Multi-particle collisions in the hadronic stage

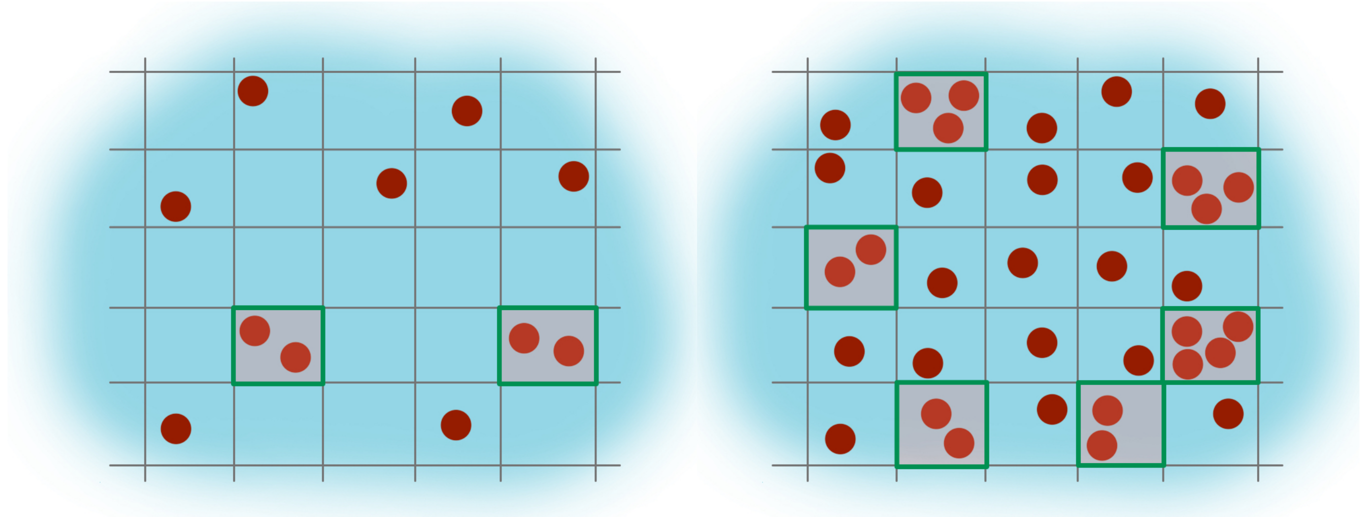
Quark Matter 2022, Krakow

Jan Staudenmaier[1,2], Oscar Garcia-Montero[2], Juan M. Torres-Rincon[7,2], Dmytro Oliinychenko[3] & Hannah Elfner[4,2,5,6]

Multi-particle interactions in hadronic transport

smash

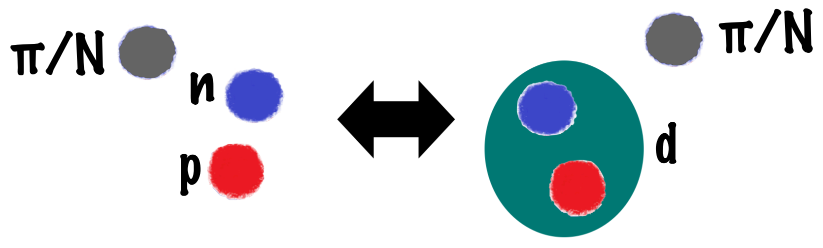
- Relevant in high-density collisions at new facilities like FAIR or RHIC-BES and for production of certain hadron species
- Included 3- and 5-body reactions in hadronic transport approach SMASH **employing stochastic collision criterion**
- Significant for particle abundances studying the late hadronic collision stages within hybrid approaches



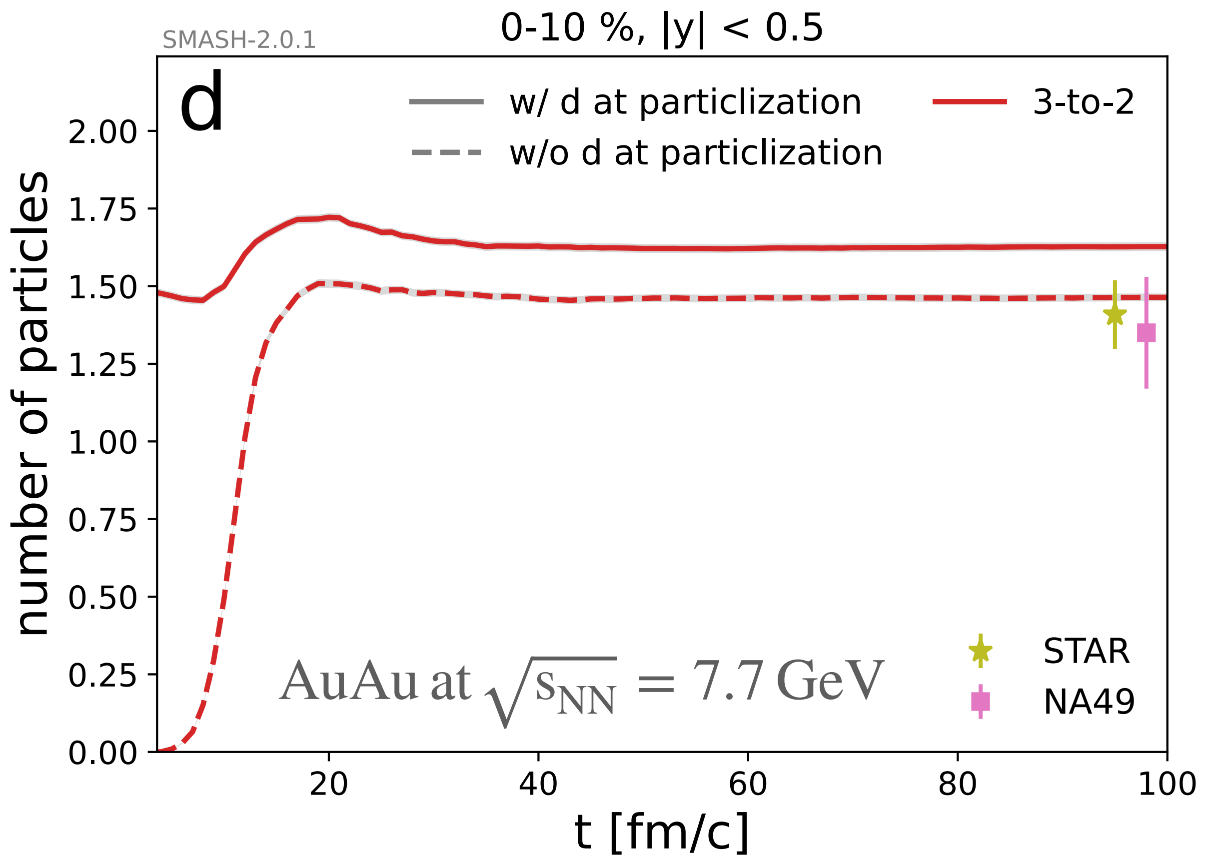
https://smash-transport.github.io

Phys.Rev.C 94 054905 (2016)

Deuteron catalysis

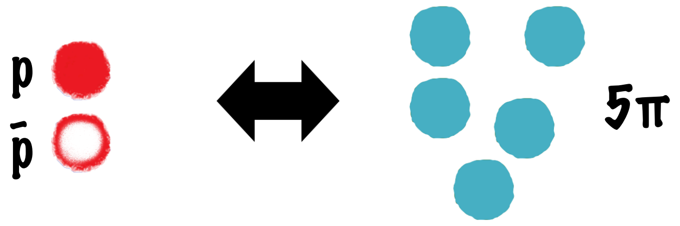


- Contrast assumptions of thermal and coalescence models
- Final **yield independent from the number of deuterons on** the Cooper-Frye **hyper-surface**
- Apparent survival of deuterons explained by deuterons in partial chemical equilibrium with nucleons ("*snowballs in hell*")

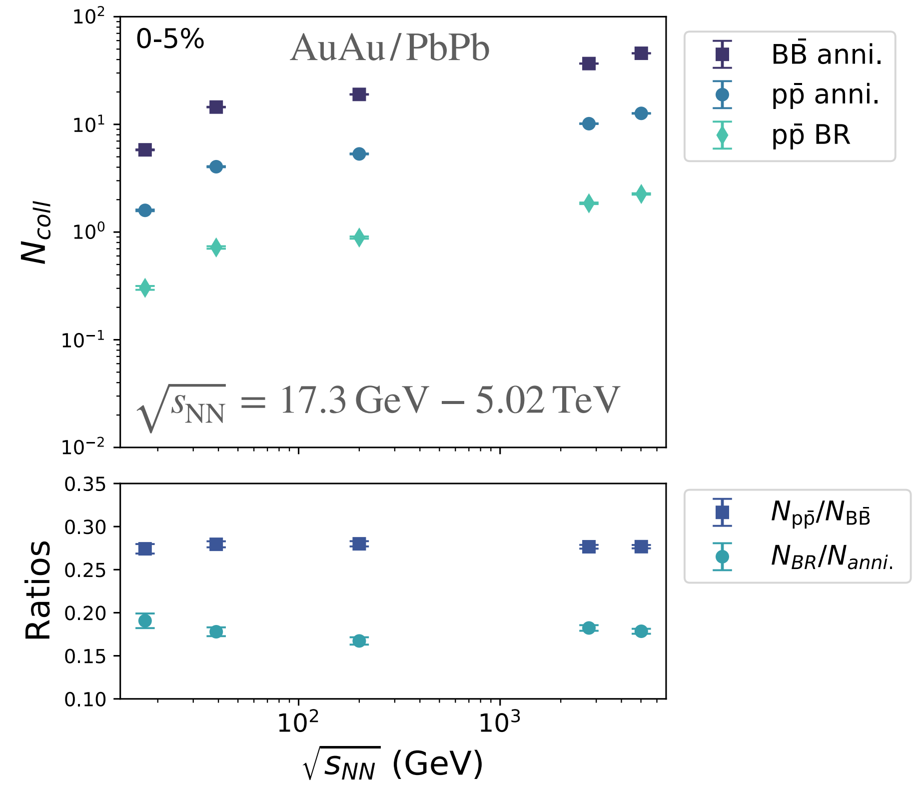


Phys. Rev. C 104, 034908 (2021)

Proton-antiproton annihilation



- Direct 5-body reactions allow to investigate relevance of back-reaction microscopically for the first time
- Back-reaction for 15-20% of all annihilations, leads to **regeneration of half of (anti-)proton yield lost** due to annihilations at mid-rapidity
- Relevant for constraining the QCD transport coefficients with Bayesian techniques and historically motivated by "*proton anomaly*“



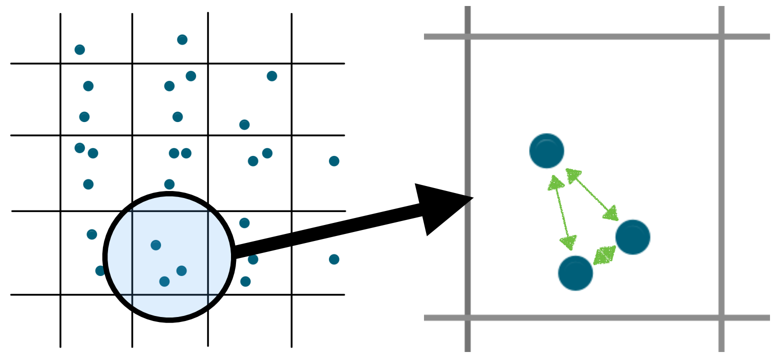
arXiv: 2107.08812 (accepted by PRC)

1 Wayne State University, Detroit
2 Goethe University, Frankfurt
3 University of Washington, Seattle
4 GSI Helmholtzzentrum für Schwerionenforschung
5 Frankfurt Institute for Advanced Studies
6 Helmholtz Research Academy Hesse for FAIR (HFHF)
7 Universitat de Barcelona

Multi-particle interactions in hadronic transport

Phys.Rev.C 94 054905 (2016)

smash
https://smash-transport.github.io



$$P_{n\to m} = \frac{\Delta N_{\mathrm{coll}}^{n\to m}}{\Delta N_1 \Delta N_2 \ldots \Delta N_n}$$

- Multi-particle reactions in the **literature**:
  - Stochastic collision criterion as an optimization idea
    A. 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.
  - Deuteron catalysis: $Npn \leftrightarrow Nd, \pi pn \leftrightarrow \pi d$
    P. Danielewicz and G. Bertsch, Nucl. Phys. A, vol. 533, pp. 712–748, 1991.
    K.-J. Sun, R. Wang, C. M. Ko, Y.-G. Ma, and C. Shen, 2021, 2106.12742.
  - Baryon-antibaryon annihilation: $B\bar{B} \leftrightarrow n$ mesons
    W. Cassing, Nucl. Phys. A, vol. 700, pp. 618–646, 2002, nucl-th/0105069.
    E. Seifert and W. Cassing, Phys. Rev. C, vol. 97, no. 4, p. 044907, 2018, 1801.07557 and Phys. Rev. C, vol. 97, no. 2, p. 024913, 2018, 1710.00665.
  - Gluon Bremsstrahlung: $gg \leftrightarrow ggg$
    Z. Xu and C. Greiner, Phys. Rev. C, vol. 71, p. 064901, 2005, hep-ph/0406278.

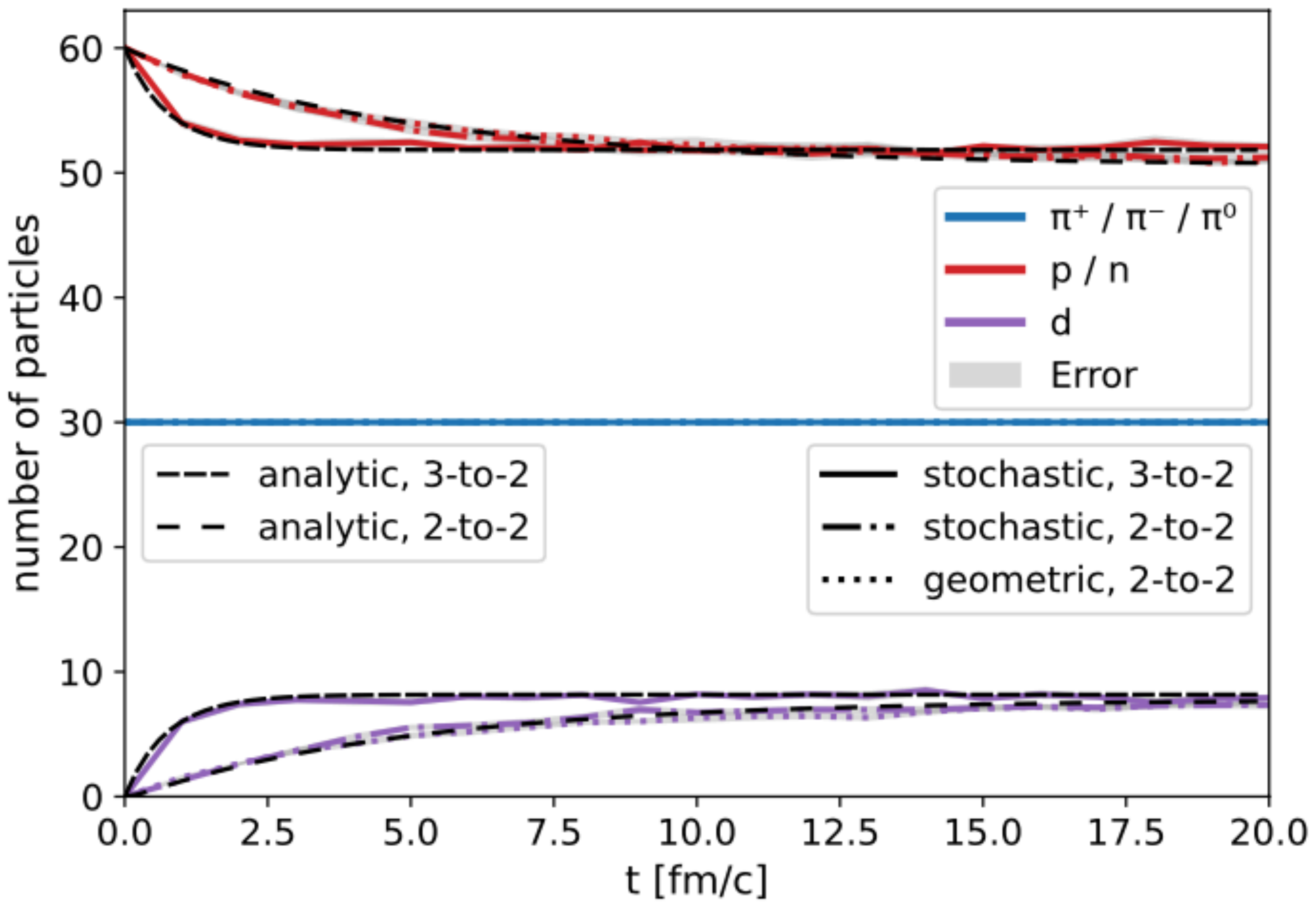
$Npn \leftrightarrow Nd,\ \pi pn \leftrightarrow \pi d$

$$P_{3\to 2} = \frac{g_1' g_2'}{g_1 g_2 g_3} \frac{S_{123}}{S_{12}'} \frac{1}{4E_1E_2E_3} \frac{\Delta t}{(\Delta^3 x)^2} \frac{\lambda}{\Phi_3\, 8\pi s} \sigma_{2\to 3}$$

$p\bar{p} \leftrightarrow 5\pi$

$$P_{5\to 2} = \frac{g_1' g_2'}{g_1 g_2 g_3 g_4 g_5} \frac{S_{12345}}{S_{12}'} \frac{1}{32E_1E_2E_3E_4E_5} \frac{\Delta t}{(\Delta^3 x)^4} \frac{\lambda}{\Phi_5} \frac{1}{4\pi s} \sigma_{2\to 5}$$

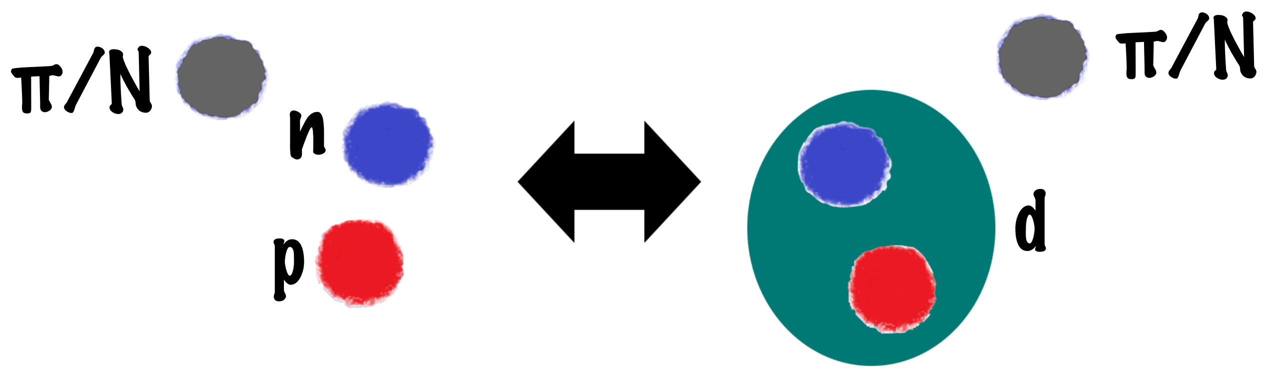
- Stochastic collision criterion derived using the Boltzmann collision integral
- Systematic **verification** of equilibration and detailed balance in infinite matter (*box*) calculation → comparison against rate equations Y. Pan and S. Pratt, Phys. Rev. C 89, 044911. 2014.
  $N_i = V n_i^{th} \lambda_i\,, \quad R_{ab} = \langle \sigma_{ab} v_{rel} \rangle n_a^{th} n_b^{th} \lambda_a \lambda_b$
- **Faster equilibration** when including multi-particle reactions



Jan Staudenmaier, Oscar Garcia-Montero, Juan M. Torres-Rincon, Dmytro Oliinychenko & Hannah Elfner

Deuteron catalysis

Phys. Rev. C 104, 034908 (2021)



- 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)

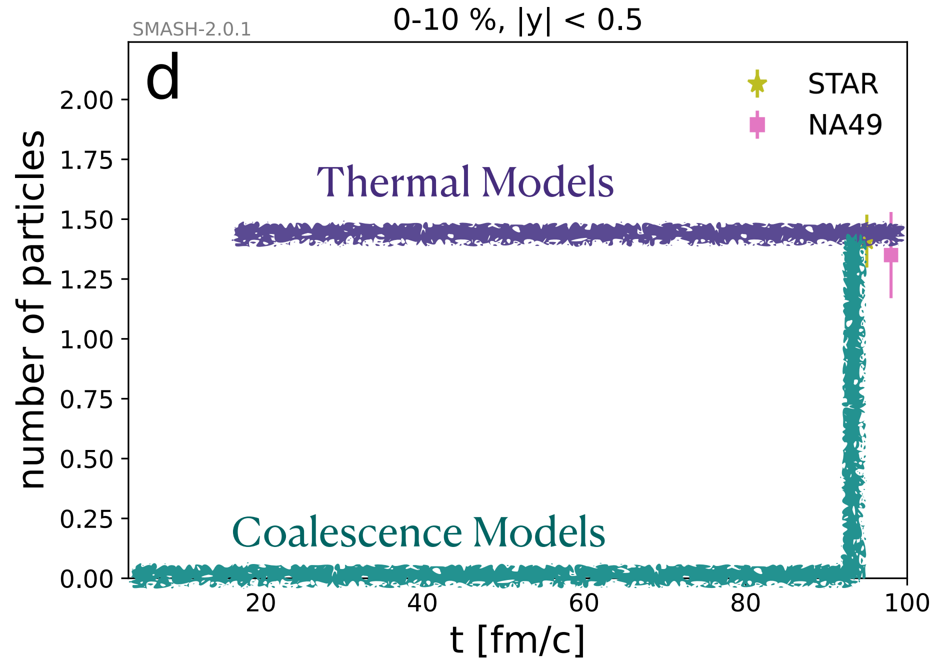
- Deuterons in **chemical equilibrium with nucleons** ("snowballs in hell")

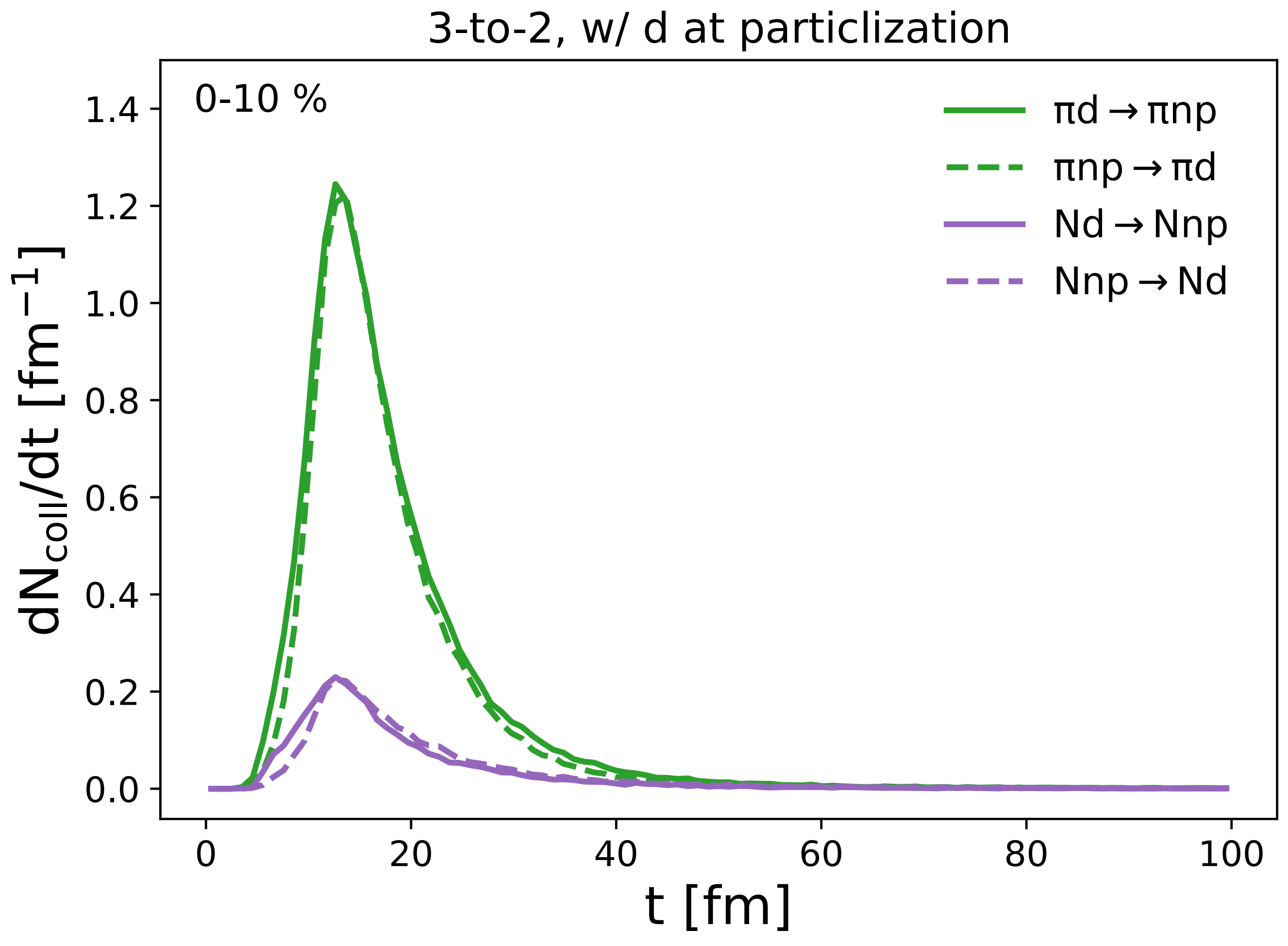
- Work based on previous approach limited to binary reactions
  D. Oliinychenko, L.-G. Pang, H. Elfner, and V. Koch, Phys. Rev. C 99, 044907 (2019)
  D. Oliinychenko, Chun Shen and V. Koch, Phys. Rev. C 103, 034913 (2021)

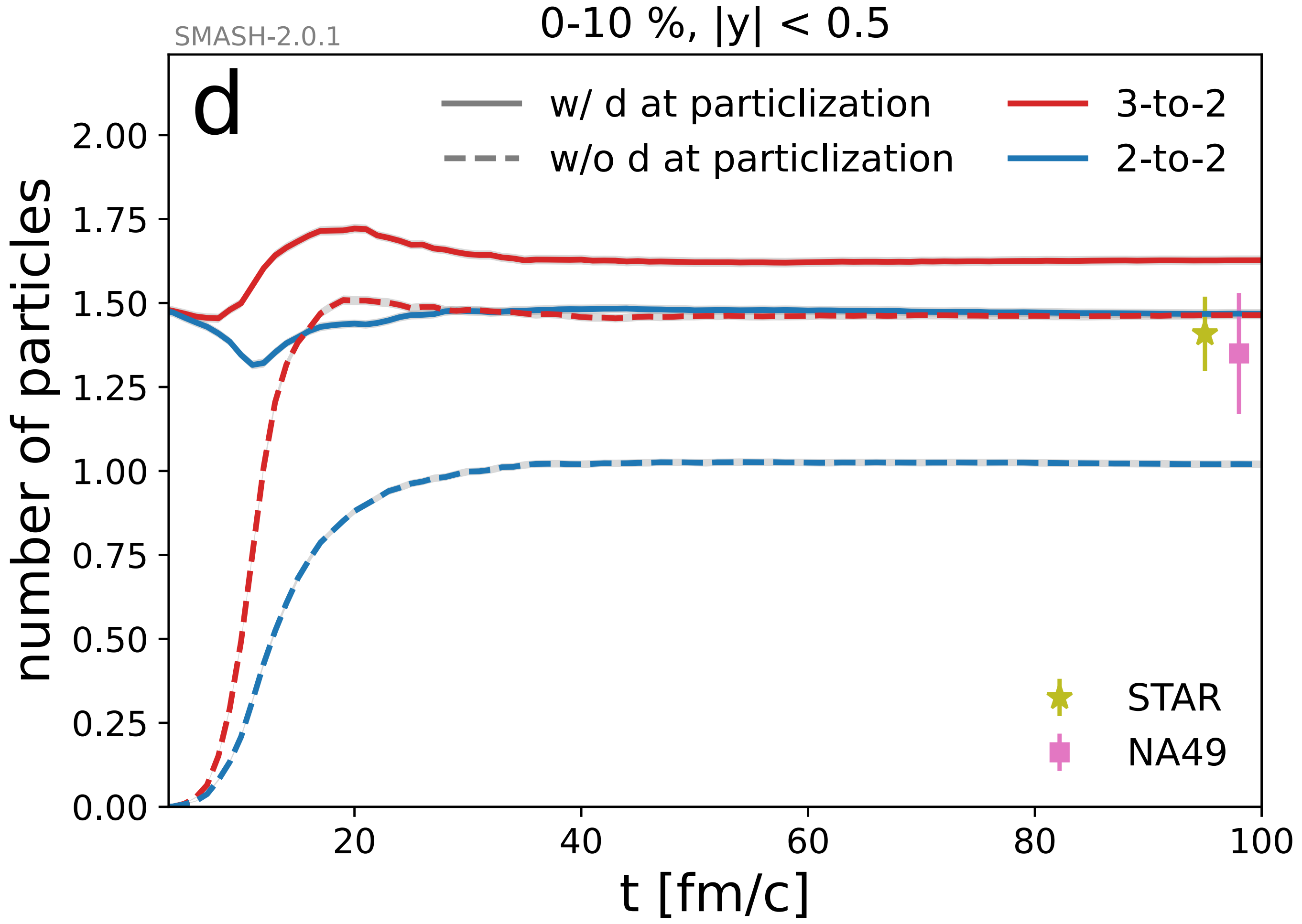
  - **Multi-step reaction chain** with d' resonance: $\pi d \leftrightarrow \pi d' \leftrightarrow \pi np$

  - **Comparison** to multi-particle reactions **confirms previous results**

  - Faster equilibration of direct multi-particle reactions leads to even closer final yields for both particlization scenarios





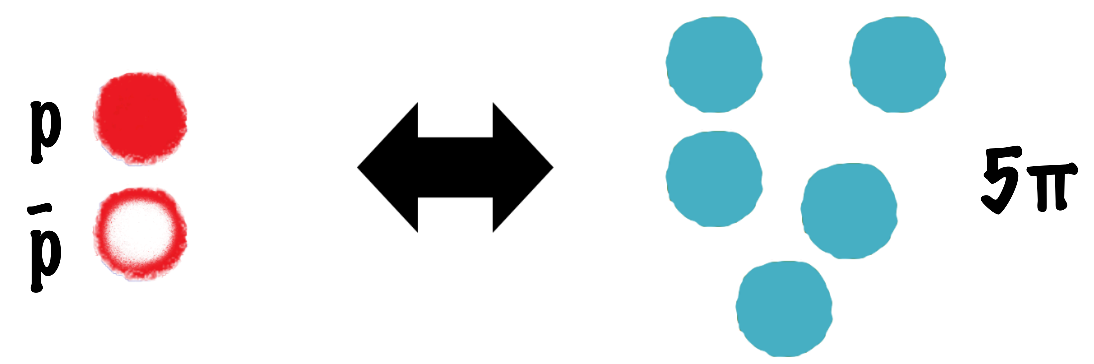


- Extension to A=3 nuclei using 4-to-2 reactions possible
  ➝ (hyper-) triton and Helium-3

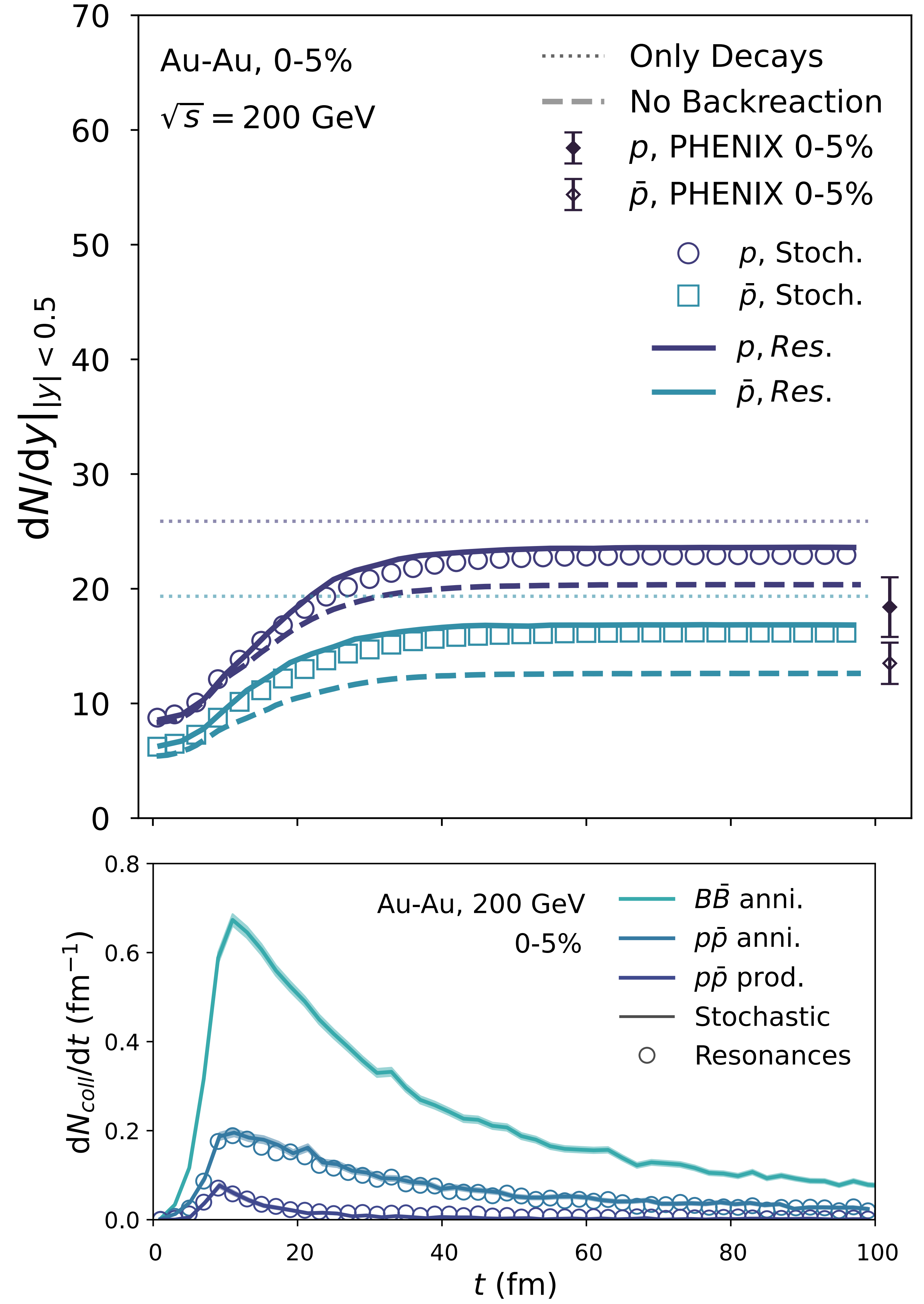
Jan Staudenmaier, Oscar Garcia-Montero, Juan M. Torres-Rincon, Dmytro Oliinychenko & Hannah Elfner

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 back-reaction? E. Seifert and W. Cassing, Phys. Rev. C, vol. 97, no. 4, p. 044907, 2018 Y. Pan and S. Pratt, Phys. Rev. C, vol. 89, no. 4, p. 044911, 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



* 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 + QM22 Talk by Pok Man Lo (T06)

Jan Staudenmaier, Oscar Garcia-Montero, Juan M. Torres-Rincon, Dmytro Oliinychenko & Hannah Elfner