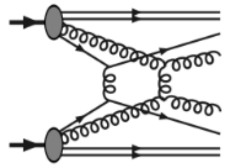


Figure T. Sjöstrand

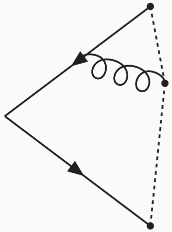
$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

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

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

The Lund String (80's: Andersson, Bo et al. Z.Phys. C3 (1980) 223, Z.Phys. C20 (1983) 317)

- Non-perturbative phase of final state.
- Confined colour fields ≈ *strings* with tension $\kappa \approx 1$ GeV/fm.



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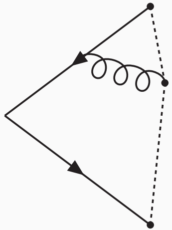

Lund symmetric fragmentation function

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right).$$

a and b related to total multiplicity.

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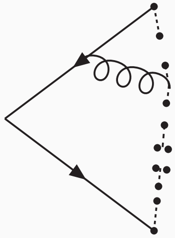

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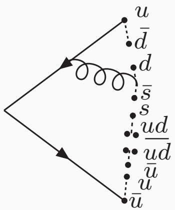

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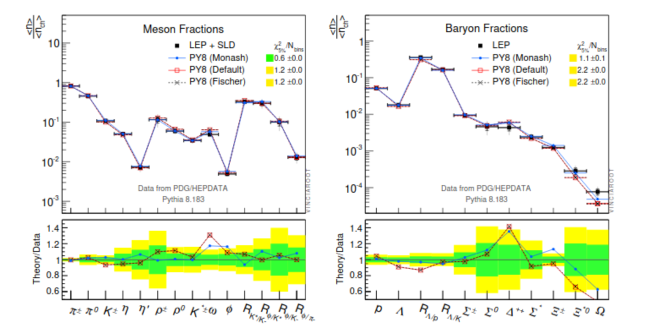
Light flavour determination

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

Related to κ by Schwinger equation.

Flavours constrained by LEP

- Strings make strong predictions about kinematics.
- Quark/di-quark masses unclear – have to rely on data.
- End of the day $\mathcal{O}(10)$ parameters.
- LEP delivers a single string.



(P. Skands: 1404.5630)

- Used for ep (HERA) and pp (RHIC/LHC) predictions.

What's the big deal about pp collectivity?!

- Above pp description: Summary of 40 years of successful phenomenology. Cannot describe collective effects.
- The AA models: Vastly different in assumptions – how well can they hold at very low multiplicity?
- Two paradigms at the price of one!

 Reconciliation! Maybe complementary descriptions?

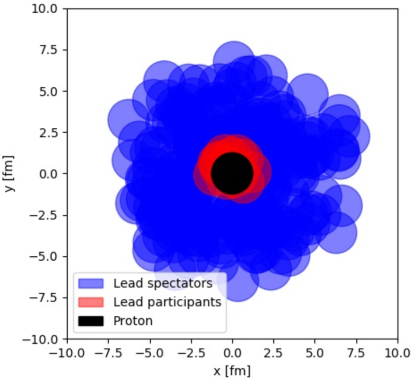
 One has got to give! We cannot have both strings and thermalization.

Our contribution: as well as possible without QGP

1. Glauber geometry with Gribov colour fluctuations.
2. Attention to diffractive excitation & forward production.
3. Let Lund strings interact with each other.
4. Hadronization and subsequent rescatterings.

Step 1: Glauber model, add fluctuations

- Concept: Cross sections determine which nucleons interact.
- Added: b-dependent fluctuations $\rightarrow$ ability to determine *how* they interact.
- Trigger process can be specified $\rightarrow$ produced by most central sub-collision.



Cross section colour fluctuations

- Cross section fluctuates event by event: important for pA, $\gamma^* A$ and less AA.
- Projectile remains frozen through the passage of the nucleus.
- Consider fixed state (k) projectile scattered on single target nucleon:

$$\Gamma_k(\vec{b}) = \langle\psi_S|\psi_I\rangle = \langle\psi_k, \psi_t|\hat{T}(\vec{b})|\psi_k, \psi_t\rangle =$$
$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b})\langle\psi_k, \psi_t|\psi_k, \psi_t\rangle =$$
$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \equiv \langle T_{tk}(\vec{b})\rangle_t$$

- And the relevant amplitude becomes $\langle T^{(nN_i)}_{t_i,k}(\vec{b}_{ni})\rangle_t$

Fluctuating nucleon-nucleon cross sections

- Let nucleons collide with total cross section $2\langle T\rangle_{p,t}$
- Inserting frozen projectile recovers total cross section.
- Consider instead inelastic collisions only (color exchange, particle production):

$$\frac{\mathrm{d}\sigma_{\mathrm{inel}}}{\mathrm{d}^2\vec{b}} = 2\langle T(\vec{b})\rangle_{p,t} - \langle T(\vec{b})\rangle_{p,t}^2.$$

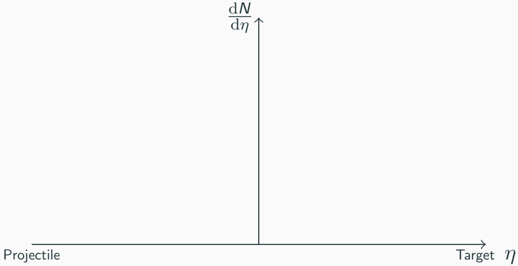
- Frozen projectile will not recover original expression, but requre target average first.

$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = 2\langle T_k(\vec{b})\rangle_p - \langle T_k^2(\vec{b})\rangle_p = 2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p$$

- Need a calculation of T. Can be parametrized.

Wounded nucleons (Inspired by Białas and Czyz)

- 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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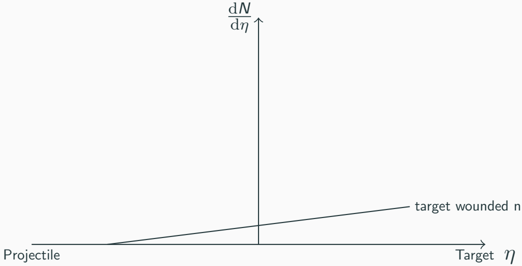

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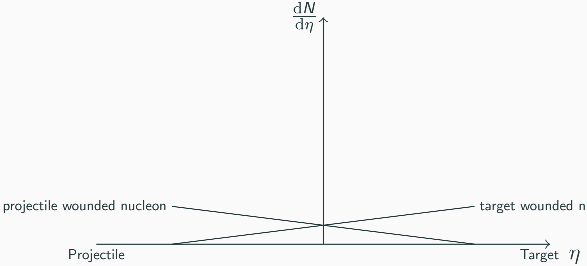

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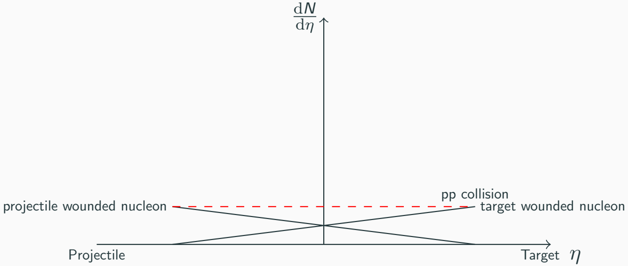

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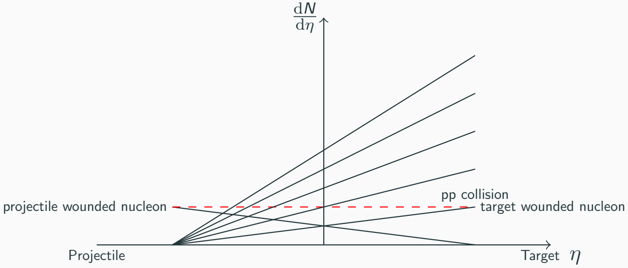

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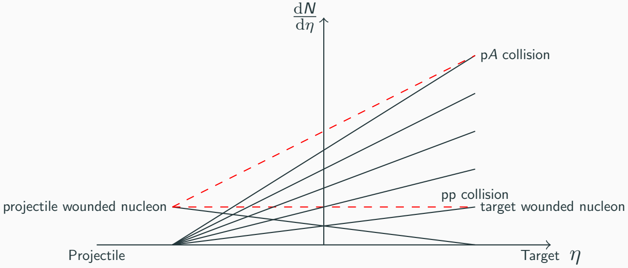

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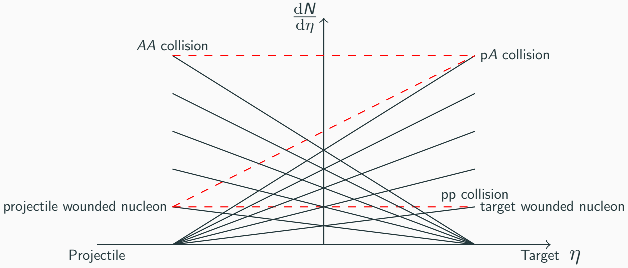
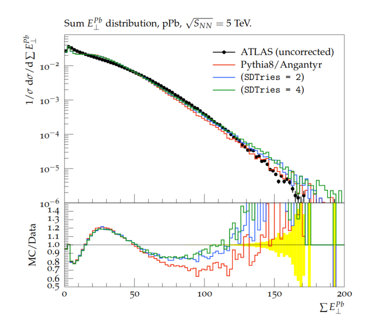
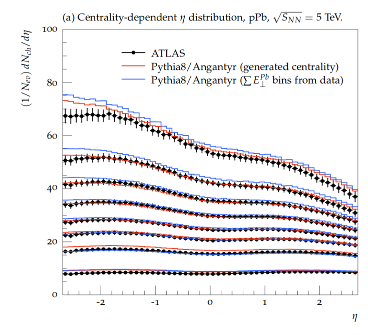


Some results - pPb

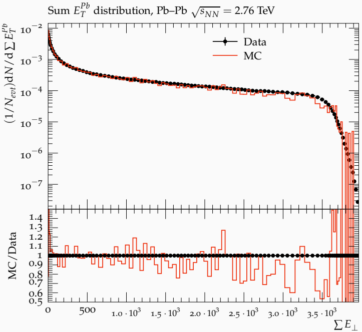
- Centrality measures are delicate, but well reproduced.
- So is charged multiplicity.

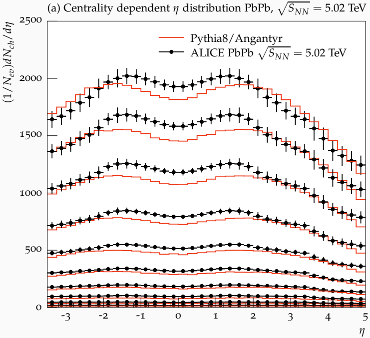




Basic quantities in AA

- Reduces to normal Pythia in pp. In AA:
    1. Good reproduction of centrality measure.
    2. Particle density at mid–rapidity.

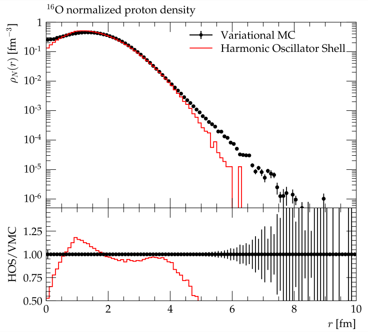




- Clean slate for new models!

Switching geometry: what about OO collisions?

- Default Woods-Saxon, unsuitable for $A < 17$ nuclei.
- WiP: More geometries with to be added. User definable through `HeavyIonUserHooks`.
- Problem: How to estimate parameters? Theory? Data fits?

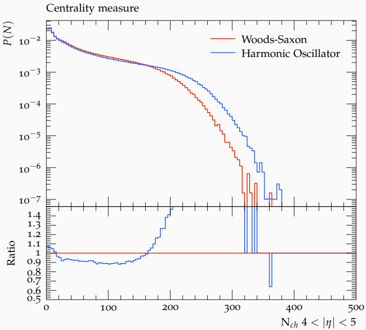


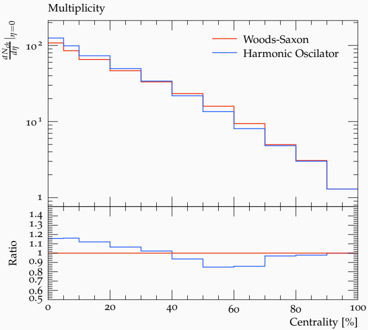
$$\rho(r) = \frac{4}{\pi^{3/2} C^3} \left(1 + \frac{(A-4)r^2}{6C^2}\right) \exp(-r^2/C^2)$$

$$C^2 = \left(\frac{5}{2} - \frac{4}{A}\right)^{-1} (\langle r^2 \rangle_A - \langle r^2 \rangle_p)$$

Large differences forward

- Mock centrality measure: N_{ch} in $4 < |\eta| < 5$.
- $\sqrt{s_{NN}} = 5020$ GeV, $\tau_{0max} = 10$ mm/c, $\approx$ 3K events/minute/thread.

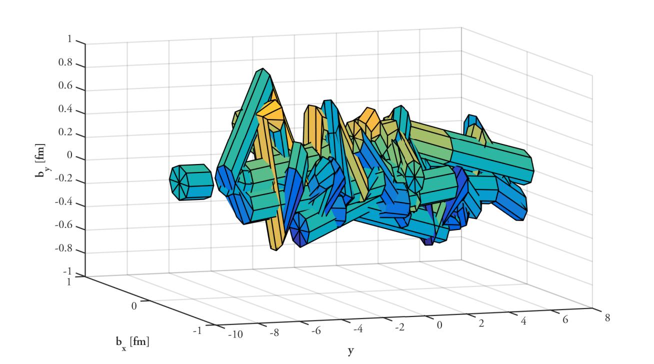




- Angantyr a versatile and public model – but of course needs some input.

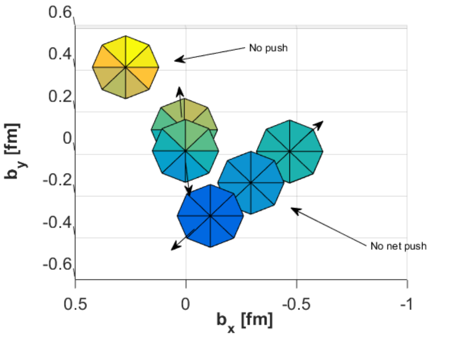
How to add space-time dependence to Lund strings?

- Shopping list:
  1. Space time structure (KISS for now, convolution of 2D Gaussians, Lorentz contracted in z-direction).
  2. What effect could generate flow?
  3. What effect could change the string tension?



Shoving: The cartoon picture (CB, Gustafson, Lönnblad: 1710.09725, +=Chakraborty: 2010.07595)

- Strings push each other in transverse space.
- Colour-electric fields $\rightarrow$ classical force.



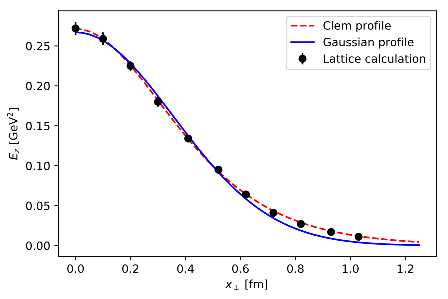
👍 Transverse-space geometry.

👍 Particle production mechanism.

?? String radius and shoving force

MIT bag model, dual superconductor or lattice?

- Easier analytic approaches, eg. bag model:
  $\kappa = \pi R^2[(\Phi/\pi R^2)^2/2 + B]$
- Bad: R uncertain, shape of field is 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:

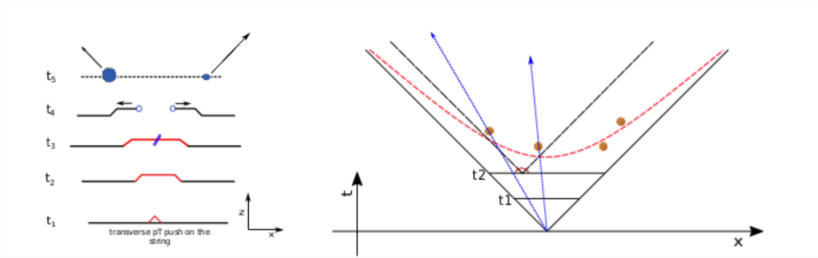
$$E = N \exp(-\rho^2/2R^2)$$

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

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

Monte Carlo details

- Distance $d_\perp$ calculated in a frame where strings lie in parallel planes.
- Everything is two-string interactions.
- The shoving action implemented as a parton shower.
- Push propagated along string, and distributed on final state hadrons.



Rope Hadronization (JHEP 1503 (2015) 148 – explored heavily in 80's and 90's!)

- After shoving, strings (p and q) still overlap.
- Combines 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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Easily calculable using SU(3) recursion relations

$$\{p, q\} \otimes \vec{3} = \{p+1, q\} \oplus \{p, q+1\} \oplus \{p, q-1\}$$

$$\underbrace{\begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \ldots \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix}}_{\text{All anti-triplets}} \underbrace{\otimes \square \otimes \square \otimes \ldots \otimes \square}_{\text{All triplets}}$$

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- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Fragmenting the multiplets

- Highest multiplet = highest string tension.
- Intermediate multiplets = string junctions, carry baryon number.
- Rope breaks one string at a time, reducing the *remaining* tension.

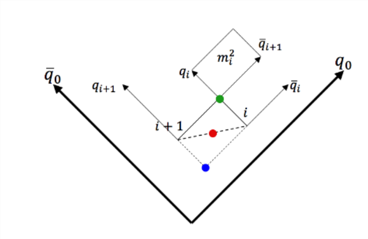
Strangeness enhanced by:

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

- QCD + geometry extrapolation from LEP.
- Can *never* do better than LEP description!

Rescattering (CB, Utheim, Sjöstrand, Ferreres-Solé: 2103.09665, 2005.05658, 1808.04619)

- Rescattering requires hadron space–time vertices.
- Key difference to existing approaches: 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.
- Extensions towards cosmic cascades coming.

Microscopic final state collectivity in summary

- Proposal: Model microscopic dynamics with interacting Lund strings
- Additional input fixed or inspired by lattice, few tunable parameters.

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$\tau \approx 0.6$ **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.

$\tau \approx 1.4$ **fm:** Strings will hadronize. Possibly as a colour rope.

$\tau > 1.4$ **fm:** Possibility of hadronic rescatterings.

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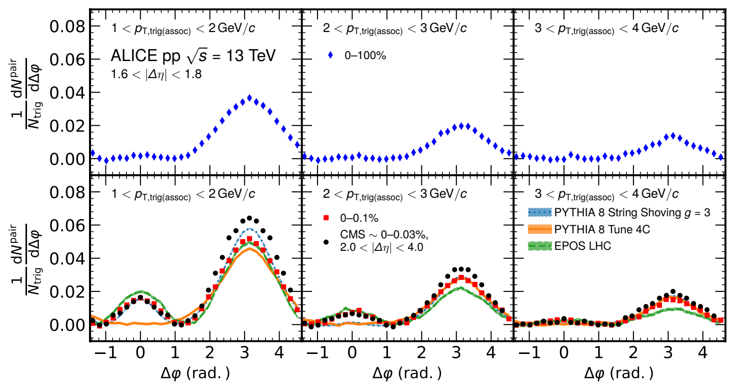
Shoving results

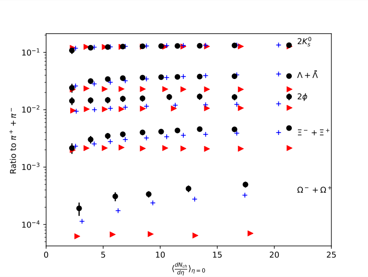
- The pp ridge (and much more, see 2010.07595).
- Here compared to ALICE: apply cuts and biases as you wish (even Z tags, see 1901.07447)



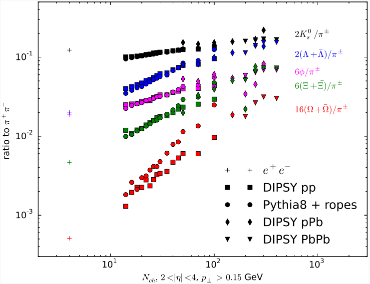
(ALICE: 2101.03110)

Rope results

- Good description of strangeness enhancement.
- Left pp final calculation, right pp-AA preliminary results (WiP).

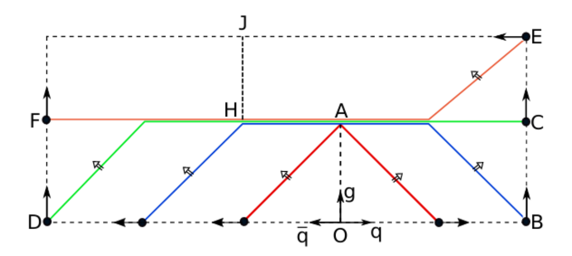


(Data in black (ALICE))



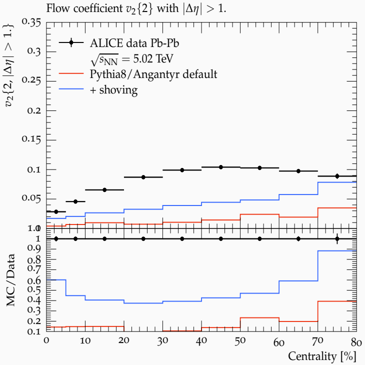
Did you skip shoving for AA?

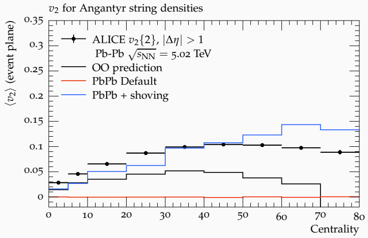
- Adding small pushes propagating along the string is difficult!
- Current problem: "secondary" string pieces arising from origami regions.
- If only there were no soft gluons around...



Shoving results PbPb (and OO)

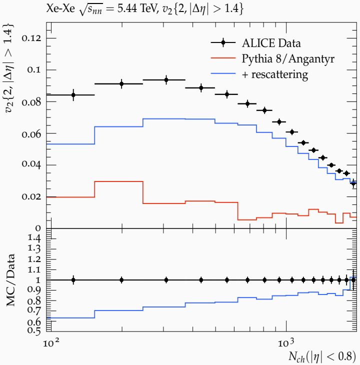
- Missing origami regions, realistic initial states (left).
- Toy model configuration (right)
- Both lacking hadronic rescattering, which also plays a role.

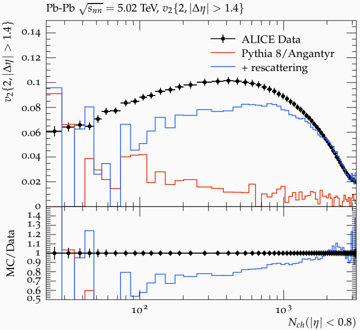




Rescatterings

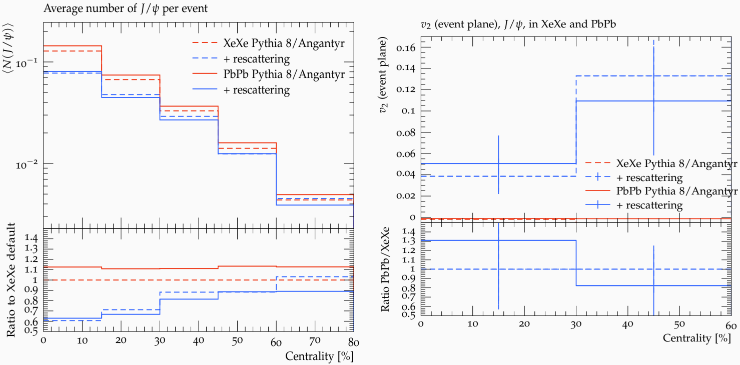
- Early time hadronization means large effect from rescatterings.
- High multiplicity v_2 well described, no shoving included here.
- Larger effect for PbPb than XeXe.





Rescattering charm

- Includes additive quark model for charm cross sections.
- Large effect for J/ψ (dissociation, flow). Early production.
- Full comparison to data needed.



Summary and future

- Heavy ion physics traditionally different from high energy pp.
- Small system collectivity (LHC) blurred the lines.
- $\rightarrow$ Pythia a multi-purpose heavy ion generator without QGP.
  1. Angantyr model extending the MPI picture.
  2. Pluggable nuclear geometries (eg. OO).
  3. String shoving for flow (not public in AA yet).
  4. Rope hadronization for strangeness (not public in AA yet).
  5. Hadronic rescattering machinery.
- Next step is making them all talk together – a coherent heavy ion model.
- Interactions welcome, many exciting possibilities for R3, EIC and cosmics.

Thank you for the invitation!