Monte Carlo Event Generators — IV

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Outline of Lectures

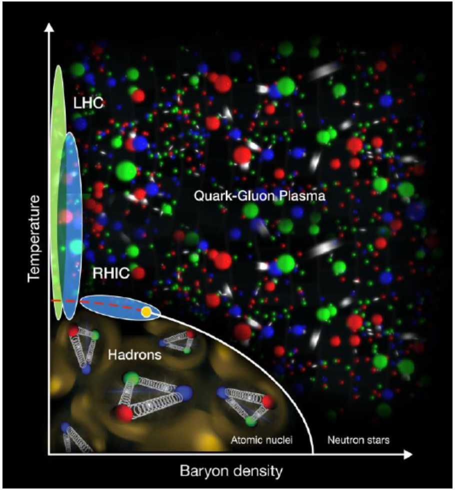
- Lecture I: Basics of Monte Carlo methods, the event generator strategy, matrix elements, LO/NLO, ...
- Lecture II: Parton showers, initial/final state, (matching/merging), hadronization, decays. ...
- Lecture III: Minimum bias, multi-parton interactions, pile-up, summary of general purpose event generators and tools, ...
- Lecture IV: Protons vs. heavy ions, Glauber calculations, initial/final-state interactions, ...

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145. See also arXiv:2605.16036.

Outline of Lecture IV

- Heavy Ions Introduction
- The Glauber formalism
  - Distributing nucleons in a nuclei
  - The standard Glauber implementations
- The Initial State
  - Color Glass Condesate
- The Final State
  - Quark-Gluon Plasma
  - Wounded Nucleons
- Heavy Ion Generators
  - HIJING
  - EPOS
  - AMPT
  - JETSCAPE
  - PYTHIA8/Angantyr
  - Comparison to data

QCD phase diagram

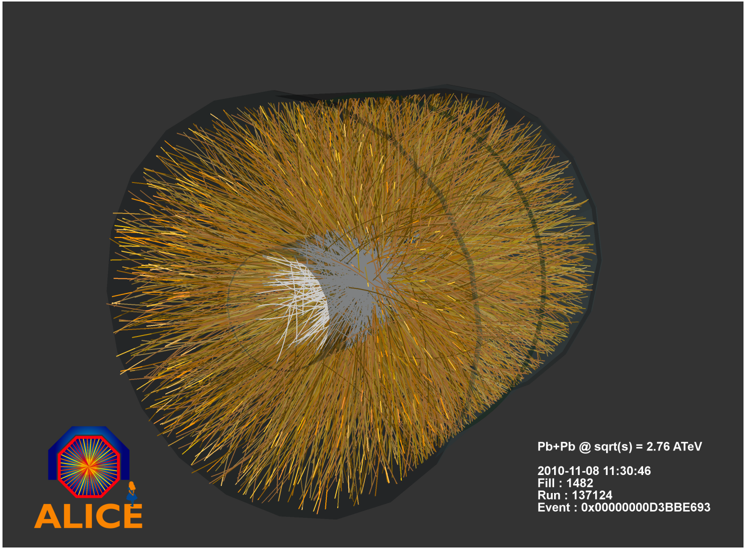


$T_C \sim 170$ MeV$\sim 2 \cdot 10^{12}$ K

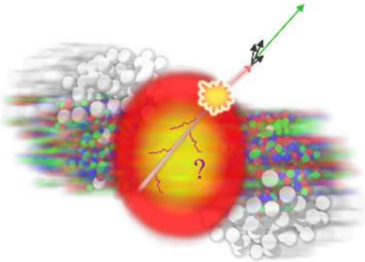
pp vs. *AA* (from the pp point of view)

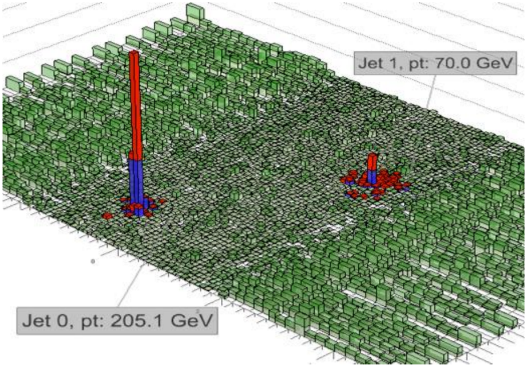
My first reactions when encountering Heavy Ion physics:

- That's just smashing bunches of nucleons together!
- Who is this Glauber guy anyway?
- You do you mean with centrality?
- When is many particles too many?
- I'm from Lund, I want to use string fragmentation!
- You measured what?
- Are you really seeing the Quark–Gluon Plasma?

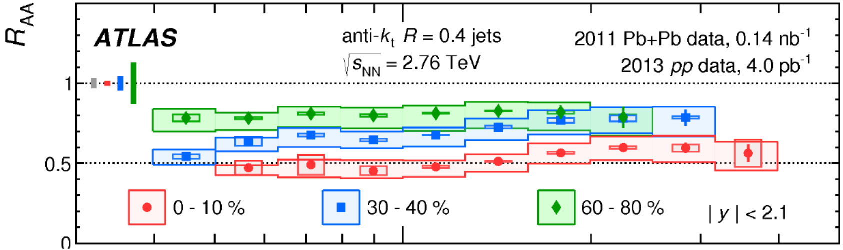

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

Jet quenching





The R_{AA} factor



$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

$<T_{AA}>\sigma^{pp} = <N_{coll}>$

N_{coll} is the # of binary collisions

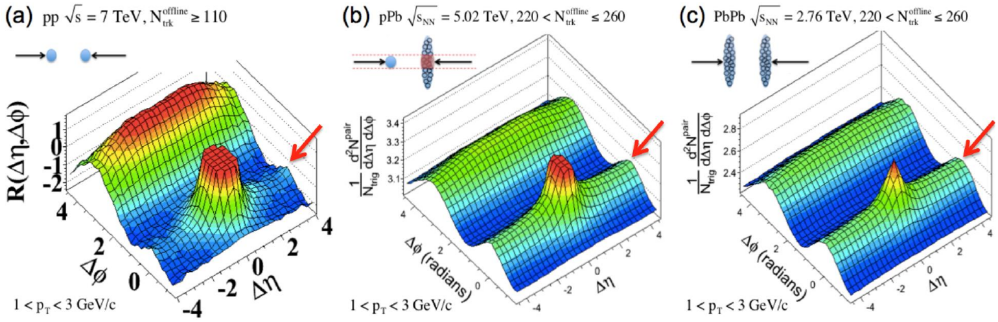
For perturbative QCD processes:

R_{AA}<1: suppression

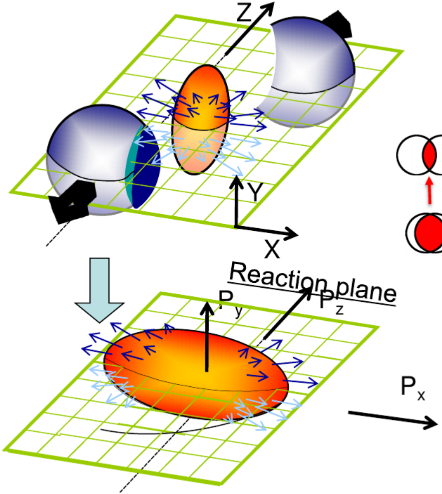
R_{AA}=1: no nuclear effects

R_{AA}>1: enhancement

The ridge

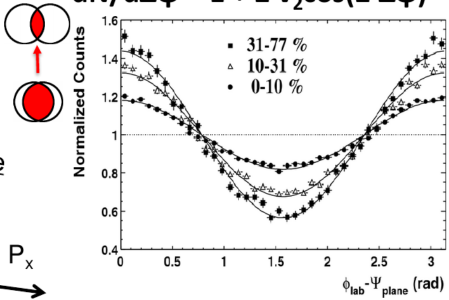

(a) pp √s = 7 TeV, N_trk^offline ≥ 110
R(Δη,Δφ)
Δφ
Δη
1 < p_T < 3 GeV/c
(b) pPb √s_NN = 5.02 TeV, 220 < N_trk^offline ≤ 260
Δφ (radians)
Δη
1 < p_T < 3 GeV/c
(c) PbPb √s_NN = 2.76 TeV, 220 < N_trk^offline ≤ 260
Δφ (radians)
Δη
1 < p_T < 3 GeV/c

Flow

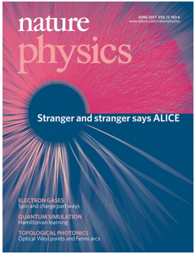


Fourier decomposition:

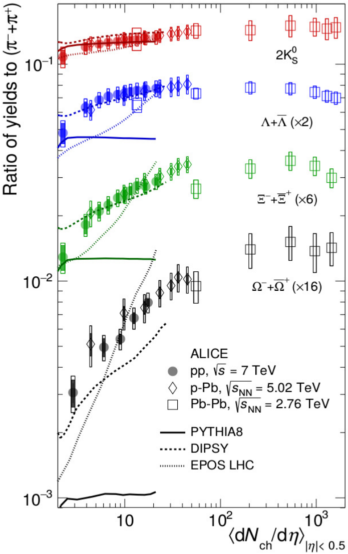
$$dN/d\Delta\phi = 1 + 2\, v_2 \cos(2\,\Delta\phi)$$



Strangeness enhancement

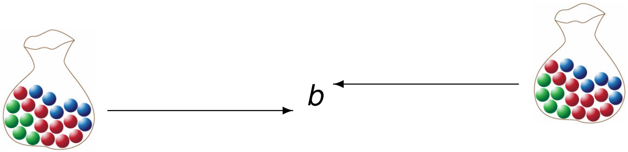


Nature Phys. 13 (2017) 535-539



The Glauber formalism

- How do we model the geometrical distribution of nucleons in colliding nuclei?
- How do we determine which nucleon interacts with which nucleon?
- How do they interact?



Distributing nucleons in a nuclei

There are advanced models for the shell-structure of nuclei — we will not be that advanced.

Assume a simple density of nucleons based on the (spherically symmetric) Woods–Saxon potential

$$\rho(r) = \frac{\rho_0(1 + wr^2/R^2)}{1 + \exp((r - R)/a)}$$

- R is the radius of the nucleus
- a is the *skin width*
- w can give a varying density but is typically $= 0$

For a nucleus (Z, A), we simply generate A nucleon positions randomly according to some density provile

$$P(\vec{r}_i) = \rho(r_i) d^3\vec{r}_i$$

The Woods–Saxon parameters are tuned to measurements of (low enegry) charge distributions assuming some charge distribution of each nucleon (proton).

We normally assume iso-spin invariance (p≈n).
There are absolutely no correlations between the nucleons.

What happens if two nucleons end up in the same place?

We can get some correlations if we assume that nucleons have a hard core, R_h, and require $\Delta r_{ij} > 2R_h$

If you generate a nucleon which is too close to a previously generated nucleon you could either

- generate a new position for the last one (efficient, but may give a bias)
- throw away everything and start over (inefficient, unbiased)

There are many implementations of this, and most experiments have their own. Typical parameters for $A > 16$ are
(from the GLISSANDO program):

R (fm)	a	w	R_h
$(1.120A^{1/3} - 0.860A^{-1/3})$	0.540	0	0
$(1.100A^{1/3} - 0.656A^{-1/3})$	0.459	0	0.45

[nucl-th/0710.5731, nucl-th/1310.5475]

We can estimate the *AA* cross section assuming the nuclei are like black disks,

$$\sigma^{AA} = \int_{-\infty}^{\infty} d^2\vec{b}\frac{d\sigma^{AA}(b)}{d^2\vec{b}} = 4\pi R^2$$

where

$$\frac{d\sigma^{AA}(b)}{d^2\vec{b}} = \begin{cases} 1 : & \text{b<2R} \\ 0 : & \text{b>2R} \end{cases}$$

We can also look at the positions of the individual nucleons:

$$\frac{d\sigma^{AA}(b)}{d^2\vec{b}} = 1 - \prod_{i,j} \int d^2\vec{r}_i d^2\vec{r}_j \left(1 - \frac{d\sigma^{NN}(b_{ij})}{d^2\vec{b}}\right) \rho(\vec{r}_i)\rho(\vec{r}_j)$$

where $b_{ij} = \left|\vec{b} + \vec{r}_i - \vec{r}_j\right|$.

But we have to think about which cross section we are talking about. Total? Non-diffractive? Inelastic?

The standard (naive) Glauber implementation

Estimate the distribution in number of participants in a $\mathrm{p}A$ or AA collision.

- Distribute the nucleons randomly according to Woods–Saxon
- Monte-Carlo the b-distributions (typically in a square with side $\sim 4R$).
- Count the number of nucleons in the target that is within a distance $d = \sqrt{\sigma/2\pi}$ from any of the projectile nucleons. (Gives you N_{coll} and N_{part}.)

Normally no fluctuations, but includes diffractively wounded nucleons by using $\sigma = \sigma_{\mathrm{abs}}^{\mathrm{NN}} + \sigma_{\mathrm{dex}}^{\mathrm{NN}} = \sigma_{\mathrm{tot}}^{\mathrm{NN}} - \sigma_{\mathrm{el}}^{\mathrm{NN}}$.

Centrality

Centrality, N_{coll} and N_{part} are NOT observables.

- Do a Glauber simulation, and see how many collisions you get as a function of impact parameter. Divide up the distribution in percentiles.
- Measure some observable that indicates some kind of *event activity* — typically myltiplicity or summed transverse momenta. Divide also this into percentiles.
- Assume that events in the top percentile of activity corresponds to the most central percentile of collisions in your Glauber calculation.
- Read off the average number of *NN* collisions in that percentile.

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Centrality, N_{coll} and N_{part} are Model-dependent observables.

A more sofisticated Glauber implementation

Assume a fluctuating *NN* cross section (a.k.a. Glauber–Gribov colour fluctuations)

$$P(\sigma) = \rho \frac{\sigma}{\sigma + \sigma_0} \exp\left\{ -\frac{(\sigma/\sigma_0 - 1)^2}{\Omega^2} \right\}$$

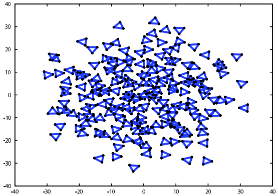
with

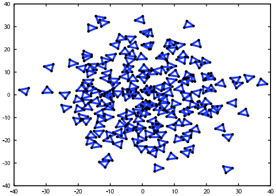
$$T(b,\sigma) \propto \exp\left(-cb^2/\sigma\right).$$

For $\mathrm{p}A$ this gives a longer tail out to a large number of wounded nucleons.

[Strikman et al. hep-ph/1301.0728]

Sample Au-Au event





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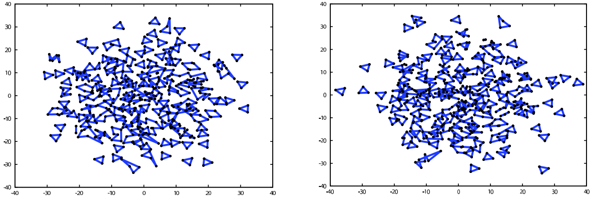

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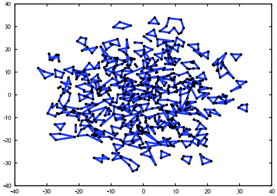

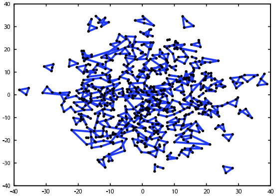

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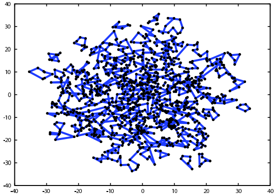

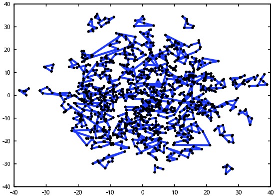

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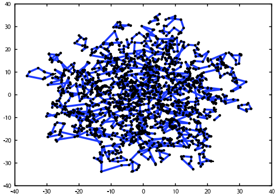

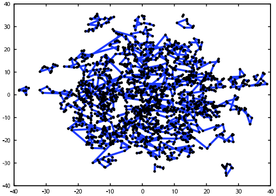

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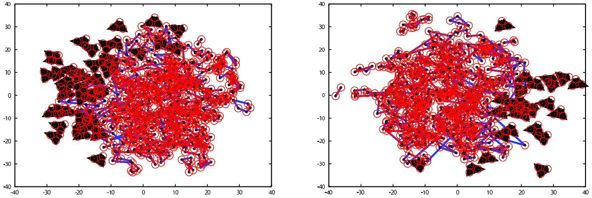

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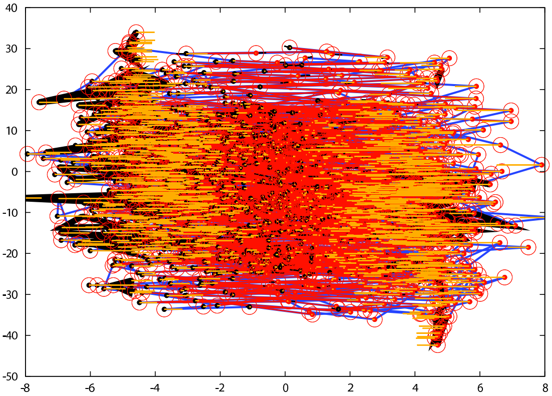

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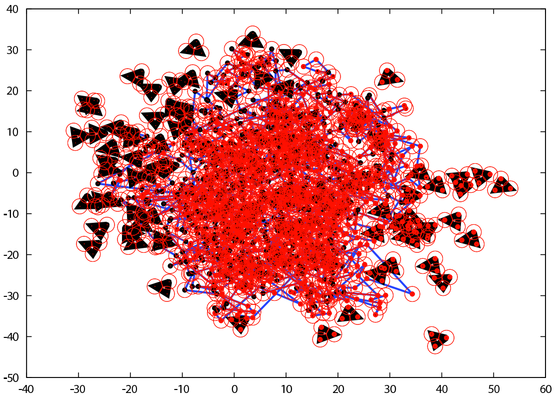


Color Glass Condesate (CGC)

A mean-field statistical aproach to the density of gluons.

- Color: It's American, and yes, it's QCD
- Glass: Solid on short timescales, amorphous on long.
- Condensate: There are a lot of gluons.

Includes Saturation of gluons.

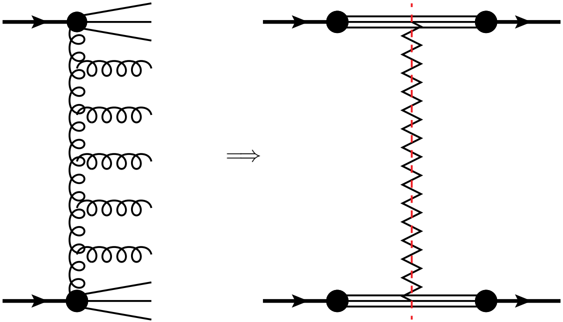
In standard DGLAP the gluon density increases rapidly with decreasing x. Also in BFKL. Somewhere it has to stop, $g + g \to g$ = Saturation

$$Q_{\mathrm{sat}} = Q_0^2 \left(\frac{x}{x_0}\right)^{\lambda}$$

CGC starts with an initial gluon density at some $x \sim 0.01$, and evolves it to smaller x using a (non-linear) renormalization group equation (JIMWLK $\sim$ BFKL $+$ Saturation)

The initial density is folded with the nucleon distribution in b.

The Cut Pomeron picture



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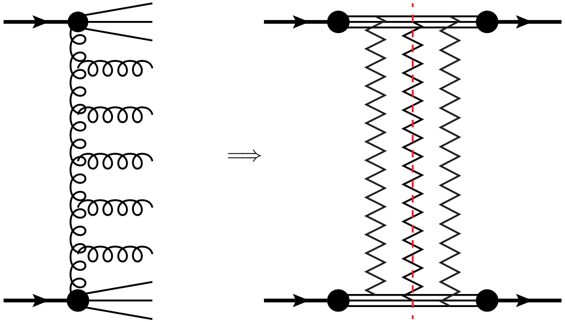

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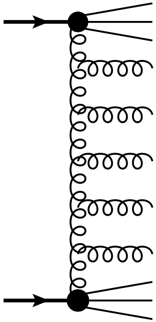
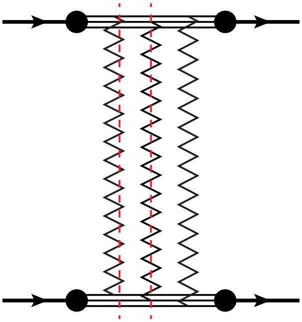


$\Longrightarrow$



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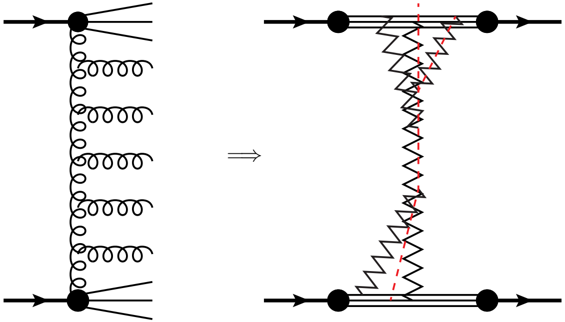
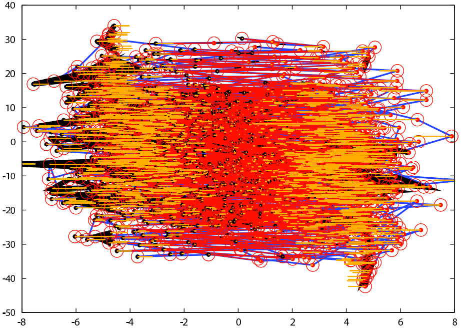


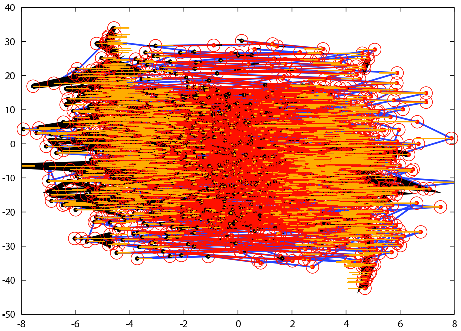
Each cut pomeron will give rise to a string (or two) spanned between two colliding nucleons, or between a nucleon and another Pomeron.

The Final State



Model each gluon/dipole individually?

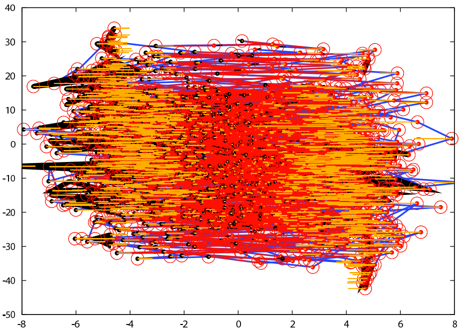
The Final State



Model each gluon/dipole individually?

Or give up and use statistical methods?

The Final State

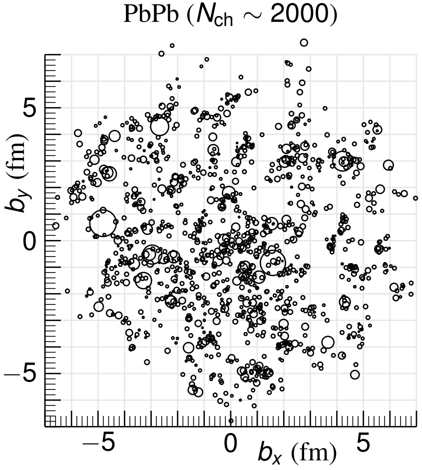


Model each gluon/dipole individually?

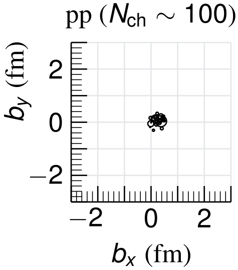
Or give up and use statistical methods?

Or both?

Dipoles/Strings crossing $\eta = 0$



$t = 0.1$ fm/c



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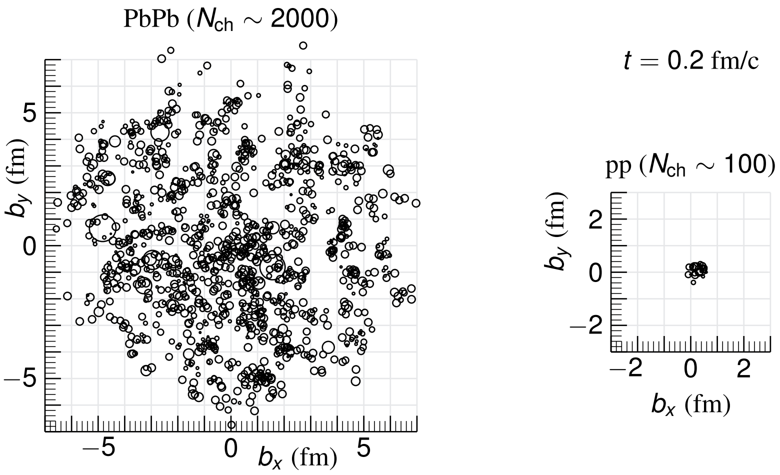
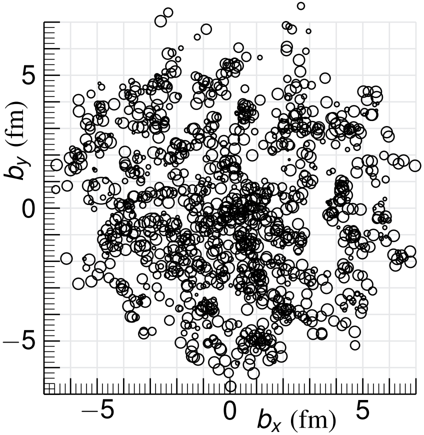


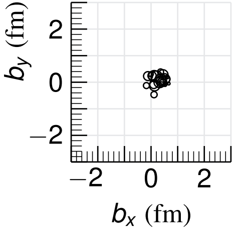
Dipoles/Strings crossing $\eta = 0$

PbPb ($N_{ch} \sim 2000$)



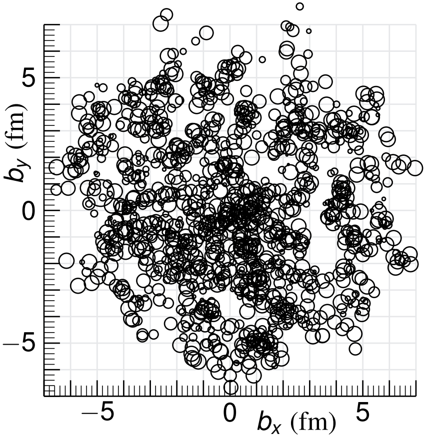
$t = 0.3$ fm/c

pp ($N_{ch} \sim 100$)



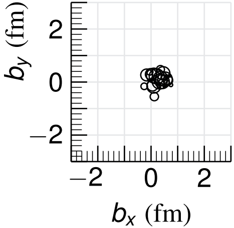
Dipoles/Strings crossing $\eta = 0$

PbPb ($N_{ch} \sim 2000$)



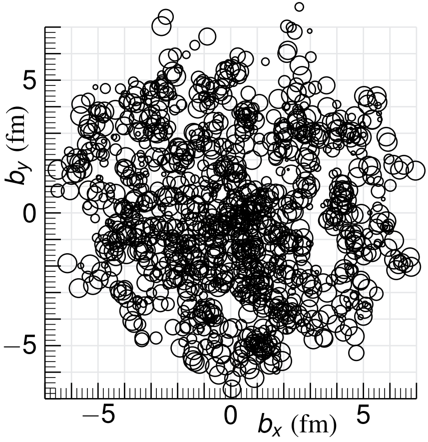
$t = 0.4$ fm/c

pp ($N_{ch} \sim 100$)



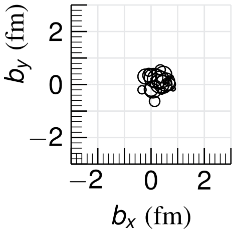
Dipoles/Strings crossing $\eta = 0$

PbPb ($N_{ch} \sim 2000$)



$t = 0.5$ fm/c

pp ($N_{ch} \sim 100$)



Quark-Gluon Plasma

Construct the the energy momentum density and the flavour flow vector for all point in space at an initial proper time $\tau = \tau_0$:

$$T^{\mu\nu}(x) = \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i)$$

$$N_q^\mu(x) = \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i g(x - x_i)$$

- $q_i = u, d, s$
- δp is the momentum of the parton (or string segment)
- $g(x)$ is a smoothing kernel with some assumed width

Relativistic hydrodynamics

The individual flavour flow is a conserved current

$$\partial_\nu N_q^\nu = 0$$

So is the energy–momentum tensor

$$\partial_\nu T^{\mu\nu} = 0$$

Typically divide up in small cells, get the velocity vector u^ν in the restframe of each cell (comoving frame) and evolve.

but we have four only equations for $T^{\mu\nu}$ so we need to have extra assumptions.

Ideal fluid

In the comoving frame:

- $T^{00} = \varepsilon$: energy density
- $T^{0i} = 0$: no energy flow
- $T^{i0} = 0$: no momentum flow
- $T^{ij} = \delta_{ij}p$: isotropic pressure

But it s also possible to include viscous effects. . .

Freezeout = Hadronisation and Rescattering

After the evolution we convert $T^{\mu\nu}$ and N_q^{μ} back into particles (Hadrons). This happens at some given hypersurface at some freeze-out time τ_f.

There is still a fairly high density of hadrons, and we expect some rescattering:

$$h_1 + h_2 \to h' \quad \text{or} \quad h_1 + h_2 \to h'_1 + h'_2 \quad \text{or} \quad h_1 + h_2 \to h'_1 + h'_2 + h'_3 + \cdots$$

After which we have free-streaming hadrons.

Freezeout = Hadronisation and Rescattering

After the evolution we convert $T^{\mu\nu}$ and N_q^{μ} back into particles (Hadrons). This happens at some given hypersurface at some freeze-out time τ_f.

Sorry, I don't understand this enough myself

There is still a fairly high density of hadrons, and we expect some rescattering:

$$h_1 + h_2 \to h' \quad \text{or} \quad h_1 + h_2 \to h'_1 + h'_2 \quad \text{or} \quad h_1 + h_2 \to h'_1 + h'_2 + h'_3 + \cdots$$

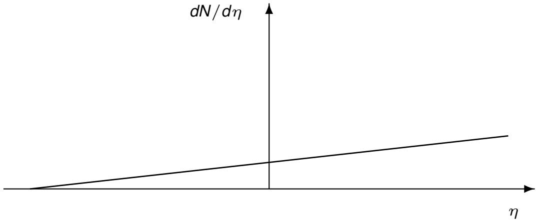
c.f. the model in PYTHIA

After which we have free-streaming hadrons.

The Wounded Nucleon model

A simple model by Białas and Czyż, implemented in Fritiof

Each wounded nucleon contributes with hadrons according to a multiplicity function $F(\eta)$, fitted to data, and approximately looks like



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

(single wounded nucleon)

[Nucl.Phys.B111(1976)461, J.Phys.G35(2008)044053, Nucl.Phys.B281(1987)289.]

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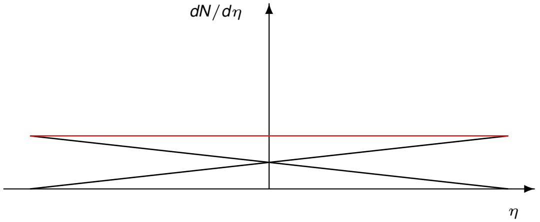

$$\frac{dN}{d\eta} = \quad F(\eta) + \quad F(-\eta) \qquad \text{(pp)}$$

[Nucl.Phys.B111(1976)461, J.Phys.G35(2008)044053, Nucl.Phys.B281(1987)289.]

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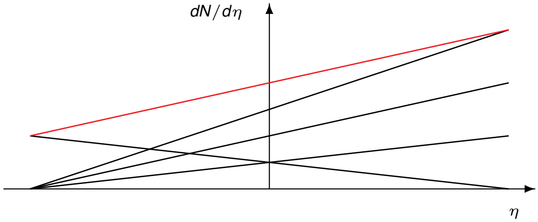

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (\mathrm{p}A)$$

[Nucl.Phys.B111(1976)461, J.Phys.G35(2008)044053, Nucl.Phys.B281(1987)289.]

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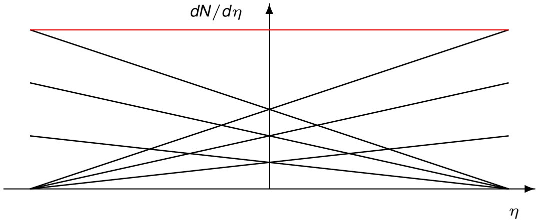


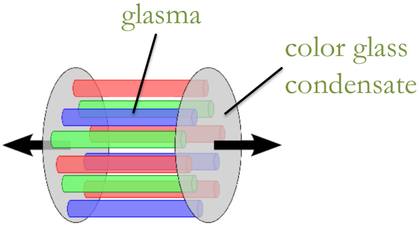
$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

[Nucl.Phys.B111(1976)461, J.Phys.G35(2008)044053, Nucl.Phys.B281(1987)289.]

In Fritiof this was modelled by stretching out a string from each wounded nucleon with an invariant mass distributed as dm_X/m_X, which reproduces $F(\eta) \propto \eta - \eta_0$.

Note that there are no collective effects here. But nevertheless Fritiof reproduced most data: No clear evidence for QGP until the late nineties.

IP-GLASMA



Final state version of the Color Glass Condensate .

After a collision of the condensates, filament-like structures with longitudinally aligned colour electric and magnetic fields arise (not strings, but somewhat similar)

Breaks down to a normal QGP after $\tau \sim 0.5$ fm/c.

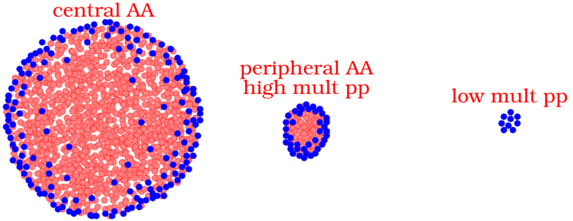
HIJING

(one of the standard HI generators)

- Inspired by Fritiof
- Hard scatterings with nuclear PDFs + Shadowing
- Soft radiation with ARIADNE
- String fragmentation

EPOS: Core – Corona

- Start with the Pomeron picture.
- Create strings
- Divide up:
  - Core: If the density of strings is high, chop them up and use relativistic hydrodynamics.
  - Corona: For lower densities, allow for hard interactions and perturbative ISR/FSR/MPI evolution



AMPT

(Another standard HI generator with collective effects)

- Same initial state as HIJING
- String melting
  - String fragmentation
  - Convert back to $q\bar{q}$
  - Evolve in time with elastic scattering
  - Nearest neighbour recombination into hadrons
- Hadron rescattering

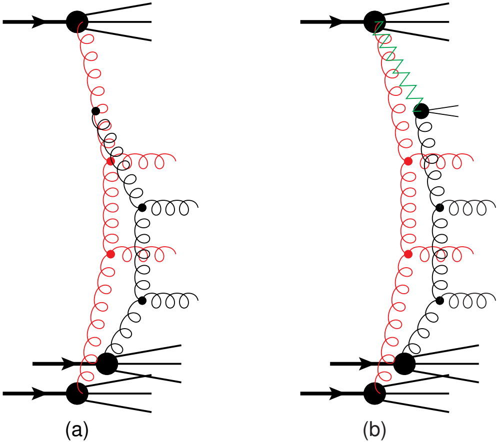
JETSCAPE

A modular framework for modelling jets in HI collisions, where you can plug in

- Your favourite Glauber model
- Your favourite QGP model (with or without Glasma)
- A model for generating pp events with jet evolution influenced by the QGP (and vice versa). E.g. JEWEL.
- Your favourite hadronisation model
- Your favourite hadron rescattering model.

Heavy Ions in PYTHIA8: Angantyr

- Glauber model with advanced fluctuation treatment
- Divides *NN* interactions into absorptive, single or double diffractive.
- Also differentiates absorptive interactions:
  - Primary: is modelled as a PYTHIA non-diffractive pp event.
  - Secondary: an interaction with a nucleon that has already had an interaction with another. Modelled as a (modified) (non-)diffractive excitation event (similar to dm_X/m_X in Fritiof).
- All sub-events generated on parton level and merged together into a consisten p*A* or *AA* event and then hadronised.


(a)
(b)

Signal processes

Not only min-bias. Rather than just generating non-diffractive events, The first absorptive sub-event can be generated using any hard process in PYTHIA8, giving the final event a weight $N_A\sigma_{hard}/\sigma_{ND}$.

No nuclear PDFs needed.

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No nuclear PDFs needed.

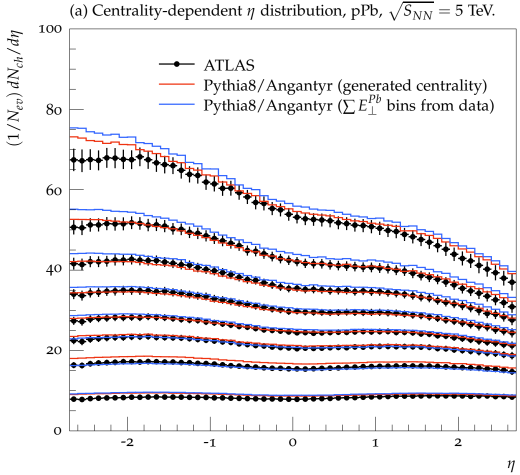
(not perfect yet)

Comparison to data

Several parameters in addition to the pp PYTHIA8 ones.

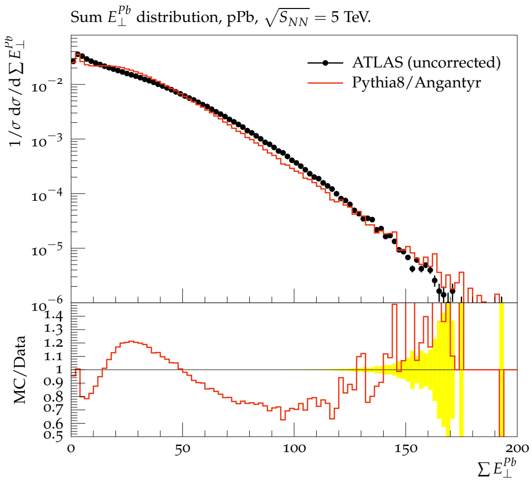
- Nucleon distributions can in principle be measured independently.
- *NN* cross section fluctuations are fitted to (semi-) inclusive pp cross sections (total, non-diffractive, single and double diffractive, elastic, and elastic slope) for given $\sqrt{s_{NN}}$.
- Diffractive parameters for secondary absorptive collisions, "tuned" to non-diffractive pp PYTHIA.
- M_X distribution: $dM_X^2/M_X^{2(1+\epsilon)}$, could be tuned (to p*A*), but we choose $\epsilon = 0$.
- Few other choices concerning energy momentum conservation which do not have large impact.

Eta distribution in pPb

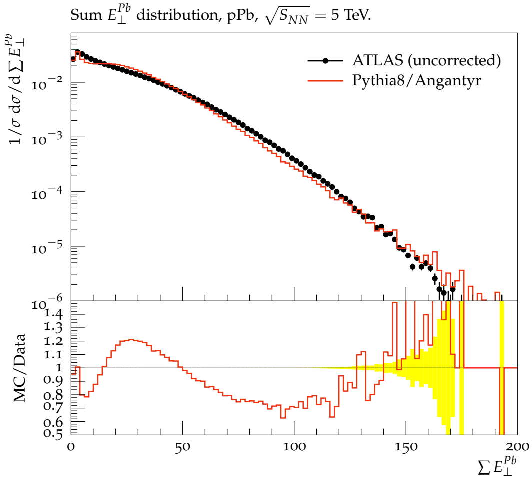


[arXiv:1508.00848]

Centrality in pPb

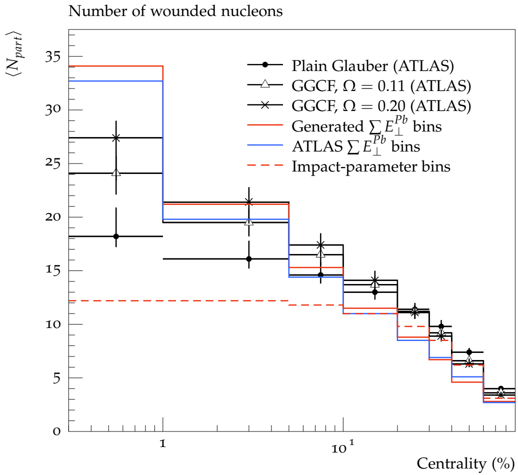


Centrality in pPb

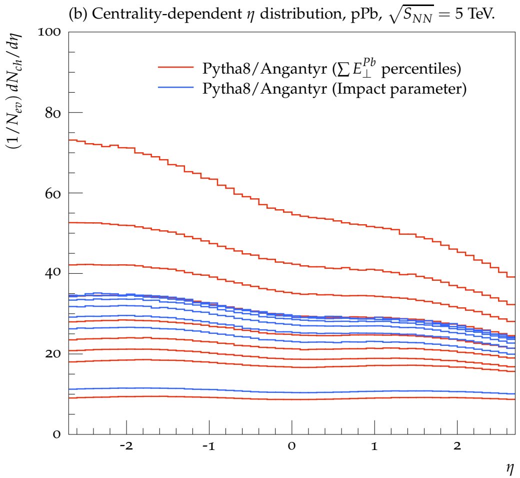


What was actually measured in the previous slide is a correlation between the η-distribution and the forward activity.

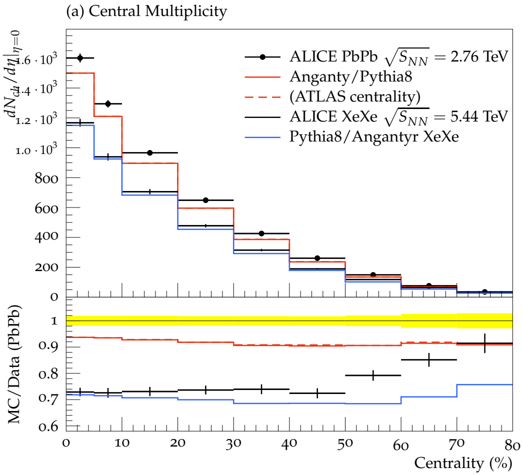
p–Pb number of participants

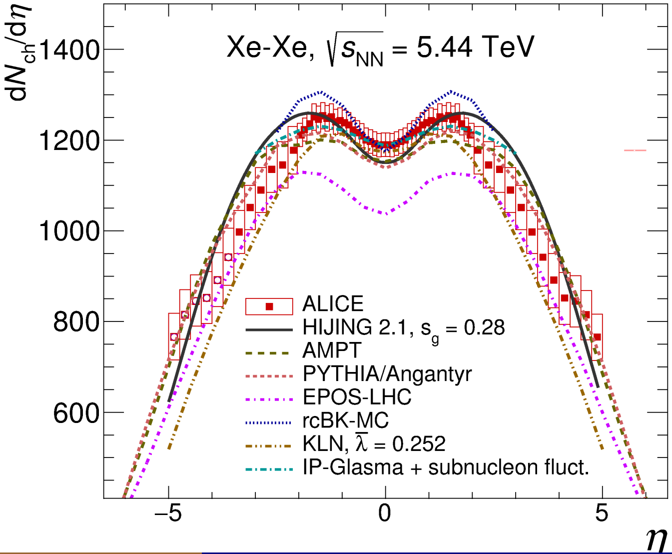


p–Pb η-distribution

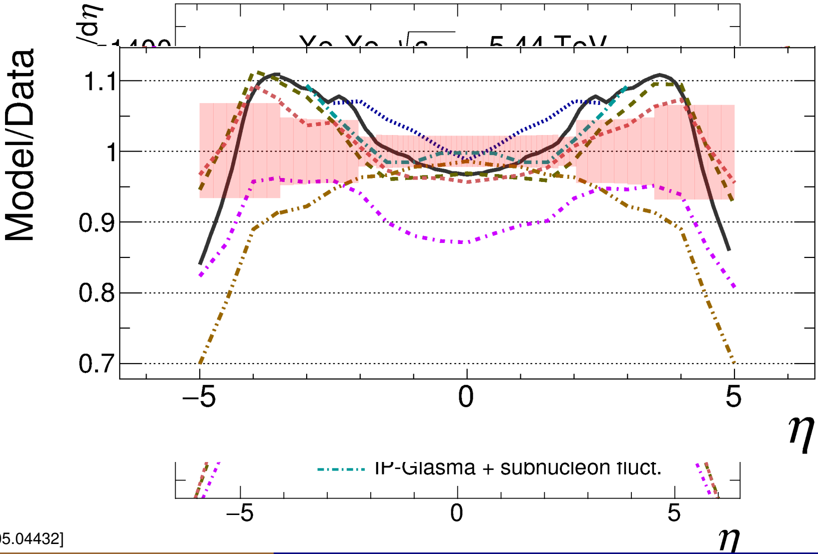


Central multiplicity in PbPb





[arXiv:1805.04432]



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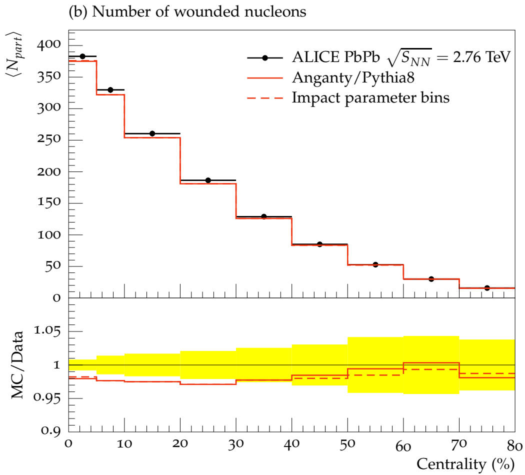
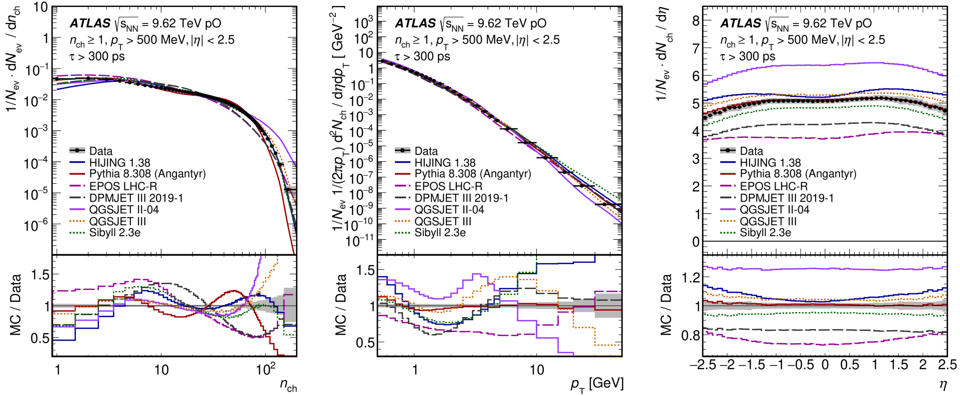
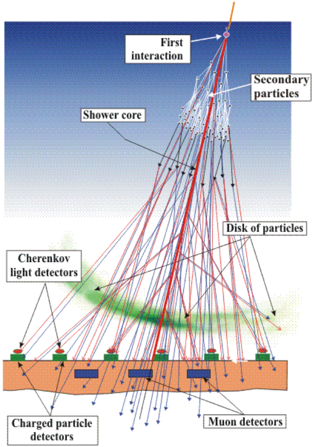
Pb–Pb number of participants

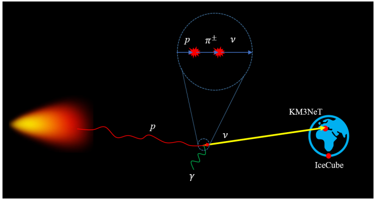


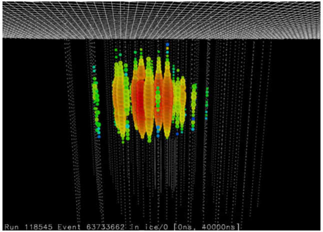
Recent pO results



Ultra-relativistic Cosmic Rays







Go generate yourself!

```
pythia.readString("Beams:idA = 1000822080");
pythia.readString("Beams:idB = 1000822080");
pythia.readString("Beams:eCM = 2760.0");
pythia.init();
pythia.next();
```

Summary

- Heavy-Ion collisions are messy
- Not just overlayed *NN* collisions
- Initial state effects (saturation, fluctuations, . . .)
- Final state effects (QGP, hydrodynamics, string interactions, flow, jet-quenching, rescattering, . . .)

Final Comments

By tradition HI and HEP (and Astro-physics) have been separate communities

- LHC brought them together
- There are collective effects in pp
- There are jets in AA
- There are high-energy cosmic particles
- We can (and need to) learn from each other
- We should also look beyond colliders.

Outline of Lectures

- Lecture I: Basics of Monte Carlo methods, the event generator strategy, matrix elements, LO/NLO, ...
- Lecture II: Parton showers, initial/final state, (matching/merging), hadronization, decays. ...
- Lecture III: Minimum bias, multi-parton interactions, pile-up, summary of general purpose event generators and tools, ...
- Lecture IV: Protons vs. heavy ions, Glauber calculations, initial/final-state interactions, ...

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145. See also arXiv:2605.16036.

String fragmentation

Formally based on one-dimensional, massless, relativistic strings.

- $V(r) \propto r$ gives a constant string tension
  $\kappa \sim 1$ GeV/fm
- The string breaks by $q\bar{q}$ pairs tunnelling out of the vacuum
  $P \propto \exp(-\pi(m_q^2 + k_\perp^2)/\kappa)$
- Strings are stretched between a quark and an anti-quark with gluons in between acting as kinks.
- Hadrons are chopped off from the ends with the Lund symmetric fragmentation function
  $f(z) \propto \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$

But strings are not one-dimensional. We can estimate both the tension and the radius of a QCD string on the lattice: $R = 0.25 - 1.0$ fm.

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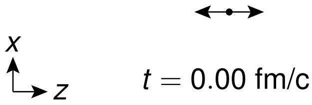

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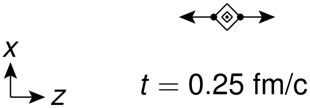

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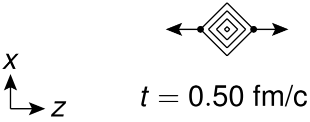

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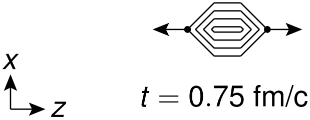

$t = 0.75$ fm/c

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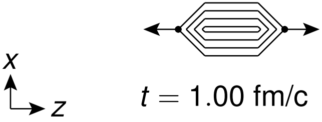

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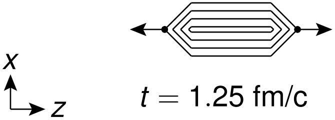

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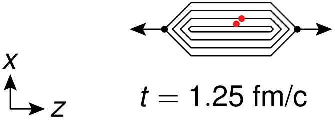

String Interactions: GLEIPNIR

- Overlapping anti-parallel strings may attenuate each other.
- Overlapping strings may repel each other
- Overlapping strings will have an increased string tension, making it easier to produce eg. strange hadrons.

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[work in progress: H. Shah, T Lundberg]

String Interactions: GLEIPNIR

- Overlapping anti-parallel strings may attenuate each other.
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  String Shoving $\Rightarrow$ ridges and flow
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[work in progress: H. Shah, T Lundberg]

[arXiv:1710.09725, arXiv:2010.07595]

String Interactions: GLEIPNIR

- Overlapping anti-parallel strings may attenuate each other.
  Swing, Colour reconnections ⇒ ?
- Overlapping strings may repel each other
  String Shoving ⇒ ridges and flow
- Overlapping strings will have an increased string tension, making it easier to produce eg. strange hadrons.
  Rope Hadronisation ⇒ strangeness enhancement

[work in progress: H. Shah, T Lundberg]

[arXiv:1710.09725, arXiv:2010.07595]

[arXiv:1412.6259, arXiv:2202.12783, arXiv:2205.11170]

String repulsion: Shoving

The string endpoints (quarks and gluons) carry longitudinal momentum, but the string itself cannot.

The shoving between parallel strings gives a transverse push according to

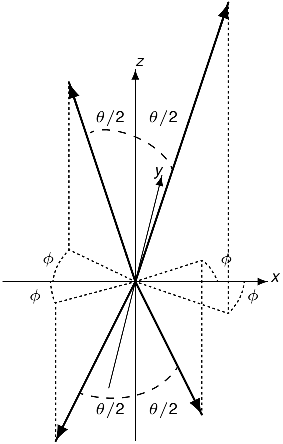
$$\frac{dp_\perp}{dt\,dz} = \frac{g\kappa\delta_\perp(t)}{R^2}\exp\left(-\frac{\delta_\perp^2(t)}{4R^2}\right).$$

This push must be parallel to both string pieces.

There is no frame where two random string pieces are parallel.

But there is always a frame where they lie in parallell planes at any given time.

The parallel string frame



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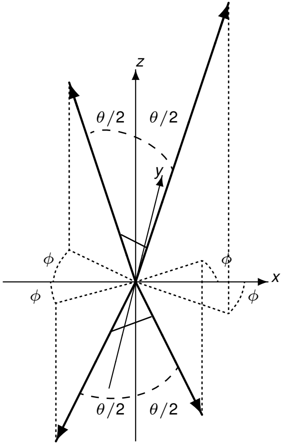

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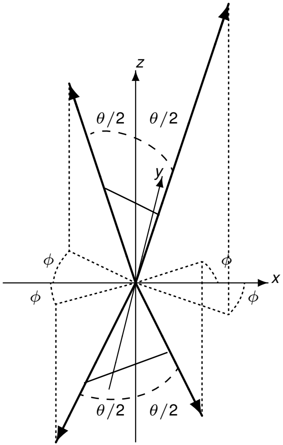

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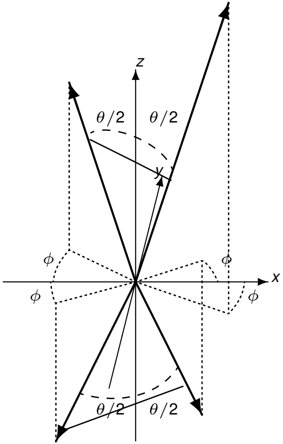
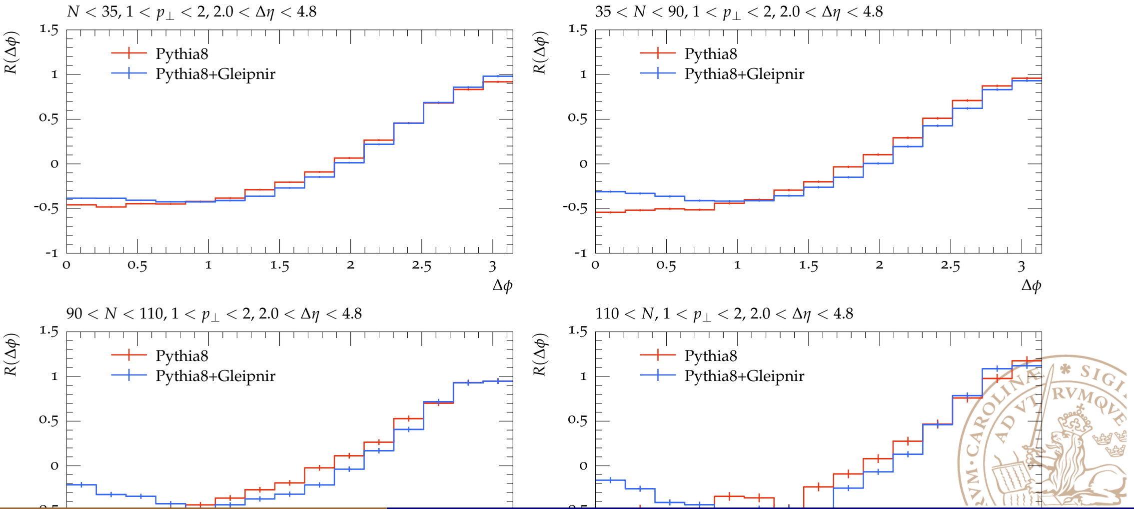
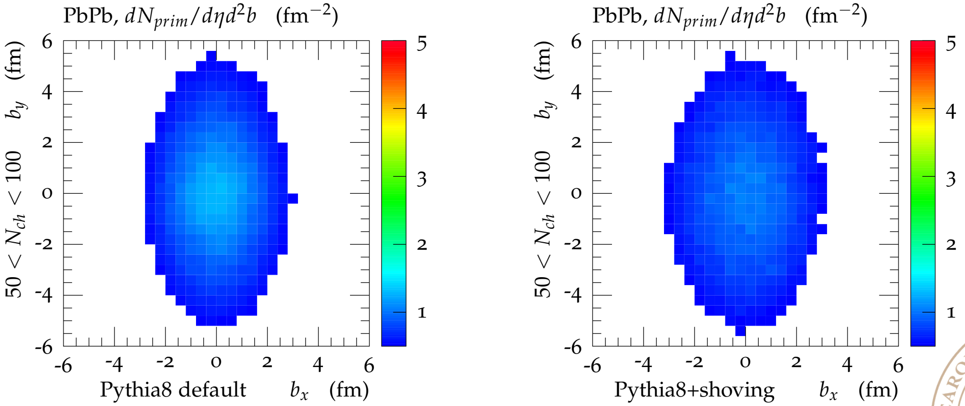


- Use (simplified) space-time information of all partons.
- Transform to parallel frame for every pair of string pieces.
- Calculate and collect small nudges, ordered in time.
- Apply the nudges to the produced primary hadrons (both position and momenta).

We have a ridge!



Flow in PbPb (Angantyr)



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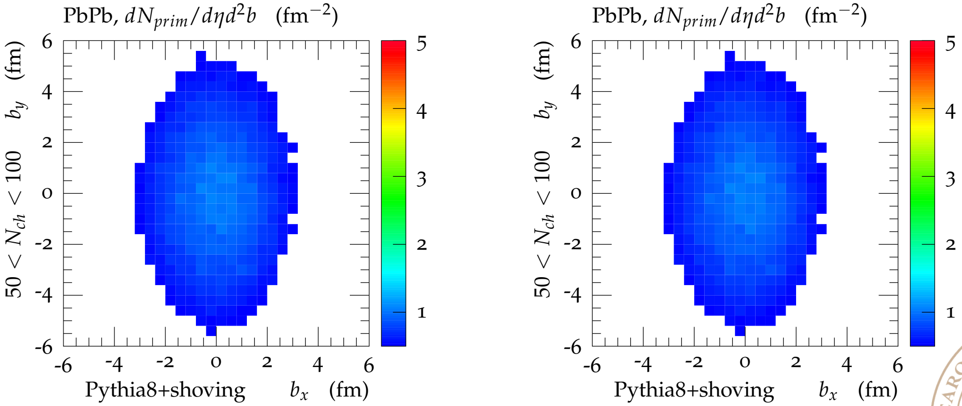

Rope hadronisation

Overlapping strings will give a higher string tension.

From lattice calculations $\kappa \propto C_2$.

In a rope with p parallel and q anti-parallel, completely overlapping strings we have

$$\kappa_{\{p,q\}} = \frac{1}{4}\left(p^2 + pq + q^2 + 3p + 3q\right)\kappa_{\{1,0\}}$$

The relative probability to produce a strange quark in a break-up, compared to a light quark is

$$P \propto \exp(\pi(m_s^2 - m_d^2)/\kappa_{\text{eff}}),$$

$$\text{where} \quad \kappa_{\text{eff}} = \kappa_{\{p,q\}} - \kappa_{\{p-1,q\}}$$

is the *reduction* of the string tension.

- Strings are not parallel ⇒ the parallel frame
- Strings are not completely overlapping

$$\begin{aligned}\mathcal{I}(\delta_y, \delta_z, \phi) &= \int d^2\rho \mathbf{E}_1(\rho) \cdot \mathbf{E}_2(\rho) \\ &= 2\pi E_0^2 R^2 \frac{\cos\phi}{\cos\frac{\phi}{2}} \exp\left(-\frac{\delta_y^2 \cos\frac{\phi}{2} + \delta_z^2}{4R^2}\right).\end{aligned}$$

- Again use pairwise interactions, and sum up (fractional) p and q.
- Adjust the hadronisation parameters in PYTHIA8 in each break-up.

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$$\mathcal{I}(\delta_y, \delta_z, \phi) = \int d^2\rho \mathbf{E}_1(\rho) \cdot \mathbf{E}_2(\rho)$$
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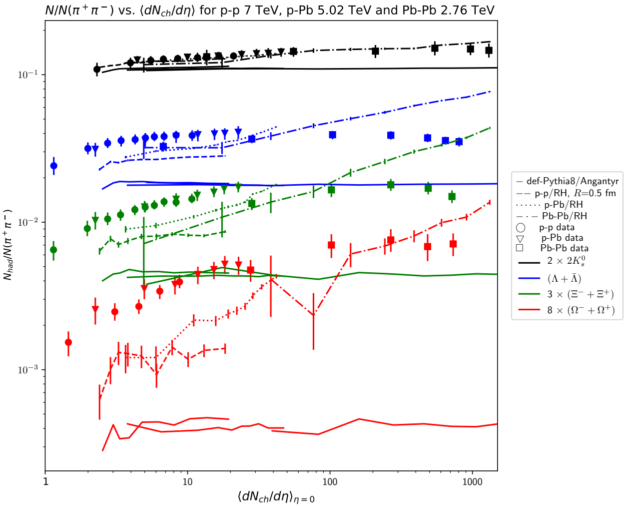
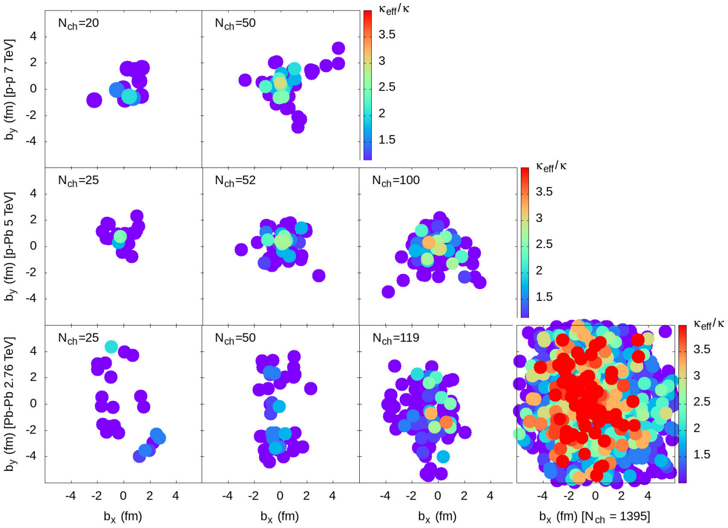
- Again use pairwise interactions, and sum up (fractional) p and q.
- Adjust the hadronisation parameters in PYTHIA8 in each break-up.
  (A bit messy, especially for baryons)

[arXiv:2201.06316]


$N/N(\pi^+\pi^-)$ vs. $\langle dN_{ch}/d\eta\rangle$ for p-p 7 TeV, p-Pb 5.02 TeV and Pb-Pb 2.76 TeV
$N_{had}/N(\pi^+\pi^-)$
$\langle dN_{ch}/d\eta\rangle_{\eta=0}$
10^{-1}
10^{-2}
10^{-3}
1
10
100
1000
def-Pythia8/Angantyr
p-p/RH, R=0.5 fm
p-Pb/RH
Pb-Pb/RH
p-p data
p-Pb data
Pb-Pb data
$2\times 2K^0_s$
$(\Lambda+\bar\Lambda)$
$3\times(\Xi^-+\Xi^+)$
$8\times(\Omega^-+\Omega^+)$


N$_{ch}$=20
N$_{ch}$=50
N$_{ch}$=25
N$_{ch}$=52
N$_{ch}$=100
N$_{ch}$=25
N$_{ch}$=50
N$_{ch}$=119
κ_{eff}/κ
b$_y$ (fm) [p-p 7 TeV]
b$_y$ (fm) [p-Pb 5 TeV]
b$_y$ (fm) [Pb-Pb 2.76 TeV]
b$_x$ (fm)
b$_x$ (fm) [N$_{ch}$ = 1395]

Shoving and Ropes are implemented in the same framework (Gleipnir), but so far they don't work well together.

Shoving will dilute the strings, especially for high string densities.

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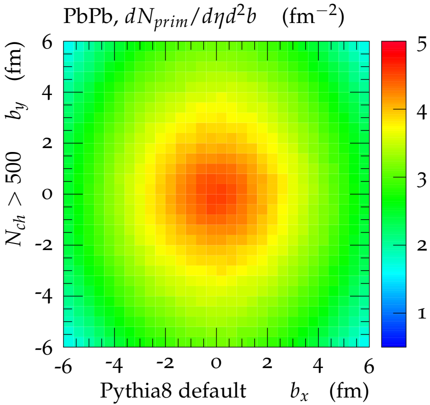

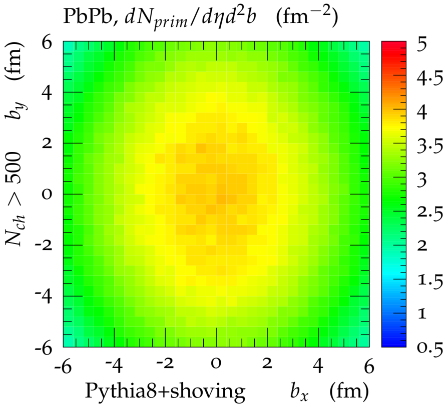

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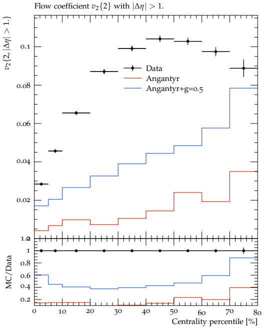

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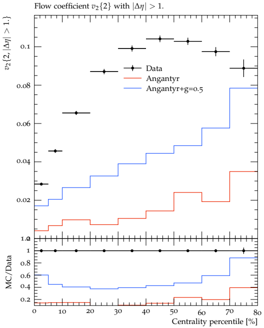

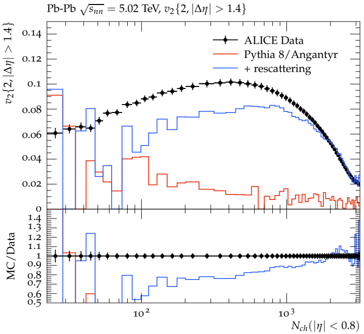

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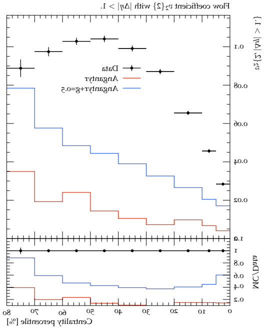

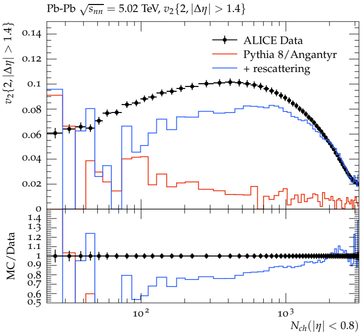

Summary

- Heavy-Ion collisions are messy
- Not just overlayed *NN* collisions
- Initial state effects (saturation, fluctuations, . . .)
- Final state effects (QGP, hydrodynamics, string interactions, flow, jet-quenching, rescattering, . . .)

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Tutorial this afternoon:

`http://home.thep.lu.se/~leif/misc/angantyr-tutorial.tgz`

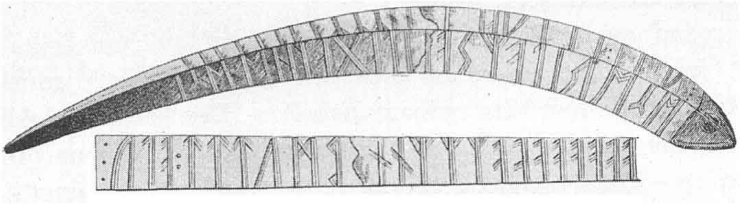
Final Comments

By tradition HI and HEP have been separate communities

- LHC brought them together
- There are collective effects in pp
- There are jets in *AA*
- We can (and need to) learn from each other

Questions!

Galdr



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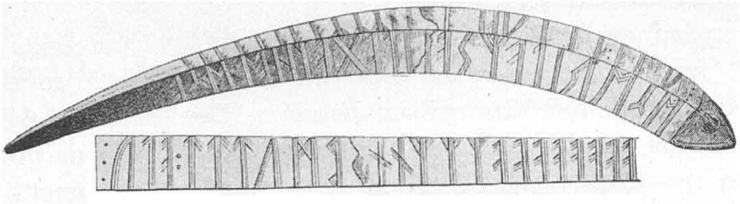

EK ERILAR SAWILAGAR HATEKA

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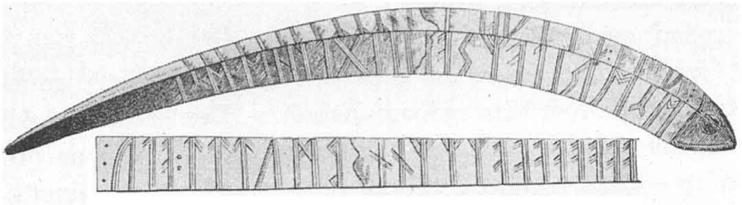

EK	ERILAR	SAWILAGAR	HATEKA
I	the rune master	magic	is my name