Multi-Parton Interactions and Underlying Event: A PYTHIA perspective

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Introduction

- A brief overview of Pythia's venture into heavy ion physics.
- Why?
  - Heavy ion phenomena in pp at LHC spurred interest.
  - Pythia often used as "baseline" tool.
- But! Underlying models $! =$ Pythia implementation.

Can we deliver a better baseline?

... or make the Quark–Gluon Plasma redundant?

Most importantly:

◇ New opportunities for non-perturbative QCD

- This talk: a microscopic, plasma free approach.
  1. Heavy ions in Pythia: MPIs from pp to AA.
     ◇ The Angantyr model, cross sections & basic observables.
  2. Microscopic collectivity.
     ◇ The shoving model & effects from hadronic rescatterings.
  3. Towards the EIC.

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

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

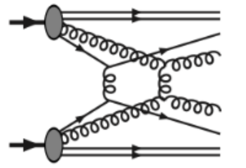


Figure T. Sjöstrand

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

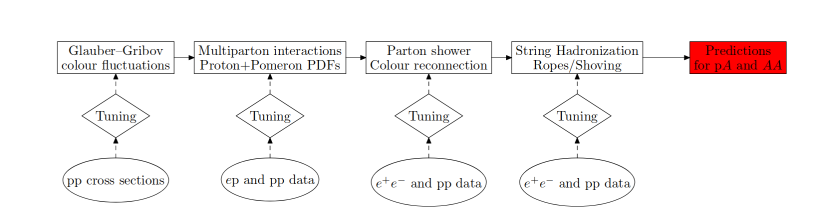
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

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

- Picture blurred by CR, but holds in general.

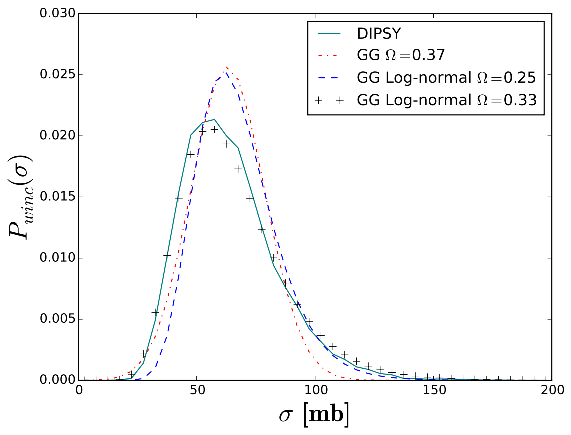
Angantyr – the Pythia heavy ion model (CB, G. Gustafson, L. Lönnblad: arXiv:1607.04434, += Shah: arXiv:1806.10820)

- Pythia MPI model extended to heavy ions since v. 8.235.
    1. Glauber geometry with Gribov colour fluctuations.
    2. Attention to diffractive excitation & forward production.
    3. Hadronize with Lund strings.



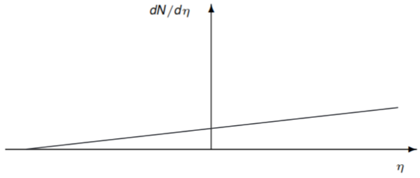
Glauber–Gribov colour fluctuations

- Cross section has EbE colour fluctuations.
- Parametrized in Angantyr, fitted to pp (total, elastic, diffractive).



Particle production: Wounded nucleons

- Simple model by Białas and Czyz.
- Wounded nucleons contribute equally to multiplicity in η.
- Originally: Emission function $F(\eta)$ fitted to data.



$$\frac{dN}{d\eta} = F(\eta)$$ (single wounded nucleon

- Angantyr: No fitting to HI data, but include model for emission function.
- Model fitted to reproduce pp case, high $\sqrt{s}$, can be retuned down to 10 GeV.

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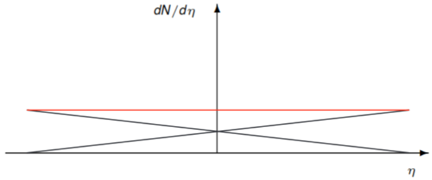

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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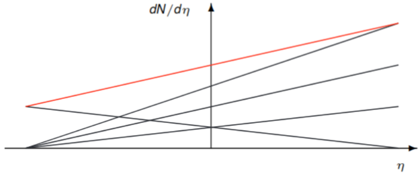

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad \text{(pA)}$$

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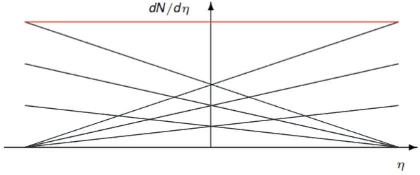

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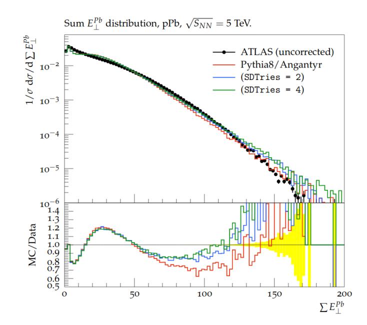
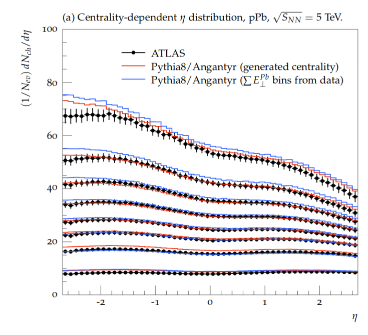
Some results - pPb

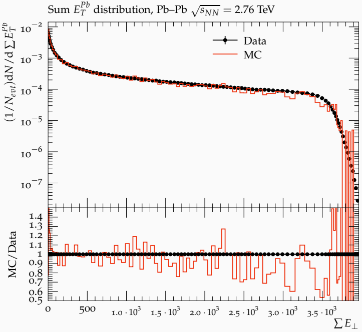
- Centrality measures are delicate, but well reproduced.
- So is charged multiplicity.

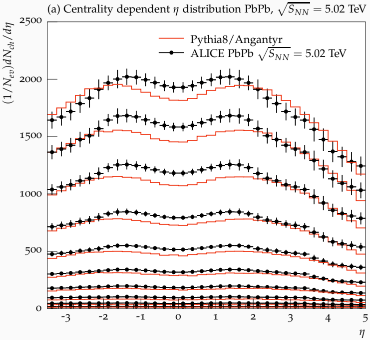




Basic quantities in AA

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

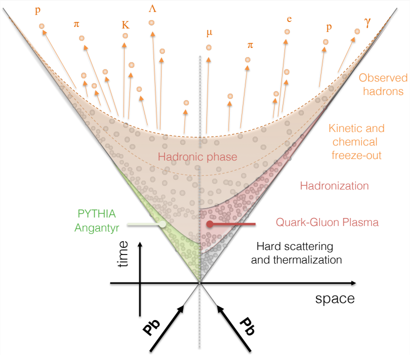




- Necessary baseline for any full model.

A clean canvas!

- Angantyr is a foundation on which models for collective behaviour can be added.
- The rest of the talk: Microscopic collectivity & hadronic rescatterings w. URQMD.



(Figure: D. D. Chinellato)

Microscopic final state collectivity

- We need more than colour reconnection! Where is the geometry?
- 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.

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

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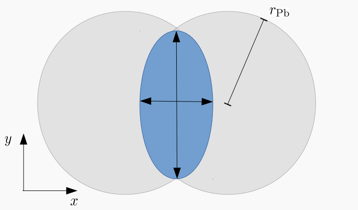
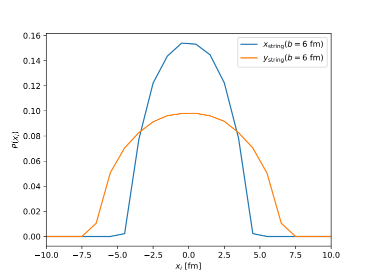
Shoving: Why is AA so difficult?

- Formalism: See talk by Smita Chakraborty Tue. C1 III
- In pp two crude approximations were made:
  1. All strings straight and parallel to the beam axis.
  2. Pushes can be added as soft gluons.
- This gives problems in AA, which we are solving:
  - 👍 Beam axis → parallel frame (Talk by Smita Chakraborty).
  - 👍 Soft gluons → push on hadrons.
  - 👎 Straight strings → treatment of gluon kinks? (WiP).
- Enough for a toy run!

A toy example

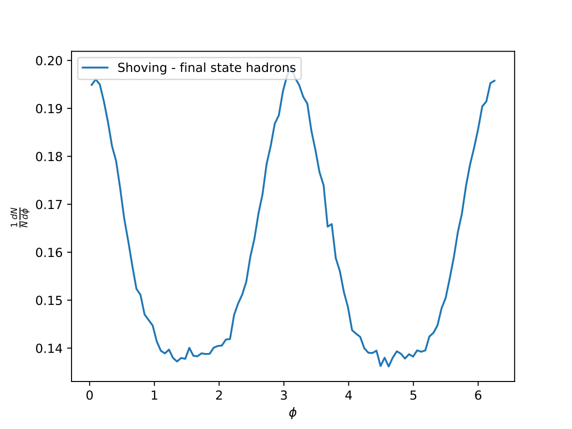
- Consider an elliptical overlap region filled with straight strings (no gluons).
- Same shoving parameters as for pp.





Toy results (Data: ALICE PRL 116 (2016) 132302)

- To take away: The mechanism gives a resonable response.
- A local mechanism *can* result in global features.



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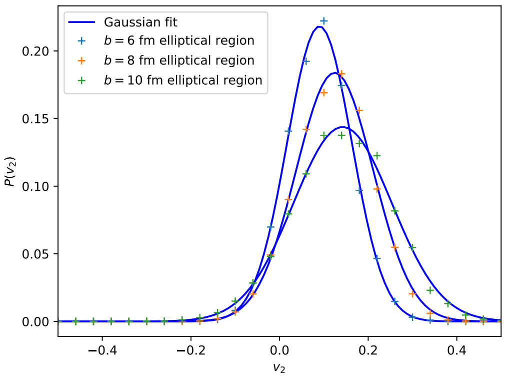

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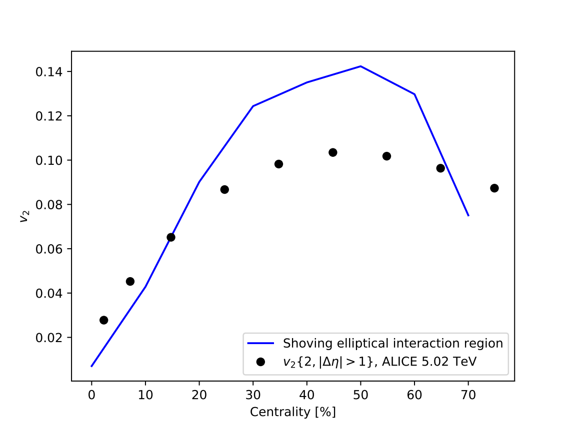

A Z-boson changes the kinematics (CB: arXiv:1901.07447)

- The presence of a Z should not change the physics.
- It *can* introduce kinematical biases: MC implementation will handle this.
- Measured by ATLAS (ATLAS-CONF-2017-068).

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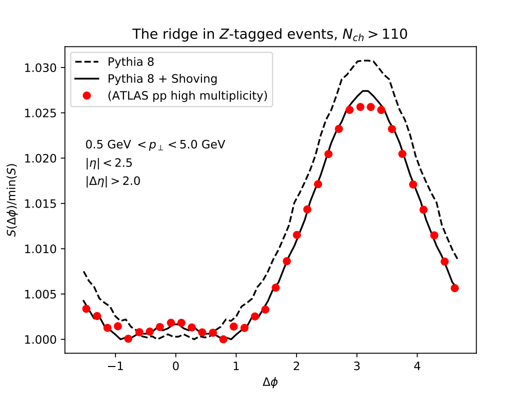
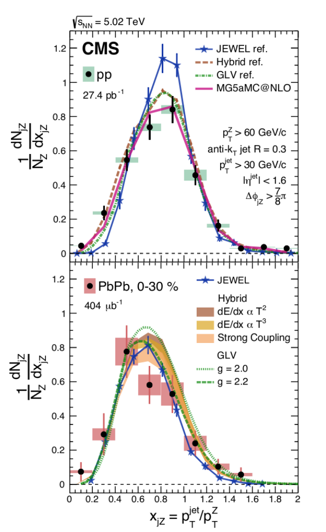
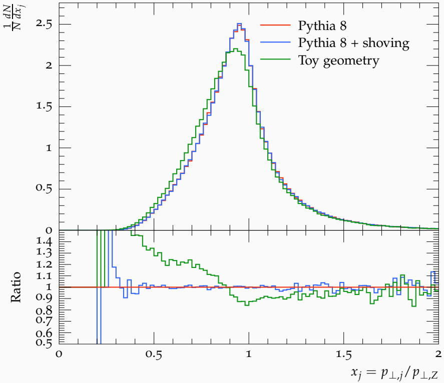


Source of jet modifications? (CB: arXiv:1901.07447)

- Toy geometry: Let the jet hadronize inside a pp collision.
- Qualitative similarities with AA results (CMS: PRL 119 (2017) 8).

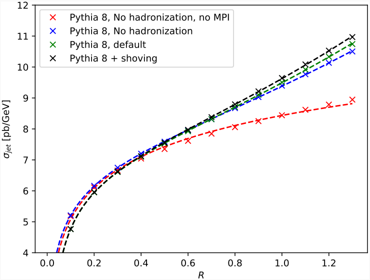


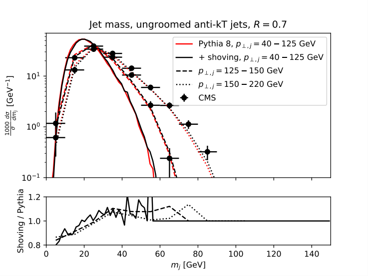
- AA possibility ahead!
- pp: modifications on jet edge.



Modifications on the edge

- Can be quantified: Same level as hadronization correction in $\sigma_{jet}(R)$.
- Perhaps measurable with better low-$p_\perp$ coverage?





Final state interactions with Angantyr+URQMD (da Silva et al. 2002.10236 [hep-ph])

- Hadronic final state interactions matter!
  1. Non-fluid scenario, short times.
  2. Made possible by hadron vertex model (see backup).
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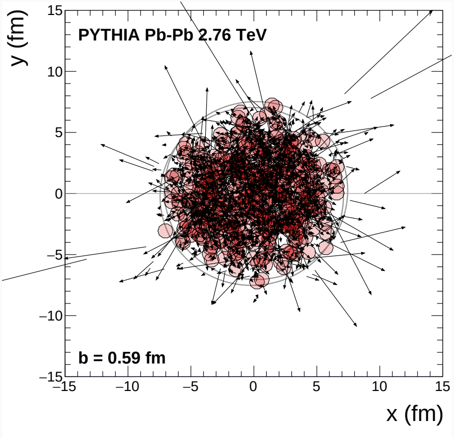

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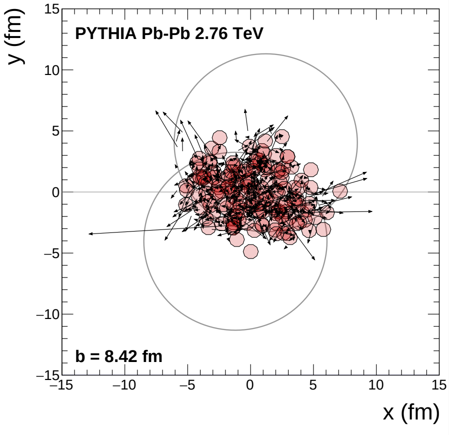

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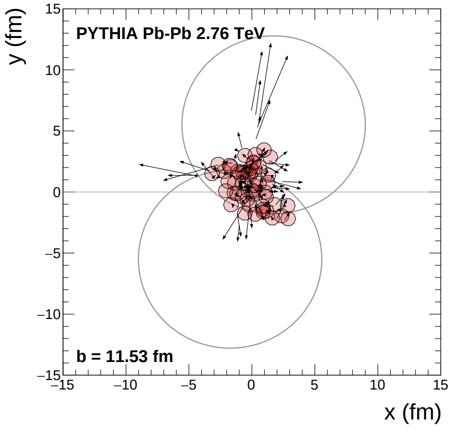
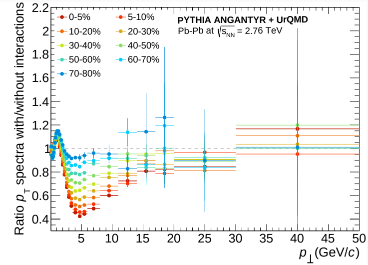
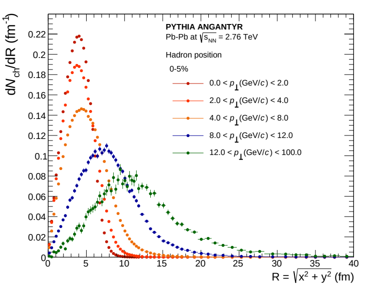


Effects on $p_\perp$-spectra

- Pythia will hadronize early, compared to eg. hydro.
- Denser state $\rightarrow$ more hadronic rescatterings.
- Non-trivial dependence on hadron $p_\perp$.

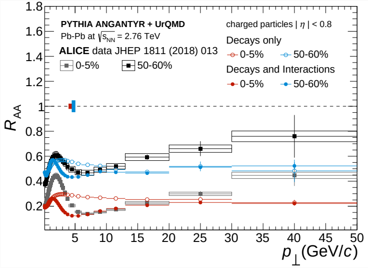


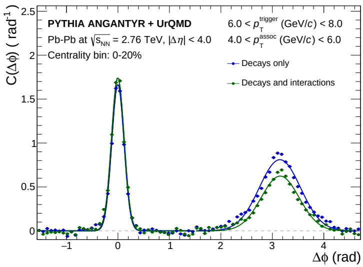


- Not quantitative *description* of data, but improved baseline.
- Note: No free parameters for AA.

Effect on observables

- Effect between $3 < p_{\perp} 15$ GeV quantified in R_{AA}.
- Two-particle correlations further dissect:
  1. Away side structure further suppressed. Hard hadron produced further towards the surface.
  2. Correct hadron vertices key!
  3. Effect too small to fully explain STAR measurements.





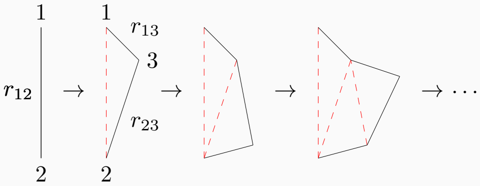
Towards EIC (WIP: with Ilkka Helenius; CB & C. O. Rasmussen: 1907.12871 [hep-ph])

- Extending Angantyr to EIC requires knowledge of fluctuating $\sigma_{abs}(Q^2)$.
- Mueller dipole BFKL as parton shower.

Dipole splitting and interaction

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y\ \mathrm{d}^2\vec{r}_3} = \frac{N_c\alpha_s}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2}\Delta(y_{\min}, y),$$

$$f_{ij} = \frac{\alpha_s^2}{2}\log^2\left(\frac{r_{13}r_{24}}{r_{14}r_{24}}\right).$$



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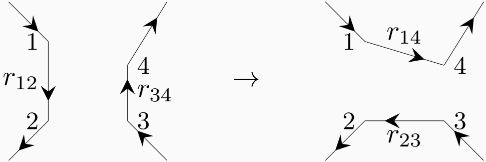
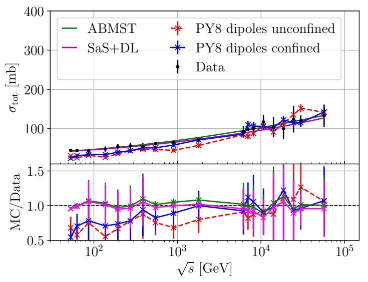
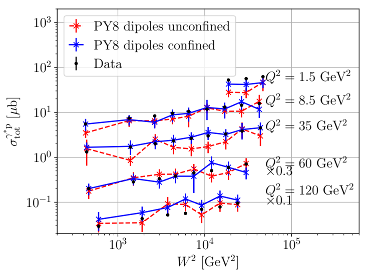


Everything fitted to cross sections

- Avoids fitting to predictions.
- Unitarized dipole-dipole amplitude plus Good-Walker.

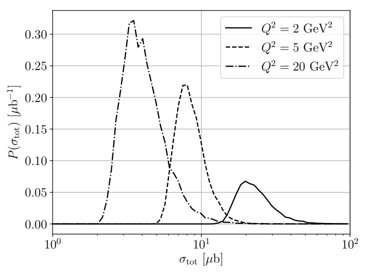
$$T(\vec{b}) = 1 - \exp\left(-\sum f_{ij}\right), \sigma_{tot} = \int d^2\vec{b}\, 2T(\vec{b})$$

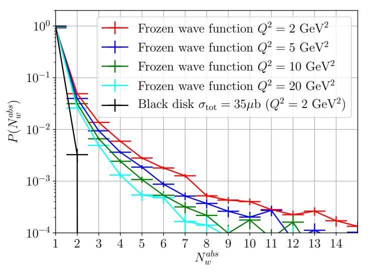




Glauber for $\gamma^* A$

- Correct fluctuations and freezing is neccesary.
- Next steps: Sampling of photon flux (UPCs) and full integration with final states.





Summary: How far can we get without QGP?

Angantyr offers an improved Pythia "baseline".

Non-QGP effects leave less room for a thermalised plasma.

- A basic heavy ion model, wo. collective effects:
  - ◇ good description of multiplicity and centrality in pA and AA.
  - ◇ EIC underlying events are coming.
- Microscopic collectivity.
  - ◇ extending string description with ropes & shoving.
  - ◇ made for flow, but extends dynamically to jet effects.
  - ◇ hadronic rescattering effects adds similar effects: unified implementation desireable.

Thank you for the invitation!
Thank you organizing an online conference!

Some additional material

Color reconnection? What's that?

- Many partonic subcollisions ⇒ Many hadronizing strings.
- But! $N_c = 3$, not $N_c = \infty$ gives interactions.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

$$\mathcal{P}_{merge} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0})^2 + p_\perp^2}$$

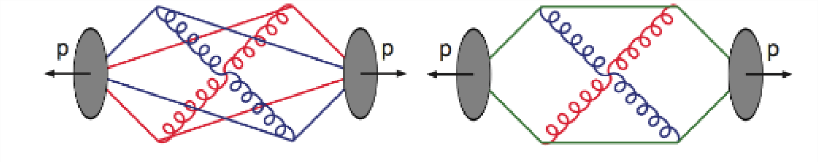


Figure T. Sjöstrand

- Actual merging by minimization of "potential energy":

$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2}E/m_0)$$

Colour Reconnection – microscopic collectivity?

(Ortiz et al.: 1303.6326, CB QM18: 1807.05217 & mcplots.cern.ch)

- Mechanism allows cross–talk over an event.
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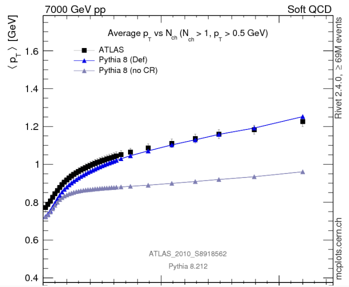
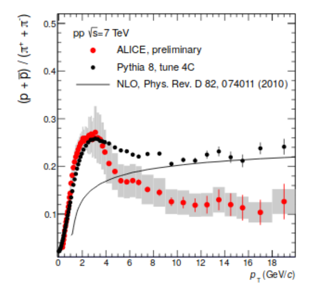
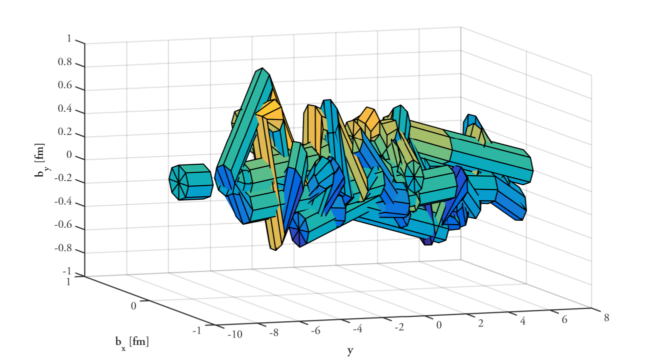




The importance of the initial state

- Space–time information is important: We rely on models! Also true for hydro.
- Here: Overlapping 2D Gaussians (p mass distribution).
- Figure string $R = 0.1$ fm, reality $R \sim 0.5$ fm.



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- Space–time information is important: We rely on models! Also true for hydro.
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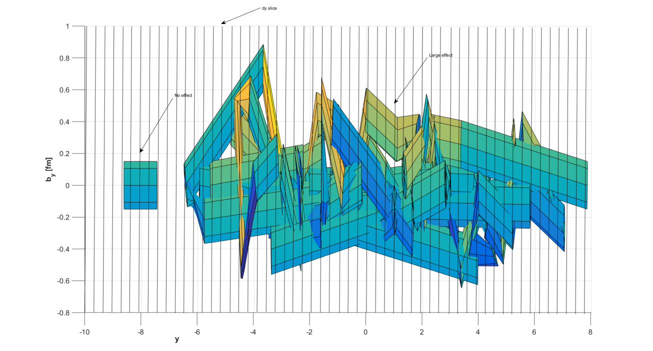

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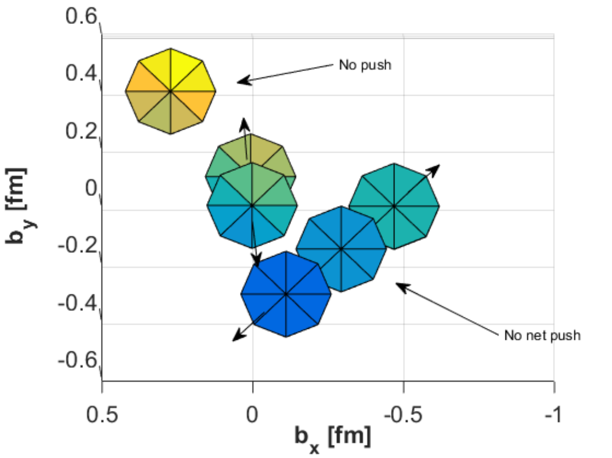
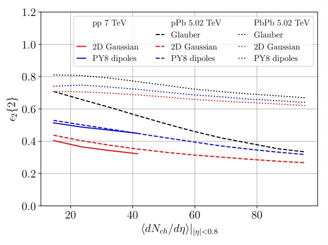
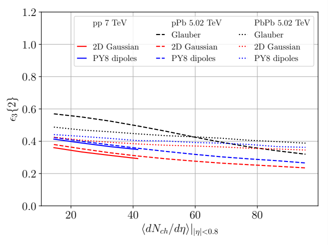


Geometry in pp, pA and AA

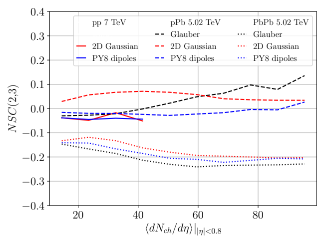
- Assuming $\epsilon_{2,3} \propto v_{2,3}$.
- Dipole model: $\epsilon_{2,3}$ equal for pp and pPb.

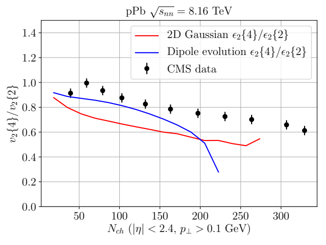




Flow fluctuations: Looking inside

- Flow fluctuations and normalized symmetric cumulants.
- Best discrimination in pPb.
- Dipole evolution → negative $NSC(2,3)$ in pPb.

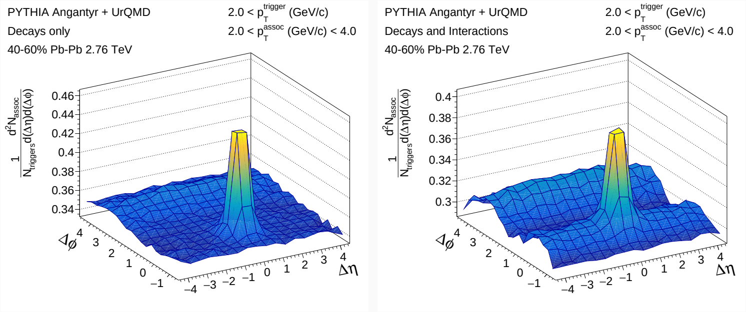




- *Important to develop realistic initial states.*
- *Point stands also for hydro.*

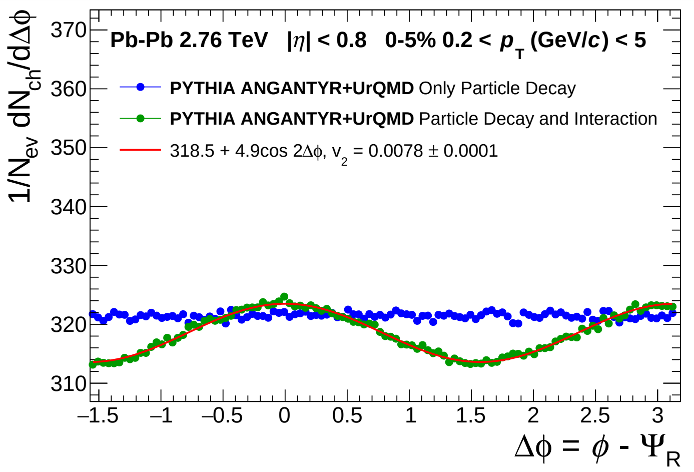
Results – flow

- Rescattering produces correlations long-range in η (the double ridge).
- Previously seen, but not at these energies, with general purpose MC input (Bleicher *et al.* arXiv:nucl-th/0602009).



Results – flow

- Understanding model influence: Correlations wrt. event plane calculated from Pythia Glauber.
- Automatic removal of jet peak.



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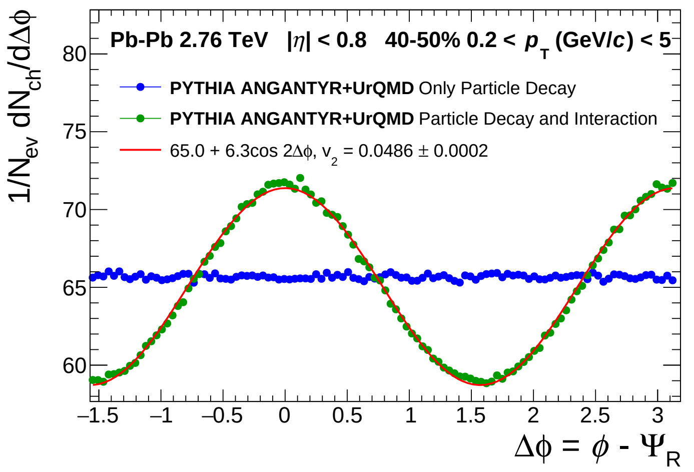

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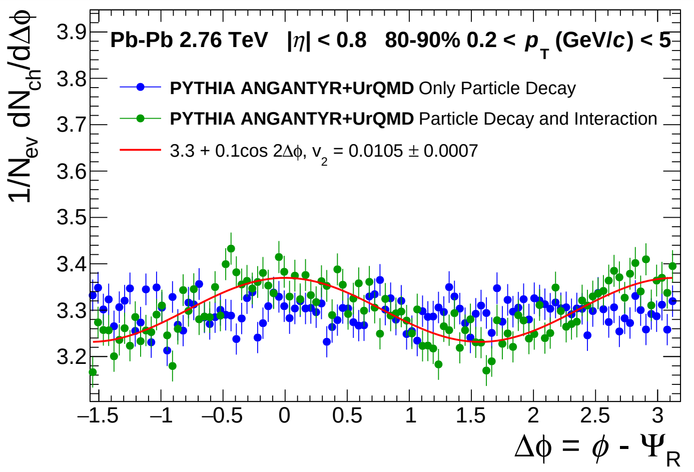
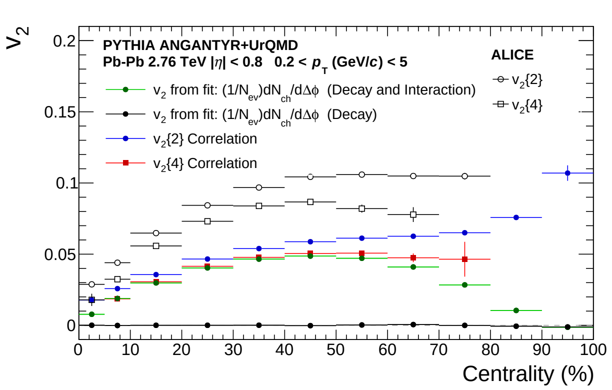


Results – elliptic flow coefficients

- v_2 vs centrality: same dynamics as in ALICE data, but 50% magnitude; v_2 via cumulants similar to v_2 with correlations wrt. event plane



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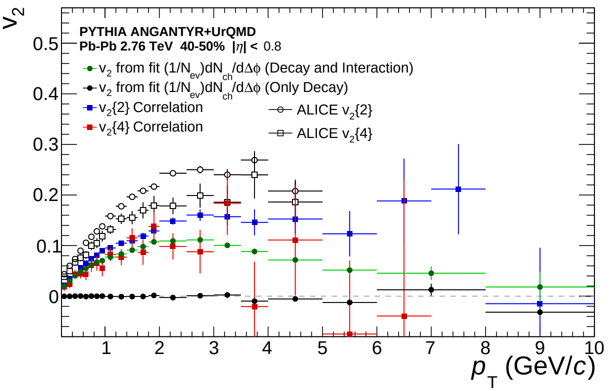


- Similar conclusion from $v_2(p_\perp)$

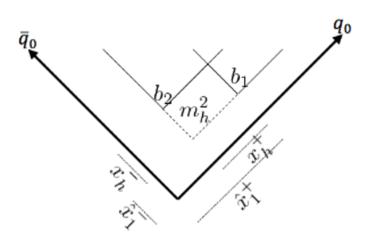
String kinematics (B. Andersson et al.: Phys. Rept.97(1983) 31)

- Lund string connects $q\bar{q}$, tension $\kappa = 1\text{GeV}/\text{fm}$.
- String obey yo–yo motion:

$$p_{q_0/\bar{q}_0} = \left(\frac{E_{cm}}{2} - \kappa t\right)(1;0,0,\pm 1).$$

- String breaks to hadrons with 4-momenta:

$$p_h = x_h^+ p^+ + x_h^- p^- \text{ with } p^\pm = p_{q_0/\bar{q}_0}(t=0)$$



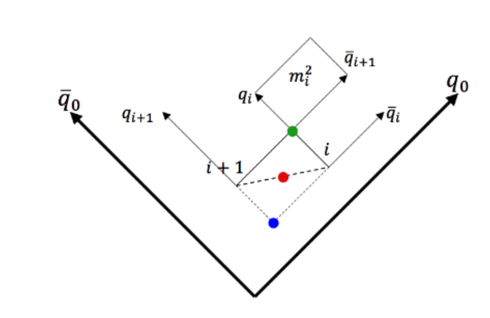
- ... which gives breakup vertices in momentum picture.

Hadron vertex positions (Ferreres-Solé & Sjöstrand: 1808.04619)

- Translate 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.

String shoving (CB, Gustafson, Lönnblad: 1612.05132, 1710.09725)

- Strings = interacting vortex lines in superconductor.
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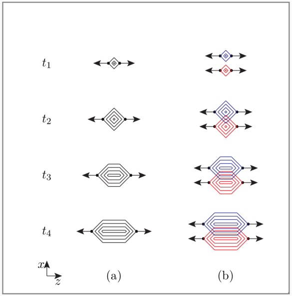

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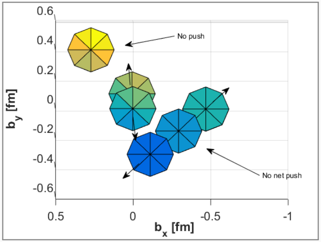

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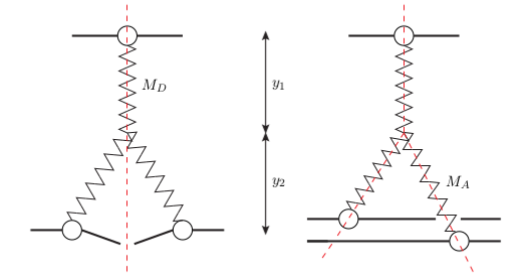
The emission function

- Similarity: triple-Pomeron diagrams.



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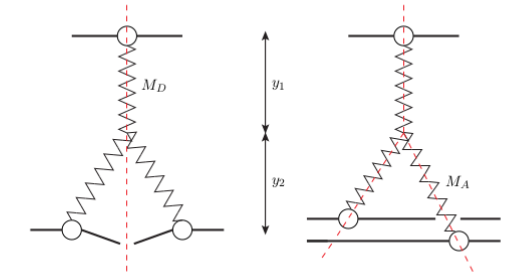

Diagram weight proportial to $(1+\Delta = \alpha_{\mathbb{P}}(0))$

$$\frac{\mathrm{d}s}{s^{(1-2\Delta)}} \frac{dM_D^2}{(M_D^2)^{(1+\Delta)}} \text{ diffractive excitation,}$$

$$\frac{\mathrm{d}s}{s^{(1-\Delta)}} \frac{dM_A^2}{(M_A^2)^{(1-\Delta)}} \text{ secondary absorption.}$$

Glauber for $\gamma^* A$

- Results in fluctuating γ^*-nucleon absorptive cross section.

Wounded nucleon cross section gets frozen

1st:

$$\int \mathrm{d}z \int \mathrm{d}^2\vec{r}\,(|\psi_L(z,\vec{r})|^2 + |\psi_T(z,\vec{r})|^2)(2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p).$$

Further:

$$2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p,$$

- First ingredient of "soft QCD" EIC generator.