Predicting strangeness yields in small and large systems with PYTHIA8/Angantyr

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Goals

- Aim: Observing Quark Gluon Plasma signatures within the Lund string model (PYTHIA and ANGANTYR)
- We want to observe:
  - Imprint of initial geometric anisotropy in the final state particles
    $\Longrightarrow$ correlation between particles separated in large units of rapidity
  - Modification of large Q^2 processes in small and large systems
    $\Longrightarrow$ Jet quenching &
    $\Longrightarrow$ Change in production yields of heavy flavours, e.g. strange and charm, hadrons

Physical motivation: string shoving & rope hadronization

Inclusion of string interactions

- ✓ In transverse coordinate space $\Longrightarrow$ rope hadronization
- ✓ In colour space $\Longrightarrow$ colour reconnection, colour swing
- ✓ In 3 dimensional coordinate space $\Longrightarrow$ string shoving

QGP signatures

Final-state collective effects
Jet quenching
Strangeness enhancement

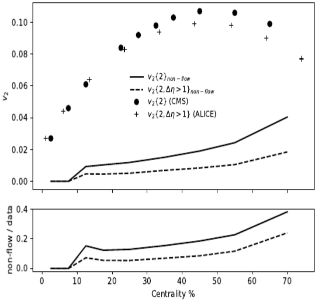
$\Rightarrow$

Underlying mechanisms

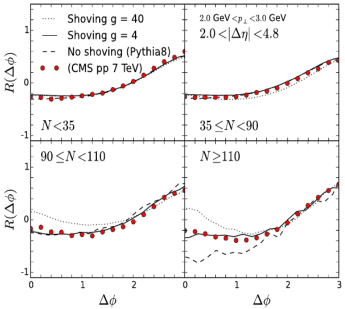
String shoving
Colour reconnection
Rope hadronization

Other mechanisms at work: Hadronic rescattering in PYTHIA

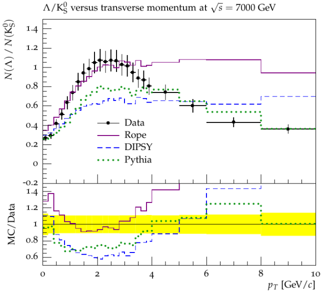
Implementations till date: ANGANTYR, shoving & ropes



(a) ANGANTYR $v_2\{2\}$ performance for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV[†]



(b) Two particle correlation in p-p collisions at 7 TeV*



(c) Λ/K_s^0 ratio in DIPSY compared to CMS data for p-p at $\sqrt{s} = 7$ TeV[‡]

[†]Bierlich, et al., J. High Energ. Phys. 2018, 134 (2018), *Bierlich, et al., Phys.Lett.B 779 (2018) 58-63, [‡]Bierlich, et al., J. High Energ. Phys. 2015, 148 (2015)

String shoving: Gaussian colour field and interaction force

A string of radius R will have a colour electric field of the Gaussian nature:

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

Corresponding force $f(d_\perp)$ per unit length between two such strings will be:

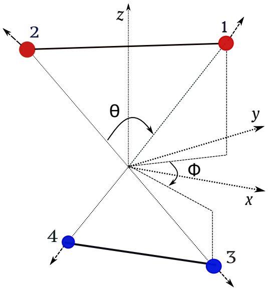
$$f(d_\perp) = \frac{dE_{int}}{dd_\perp} = \frac{g\kappa d_\perp}{R^2} exp\left(-\frac{d_\perp^2(t)}{4R^2}\right)$$

where $E_{int} = \int [(E_1 + E_2)^2 - E_1^2 - E_2^2]$ and g is a tunable parameter($\sim \mathcal{O}(1)$).

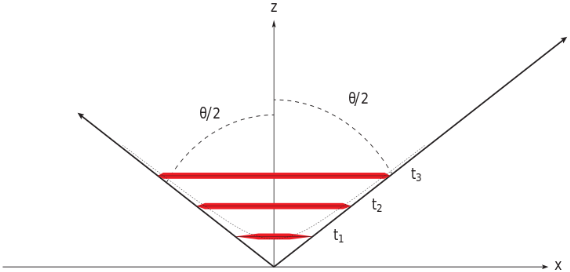
† Bierlich C., Gustafson G., Lönnblad L., Collectivity without plasma in hadronic collisions, Phys.Lett.B 779 (2018) 58-63

Strings in the parallel frame

With **two constraints** in string evolution: maximum width R_0 and hadronization time τ_{Had}



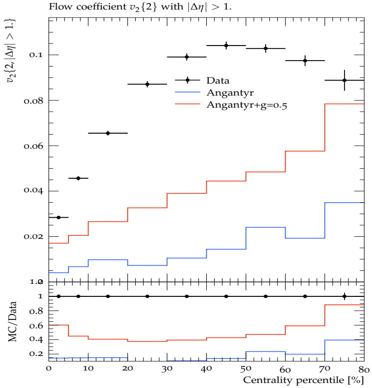
(a) Parallel frame with opening angle θ and skewness angle ϕ

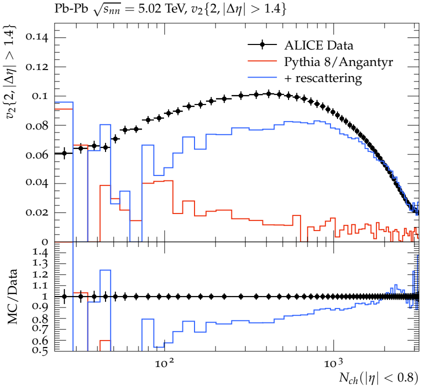


(b) Evolution of string width in the parallel frame

† Bierlich, C., Chakraborty, S., Gustafson, G. et al. Setting the string shoving picture in a new frame, J. High Energ. Phys. 2021, 270 (2021)

$v_2\{2\}$ in Pb-Pb with shoving & rescattering





At $\sqrt{s_{NN}}$ =5.02 TeV, (left) $v_2\{2\}$ vs. centrality with only string shoving g = 0.5†, (right) $v_2\{2\}$ vs $\langle N_{ch}\rangle$ with only rescattering‡ (See talk by Marius Utheim on Monday afternoon)

†Bierlich, et. al., J. High Energ. Phys. 2021, 270 (2021), ‡Bierlich, et. al., Eur.Phys.J.A 57 (2021) 7, 227.

New implementation: Rope hadronization in the parallel frame

Motivation

- To capture the essence of wider colour flux tubes when two strings are close in the transverse co-ordinate space
- Resultant higher effective string tension κ_{eff}
- Higher yield of strange quarks $\rightarrow$ strangeness enhancement

First implementation in DIPSY, with subsequent PYTHIA hadronization

✓ Stacking of strings to form a rope

✓ Formation of higher colour multiplets at the ends of colour dipoles

✓ Hadronization occurs for each string separately in the MC implementation

† Bierlich C., Gustafson G., Lönnblad, L. et al. Effects of overlapping strings in pp collisions, J. High Energ. Phys. 2015, 148 (2015)

Rope formation

- A SU(3) multiplet can be specified by two quantum numbers p and q
- A state corresponds to p coherent triplets + q coherent antitriplets

Corresponding multiplicity is given by

$$N = \frac{1}{2}(p+1)(q+1)(p+q+2)$$

† Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).

Higher string tension κ_{eff}

- From lattice calculations: Tension in an isolated static rope is proportional to the quadratic Casimir operator C_2
- Relative strength of the "rope tension"

$$C_2(p,q)/C_2(1,0) = \frac{1}{4}(p^2 + pq + q^2 + 3p + 3q)$$

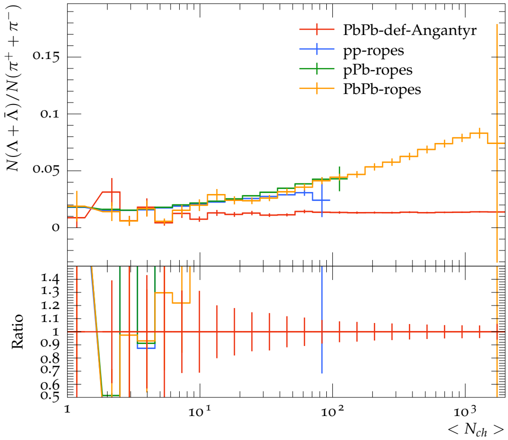
- For breakup via the transition $\{p+1, q\} \rightarrow \{p, q\}$:

$$\text{effective string tension } \kappa_{eff} = \frac{2p+q+4}{4}\kappa$$

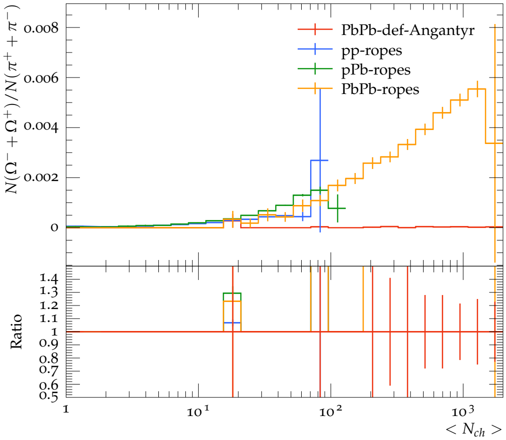
† Bierlich C., Gustafson G., Lönnblad, L. et al., J. High Energ. Phys. 2015, 148 (2015).

PRELIMINARY RESULTS

I: pp 13 TeV, p-Pb 5.02 TeV and Pb-Pb 2.76 TeV strangeness yields with MONASH tune

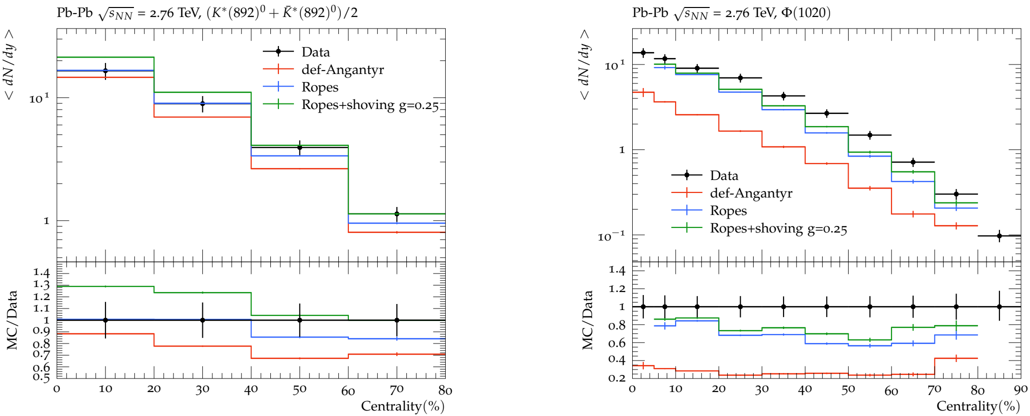


(a) $(\Lambda + \bar{\Lambda})/(\pi^{+} + \pi^{-})$ ratio in $|\eta| < 0.5$



(b) $(\Omega^{-} + \Omega^{+})/(\pi^{+} + \pi^{-})$ ratio in $|\eta| < 0.5$

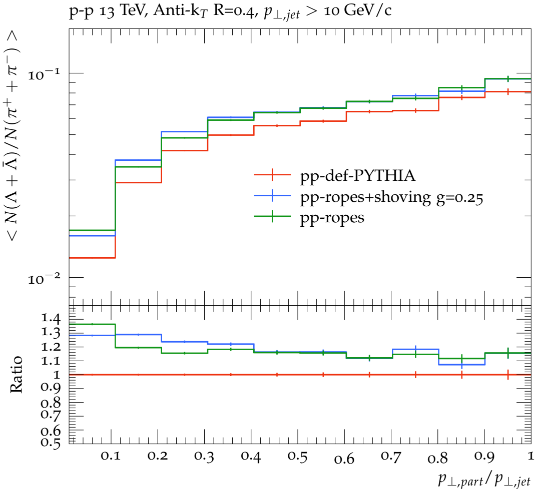
II: Strangeness in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV with MONASH tune

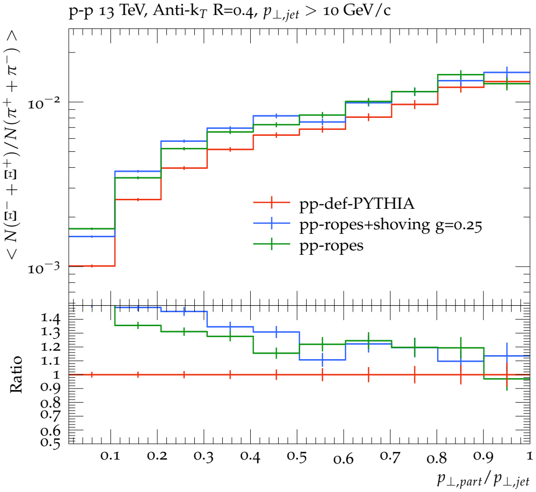


(Left) K^{*0} and (right) $\Phi(1020)$ yields vs. centrality.

†ALICE collaboration, $K^{*0}$and $\Phi(1020)$ production in Pb-Pb collisions at 2.76 TeV, Phys.Rev.C 91 (2015) 024609, 2015.

III: Strangeness in jets p-p in PYTHIA8 with MONASH tune

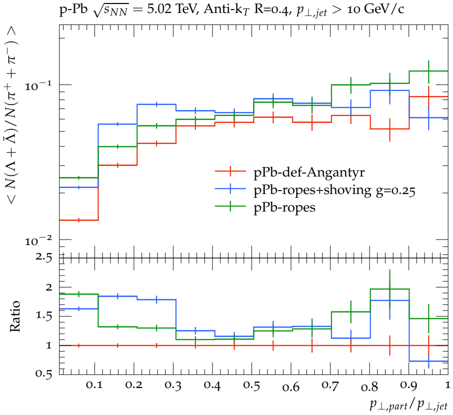




Anti-k$_\perp$ R=0.4, $p_{\perp,jet} > 10$ GeV/c, $|\eta_{jet}| < 2.1$, $|\eta_{particle}| < 1.9$, $\Delta\Phi_{jet,particle} > 2\pi/3$

IV: Strangeness in jets p-Pb in PYTHIA8/Angantyr with MONASH tune

Anti-$k_\perp$ R=0.4,
$p_{\perp,jet} > 10$ GeV/c,
$|\eta_{jet}| < 2.1$,
$|\eta_{particle}| < 1.9$,
$\Delta\Phi_{jet,particle} > 2\pi/3$



Similarly, the analysis can be done in A-A systems → ongoing work.

Wanted: Rivet analyses for strangeness in jets for p-A and A-A

Summary

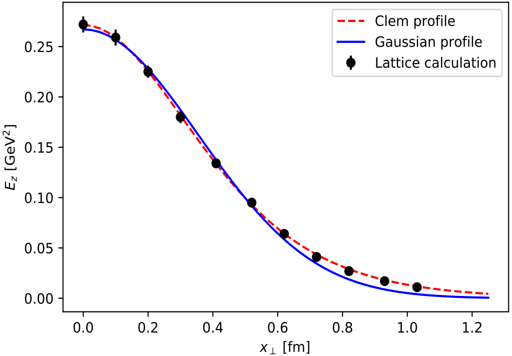
- Conclusions from the performance so far:
  - Better description of strangeness production in high-multiplicity p-p with new implementation of rope hadronization and string shoving
  - **Novelty**: parallel frame $\rightarrow$ jet analyses possible
  - **Novelty**: parallel frame $\rightarrow$ string interactions in all systems - for both min-bias and jetty events
  - Required: tuning to p-p data with new implementation
- Outlook:
  - ○ Upcoming in ANGANTYR and PYTHIA8: GLEIPNIR module
  - ✓ Implementation of string shoving and rope hadronization in the parallel frame
  - ✓ Generation of heavy-ion events with jet trigger including string interactions

BACKUP

More about g

Dominating colour electric field

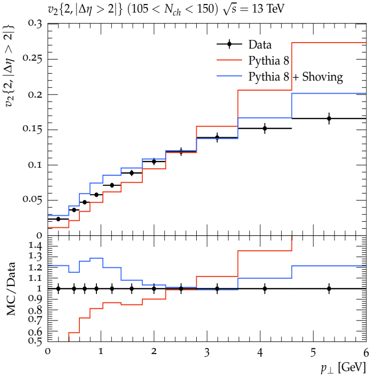
$\rightarrow$ g $\sim \mathcal{O}(1)$



Profile of the electric field from the lattice calculation[1] compared to the fit by Clem[2] and a Gaussian distribution

1. Baker, M., Cea, P., Chelnokov, V. et al. The confining color field in SU(3) gauge theory. Eur. Phys. J. C 80, 514 (2020).

$v_2\{2\}$ vs. pT for pp $\sqrt{s} = 13$ TeV



$v_2\{2\}$ versus $p_\perp$ in high multiplicity events. Data from pp collisions at 13 TeV[1]

1. CMS collaboration, Evidence for collectivity in pp collisions at the LHC, Phys. Lett. B 765(2017) 193 [arXiv:1606.06198]

$v_2\{8\}$ vs. N_{ch} for Pb-Pb at 5.02 TeV