Collectivity in small systems: a microscopic perspective

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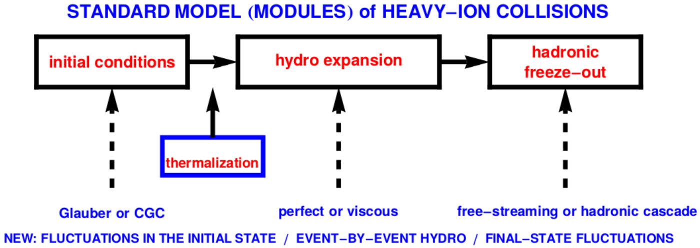
Secondo incontro sulla fisica con ioni pesanti a LHC

Why is collectivity in small systems so interesting?

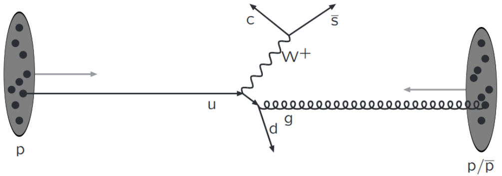
- Collectivity in small systems challenges two paradigms at once!
- On one hand: How far down in systems size does the "SM of heavy ions" remain?
- On the other hand: Can the standard tools for min bias pp (PYTHIA8 , HERWIG 7 etc) remain standard?



(Figure credit: W. Florkowski)

- When does the assumptions of deconfinement and thermalization break down?

Bottom up: The PYTHIA8 picture (Figure credit: T. Sjöstrand)



- Built on perturbative QCD + Lund strings.
- Works very well for most pp applications
- Really throw away 30 years of succesful phenomenology?

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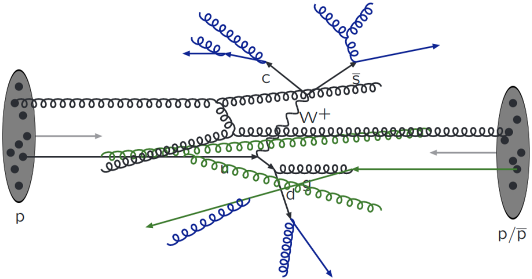

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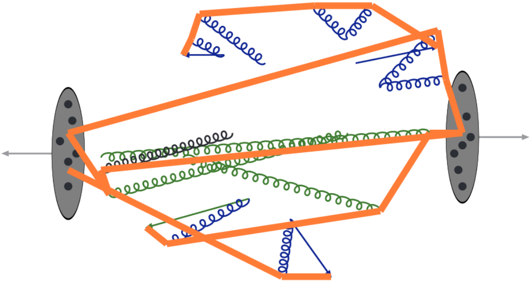

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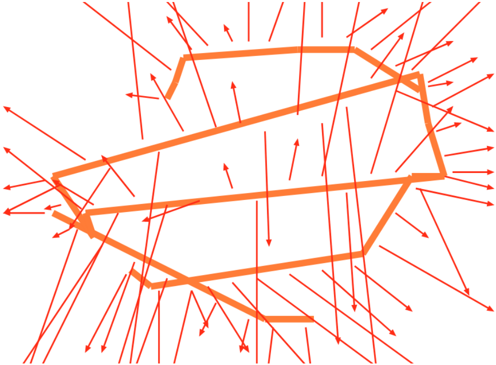

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Microscopic collectivity: Extending the PYTHIA8 picture

- Since last Friday PYTHIA8 has been extended to:
  1. Stacking multiple pp events to a pA or AA event.
  2. Use "Rope Hadronization" to describe strangeness enhancement.
  3. Use "String Shoving" for long range correlations (the "ridge").
  4. Transistion period from DIPSY .
- This talk:
  1. Multiparticle production (MPI model and Lund string).
  2. Rope Hadronization (strangeness).
  3. String shoving (two particle correlations).
  4. Extending to heavy ion (Angantyr framework).
- Several other models in PYTHIA8 (colour reconnection, junctions, popcorn baryons, thermalized strings ...) – please ask me afterwards.
- Try it yourself: `http://home.thep.lu.se/Pythia`

Particle production: MPIs (Sjöstrand and Skands: arXiv:hep-ph/0402078)

- Several partons taken from the PDF (dilute proton wavefunction).
- Hard sub-collisions with $2 \to 2$ ME:

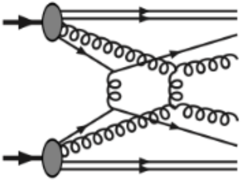


Figure T. Sjöstrand

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

- 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).
- Further emission by parton shower.

Concepts of String Hadronization (hep-ph/0603175)

- Linear confinement potential $V(r) \approx \kappa r$, confirmed on the lattice.
- Valid for large distances – for small distances perturbation theory should be valid.

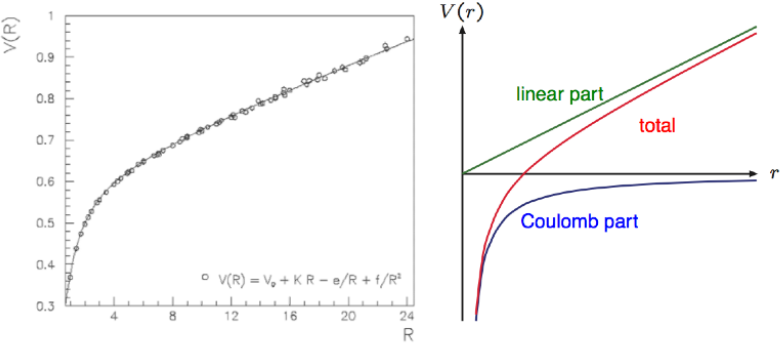
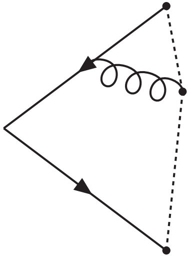


Figure credit: T. Sjöstrand

- Very simple, but powerful, picture.

Lund String Hadronization (See *e.g.* hep-ph/0603175)

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



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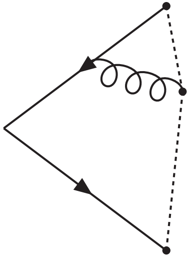

Lund symmetric fragmentation function

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

a and b related to total multiplicity.

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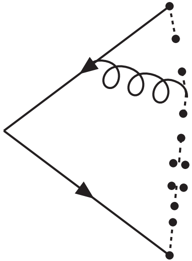

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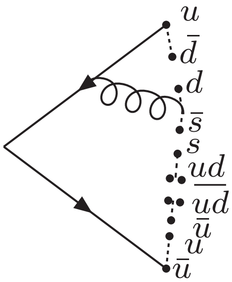

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Flavours determined by relative probabilities

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

Probabilities related to κ by Schwinger equation.

Color reconnection in PYTHIA8

- Many partonic subcollisions ⇒ Many hadronizing strings.
- Parton shower + string does not describe pp data.
  1. Too much multiplicity.
  2. No $< p_\perp > (N_{ch})$ dependence.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

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

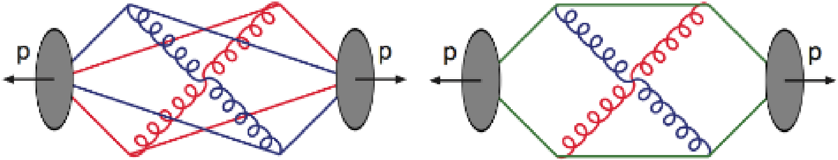


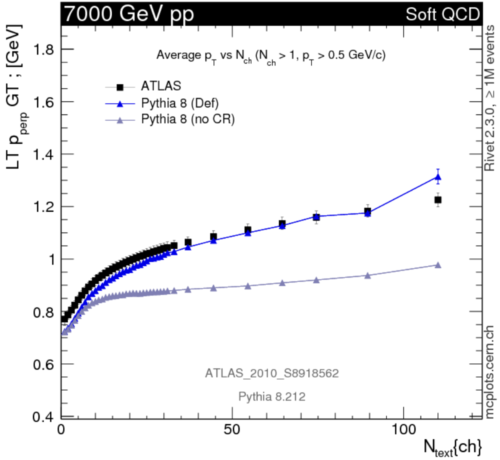
Figure credit T. Sjöstrand

- Actual merging is decided by minimization of "potential energy":

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

Best known effect: $< p_\perp > (N_{ch})$ (Data ATLAS: arXiv:1012.5104 [hep-ex])

- PYTHIA8 with CR describes this.
- Simple model enough to describe behaviour "on average".
- Flow-like behaviour from CR, but not enough to describe data (A. Ortiz Velasquez et al., Phys. Rev. Lett. 111 (2013) 0420001)



Lessons so far

- Strings are already a collective phenomenon, but not enough to describe even basic features of pp collisions, such as $dN/d\eta$ or $< p_\perp > (N_{ch})$.

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- "Colour reconnection" is an umbrella term for all types of correction of the $N_c = \infty$ approximation of the parton shower.
- More advanced models of CR exist (and are shown to have effects even in e^+e^-) (see eg. Christiansen and Skands: arXiv:1505.01681 [hep-ph], CB in arXiv:1702.01329 [hep-ph]).

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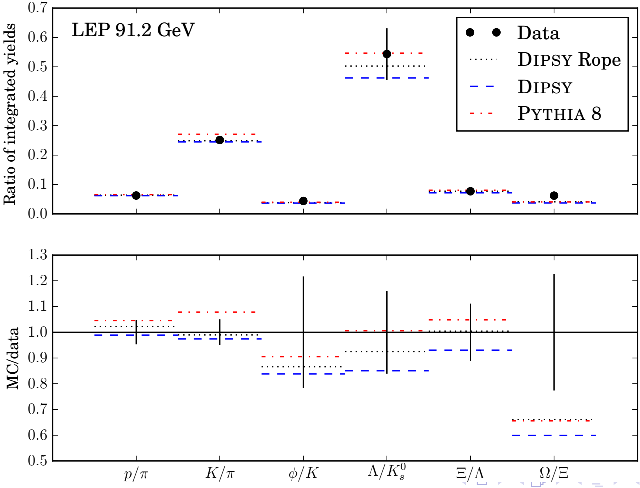
- More advanced models of CR exist (and are shown to have effects even in e^+e^-) (see eg. Christiansen and Skands: arXiv:1505.01681 [hep-ph], CB in arXiv:1702.01329 [hep-ph]).
- Rest of the talk: Newer developments where strings are also allowed to interact.

A look at the flavour description (CB and Christiansen arXiv:1507.02091 [hep-ph])

- Hadronic flavour tuned to e^+e^- data.
- Description works well here (Data SLD, LEP and PDG avg.).



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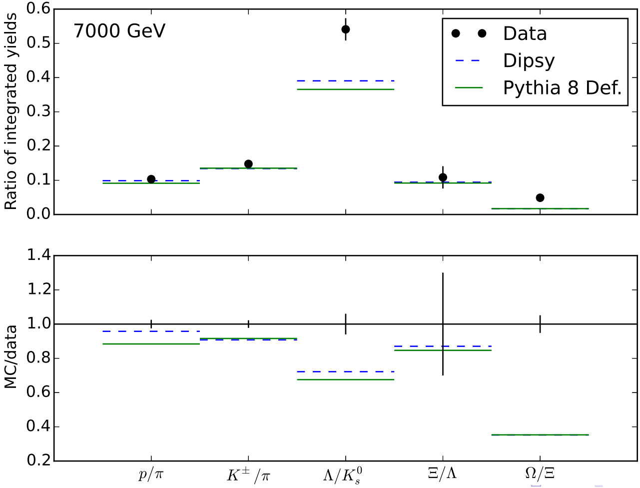
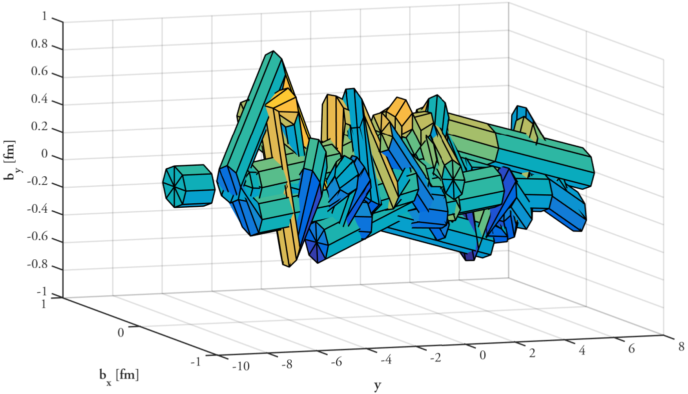
- Description works well here (Data SLD, LEP and PDG avg.).
- Not even inclusively in pp (Data: ATLAS, CMS, ALICE, LHCb).



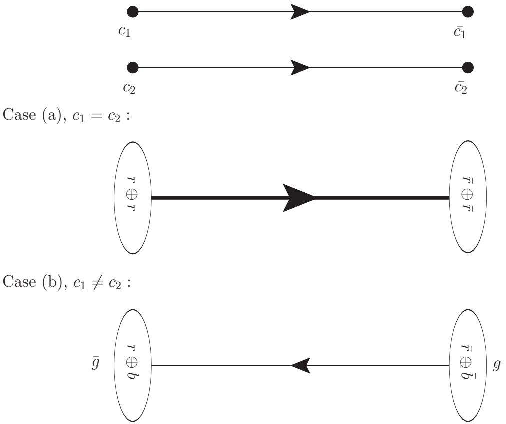
What to do in busy events?

- Even small system collisions are quite busy.
- Remember: Strings are flux tubes *i.e.* confined fields.
- Interference in overlap regions must be treated.



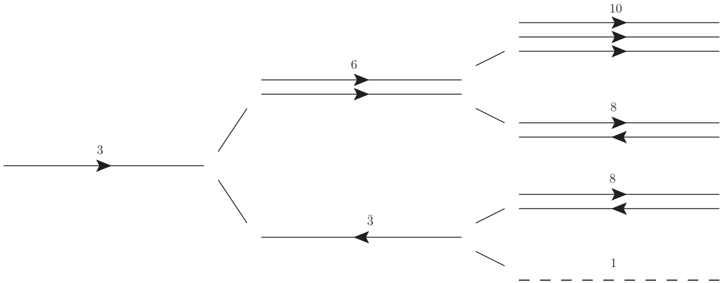
Rope hadronization

- The simplest example: Two $q\bar{q}$ pairs act coherently.
- Two distinct possibilities:



Three classes of effects

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



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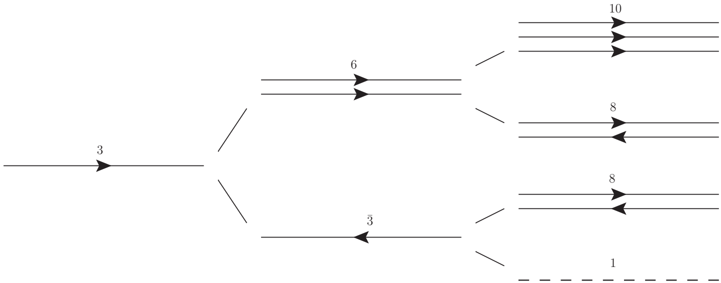

- Three options
  1. Highest multiplet.
  2. Lower multiplet (junction structure).
  3. Singlet.
- Focus on the highest multiplet.

Highest multiplet

- Go from overlapping strings (p and q) to highest multiplet.
- Hadronize highest 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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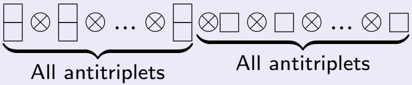
SU(3) recursion relations

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



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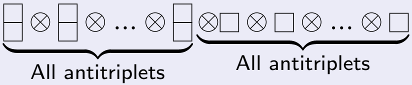

- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p + 1)(q + 1)(p + q + 2)$.
- N serves as a state's weight in the random walk.

Effect on hadronization parameters

Large effect on hadron flavours

- Strange quark breakup suppression:

$$\rho_0 = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho}(\kappa) = \rho_0^{\frac{\kappa_0}{\kappa}}.$$

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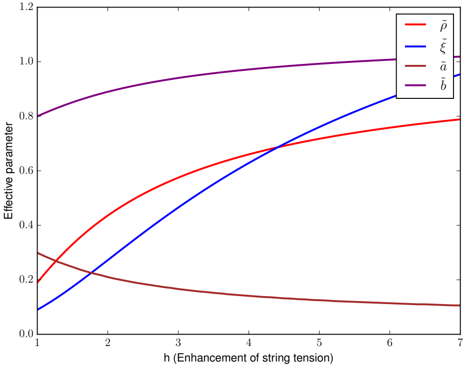
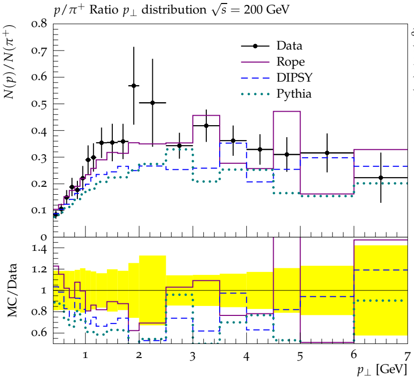
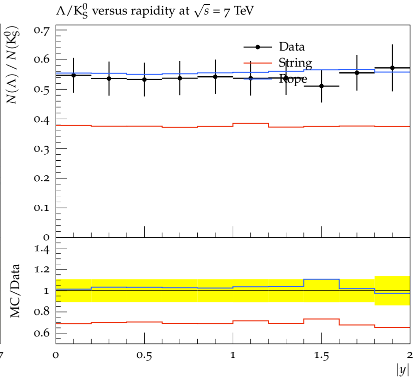


Effect in pp Data: STAR and CMS

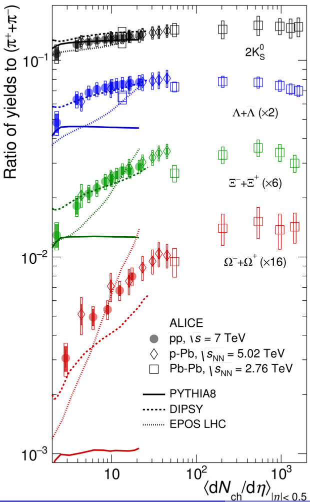
- Important to compare apples to apples.
- The Rivet framework provides this (arXiv:1003.0694 [hep-ph]).
- Precise predictions require precise comparisons.





Strangeness and system size (ALICE: Nature Phys. 13 (2017) 535-539)

- Own comparison – important with apples to apples comparison with data.
- Early sub-jet studies (Mangano and Nachman: arXiv:1708.08369 [hep-ph]).



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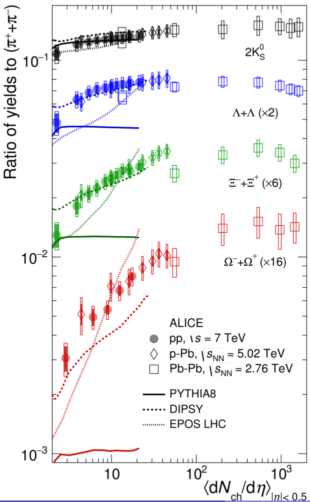
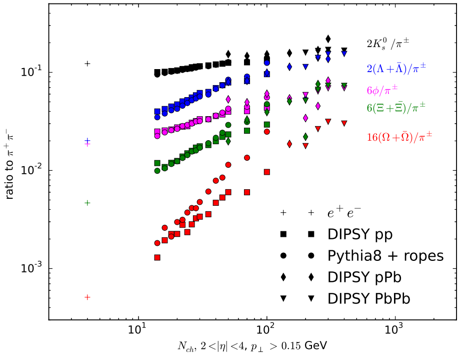
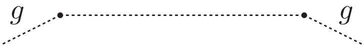




What about the ϕ meson?

Double suppression

- The ϕ is an excellent laboratory for strangeness effects.
- Two *s*-breaks means twice suppression and added sensitivity.



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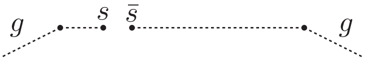

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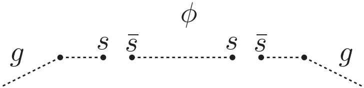

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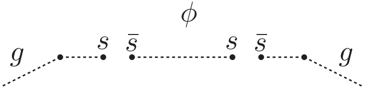
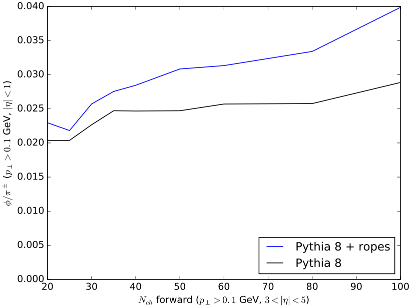
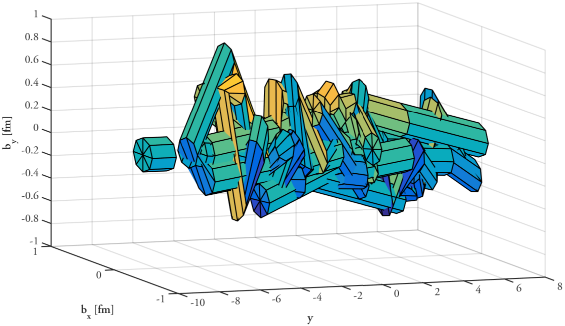




String shoving (CB et al. arXiv:1612.05132 [hep-ph])

- Overlapping strings push each other, generates transverse pressure.
- Earlier analytic + toy MC studies (Abramovsky et al. JETP Lett. 47 (1988) 337-339, Altsybeev arXiv:1502.03608 [hep-ph])
- Now in PYTHIA8 implementation: User can supply own IS model.



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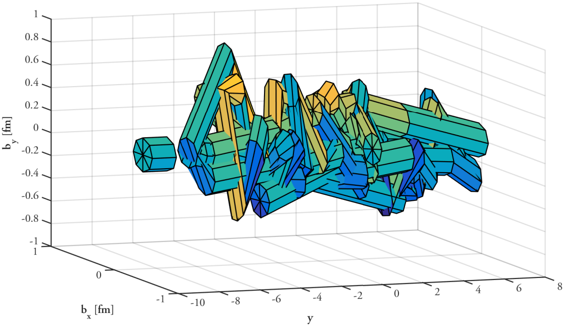


- No assumption of thermalized plasma.
- Not even deconfined plasma!

The shoving pressure

- $p_\perp$ push on string segment, length δl, time interval δt.
- If everything starts in a point at $t = 0$ then $\delta l = t\delta y$.

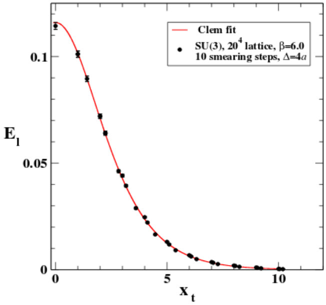
$$\delta p_{\perp 12} = f_{12} \cdot \delta l \delta t = f_{12} \cdot t\delta y \delta t$$

- The force is f; chromoelectric field of effective dual s.c. (lattice).
- Approximate with Gaussian:

$$E_l = C_0 \exp\left(-\frac{x_\perp^2}{2R^2}\right)$$

- Interaction energy between two vortex lines gives force:

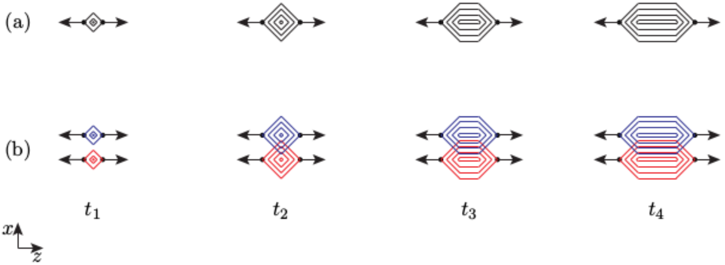
$$f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$



(Cea et al. arXiv:1404.1172 [hep-lat])

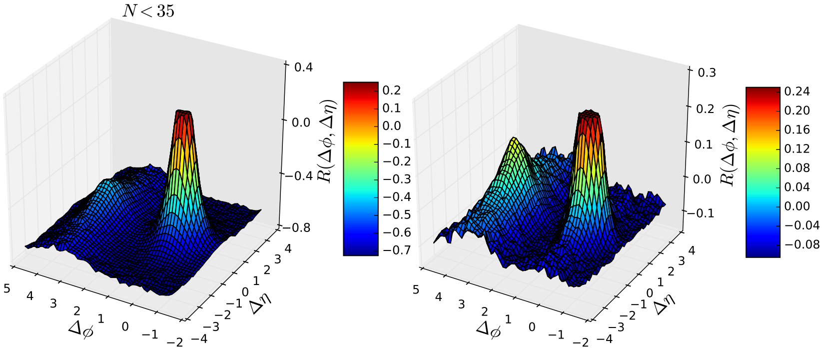
Time evolution

- Assume (crudely) three separate phases.
  1. Strings propagate freely.
  2. Strings shove each other.
  3. Strings hadronize at equilibrium size.
- Simulate field push as small excitation gluons.



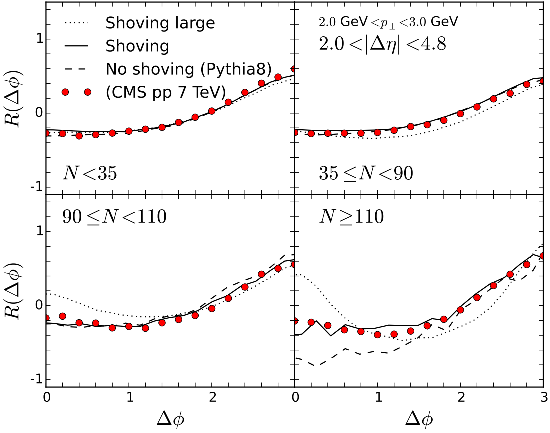
Ridge

- Appeance of a ridge at high event multiplicity.



Ridge II

- One-dimensional projections in qualitative agreement with data.
- Own, qualitative, comparison to CMS (CMS arXiv:1009.4122 [hep-ex]).
- ...quantitative, common comparisons (Rivet) are needed.
- Efforts from ALICE ongoing.



new fig

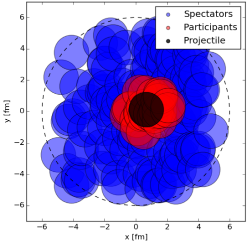
Extrapolate to AA: Glauber + fluctuations (CB et al: arXiv:1607.04434 [hep-ph])

- Q: How can we extrapolate "minimum bias pp" to "minimum bias pA and AA".
- Q: What do we need to reproduce "centrality" $\propto$ forward particle production?
- Wounded nucleons updated to include fluctuations in target and projectile (SD + DD).

$$\Im(A_{el}) = \frac{1}{2}(|A_{el}|^2 + P_{abs}); T \equiv -iA_{el} \Rightarrow$$

$$\frac{d\sigma_{el}}{d^2b} = \langle T(b) \rangle^2 , \frac{d\sigma_{tot}}{d^2b} = 2\langle T(b) \rangle$$

$$\frac{d\sigma_{abs}}{d^2b} = 2\langle T(b) \rangle - \langle T(b) \rangle^2$$



The wounded cross section

- Fluctuations related to diffractive excitations: Good-Walker.

$$\frac{d\sigma_{tot}}{d^2b} = 2\left\langle T \right\rangle_{t,p}, \ \frac{d\sigma_{el}}{d^2b} = \left\langle T \right\rangle_{t,p}^2, \ \frac{d\sigma_{SD,(p|t)}}{d^2b} = \left\langle \left\langle T \right\rangle_{(t|p)}^2 \right\rangle_{(p|t)} - \left\langle T \right\rangle_{p,t}^2$$

$$\frac{d\sigma_{DD}}{d^2b} = \left\langle T^2 \right\rangle_{p,t} - \left\langle \left\langle T \right\rangle_{t}^2 \right\rangle_{p} - \left\langle \left\langle T \right\rangle_{p}^2 \right\rangle_{t} + \left\langle T \right\rangle_{p,t}^2$$

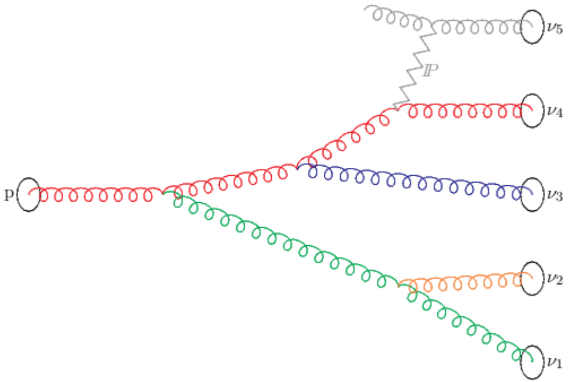
- The *wounded* cross section is the sum of:

$$\frac{d\sigma_{w}}{d^2b} = \frac{d\sigma_{abs}}{d^2b} + \frac{d\sigma_{SD,t}}{d^2b} + \frac{d\sigma_{DD}}{d^2b} = 2\left\langle T \right\rangle_{p,t} - \left\langle \left\langle T \right\rangle_{t}^2 \right\rangle_{p}.$$

- Contributions to "centrality" observable: absorptively wounded, diffractively wounded, NOT elastically scattered.
- We need now to calculate $T(b)$ – Glauber–Gribov approach (Alvioli and Strikman: arXiv:1301.0728 [hep-ph])..

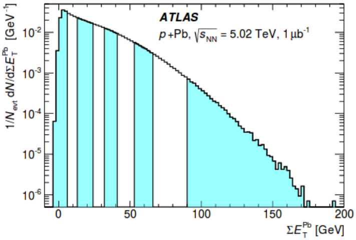
Full final states: Angantyr framework (Included in PYTHIA8)

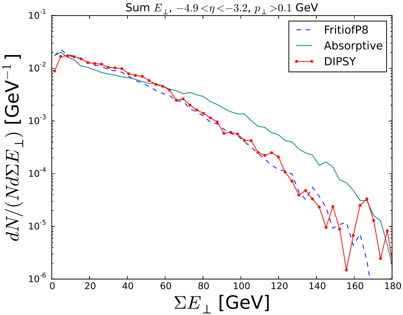
- One absorptive collision contributes to full rapidity span.
- The rest contributes similarly to diffractive excitation (plus a colour exchange).
- Implementation in PYTHIA8 , but idea is general.



Results (Data: ATLAS: 1508.00848 [hep-ex])

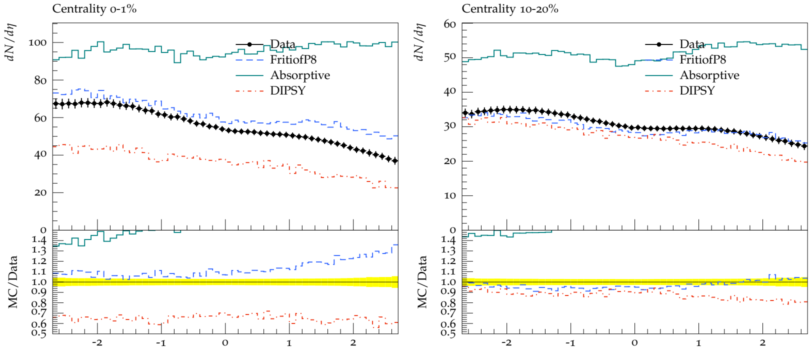
- Very good agreement with centrality observable.
- "Absorptive" overshoots.
- Measuring the exact region where diffractive excitation is important.





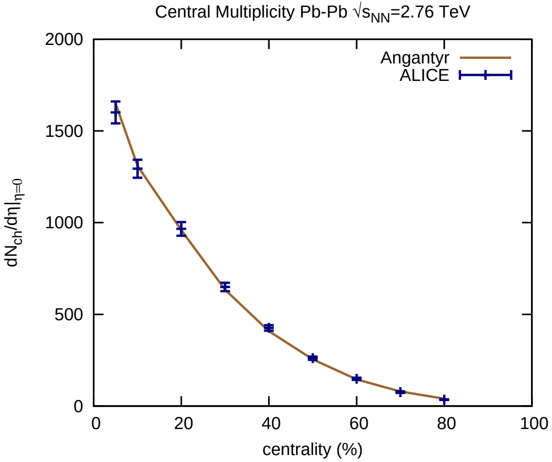
Multiplicity in pA

- Reproducing central collisions well.
- Comparison by own Rivet routine – implementation by exp. would be better.



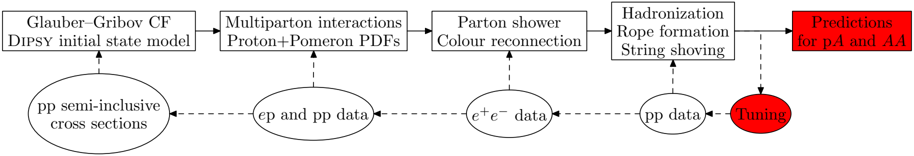
Multiplicity in *AA* (Data: ALICE: arXiv:1012.1657 [nucl-ex])

- Repeating the exercise for *AA*.
- Multiplicity at $\eta = 0$ reproduced well.



Summary

- The Lund MC generators are built on parton showers and Lund string.
- Some collectivity is there from the beginning, but not enough.
- Extending with models built for *pp* (ongoing).
- Extrapolation to *AA* (ongoing).

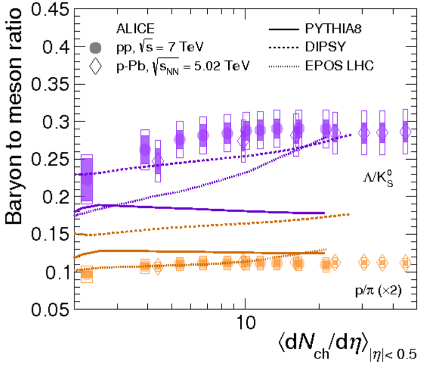


Thank you for your attention!

Bonus slides

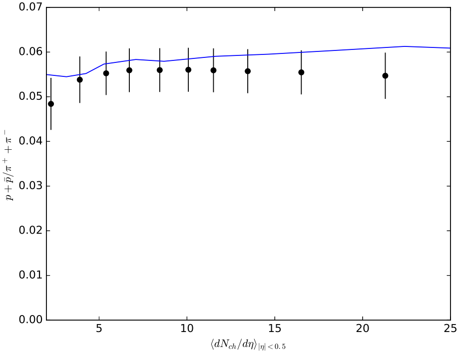
What about the protons?

- Difference between "parameter level" and "particle level" predictions.
- Indeed the rise in p/π is very small.



What about the protons?

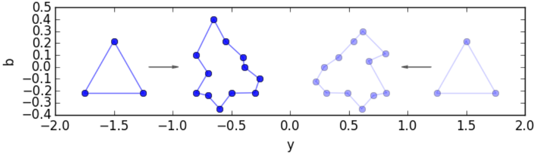
- Difference between "parameter level" and "particle level" predictions.
- Indeed the rise in p/π is very small.
- Pythia standard tune + changing popcorn parameter seems to solve problem
- Plugin still on "toy level" – full treatment to be included in Pythia8.
- Very preliminary comparison (Thanks to C. H. Christensen, ALICE).



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

- Partonic model in impact parameter space:
  Dipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**.
- LL-BFKL with some corrections built on Mueller dipole model (Mueller and Patel arXiv:hep-ph/9403256).
- Proton/Nucleus structure built up dynamically from dipole splittings:

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



- Optical theorem gives: $T(b) = 1 - \exp\left(-\sum_{ij} f_{ij}\right)$
- Builds up initial state + collision in impact parameter space.