Heavy-Ion modelling with Angantyr

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Outline

- Introduction
- The **Angantyr** model
  - Glauber–Gribov modelling
  - Building Final states
- Towards the EIC

Fritiof vs. Angantyr

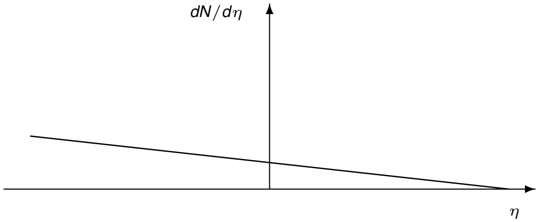
Fritiof

Fritiof vs. Angantyr

Wounded nucleons

A simple model by Białas and Czyż, implemented in Fritiof

Each wounded nucleon contributes according to a multiplicity 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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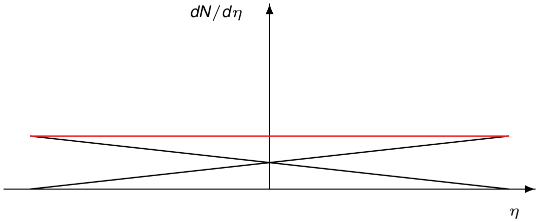

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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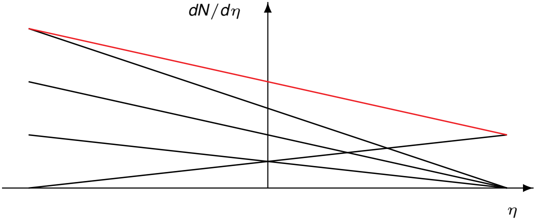

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (pA)$$

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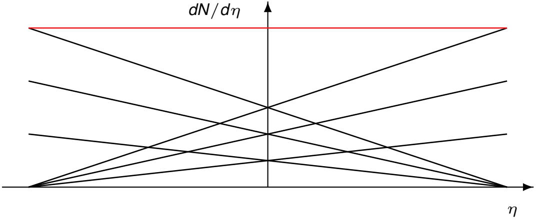

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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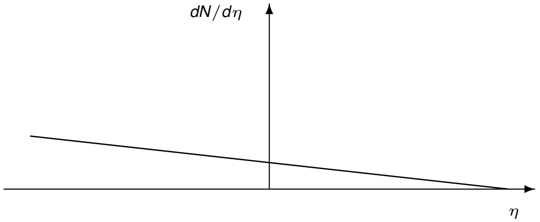

$$\frac{dN}{d\eta} = \quad F(\eta)$$

Fritiof: single string dM_X^2/M_X^2

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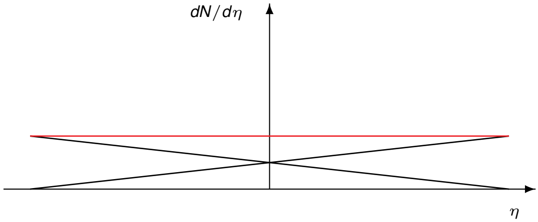

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Fritiof: pp

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How will Angantyr kill Fritiof?

- Improve Glauber calculation by including fluctuations
- Use Good – Walker picture, where fluctuation ⇔ diffractive excitation, for detailed modelling of semi-inclusive *NN* cross sections.
- Use the full PYTHIA8 MPI machinery for wounded nucleons modelled as (high mass) diffraction events.
- Identify primary ND sub-collisions models with the full PYTHIA8 ND pp machinery.
- Include collective effects

[arXiv:1607.04434]

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Standard Glauber modelling

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 $= 0$

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

Fitted to low-energy eA data.

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

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 are within a distance $d = \sqrt{\sigma/2\pi}$ from any of the projectile nucleons. (Gives you N_{coll} and N_{part}.)

Good–Walker

Assume that a projectile with some kind of internal structure interacts with a structureless target. The projectile can have different mass-eigenstates, Ψ_i, 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

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

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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

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

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

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

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.

$$\frac{d\sigma^{\mathrm{NN}}_{\mathrm{Dp}}(b)}{d^2\vec{b}} = \langle\langle T(b)\rangle^2_t\rangle_p - \langle\langle T(b)\rangle_t\rangle^2_p$$

$$\frac{d\sigma^{\mathrm{NN}}_{\mathrm{Dt}}(b)}{d^2\vec{b}} = \langle\langle T(b)\rangle^2_t\rangle_p - \langle\langle T(b)\rangle_p\rangle^2_t$$

$$\frac{d\sigma^{\mathrm{NN}}_{\mathrm{DD}}(b)}{d^2\vec{b}} = \langle\langle T(b)^2\rangle_t\rangle_p - \langle\langle T(b)\rangle^2_p\rangle_t - \langle\langle T(b)\rangle^2_t\rangle_p + \langle\langle T(b)\rangle_t\rangle^2_p$$

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

$$\frac{d\sigma^{\mathrm{NN}}_{\mathrm{w,t}}(b)}{d^2\vec{b}} = \frac{d\sigma^{\mathrm{NN}}_{\mathrm{abs}}(b)}{d^2\vec{b}} + \frac{d\sigma^{\mathrm{NN}}_{\mathrm{DD}}(b)}{d^2\vec{b}} + \frac{d\sigma^{\mathrm{NN}}_{\mathrm{Dt}}(b)}{d^2\vec{b}}$$
$$= \frac{d\sigma^{\mathrm{NN}}_{\mathrm{tot}}(b)}{d^2\vec{b}} - \frac{d\sigma^{\mathrm{NN}}_{\mathrm{el}}(b)}{d^2\vec{b}} - \frac{d\sigma^{\mathrm{NN}}_{\mathrm{Dp}}(b)}{d^2\vec{b}}$$
$$= 2\langle T(b)\rangle_{tp} - \langle\langle T(b)\rangle_t^2\rangle_p$$

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

A first implementation of this by Strikman et al. assumed 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

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

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

[Strikman et al. hep-ph/1301.0728]

In Angantyr we instead have separately fluctuating projectile and target:

$$P(r_{p/t}) = \frac{r_{p/t}^{k-1} e^{-\beta r_{p/t}} \beta^k}{\Gamma(k)}$$

with an amplitude

$$T(\boldsymbol{b}, r_p, r_t) = T_0(r_p + r_t)\Theta\left(\sqrt{\frac{(r_p + r_t)^2}{2T_0}} - b\right).$$

where the opacity of the semi-transparent disk now depends on r_p and r_t:

$$T_0(r_p + r_t) = \left(1 - \exp\left(-\pi(r_p + r_t)^2/\sigma_t\right)\right)^{\alpha}.$$

The fluctuation parameters ($k, \beta, \alpha, \sigma_0$) can now be fitted to reproduce (measured) semi-inclusive *NN* cross sections (total, elastic, non-diffractive, wounded target/projectile).

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In an *AA* we can then generate an *r* for each projectile and target nucleon and for each pair we can calculate the probability for non-diffractive scattering.

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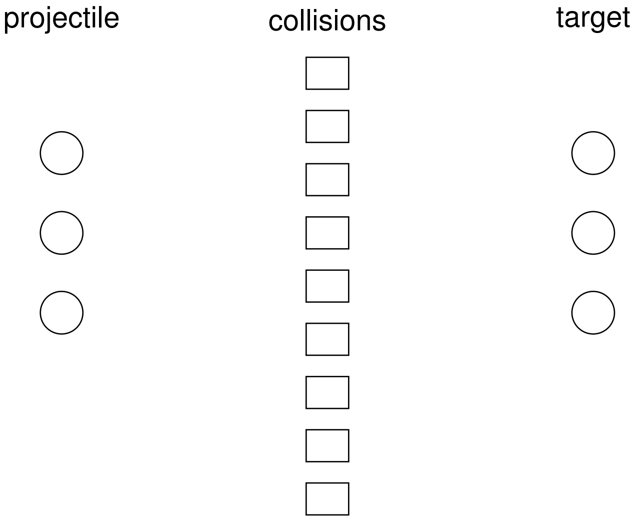
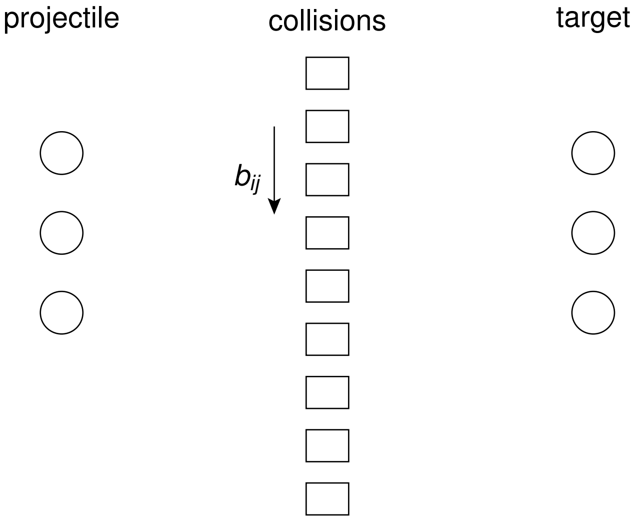
In an *AA* we can then generate an r for each projectile and target nucleon and for each pair we can calculate the probability for non-diffractive scattering.

Since the probability of diffractive excitation depends on the fluctuations we also generate an auxiliary r' to gauge the these.

In this way we can for each pair determine **if** they interact, but also **how** they interact.


projectile
target


projectile
collisions
target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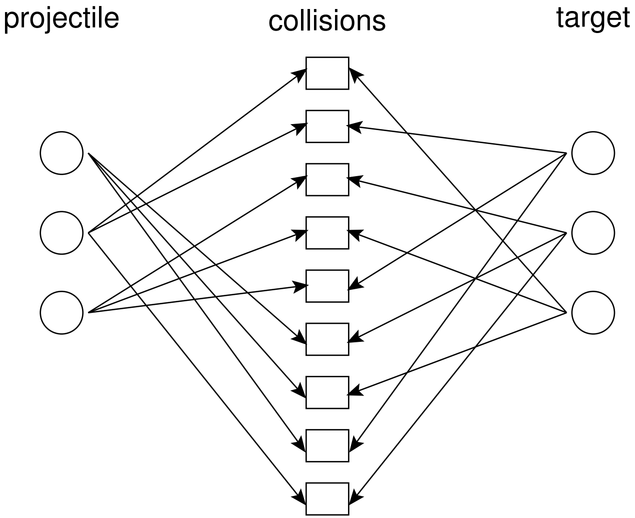
collisions
target
b_{ij}


projectile
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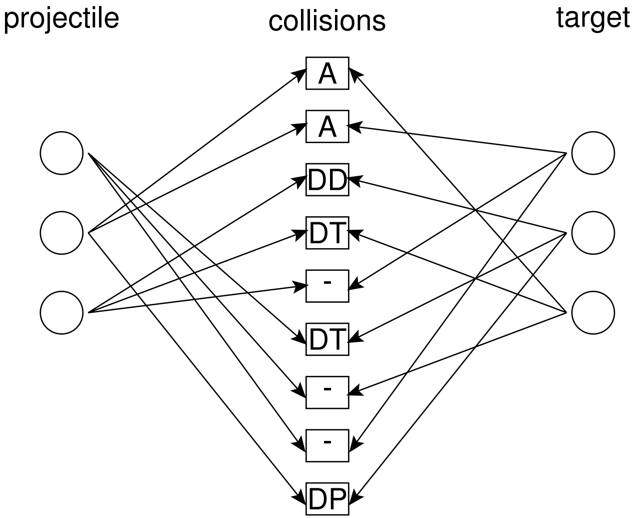
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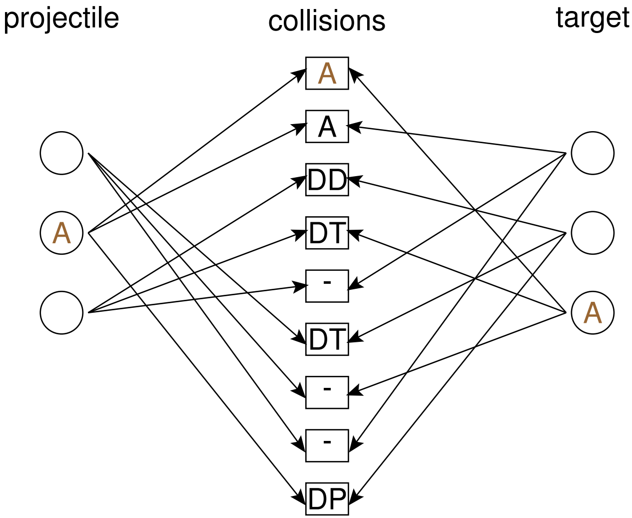
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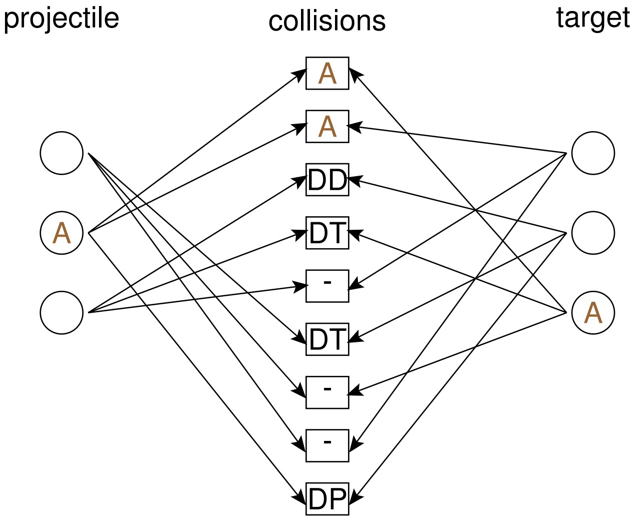
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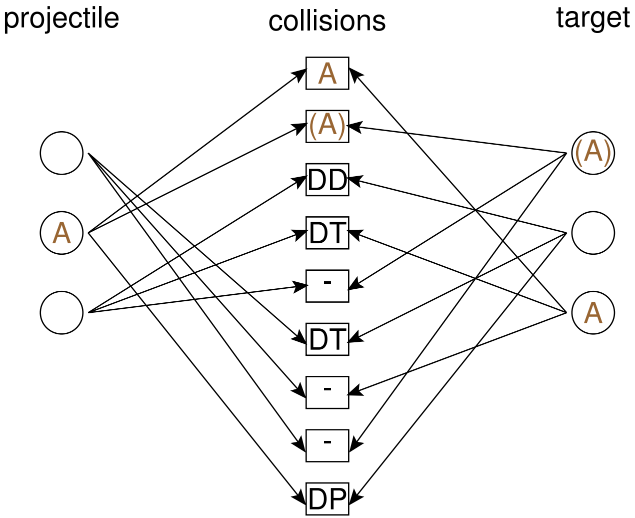
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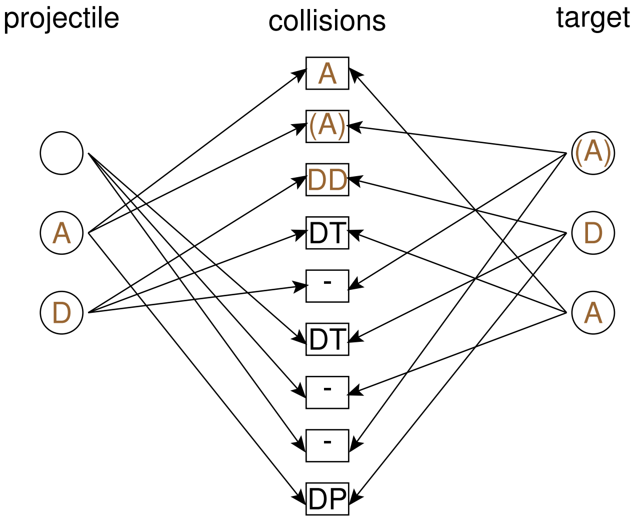
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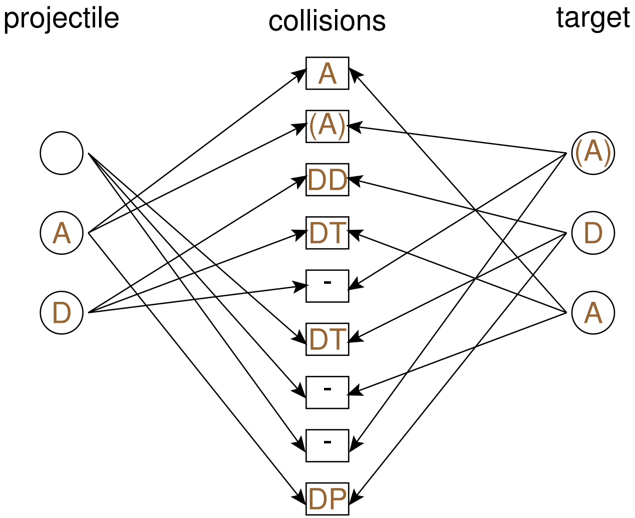
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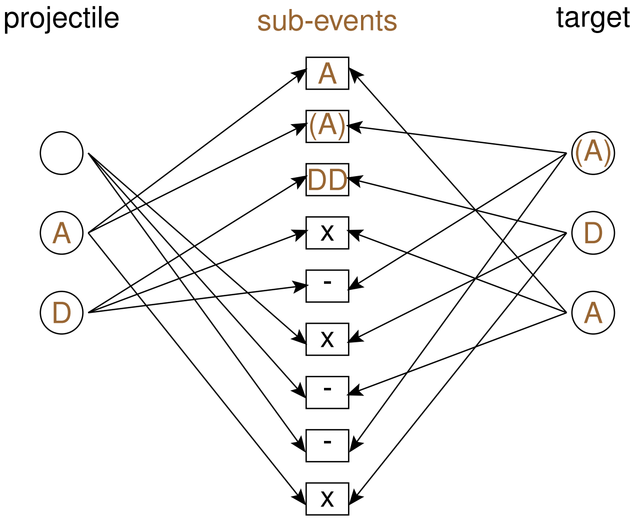
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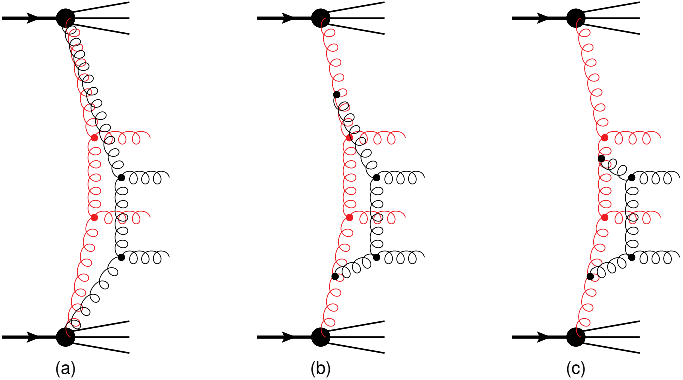
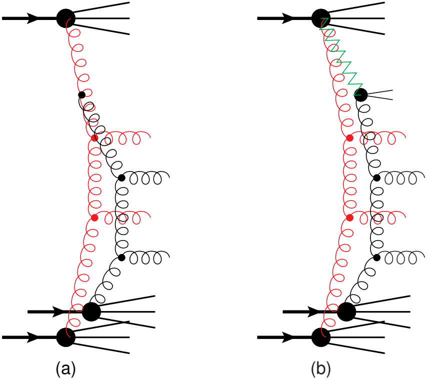
Building Final States

Angantyr builds up the final state of *AA* collisions by simply stacking *NN* collisions from PYTHIA on top of each other.

- Full non-diffractive *NN* collisions.
- *Secondary* non-diffractive *NN*
- Diffractive excitation (single and double)
- (elastic)


(a)
(b)
(c)


(a)
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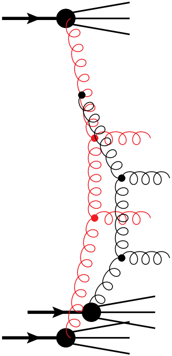

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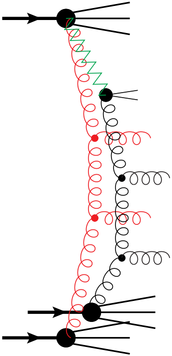

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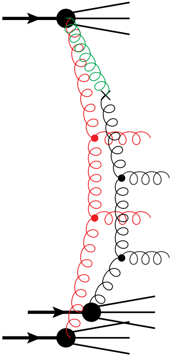
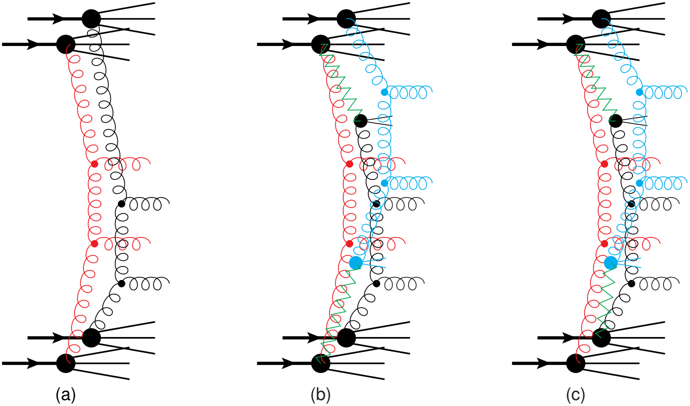


(upcoming)


(a)
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The Angantyr model for heavy-ion collisions

- Glauber modelling with fluctuations
  Identify *NN* sub-collisions
  - Which nucleons interact with which?
  - How do they interact?
  - Primary and secondary sub-collisions.
- Generate *NN* sub-events using the full PYTHIA8 MPI machinery.
  - Use generated *b* for MPI.
  - Insert signal processes if required.
- Merge parton-level sub-events together.
- Hadronise.

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Complete, fully exclusive hadronic heavy-ion final states.

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 for given $\sqrt{s_{NN}}$.
- Diffractive parameters for secondary absorptive collisions, "tuned" to non-diffractive PYTHIA pp.
  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 related energy momentum conservation which do not have large impact.

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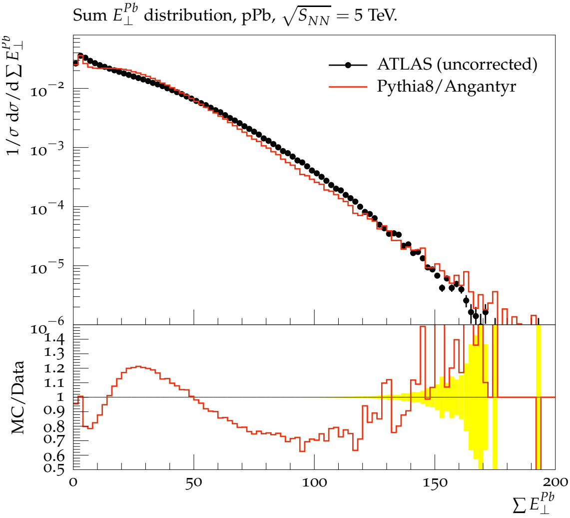
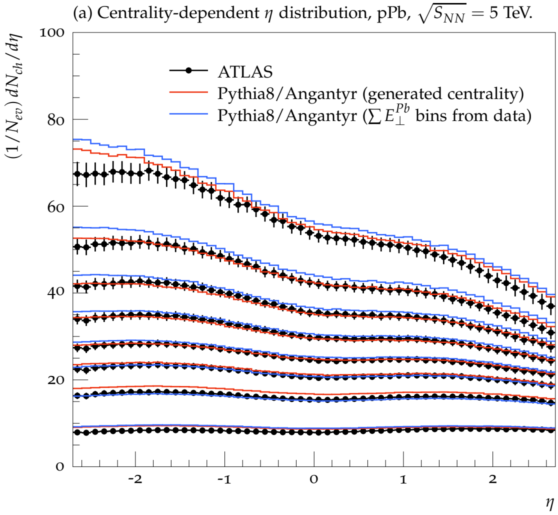
p–Pb centrality



[arXiv:1508.00848]

p–Pb η-distribution



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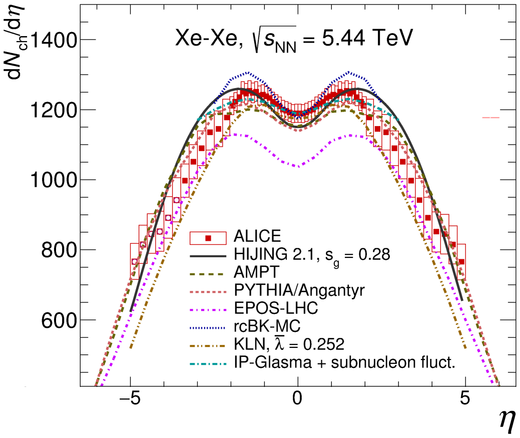
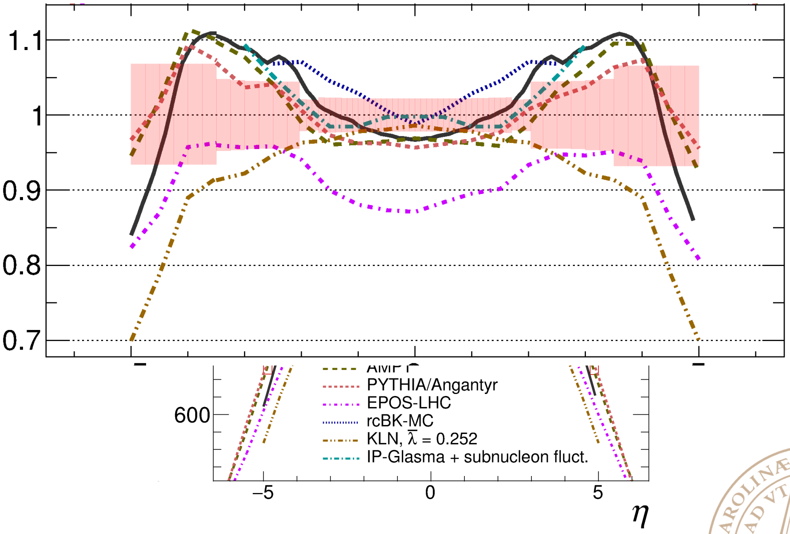
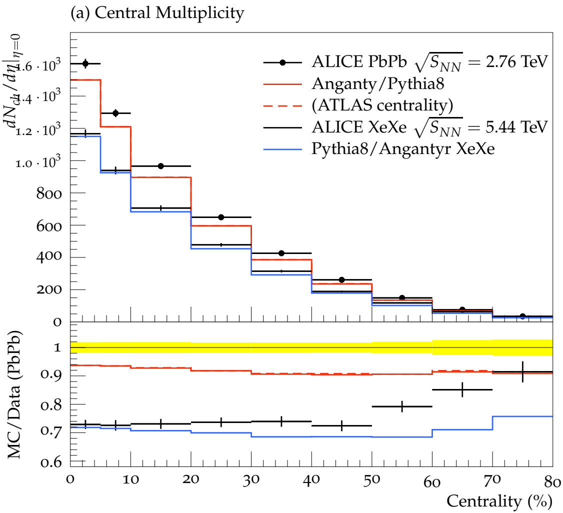


[arXiv:1805.04432]



[arXiv:1805.04432]

Pb–Pb central multiplicity



[arXiv:1012.1657]

Angantyr and the EIC

Angantyr and the EIC

- We need $eA \Longrightarrow \gamma^{(\star)}A \longrightarrow [q-\bar{q}]A$
- We need $[q-\bar{q}]N$ cross sections
- Fluctuations in these cross sections are important (c.f. $\mathrm{p}A$)
- We need to model (multiple) $[q-\bar{q}]N$ final states both DIS- and VMD-like dipoles
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Angantyr and the EIC

- We need e$A \Longrightarrow \gamma^{(\star)}A \longrightarrow [q-\bar{q}]A$
- We need $[q-\bar{q}]N$ cross sections
- Fluctuations in these cross sections are important (c.f. $\mathrm{p}A$)
- We need to model (multiple) $[q-\bar{q}]N$ final states
  both DIS- and VMD-like dipoles
- We need collective effect

Conclusions

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- Any AA' collision (and many hA) can be modelled
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Thanks!

Questions?

Taxi?