SMASH Status and Plans

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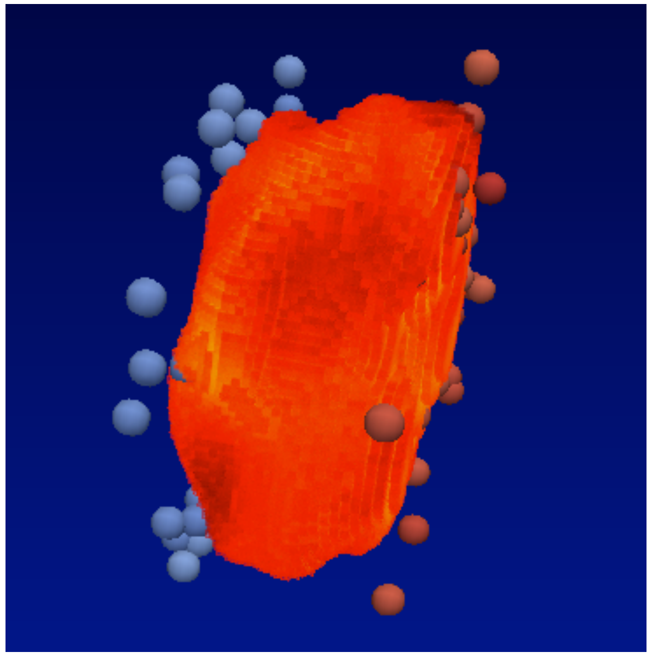
September 22nd 2023, TMEP Workshop, GSI

Why a new 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)



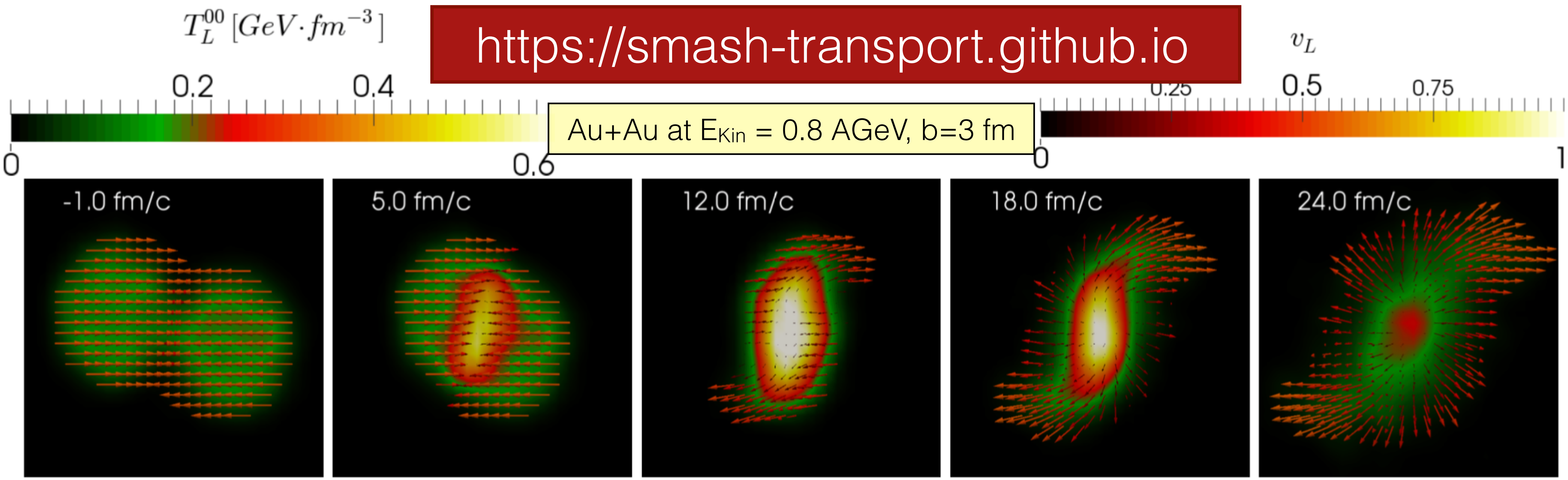
- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, ROOT, HepMC, RIVET
  - Used as a library by many groups for afterburner

https://smash-transport.github.io



* Simulating Many Accelerated Strongly-Interacting Hadrons

The SMASH Team

- In Frankfurt:
  - Gabriele Inghirami
  - Alessandro Sciarra
  - Hendrik Roch
  - Justin Mohs
  - Jan Hammelmann
  - Niklas Götz
  - Renan Hirayama
  - Nils Saß
  - Carl Rosenkvist
  - Antonio Bozic
  - Lucas Constantin
  - Timo Füle
  - Robin Sattler

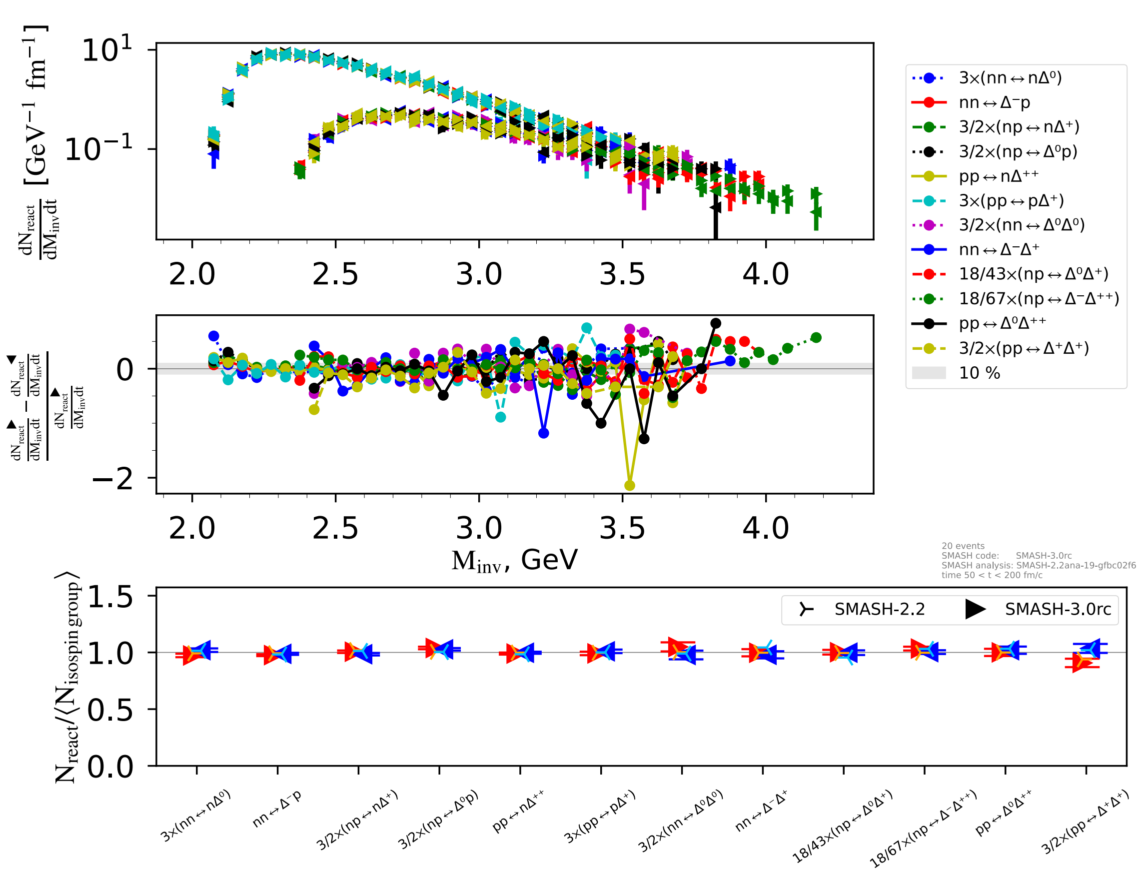
- In US/Bielefeld/Slovakia:
  - Agnieszka Sorensen
  - Oscar Garcia-Montero
  - Zuzana Paulinyova

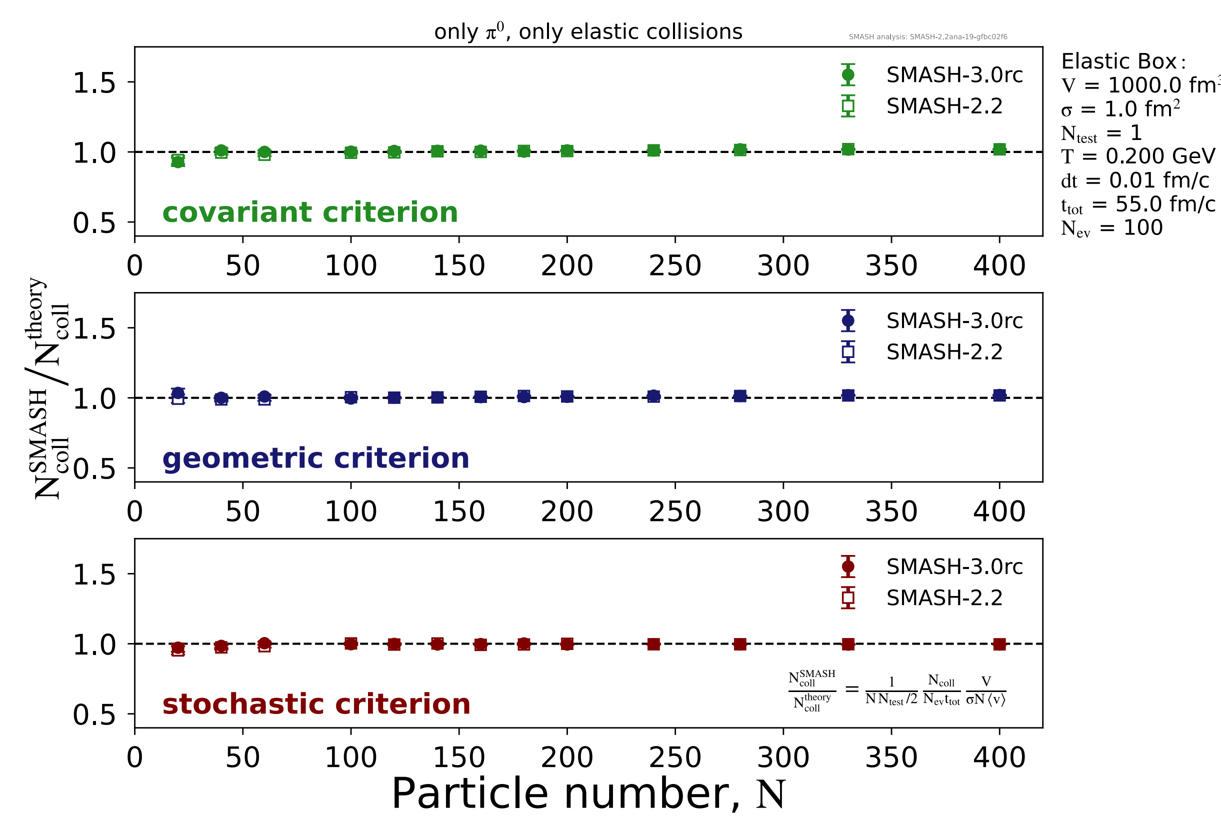
Group excursion in May 2022

Transparent Development

- Stringent rules for software development
  - Each newly implemented feature goes through an internal review process
  - ~100 unit tests, enforced documentation and user guide
- For each new public version physics analysis suite is run (as well open source available)

https://github.com/smash-transport/smash-analysis





Degrees of Freedom

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

Nuclear Structure

- Deformations can be given by parameters
- Input from nuclear wave functions including NN correlations, neutron skin, etc

J. Hammelmann et al, PRC 101, 2020

- Nuclear configurations generated using $|\Psi|^2$ as a probability density

$$\Psi(\vec{r}_1, \ldots, \vec{r}_A) = \prod_{i<j}^{A} \hat{f}(r_{ij}) \Phi(\vec{r}_1, \ldots, \vec{r}_A)$$

- Spin-isospin correlation operators from variational calculations

$$\hat{f}(r_{ij}) = \sum_{n=(1,\sigma,\mathbb{S})\otimes 1\tau} \hat{f}^{(n)}(r_{ij})$$

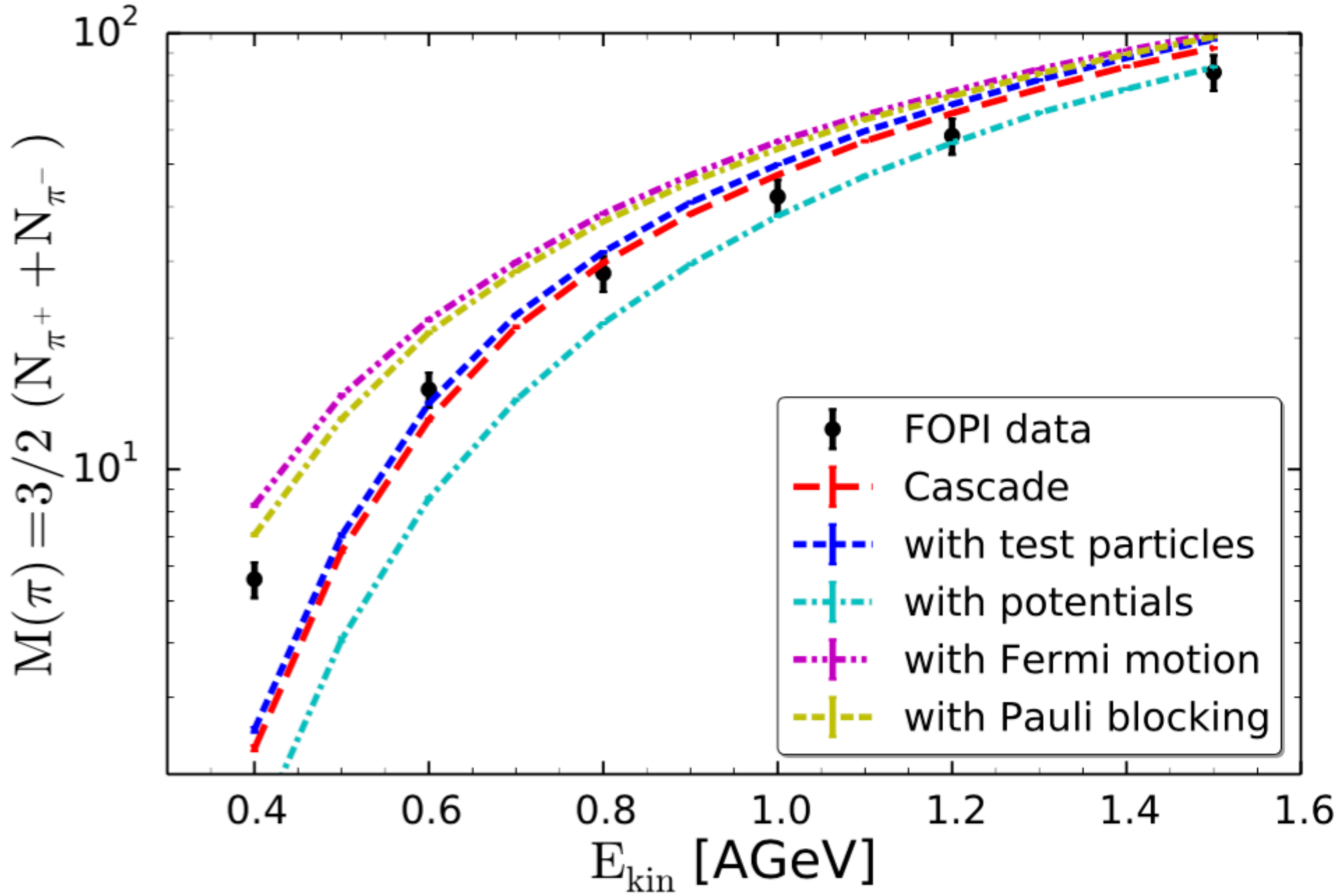
- Reproduces any nuclear profiles and two-body densities of several nuclei by inclusion of NN correlations

M. Alvioli, H.-J. Drescher, M. Strikman, PLB 680 (2009)

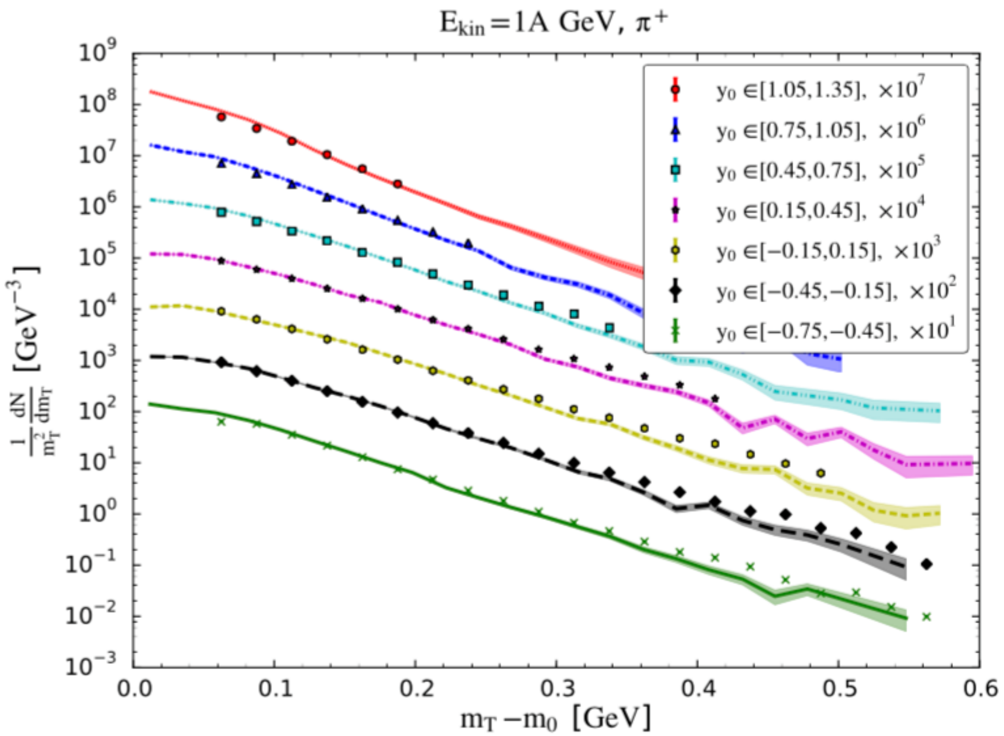
- Added neutron skin and deformations where appropriate
- Plan: Include momentum space correlations; Isobar calculation; Initial state studies at high beam energies

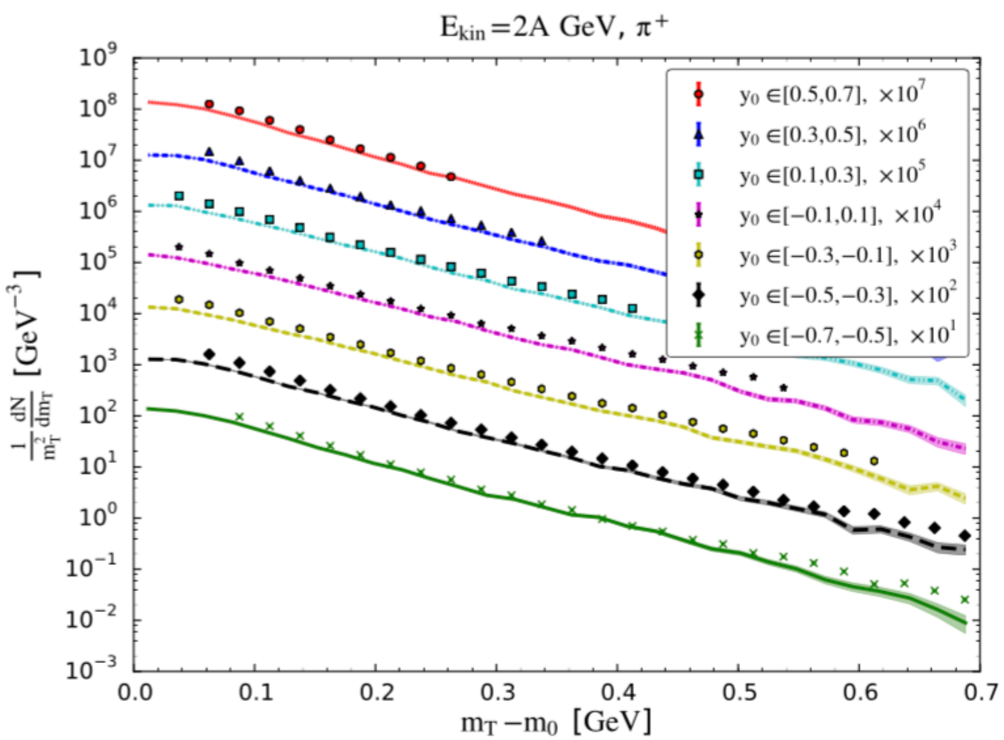
Pion Production in Au+Au

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



Note: consecutive addition of features



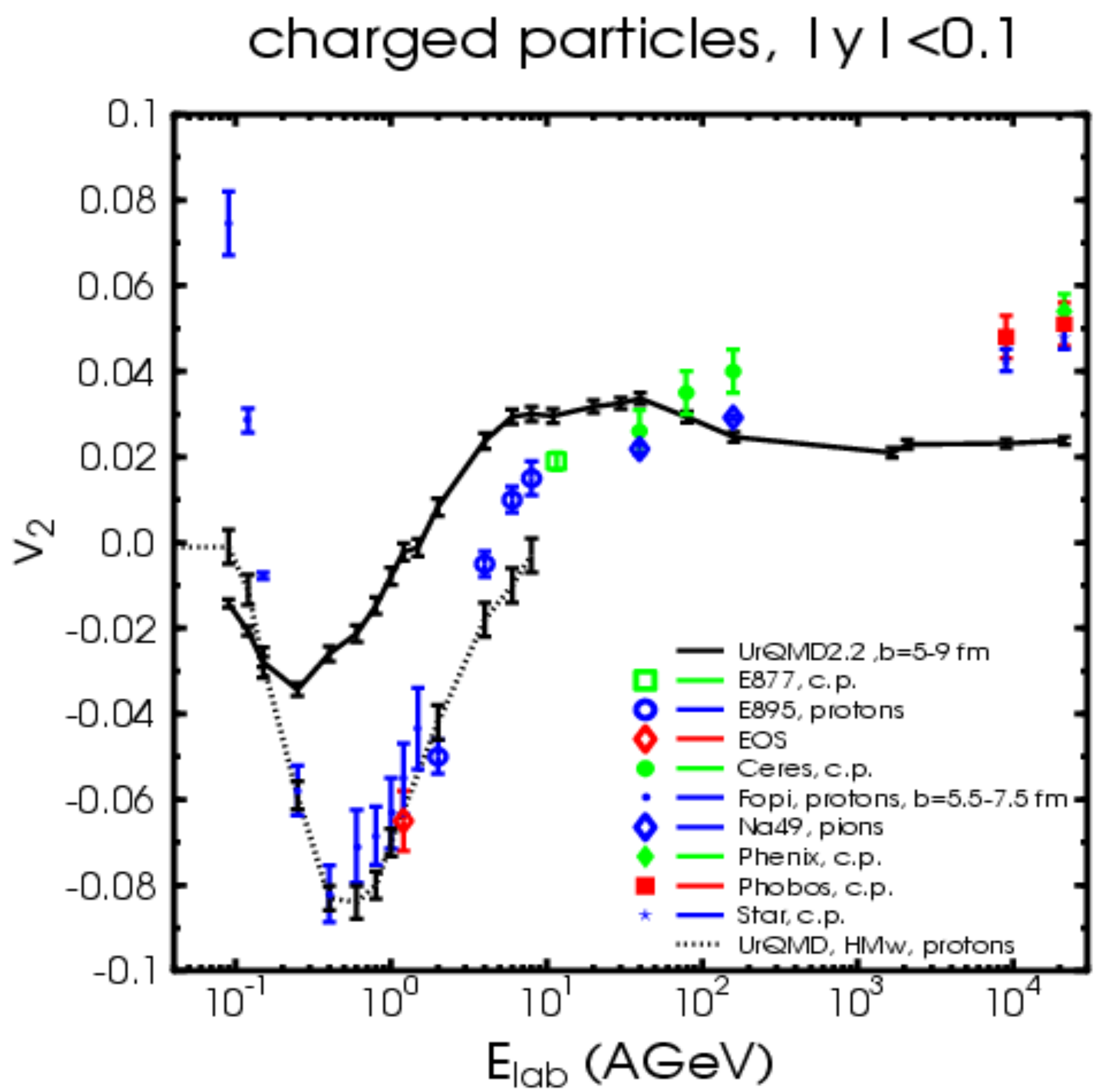


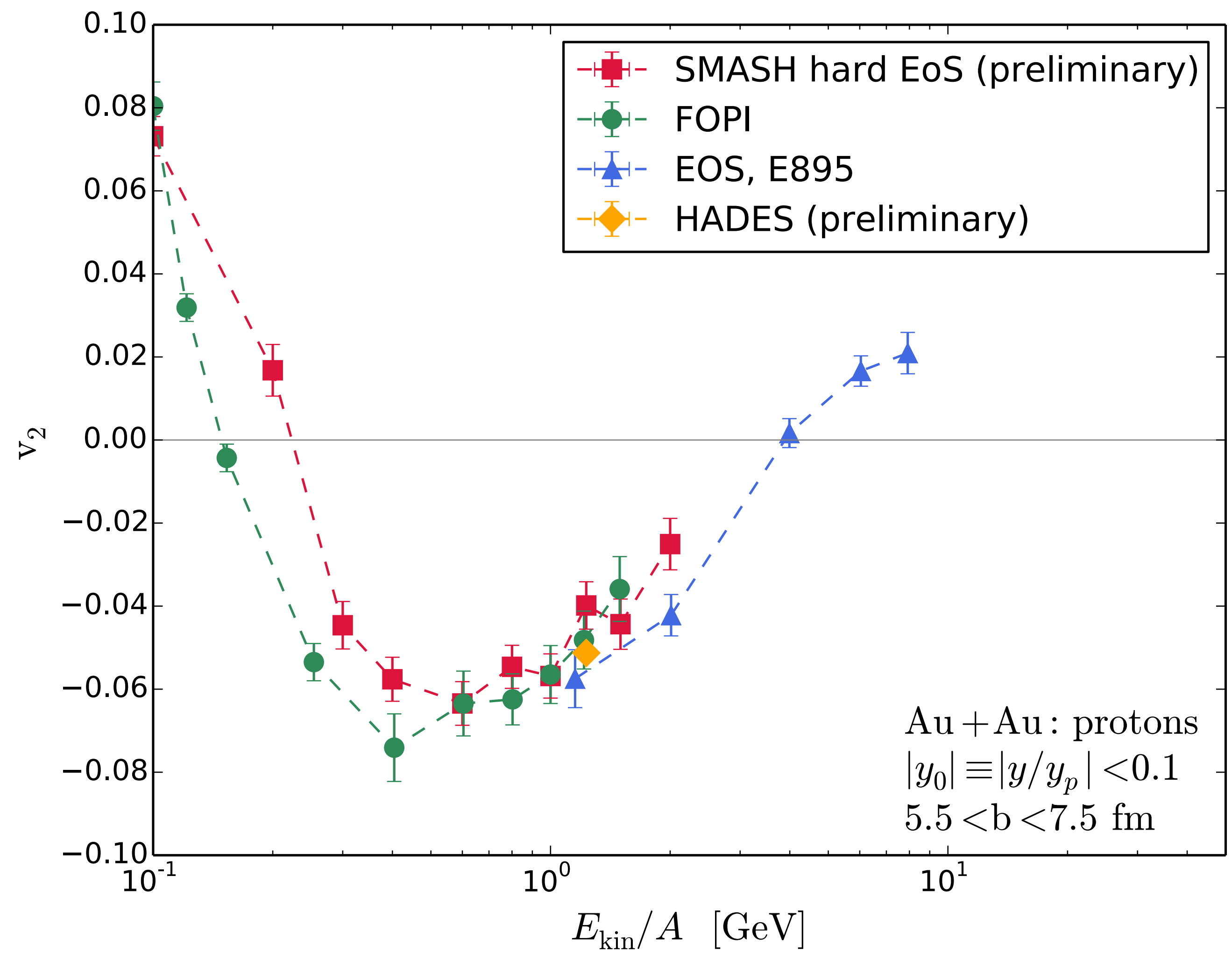
J. Weil et al, PRC 94 (2016)

Collective Flow -v_2

- Directed and elliptic flow are compared to available data from FOPI and HADES

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





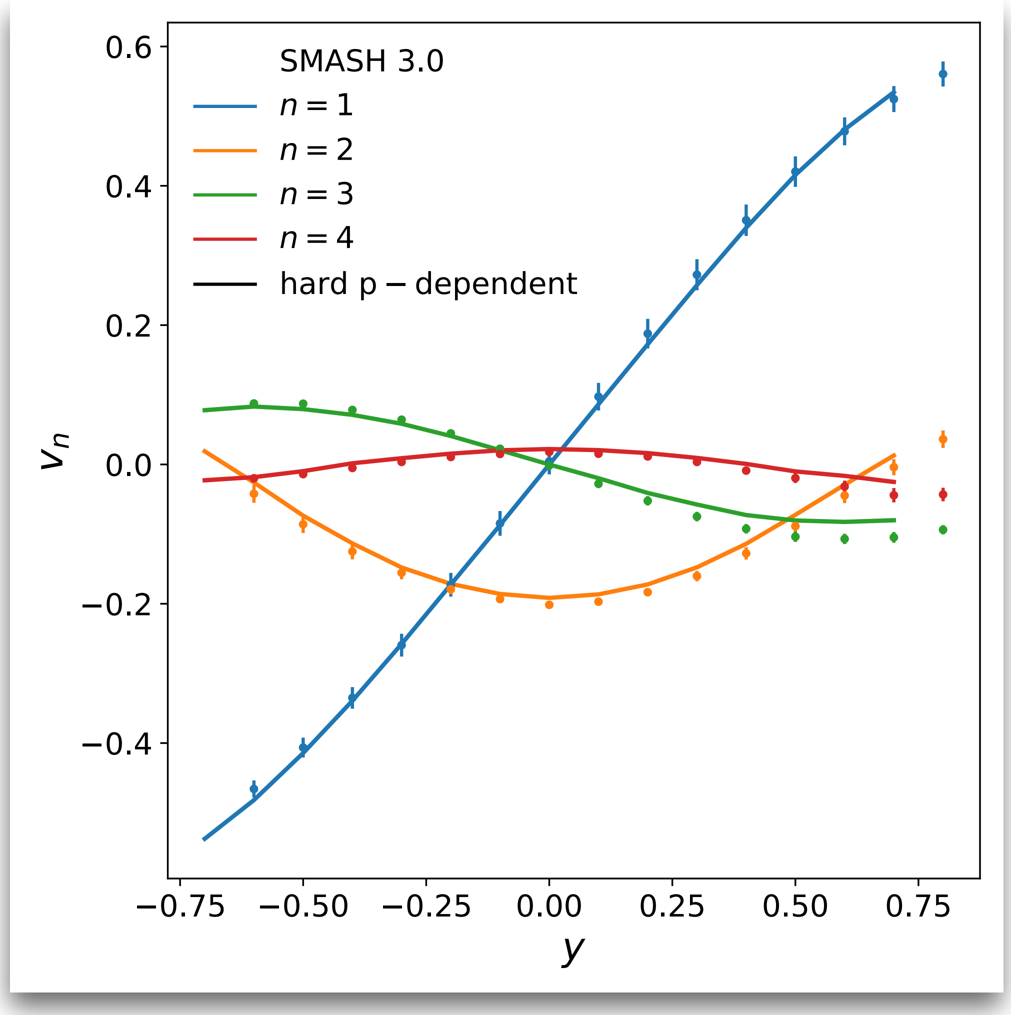
H.Petersen (now Elfner) et al, NPA 982, 2019

- SMASH agrees well with previous UrQMD calculation

Progress on Potentials

- Coulomb potential has been implemented
- VDF potential has been developed (see Agnieszka Sorensen), external project contributing to SMASH
- Momentum dependence for Skyrme has been implemented (see talk by Justin Mohs)
- Symmetry energy is available with variations from TMEP project
  - Plan: Bayesian analysis with HADES data; Comparison to FOPI data with A. Andronic et al

HADES data from PRL 125, 2020



Light Clusters

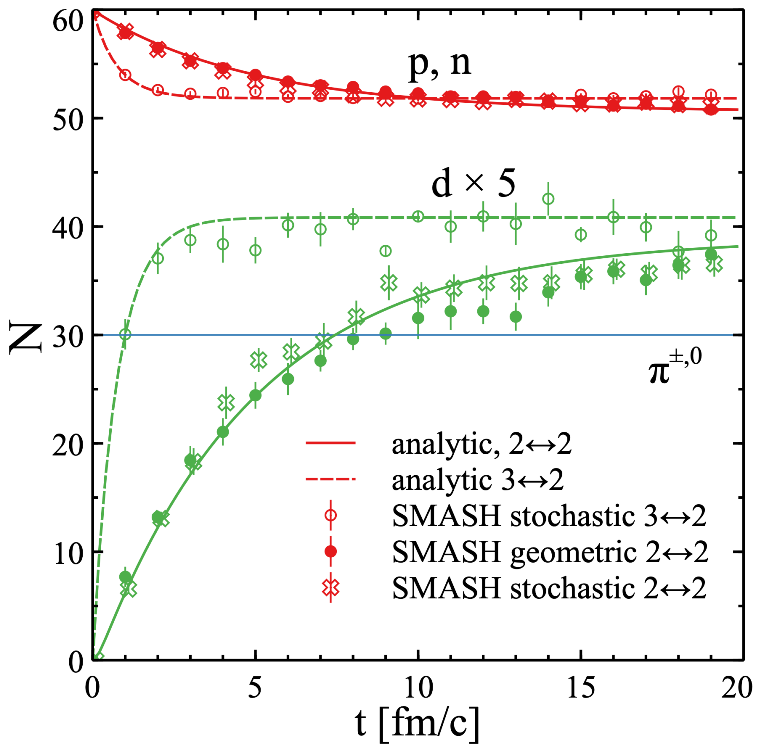
- Microscopic formation and destruction of deuterons
  - Via fictitious deuteron resonance
  - Via explicit 3<->2 reactions

Implemented reactions

$\pi d \leftrightarrow \pi np$ $\quad Nd \leftrightarrow Nnp$

$\pi d \leftrightarrow NN$ $\quad \bar{N}d \leftrightarrow \bar{N}np$

+elastic channels



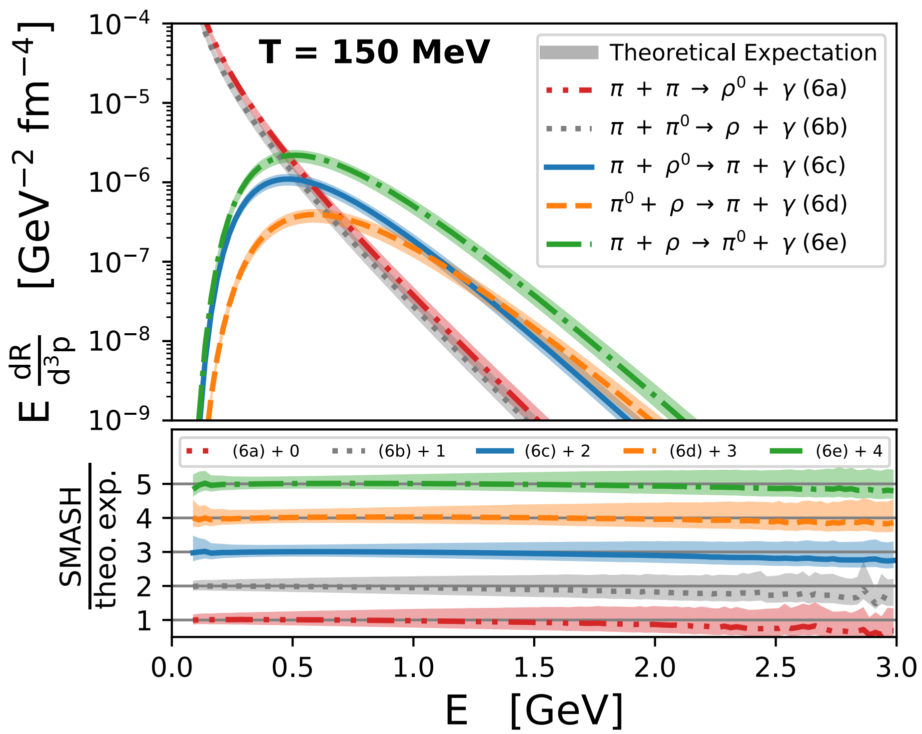
  - In progress: Extended to 3N clusters and Hypertriton, but lots of unknown cross-sections and properties, also approximation as point particle gets worse

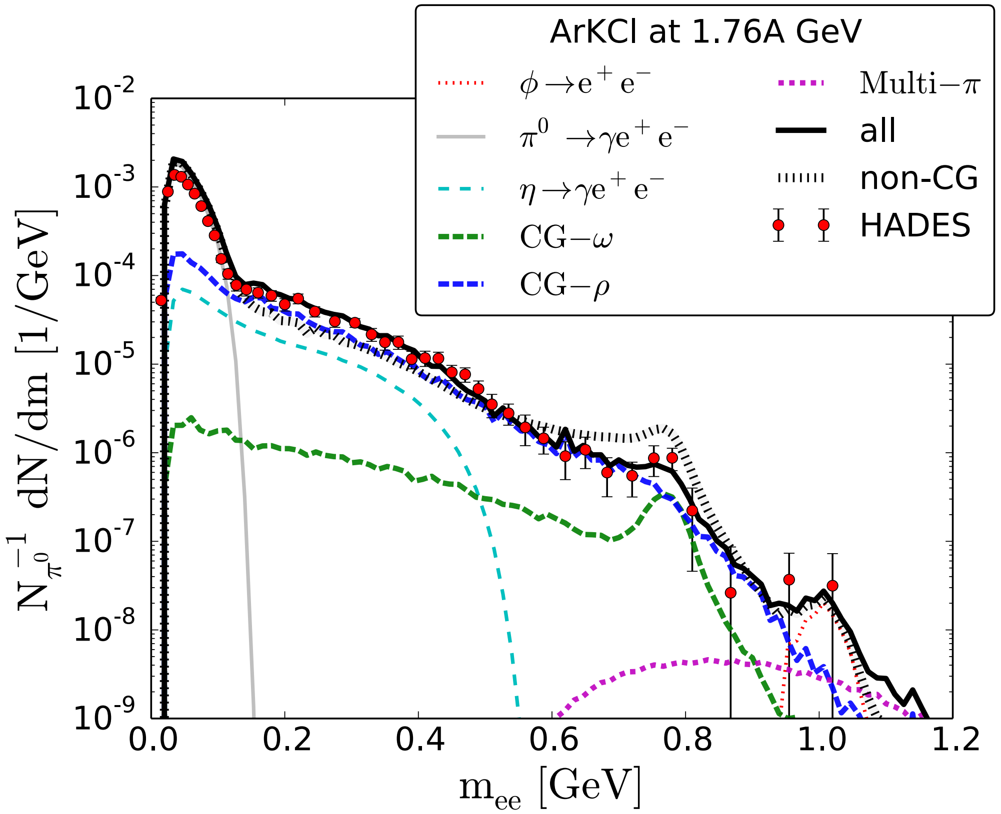
D. Oliinychenko et al, *Phys.Rev.C* 99 (2019)
J. Staudenmaier et al, *Phys.Rev.C* 104 (2021)

- Coalescence-based clustering algorithm
  - Similar to the one used in UrQMD studies by Hillmann et al
  - Collaborating with Spieß et al to improve centrality map for HADES data (as an example to establish procedure)

Electromagnetic Probes

- Dileptons and photons implemented perturbatively
- Dileptons systematically compared to HADES data (including coarse-graining) J. Staudenmaier et al, Phys.Rev.C 98 (2018)
- Photons in afterburner compared to hydrodynamic emission A. Schäfer et al, Phys. Rev. D 99 (2019), Phys.Rev.C 105 (2022)
- Plan: Dilepton flow compared to HADES data; Prediction for excitation function for CBM



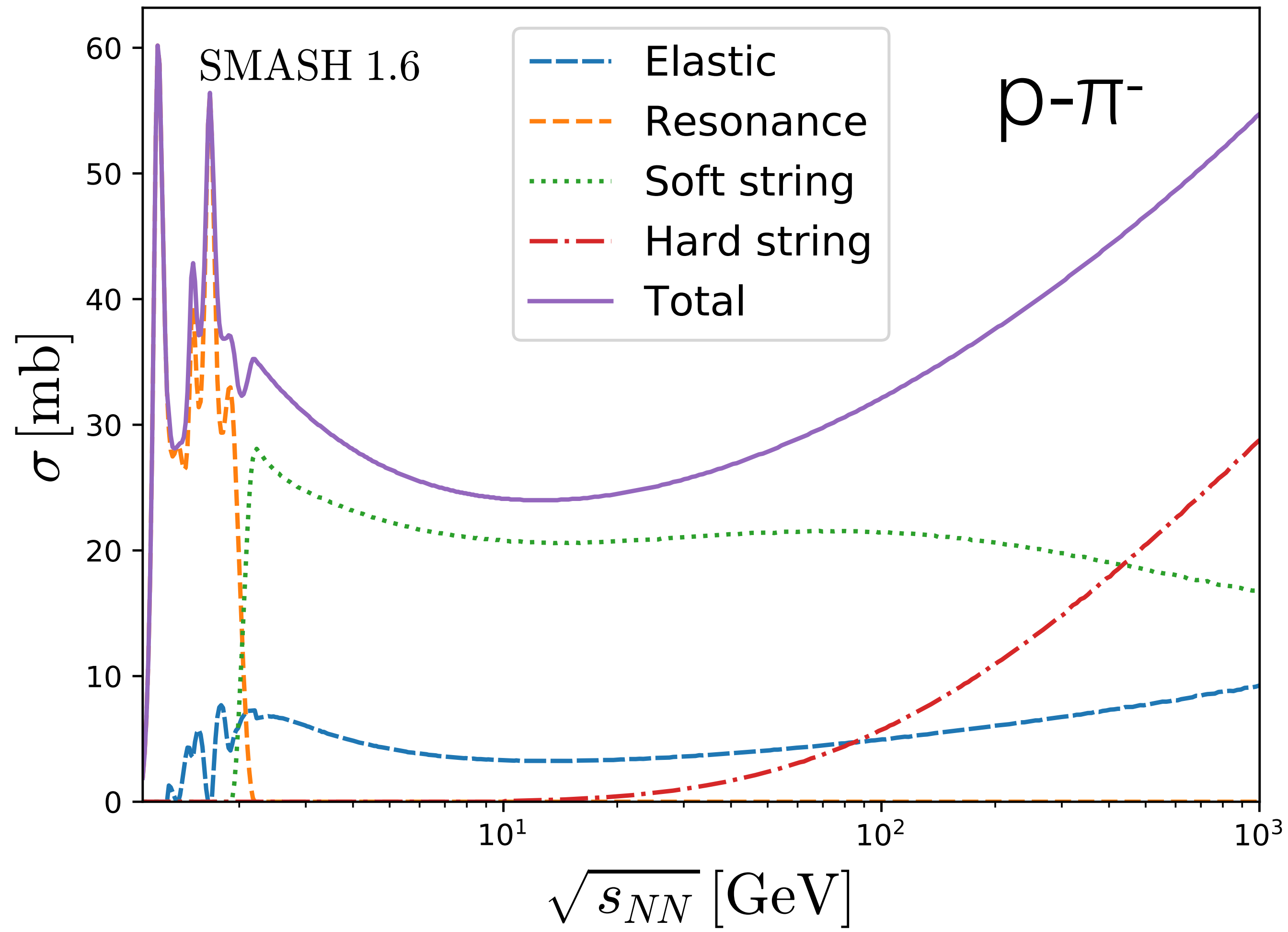


Moving to Higher Energies

- 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



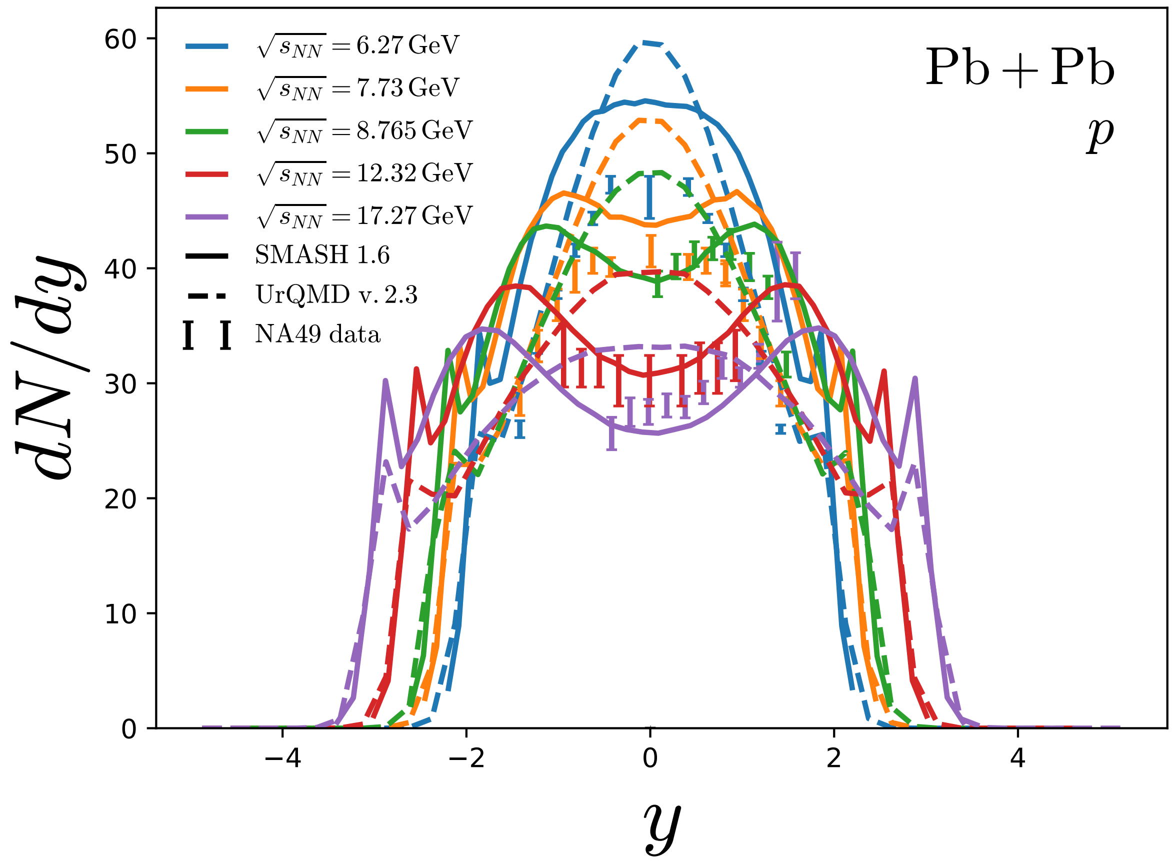
- Hard strings
  - Fully treated by Pythia
  - All species mapped to pions and nucleons

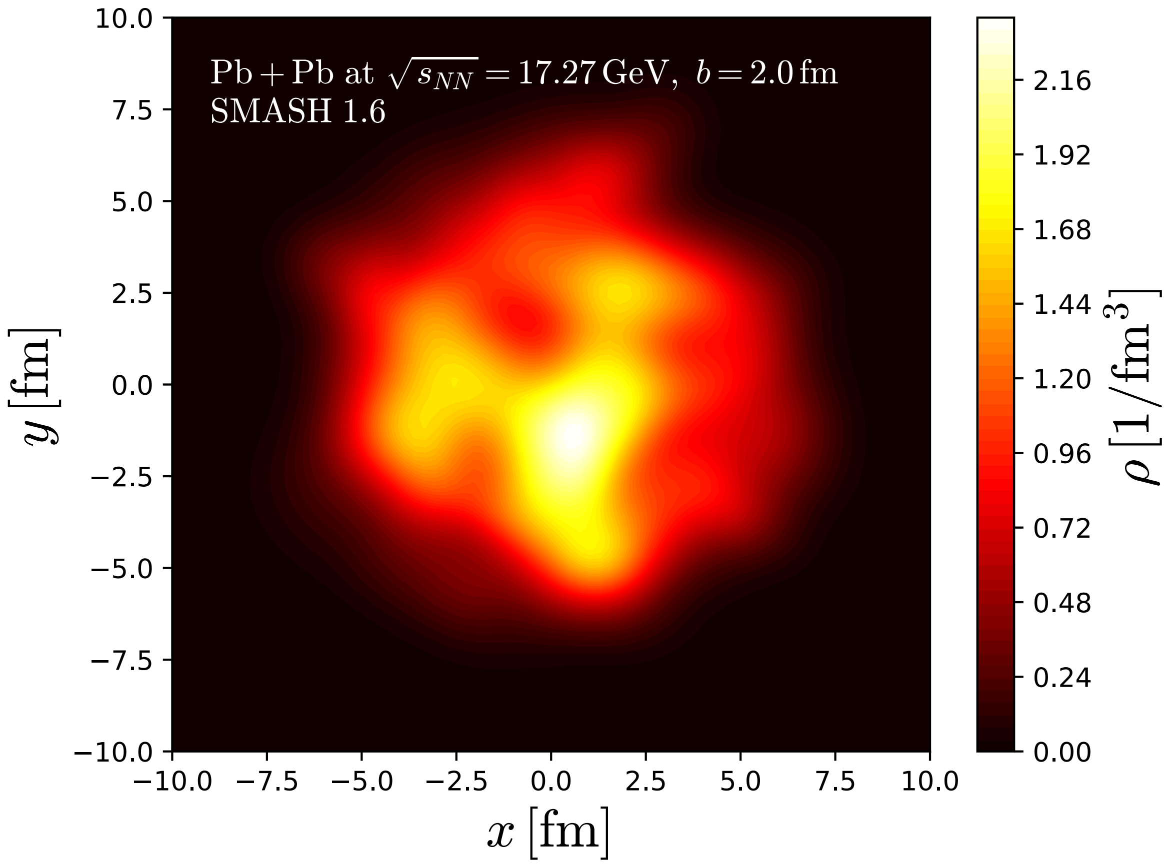
- Note: SMASH-2.0 includes optimised Pythia calls to reduce run-time

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)





- Important first step for studying more involved observables

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

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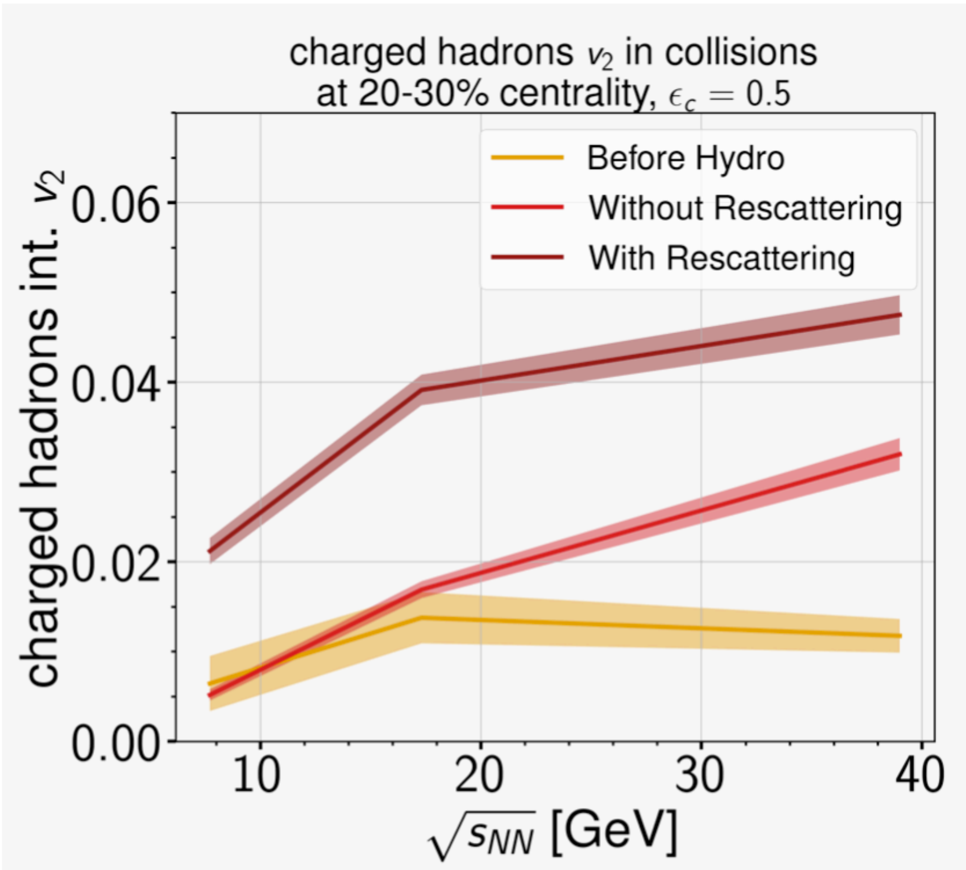
smash-hadron-sampler
- Cooper-Frye sampler
- Particlization of fluid elements

+

SMASH
- Hadronic transport approach
- Evolution of hadronic rescattering

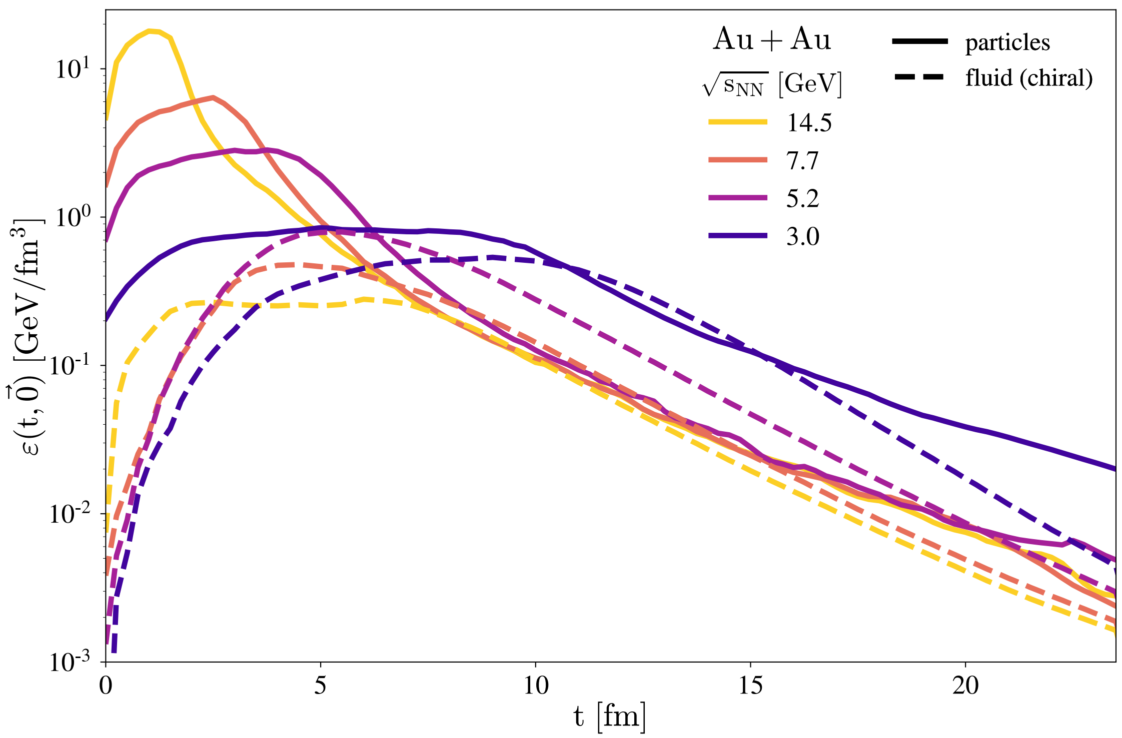


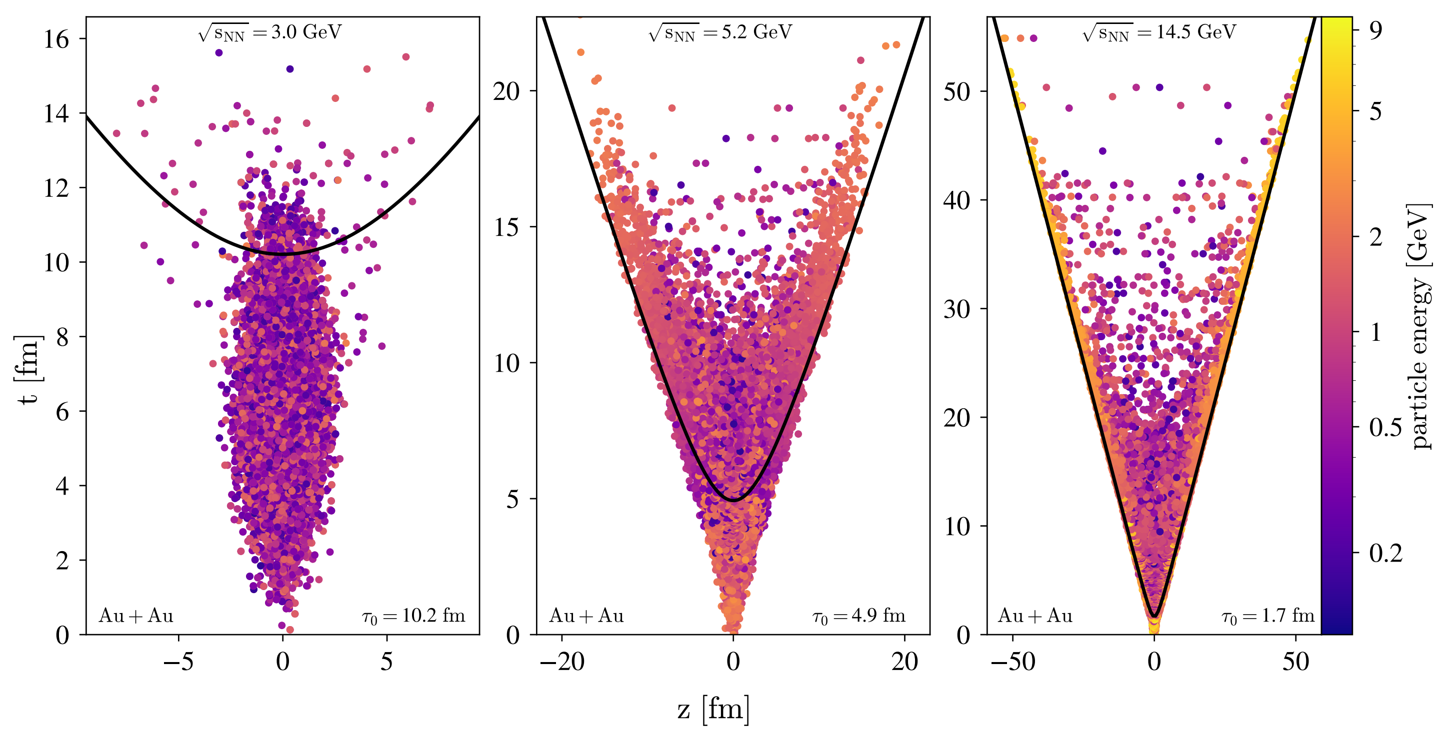
N. Götz and HE, *Phys.Rev.C* 106 (2022)

A. Schäfer et al., Eur.Phys.J.A 58 (2022)
Huovinen et al.: Eur. Phys. J A 48 (2012)
Karpenko et al.: PRC 91, 064901 (2015)
Karpenko et al.: Comput. Phys. Commun. 185 (2014)

Dynamical Initial State

- SMASH particles are converted to fluid when the cells get to high enough energy density
- Allows to apply hybrid approach down to ~1 GeV/nucleon
- Phase transition can be controlled within hydrodynamics

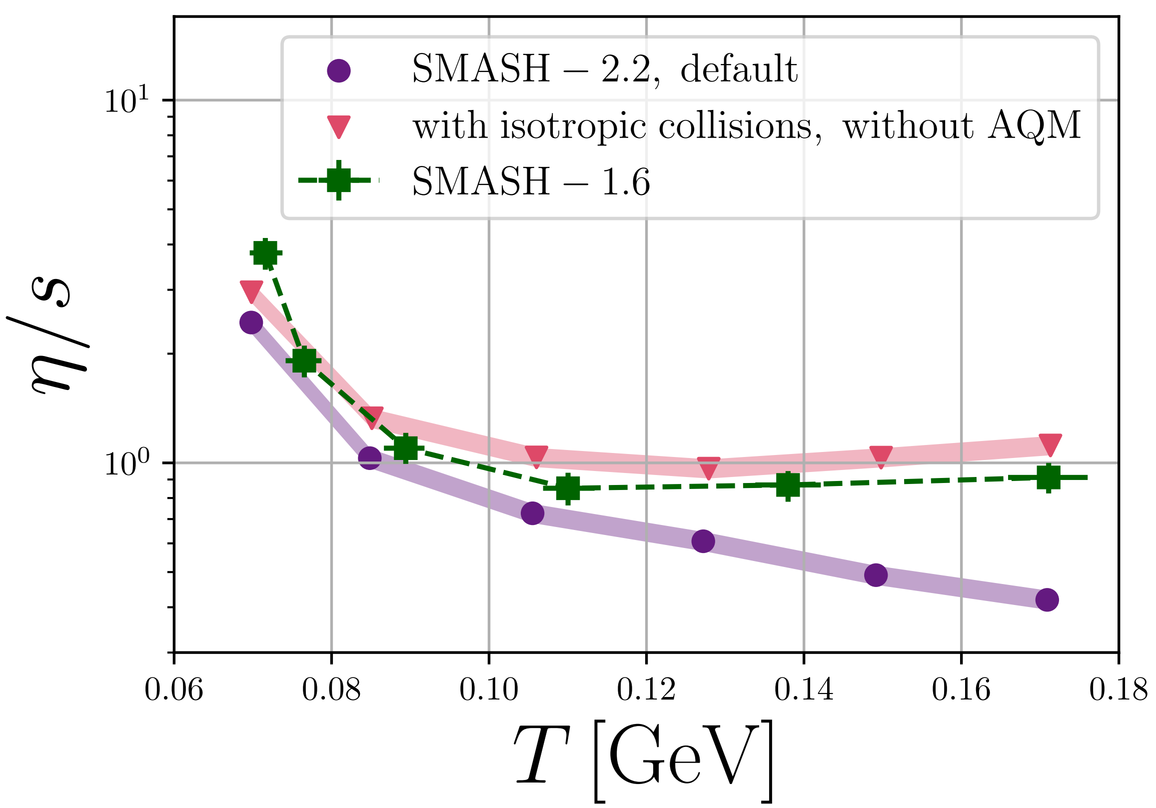


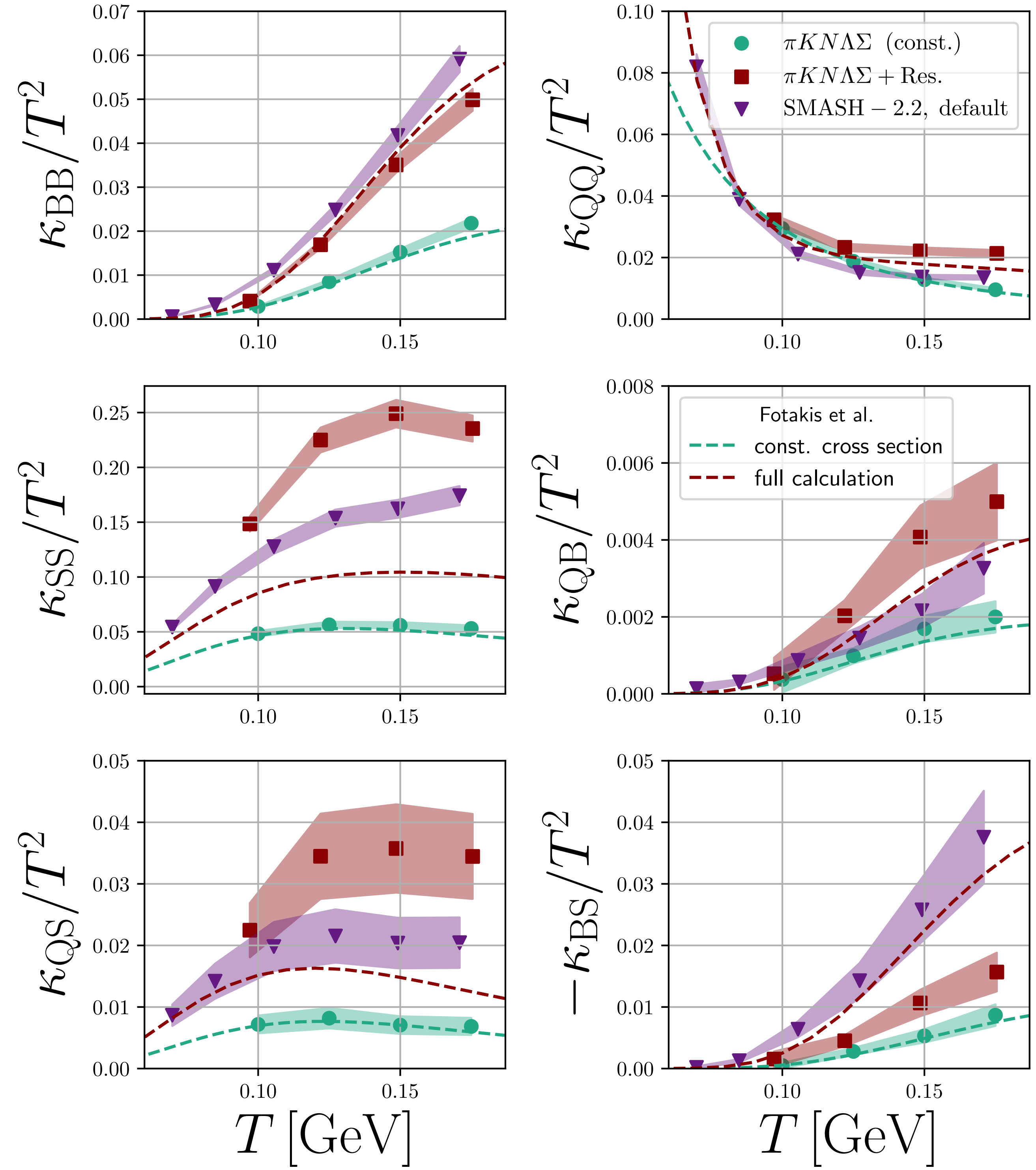


R. Hirayama, work in progress

Transport Coefficients

- Shear and bulk viscosity as a function of temperature
- (Cross-) conductivities for all charges B, S, Q as a function of temperature





J. Hammelmann, J. Staudenmaier and HE, arXiv:2307.15606

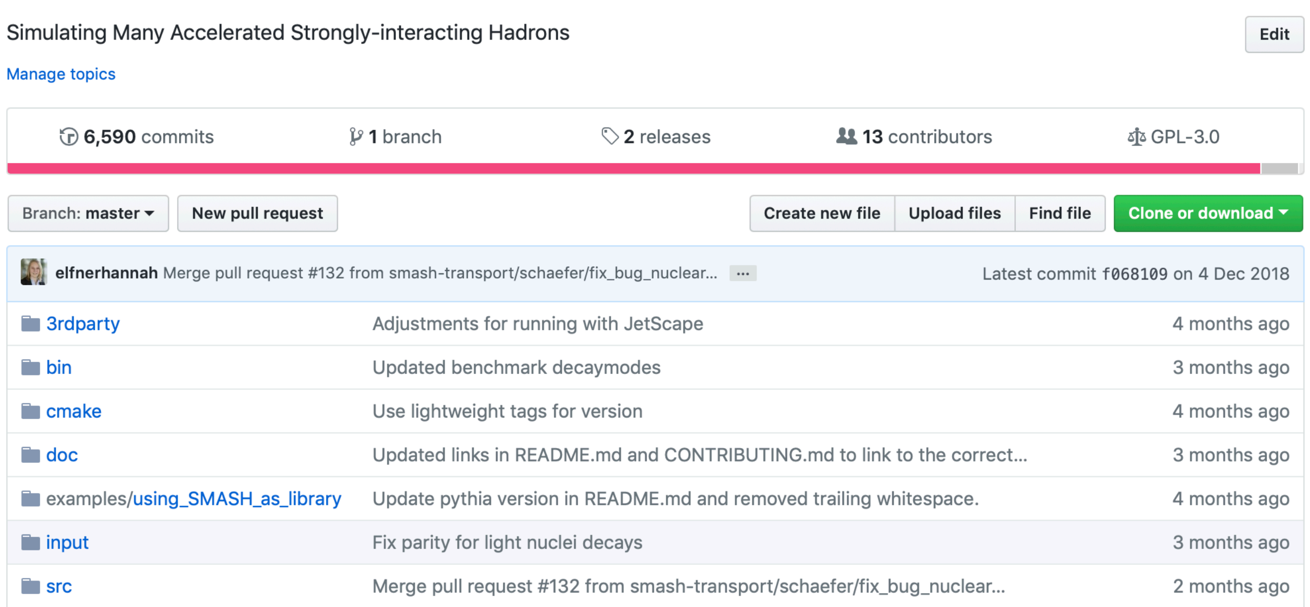
Other Plans

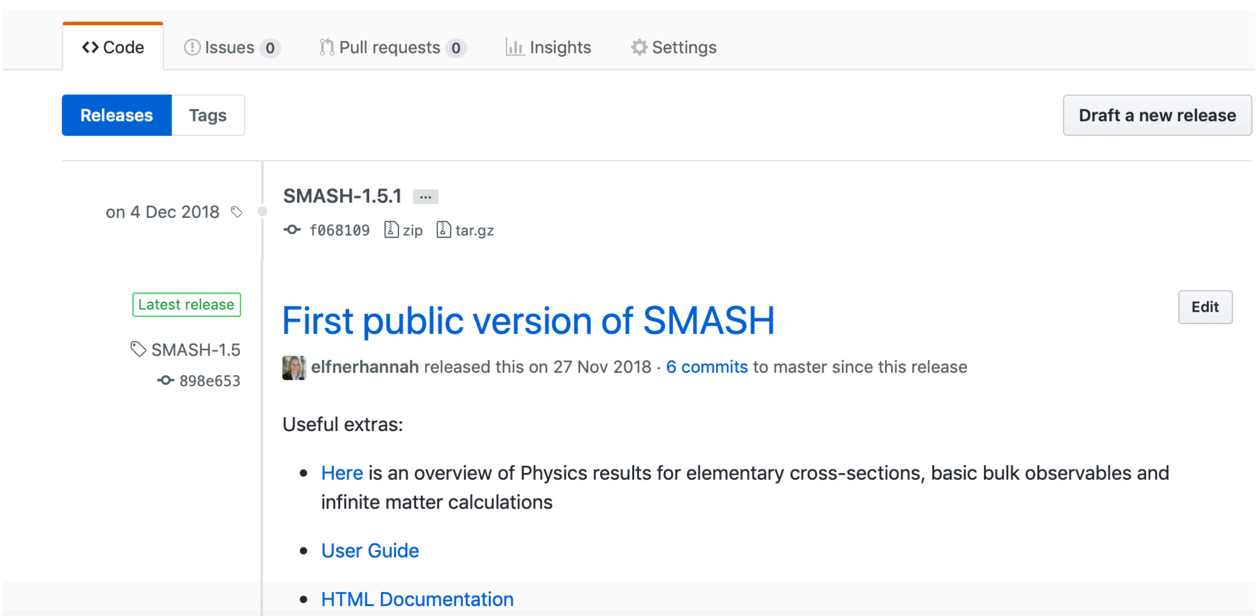
- Further collaboration with JETSCAPE/XSCAPE and MUSES
- Strangeness production
  - Fix elementary production and resonance properties with statistical analysis
  - Look at hyperon-nucleon potentials
- Angular momentum and spin
  - Global angular momentum has been analyzed
  - Spin for hadronic reactions -> work in progress
- Conserved charge fluctuations
  - Influence of conservation laws and cuts
  - Fate during hadronic rescattering

Open Source Strategy

- Visit the webpage to find publications and link to SMASH-3.0 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-3.0 has HepMC and RIVET





Summary

- SMASH has been developed as a new hadronic transport approach
  - Bulk observables are in reasonable agreement with experimental data
  - Electromagnetic radiation is incorporated
  - Baryon stopping within string model
  - Hybrid approach for beam energy scan
- Plans:
  - More robust study of nuclear EoS with comparison to new HADES flow data
  - New PhD student focusing on strangeness production
  - EM probes from dynamic hybrid approach