SMASH Hadronic Transport and Hybrid Approach

Hannah Elfner

September 15th 2022, HFHF Retreat, Castiglione della Pescaia

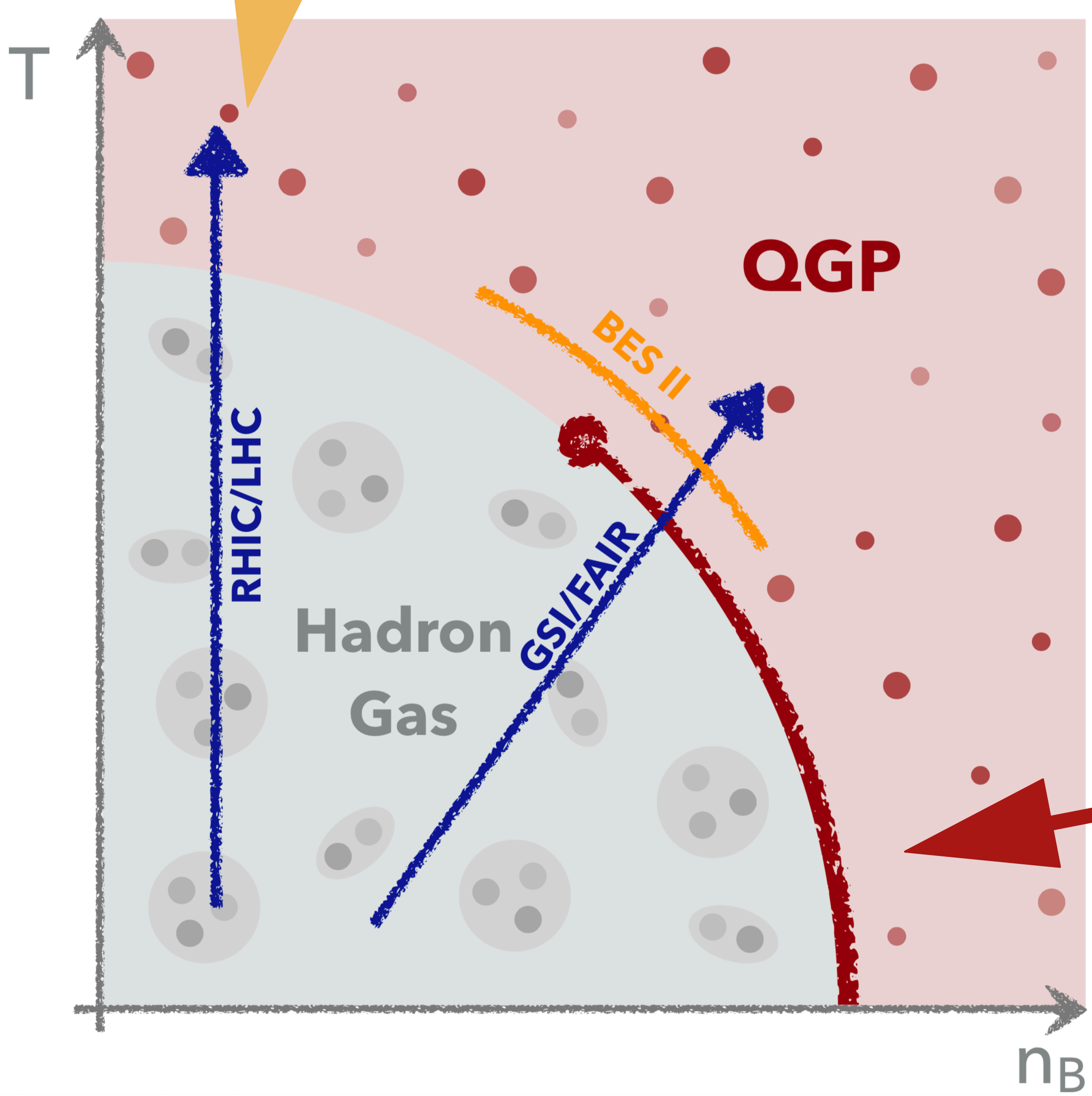
Outline

- SMASH transport approach
  - Status and recent developments
- SMASH Hybrid Approach
  - Interfacing SMASH and vHLLE
  - Particle production at SPS/BES energies
  - μ_B dependence of transport coefficients
- Summary

SMASH Transport Approach

The Phase Diagram

Standard approach at high energies
- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic rescattering



- Two regimes with well-established approaches
- Goals:
  – Constraints on the equation of state of nuclear matter
  – Determine limit of applicability of hadronic transport approach
  – Qualitative signatures of first order phase transition

Standard approach at low beam energies
- Hadronic transport approaches
- Resonance dynamics
- Nuclear potentials

Simulating Many Accelerated Strongly-Interacting Hadrons

- Hadronic transport approach:
  - Includes > 150 mesons and baryons
  - Based on relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\text{coll}}$$

  - Open source code: C++, Git, Python Analysis Suite
  - Already used by HADES, CBM, JETSCAPE, BEST and individuals

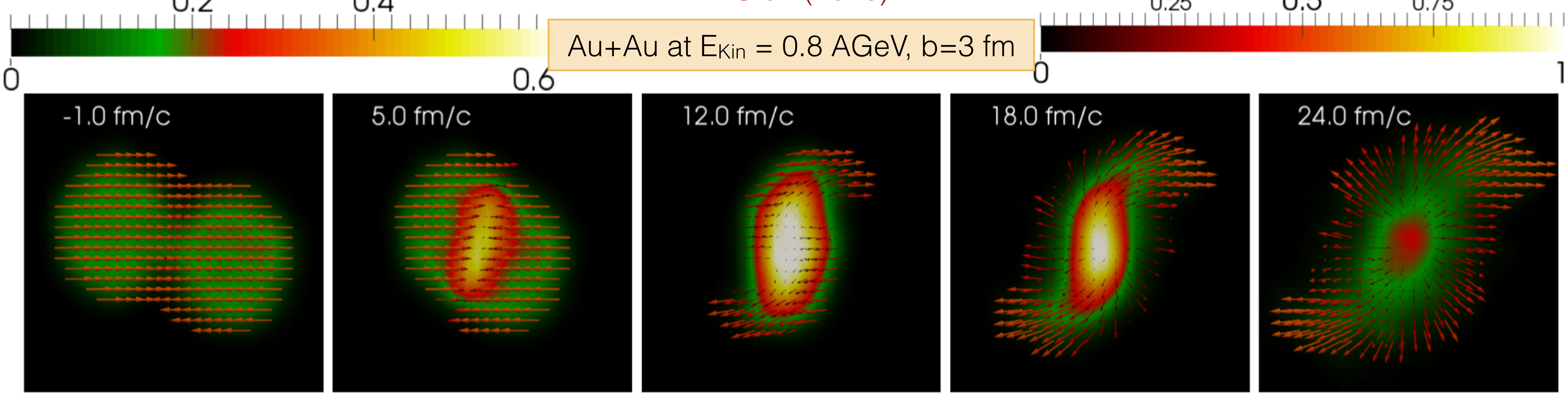
smash

https://smash-transport.github.io

Energy density [GeV/fm³]

J. Weil, HP (now Elfner) et al, PRC 94 (2016)

Landau frame velocity (arrows)



The SMASH Team

- In Frankfurt:
  - Gabriele Inghirami
  - Alessandro Sciarra
  - Jan Staudenmaier
  - Zuzana Paulinyova
  - Justin Mohs
  - Jan Hammelmann
  - Niklas Götz
  - Renan Hirayama
  - Nils Saß
  - Antonio Bozic
  - Lucas Constantin
  - Julia Gröbel
  - Branislav Balinovic
  - + Anna Schäfer

- In US/Bielefeld:
  - Dmytro Oliinychenko
  - Agnieszka Sorensen
  - Oscar Garcia-Montero

Group excursion in May 2022

Degrees of Freedom

- Easily configurable by human-readable input files

N	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^-_{1672}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^-_{2250}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}	
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}	
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}		
N_{1720}		Λ_{1830}	Σ_{2250}		
N_{1875}		Λ_{1890}			
N_{1900}		Λ_{2100}			
N_{1990}		Λ_{2110}			
N_{2060}		Λ_{2350}			
N_{2080}					
N_{2100}					
N_{2120}					
N_{2190}					
N_{2220}					
N_{2250}					

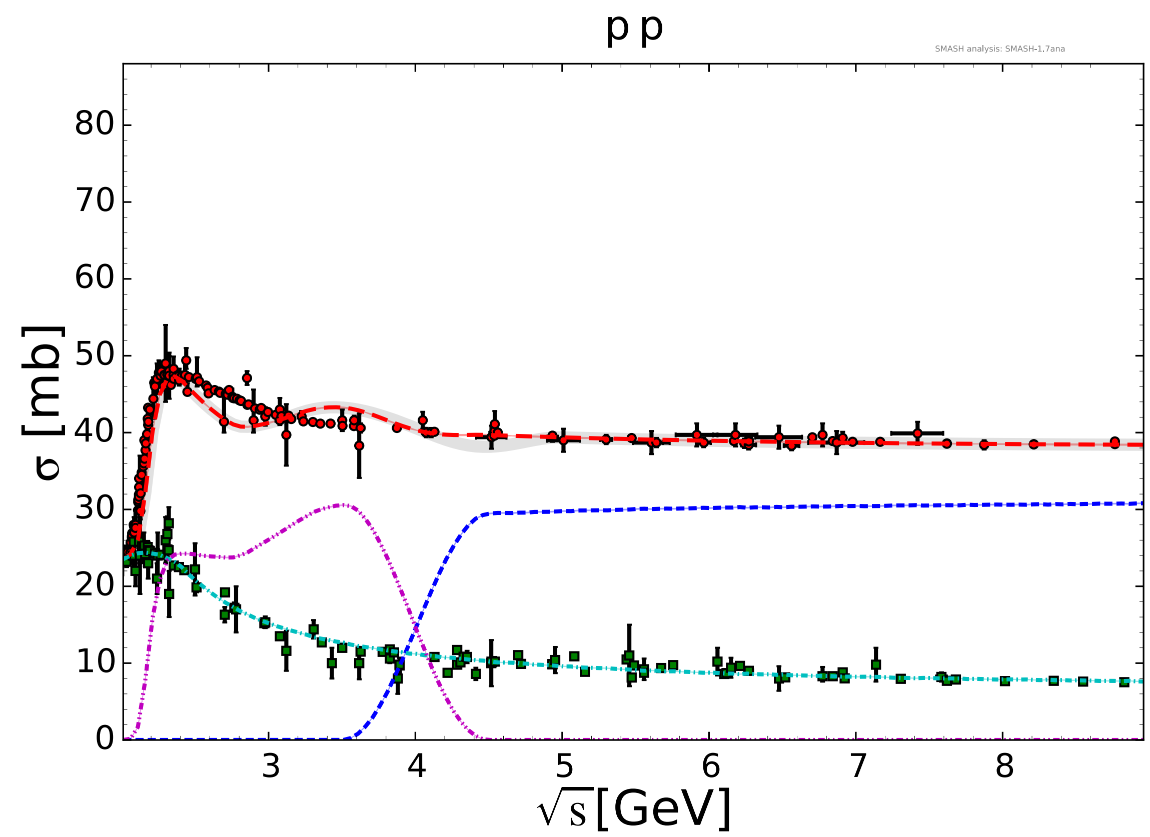
As of SMASH-1.7

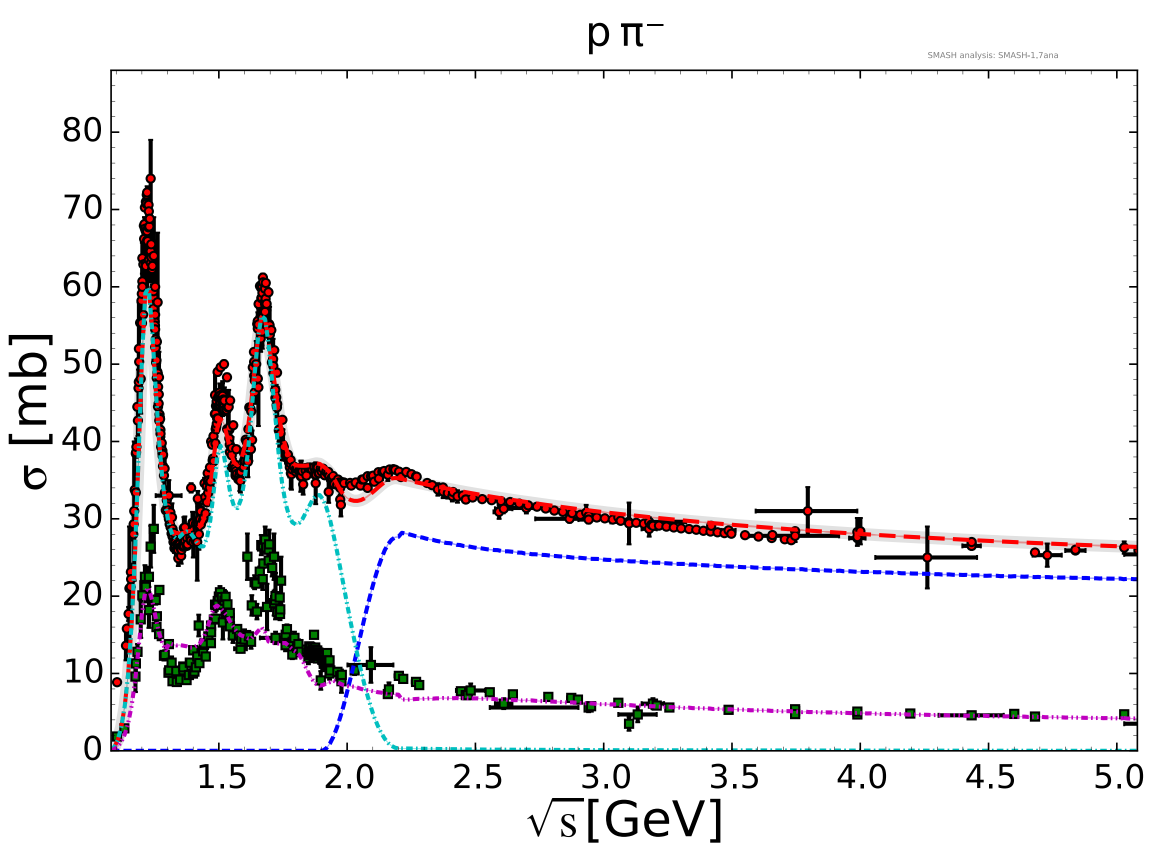
Unflavored				Strange
π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
π_{1300}	$f_{0\ 1370}$	$f_2'{}_{1525}$		K^*_{892}
π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
	$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
η_{1405}		$f_{1\ 1285}$		K^*_{1680}
η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
	ϕ_{1680}			$K_3^*{}_{1780}$
σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
	$h_{1\ 1170}$			$K_4^*{}_{2045}$
ρ_{776}		$\pi_{1\ 1400}$		
ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
ρ_{1700}				
	$a_{1\ 1260}$	$\eta_{2\ 1645}$		
ω_{783}				
ω_{1420}		$\omega_{3\ 1670}$		
ω_{1650}				

- + corresponding antiparticles
- Perturbative treatment of photons and dileptons
- Isospin symmetry

- Mesons and baryons according to particle data group
- Isospin multiplets and anti-particles are included

Elementary Cross Sections



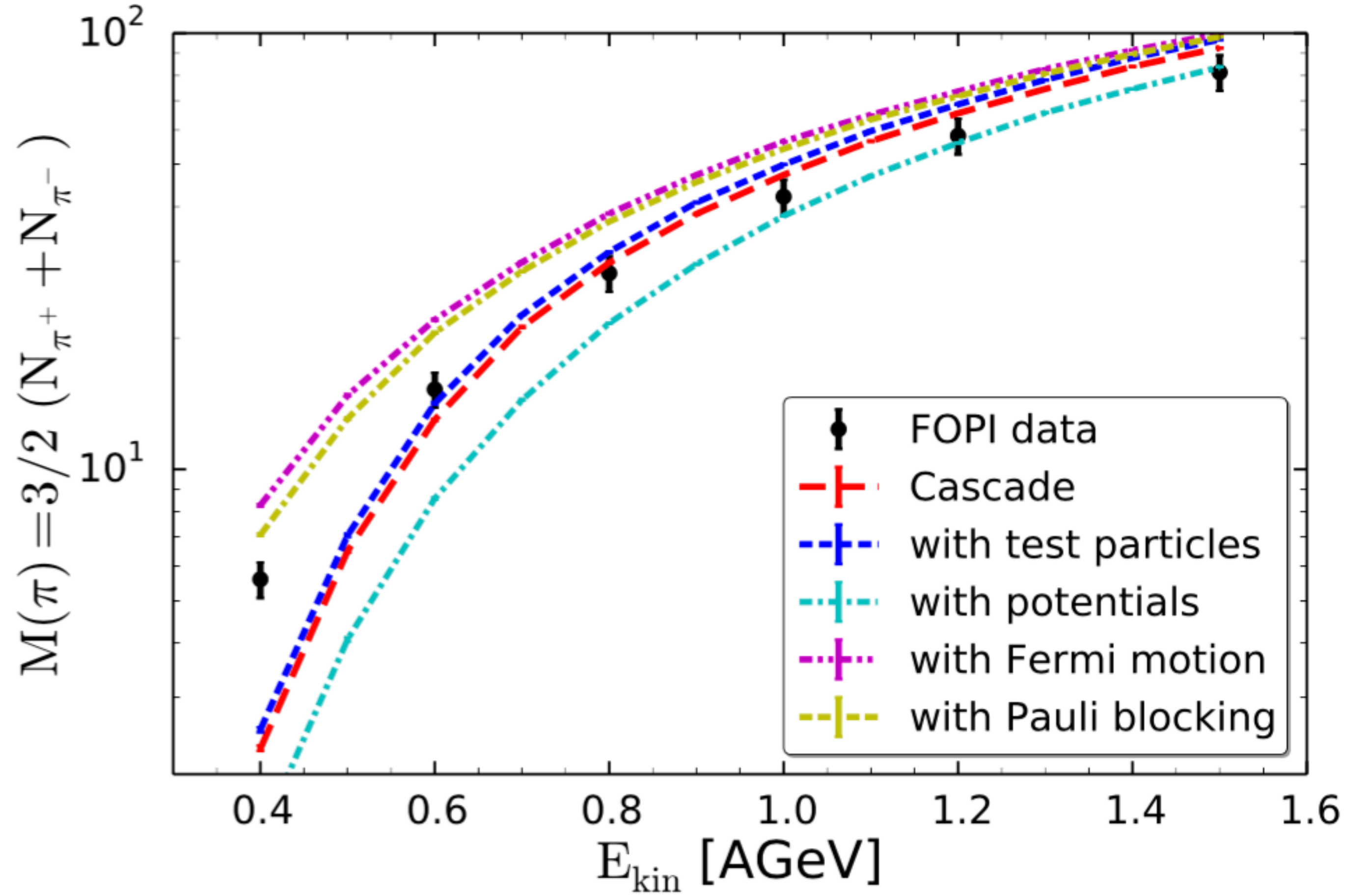


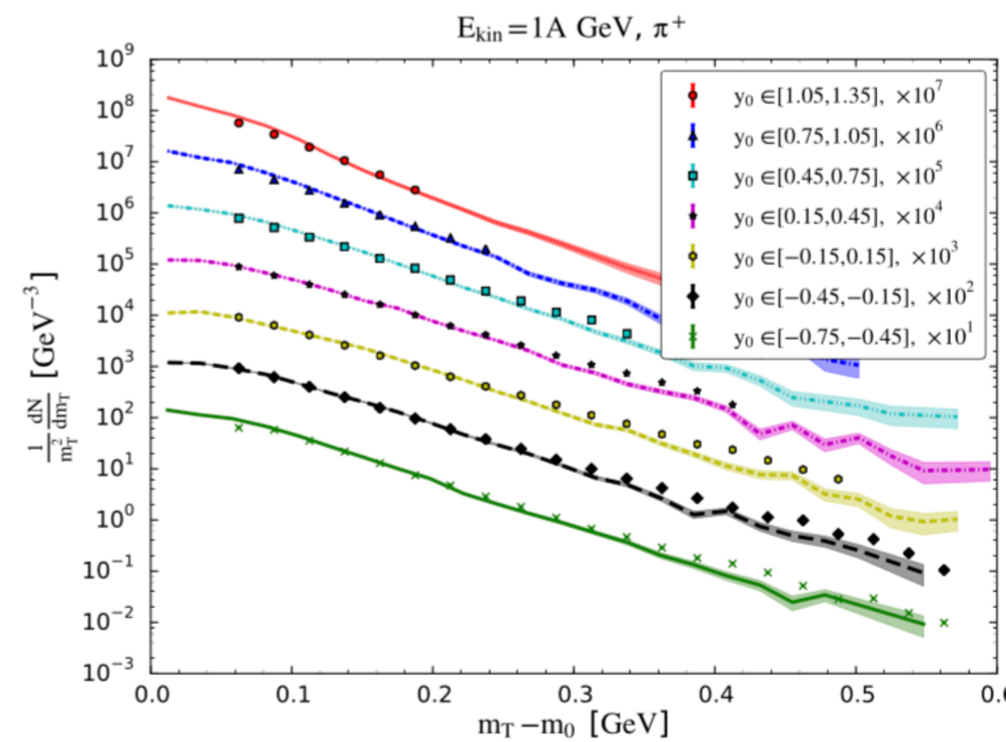
- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Transition from resonances to strings at intermediate energies

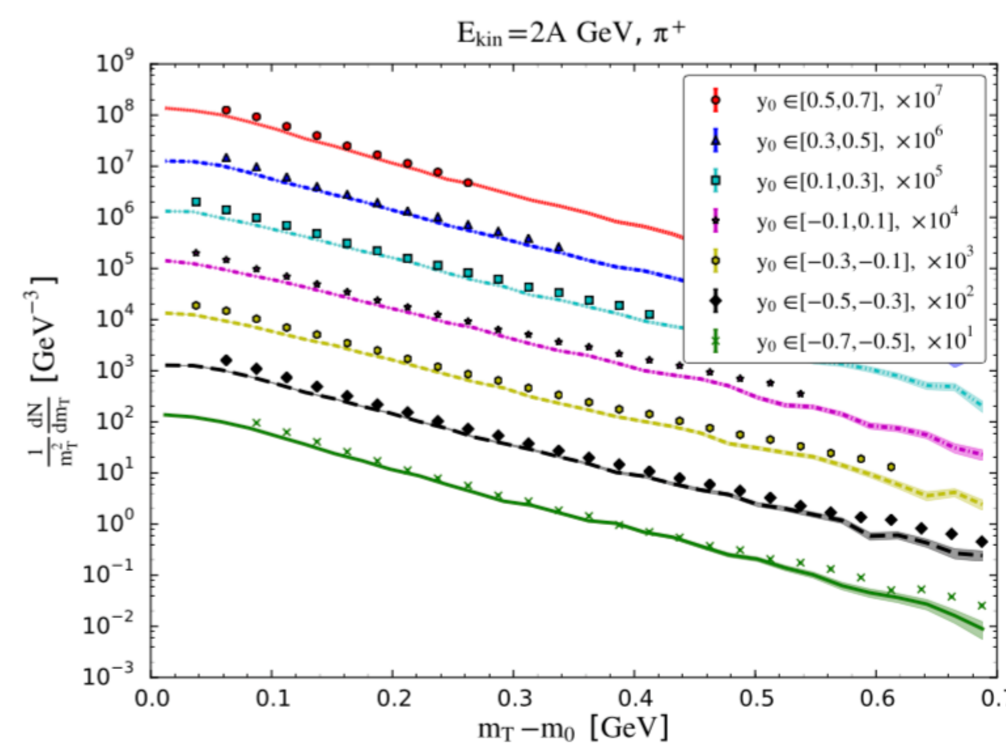
J. Weil et al, PRC 94 (2016)

Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Nice agreement with SIS experimental data







Note: consecutive addition of features

J. Weil et al, PRC 94 (2016)

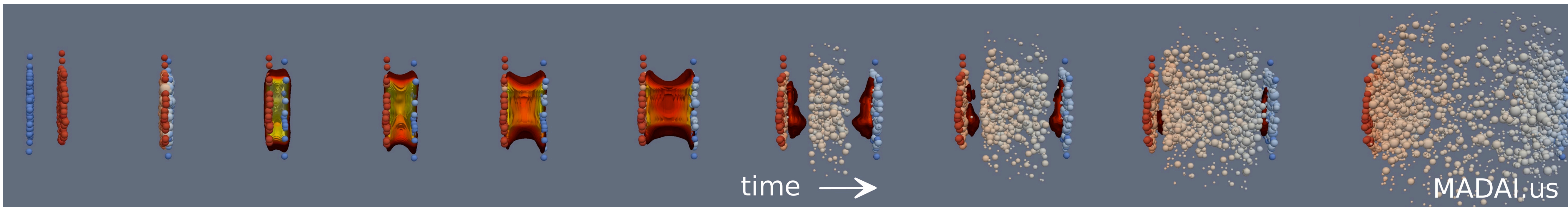
Recent Developments

- Hybrid approach with vHLLE -> main topic of today's talk
- Update of nuclear mean fields
  - Coulomb field and momentum dependence
  - Clustering for light nuclei
- Multi-particle interactions (see Jan Staudenmaier)
  - 2<->1, 2<->2, 2<->3, 5<->2, … with stochastic rates
- Study collisional broadening (see Renan Hirayama)
- Fluctuations of conserved quantities
  - Effect of hadronic rescattering on skewness, kurtosis etc (work in progress by Jan Hammelmann)
- Improved interface for usage as third party library (e.g. in JETSCAPE

SMASH Equilibration and Higher Beam Energies

Time Evolution of Heavy-Ion Collisions

- Detailed dynamical modeling is essential to learn something about hot and dense QGP stage



$1x\ 10^{-23}$ s

10×10^{-23} s

30×10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

Hybrid approaches are current tool of choice

Hybrid approaches

Transport

Microscopic description of the whole phase-space distribution

Non-equilibrium evolution based on the Boltzmann equation

$$(p^\mu \partial_\mu) f = I_{coll}$$

Partonic or hadronic degrees of freedom

Cross-sections are calculable using different techniques

Phase transition?

Hydrodynamics

Macroscopic description

Local equilibrium is assumed

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu (n u^\mu) = 0$$

+viscous corrections

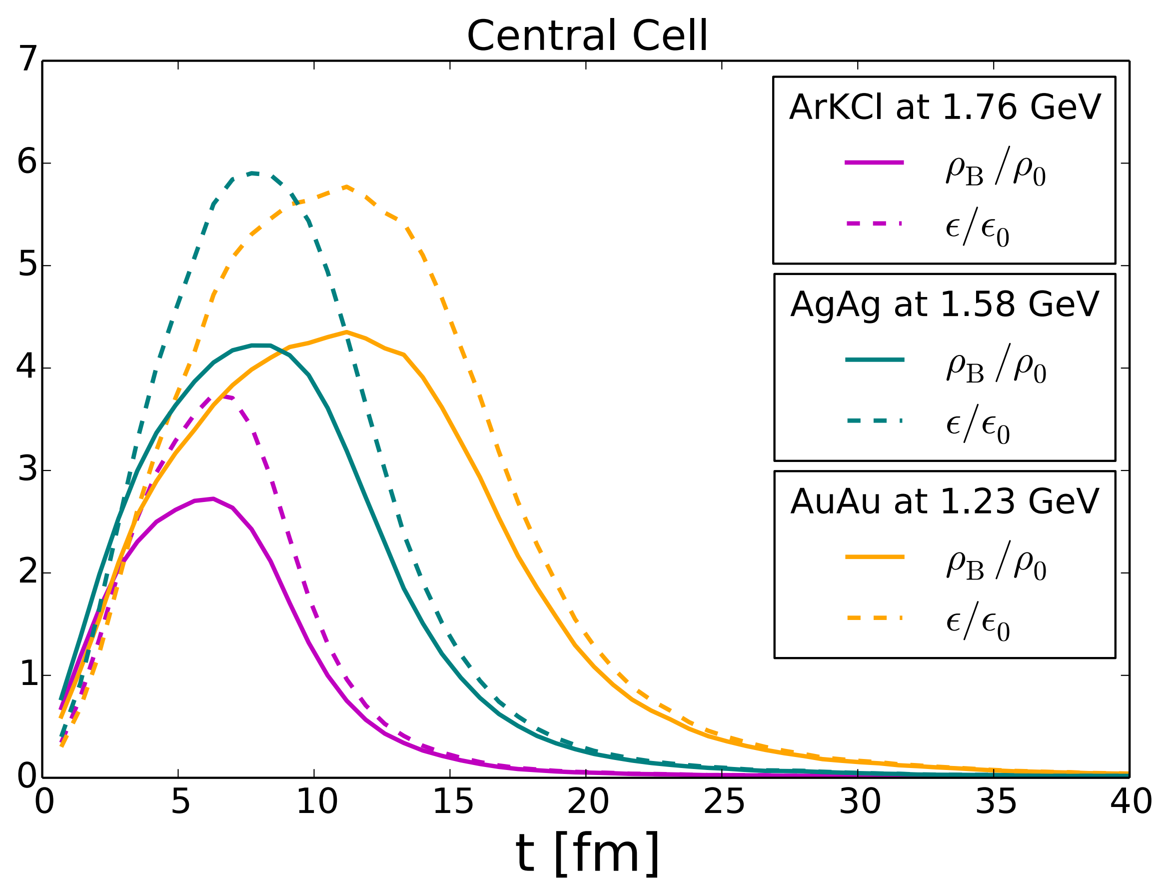
Propagation according to conservation laws

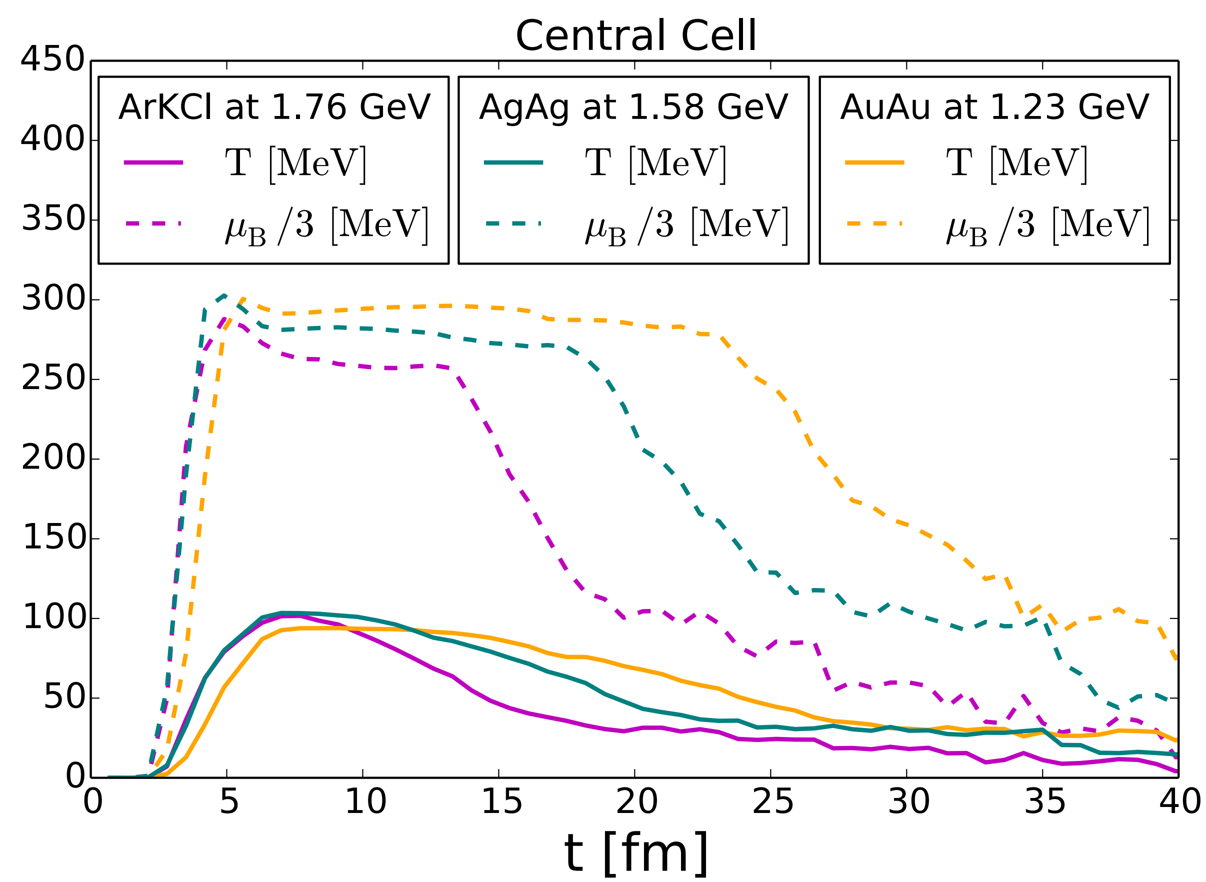
Equation of state is an explicit input

Boundary conditions: Breakdown of equilibrium assumptions?

Time Evolution

- Density and temperature in a central cell for heavy ion collisions at SIS-18 energies





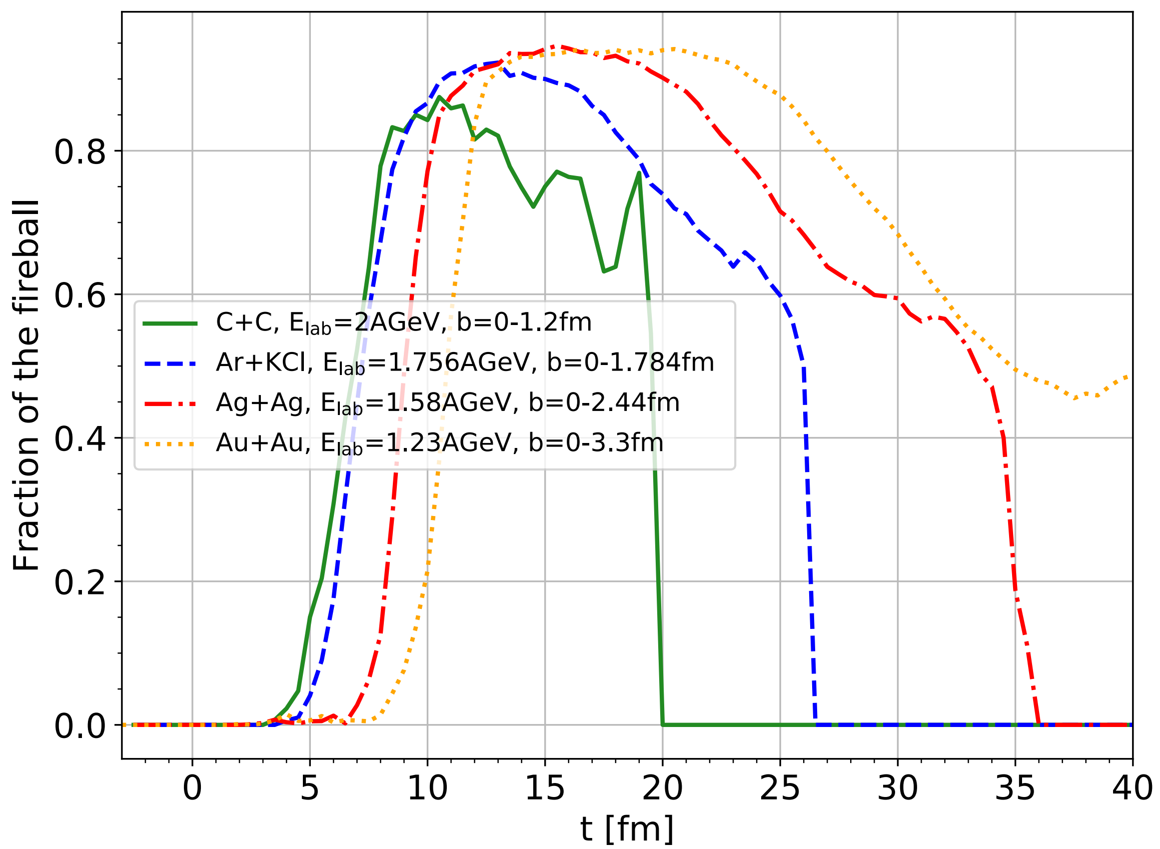
J. Staudenmaier, N. Kübler and HE, PRC 103, 2021

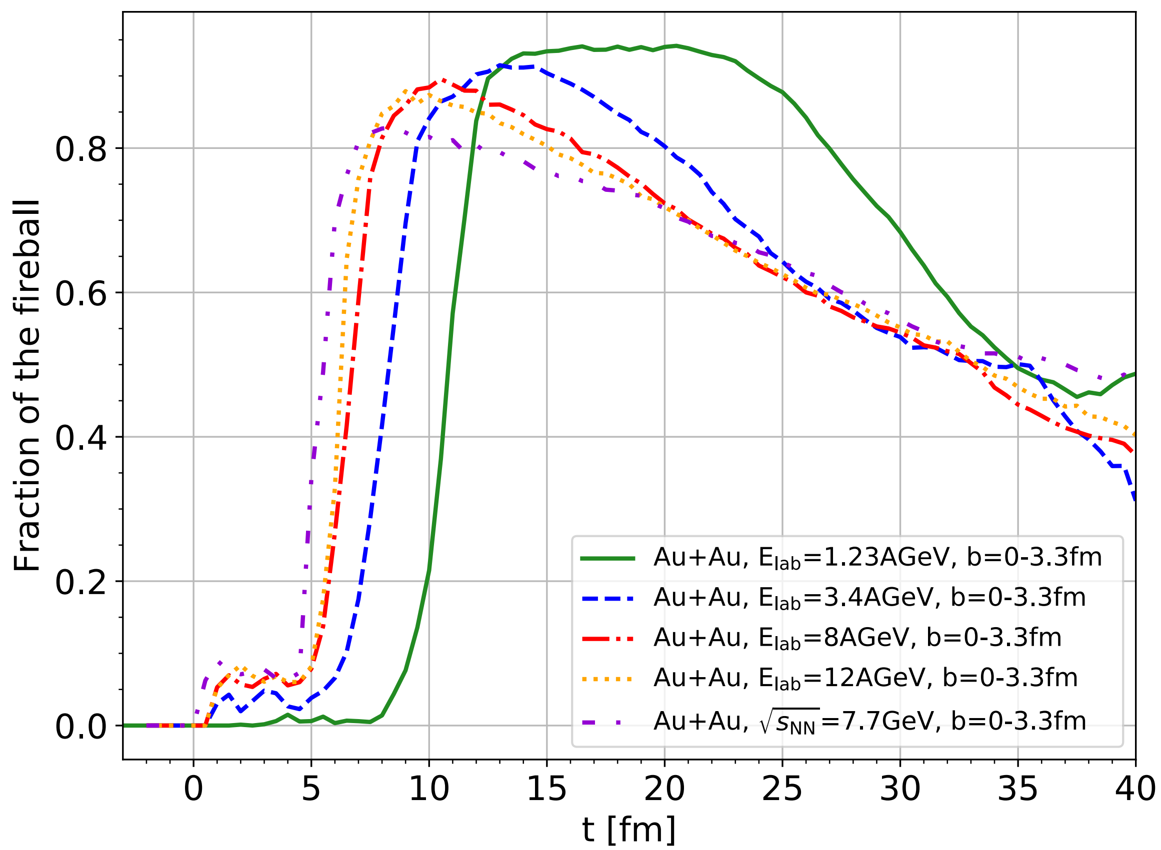
- 2-4 times nuclear ground state density reached

Local Equilibrium

- Percentage of fireball close to local equilibrium in different collision systems (left) and in Au+Au collisions at different beam energies (right)

X, Y < 0.3 and ε > 1 MeV/fm³





- Calculation within coarse-grained SMASH hadronic transport approach by investigating properties of $T^{\mu\nu}$

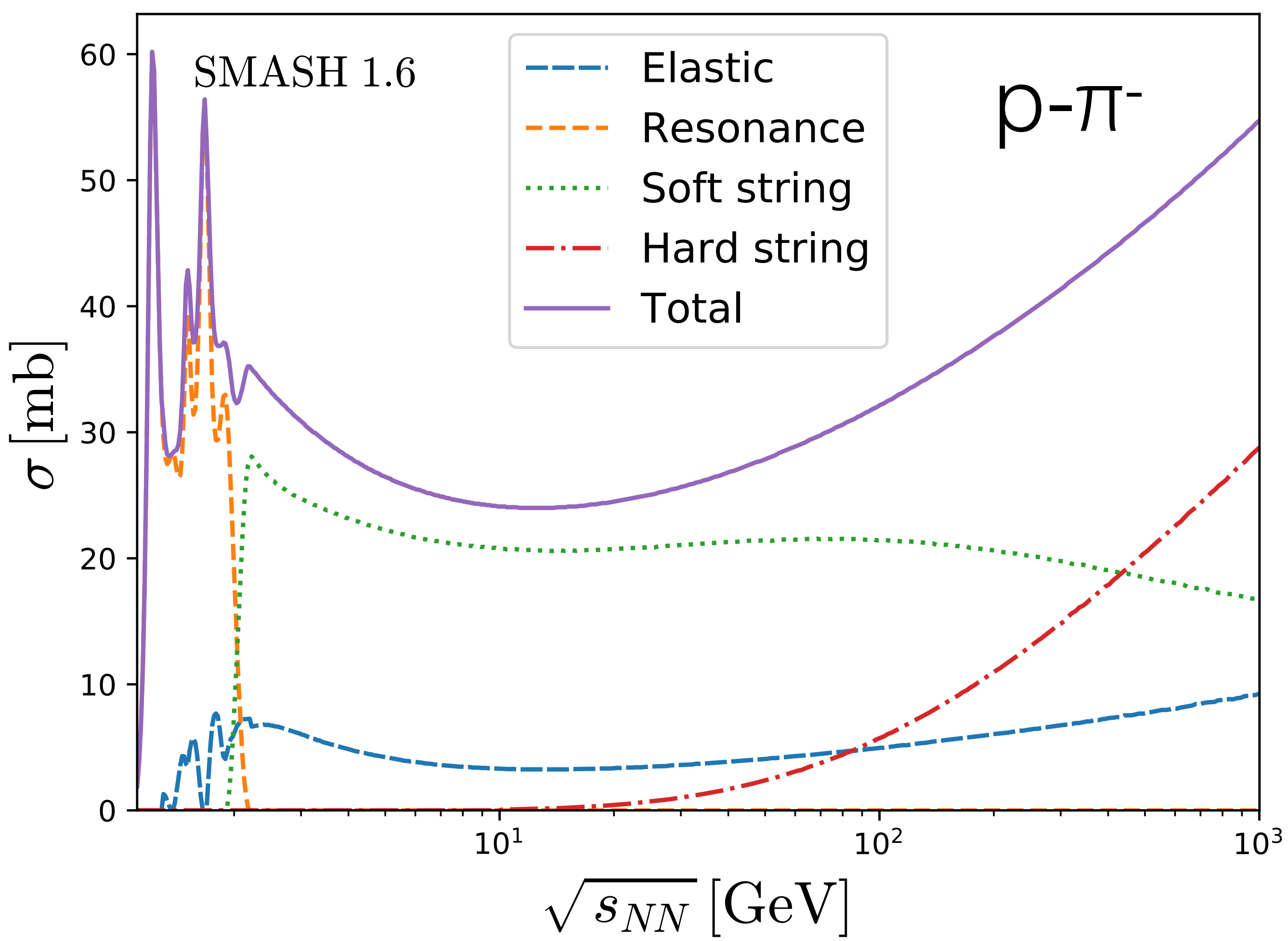
G. Inghirami and H. Elfner, EPJC 82 (2022)

Moving to Higher Energies

- High energy cross-section is dominated by string excitation and fragmentation

J. Mohs, S. Ryu and HE, *J.Phys.G* 47 (2020)

- Soft strings
  - Pythia is only employed for fragmentation
  - Single-diffractive, double diffractive and non-diffractive processes



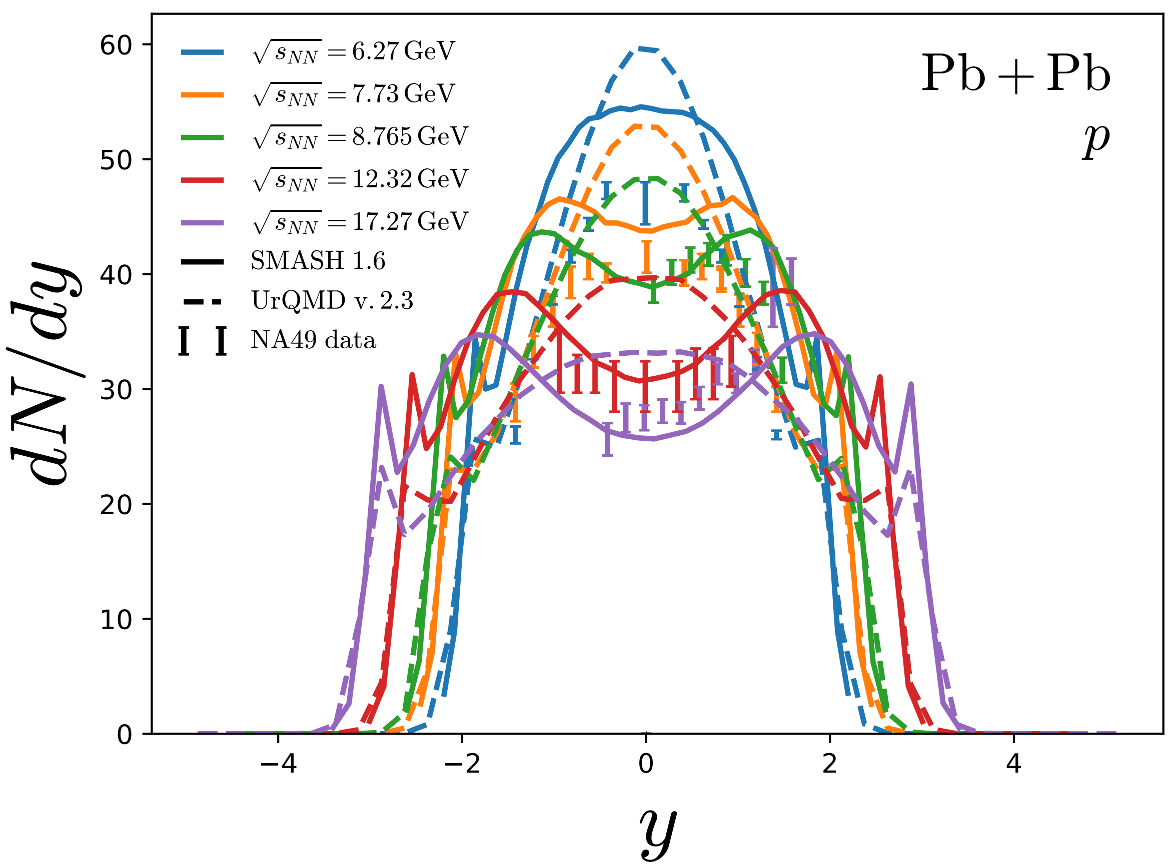
- Hard strings
  - Fully treated by Pythia
  - All species mapped to pions and nucleons

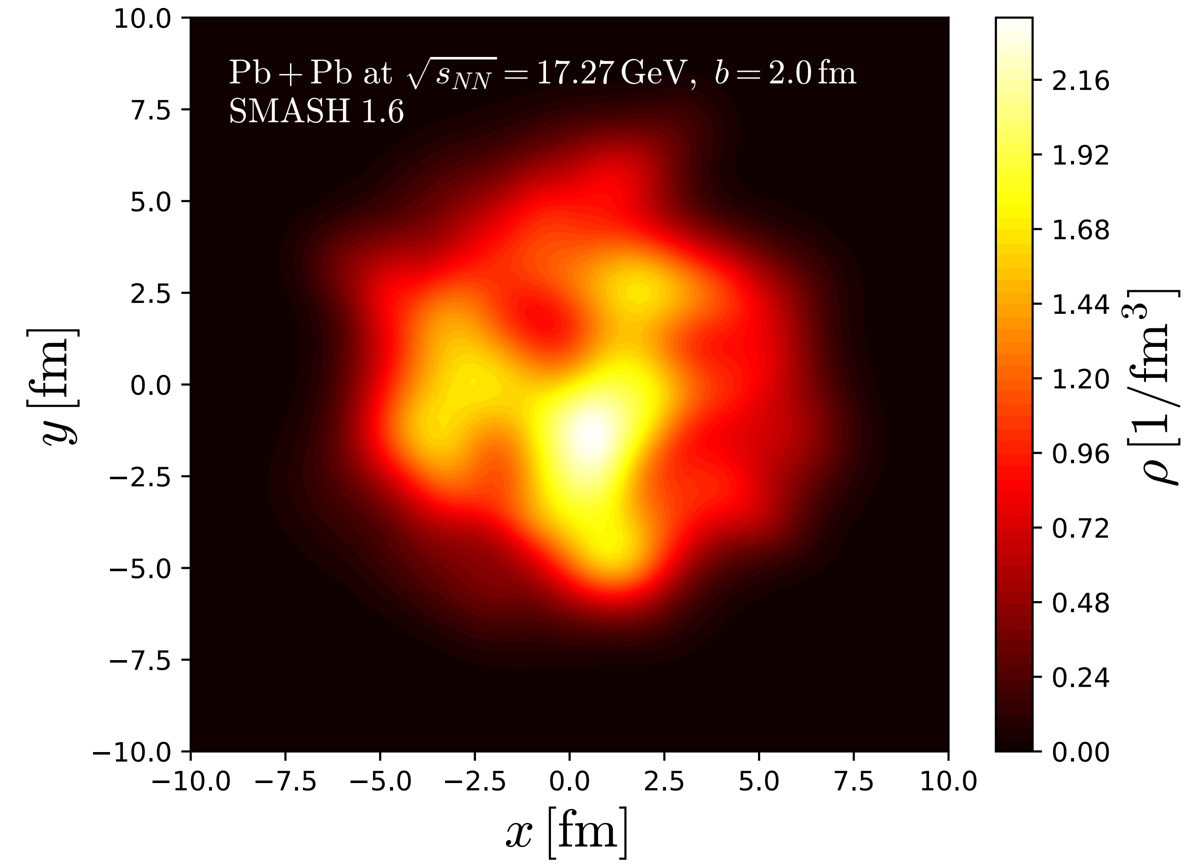
- Note: SMASH-2.0 includes optimised Pythia calls to reduce run-time

Baryon Stopping and Initial State

- All parameters of the string model are tuned to elementary pp data from SPS
- Proton rapidity spectrum is described over a large range of beam energies

J. Mohs, S. Ryu, HE *J.Phys.G* 47 (2020)





- Outlook: Employ SMASH as dynamical initial state

SMASH Hybrid Approach

SMASH-vHLLE Hybrid Approach

- Modular hybrid approach for intermediate and high energy heavy-ion collisions
- Open source and public

https://github.com/smash-transport/smash-vhlle-hybrid

SMASH
- Hadronic transport approach
- Initial conditions

+

vHLLE
- 3+1 D viscous hydrodynamics (event-by-event)
- Cornelius routine for hypersurface

+

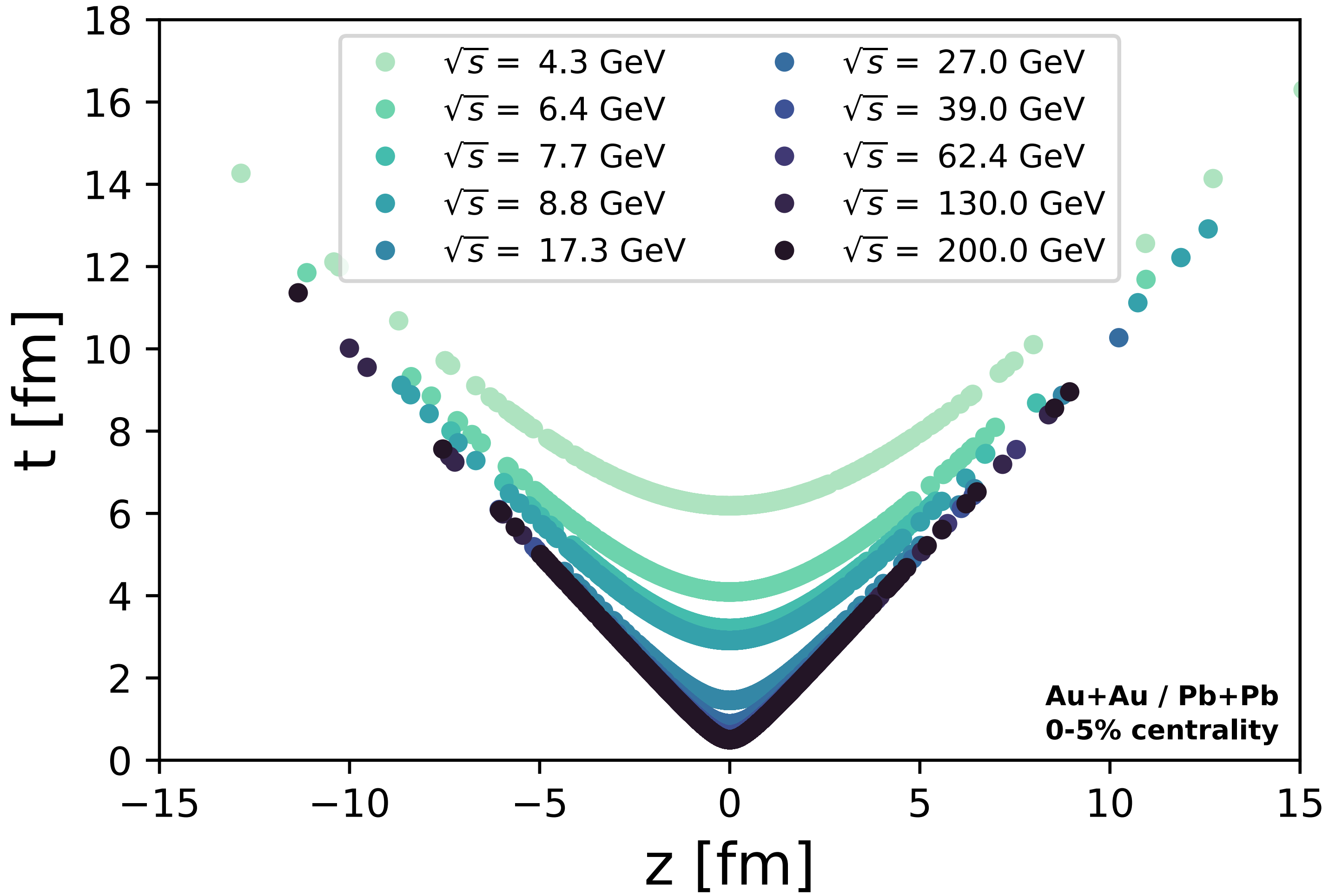
smash-hadron-sampler
- Cooper-Frye sampler
- Particlization of fluid elements

+

SMASH
- Hadronic transport approach
- Evolution of hadronic rescattering

A. Schäfer et al., arXiv: 2112.08724
Weil et al.: PRC 94 (2016)
DOI: 10.5281/zenodo.3484711
Huovinen et al.: Eur. Phys. J A 48 (2012)
Karpenko et al.: PRC 91, 064901 (2015)
Karpenko et al.: Comput. Phys. Commun. 185 (2014)

Initial Conditions from SMASH



- Nuclei are initialised according to Woods-Saxon profiles
- Propagation and collisions until full overlap time

$$\tau_0 = \frac{R_p + R_t}{\sqrt{\left(\frac{\sqrt{s_{\mathrm{NN}}}}{2m_N}\right)^2 - 1}}$$

A. Schäfer, PhD thesis

- Full energy-momentum tensor and charge distributions (B, S, Q) at constant τ hypersurface
- Fluctuations from nucleon positions and initial collisions
- Particles are smeared with Gaussian distributions

vHLLE

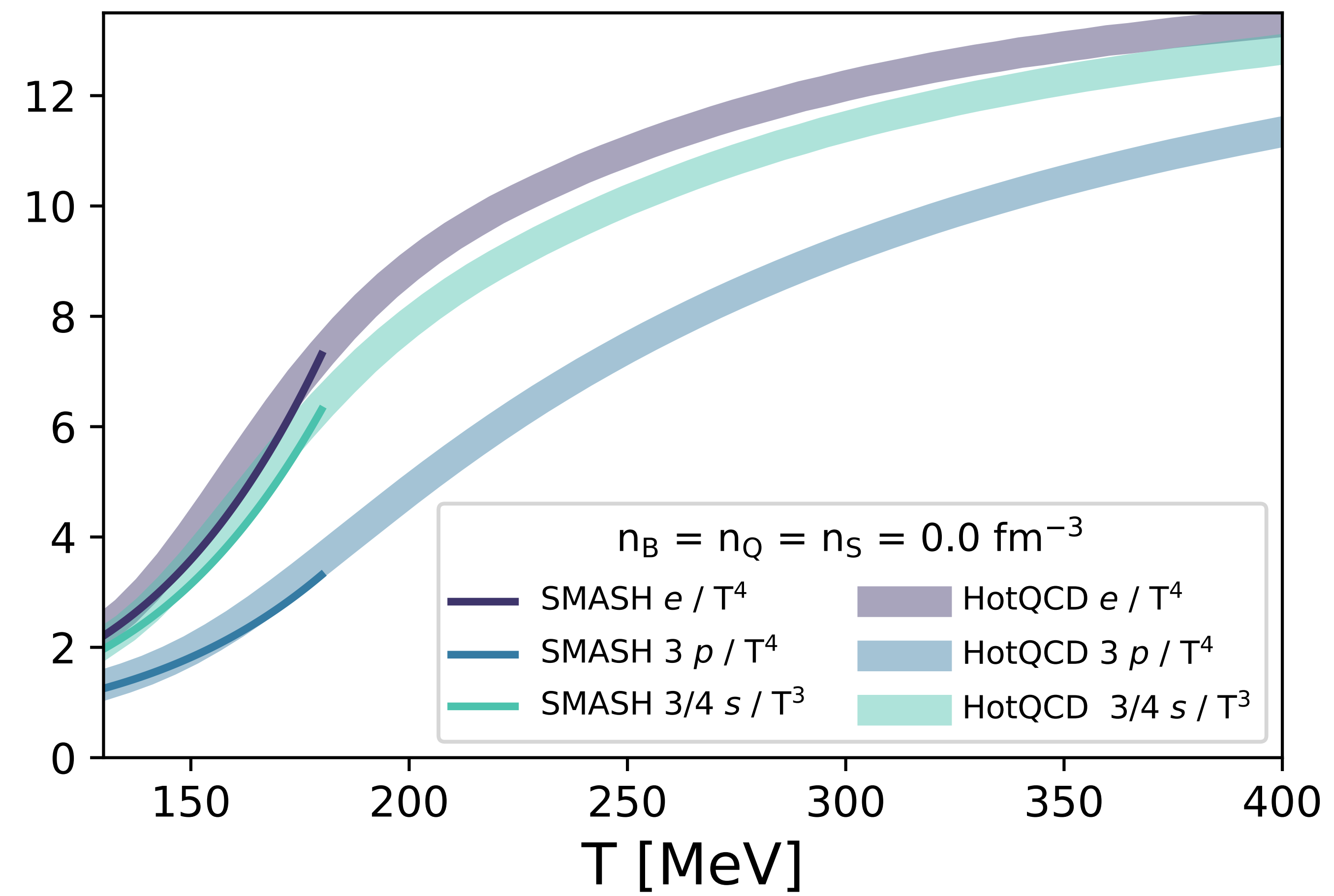
- 3+1 dimensional viscous hydrodynamic evolution
- Shear (and bulk) viscosity are included

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu J_i^\mu = 0 \quad i = B, Q, S$$

- Equation of state from chiral model (update in progress)

J. Steinheimer, S. Schramm and H. Stöcker, J.Phys.G 38 (2011)

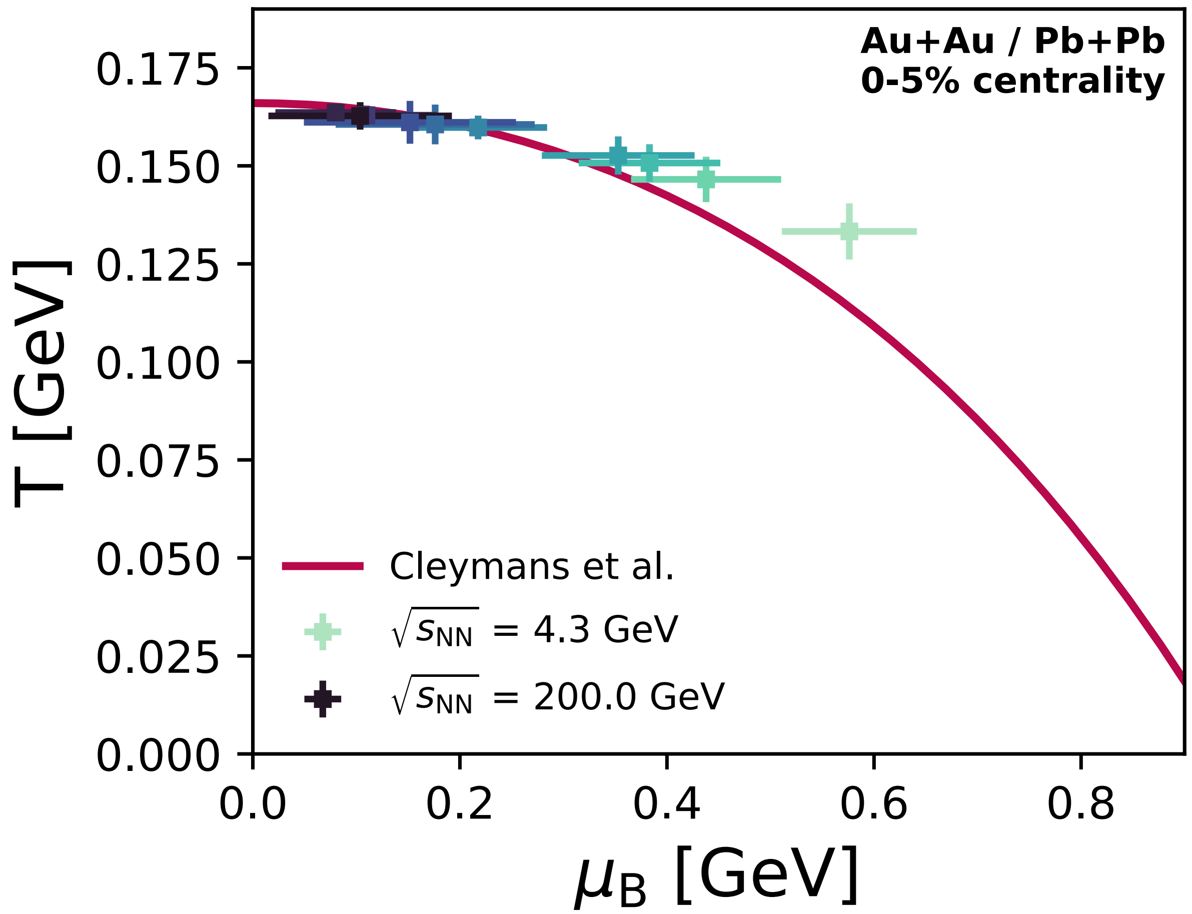
- For correct mapping of degrees of freedom on hypersurface the SMASH hadron gas equation of state is used
- $(e, n_B, n_Q) \rightarrow (T, p, \mu_B, \mu_Q, \mu_S)$



Karpenko et al.: PRC 91, 064901 (2015)
Karpenko et al.: Comput. Phys. Commun. 185 (2014)

Cooper-Frye Particlization

- Constant energy density hypersurface of ~2-5*ε_0 is constructed
- All SMASH hadron species are sampled according to thermal distribution functions (with δf correction for shear viscosity according to Grad 14 moment)



- Work in progress:
  - Sampling according to micro canonical ensemble
    D. Oliinychenko, V. Koch, PRL 123 (2019)
  - Finite spectral functions for resonances at sampling

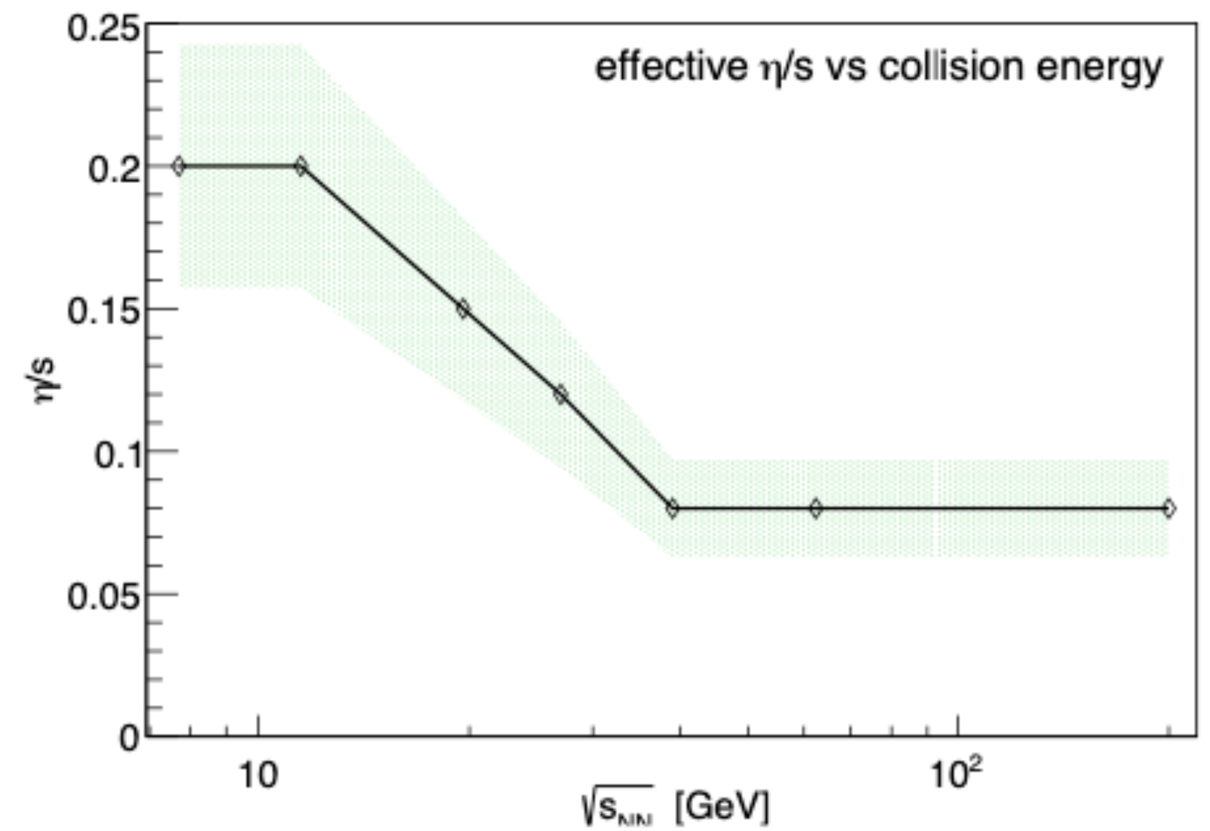
Parameter choices

- Parameters for initial state granularity and transport coefficients similar to prior UrQMD-vHLLE hybrid

System	$\sqrt{s}$	η/s	$R_\perp$	R_η
Au + Au	7.7 GeV	0.2	1.4	1.2
Pb + Pb	8.8 GeV	0.2	1.4	1.0
Pb + Pb	17.3 GeV	0.15	1.4	0.7
Au + Au	27.0 GeV	0.12	1.0	0.5
Au + Au	39.0 GeV	0.08	1.0	0.3
Au + Au	62.4 GeV	0.08	1.0	0.6
Au + Au	130.0 GeV	0.08	1.0	0.8
Au + Au	200.0 GeV	0.08	1.0	1.0

Parameters for hydrodynamical evolution, unless stated differently on the plots

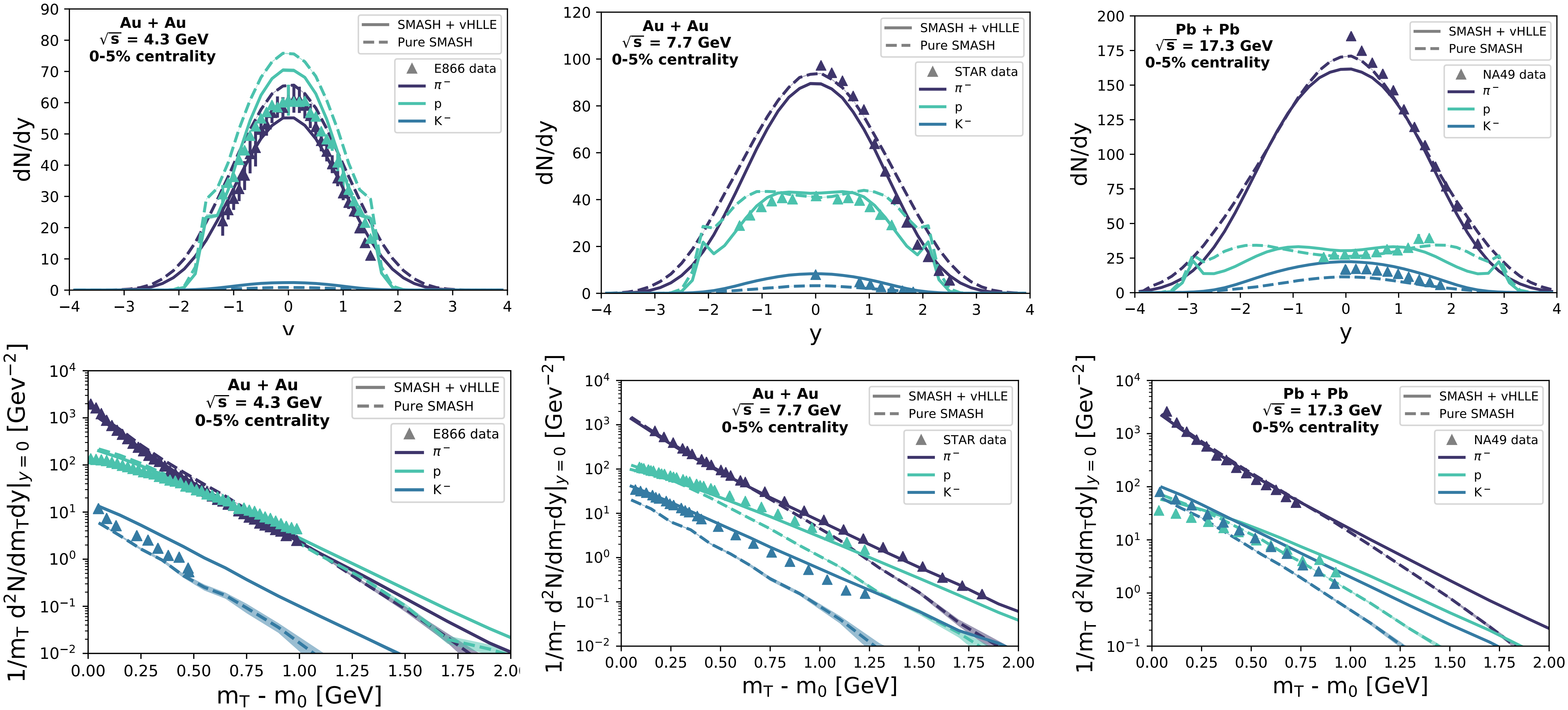
$R_\perp$, R_η: transverse and longitudinal smearing parameter



Y. Karpenko et al, PRC 91, 2015

- Current work: Constant shear viscosity and bulk viscosity is neglected

Particle Spectra



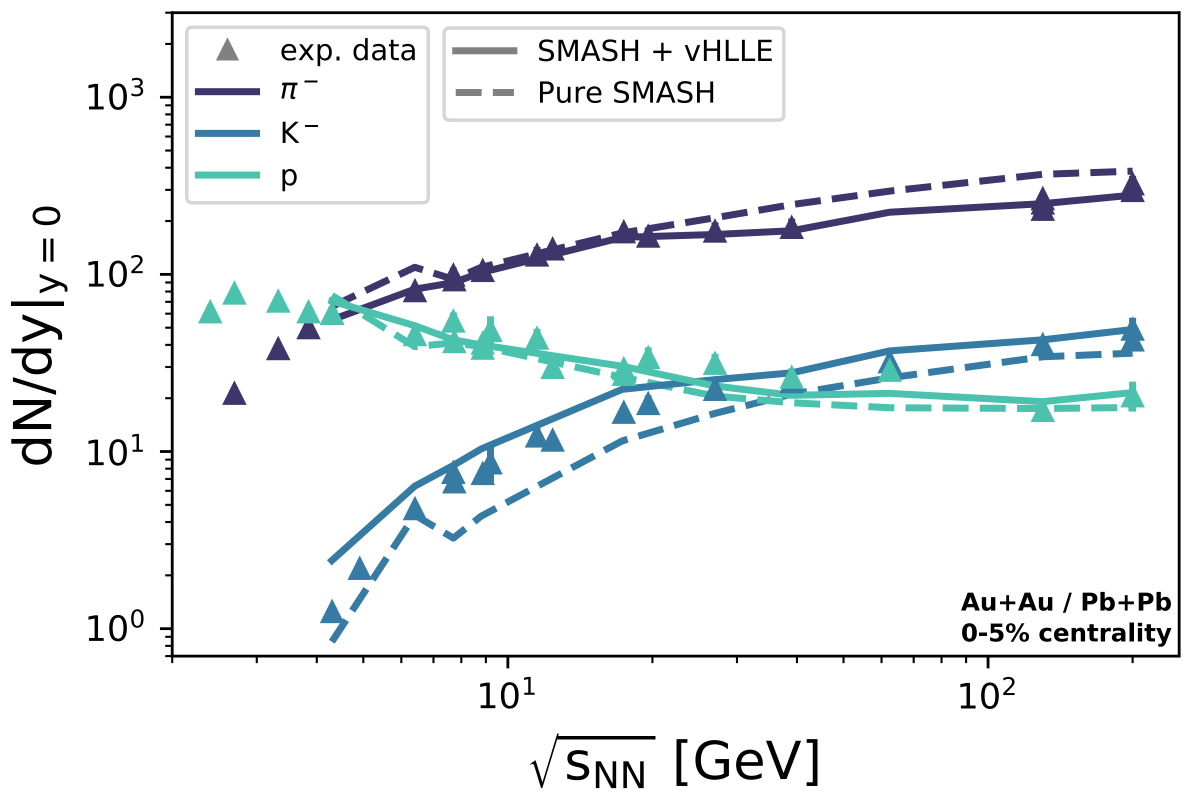
- Rapidity and transverse mass spectra of pions, kaons, protons at different energies -> Hybrid approach in decent agreement with measurements

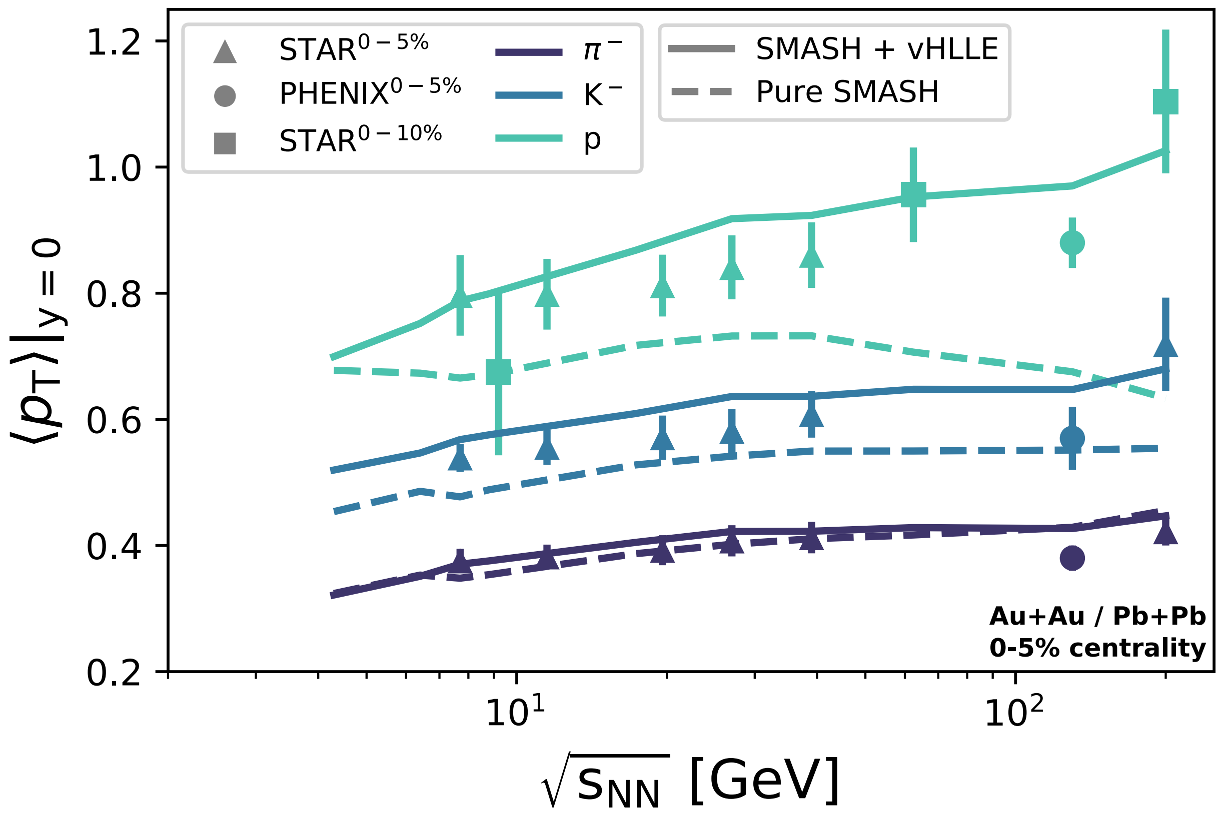
A. Schäfer et al., arXiv: 2112.08724

Excitation Function

- Particle yields at midrapidity are well described over a large range of beam energies

A. Schäfer et al., arXiv: 2112.08724



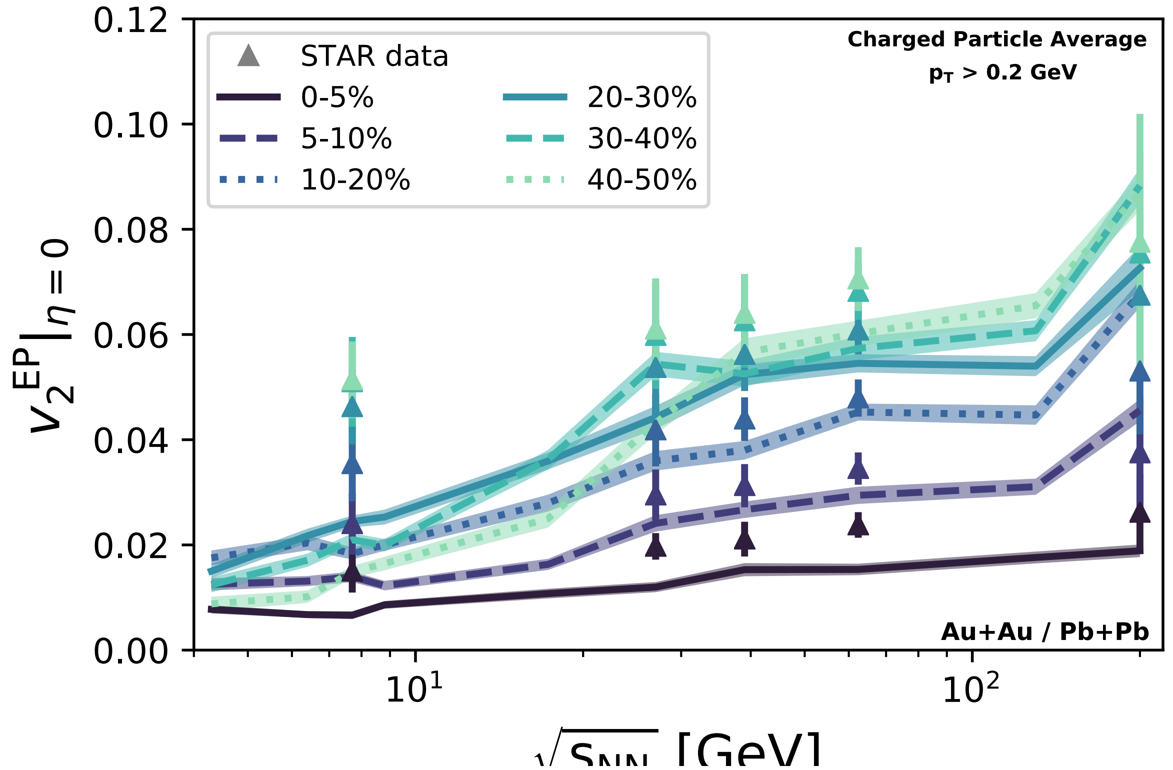


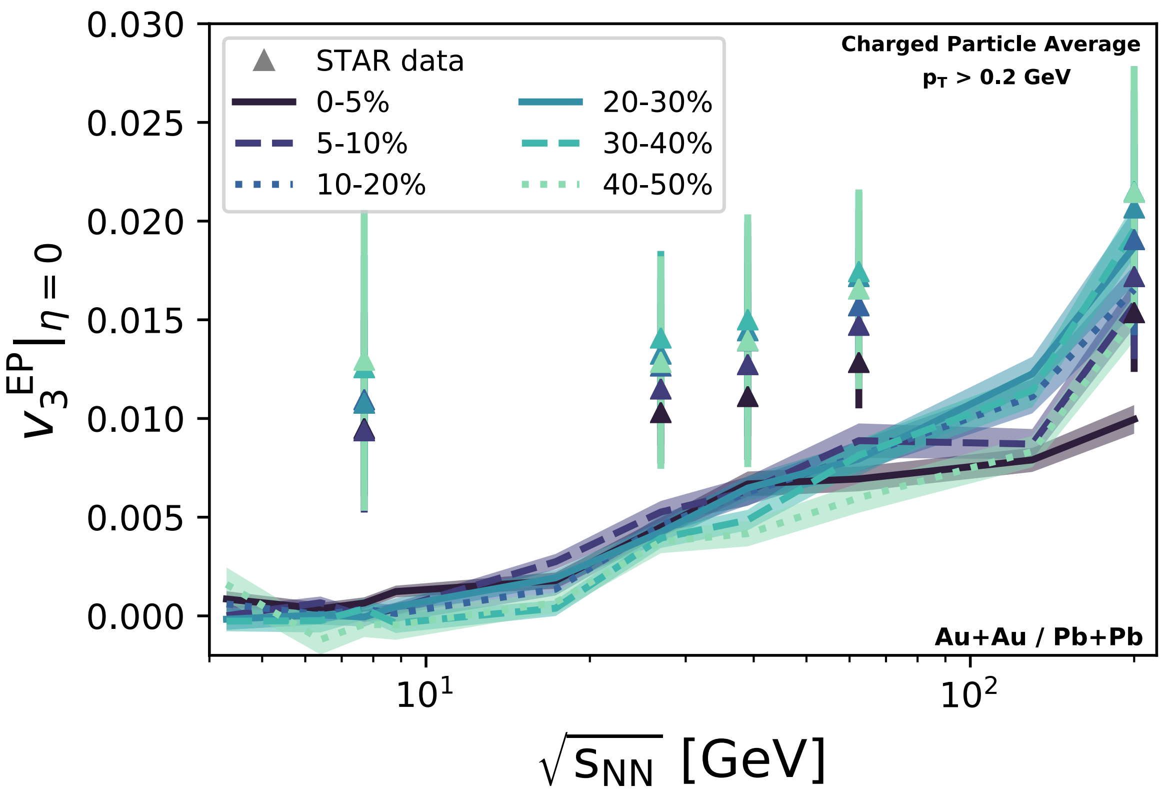
- Mean transverse momentum is also well described by the hybrid approach (too small in pure SMASH)
- More strangeness production and larger radial flow from hydrodynamics necessary from $\sqrt{s_{NN}}$ ~ 10 GeV

Anisotropic Flow

- Integrated v_2 and v_3 for charged particles
- v_2: Good agreement with STAR data at high energies and in central collisions
- v_3: STAR data underestimated at all energies and centralities
- Potential explanation:
  - Too short lifetime of the hydrodynamical fireball
  - Initial state fluctuations washed out in smearing process

A. Schäfer et al., arXiv: 2112.08724



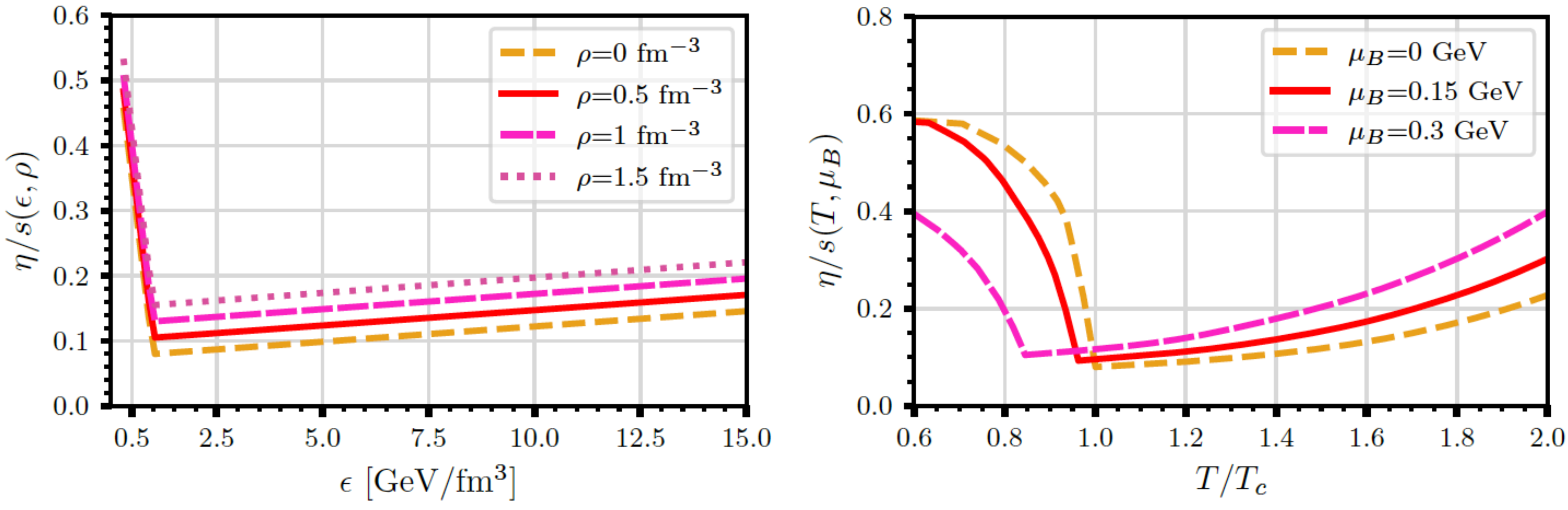


μ_B dependence of η/s

Parametrization of η/s

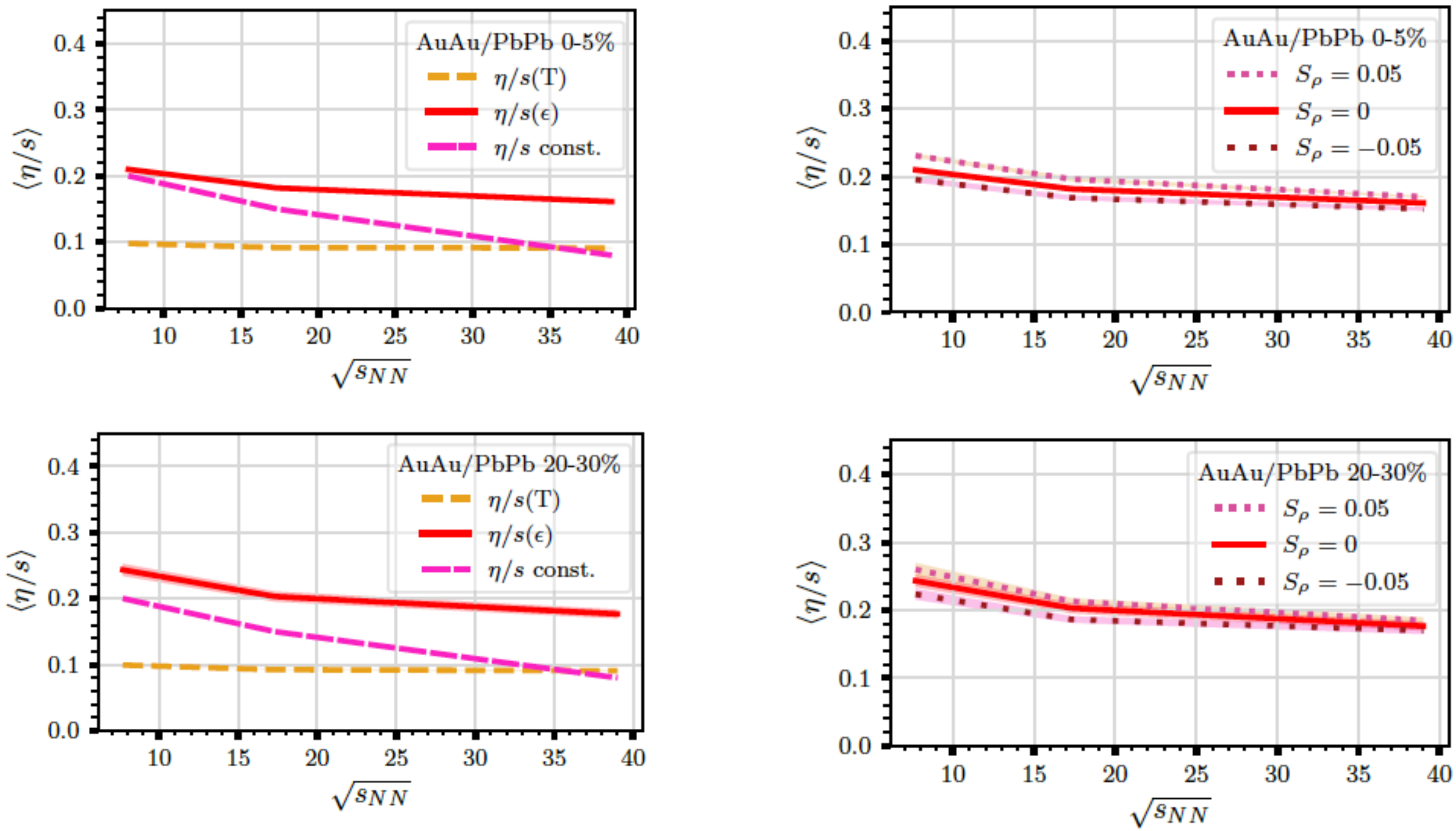
- Parametrization in energy and net baryon density instead of temperature and chemical potential
- Linear dependence above and below a minimal shear viscosity/entropy ratio

N. Götz, HE, arXiv:2207.05778



- Matched to pQCD and SMASH box calculation

Effective Shear Viscosity

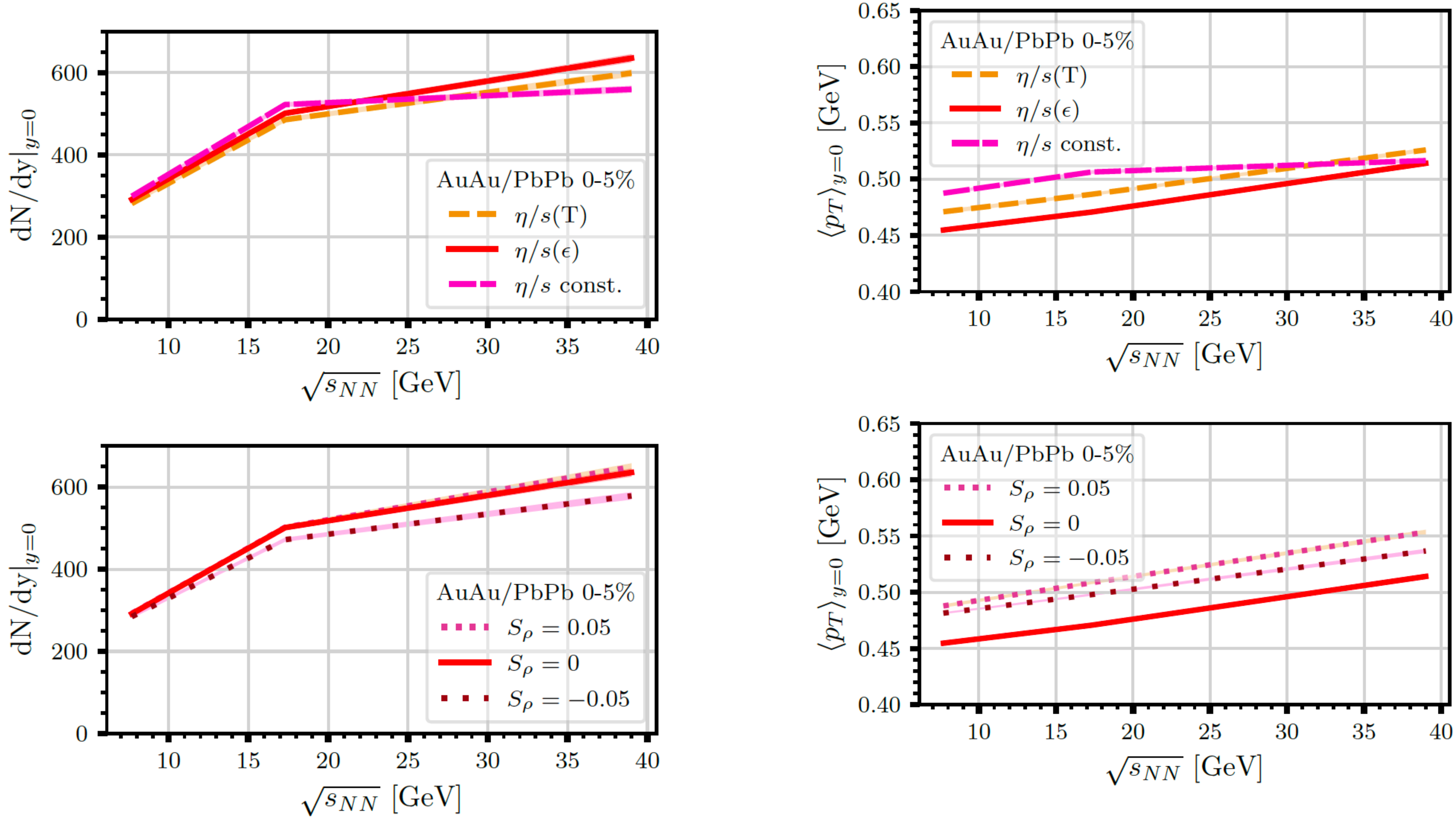


N. Götz, HE, arXiv:2207.05778

- Integrated shear viscosity is larger in our calculation than in temperature dependent or constant case
- Explicit density dependence has only minor effect

Yields and Transverse Momenta

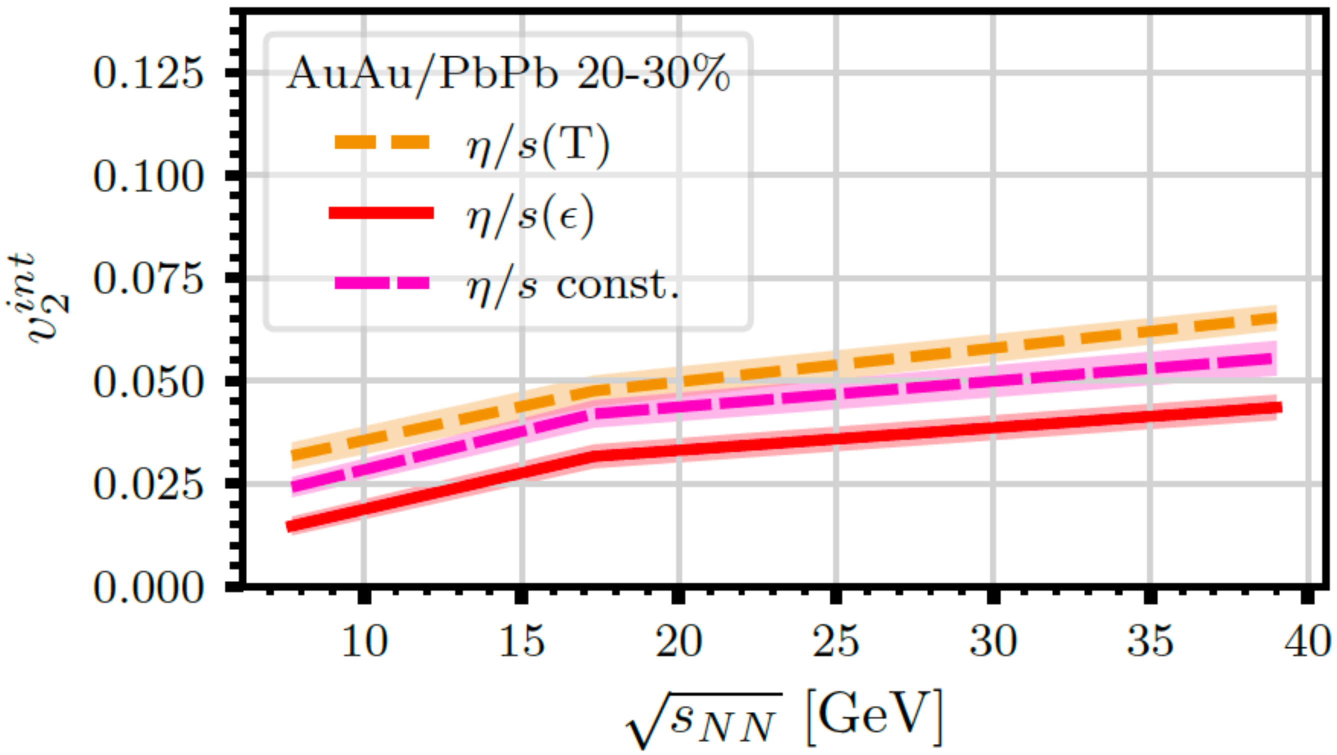
- Charged particle yields are not affected much



- Average transverse momentum decreases with higher viscosity, density dependence is visible

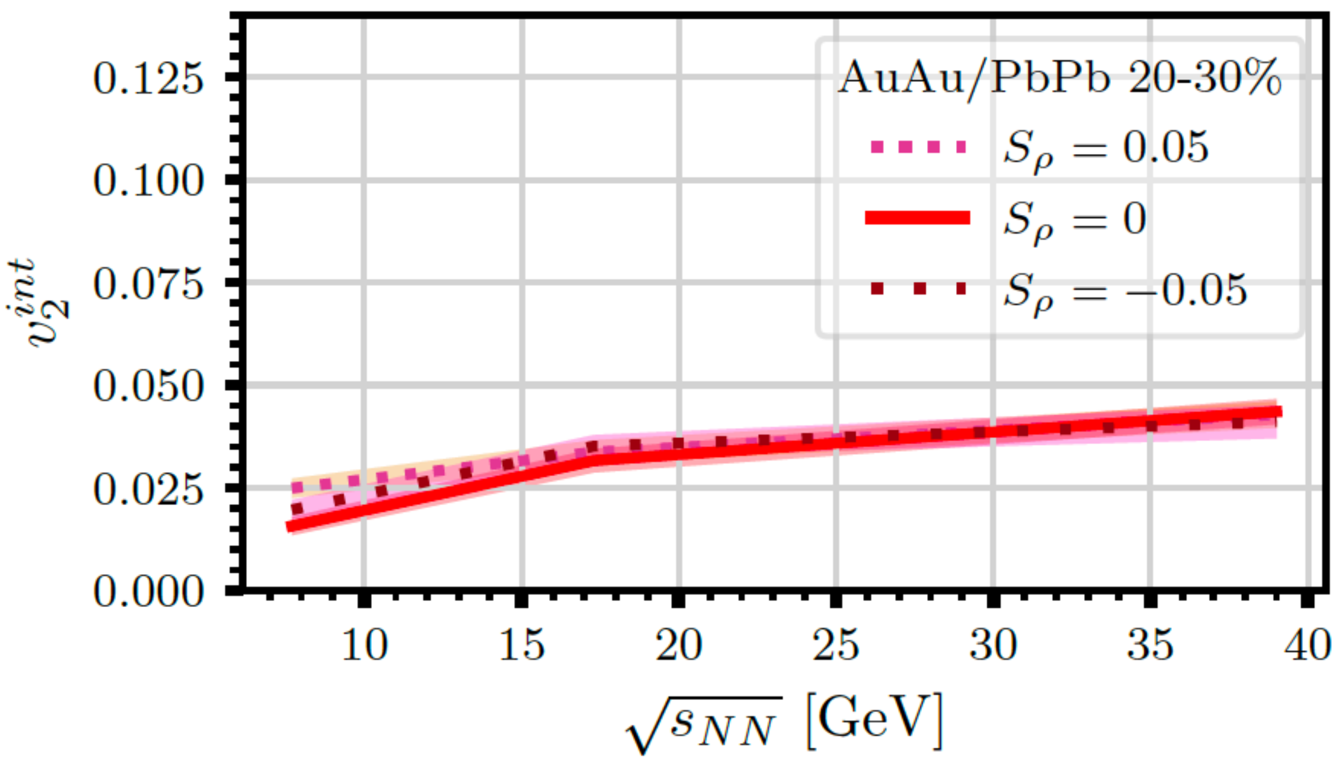
N. Götz, HE, arXiv:2207.05778

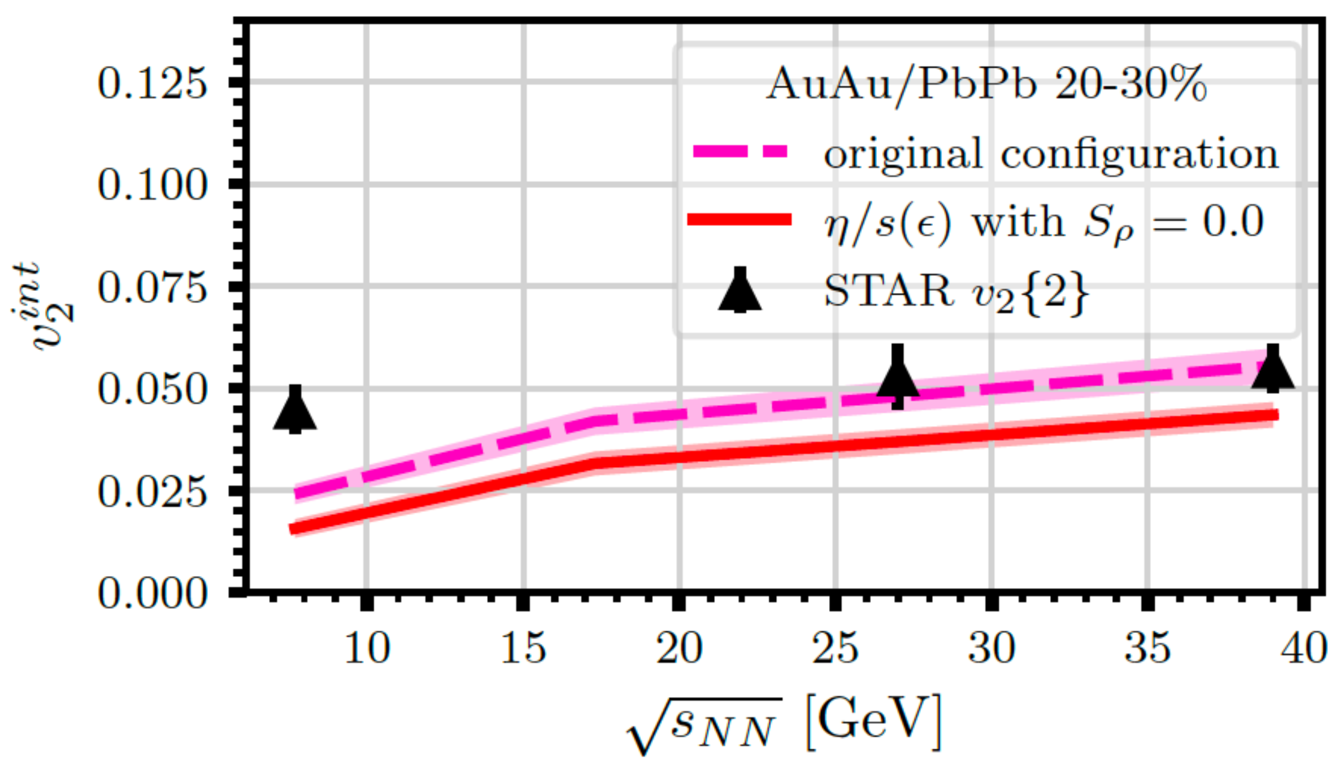
Elliptic Flow



- Elliptic flow decreases with increasing viscosity as expected
- Density dependence does not have a big effect

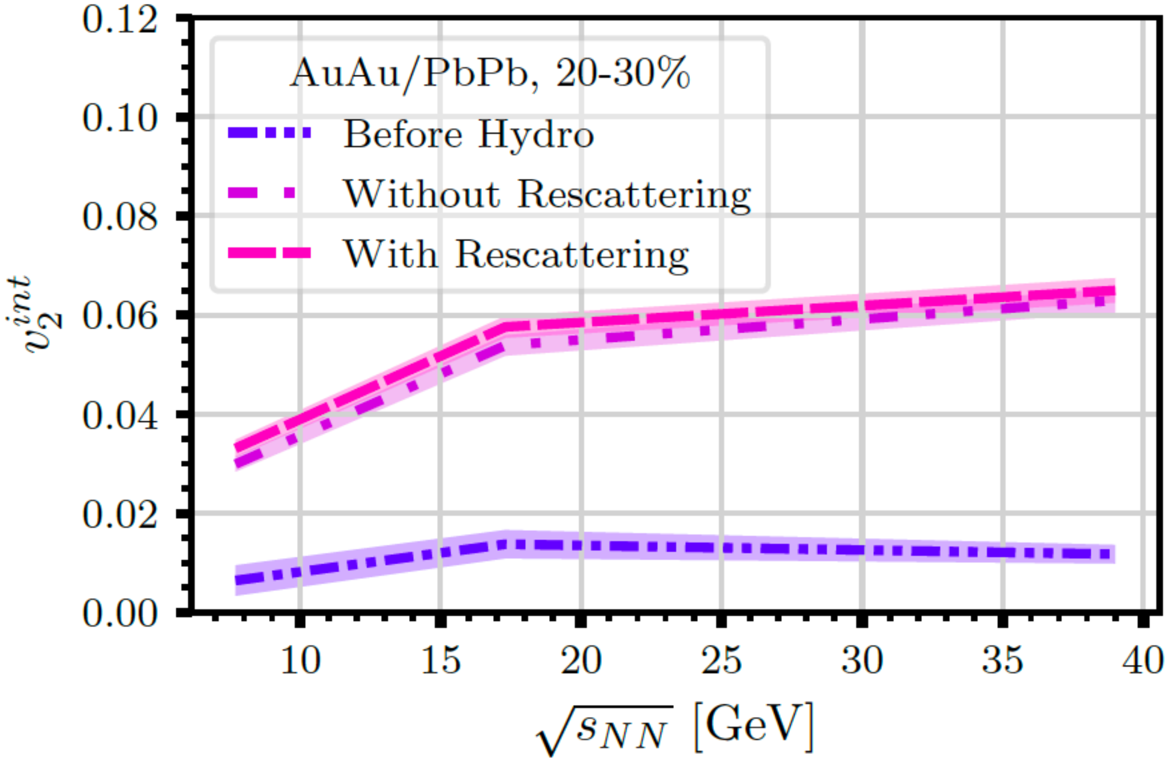
N. Götz, HE, arXiv:2207.05778



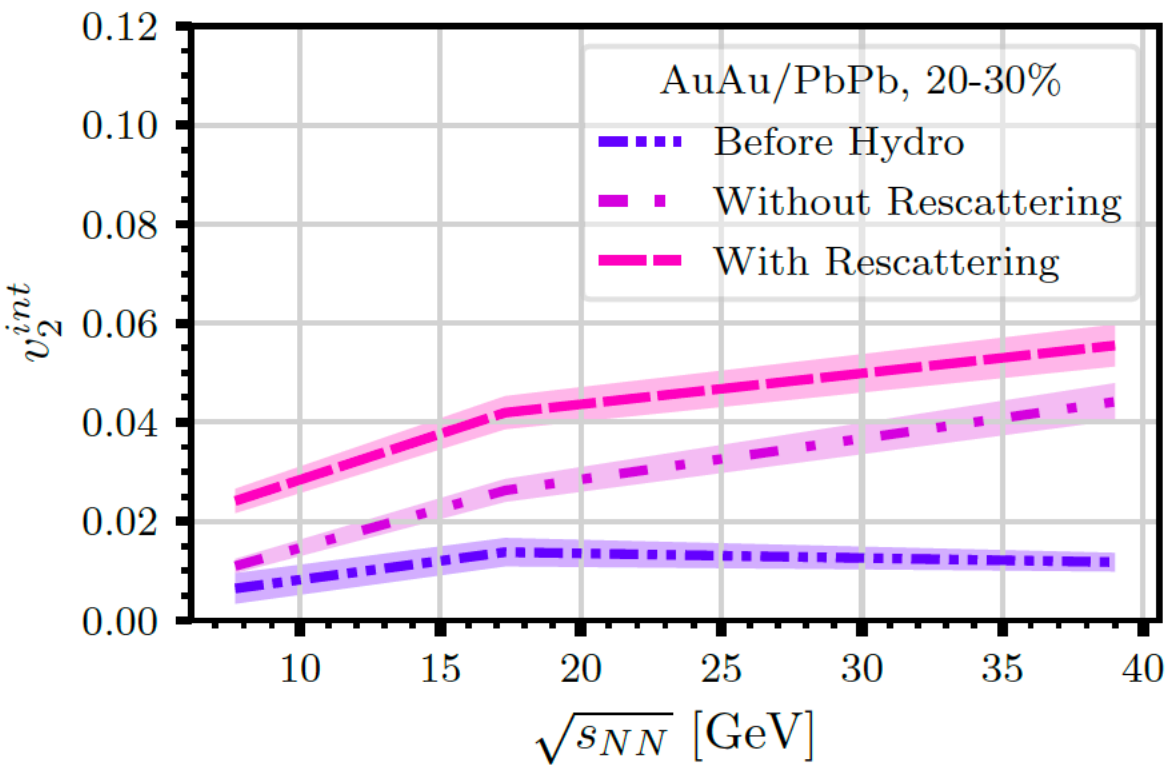


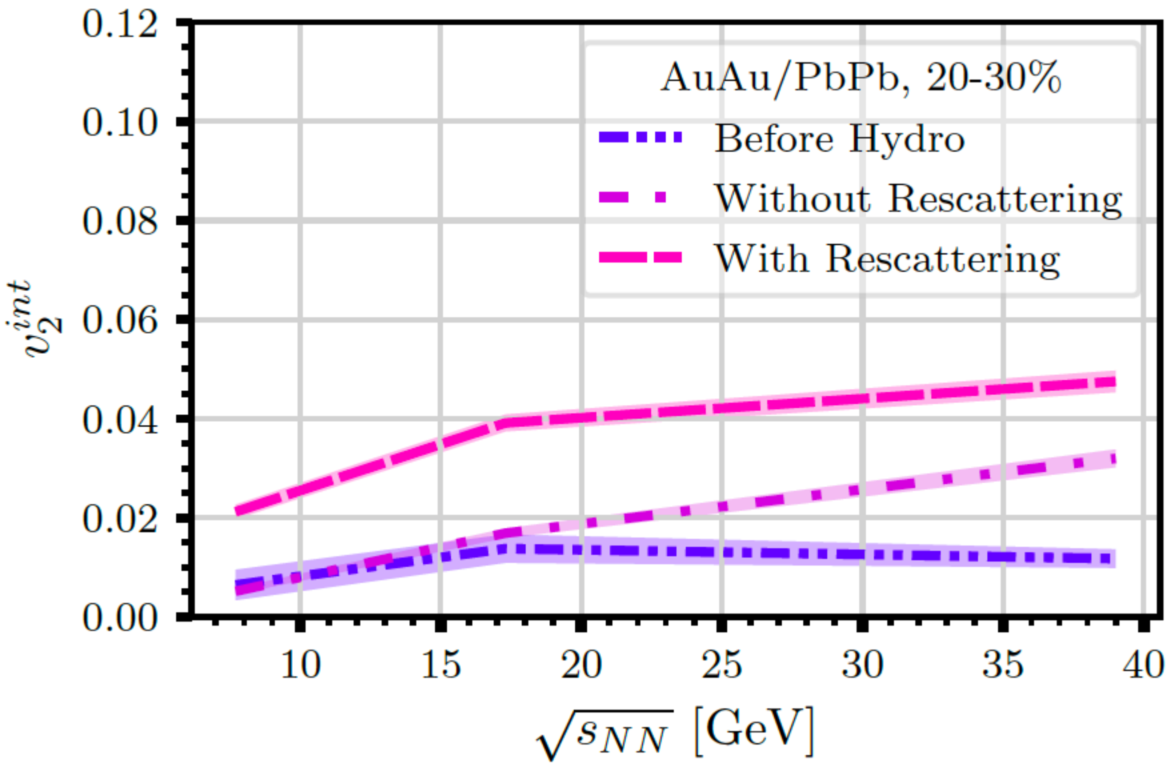
Flow from Stages

N. Götz, HE, arXiv:2207.05778



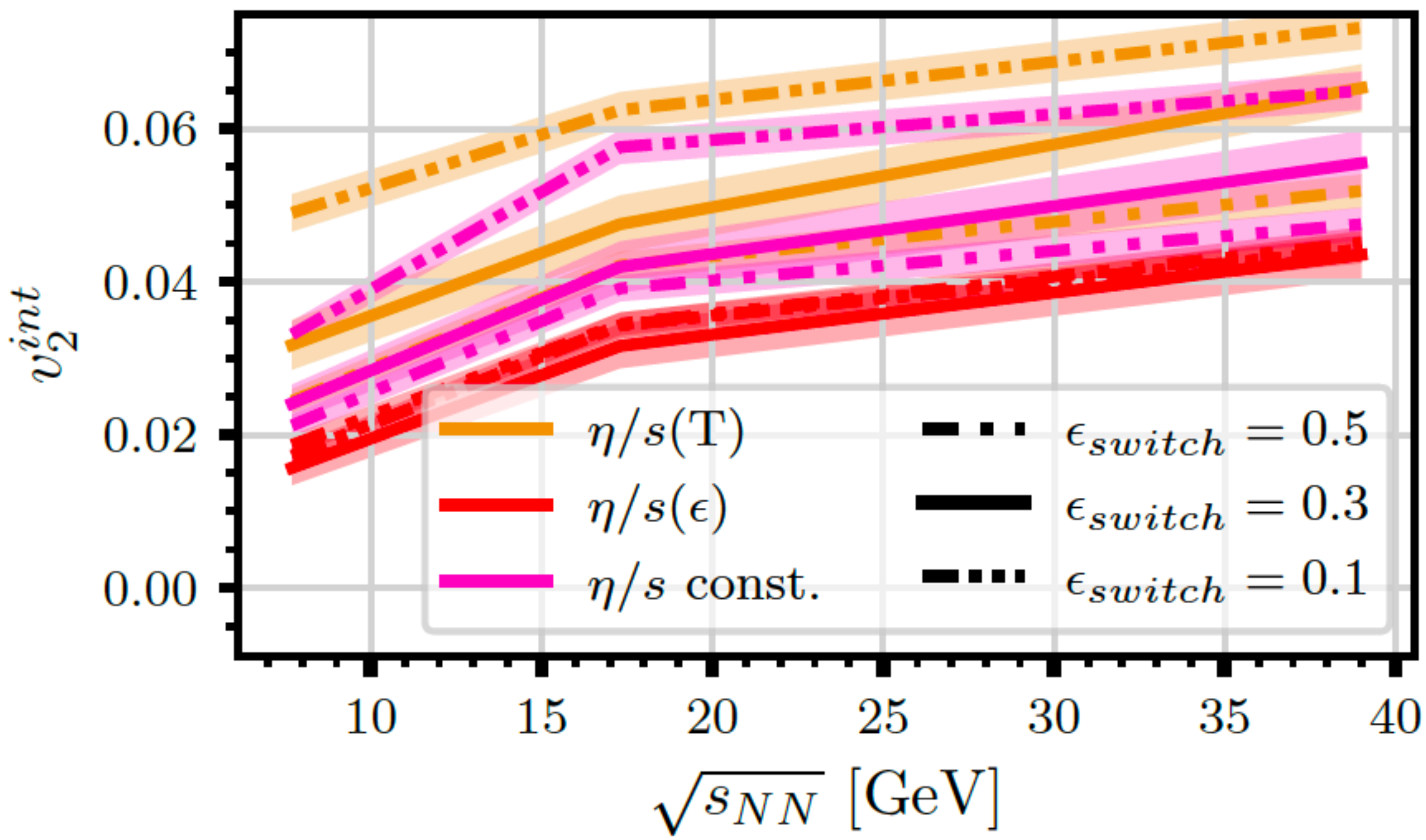
- Depending on switching energy density more flow is developed within hydrodynamic stage or transport stage
- Shown 0.1, 0.3, 0.5 GeV/fm^3





Independence of Switching

- The energy density dependent parametrization of the shear viscosity allows to have the final flow independent of the switching transition criterion



- Hint that the viscosity in the hadronic stage is similar in SMASH and the hybrid approach

N. Götz, HE, arXiv:2207.05778

Summary

- Hybrid approaches based on relativistic hydrodynamics and hadron transport provide realistic dynamical description
- SMASH hadronic transport has been coupled to vHLLE viscous hydrodynamics
- Particle production and flow at intermediate beam energies is better described within hybrid than in pure transport approach
- Transport coefficients depend on temperature and density
- Added an energy density dependence and an explicit net baryon density dependence for shear viscosity
- Average transverse momentum is sensitive to density dependence of shear viscosity
- Elliptic flow is independent of switching transition criterion, when energy density dependent transport coefficient is used
- Outlook: Bulk viscosity and dynamical initialization

How to Use SMASH?

- Visit the webpage to find publications and link to SMASH-2.2 results https://smash-transport.github.io
- Download the code at https://github.com/smash-transport/smash
- Checkout the Analysis Suite at https://github.com/smash-transport/smash-analysis
- Find user guide and documentation at https://github.com/smash-transport/smash/releases
- Animations and Visualization Tutorial under https://smash-transport.github.io/movies.html

SMASH-2.2 has HepMC and RIVET