Pythia, DIPSY and Angantyr – past, present and future

with focus on collectivity and heavy ion physics

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Lund University

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Thank you ALICE, for all the beautiful data!

- Tales from the belly of the MC generators: DIPSY and Pythia.
  - Generators with focus on soft QCD.
  - Both capable of colliding HI beams.
  - Extensive use of Lund strings.
- Both are generators without QGP. Idea is:
  - Most observables in pp can be explained without QGP.
  - Collectivity = small effect, added as correction.
  - Long term: What happens when we extrapolate to AA?
- This talk:
  1. Past: The basic formalism, and results $\approx$ 2014
  2. Present: Ropes and shoving in Pythia, Angantyr and possibilities.
  3. Future: Many prospects – three things I work on right now.

Past

Pythia

- Obviously very well known.

Pythia

- Obviously very well known.

Information | References (417) | Citations (10001) | Files | Plots

PYTHIA 6.4 Physics and Manual

Torbjorn Sjostrand (Lund U., Dept. Theor. Phys.), Stephen Mrenna, Peter Z. Skands (Fermilab)

Mar 2006 - 576 pages

JHEP 0605 (2006) 026
DOI: 10.1088/1126-6708/2006/05/026
FERMILAB-PUB-06-052-CD-T, LU-TP-06-13
e-Print: hep-ph/0603175 | PDF

- Here: Soft QCD (MPI model) + CR + strings.
- MPIs crucial for high energy pp collisions.

MPIs in Pythia 8: proton collisions (Sjöstrand and Skands: arXiv:hep-ph/0402078)

- Several partons from the PDF.
- Hard subcollisions with $2 \to 2$ ME:

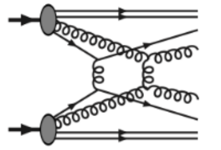


Figure T. Sjöstrand

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > ...$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp \right]$$

- Number distribution narrower than Poissonian (momentum and flavour rescaling).

Color reconnection

- Many partonic subcollisions ⇒ Many hadronizing strings.
- But! $N_c = 3$, not $N_c = \infty$ gives interactions.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

$$\mathcal{P}_{merge} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0})^2 + p_\perp^2}$$

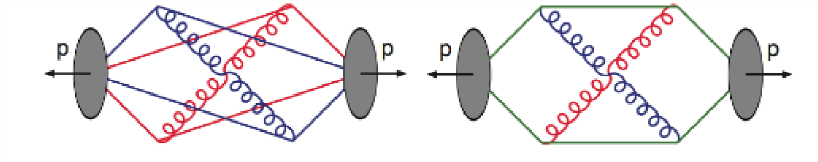


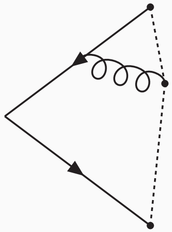
Figure T. Sjöstrand

- Actual merging decided by minimization of:

$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2}E/m_0)$$

The Lund String (80's: Andersson et al. Z.Phys. C3 (1980) 223, Z.Phys. C20 (1983) 317)

- Non-perturbative phase of final state.
- Confined colour fields $\approx$ *strings* with tension $\kappa \approx 1$ GeV/fm.



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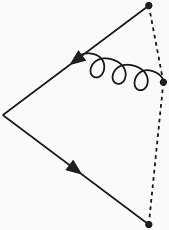

Lund symmetric fragmentation function

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right).$$

a and b related to total multiplicity.

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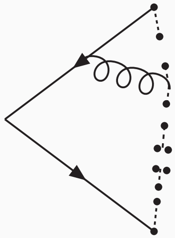

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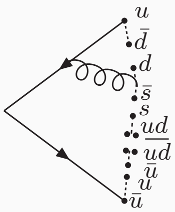

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Light flavour determination

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

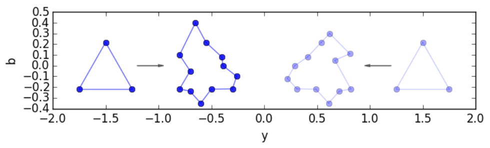
Related to κ by Schwinger equation.

The DIPSY model (Flensburg et al. arXiv:1103.4321 [hep-ph])

- A very different view on MPIs, built on Mueller dipole model (Mueller and Patel arXiv:hep-ph/9403256).
- Proton structure built up dynamically from dipole splittings:

Model implemented as a MC event generator
Dipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**.

$$\frac{dP}{dY} = \frac{3\alpha_s}{2\pi^2} d^2\vec{z} \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2(\vec{z}-\vec{y})^2}, \; f_{ij} = \frac{\alpha_s^2}{8}\left[\log\left(\frac{(\vec{x}_i-\vec{y}_j)^2(\vec{y}_i-\vec{x}_j)^2}{(\vec{x}_i-\vec{x}_j)^2(\vec{y}_i-\vec{y}_j)^2}\right)\right]^2$$



- MPIs are included by construction.
- No PDFs (also: no quarks, no ME $\Rightarrow$ few hard jets).

DIPSY and Ropes (CB, Gustafson, Lönnblad & Tarasov: 1412.6259)

- Utilize knowledge of string postitions – strings (p and q) still overlap.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

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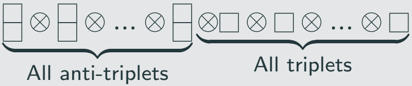
$$\{p, q\} \otimes \vec{3} = \{p+1, q\} \oplus \{p, q+1\} \oplus \{p, q-1\}$$



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- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p + 1)(q + 1)(p + q + 2)$.

CR collectivity is short range in rapidity

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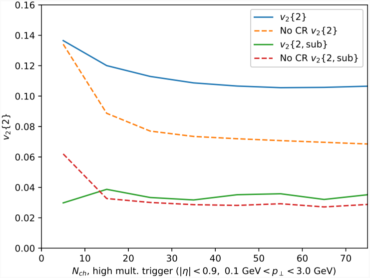
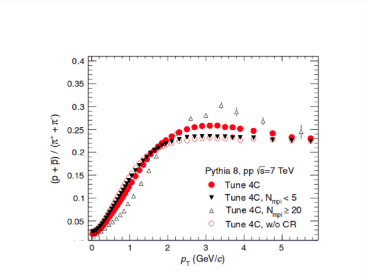
Quantifying its contribution

- Moves protons to measured phase space (Velasquez *et al.* PRL 111 (2013) 042001).
- Contribution to radial component, short range in y.

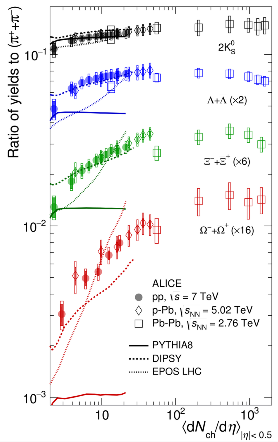




Contribution to $v_2\{2\}$ disappears: CR not long range.

Strangeness enhancement

- A game of *density*.
- Good description of strangeness enhancement.



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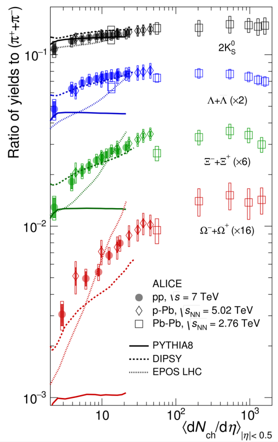
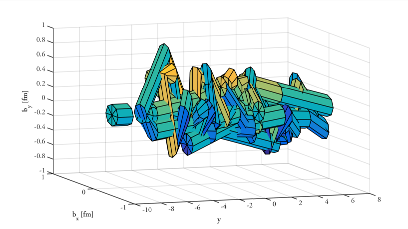


- DIPSY can make use of its impact parameter picture.



Present

String shoving (CB, Gustafson, Lönnblad: 1612.05132, 1710.09725)

- Strings = interacting vortex lines.
- For $t \to \infty$, profile known from lQCD (Cea *et al.*: PRD89 (2014) no.9, 094505):

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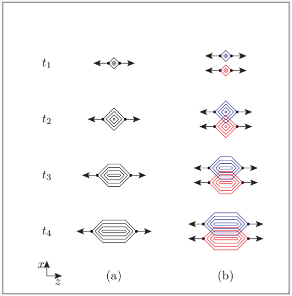
$$\mathcal{E}(r_\perp) = C \exp\left(-r_\perp^2/2R^2\right)$$

$$E_{int}(d_\perp) = \int d^2 r_\perp \mathcal{E}(\vec{r}_\perp)\mathcal{E}(\vec{r}_\perp - \vec{d}_\perp)$$

$$f(d_\perp) = \frac{dE_{int}}{dd_\perp} = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2(t)}{4R^2}\right).$$



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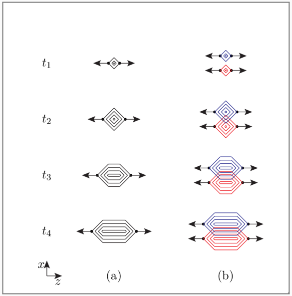
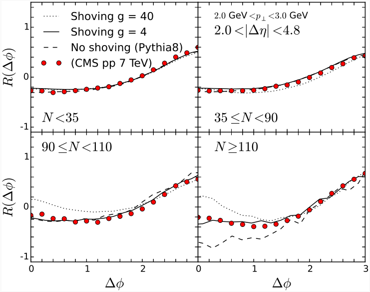


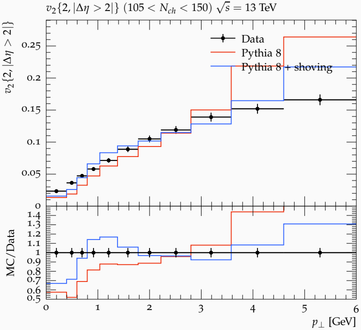
- Dominated by electric field $\to g = 1$.

- Reality:
  - **Type 1** Energy to destroy vacuum.
  - **Type 2** Energy in current.

Some Results: shoving

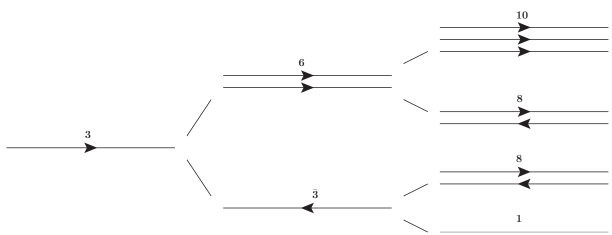
- Reproduces the pp ridge with suitable choice of g parameter.
- Improved description of $v_2 2|\Delta eta| > 2.(p_\perp)$ at high multiplicity.



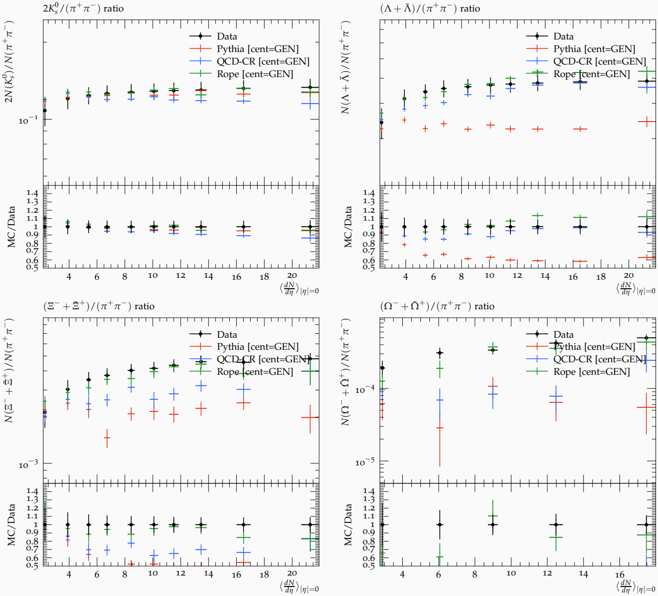


Ropes in Pythia

- The rope framework ported from DIPSY to Pythia.
- Requires space–time picture.
- Here: Overlapping 2D Gaussians (p mass distribution).
- All lower multiplets handled by CR.



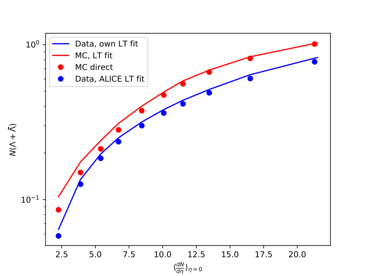
Results

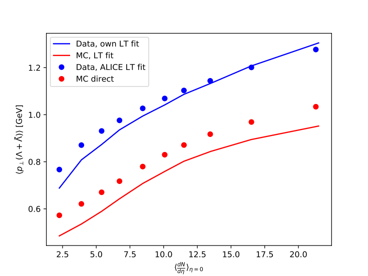


$2K_s^0/(\pi^+\pi^-)$ ratio
$2N(K_s^0)/N(\pi^+\pi^-)$
$(\Lambda+\bar{\Lambda})/(\pi^+\pi^-)$ ratio
$N(\Lambda+\bar{\Lambda})/N(\pi^+\pi^-)$
$(\Xi^-+\bar{\Xi}^+)/(\pi^+\pi^-)$ ratio
$N(\Xi^-+\bar{\Xi}^+)/N(\pi^+\pi^-)$
$(\Omega^-+\bar{\Omega}^+)/(\pi^+\pi^-)$ ratio
$N(\Omega^-+\bar{\Omega}^+)/N(\pi^+\pi^-)$
Data
Pythia [cent=GEN]
QCD-CR [cent=GEN]
Rope [cent=GEN]
MC/Data
$\langle \frac{dN}{d\eta} \rangle_{|\eta|=0}$

An aside about Levy–Tsallis fits

- Extrapolated spectra are difficult to compare to!
- For Pythia: Yields matches the fit, $\langle p_\perp \rangle$ not.



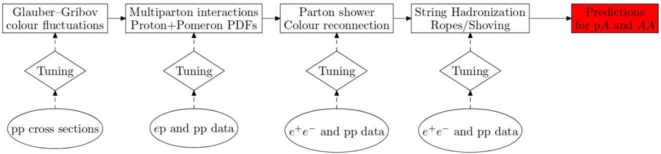


Take home message

MC: Don't rely on fits for average quantities when the spectrum is off.
Pythia still has problems describing this. Shoving could improve matters.

Angantyr

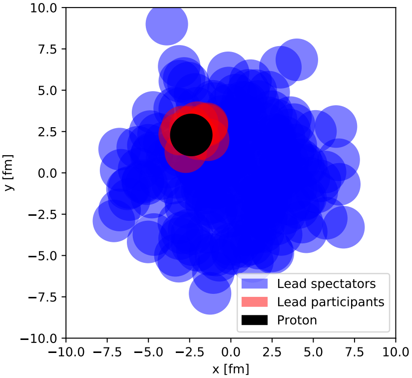
- Extending the Pythia MPI model to Heavy Ions.
    1. Only tuning to pp, add Glauber for nuclear geometry.



- Focus on cross section fluctuations (Glauber–Gribov) and correct handling of diffractive excitation.

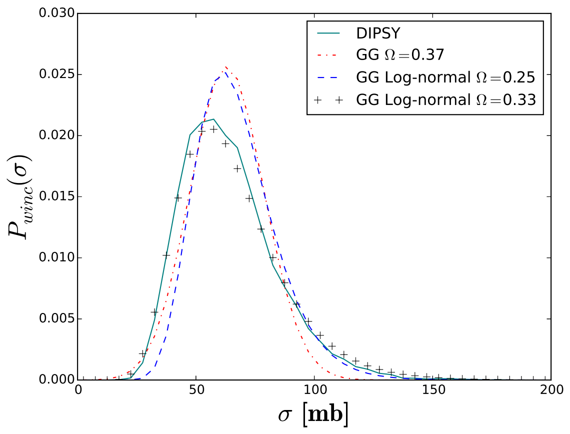
Glauber initial state

- Determine which nucleons are "wounded".
- Geometric picture only relies on pp cross section.



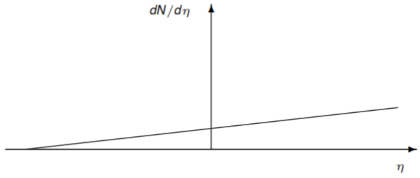
Glauber–Gribov colour fluctuations

- Cross section has EbE colour fluctuations.
- Parametrized in Angantyr, fitted to pp (total, elastic, diffractive).



Particle production: Wounded nucleons

- Simple model by Białas and Czyz.
- Wounded nucleons contribute equally to multiplicity in η.
- Originally: Emission function $F(\eta)$ fitted to data.



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

- Angantyr: No fitting to HI data, but include model for emission function.
- Model fitted to reproduce pp case, high $\sqrt{s}$, can be retuned down to 10 GeV.

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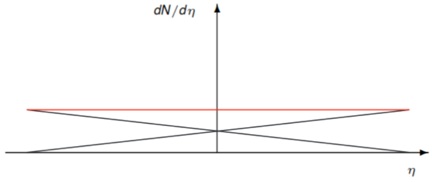

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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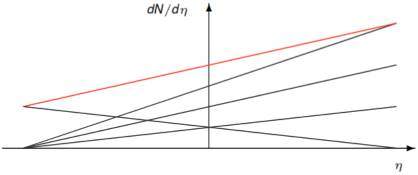

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad \text{(p}A\text{)}$$

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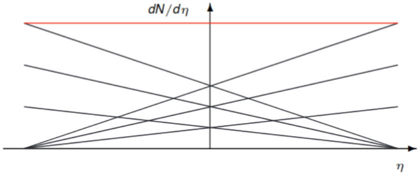

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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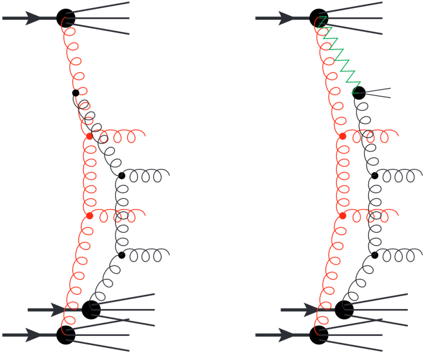
The emission function

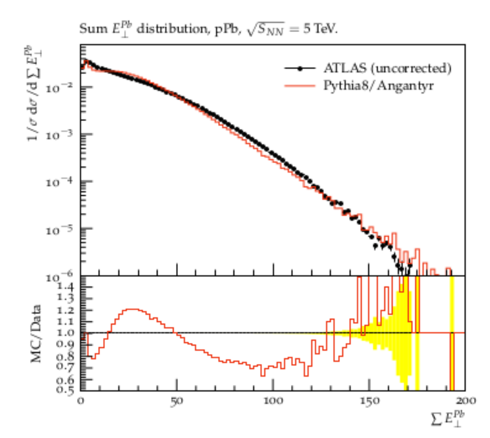
- A schematic view of a pD collision. Contains 3 wounded nucleons.
- First two are a normal non-diffractive pp event.
- The second one is modelled as a single diffractive event.
- Generalizes to all pA and AA collisions.



(a) (b)

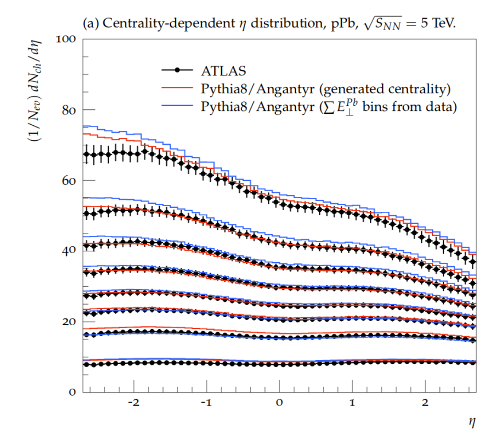
Some results - pPb

- Centrality measures are delicate, but well reproduced.



Some results - pPb

- Multiplicity distributions well reproduced.



Some results - PbPb

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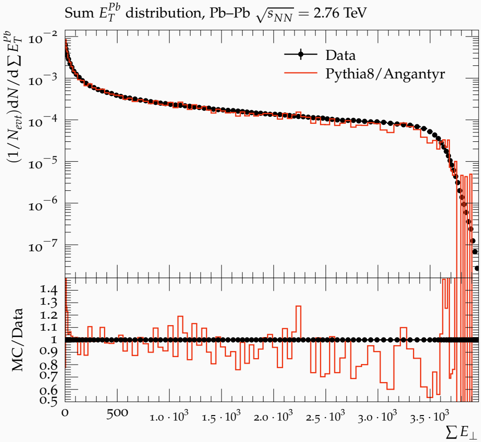
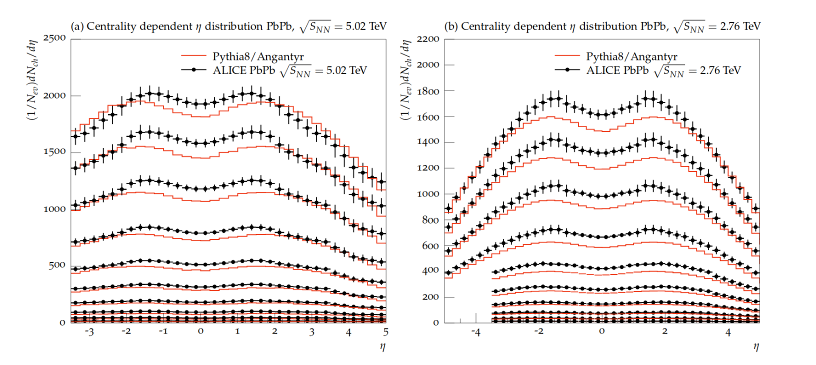


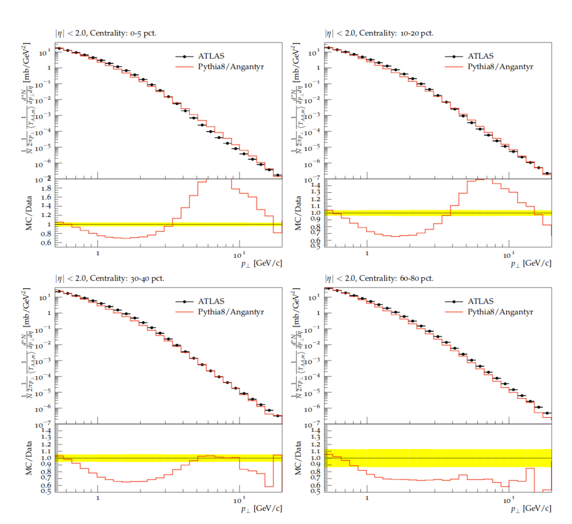
Some results - PbPb

- Multiplicity distributions well reproduced.
- Also XeXe (prediction) including up–tick.



Some results - PbPb

- Spectra to a lesser degree, no collective effects so far.



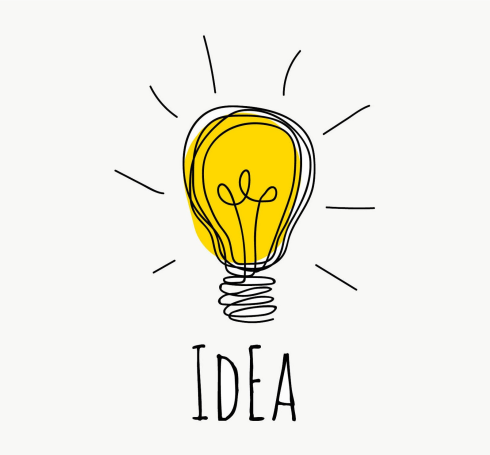
Easy to use!

```cpp
#include "Pythia8/Pythia.h"
#include "Pythia8/HeavyIons.h"

using namespace Pythia8;

// This is a one-slide example program demonstrating Heavy Ion
// functionality.
int main() {
  Pythia pythia;
  // Setup the beams.
  pythia.readString("Beams:idA = 1000822080");
  pythia.readString("Beams:idB = 1000822080"); // The lead ion.
  pythia.readString("Beams:eCM = 2760.0");
  // Sum up the weights of all generated events.
  double sumw = 0.0;
  // Count the number of charged particles.
  double ncEvent = 0.0;
  // Initialise Pythia.
  pythia.init();
  for ( int iEvent = 0; iEvent < 1000; ++iEvent ) {
    if ( !pythia.next() ) continue;
    double nc = 0.0;
    for (int i = 0; i < pythia.event.size(); ++i) {
      Particle & p = pythia.event[i];
      if ( p.isFinal() ) {
        if ( p.isCharged() && p.pT() > 0.1 && abs(p.eta()) < 0.5 ) ++nc;
      }
    }
    sumw += pythia.info.weight();
    ncEvent += nc * pythia.info.weight();
  }
  cout << "Charged multiplicity density at mid-eta: " << ncEvent / sumw << endl;
  return 0;
}
```

- Fully integrated with Pythia.
- Internal or external ME's.
- Support for several nuclei.
- C++, Python interface distributed w. Pythia.
- Output: Rivet, HepMC, ROOT6 trees.

Two ideas

- MC implementation of models allows development of observables.
- Crucial: Physics can be "switched off", in a way it cannot in nature.

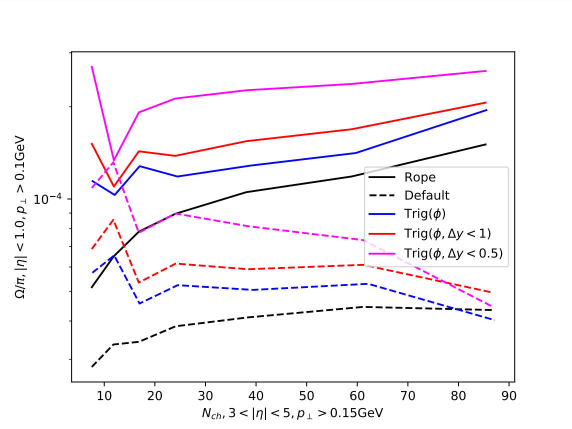


Can we get a better handle on strangeness enhancement? (CB, in prep.)

- We can do better than inclusive rates.
- Accessing longitudinal (rapidity) structure: Correlation measurements.
- Consider ropes in a ϕ-triggered event.
  1. Even in e^+e^- we bias to more strange production,
  2. In pp we can assess the difference wrt. default strings.
  3. Moving closer to the ϕ production rapidity gives larger string tension.
- Statistics hungry analysis – something for HL-LHC?

Preliminary: pp @ 13 TeV (Pythia8 + ropes)

- Input for discussion:
  1. Sensible measurement?
  2. What does thermal models say?
  3. Can we remove the neigbor bias? (require neighbor etc.)



What about shoving and jets? (CB: 1901.07447)

- String dynamics ought to be universal.
- Consider now:
    1. Events with a Z-boson present.
    2. Events with Z+jet.
- $Z \to l^+ l^-$ not affected by shoving.
- Provides kinematics handle.

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Common statement:

- ◇ FS interactions → flow should also affect jets.
- ◇ The shoving model provides a framework to study such effects.
- ◇ This does not mean that shoving is the full story.

Try just a Z-boson

- The presence of a Z should not change the physics.
- It *can* introduce kinematical biases.
- Recently measured by ATLAS (ATLAS-CONF-2017-068).

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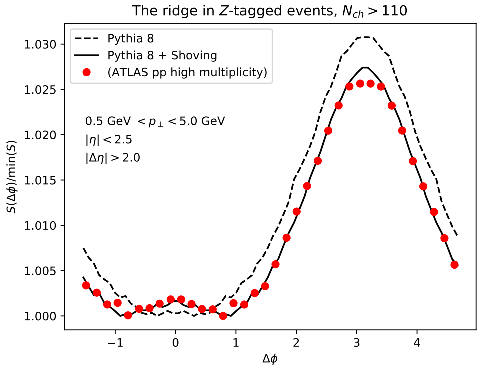
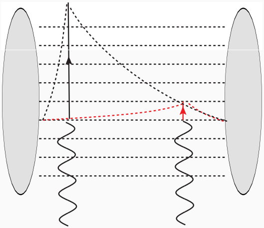
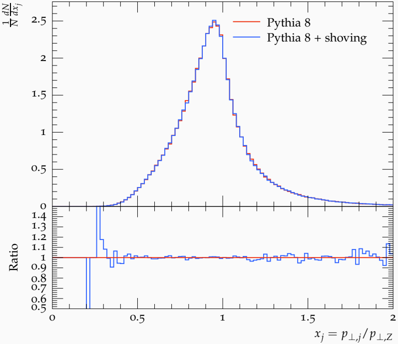


What is the effect of shoving?

- Nothing! Surprised?
- Of course not – the effect is geometrically surpressed.
- Toy geometry: Let jet hadronize "inside".
- Mimic the effect in AA collisions.





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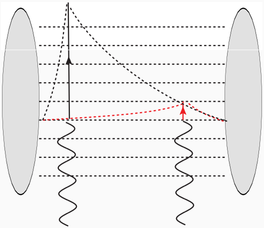
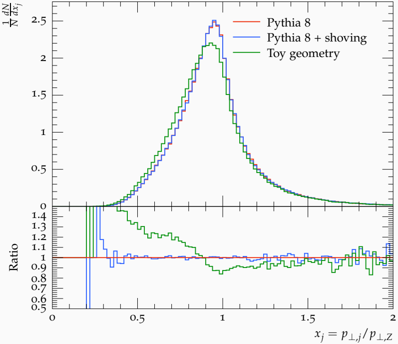
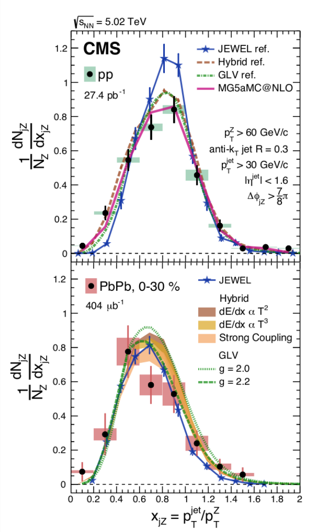
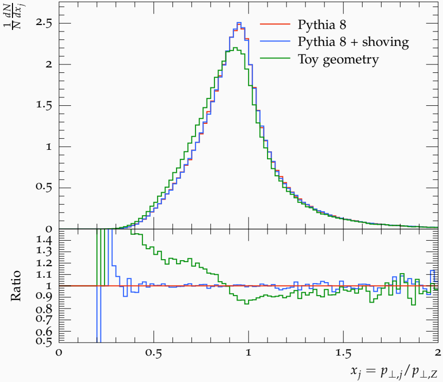




Qualitative similarities (CMS: 1702.01060)



- Need better obsevables.
- Soft modifications on jet edge (large R).



Hadrochemistry

- Hadrochemistry indirectly affected through basic string equations.
- Study inclusive quantities: Average hadron mass and total jet charge: $\langle m_h \rangle = \frac{1}{N_p} \sum_i^{N_p} m_{h,i}$, $Q_j = \sum_i^{N_p} q_{h,i}$

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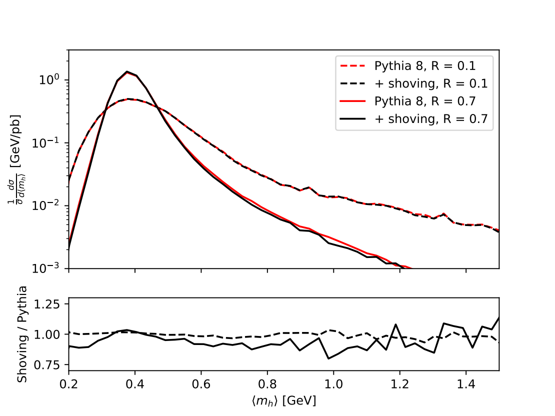

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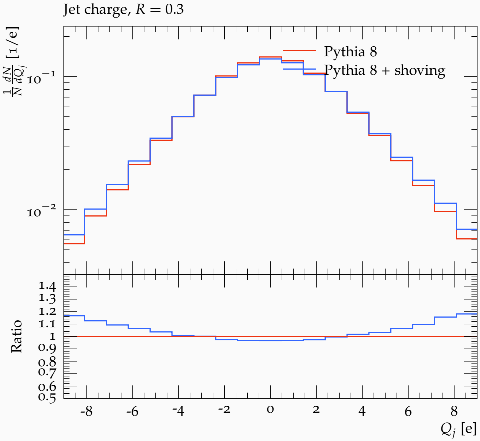

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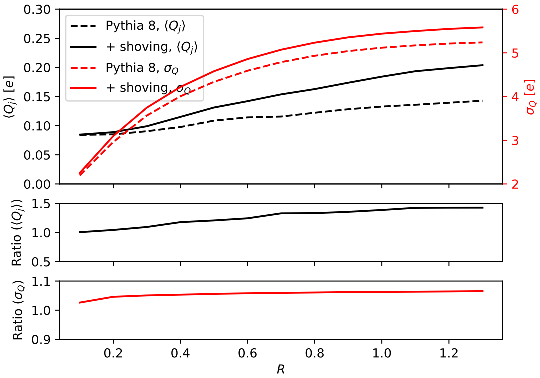


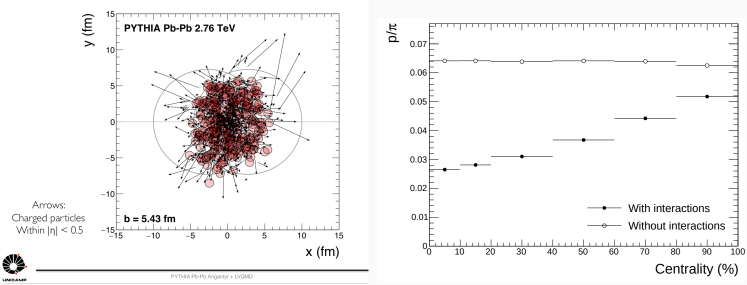
Future

Obvious extensions

- Extension of ropes and shoving to pA and AA an obvious venue.
- Very active, still few results.
- In the framework of CLASH, see `www.hep.lu.se/clash`

Final state interactions in Angantyr (w. D. Chinellato & A. da Silva)

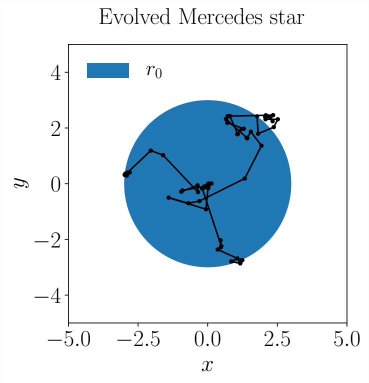
- Hadronic interactions in final state with URQMD.
- Hardon vertices from string model (Ferreres-Solé & Sjöstrand: 1808.04619).

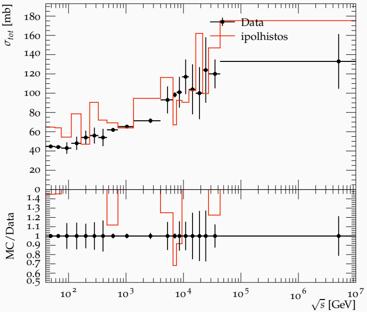


- Definitely neccesary ingredient for ropes in AA collisions.
- Many interesting prospects, resonances, effects on jets etc.
- Maybe possible to investigate pp as well.

Improving the Pythia space–time picture (w. C.O. Rasmussen)

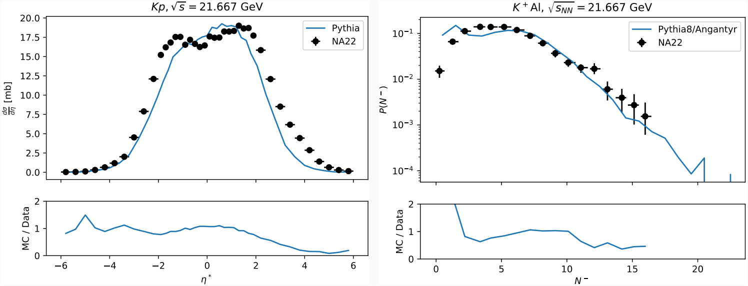
- Mueller dipole QCD (re: DIPSY) interesting features for space time model.
  1. Perturbative calculation (+ non-perturbative corrections).
  2. Structure parameters fitted to cross sections.
- Goal: Mueller dipoles → space time information to Pythia MPIs.





The cosmic connection (w. A. Fedynitch, J. Koskinen & I. Storehaug)

- Uncertainties on cosmic data ← uncertainty on hadronic MCs.
- ... this is in turn limited by lack of good data.
- Use Pythia/Angantyr for cosmic data.
- Relies heavily on data from NA-22 days.



Opportunity for ALICE

Particle production with PID in pO at high energies.
Valuable cross–collaboration output.

Instead of a summary: The experimental wishlist

- Strangeness in pp:
  1. The ϕ is a sensitive probe.
  2. Triggered ratios $\rightarrow$ higher resolution.
  3. $p_{\perp}$ of heavy hadrons continues to puzzle us.
- Correlations:
  1. Continued efforts on precise flow measurements & SC's important for geometry. TH is lacking behind.
  2. Z-triggered jets a window to SS jet modifications.
  3. Shoving gives effects on jet chemistry.
- AA particle production:
  1. Centrality measures unfolded.
  2. Strong case for Oxygen collisions also from cosmic ray community.

Thank you!