Strangeness production in nucleus-nucleus collisions at SIS energies

Compact Stars in the QCD Phase Diagram VI, Dubna
27.09.2017

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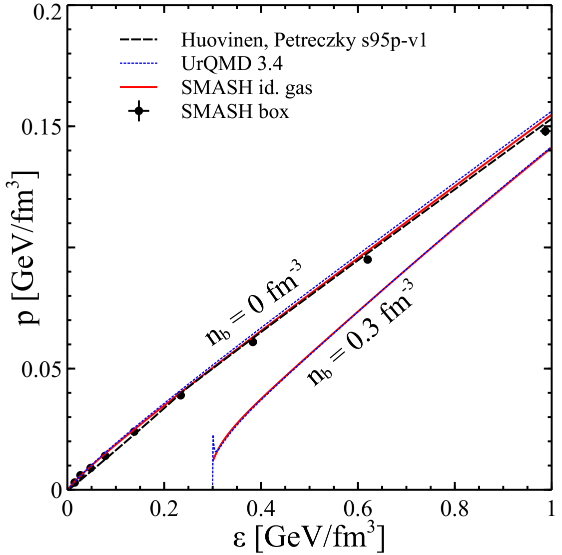
SMASH transport approach

- $2 \leftrightarrow 2$ and $2 \leftrightarrow 1$ hadronic reactions
- 56 meson and 60 baryon species (+ anti particles)
  = most of established hadrons from PDG made of *uds*
- Modi: Nuclear collisions, infinite matter, afterburner for hydro
- Dileptons and photons
- Full ensemble: $N \rightarrow N \cdot N_{\text{test}}$, $\sigma \rightarrow \sigma / N_{\text{test}}$
- Open source code will be published
- Test physics at SIS energies, baseline for future NICA/FAIR predictions

J. Weil et al. In: *Phys. Rev.* C94.5 (2016), p. 054905. arXiv: 1606.06642 [nucl-th]

Equation of state



- SMASH hadron gas vs. UrQMD vs. lattice QCD

Collision finding

- Geometric collision criterion (as used by UrQMD):

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \qquad (1)$$

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

$$t_{\text{coll}} = -\frac{(\vec{x}_a - \vec{x}_b)(\vec{v}_a - \vec{v}_b)}{(\vec{v}_a - \vec{v}_b)^2} \qquad (3)$$

- Products of same reaction are forbidden to collide again
- Grid with cell size $\sqrt{\sigma_{\text{max}}/(\pi N_{\text{test}})}$ for collision finding

Comparison to exact solution of Boltzmann equation

- Boltzmann equation in curved spacetime

$$p^\mu \frac{\partial f(x,p)}{\partial x^\mu} + p_\lambda p^\mu \Gamma^\lambda_{\mu i} \frac{\partial f(x,p)}{\partial p_i} = C(f) \qquad (4)$$

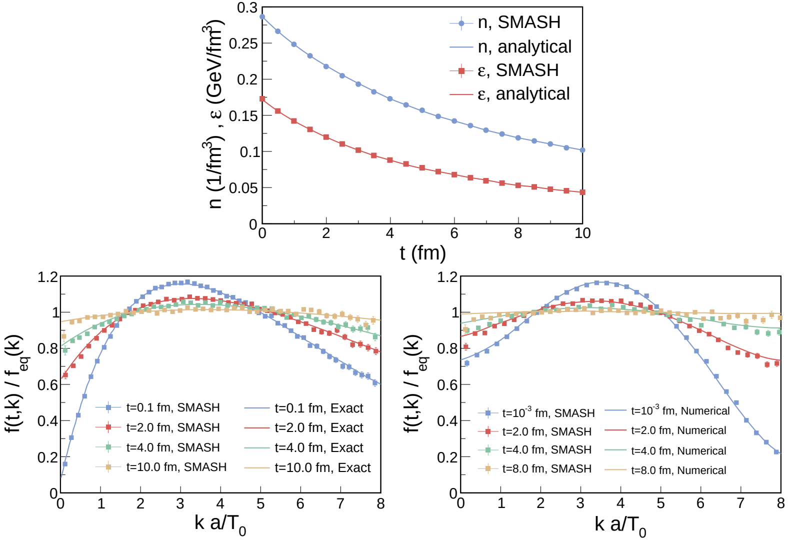
- Expanding universe with Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = dt^2 - a(t)^2(dx^2 + dy^2 + dz^2) \qquad (5)$$

- Infinite gas of massless particles with constant elastic cross section
- An analytic solution exists

D. Bazow et al. In: *Phys. Rev.* D94.12 (2016), p. 125006. arXiv: 1607.05245 [hep-ph]

Comparison to exact solution of Boltzmann equation



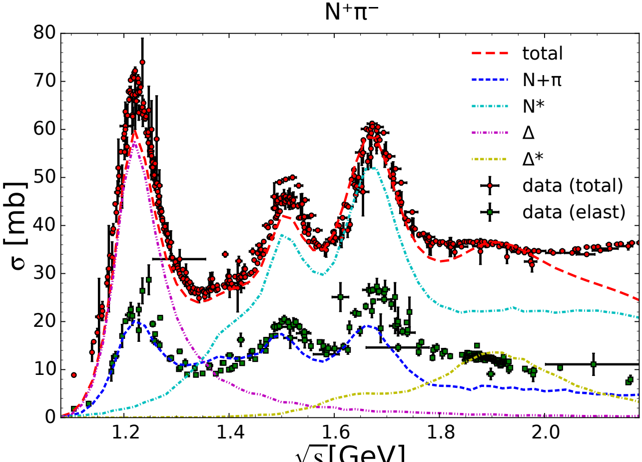
J. Tindall et al. In: *Phys. Lett.* B770 (2017), pp. 532–538. arXiv: 1612.06436 [hep-ph]

Hadronic interaction via resonances

- 106 hadron species $\Rightarrow$ 10 000s of possible pairs (most cross sections never measured)
- Calculate $1 \leftrightarrow 2$ cross section from resonance masses, decay widths and branching ratios
- Approximations: $M \rightarrow N$ by cascading $1 \leftrightarrow 2$ and isospin symmetry
- Maintains detailed balance
- Problems: Branching ratios only sparsely known, some reactions not resonant, limited in energy
- Use measured elementary cross section to additionally constrain branching ratios

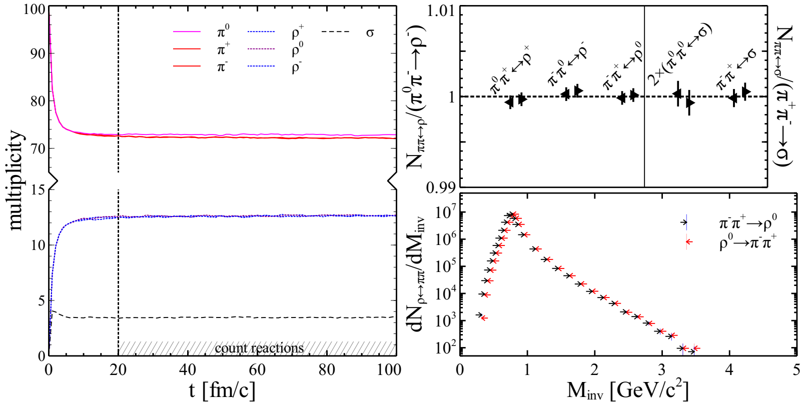
Cross section in SMASH

- Calculated from resonance masses, decay widths and branching ratios
- Parametrization of experimental data for non-resonant cross sections

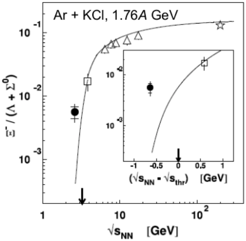


Test detailed balance in a $\pi\rho\sigma$ box

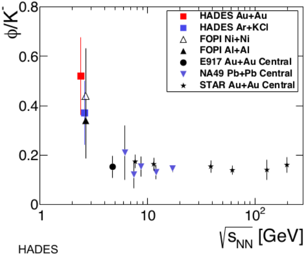
- Initialize periodic box with pions
- Wait until it equilibrates
- Count and compare number of forward and backward reactions



Strangeness in heavy-ion collisions



HADES
PRL **103** (2009) 132301



HADES
arXiv:1703.08418

- Strangeness produced during heavy-ion collision
  $\Rightarrow$ interesting probe for studying evolution of the reaction
- High ϕ, Ξ measured by HADES $\rightarrow$ sub-threshold strangeness enhancement
- KN potentials? In-medium cross sections?
- Production mechanism in equilibrium (thermal model) and non-equilibrium (resonances)?

See Christoph Blume's talk at SQM 2017

Strangeness production via resonances in SMASH

- Kaons and 11 kaonic resonances (+ anti particles)
- Λ, Σ, Ξ, Ω and 28 resonances (+ anti particles)
- K^+ production ($Y \in \{\Lambda, \Sigma\}$):

$$NN \to NN^*/\Delta^* \to NYK \tag{6}$$

- K^- production:

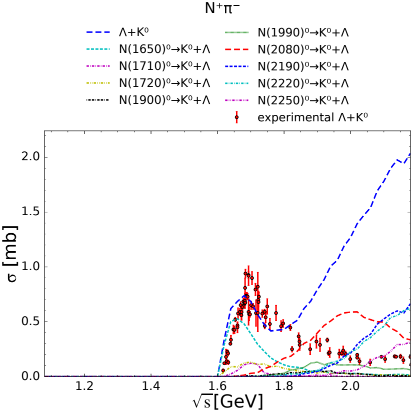
$$NN \to N^*/\Delta^* ... \to Y ... \to Y^* ... \to \bar{K} ... \tag{7}$$
$$\pi Y \leftrightarrow \bar{K} N \tag{8}$$

- Strangeness exchange (8) absorbs K^-

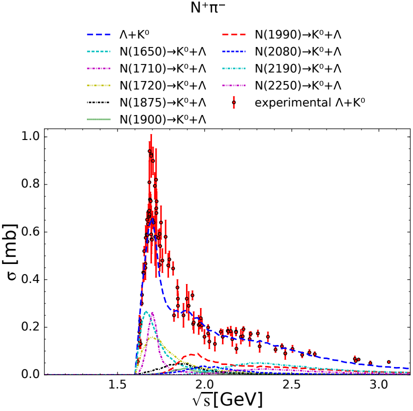
G. Graef et al. In: *Phys. Rev.* C90 (2014), p. 064909. arXiv: 1409.7954 [nucl-th]

Tuning branching ratios

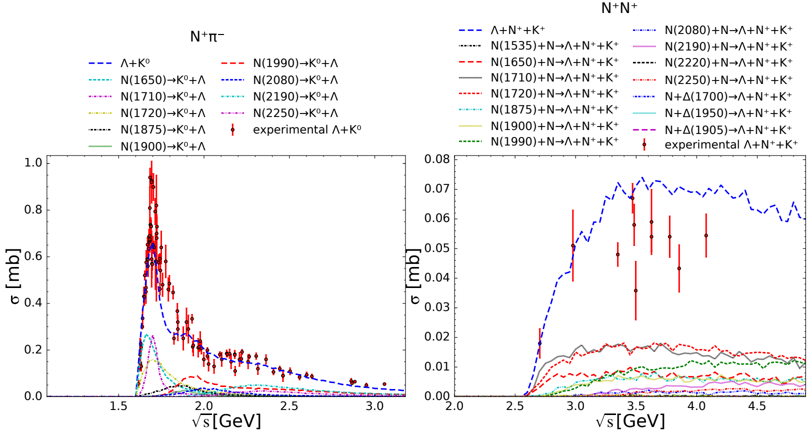
before



after

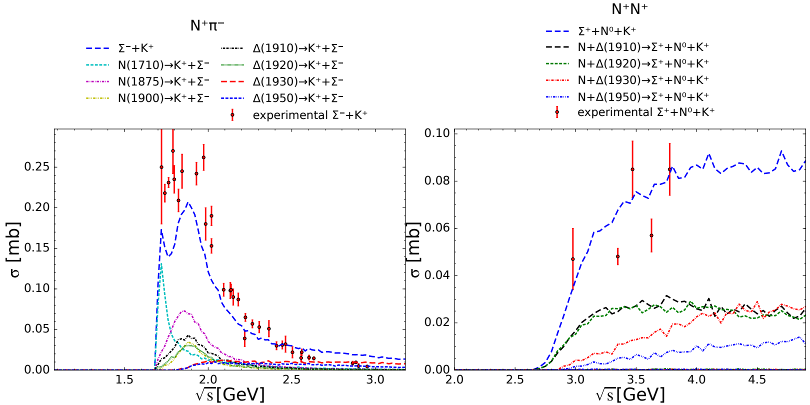


Λ production



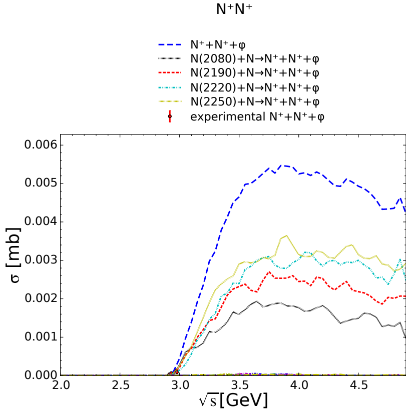
- Relevant branching ratios: $N^* \to \Lambda K, \pi N$

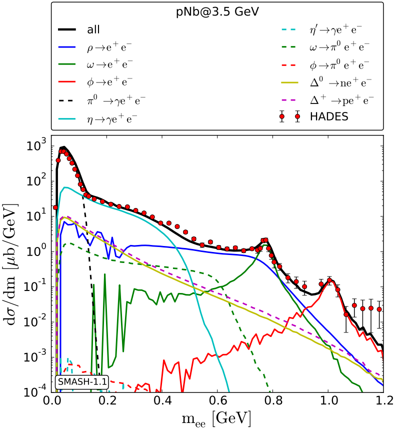
Σ production



- Relevant branching ratios: $N^*, \Delta^* \to \Sigma K, \pi N$

ϕ production

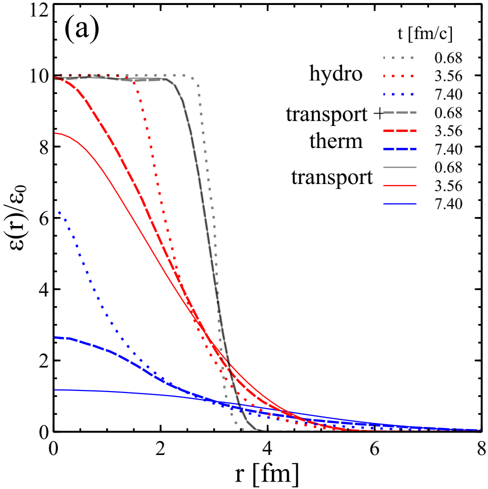




- $pp \to pp\phi \to ppK^+\bar{K}^-$ only measured at theshold
- ϕ production not well constrained by cross section
- Significant ϕ peak in p Nb dileptons
- Model ϕ production via $N^*(> 2000) \to N\phi$

J. Steinheimer et al. In: *J. Phys.* G43.1 (2016), p. 015104. arXiv: 1503.07305 [nucl-th]

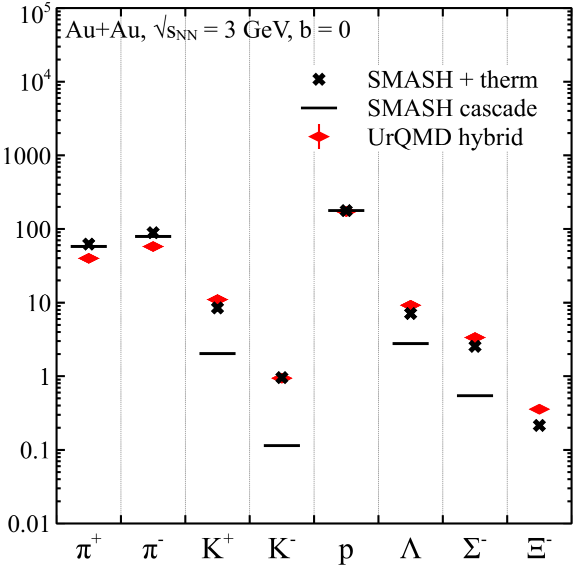
Particle production with forced thermalization



- Force thermalization in regions of high density by resampling particles
- Local, not global
- Effective many-particle scattering
- Similar to hydro-hybrid model, but more dynamic

D. Oliinychenko et al. In: *J. Phys.* G44.3 (2017), p. 034001. arXiv: 1609.01087 [nucl-th]

Forced canonical thermalization vs. cascade + hydro

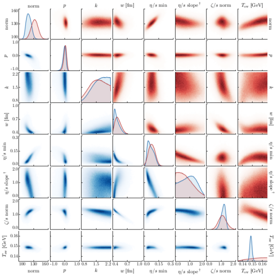


- Strangeness enhancement comparable to hybrid approach

Conclusion

- Elementary K, Λ, Σ, ϕ production at low energies can be reasonably modeled via resonances
- Dilepton data for p Nb constrains ϕ production
- Effective many-particle interactions by forced thermalization enhance strangeness production

Outlook



J. E. Bernhard et al. In: *Phys. Rev.* C94.2 (2016), p. 024907. arXiv: 1605.03954 [nucl-th]

- Future work: use Bayesian modeling for tuning branching ratios
- Higher energies require string fragmentation
- More detailed comparisons of resonance approach and forced thermalization are planned

Resonances in SMASH

- Breit-Wigner spectral function

$$\mathcal{A}(m) = \frac{2N}{\pi} \frac{m^2\Gamma(m)}{(m^2 - m_0^2)^2 + m^2\Gamma(m)^2} \tag{9}$$

- Manley-Saleski ansatz[1] for off-shell decay branching ratio

$$\Gamma_{R\to ab} = \Gamma^0_{R\to ab} \frac{\rho_{ab}(m)}{\rho_{ab}(m_0)} \tag{10}$$

$$\rho_{ab}(m) = \int dm_a dm_b\, \mathcal{A}_a(m_a)\mathcal{A}_b(m_b) \frac{p_f}{m} B_L^2(p_f R)\mathcal{F}_{ab}^2(m) \tag{11}$$

- Post form factor[2] for unstable decay products

$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + (s_0 - m_0^2)^2/4}{\lambda^4 + \left(m^2 - (s_0 + m_0^2)/2\right)^2} \tag{12}$$

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[1] D. M. Manley et al. *Phys. Rev.* D45 (1992), pp. 4002–4033.

[2] M. Post et al. *Nucl. Phys.* A741 (2004), pp. 81–148. arXiv: `nucl-th/0309085`.

Cross sections in SMASH

- $2 \to 1$ resonance production

$$\sigma_{ab\to R}(s) = \frac{2J_R + 1}{(2J_a + 1)(2J_b + 1)} \mathcal{S}_{ab} \frac{2\pi^2}{p_i^2} \Gamma_{ab\to R}(s) \mathcal{A}(\sqrt{s}) \tag{13}$$

- $2 \to 2$ resonance production

$$\begin{aligned} \sigma_{ab\to Rc}(s) = &\sum_I \left(C_{ab}(I) C_{Rc}(I)\right)^2 \frac{|M|^2_{ab\to Rc}(s, I)}{16\pi} \\ &\times \frac{(2J_R + 1)(2J_c + 1)}{s\, p_i} \frac{4\pi}{p^i_{\text{cm}}} \int dm \mathcal{A}(m) p_f \end{aligned} \tag{14}$$

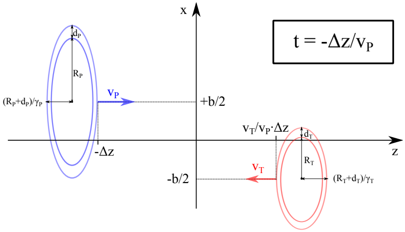
- Can model most cross sections like this,
  some have to be parametrized instead

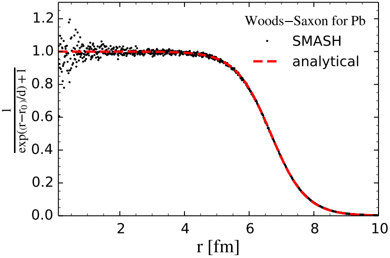
Modifying particle species and decay modes in SMASH

```
# NAME MASS[GEV] WIDTH[GEV] PDG

########## unflavored mesons ##########

               0.138   7.7e-9      111     211
               0.548   1.31e-6     221
               0.800   0.400   9000221
               0.776   0.149       113     213
               0.783   8.49e-3     223
’              0.958   1.98e-4     331
f(980)         0.990   0.070   9010221
...

########## N baryons ###################

N       0.938 0         2112    2212
N(1440) 1.462 0.350    12112   12212
N(1520) 1.515 0.115     1214    2124
N(1535) 1.535 0.150    22112   22212
N(1650) 1.655 0.140    32112   32212
N(1675) 1.675 0.150     2116    2216
```

```
N(1440)
0.60   1  N
0.24   1
0.16   0  N

N(1520)
0.65   2  N
0.10   0
0.10   2
0.15   0  N

N(1535)
0.50   0  N
0.40   0  N
0.06   0  N(1440)
0.02   0  N
0.02   0  N

N(1650)
0.69   0  N
0.10   0  N
0.08   0   K
0.01   0  N
0.12   2  N
```

Nucleus collision





- Woods-Saxon distribution

$$\frac{dN}{dr} = \frac{\rho_0}{\exp(\frac{r-r_0}{d}) + 1} \tag{15}$$

- Deformed nuclei

Fermi motion

- Local density approximation

$$p_F(\vec{r}) = \hbar c \sqrt[3]{3\pi^2 \rho(\vec{r})} \tag{16}$$

- Sample momenta p_i from Fermi sphere in nucleus rest frame
- Boost Fermi momenta to calculation frame

$$p'_{iz} = \gamma(p_{iz} + \beta E_i) = \gamma p_{iz} + \frac{p_A}{A} \tag{17}$$

- Without potentials:
  Ignore Fermi motion for propagation until first interaction

Skyrme and symmetry potential

$$U = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2S_{\text{pot}}\frac{\rho_p - \rho_n}{\rho_0}\frac{I_3}{I} \tag{18}$$

$$H_i = \sqrt{\vec{p}_i^2 + m_i^2} + U(\vec{r}_i) \tag{19}$$

where

$$a = -209.2\,\text{MeV} \quad b = 156.4\,\text{MeV} \quad c = 1.35 \quad S_{\text{pot}} = 18\,\text{MeV} \tag{20}$$

- Nucleus-nucleus only
- Soft potential with incompressibility $K_0 = 240\,\text{MeV}$
- Makes nucleus stable despite Fermi motion

Pauli blocking

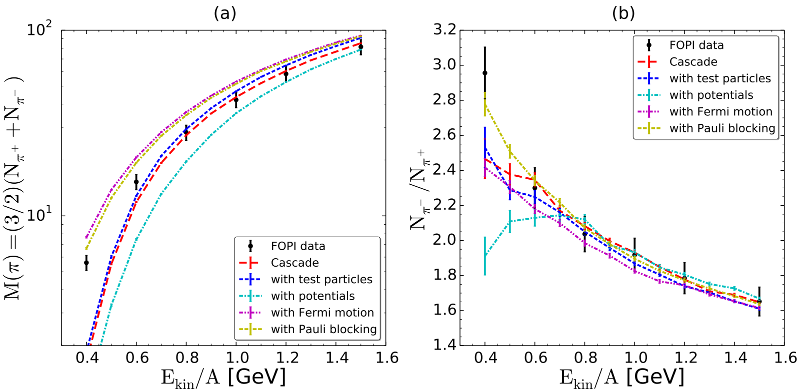
- Collision integral in Boltzmann-Uehling-Uhlenbeck equation

$$C(f) = \frac{1}{2} \int \frac{d^3 p_2}{E_2} \frac{d^3 p_1'}{E_1} \frac{d^3 p_2'}{E_2'} W(p_1, p_2, p_1', p_2') \times \left(f_1' f_2' (1 \pm f)(1 \pm f_2) - f f_2 (1 \pm f_1')(1 \pm f_2') \right) \tag{21}$$

- Pauli blocking and Bose enhancement
- Reject reactions with probability

$$P = 1 - \prod_{\text{final state fermion } i} (1 - f_i) \tag{22}$$

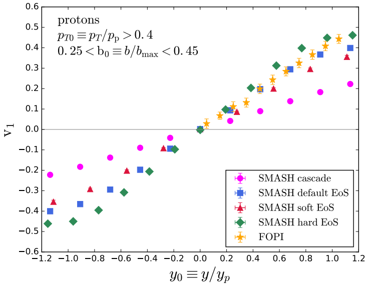
Pion production in central gold-gold collisions

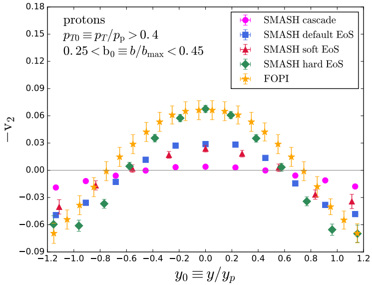


W. Reisdorf et al. In: *Nucl. Phys.* A781 (2007), pp. 459–508. arXiv: `nucl-ex/0610025`

- Yield overestimated, but ratio reproduced
- FOPI pion multiplicities sensitive to nucleonic potentials and Pauli blocking

Flow in gold-gold collisions at $E_{\text{kin}} = 1A$ GeV





- Sensitive to parameters of nucleonic potentials
- Hard equation of state reproduces data best

W. Reisdorf et al. In: *Nucl. Phys.* A876 (2012), pp. 1–60. arXiv: 1112.3180

Analysis suite

- Extensive collection of tests for the model
- Fully automated, checked for every SMASH release
- Consistency checks:
  - Detailed balance: Check equilibrium in thermalized box
  - Elastic box: Comparison to ideal gas expectations
- Comparison to experimental data:
  - Angular distributions: pp, np at $\sqrt{s} \approx 2.5\,\mathrm{GeV}$
  - Elementary cross sections: NN, πN, $\pi\pi$, KN
  - FOPI pions: π multiplicites for $E_{\mathrm{kin}} = 0.4 - 1.5A\,\mathrm{GeV}$
  - Spectra: dN/dy and dN/dm_T for π and p in AuAu at $E_{\mathrm{kin}} = 1.5A\,\mathrm{GeV}$ and CC at $E_{\mathrm{kin}} \in \{1, 2\}A\,\mathrm{GeV}$
- Of interest to other models targeting NICA/FAIR energies?
- Systematic comparison of models?