Hadrochemistry and flow from PYTHIA's point of view

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Introduction

- Small systems collectivity is becoming precision physics!
- Models are plentiful, detailed knowledge needed to falsify:
    - On th. side: Detailed knowledge about experimental conditions (triggers, particle definitions, centrality definitions, "what is a cumulant?"...).
    - On exp. side: What is the physics content of the models, how do they differ? ("Pythia with color reconnection explains it...").

Pythia perspective

- Not one, but several models strung together!
- Underlying models ! = Pythia implementation.
- Pythia has no Quark–Gluon Plasma.

- This talk: hadrochemistry and flow, the physics content.
    1. MPIs and color reconnections.
    2. Rope hadronization.
    3. String shoving.
    4. The importance of the initial state.

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

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

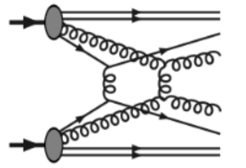


Figure T. Sjöstrand

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

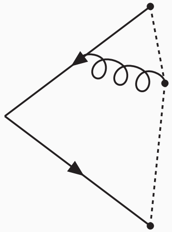
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > ...$ from:

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

- Picture blurred by CR, but holds in general.

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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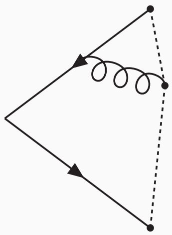

Lund symmetric fragmentation function

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

a and b related to total multiplicity.

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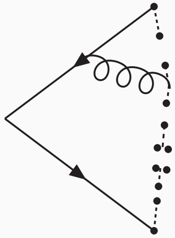

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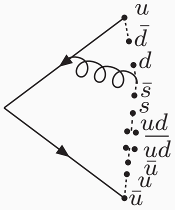

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Light flavour determination

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

Related to κ by Schwinger equation.

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-$p_\perp$.

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

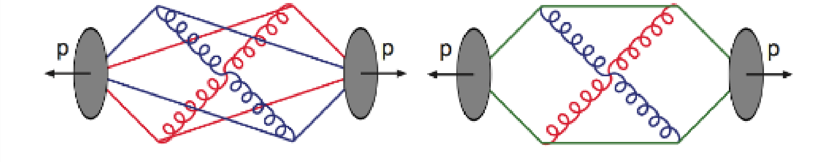


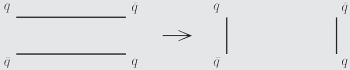
Figure T. Sjöstrand

- Actual merging by minimization of "potential energy":

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

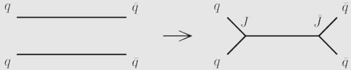
- Possible structures from QCD-inspired weight.
- Selection relies on λ-measure (potential energy).

Ordinary string reconnection



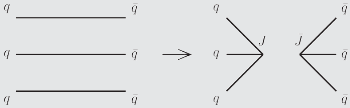
(q$\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



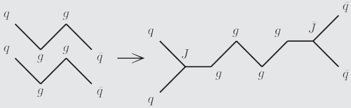
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



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

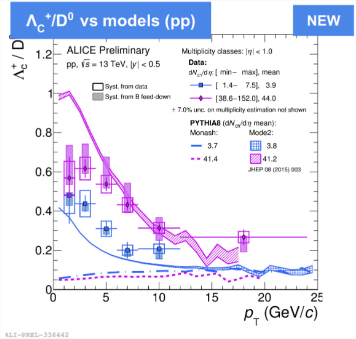
Zipping reconnection



(Depends on number of gluons)

Charmed baryons (Christopher Hills (ALICE), Hard Probes 2020)

- Good laboratory – highlights the effects!
- Changes the relative baryon/meson production rate.
- Keep the amount of charm fixed!



- ➢ Significant enhancement with multiplicity
- ➢ Described well with Pythia including colour reconnection

Colour Reconnection – microscopic collectivity?

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

- Mechanism allows cross–talk over an event.
- Needed for multiplicity & $\langle p_\perp \rangle$.
- Produces flow–like effect.
- Additional baryons!

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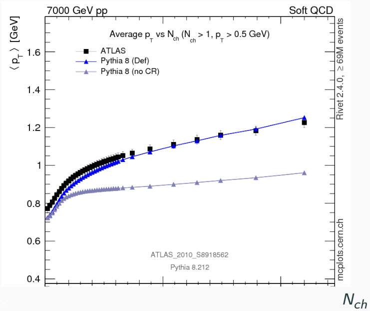

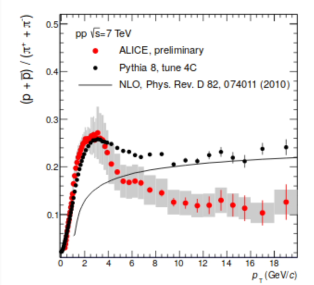

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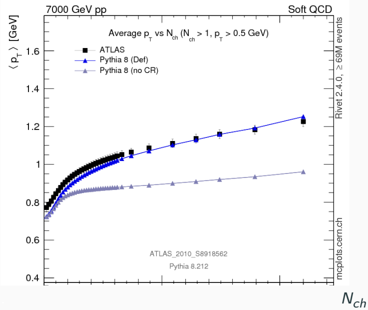

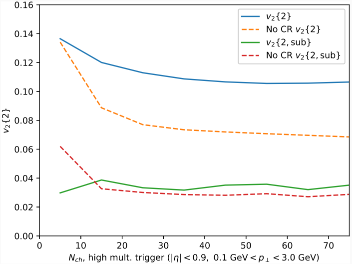

Rope Hadronization (JHEP 1503 (2015) 148 – explored heavily in 80's and 90's!)

- 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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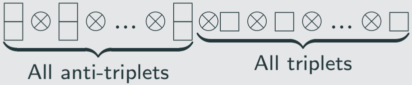
Easily calculable using SU(3) recursion relations

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



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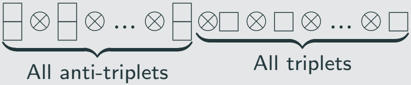
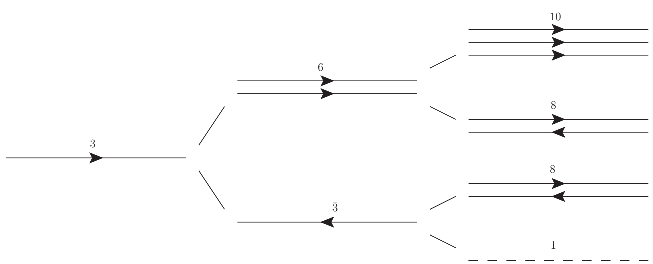


- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Divide and conquer!

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



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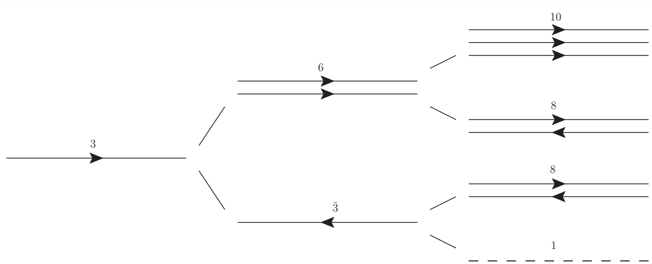


Three conceptual options

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

Lower multiplets & singlets $\rightarrow$ QCD colour reconnection.

The highest multiplet

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

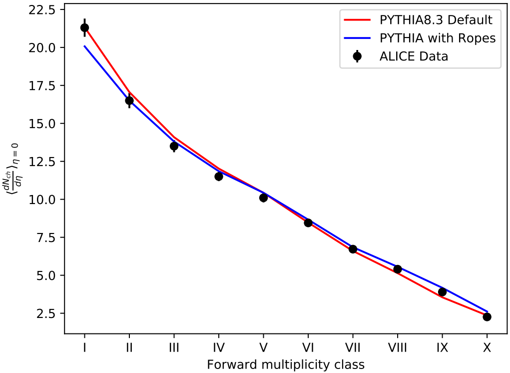
Strangeness enhanced by:

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

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

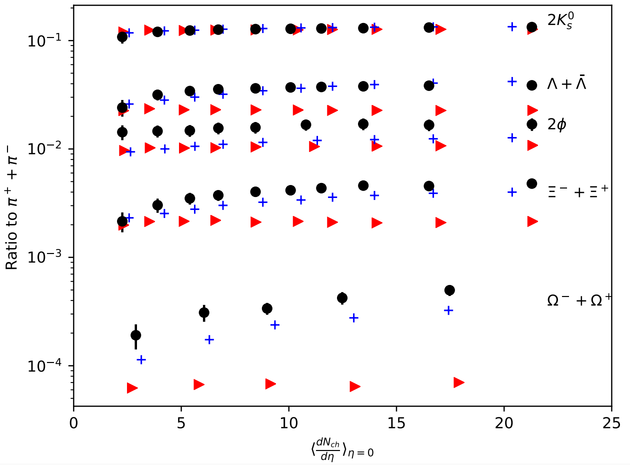
Forward/central multiplicity folding

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



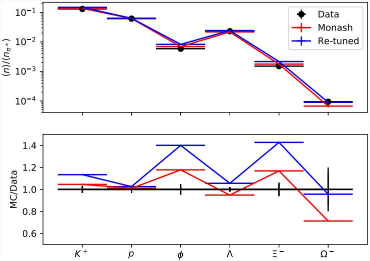
Strangeness enhancement

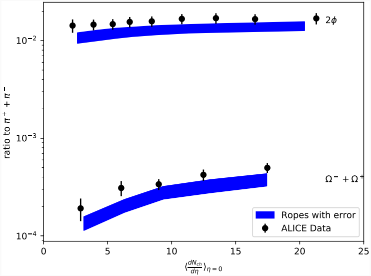
- Red: Pythia 8 Default, Blue: Pythia 8 w. Ropes, Black: ALICE data.



An aside about LEP constraints

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

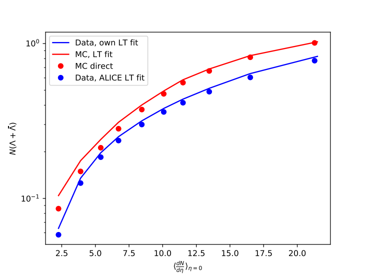


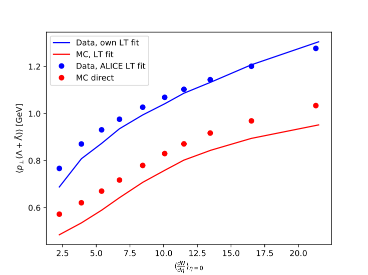


- Even LEP leaves room for model development!
- ...and LHC allows for catching suspicious data!
- Needs: Apples-to-apples comparison to data.

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.

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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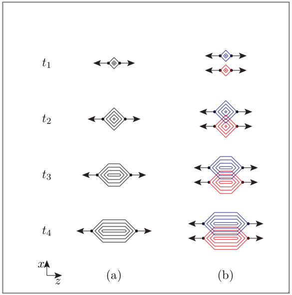

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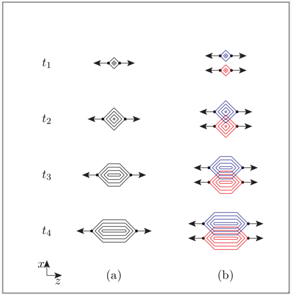
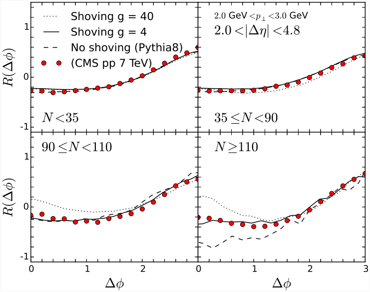
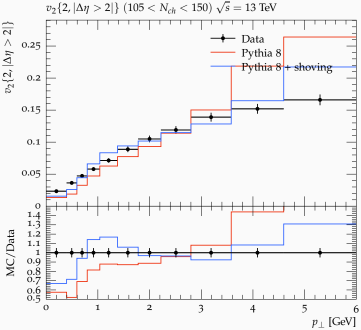


- All energy in electric field $\to g = 1$.
- Reality:
  Type 1 SC Energy to destroy vacuum.
  Type 2 SC Energy in current.

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?



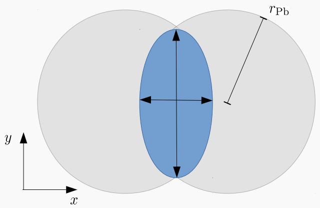


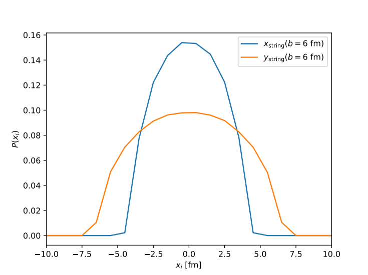
Shoving: Why is AA so difficult?

- In pp two crude approximations were made:
  1. All strings straight and parallel to the beam axis.
  2. Pushes can be added as soft gluons.
- This gives problems in AA, which we are solving:
  - 👍 Beam axis $\rightarrow$ parallel frame.
  - 👍 Soft gluons $\rightarrow$ push on hadrons.
  - 👎 Straight strings $\rightarrow$ treatment of gluon kinks? (WiP).
- Enough for a toy run!

A toy example

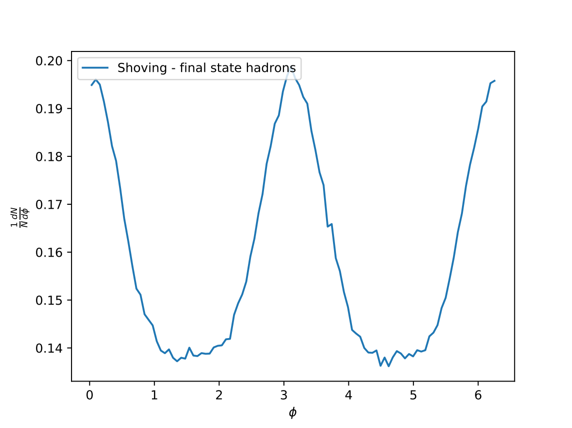
- Consider an elliptical overlap region filled with straight strings (no gluons).
- Same shoving parameters as for pp.





Toy results (Data: ALICE PRL 116 (2016) 132302)

- To take away: The mechanism gives a resonable response.
- A local mechanism *can* result in global features.



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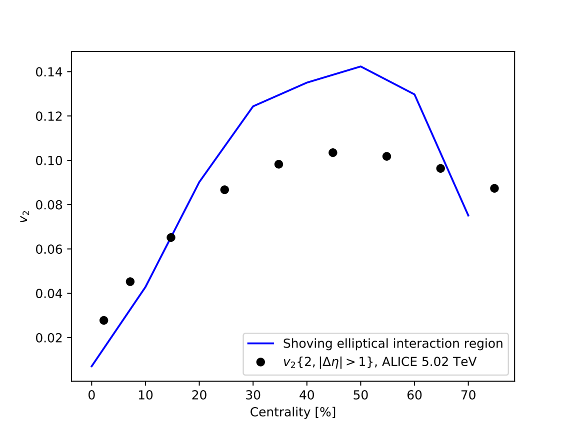
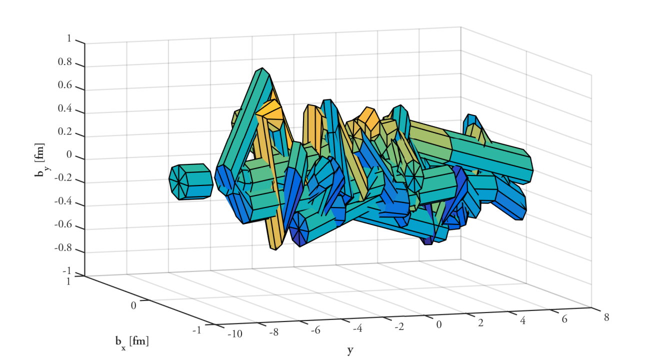


The importance of the initial state

- 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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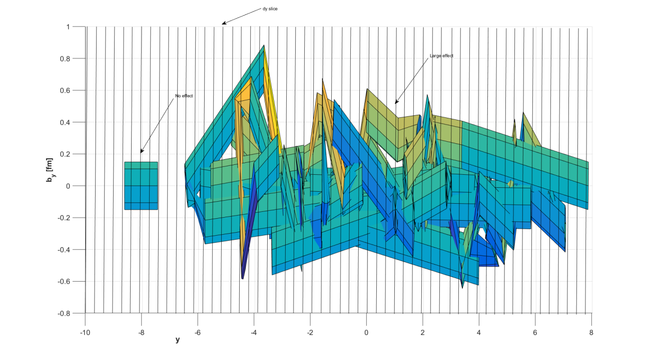

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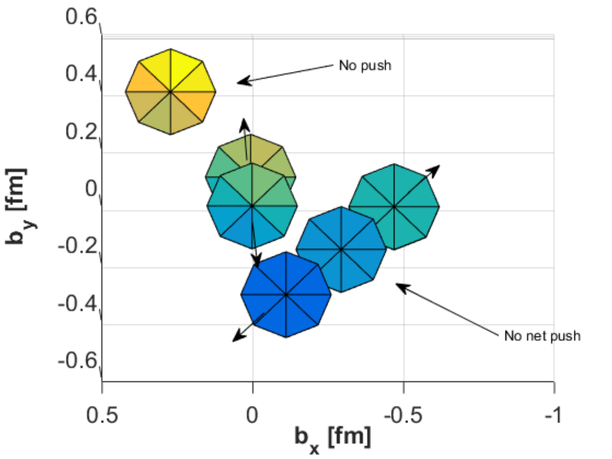


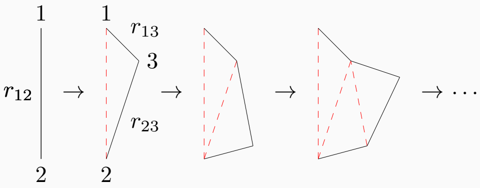
A more realistic model (WIP: with Ilkka Helenius; CB & C. O. Rasmussen: 1907.12871 [hep-ph])

- Initial state cascade/hot-spots from perturbative QCD.
- Mueller dipole BFKL as parton shower.

Dipole splitting and interaction

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

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



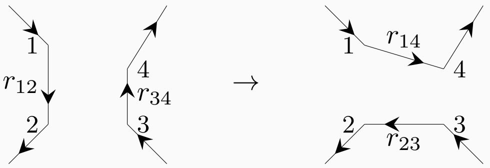
A more realistic model (WIP: with Ilkka Helenius; CB & C. O. Rasmussen: 1907.12871 [hep-ph])

- Initial state cascade/hot-spots from perturbative QCD.
- Mueller dipole BFKL as parton shower.

Dipole splitting and interaction

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

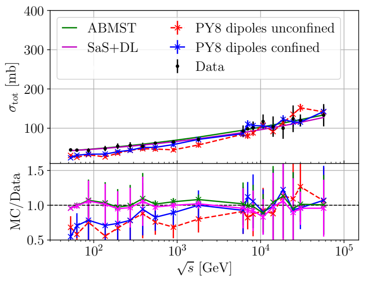
$$f_{ij} = \frac{\alpha_s^2}{2}\log^2\left(\frac{r_{13}r_{24}}{r_{14}r_{24}}\right).$$

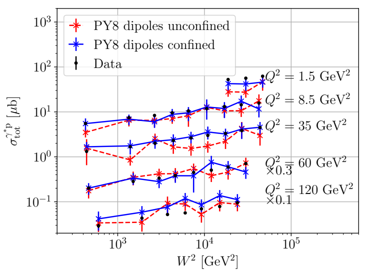


Everything fitted to cross sections

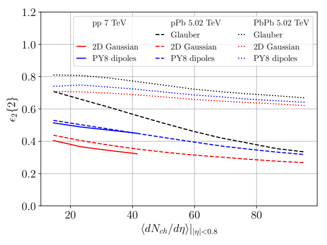
- Avoids fitting to predictions.
- Unitarized dipole-dipole amplitude plus Good-Walker.

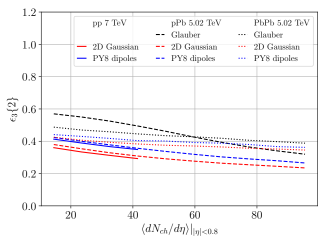
$$T(\vec{b}) = 1 - \exp\left(-\sum f_{ij}\right), \sigma_{tot} = \int d^2\vec{b}\, 2T(\vec{b})$$





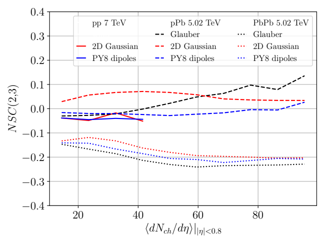
- Assuming $\epsilon_{2,3} \propto v_{2,3}$.
- Dipole model: $\epsilon_{2,3}$ equal for pp and pPb.

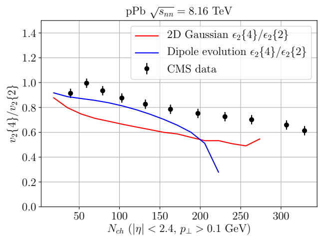




Flow fluctuations: Looking inside

- 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.*

Rivet (for heavy ions) (2001.10737)

- Comparison between model and experiment is crucial!
- It is important to get analysis details exactly right.
- Recent joint project between ALICE & MC community.
- Easy implementation of triggers, primary particiles, centrality classes, flow...

```cpp
/// Perform the per-event analysis
void analyze(const Event& event) {

  // Charged, primary particles with at least pT = 50 MeV
  // in eta range of |eta| < 0.5
  Particles chargedParticles =
    applyProjection<ALICE::PrimaryParticles>(event,"APRIM").particles();

  // Trigger projections
  const ChargedFinalState& vz1 =
    applyProjection<ChargedFinalState>(event,"VZERO1");
  const ChargedFinalState& vz2 =
    applyProjection<ChargedFinalState>(event,"VZERO2");
  const ChargedFinalState& spd =
    applyProjection<ChargedFinalState>(event,"SPD");
  int fwdTrig = (vz1.particles().size() > 0 ? 1 : 0);
  int bwdTrig = (vz2.particles().size() > 0 ? 1 : 0);
  int cTrig = (spd.particles().size() > 0 ? 1 : 0);

  if (fwdTrig + bwdTrig + cTrig < 2) vetoEvent;

  const CentralityProjection& centrProj =
    apply<CentralityProjection>(event, "V0M");
  double centr = centrProj();
  if (centr > 80) vetoEvent;
  // Calculate number of charged particles and fill histogram
  double nch = chargedParticles.size();
  _histNchVsCentr->fill(centr, nch);
}
```

Instead of a conclusion: Call for action!

- Transition to precision science – activity on the MC side. (also in eg. HERWIG)
- New kid on the block: Rivet for heavy ions, strong pheno/ALICE collaboration.
- Rivet is a tool we can and should use to strengthen understanding.
- It is more than just another analysis framework...

A means to meet stratetic decisions about th/exp collaboration!

- Not just re-working old analyses, but also:
  1. Keeping theorists honest!
  2. Valuable input for tuning efforts.
  3. Precise communication of predictions & exp. constraints.
  4. Valuable for upgrade discussions?
- Definitely something to build on in the future!

Thank you for the invitation!