

# Collective effects in the dense matter using transport approach (SMASH / UrQMD)

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LBNL with V. Koch  
PhD at FIAS with H. Elfner (Petersen)  
[Weil et al, PRC 94 \(2016\) no.5, 054905](#)  
[Steinberg et al. \[arXiv:1809.03828\]](#)  
[M. Mayer, master thesis](#)  
[Staudenmaier et al. \[arXiv:1711.10297\]](#)



Thanks to SMASH team! (incomplete on the pic)



October 3, 2018

# Outlook

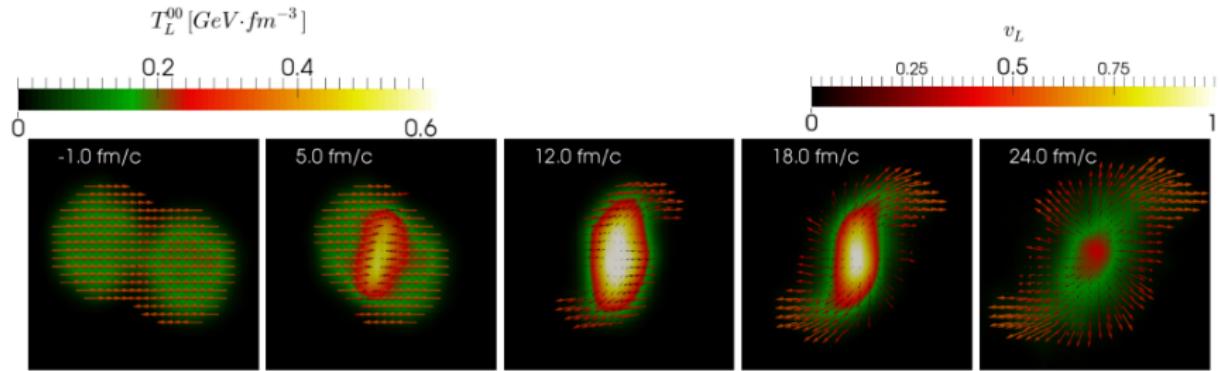
- SMASH transport approach
  - ▶ Degrees of freedom
  - ▶ Interactions
  - ▶ Selected cross-sections
- Observables at SIS energies
  - ▶ Pions
  - ▶ Strangeness production
  - ▶ Flow
  - ▶ Dileptons

# Why new transport approach?

- Hadronic transport approaches are successfully applied for the dynamical evolution of heavy ion collisions
- Hadronic non-equilibrium dynamics is crucial for
  - ▶ Full/partial evolution at low/intermediate beam energies
  - ▶ Late stage rescattering at high beam energies (RHIC/LHC)
- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

# SMASH transport approach

**S**imulating  
**M**ultiple  
**A**ccelerated  
**S**trongly-interacting  
**H**adrons



- Monte-Carlo solver of relativistic Boltzmann equations

BUU type approach, testparticles ansatz:  $N \rightarrow N \cdot N_{test}$ ,  $\sigma \rightarrow \sigma / N_{test}$

- Degrees of freedom
  - ▶ most of established hadrons from PDG up to mass 2.5 GeV
  - ▶ strings: do not propagate, only form and decay to hadrons

- Propagate from action to action (timesteps only for potentials)  
action  $\equiv$  collision, decay, wall crossing

- Geometrical collision criterion:  $d_{ij} \leq \sqrt{\sigma/\pi}$

- Interactions:  $2 \leftrightarrow 2$  and  $2 \rightarrow 1$  collisions, decays, potentials, string formation  
(soft - SMASH, hard - Pythia 8) and fragmentation via Pythia 8

- C++ code, git version control, will be public at github by November

# SMASH: initialization

- “collider” - elementary or AA reactions,  $E_{beam} \gtrsim 0.5 A$  GeV
- “box” - infinite matter simulations
  - detailed balance tests, computing transport coefficients, thermodynamics of hadron gas  
[Rose et al., PRC 97 \(2018\) no.5, 055204](#)
- “sphere” - expanding system
  - testing collision term via comparison to analytical solution of Boltzmann equation,  
[Tindall et al., Phys.Lett. B770 \(2017\) 532-538](#)
- “list” - hadronic afterburner after hydrodynamics

# SMASH: degrees of freedom

N	$\Delta$	$\Lambda$	$\Sigma$	$\Xi$	$\Omega$	Unflavored			Strange	
$N_{938}$	$\Delta_{1232}$	$\Lambda_{1116}$	$\Sigma_{1189}$	$\Xi_{1321}$	$\Omega^{-}_{1672}$	$\pi_{138}$	$f_0 980$	$f_2 1275$	$\pi_2 1670$	$K_{494}$
$N_{1440}$	$\Delta_{1620}$	$\Lambda_{1405}$	$\Sigma_{1385}$	$\Xi_{1530}$	$\Omega^{-}_{2250}$	$\pi_{1300}$	$f_0 1370$	$f_2' 1525$		$K^*_{892}$
$N_{1520}$	$\Delta_{1700}$	$\Lambda_{1520}$	$\Sigma_{1660}$	$\Xi_{1690}$		$\pi_{1800}$	$f_0 1500$	$f_2 1950$	$\rho_3 1690$	$K_1 1270$
$N_{1535}$	$\Delta_{1905}$	$\Lambda_{1600}$	$\Sigma_{1670}$	$\Xi_{1820}$			$f_0 1710$	$f_2 2010$		$K_1 1400$
$N_{1650}$	$\Delta_{1910}$	$\Lambda_{1670}$	$\Sigma_{1750}$	$\Xi_{1950}$		$\eta_{548}$		$f_2 2300$	$\phi_3 1850$	$K^*_{1410}$
$N_{1675}$	$\Delta_{1920}$	$\Lambda_{1690}$	$\Sigma_{1775}$	$\Xi_{2030}$		$\eta'_{958}$	$a_0 980$	$f_2 2340$		$K_0^* 1430$
$N_{1680}$	$\Delta_{1930}$	$\Lambda_{1800}$	$\Sigma_{1915}$			$\eta_{1295}$	$a_0 1450$		$a_4 2040$	$K_2^* 1430$
$N_{1700}$	$\Delta_{1950}$	$\Lambda_{1810}$	$\Sigma_{1940}$			$\eta_{1405}$		$f_1 1285$		$K^*_{1680}$
$N_{1710}$		$\Lambda_{1820}$	$\Sigma_{2030}$			$\eta_{1475}$	$\phi_{1019}$	$f_1 1420$	$f_4 2050$	$K_2 1770$
$N_{1720}$		$\Lambda_{1830}$	$\Sigma_{2250}$				$\phi_{1680}$			$K_3^* 1780$
$N_{1875}$		$\Lambda_{1890}$				$\sigma_{800}$		$a_2 1320$		$K_2 1820$
$N_{1900}$		$\Lambda_{2100}$					$h_1 1170$			$K_4^* 2045$
$N_{1990}$		$\Lambda_{2110}$				$\rho_{776}$		$\pi_1 1400$		
$N_{2080}$		$\Lambda_{2350}$				$\rho_{1450}$	$b_1 1235$	$\pi_1 1600$		
$N_{2190}$						$\rho_{1700}$				
$N_{2220}$							$a_1 1260$	$\eta_2 1645$		
$N_{2250}$						$\omega_{783}$			$\omega_3 1670$	
						$\omega_{1420}$				
						$\omega_{1650}$				

- Isospin symmetry
- Perturbative treatment of non-hadronic particles (photons, dileptons)

Hadrons and decay modes configurable via human-readable files

# Interactions in SMASH

- Resonance formation and decay

Ex.  $\pi\pi \rightarrow \rho \rightarrow \pi\pi$ , quasi-inelastic scattering  
 $\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$

- (In)elastic 2 → 2 scattering

parametrized cross-sections  $\sigma(\sqrt{s}, t)$  or  
isospin-dependent matrix elements  $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

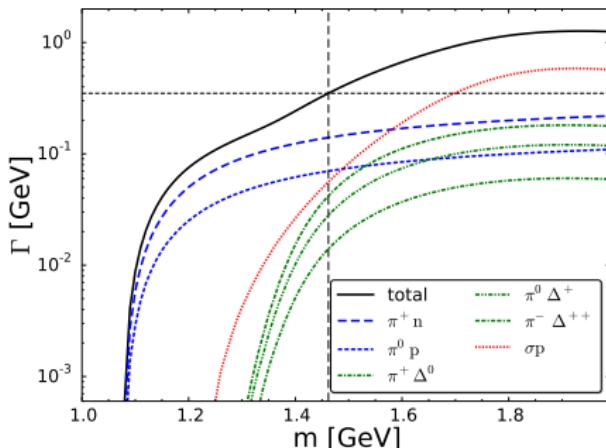
$2 \rightarrow n$  processes

- Potentials

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$N(1440)^+$



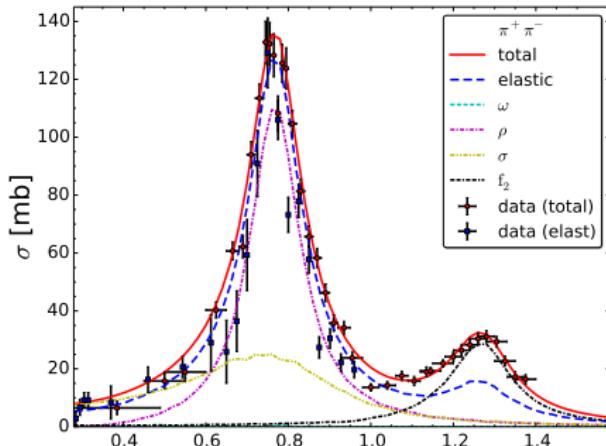
For every resonance:

- Breit-Wigner spectral function  $\mathcal{A}(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - M_0^2)^2 + m^2 \Gamma(m)^2}$
- Mass dependent partial widths  $\Gamma_i(m)$

Manley formalism for off-shell width [Manley and Saleski, Phys. Rev. D 45, 4002 \(1992\)](#)  
Total width  $\Gamma(m) = \sum_i \Gamma_i(m)$

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Total width  $\Gamma(m) = \sum_i \Gamma_i(m)$
- $2 \rightarrow 1$  cross-sections from detailed balance relations

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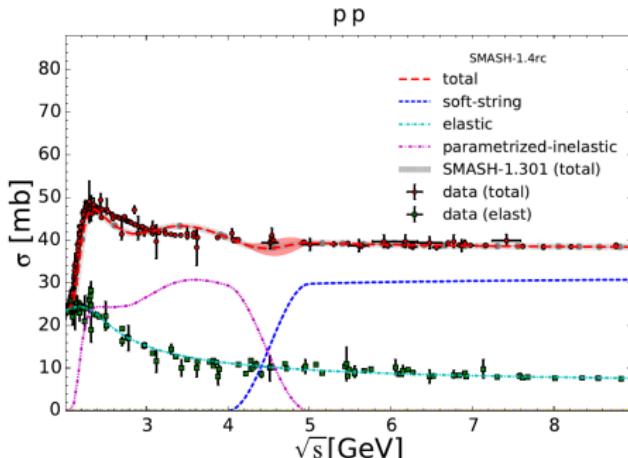
$2 \rightarrow n$  processes

- Potentials

- $NN \rightarrow NN^*$ ,  $NN \rightarrow N\Delta^*$ ,  $NN \rightarrow \Delta\Delta$ ,  $NN \rightarrow \Delta N^*$ ,  $NN \rightarrow \Delta\Delta^*$

angular dependencies of  $NN \rightarrow XX$  cross-sections implemented

- Strangeness exchange  $KN \rightarrow K\Delta$ ,  $KN \rightarrow \Lambda\pi$ ,  $KN \rightarrow \Sigma\pi$



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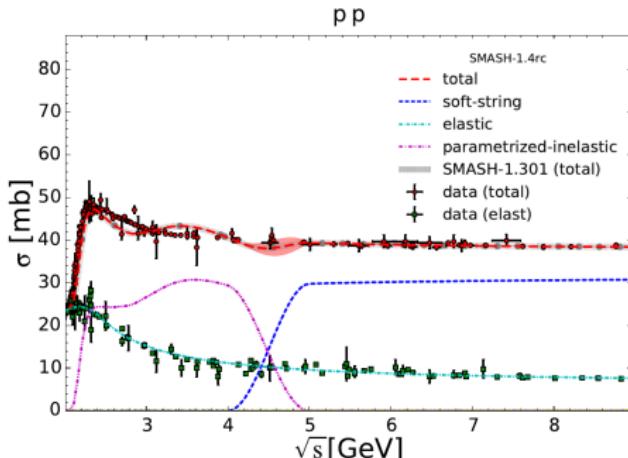
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$2 \rightarrow n$  processes

- Potentials

string model parameters  
currently under tuning  
using NA61 pp data  
Justin Mohs master thesis

- String (soft or hard) fragmentation: always via Pythia 8

- Hard scattering and string formation: Pythia

- Soft string formation: SMASH

- ▶ single/double diffractive
- ▶  $B\bar{B}$  annihilation
- ▶ non-diffractive

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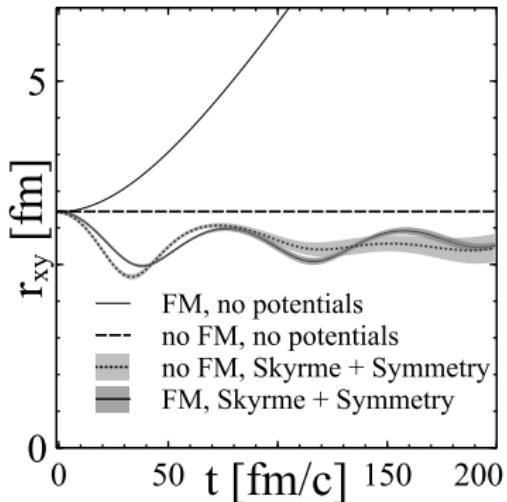
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## Transverse radius of Cu



- Skyrme and symmetry potential

$$U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}} \frac{\rho_{I3}}{\rho_0}$$

$\rho$  - Eckart rest frame baryon density

$\rho_{I3}$  - Eckart rest frame density of  $I_3/I$

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

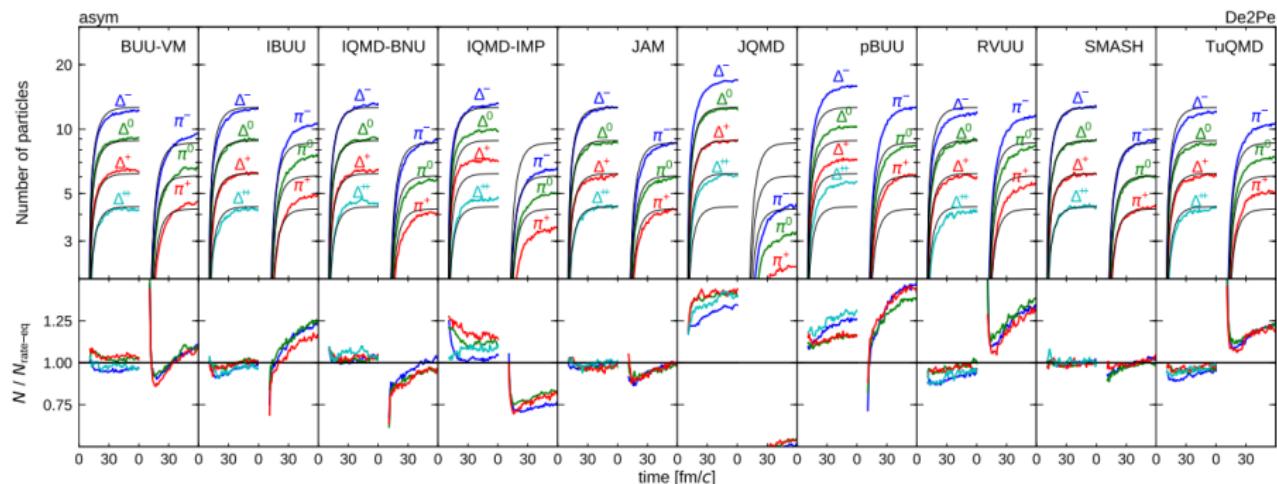
corresponds to incompressibility  $K = 240$  MeV

assures stability of a nucleus with Fermi motion

# Transport code comparison project

Zhang et al., PRC 97, 034625 (2018); Ono et al., in preparation

- Same “homework” for many codes, all physics identical
- Quantifying transport code uncertainty
- Compare to analytical solutions of Boltzmann equation

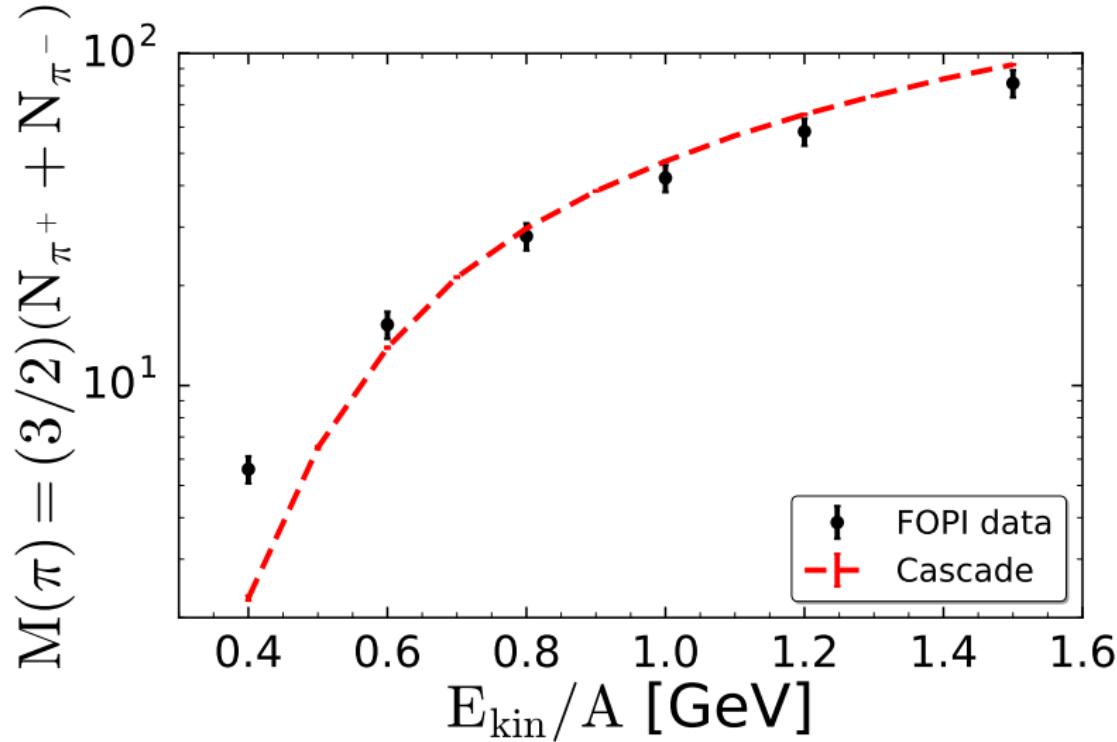


SMASH compares well to analytic solutions

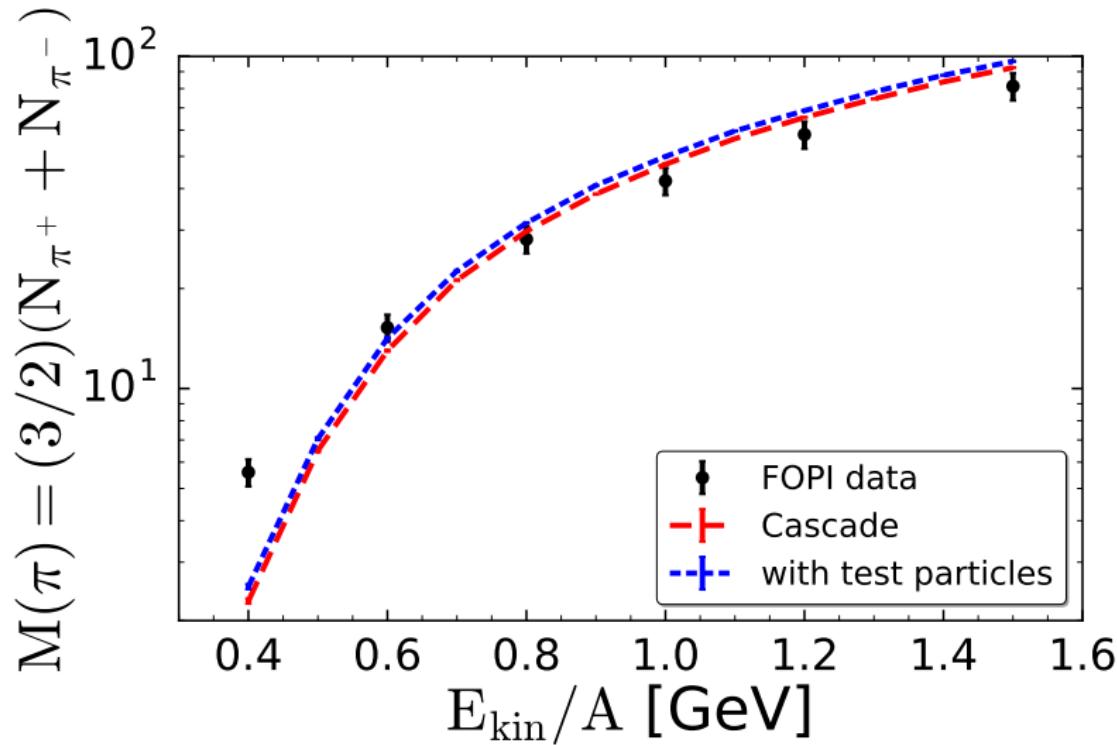
# Pion production

J. Weil *et al.*, PRC 94 (2016) no.5, 054905

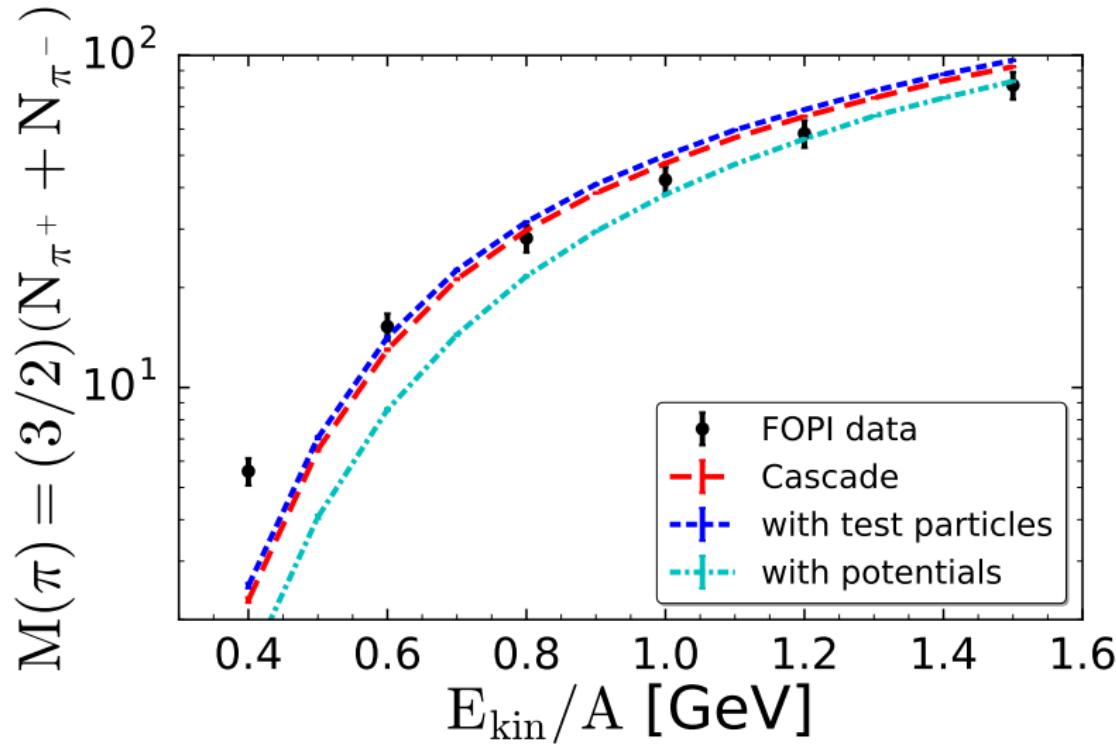
# FOPI pion multiplicities in central Au+Au with SMASH



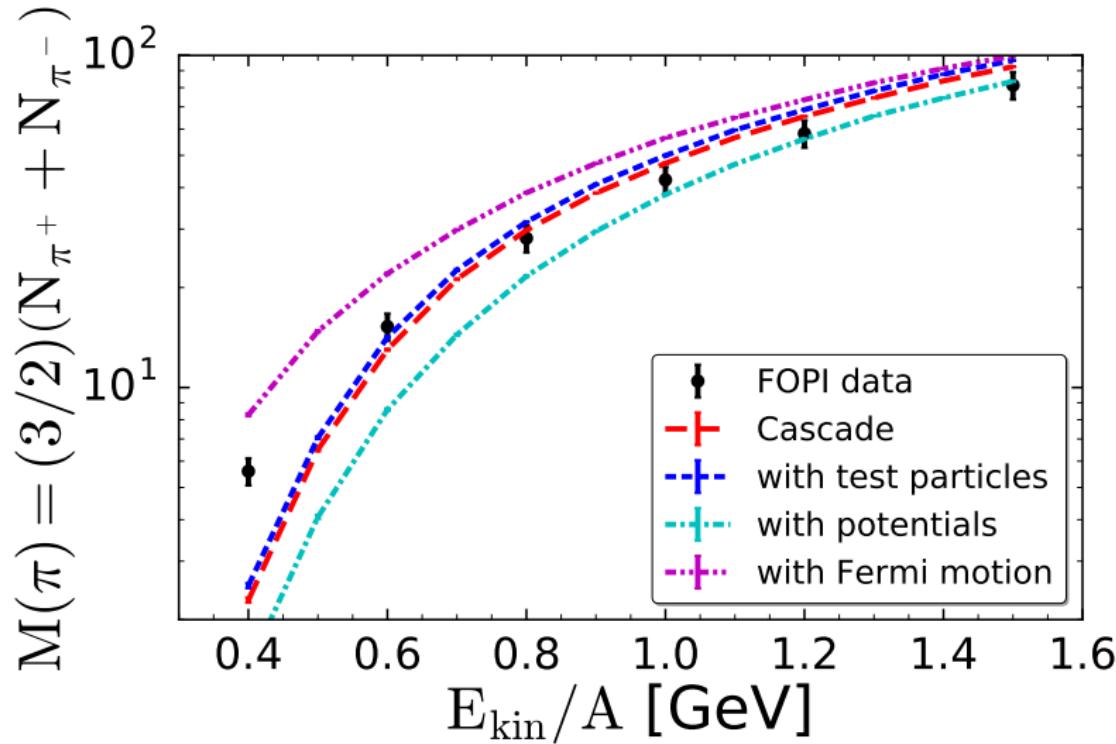
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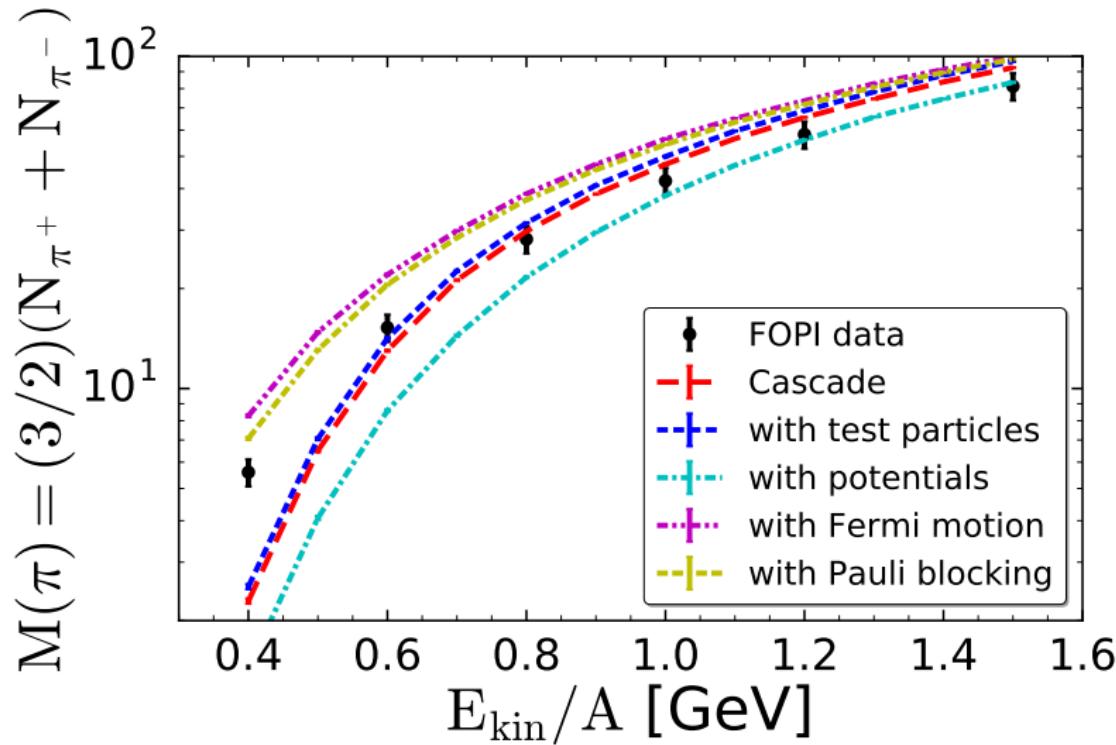
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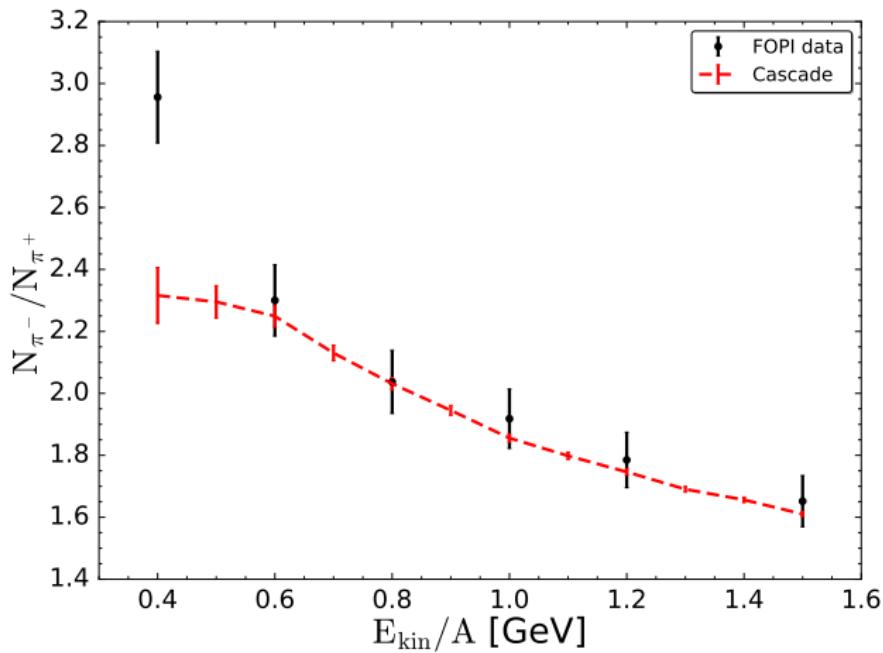


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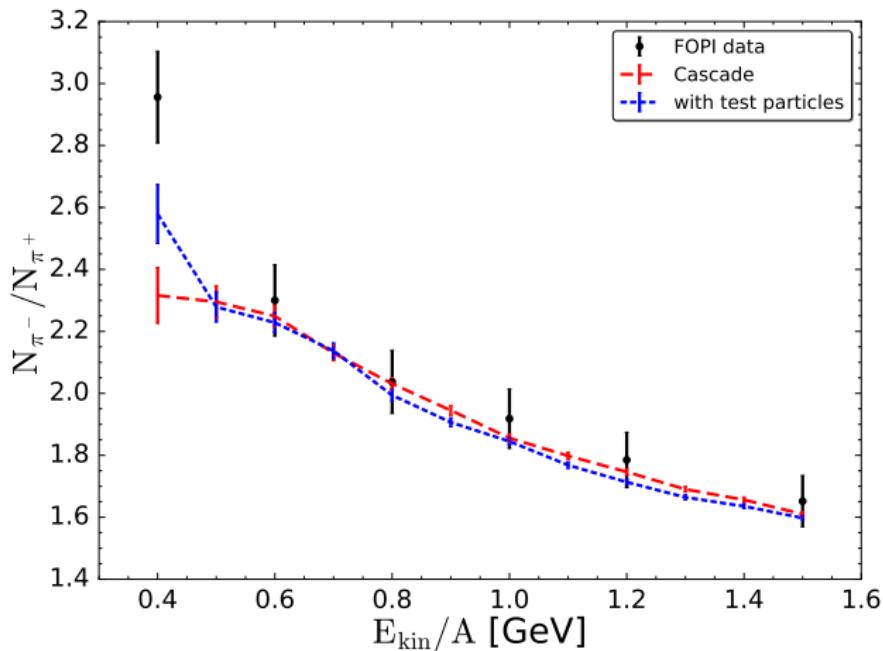
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$\pi^-/\pi^+$  is supposed to be sensitive to symmetry energy



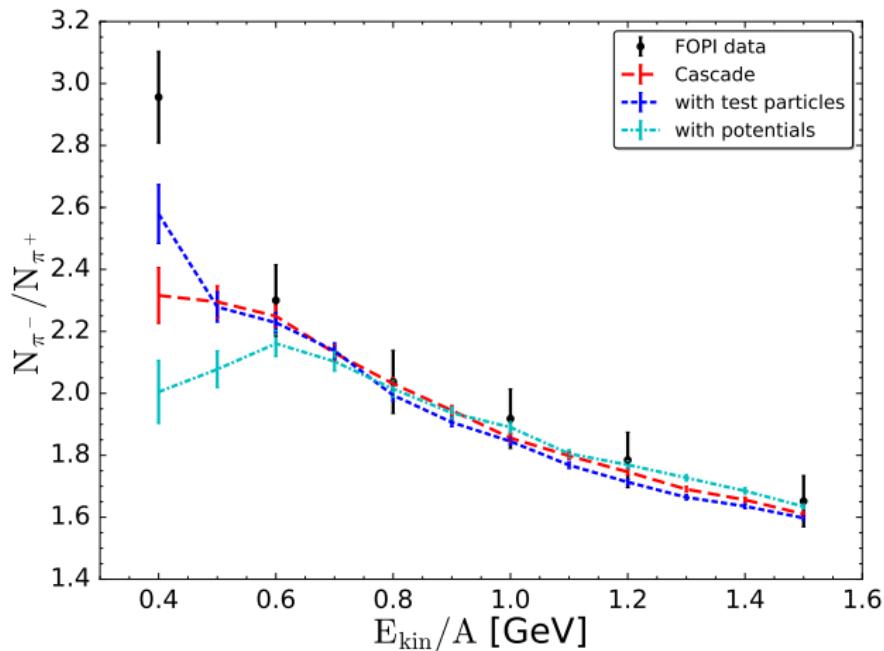
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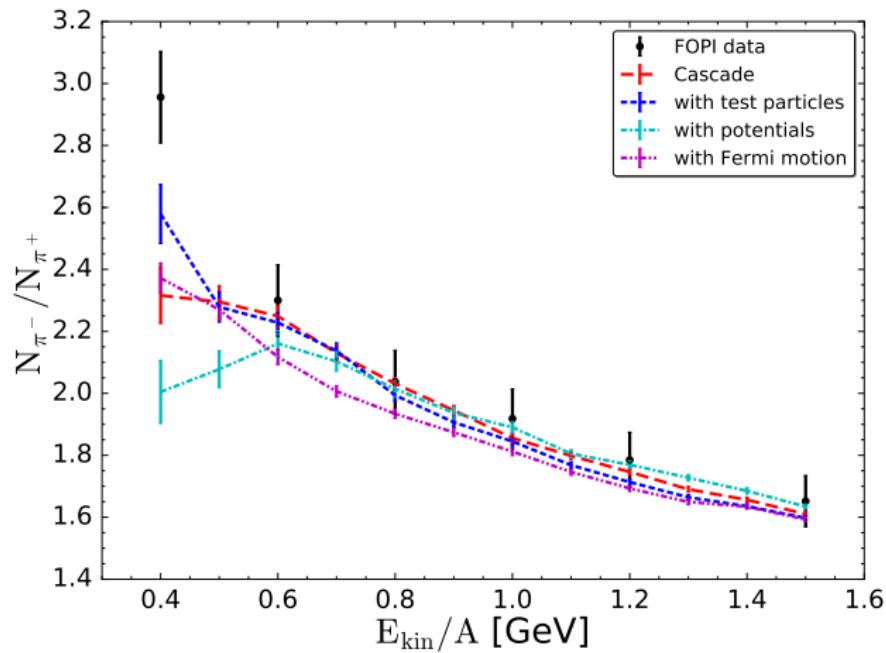
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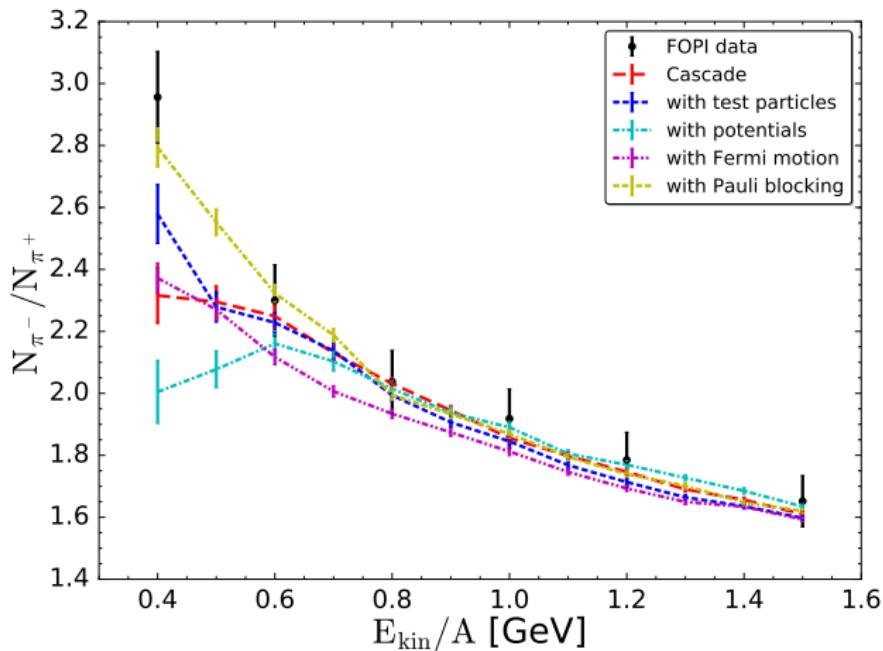
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# Strangeness production

Steinberg et al. [arXiv:1809.03828]

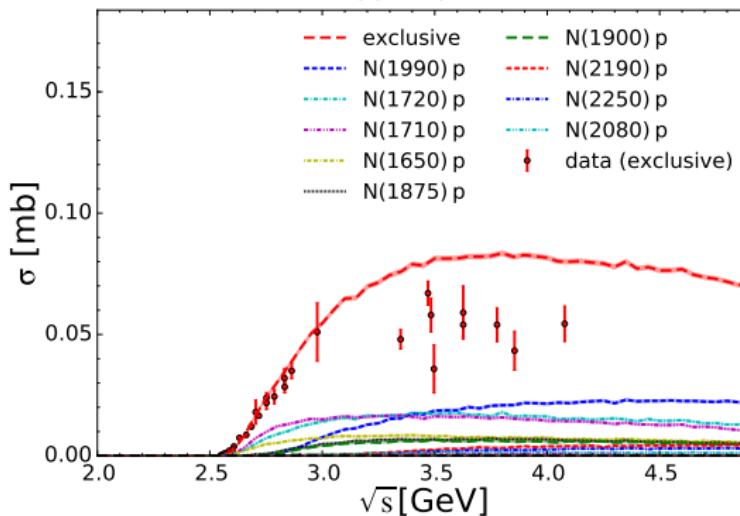
# Kaon production in SMASH

Steinberg et al. [arXiv:1809.03828]

$K^+, K^0: NN \rightarrow NB^* \rightarrow NYK$

$\bar{K}^-, \bar{K}^0: NN \rightarrow NB^* \rightarrow NYK, \pi Y \rightarrow Y^* \rightarrow \bar{K}N$

Kaon production is sensitive to branching ratios  
 $pp \rightarrow \Lambda p K^+$



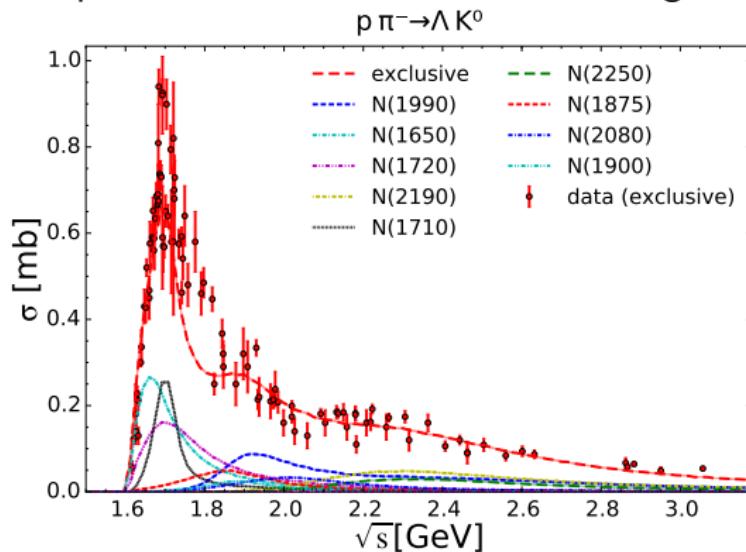
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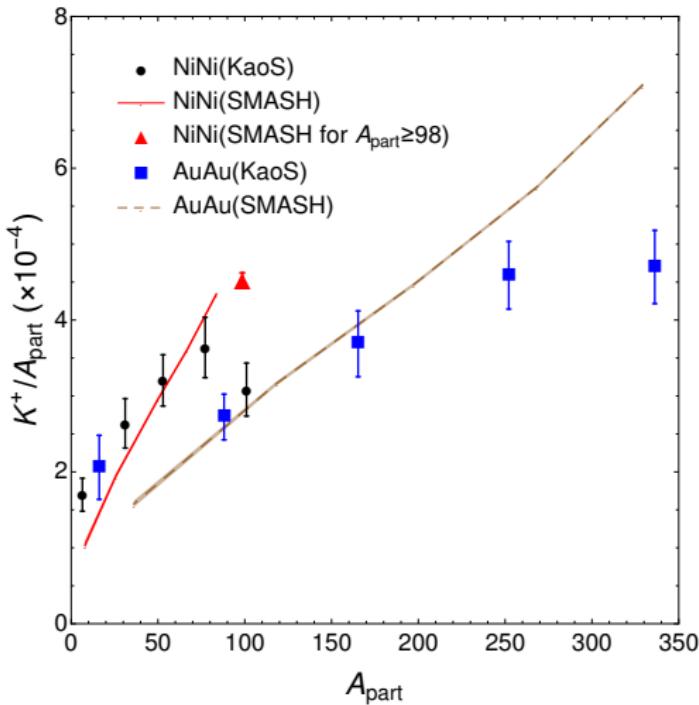
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# Kaon production results: NiNi and AuAu at 1.5 A GeV

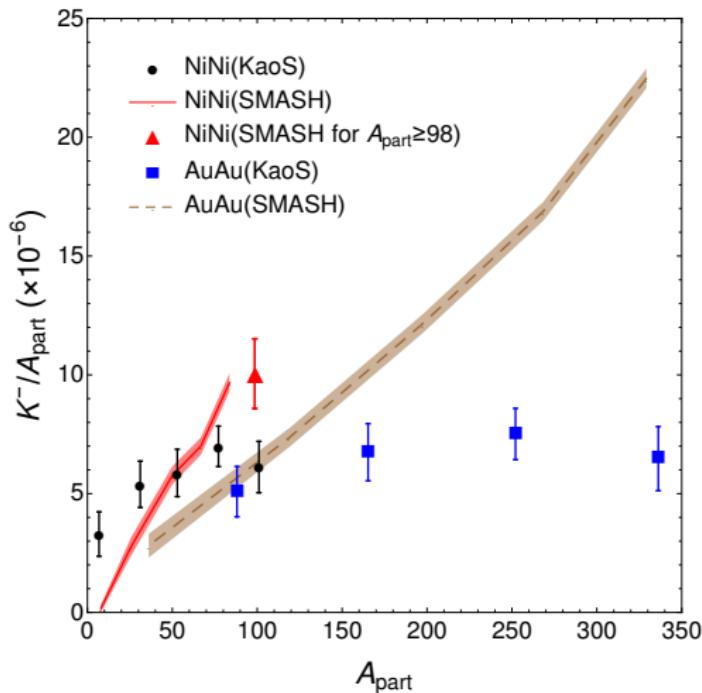
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Kaons  $\approx$  reproduced at small  $A_{\text{part}}$ , overestimated at large  $A_{\text{part}}$

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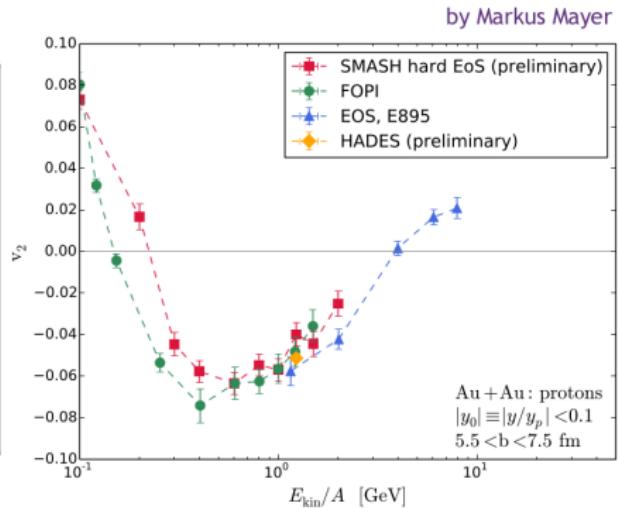
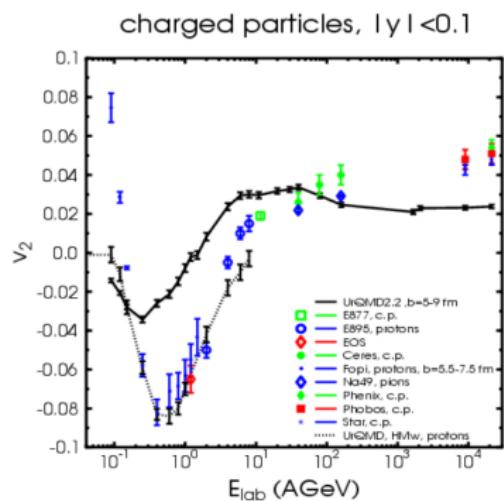
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# Flow

master thesis of Markus Mayer

# Integrated $v_2$ : SMASH vs. UrQMD

HP et al., Phys. Rev. C74 (2006) 064908



SMASH  $v_2$  comparable to UrQMD

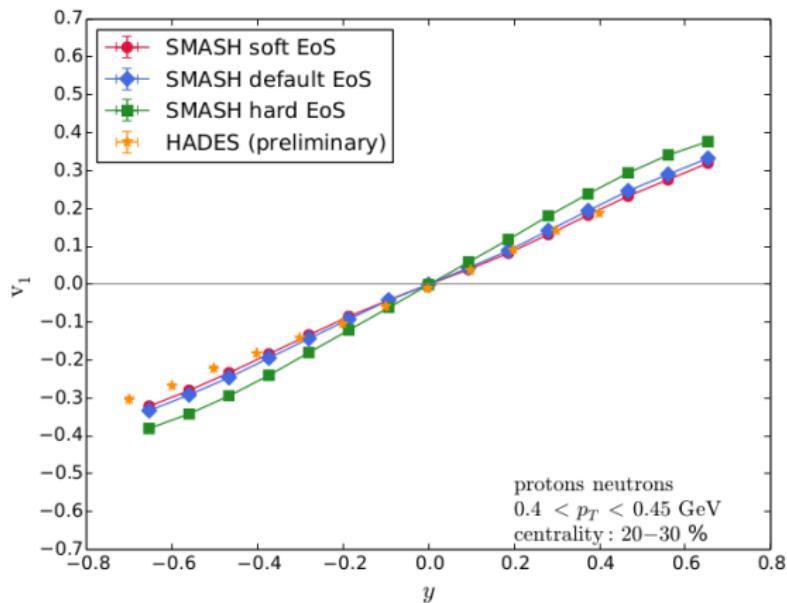
# Comparing SMASH to AuAu at 1.23 a GeV from HADES

- Only comparing selected energy, and centrality here
- More details in master thesis of M. Mayer
- FOPI results at 1.0 and 1.5 A GeV vs. SMASH are similar

$$U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}} \frac{\rho^{1/3}}{\rho_0}$$

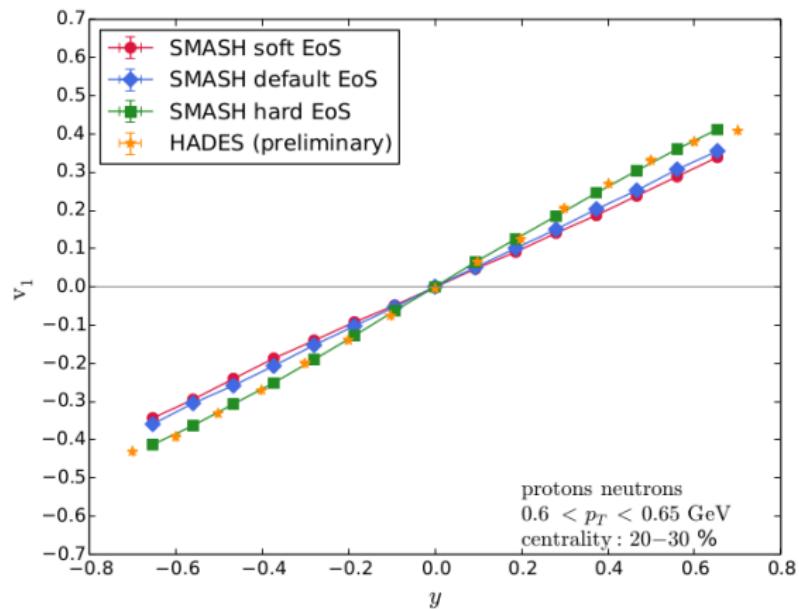
	Soft	Default	Hard
a[MeV]	-356	-209	-124
b[MeV]	303	156.4	71
$\tau$	1.17	1.35	2.0
K[MeV]	200	240	380

# HADES Au+Au: $v_1$ at $E_{Kin} = 1.23 A$ GeV



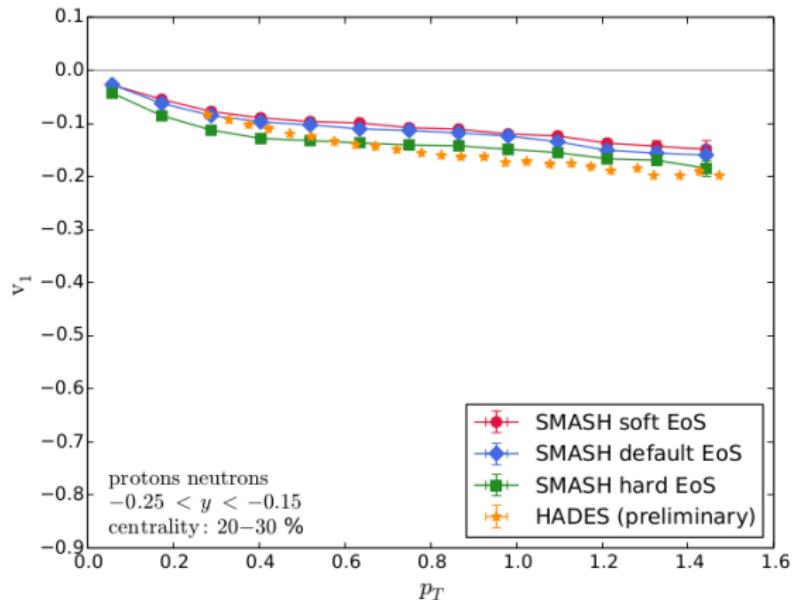
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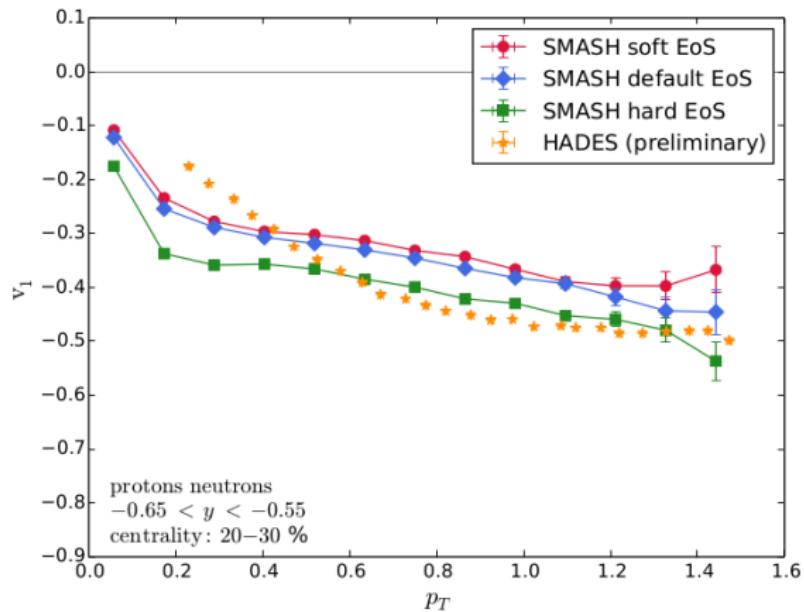
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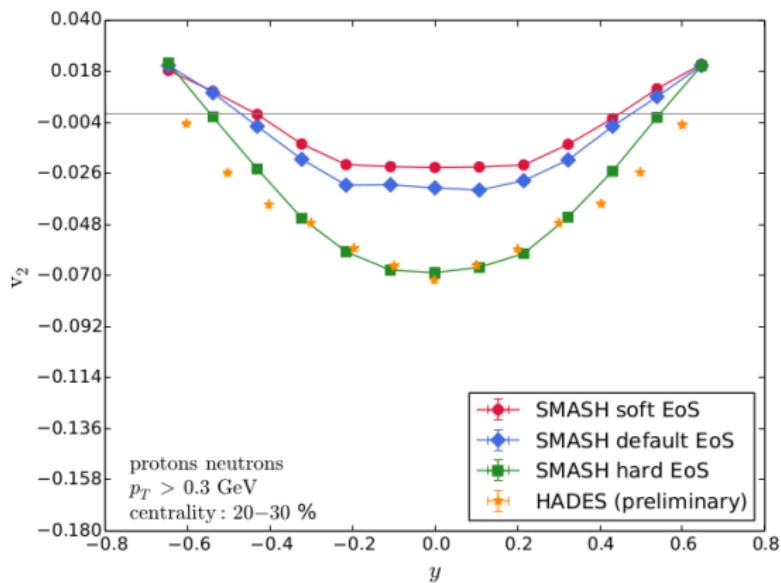
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$v_1$  sensitivity to equation of state is not as large  
But: naive potential, description is not perfect

# HADES Au+Au: $v_2$ and $v_3$ at $E_{Kin} = 1.23 \text{ A GeV}$

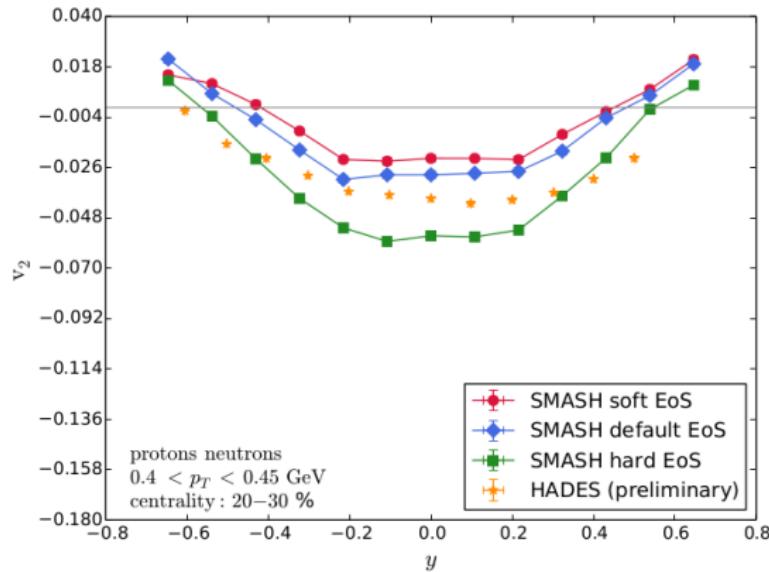


$v_2$  and  $v_3$  consistently suggest harder EoS

Similarly to UrQMD [hep-ph/0608189](#), but contrary to IQMD [1501.05246](#)

But: naive potential, clustering to light nuclei, needs more research

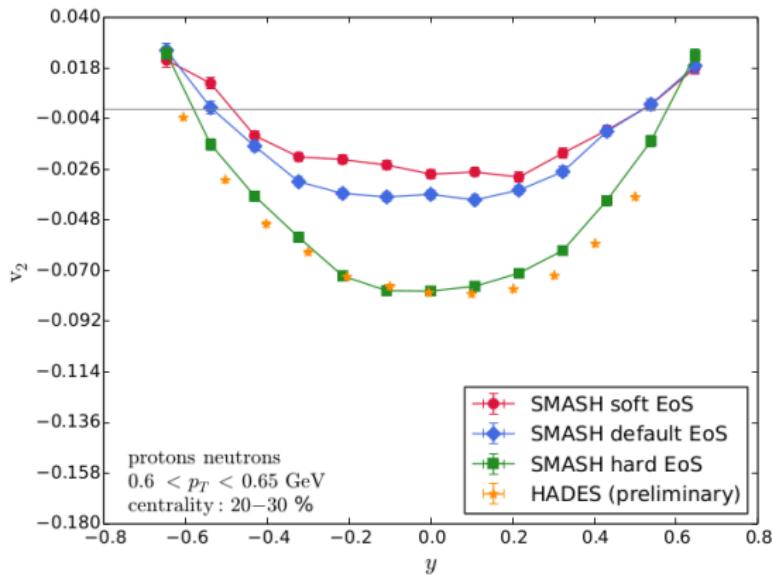
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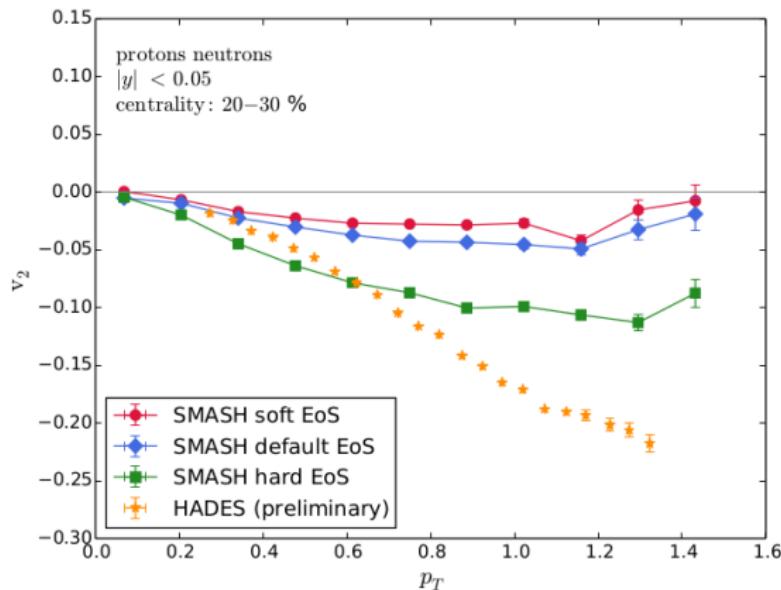
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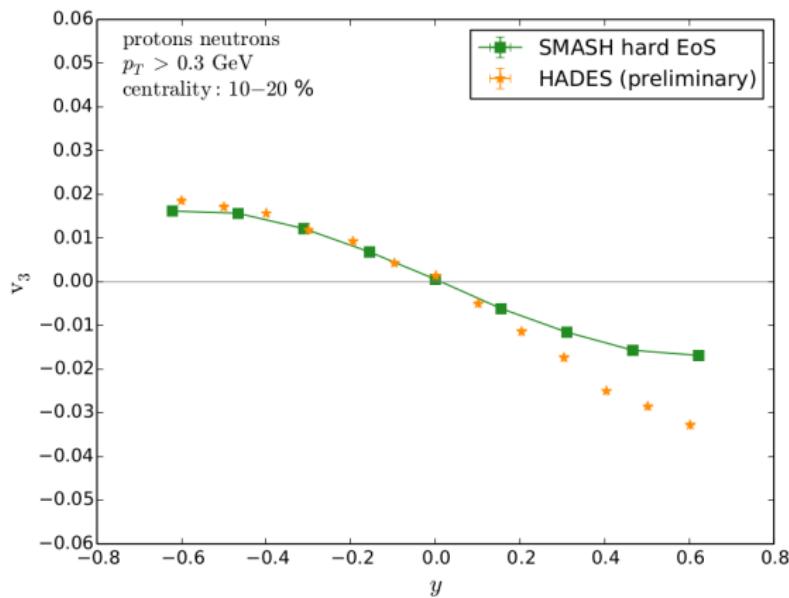
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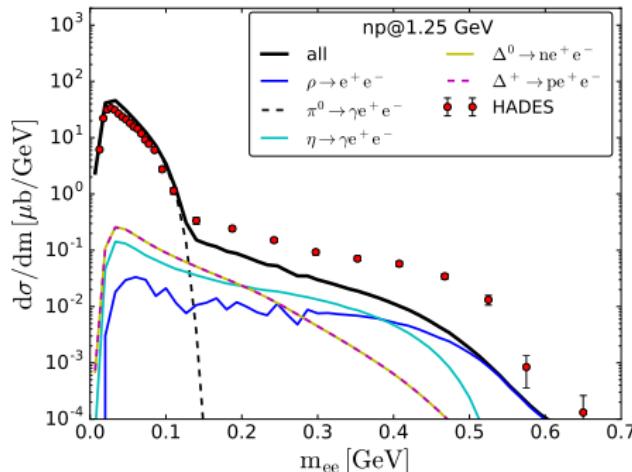
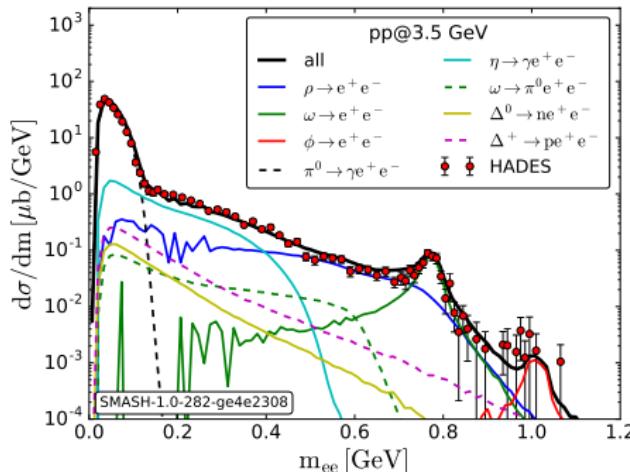
# Dileptons

[Staudenmaier et al., 1711.10297](#)

# Dileptons with SMASH in pp and np

HADES p+p 3.5 GeV and n+p 1.25 GeV

- Dilepton decays included into spectral functions of hadrons specifically SMASH feature
- Shining method  $\implies$  need less statistics



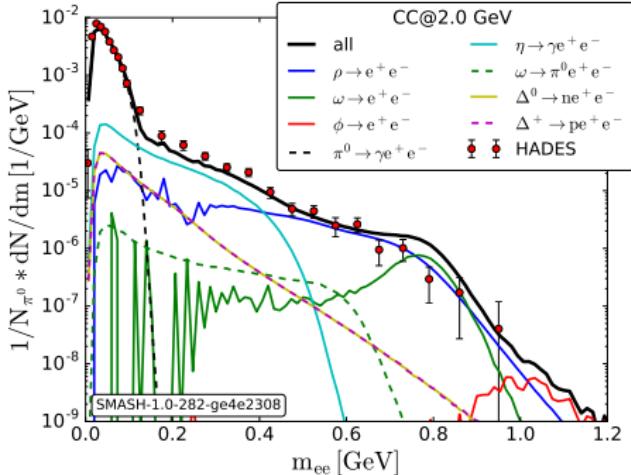
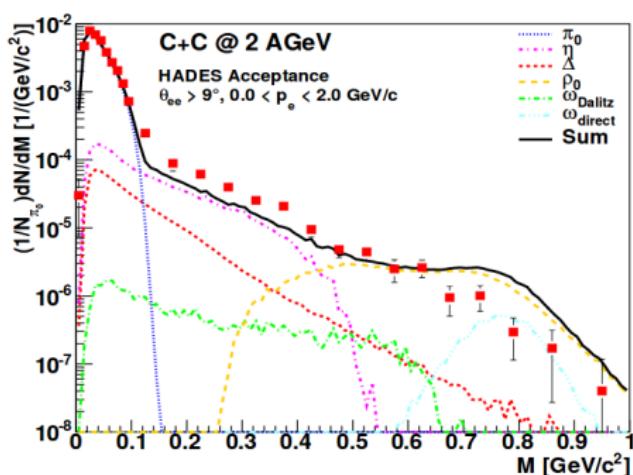
pp at 1.25, 2.2, 3.5 GeV described well, np not so much  
similar to other codes,  $np \rightarrow d\eta?$ ,  $np \rightarrow de^+e^-?$ , simulating  
 $pd \rightarrow X + e^+e^-$

# Dileptons with SMASH vs. UrQMD

HADES C+C 2.0 GeV

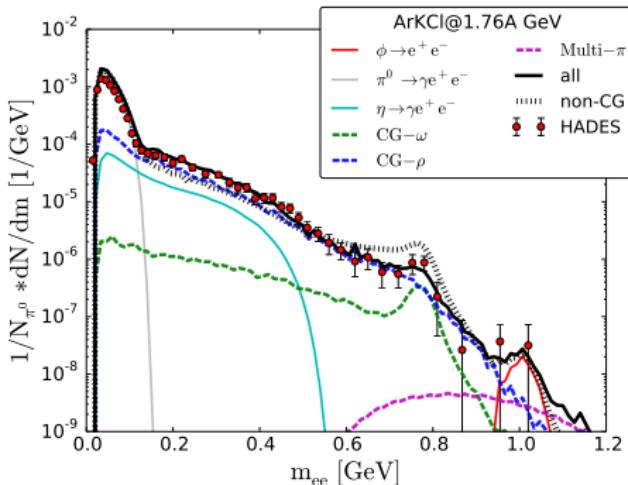
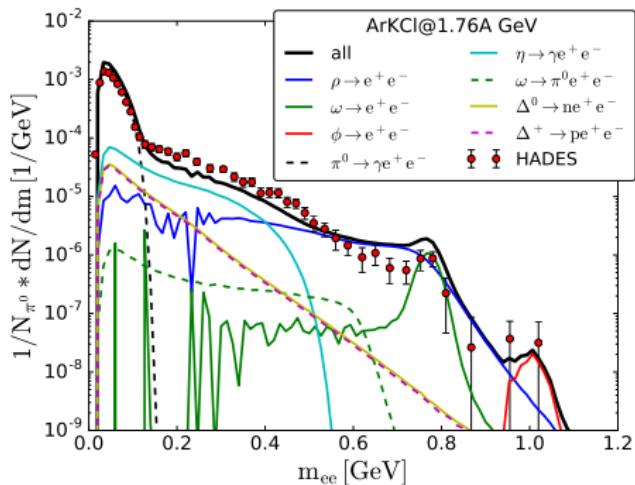
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

Staudenmaier et al., 1711.10297



Similar results. Spectral function of  $\rho$  in SMASH accounts for its dilepton decays  $\rightarrow$  slightly better agreement with data. Agreement is worse in CC at 1 GeV.

# Dileptons: Ar+KCl 1.76 GeV



For larger systems SMASH hadronic treatment is not enough. Adding coarse-graining to SMASH, following S. Endres, changes  $\rho$  and  $\omega$  contributions and describes data better.

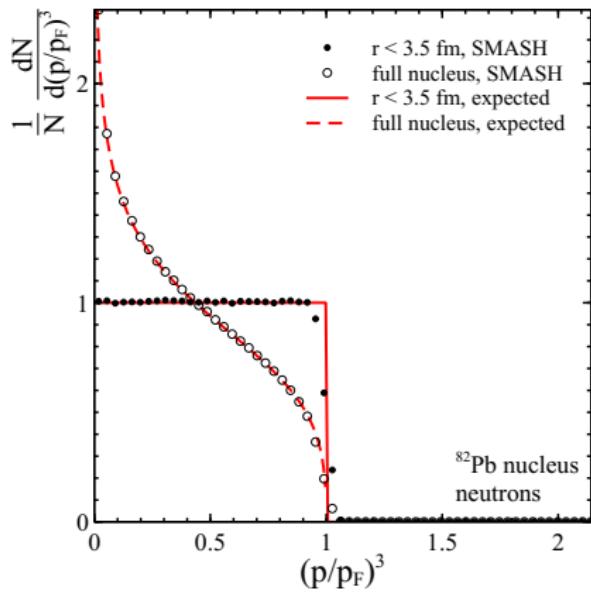
## Summary

- Active investigations ongoing with SMASH at SIS / FAIR energies
- Particle production, in particular pions: sensitive to Fermi motion and Pauli blocking, not only potentials
- Strangeness: sensitive to branching ratios, hard to describe at large multiplicity
- Flows: sensitive to EoS, nuclear matter EoS is likely already in the data, but challenging to extract
- Dileptons: small systems well-described by SMASH hadronic contributions, large systems need medium effects

# Thank you for your attention!

# Fermi motion

- Nucleons are fermions  $\implies$  Pauli blocking
- Filling Fermi-sphere in momentum space,  $p_F(\vec{r}) = \hbar c (3\pi^2 \rho(\vec{r}))^{1/3}$
- Sampling momenta  $p_i$  from Fermi-sphere in the nucleus rest frame
- Boost:  $p'_{iz} = \gamma(p_{iz} + \beta E_i) = \gamma p_{iz} + \frac{p_A}{M_A} \frac{M_A}{A} = p_{\text{beam}} + \gamma p_{iz}$



# Pauli blocking

- Boltzmann equation:

$$p^\mu \frac{\partial f}{\partial x^\mu} = \frac{1}{2} \int \frac{d^3 p_2}{E_2} \frac{d^3 p'_1}{E_1} \frac{d^3 p'_2}{E'_2} \times W(p_1, p_2 \rightarrow p'_1, p'_2) \\ \times (f'_1 f'_2 - f f_2)$$

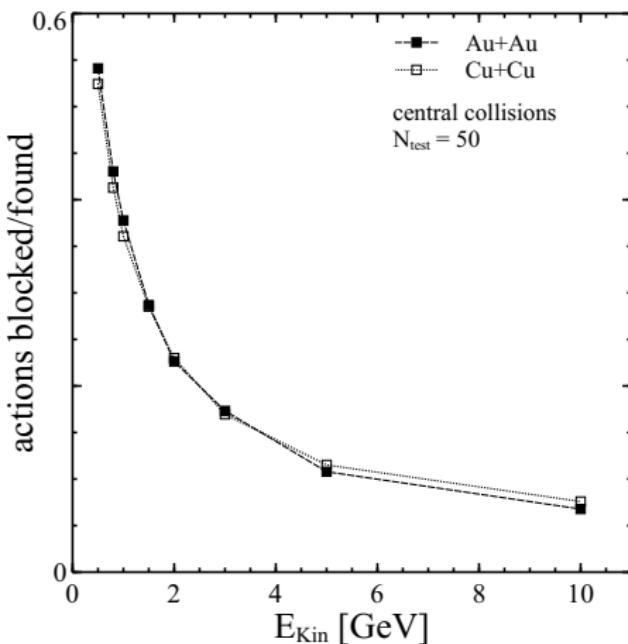
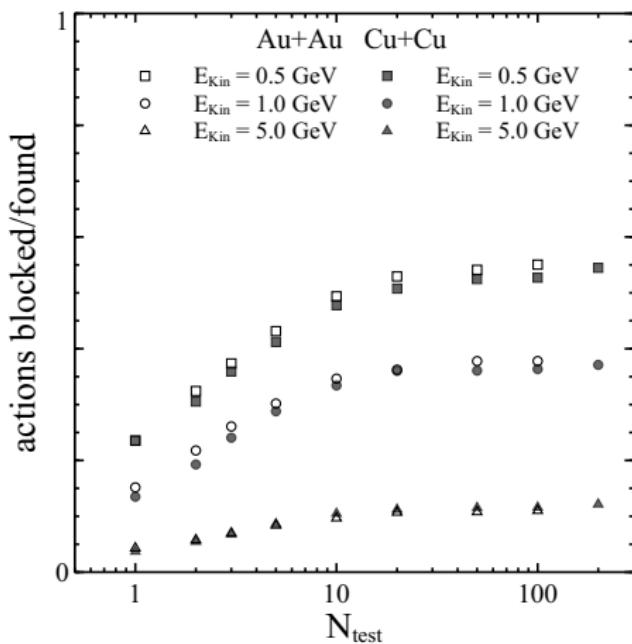
- Boltzmann-Uehling-Uhlenbeck equation

$$p^\mu \frac{\partial f}{\partial x^\mu} = \frac{1}{2} \int \frac{d^3 p_2}{E_2} \frac{d^3 p'_1}{E_1} \frac{d^3 p'_2}{E'_2} \times W(p_1, p_2 \rightarrow p'_1, p'_2) \\ \times (f'_1 f'_2 (1 \pm f)(1 \pm f_2) - f f_2 (1 \pm f'_1)(1 \pm f'_2))$$

- $(1 - f)$  as a multiplicative factor to cross-section
- Reject reactions with probability  $1 - \prod_i (1 - f_i)$ 
  - ▶ Product over all fermions in final state
  - ▶  $f_i$  - phase-space density at fermion position

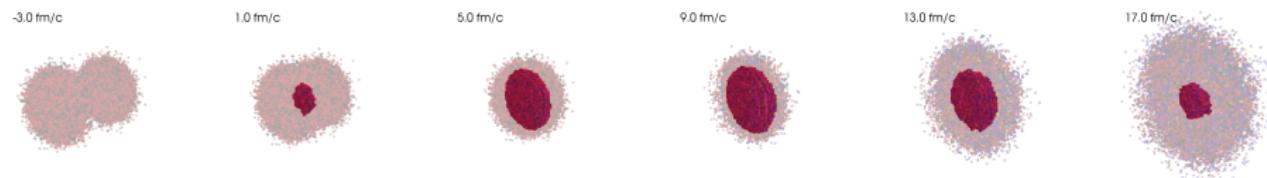
# Pauli blocking II

- Computing phase-space density requires statistics  $\implies$  large  $N_{\text{test}}$
- At large energies Pauli blocking is not important



# Forced canonical thermalization

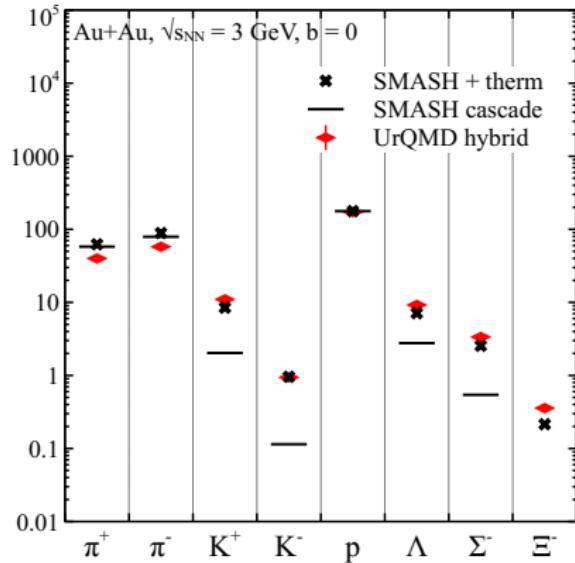
- Applicability of Boltzmann equation breaks at large density  
 $l_{mfp} \gg \lambda_{Compton}$  does not hold anymore
- Switching to hydrodynamics at high density?  
A possible and established way  
however has difficulties, especially at low collision energies  
DO, Petersen, Phys.Rev. C91 (2015) no.2, 024906
- Suggestion: local forced thermalization in the regions of high density  
Effectively simulates intensive interactions and/or formation of quark-gluon plasma  
DO, Petersen, J.Phys. G44 (2017) no.3, 034001



central Au+Au collision,  $E_{kin} = 2$  GeV,  $N_{test} = 100$ , purple region - thermalization region,  
energy density of switching  $0.3$  GeV/fm $^3$

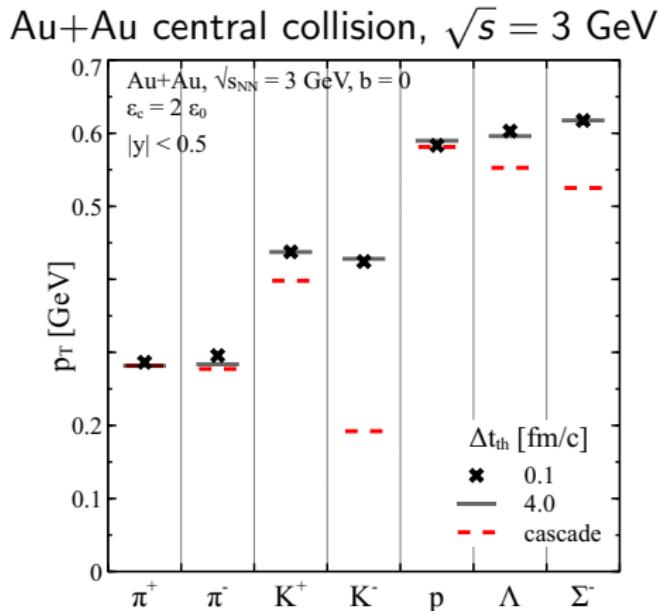
# Effects of forced thermalization: multiplicities

Au+Au central collision,  $\sqrt{s} = 3$  GeV



Thermalization leads to strangeness enhancement - similarly to UrQMD hybrid

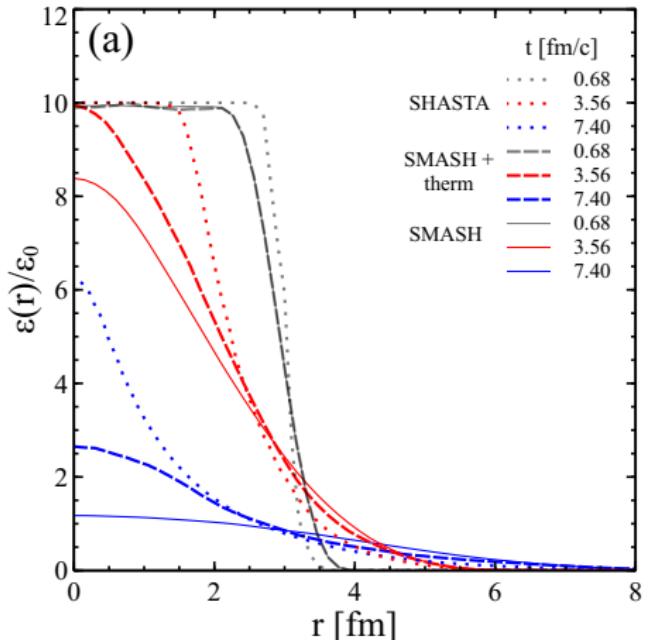
# Effects of forced thermalization: transverse momenta



Thermalization leads to pressure isotropization and transversve push

# Forced thermalization: expanding sphere setup

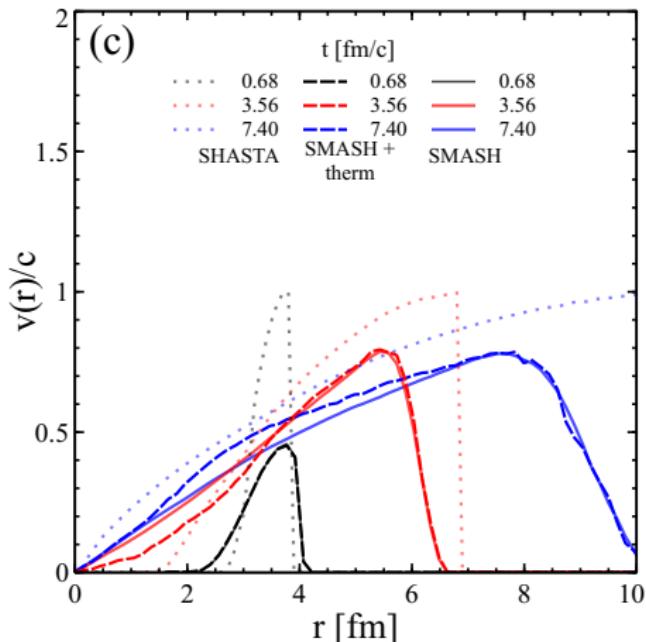
Evolution of  $R = 3$  fm sphere, initial  $\epsilon = 10\epsilon_0$ ,  $n_B = 0$ .  
Thermalization at  $\epsilon > 2\epsilon_0$  every  $\Delta t_{th} = 1$  fm.



SMASH + thermalization is between transport and hydro

# Forced thermalization: expanding sphere setup

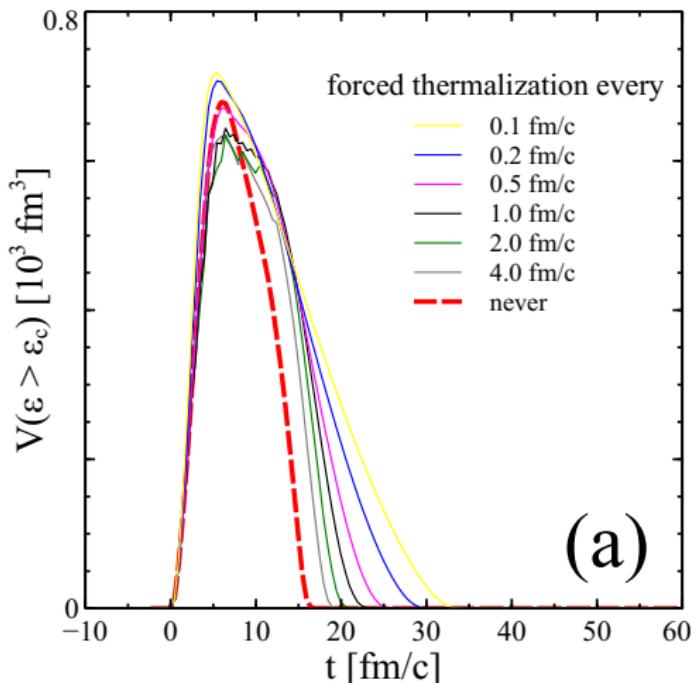
Evolution of  $R = 3$  fm sphere, initial  $\epsilon = 10\epsilon_0$ ,  $n_B = 0$ .  
Thermalization at  $\epsilon > 2\epsilon_0$  every  $\Delta t_{th} = 1$  fm.



SMASH + thermalization is between transport and hydro

# Effects of forced thermalization

Au+Au central collision,  $\sqrt{s} = 3 \text{ GeV}$ ,  $\epsilon_c = 2\epsilon_0$



High-density region exists longer

# $\langle T \rangle$ and $\langle \mu_B \rangle$ in the thermalization region

