Small Systems: Theory
Heavy-ion like phenomena in proton-proton collisions

Christian Bierlich
bierlich@thep.lu.se

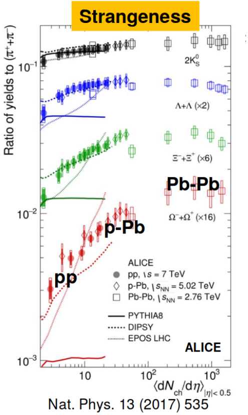
Lund University

Oct 31, 2017
High Luminosity Workshop CERN

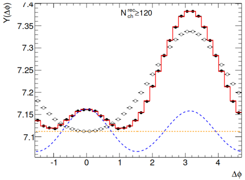
Why is collectivity in small systems so interesting?

- Collectivity in small systems challenges two paradigms at once!
  1. How far down in systems size does the "SM of heavy ions" remain?
  2. Can the standard tools for min bias pp remain standard?

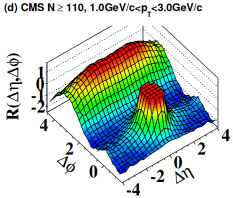
"Huge potential to learn about underlying dynamics, i.e. non-perturbative QCD." (JFGO, this WS)



(ALICE pp 7 TeV)



(ATLAS pp 13 TeV)



(CMS pp 7 TeV)

The "microscopic model" of collectivity at a glance

- Collective effects, based on interacting Lund strings (In PYTHIA8 v. 8.230).
- Additional input fixed or inspired by lattice, few tunable parameters.
- Collectivity without plasma? (CB, Gustafson, Lönnblad: arXiv:1710.09725 [hep-ph])
- Improving strangeness with ropes (CB, Gustafson, Lönnblad, Tarasov: arXiv:1412.6259 [hep-ph])
- Extendable to pA and AA through Angantyr (CB, Gustafson, Lönnblad, arXiv:1607.04434).

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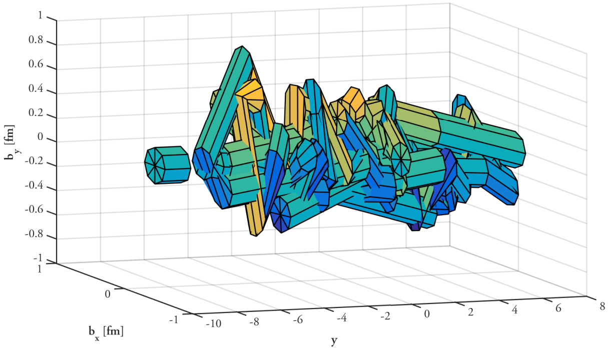
1. $t \approx 0$ fm. Strings no transverse extension. No interactions, partons may propagate.
2. $t \approx 0.6$ fm. Parton shower ends. Depending on "diluteness", strings may shove each other around.
3. $t \approx 1$ fm. Strings reach full transverse extension. Shoving effect maximal.
4. $t \approx 2$ fm. Strings will hadronize. Possibly as a colour multiplet (a "Rope").

Case I: The "ridge" in small systems

- One of the surprises of small systems.
- Hard to quantify, when N_{ch} small, without large rapidity gap.
- This talk: A new model for transporting IS parton profile to FS.
- Strings allowed to "shove" each other $\rightarrow$ transverse pressure.
- Many similarities with a perfect liquid but...

No assumption of a deconfined nor thermalized plasma.

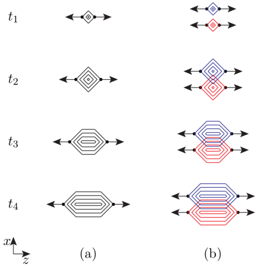


Interactions between strings (CB, Gustafson, Lönnblad: arXiv:1710.09725 [hep-ph])

- Strings are vortex lines in S.C.
- For $t \to \infty$, profile known from lQCD (Cea et al. arXiv:1404.1172 [hep-lat]) giving:

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

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



- Reality:

  Type 1 Energy to destroy vacuum.

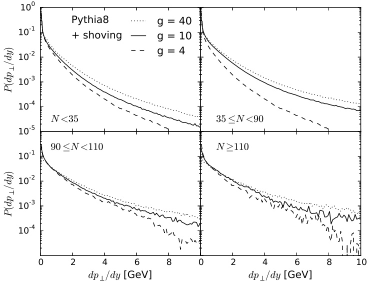
  Type 2 Energy in current.

- Pairwise, momentum conserving, "kicks".
- Includes "medium recoil" by construction, promise for including jets.

Resolving the kicks

- We resolve kicks as gluons – not best approach.
- When is a gluon free of the string?

$$\lambda_g \approx 2\pi k_\perp, l_{ur} = k_\perp/2\kappa \Rightarrow k_{\perp,0} \gtrsim 1.6\text{GeV}$$



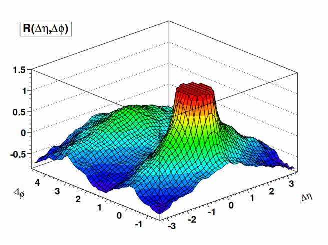
- Better (future improvement):

Soft Put directly on hadrons.

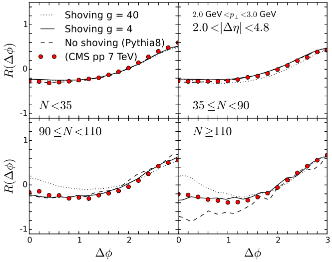
Hard Resolved gluons (also effects for sub-jet observables).

The ridge from interacting strings

- Ridge produced by string shoving, or hydrodynamical expansion.
- Consequences for the deconfined thermalized plasma?
- What can we do to discriminate between models?
  1. Better understanding of IS geometry (PYTHIA8 open interface)?
  2. Interplay with FS interactions (particle production + jet quenching)?



(EPOS with hydro, arXiv:1011.0375)



(PYTHIA8 with shoving)

QCD coherence and Colour Reconnection?

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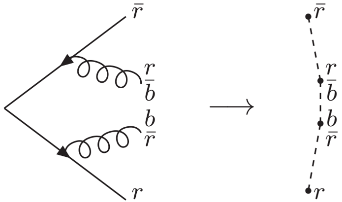

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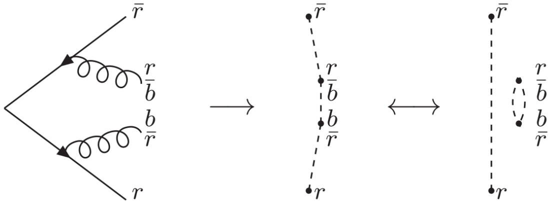

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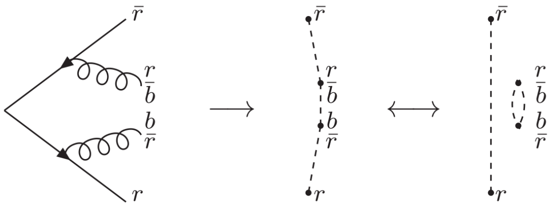

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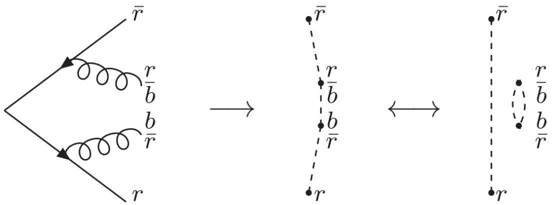
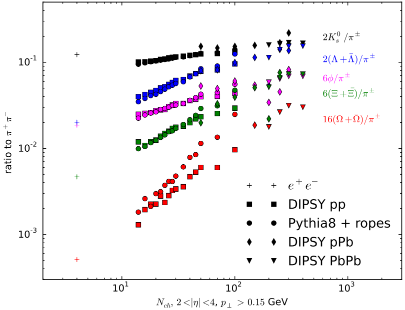


- Recently more rigorous attempt in coherence "toy model" (Blok *et al.*: arXiv:1708.08241 [hep-ph]).
- Open question how/if "CR" can explain collectivity, or if FS interactions are indeed needed.

Case II: Strangeness across systems

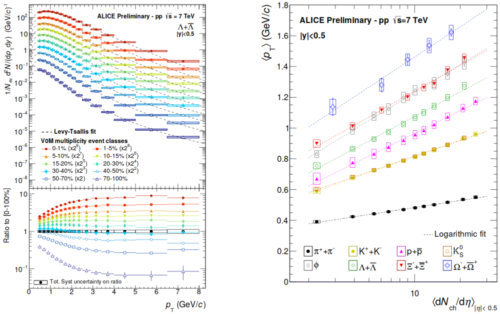
- Smooth transition surprising – does it hold for high mult. pp?
- Explained well by DIPSY + Rope Hadronization across systems.
- In PYTHIA8 for pp, AA coming soon. Rivet for comparisons would be useful.
- Now $t \sim$ 2fm.
- Strings fragment together in colour multiplets ("Ropes").
- Ropes have higher string tension, giving more strange quarks.
- (Maybe even c (and b))

(*eg.* Pop *et al.* arXiv:1306.0885 [hep-ph])



An aside: Problematic extrapolation

- Comparing theory to relevant measurements, technical problems arise.
- Levy-Tsallis fitting introduces a convoluted model uncertainty which is not neccesary.

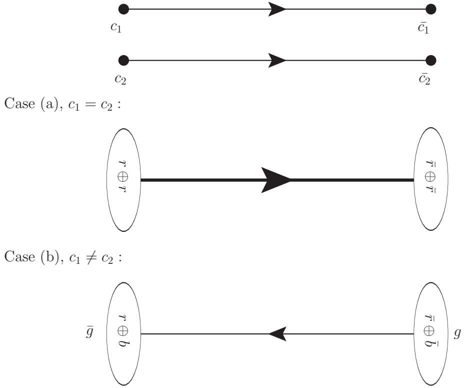


(L. Bianchi for ALICE: arXiv:1604.6736)

- Resolution: Publish what is actually measured.
- Rivet for model independent comparison.

The Rope Hadronization model

- Idea from 1980's. Many different implementations. (Biro *et al.*: Nucl.Phys. B245 (1984) 449-468, 238 citations.)
- Two (triplet) strings acts coherently.



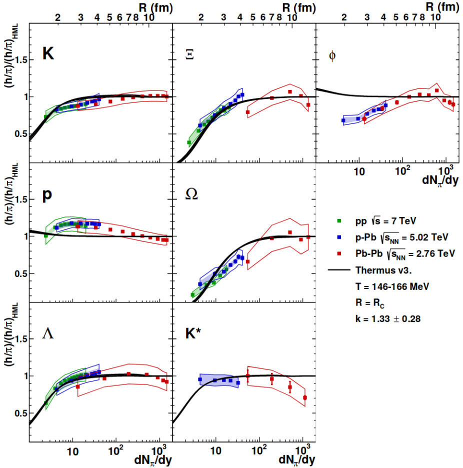
- More strange quark from higher string tension.

$$\exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right)$$

- Exponential surpresseion makes c and b very rare for $\kappa = 1$ GeV/fm.
- At $\kappa = 7 - 10$GeV/fm, c becomes relevant – feasible in very high mult pp or AA.

Contrasting with thermal models (Vislavicius and Kalweit: arXiv:1610.03001 [hep-ex])

- Thermus gets several features by relating N_{ch} to system size.
- Several points: ϕ is of importance, apples to apples on x-axis, transistion region between high mult pp and AA.



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- Jet flavour chemistry for pp.
- Sub-jet studies initiated, but still preliminary (Mangano and Nachman: arXiv:1708.08369 [hep-ph])