EMMI Rapid Reaction Task Force (RRTF)

8-12 April 2024

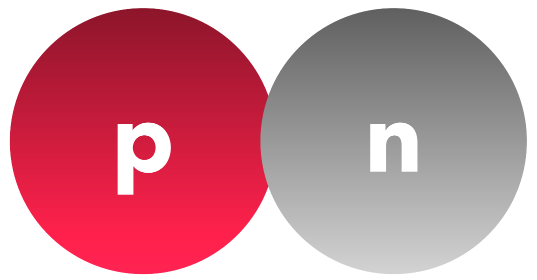
Understanding light (anti-)nuclei production at RHIC and LHC

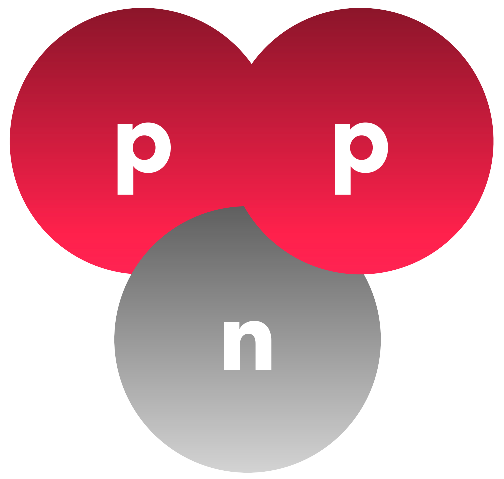
Dynamic light nuclei production in SMASH

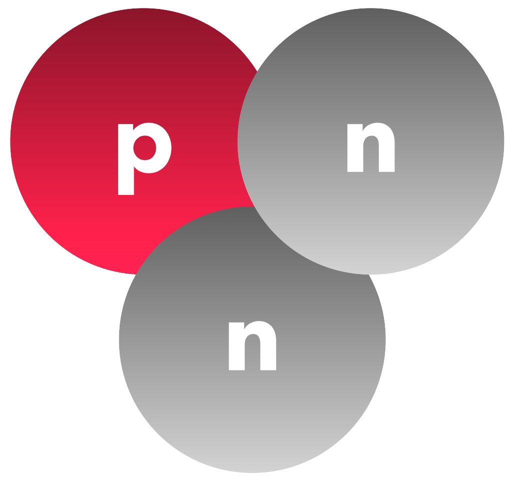
Martha Ege, Justin Mohs and Hannah Elfner

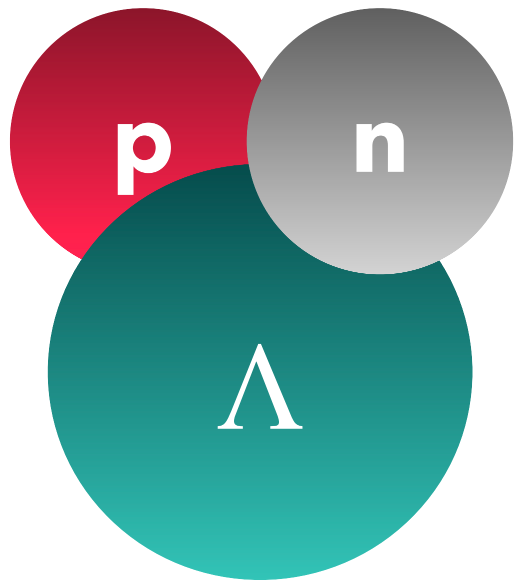
Introduction

- Production of light nuclei in central Au-Au and Pb-Pb collisions
- Framework originally developed for highest RHIC and LHC energies
- RHIC Beam Energy Scan II: 7.7 up to 19.6 GeV
- The investigated nuclei are: deuteron d, helium ^{3}He, triton t and hypertriton $^3_\Lambda$H
- Loosely bound objects: a few 100 keV ($^3_\Lambda$H) up to a few MeV (d, t, ^{3}He)



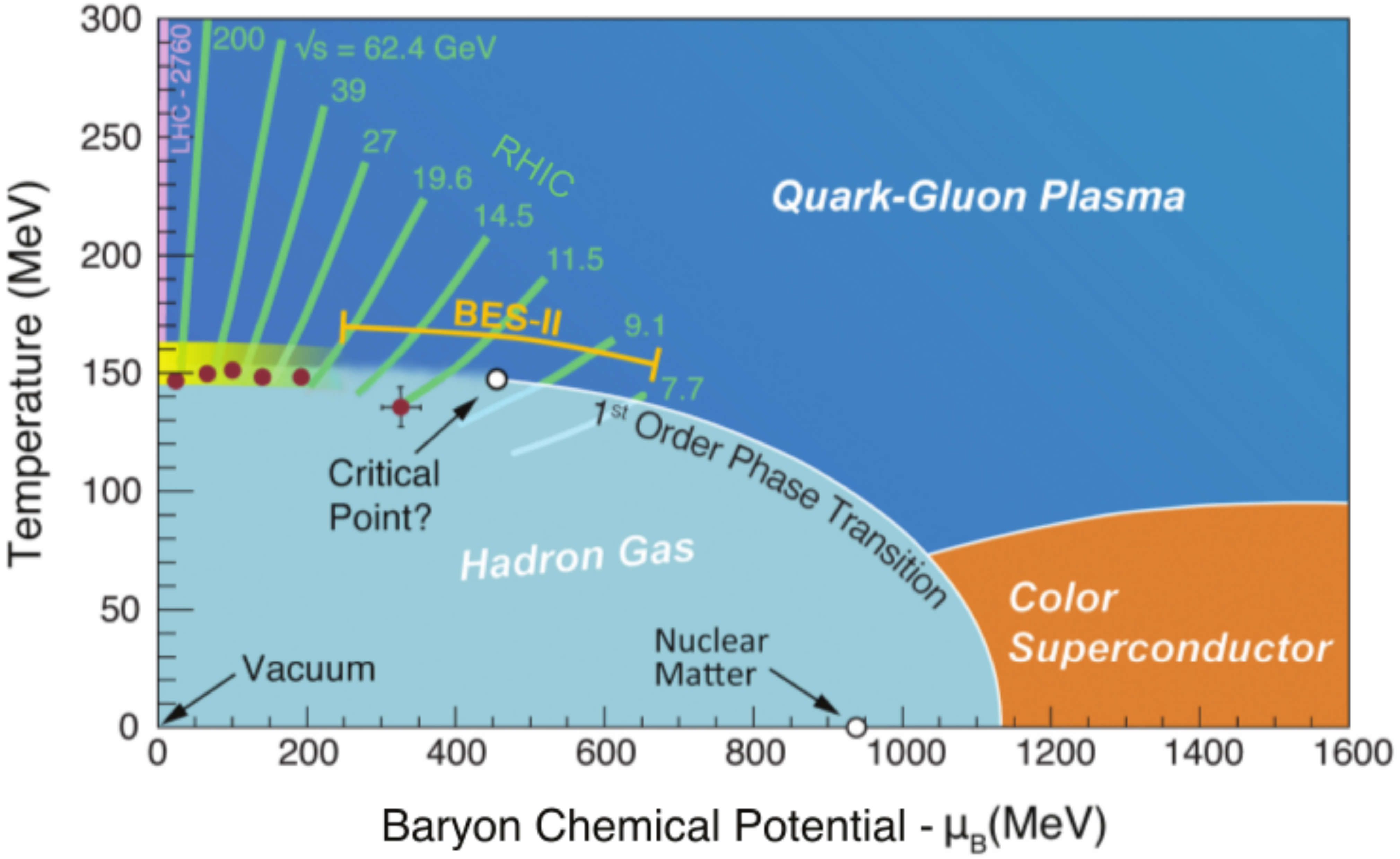






Motivation

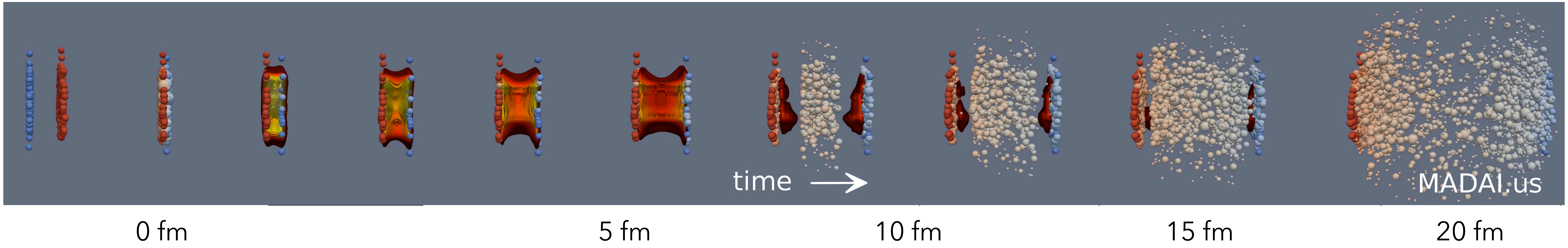
- How can nuclei with low binding energies form at high temperatures? (*Snowballs in hell*)
  see Oliinychenko *et al.*, Phys.Rev. C99 (2019)
- Investigate with a dynamical model
- Compare to coalescence approach
- Study the QCD phase diagram and the critical point
- Compare to recent data from STAR experiment



https://www.usqcd.org/extreme.html

Model description

- Hydrodynamic evolution + hadronic rescattering



MUSIC:
3+1D viscous hydro

switch at $\epsilon = 0.26\mathrm{GeV/fm}^3$

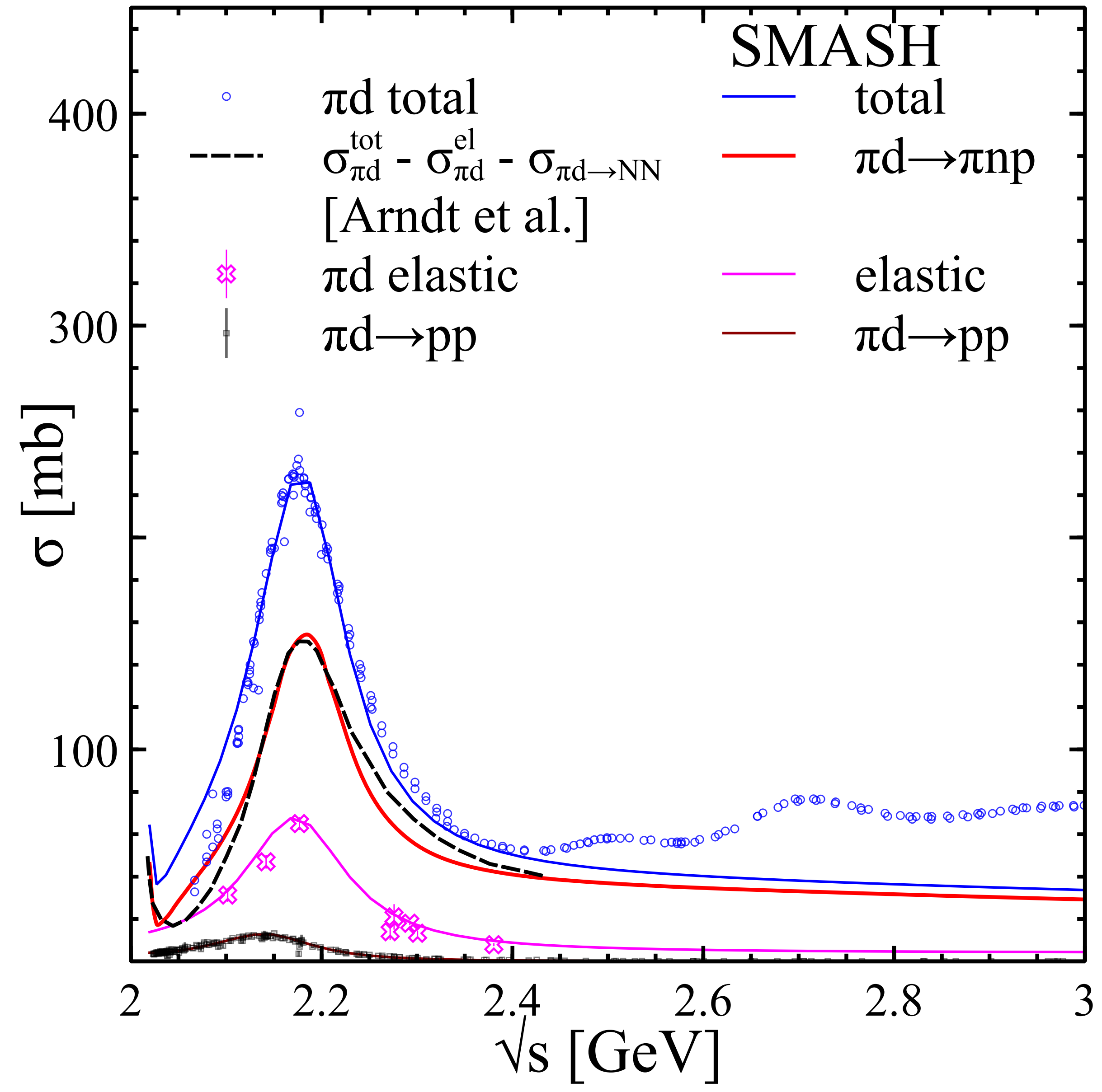
SMASH:
hadronic afterburner

Schenke *et al*., Phys.Rev.C 82 (2010)

Weil *et al*., Phys.Rev.C 94 (2016)

Model description

- SMASH - *Simulating Many Accelerated Strongly-interacting Hadrons*
  https://smash-transport.github.io
- Optionally treat nuclei as degrees of freedom
- Produce the nuclei in multi-particle reactions:
  $d\pi \leftrightarrow NN \quad dX \leftrightarrow npX \quad {}^3\mathrm{He}X \leftrightarrow nppX \quad tX \leftrightarrow nnpX \quad {}^3_\Lambda\mathrm{H}X \leftrightarrow np\Lambda X$
  where X can either be a pion or a nucleon (n, p)
- Realized with a stochastic collision criterion
  Staudenmaier *et al.*, Phys.Rev.C 104 (2021)
- Alternatively create nuclei by coalescence



Oliinychenko *et al.*, Phys.Rev. C99 (2019)

Stochastic collision criterion

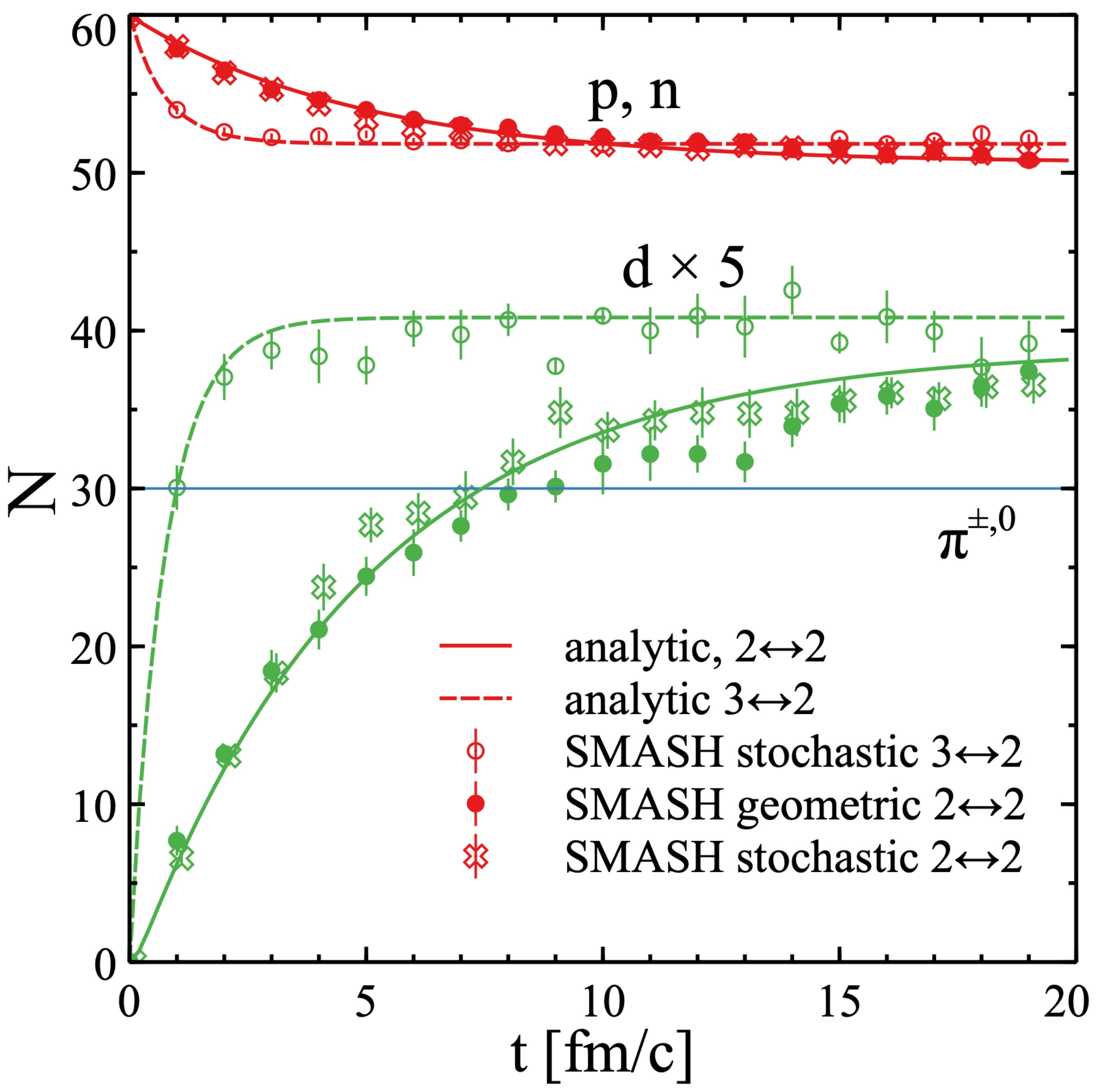
- Divide space into grid cells with volume $\Delta^3 x$
- For 2 to 2 reactions:

$$P_{2\to2} = \frac{\Delta t}{\Delta^3 x} v_{\mathrm{rel}} \sigma_{2\to2}(\sqrt{s})$$

- For 3 to 2 reactions:

$$P_{3\to2} = \left(\frac{g_{1'}g_{2'}}{g_1 g_2 g_3}\right) \frac{S!}{S'!} \frac{\Delta t}{(\Delta^3 x)^2} \frac{E_{1'}E_{2'}}{2E_1E_2E_3} \frac{\Phi_2(s)}{\Phi_3(s)} v_{\mathrm{rel}} \sigma_{2\to3}(\sqrt{s})$$

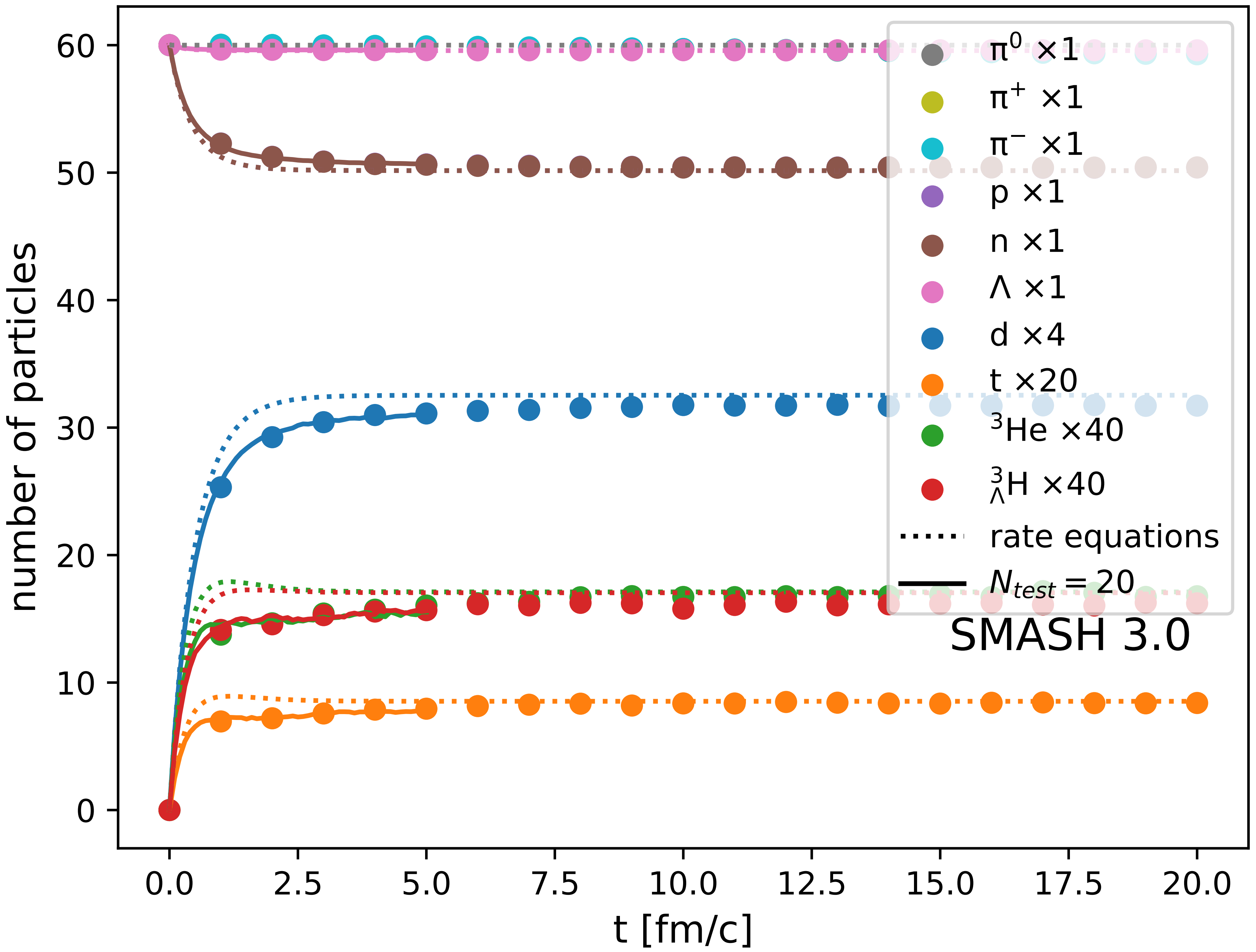
- Faster approach equilibrium with multi-particle reactions



Staudenmaier *et al.*, Phys.Rev.C 104 (2021)

Box results

- Particle multiplicities over time in a box
- Compare to analytical solutions from rate equations
- Equilibrium multiplicities are correctly reproduced
- Slower equilibration compared to rate eq. not yet understood

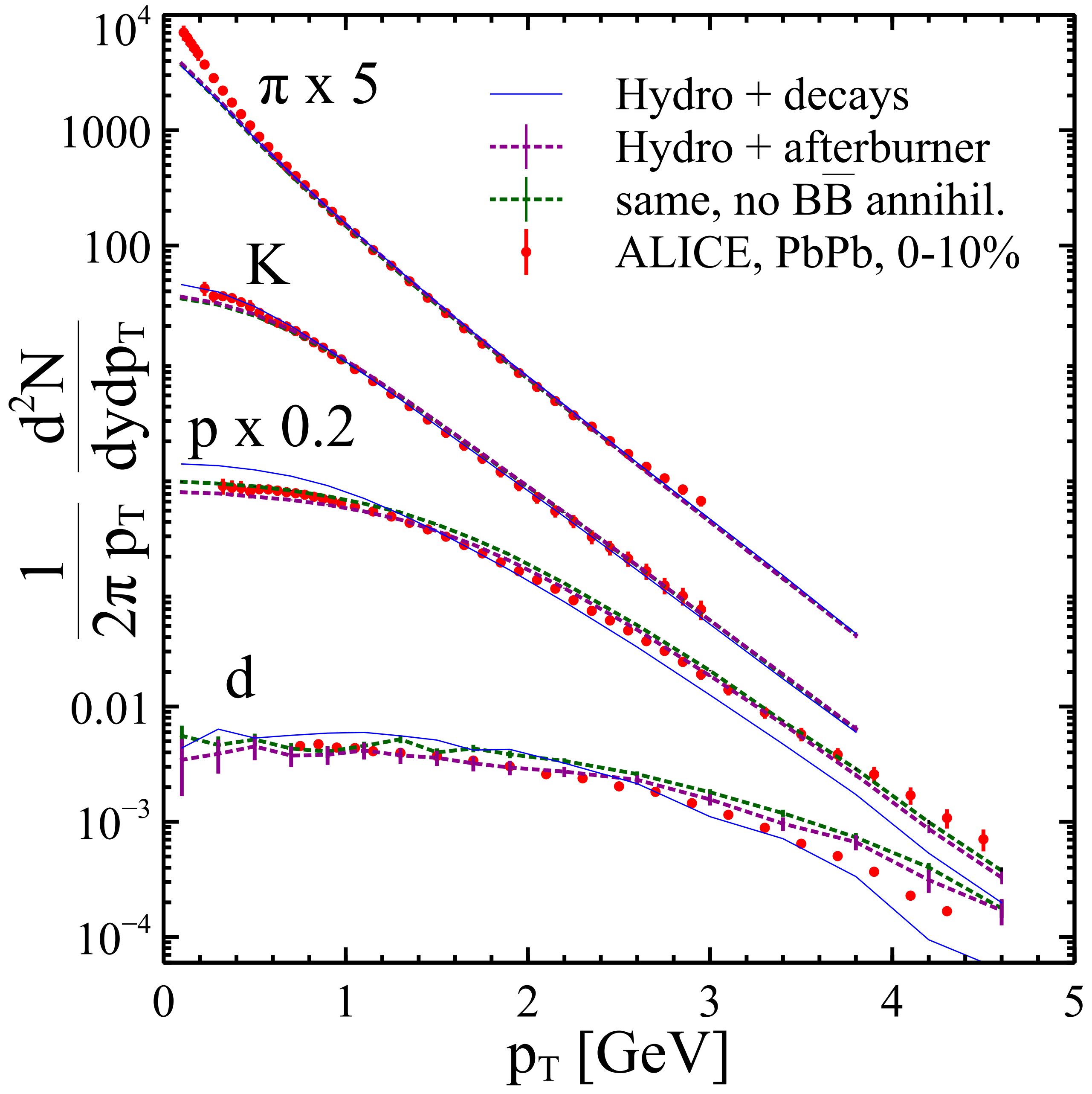


Test in a box of $(10\text{ fm})^3$ and $T = 150$ MeV

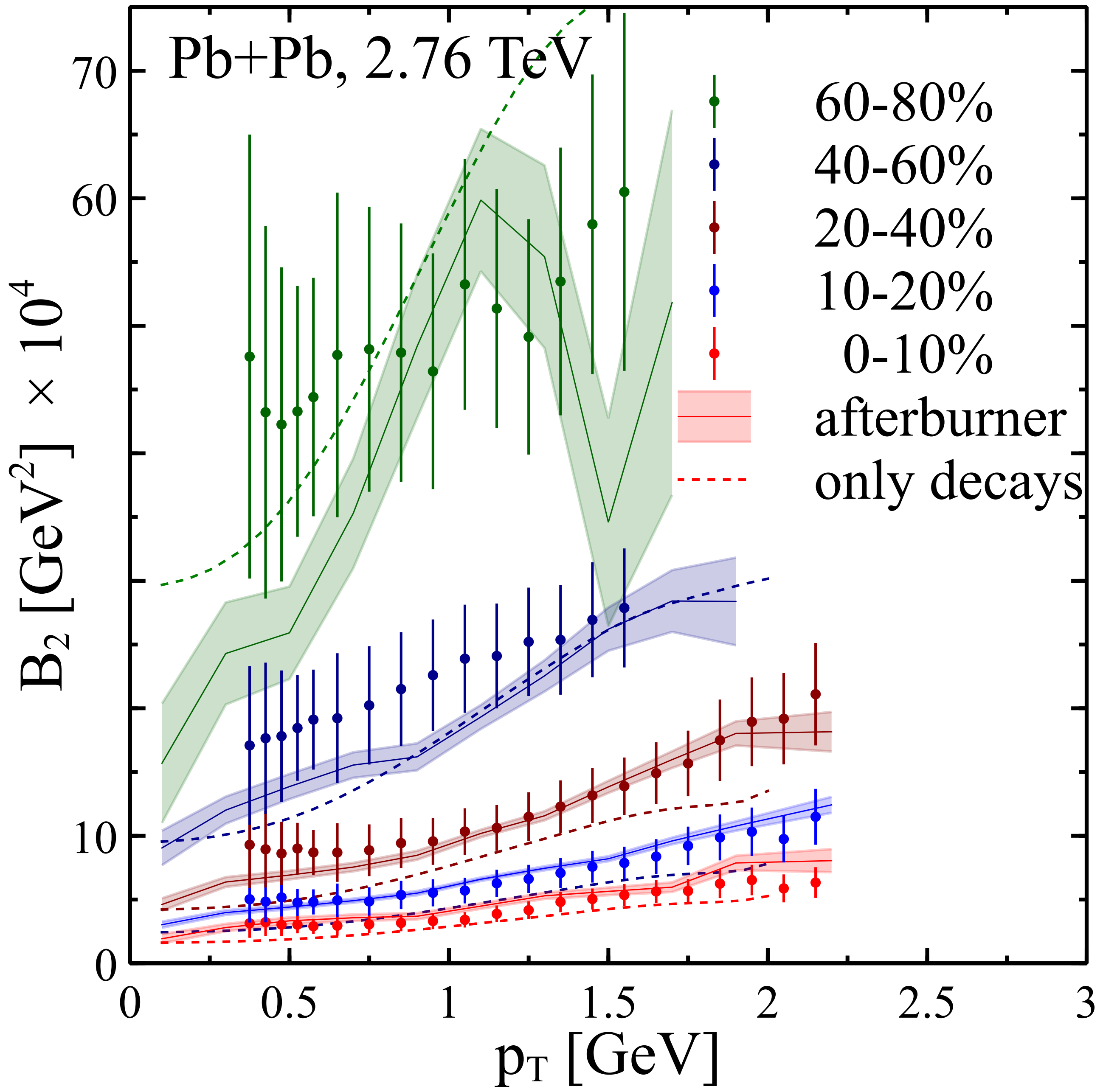
Transverse momentum spectra

- p_T -spectra and coalescence parameter B_2 for LHC-energies
- Deuterons are formed via intermediate resonance
- Good description of the data points

$$B_2(p_T) = \frac{\left.\frac{1}{2\pi}\frac{d^3N_d}{p_T dp_T dy}\right|_{p_T^d=2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^3N_p}{p_T dp_T dy}\right)^2}$$



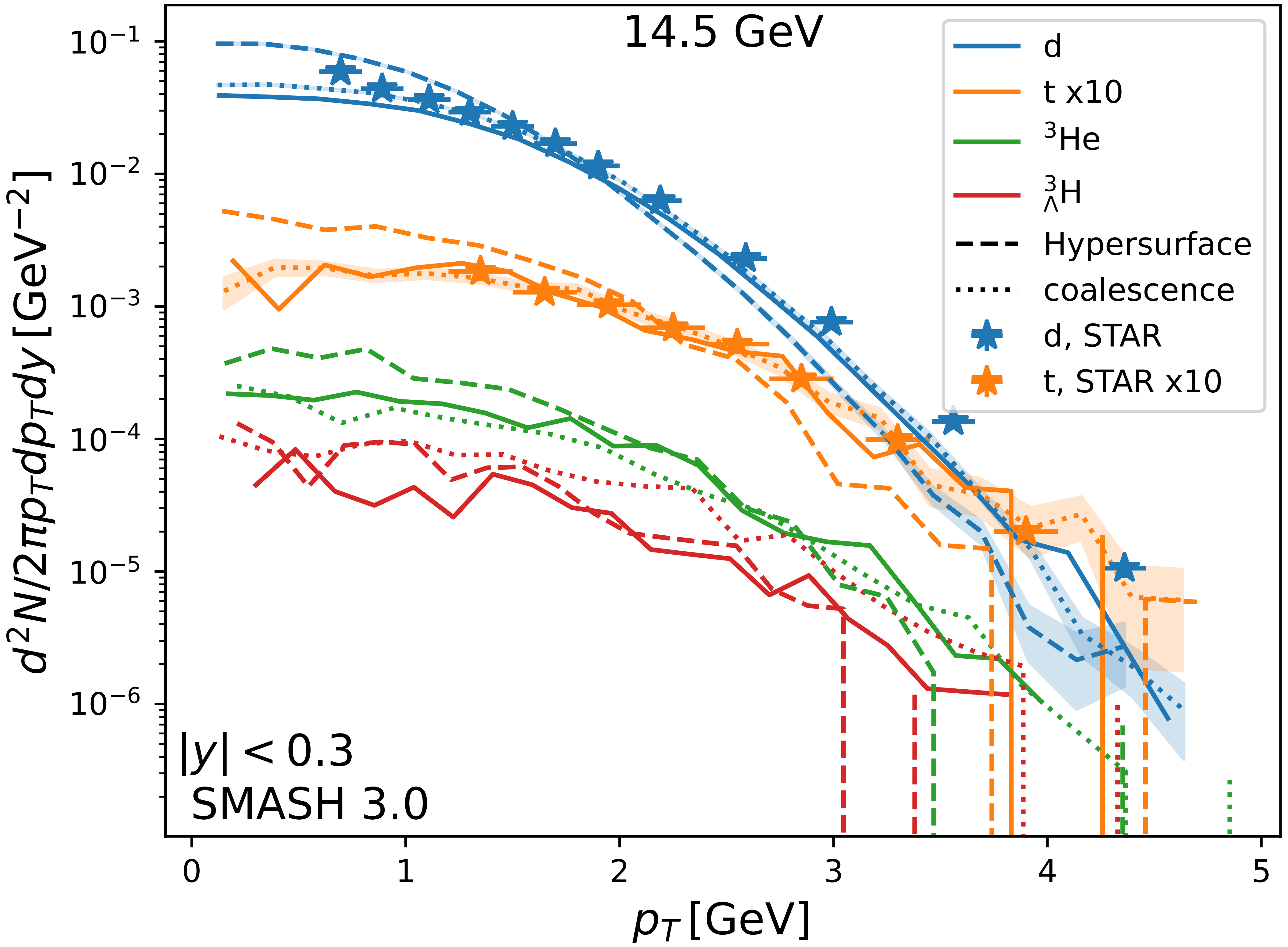
Oliinychenko *et al.*, Phys.Rev. C99 (2019)



Oliinychenko *et al.*, MDPI Proc. (2018)

Transverse momentum spectra

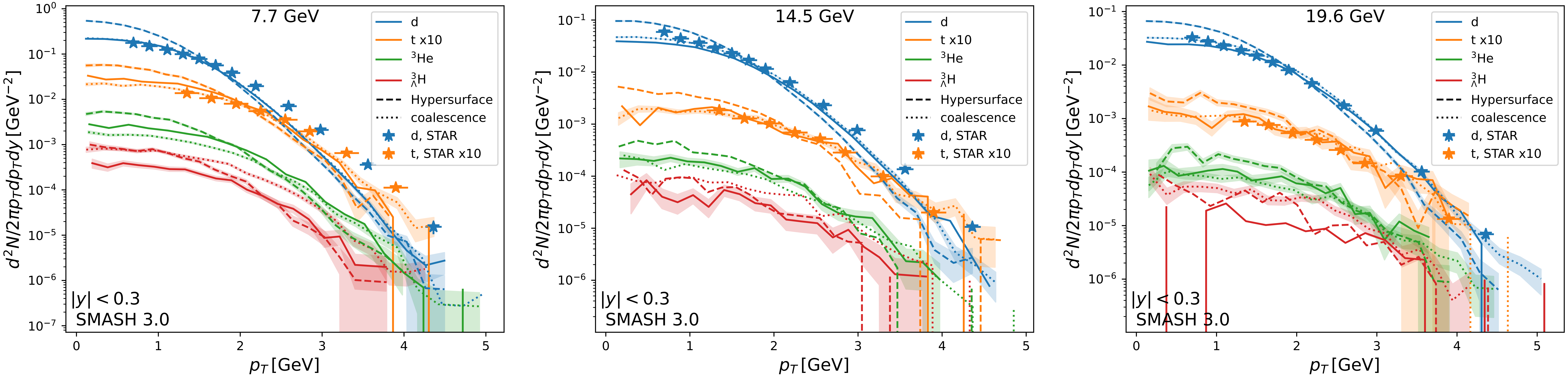
- Production of A=2 and A=3 nuclei with multi-particle reactions or coalescence
- Coalescence: Nuclei are formed if the nucleons are close enough in phase space
- Chosen parameters: $\Delta r = 3\text{fm}$, $\Delta p = 0.3\text{GeV}$
- Afterburner stage is important to describe the spectra correctly



STAR collaboration, Phys.Rev.C 99 (2019)

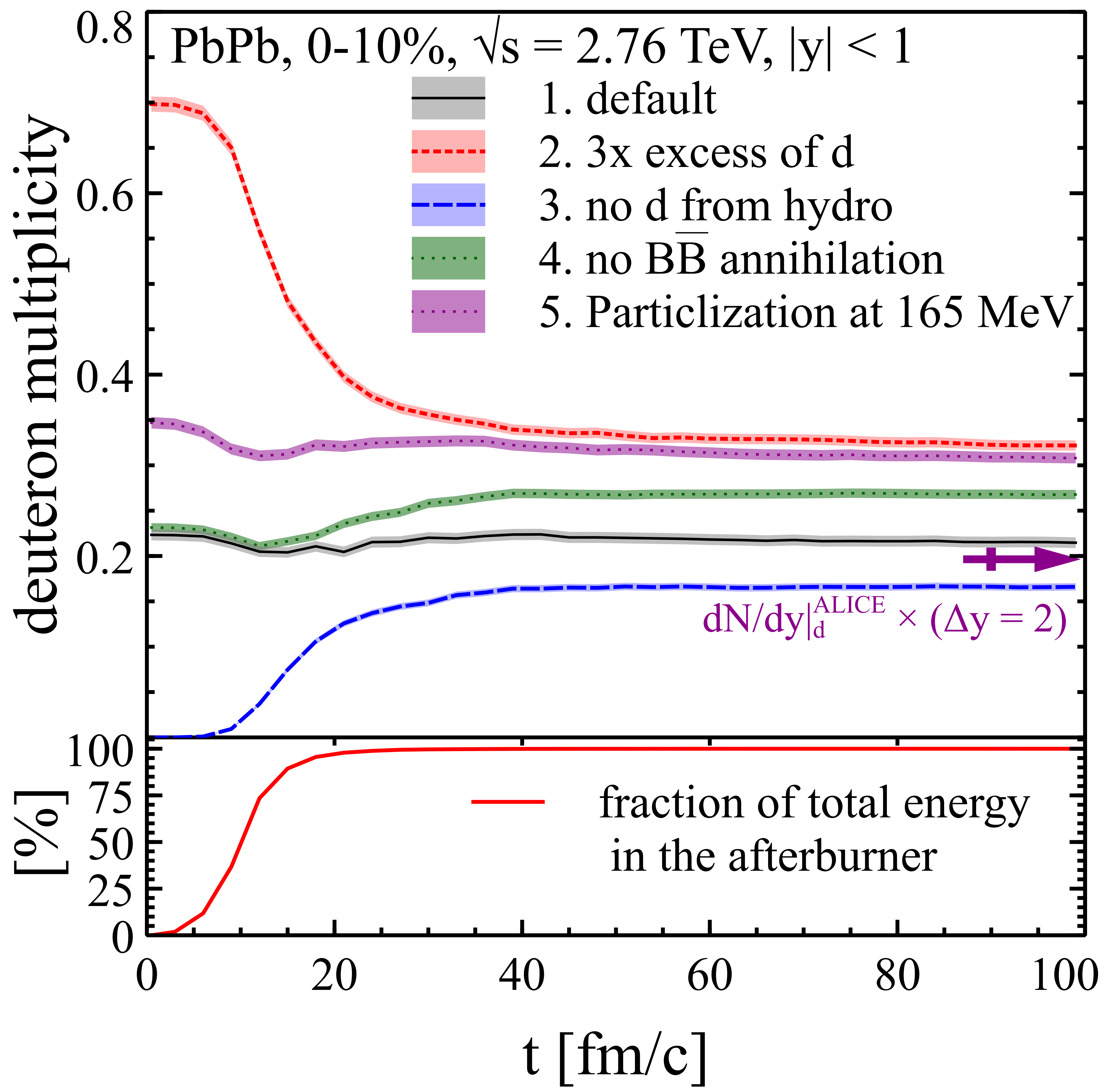
STAR collaboration, Phys.Rev.Lett. 130 (2023)

Transverse momentum spectra



Multiplicities

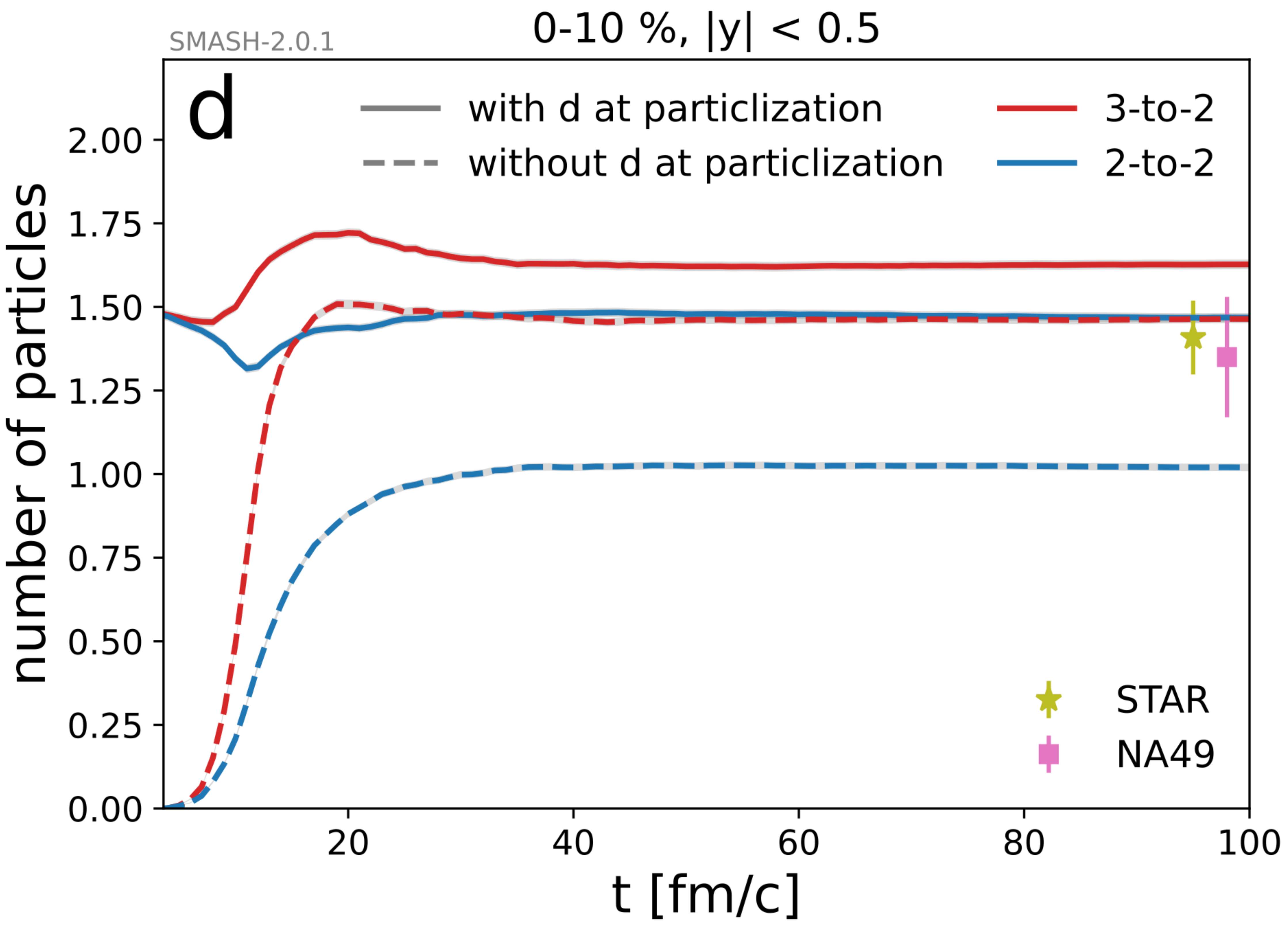
- Number of deuterons over time at LHC energies
- Compare different sampling scenarios
- All scenarios lead to a similar deuteron yield at the end
- This demonstrates how large the effect of the afterburner is for deuteron production
- The reactions have almost enough time to drive deuteron yield to the same value



Oliinychenko *et al.*, Phys.Rev. C99 (2019)

Multiplicities

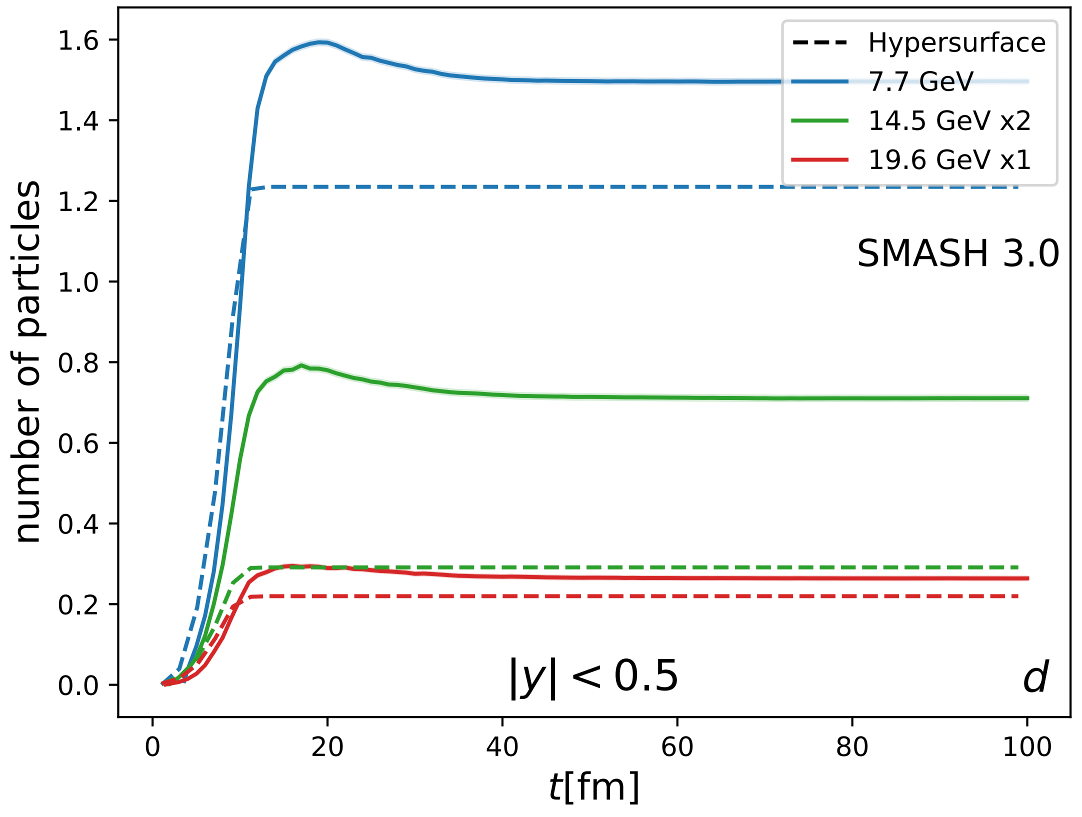
- Number of deuterons over time at 7.7 GeV (RHIC)
- Compare particlization with and without deuterons
- Compare multi-particle reactions to intermediate resonance treatment
- Quick equilibration of multi-particle reactions leads to similarity between the two particlization scenarios

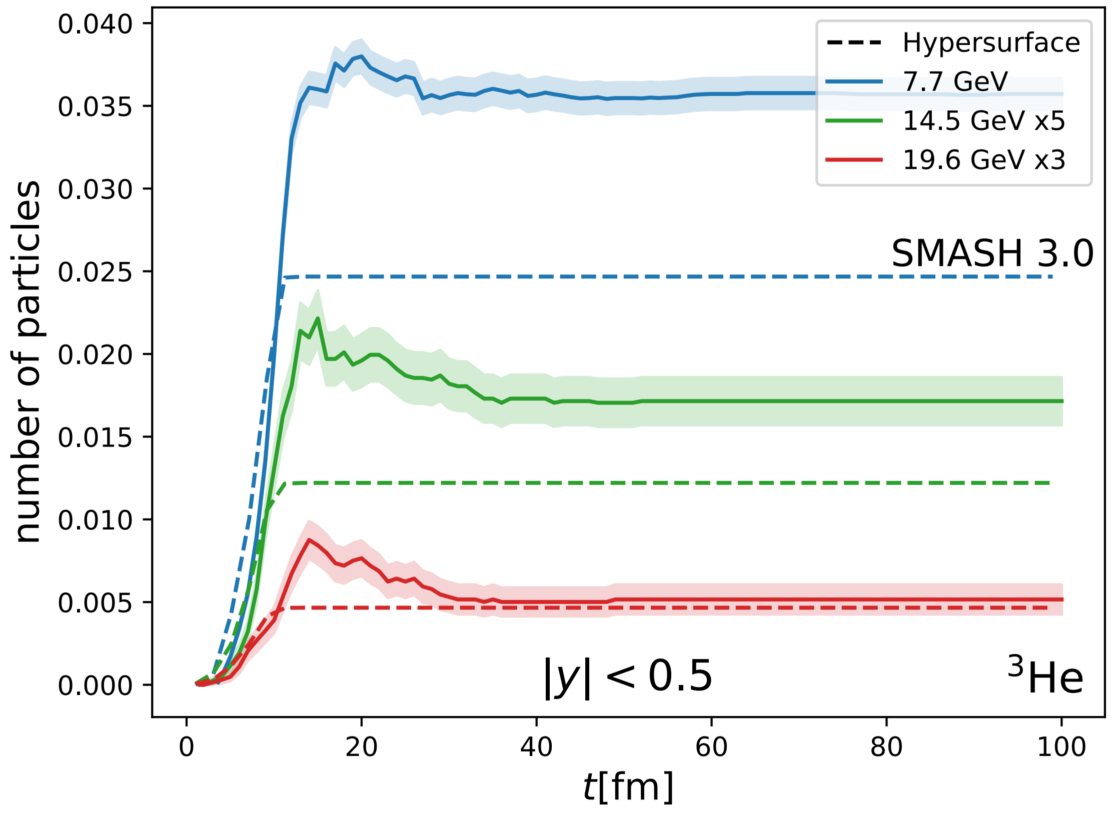


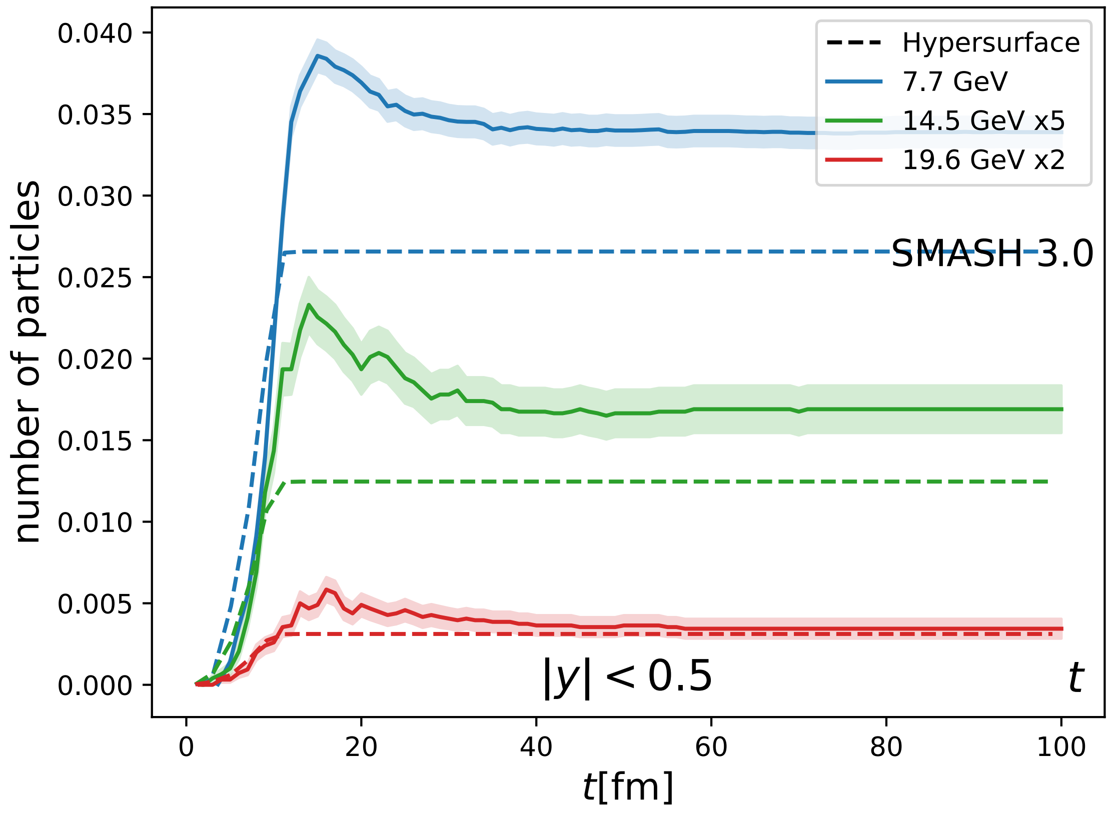
Staudenmaier *et al.*, Phys.Rev.C 104 (2021)

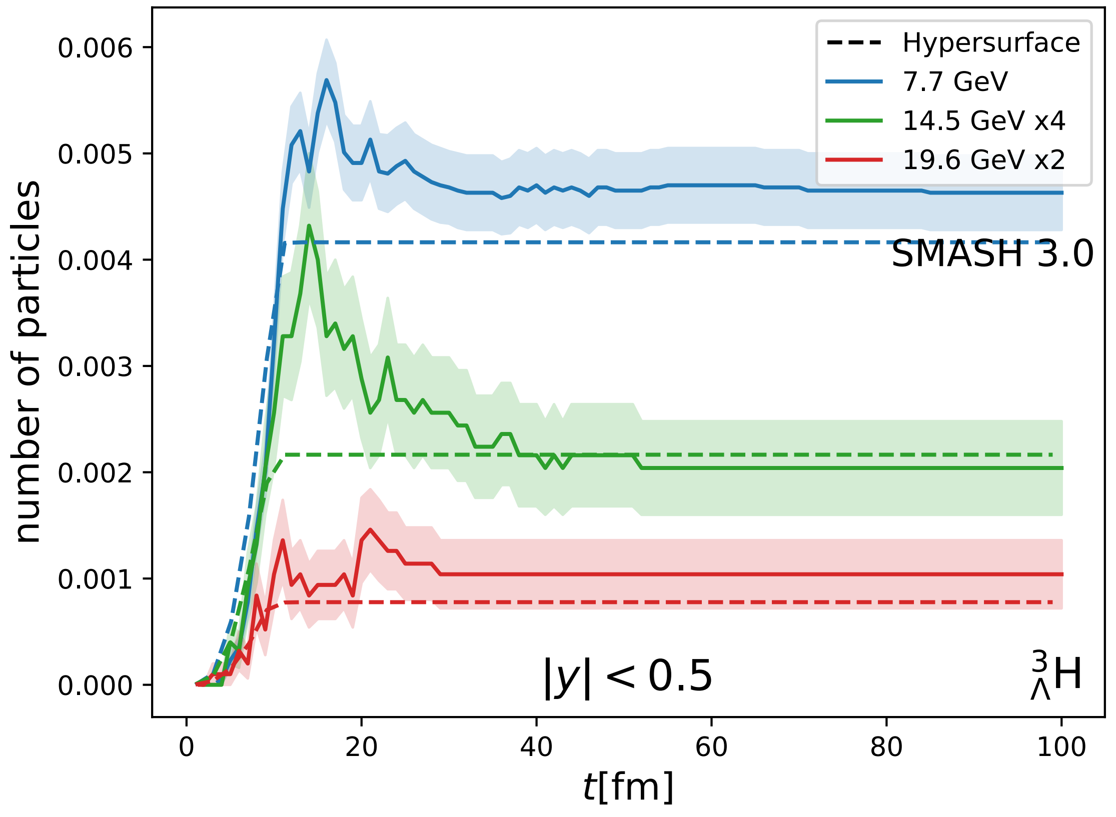
Multiplicities

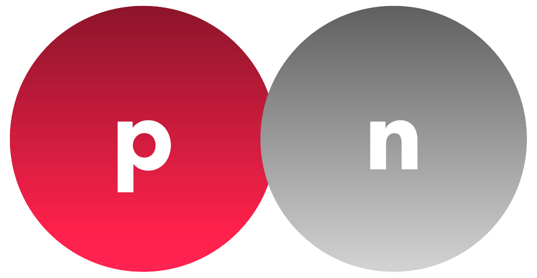
- Mid-rapidity multiplicities of light nuclei as a function of time

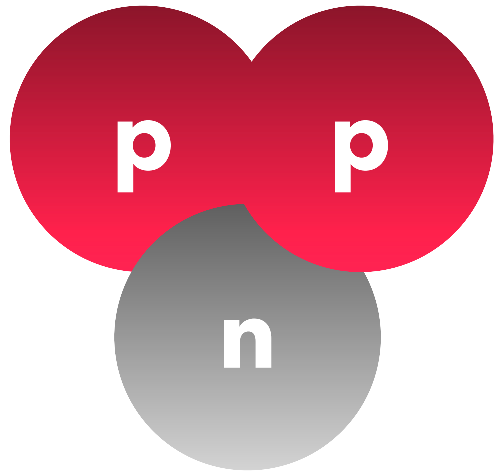


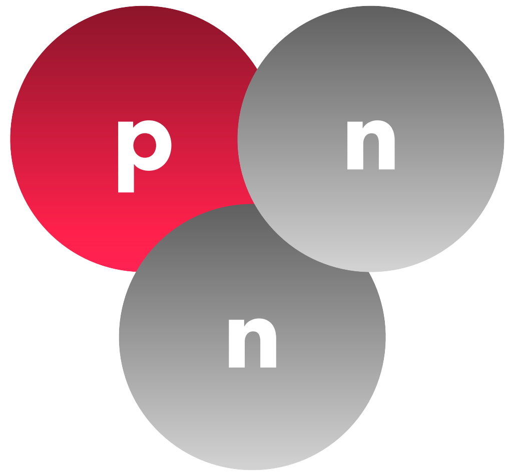


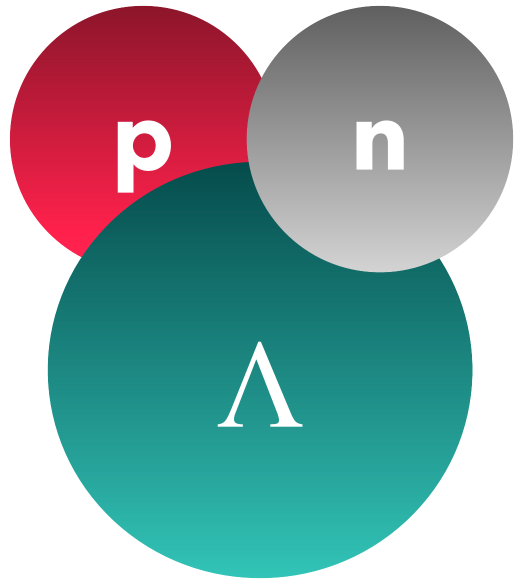






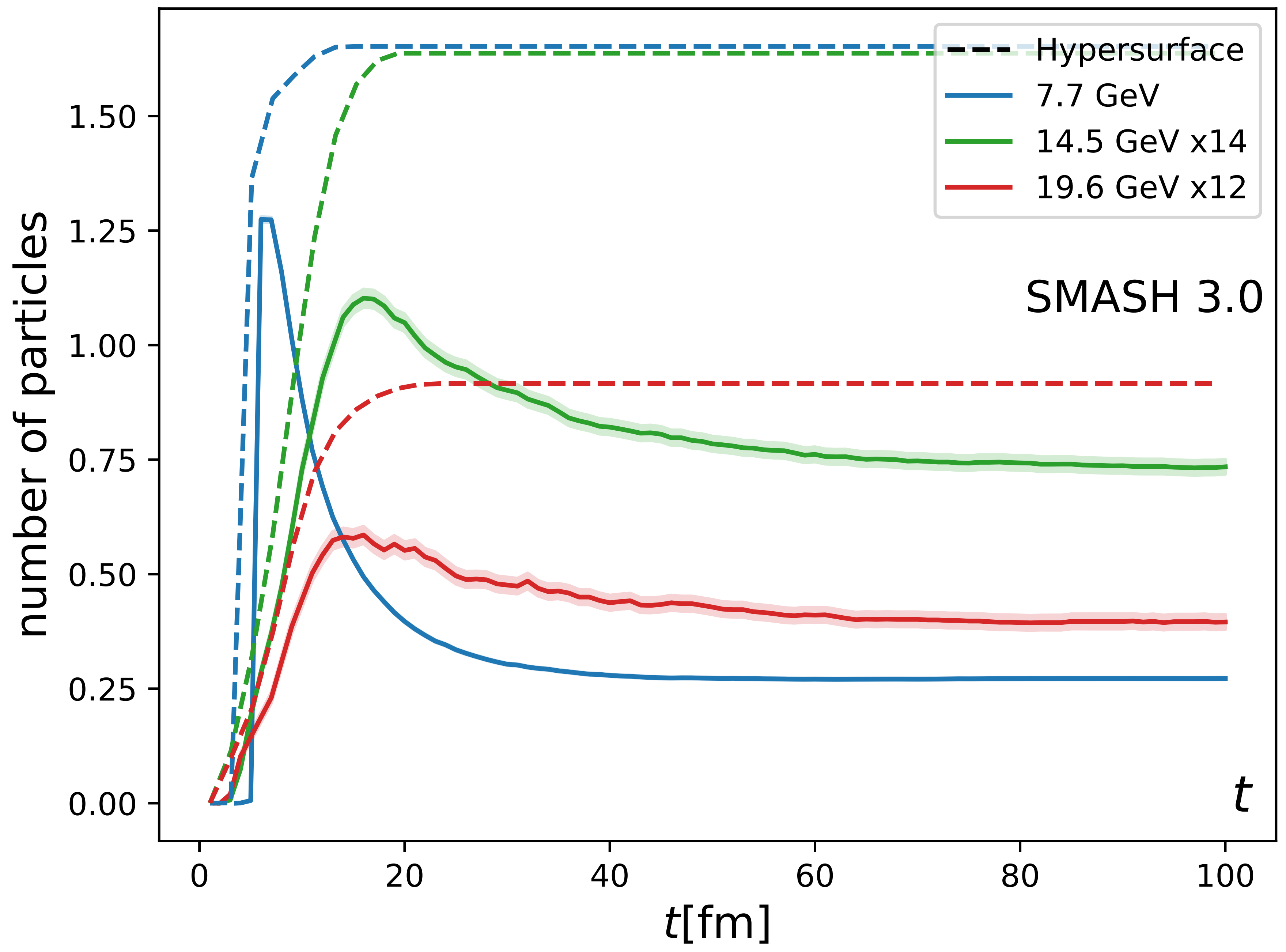


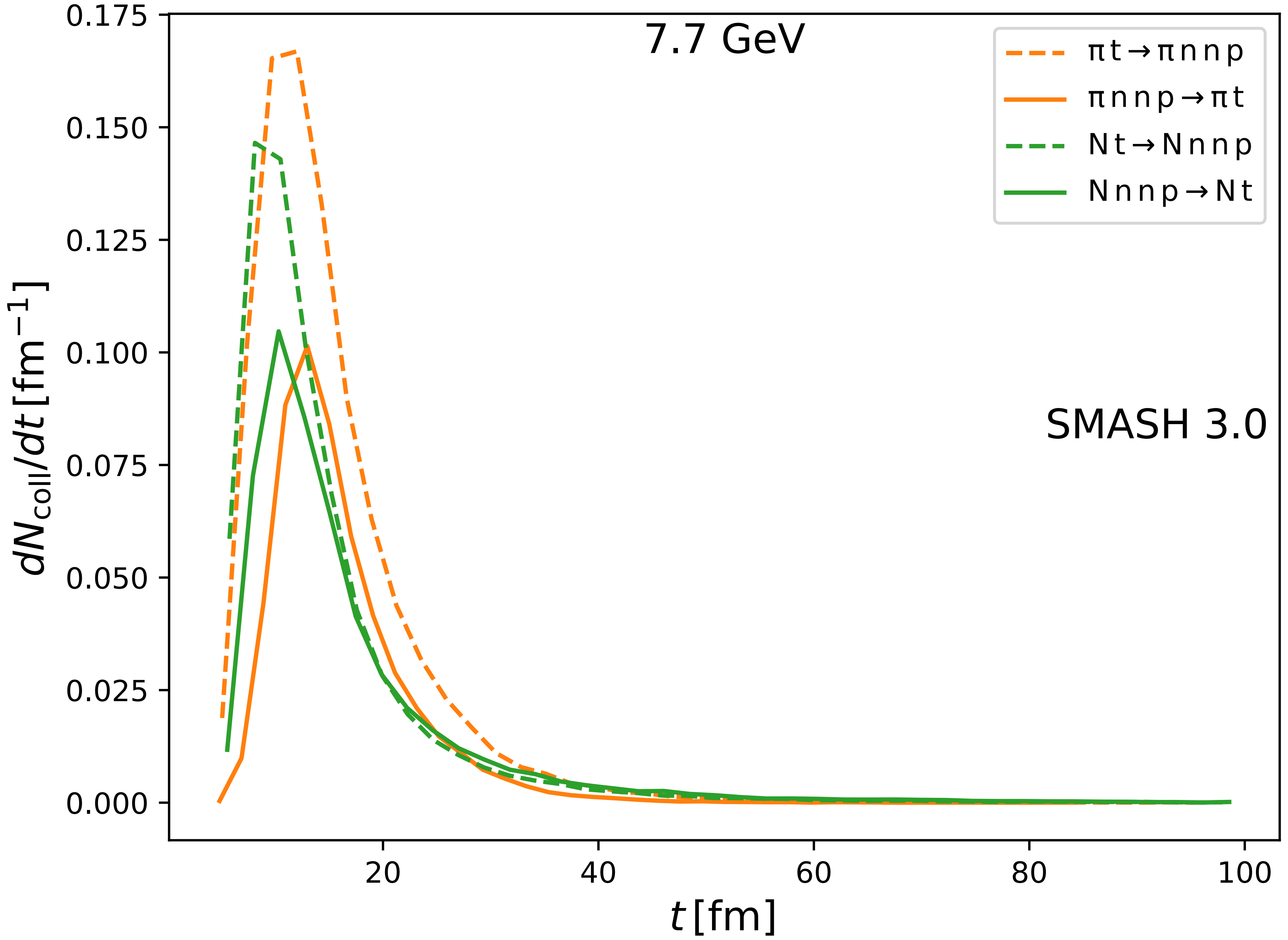




4π multiplicities and production mechanisms

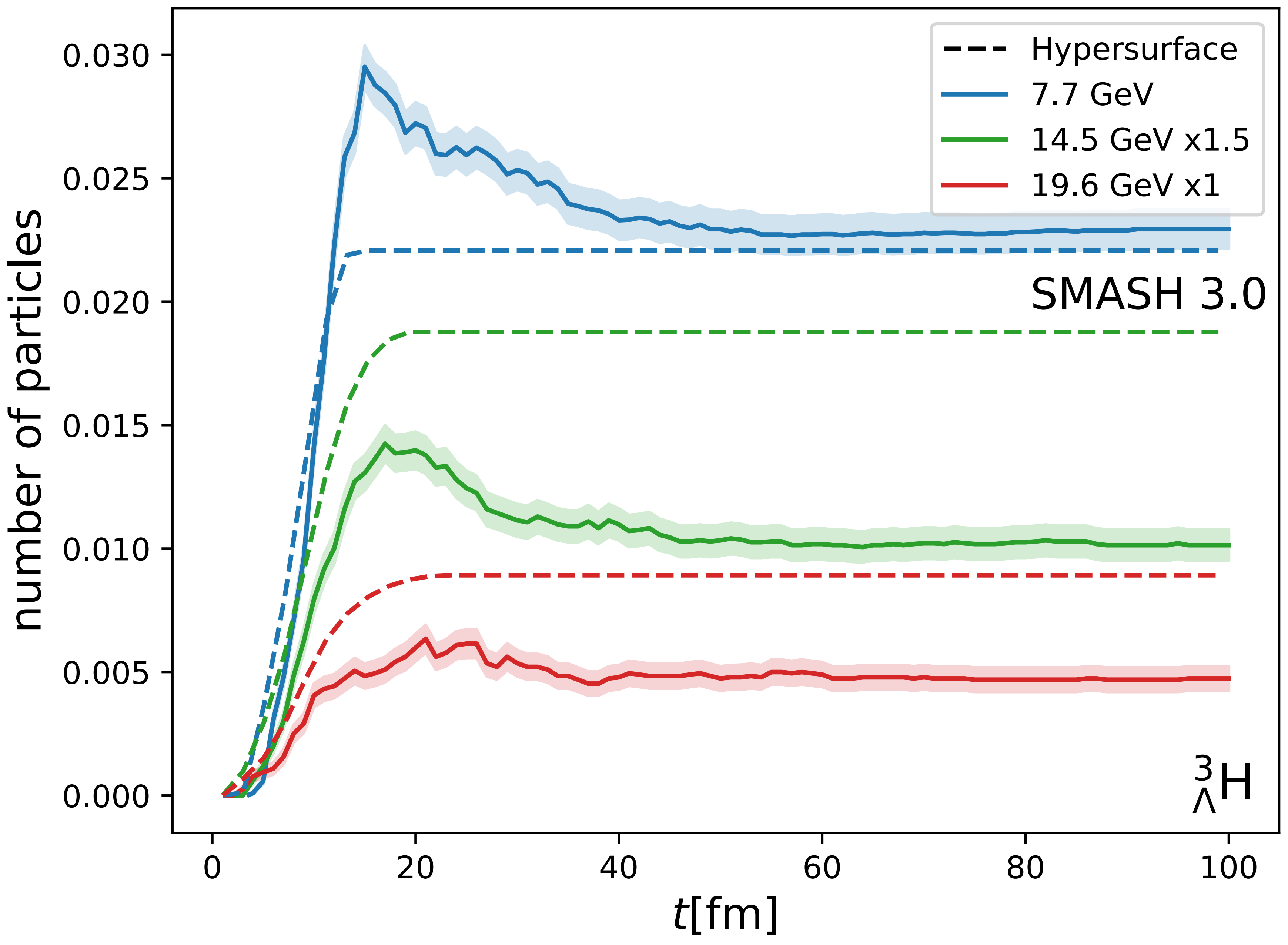
- Helium and triton show similar behavior:
  nuclei disintegration dominates ⇒ rescattering reduces yields

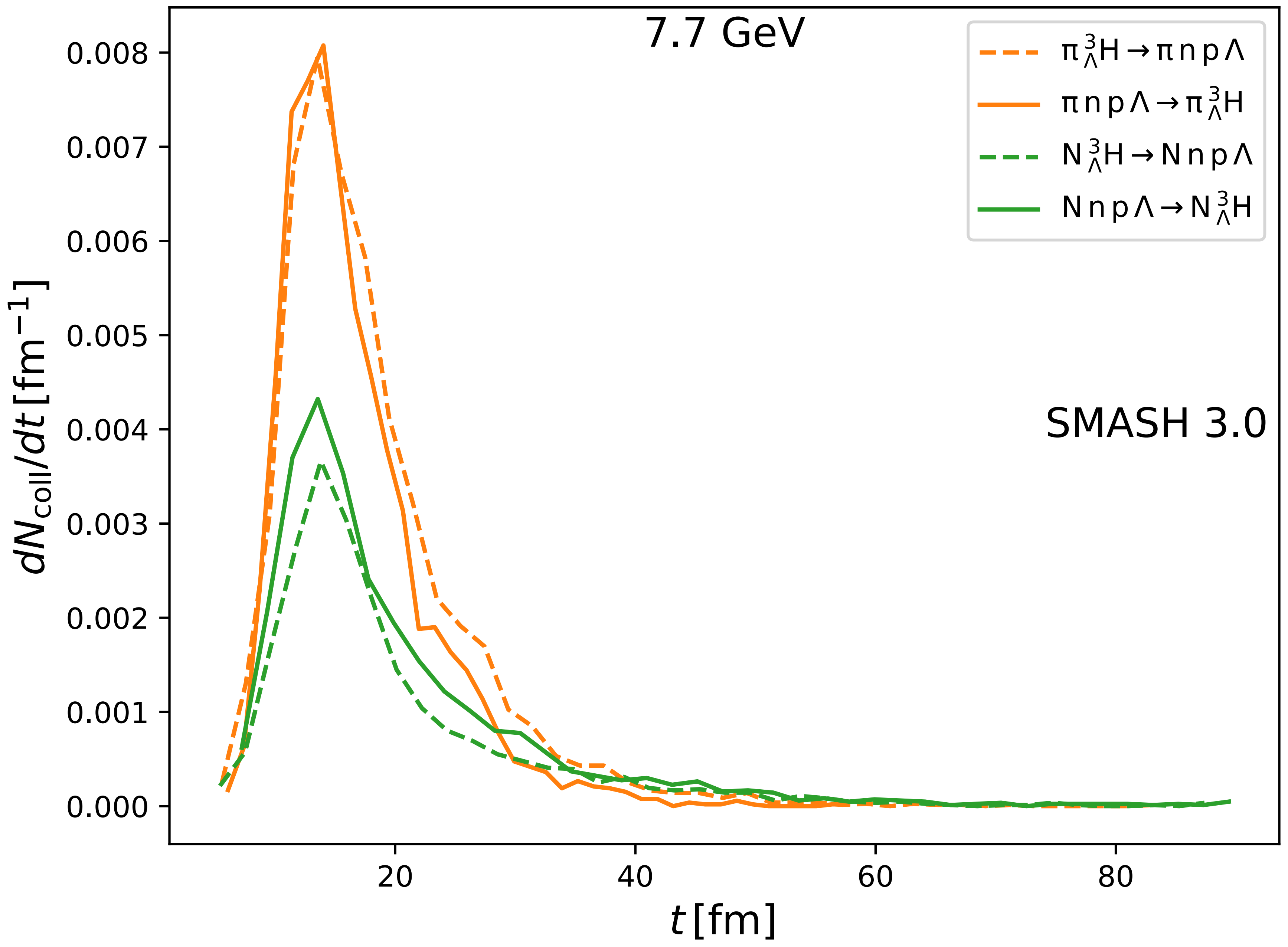




4π multiplicities and production mechanisms

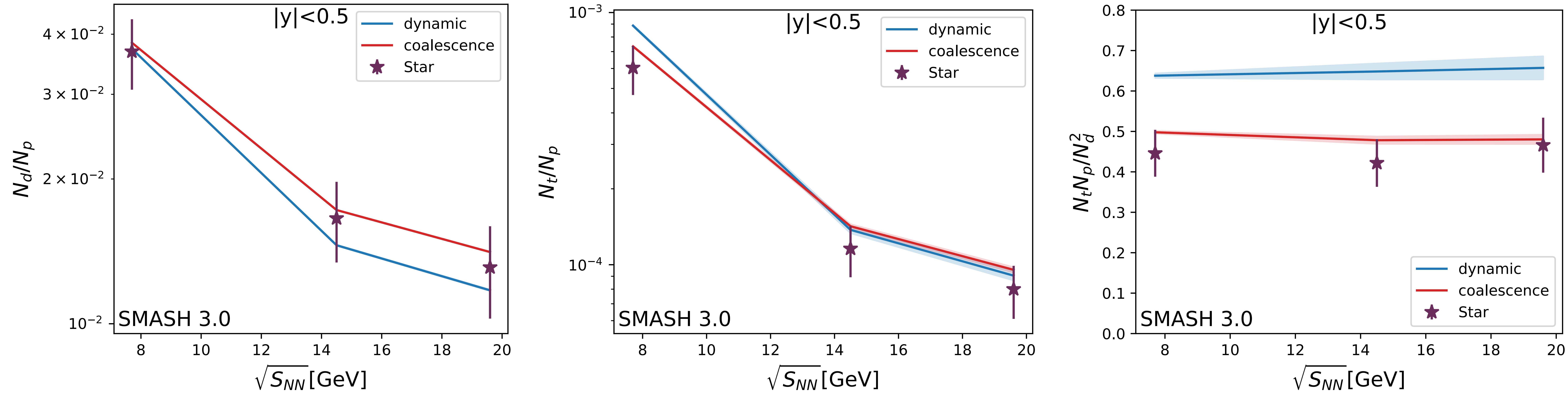
- Hypertriton production and destruction are balanced
  ⇒ yields equal to hypersurface at the end





Particle ratios

- The single ratios are well described
- The double ratio is related to the critical point



STAR collaboration, Phys.Rev.Lett. 130 (2023)

Summary

- Dynamic production of light nuclei in SMASH with multi-particle reactions
- p_T -spectra and B_2-spectra for different energies fit the data points from STAR and ALICE
- Multiplicities and collision rates: investigation of the different processes
- Particle ratios are calculated and compared to STAR data

Outlook

- Sensitivity for numerical details
- ${}^{3}_{\Lambda}$H production in CC-collision at HADES-energies

Stochastic collision criterion

Staudenmaier *et al.*, Phys.Rev.C 104 (2021)

- Probability for a reaction of a given particle set
- Defined as the number of reactions over the number of all possible particle combinations $\Delta N_{\text{reactions}}$ inside a sub-volume $\Delta^3 x$ and time interval ΔT:

$$P_{n\to m} = \frac{\Delta N_{\text{reactions}}}{\Pi_{j=1}^{n} \Delta N_i}$$

- Calculated collision criterions are: $P_{2\to 2} = \frac{\Delta t}{\Delta^3 x} v_{\text{rel}} \sigma_{2\to 2}(\sqrt{s})$ (for d)

$$P_{3\to 2} = \left(\frac{g_{1'} g_{2'}}{g_1 g_2 g_3}\right) \frac{S!}{S'!} \frac{\Delta t}{(\Delta^3 x)^2} \frac{E_{1'} E_{2'}}{2E_1 E_2 E_3} \frac{\Phi_2(s)}{\Phi_3(s)} v_{\text{rel}} \sigma_{2\to 3}(\sqrt{s}) \quad \text{(for d)}$$

$$P_{4\to 2} = \left(\frac{g_{1'} g_{2'}}{g_1 g_2 g_3 g_4}\right) \frac{S!}{S'!} \frac{\Delta t}{(\Delta^3 x)^3} \frac{1}{16 E_1 E_2 E_3 E_4} \frac{\lambda(s; m_{1'}^2, m_{2'}^2)}{\Phi_4} \frac{\sigma_{2\to 4}(\sqrt{s})}{4\pi s} \quad \text{(for } {}^3\text{He, t, } {}^3_\Lambda\text{H)}$$

Rate equations

- Time dependent particle multiplicities: $N_i = V n_i^{th}(T)\lambda_i$

  with $n_i^{th}(T) = \frac{g_i T}{2pi^2 h^3} \int dM M^2 K_2(M/T) A(M)$

- Rate equations:

$$n_d^{th}\dot{\lambda}_d = (R_{\pi d} + R_{Nd})(\lambda_p^2 - \lambda_d)$$

$$n_p^{th}\dot{\lambda}_N = -(R_{\pi d} + R_{Nd})(\lambda_p^2 - \lambda_d)$$

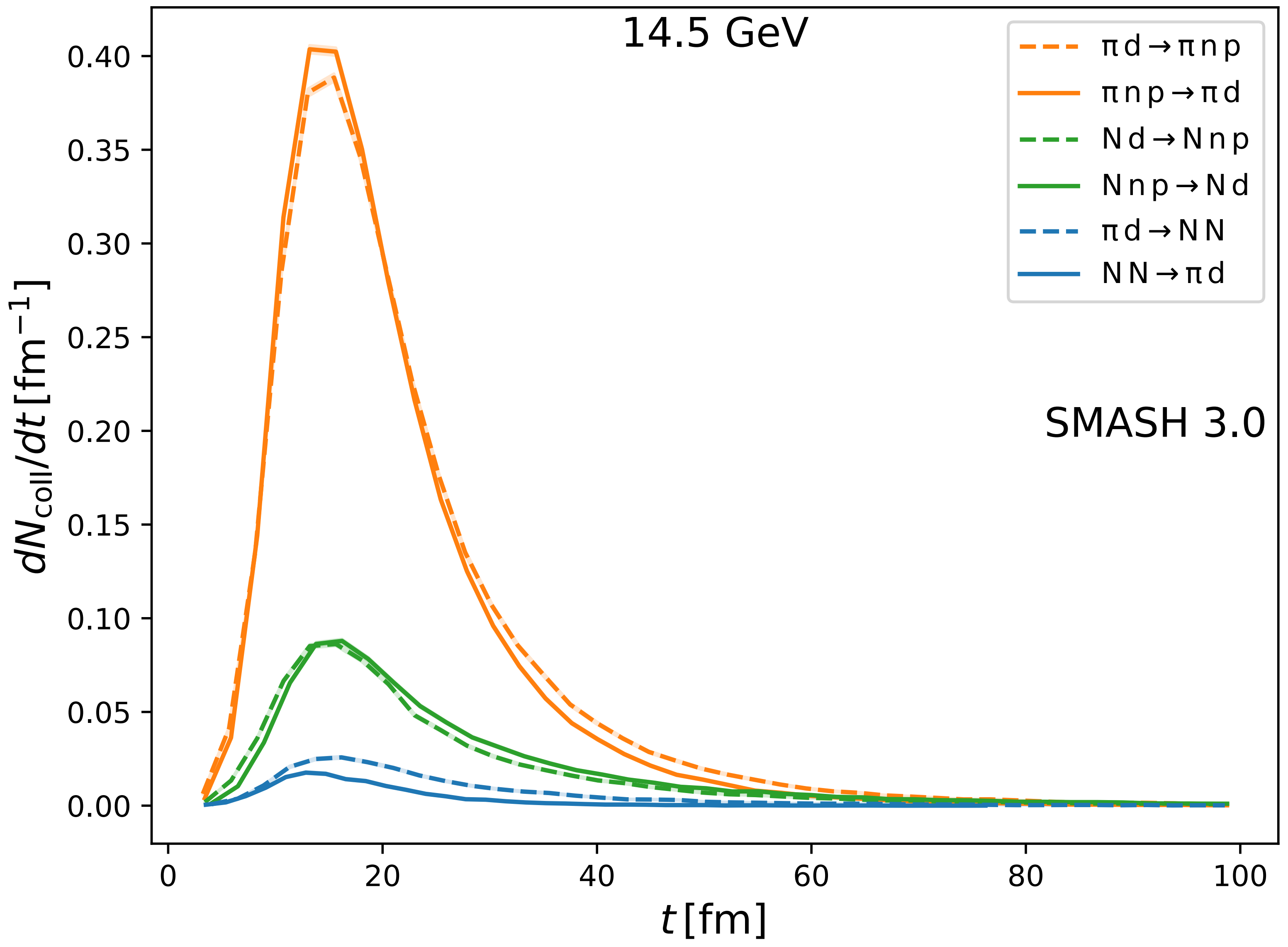
$$\dot{\lambda}_\pi = 0$$

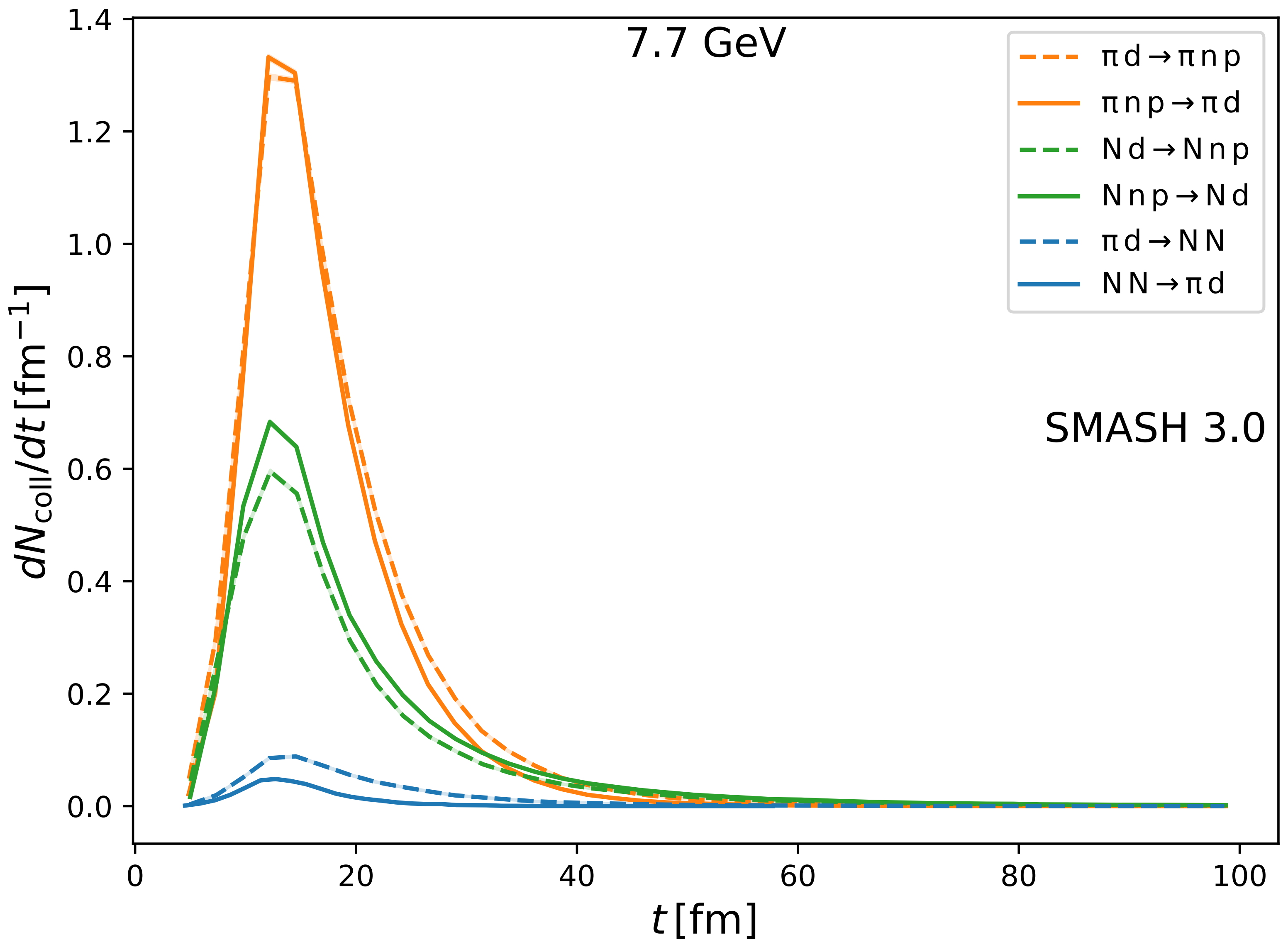
$$R_{\pi d} = \langle \sigma v_{\mathrm{rel}} \rangle_{\pi d} n_\pi^{th} n_d^{th} \lambda_\pi$$

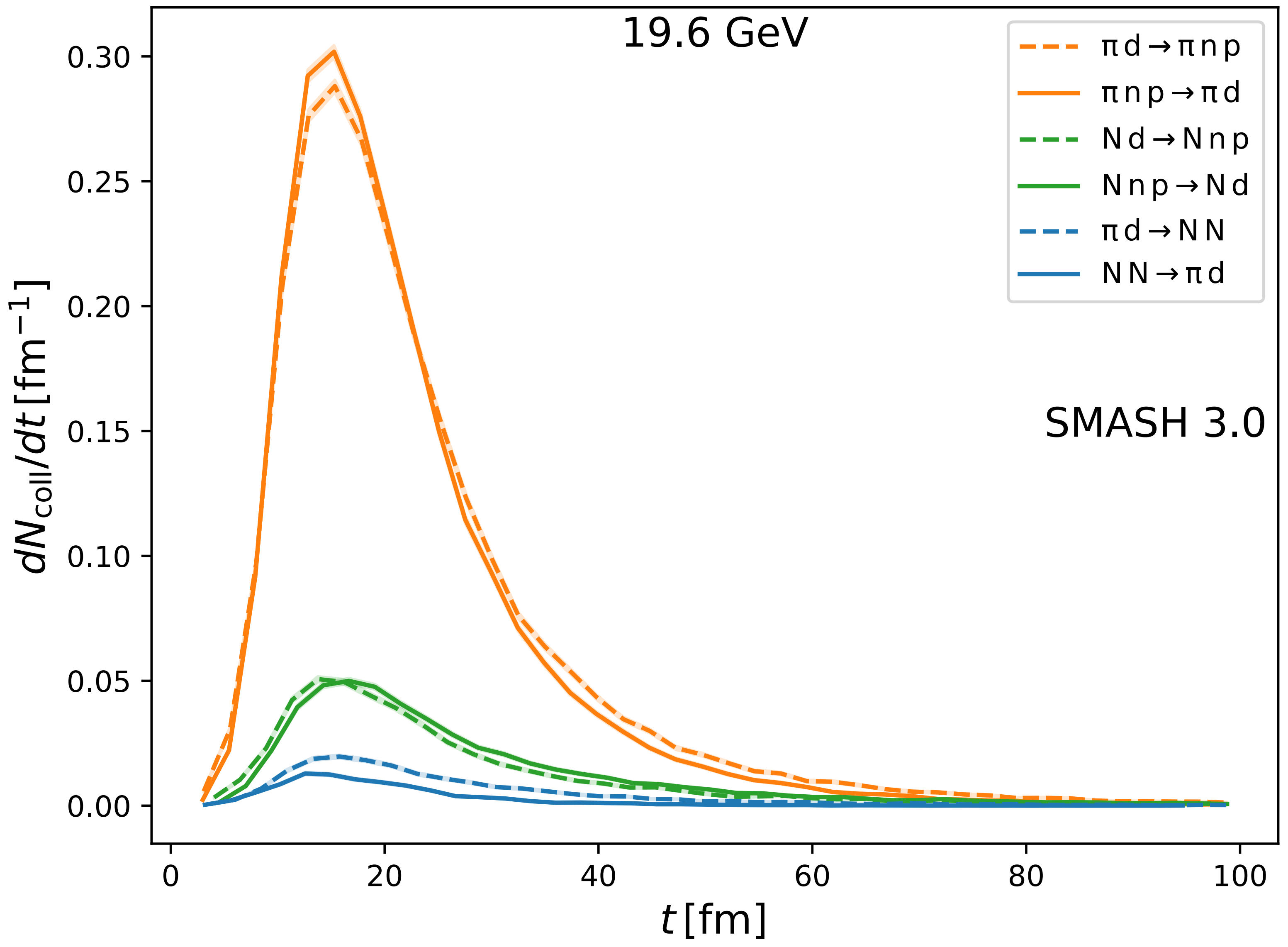
$$R_{Nd} = \langle \sigma v_{\mathrm{rel}} \rangle_{Nd} 2 n_p^{th} n_d^{th} \lambda_N$$

Collision rates

- Production mechanisms for deuterons at 7.7, 14.5 and 19.6 GeV

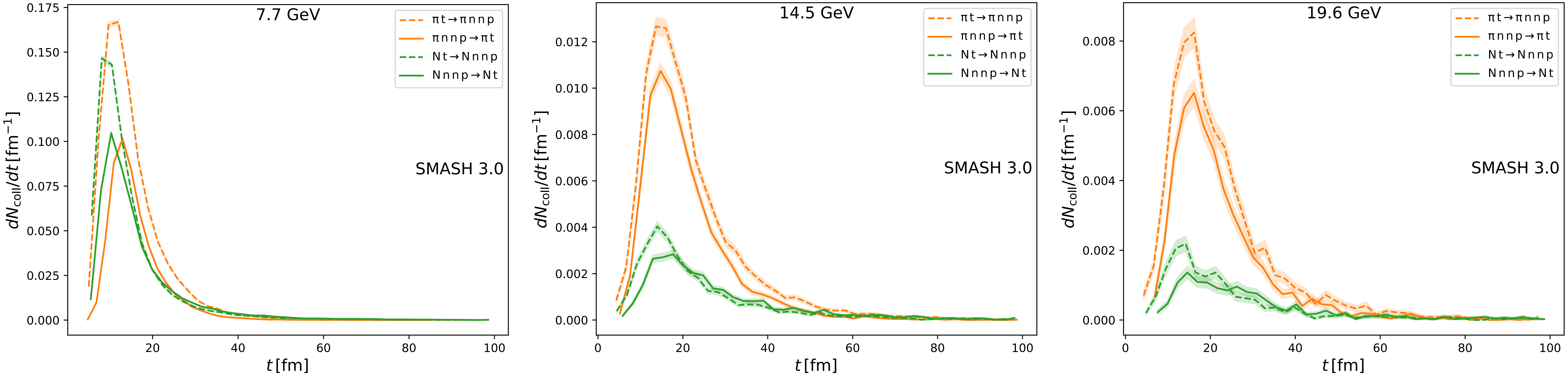






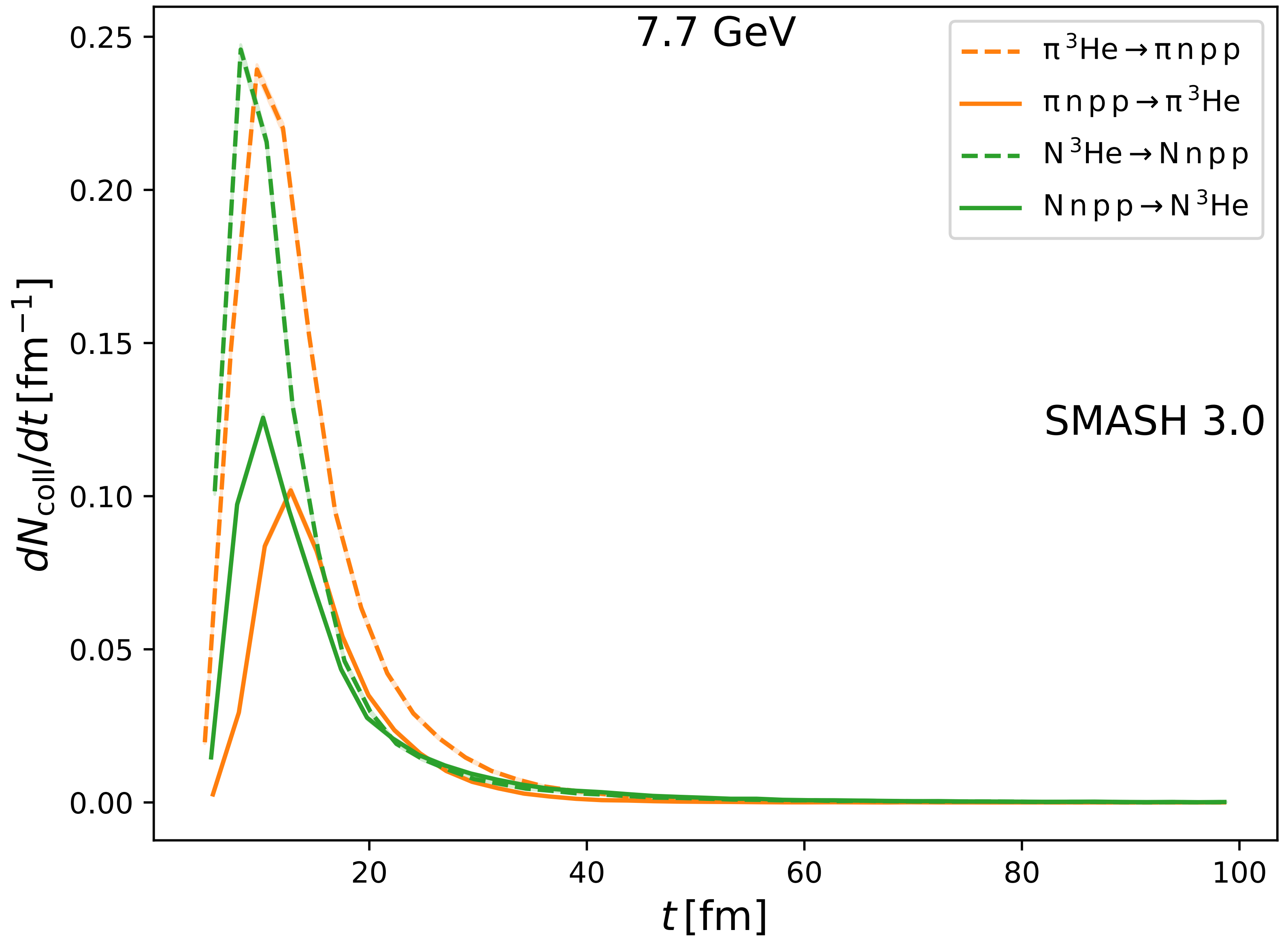
Collision rates

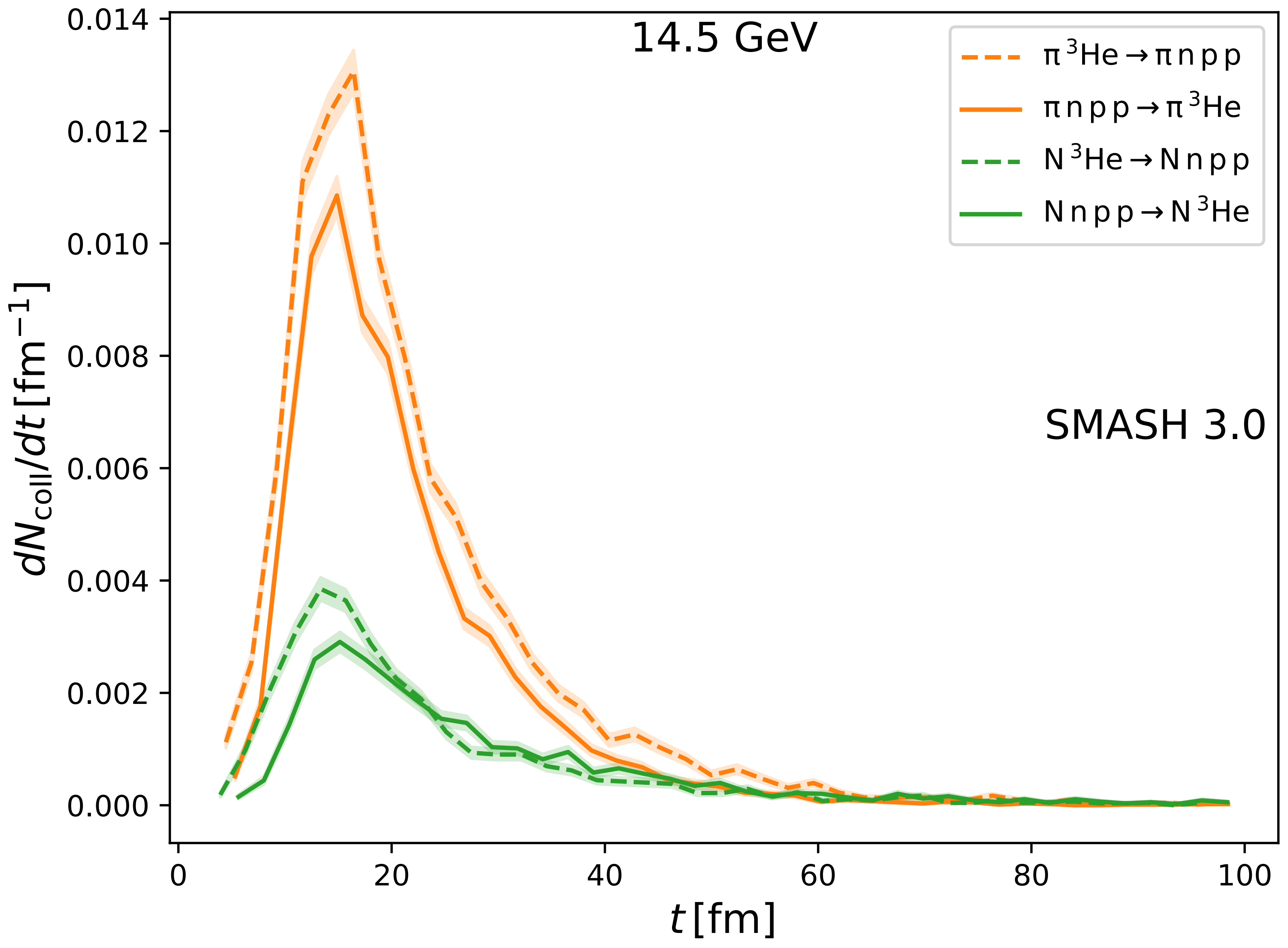
- Production mechanisms for tritons at 7.7, 14.5 and 19.6 GeV

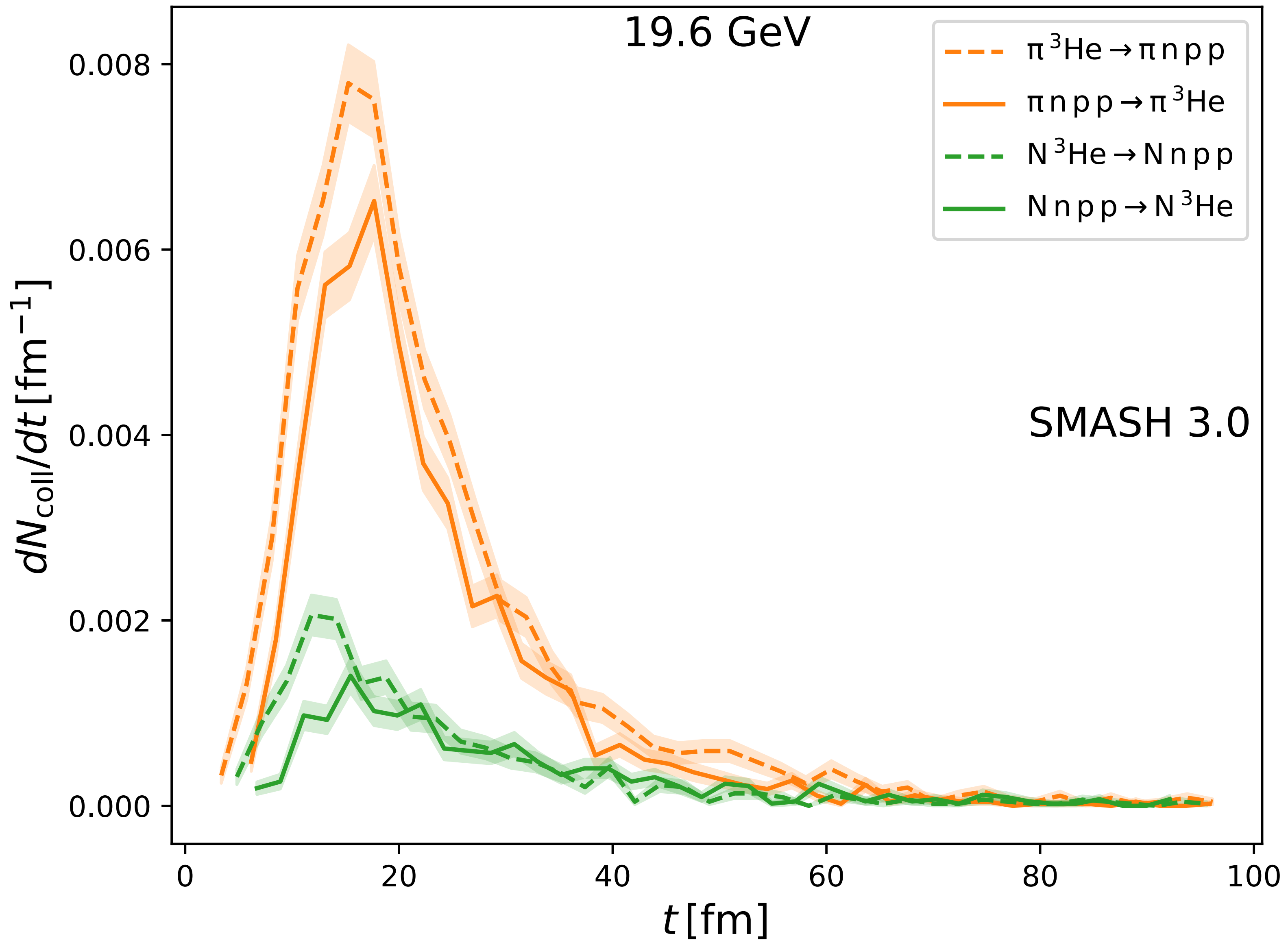


Collision rates

- Production mechanisms for heliums at 7.7, 14.5 and 19.6 GeV







Collision rates

- Production mechanisms for hypertritons at 7.7, 14.5 and 19.6 GeV