A microscopic perspective on heavy ion physics

news on PYTHIA, Angantyr and string interactions

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Introduction

- Small system collectivity: The most surprising LHC outcome!
- Challenges all around the board:
  - How far down in system size can the "SM of Heavy Ions" remain?
  - Can the standard tools for min bias pp remain standard?

Most important question for QCD phenomenology!

◇ Does similar signatures across systems share physics origin?

- This talk: a microscopic, plasma free approach.
  1. MPIs and collectivity from string interactions.
     ◇ flow, strangeness and possible jet modifications.
  2. MPIs from pp to AA: The Angantyr model.
     ◇ basic quantities, centrality and final state rescatterings.

MPIs in PYTHIA8 pp Sjöstrand and Skands: arXiv:hep-ph/0402078

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

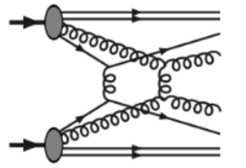

Figure T. Sjöstrand

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

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

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

- Picture blurred by CR, but holds in general.

Color reconnection? What's that?

- Many partonic subcollisions $\Rightarrow$ 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-$p_\perp$.

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

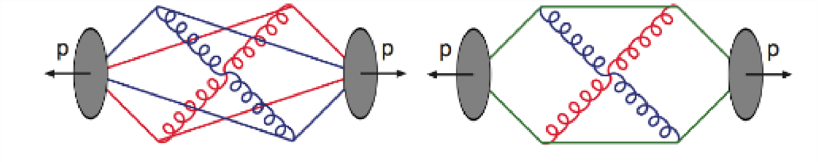

Figure T. Sjöstrand

- Actual merging by minimization of "potential energy":

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

Colour Reconnection – microscopic collectivity?

(Ortiz et al.: 1303.6326, CB QM18: 1807.05217 & mcplots.cern.ch)

- 👍 Mechanism allows cross–talk over an event.
- 👍 Based on physics effect.
- 👍 Needed for multiplicity & $\langle p_\perp \rangle$.
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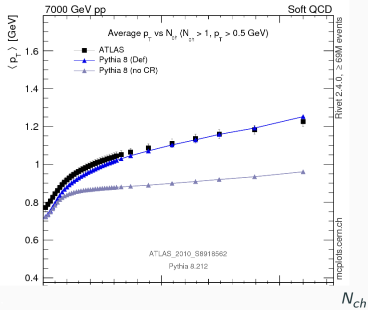

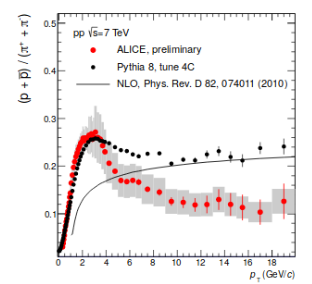

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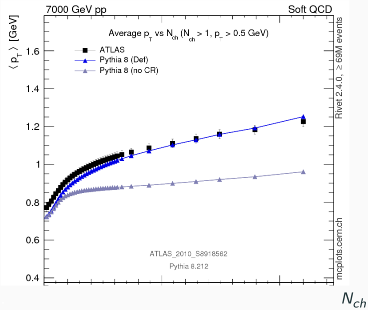

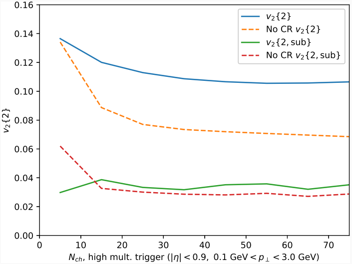

Microscopic final state collectivity

- Clearly we need more! Where is the geometry?
- Proposal: Model microscopic dynamics with interacting Lund strings
- Additional input fixed or inspired by lattice, few tunable parameters.

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$\tau \approx 0$ **fm:** Strings no transverse extension. No interactions, partons may propagate.

$\tau \approx 0.6$ **fm:** Parton shower ends. Depending on "diluteness", strings may shove each other around.

$\tau \approx 1$ **fm:** Strings at full transverse extension. Shoving effect maximal.

$\tau \approx 2$ **fm:** Strings will hadronize. Possibly as a colour rope.

$\tau > 2$ **fm:** Possibility of hadronic rescatterings.

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

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

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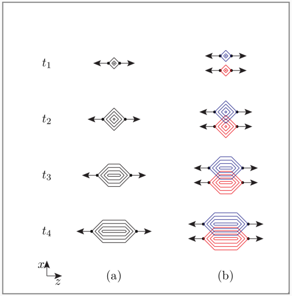

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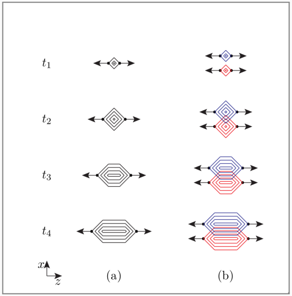

- All energy in electric field $\to g = 1$.
- Reality:
  Type 1 SC Energy to destroy vacuum.
  Type 2 SC Energy in current.

Shoving: Prehistoric origins

- 1st law of QCD phenomenology: When you think you have a good idea...

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- Highly underappreciated paper – $\mathcal{O}(10)$ citations.

Long-range azimuthal correlations in multiple-production processes at high energies

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(Submitted 18 January 1988)
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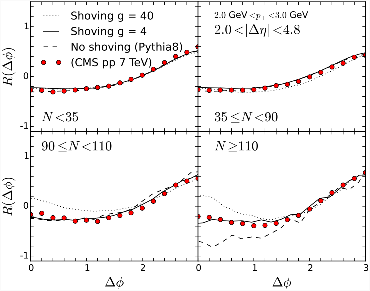
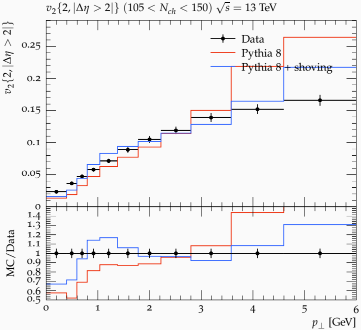
6. In an interaction of heavy nuclei with nuclei, many overlapping quark tubes form, and a large azimuthal asymmetry may be observed.[2)] Furthermore, since an $A \times A$ collision is noncentral on the average, the system of quark tubes fills a transversely anisotropic region. It is clear geometrically that its anisotropy is oriented along the impact parameter of the collision. We might thus expect correlations between the azimuthal distribution of secondary hadrons and the azimuthally anisotropic distribution of the decay products of the nucleus.

Again, we wish to emphasize that data on the azimuthal asymmetry in soft multiple-production processes may contain some very nontrivial information.

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.
- Low multiplicity not reproduced well – problems for jet fragmentation?





What about 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.

Step 1: 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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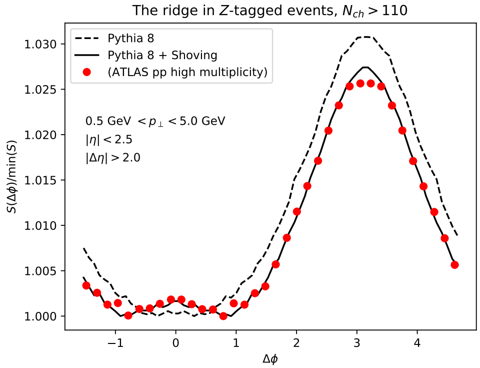
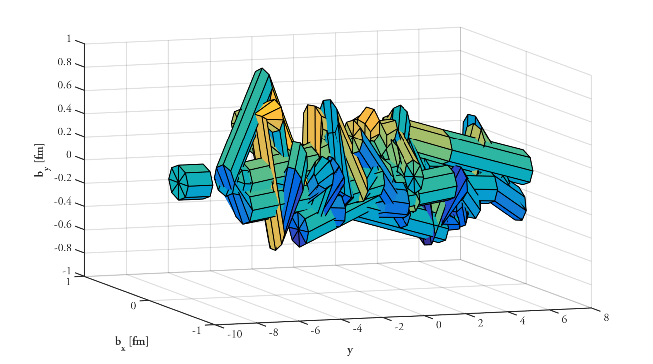


Before introducing a jet...

- Space–time information is important!
- Here: Overlapping 2D Gaussians (p mass distribution).
- Figure string $R = 0.1$ fm, reality $R \sim 0.5$ fm.



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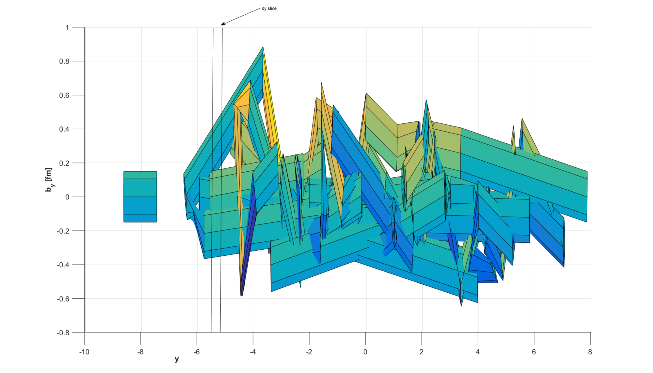

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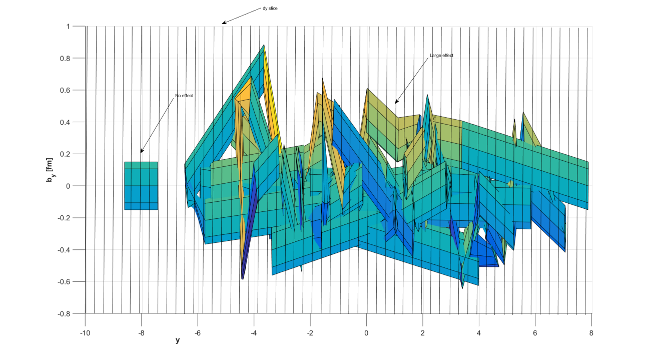

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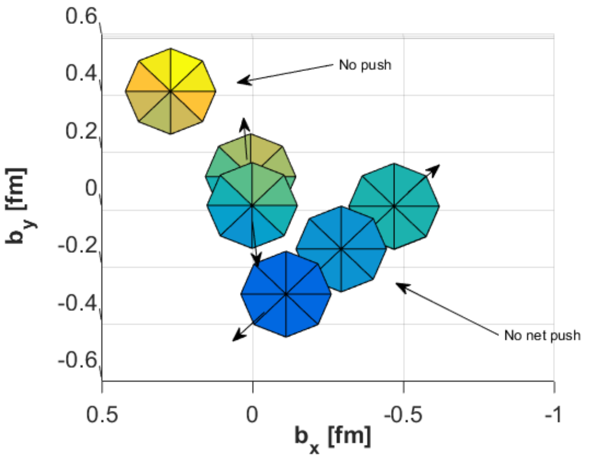

What is the effect of shoving?

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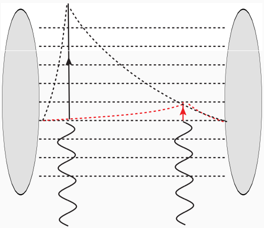
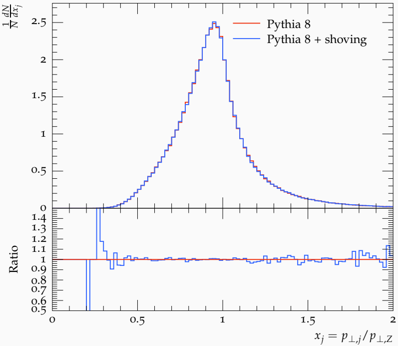
- Of course not – the effect is geometrically surpressed.
- Toy geometry: Let jet hadronize "inside".
- Mimic the effect in AA collisions.





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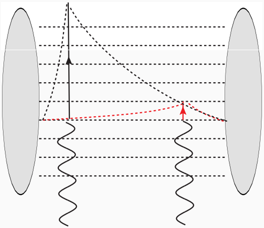
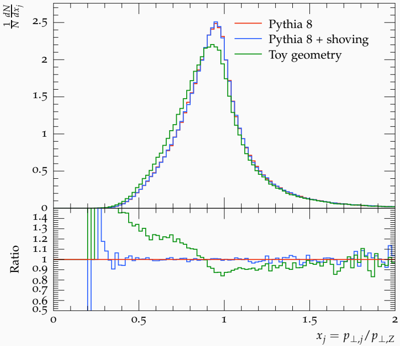
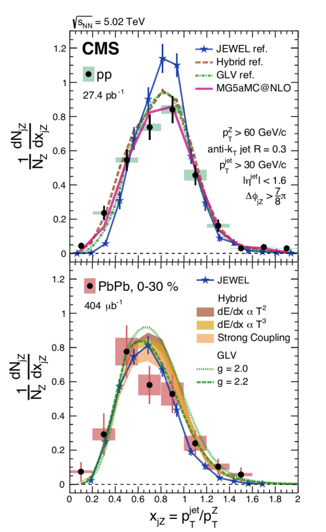
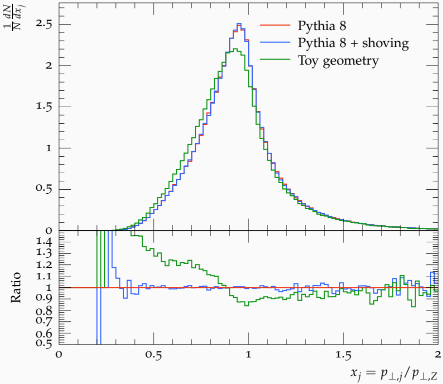




Qualitative similarities (CMS: 1702.01060)

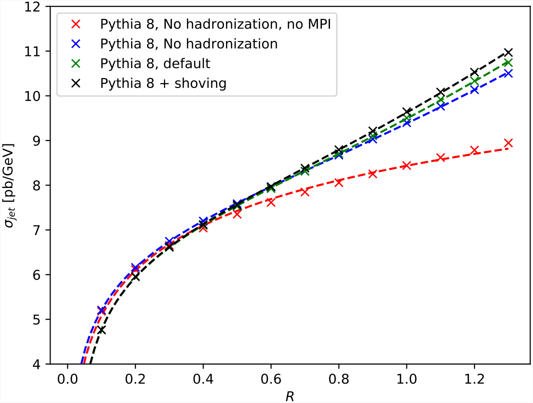


- Need better obsevables.
- Soft modifications on jet edge (large R).



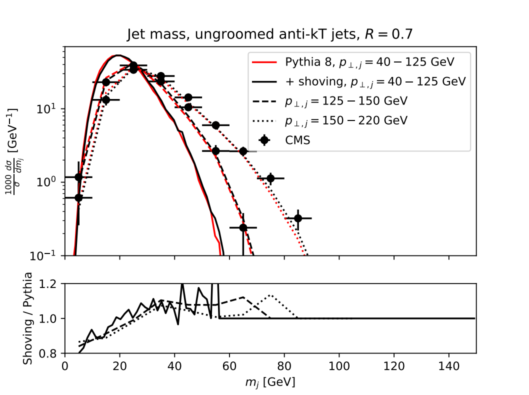
Jet cross section

- Integrate leading jet spectrum: $\sigma_j = \int_{p_{\perp,0}}^{\infty} dp_{\perp,j} \frac{d\sigma}{dp_{\perp,j}}$
- Expectation: $\langle dp_\perp / d\eta \rangle \propto f\left(\langle d_\perp \rangle\right) \Rightarrow \Delta\sigma_j \propto R^2$
- Effect probably too small to measure.



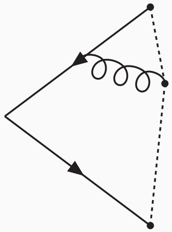
Jet mass

- Calorimetric quantities like jet mass good for experiments.
- Affects the soft jet "corona" or soft jets.
- Difficult with present data - task for HL-LHC?
- Investigate anti-soft-drop? Soft-keep?



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

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



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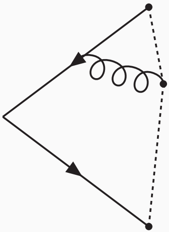

Lund symmetric fragmentation function

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

a and b related to total multiplicity.

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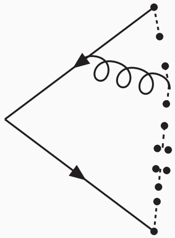

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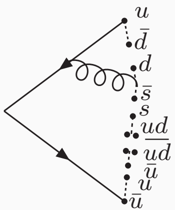

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Light flavour determination

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

Related to κ by Schwinger equation.

Rope Hadronization (JHEP 1503 (2015) 148 – explored heavily in 80's and 90's!)

- After shoving, 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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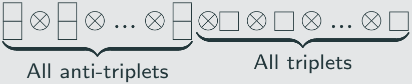

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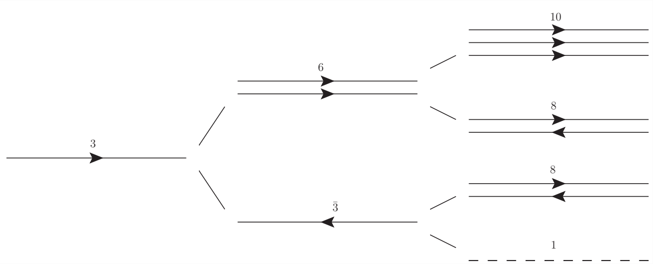
$$\underbrace{\begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix} \otimes \ldots \otimes \begin{smallmatrix}\square\\\square\end{smallmatrix}}_{\text{All anti-triplets}} \underbrace{\otimes \square \otimes \square \otimes \ldots \otimes \square}_{\text{All triplets}}$$

- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Divide and conquer!

- Consider now the *stacking* of such pairs.
- SU(3) multiplet structure decided by random walk.



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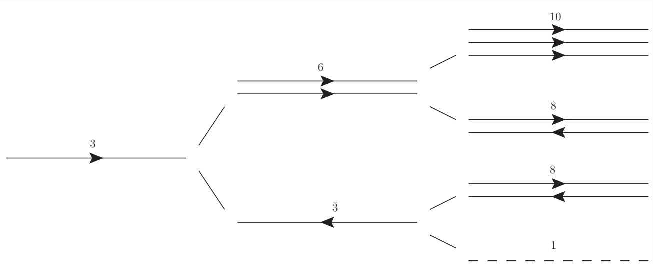


Three conceptual options

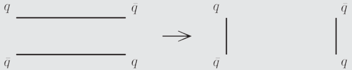
1. Highest multiplet (Rope).
2. Lower multiplet (junction structure).
3. Singlet.

Lower multiplets & singlets → QCD colour reconnection.

Junction CR (Christiansen and Skands arXiv:1505.01681 [hep-ph])

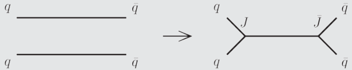
- Possible structures from QCD-inspired weight.
- Selection relies on λ-measure (potential energy).

Ordinary string reconnection



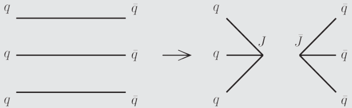
($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



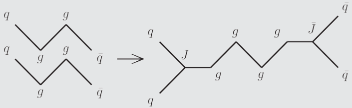
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



(Depends on number of gluons)

The highest multiplet

- Remaining structure joins in a rope.
- Rope breaks one string at a time, reducing the *remaining* tension.
- Junctions carry baryon number.

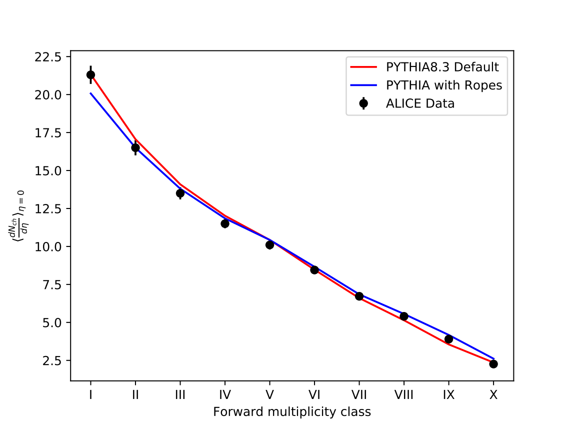
Strangeness enhanced by:

$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- QCD + geometry extrapolation from LEP.
- Can *never* do better than LEP description!

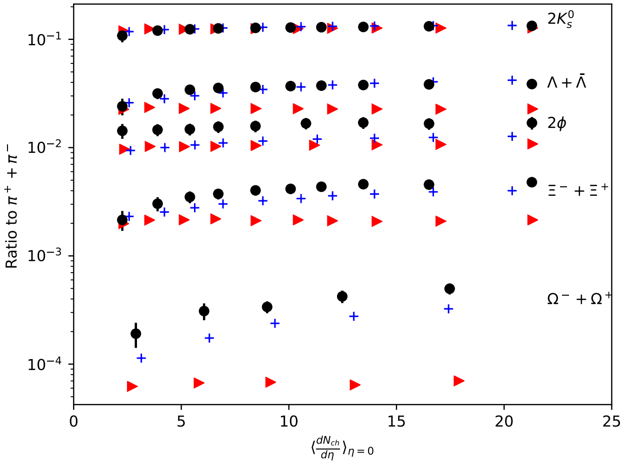
Forward/central multiplicity folding

- Full, honest comparison requires reproduction of centrality-measure.
- Recently possible in the Rivet project (rivet.hepforge.org, ask for details)



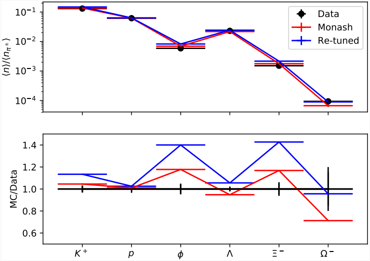
Strangeness enhancement

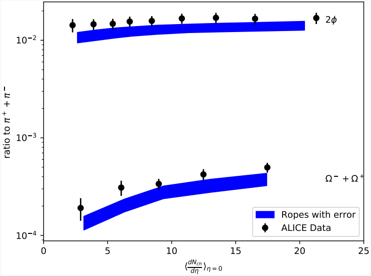
- Fair description, but quantitavely off in places.
- Most interesting for further microscopic development!



The LEP constraints (An aside, CB in prep.)

- Statement: Pythia describes LEP correctly!
- Truth: ... well, mostly!





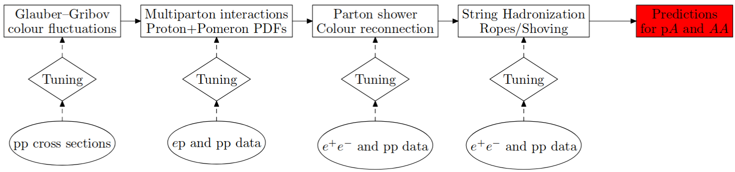
- Even LEP leaves room for model development!
- ...and LHC allows for catching suspicious data!
- Needs: Apples-to-apples comparison to data.

Summary of pp part

- String interactions to explain collective phenomena in pp.
  - String shoving for flow.
  - Rope hadronization & junctions for strangeness.
- Can reveal venues for jet modifications in pp.
- Can shed light on old data from LEP.
- Next: Going to heavy ion physics.

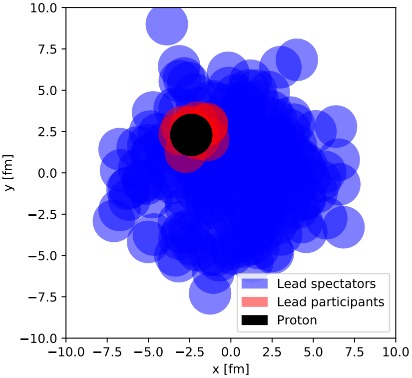
Angantyr – the Pythia heavy ion model (CB, G. Gustafson, L. Lönnblad: JHEP 1610 (2016) 139, += Shah: JHEP 1810 (2018) 134)

- Pythia MPI model extended to heavy ions since v. 8.235.
    1. Glauber geometry with Gribov colour fluctuations.
    2. Attention to diffractive excitation & forward production.
    3. Hadronize with Lund strings.



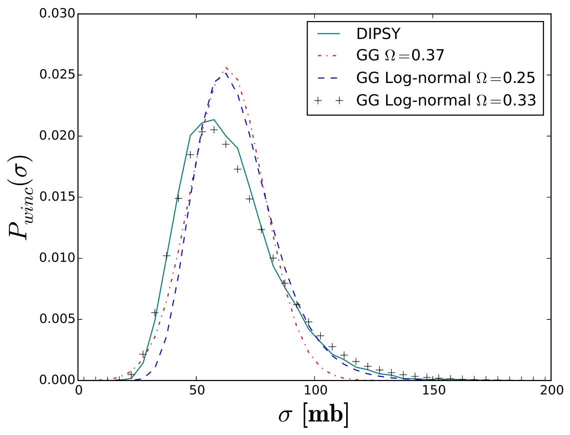
Glauber initial state

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



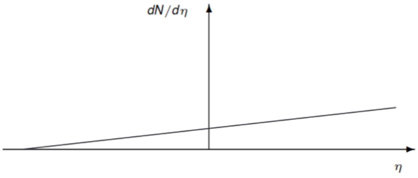
Glauber–Gribov colour fluctuations

- 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.



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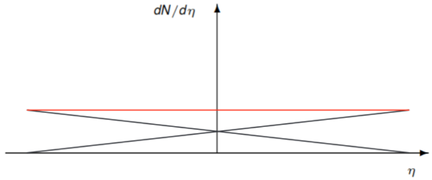

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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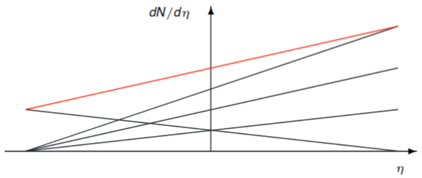

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad \text{(p}A\text{)}$$

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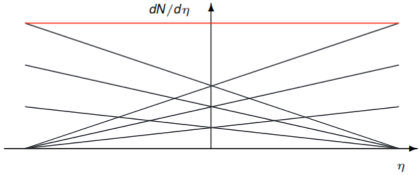
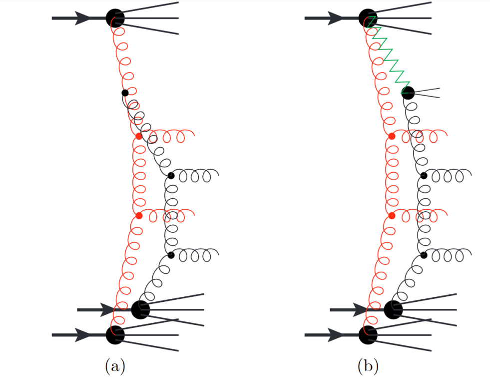


$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

- 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.

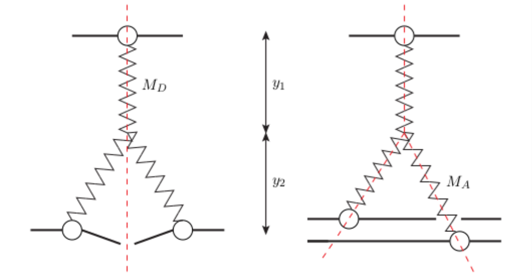
The emission function

- 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.



Secondary absorptive interactions

- Similarity: triple-Pomeron diagrams.



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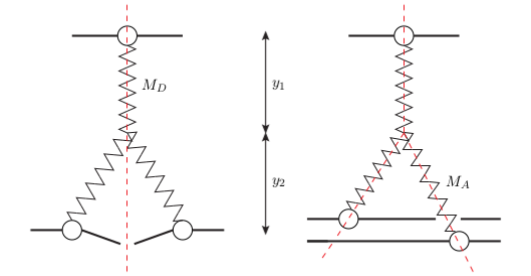


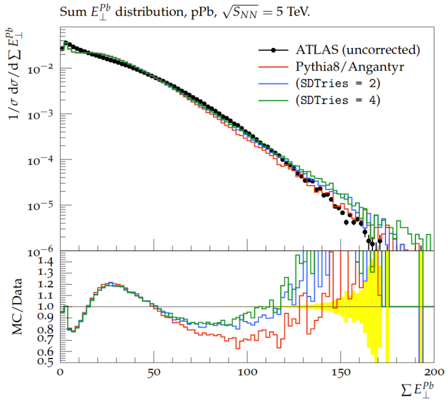
Diagram weight proportial to $(1 + \Delta = \alpha_{\mathbb{P}}(0))$

$$\frac{ds}{s^{(1-2\Delta)}} \frac{dM_D^2}{(M_D^2)^{(1+\Delta)}} \text{ diffractive excitation,}$$

$$\frac{ds}{s^{(1-\Delta)}} \frac{dM_A^2}{(M_A^2)^{(1-\Delta)}} \text{ secondary absorption.}$$

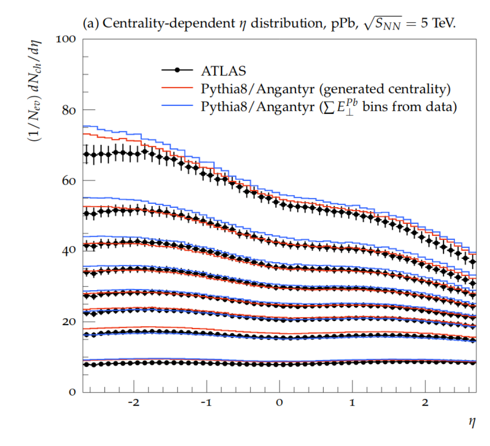
Some results - pPb

- Centrality measures are delicate, but well reproduced.



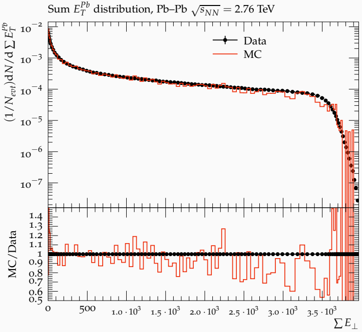
Some results - pPb

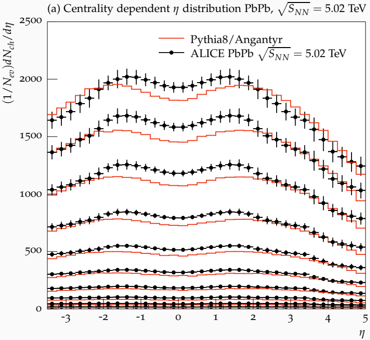
- Multiplicity distributions well reproduced.



Basic quantities in AA

- Reduces to normal Pythia in pp, in pA in AA:
    1. Good reproduction of centrality measure.
    2. Particle density at mid–rapidity.





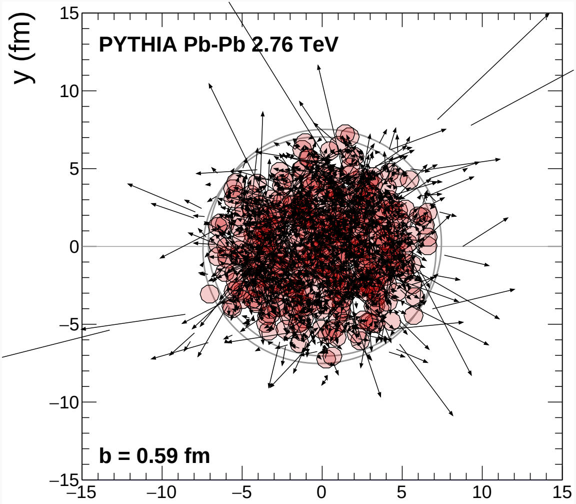
- Necessary baseline for any full model.
- FS needs hadronization mechanism.

So... collectivity in AA?

- Ropes and shoving in AA a work in progress.
- Conceptual difficulty:
  1. Strings live about 2 fm before hadronization.
  2. A QGP lives $\approx$ 10 times longer!
  3. How can we get the neccesary amount of flow?

Final state interactions in AA (CB, D. D. Chinellato, A. Vieira, J. Takahashi: in prep.)

- Hadronic final state interactions matters in AA.
- Especially in non-fluid scenario, with short times.
- Pythia/Angantyr + URQMD.



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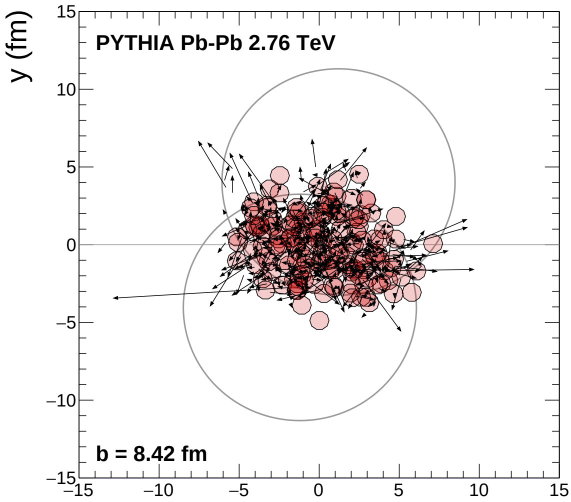

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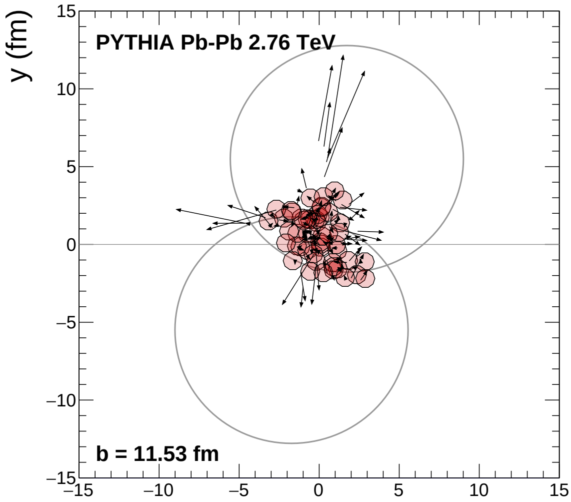
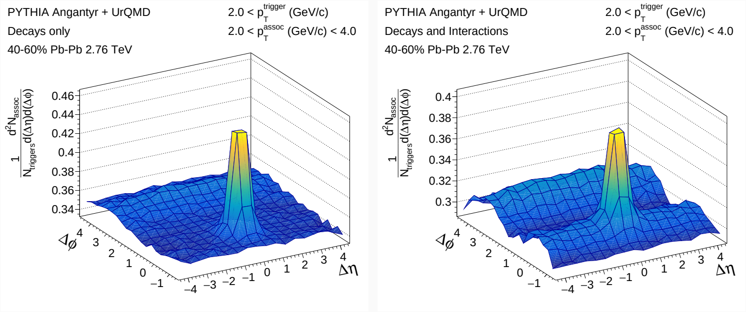


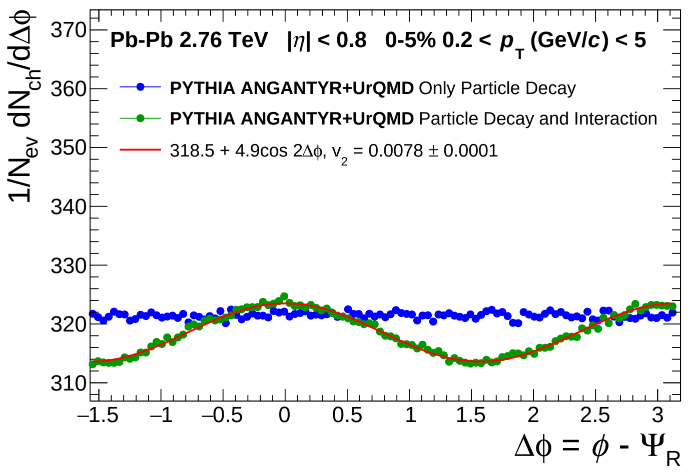
Results – flow

- Rescattering produces correlations long-range in η (the double ridge).
- Previously seen, but not at these energies, with general purpose MC input (Bleicher *et al.* arXiv:nucl-th/0602009).



Results – flow

- Understanding model influence: Correlations wrt. event plane calculated from Pythia Glauber.
- Automatic removal of jet peak.



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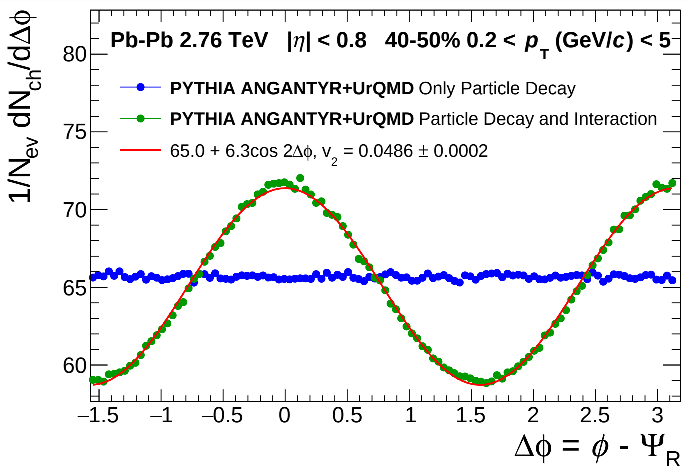

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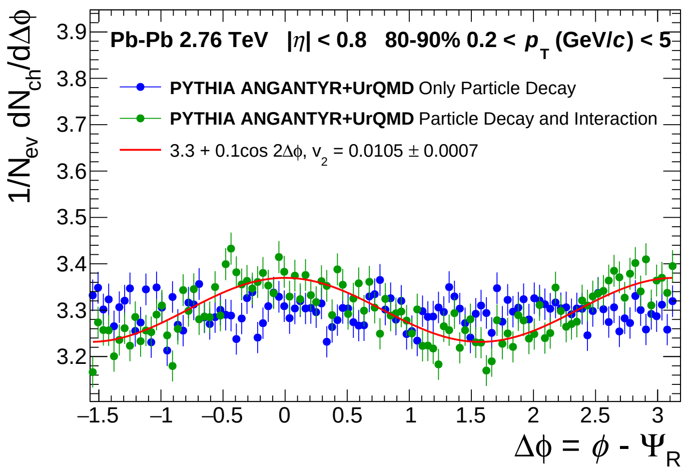
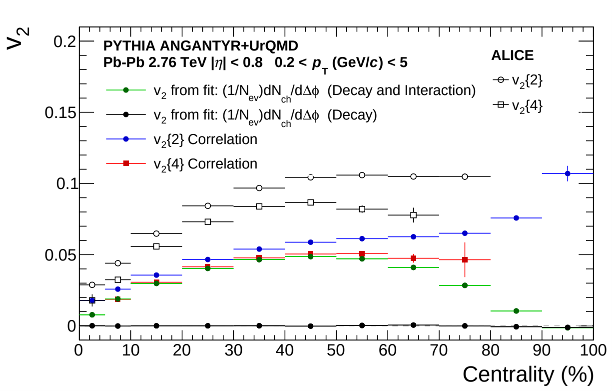


Results – elliptic flow coefficients

- v_2 vs centrality: same dynamics as in ALICE data, but 50% magnitude; v_2 via cumulants similar to v_2 with correlations wrt. event plane



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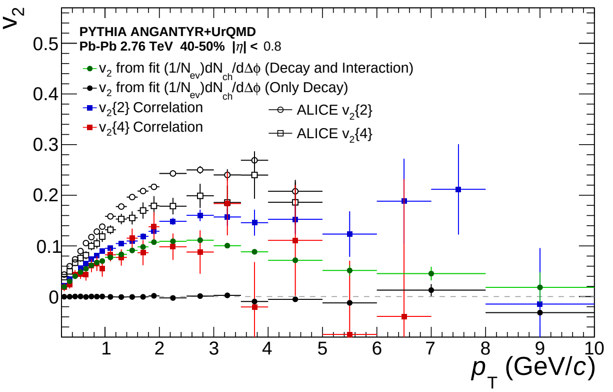
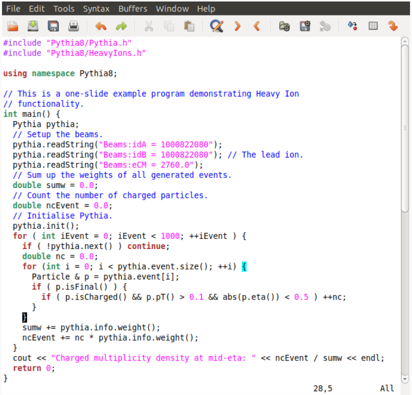


- Similar conclusion from $v_2(p_\perp)$

Summary of the AA part

- pA and AA collisions in PYTHIA.
- Focus on soft productions.
- Key: Cross section fluctuations & secondary absorption.
- Early results PYTHIA + URQMD promising aspects.
- Easy to use: Download and run.
- To come: microscopic collectivity in AA.




```
#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;
}
```

Summary

Most important question for QCD phenomenology!

◇ Does similar signatures across systems share physics origin?

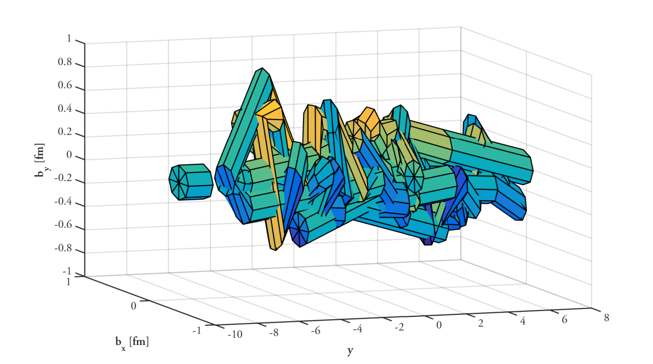
- Answer requires combined effort from:
  - ◇ pp & HI, low & high energy.
  - ◇ theory, phenomenology and experiment.
- This talk "small" $\rightarrow$ "large".
  - ◇ "large" $\rightarrow$ "small" just as crucial.
  - ◇ all approaches: apples-to-apples comparisons to data important.
- Common problem: key future experiments.
  - ◇ qualitative differences between thermalised and non-thermalised approaches?
  - ◇ what can ultra-small systems tell us? (e^+e^-, UPCs, EIC...)
  - ◇ many possibilities for collaboration.
- Exciting times for heavy ion physics ahead...
- ... if we know what questions to ask!

Thank you for the invitation!

Some additional material

The importance of the initial state

- Space–time information is important: We rely on models! Also true for hydro.
- Here: Overlapping 2D Gaussians (p mass distribution).
- Figure string $R = 0.1$ fm, reality $R \sim 0.5$ fm.



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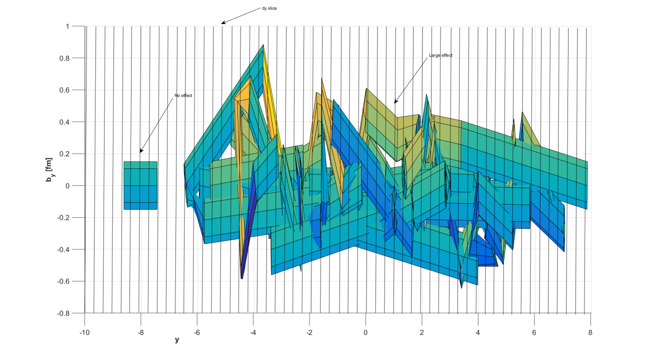

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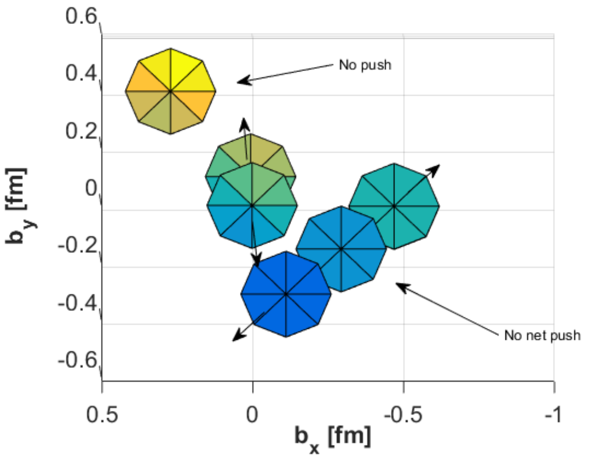


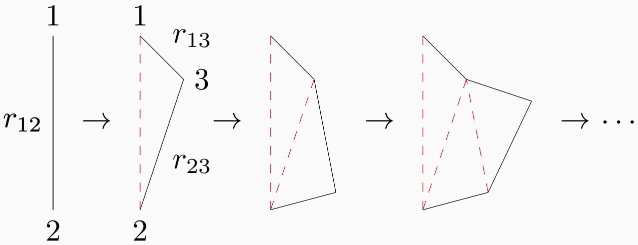
Constraining the initial state (CB and C. O. Rasmussen: 1907.12871 [hep-ph])

- *Ad hoc* models of the initial state not optimal.
- Mueller dipole BFKL as parton shower (from Pythia 8.3X).

Dipole splitting and interaction

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y\ \mathrm{d}^2\vec{r}_3} = \frac{N_c\alpha_s}{2\pi^2}\frac{r_{12}^2}{r_{13}^2 r_{23}^2}\Delta(y_{\min}, y),$$

$$f_{ij} = \frac{\alpha_s^2}{2}\log^2\left(\frac{r_{13}r_{24}}{r_{14}r_{24}}\right).$$



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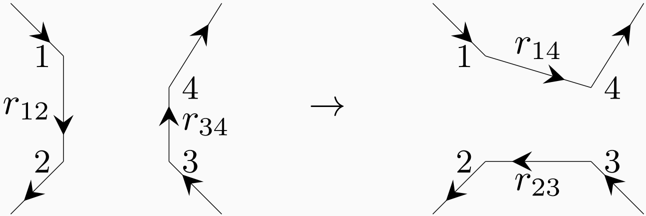
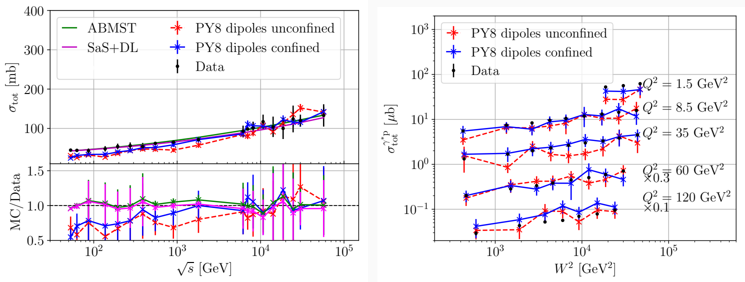


Everything fitted to cross sections

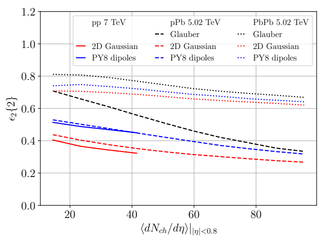
- Avoids fitting to predictions.
- Unitarized dipole-dipole amplitude plus Good-Walker.

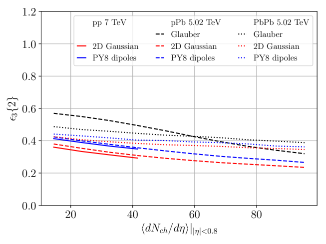
$$T(\vec{b}) = 1 - \exp\left(-\sum f_{ij}\right), \sigma_{tot} = \int d^2\vec{b}\, 2T(\vec{b})$$



Geometry in pp, pA and AA

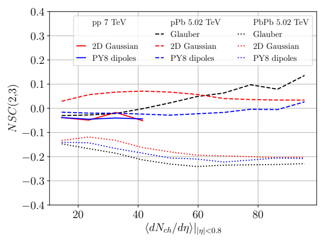
- Assuming $\epsilon_{2,3} \propto v_{2,3}$.
- Dipole model: $\epsilon_{2,3}$ equal for pp and pPb.

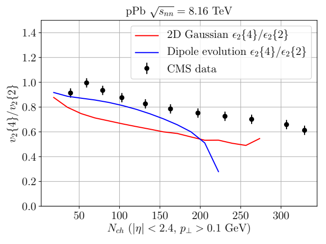




Flow fluctuations: Looking inside

- Flow fluctuations and normalized symmetric cumulants.
- Best discrimination in pPb.
- Dipole evolution $\rightarrow$ negative $NSC(2,3)$ in pPb.





- *Important to develop realistic initial states.*
- *Point stands also for hydro.*

Jet shoving: Hadrochemistry

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

Jet shoving: Hadrochemistry

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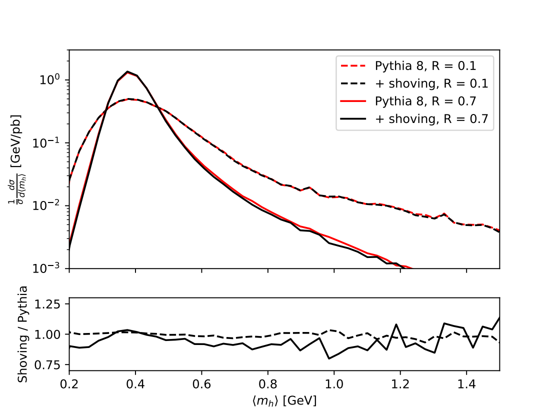
- Study inclusive quantities: Average hadron mass and total jet charge: $\langle m_h \rangle = \frac{1}{N_p} \sum_i^{N_p} m_{h,i}$, $Q_j = \sum_i^{N_p} q_{h,i}$



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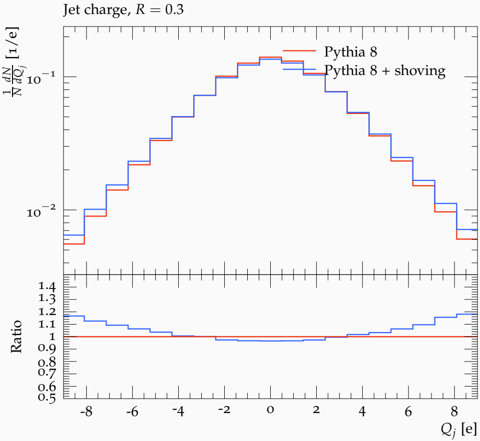

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