Heavy Ions

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

My immediate reactions when encountering Heavy Ion physics:

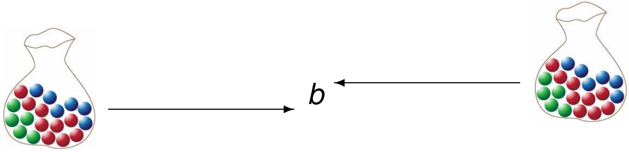
- Who is this Glauber guy anyway?
- That's just smashing bunches of nucleons together!
- You do you mean with centrality?
- When is many particles too many?
- I'm from Lund, I want to use string fragmentation!
- You measured what?

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 $= 1$

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 invarians (p≈n).
There are absolutely no correlations between the nuclei.

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

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

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 eigenstates we get the elastic cross section for the incoming state

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

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

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

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

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

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.

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

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

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

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 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 $\mathrm{p}A$ or AA collision.

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

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

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This is your exercise!

A more sofisticated Glauber implementation

Assume a fluctuating *NN* cross section

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

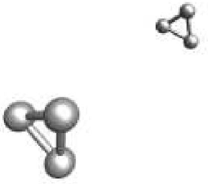
with

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

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

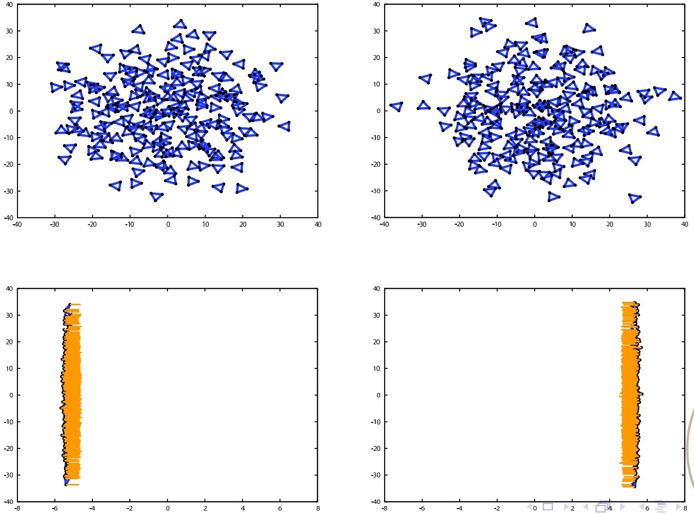
[Strikman et al. hep-ph/1301.0728]

The Initial State



[DIPSY: hep/ph/1103.4321]

Sample Au-Au event



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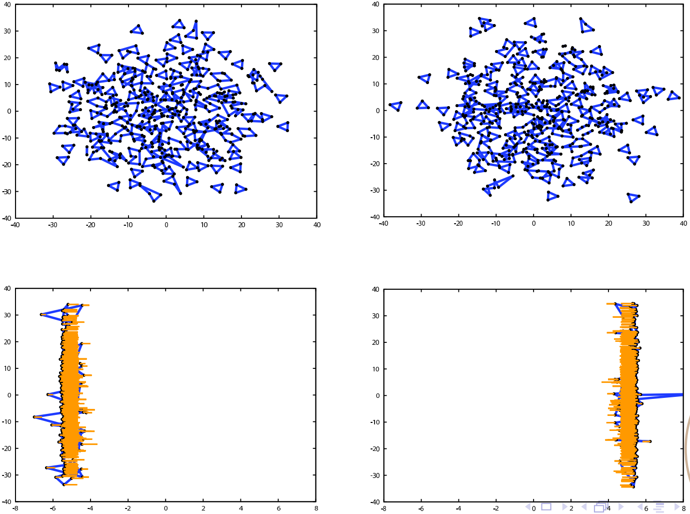

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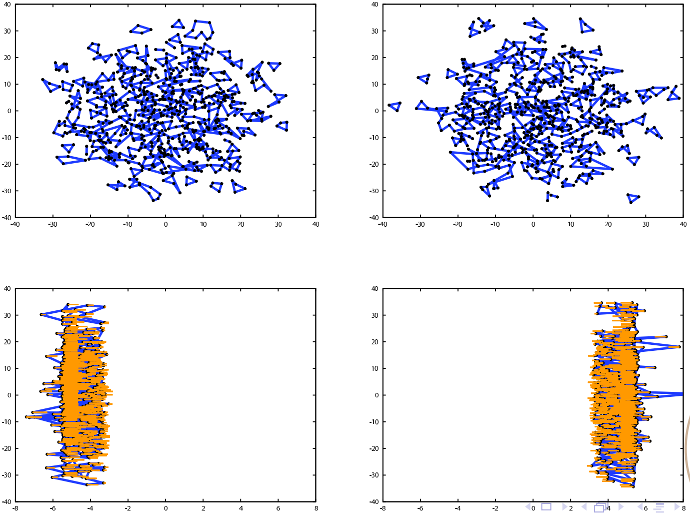

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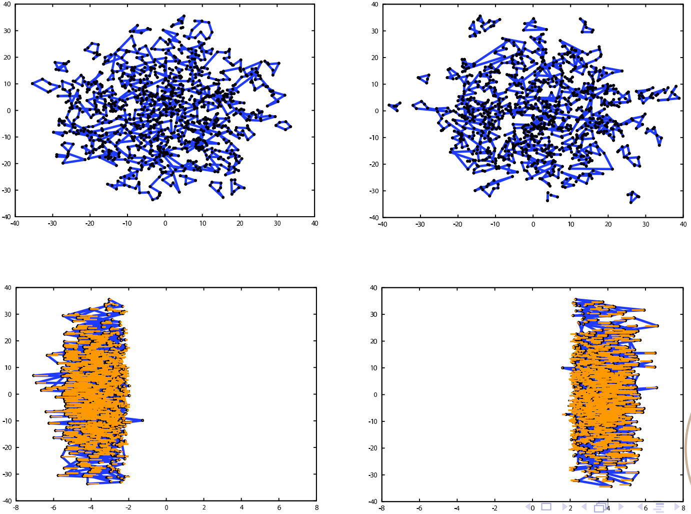

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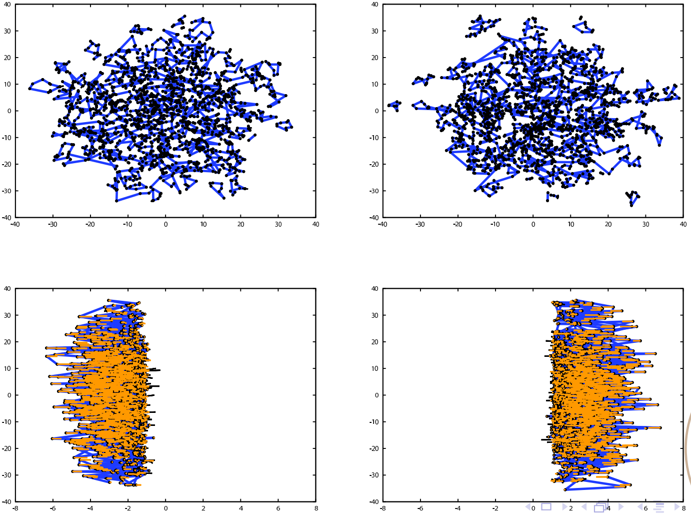

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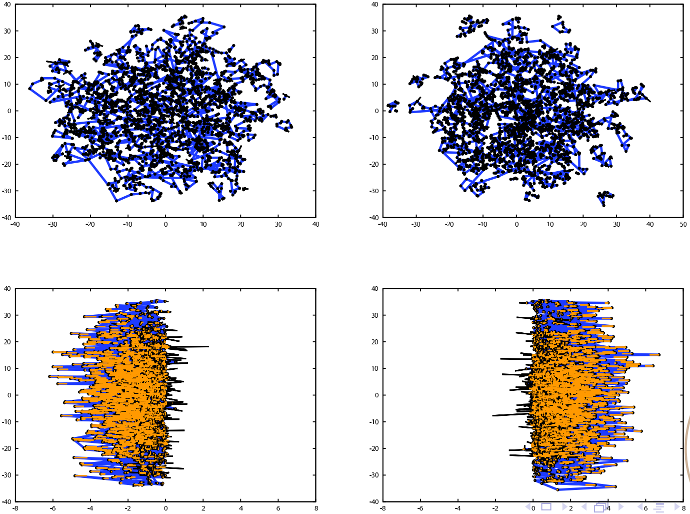

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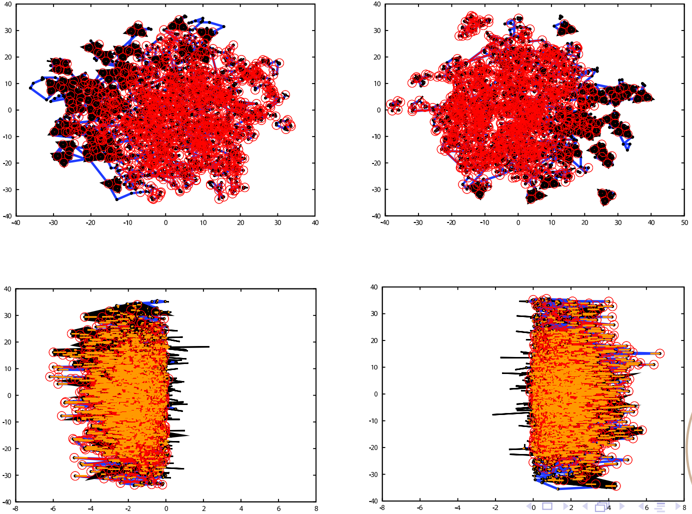

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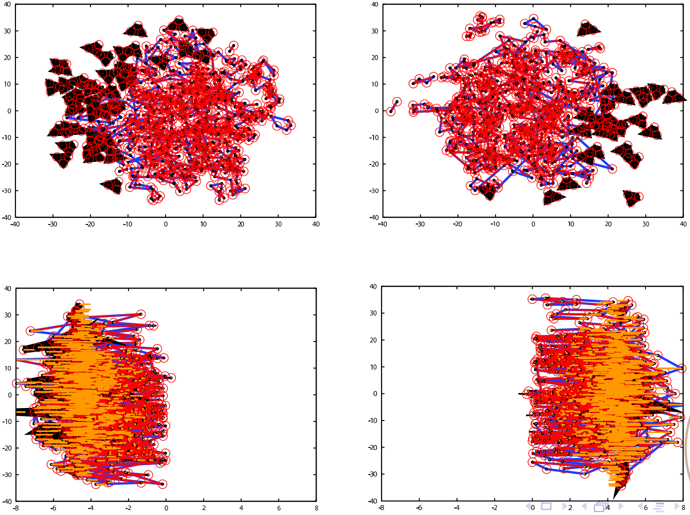

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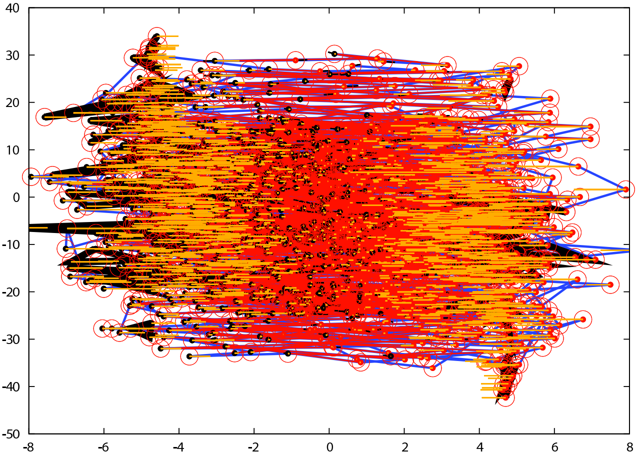

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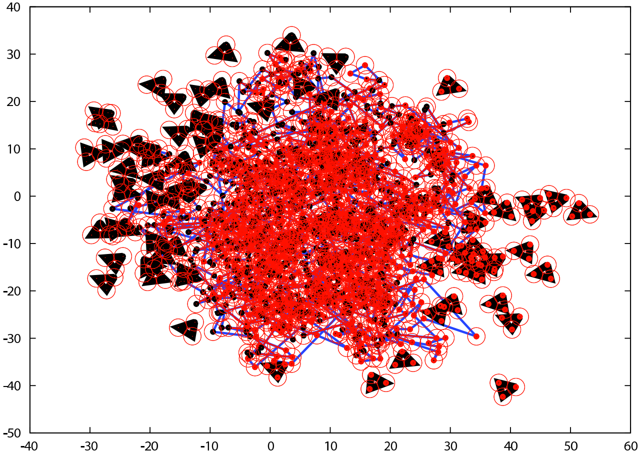


Color Glass Condesate (CGC)

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

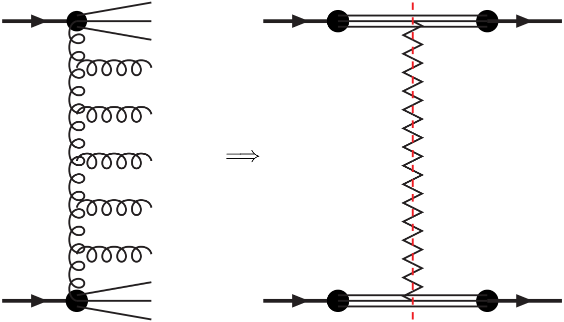
$$Q_{\rm sat} = Q_0^2 \left(\frac{x}{x_0}\right)^{\lambda}$$

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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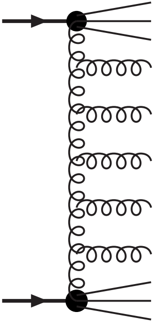
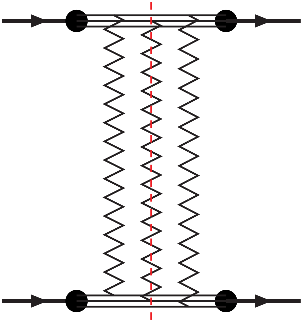


$\Longrightarrow$



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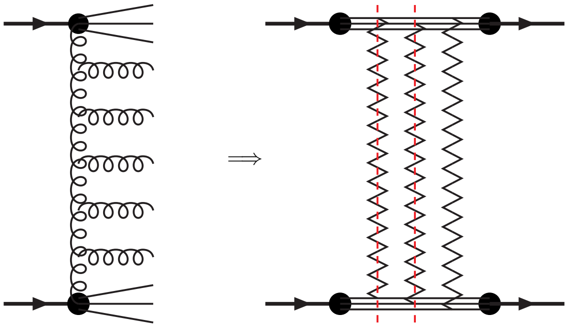

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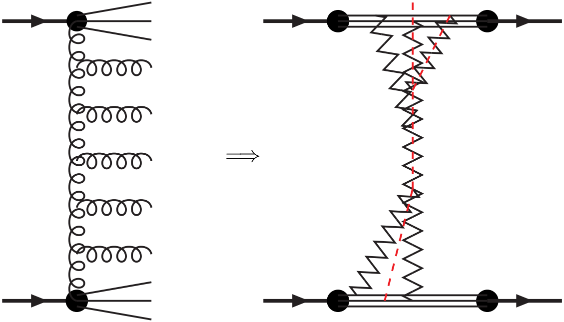
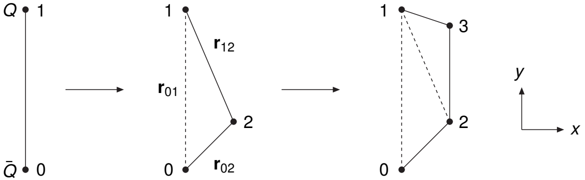


Each cut pomeron will give rise to a string (or two) spanned between two colliding nucleons, or between a nucleon and another Pomeron.

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:

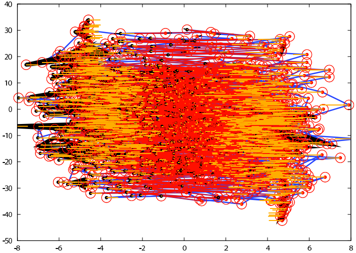
- $F = \sum_{ij} f_{ij} \qquad f_{(12)(34)} \propto \alpha_s^2 \ln^2\left(\frac{r_{13}r_{24}}{r_{14}r_{23}}\right)$
- Unitarize to get saturation effects $T = 1 - e^{-F}$

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.

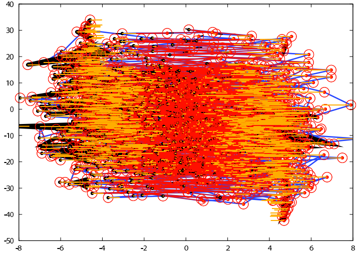
Models all kinds of fluctuations and correlations.

The Final State



Model each gluon/dipole individually?

The Final State



Model each gluon/dipole individually?

Or give up and use statistical methods?

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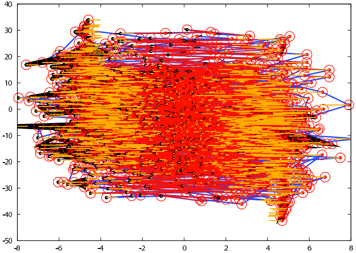

Model each gluon/dipole individually?

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 $\tau = \tau_0$:

$$
\begin{aligned}
T^{\mu\nu}(x) &= \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i) \\
N_q^\mu(x) &= \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i g(x - x_i)
\end{aligned}
$$

- $q_i = u, d, s$
- 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:

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

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Sorry, I don't understand this enough myself

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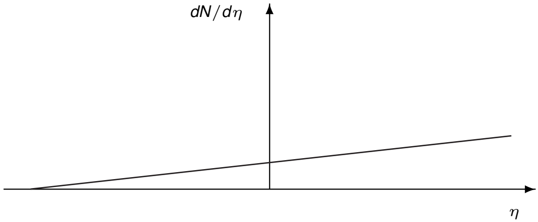
$$h_1 + h_2 \to h' \quad \text{or} \quad h_1 + h_2 \to h_1' + h_2'$$

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



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

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

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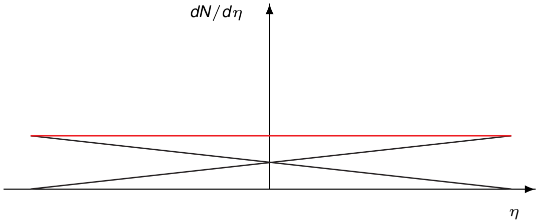

$$\frac{dN}{d\eta} = \quad F(\eta) + \quad F(-\eta) \qquad\qquad (\mathrm{pp})$$

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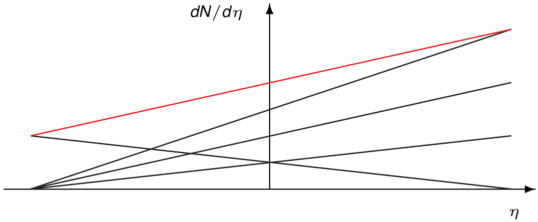

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (\mathrm{p}A)$$

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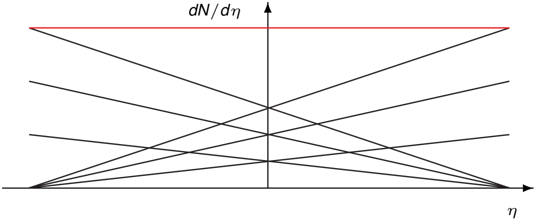


$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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

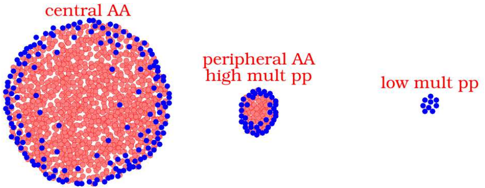
In Fritiof this was modelled by stretching out a string from each wounded nucleon with an invariant mass distributed as dm_X/m_X, which reproduces $F(\eta) \propto \eta - \eta_0$.

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

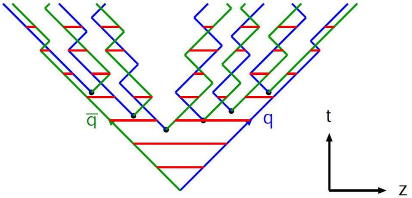
The EPOS generator uses a *Core–Corona* model:

- 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



Interacting Strings

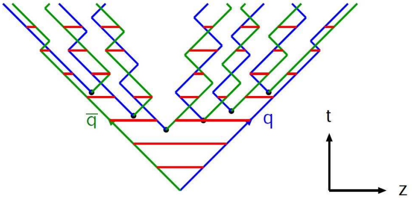
The Lund Model



- The tunnelling mechanism: $\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$
- The fragmentation function: $p(z) = N\frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$
- Many parameters depends (implicitly) on κ.

Interacting Strings

The Lund Model



- The tunnelling mechanism: $\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} \equiv e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$
- The fragmentation function: $p(z) = N\frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$
- Many parameters depends (implicitly) on κ.

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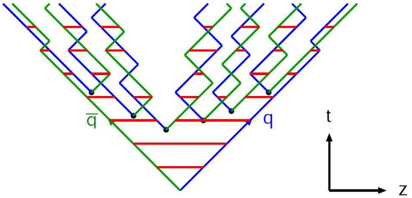

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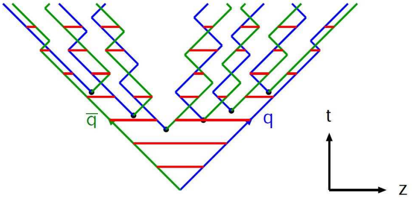

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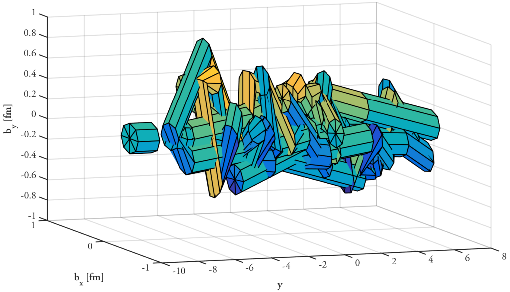
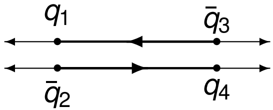
Overlapping strings

- How do we treat strings that overlap in space–time?



Take the simplest case of two simple, un-correlated, completely overlapping strings, with opposite colour flow.



- 1/9: A colour-singlet
- 8/9: A colour-octet

The string tension affects all details in the Lund string fragmentation.
It is proportional to the Casimir operator $C_2^{(8)} = \frac{9}{4} C_2^{(3)}$.

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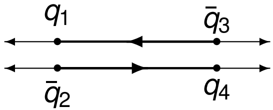

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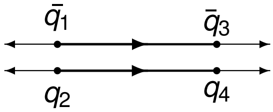
And for parallel colour flows:.



- 1/3: An anti-triplet
- 2/3: A sextet

$$C_2^{(6)} = \frac{5}{2} C_2^{(3)}$$

The anti-triplet case is related to string junctions and baryon production (popcorn mechanism).

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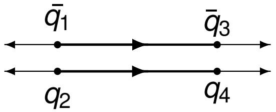

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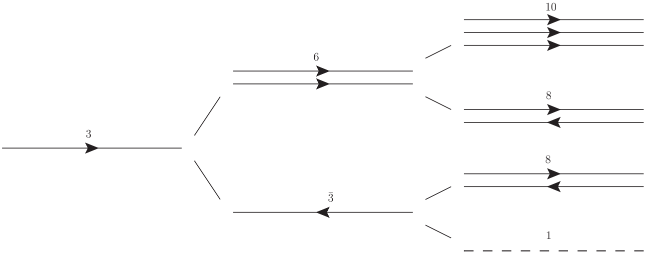
A random walk in colour-space



[Nucl.Phys.B254(1984)449]

The Rope Model

- Partially overlapping string pieces in impact parameter and rapidity.
- Reconnect to get colour singlets.
- Random walk for the rest to get higher colour multiplets (ropes).
- The rope will break one string at the time.
- Calculate an effective string tension of a break-up, e.g.
  - the first string to break in a sextet has an effective $\kappa_{\mathrm{eff}} \propto C_2^6 - C_2^3 = \frac{3}{2} C_2^3$
  - The second breakup has standard $\kappa \propto C_2^3$
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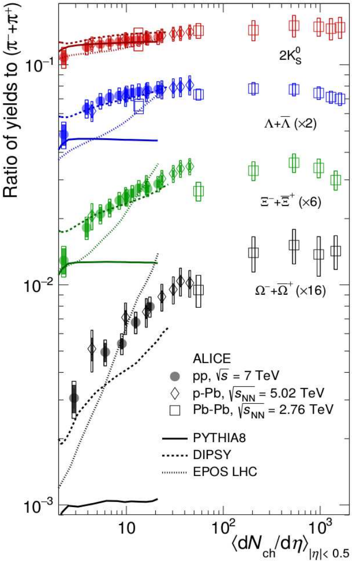
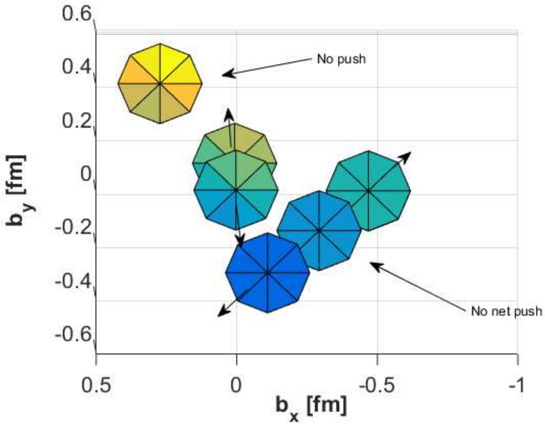

Ratio of yields to $(\pi^-+\pi^+)$
10^{-1}
10^{-2}
10^{-3}
10
10^2
10^3
$\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$
$2K^0_S$
$\Lambda+\overline{\Lambda}$ (×2)
$\Xi^-+\overline{\Xi}^+$ (×6)
$\Omega^-+\overline{\Omega}^+$ (×16)
ALICE
pp, $\sqrt{s}$ = 7 TeV
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
PYTHIA8
DIPSY
EPOS LHC

Will overlapping strings in high multiplets generate a transverse pressure?



[JETP Lett.47(1988)337]

Rope Shoving

- All strings are sliced into *dy* slices.
- In each (small) time–step *dt*, each string will get a kick from other strings:

$$\frac{dp_\perp}{dydt} = \frac{C_0 td}{R^2} \exp\left(-\frac{d^2}{2R^2}\right).$$

- Momentum conservation is observed.
- Transverse kicks resolved pairwise.
- Longitudinal recoil absorbed by kicking dipole.

"kick" $\rightarrow$ "kink" $=$ gluon

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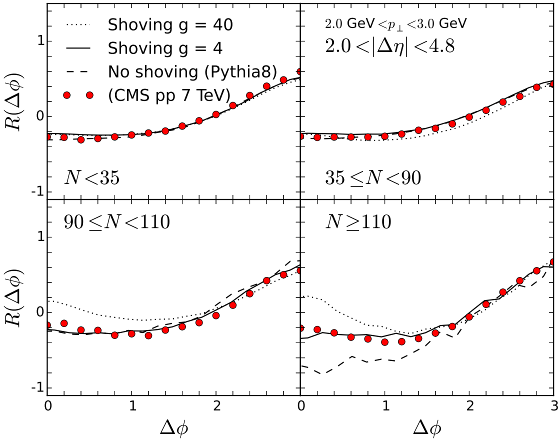
This could give rise to a Ridge!

"kick" $\rightarrow$ "kink" $=$ gluon


Shoving g = 40
Shoving g = 4
No shoving (Pythia8)
(CMS pp 7 TeV)
2.0 GeV <p⊥ <3.0 GeV
2.0 <|Δη| <4.8
N <35
35 ≤N <90
90 ≤N <110
N ≥110
R(Δφ)
Δφ
1
0
-1
2
3

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 $\mathrm{p}A$ or AA event and then hadronised.

  (No string interactions yet.)

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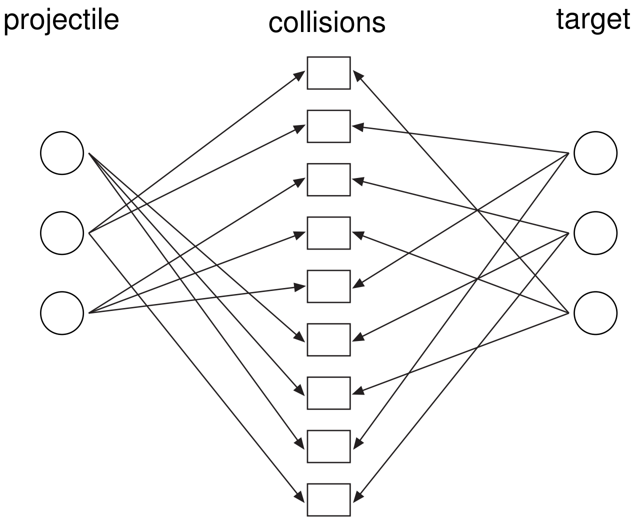
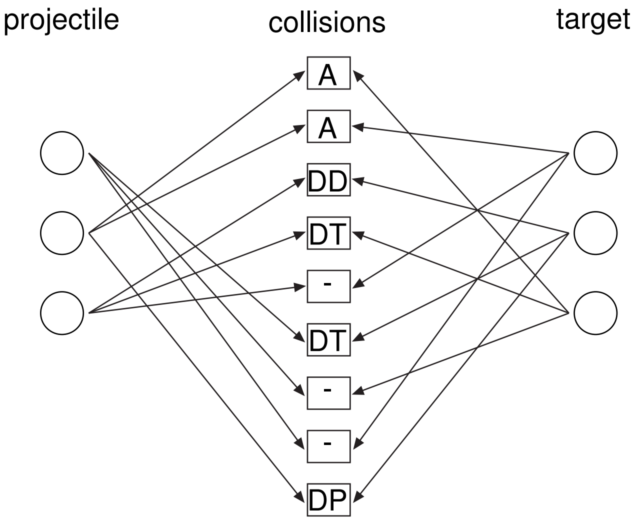
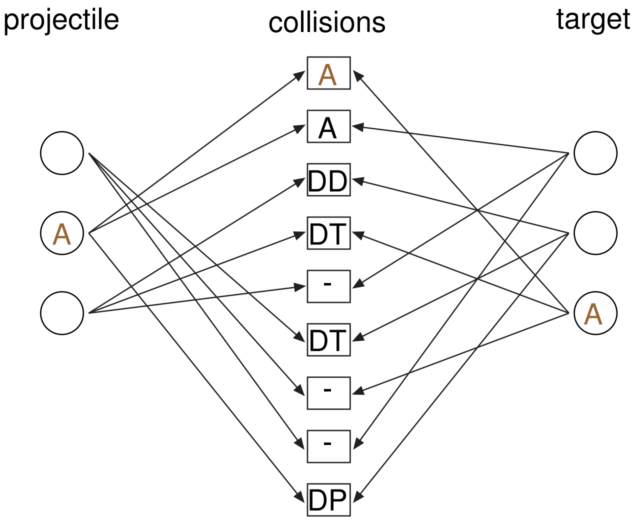
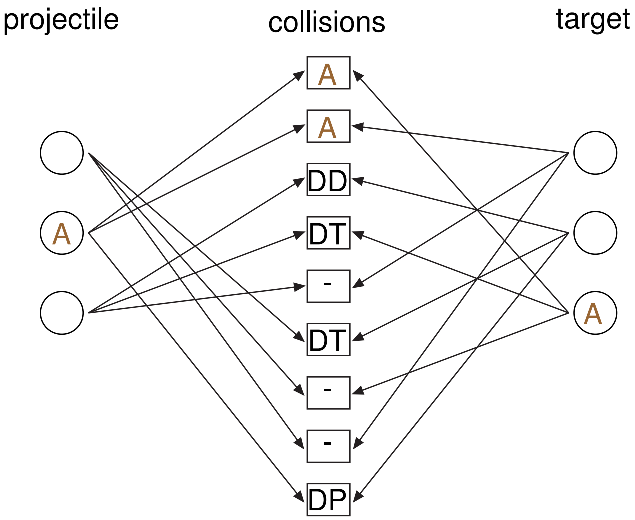
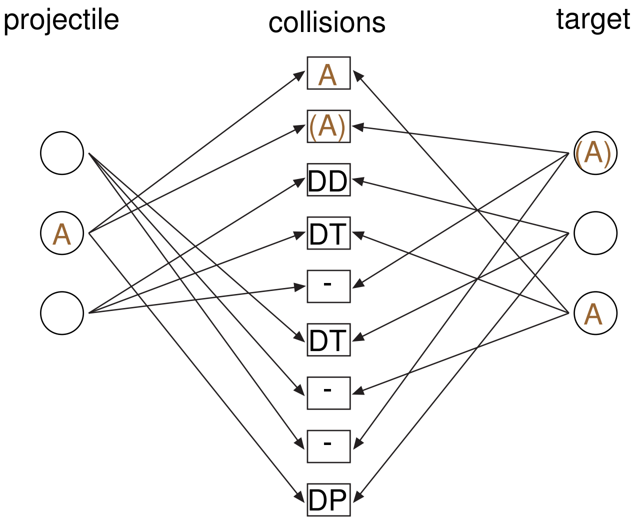
projectile target

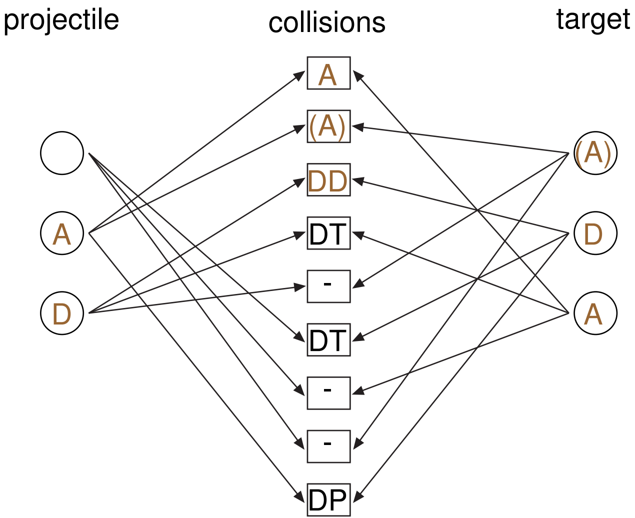

projectile
collisions
target


projectile
collisions
target
A
A
DD
DT
-
DT
-
-
DP


projectile
collisions
target
A
A
A
DD
DT
-
DT
-
-
DP
A


projectile
collisions
target
A
A
DD
DT
-
DT
-
-
DP
A
A


projectile
collisions
target
A
(A)
DD
DT
-
DT
-
-
DP
A
(A)
A


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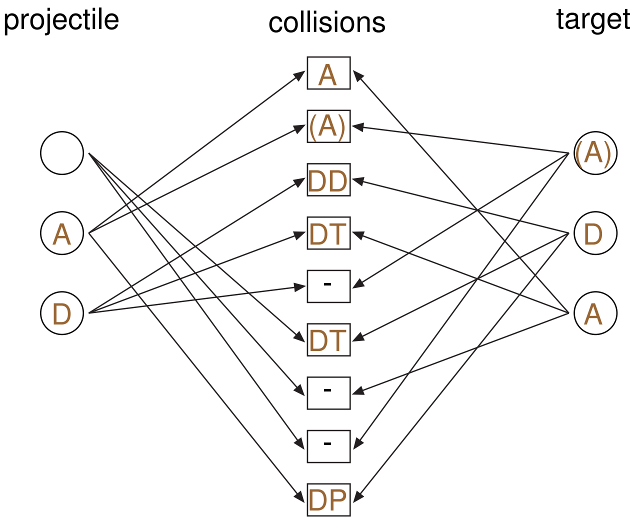
DP
A
D
(A)
D
A


projectile
collisions
target
A
(A)
DD
DT
-
DT
-
-
DP
A
D
(A)
D
A

Signal processes

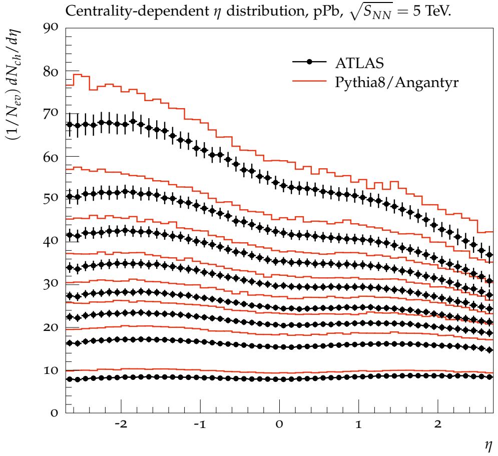
Not only min-bias. Rather than just generating non-diffractive events, The first absorptive sub-event can be generated using any hard process in PYTHIA8, giving the final event a weight $N_A\sigma_{hard}/\sigma_{ND}$.

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



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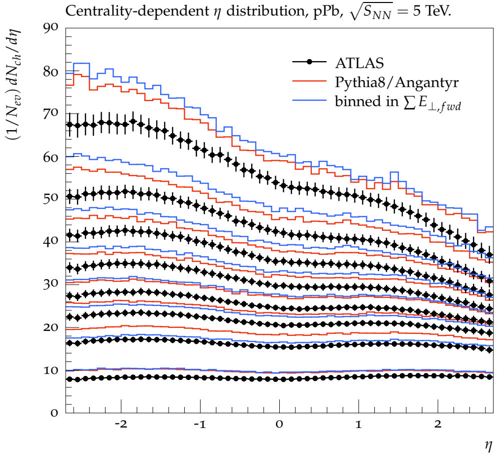
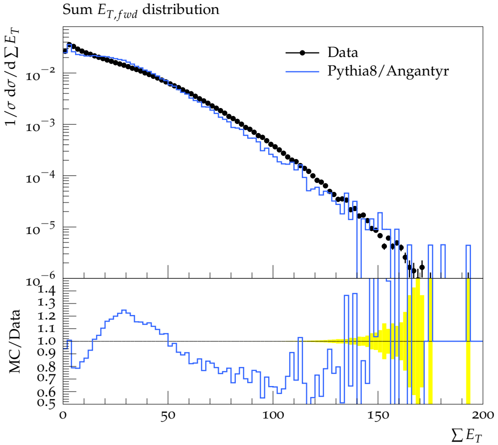


Centrality in pPb



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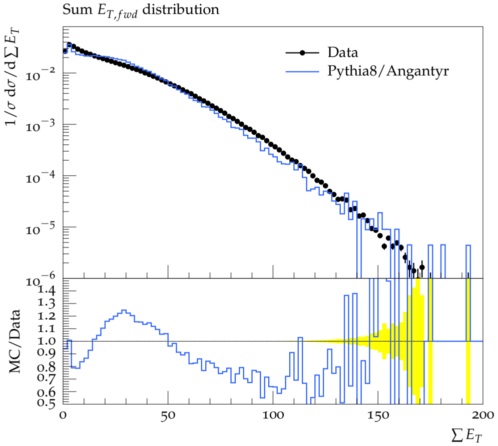
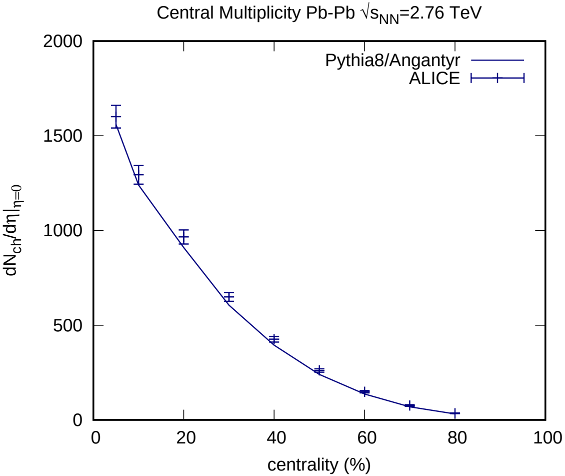


What was actually measured in the previous slide is a correlation between the η-distribution and the forward activity.

Central multiplicity in PbPb



Go generate youself!

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

Unfortunately no proper Rivet analysed available.

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