Strangeness production in heavy-ion collisions at SIS energies

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SMASH transport approach

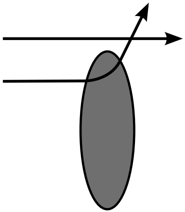
- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- 56 meson and 60 baryon species (+ anti particles)
  = most of established hadrons from PDG (2017) made of *uds*
- Use cases: Nuclear collisions, infinite matter, afterburner for hydro
- Dileptons and photons
- Open source code will be published this year
- Test physics at SIS energies ($E_{\mathrm{kin}} = 0.5 - 3.5A\,\mathrm{GeV}$), baseline for future NICA/FAIR predictions ($\approx 10A\,\mathrm{GeV}$)

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

Collision finding

- Geometric collision criterion (as used by UrQMD):

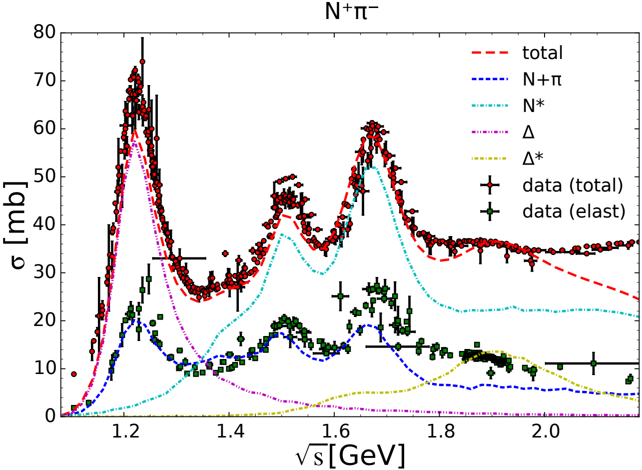
$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \quad (1)$$



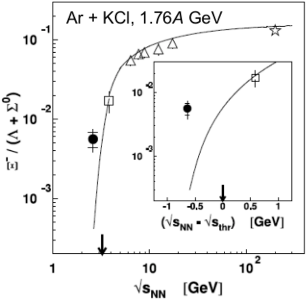
- Products of same reaction are forbidden to collide again
- Grid with cell size $\sqrt{\sigma_{\text{max}}/(\pi N_{\text{test}})}$ for collision finding

Cross section in SMASH

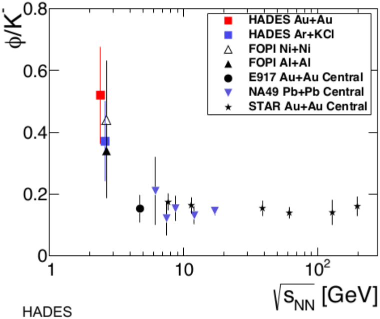
- Calculated from resonance masses, decay widths and branching ratios
- Parametrization of experimental data for non-resonant cross sections



Strangeness in heavy-ion collisions



HADES
PRL **103** (2009) 132301



HADES
arXiv:1703.08418

- Interesting probe for studying evolution of HIC
- High ϕ, Ξ measured by HADES $\rightarrow$ sub-threshold strangeness enhancement
- $KN/\bar{K}N$ potentials? In-medium cross sections?
- Production mechanism in equilibrium (thermal model) and non-equilibrium (resonances)?

C. Blume. In: *Strangeness in Quark Matter*. 2017. arXiv: 1710.07508

Strangeness production via resonances in SMASH

- Kaons and 11 kaonic resonances (+ anti particles)
- Λ, Σ, Ξ, Ω and 27 resonances (+ anti particles)
- Most important channels in heavy-ion collisions:
  - K^+ production ($Y \in \{\Lambda, \Sigma\}, B^* \in \{N^*, \Delta^*\}$):

$$NN \to NB^* \to NYK \quad \pi N \to B^* \to YK \tag{2}$$

  - K^- production:

$$NN \to NB^* \to NYK \quad \pi Y \to Y^* \to \bar{K}N \tag{3}$$

$$\pi Y \leftrightarrow \bar{K}N \quad \text{(non-resonant)} \tag{4}$$

$$N^* \to \phi N \to K\bar{K}N \tag{5}$$

- No $BY \to NY^* \to NN\bar{K}$ channel

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

Experimental branching ratios (2016-2017)

	branching ratio $N^* \to \Lambda K$		
resonance	PDG[1]	HADES[2]	SMASH
$N(1650)$	$5-15\%$	$7 \pm 4\%$	4%
$N(1710)$	$5-25\%$	$15 \pm 10\%$	13%
$N(1720)$	$4-5\%$	$8 \pm 7\%$	5%
$N(1875)$	> 0	$4 \pm 2\%$	2%
$N(1880)$		$2 \pm 1\%$	
$N(1895)$		$18 \pm 5\%$	
$N(1900)$	$2-20\%$	$5 \pm 5\%$	2%
$N(1990)$			2%
$N(2080)$			0.5%
$N(2190)$	$0.2-0.8\%$		0.8%
$N(2250)$	0		0.5%

[1] C. Patrignani et al. *Chin. Phys.* C40.10 (2016), p. 100001.
[2] R. Münzer et al. (2017). arXiv: `1703.01978 [nucl-ex]`.

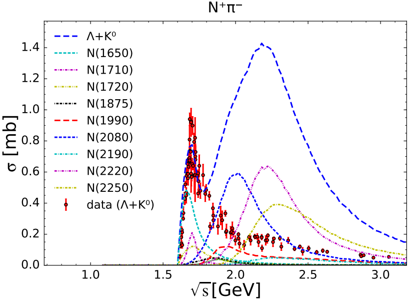
Experimental branching ratios (2018)

resonance	branching ratio $N^* \to \Lambda K$ PDG[1]	HADES	SMASH
$N(1650)$	$5 - 15\%$	$7 \pm 4\%$	4%
$N(1710)$	$5 - 25\%$	$15 \pm 10\%$	13%
$N(1720)$	$4 - 5\%$	$8 \pm 7\%$	5%
$N(1875)$	> 0	$4 \pm 2\%$	2%
$N(1880)$	$12 - 28\%$	$2 \pm 1\%$	
$N(1895)$	$13 - 23\%$	$18 \pm 5\%$	
$N(1900)$	$2 - 20\%$	$5 \pm 5\%$	2%
$N(1990)$			2%
$N(2060)$	> 0		
$N(2080)$			0.5%
$N(2100)$	> 0		
$N(2120)$	0		
$N(2190)$	$\Lambda K^* : 0.2 - 0.8\%$		0.8%
$N(2250)$	0		0.5%

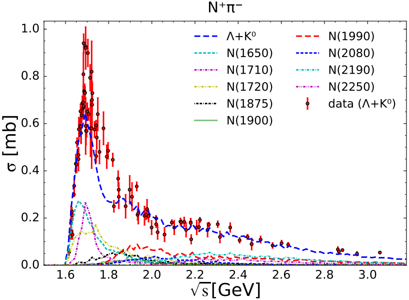
[1] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Tuning branching ratios

before
(based on PDG and UrQMD)

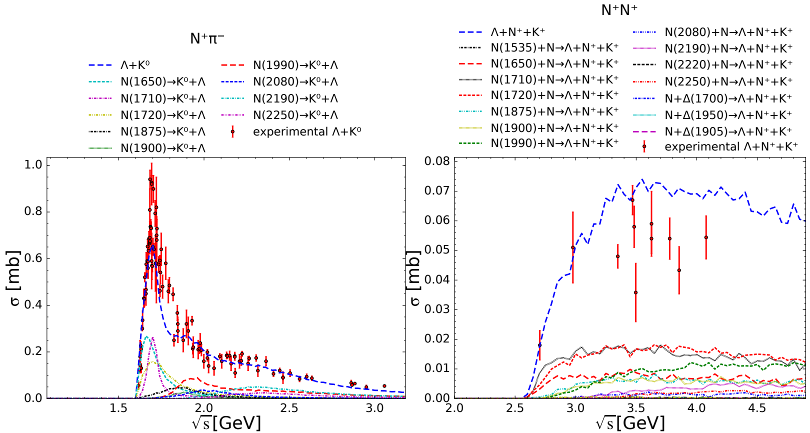


after
(tuned to exclusive cross section)



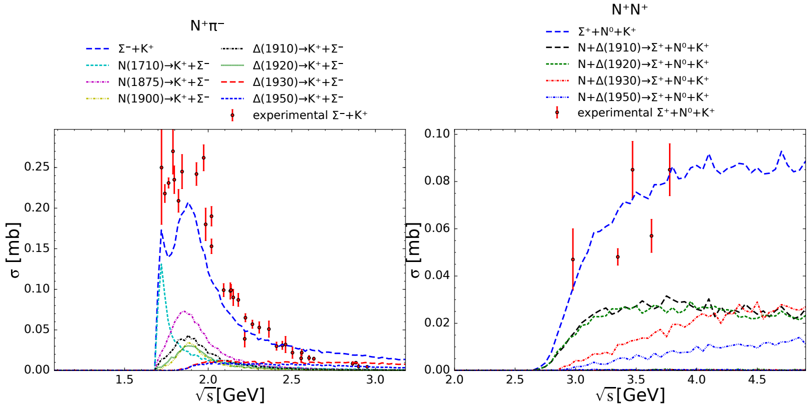
- Improve cross section by reducing $N(2080), N(2220), N(2250) \to \Lambda K, N\pi$

Λ production



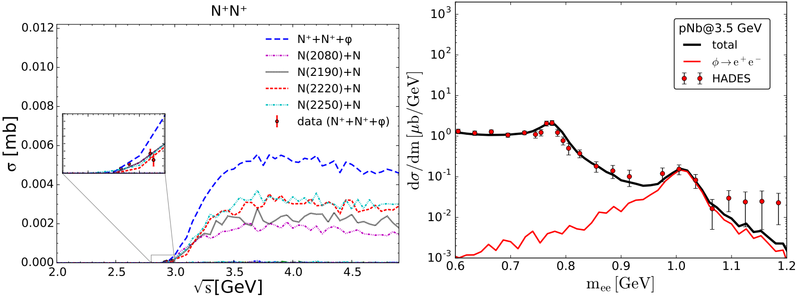
- Relevant branching ratios: $N^* \to \Lambda K, \pi N$

Σ production



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

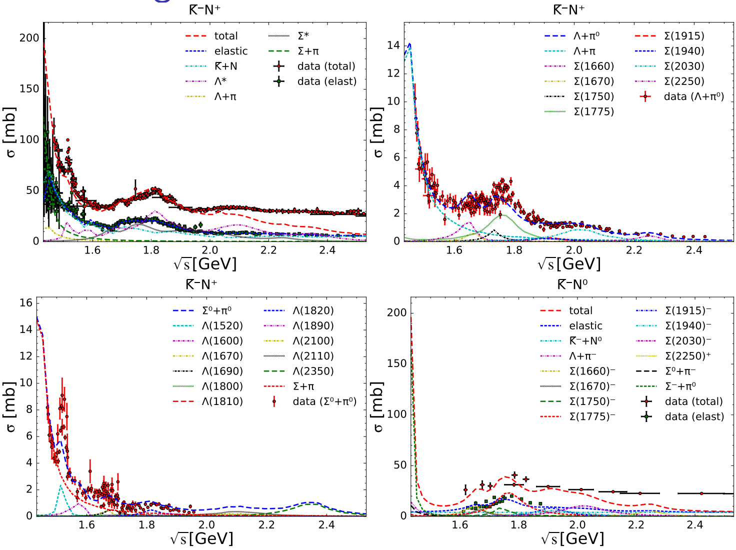
ϕ production



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

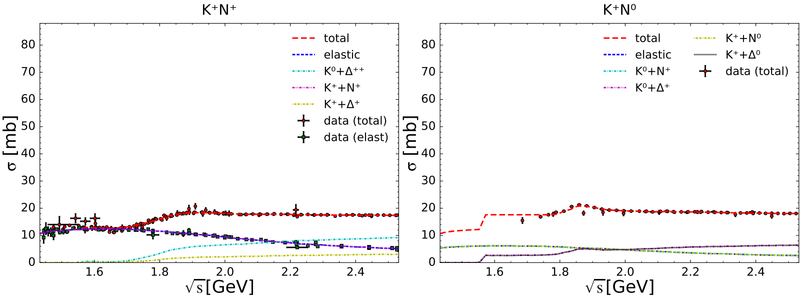
J. Steinheimer et al. In: *J. Phys.* G43.1 (2016), p. 015104. arXiv: 1503.07305 [nucl-th]

$\bar{K}N$ scattering



- Y^* contribution + elastic background + charge exchange + strangeness exchange (like UrQMD)

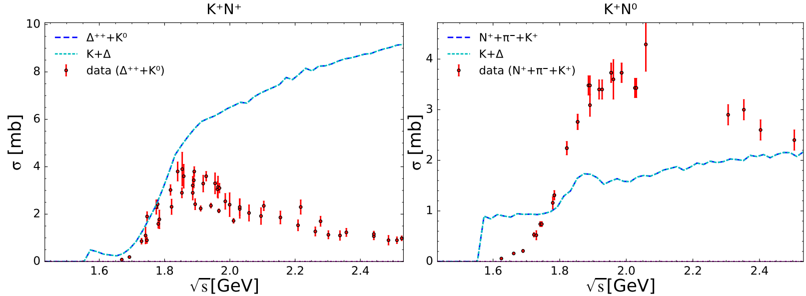
KN scattering



- K rescattering significantly affects kinematics[3]
- Elastic background + charge exchange + single-pion production (like GiBUU)
- Not designed to describe exclusive cross sections

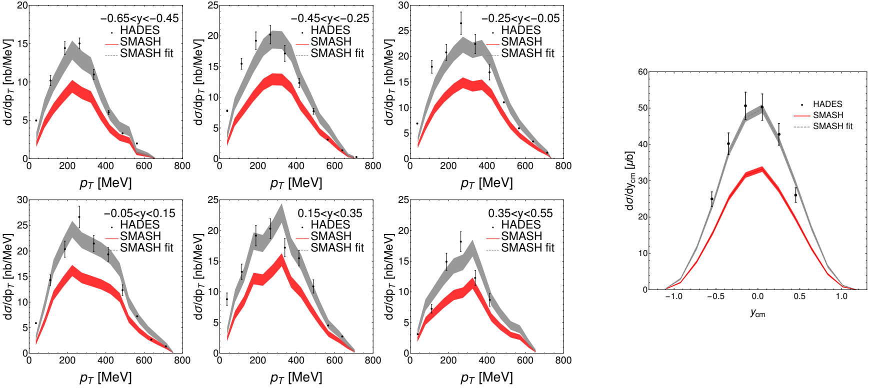
[3] C. Hartnack et al. *Phys. Rept.* 510 (2012), pp. 119–200. arXiv: `1106.2083 [nucl-th]`.

KN exclusive cross section



- $K^+p \to \Delta^{++}K^0$: Not enough pions in the final state?
- $K^+n \to p\pi^-K^+$: Not well reproduced
- Single-pion production too simplistic
- Probably not important for kaon rescattering

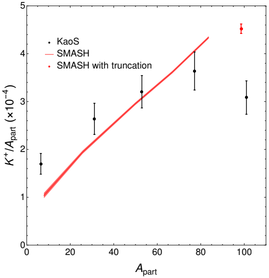
K_S^0 production in proton-proton at $E_{\text{kin}} = 3.5\,\text{GeV}$

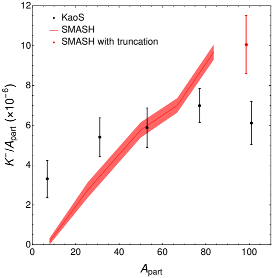


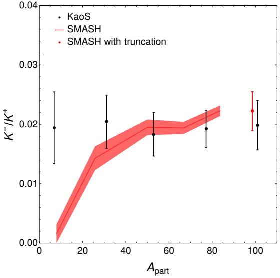
G. Agakishiev et al. In: *Phys. Rev.* C90 (2014), p. 054906. arXiv: 1404.7011 [nucl-ex]

- Assuming long-short symmetry: $\sigma_{K_S^0} = 0.5\sigma_{K^0} + 0.5\sigma_{\bar{K}^0}$
- Cross section too low by factor 1.5 (red), grey lines scaled accordingly (similar to GiBUU)

$K^{\pm}$ production in ^{58}Ni-^{58}Ni at $E_{kin} = 1.5A$ GeV



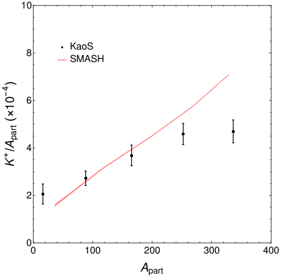


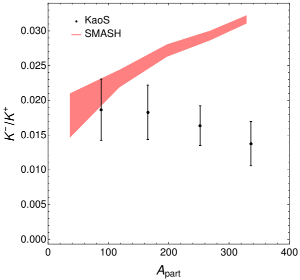


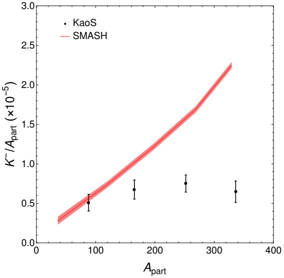
- Decent agreement with KaoS for ratio
- Absolute yields reasonable, but trend different (similar to IQMD)

A. Forster et al. In: *J. Phys.* G31.6 (2005), S693–S700. arXiv: nucl-ex/0411045 [nucl-ex]

$K^{\pm}$ production in gold-gold at $E_{\text{kin}} = 1.5A$ GeV



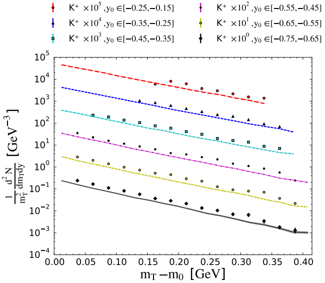


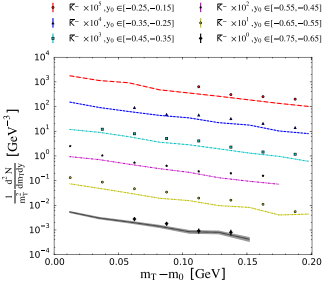


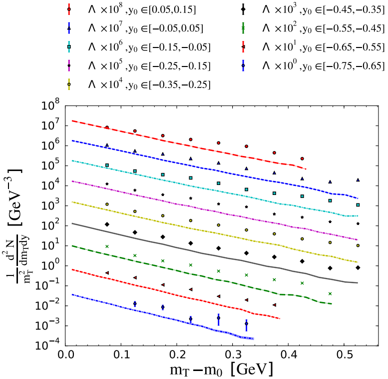
- Overestimation for high number of participants, more so for K^- than K^+
- Similar to IQMD

A. Forster et al. In: *J. Phys.* G31.6 (2005), S693–S700. arXiv: `nucl-ex/0411045 [nucl-ex]`

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



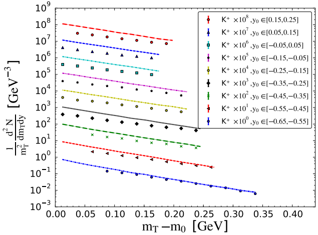


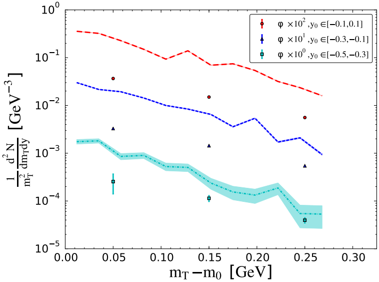


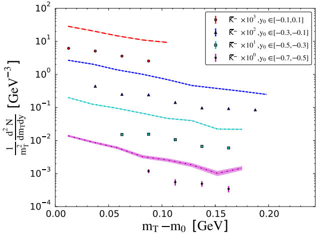
- HADES ArKCL compared to SMASH CaCa
- Kaons slightly and Λ significantly underestimated with wrong slope

G. Agakishiev et al. In: *Eur. Phys. J.* A47 (2011), p. 21. arXiv: 1010.1675 [nucl-ex]

Strangeness production in AuAu at $E_{\text{kin}} = 1.23\,\text{GeV}$



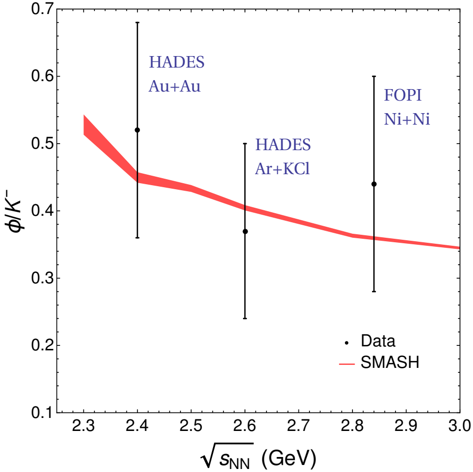




- HADES AuAu compared to SMASH
- K^+ overestimated at midrapidities, K^- and ϕ at all rapidities

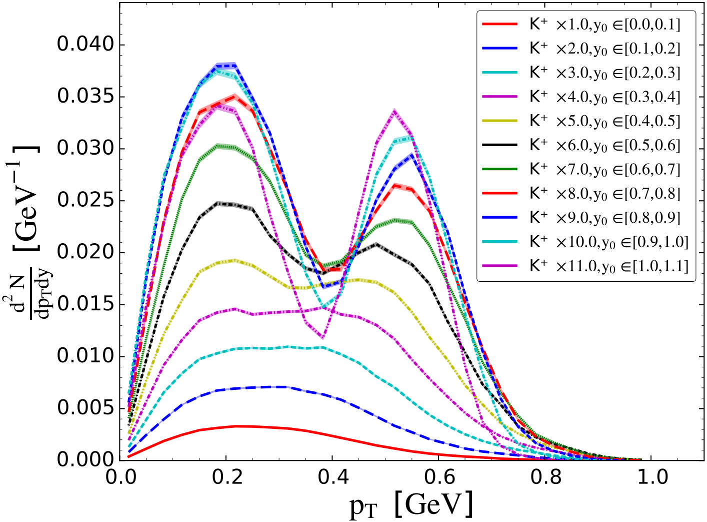
J. Adamczewski-Musch et al. In: *Phys. Lett.* B778 (2018), pp. 403–407. arXiv: 1703.08418 [nucl-ex]

ϕ/K^- ratio in AuAu



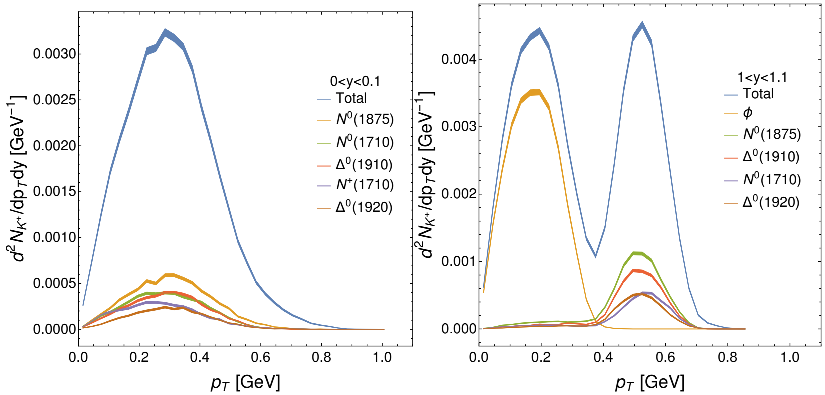
- SMASH AuAu compared to several systems
- Ratio well reproduced

K^+ production in $\pi^- C$ at $E_{\rm kin} = 1.7\,$GeV



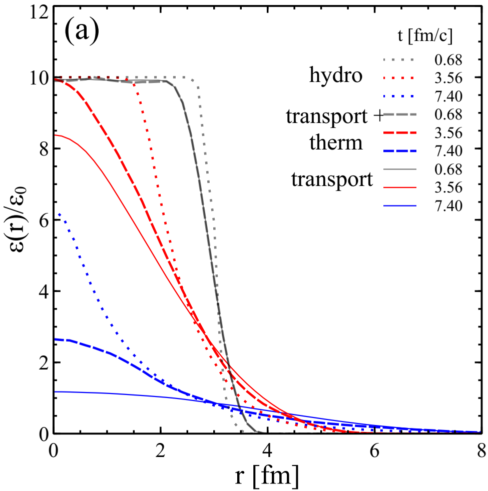
- Measured by HADES (not yet public)
- SMASH: Unphysical second peak at high rapidity

Contribution of resonances to pion beam



- Second peak from heavy resonances
- Not enough particles in final state of B^* decay?

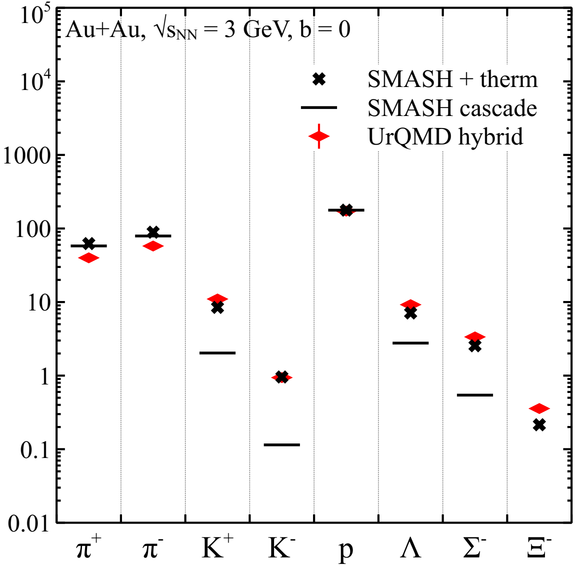
Particle production with forced thermalization



- 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

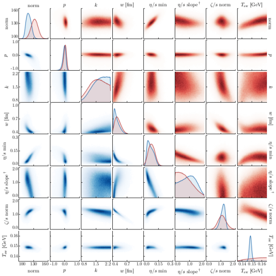


- Strangeness enhancement comparable to hybrid approach

Conclusion

- Elementary K, Λ, Σ, ϕ production at low energies can be reasonably modeled via resonances
- Dilepton data for p Nb constrains ϕ production
- Strangeness production at midrapidity in large systems overestimated
  $\Rightarrow$ missing in medium-effects? (KN potentials, in-medium cross section/width)
- Pion beam very sensitive to resonance properties
- Not enough pions in final state of B^* decay?
- Effective many-particle interactions by forced thermalization enhance strangeness production

Outlook

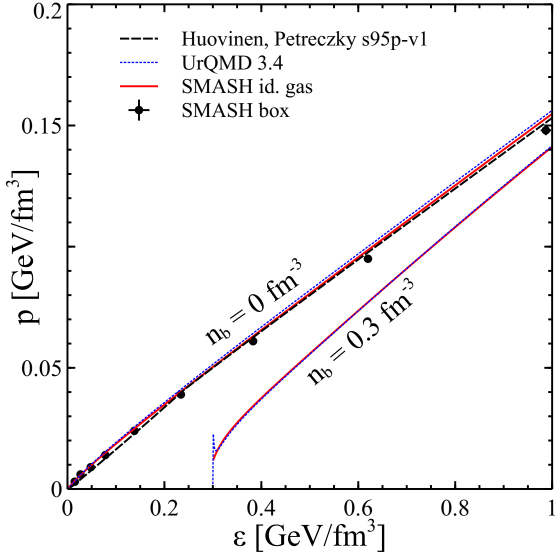


J. E. Bernhard et al. In: *Phys. Rev.* C94.2 (2016), p. 024907. arXiv: `1605.03954 [nucl-th]`

- Future work: use Bayesian modeling for tuning branching ratios
- Higher energies require string fragmentation and additive quark model
- More sophisticated hyperon-nucleon potential[4] planned

[4] S. Petschauer et al. *Eur. Phys. J.* A52.1 (2016), p. 15. arXiv: `1507.08808 [nucl-th]`.

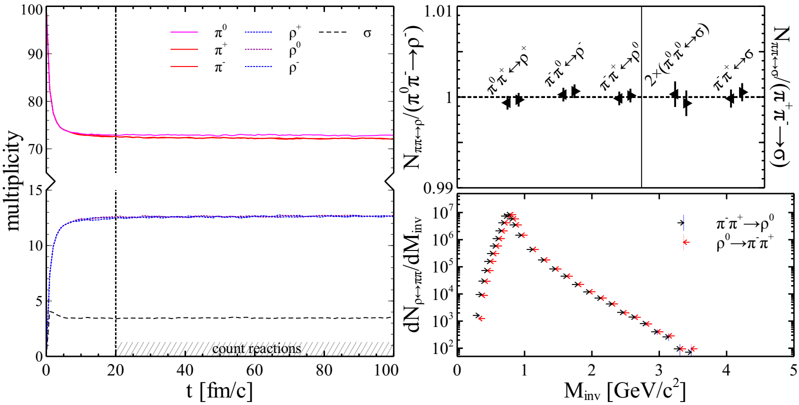
Equation of state



- SMASH hadron gas vs. UrQMD vs. lattice QCD

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



Comparison to exact solution of Boltzmann equation

- Boltzmann equation in curved spacetime

$$p^\mu \frac{\partial f(x,p)}{\partial x^\mu} + p_\lambda p^\mu \Gamma^\lambda_{\mu i} \frac{\partial f(x,p)}{\partial p_i} = C(f) \qquad (6)$$

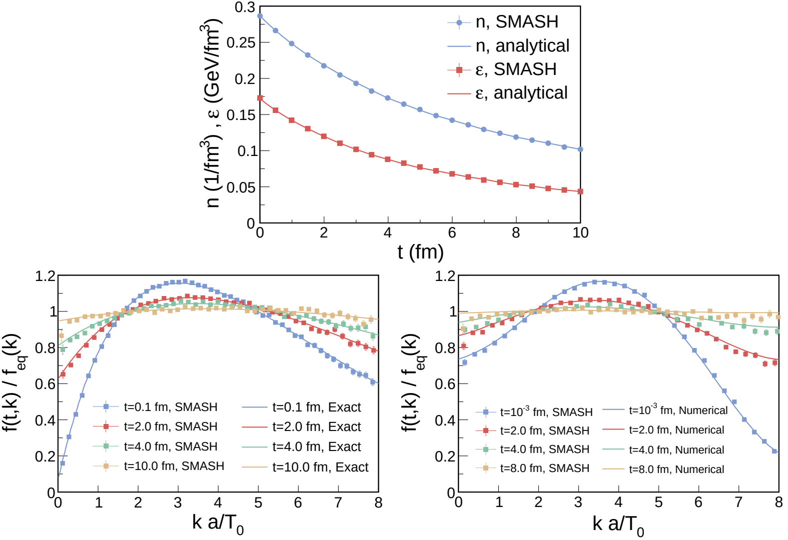
- Expanding universe with Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = dt^2 - a(t)^2(dx^2 + dy^2 + dz^2) \qquad (7)$$

- 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]

Resonances in SMASH

- Breit-Wigner spectral function

$$\mathcal{A}(m) = \frac{2N}{\pi} \frac{m^2\Gamma(m)}{(m^2 - m_0^2)^2 + m^2\Gamma(m)^2} \tag{8}$$

- Manley-Saleski ansatz[5] for off-shell decay branching ratio

$$\Gamma_{R\to ab} = \Gamma^0_{R\to ab} \frac{\rho_{ab}(m)}{\rho_{ab}(m_0)} \tag{9}$$

$$\rho_{ab}(m) = \int dm_a dm_b \, \mathcal{A}_a(m_a)\mathcal{A}_b(m_b) \frac{p_f}{m} B_L^2(p_f R)\mathcal{F}_{ab}^2(m) \tag{10}$$

- Post form factor[6] for unstable decay products

$$\mathcal{F}_{ab}(m) = \frac{\lambda^4 + (s_0 - m_0^2)^2/4}{\lambda^4 + \left(m^2 - (s_0 + m_0^2)/2\right)^2} \tag{11}$$

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

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

Cross sections in SMASH

- $2 \to 1$ resonance production

$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)}\mathcal{S}_{ab}\frac{2\pi^2}{p_i^2}\Gamma_{ab\to R}(s)\mathcal{A}(\sqrt{s}) \tag{12}$$

- $2 \to 2$ resonance production

$$\begin{aligned}\sigma_{ab\to Rc}(s) = &\sum_I \left(C_{ab}(I)C_{Rc}(I)\right)^2 \frac{|M|^2_{ab\to Rc}(s,I)}{16\pi} \\ &\times \frac{(2J_R+1)(2J_c+1)}{s\,p_i}\frac{4\pi}{p^i_{\mathrm{cm}}}\int dm\mathcal{A}(m)p_f\end{aligned} \tag{13}$$

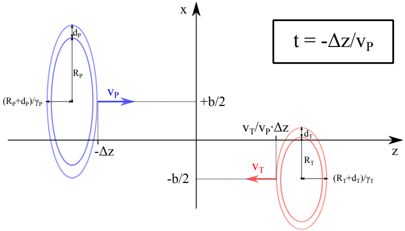
- Can model most cross sections like this, some have to be parametrized instead

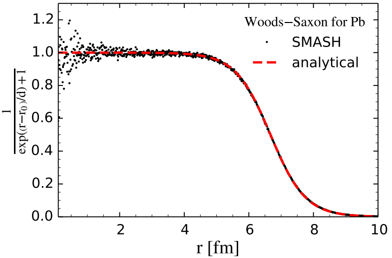
Modifying particle species and decay modes in SMASH

```
# 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
```

Nucleus collision





- Woods-Saxon distribution

$$\frac{dN}{dr} = \frac{\rho_0}{\exp(\frac{r-r_0}{d}) + 1} \tag{14}$$

- Deformed nuclei

Fermi motion

- Local density approximation

$$p_F(\vec{r}) = \hbar c \sqrt[3]{3\pi^2 \rho(\vec{r})} \tag{15}$$

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

$$p'_{iz} = \gamma(p_{iz} + \beta E_i) = \gamma p_{iz} + \frac{p_A}{A} \tag{16}$$

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

Skyrme and symmetry potential

$$U = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2S_{\mathrm{pot}}\frac{\rho_p - \rho_n}{\rho_0}\frac{I_3}{I} \tag{17}$$

$$H_i = \sqrt{\vec{p}_i^{\,2} + m_i^2} + U(\vec{r}_i) \tag{18}$$

where

$$a = -209.2\,\mathrm{MeV} \quad b = 156.4\,\mathrm{MeV} \quad c = 1.35 \quad S_{\mathrm{pot}} = 18\,\mathrm{MeV} \tag{19}$$

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

Pauli blocking

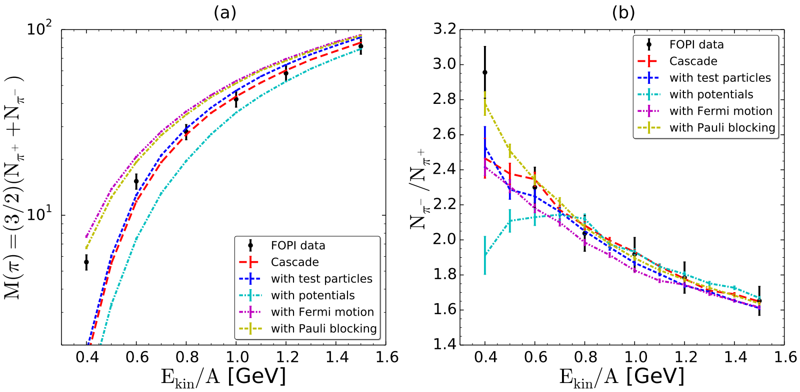
- Collision integral in Boltzmann-Uehling-Uhlenbeck equation

$$C(f) = \frac{1}{2}\int \frac{d^3p_2}{E_2}\frac{d^3p_1'}{E_1}\frac{d^3p_2'}{E_2'} W(p_1, p_2, p_1', p_2') \times \left(f_1' f_2' (1 \pm f)(1 \pm f_2) - f f_2 (1 \pm f_1')(1 \pm f_2')\right) \tag{20}$$

- Pauli blocking and Bose enhancement
- Reject reactions with probability

$$P = 1 - \prod_{\text{final state fermion } i} (1 - f_i) \tag{21}$$

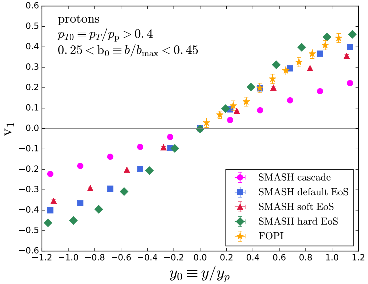
Pion production in central gold-gold collisions

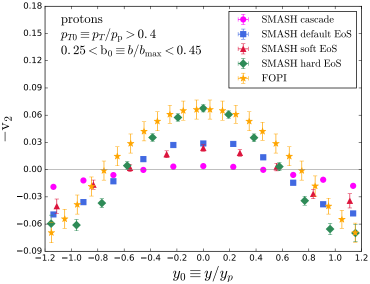


W. Reisdorf et al. In: *Nucl. Phys.* A781 (2007), pp. 459–508. arXiv: nucl-ex/0610025

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

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





- 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 $\sqrt{s} \approx 2.5\,\text{GeV}$
  - Elementary cross sections: NN, πN, $\pi\pi$, KN
  - FOPI pions: π multiplicites for $E_{\text{kin}} = 0.4 - 1.5A\,\text{GeV}$
  - Spectra: dN/dy and dN/dm_T for π and p in AuAu at $E_{\text{kin}} = 1.5A\,\text{GeV}$ and CC at $E_{\text{kin}} \in \{1, 2\}A\,\text{GeV}$
- Of interest to other models targeting NICA/FAIR energies?
- Systematic comparison of models?