Microscopic collectivity: The ridge and strangeness enhancement from string–string interactions in Pythia8

Christian Bierlich
bierlich@thep.lu.se

Lund University / University of Copenhagen

May 15, 2018
Quark Matter 2018, Venice

Where heavy ions meet proton–proton

- Heavy ion collisions: QGP assumption enables effective theories.
- Monte Carlos for pp/PYTHIA8 :
  1. MPIs treated almost independently, no spatial structure.
  2. Parton Shower + Colour Reconnection generally successful ...
  3. ... but ridge, strangeness enhancement etc. *not foreseen* by pp models.
  4. Opportunity to study the (non–perturbative) dynamics of QCD.
  5. Approach based on *corrections* in dense environments.

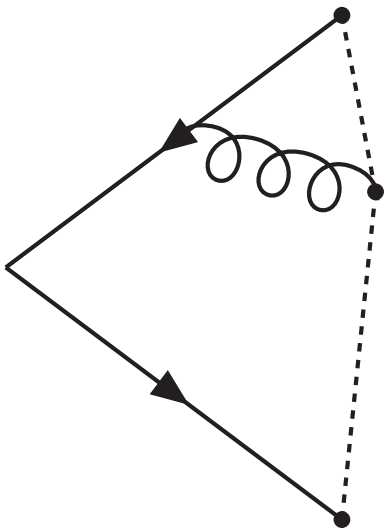
Where heavy ions meet proton–proton

- Heavy ion collisions: QGP assumption enables effective theories.
- Monte Carlos for pp/PYTHIA8 :
  1. MPIs treated almost independently, no spatial structure.
  2. Parton Shower + Colour Reconnection generally successful ...
  3. ... but ridge, strangeness enhancement etc. *not foreseen* by pp models.
  4. Opportunity to study the (non–perturbative) dynamics of QCD.
  5. Approach based on *corrections* in dense environments.
- This talk:
  1. String hadronization and Colour Reconnection.
  2. Microscopic collectivity:

     String shoving: the "ridge" and flow.
     Rope formation: strangeness.
  3. Perspectives – AA, γ^* A and jet quenching.

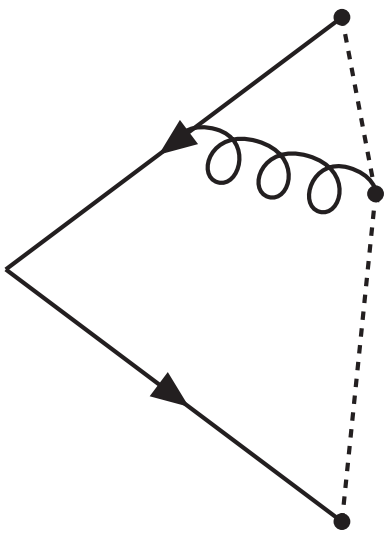
Hadronization in pp: It all starts with a string (See *e.g.* hep-ph/0603175)

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



Hadronization in pp: It all starts with a string (See *e.g.* hep-ph/0603175)

- Non-perturbative phase of final state.
- Confined colour fields $\approx$ *strings* with tension $\kappa \approx 1$ GeV/fm.
- *Breaking*/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.



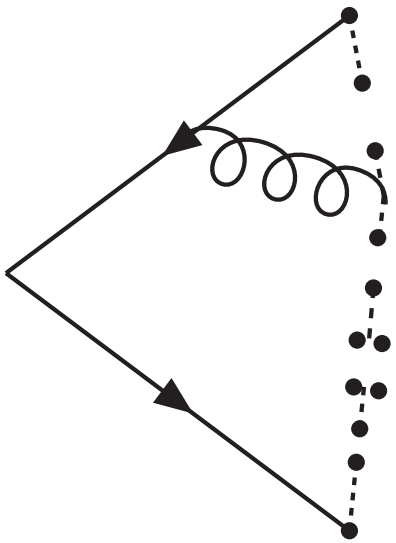
Lund symmetric fragmentation function

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

a and b related to total multiplicity.

Hadronization in pp: It all starts with a string (See *e.g.* hep-ph/0603175)

- Non-perturbative phase of final state.
- Confined colour fields $\approx$ *strings* with tension $\kappa \approx 1$ GeV/fm.
- *Breaking*/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.



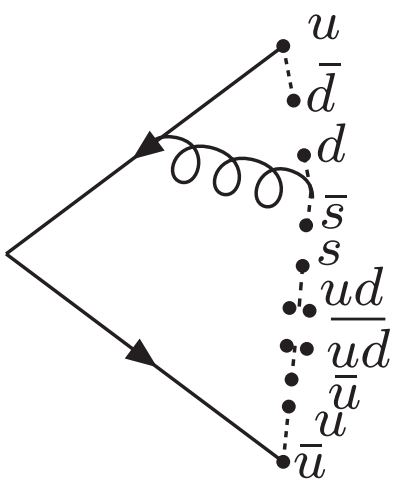
Lund symmetric fragmentation function

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

a and b related to total multiplicity.

Hadronization in pp: It all starts with a string (See *e.g.* hep-ph/0603175)

- Non-perturbative phase of final state.
- Confined colour fields $\approx$ *strings* with tension $\kappa \approx 1$ GeV/fm.
- *Breaking*/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.



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.

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.

The role of Colour Reconnection and non-flow

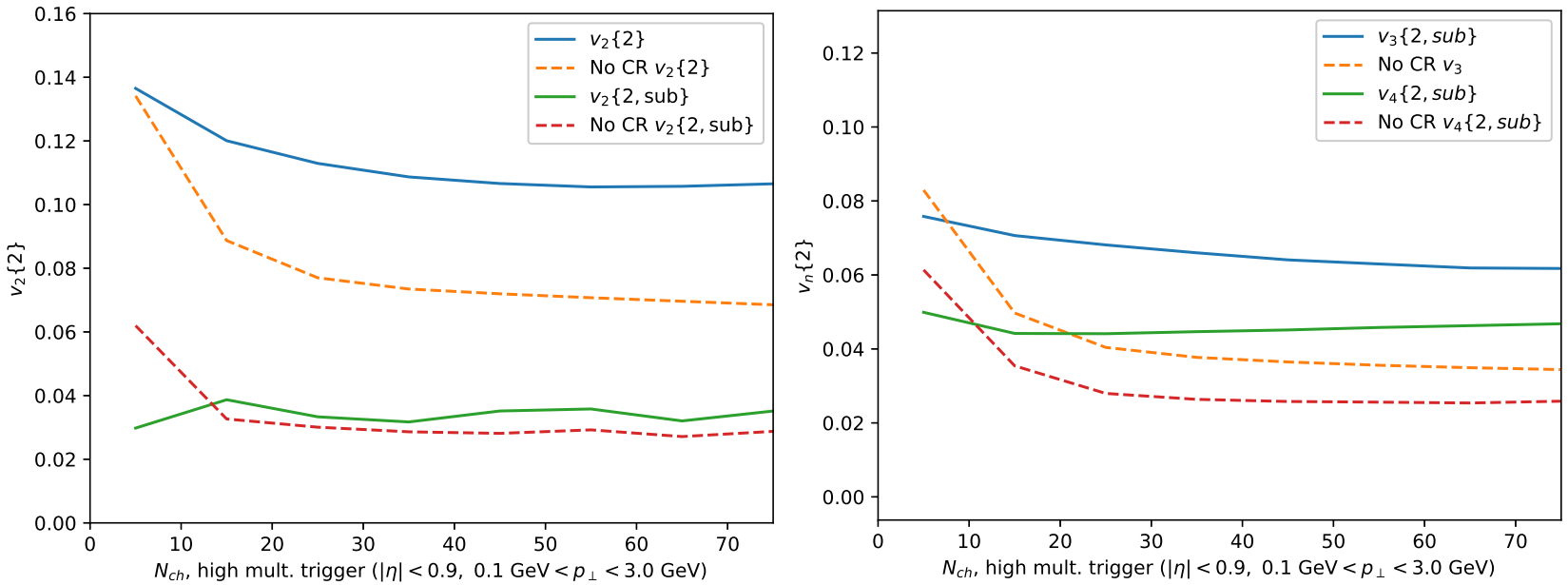
CR = reshuffling string configurations (See also: T. Sjöstrand, QM18).

The role of Colour Reconnection and non-flow

CR = reshuffling string configurations (See also: T. Sjöstrand, QM18).

Quantifying its contribution

- Introduces "flow–like" effects (Velasquez *et al.* PRL 111 (2013) 042001).
- Remove the "like", or is it "non-flow"? (CB, V. Pacík, Y. Zhou, in prep.)



(pp at $\sqrt{s} = 13$ TeV, $v_2 : \Delta\eta > 1.4$, $v_{3,4} : \Delta\eta > 1.0$)

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

Coefficients are ordered $v_2 > v_3 > v_4$.

The microscopic model of collectivity

- Clearly we need more! Where is the geometry?
- Proposal: Model microscopic dynamics with interacting Lund strings

  (In PYTHIA8 v. 8.235; CB, Gustafson, Lönnblad: PLB779 (2018) 58-63; CB: arXiv:1606.09456 [hep-ph]; CB, Gustafson, Lönnblad, Tarasov: JHEP 1503 (2015) 148)
- Additional input fixed or inspired by lattice, few tunable parameters.

The microscopic model of collectivity

- Clearly we need more! Where is the geometry?
- Proposal: Model microscopic dynamics with interacting Lund strings

  (In PYTHIA8 v. 8.235; CB, Gustafson, Lönnblad: PLB779 (2018) 58-63; CB: arXiv:1606.09456 [hep-ph]; CB, Gustafson, Lönnblad, Tarasov: JHEP 1503 (2015) 148)
- Additional input fixed or inspired by lattice, few tunable parameters.

$\tau \approx 0$ 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.

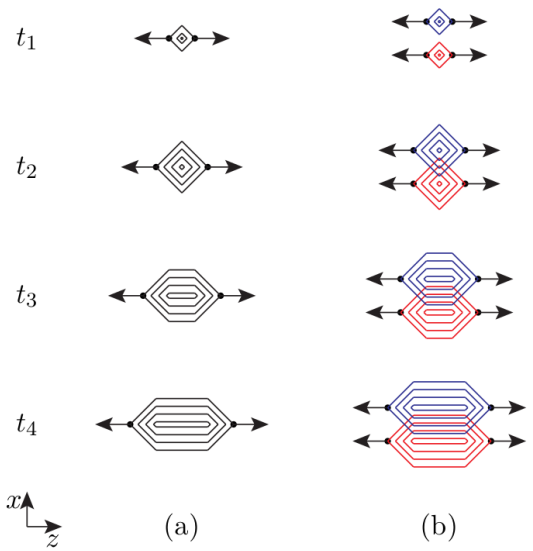
String shoving with simple geometry (PLB779 (2018) 58-63)

- Strings = interacting vortex lines. (Old idea: Abramovsky *et al.*: JETP Lett 47 (1988) 337.)
- For $t \to \infty$, profile known from IQCD (Cea *et al.*: PRD89 (2014) no.9, 094505):

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

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

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

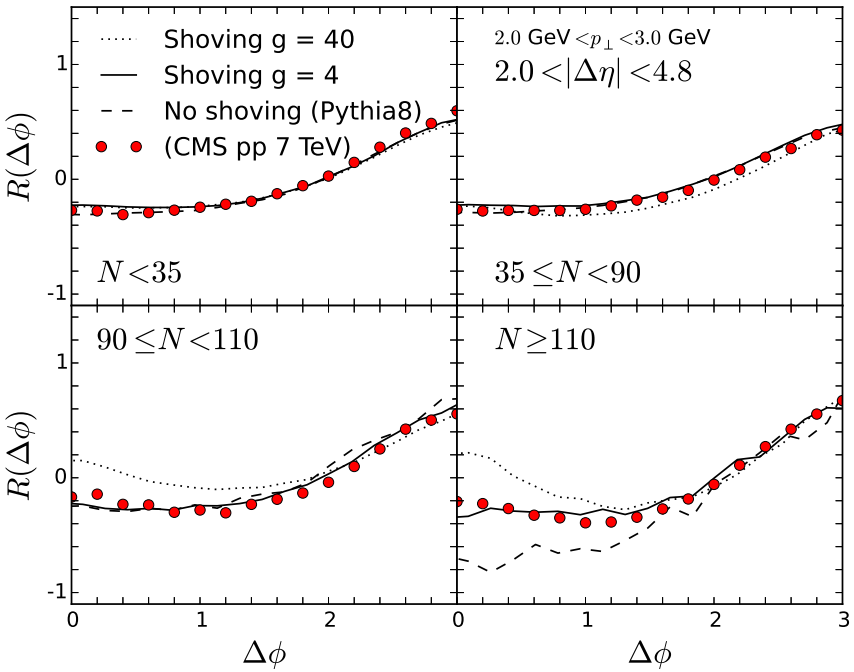


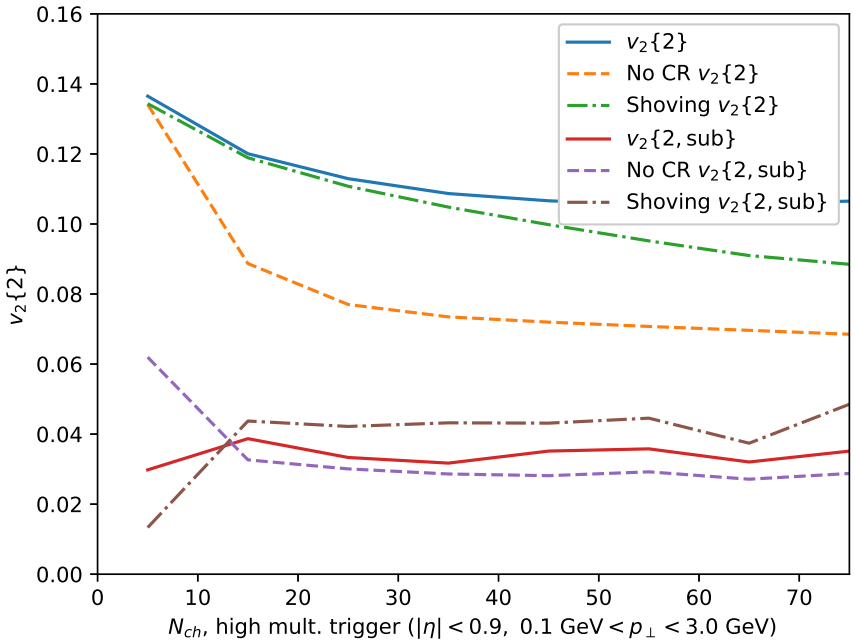
- Dominated by electric field $\to g = 1$.

- Reality:
  - Type 1 Energy to destroy vacuum.
  - Type 2 Energy in current.
- Pairwise, momentum conserving, "kicks".
- Room for improvement: How to add a "kick" to a field?

The ridge and effects on $v_2\{2, sub\}$

- Depends on initial state geometry – approximated by overlapping 2D Gaussians (room for improvement!).
- Reproduces ridge with reasonable choice of $g = 4$.
- Can be quantified in flow coefficients – higher orders unfeasible without better geometrical understanding.





(pp at $\sqrt{s} = 13$ TeV, v_2 : $\Delta\eta > 1.4$)

Rope Hadronization (JHEP 1503 (2015) 148)

- After shoving strings (p and q) still overlap.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

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

Rope Hadronization (JHEP 1503 (2015) 148)

- After shoving strings (p and q) still overlap.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

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

Easily calculable using SU(3) recursion relations

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

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

Rope Hadronization (JHEP 1503 (2015) 148)

- After shoving strings (p and q) still overlap.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

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

Easily calculable using SU(3) recursion relations

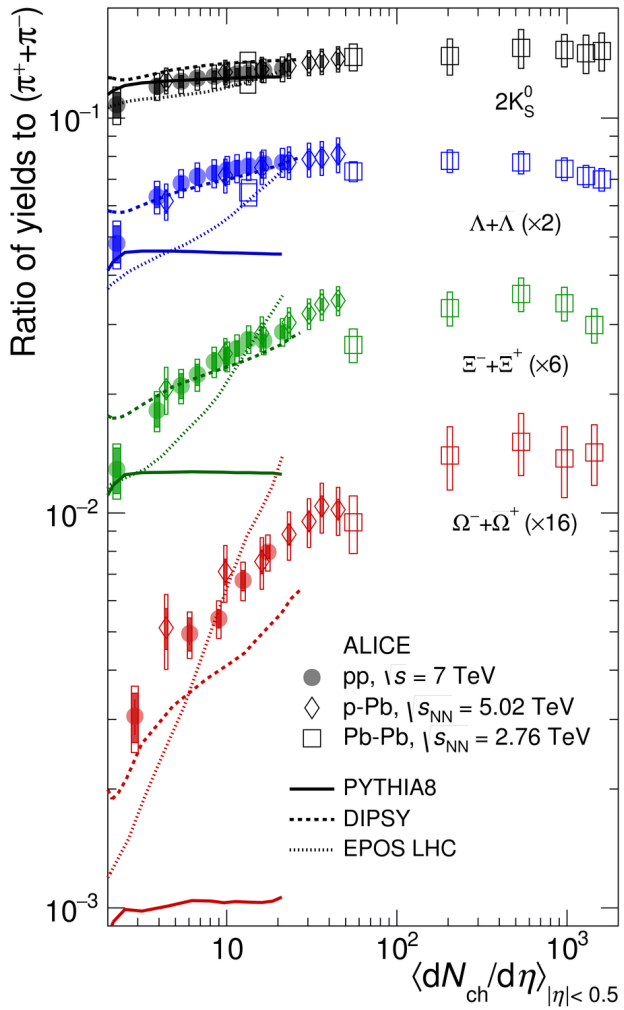
$$\{p,q\} \otimes \vec{3} = \{p+1,q\} \oplus \{p,q+1\} \oplus \{p,q-1\}$$

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

- 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.

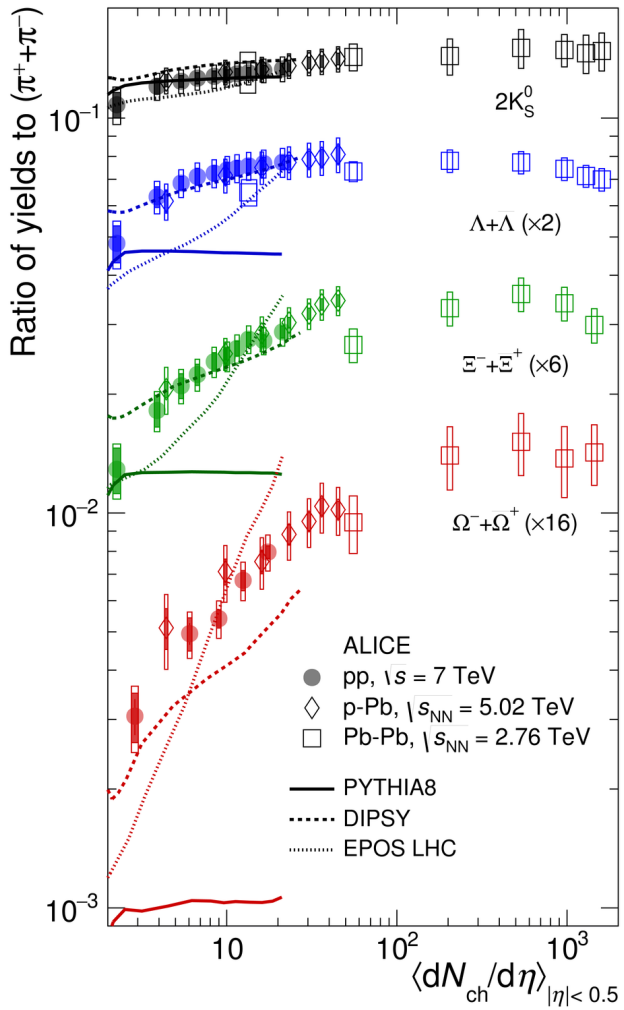
Strangeness enhancement

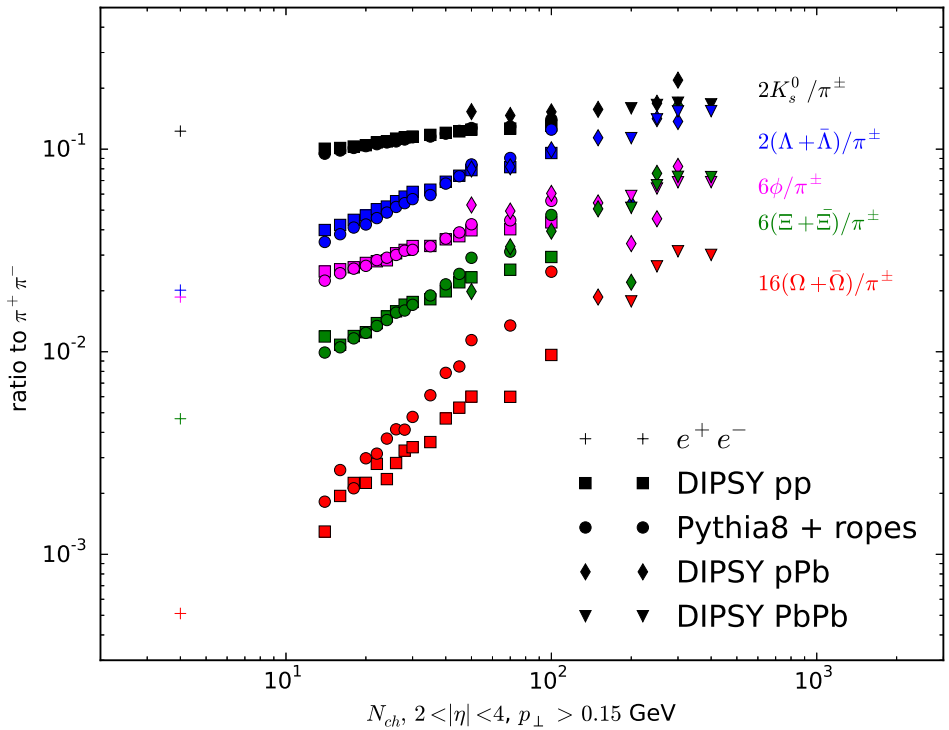
- Less sensitive on geometry – a game of *density*.
- Described strangeness enhancement from pp to *AA*.
- No direct comparison to unfolded data ... yet.



Strangeness enhancement

- Less sensitive on geometry – a game of *density*.
- Described strangeness enhancement from pp to *AA*.
- No direct comparison to unfolded data ... yet.

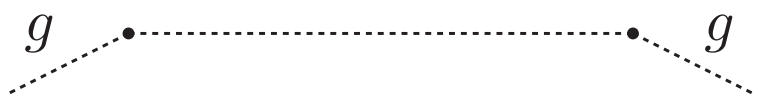


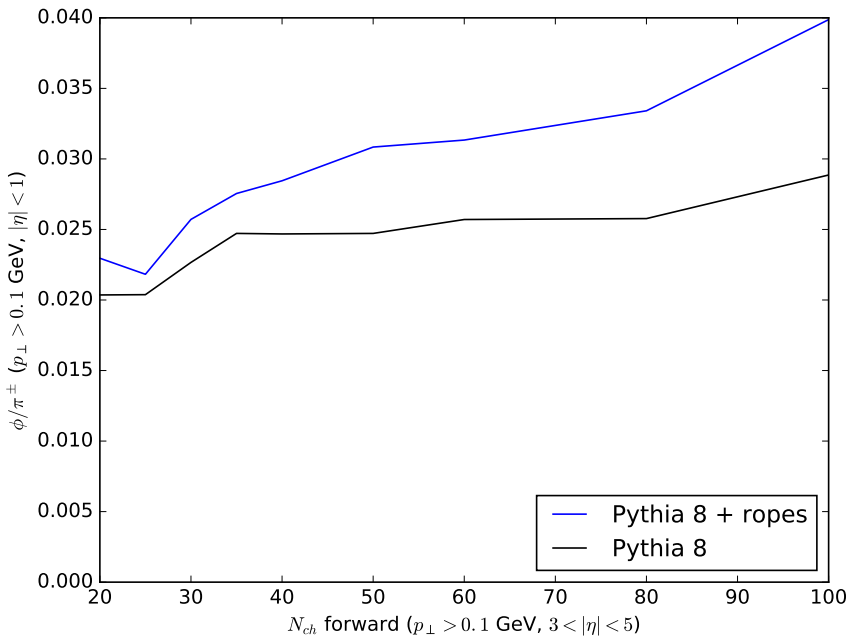


The importance of ϕ production

Very interesting new data!

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

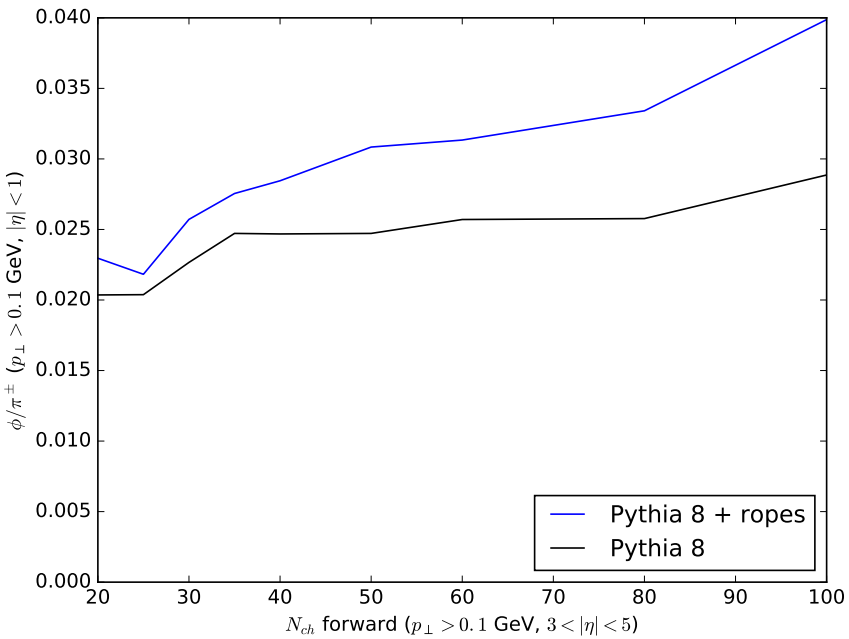




The importance of ϕ production

Very interesting new data!

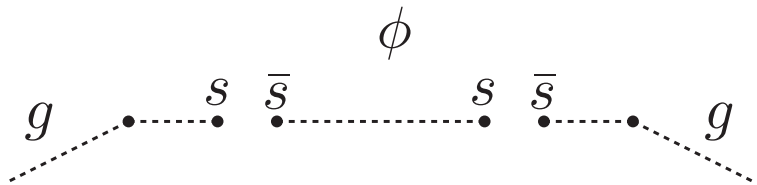
- The ϕ is an excellent laboratory for strangeness effects.
- Two s-breaks means squared suppression and added sensitivity.

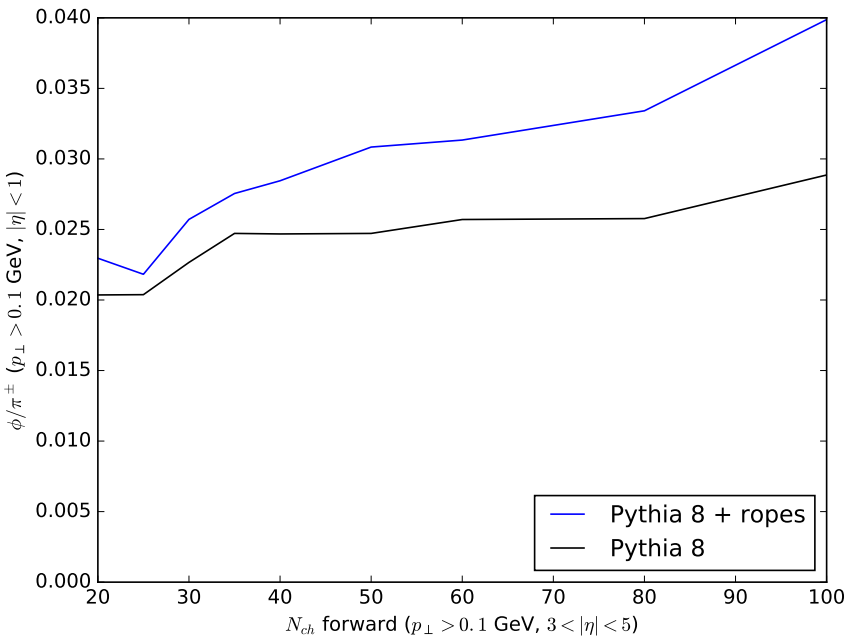


The importance of ϕ production

Very interesting new data!

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





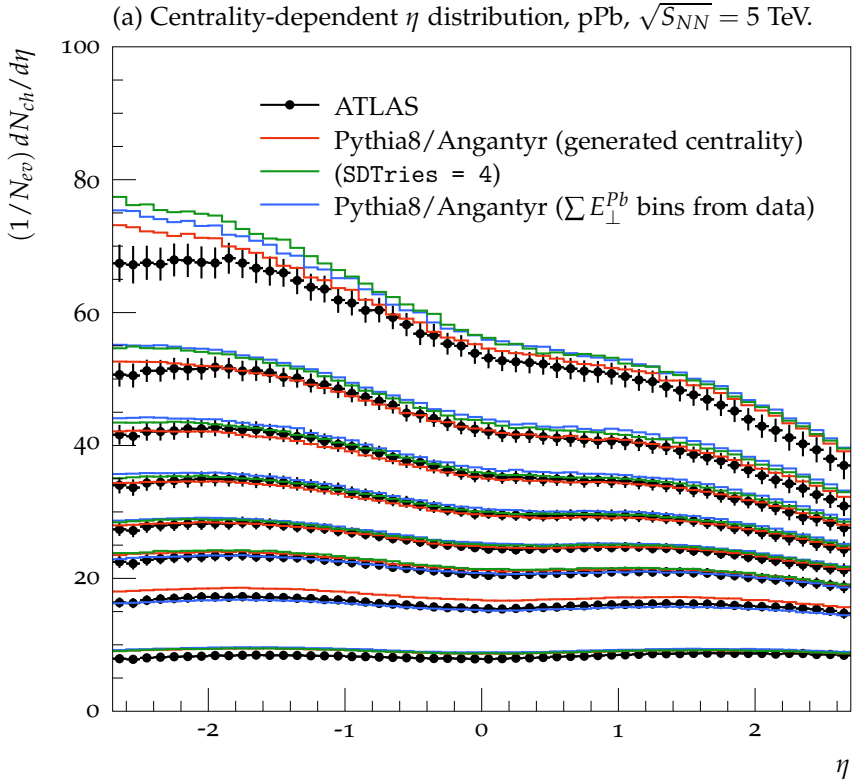
The current status

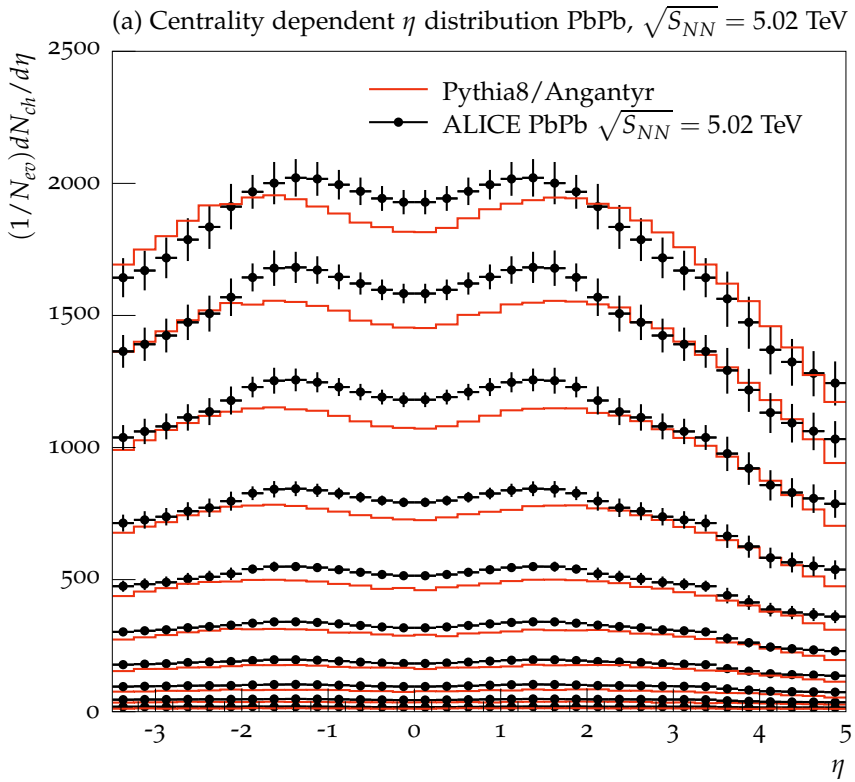
- Introduced a microscopic model for collectivity.
- String shoving for ridge and flow, rope formation for strangeness.
- Microscopic degrees of freedom are *string pieces* between partons.
- Implemented in PYTHIA8 , but:
  1. Initial state correlations/saturation largely ignored.
  2. Proton geometry from naïve model.
  3. Extra gluons from string kicks gives technical problems.
- Remaining talk: Some perspectives.

Perspective I: Angantyr – PYTHIA8 for AA collisions

- Initial state geometry less fluctuation dominated.
- ... but MPI model must be extended to nuclear collisions.

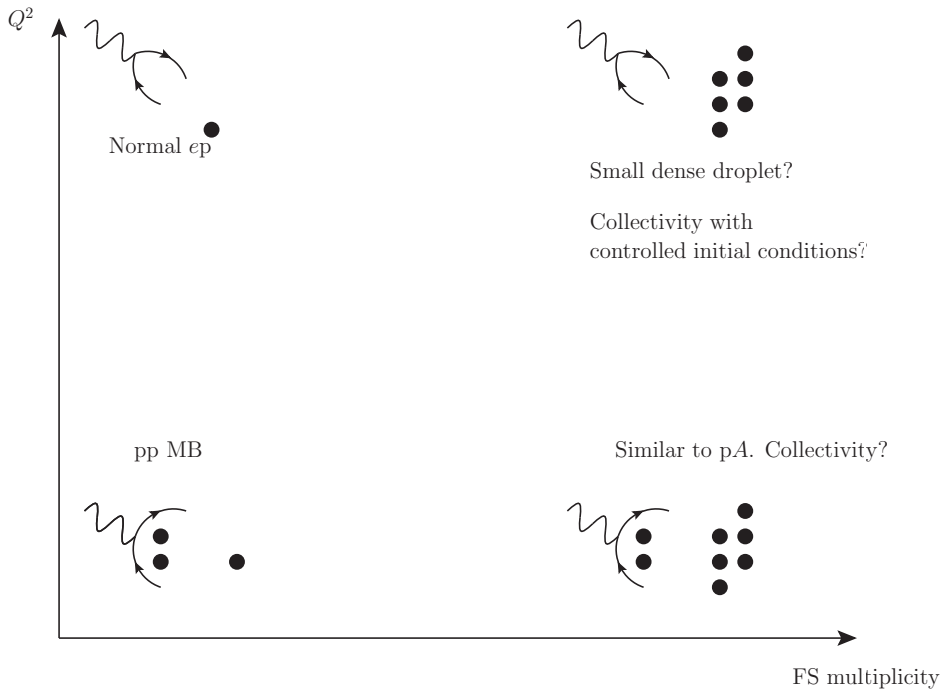
  (CB, G. Gustafson, L. Lönnblad: JHEP 1610 (2016) 139; CB, G. Gustafson, L. Lönnblad, H. Shah: in prep.).
- See poster by Harsh Shah (739).





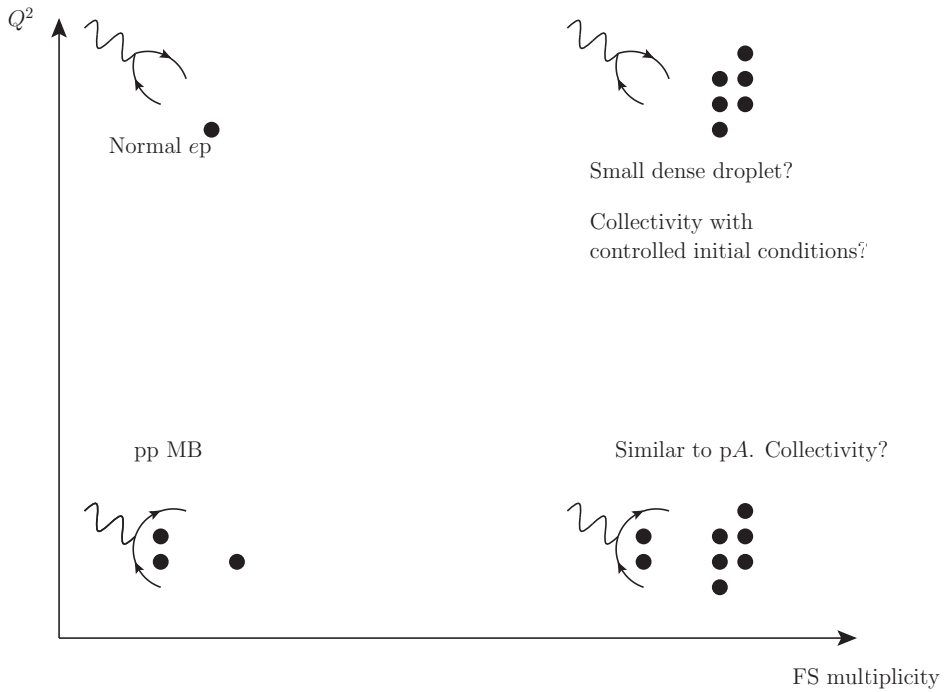
Perspective II: γ^*A collisions

- Small system with size if IS under perturbative control.
- New possible collider interesting for this community.
- Knowledge of Q^2 provides an additional handle.

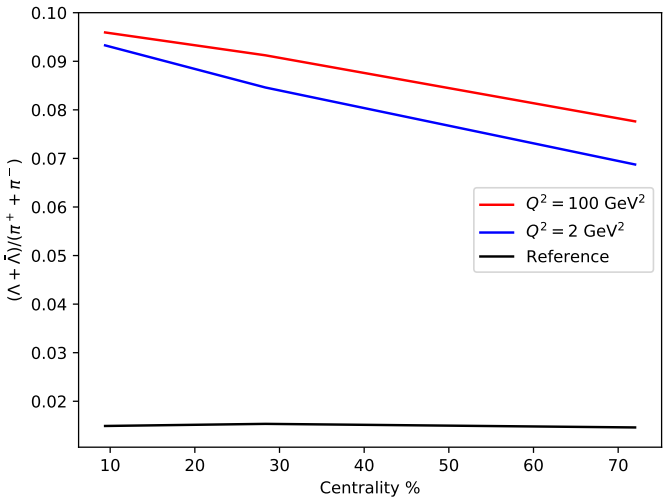


Perspective II: γ^*A collisions

- Small system with size if IS under perturbative control.
- New possible collider interesting for this community.
- Knowledge of Q^2 provides an additional handle.



DIPSY toy calc. ($\gamma^* Au$, $\sqrt{s_{\gamma^* N}} = 200$ GeV).



Perspective III: Jet modifications by shoving

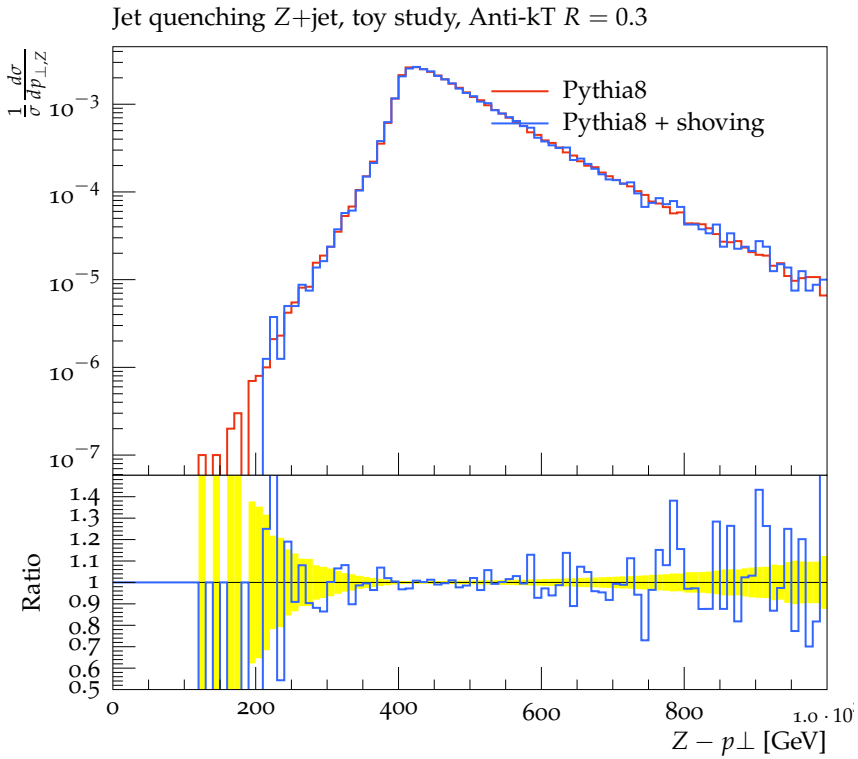
- Very sensitive to geometry. Disabled in PYTHIA8 .

Perspective III: Jet modifications by shoving

- Very sensitive to geometry. Disabled in PYTHIA8 .

Toy calculation – not real events!

- Z+jet at 7 TeV, in pp interaction region center.
- No jet escaping + all strings at equilibrium size.

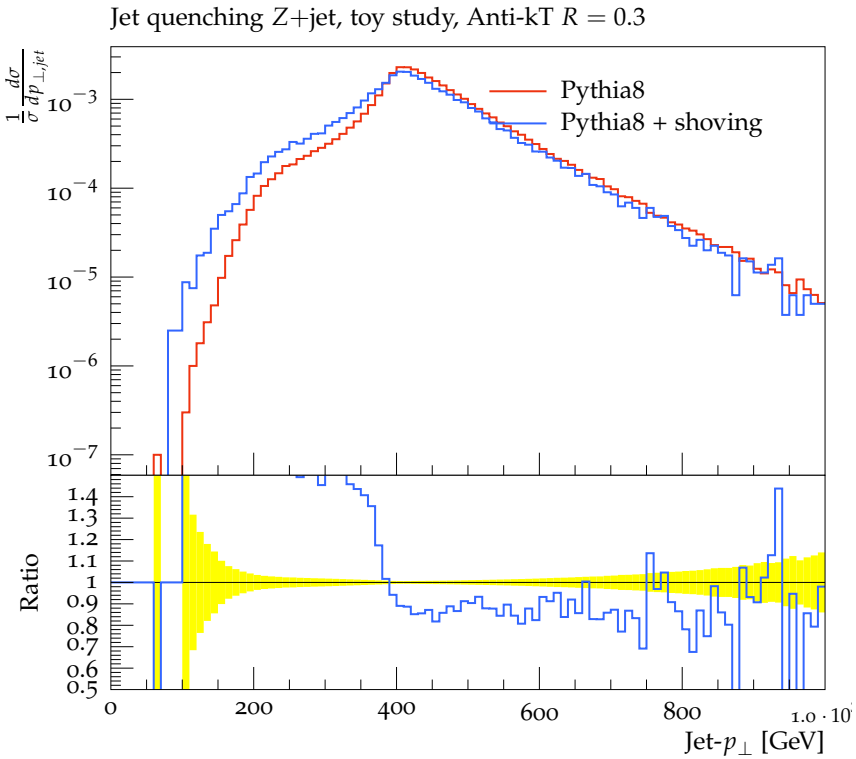


Perspective III: Jet modifications by shoving

- Very sensitive to geometry. Disabled in PYTHIA8 .

Toy calculation – not real events!

- Z+jet at 7 TeV, in pp interaction region center.
- No jet escaping + all strings at equilibrium size.

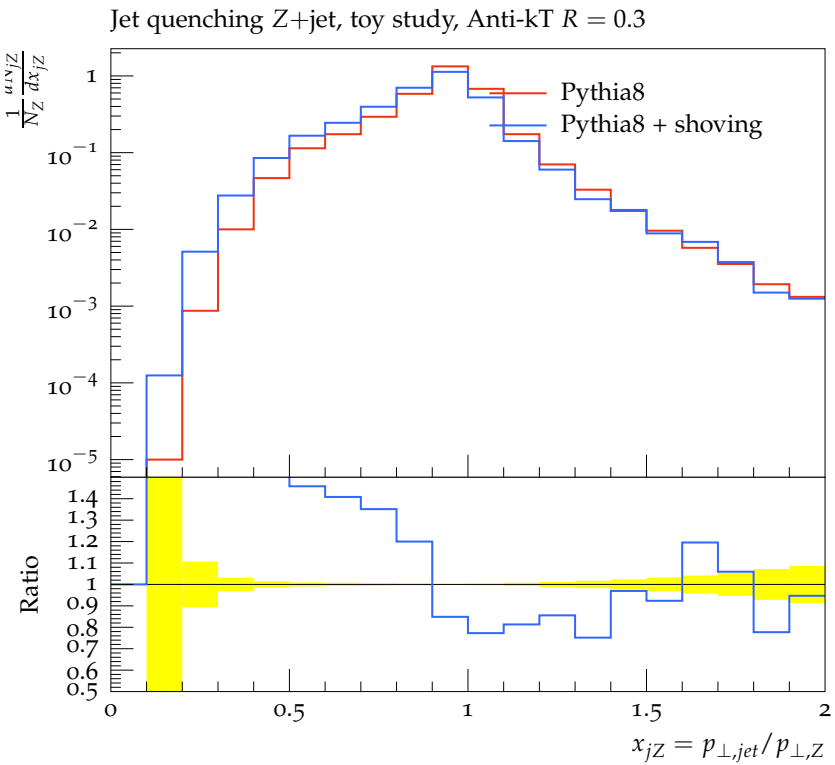


Perspective III: Jet modifications by shoving

- Very sensitive to geometry. Disabled in PYTHIA8 .

Toy calculation – not real events!

- Z+jet at 7 TeV, in pp interaction region center.
- No jet escaping + all strings at equilibrium size.



- Modifications to hadronization? (Nachman and Mangano: EPJC 78 (2018) 4, 343)

Summary

- Modifications to string hadronization based on microscopic interactions.
- Dependence on initial state geometry is crucial.

  Strangeness on *density* $\rightarrow$ rope formation.
  Ridge + flow on *shape of interaction region* $\rightarrow$ string shoving.
  Jet modifications on *microscopic structure* $\rightarrow$ ... both?

Summary

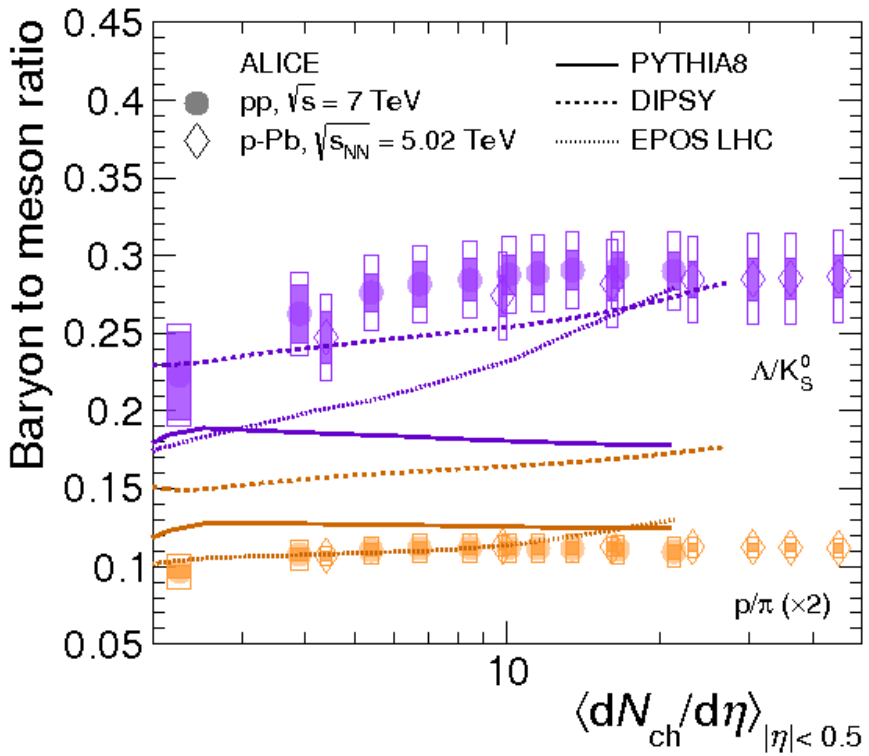
- Modifications to string hadronization based on microscopic interactions.
- Dependence on initial state geometry is crucial.

  Strangeness on *density* $\rightarrow$ rope formation.
  Ridge + flow on *shape of interaction region* $\rightarrow$ string shoving.
  Jet modifications on *microscopic structure* $\rightarrow$ ... both?
- Extensions to heavy ions ongoing.
  - Already good description of single particle observables.
  - Angantyr available in PYTHIA8 (v.8.235).
  - Strangeness well described using old DIPSY implementation.

Thank you!

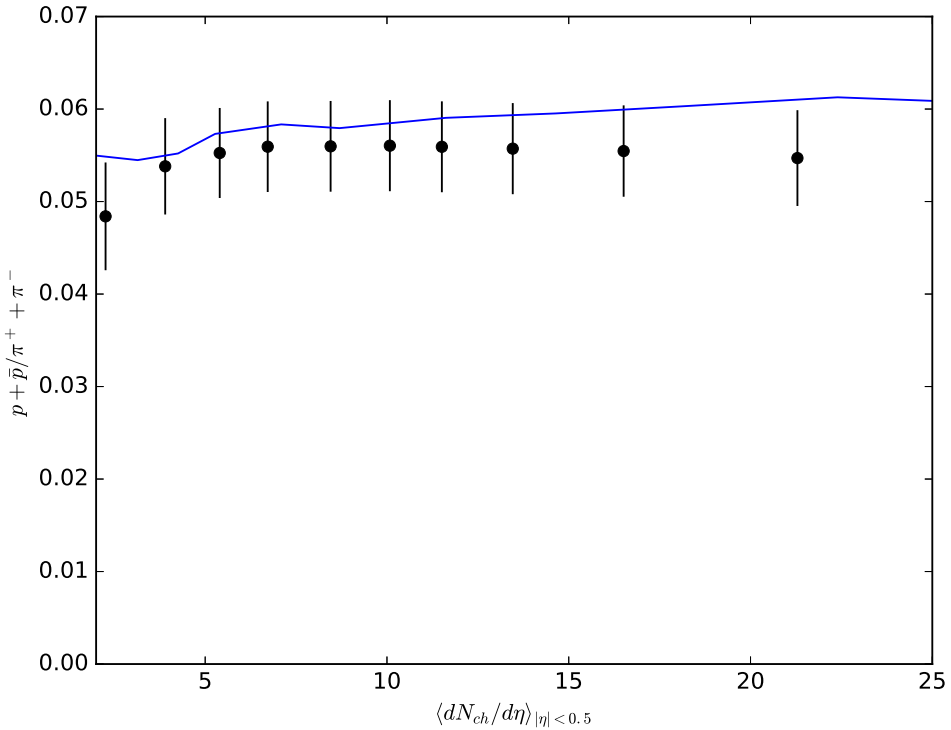
What about the protons?

- Ratio can be explained.
- But dynamics of baryon production is still not understood.
- Important result from ALICE: Eur. Phys. J. C77 (2017) 569
- EPOS points to baryon–baryon annihilations.



What about the protons?

- Ratio can be explained.
- But dynamics of baryon production is still not understood.
- Important result from ALICE: Eur. Phys. J. C77 (2017) 569
- EPOS points to baryon–baryon annihilations.



Angantyr $p_\perp$ spectra

- PbPb @ 5.02 TeV/nn by ATLAS.