LUND UNIVERSITY

ANGANTYR

Heavy ions in Pythia8

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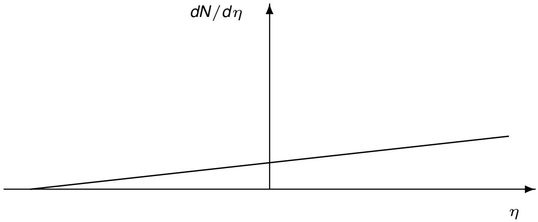
Outline

- Fritiof
- Multi-parton interactions
- New Glauber models
- Angantyr vs. LHC
- Summary

The Wounded Nucleon model and Fritiof

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



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

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

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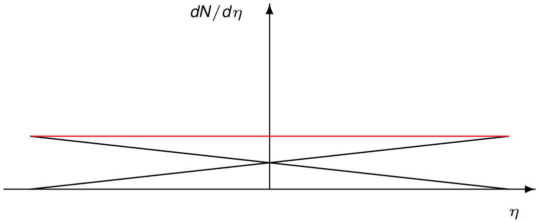

$$\frac{dN}{d\eta} = \quad F(\eta) + \quad F(-\eta) \qquad\qquad \text{(pp)}$$

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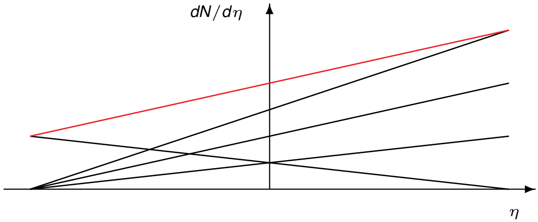

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (\mathrm{p}A)$$

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

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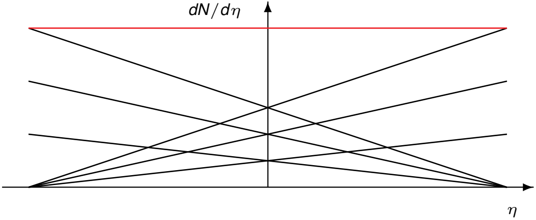

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

[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. (c.f. high-mass diffraction).

Each string gives a flat rapidity distribution, so This gives $F(\eta) \sim \eta - \eta_0$.

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

What's missing in Fritiof?

- QGP?
- Jets
- Multi-parton interactions
- Initial state fluctuations
- Interactions between strings

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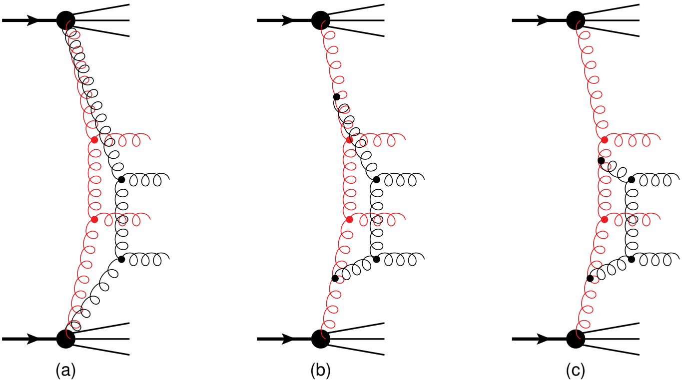
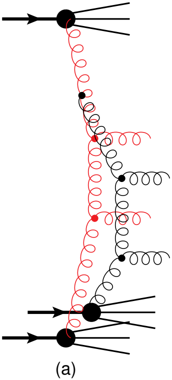
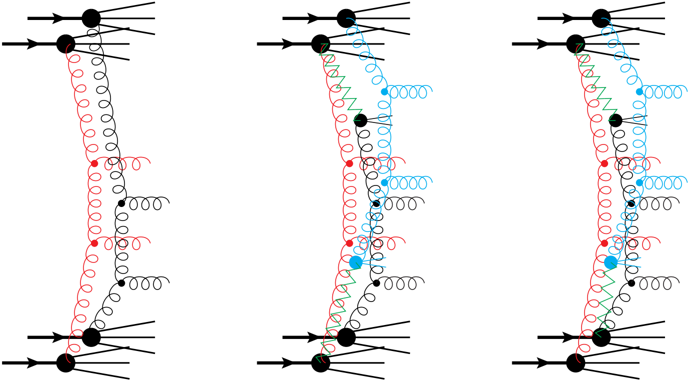
Multiple interactions in pp



MPI in pA



MPI in *AA*



(a) (b) (c)

Primary *NN* collisions should be treated as normal pp events Pythia, including MPI.

Secondary collisios can be treated *as if* they are diffractive scatterings, using Pythia's pomeron–proton machinery, including MPI.

We can also have primary diffractive collisions.

Initial state fluctuations

Understanding initial state fluctuations is important for inferring correctly the number of collisions and wounded nucleons from a centrality estimator.

It is also important for understanding the contribution from *NN* collisions.

Fluctuations in the initial state is fundamentally connected to Diffraction.

Good & Walker (Pumplin & Miettinen)

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

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

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.

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

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

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

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

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

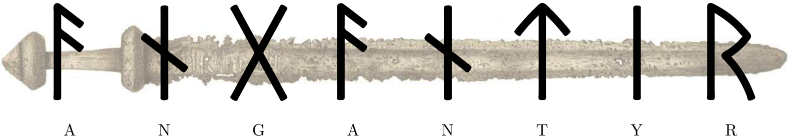
and thus only depends on the fluctuations in the projectile, but only on average properties of the target itself.

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

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

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

Angantyr: Heavy Ions in PYTHIA8



Angantyr: Heavy Ions in PYTHIA8

- Glauber model with advanced fluctuation treatment
  - Similar to Strikman's *colour fluctuations* but fluctuations in both projective and target, rather than in *NN* cros section.
- 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 pA or AA event and then hadronised.

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Signal processes

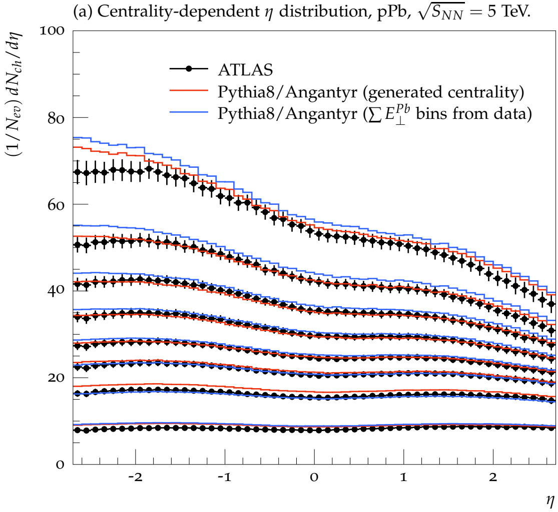
Not only min-bias. Rather than just generating non-diffractive events, The first absorptive sub-event can be generated using any hard process in PYTHIA8, giving the final event a weight $N_A\sigma_{hard}/\sigma_{ND}$.

Comparison to data

Several parameters in addition to the pp PYTHIA8 ones.

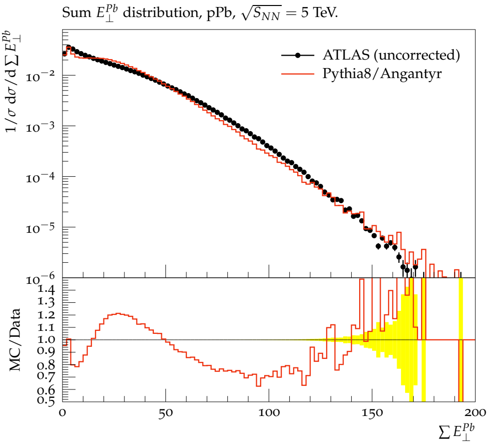
- Nucleon distributions can in principle be measured independently.
- *NN* cross section fluctuations are fitted to (semi-) inclusive pp cross sections (total, non-diffractive, single and double diffractive, elastic, and elastic slope) for given $\sqrt{s_{NN}}$.
- Diffractive parameters for secondary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



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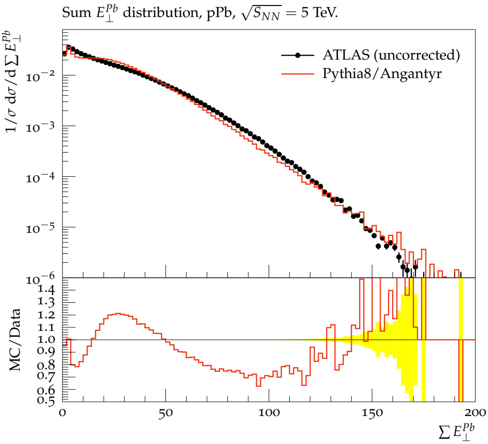
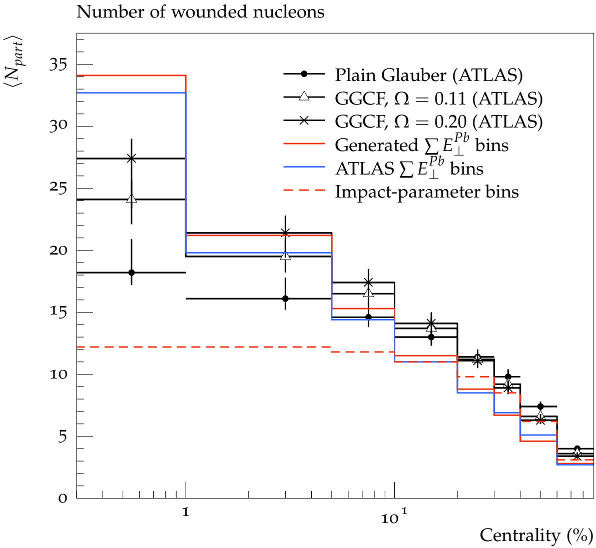
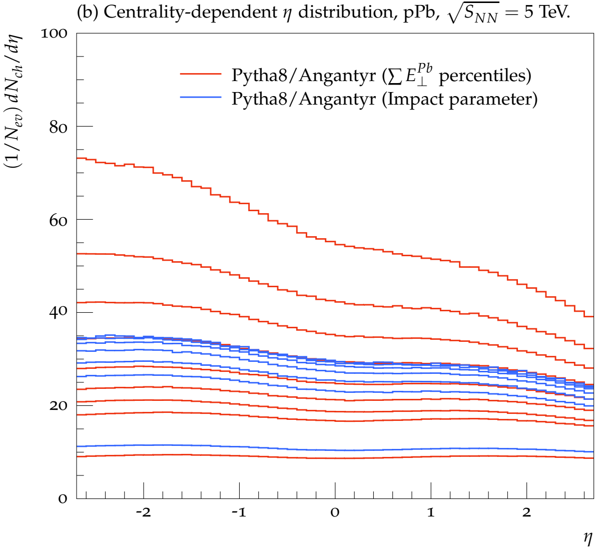


What was actually measured in the previous slide is a correlation between the η-distribution and the forward activity.

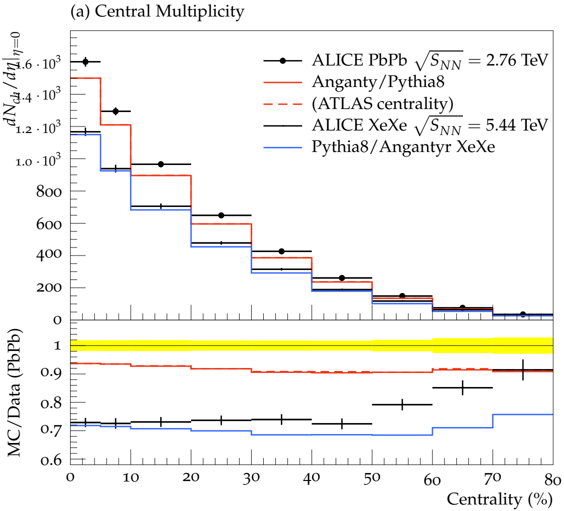
p–Pb number of participants

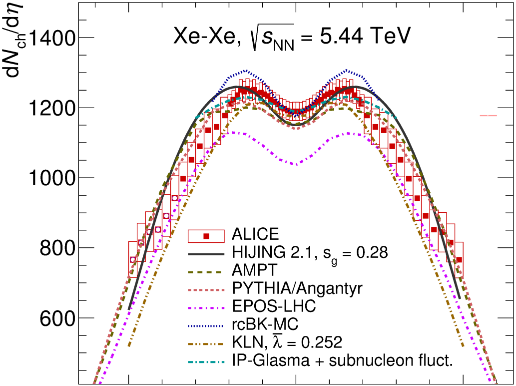


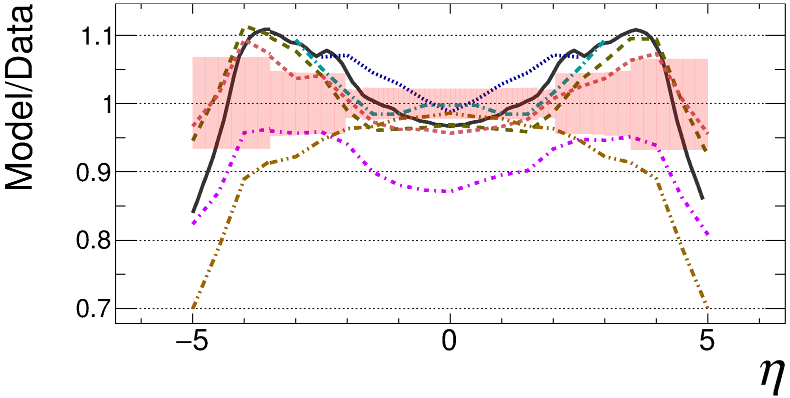
p–Pb η-distribution

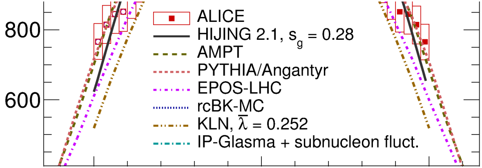


Central multiplicity in PbPb and XeXe



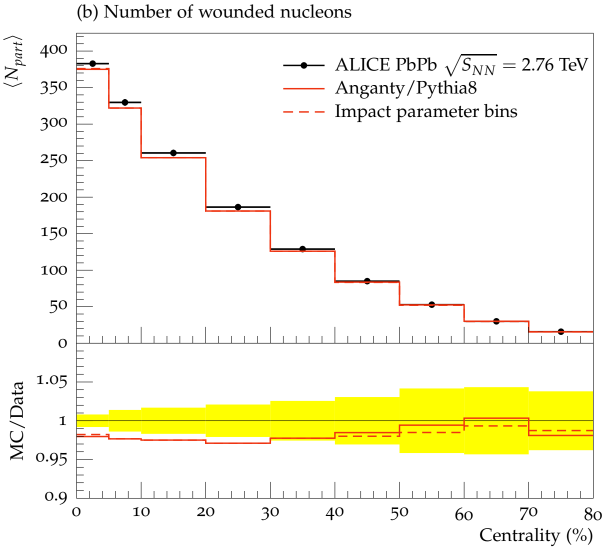

Xe-Xe, $\sqrt{s_{NN}}$ = 5.44 TeV
$dN_{ch}/d\eta$
1400
1200
1000
800
600
ALICE
HIJING 2.1, s_g = 0.28
AMPT
PYTHIA/Angantyr
EPOS-LHC
rcBK-MC
KLN, $\bar{\lambda}$ = 0.252
IP-Glasma + subnucleon fluct.





[arXiv:1805.04432]

Pb–Pb number of participants



Go generate yourself!

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

Maybe already this evening.

Go generate yourself!

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

Maybe already this evening.

Jets? No problem!

```
pythia.readString("HardQCD:all = on"");
pythia.readString("PhaseSpace:pTHatMin = 20");
```

Summary

- Angantyr makes a naive(?) extrapolation of PYTHIA8 from pp to p*A* and *AA*
- Includes fluctuations in Glauber simulation
- Includes jets and multiple interactions
- Does **not** include string interactions yet

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Outlook

We have three models for string interactions

- Colour reconnections (Swing)
- String *Shoving*
- *Rope* hadronisation

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All give "collective" modifications in pp with promising results.

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Currently being implemented for HI

Thanks!

Vetenskapsrådet

MCnet
Marie Curie Actions
Human resources and mobility

European Research Council
Established by the European Commission

Knut and Alice Wallenberg Foundation

CLASH

Rivet (since v2.7.0)

```
rivet PBPBMINBIAS.hepmc -a ALICE_2015_PBPBCentrality -o CentCalib.yoda
```

Rivet (since v2.7.0)

```
rivet PBPBMINBIAS.hepmc -a ALICE_2015_PBPBCentrality -o CentCalib.yoda
rivet PbPb-kt1-1.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-1.yoda
rivet PbPb-kt1-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-2.yoda
...
rivet PbPb-kt2-1.hepmc -p CentCalib -a ALICE_2012_I930312.yoda:cent=GEN -o PbPb-kt2-1.yoda
rivet PbPb-kt2-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt2-2.yoda
...
```

`cent=GEN` means centrality based on generated centrality observable (`IMP` would mean generated impact parameter)

Rivet (since v2.7.0)

```
rivet PBPBMINBIAS.hepmc -a ALICE_2015_PBPBCentrality -o CentCalib.yoda
rivet PbPb-kt1-1.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-1.yoda
rivet PbPb-kt1-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-2.yoda
...
rivet PbPb-kt2-1.hepmc -p CentCalib -a ALICE_2012_I930312.yoda:cent=GEN -o PbPb-kt2-1.yoda
rivet PbPb-kt2-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt2-2.yoda
...
rivet-merge -e PbPb-kt1-?.yoda -o PbPb-kt1.yoda
rivet-merge -e PbPb-kt2-?.yoda -o PbPb-kt2.yoda
...
```

`-e` indicates that the samples in the different files are equivalent.

Rivet (since v2.7.0)

```
rivet PBPBMINBIAS.hepmc -a ALICE_2015_PBPBCentrality -o CentCalib.yoda
rivet PbPb-kt1-1.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-1.yoda
rivet PbPb-kt1-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-2.yoda
...
rivet PbPb-kt2-1.hepmc -p CentCalib -a ALICE_2012_I930312.yoda:cent=GEN -o PbPb-kt2-1.yoda
rivet PbPb-kt2-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt2-2.yoda
...
rivet-merge -e PbPb-kt1-?.yoda -o PbPb-kt1.yoda
rivet-merge -e PbPb-kt2-?.yoda -o PbPb-kt2.yoda
...
rivet-merge PbPb-kt?.yoda -o PbPb.yoda
```

`-e` indicates that the samples in the different files are equivalent.
without `-e` indicates that the samples are non-overlapping

Rivet (since v2.7.0)

```
rivet PBPBMINBIAS.hepmc -a ALICE_2015_PBPBCentrality -o CentCalib.yoda
rivet PbPb-kt1-1.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-1.yoda
rivet PbPb-kt1-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt1-2.yoda
...
rivet PbPb-kt2-1.hepmc -p CentCalib -a ALICE_2012_I930312.yoda:cent=GEN -o PbPb-kt2-1.yoda
rivet PbPb-kt2-2.hepmc -p CentCalib.yoda -a ALICE_2012_I930312:cent=GEN -o PbPb-kt2-2.yoda
...
rivet-merge -e PbPb-kt1-?.yoda -o PbPb-kt1.yoda
rivet-merge -e PbPb-kt2-?.yoda -o PbPb-kt2.yoda
...
rivet-merge PbPb-kt?.yoda -o PbPb.yoda
rivet-merge PbPb.yoda pp.yodao -o final.yoda
rivet-mkhtml final.yoda
```

`rivet-mkhtml` produces a web page with all the plots.