Hadronization, Soft Modelling and Heavy Ions (2)

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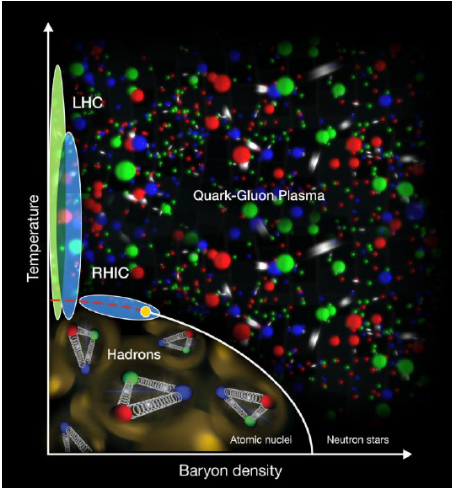
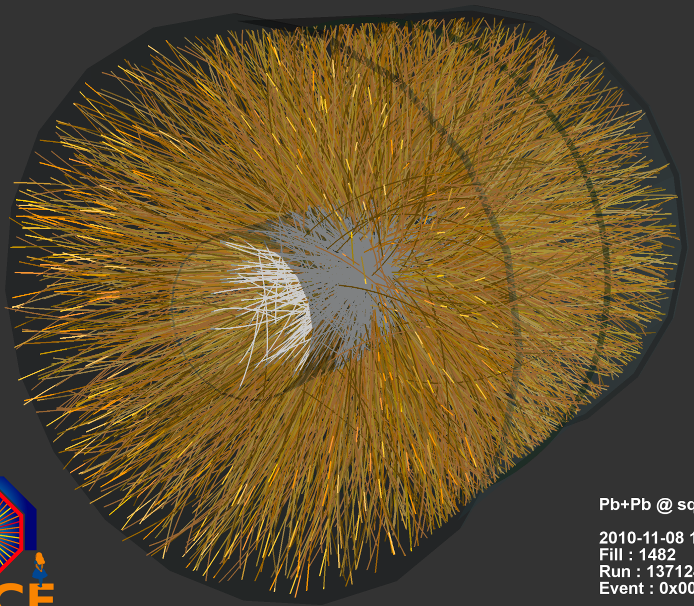
pp vs. *AA* (from the pp point of view)

My immediate 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?



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



Pb+Pb @ sqrt(s) = 2.76 ATeV

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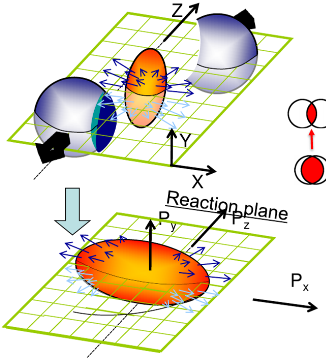
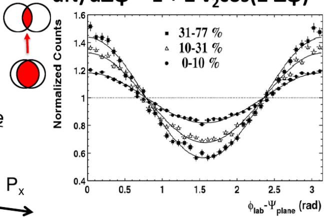
Flow

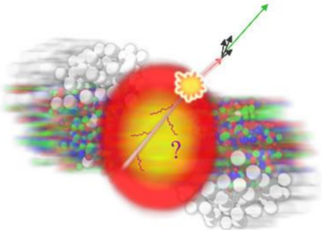


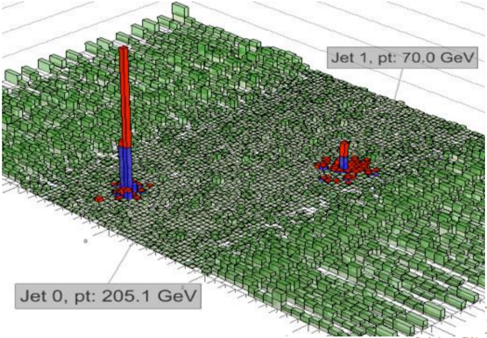
Fourier decomposition:

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

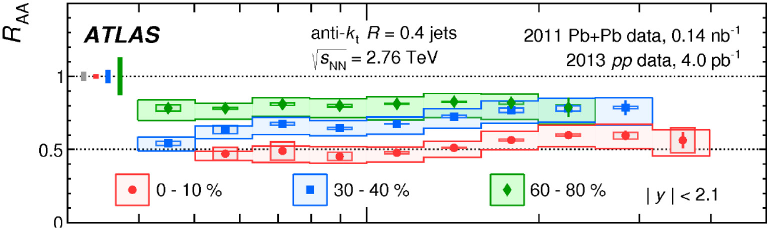


Jet quenching





The R_{AA} factor



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

$\langle T_{AA}\rangle \sigma^{pp} = \langle N_{coll}\rangle$

N_{coll} is the # of binary collisions

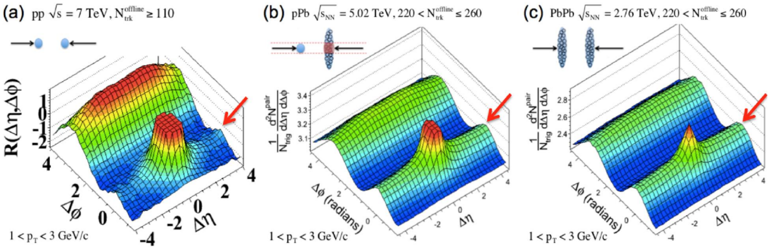
For perturbative QCD processes:

R_{AA}<1: suppression

R_{AA}=1: no nuclear effects

R_{AA}>1: enhancement

The ridge

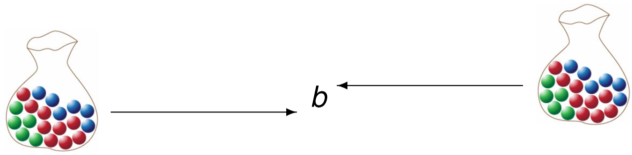

(a) pp $\sqrt{s}$ = 7 TeV, $N_{trk}^{offline} \geq 110$
R(Δη,Δφ)
Δφ
Δη
1 < p_T < 3 GeV/c
(b) pPb $\sqrt{s_{NN}}$ = 5.02 TeV, 220 < $N_{trk}^{offline} \leq 260$
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
Δφ (radians)
Δη
1 < p_T < 3 GeV/c
(c) PbPb $\sqrt{s_{NN}}$ = 2.76 TeV, 220 < $N_{trk}^{offline} \leq 260$
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
Δφ (radians)
Δη
1 < p_T < 3 GeV/c

Outline

- The Glauber model(s)
- Nuclear effect in the initial state
- Collective effect in the final state
- Heavy Ions in PYTHIA8

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

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

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$\approx$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* 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-difractive? Inelastic?

Interactions between nucleons

Let's assume that a projectile with some kind of internal structure interacts with a structureless target. The projectile can have different mass-eigenstates, Ψ_i, and these can be different from the eigenstates of the (diffractive) interaction, Φ_k.

$$\Psi_i = \sum_k c_{ik}\Phi_k \quad \text{with} \quad \Psi_0 = \Psi_{in}.$$

With an elastic amplitude T_k for each interaction eigenstate we get the elastic cross section for the incoming state

$$\frac{d\sigma_{\mathrm{el}}(b)}{d^2\vec{b}} = |\langle\Psi_0|T|\Psi_0\rangle|^2 = \left(\sum_k |c_{0k}|^2 T_k\right)^2 = \langle T\rangle^2.$$

For a completely black target and projectile, we know from the optical theorem that the elastic cross section is the same as the absorptive cross section and

$$\sigma_{\rm el} = \sigma_{\rm abs} = \sigma_{\rm tot}/2$$

but with substructure and fluctuations we have also diffractive scattering with the amplitude

$$\langle \Psi_i \,|T|\, \Psi_0 \rangle = \sum_k c_{ik} T_k c^*_{0k}$$

and

$$\frac{d\sigma_{\rm diff}(b)}{d^2\vec{b}} = \sum_i \langle \Psi_0 | T | \Psi_i \rangle \langle \Psi_i | T | \Psi_0 \rangle = \langle T^2 \rangle.$$

The importance of fluctuations

We see now that diffractive excitation to higher mass eigenstates is given by the fluctuations

$$\frac{d\sigma_{\mathrm{dex}}(b)}{d^2\vec{b}} = \frac{d\sigma_{\mathrm{diff}}(b)}{d^2\vec{b}} - \frac{d\sigma_{\mathrm{el}}(b)}{d^2\vec{b}} = \langle T^2(b)\rangle - \langle T(b)\rangle^2$$

When looking at *AA* interactions we may assume that the state of each nucleon is frozen during the interaction according to the eikonal approximation.

We also assume the elastic nucleon scattering amplitude is purely imaginary and $T(b) \equiv -iA(b)$ giving $0 \leq T \leq 1$ from unitarity.

We can now also write down the total and absorptive (aka. non-diffractive) cross section, and we can look at the situation where both the projectile and target nucleon has a sub-structure:

$$\begin{aligned}
\frac{d\sigma_{\mathrm{tot}}^{\mathrm{NN}}(b)}{d^2\vec{b}} &= 2\langle T(b)\rangle \\
\frac{d\sigma_{\mathrm{abs}}^{\mathrm{NN}}(b)}{d^2\vec{b}} &= 2\langle T(b)\rangle - \langle T^2(b)\rangle \\
\frac{d\sigma_{\mathrm{el}}^{\mathrm{NN}}(b)}{d^2\vec{b}} &= \langle T(b)\rangle^2 \\
\frac{d\sigma_{\mathrm{dex}}^{\mathrm{NN}}(b)}{d^2\vec{b}} &= \langle T^2(b)\rangle - \langle T(b)\rangle^2
\end{aligned}$$

We can also divide the diffractive excitation depending on whether the target or projective nucleon is excited.

$$\frac{d\sigma_{\mathrm{Dp}}^{\mathrm{NN}}(b)}{d^2\vec{b}} = \langle\langle T(b)\rangle_t^2\rangle_p - \langle\langle T(b)\rangle_t\rangle_p^2$$

$$\frac{d\sigma_{\mathrm{Dt}}^{\mathrm{NN}}(b)}{d^2\vec{b}} = \langle\langle T(b)\rangle_t^2\rangle_p - \langle\langle T(b)\rangle_p\rangle_t^2$$

$$\frac{d\sigma_{\mathrm{DD}}^{\mathrm{NN}}(b)}{d^2\vec{b}} = \langle\langle T(b)^2\rangle_t\rangle_p - \langle\langle T(b)\rangle_p^2\rangle_t - \langle\langle T(b)\rangle_t^2\rangle_p + \langle\langle T(b)\rangle_t\rangle_p^2$$

We note in particular that the probability of a target nucleon being wounded is given by

$$\begin{aligned}
\frac{d\sigma_{\mathrm{Wt}}^{\mathrm{NN}}(b)}{d^2\vec{b}} &= \frac{d\sigma_{\mathrm{abs}}^{\mathrm{NN}}(b)}{d^2\vec{b}} + \frac{d\sigma_{\mathrm{DD}}^{\mathrm{NN}}(b)}{d^2\vec{b}} + \frac{d\sigma_{\mathrm{Dt}}^{\mathrm{NN}}(b)}{d^2\vec{b}} \\
&= \frac{d\sigma_{\mathrm{tot}}^{\mathrm{NN}}(b)}{d^2\vec{b}} - \frac{d\sigma_{\mathrm{el}}^{\mathrm{NN}}(b)}{d^2\vec{b}} - \frac{d\sigma_{\mathrm{Dp}}^{\mathrm{NN}}(b)}{d^2\vec{b}} \\
&= 2\langle T(b)\rangle_{tp} - \langle\langle T(b)\rangle_t^2\rangle_p
\end{aligned}$$

and thus only depends on the fluctuations in the projectile, but only on average properties of the target itself.

Introducing the S-matrix, $S(b) = 1 - T(b)$ we see that the individual absorbtive and wounded cross sections factorises for $\mathrm{p}A$

$$\frac{d\sigma^{\mathrm{pA}}_{\mathrm{abs}}(b)}{d^2\vec{b}} = 1 - \prod_j \left(1 - \frac{d\sigma^{\mathrm{NN}}_{\mathrm{abs}}(b_j)}{d^2\vec{b}}\right) = 1 - \prod_j \langle S^2(b_j)\rangle_{tp}$$

$$\frac{d\sigma^{\mathrm{pA}}_{\mathrm{Wt}}(b)}{d^2\vec{b}} = 1 - \prod_j \left(1 - \frac{d\sigma^{\mathrm{NN}}_{\mathrm{Wt}}(b_j)}{d^2\vec{b}}\right) = 1 - \prod_j \langle\langle S(b_j)\rangle_t^2\rangle_p$$

The standard (naive) Glauber implementation

Estimate the distribution in number of participants in a pA 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 $\sigma = \sigma_{\mathrm{abs}}^{\mathrm{NN}} + \sigma_{\mathrm{dex}}^{\mathrm{NN}} = \sigma_{\mathrm{tot}}^{\mathrm{NN}} - \sigma_{\mathrm{el}}^{\mathrm{NN}}$.

A more sofisticated Glauber implementation

Assume a fluctuating *NN* cross section

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

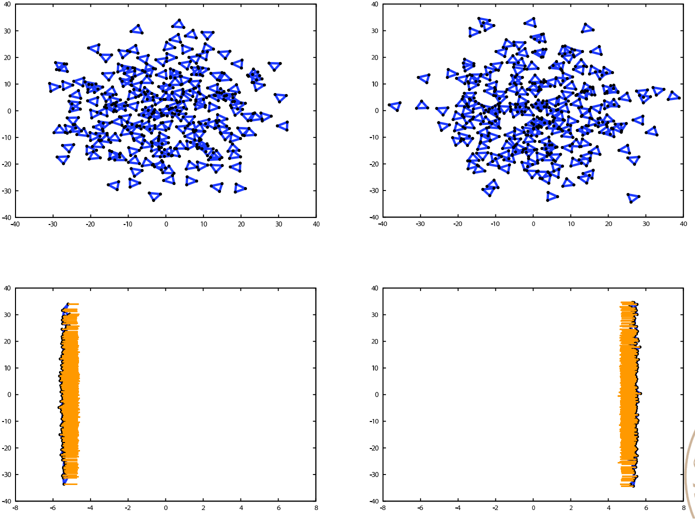
with

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

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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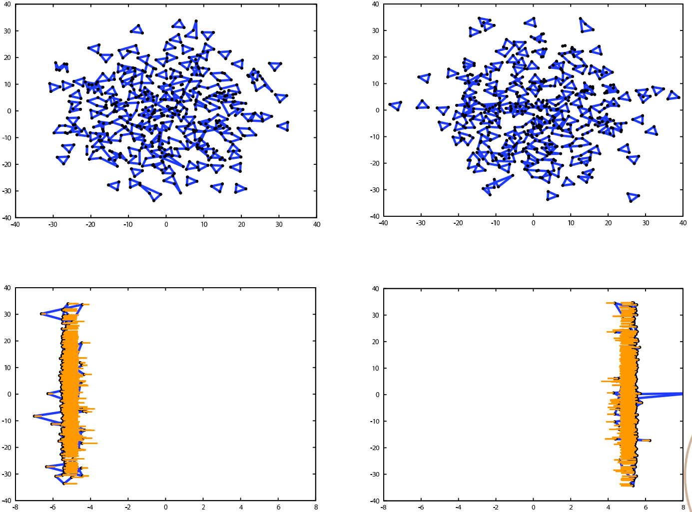

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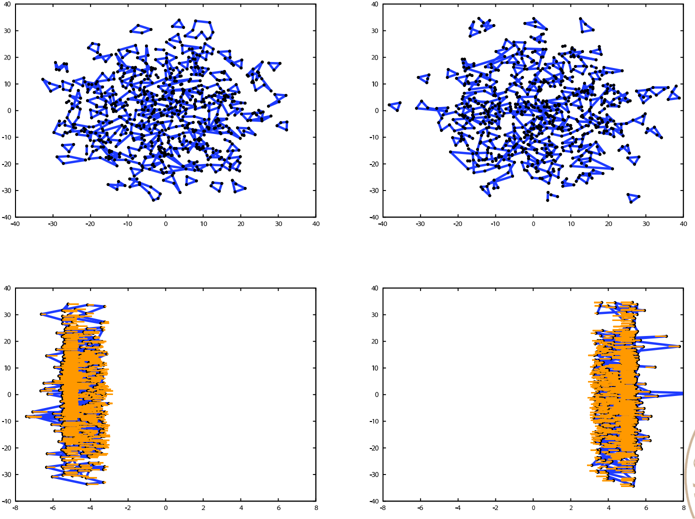

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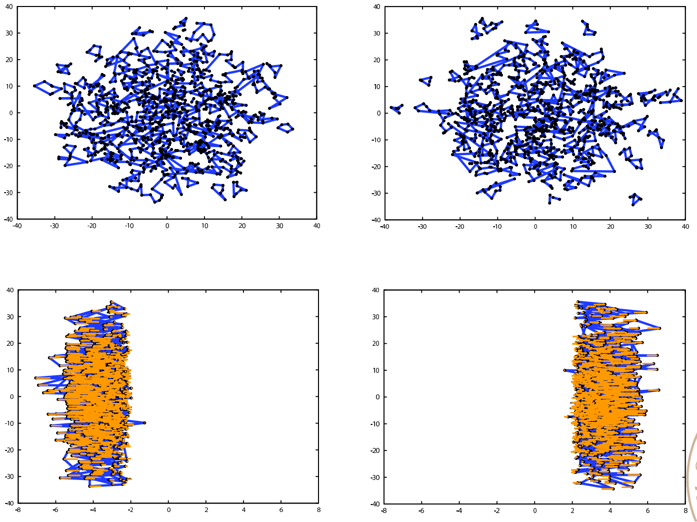

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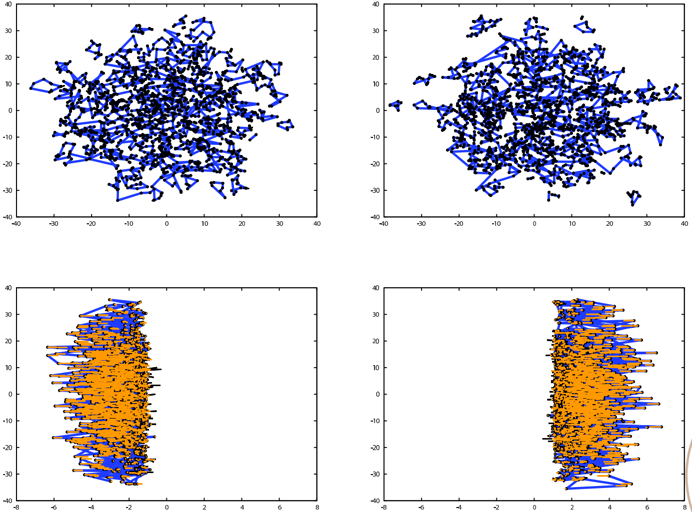

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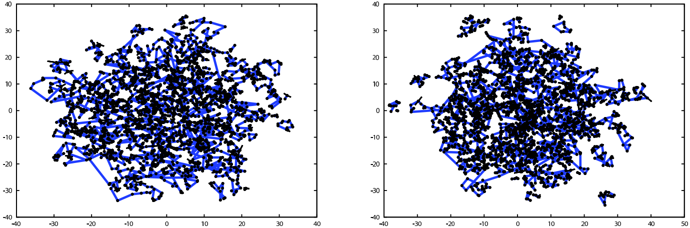

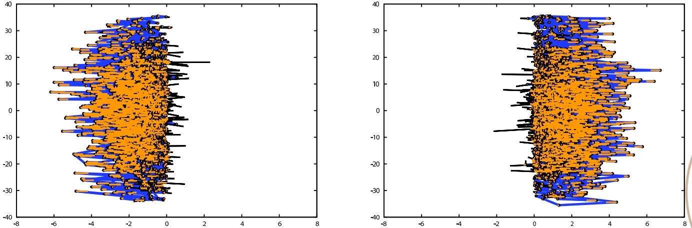

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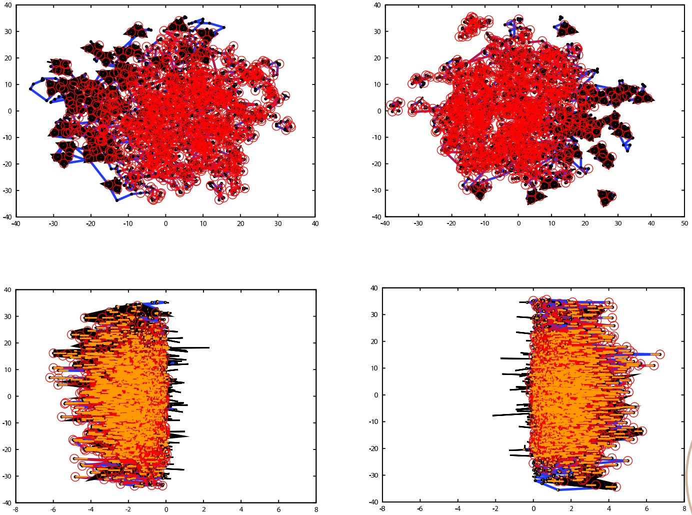

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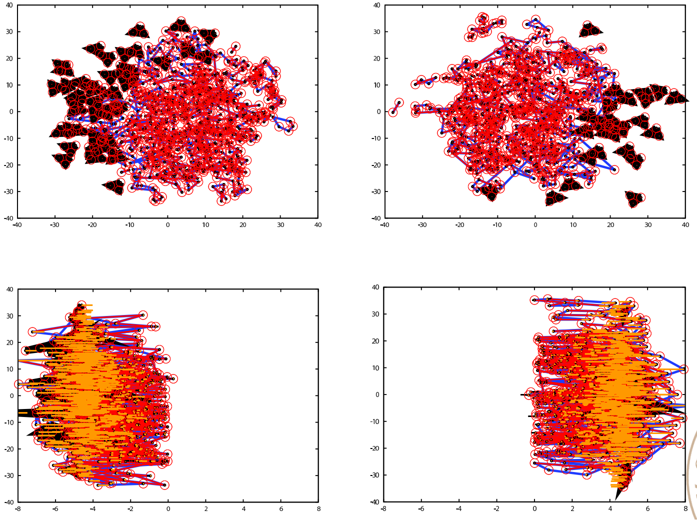

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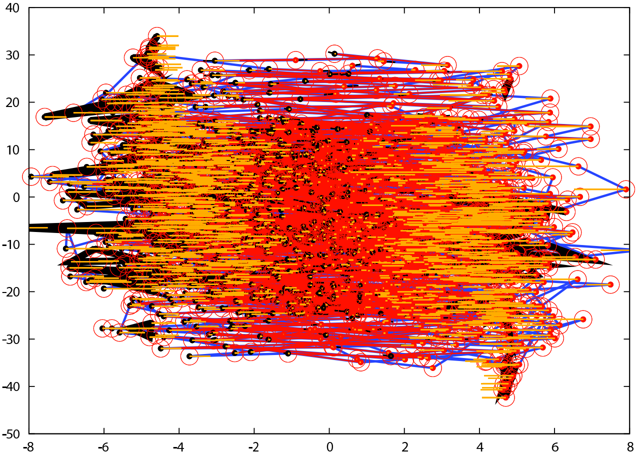

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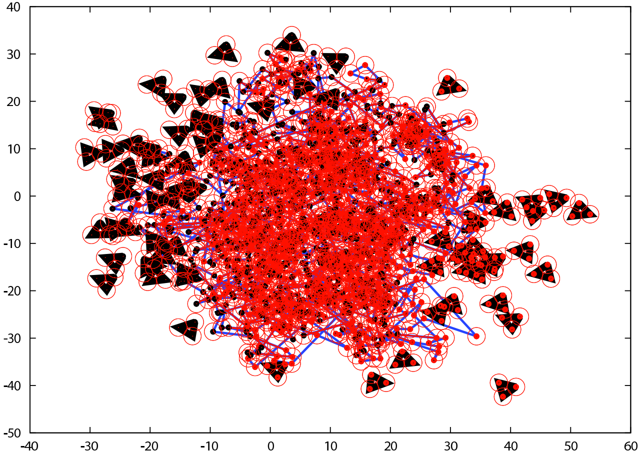


Color Glass Condesate (CGC)

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

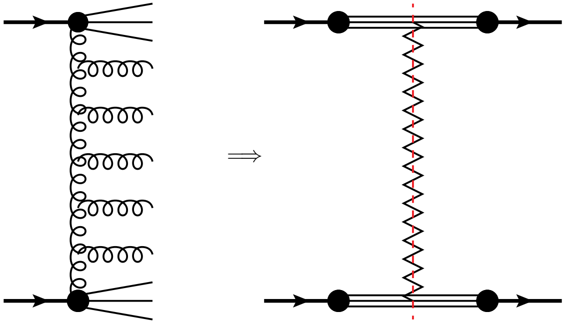
$$Q_{\mathrm{sat}} = Q_0^2 \left(\frac{x}{x_0} \right)^{\lambda}$$

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.

IP-Glasma model is similar but uses DGLAP $+$ Saturation.

The Cut Pomeron picture



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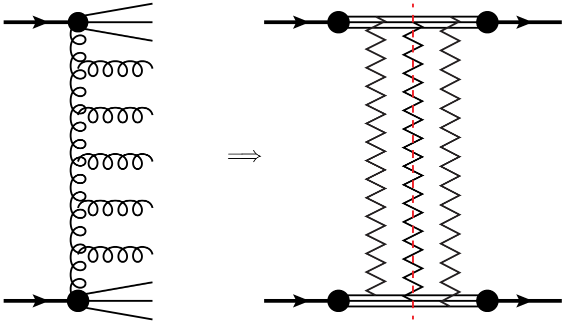

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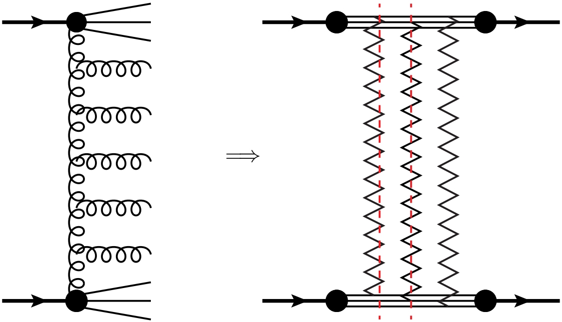

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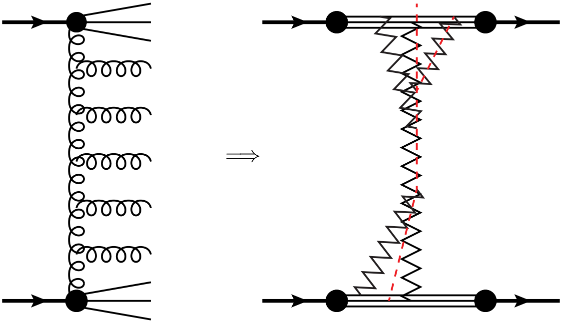
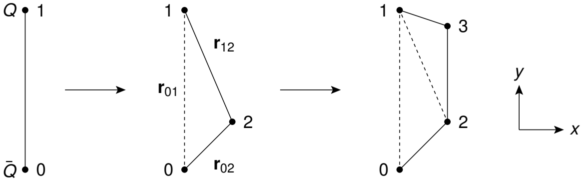


Each cut pomeron will give rise to a string (or two) spanned between two colliding nucleons, or between a nucleon and another Pomeron.

The DIPSY model

More or less same ingredients as the CGC, but generating each gluon explicitly using the (mueller) dipole model.



- Mueller's formulation of BFKL
- $\frac{dP}{dy} = \frac{\bar{\alpha}}{2\pi} d^2 r_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2}$
- Dipoles in impact parameter space, evolved in rapidity
- Builds up virtual Fock-states of the proton

The interaction

Dipole–dipole interaction:

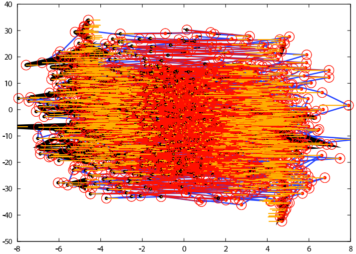
- $F = \sum_{ij} f_{ij} \qquad f_{(12)(34)} \propto \alpha_s^2 \ln^2\left(\frac{r_{13}r_{24}}{r_{14}r_{23}}\right)$
- Unitarize to get saturation effects $T = 1 - e^{-F}$

Saturation in the evolution with the Swing model

- Colour reconnection
- Two dipoles with the same colour may reconnect.
- Does not reduce the number of dipoles, but smaller dipoles are favoured, and these have weaker interactions.
- Also reconnections between different nucleons in a nuclei.

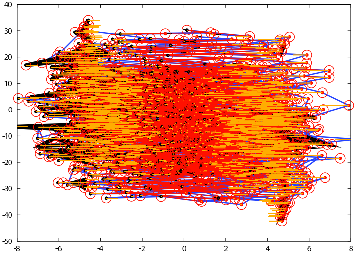
Models all kinds of fluctuations and correlations.

The Final State



Model each gluon/dipole individually?

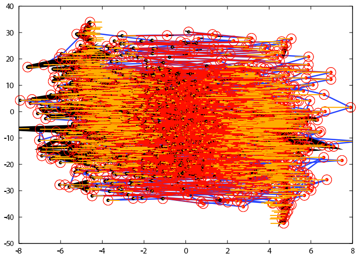
The Final State



Model each gluon/dipole individually?

Or give up and use statistical methods?

The Final State



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Or give up and use statistical methods?

Or both?

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 no momentum
- $T^{ij} = \delta_{ij} p$: 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.

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

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

Freezeout = Hadronisation and Rescattering

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Sorry, I don't understand this enough myself

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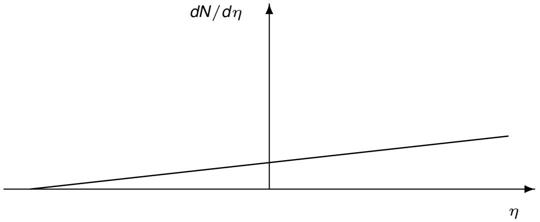
c.f. the model in PYTHIA

The Wounded Nucleon model

A simple model by Białas and Czyż, implemented in Fritiof

Each wounded nucleon contributes with hadrons according to a 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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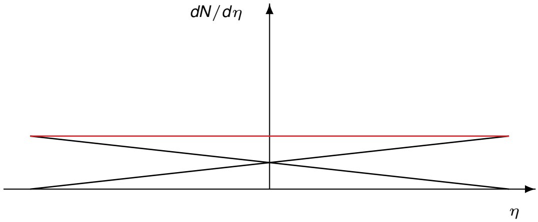

$$\frac{dN}{d\eta} = \quad F(\eta) + \quad F(-\eta) \qquad\qquad \text{(pp)}$$

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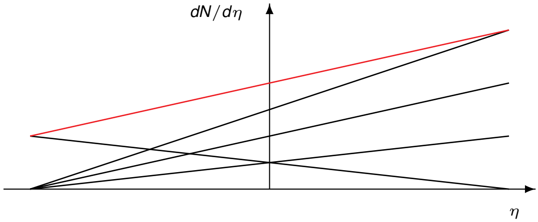

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (\mathrm{p}A)$$

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

The Wounded Nucleon model

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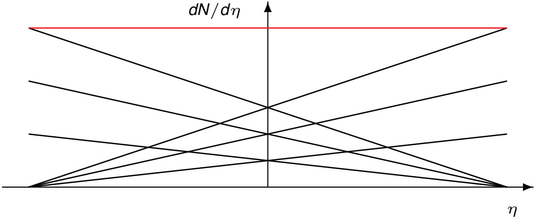


$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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

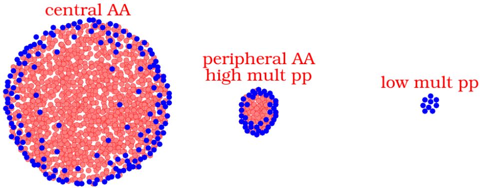
In Fritiof this was modelled by stretching out a string from each wounded nucleon with an invariant mass distributed as dm_X/m_X, which reproduces $F(\eta) \propto \eta - \eta_0$.

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

Core – Corona

The EPOS generator uses a *Core–Corona* model:

- 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



HIJING

(one of the standard HI generators)

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

AMPT

(Another standard HI generator with collective effects)

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

Heavy Ions in PYTHIA8

- 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) diffractive excitation event (with dm_X/m_X as in Fritiof).
- All sub-events generated on parton level and merged together into a consisten p*A* or *AA* event and then hadronised.

  (No string interactions yet.)

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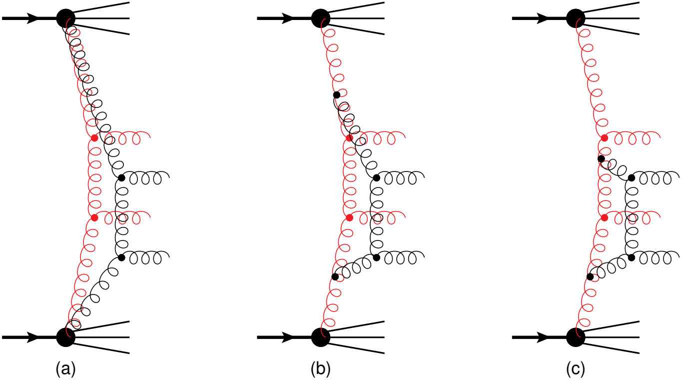
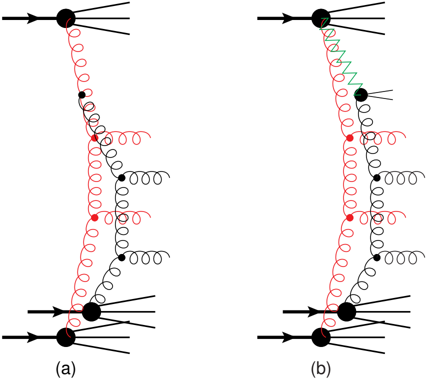
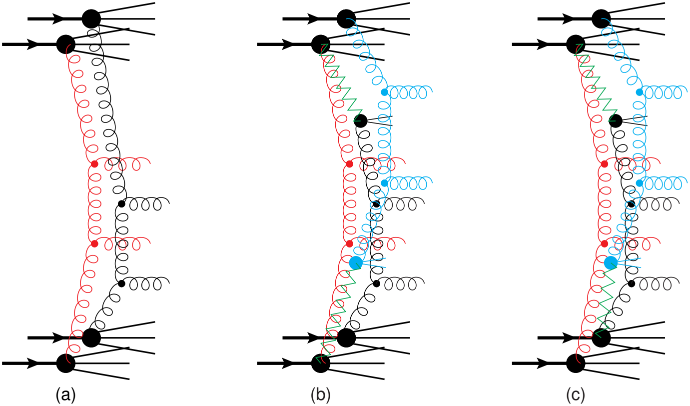
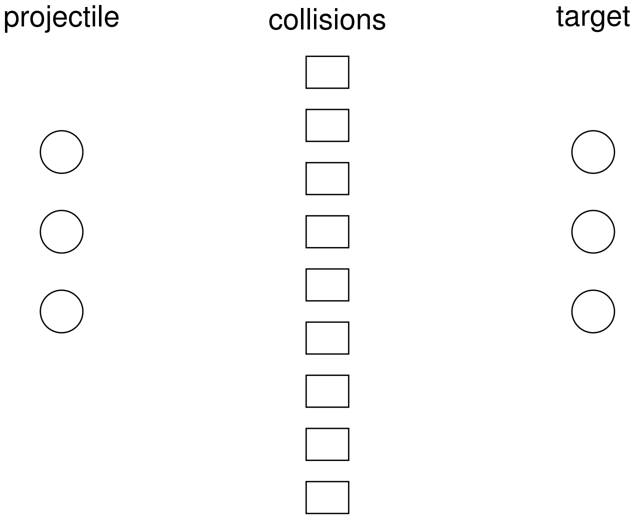
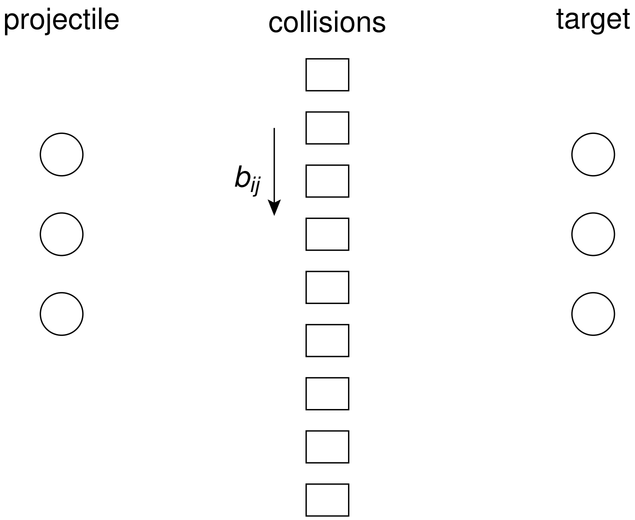

(a)
(b)
(c)

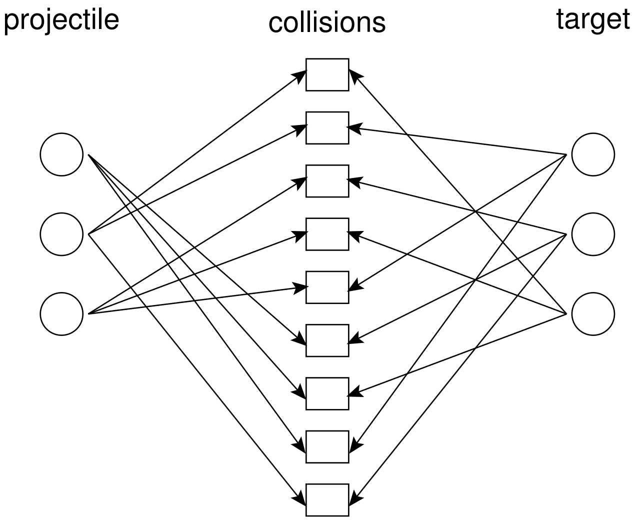

(a)
(b)

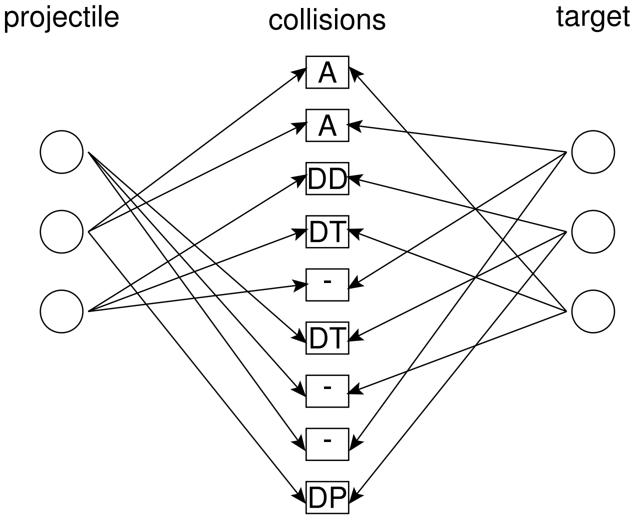

(a)
(b)
(c)


projectile
target


projectile
collisions
target


projectile
collisions
target
b_{ij}


projectile
collisions
target


projectile
collisions
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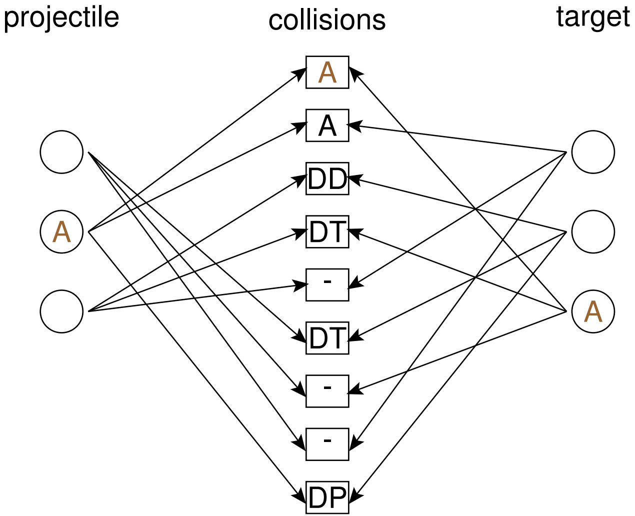
DP


projectile
collisions
target
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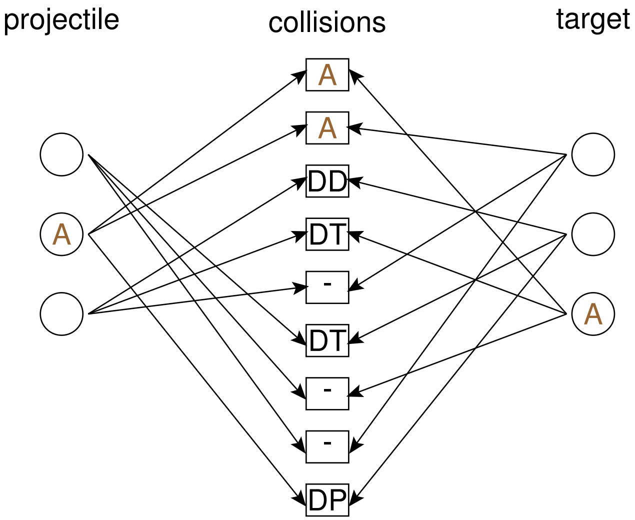
projectile
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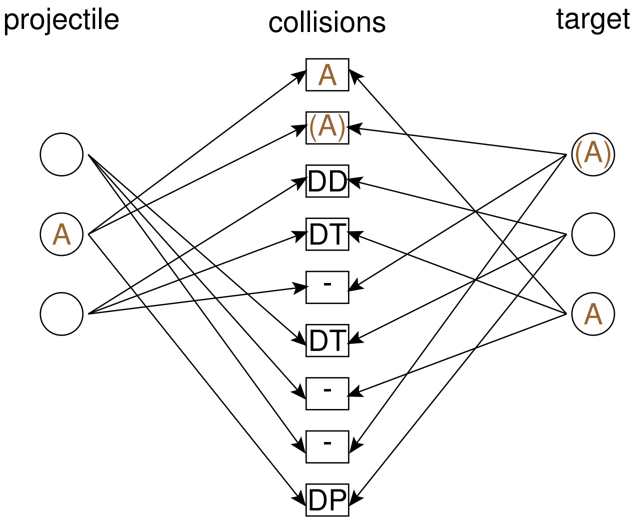
projectile
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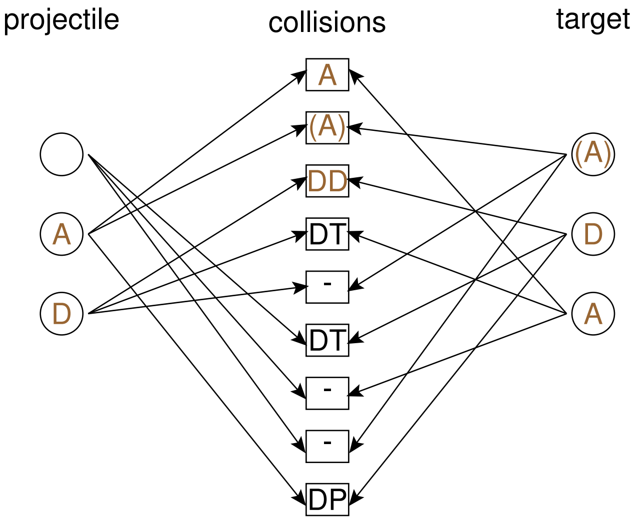
projectile
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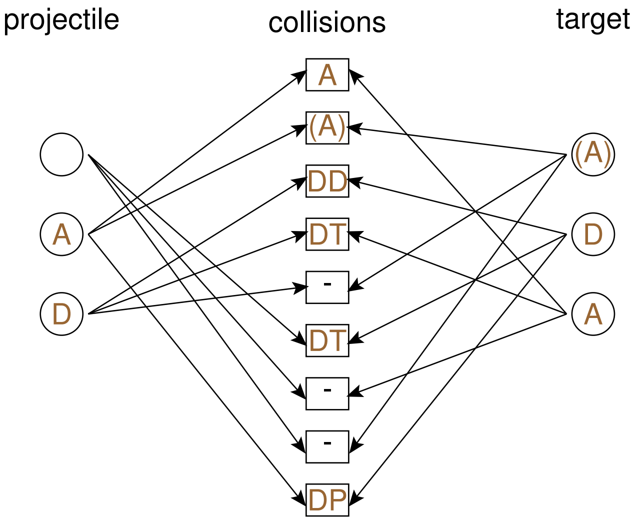
projectile
collisions
target
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A
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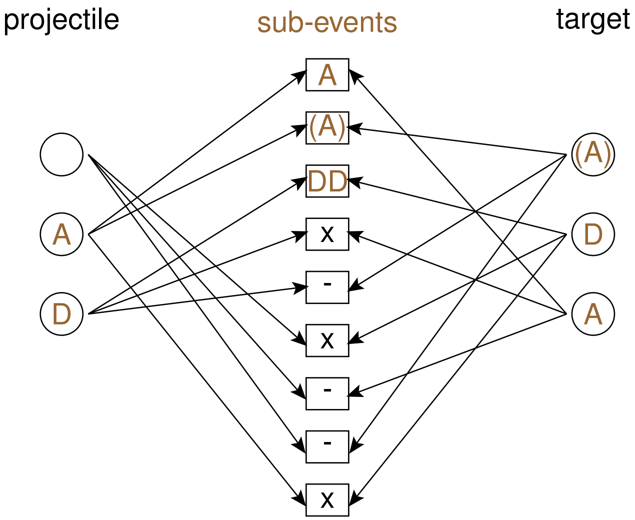
(A)
D
A


projectile
sub-events
target
A
(A)
DD
x
-
x
-
-
x
A
D
(A)
D
A

Signal processes

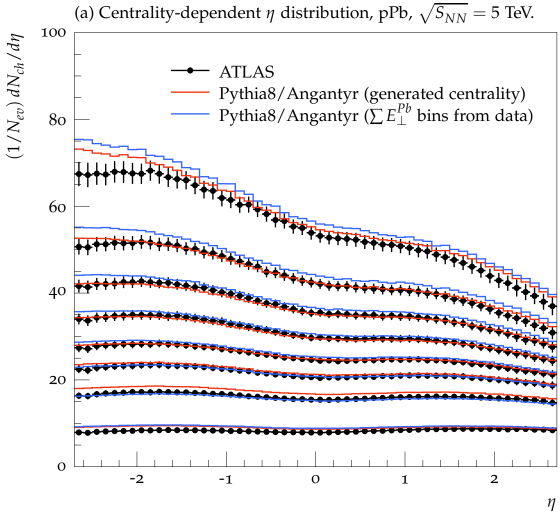
Not only min-bias. Rather than just generating non-diffractive events, The first absorptive sub-event can be generated using any hard process in PYTHIA8, giving the final event a weight $N_A\sigma_{hard}/\sigma_{ND}$.

Comparison to data

Several parameters in addition to the pp PYTHIA8 ones.

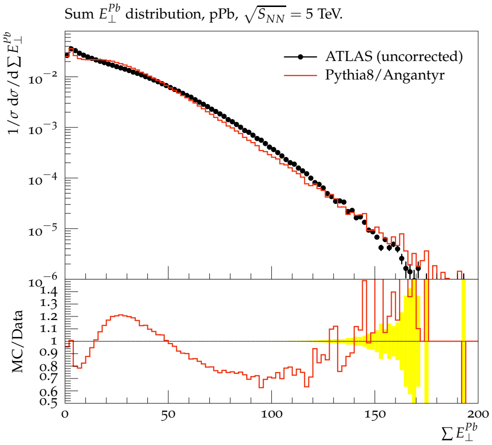
- Nucleon distributions can in principle be measured independently.
- *NN* cross section fluctuations are fitted to (semi-) inclusive pp cross sections (total, non-diffractive, single and double diffractive, elastic, and elastic slope) for given $\sqrt{s_{NN}}$.
- Diffractive parameters for secondary absorptive collisions, “tuned” to non-diffractive 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

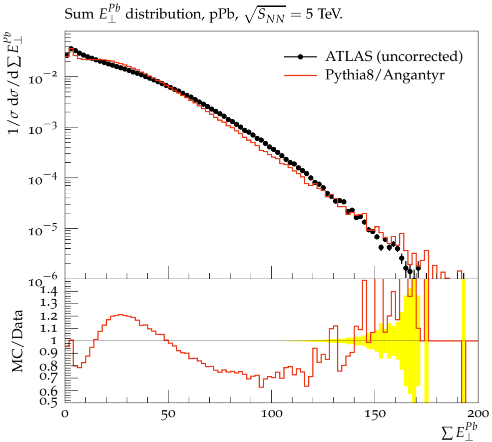


[arXiv:1508.00848]

Centrality in pPb

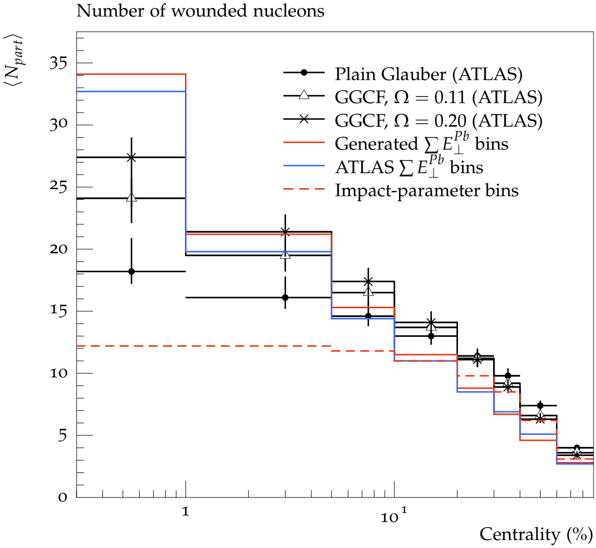


Centrality in pPb

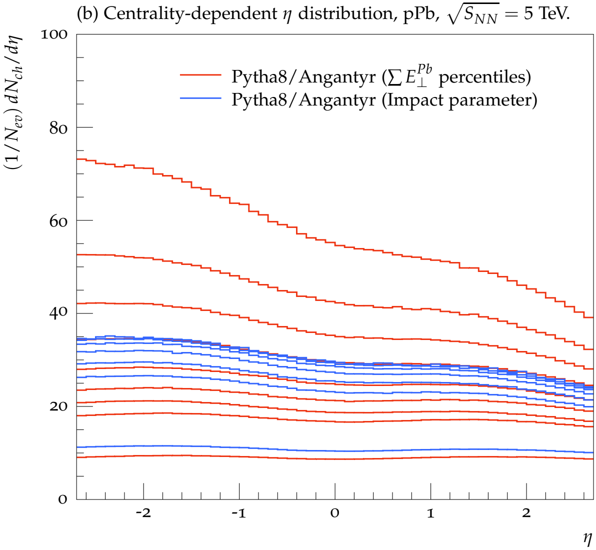


What was actually measured in the previous slide is a correlation between the η-distribution and the forward activity.

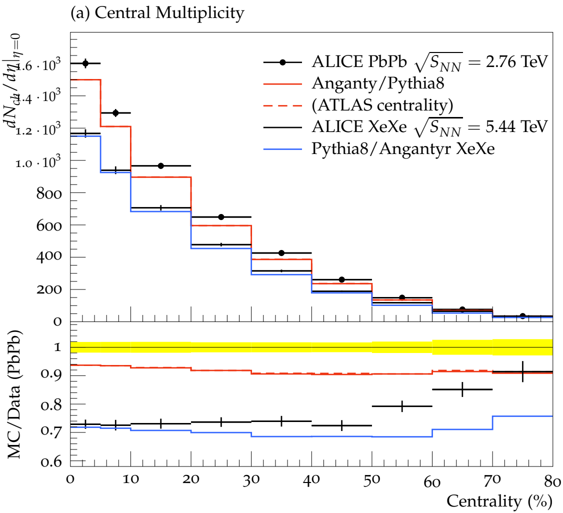
p–Pb number of participants

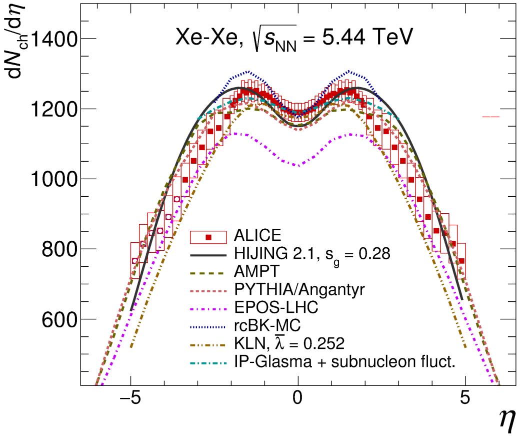


p–Pb η-distribution

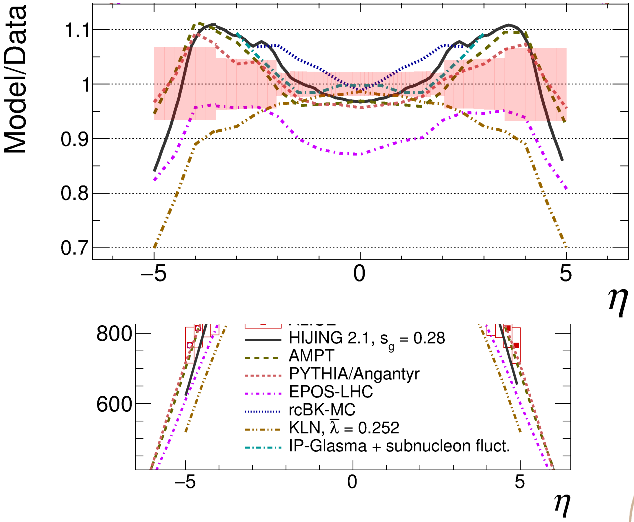


Central multiplicity in PbPb





[arXiv:1805.04432]



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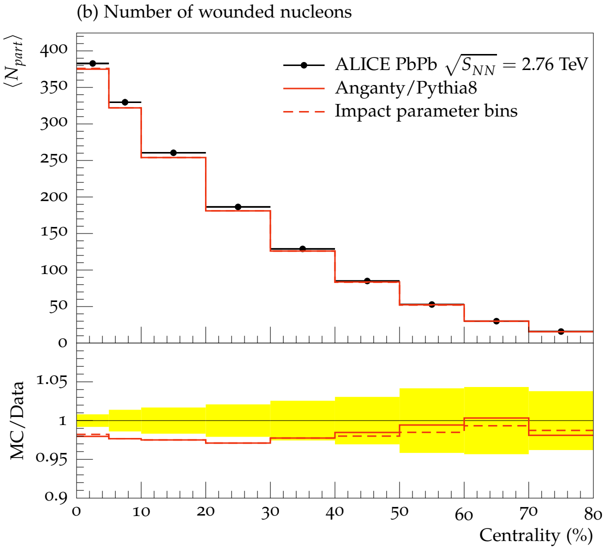
Pb–Pb number of participants



Go generate yourself!

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

String Interactions

So far there are no collective effects in Angantyr

(but we are working on it).

What happens when strings overlap in the final state?
(They are not really 1D: $R \sim 1$ fm)

- Colour reconnections between individual sub-collisions.
- Overlapping strings may repel each other.
- Overlapping strings may increase the string tension
- Final-state hadrons may collide

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  Swing
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  Rope hadronization $\rightarrow$ strangeness enhancement
- Final-state hadrons may collide
  Rescattering (already in PYTHIA)

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 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