Strangeness Production in SMASH

Carl B. Rosenkvist

November 13, 2025

FIAS Frankfurt Institute for Advanced Studies

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

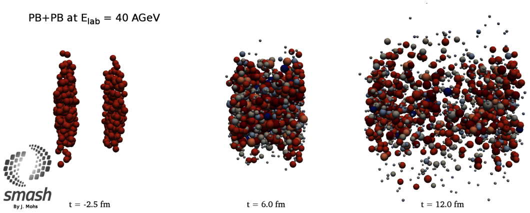
Outline

Simulating Many Accelerated Strongly-interacting Hadrons (SMASH)

- Relativistic hadronic transport (Boltzmann eq.):

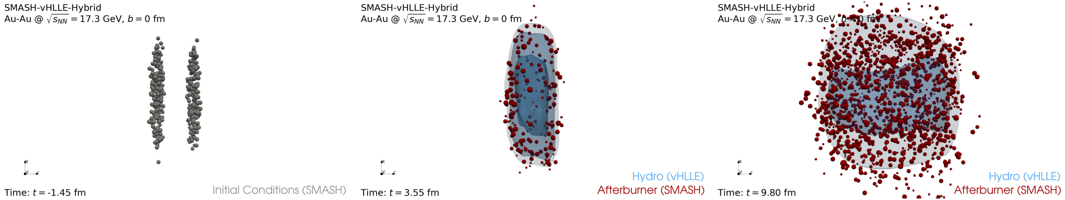
$$p^\mu \partial_\mu f_i + m_i F^\alpha \partial_\alpha^p f_i = C^i_{\text{coll}}$$

- Interactions:
  - Collision criterion: $b_\perp < \sqrt{\sigma/\pi}$
  - 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
- The visualizations are taken from `https://smash-transport.github.io/movies-hybrid.html`

Reference: SMASH hybrid approach [1]

Resonance Spectral Function

- Resonances are propagated as finite-lifetime degrees of freedom.
- Their mass distribution is described by a relativistic Breit–Wigner form:

$$\mathcal{A}(m) = \frac{m^2\Gamma(m)}{(m^2 - m_0^2)^2 + m^2\Gamma(m)^2}$$

- m_0: pole mass, $\Gamma(m)$: mass-dependent total width.
- Ensures proper normalization of the spectral shape in transport calculations.

Mass-Dependent Widths (Manley *et al.*)

- Partial decay widths depend on the available phase space and thus vary with the resonance mass:

$$\Gamma_{R\to a+b}(m) = \Gamma^0_{R\to a+b}\,\frac{\rho_{ab}(m)}{\rho_{ab}(m_0)}$$

- $\rho_{ab}(m)$: two-body phase-space factor including the spectral functions of the daughter particles:

$$\rho_{ab}(m) = \int dm_a\, dm_b\, \mathcal{A}_a(m_a)\, \mathcal{A}_b(m_b)\, \frac{|\vec{p}_f|}{m}\, B_L(|\vec{p}_f| R)\, \mathcal{F}^2_{ab}(m)$$

B_L: Blatt–Weisskopf barrier factor, L: orbital angular momentum, R: interaction radius, $\mathcal{F}_{ab}$: form factor.

- Each resonance is therefore defined by its pole mass, width and branching ratios — all of which determine its contribution to observables.

Resonances & Genetic Algorithms

Exploring uncertainties through evolutionary optimization

Why Study Resonance Parameter Stability?

- Resonances are characterized by many parameters — pole masses, total width and branching ratios.
- These quantities often have large experimental uncertainties. For example, according to the PDG, the $N(1900)$ resonance has bounds on its decay mode $\Lambda + K$ ranging from 2% to 20%.
- With many overlapping resonances contributing to a given observable, such uncertainties can accumulate and propagate in non-trivial ways.
- Understanding the impact of these parameter variations is essential for interpreting observables sensitive to resonance dynamics.

Emulation of Resonance Contributions

- Full transport runs for rare (strange) channels are CPU expensive.
- **Idea:** emulate results using resonance and string cross sections.

Effective cross section:

$$\sigma_{d+i} \approx \sigma_{\text{string}\to d+i} + \sum_{N^*} \sigma_{N^*} \left\langle \frac{\Gamma_{N^*\to d}}{\Gamma_{N^*}} \right\rangle$$

Mean branching ratio:

$$\left\langle \frac{\Gamma_{N^*\to d}}{\Gamma_{N^*}} \right\rangle = \frac{1}{\mathcal{N}} \int dm\, \mathcal{A}(m) \frac{\Gamma_{N^*\to d}(m)}{\Gamma_{N^*}(m)}$$

$\mathcal{N} = \int dm\, \mathcal{A}(m)$ ensures normalization. For $2 \to 1$ reactions (e.g. $\pi p \to N^*$), $m = \sqrt{s}$ is fixed.

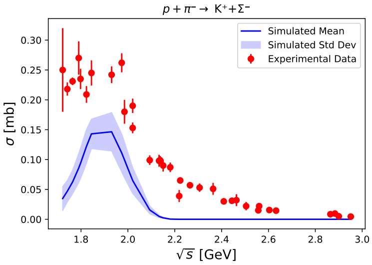
Parameter bounds

Resonance	Mode	Upper	Lower	SMASH-3.1
N(1650)	Λ K	15.0	5.0	4.0
N(1710)	Λ K	25.0	5.0	13.0
N(1720)	Λ K	19.0	4.0	5.0
N(1875)	Λ K	2.0	1.0	4.0
N(1880)	Λ K	3.0	1.0	2.0
N(1895)	Λ K	23.0	3.0	18.0
N(1900)	Λ K	20.0	2.0	2.0
N(1990)	Λ K	6.1	5.9	3.0
N(2060)	Λ K	20.0	10.0	1.0
N(2080)	Λ K	2.0	1.0	0.5
N(2100)	Λ K	1.0	0.0	1.0
N(2250)	Λ K	3.0	1.0	0.2
N(1710)	Σ K	1.0	0.0	1.0
N(1875)	Σ K	1.1	0.3	4.0
N(1880)	Σ K	24.0	10.0	10.0
N(1895)	Σ K	20.0	6.0	11.0
N(1900)	Σ K	7.0	3.0	3.0
N(1990)	Σ K	1.0	0.0	3.0
N(2060)	Σ K	5.0	1.0	4.0
Δ(1900)	Σ K	1.0	0.0	1.0
Δ(1910)	Σ K	14.0	4.0	4.0
Δ(1920)	Σ K	6.0	2.0	3.0
Δ(1930)	Σ K	1.0	0.0	4.0
Δ(1950)	Σ K	0.5	0.3	0.5
N(2080)	N ϕ	1.0	0.0	1.0
N(2100)	N ϕ	1.0	0.0	1.0
N(2120)	N ϕ	1.0	0.0	1.0
N(2190)	N ϕ	1.0	0.0	1.0
N(2220)	N ϕ	1.0	0.0	1.0
N(2250)	N ϕ	1.0	0.0	1.0
N(1880)	N $a_0(980)$	5.0	1.0	2.0
Δ(1920)	N $a_0(980)$	1.0	0.0	1.0
N(2080)	N $f_0(980)$	1.0	0.0	0.1
N(2190)	N $f_0(980)$	1.0	0.0	0.1
N(2220)	N $f_0(980)$	1.0	0.0	0.1
N(2250)	N $f_0(980)$	1.0	0.0	0.1

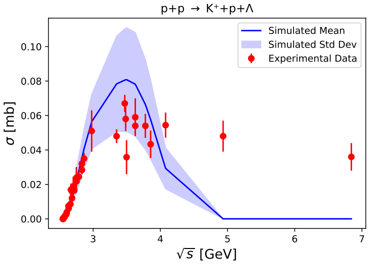
Resonance	Mass[GeV] SMASH-3.1	Width[GeV] SMASH-3.1	Mass[GeV] Bounds	Width[GeV] Bounds
N(1440)	1.440	0.350	1.36-1.38	0.18-0.205
N(1520)	1.515	0.110	1.505-1.515	0.105-0.12
N(1535)	1.530	0.150	1.5-1.52	0.08-0.13
N(1650)	1.650	0.125	1.65-1.68	0.1-0.17
N(1675)	1.675	0.145	1.65-1.66	0.12-0.15
N(1680)	1.685	0.120	1.66-1.68	0.11-0.135
N(1700)	1.720	0.200	1.65-1.75	0.1-0.3
N(1710)	1.710	0.140	1.65-1.75	0.08-0.16
N(1720)	1.720	0.250	1.66-1.71	0.15-0.3
N(1875)	1.875	0.250	1.85-1.95	0.1-0.22
N(1880)	1.880	0.400	1.82-1.9	0.18-0.28
N(1895)	1.895	0.120	1.89-1.93	0.08-0.14
N(1900)	1.900	0.200	1.9-1.94	0.09-0.16
N(1990)	1.990	0.500	1.9-2.1	0.2-0.4
N(2060)	2.100	0.400	2.02-2.13	0.35-0.43
N(2080)	2.000	0.350	1.85-1.92	0.12-0.25
N(2100)	2.100	0.260	2.05-2.15	0.24-0.34
N(2120)	2.120	0.300	2.05-2.15	0.2-0.36
N(2190)	2.180	0.400	1.95-2.15	0.3-0.5
N(2220)	2.220	0.400	2.13-2.2	0.36-0.48
N(2250)	2.250	0.470	2.1-2.2	0.35-0.5
Δ(1620)	1.610	0.130	1.59-1.61	0.08-0.14
Δ(1700)	1.710	0.300	1.64-1.69	0.2-0.3
Δ(1900)	1.860	0.250	1.83-1.9	0.18-0.3
Δ(1905)	1.880	0.330	1.75-1.8	0.26-0.34
Δ(1910)	1.900	0.300	1.8-1.9	0.2-0.5
Δ(1920)	1.920	0.300	1.85-1.95	0.2-0.4
Δ(1930)	1.950	0.300	1.82-1.88	0.3-0.45
Δ(1950)	1.930	0.280	1.87-1.89	0.22-0.26

Parameter Stability: Motivation for a Systematic Approach

- Vary resonance parameters within PDG bounds and emulate exclusive strange cross sections.
- Compare mean $\pm 1\sigma$ bands to data from [2–13] for different channels.
- Some channels are better constrained while some are not $\Rightarrow$ need a systematic treatment.



$\pi^- p \to K^+ + \Sigma^-$: data often several σ away from the band.



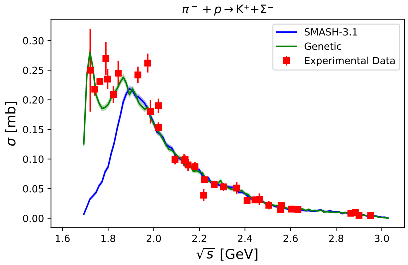
$pp \to K^+ + p + \Lambda$: data mostly within the 1σ band.

Genetic Algorithm: Concept & Implementation

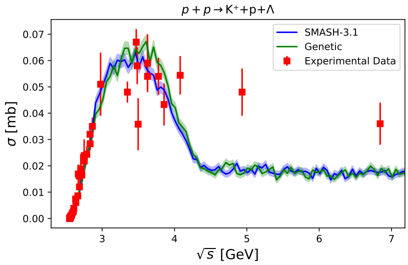
- **Goal:** Optimize resonance parameters to reproduce experimental cross sections.
- Population-based evolutionary search — robust against noise and local minima.
- Steps per generation:
  1. Evaluate fitness of all parameter sets.
  2. Select the top 50% for reproduction.
  3. Apply **crossover:** random uniform mixing of parent parameters.
  4. Apply **mutation:** each parameter has a 10% chance to randomize.
- Repeat until convergence or fixed number of generations.
- **Advantage:** Embarrassingly parallel — each candidate can run on a separate CPU.

Results: After Genetic Fitting

- Genetic algorithm tuned resonance masses, widths, and branching ratios.
- pp channels remain similar; πp reactions show clear improvement.
- Fitted parameters reproduce experimental data more consistently.



$\pi^- p \to K^+ + \Sigma^-$: improved fit after GA.



$pp \to K^+ + p + \Lambda$: stable.

Conclusion: Genetic Algorithm Fitting

- The genetic algorithm systematically optimized resonance parameters within PDG bounds.
- Significant improvement for πp channels; overall better consistency with experimental data.
- Parameters included in SMASH 3.2 release.
- Demonstrates that stochastic optimization provides a robust and efficient approach for transport model tuning.

Full results published in:

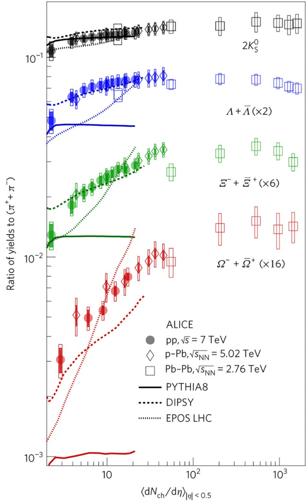
Systematic Optimization of Resonance Parameters in a Transport Approach
C. B. Rosenkvist and H. Elfner,
Phys. Rev. C 112 (2025) 014911
inspirehep.net/literature/2897898 — arXiv:2503.05504 [hep-ph]

Color Ropes in Hadronization

Overlapping strings $\Rightarrow$ enhanced color field strength $\Rightarrow$ Strangeness enhancement

Collectivity from Nucleon–Nucleon Interactions

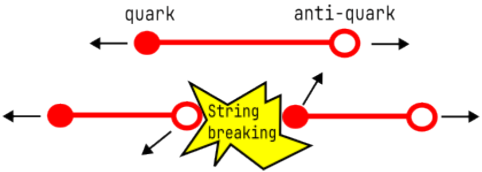
- Strangeness enhancement is a classic QGP signature in A+A collisions.
- Hydro+transport (core–corona) models reproduce this behavior well.
- Yet similar collective trends appear in high-multiplicity *pp* events (ALICE [14]).
- $\Rightarrow$ Suggests collectivity may already emerge in NN interactions, possibly driven by *string dynamics*.



Color flux tubes (Strings)

- The linear part of the $q\bar{q}$ potential, $V(r) = \kappa r$, is modeled as a **relativistic massless string** with tension $\kappa \sim 1$ GeV/fm.
- As the quarks separate, this string stores potential energy.
- When stretched, it breaks via the **Schwinger mechanism**, creating new $q\bar{q}$ pairs:

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



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)[15]

- SU(3) based color reconnection (string recombination) $\Rightarrow$ baryons
- String shoving(repulsive interactions) $\Rightarrow$ flow / ridge
- Rope hadronization(overlapping color fields) $\Rightarrow$ strangeness
- Extended to Heavy-ion via Angantyr

Macroscopic (Percolation)[16]

- String density in overlap region #strings/(transverse overlap region)
- Critical density of strings $\Rightarrow$ 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

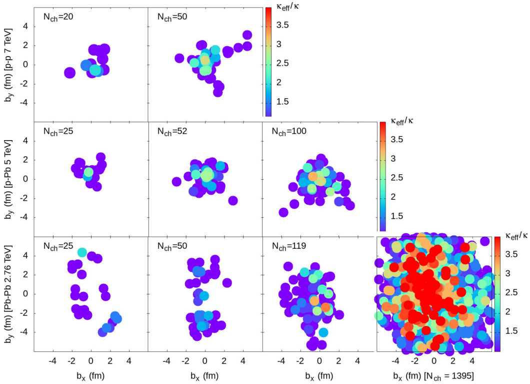
$$\kappa_{\text{eff}} > \kappa$$

- Strangeness suppression (Schwinger mechanism)

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

- Example values:

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



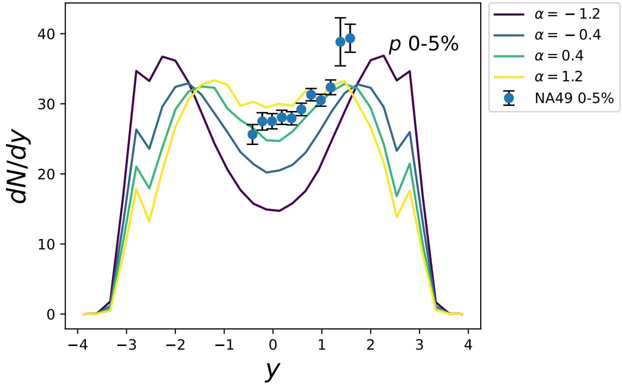
String tension vs. system size and centrality, obtained with Angantyr in [17]

Main Idea: Implementing String Interactions

- Represent strings as pre-hadronic particles with a **finite lifetime** and **finite volume** at fragmentation.
- Propagate these strings dynamically.
- Model local string overlap by counting strings per cell in SMASH.
- Overlaps $\Rightarrow$ modified effective tension and altered fragmentation pattern.
- Aim: study how string interactions generate collectivity and compare to SMASH+hydro.

String Stopping

- **SMASH:** baryon stopping arises from unformed hadron interactions and leading baryon dynamics.
- **With string transport:** strings replace unformed hadrons and no leading baryon at collision time.
- **Consequence:** strings escaping the medium before fragmenting $\Rightarrow$ no stopping.
- **Remedy:** allow string–hadron scatterings that excite hadrons to strings, sampled as $dN/dM \propto M^{-\alpha}$.



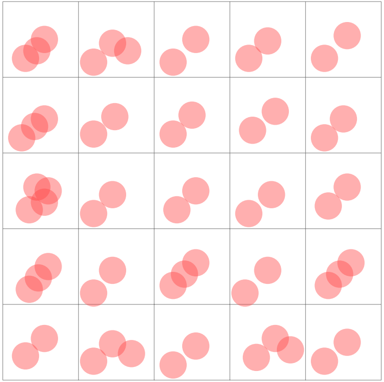
Proton rapidity in Pb+Pb, 158 AGeV

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

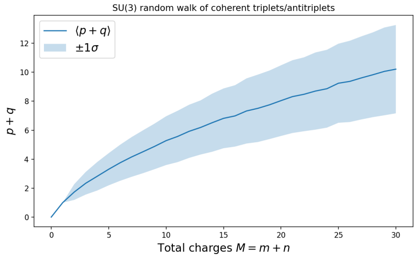
$$\{p, q\} \otimes \{1, 0\} \to \{p + 1, q\},$$

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

with weight

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

- Repeated steps $\Rightarrow$ 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 grows with the quadratic Casimir C_2. Since C_2 is defined only up to a normalization, we normalize it to the triplet $\{1, 0\}$, i.e. the tension of a single string.
- **Following Bierlich et al. we define the rope tension as:**

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

  which expresses the relative strength of the rope tension for a representation $\{p, q\}$.
- **Effective tension in a string break:** Since fragmentation proceeds via tunneling, the relevant quantity is the *released tension*:

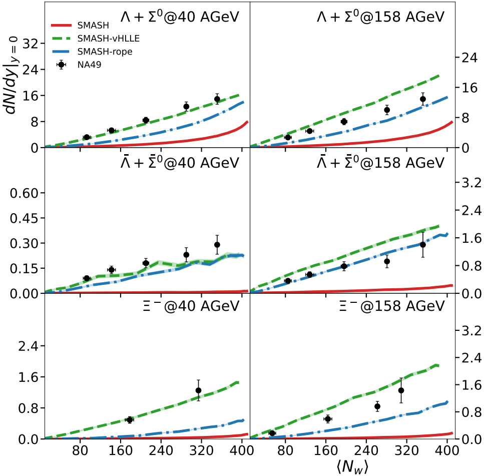
$$\kappa_{\text{eff}} = \kappa_{\text{before}} - \kappa_{\text{after}} \quad (\{p,q\} \to \{p',q'\}).$$

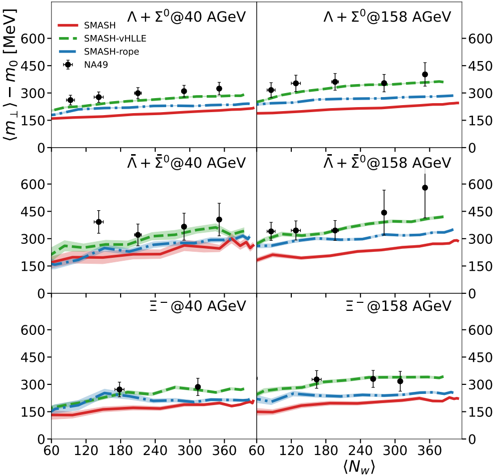
Lattice QCD supports Casimir scaling at the $\sim$5% level up to 1 fm [18].

Recap: What Are We Doing with Strings?

- Treat Lund strings as explicit objects with finite lifetime and fragmentation volume.
- Allow string–hadron scatterings so that strings do not simply escape (restores baryon stopping).
- In each SMASH cell, count the local string content and sample a **rope multiplicity**.
- This rope multiplicity sets the **effective tension** in that cell (via the SU(3) random walk and Casimir scaling).
- Fragment strings with this cell-dependent tension $\Rightarrow$ modified Schwinger suppression and enhanced strangeness.

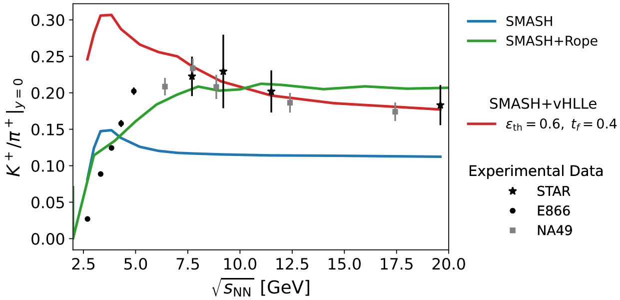
Centrality Dependence of Yields and $\langle m_T \rangle$





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

- K/π excitation function probes changes in the effective degrees of freedom
- Confront data with SMASH+vHLLE including *dynamical fluidization* [19]
- Test sensitivity to pre-hadronic (string / rope) dynamics



Is pre-thermal strangeness production important?

Can rope formation and fluidization work consistently together?

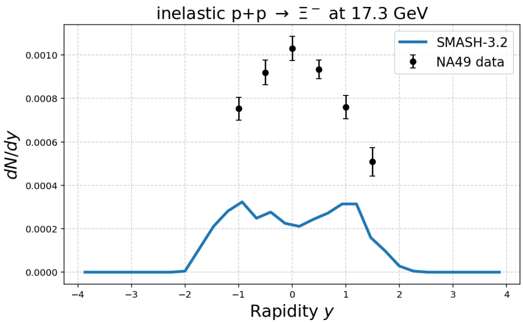
Conclusions and Outlook

- Implemented **string transport and rope formation** in SMASH: overlapping strings $\Rightarrow$ larger effective tension.
- Centrality dependence of yields and $\langle m_T \rangle$ was improved with ropes. Best description with hydro.
- 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.

Incoming strangeness improvements for future SMASH releases

Future improvements: Strangeness production

- SMASH was never tuned for multi-strange baryon production in p+p!
- Refine **string fragmentation** to better reproduce strange yields in p+p
- Establish a reliable **baseline for heavy-ion collisions**
- Particularly important for **peripheral events**



Aim: Improved strangeness production from strings in **SMASH 3.4**

Underproduction of Ξ^- in SMASH p+p at 17 GeV

Thank you for listening!

References I

[1] 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].

[2] J. T. Balewski et al. In: *Phys. Lett. B* 420 (1998), p. 211. arXiv: nucl-ex/9803003.

[3] S. Sewerin et al. In: *Phys. Rev. Lett.* 83 (1999), p. 682. arXiv: nucl-ex/9811004.

[4] P. Kowina et al. In: *Eur. Phys. J. A* 22 (2004), p. 293. arXiv: nucl-ex/0402008.

[5] S. Abd El-Samad et al. In: *Phys. Lett. B* 688 (2010), p. 142. arXiv: 1003.0603.

[6] M. Abdel-Bary and others (COSY-TOF). In: *Eur. Phys. J. A* 46 (2010), p. 27. arXiv: 1008.4287.

[7] R. Bilger et al. In: *Phys. Lett. B* 420 (1998), p. 217.

[8] S. Abdel-Samad and others (COSY-TOF). In: *Phys. Lett. B* 632 (2006), p. 27.

[9] A. Baldini. "NUMERICAL DATA AND FUNCTIONAL RELATIONSHIPS IN SCIENCE AND TECHNOLOGY. GRP. 1: NUCLEAR AND PARTICLE PHYSICS. VOL. 12: TOTAL CROSS-SECTIONS FOR REACTIONS OF HIGH-ENERGY PARTICLES (INCLUDING ELASTIC, TOPOLOGICAL, INCLUSIVE AND EXCLUSIVE REACTIONS). SUBVOL". In: *Landolt-Börnstein. New Series, 1/12B* (1988). Ed. by V. Flaminio et al.

[10] Yu. Valdau et al. In: *Phys. Rev. C* 81 (2010), p. 045208. arXiv: 1002.3459.

[11] Yu. Valdau et al. In: *Phys. Lett. B* 652 (2007), p. 245. arXiv: nucl-ex/0703044.

[12] C. M. Ko. In: *Phys. Lett. B* 120 (1983), p. 294.

[13] M. Wolke. PhD thesis. University of Bonn, 1998.

[14] 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].

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

[16] 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.

References II

[17] 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].

[18] 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.

[19] 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.