Strangeness production from rare decays of heavy baryonic resonances and multi-particle interactions

Strangeness in Quark Matter 2022, Busan

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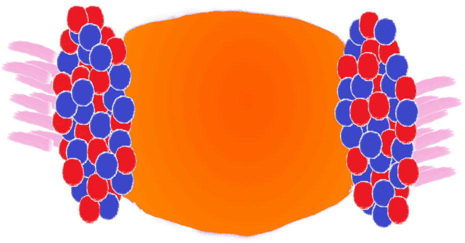
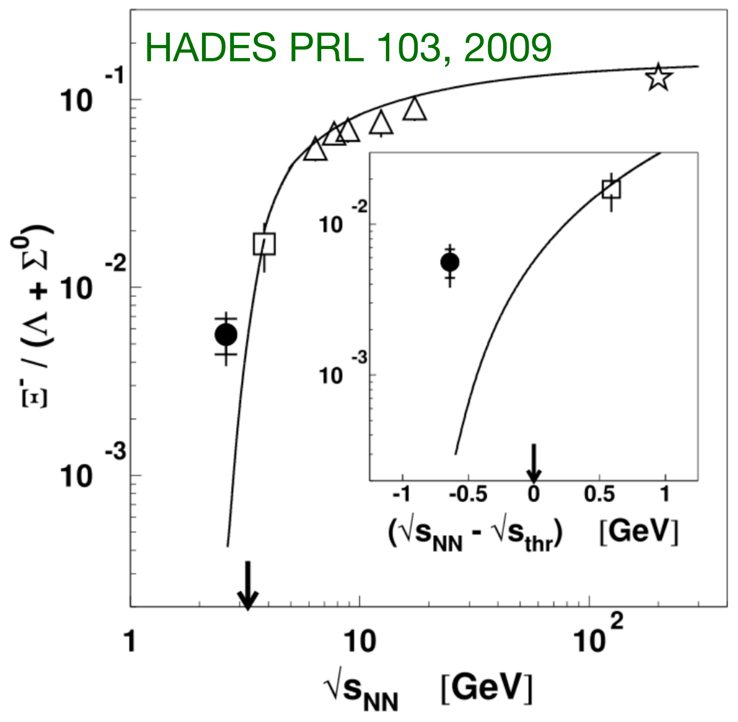
Strangeness in low-energy collisions



- At low beam energies higher yields of double-strange hadrons were observed than theoretically expected → Medium effects?
- Explore **previously suggested mechanism** to produce strangeness from heavy baryonic decays
  J. Steinheimer and M. Bleicher, J. Phys., G43, 2016 (UrQMD)
- Employ hadronic transport approach **SMASH** to study strangeness production from hadron interactions
  https://smash-transport.github.io

smash



Phys.Rev.C 94 054905 (2016)

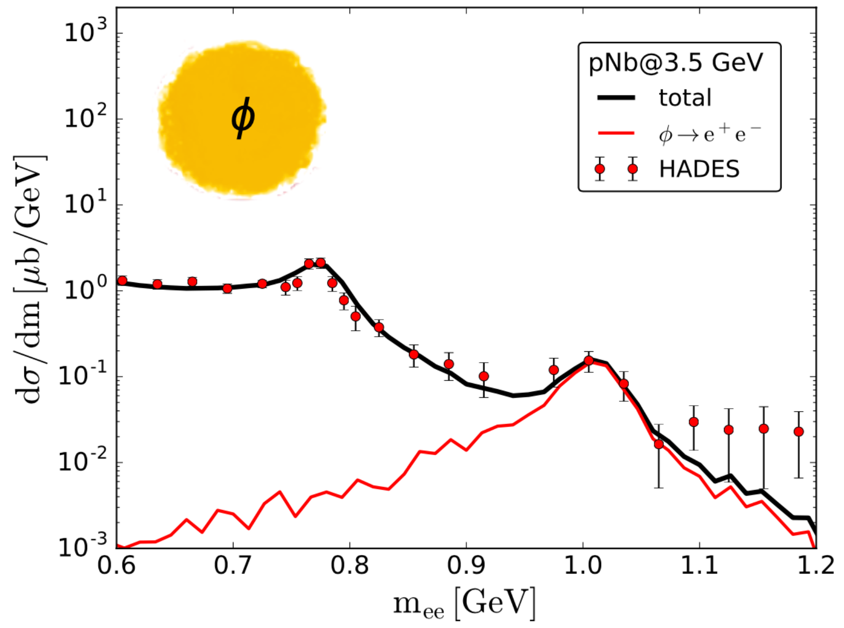
ϕ and Ξ from rare N* decays

$$N^* \rightarrow N\phi$$
$$N^* \rightarrow \Xi K K$$

- **Constrain decay branching ratios with available particle production and dilepton data** from elementary reactions
- Able to **reproduce ϕ** and Ξ production for **existing data** with one free parameter, including for larger nucleus-nucleus like ArKCl
- Predictions for upcoming experimental data (AgAg)

Ξ

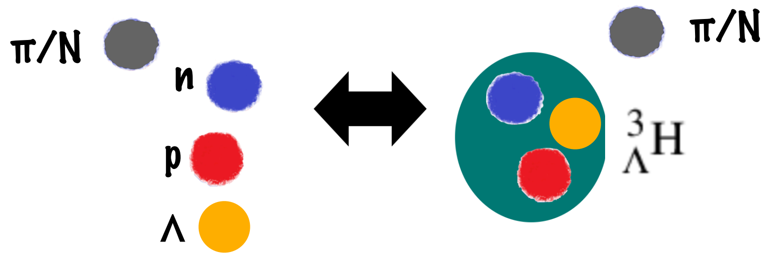
$N(\Xi^-)$	pNb	ArKCl
SMASH	2.04×10^{-4}	1.95×10^{-4}
HADES	$(2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$	$(2.3 \pm 0.9) \times 10^{-4}$



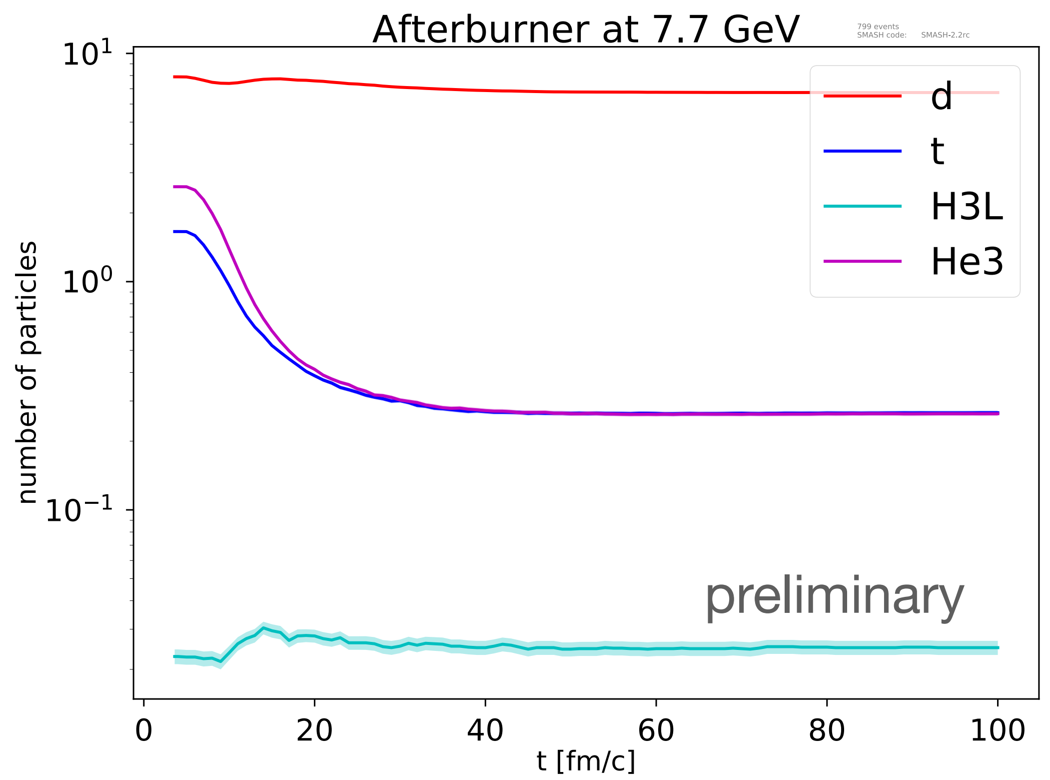
$$BR_{N^* \rightarrow \phi N} = 0.001$$
$$BR_{N^* \rightarrow \Xi K K} = 0.5$$

Phys. Rev. C 99, 064908 (2019), Phys. Rev. C 103, 044904 (2021)

Multi-particle interactions



- Relevant in high-density collisions at new facilities and programs like FAIR or RHIC-BES
- **Multi-particle reactions** are **significant for particle abundances** as recently shown for deuteron catalysis and p$\bar{\text{p}}$ annihilations
- Possible to **extend** stochastic collision framework to the strangeness sector, in particular to the production of other light nuclei like **hyper-triton** via 4-to-2 reactions



Phys. Rev. C 104, 034908 (2021), 2107.08812 (accepted by PRC)

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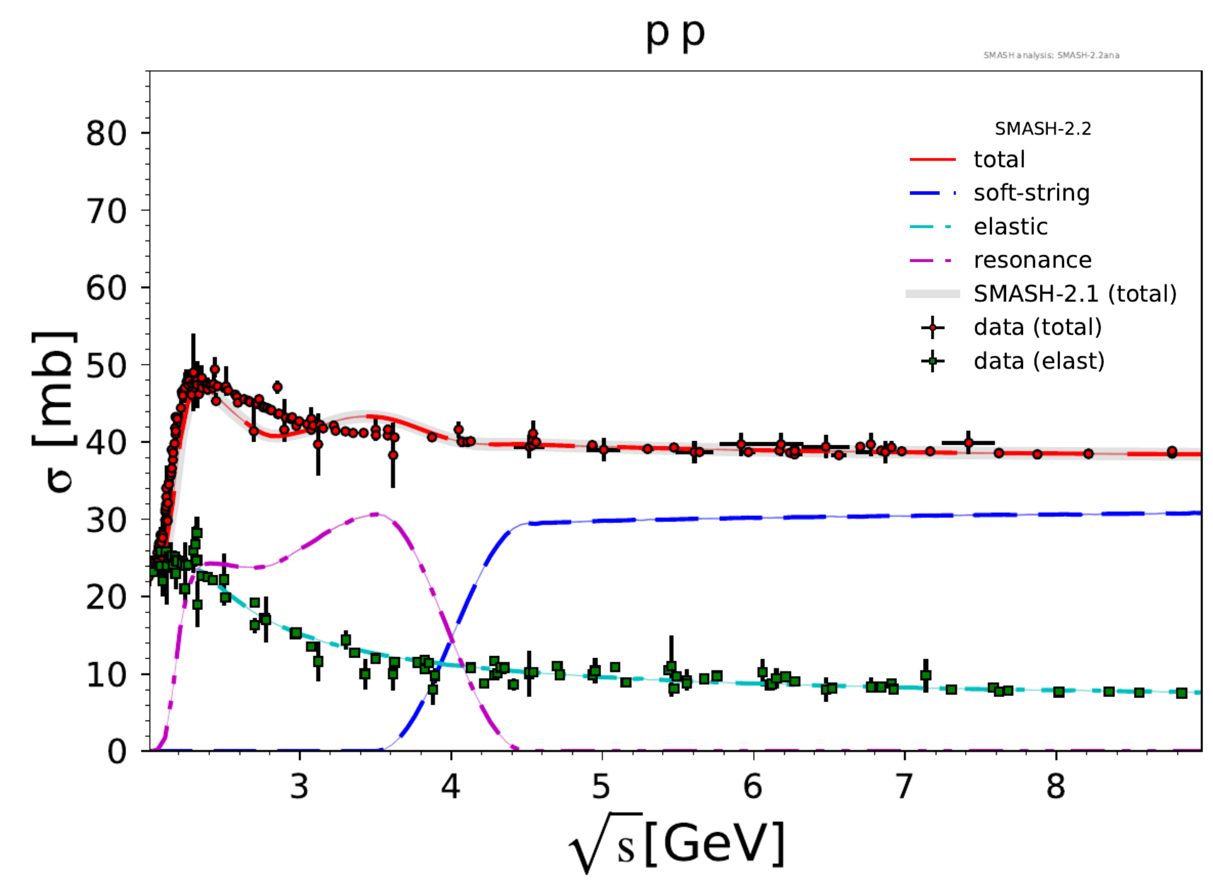
Strangeness production in SMASH

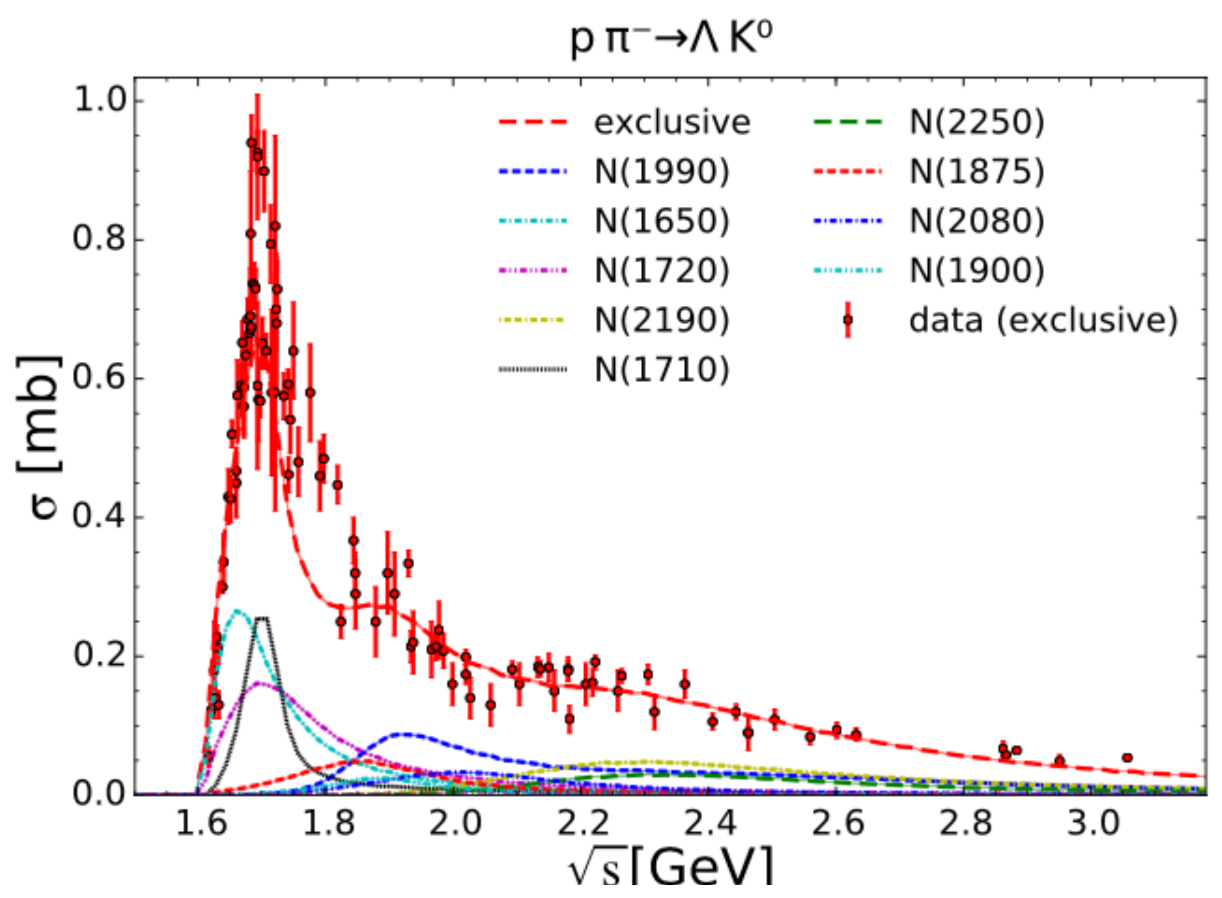
Phys. Rev. C 99, 064908 (2019), Phys. Rev. C 103, 044904 (2021)

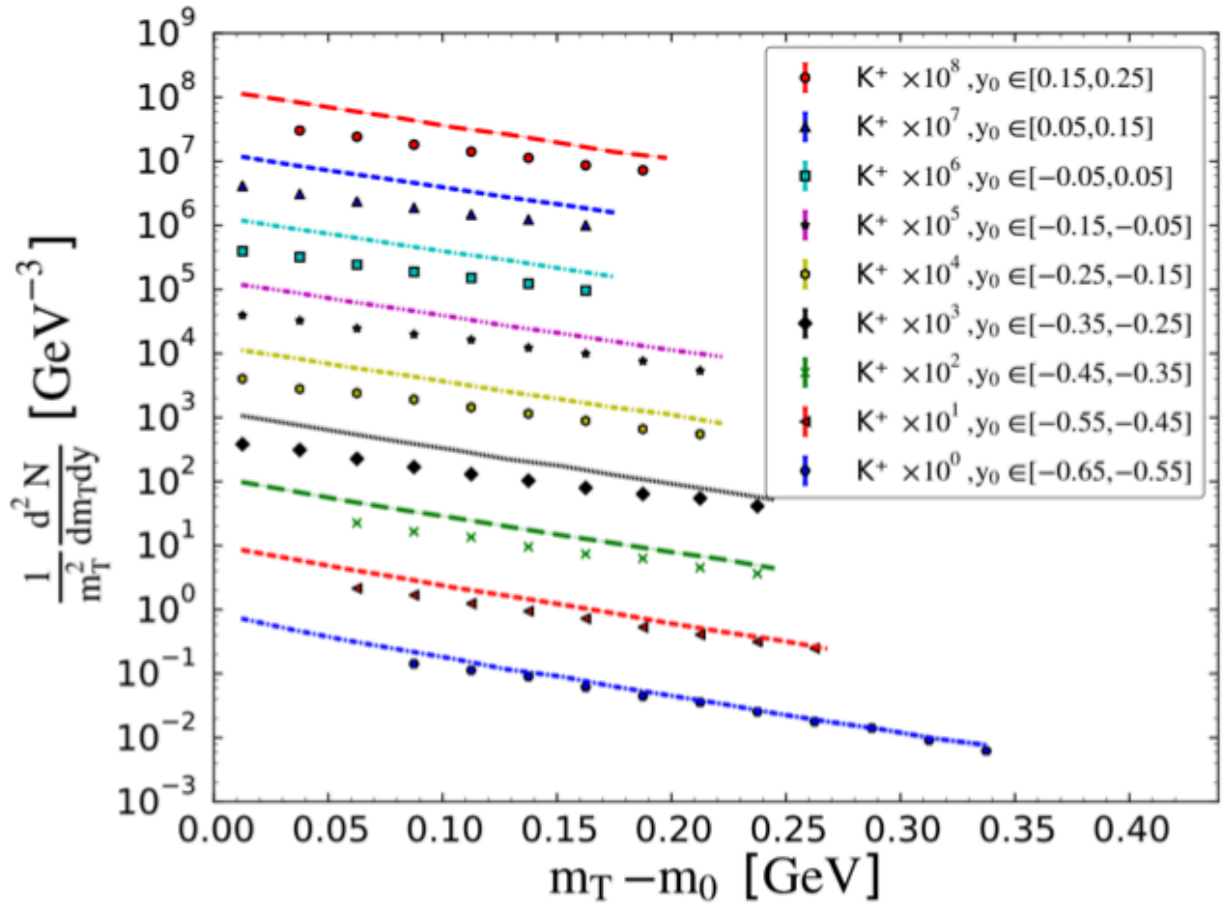
smash

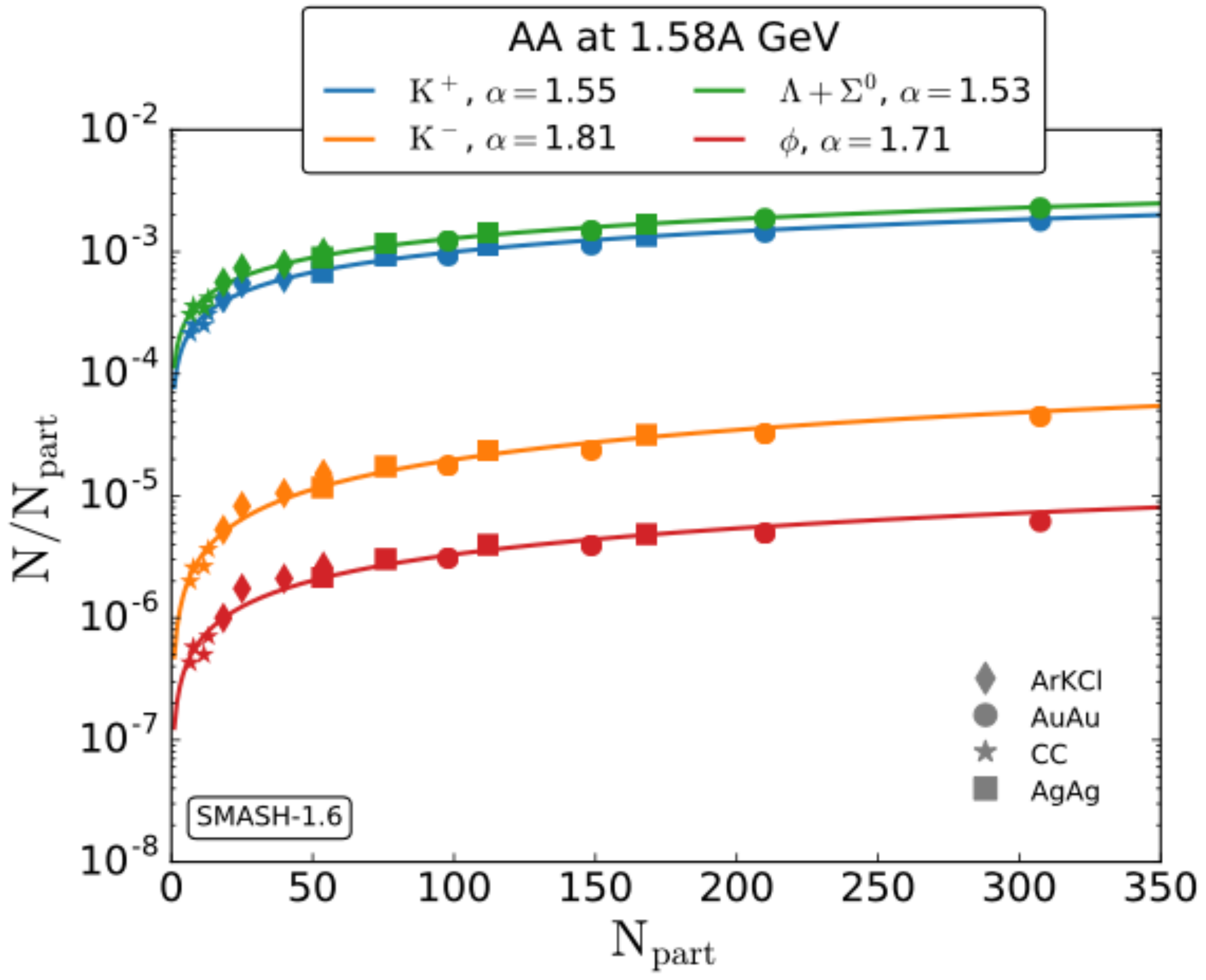
https://smash-transport.github.io

- SMASH is hadronic transport approach employing hadronic degrees of freedom from the PDG up to a mass of 2.3 GeV
- The elementary cross sections are carefully constrained to reproduce available experimental data
- Kaons are produced by
  - Decays of baryonic resonances
  - Strangeness exchange in a pion-hyperon scattering
  - Feed-down from ϕ decays
- Constraint on elementary reactions is not sufficient to reproduce K production in nucleus-nucleus collisions
- N_{part}-scaling is close to experimental values









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Production ϕ and Ξ

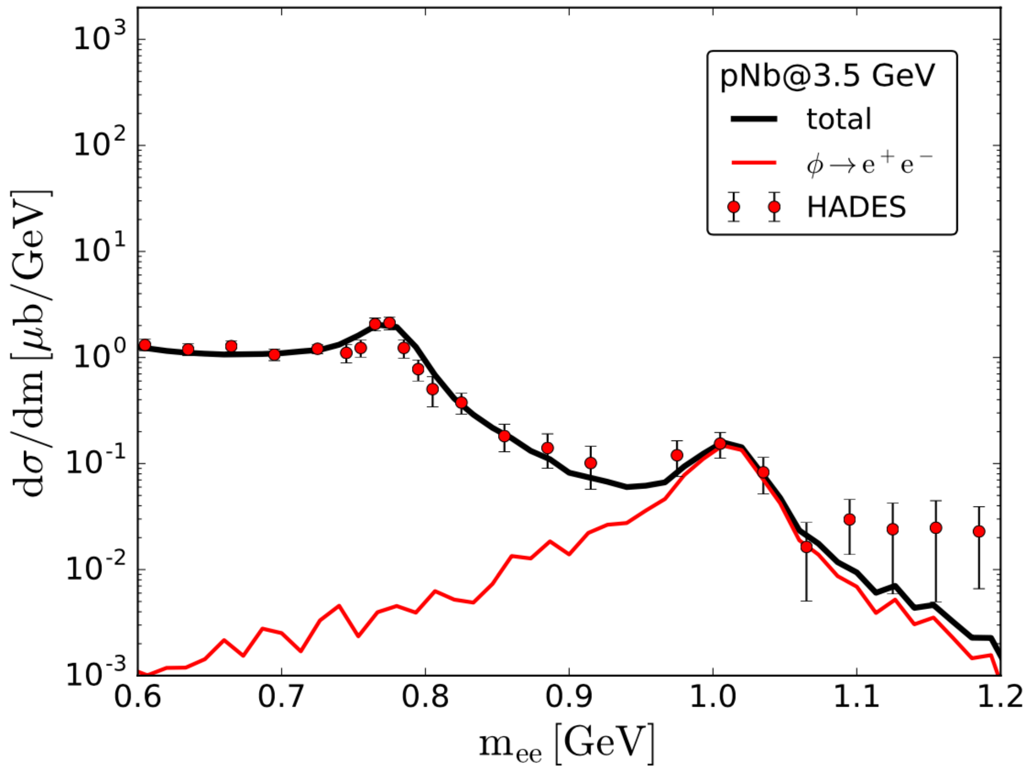
Phys. Rev. C 99, 064908 (2019), Phys. Rev. C 103, 044904 (2021)

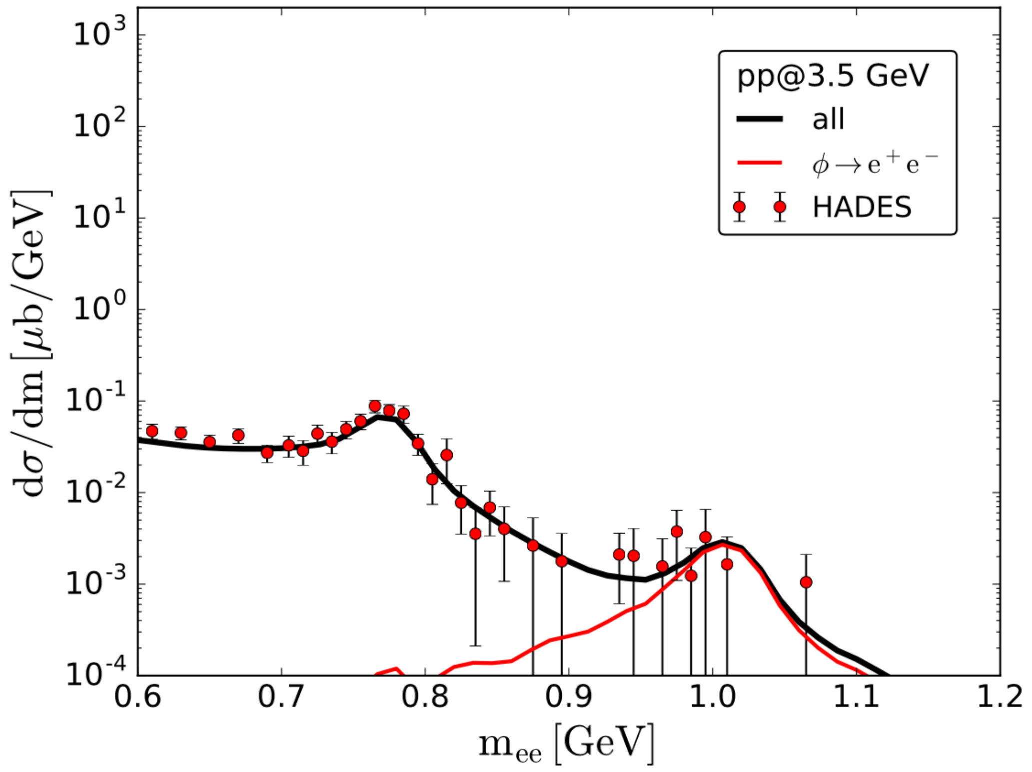
- Approach: Produce ϕ and Ξ from the decay of heavy N* resonances
  J. Steinheimer and M. Bleicher, J. Phys., G43, 2016 (UrQMD)
  - Constrain branching with elementary data
  - Compare and predict production for larger system

$$N^* \rightarrow N\phi$$
$$N^* \rightarrow \Xi KK$$

$$BR_{N^*\rightarrow\phi N} = 0.001$$
$$BR_{N^*\rightarrow\Xi KK} = 0.5$$

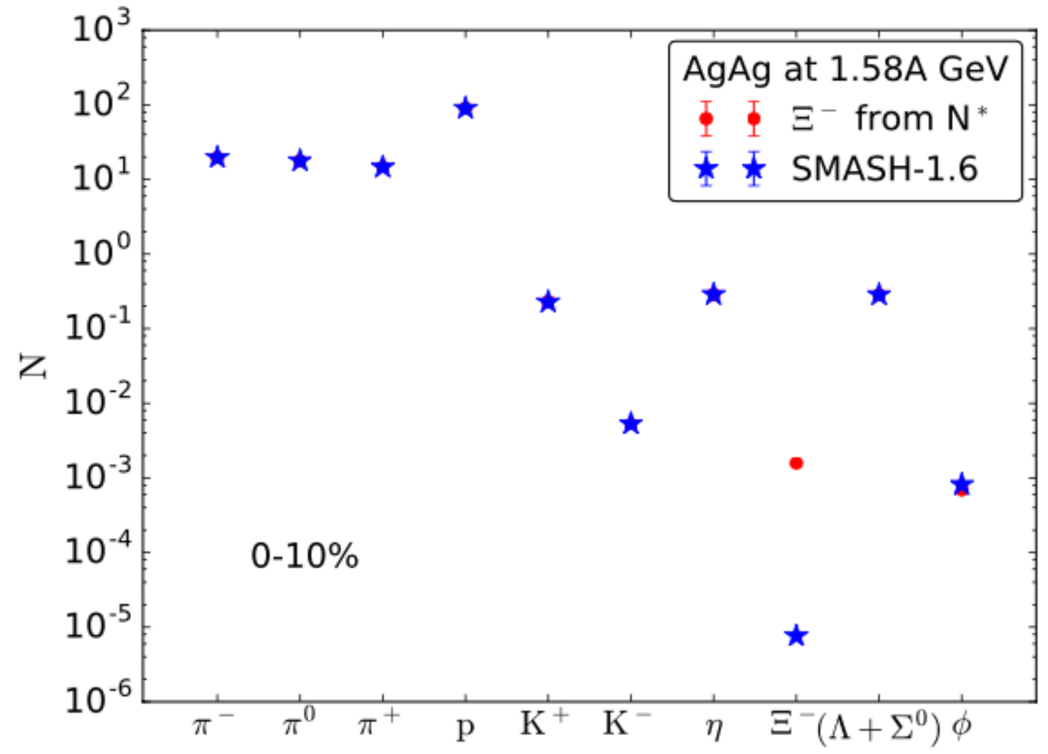
- Possible to describe existing experimental data for multiplicity and multiplicity ratios as well as dilepton production with one free parameter (medium effects?)
  - Overall higher values for branching ratios compared to results with UrQMD
  - Ratio of branching ratios is the same i.e. the relative production of ϕ compared to Ξ





$N(\Xi^-)$	pNb	ArKCl
SMASH-1.6	≈ 0.0	6.25×10^{-7}
Ξ^- from N*	2.04×10^{-4}	1.95×10^{-4}
HADES	$(2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$	$(2.3 \pm 0.9) \times 10^{-4}$

$\Xi^-/(\Lambda+\Sigma^0)$	pNb	ArKCl
SMASH-1.6	≈ 0.0	1.1×10^{-5}
Ξ^- from N*	1.5×10^{-2}	4.5×10^{-3}
HADES	$(1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$	$(5.6 \pm 1.2^{+1.8}_{-1.7}) \times 10^{-3}$



AgAg	$N(\Xi^-)$	$\Xi^-/(\Lambda+\Sigma^0)$
SMASH-1.6	8.50×10^{-6}	2.71×10^{-5}
Ξ^- from N*	1.78×10^{-3}	5.63×10^{-3}

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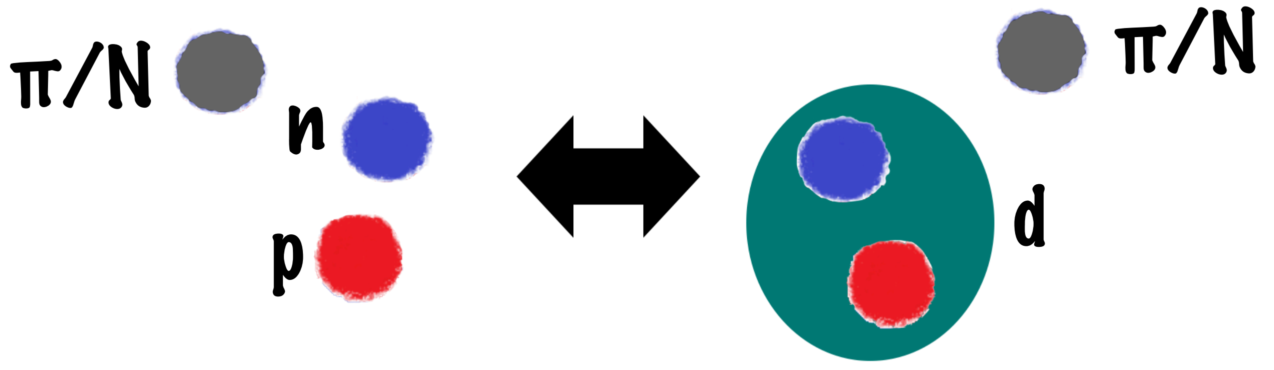
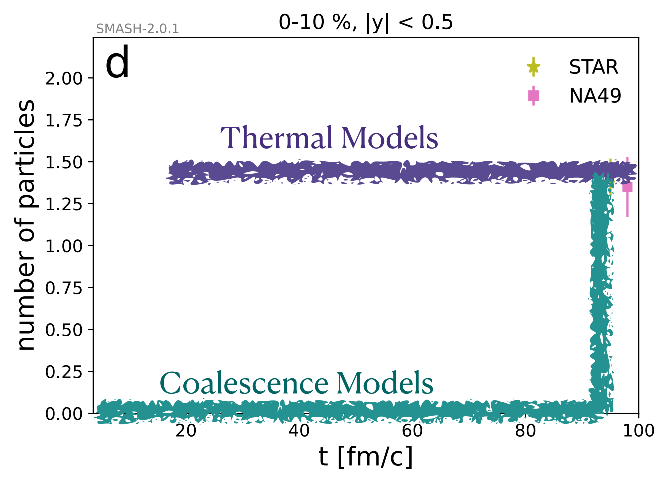
Light nuclei catalysis

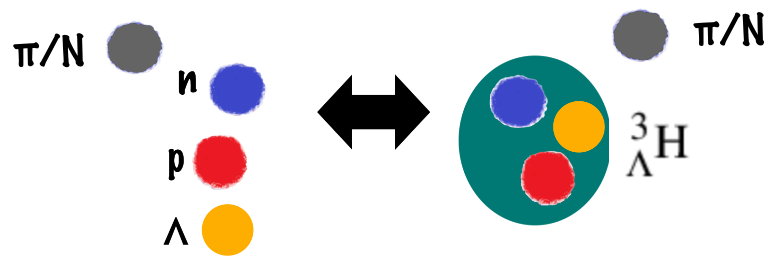
Phys. Rev. C 104, 034908 (2021)

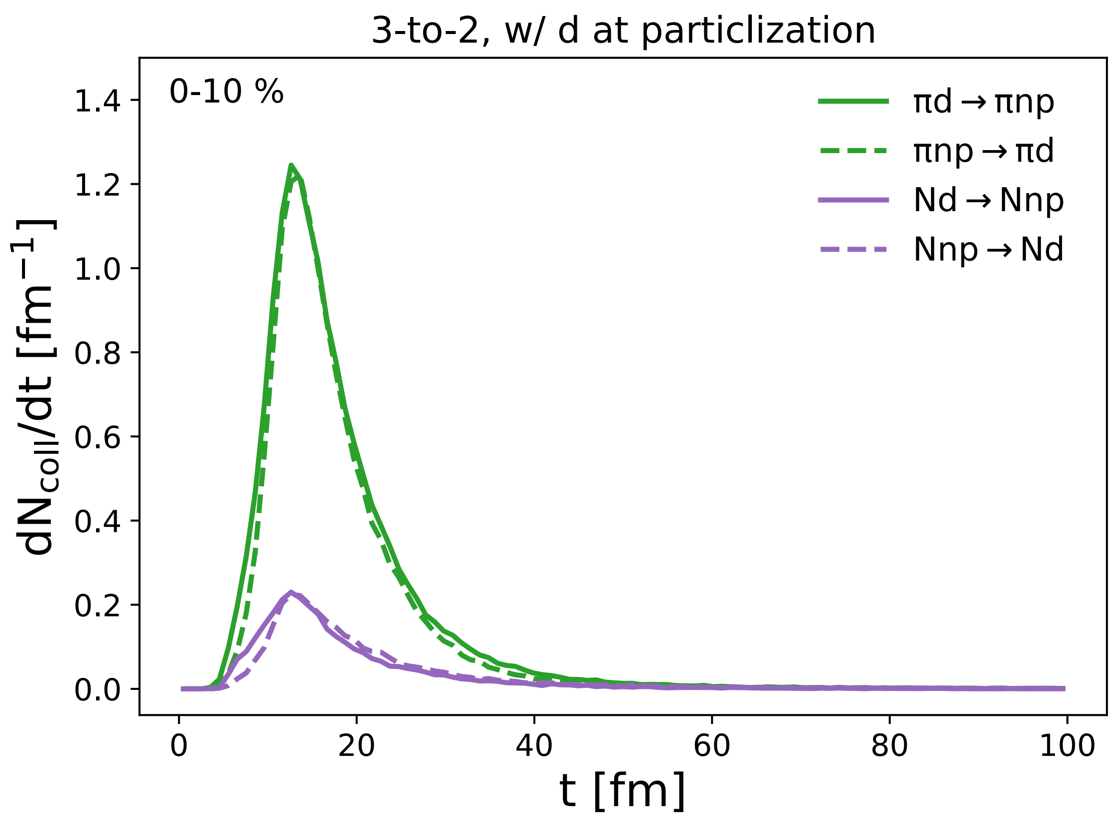


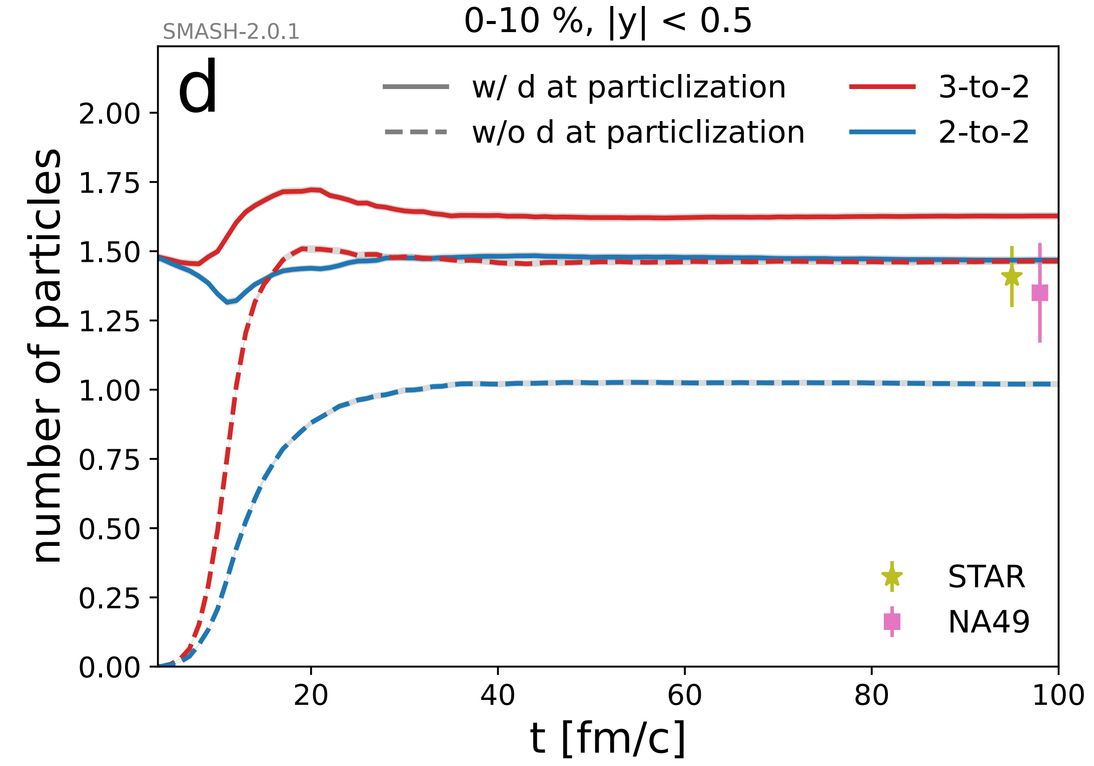
- Stochastic collision criterion derived using the Boltzmann collision integral is able to treat multi-particle reactions Lang, H. Babovsky, W. Cassing, U. Mosel, H.-G. Reusch, and K. Weber, Journal of Computational Physics, vol. 106, no. 2, pp. 391 – 396, 1993. P. Danielewicz and G. Bertsch, Nucl. Phys. A, vol. 533, pp. 712–748, 1991.
- Produce light nuclei by catalysis reactions with π or N
- Hybrid model calculation for AuAu at $\sqrt{s_{NN}} = 7.7\,\mathrm{GeV}$: Hydro stage employing `MUSIC v3.0` and SMASH afterburner Phys. Rev. C 82, 014903 (2010), Phys. Rev. C 85, 024901 (2012), Phys. Rev. C 93, 044906 (2016) Phys. Rev. C 102, 014909 (2020)
- Deuterons in **chemical equilibrium with nucleons** ("snowballs in hell")
- Dynamic approach allows to contrast thermal model and coalescence assumption

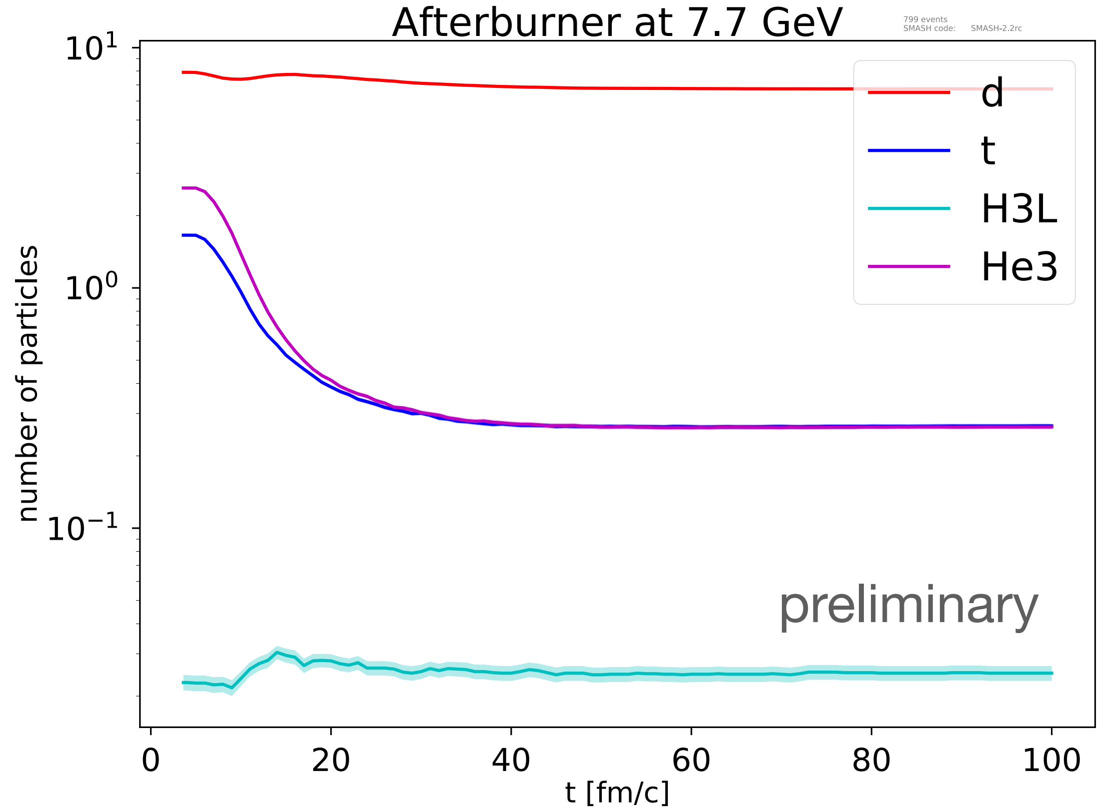


- Work based on previous approach limited to binary reactions, which employed multi-step reaction chain with d' resonance: $\pi d \leftrightarrow \pi d' \leftrightarrow \pi np$
  D. Oliinychenko et al. Phys. Rev. C 99, 044907 (2019) & Phys. Rev. C 103, 034913 (2021) &
- Extension to A=3 nuclei using 4-to-2 reactions in preparation → (Hyper-) triton and Helium-3









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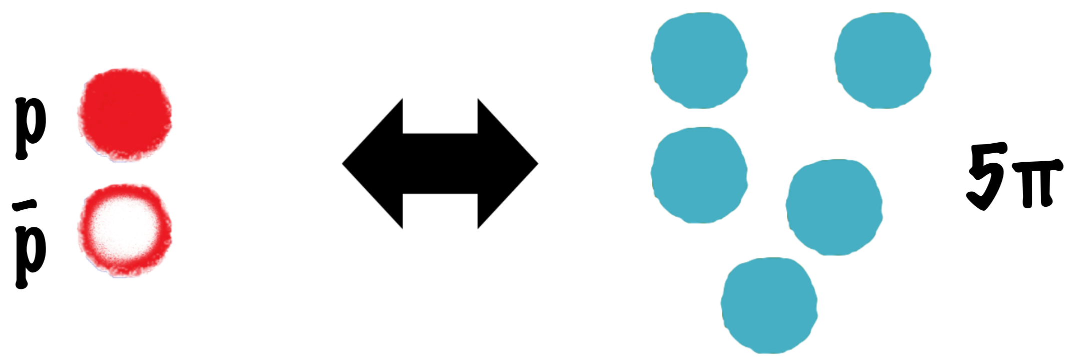
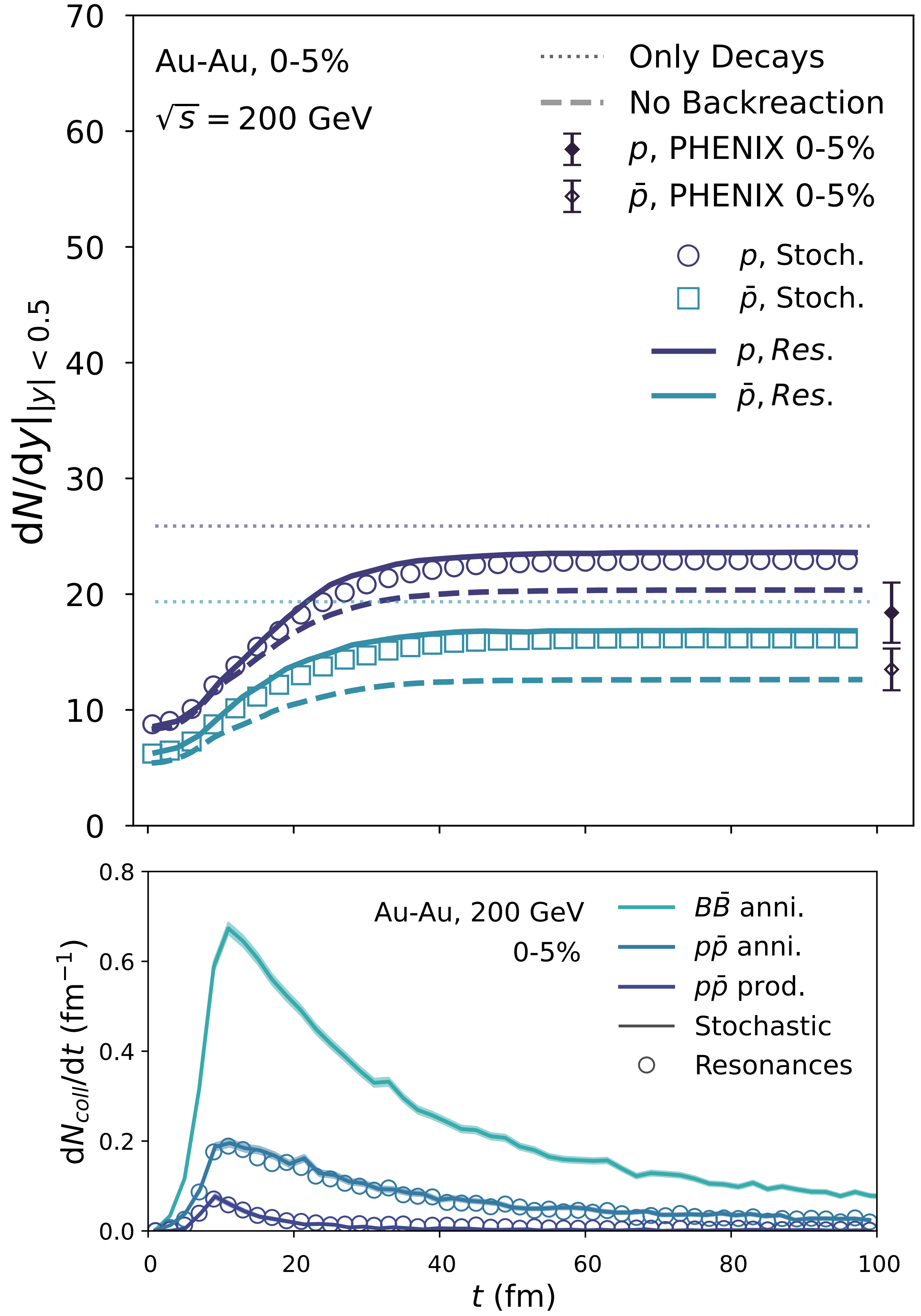
Proton-antiproton annihilation

arXiv: 2107.08812



- LHC data was overestimated* by thermal models („proton anomaly")
  → Role of annihilations? J. Stachel, A. Andronic, P. Braun-Munzinger, and K. Redlich, J. Phys. Conf. Ser., vol. 509, p. 012019, 2014, K. Werner, I. Karpenko, T. Pierog, M. Bleicher, and K. Mikhailov, Phys. Rev. C, vol. 82, p. 044904, 2010, J. Steinheimer, J. Aichelin, and M. Bleicher, Phys. Rev. Lett., vol. 110, no. 4, p. 042501, 2013
- **Relevance of multi-particle** back-**reactions**? E. Seifert and W. Cassing, Phys. Rev. C, vol. 97, 2018 Y. Pan and S. Pratt, Phys. Rev. C, vol. 89, 2014.
- **First direct 5-body reaction treatment** in transport approach (average number of π produced in $p\bar{p}$ annihilation)
- Hybrid model calculation employing the SMASH-vHLLE-Hybrid approach for AuAu/PbPb at $\sqrt{s_{\mathrm{NN}}} = 17.3\,\mathrm{GeV} - 5.02\,\mathrm{TeV}$ Schäfer et al., arXiv:2112.08724
- Interplay of annihilation and its backreaction in the late stage **important for** (anti-) **proton yield**
- Also explored alternative approach with resonances and multiple binary steps
  - Reaction chain: $N\bar{N} \leftrightarrow h_1\rho \leftrightarrow \rho\pi\pi\pi \leftrightarrow 5\pi$
  - Results of multi-particle reaction and multi-step reaction in agreement
  - Similar to the approach within (P)HSD, which included strangeness production
    E. Seifert and W. Cassing, Phys. Rev. C, vol. 97, 2018



* since alleviated by the inclusion of π-N interaction terms: A. Andronic, P. Braun-Munzinger, B. Friman, P. M. Lo, K. Redlich and J. Stachel, Phys. Lett. B 792, 2019

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