Particle production in nucleus-nucleus and pion-nucleus collisions at $E_{\mathrm{kin}} = 0.4 - 2A\,\mathrm{GeV}$

Critical Point and Onset of Deconfinement 2016, Wrocław
June 2, 2016

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HELMHOLTZ ASSOCIATION
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

SMASH: A new transport approach

- SMASH: Smashing Many Accelerated Strongly-interacting Hadrons
- Microscopic simulation of hadronic reactions
- Solve relativistic Boltzmann equation for hadron species i:

$$p^{\mu}\partial_{\mu}f_i(x,p) = C^i_{\text{coll}} \tag{1}$$

- Motivation:
  - Understanding hadronic phase in heavy-ion collisions
  - Modeling non-equilibrium phenomena and microscopic physics
  - Open, maintainable, extensible code

Basic features

- Mesons:
  - π, ρ, η, ω, ϕ, σ, f_2
  - K, $K^*(892)$, $K^*(1410)$
- Baryons:
  - N, N^*, up to 2.25 GeV
  - Δ, Δ^*, up to 1.95 GeV
  - Λ, Λ^*, up to 1.89 GeV
  - Σ, Σ^*, up to 1.915 GeV
  - Ξ, Ω
- $2 \leftrightarrow 2$ and $2 \leftrightarrow 1$ reactions
- Skyrme and symmetry potential
- Fermi motion
- Pauli blocking
- Dileptons

Collision criterion

- Geometric collision criterion (as used by UrQMD) using the transverse distance in c.o.m. frame:

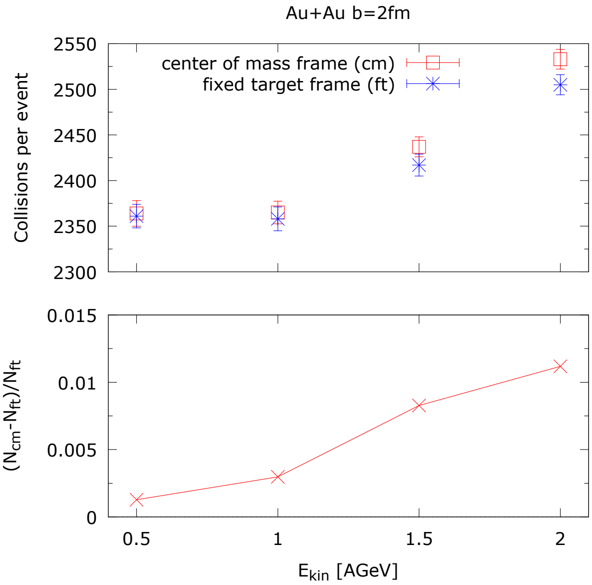
$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \tag{2}$$

$$d_{\text{trans}}^2 = (\vec{r}_a - \vec{r}_b)^2 - \frac{\left((\vec{r}_a - \vec{r}_b)(\vec{p}_a - \vec{p}_b)\right)^2}{(\vec{p}_a - \vec{p}_b)^2} \tag{3}$$

$$t_{\text{coll}} = -\frac{(\vec{x}_a - \vec{x}_b)(\vec{v}_a - \vec{v}_b)}{(\vec{v}_a - \vec{v}_b)^2} \tag{4}$$

- Not Lorentz invariant

Frame dependence of collision number



Skyrme and symmetry potential

$$U = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2S_{\text{pot}}\frac{\rho_p - \rho_n}{\rho_0}\frac{I_3}{I} \tag{5}$$

$$H_i = \sqrt{\vec{p}_i^2 + m_i^2} + U(\vec{r}_i) \tag{6}$$

where

$$a = -209.2\,\text{MeV} \quad b = 156.4\,\text{MeV} \quad \tau = 1.35 \quad S_{pot} = 18\,\text{MeV}$$

- Soft potential with incompressibility $K_0 = 240\,\text{MeV}$

Decay width

- Manley-Saleski ansatz for off-shell decay branching ratio:

$$\Gamma_{R\to ab}(m) = \Gamma^0_{R\to ab}\frac{\rho_{ab}(m)}{\rho_{ab}(m_0)} \tag{7}$$

$$\rho_{ab}(m) = \int dm_a^2 dm_b^2 \mathcal{A}_a(m_a^2)\mathcal{A}_b(m_b^2)\frac{p_f}{m}B_L^2(p_f R)\mathcal{F}_{ab}(m) \tag{8}$$

- Example: L=1 decay with stable daughters (e.g. $\Delta \to \pi N$)

$$\Gamma(m) = \Gamma_0\frac{m_0}{m}\left(\frac{p_f}{p_{f0}}\right)^3\frac{p_{f0}^2+\Lambda^2}{p_f^2+\Lambda^2} \tag{9}$$

Cross sections: theory

- $2 \to 1$ resonance production

$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)}\mathcal{S}_{ab}\frac{2\pi^2}{p_i^2}\Gamma_{ab\to R}(s)\mathcal{A}(\sqrt{s}) \qquad (10)$$

- $2 \to 2$ resonance production

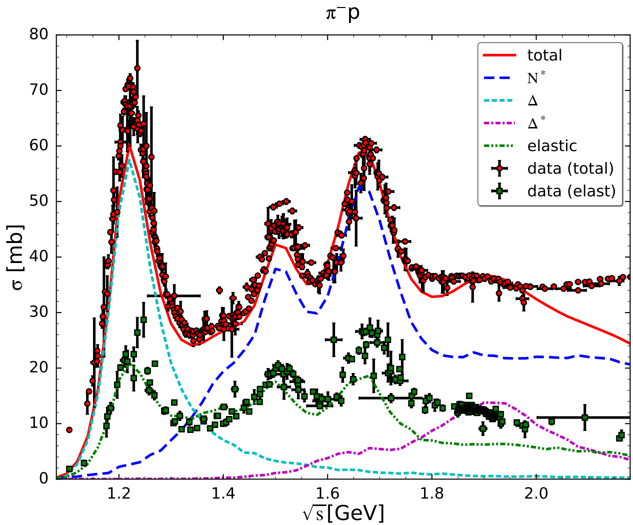
$$\sigma_{ab\to Rc}(s) = C_I^2\frac{|M|^2_{ab\to Rc}}{64\pi^2 s}\frac{4\pi}{p_i}\int dm\mathcal{A}(m)p_f \qquad (11)$$

where

$$\mathcal{A}(m) = \frac{1}{\pi}\frac{m\Gamma(m)}{(m^2-m_0^2)^2+m^2\Gamma(m)^2} \qquad (12)$$

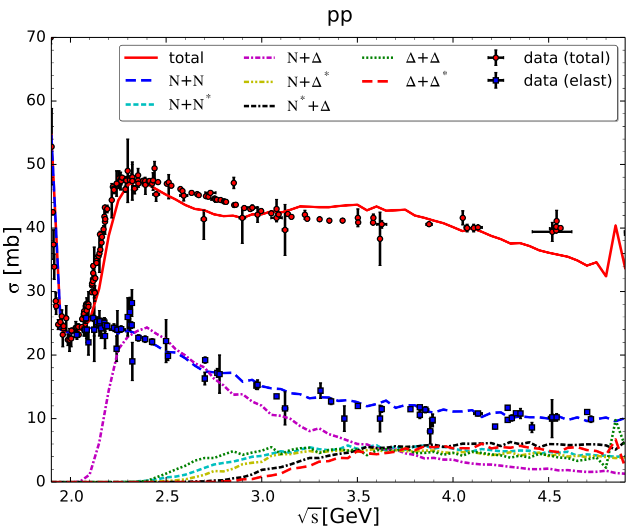
(Breit-Wigner, no in-medium modifications)

Cross sections compared to data



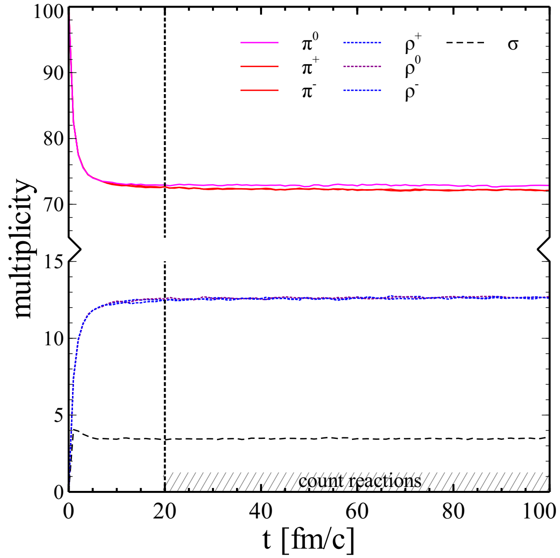
- Cross section fully described via excitation of resonances

Cross sections compared to data



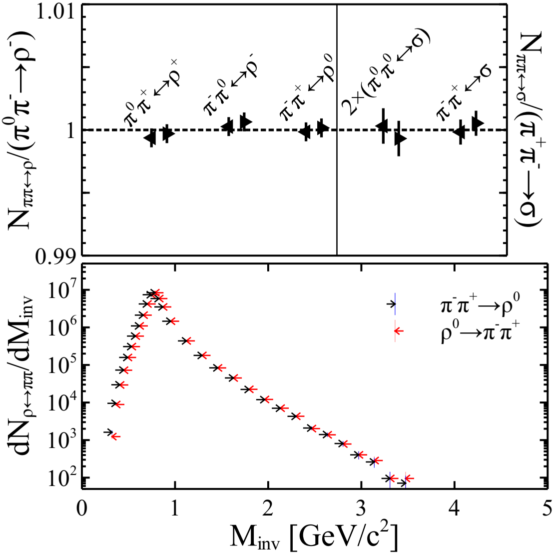
- Elastic cross section fitted to PDG data

Detailed balance



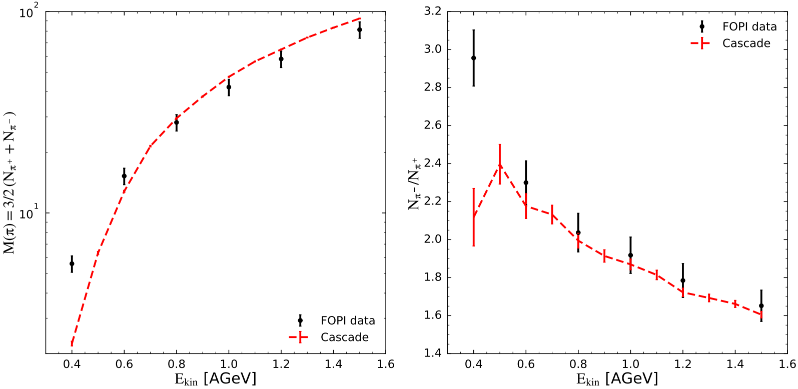
- Wait until box with limited species is in chemical equilibrium

Detailed balance



- Compare number of forward and backward reactions

FOPI pion production in AuAu at $E_{kin} \in [0.4, 1.5] A$ GeV



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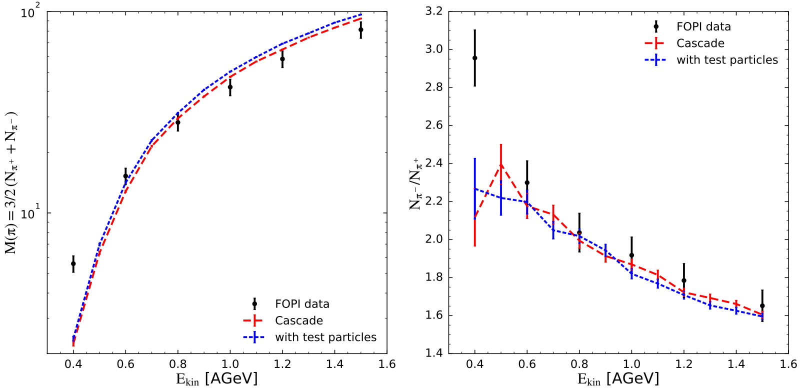

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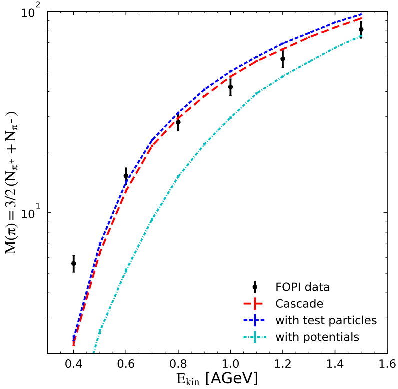

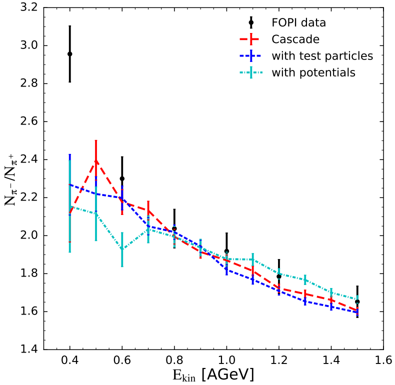

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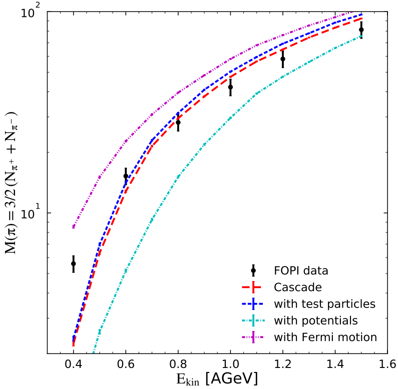

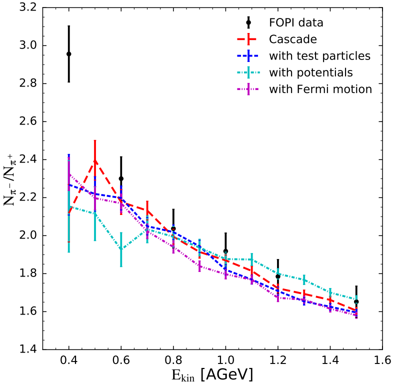

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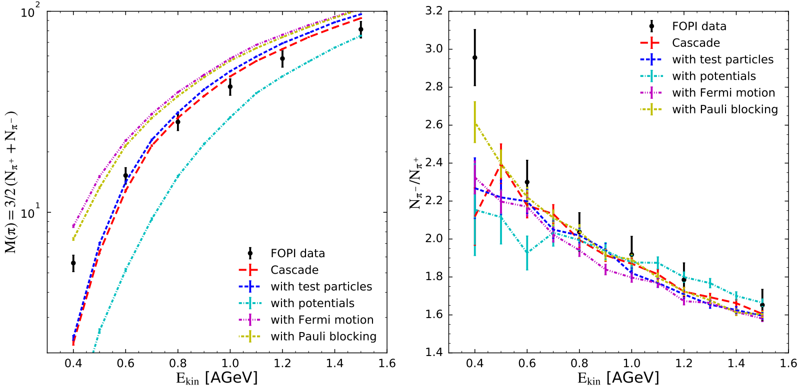
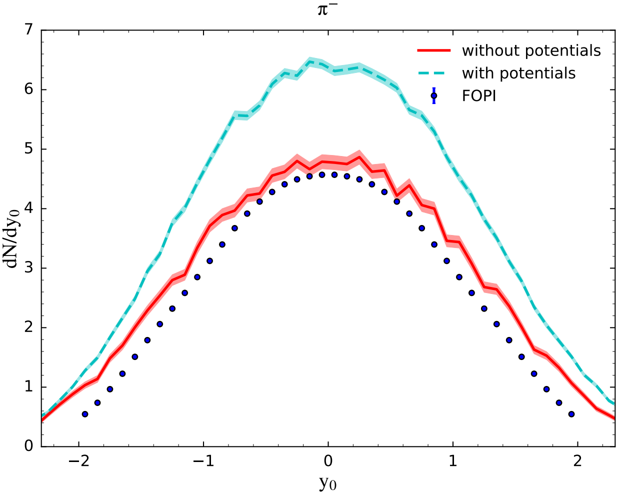


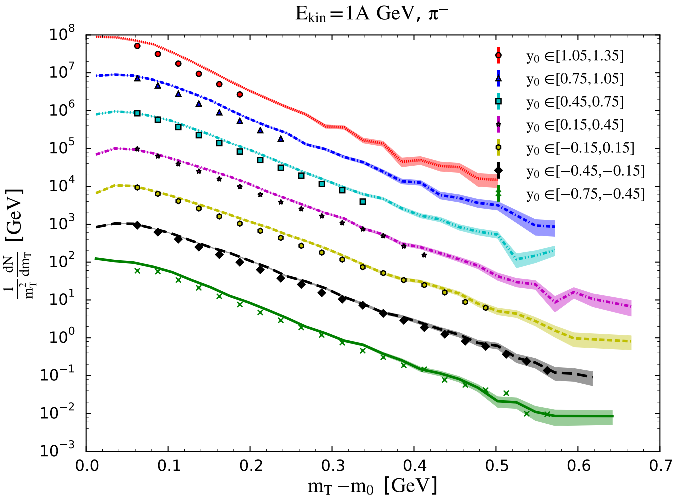
- Ratio reproduced, but total number overestimated
- Likely due to missing in-medium corrections to cross sections

FOPI rapidity spectra in AuAu at $E_{\text{kin}} = 0.8A\,\text{GeV}$



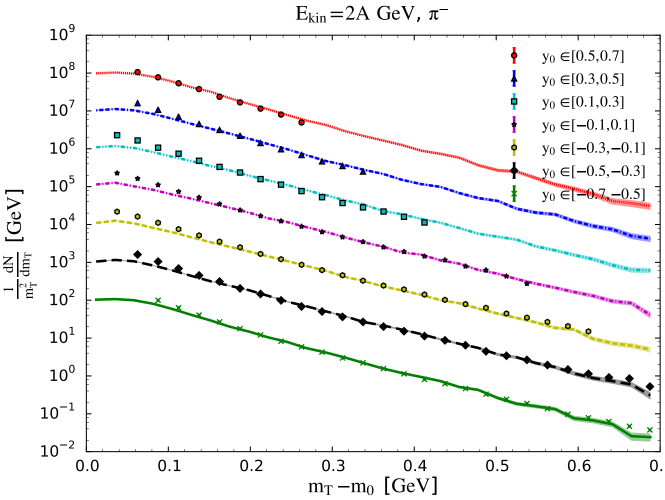
- Overestimation consistent with previous plot; correct shape

HADES transverse mass spectra in CC at $E_{kin} = 1A$ GeV



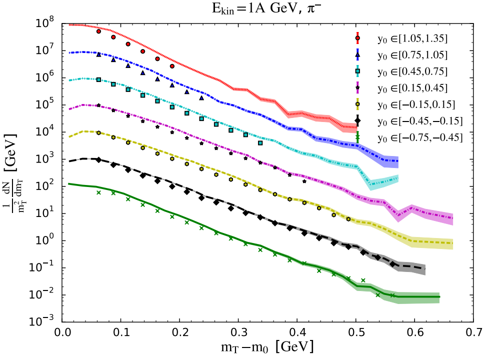
- Overestimation at high rapidities

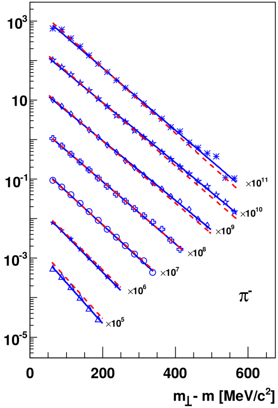
HADES transverse mass spectra in CC at $E_{\text{kin}} = 2A$ GeV



- Underestimation at mid rapidity and low m_T

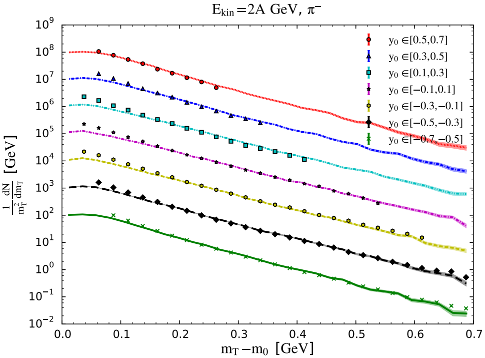
HADES transverse mass spectra vs. UrQMD (1A GeV)

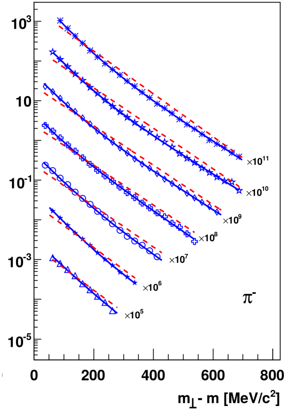




Agakishiev et al, Eur.Phys.J. A40 (2009) 45-59

HADES transverse mass spectra vs. UrQMD (2A GeV)





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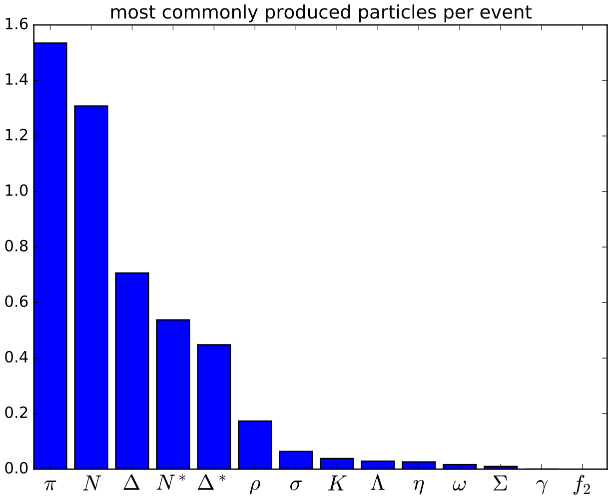
HADES pion beam

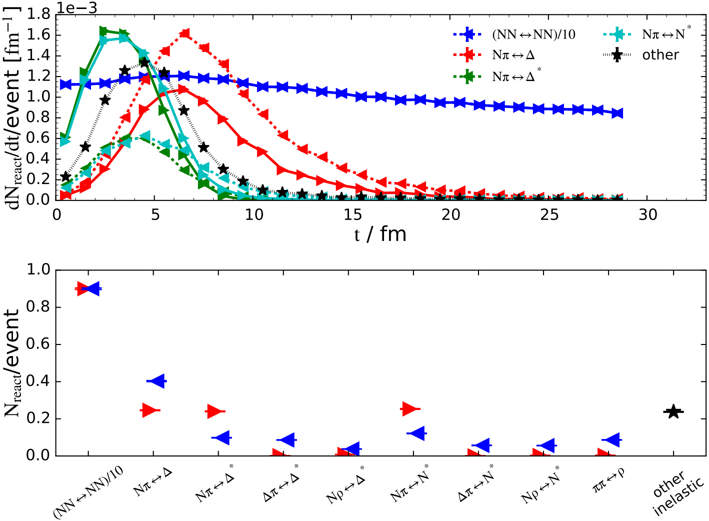
- Upcoming HADES data: $\pi^- C$ (and $\pi^- W$) collisions at $E_{\text{kin}} = 1.7\,\text{GeV}$
- Corresponds to $\sqrt{s} \approx 2.1\,\text{GeV}$,
  requires heavy N^* resonances for $\pi^- p$ cross section
  (little experimental data on branching ratios)

Pion beam: predicted particle production



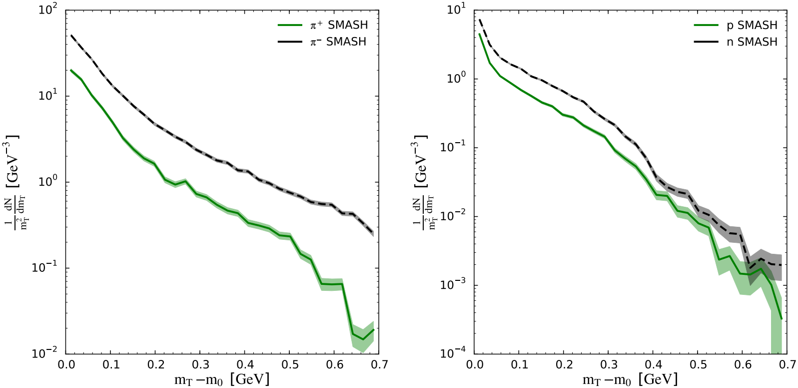
- Good statistics for strangeness

Predicted reactions in $\pi^- C$ at $E_{kin} = 1.7\,\text{GeV}$



- Δ^* and N^* produced before Δ; no equilibrium

HADES transverse mass spectra in π^-C at $E_{\mathrm{kin}} = 1.7\,\mathrm{GeV}$



Summary and outlook

- SMASH reproduces experimental pion multiplicities and momentum spectra at low energies fairly well
- Extensible implementation of hadronic transport
- Work in progress:
  - Strangeness
  - String fragmentation
  - Photons
- Future work:
  - Interface to hydro
  - Many-particle interactions, stochastic rates

The SMASH team

Currently:

- Hannah Petersen (group leader)
- Janus Weil, Long-Gang Pang, Juan M. Torres-Rincon (postdocs)
- Dima Oliinychenko, Jean-Bernard Rose, V.S. (PhD students)
- Anna Schäfer, Jan Staudenmeyer, Markus Mayer, Christian Schwarz (master students)
- Niklas Ehlert, Justin Mohs, Ömür Erkiner, Niklas Cichutek (bachelor students)

Previously:

- Max Attems, Jussi Auvinen, Björn Bäuchle, Matthias Kretz, Marcel Lauf