Angantyr, strings and all that

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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?

- This talk: an overview, with lots of questions!
  1. Heavy ions in Pythia: MPIs from pp to AA.
  2. String interactions, ropes, shoving and details.
  3. Hadronic rescatterings.
  4. Proton sub-structure with Mueller dipoles.
  5. MPIs at EIC..

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

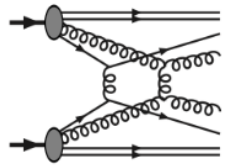


Figure T. Sjöstrand

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

$$\frac{d\sigma_{2\to2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

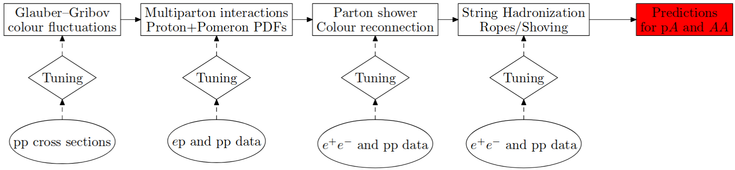
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \dots$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to2}}{dp_\perp} \exp\left[-\int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp\right]$$

- Picture blurred by CR, but holds in general.

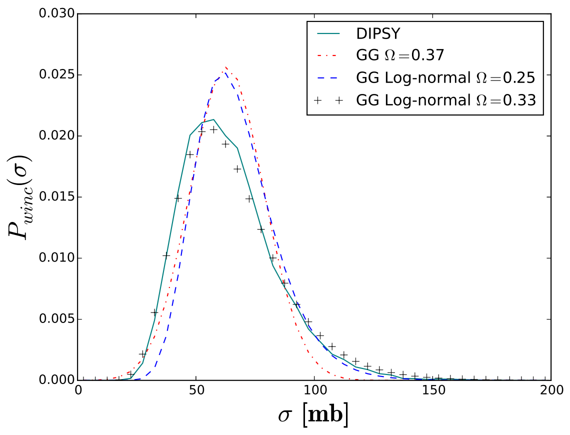
Angantyr – the Pythia heavy ion model (CB, G. Gustafson, L. Lönnblad: arXiv:1607.04434, += Shah: arXiv:1806.10820)

- 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.



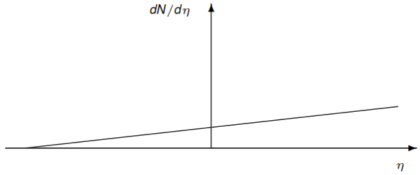
Glauber–Gribov colour fluctuations

- 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.



$$\frac{dN}{d\eta} = \quad F(\eta)$$ (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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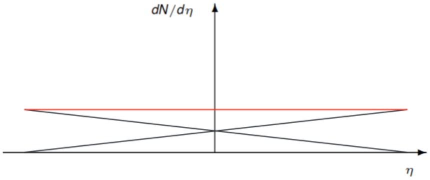

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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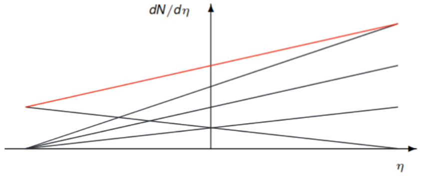

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (pA)$$

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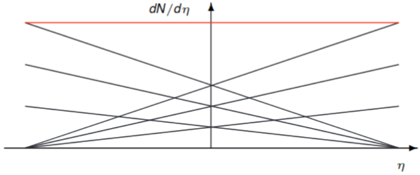

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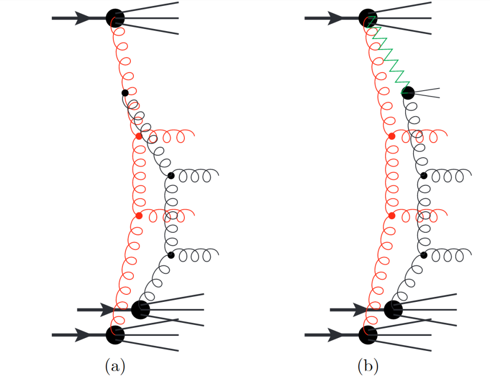
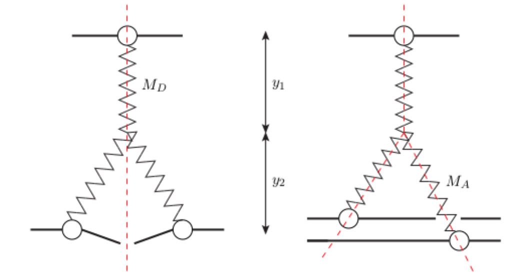
The emission function

- A schematic view of a pD collision. Contains 3 wounded nucleons.
- First two are a normal non-diffractive pp event.
- The second one is modelled as a single diffractive event.
- Generalizes to all pA and AA collisions.



Secondary absorptive interactions

- Similarity: triple-Pomeron diagrams.



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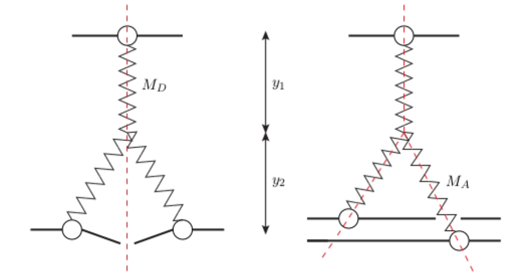


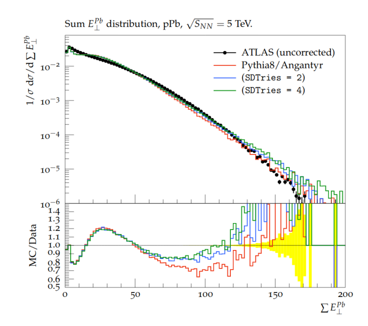
Diagram weight proportial to $(1+\Delta = \alpha_{\mathbb{P}}(0))$

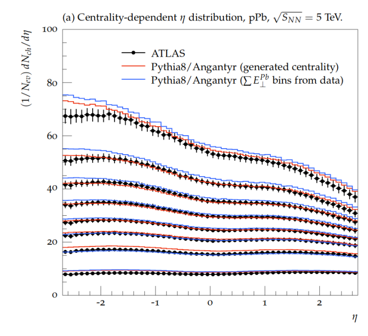
$$\frac{ds}{s^{(1-2\Delta)}}\,\frac{dM_D^2}{(M_D^2)^{(1+\Delta)}}\ \text{diffractive excitation,}$$

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

Some results - pPb

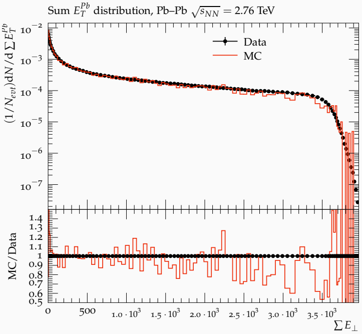
- Centrality measures are delicate, but well reproduced.
- So is charged multiplicity.

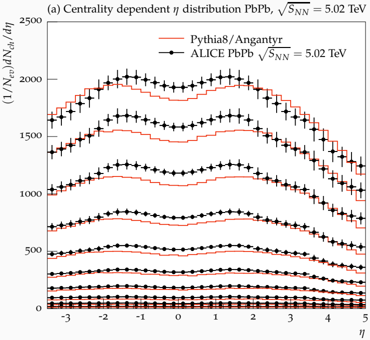




Basic quantities in AA

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

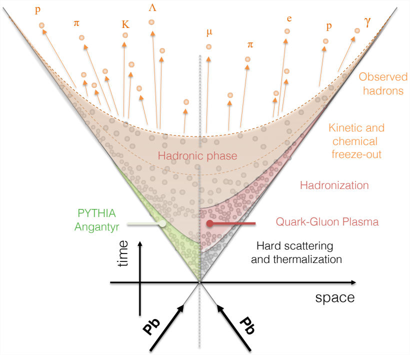




- Necessary baseline for any full model.

A clean canvas!

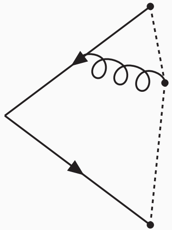
- Angantyr is a foundation on which models for collective behaviour can be added.
- The rest of the talk: Microscopic collectivity & hadronic rescatterings w. URQMD.



(Figure: D. D. Chinellato)

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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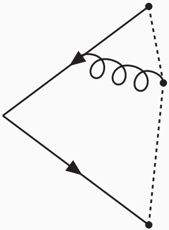

Lund symmetric fragmentation function

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

a and b related to total multiplicity.

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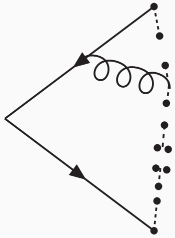

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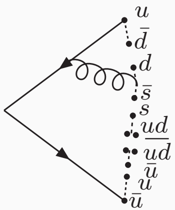

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Light flavour determination

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

Related to κ by Schwinger equation.

Color reconnection? What's that?

- Many partonic subcollisions $\Rightarrow$ 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-$p_\perp$.

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

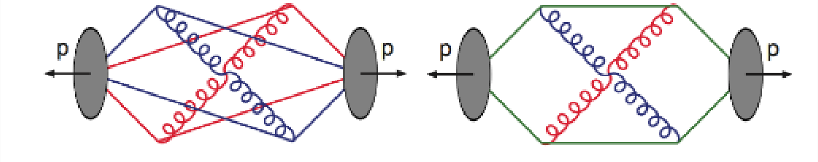

Figure T. Sjöstrand

- 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.
- Based on physics effect.
- Needed for multiplicity & $\langle p_\perp \rangle$.
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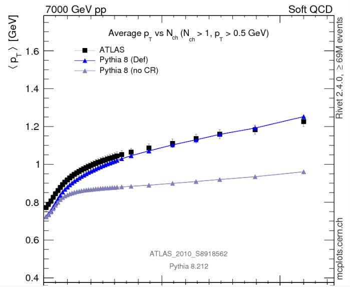
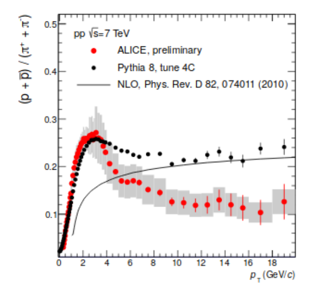


N_{ch}



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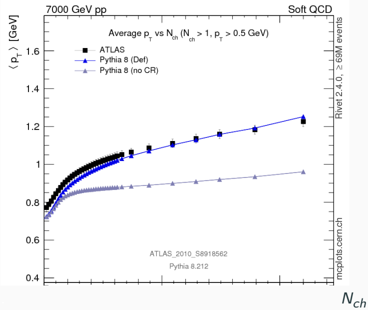

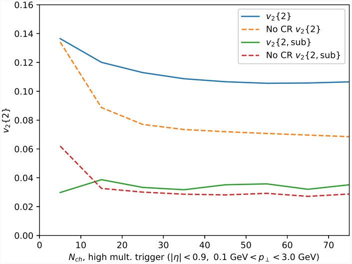

Microscopic final state collectivity

- Clearly we need more! 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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$\tau \approx 0$ **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.

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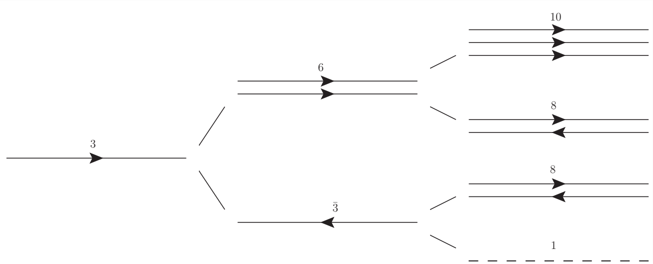
- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Divide and conquer!

- Consider now the *stacking* of such pairs.
- SU(3) multiplet structure decided by random walk.



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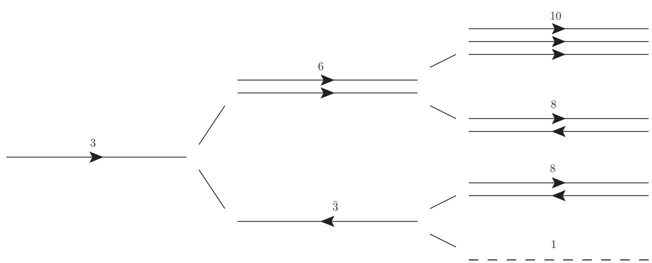


Three conceptual options

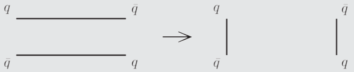
1. Highest multiplet (Rope).
2. Lower multiplet (junction structure).
3. Singlet.

Lower multiplets & singlets $\rightarrow$ QCD colour reconnection.

Junction CR (Christiansen and Skands arXiv:1505.01681 [hep-ph])

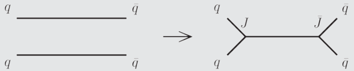
- Possible structures from QCD-inspired weight.
- Selection relies on λ-measure (potential energy).

Ordinary string reconnection



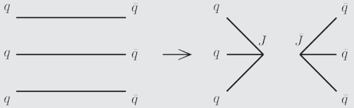
($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



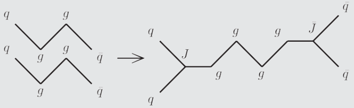
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



(Depends on number of gluons)

The highest multiplet

- Remaining structure joins in a rope.
- Rope breaks one string at a time, reducing the *remaining* tension.
- Junctions carry baryon number.

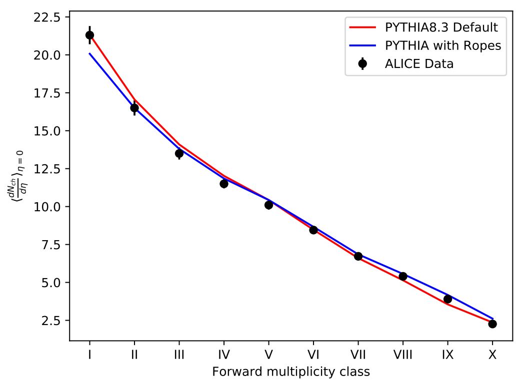
Strangeness enhanced by:

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

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

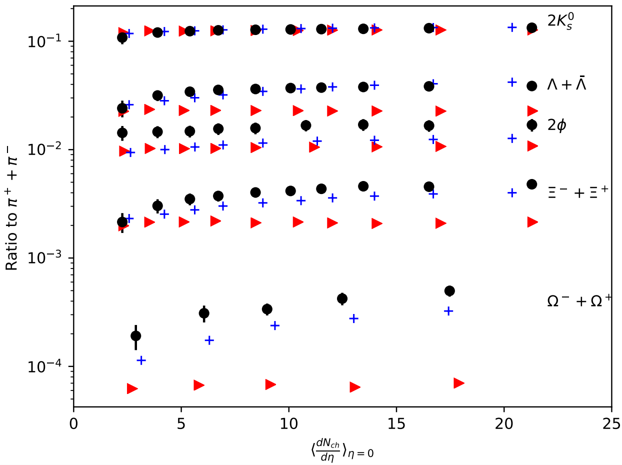
Forward/central multiplicity folding

- Full, honest comparison requires reproduction of centrality-measure.
- Recently possible in the Rivet project (rivet.hepforge.org, ask for details)



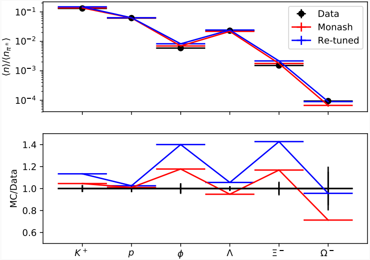
Strangeness enhancement

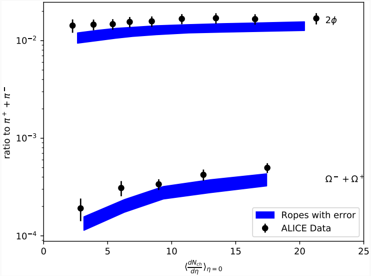
- Fair description, but quantitatively off in places.
- Most interesting for further microscopic development!



An aside about LEP constraints

- Statement: Pythia describes LEP correctly!
- Truth: ... well, mostly!

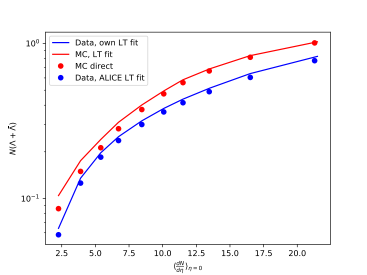


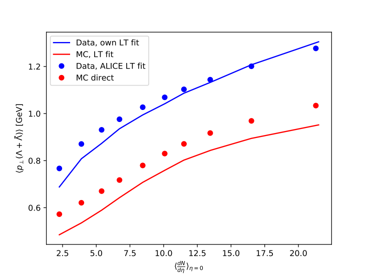


- Even LEP leaves room for model development!
- ...and LHC allows for catching suspicious data!
- Needs: Apples-to-apples comparison to data.

An aside about Levy–Tsallis fits

- Extrapolated spectra are difficult to compare to!
- For Pythia: Yields matches the fit, $\langle p_\perp \rangle$ not.





Take home message

MC: Don't rely on fits for average quantities when the spectrum is off.
Pythia still has problems describing this. Shoving could improve matters.

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

- Strings = interacting vortex lines in superconductor.
- For $t \to \infty$, profile known from lQCD (Cea *et al.*: PRD89 (2014) no.9, 094505):

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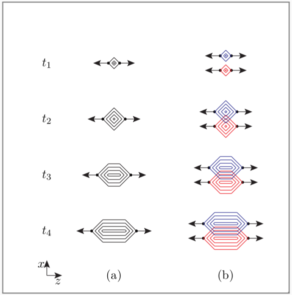

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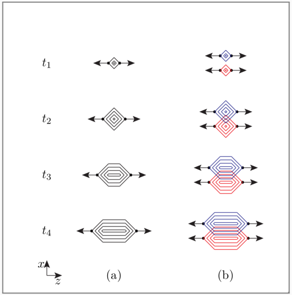

- All energy in electric field $\to g = 1$.

- Reality:
  Type 1 SC Energy to destroy vacuum.
  Type 2 SC Energy in current.

Shoving: Prehistoric origins

- 1st law of QCD phenomenology: When you think you have a good idea...

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Long-range azimuthal correlations in multiple-production processes at high energies

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(Submitted 18 January 1988)
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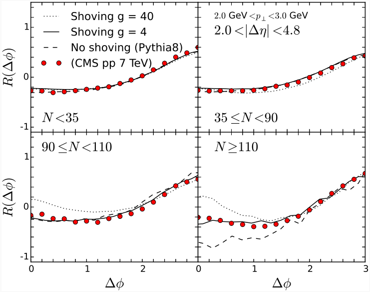
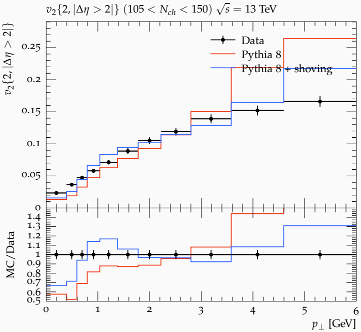
6. In an interaction of heavy nuclei with nuclei, many overlapping quark tubes form, and a large azimuthal asymmetry may be observed.[2)] Furthermore, since an $A \times A$ collision is noncentral on the average, the system of quark tubes fills a transversely anisotropic region. It is clear geometrically that its anisotropy is oriented along the impact parameter of the collision. We might thus expect correlations between the azimuthal distribution of secondary hadrons and the azimuthally anisotropic distribution of the decay products of the nucleus.

Again, we wish to emphasize that data on the azimuthal asymmetry in soft multiple-production processes may contain some very nontrivial information.

Some Results: shoving

- Reproduces the pp ridge with suitable choice of g parameter.
- Improved description of $v_2 2|\Delta eta| > 2.(p_\perp)$ at high multiplicity.
- Low multiplicity not reproduced well – problems for jet fragmentation?



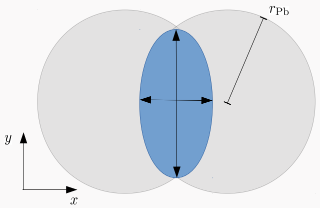


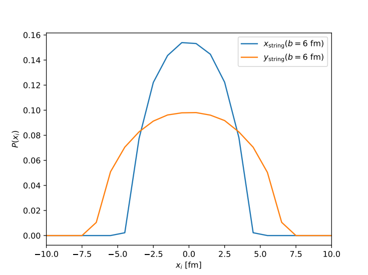
Shoving: Why is AA so difficult?

- 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 $\rightarrow$ parallel frame.
    - 👍 Soft gluons $\rightarrow$ push on hadrons.
    - 👎 Straight strings $\rightarrow$ treatment of gluon kinks? (WiP).
- Enough for a toy run!

A toy example

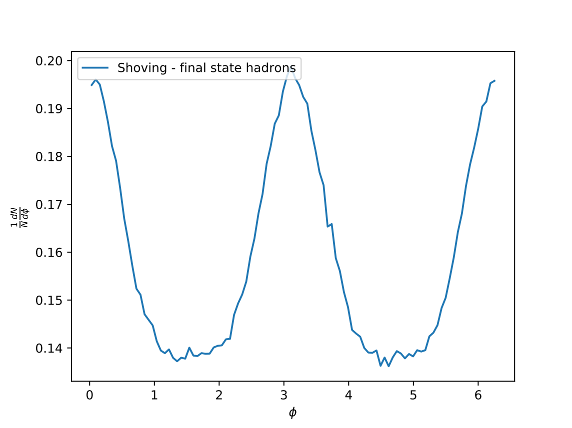
- Consider an elliptical overlap region filled with straight strings (no gluons).
- Same shoving parameters as for pp.





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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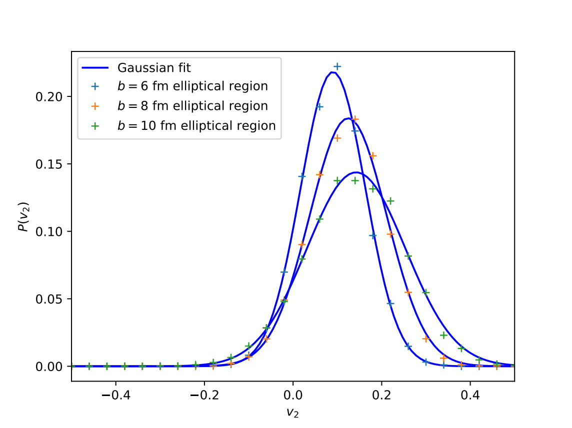

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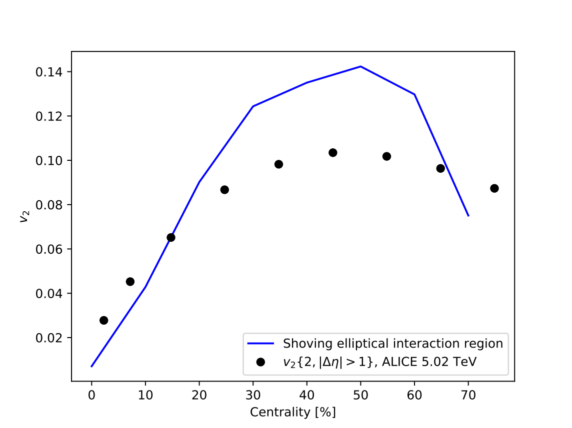

A Z-boson changes the kinematics (CB: arXiv:1901.07447)

- 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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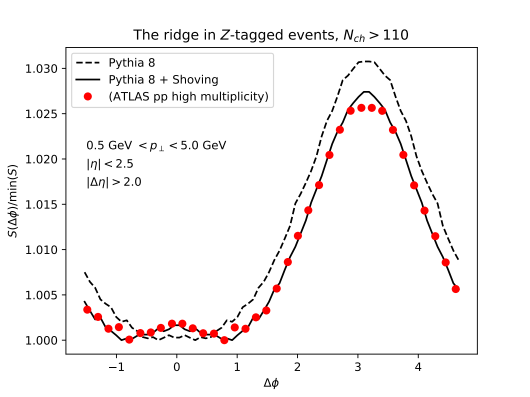
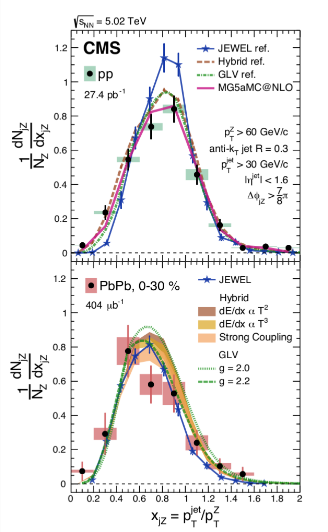
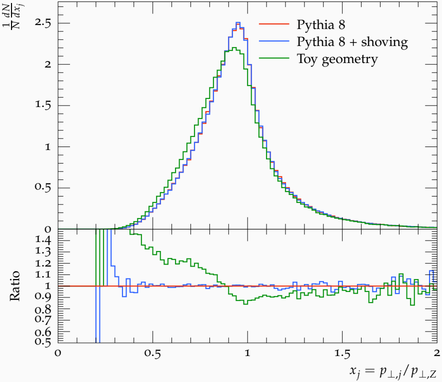


Source of jet modifications? (CB: arXiv:1901.07447)

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

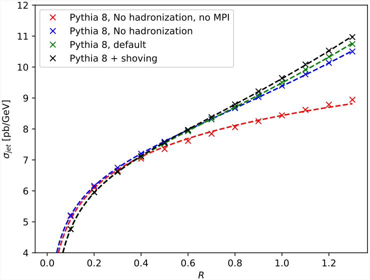


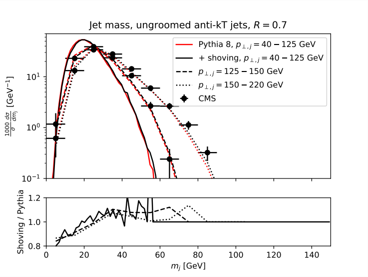
- AA possibility ahead!
- pp: modifications on jet edge.



Modifications on the edge

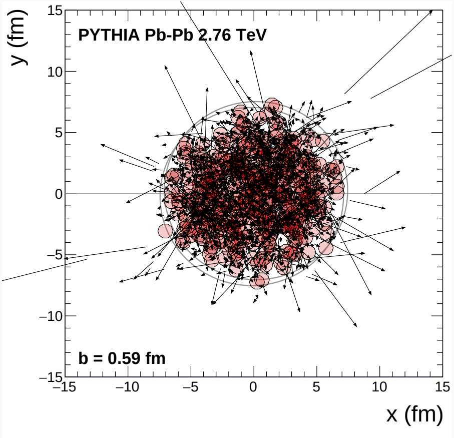
- Can be quantified: Same level as hadronization correction in $\sigma_{jet}(R)$.
- Perhaps measurable with better low-$p_\perp$ coverage?





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).
  3. Coming natively to Pythia (Sjöstrand and Utheim: arXiv:2005.05658).



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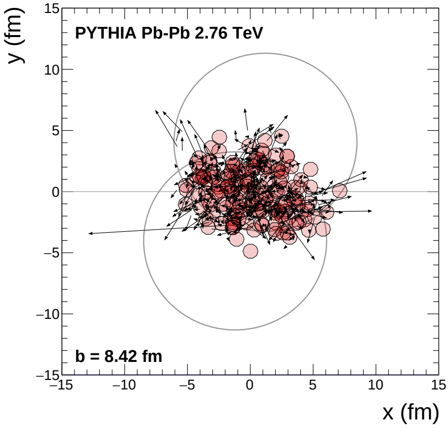

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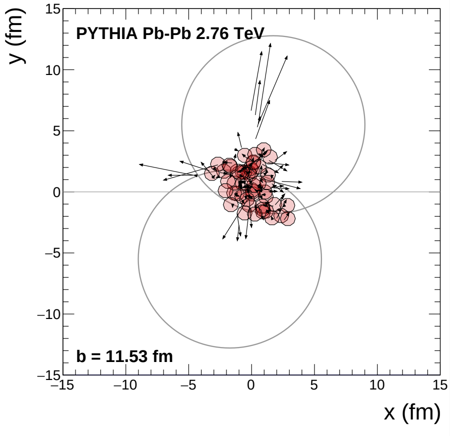
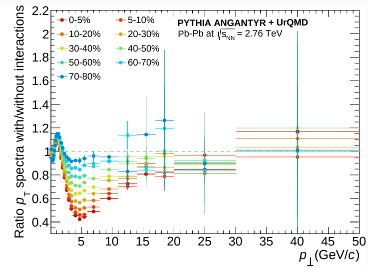
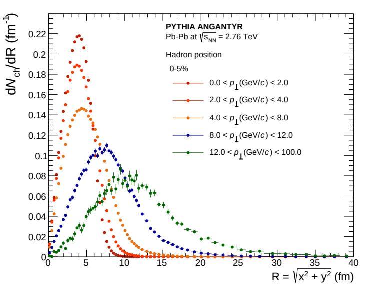


Effects on $p_\perp$-spectra

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

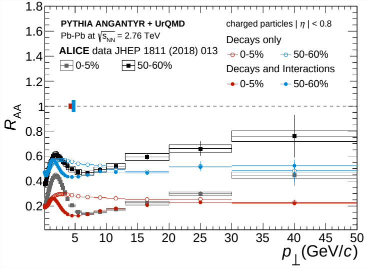


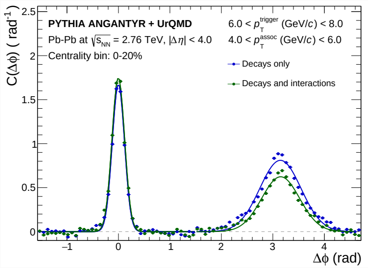


- Not quantitative *description* of data, but improved baseline.
- Note: No free parameters for AA.

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.





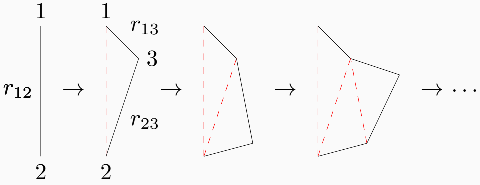
Towards EIC (WIP: with Ilkka Helenius; CB & C. O. Rasmussen: 1907.12871 [hep-ph])

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

Dipole splitting and interaction

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

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



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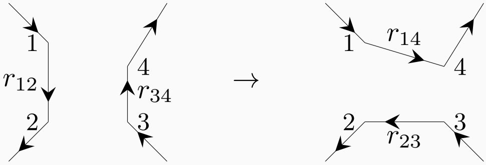
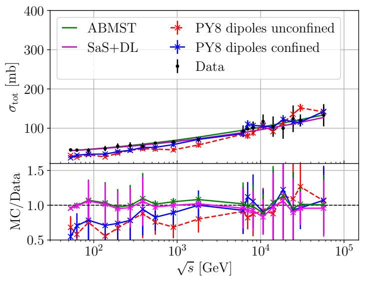
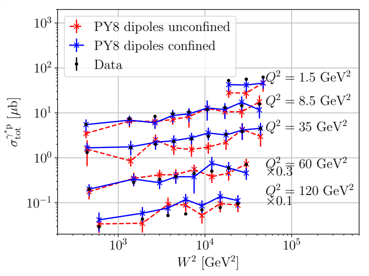


Everything fitted to cross sections

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

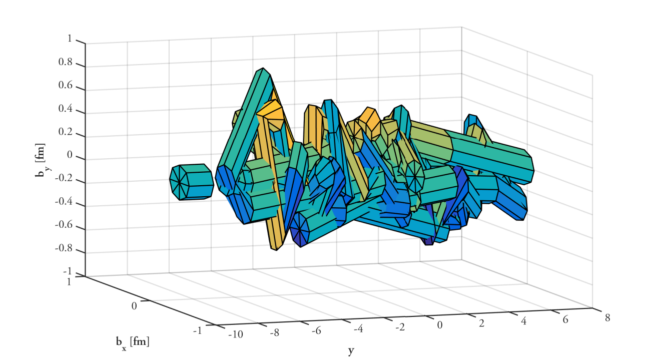
$$T(\vec{b}) = 1 - \exp\left(-\sum f_{ij}\right), \sigma_{tot} = \int d^2\vec{b}\, 2T(\vec{b})$$





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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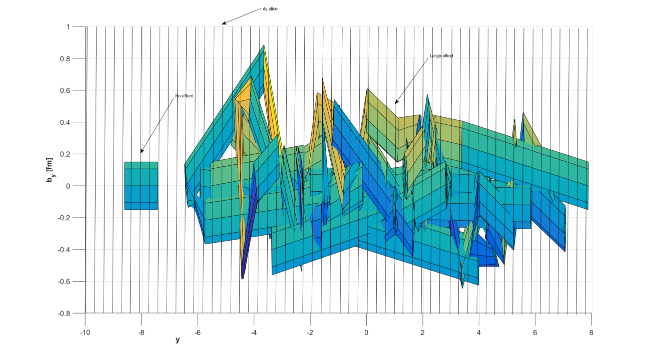

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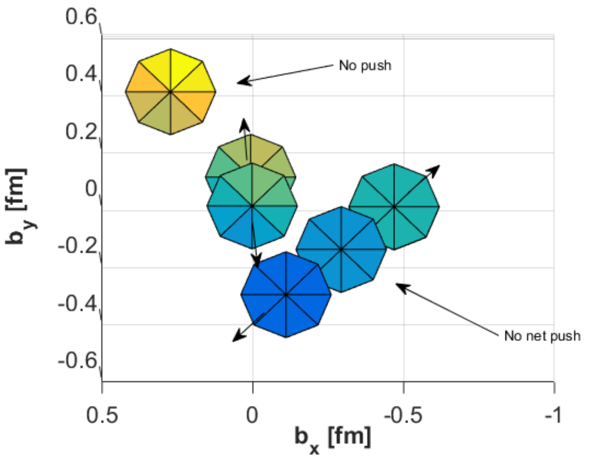
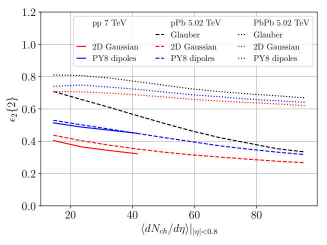
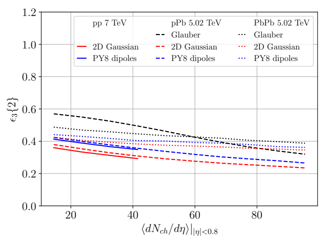


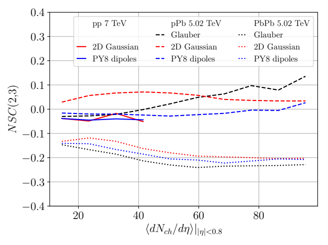
Geometry in pp, pA and AA

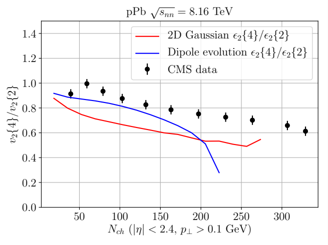
- Assuming $\epsilon_{2,3} \propto v_{2,3}$.
- Dipole model: $\epsilon_{2,3}$ equal for pp and pPb.





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

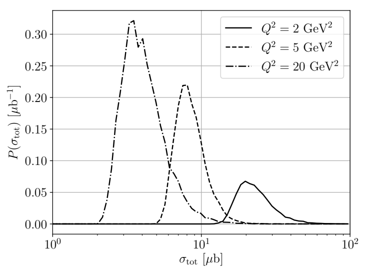


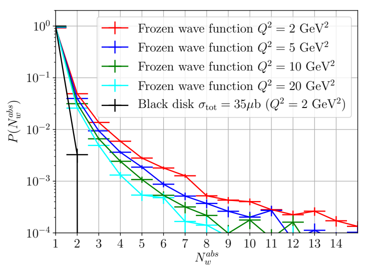


- *Important to develop realistic initial states.*
- *Point stands also for hydro.*

Glauber for $\gamma^* A$

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





Thank you for the discussion!

- A summary?
- Ok, Angantyr is here, and you can use it.
- Strings can do many interesting things.
- Hadronic rescatterings matters more with a dense hadron gas.
- We can calculate some proton sub-structure with perturbative techniques.

File Edit Tools Syntax Buffers Window Help

```cpp
#include "Pythia8/Pythia.h"
#include "Pythia8/HeavyIons.h"

using namespace Pythia8;

// This is a one-slide example program demonstrating Heavy Ion
// functionality.
int main() {
  Pythia pythia;
  // Setup the beams.
  pythia.readString("Beams:idA = 1000822080");
  pythia.readString("Beams:idB = 1000822080"); // The lead ion.
  pythia.readString("Beams:eCM = 2760.0");
  // Sum up the weights of all generated events.
  double sumw = 0.0;
  // Count the number of charged particles.
  double ncEvent = 0.0;
  // Initialise Pythia.
  pythia.init();
  for ( int iEvent = 0; iEvent < 1000; ++iEvent ) {
    if ( !pythia.next() ) continue;
    double nc = 0.0;
    for (int i = 0; i < pythia.event.size(); ++i) {
      Particle & p = pythia.event[i];
      if ( p.isFinal() ) {
        if ( p.isCharged() && p.pT() > 0.1 && abs(p.eta()) < 0.5 ) ++nc;
      }
    }
    sumw += pythia.info.weight();
    ncEvent += nc * pythia.info.weight();
  }
  cout << "Charged multiplicity density at mid-eta: " << ncEvent / sumw << endl;
  return 0;
}
```

28,5 All

Thank you for the invitation!

Some additional material

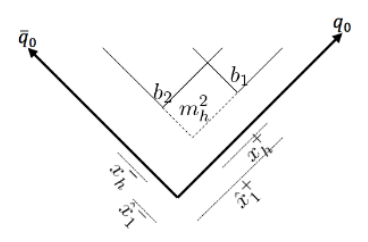
String kinematics (B. Andersson et al.: Phys. Rept.97(1983) 31)

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

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



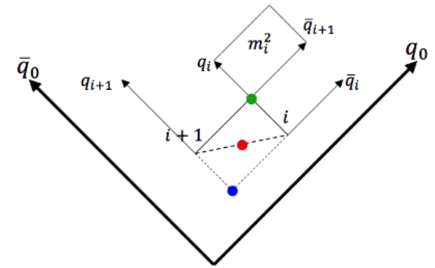
- ... which gives breakup vertices in momentum picture.

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.

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.