Collectivity in Hadronic Collisions from final-state string dynamics

Leif Lönnblad

Department Physics
Lund University

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Collectivity and Strings

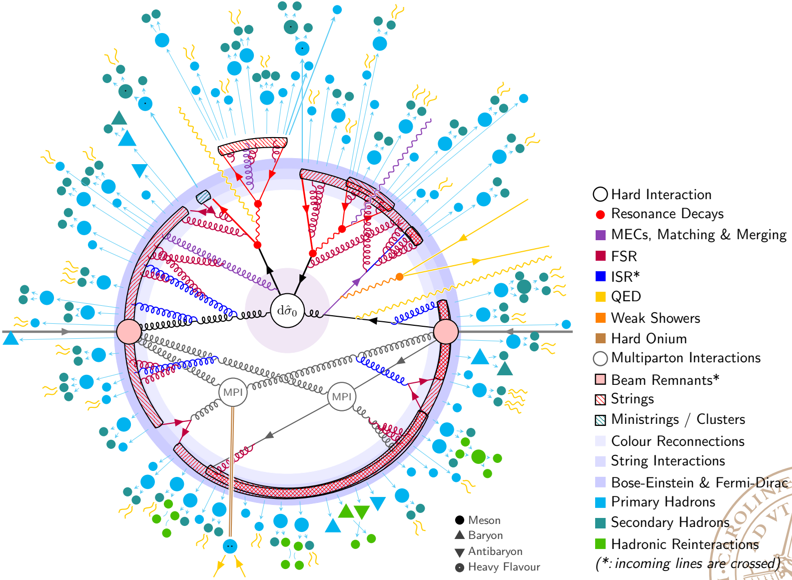
- Heavy Ions in PYTHIA8: Angantyr
- Strings
  - in vacuum
  - in a dense system
- String interactions: Gleipnir
  - Colour reconnections
  - String repulsion
  - Rope hadronisation

Angantyr: Heavy Ions in PYTHIA8

PYTHIA8 describes a wide range of pp measurements from the LHC and elsewhere.

Can we describe Heavy Ion Collisions by just stacking a bunch of pp events on top of each other?

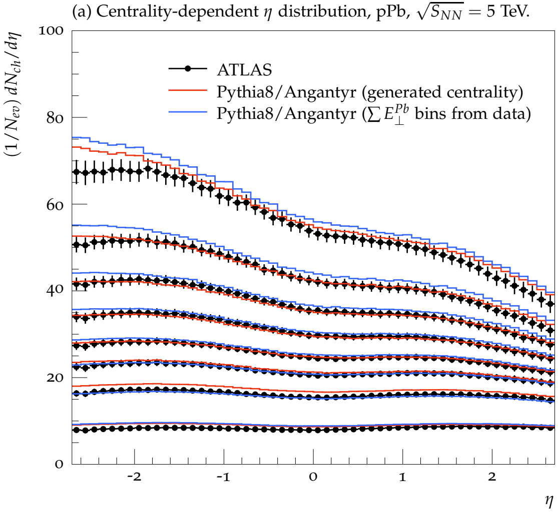
[arXiv:1607.04434, arXiv:1806.10820]



[arXiv:2203.11601]

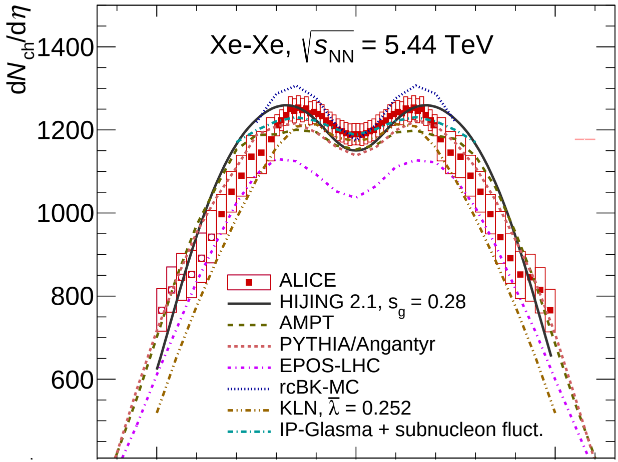
- Glauber calculation including Glauber–Gribov-like fluctuations
- Special treatment of multiple inelastic non-diffractive scattering, giving Nuclear shadowing
- Standard PYTHIA8 Multi-parton interactions (including *saturation*)
- Standard PYTHIA8 String fragmentation

It works!



[arXiv:1508.00848]

It works even in AA!



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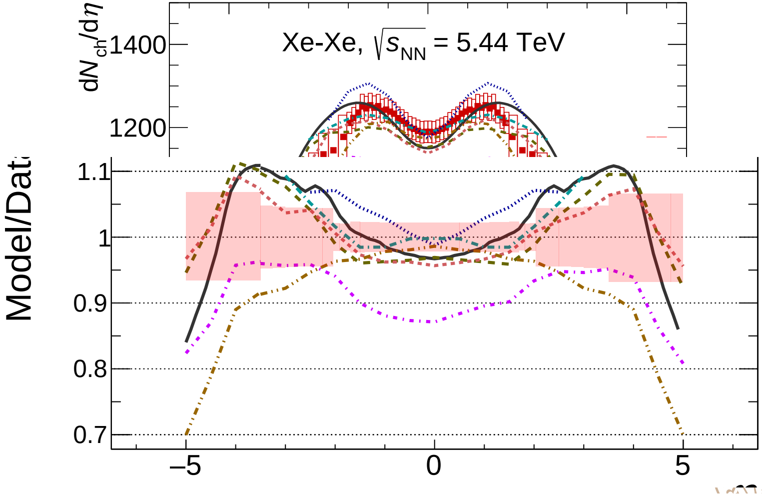

Where is the Quark-Gluon Plasma?

There is NO Quark-Gluon Plasma!

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There is only

- Multi-parton interaction with (semi-)hard scattering
- parton showers
- and string fragmentation

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But where is the collectivity?

String fragmentation

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

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

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

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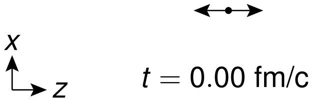

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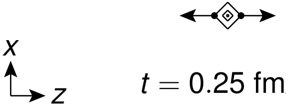

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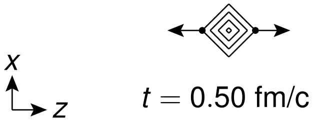

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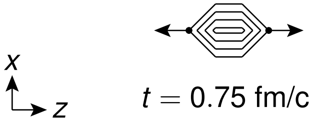
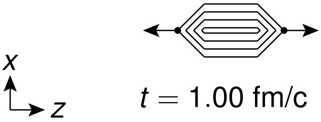


$t = 0.75$ fm/c

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



$t = 1.00$ fm/c

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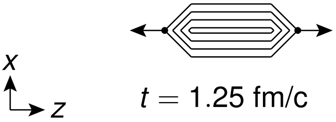

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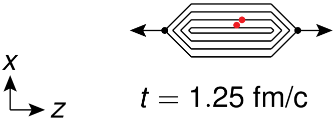
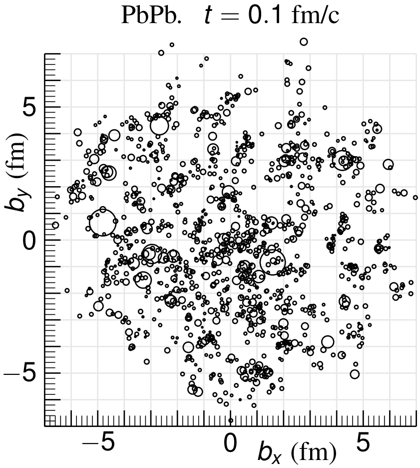
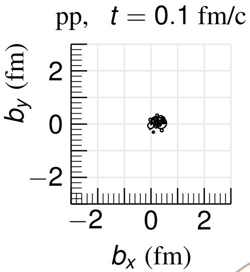
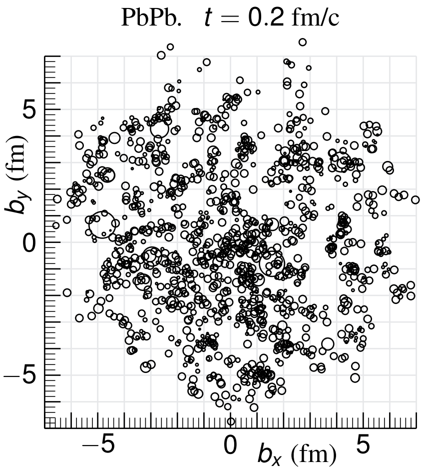
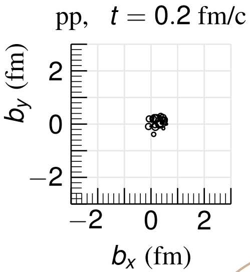
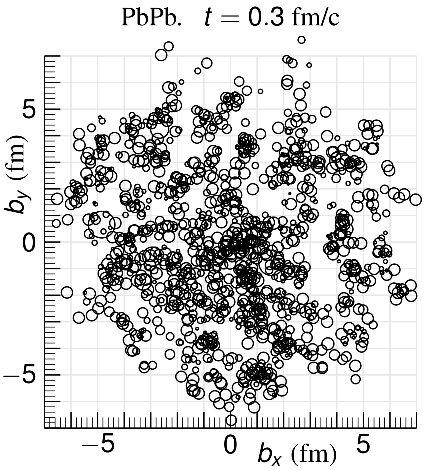


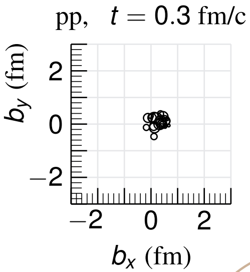

PbPb. $t = 0.1$ fm/c
b_y (fm)
5
0
−5
−5
0
5
b_x (fm)

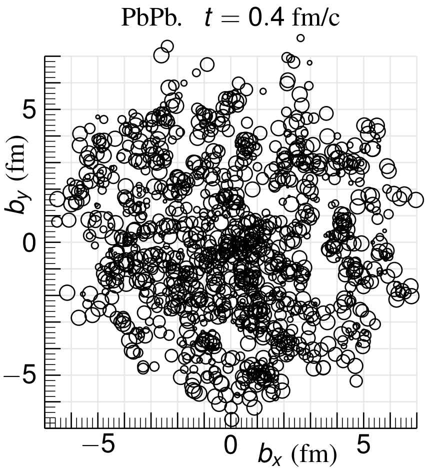

pp, $t = 0.1$ fm/c
b_y (fm)
2
0
−2
−2
0
2
b_x (fm)

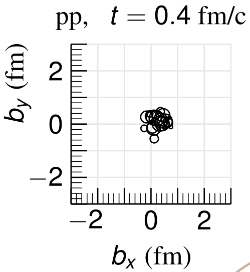

PbPb. $t = 0.2$ fm/c
b_y (fm)
5
0
−5
−5
0
5
b_x (fm)

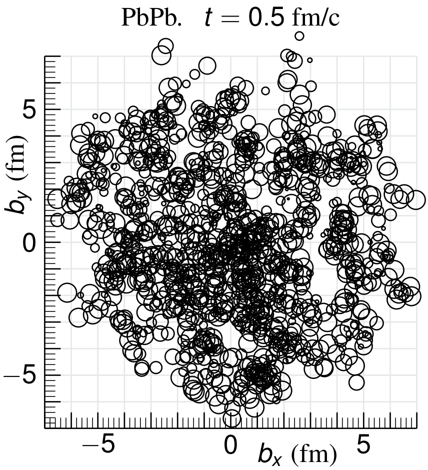

pp, $t = 0.2$ fm/c
b_y (fm)
2
0
−2
−2
0
2
b_x (fm)

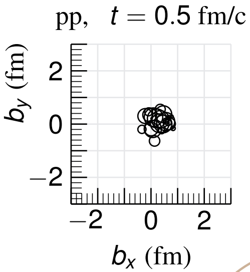

PbPb. $t = 0.3$ fm/c
b_y (fm)
b_x (fm)
5
0
−5
−5
0
5


pp, $t = 0.3$ fm/c
b_y (fm)
b_x (fm)
2
0
−2
−2
0
2


PbPb. $t = 0.4$ fm/c
b_y (fm)
5
0
−5
−5
0
5
b_x (fm)


pp, $t = 0.4$ fm/c
b_y (fm)
2
0
−2
−2
0
2
b_x (fm)


PbPb. $t = 0.5$ fm/c
b_y (fm)
5
0
−5
−5
0
5
b_x (fm)


pp, $t = 0.5$ fm/c
b_y (fm)
2
0
−2
−2
0
2
b_x (fm)

String Interactions: GLEIPNIR (ᚷᛚᛖᛁᛈᚾᛁᚱ)

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

[work in progress]

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[arXiv:1710.09725, arXiv:2010.07595]

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- Overlapping strings will have an increased string tension, making it easier to produce eg. strange hadrons.
  Rope Hadronisation $\Rightarrow$ strangeness enhancement

[work in progress]

[arXiv:1710.09725, arXiv:2010.07595]

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

String repulsion: Shoving

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

The shoving between parallel gives a transverse push according to a

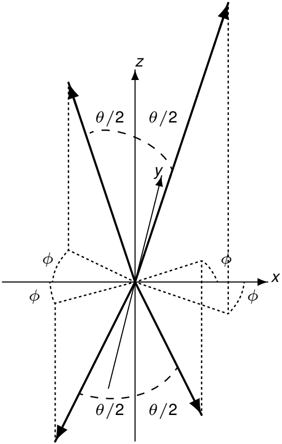
$$\frac{dp_\perp}{dt\,dz} = \frac{g\kappa\delta_\perp(t)}{R^2}\exp\left(-\frac{\delta_\perp^2(t)}{4R^2}\right).$$

This push must be parallel to both string pieces.

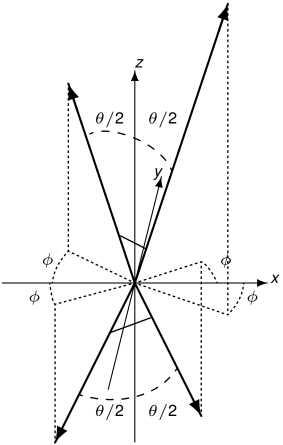
There is no frame where two random string pieces are parallel.

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

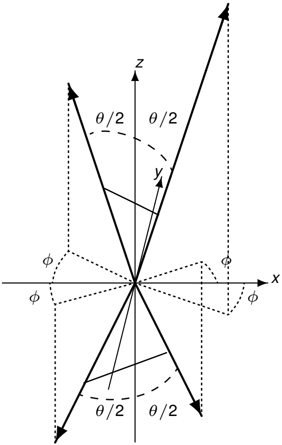
The parallel string frame



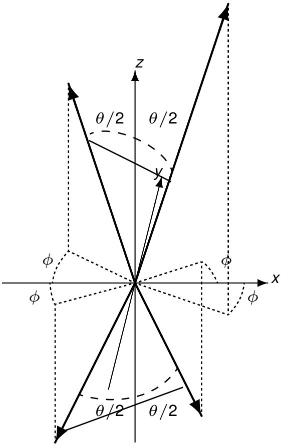
The parallel string frame



The parallel string frame

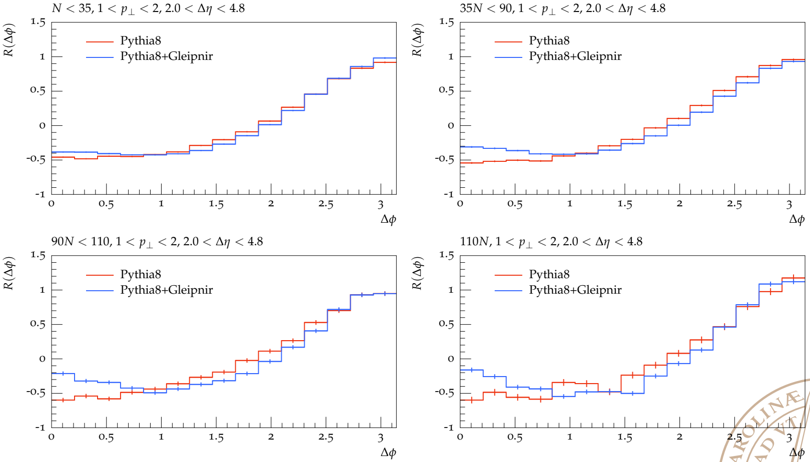


The parallel string frame

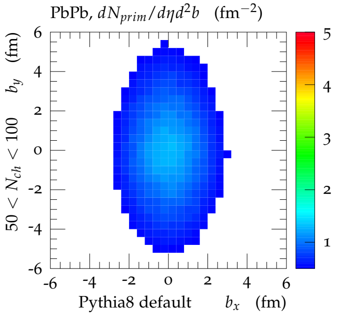


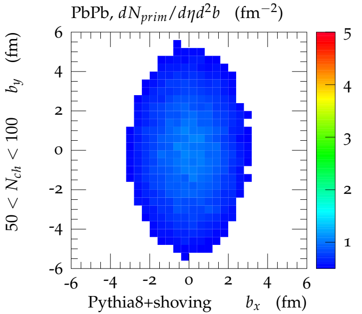
- Use (simplified) space-time information of all partons.
- Transform to parallel frame for every pair of string pieces.
- Calculate and collect small nudges, ordered in time.
- Apply the nudges to the produced primary hadrons (both position and momenta).

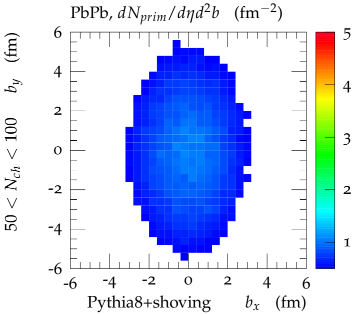
We have a ridge!

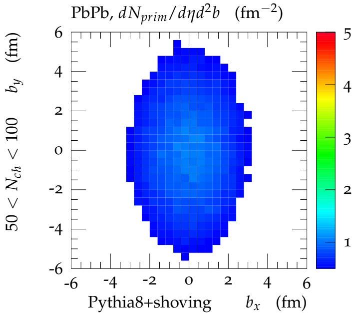


[arXiv:1009.4122]


PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8 default b_x (fm)
6
4
2
0
-2
-4
-6
5
4
3
2
1


PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8+shoving b_x (fm)
6
4
2
0
-2
-4
-6
5
4
3
2
1


PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8+shoving b_x (fm)
-6 -4 -2 0 2 4 6
1 2 3 4 5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$50 < N_{ch} < 100$ b_y (fm)
Pythia8+shoving b_x (fm)
-6 -4 -2 0 2 4 6
1 2 3 4 5

Rope hadronisation

Overlapping strings will give a higher string tension.

From lattice calculations $\kappa \propto C_2$.

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

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

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

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

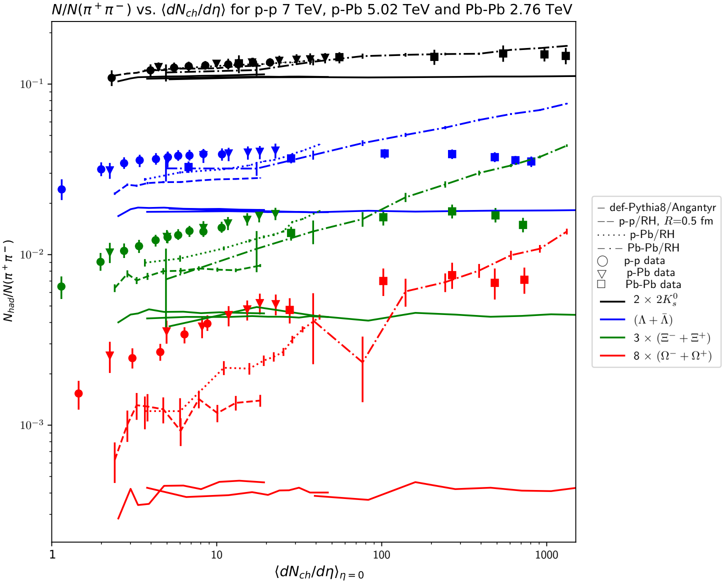
$$\kappa_{\text{eff}} = \kappa_{\{p,q\}} - \kappa_{\{p-1,q\}}$$

is the *reduction* of the string tension.

- Strings are not parallel $\Rightarrow$ the parallel frame
- Strings are not completely overlapping

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

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


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

Outlook

- Angantyr gives a reasonable description of inclusive particle production of (pp), pA and AA.
- Successfully extrapolates the pp dynamics of PYTHIA8 via pA to AA without introducing QGP dynamics.
- PYTHIA8/Angantyr brings general purpose event generators to heavy ion physics.
- Collective behaviour can be introduced via the Gleipnir models (Swing, Shoving, Ropes) as well as from hadronic rescattering.
- So far we have a qualitative description, more work is needed to get things properly working together and to compare to data.

Thanks!

Vetenskapsrådet

MCnet
Marie Curie Actions Human resources and mobility

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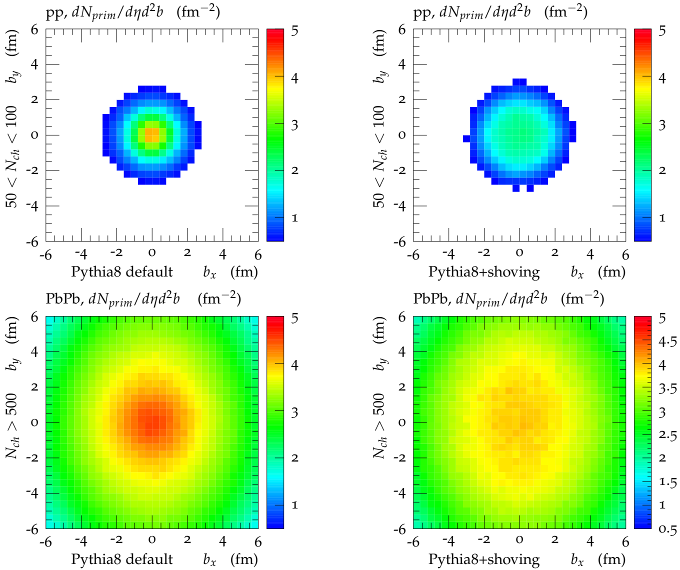
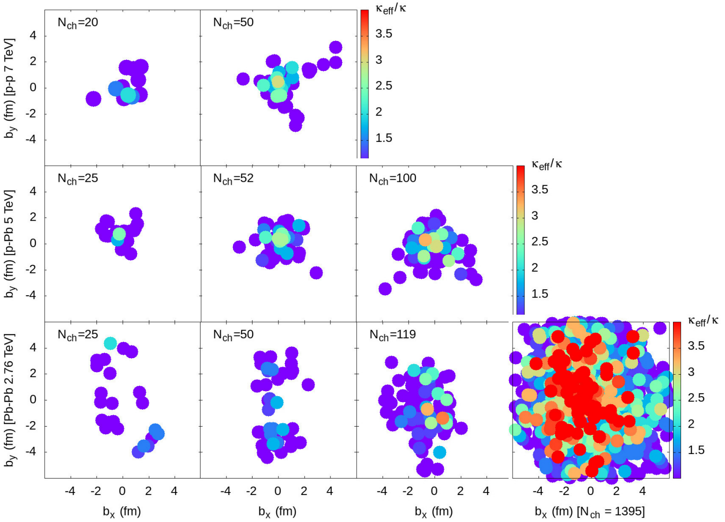
European Research Council
Established by the European Commission

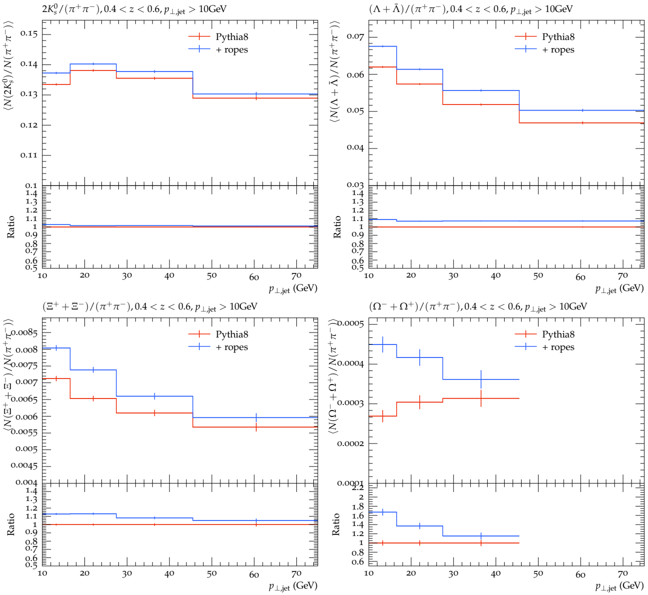
Knut and Alice Wallenberg Foundation

CLASH

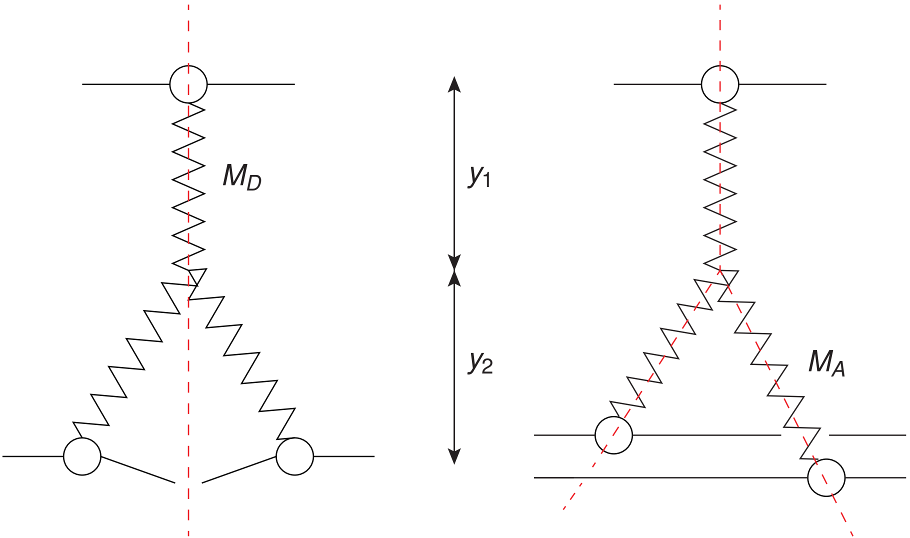
backup slides


pp, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8 default b_x (fm)
pp, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8+shoving b_x (fm)
PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$N_{ch} > 500$ b_y (fm)
Pythia8 default b_x (fm)
PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$N_{ch} > 500$ b_y (fm)
Pythia8+shoving b_x (fm)

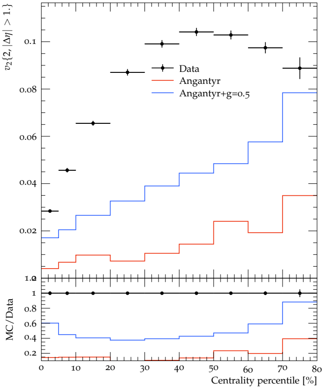

N$_{ch}$=20
N$_{ch}$=50
N$_{ch}$=25
N$_{ch}$=52
N$_{ch}$=100
N$_{ch}$=25
N$_{ch}$=50
N$_{ch}$=119
b$_y$ (fm) [p-p 7 TeV]
b$_y$ (fm) [p-Pb 5 TeV]
b$_y$ (fm) [Pb-Pb 2.76 TeV]
b$_x$ (fm)
b$_x$ (fm)
b$_x$ (fm)
b$_x$ (fm) [N$_{ch}$ = 1395]
κ$_{eff}$/κ
3.5
3
2.5
2
1.5
4
2
0
-2
-4

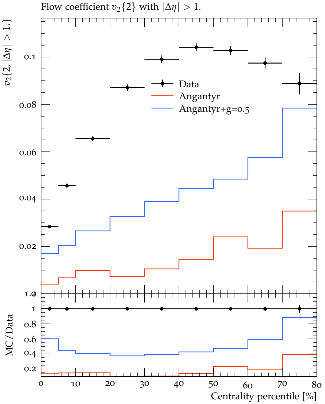

$2K_s^0/(\pi^+\pi^-), 0.4 < z < 0.6, p_{\perp,\mathrm{jet}} > 10\mathrm{GeV}$
$\langle N(2K_s^0)/N(\pi^+\pi^-)\rangle$
Pythia8
+ ropes
Ratio
$p_{\perp,\mathrm{jet}}$ (GeV)
$(\Lambda+\bar{\Lambda})/(\pi^+\pi^-), 0.4 < z < 0.6, p_{\perp,\mathrm{jet}} > 10\mathrm{GeV}$
$\langle N(\Lambda+\bar{\Lambda})/N(\pi^+\pi^-)\rangle$
Pythia8
+ ropes
Ratio
$p_{\perp,\mathrm{jet}}$ (GeV)
$(\Xi^+ + \Xi^-)/(\pi^+\pi^-), 0.4 < z < 0.6, p_{\perp,\mathrm{jet}} > 10\mathrm{GeV}$
$\langle N(\Xi^+ + \Xi^-)/N(\pi^+\pi^-)\rangle$
Pythia8
+ ropes
Ratio
$p_{\perp,\mathrm{jet}}$ (GeV)
$(\Omega^- + \Omega^+)/(\pi^+\pi^-), 0.4 < z < 0.6, p_{\perp,\mathrm{jet}} > 10\mathrm{GeV}$
$\langle N(\Omega^- + \Omega^+)/N(\pi^+\pi^-)\rangle$
Pythia8
+ ropes
Ratio
$p_{\perp,\mathrm{jet}}$ (GeV)

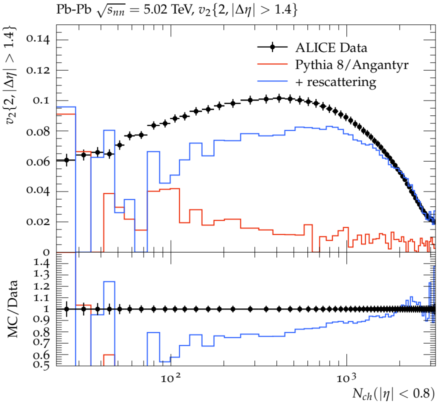
$$\hat{\sigma}_{2\to 2} \longrightarrow \hat{\sigma}_{2\to 2} \times \frac{\alpha_S(p_\perp^2 + p_{\perp 0}^2(s))}{\alpha_S(p_\perp^2)} \times \frac{p_\perp^4}{\left(p_\perp^2 + p_{\perp 0}^2(s)\right)^2}$$

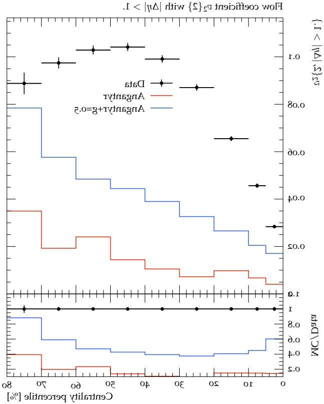

M_D
y_1
y_2
M_A

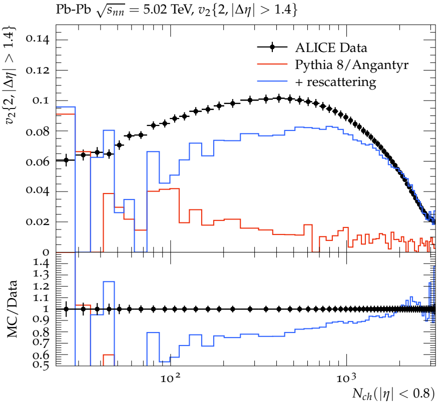
Flow coefficient $v_2\{2\}$ with $|\Delta\eta| > 1.$




Flow coefficient $v_2\{2\}$ with $|\Delta\eta| > 1.$
$v_2\{2, |\Delta\eta| > 1.\}$
Data
Angantyr
Angantyr+g=0.5
MC/Data
Centrality percentile [%]


Pb-Pb $\sqrt{s_{nn}}$ = 5.02 TeV, $v_2\{2, |\Delta\eta| > 1.4\}$
$v_2\{2, |\Delta\eta| > 1.4\}$
ALICE Data
Pythia 8/Angantyr
+ rescattering
MC/Data
$N_{ch}(|\eta| < 0.8)$


Flow coefficient $v_2\{2\}$ with $|\Delta\eta| > 1$.
Data
Angantyr
Angantyr+g=0.5
MC/Data
Centrality percentile [%]


Pb-Pb $\sqrt{s_{nn}}$ = 5.02 TeV, $v_2\{2, |\Delta\eta| > 1.4\}$
ALICE Data
Pythia 8/Angantyr
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$v_2\{2, |\Delta\eta| > 1.4\}$
MC/Data
$N_{ch}(|\eta| < 0.8)$