SMASH: A new hadron transport approach for heavy-ion collisions

Mini-Workshop on simulations of HIC for NICA energies, Dubna
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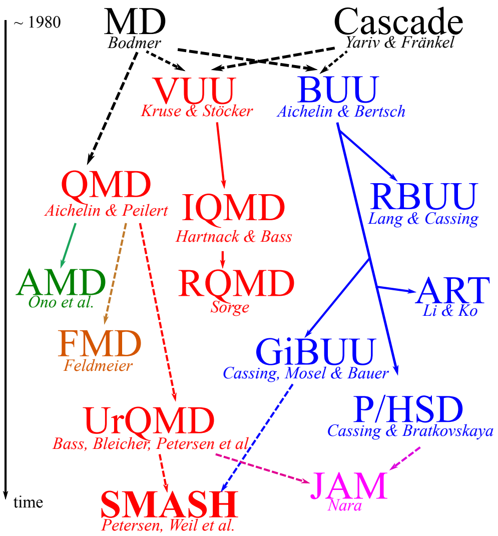
Why develop the *n*-th transport code?



- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- C++ code from scratch, version control, project management
- Extensive and automated tests
- Make it easy to extend and switch physics (e.g. different particles and decay modes)

SMASH transport approach

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

J. Weil et al. In: *Phys. Rev.* C94.5 (2016). arXiv: 1606.06642

Collision finding

- Geometric collision criterion (as used by UrQMD):

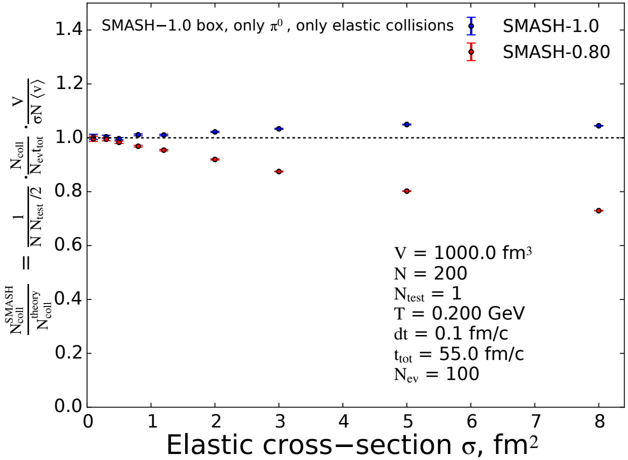
$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \quad (1)$$

$$d_{\text{trans}}^2 = (\vec{r}_a - \vec{r}_b)^2 - \frac{\big((\vec{r}_a - \vec{r}_b)(\vec{p}_a - \vec{p}_b)\big)^2}{(\vec{p}_a - \vec{p}_b)^2} \quad (2)$$

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

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

Elastic box test



- Box with constant elastic cross section
- Compare scattering rate to equilibrium expectation $n\sigma$
- SMASH 1.0: timestepless, SMASH 0.8: timesteps

Comparison to exact solution of Boltzmann equation

- Boltzmann equation in curved spacetime

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

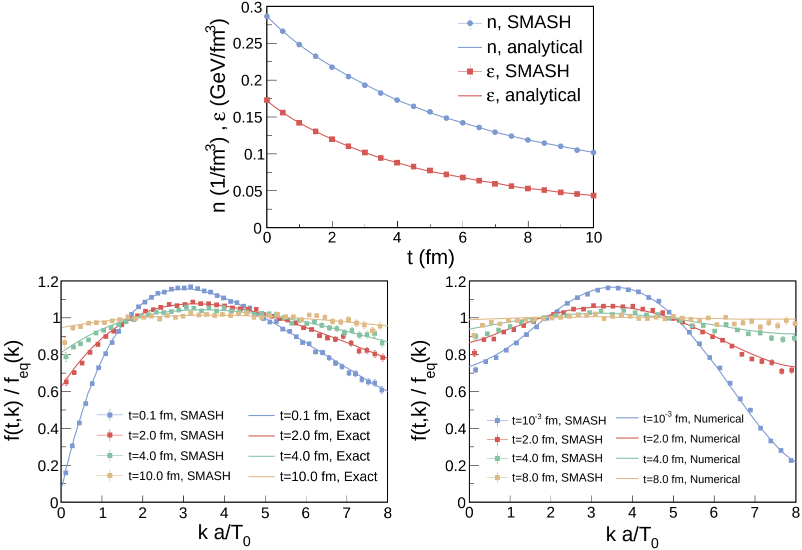
- Expanding universe with Friedmann-Lemaître-Robertson-Walker metric

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

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

D. Bazow et al. In: *Phys. Rev.* D94.12 (2016). arXiv: 1607.05245

Comparison to exact solution of Boltzmann equation



J. Tindall et al. In: (2016). arXiv: 1612.06436

Resonances in SMASH

- Breit-Wigner spectral function

$$\mathcal{A}(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - m_0^2)^2 + m^2 \Gamma(m)^2} \quad (6)$$

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

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

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

- Post form factor[2] for unstable decay products

$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + (s_0 - m_0^2)^2/4}{\lambda^4 + \left(m^2 - (s_0 + m_0^2)/2\right)^2} \quad (9)$$

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[1] D. M. Manley et al. *Phys. Rev.* D45 (1992).

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

Cross sections in SMASH

- $2 \to 1$ resonance production

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

- $2 \to 2$ resonance production

$$\sigma_{ab\to Rc}(s) = \sum_I \left(C_{ab}(I)C_{Rc}(I)\right)^2 \frac{|M|^2_{ab\to Rc}(s,I)}{16\pi} \times \frac{(2J_R+1)(2J_c+1)}{s\,p_i}\frac{4\pi}{p^i_{\mathrm{cm}}}\int dm\mathcal{A}(m)p_f \tag{11}$$

- 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 ##########

π              0.138   7.7e-9       111      211
η              0.548   1.31e-6      221
σ              0.800   0.400    9000221
ρ              0.776   0.149        113      213
ω              0.783   8.49e-3      223
η'             0.958   1.98e-4      331
f₀(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
```

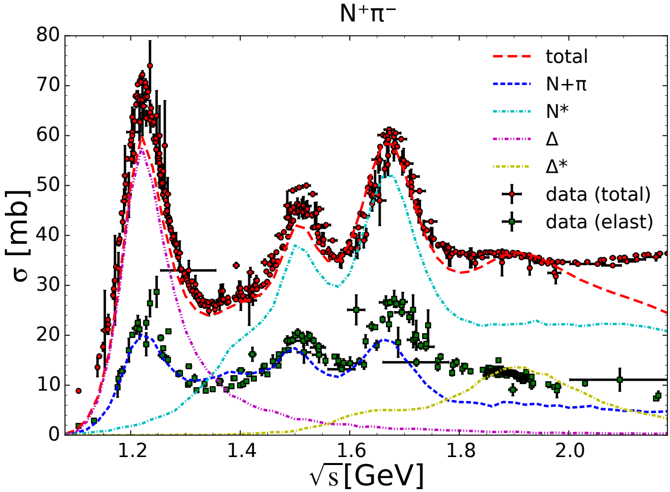
```
N(1440)
0.60   1   N π
0.24   1   Δ π
0.16   0   N σ

N(1520)
0.65   2   N π
0.10   0   Δ π
0.10   2   Δ π
0.15   0   N ρ

N(1535)
0.50   0   N π
0.40   0   N η
0.06   0   N(1440) π
0.02   0   N ρ
0.02   0   N σ

N(1650)
0.69   0   N π
0.10   0   N η
0.08   0   Λ K
0.01   0   N ρ
0.12   2   N ρ
```

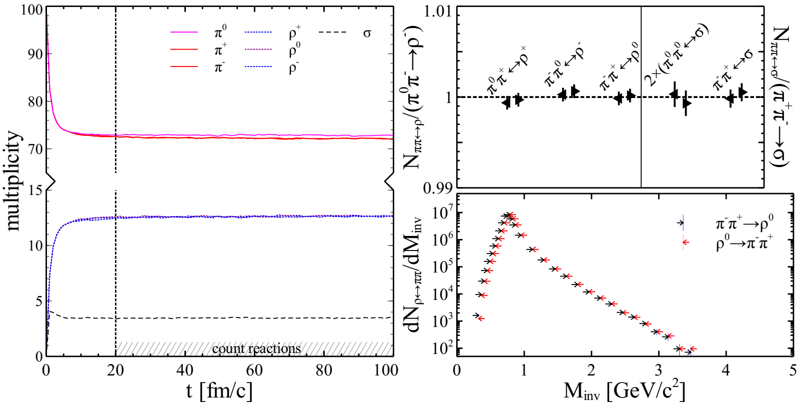
Cross section compared to experiment



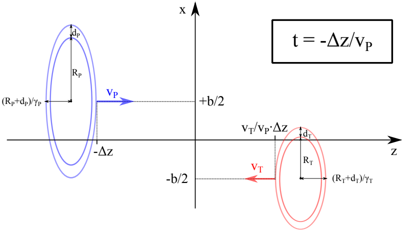
- No parametrization of cross section data necessary (unlike for instance *pp*)

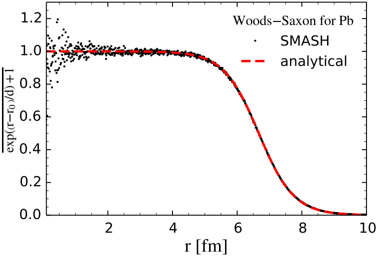
Test detailed balance in a $\pi\rho\sigma$ box

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



Nucleus collision





- Woods-Saxon distribution

$$\frac{dN}{dr} = \frac{\rho_0}{\exp(\frac{r-r_0}{d}) + 1} \tag{12}$$

- Deformed nuclei

Fermi motion

- Local density approximation

$$p_F(\vec{r}) = \hbar c \sqrt[3]{3\pi^2 \rho(\vec{r})} \tag{13}$$

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

$$p'_{iz} = \gamma(p_{iz} + \beta E_i) = \gamma p_{iz} + \frac{p_A}{A} \tag{14}$$

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

Skyrme and symmetry potential

$$U = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2S_{\text{pot}}\frac{\rho_p - \rho_n}{\rho_0}\frac{I_3}{I} \tag{15}$$

$$H_i = \sqrt{\vec{p}_i^2 + m_i^2} + U(\vec{r}_i) \tag{16}$$

where

$$a = -209.2\,\text{MeV} \quad b = 156.4\,\text{MeV} \quad c = 1.35 \quad S_{\text{pot}} = 18\,\text{MeV} \tag{17}$$

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

Pauli blocking

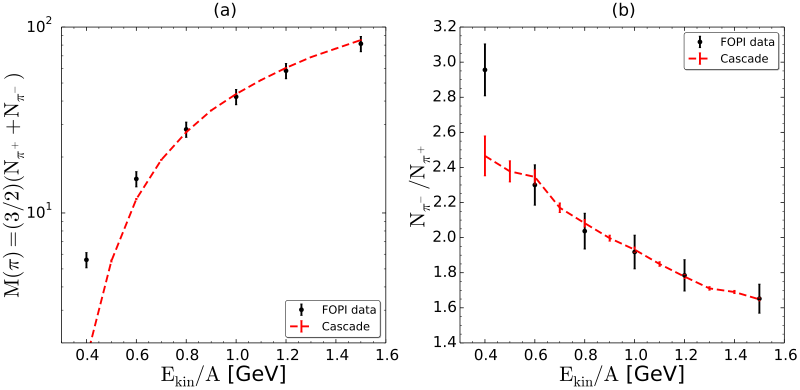
- Collision integral in Boltzmann-Uehling-Uhlenbeck equation

$$C(f) = \frac{1}{2}\int \frac{d^3p_2}{E_2}\frac{d^3p_1'}{E_1}\frac{d^3p_2'}{E_2'} W(p_1, p_2, p_1', p_2') \times \left(f_1' f_2' (1 \pm f)(1 \pm f_2) - f f_2 (1 \pm f_1')(1 \pm f_2')\right) \tag{18}$$

- Pauli blocking and Bose enhancement
- Reject reactions with probability

$$P = 1 - \prod_{\text{final state fermion } i} (1 - f_i) \tag{19}$$

Pion production in central gold-gold collisions



W. Reisdorf et al. In: *Nucl. Phys.* A781 (2007). arXiv: nucl-ex/0610025

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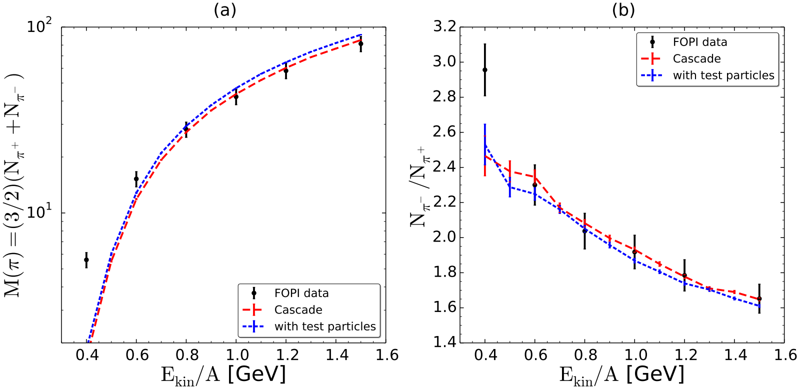

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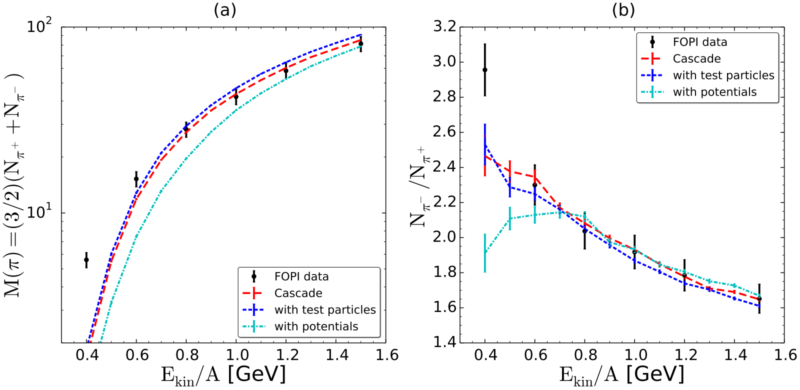

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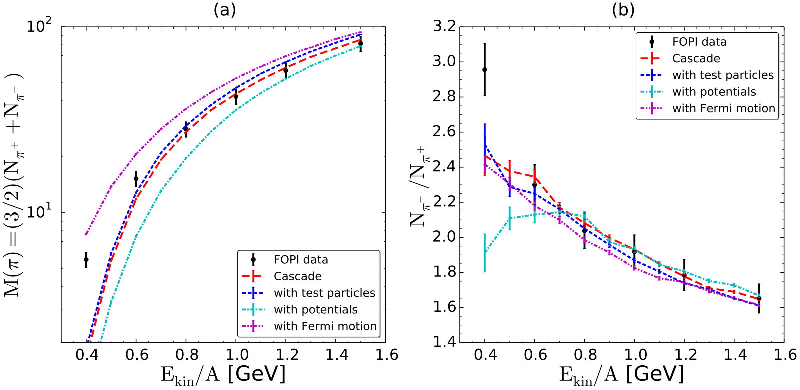

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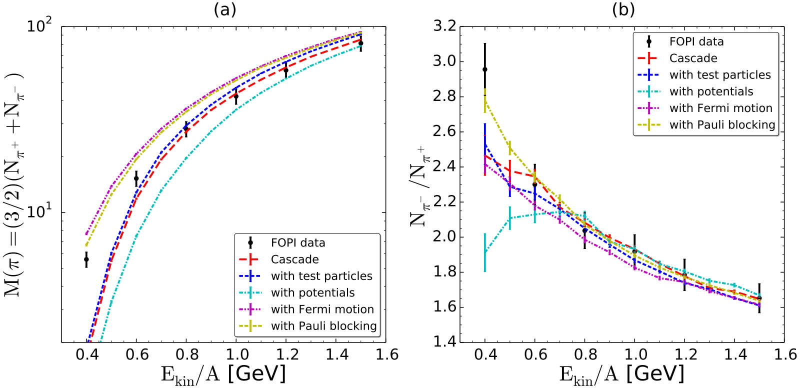

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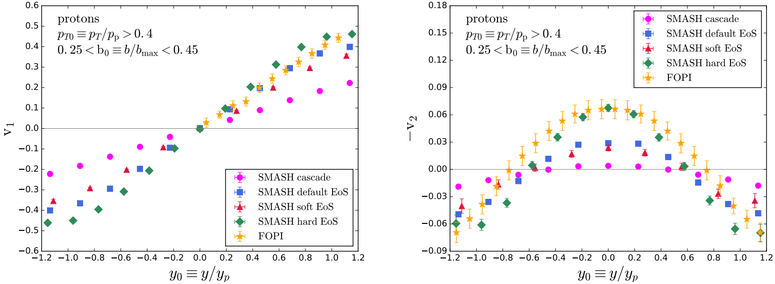
- Yield overestimated, but ratio reproduced
- FOPI pion multiplicities sensitive to nucleonic potentials and Pauli blocking

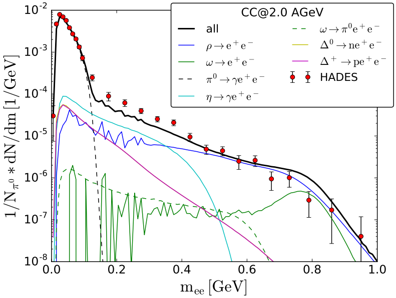
Flow in gold-gold collisions at $E_{\text{kin}} = 1A$ GeV

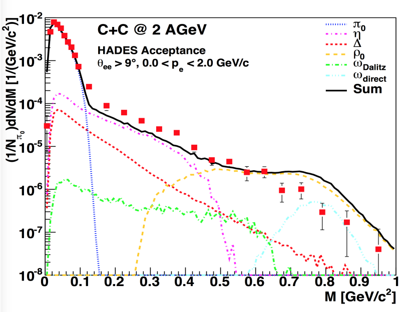


- Sensitive to parameters of nucleonic potentials
- Hard equation of state reproduces data best

W. Reisdorf et al. In: *Nucl. Phys.* A876 (2012). arXiv: 1112.3180

Dileptons in carbon-carbon at $E_{\text{kin}} = 2A$ GeV



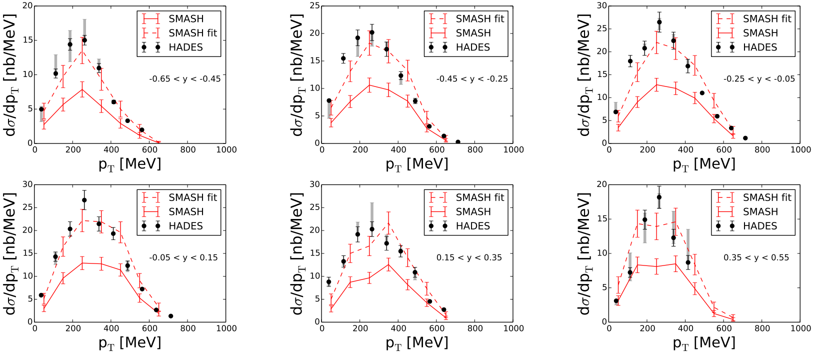


- SMASH and UrQMD compare very similar to HADES data
- Different vector meson thresholds and η yield

G. Agakichiev et al. In: *Phys. Rev. Lett.* 98 (2007). arXiv: nucl-ex/0608031

S. Endres et al. In: *J. Phys. Conf. Ser.* 426 (2013)

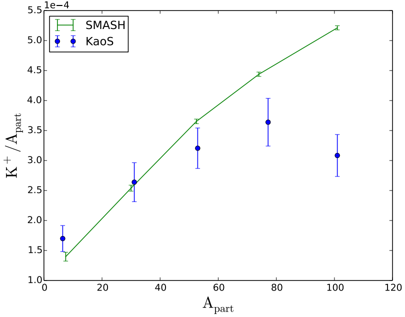
K_S^0 production in proton-proton at $E_{\mathrm{kin}} = 3.5\,\mathrm{GeV}$

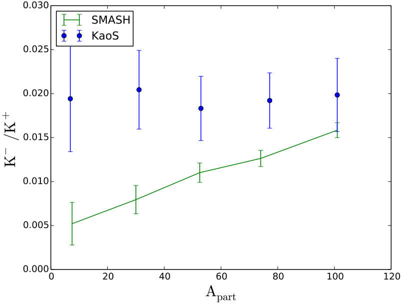


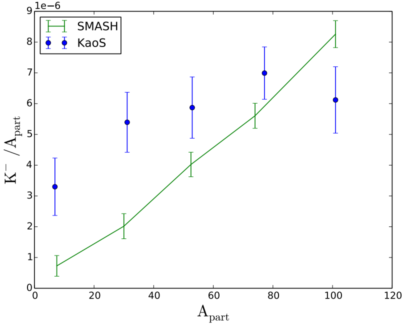
G. Agakishiev et al. In: *Phys. Rev.* C90 (2014). arXiv: 1404.7011

- $K_S^0 = 0.5 K^0 + 0.5 \bar{K}^0$
- Cross section too low by factor 1.72, dashed lines scaled accordingly
- Similar scaling necessary for other transport models

$K^{\pm}$ production in nickel-nickel at $E_{\mathrm{kin}} = 1.5A\,\mathrm{GeV}$



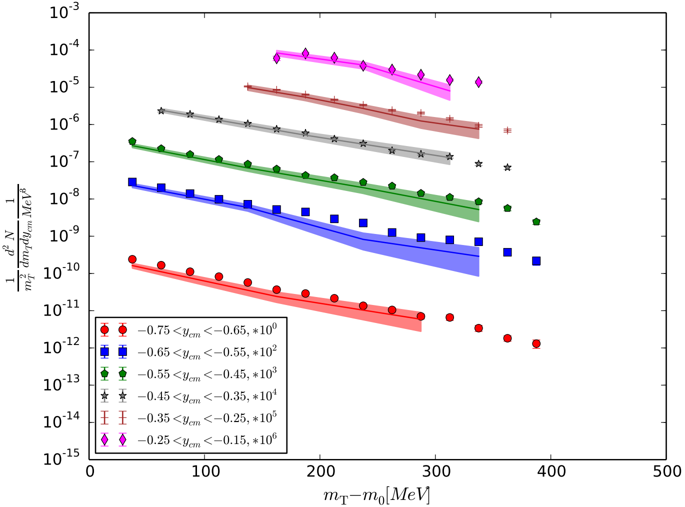




- Reasonable agreement with KaoS for ratio
- Trend for absolute yields differs (similar to other transport models)

A. Forster et al. In: *J. Phys.* G31.6 (2005). arXiv: `nucl-ex/0411045`

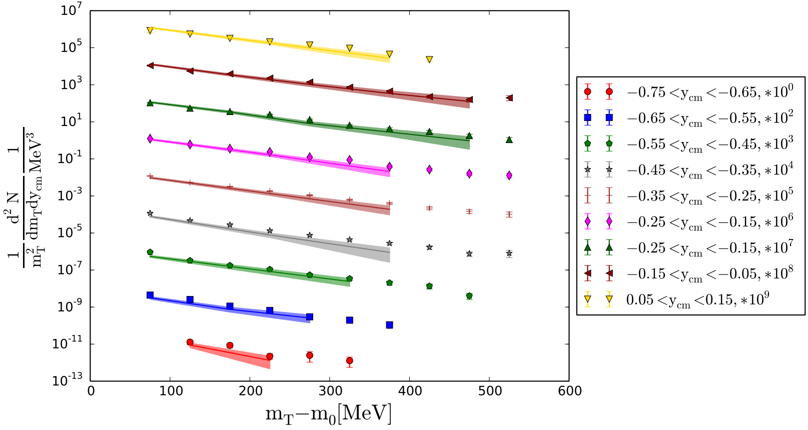
K^+ production in ArKCl at $E_{\text{kin}} = 1.76A$ GeV



G. Agakishiev et al. In: *Eur. Phys. J.* A47 (2011). arXiv: 1010.1675

- HADES ArKCL compared to SMASH CaCa

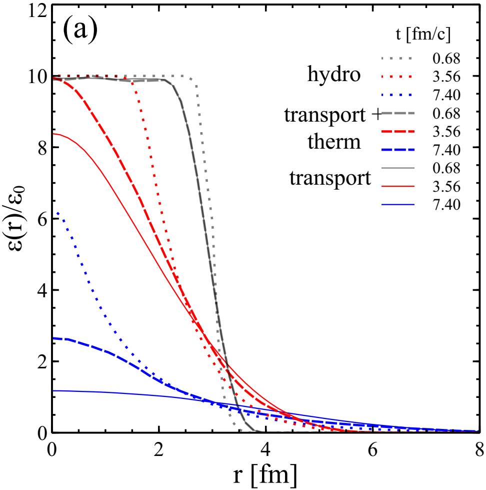
Λ production in ArKCl at $E_{\text{kin}} = 1.76A$ GeV



G. Agakishiev et al. In: *Eur. Phys. J.* A47 (2011). arXiv: `1010.1675`

- HADES ArKCL compared to SMASH CaCa

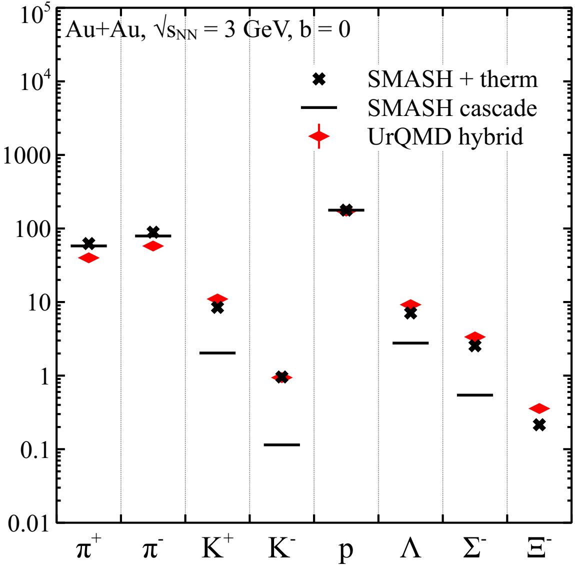
Particle production with forced thermalization



- 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). arXiv: 1609.01087

Forced canonical thermalization vs. cascade + hydro



- Strangeness enhancement comparable to hybrid approach

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?

Conclusion and outlook

- SMASH was successfully tested at SIS energies
- π, K and Λ production can be reasonably modeled via resonances
- Higher energies require string fragmentation (Pythia 8 integration is work in progress)
- Effective many-particle interactions by forced thermalization enhance strangeness production
- More detailed comparisons of resonance approach and forced thermalization are planned
- Possible collaboration on analysis suite?

Strangeness production via resonances

- Strangeness exclusively produced during collision
  $\Rightarrow$ interesting probe for studying evolution of the reaction
- Kaons and 11 kaonic resonances (+ anti particles)
- Λ, Σ, Ξ, Ω and 28 resonances (+ anti particles)
- K^+ production ($Y \in \{\Lambda, \Sigma\}$):

$$NN \to NN^*/\Delta^* \to NYK \tag{20}$$

- K^- production:

$$NN \to N^*/\Delta^* ... \to Y ... \to Y^* ... \to \bar{K} ... \tag{21}$$

$$\pi Y \leftrightarrow \bar{K} N \tag{22}$$

- Strangeness exchange (22) absorbs K^-

G. Graef et al. In: *Phys. Rev.* C90 (2014). arXiv: 1409.7954