Strangeness Production from Rope Hadronization in SMASH

Carl B. Rosenkvist

Prof. Hannah Elfner's group

July 15, 2026

FIAS Frankfurt Institute for Advanced Studies

Who am I?

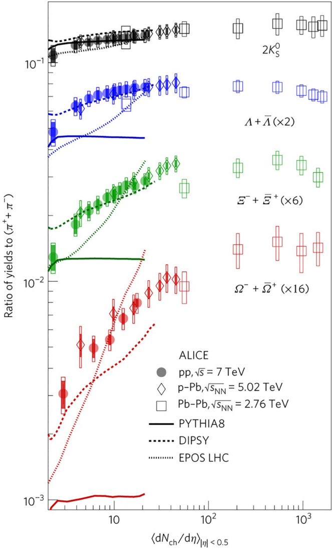
Carl B. Rosenkvist

- PhD candidate in Prof. Hannah Elfner's group
- Joined in September 2023
- M.Sc. in Lund with Prof. Leif Lönnblad
- Worked on ANGANTYR, PYTHIA's heavy-ion model
- Influenced by their philosohpy of no QGP in heavy-ion

Curious about how collective behaviour can emerge from **non-equilibrated systems**.

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*.

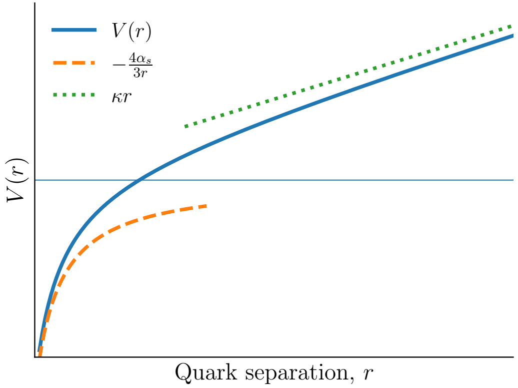


From the QCD potential to strings

- The interaction between a static $q\bar{q}$ pair is often described by the QCD potential.
- At larger distances, confinement gives a **linear** contribution:

$$V(r) \simeq -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r.$$

- The linear term can be interpreted as energy stored in a **color flux tube**.
- This flux tube behaves like a string with tension $\kappa \sim 1\ \mathrm{GeV/fm}$.



String breaking and fragmentation

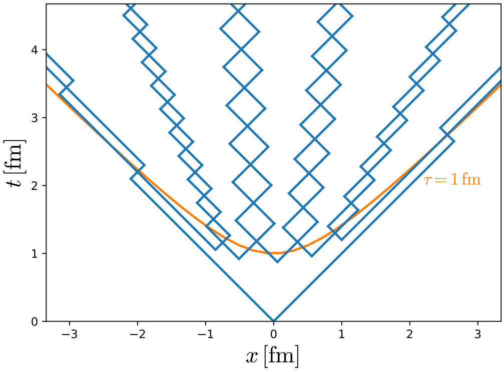
- From the linear potential, the string energy grows as

$$E_{\text{string}} \simeq \kappa r.$$

- Once large enough, the string breaks by producing a new $q\bar{q}$ pair modeled by the **Schwinger mechanism**:

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

- Repeated breaking produces color-neutral hadrons: **fragmentation**.



String breaking and hadron formation.

Flavour selection

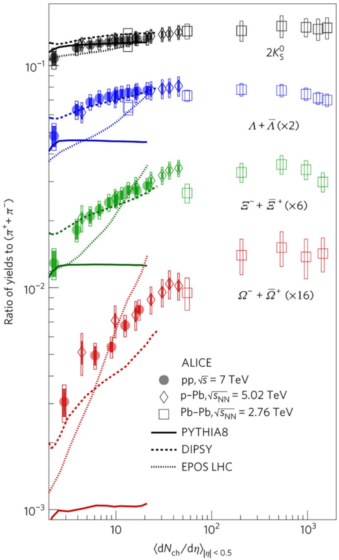
- At each string break, a new $q\bar{q}$ pair is produced.
- From the Schwinger mechanism, flavour production is mass suppressed:

$$P(q) \propto \exp\left[-\frac{\pi m_q^2}{\kappa}\right].$$

- Light flavours are therefore favoured:

$$u, d > s.$$

- The string tension κ controls the strength of this suppression.



Momentum selection

- Transverse momentum is generated by tunneling during string breaking.
- The Schwinger mechanism gives a Gaussian-like distribution:

$$P(p_T) \propto \exp\left[-\frac{\pi p_T^2}{\kappa}\right].$$

- The width of the p_T distribution is controlled by the string tension:

$$\langle p_T^2 \rangle \sim \frac{\kappa}{\pi}.$$

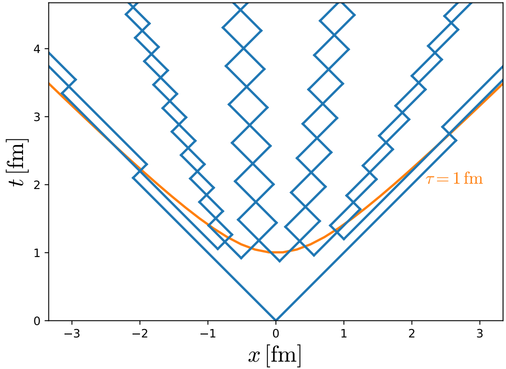
- Longitudinal momentum is sampled using the **Lund fragmentation function**:

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left[-\frac{bm_T^2}{z}\right].$$

Formation Times

- After string fragmentation, produced hadrons should eventually participate in rescattering.
- The key question is: *when* do they become active?
- Different formation-time prescriptions assign different space-time positions to newly formed hadrons.
- In SMASH, a common choice is a constant proper formation time,

$$\tau = 1\,\text{fm}.$$

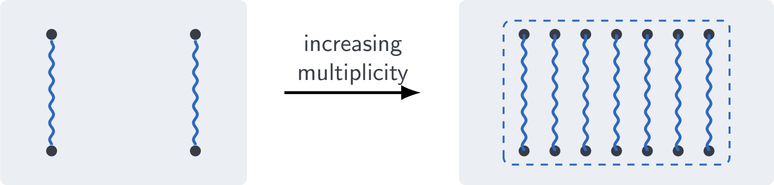


String breaking and hadron formation.

From Fragmentation to Collective Effects

Why go beyond independent string fragmentation?

Low string density **High string density**



Separated strings fragment independently

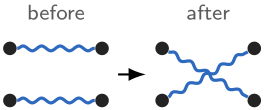
Finite-width colour fields overlap

Strings are no longer independent

String overlap enables **colour reconnection, string shoving, and rope formation**.

String interactions in Pythia

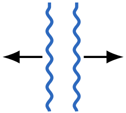
Colour reconnection



New colour topology

$\Rightarrow$ baryons and $\langle p_T \rangle$

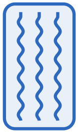
String shoving



Transverse repulsion

$\Rightarrow$ ridge / flow-like effects

Rope hadronization



Enhanced string tension

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

Microscopic interactions between overlapping strings can produce **collective-like signatures**.

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

- Overlap ⇒ higher effective tension

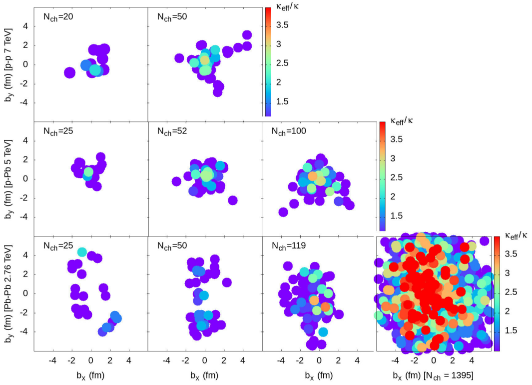
$$\kappa_{\text{eff}} > \kappa$$

- 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

Embed string dynamics directly into SMASH

1. Propagate
Represent strings as pre-hadronic objects

→ **2. Find overlap**
Count strings locally in each SMASH cell

→ **3. Modify**
Set the local effective string tension

→ **4. Analyse**
Compute final-state observables

Physics question

Can local string interactions generate collective-like behaviour without an equilibrated fluid?

Benchmark

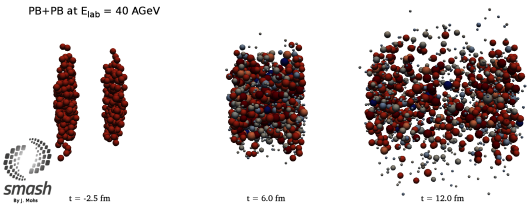
Compare the resulting observables with **SMASH+hydrodynamics**.

Simulating Many Accelerated Strongly-interacting Hadrons (SMASH)

- Relativistic hadronic transport (Boltzmann eq.):

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

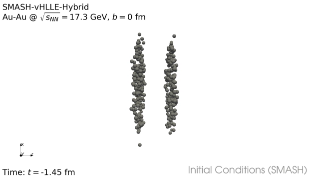
- Interactions:
  - Collision criterion: $b_\perp < \sqrt{\sigma/\pi}$
  - Cell grid: $(2.5\,\text{fm})^3 \;\Rightarrow\; \sigma_{\text{max}} \sim 200$ mb
  - Processes: elastic, resonance decays, string excitation
- Energy dependence:
  - Low $\sqrt{s}$: resonances
  - High $\sqrt{s}$: strings (Pythia)



Schematic: SMASH cascade with resonances and strings.

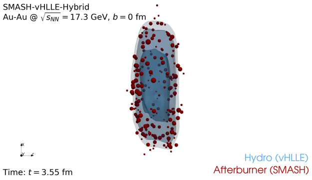
SMASH–vHLLE Hybrid Evolution

Dynamic conversion between microscopic transport and viscous hydrodynamics



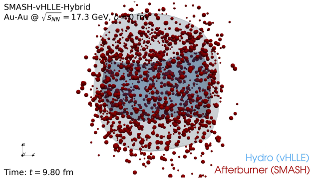
Pre-equilibrium

SMASH transport



Dynamic fluidization

Core grows locally



Fluid evolution

Viscous 3+1D vHLLE

SMASH Microscopic pre-equilibrium and corona transport → **Fluidization criterion** Local energy density $\varepsilon_{\mathrm{LRF}} > \varepsilon_{\mathrm{th}}$ → **vHLLE** Dynamic source deposition and viscous fluid evolution → **Particlization + SMASH** Cooper–Frye sampling and hadronic afterburner

String Stopping

Secondary excitations in SMASH

- Hadrons: formation time + reduced σ for leading particles.

Missing ingredient

- Transported strings do not undergo secondary excitations.
- Many escape due to their large longitudinal momentum.

Our extension

- Allow string–hadron interactions.
- Angantyr-inspired single diffractive excitation:

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

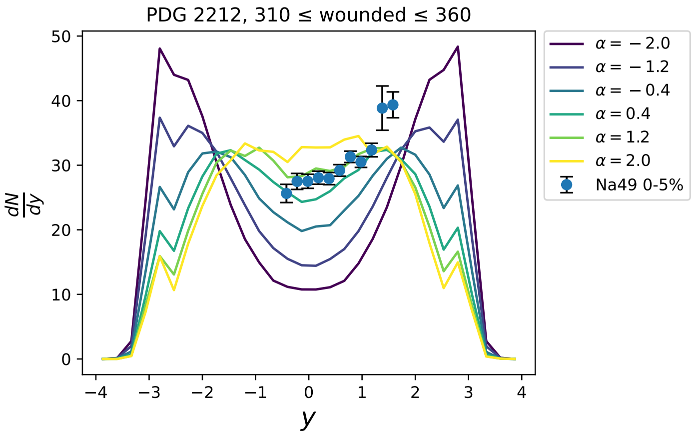
- String treated elasticly and hadron diffractivly (easy four-momentum and color-flow handling)

Tuning the String Stopping

Secondary exited string invariant mass spectrum:

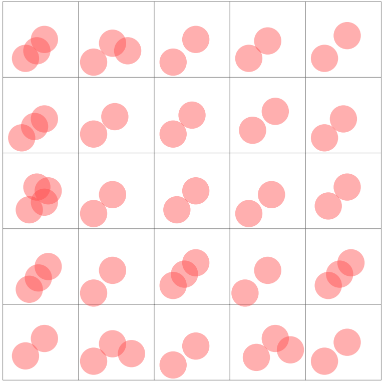
$$dM \propto \frac{1}{M^{\alpha}}$$

- α controls the excitation mass.
- Larger $\alpha \Rightarrow$ stronger stopping.
- Tune α to proton rapidity spectra.



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:

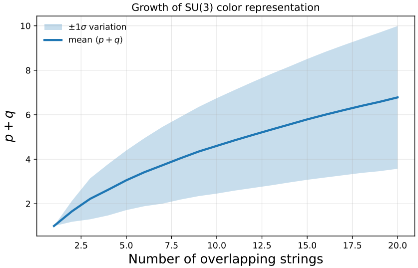
$$\{p, q\} \otimes \{1, 0\} \to \{p+1, q\},$$

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

with weight

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

- Repeated steps $\Rightarrow$ 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 $\{p, q\}$:

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

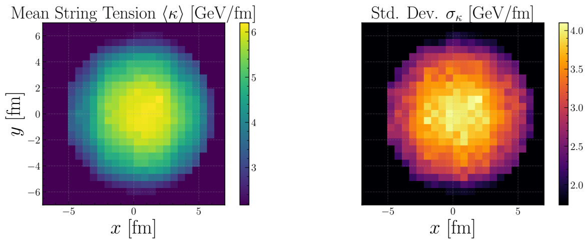
- Since fragmentation proceeds via tunneling, the *released tension* is relevant:

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

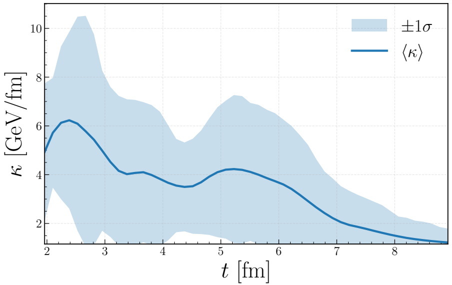
corresponding to the transition $\{p, q\}_{\text{before}} \to \{p', q'\}_{\text{after}}$.

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

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

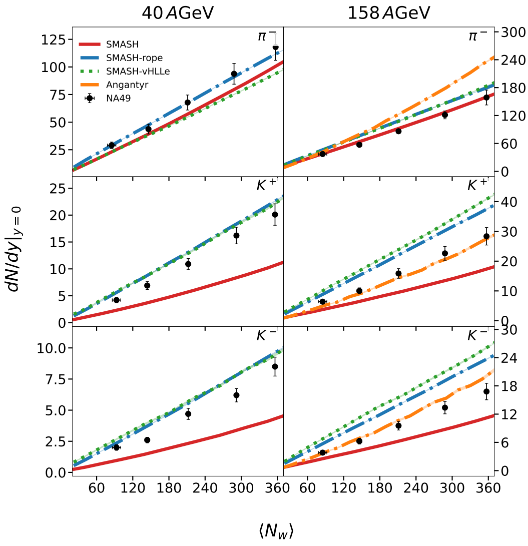


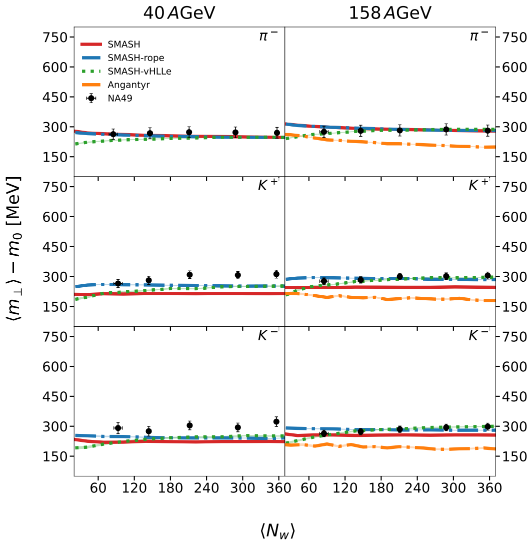
Mean string tension in a central slice; color scale shows standard deviation.



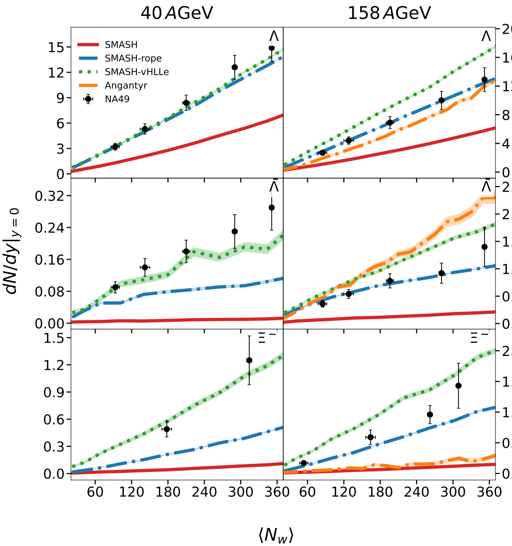
Mean string tension in a central slice as a function of time.

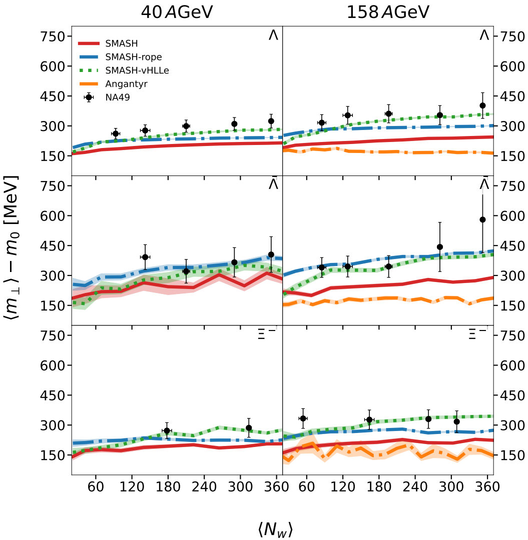
Centrality Dependence of Yields and $\langle m_T \rangle$ for Mesons



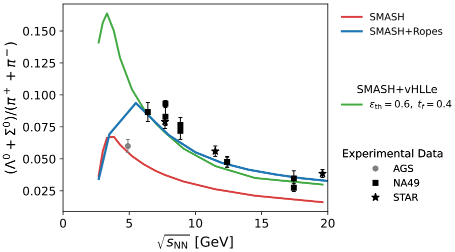


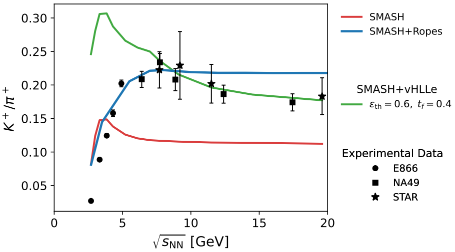
Centrality Dependence of Yields and $\langle m_T \rangle$ for Baryons

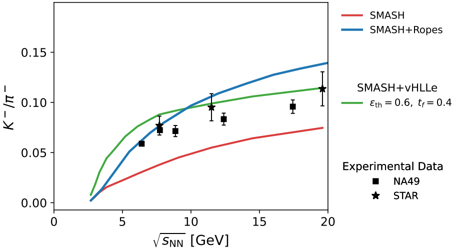




Excitation function: strange-to-pion ratios vs. $\sqrt{s_{NN}}$

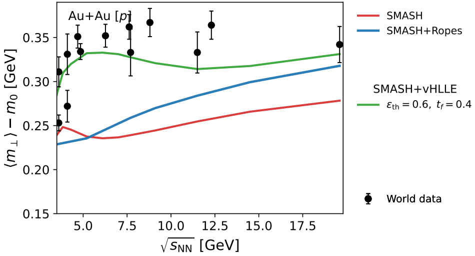


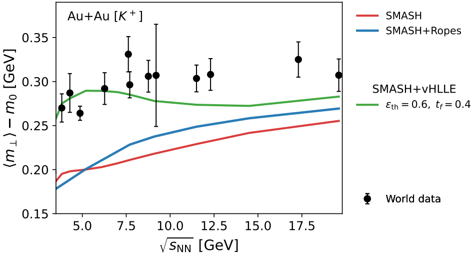


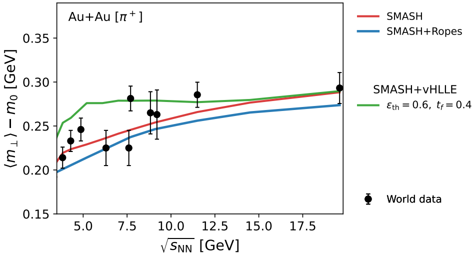


- Dynamical fluidization overestimates the ratios near the horn.
- Rope hadronization improves the horn, but misses the decrease at higher energies.
- The excitation function suggests a gradual onset of thermalization.

Mean transverse mass excitation function







- Rope formation increases the effective string tension κ.
- This broadens the Schwinger p_T distribution:
- No string shoving $\Rightarrow$ there is no additional collective transverse push.

Thermal-like Strings

A. Białas noted that if the string tension fluctuates, the usual Schwinger-like string fragmentation spectrum,

$$\frac{dn_q}{d^2p_\perp} \propto \exp\left[-\frac{\pi(m_q^2 + p_\perp^2)}{\kappa}\right], \tag{1}$$

can transform into a Boltzmann-like distribution,

$$\frac{dn_q}{d^2p_\perp} \propto \exp\left[-\frac{m_\perp}{T}\right], \tag{2}$$

with an effective temperature

$$T = \sqrt{\frac{\kappa}{2\pi}}. \tag{3}$$

The rope tension fluctuates strongly, so rope fragmentation can mimic thermal spectra.

Rope Effects on Transverse Momentum Spectra

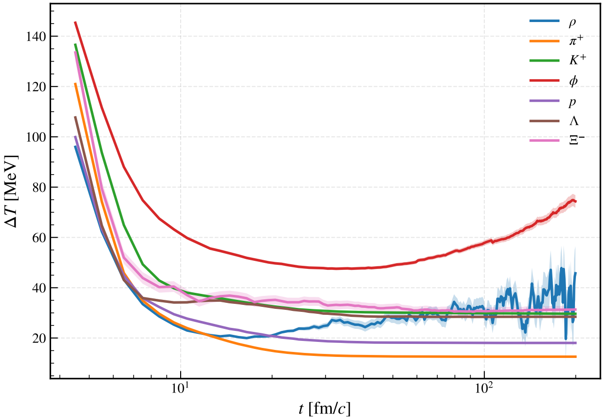
- Extract inverse slopes:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto e^{-m_T/T_{\text{slope}}}.$$

- Compare ropes vs. no ropes:

$$\Delta T_{\text{slope}} = T_{\text{slope}}^{\text{rope}} - T_{\text{slope}}^{\text{no rope}}.$$

- Stronger effect for strange hadrons.



The ordering in ΔT_{slope} reflects the enhanced strangeness production in dense ropes

Conclusions and Outlook

- String fragmentation provides a microscopic mechanism for particle production.
- Rope fragmentation increases the effective string tension and enhances strangeness production.
- Strange hadrons show the strongest hardening of the transverse-momentum spectra.

Outlook

- Use ϕ mesons and multi-strange baryons as discriminators of dense string dynamics.
- Study how these early string effects survive hadronic rescattering.
- Explore dilepton observables as cleaner probes of the early string dynamics.

Thank you for listening!

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].

[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].

[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.