SMASH - A new hadron transport approach for heavy ion collisions

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HELMHOLTZ ASSOCIATION

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

Outline

- Overview of the SMASH project
- Comparison to HADES and FOPI results
  - Gold-gold at $E_{\text{lab}} \in [0.4, 1.5] A\,\text{GeV}$
  - Carbon-carbon at $E_{\text{lab}} \in \{1, 2\} A\,\text{GeV}$
  - Rapidity and transverse mass spectra
- Predictions for HADES pion beam
  - $\pi^- p$ at $E_{\text{lab}} = 1.7\,\text{GeV}$
  - Reaction rates and particle production
  - Transverse mass spectra

Transport Approach: Big Picture

- Microscopic simulation of hadronic reactions
- Solve relativistic Boltzmann equation:

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

- Each particle represented by a number of point-like test particles
- Use Gaussian wave packets when calculating thermodynamic quantities

The SMASH Team

Currently:

- Hannah Petersen (group leader)
- Janus Weil, Long-Gang Pang (postdocs)
- Dima Oliinychenko, Jean-Bernard Rose, Vinzent Steinberg (PhD students)
- Anna Schäfer, Jan Staudenmeyer, Markus Mayer (master students)

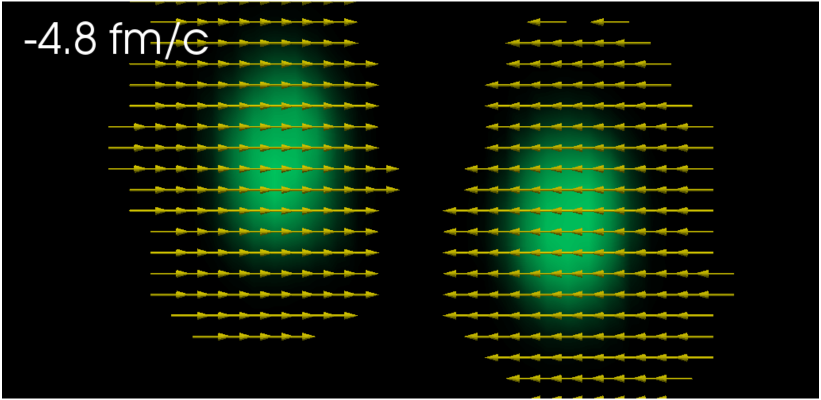
Previously:

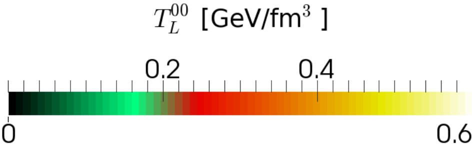
- Max Attems, Jussi Auvinen, Björn Bäuchle, Matthias Kretz, Marcel Lauf

Motivation

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

Movie: Energy Density and Velocity in *CuCu* collision



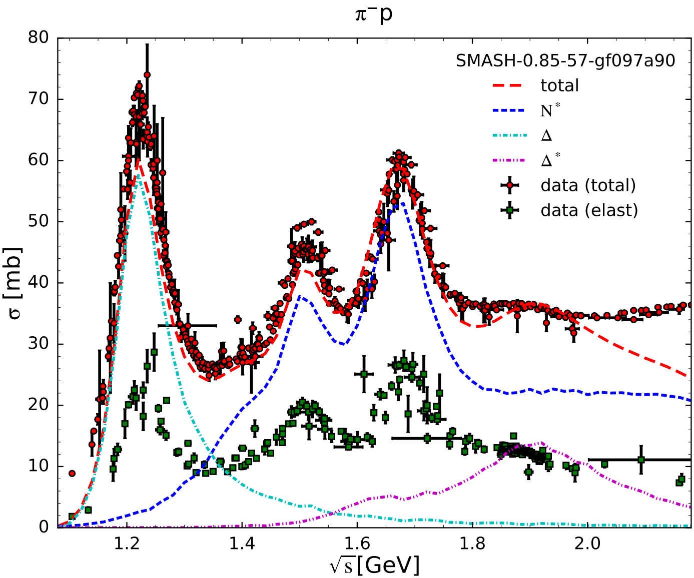


$\sqrt{s} = 3A\,\mathrm{GeV} \quad b = 3\,\mathrm{fm}$

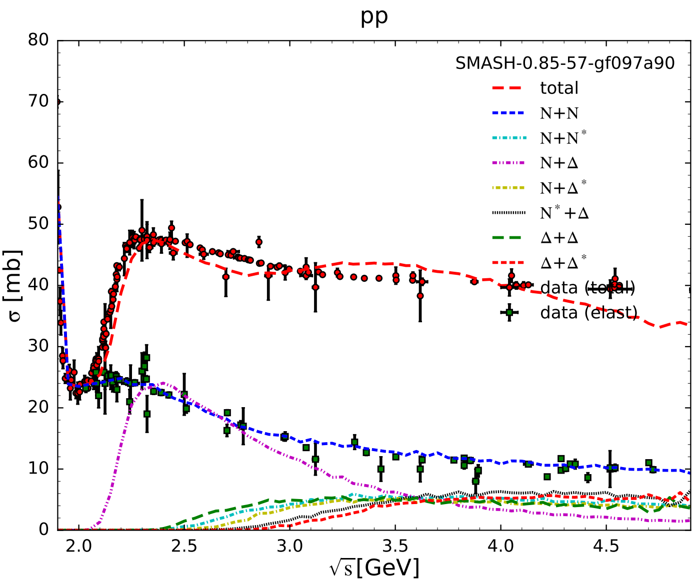
Implemented Particles

- 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

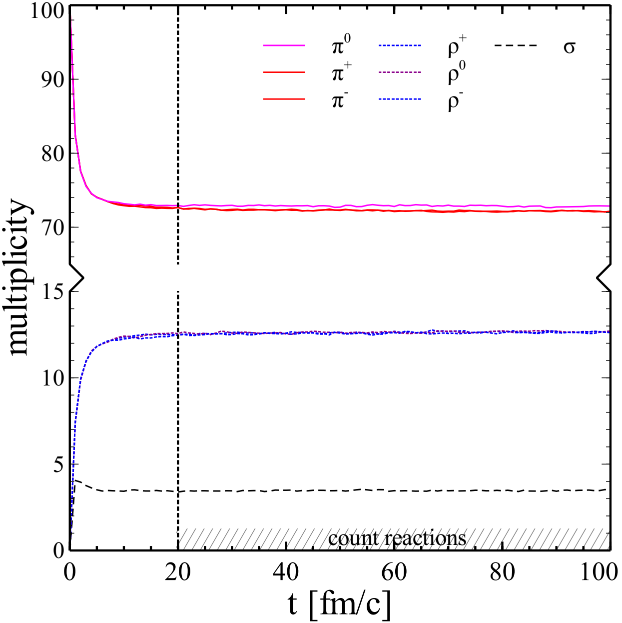
Cross Sections



Cross Sections



Detailed Balance: $\pi\rho\sigma$ Box



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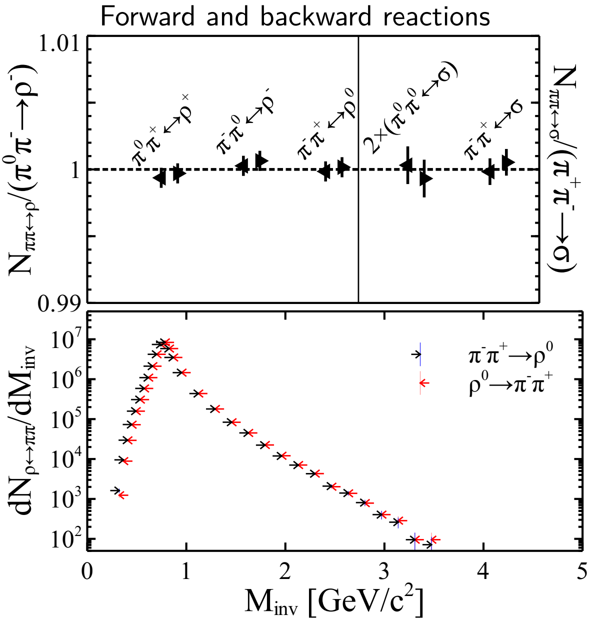


FOPI Measurements

- Gold-gold collisions at various energies
- Centrality selections using energy-ratio cuts

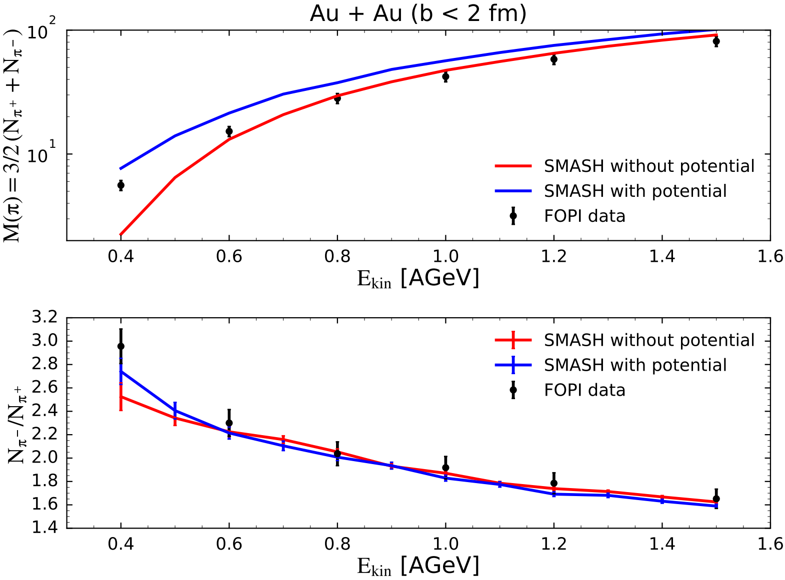
$$ERAT = \frac{E_T}{E_L} = \frac{\sum_i p_{Ti}^2/(m_i + E_i)}{\sum_i p_{Li}/(m_i + E_i)} \quad (2)$$

- Normalized rapidity:

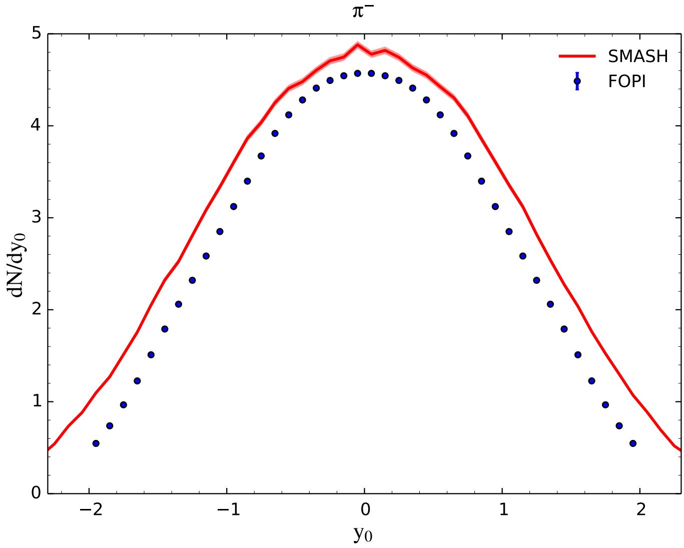
$$y_0 = \frac{y - y_{cm}}{y_{cm}} \quad (3)$$

- Simulated with SMASH
  (with and without Skyrme potential, Fermi motion, Pauli blocking)

FOPI Pion Production



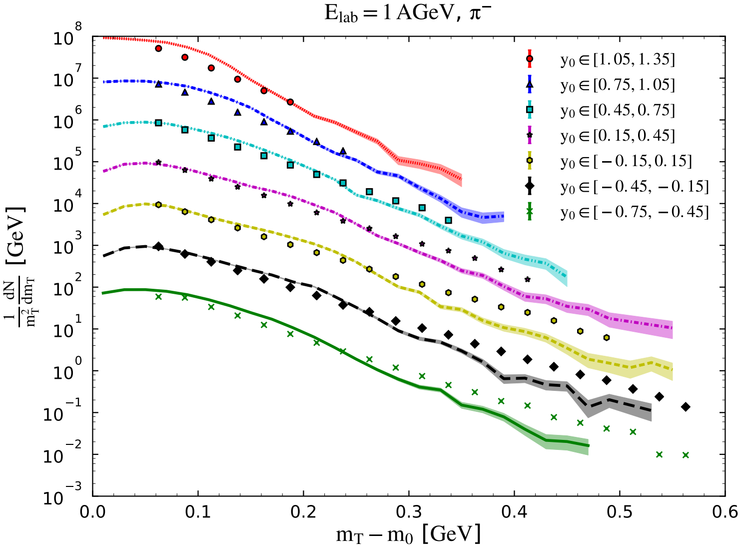
FOPI Rapidity Spectra at $E_{\text{lab}} = 0.8A\,\text{GeV}$



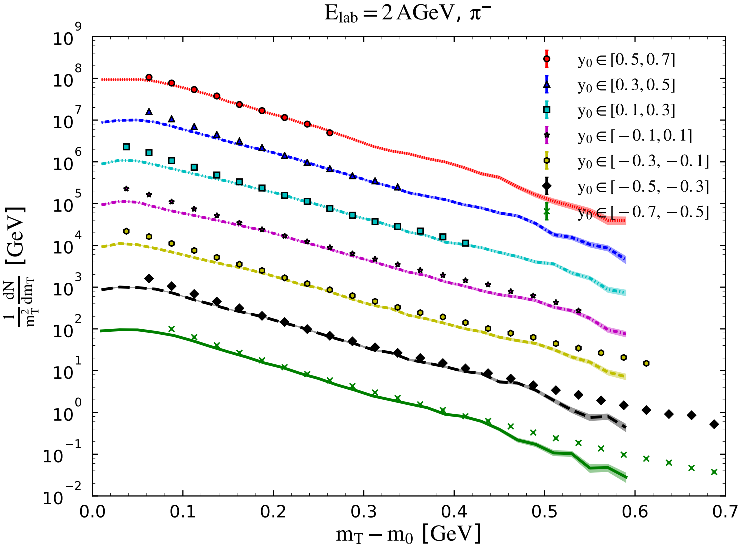
HADES Measurements

- Carbon-carbon collisions at $E_{\text{lab}} \in \{1, 2\}\, A\,\text{GeV}$
- Impact parameter distribution provided by HADES (reconstructed from another transport model)
- Simulated with SMASH (no potentials, no Fermi motion, no Pauli blocking)

HADES Transverse Mass Spectra vs. SMASH (1*A* GeV)



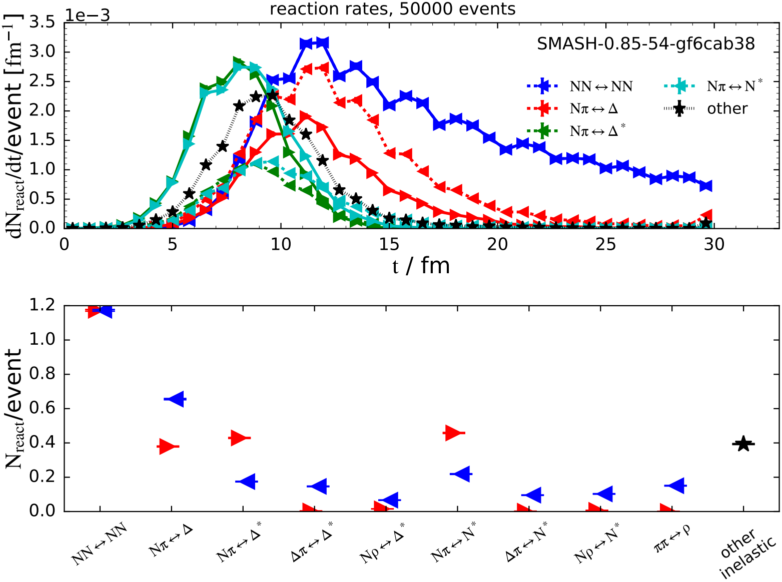
HADES Transverse Mass Spectra vs. SMASH (2*A* GeV)



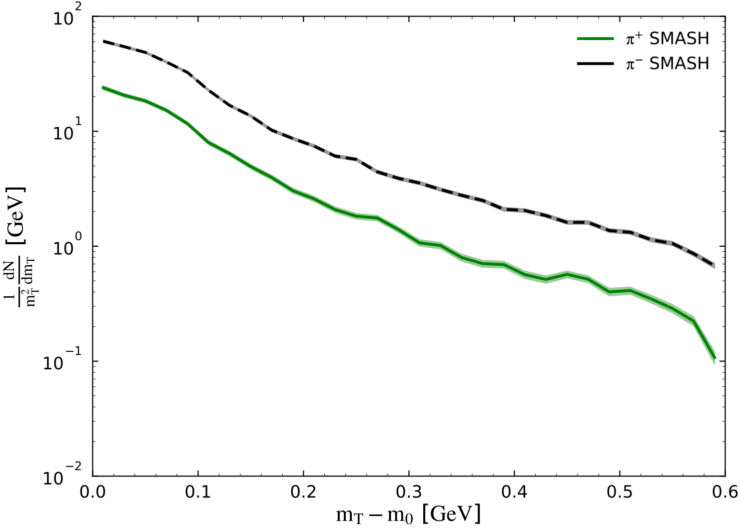
HADES Pion Beam

- Upcoming HADES data: $\pi^- C$ (and $\pi^- W$) collisions at $E_{\text{lab}} = 1.7\,\text{GeV}$
- Corresponds to $\sqrt{s} \approx 2.1\,\text{GeV}$,
  requires heavy N^* resonances for $\pi^- p$ cross section
  (little experimental data on branching ratios)
- Simulated with SMASH for $b \in [0, 2]\,\text{fm}$
- No potentials, no Fermi motion, no Pauli blocking
- Spectators (particles that only interact elastically) are ignored

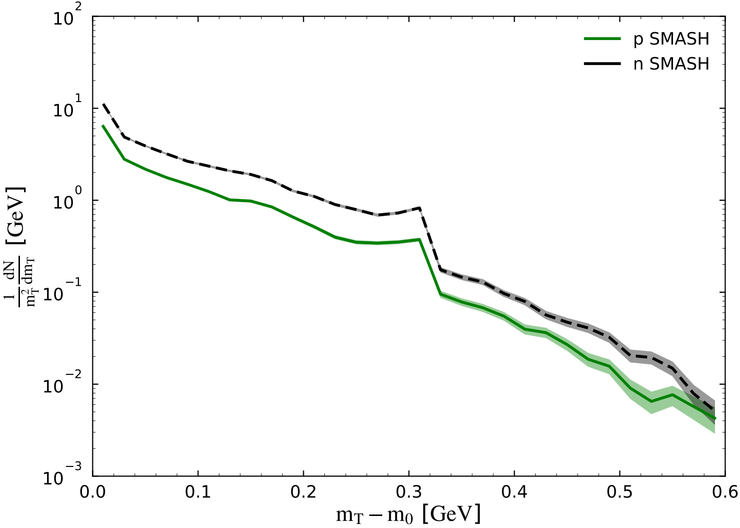
HADES Pion Beam: Predicted Reactions



HADES Pion Beam: Pion Transverse Mass



HADES Pion Beam: Nucleon Transverse Mass



Conclusion

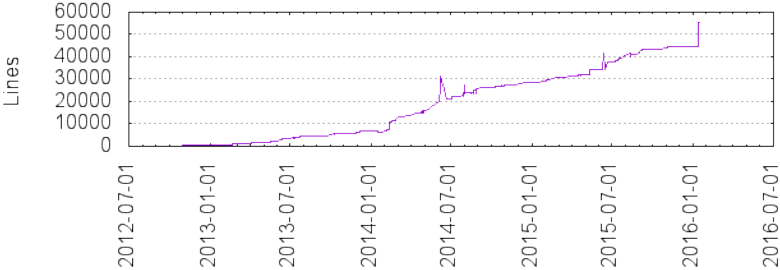
- Clean and future-proof implementation of hadronic transport
- Work in progress:
  - Strangeness
  - String fragmentation
- Future work:
  - Interface to hydro
  - Parallelization
  - Many-particle interactions, stochastic rates

Transport Approach: Reactions

- Inelastic low energy reactions:
  - Resonance excitations and decays
  - Need cross sections and branching ratios
    $\rightarrow$ Data available from PDG, but very little on heavy resonances
- Different options at high energies:
  - String fragmentation (color flux tubes)
  - Hagedorn states

SMASH: Current Status

- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- Roughly three years old
- Ca. 20 000 source lines of code,
  7 active contributors
- Almost feature parity with UrQMD
  (missing: string fragmentation)



I/O and Tests

- Input
  - Configuration file for simulation parameters and options
  - Configuration files for particles and decays
    - Very concise
    - Easy to switch
- Output
  - OSCAR, VTK, ROOT, binary
  - Easy to make movies or analyze in ROOT
- Tests
  - Separate analysis repository for regular consistency tests and comparison to experiment
  - Unit tests to check code correctness

Collision Criterion

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

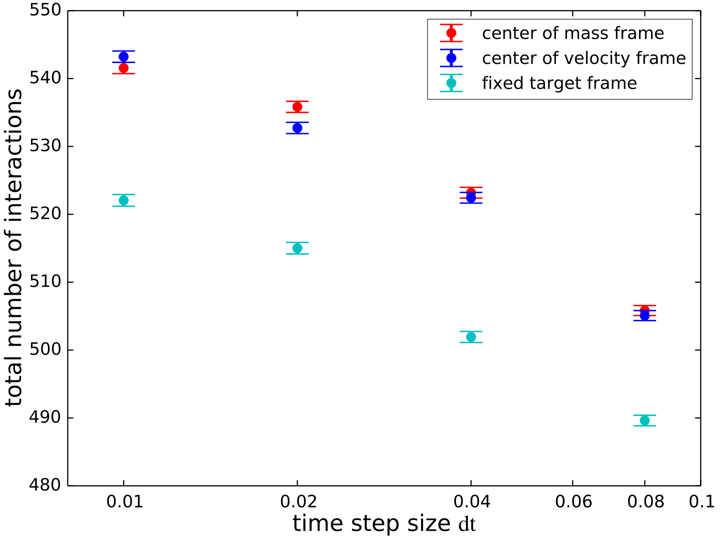
$$d_{\mathrm{trans}} < d_{\mathrm{int}} = \sqrt{\frac{\sigma_{\mathrm{tot}}}{\pi}} \tag{4}$$

$$d_{\mathrm{trans}}^2 = (\vec{r}_a - \vec{r}_b)^2 - \frac{\Big((\vec{r}_a - \vec{r}_b)(\vec{p}_a - \vec{p}_b)\Big)^2}{(\vec{p}_a - \vec{p}_b)^2} \tag{5}$$

$$t_{\mathrm{coll}} = -\frac{(\vec{x}_a - \vec{x}_b)(\vec{v}_a - \vec{v}_b)}{(\vec{v}_a - \vec{v}_b)^2} \tag{6}$$

- Not Lorentz-invariant

Frame Dependence of Particle Production



Decay Width

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

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

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

- 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

- $2 \to 1$ resonance production (Breit-Wigner)

$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)}\mathcal{S}_{ab}\frac{4\pi}{p_{\rm cm}^2}\frac{s\Gamma_{ab\to R}(s)\Gamma_R(s)}{(s-M_0)^2+s\Gamma_R(s)^2} \tag{10}$$

- $2 \to 2$

$$\sigma_{ab\to Rc}(s) = C_I^2\frac{|M|^2_{ab\to Rc}}{64\pi^2 s}\frac{4\pi}{p^i_{\rm cm}}\int dm^2\mathcal{A}(m^2)p^f_{\rm cm} \tag{11}$$

where

$$\mathcal{A}(m) = \frac{1}{\pi}\frac{m\Gamma(m)}{(m^2-M_0^2)^2+m^2\Gamma(m)^2} \tag{12}$$

Skyrme Potentials

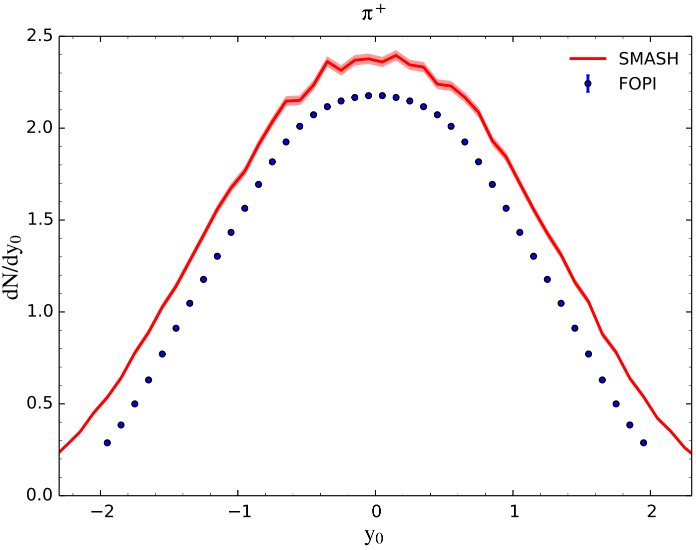
$$U = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2S_{\text{pot}}\frac{\rho_p - \rho_n}{\rho_0}\frac{I_3}{I} \tag{13}$$

$$H_i = \sqrt{\vec{p}_i^2 + m_i^2} + U(\vec{r}_i) \tag{14}$$

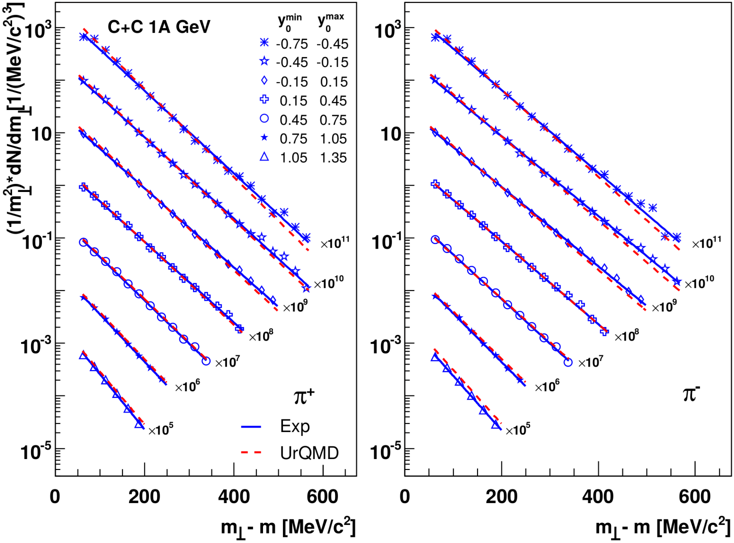
where

$$a = -209.2\,\text{MeV} \quad b = 156.4\,\text{MeV} \quad \tau = 1.53 \quad S_{pot} = 18\,\text{MeV}$$

FOPI Rapidity Spectra at $E_{\mathrm{lab}} = 0.8A\,\mathrm{GeV}$

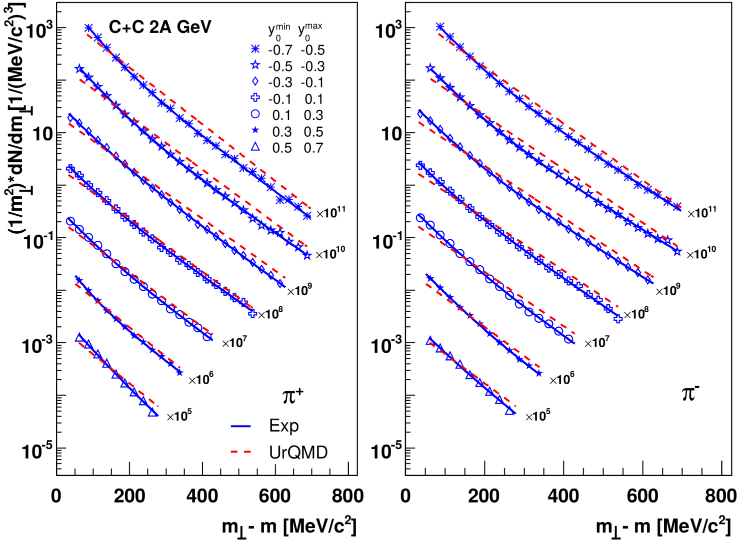


HADES Transverse Mass Spectra vs. UrQMD (1*A* GeV)



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

HADES Transverse Mass Spectra vs. UrQMD (2*A* GeV)



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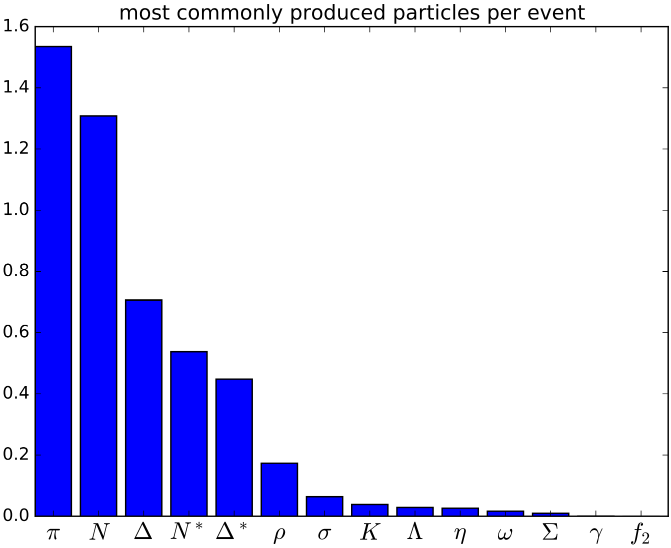
HADES Pion Beam: Predicted Particle Production



HADES Pion Beam: Nucleon Transverse Mass (p Target)