Strangeness Enhancement via Color Ropes: A Comparison with Hydrodynamics

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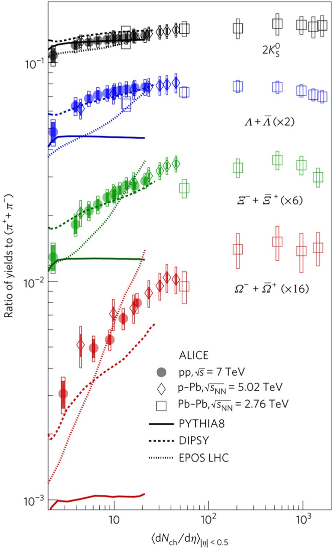
Outline

Background

- Strangeness production is a classic signal of QGP in A+A.
- Hydro + transport (core–corona) explains this enhancement well.
- But: similar collective effects appear in high-multiplicity *pp* (see figure from ALICE) [1].
- $\Rightarrow$ Hints that collectivity may emerge already at the level of elementary NN interactions, *e.g. through string dynamics*.

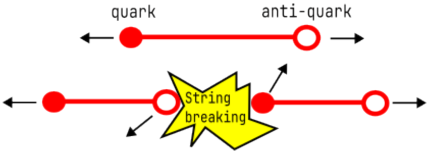


Color flux tubes (Strings)

- The color field between $q\bar{q}$ is modeled as a **string** with tension $\kappa \sim 1$ GeV/fm.
- As quarks separate, the string stores potential energy.
- When stretched, it breaks via the **Schwinger mechanism**, creating new $q\bar{q}$ pairs

$$\frac{dN_q}{d^2p_T} \propto \exp\left[-\frac{\pi(m_q^2 + p_T^2)}{\kappa}\right]$$

- Iterative breaking $\Rightarrow$ hadronization into mesons and baryons.



Schematic: A string breaking into hadrons.

Two views on collectivity from strings

Two notable approaches are being developed, focusing on **microscopic dynamics** vs. **macroscopic description**:

Microscopic (Pythia/Lund)[2]

- Colour reconnection $\Rightarrow$ baryons
- String shoving $\Rightarrow$ flow / ridge
- Rope hadronization $\Rightarrow$ strangeness
- Extended to AA via Angantyr

Macroscopic (Percolation)[3]

- String density $\xi = N_s S_1 / S_A$
- Critical $\xi_c \sim 1.2$ $\Rightarrow$ spanning cluster
- Defines $T, \epsilon, s, \eta/s$ (QCD-Lattice like EoS)

Microscopic: string-by-string dynamics — Macroscopic: emergent cluster picture

Overlapping strings $\Rightarrow$ higher κ $\Rightarrow$ more $s\bar{s}$

- Overlap $\Rightarrow$ higher effective tension

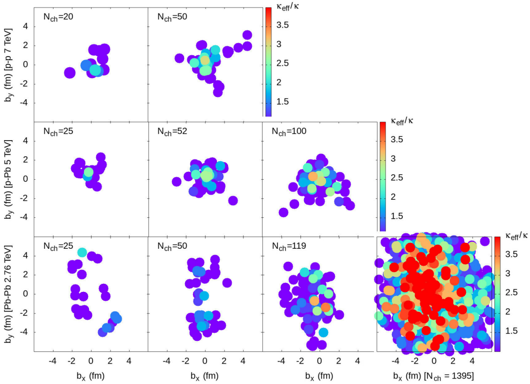
$$\kappa_{\text{eff}} > \kappa$$

- Strangeness suppression (Schwinger mechanism)

$$\rho(\kappa) = \exp\left[-\frac{\pi(m_s^2 - m_{u/d}^2)}{\kappa}\right]$$

- Example values:

$$\rho(\kappa = 1 \text{ GeV/fm}) \approx 0.08$$
$$\rho(\kappa = 3 \text{ GeV/fm}) \approx 0.43$$



String tension vs. system size and centrality, obtained with Angantyr in [4]

Main Idea: Implementing String Interactions

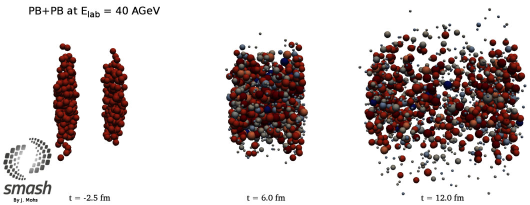
- Represent strings as pre-hadronic particles and propagate them in the transport.
- Model string overlap locally by counting strings per cell in SMASH.
- Overlaps $\Rightarrow$ modified effective tension and fragmentation.
- Goals: study how string interactions generate collectivity and compare to SMASH+hydro.

Simulating Many Accelerated Strongly-interacting Hadrons (SMASH)

- Relativistic hadronic transport (Boltzmann eq.):

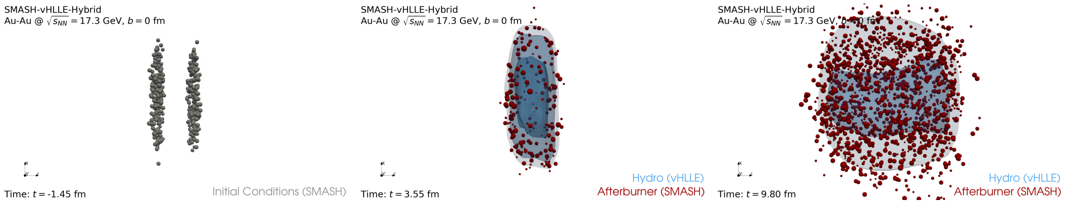
$$p^\mu \partial_\mu f_i + m_i F^\alpha \partial^p_\alpha f_i = C^i_{\text{coll}}$$

- Interactions:
  - Collision criterion: $b_\perp < \sqrt{\sigma/\pi}$
  - Cell grid: $(2.5\,\text{fm})^3 \;\Rightarrow\; \sigma_{\max} \sim 200$ mb
  - Processes: elastic, resonance decays, string excitation
- Energy dependence:
  - Low $\sqrt{s}$: resonances
  - High $\sqrt{s}$: strings (Pythia)



Schematic: SMASH cascade with resonances and strings.

SMASH+vHLLE hybrid approach



- SMASH: pre-equilibrium + hadronic afterburner
- vHLLE: 3+1D viscous hydrodynamics (hot/dense stage)
- Cooper–Frye particlization for switching
- For visuals: see Robin Sattler's talk

Reference: SMASH hybrid approach [5]

String Stopping

- **SMASH default:** unformed hadrons propagate (no string transport).
- **Extension:** transport strings as pre-hadrons.
- **Issue:** strings inherit large $p_z \Rightarrow$ many escape without interacting.
- **Remedy:** allow string-hadron interactions by exciting the hadron to a string of invariant mass:

$$dM \propto \frac{1}{M^\alpha}.$$

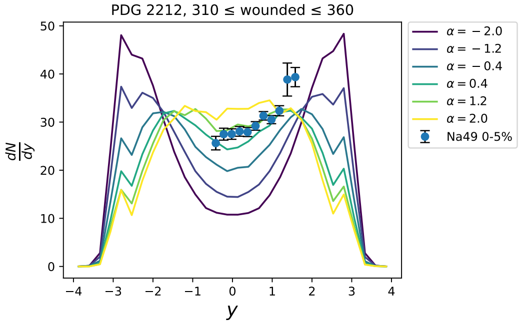
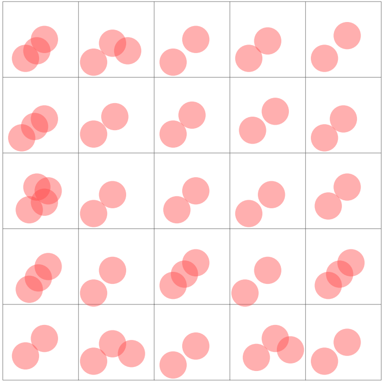


Figure: Proton rapidity spectra from Pb-Pb collisions at 158 AGeV

String Counting

- Use the SMASH interaction grid; evaluate per cell.
- Accumulate string volume in the cell: $V_{\text{strings}} = \sum_i V_i \cap \text{cell}$.
- Define overlap probability: $p_{\text{rope}} = \min\left(1,\ V_{\text{strings}}/V_{\text{cell}}\right)$.
- Sample p_{rope} to draw the rope multiplicity (number of strings merging) per cell.



Grid with multiple string volumes (overlaps visible)

Rope Formation: Random Walk in SU(3)

- Overlapping strings form a rope SU(3) multiplet $\{p, q\}$.
- Adding a triplet $\{1, 0\}$ gives:

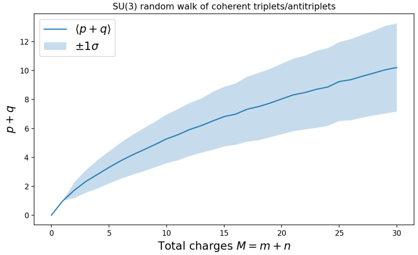
$$\{p, q\} \otimes \{1, 0\} \to \{p + 1, q\},$$

$$\{p - 1, q + 1\} \text{ or } \{p, q - 1\}$$

with weight

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

- Repeated steps ⇒ random walk; final $\{p, q\}$ sets rope tension through Casmir scaling



Random walk in SU(3) multiplets.

Based on Bierlich *et al.* (2014), inspired by Biro *et al.* (1984).

Rope tension from Casimir scaling

- **Casimir scaling:** The potential between two opposite color charges in a singlet is proportional to the quadratic Casimir operator.
- String tension in a general SU(3) representation $\{p, q\}$:

$$\kappa(\{p, q\}) = \frac{C_2(p, q)}{C_2(1, 0)}\, \kappa(\{1, 0\}), \quad C_2(p, q) = \tfrac{1}{4}\left(p^2 + q^2 + pq + 3p + 3q\right)$$

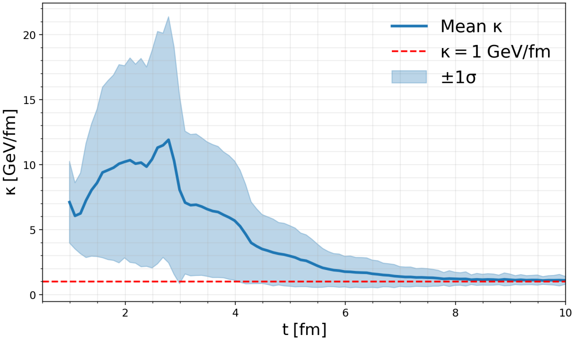
- Since fragmentation proceeds via tunneling, the *released tension* is relevant:

$$\kappa_{\text{eff}} = \kappa_{\text{before}} - \kappa_{\text{after}},$$

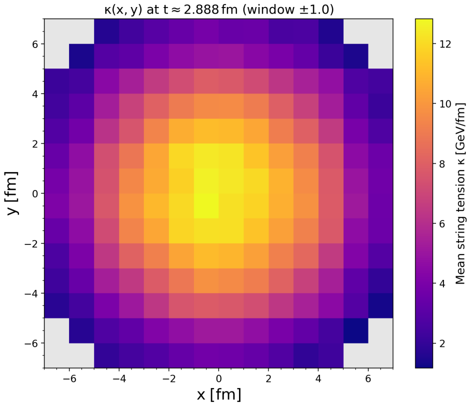
corresponding to the transition $\{p, q\} \to \{p', q'\}$.

Lattice QCD demonstrated that Casimir scaling holds within $\sim$5% up to 1 fm [6].

String tension evolution in central Pb+Pb at $\sqrt{s_{NN}} = 17.3$ GeV

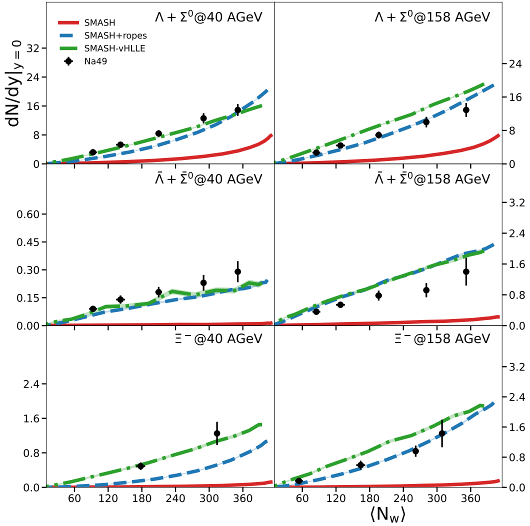


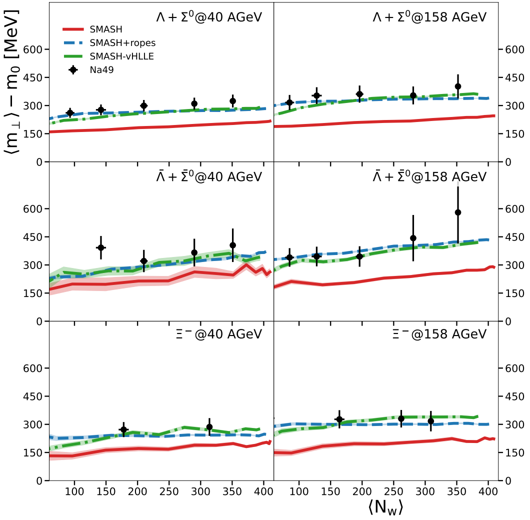
Mean $\kappa(t)$



Mean $\kappa(x, y)$ at $t \approx 3$ fm

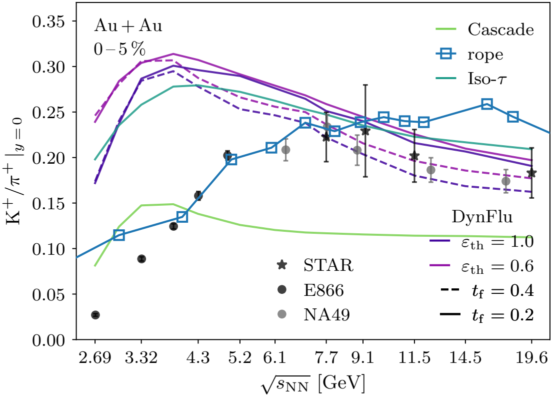
Centrality Dependence of Yields and $\langle m_T \rangle$





Excitation Function: K/π Ratios vs. $\sqrt{s_{NN}}$

- K/π excitation function probes changing degrees of freedom
- Also compare to SMASH+vHLLE with *dynamical fluidization* [7]
- ϵ_{th}: local energy density threshold for fluidization
- t_f: minimal string lifetime before fluidization



Conclusions and Outlook

- Implemented **string transport and rope formation** in SMASH: overlapping strings $\Rightarrow$ larger effective tension.
- Centrality dependence of yields and $\langle m_T \rangle$ reproduced qualitatively.
- K/π excitation function is **sensitive to string dynamics**, but the high-$\sqrt{s_{NN}}$ decrease is too weak.
- Next: extend to other string interactions (shoving, color reconnection) and address missing K/π falloff.
- **Punch line:** SMASH+Ropes vs. SMASH+Hydro $\Rightarrow$ Apples-to-apples comparison $\Rightarrow$ help clarify when hydro is needed.

References

[1] Jaroslav Adam et al. "Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions". In: *Nature Phys.* 13 (2017), pp. 535–539. DOI: 10.1038/nphys4111. arXiv: 1606.07424 [nucl-ex].

[2] Christian Bierlich. "String Interactions as a Source of Collective Behaviour". In: *Universe* 10.1 (2024), p. 46. arXiv: 2401.07585.

[3] I. Bautista, C. Pajares, and J. E. Ramírez. "String Percolation in AA and pp Collisions". In: *Revista Mexicana de Física* 65.3 (2019), p. 449. arXiv: 1905.06334.

[4] Christian Bierlich et al. "Strangeness enhancement across collision systems without a plasma". In: *Phys. Lett. B* 835 (2022), p. 137571. DOI: 10.1016/j.physletb.2022.137571. arXiv: 2205.11170 [hep-ph].

[5] Anna Schäfer et al. "Particle production in a hybrid approach for a beam energy scan of Au+Au/Pb+Pb collisions between $\sqrt{s_{\mathrm{NN}}} = 4.3$ GeV and $\sqrt{s_{\mathrm{NN}}} = 200$ GeV". In: *Eur. Phys. J. A* 58.11 (2022), p. 230. DOI: 10.1140/epja/s10050-022-00872-x. arXiv: 2112.08724 [hep-ph].

[6] Gunnar Singh Bali. "Casimir scaling of $\mathrm{SU}(3)$ static potentials". In: *Phys. Rev. D* 62 (11 2000), p. 114503. DOI: 10.1103/PhysRevD.62.114503. URL: https://link.aps.org/doi/10.1103/PhysRevD.62.114503.

[7] Renan Góes-Hirayama et al. *Pushing the hybrid approach to low beam energies with dynamic initial conditions from hadronic transport*. 2025. arXiv: 2507.19389 [hep-ph]. URL: https://arxiv.org/abs/2507.19389.

[8] T. Anticic et al. "System-size dependence of Lambda and Xi production in nucleus-nucleus collisions at 40A and 158A-GeV measured at the CERN Super Proton Synchrotron". In: *Phys. Rev. C* 80 (2009), p. 034906. DOI: 10.1103/PhysRevC.80.034906. arXiv: 0906.0469 [nucl-ex].

[9] L. Adamczyk et al. "Bulk properties of the medium produced in relativistic heavy-ion collisions from the beam energy scan program". In: *Phys. Rev. C* 96 (4 2017), p. 044904. DOI: 10.1103/PhysRevC.96.044904. URL: https://link.aps.org/doi/10.1103/PhysRevC.96.044904.

[10] B. I. Abelev et al. "Identified particle production, azimuthal anisotropy, and interferometry measurements in $\mathrm{Au} + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 9.2$ GeV". In: *Phys. Rev. C* 81 (2 2010), p. 024911. DOI: 10.1103/PhysRevC.81.024911. URL: https://link.aps.org/doi/10.1103/PhysRevC.81.024911.

[11] L. Ahle et al. "Excitation function of K+ and pi+ production in Au + Au reactions at 2/A-GeV to 10/A-GeV". In: *Phys. Lett. B* 476 (2000), pp. 1–8. DOI: 10.1016/S0370-2693(00)00037-X. arXiv: nucl-ex/9910008.

[12] S. V. Afanasiev et al. "Energy dependence of pion and kaon production in central Pb+Pb collisions". In: *Phys. Rev. C* 66 (5 2002), p. 054902. DOI: 10.1103/PhysRevC.66.054902. URL: https://link.aps.org/doi/10.1103/PhysRevC.66.054902.