Heavy-ion Collisions at Lower Collision Energies

Hannah Elfner, June 3rd, 2022

RRTF „Nuclear physics confronts relativistic collisions of isobars“, Heidelberg

Outline

- SMASH hybrid approach
  - Initial state from transport
  - Viscous hydrodynamics with charge conservation
  - Final hadronic rescattering
- Nuclear structure input
  - Current status in SMASH and future plans
  - Effects for isobar collisions
  - Nucleon-nucleon correlations
  - Color fluctuations
- Low beam energy collisions
  - Experimental opportunities
  - Theoretical description and plans

smash

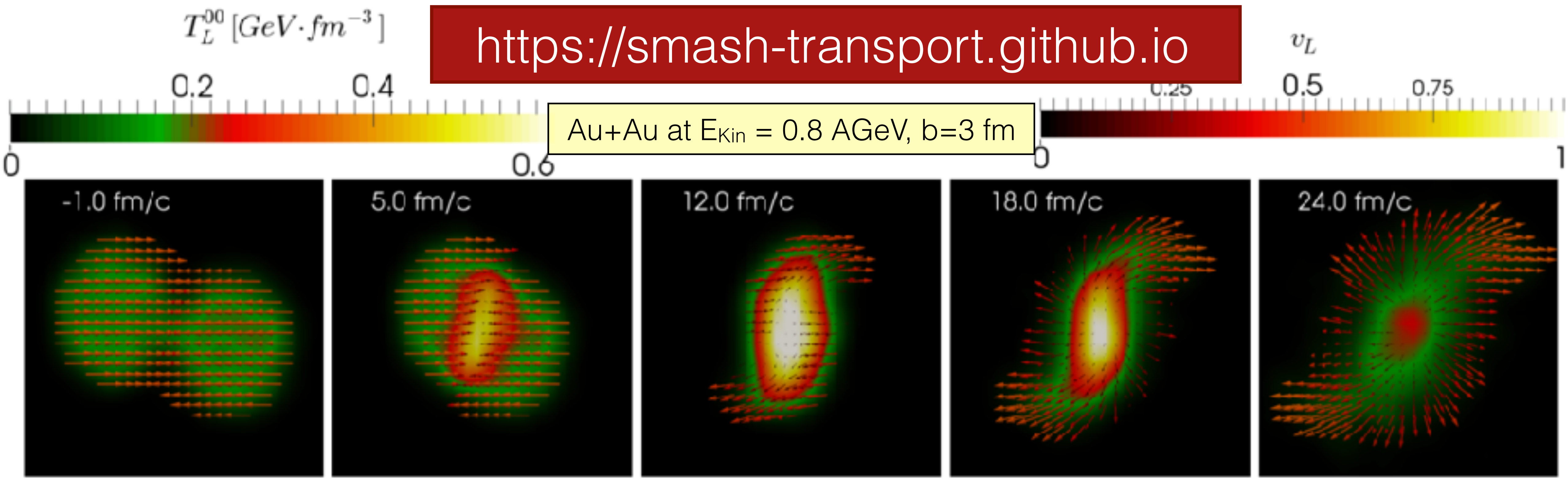
SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, HepMC, Rivet, ROOT

https://smash-transport.github.io

Au+Au at E_{Kin} = 0.8 AGeV, b=3 fm



* Simulating Many Accelerated Strongly-Interacting Hadrons

The SMASH Team

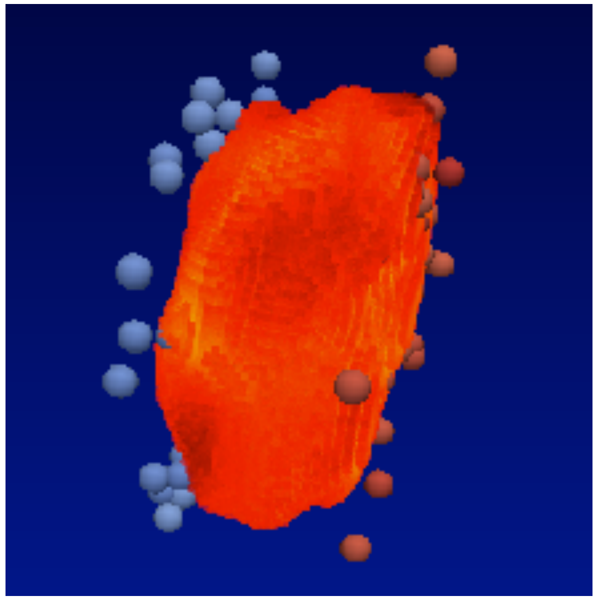
- In Frankfurt:
  - Oscar Garcia-Montero
  - Gabriele Inghirami
  - Alessandro Sciarra
  - Jan Staudenmaier
  - Justin Mohs
  - Jan Hammelmann
  - Niklas Götz
  - Renan Hirayama
  - Nils Saß
  - Jonas Rongen
  - Antonio Bozic
  - Orhan Özel
  - Lucas Constantin
  - Julia Gröbel
  - Branislav Balinovic

- In US:
  - Dmytro Oliinychenko
  - Agnieszka Sorensen

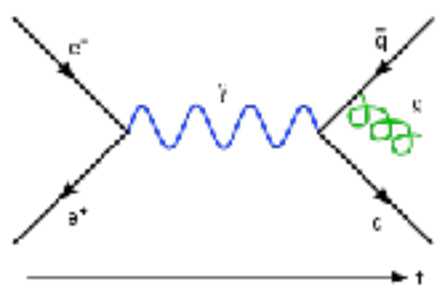
Group excursion in May 2022

SMASH Hybrid Approach

Theoretical Description

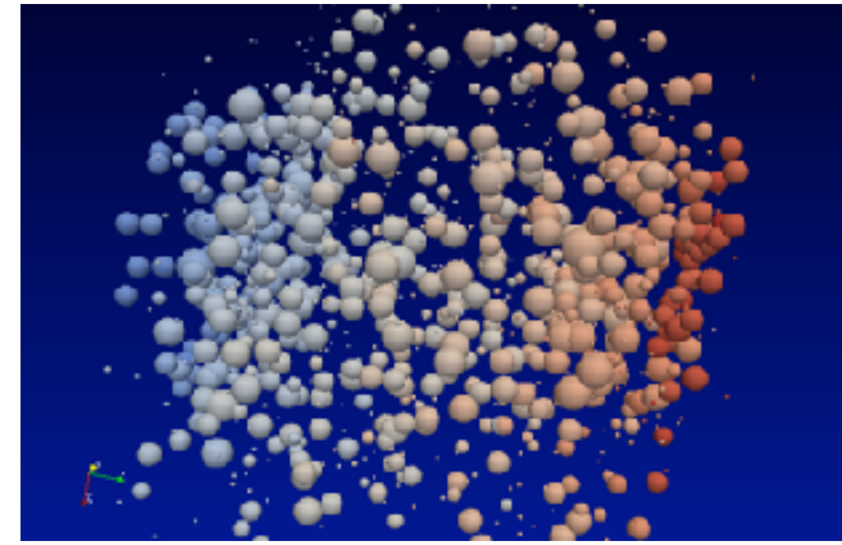


Fundamental field theory of strong interactions (QCD)

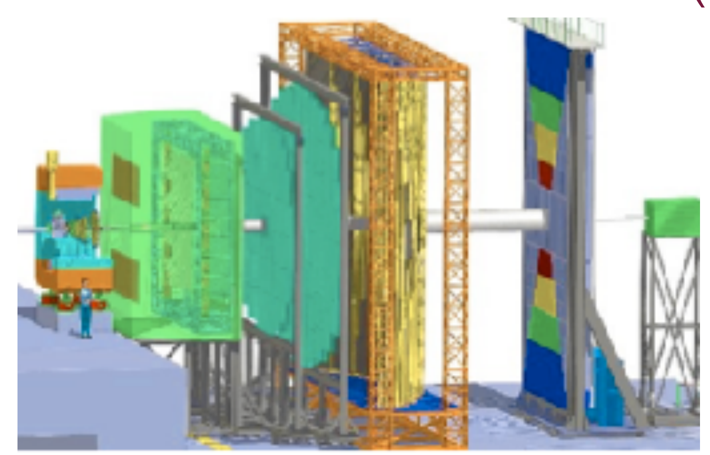


$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^{\mu} (D_{\mu})_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Dynamical description of heavy ion reactions



Measurements in the detector (CBM@FAIR)



- **Theoretical models** are essential to gain insights about the properties of the quark gluon plasma

Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector

1×10^{-23} s

10×10^{-23} s

30×10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

- Due to the short time scale of 10^{-22} seconds and the tiny volume $(10 \times 10^{-15} m)^3$ the quark gluon plasma escapes direct detection

Dynamic description of heavy ion collisions has to capture all the stages of the reaction

Hybrid Approaches

Transport

Microscopic description of the whole phase-space distribution

Non-equilibrium evolution based on the Boltzmann equation

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

Partonic or hadronic degrees of freedom

Cross-sections are calculable using different techniques

Phase transition?

Hydrodynamics

Macroscopic description

Local equilibrium is assumed

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

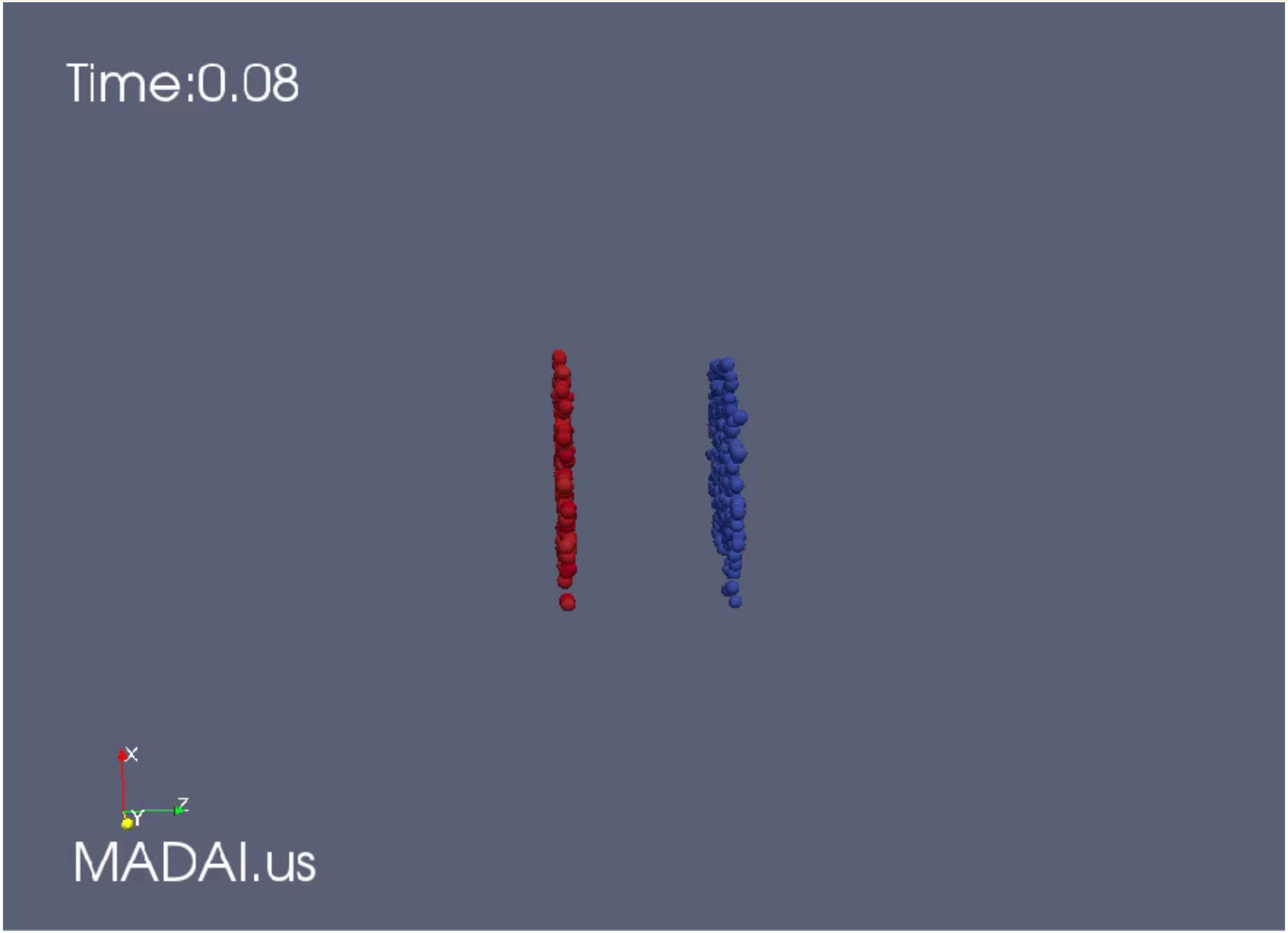
Propagation according to conservation laws

Equation of state is an explicit input

Boundary conditions: Breakdown of equilibrium assumptions?

- Combine the advantages of both approaches
- Successful description from initial to final state

One Event at RHIC Energies



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

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)

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

SMASH Basics

- Transport models provide an effective solution of the relativistic Boltzmann equation

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

- Particles represented by Gaussian wave packets for density calculations
- Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}$$

$$d^2_{\text{trans}} = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

As in UrQMD

- Test particle method

$$\sigma \mapsto \sigma \cdot N_{\text{test}}^{-1}$$

$$N \mapsto N \cdot N_{\text{test}}$$

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}					

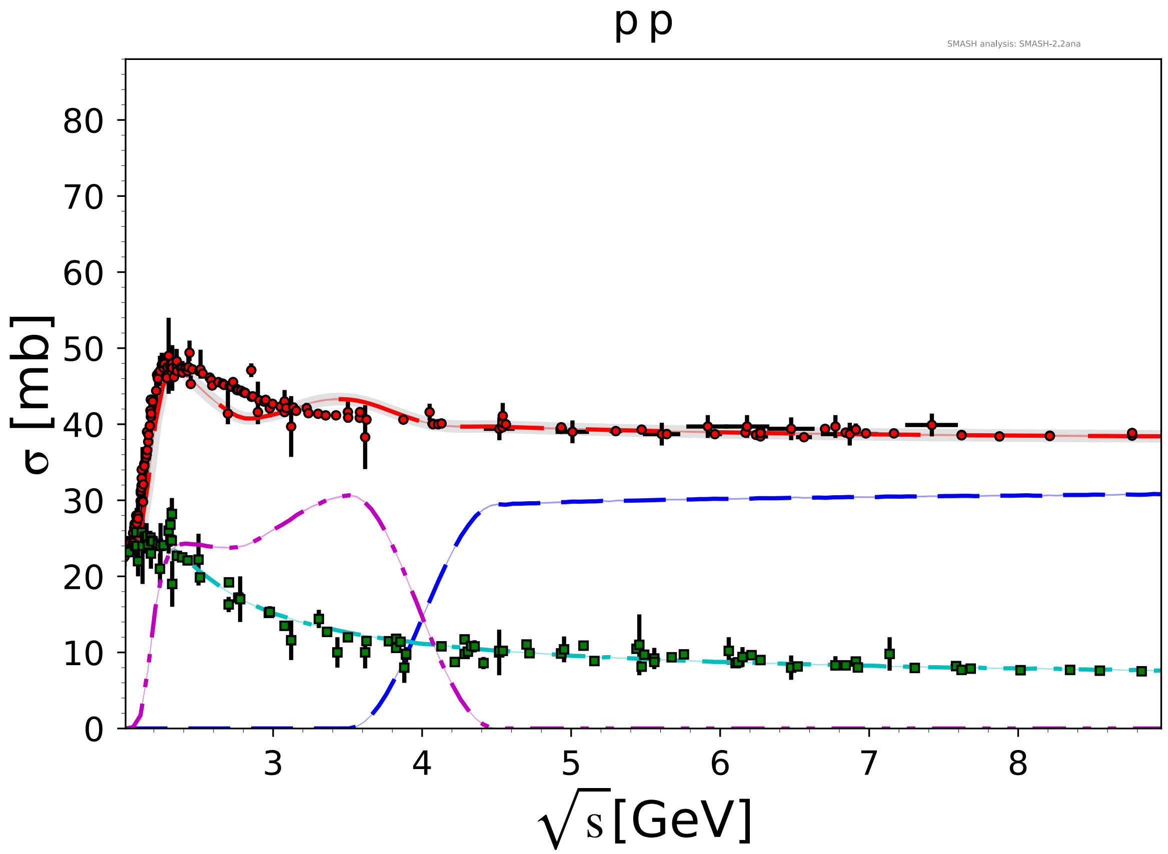
As of SMASH-1.7

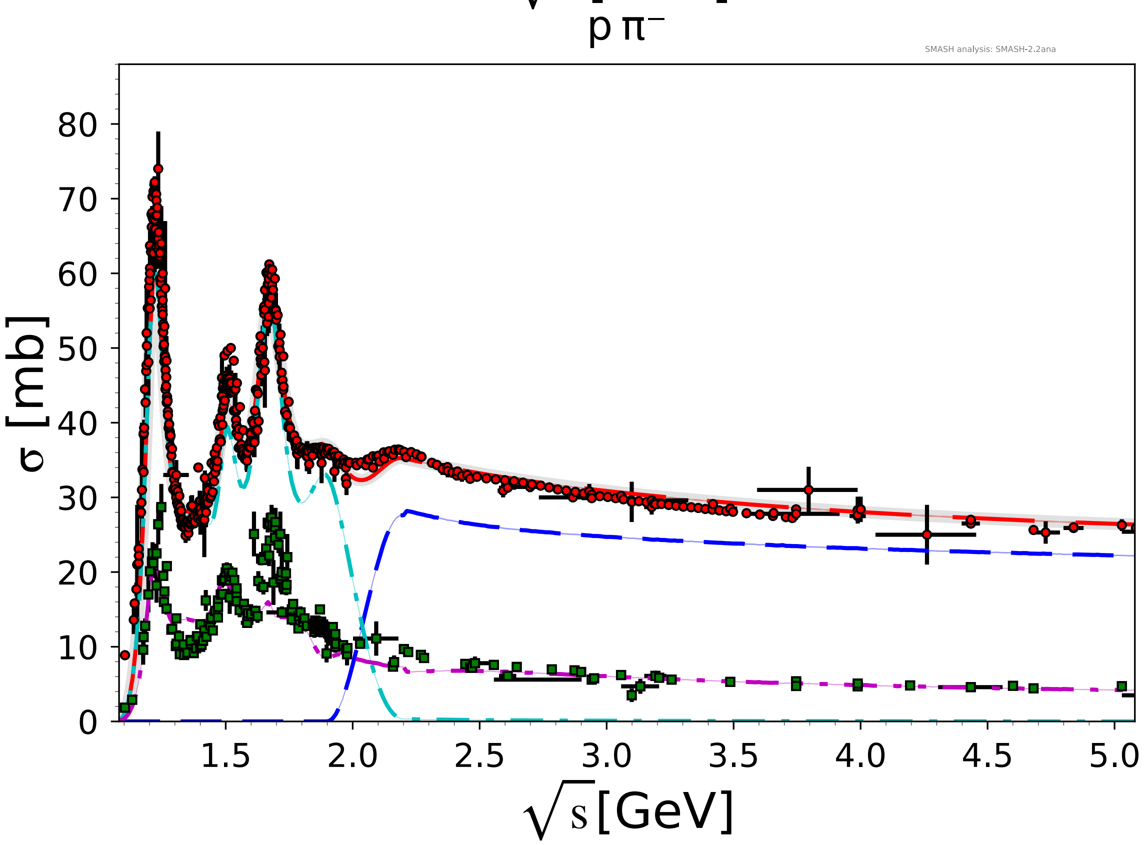
Unflavored				Strange
π_{138}	f_0 980	f_2 1275	π_2 1670	K_{494}
π_{1300}	f_0 1370	f_2' 1525		K^*_{892}
π_{1800}	f_0 1500	f_2 1950	ρ_3 1690	K_1 1270
	f_0 1710	f_2 2010		K_1 1400
η_{548}		f_2 2300	ϕ_3 1850	K^*_{1410}
η'_{958}	a_0 980	f_2 2340		K_0^* 1430
η_{1295}	a_0 1450		a_4 2040	K_2^* 1430
η_{1405}		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}		π_1 1400		
ρ_{1450}	b_1 1235	π_1 1600		
ρ_{1700}				
	a_1 1260	η_2 1645		
ω_{783}				
ω_{1420}		ω_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



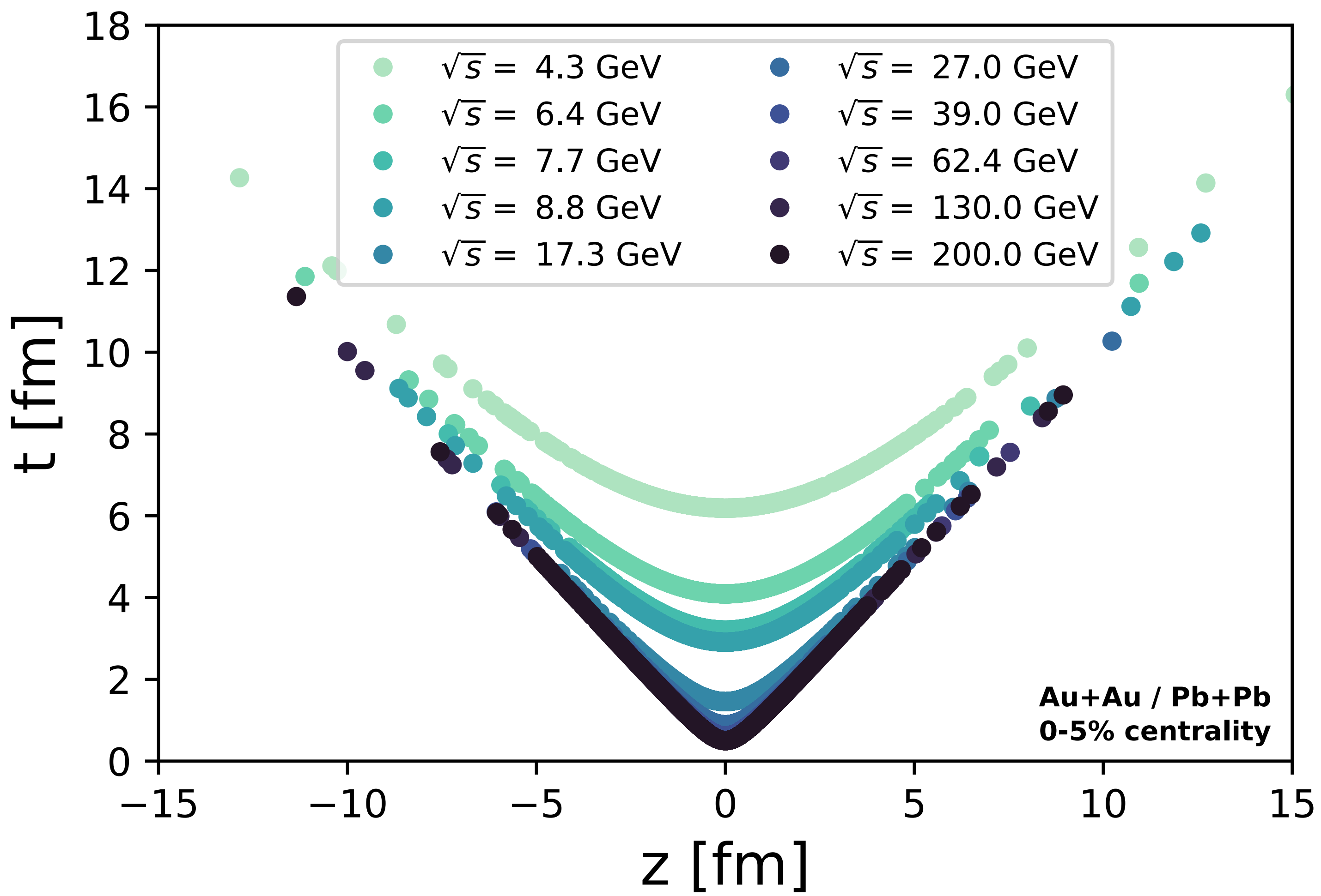


- Total cross section for pp/pπ collisions
- Parameterized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Soft strings a la UrQMD and hard strings via Pythia 8

J. Weil et al, PRC 94 (2016), updated SMASH-2.2

Initial Conditions from SMASH

A. Schäfer, PhD thesis



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

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

- 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

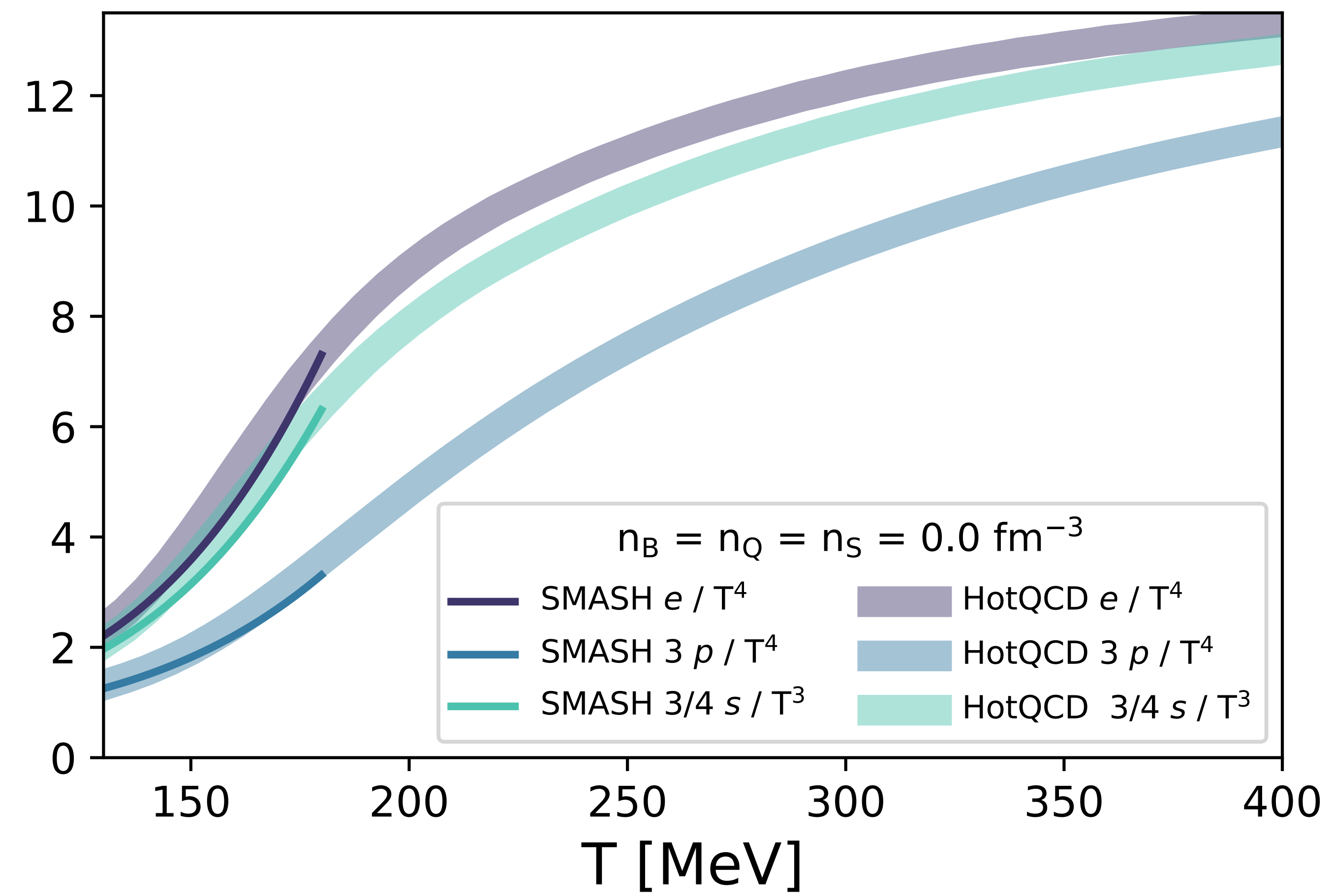
- 3+1 dimensional viscous hydrodynamic evolution
- Shear (and bulk) viscosity are included

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

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

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

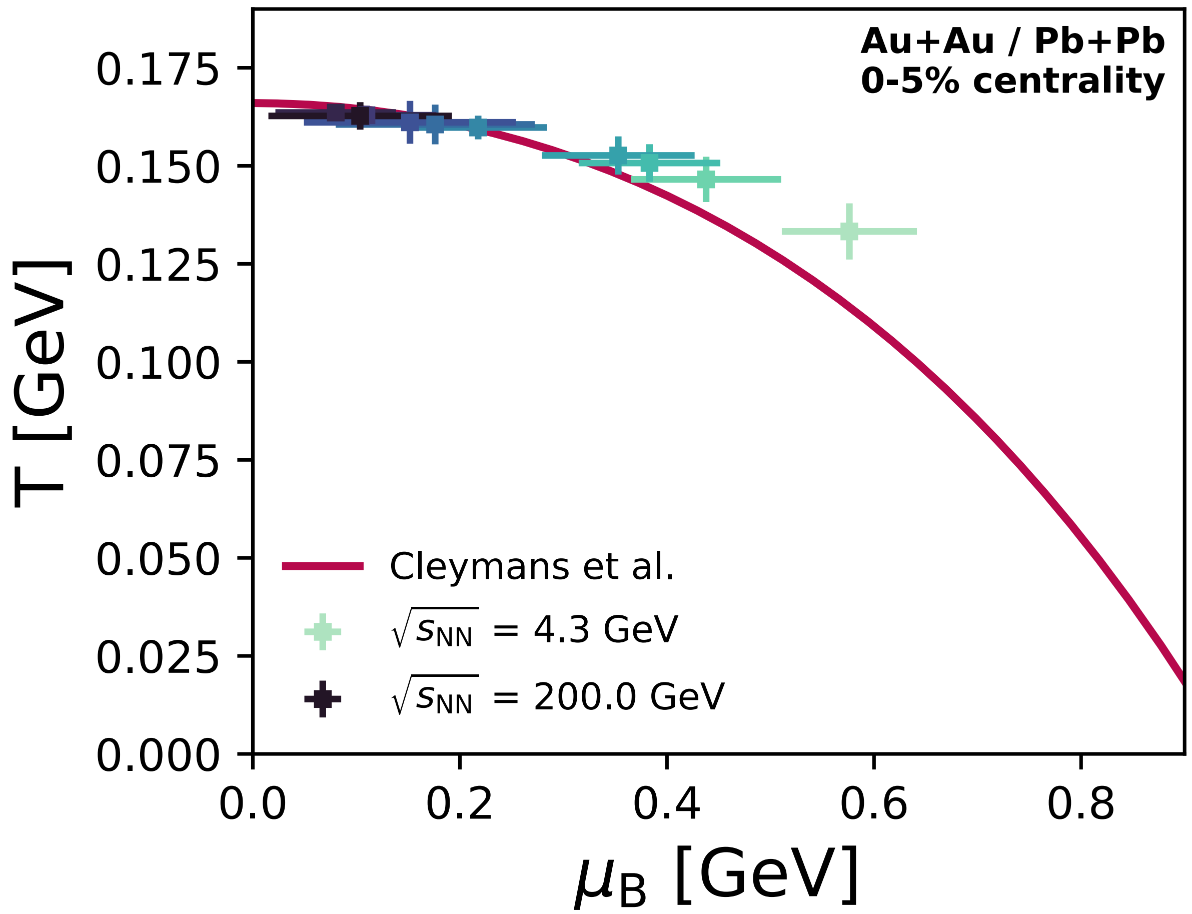
- For correct mapping of degrees of freedom on hypersurface the SMASH hadron gas equation of state is used
- $(e, n_B, n_Q) \rightarrow (T, p, \mu_B, \mu_Q, \mu_S)$



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)

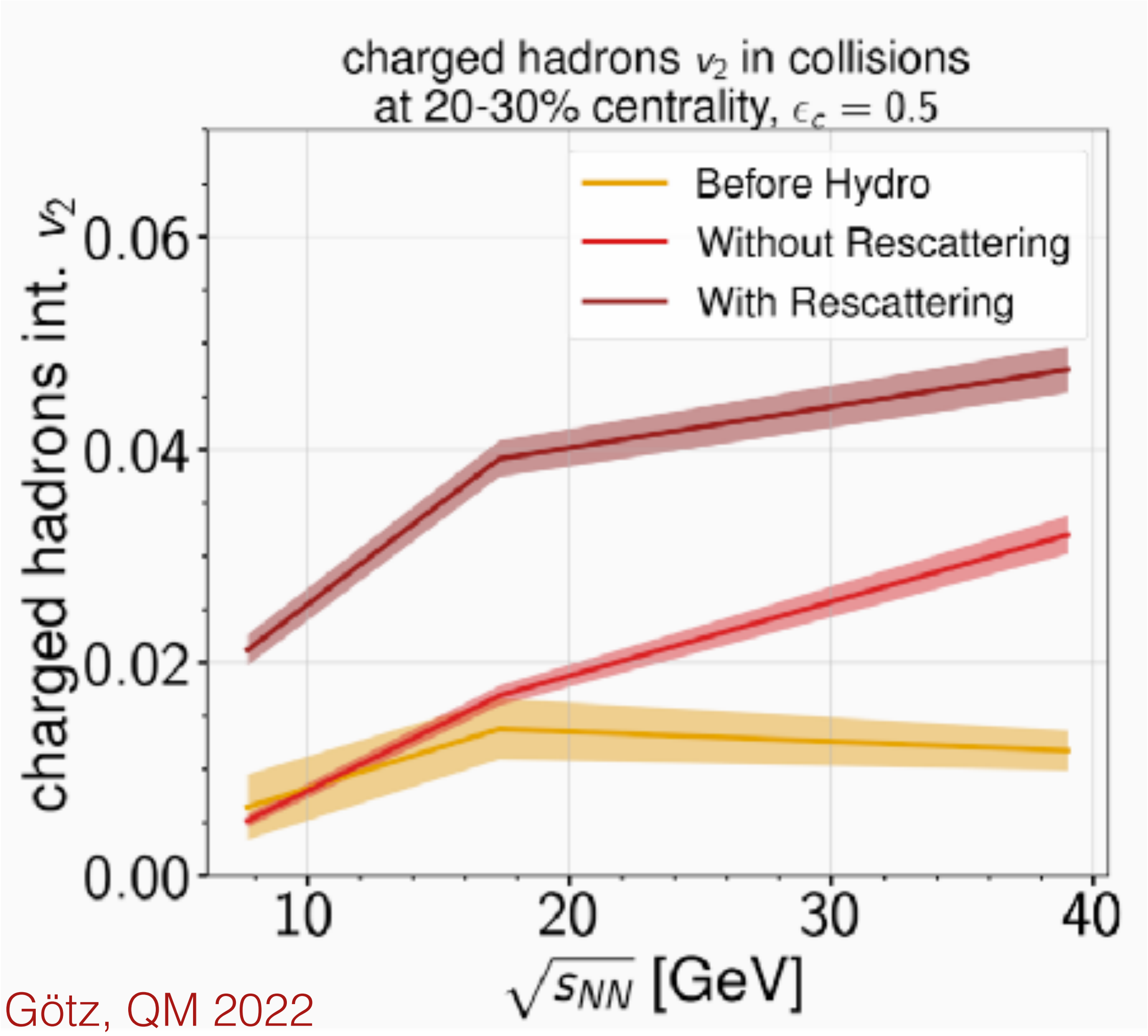


- Work in progress:
  - Sampling according to micro canonical ensemble
  - Local conservation of quantum numbers important for charge correlation observables

D. Oliinychenko, V. Koch, PRL 123 (2019)

Hadronic Rescattering

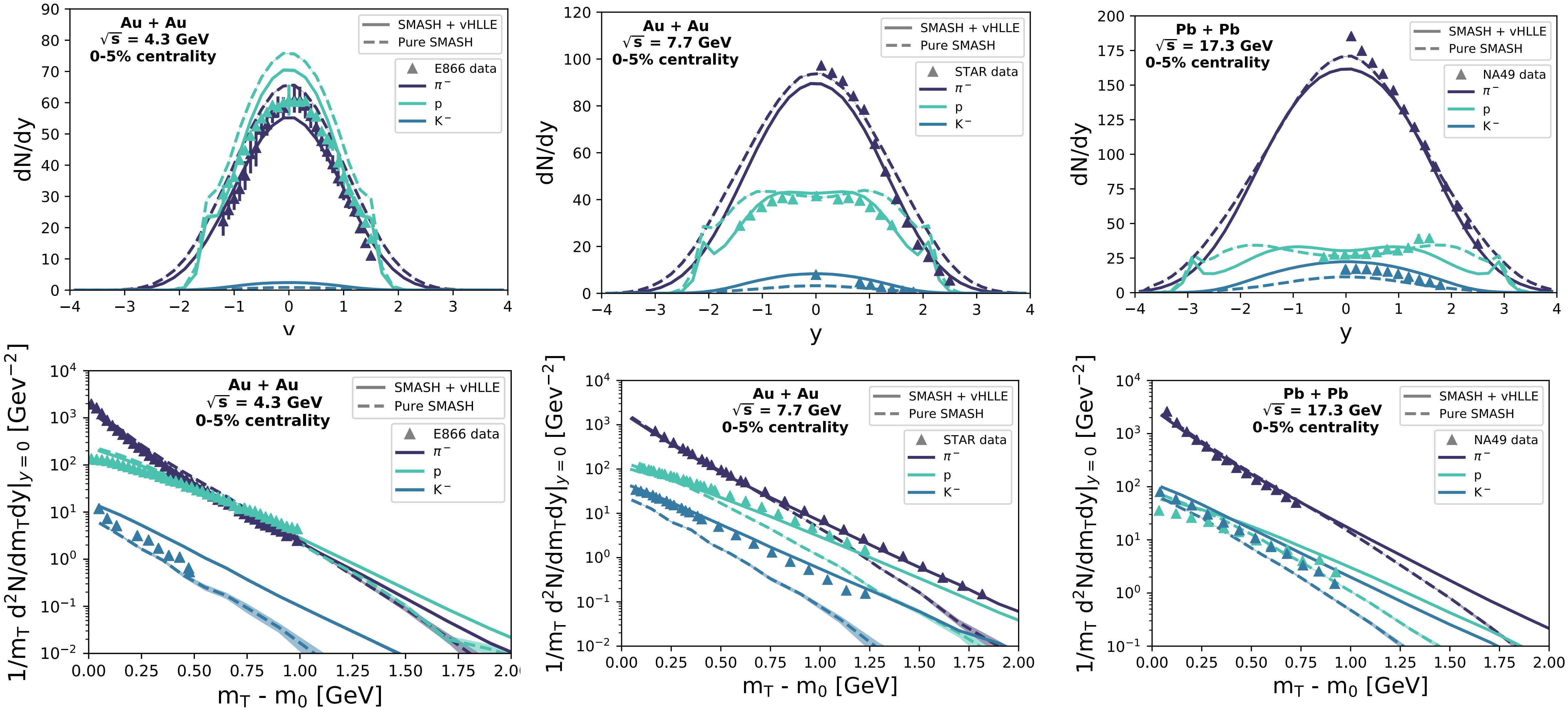
- Final state rescattering and resonance decays are handled within the hadronic transport approach SMASH
- Depending on switching transition a significant amount of elliptic flow is still generated



N. Götz, QM 2022

- Charges are naturally conserved in each binary interactions
- How does the rescattering affect charge correlation observables?

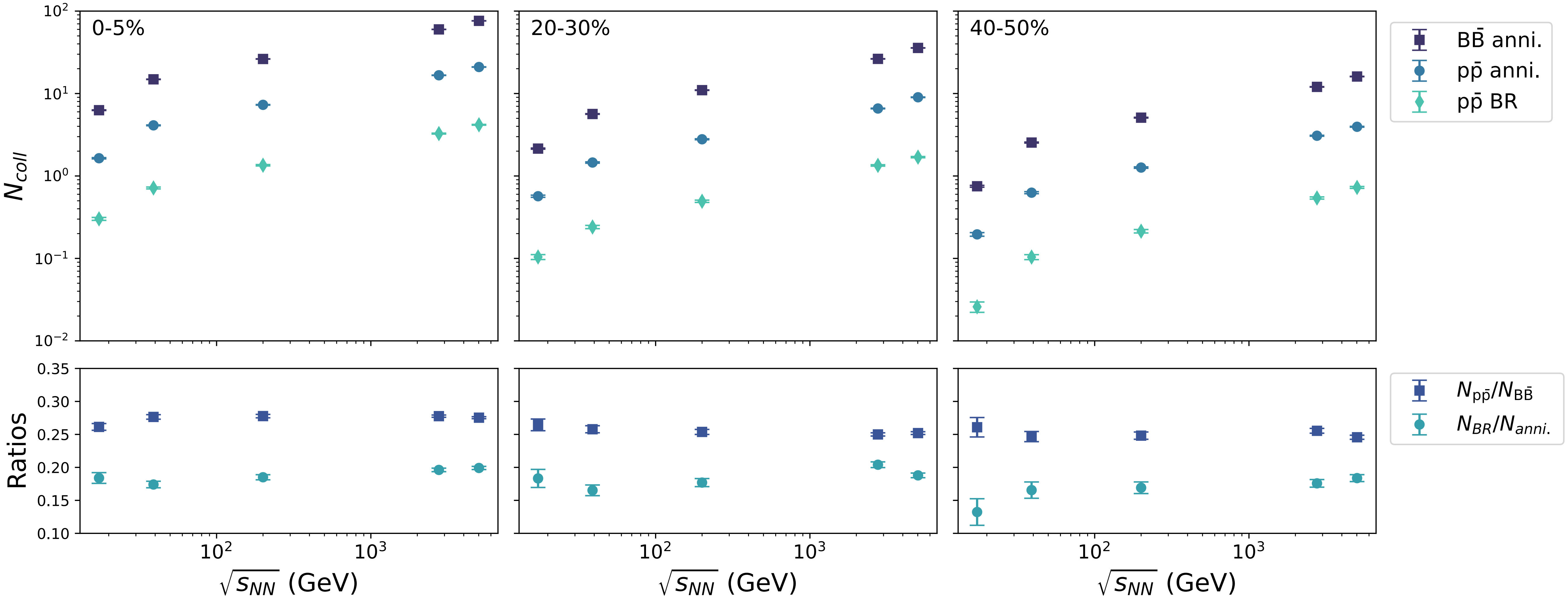
Particle Spectra



- 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

Hybrid at High Beam Energies



O. Garcia-Montero et al., arXiv:2107.08812

- SMASH hybrid also runs at highest RHIC and LHC energies
- First time the 5 π <-> p pbar reaction is included
- Backreaction refills about 50% of annihilated protons

Our Setup for RRTF Calculations

- SMASH initial conditions with optional deformations of nuclei or fully external nucleon configuration files according to nuclear wave functions
- 3+1 dimensional viscous hydrodynamic evolution with shear and bulk viscosity
- Charge conservation (B,S,Q) at all interfaces and in all stages of the reaction
- Cooper-Frye sampling optionally including conservation laws
- SMASH hadronic transport approach for final state rescattering
- -> Nils Saß and Jan Hammelmann are ready to go

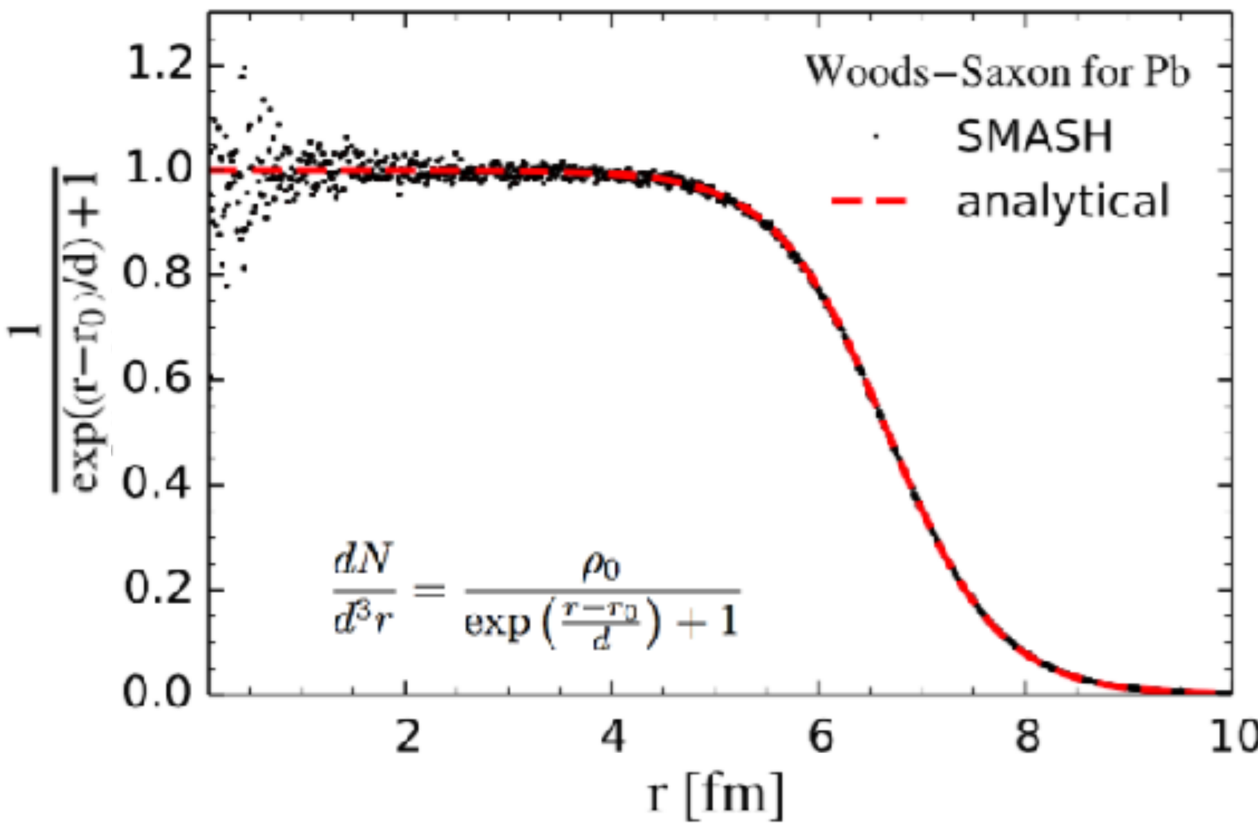
Nuclear Structure Input

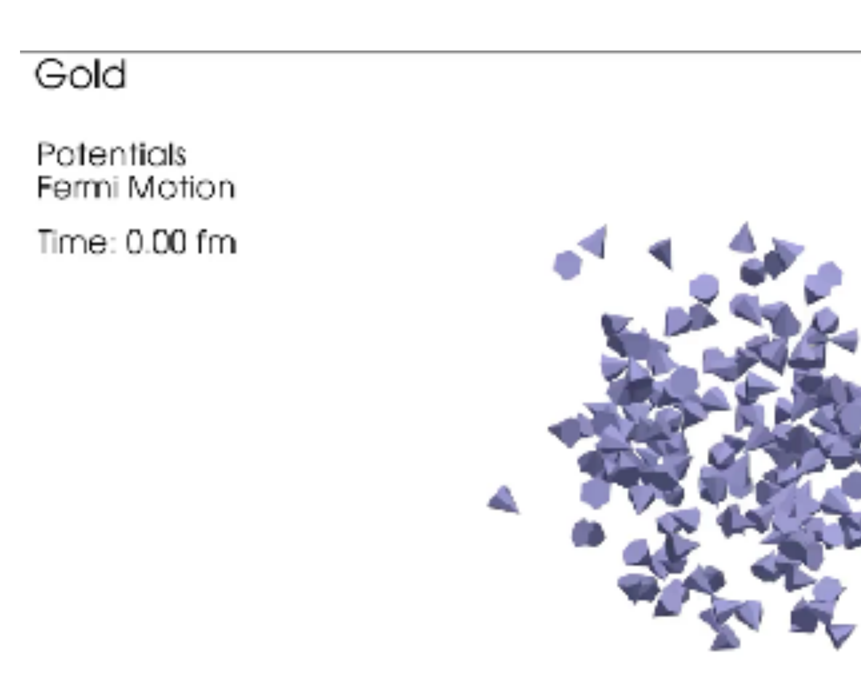
In collaboration with
Alba Soto Ontoso, Massimiliano Alvioli, Mark Strikman

Initial Conditions

- Nuclear Collisions
  - Woods-Saxon distribution in coordinate space

J. Weil et al, PRC 94 (2016)



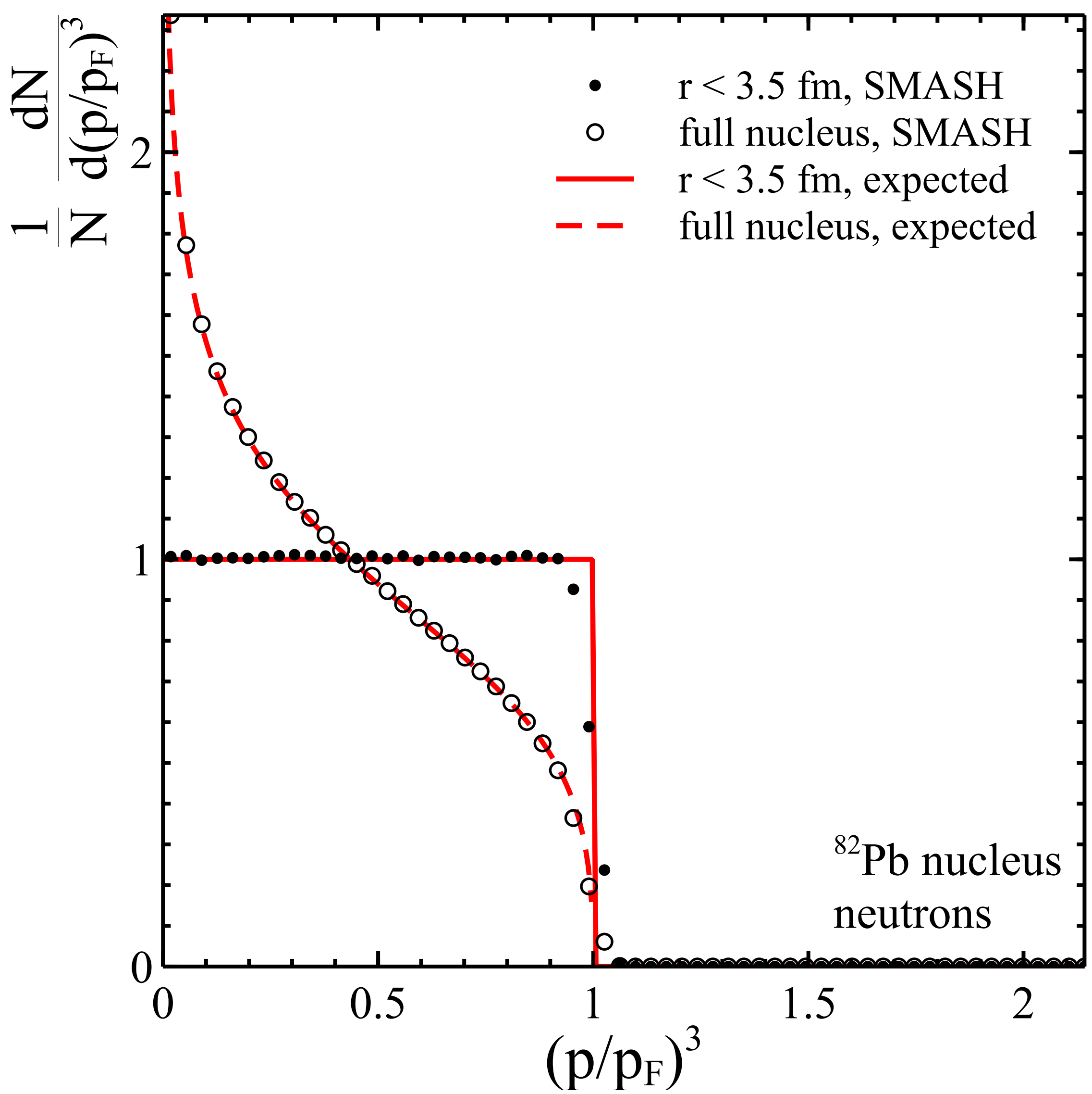


Gold nucleus with potentials and Fermi motion

  - *optional:* deformed nuclei and (frozen) Fermi motion
  - *optional*: read-in of more realistic initial states with correlations, neutron skin

Fermi Motion

- Fermi motion is randomly assigned to each nucleon depending on the local density $p_F(\vec{r}) = \hbar c(3\pi^2\rho(\vec{r}))^{1/3}$



J. Weil et al., PRC 78, 2016

- Fermi motion would lead to unstable nuclei
- Attractive part of mean field has to balance Fermi motion
- For higher beam energies where mean fields are not required
- -> Frozen Fermi motion
  - Fermi momentum is not taken into account for propagation only for collisions

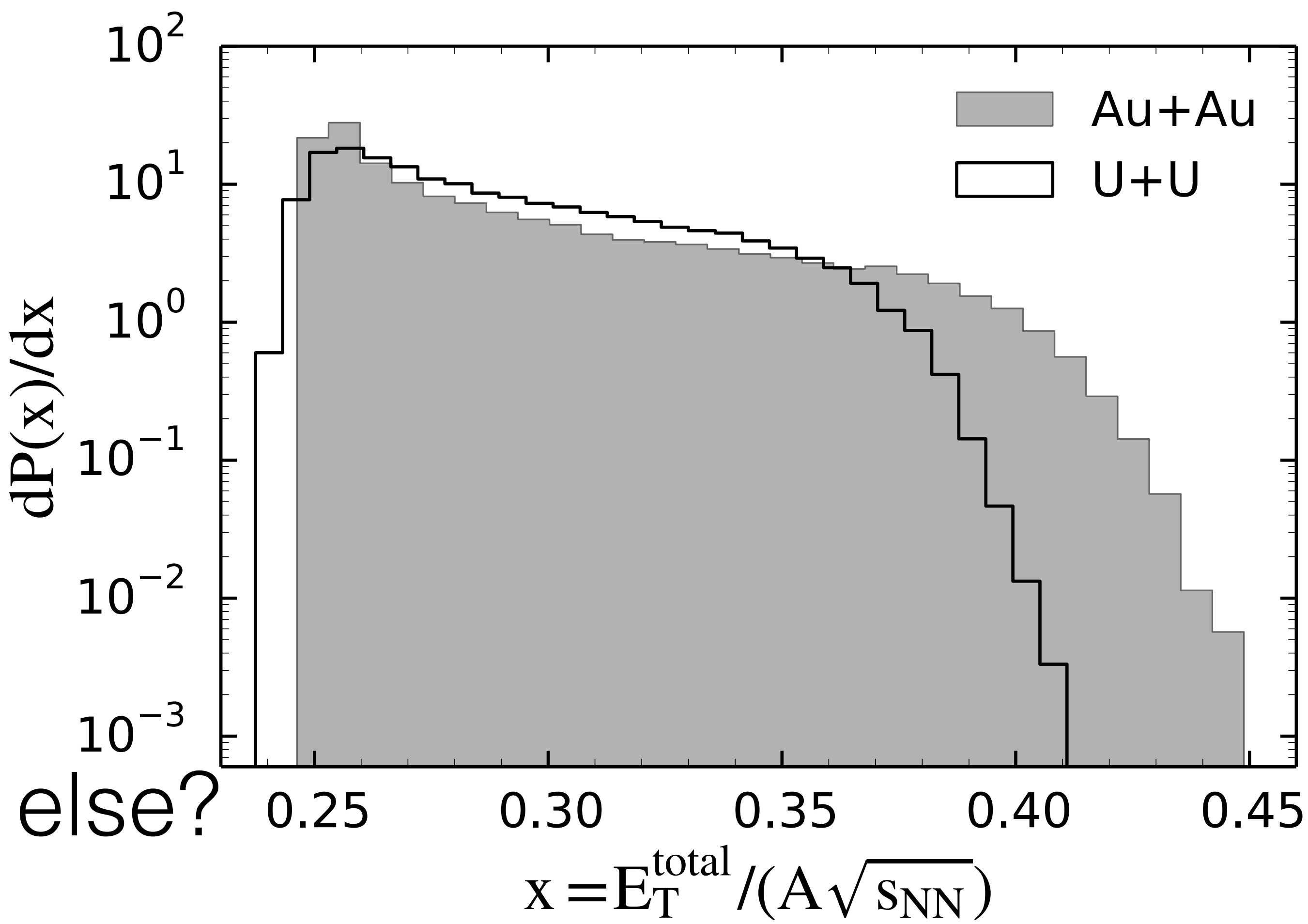
Deformation of Nuclei

- SMASH includes the most basic deformation parameters
- After sampling nucleons, the whole configuration is rotated by random Euler angles to provide independent initial states
- Specific values for certain known nuclei are provided

J. Weil et al., PRC 78, 2016

$$\rho(r,\theta,\varphi) = \frac{\rho_0}{1 + \exp\left(\frac{r - r(\theta,\varphi)}{d}\right)}$$

$$r(\theta,\varphi) = r_0\left(1 + \sum_{l=1}^{\infty}\sum_{m=-l}^{l}\beta_{lm}Y_l^m\right)$$



- BSc student works on extending this by β_3,γ +what else?

External Configurations

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

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

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

- 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
- Added neutron skin and deformations where appropriate
- Only coordinate space, momentum space unaffected

Isobar Collisions

- Investigate potential maximal effect of deformation for Ru

$$\rho(r,\theta) = \frac{\rho_0}{e^{(r-R'(\theta,\phi))/d}+1}$$

$$R'(\theta) = R_0(1+\beta_2 Y_2^0(\theta)).$$

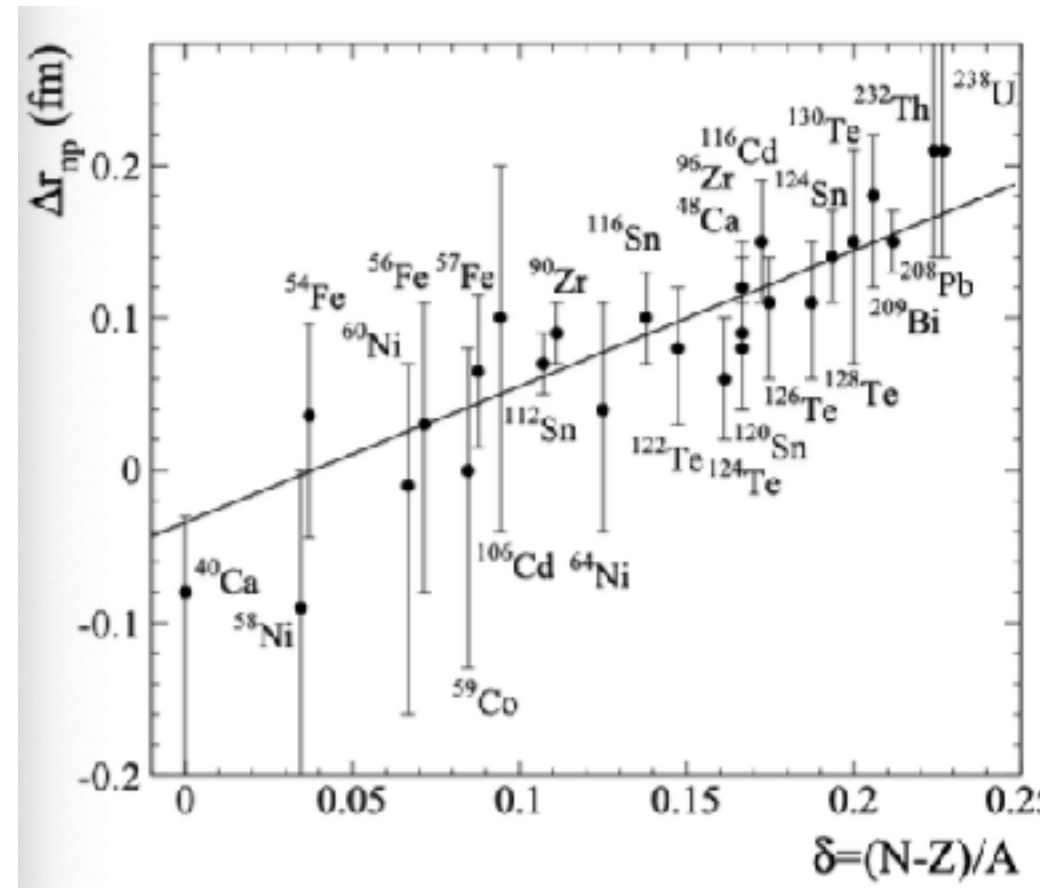
Nucleus	R_0 [fm]	d [fm]	β_2
$^{96}_{40}Zr$	5.02	0.46	0
$^{96}_{44}Ru$	5.085	0.46	0.158

- And neutron skin for Zr, choice halo $\Delta r_{np} = \langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}$

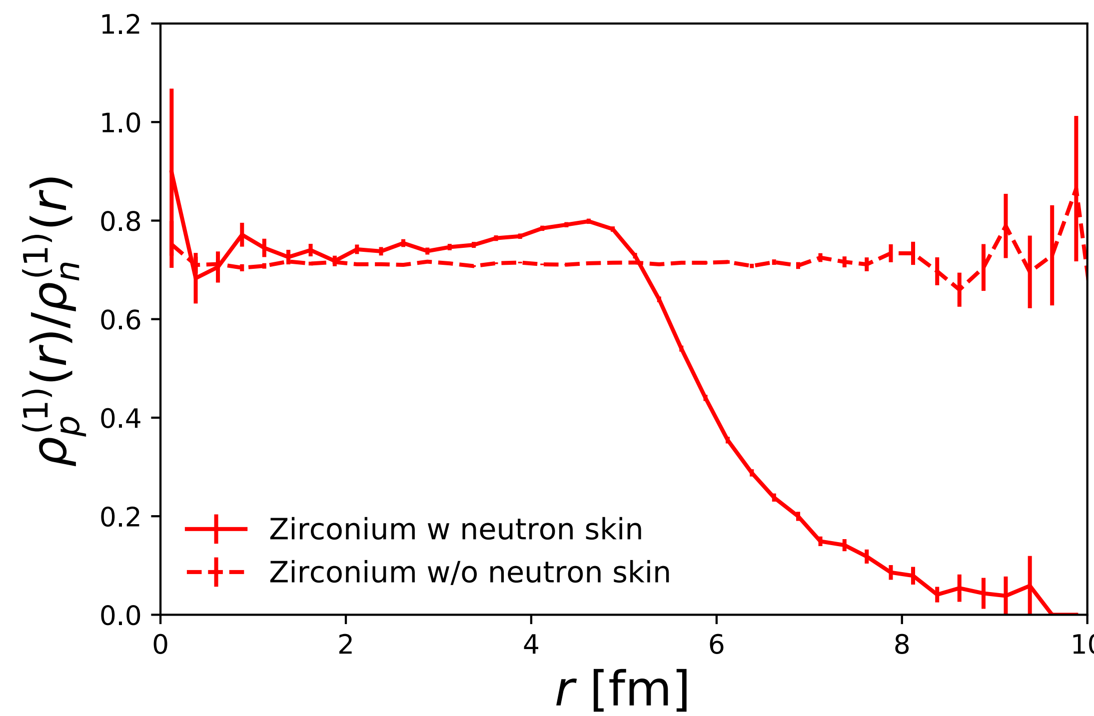
$$\Delta r_{np}\Big|_{^{96}_{40}Zr} = 0.12 \pm 0.03 \text{ fm}$$

Nucleon in $^{96}_{40}Zr$	R_0 [fm]	d [fm]
p	5.08	0.34
n	5.08	0.46

J. Hammelmann et al, *Phys.Rev.C* 101 (2020)



LEAR Collab. IJMP E 13 (2004)

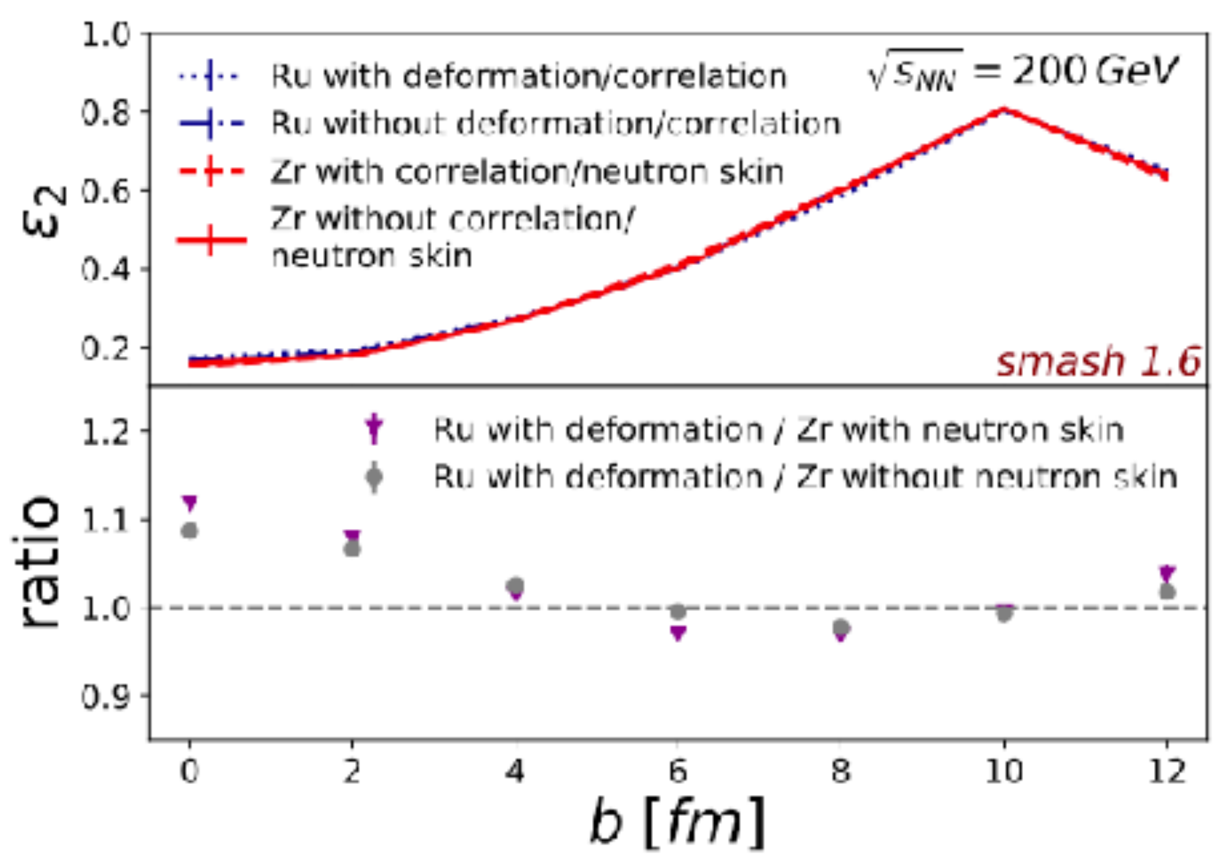


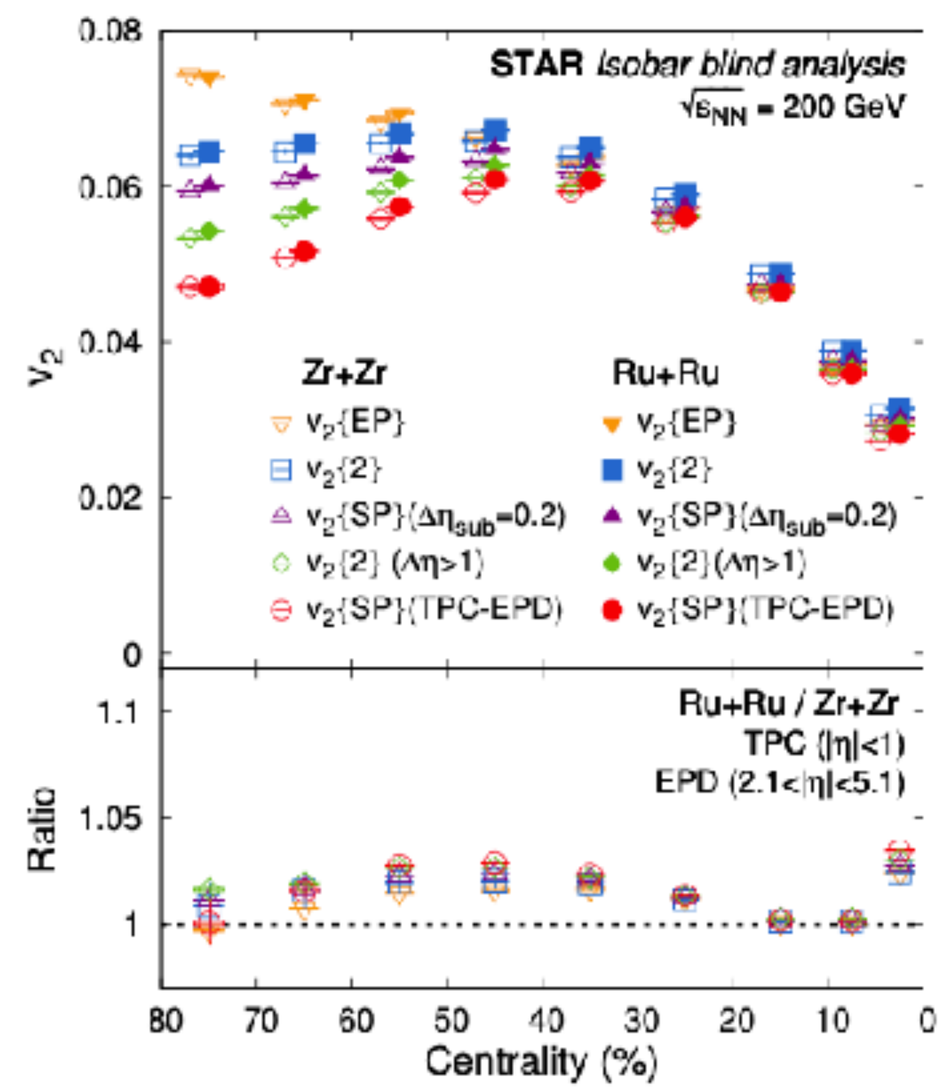
Participant Eccentricity

- Including nuclear structure effects and nucleon-nucleon correlations with initial state from full wave function

M. Alvioli, M. Strikman, PRC 100 (2019)

- Hadronic transport approach SMASH is applied until full overlap of nuclei



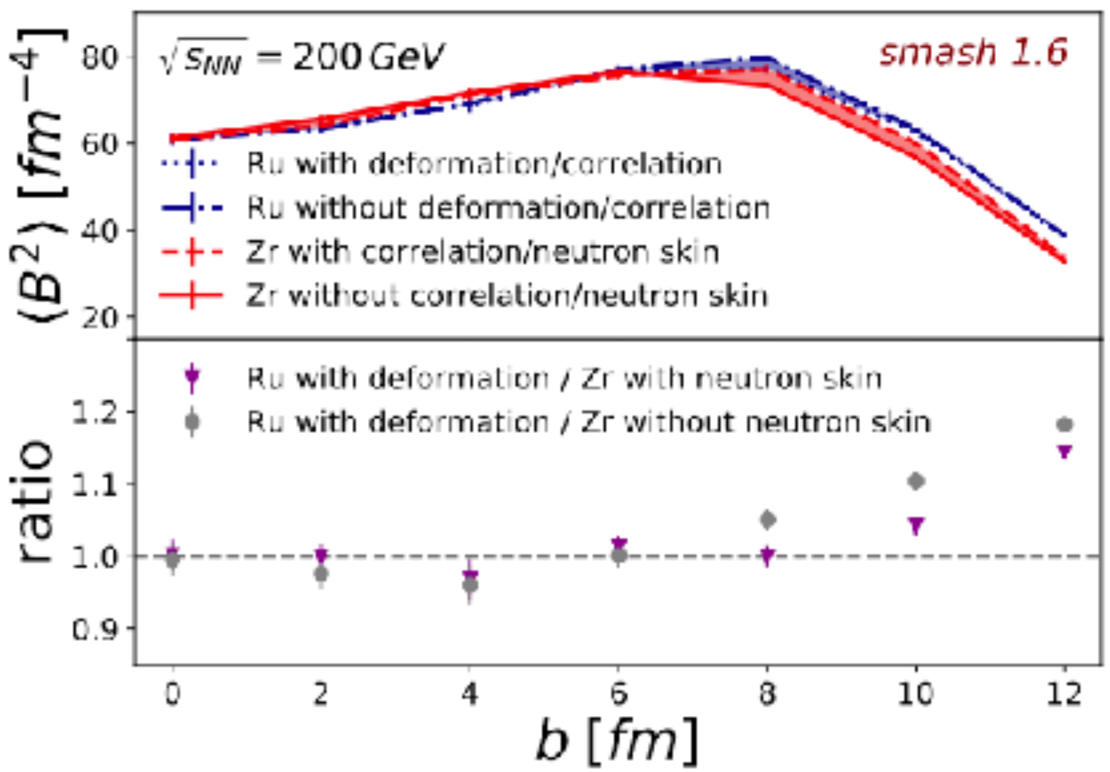


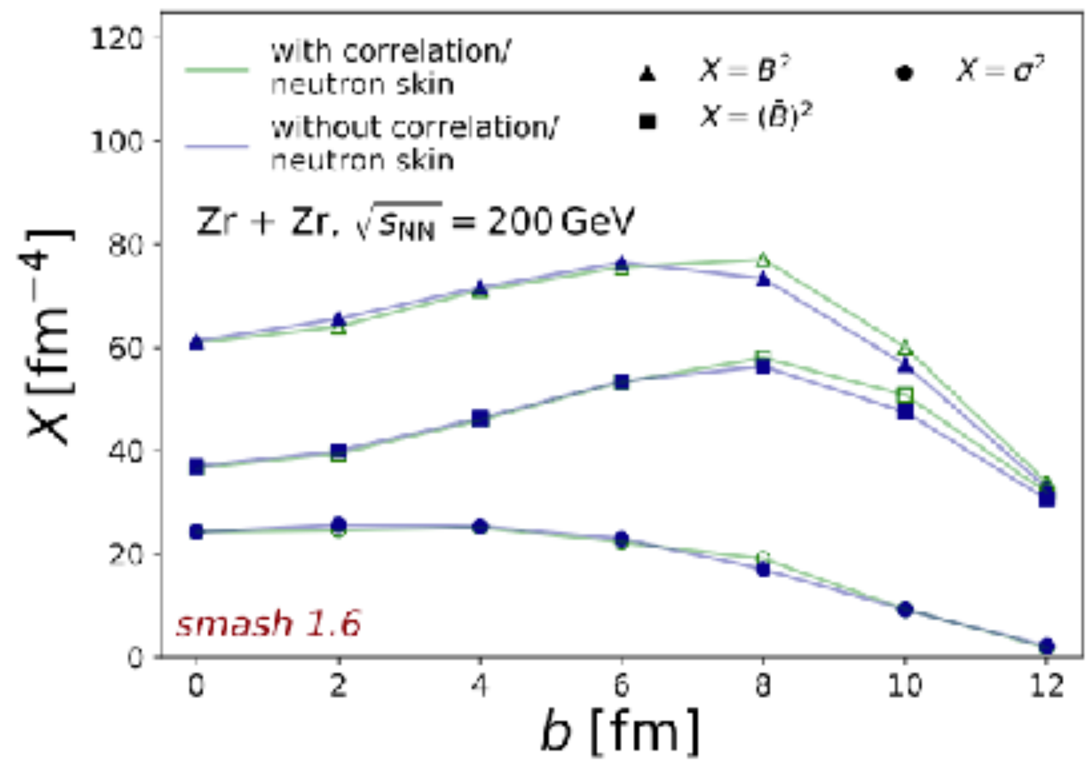
- Participant eccentricity shows differences due to deformation at small impact parameters

J. Hammelmann et al, *Phys.Rev.C* 101 (2020) and STAR collaboration, *Phys.Rev.C* 105 (2022)

Magnetic Field

- Due to the neutron skin, the charge is more concentrated in the middle -> differences in the magnetic field





J. Hammelmann et al, *Phys.Rev.C* 101 (2020)

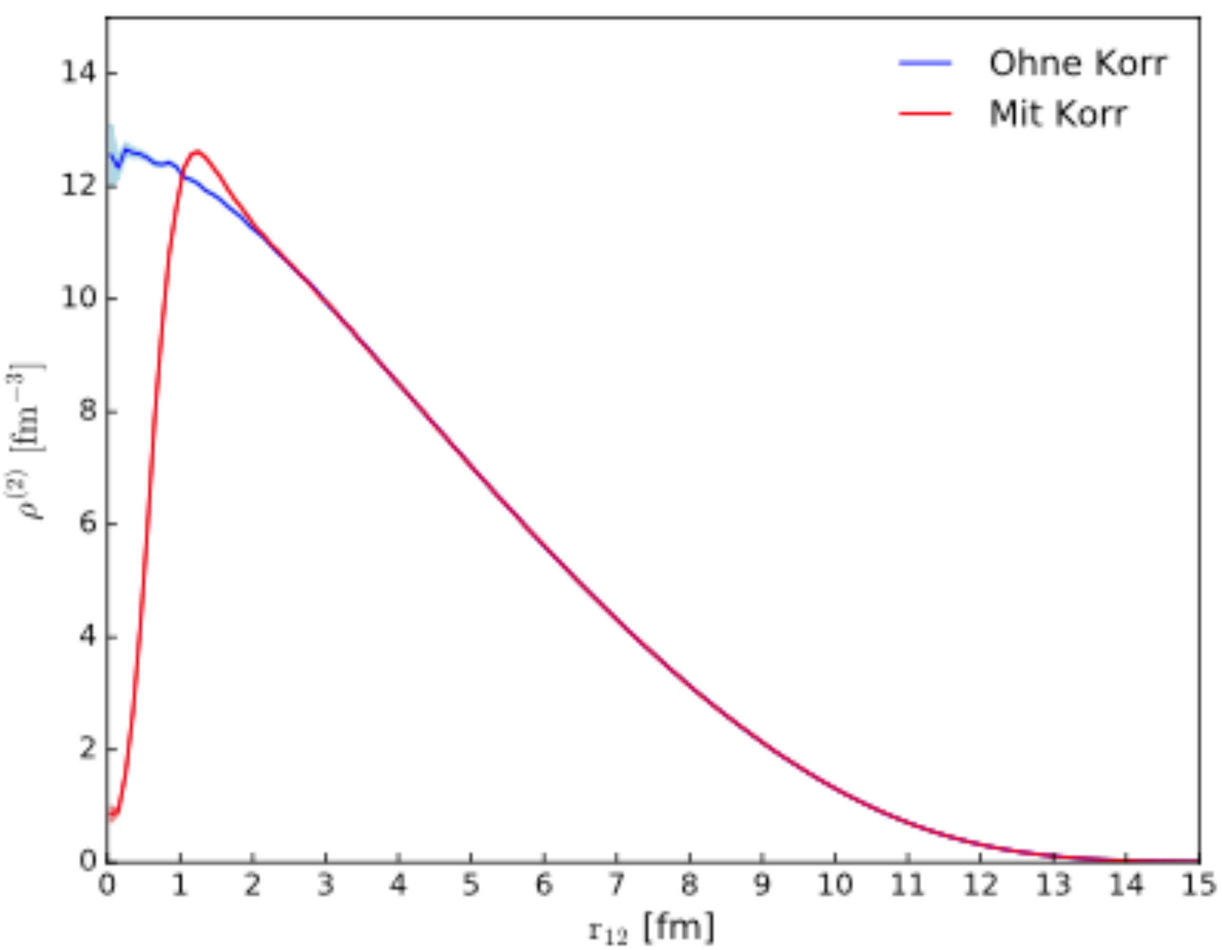
- The difference is really in the average field and not in the fluctuations
- One reason for missing difference between Ru/Zr results for CME correlators

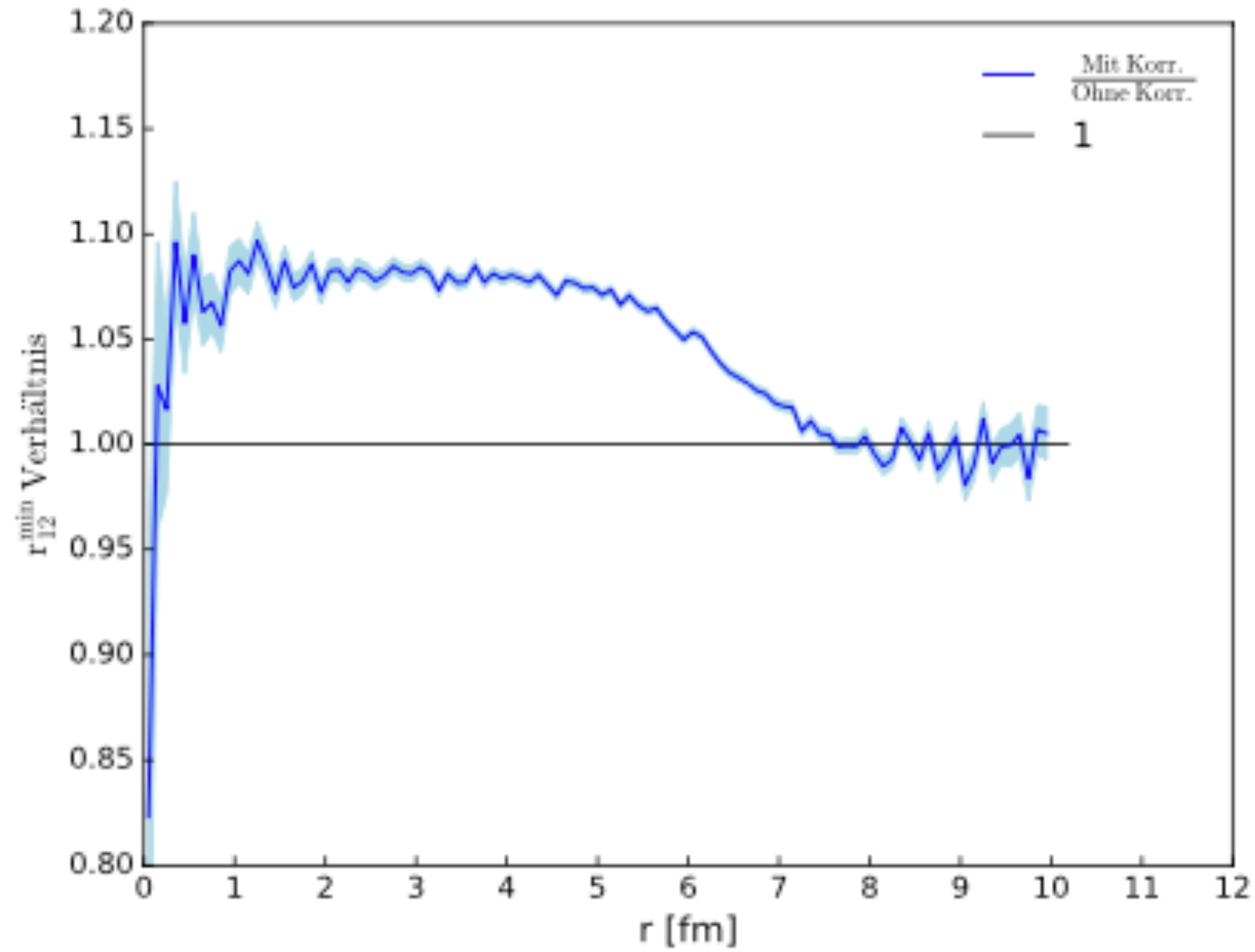
STAR collaboration, *Phys.Rev.C* 105 (2022)

NN Correlations

- Implementing nucleon nucleon correlations in the Au (and Cu) initial state in SMASH

BSc thesis, Damjan Mitrovic, 2018

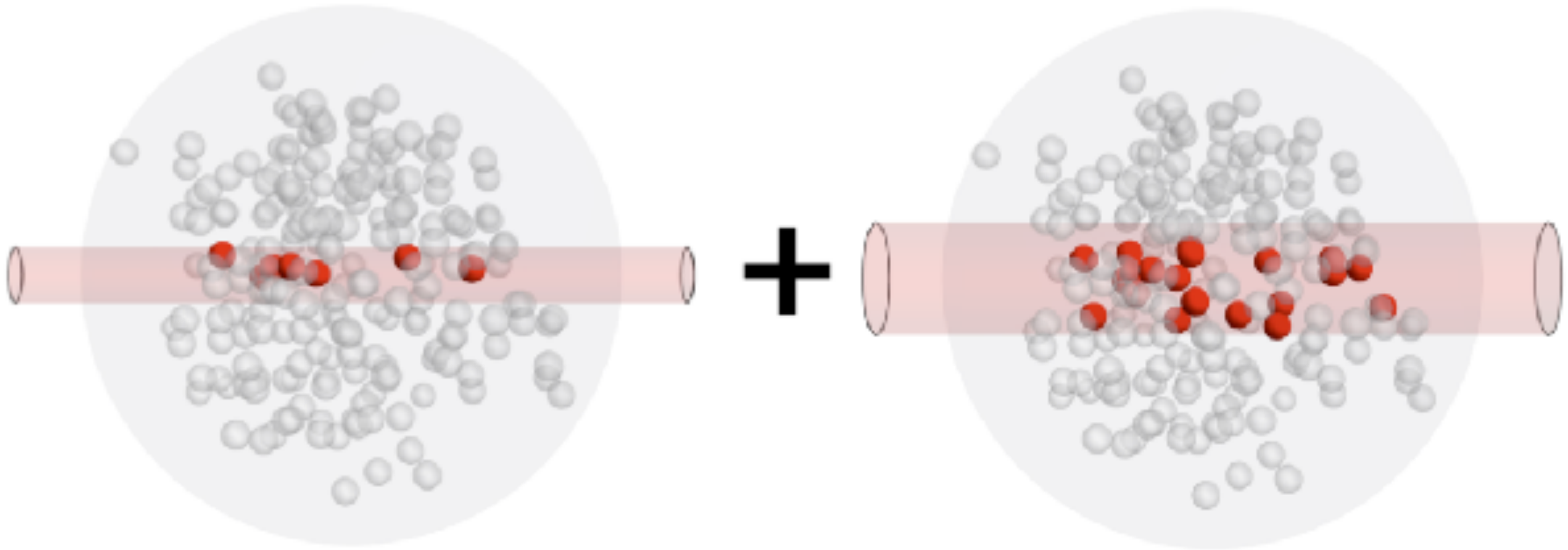




- The 2-particle distribution and the average distance shows the expected behaviour
- Other observables (eccentricities) not sensitive

Color Fluctuations

M. Alvioli et al, PRD 98 (2018)



$$P(\sigma) = \gamma \frac{\sigma}{\sigma + \sigma_0} e^{-\frac{\sigma/(\sigma_0 - 1)^2}{\Omega^2}}$$

$$\int d\sigma \sigma P(\sigma) = \sigma_{tot}$$

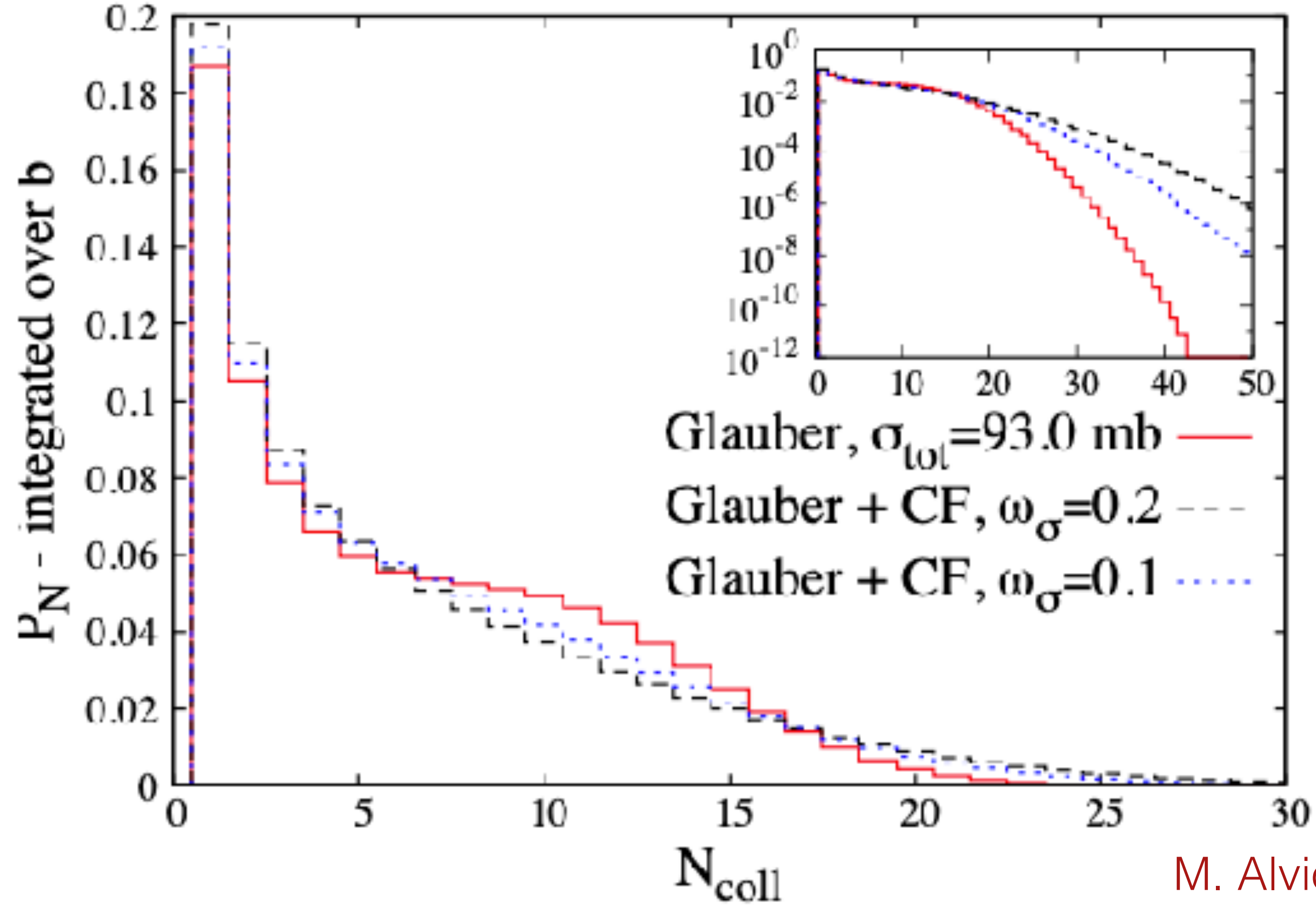
$$\frac{1}{\sigma_{tot}^2} \int d\sigma (\sigma - \sigma_{tot})^2 P(\sigma) = \omega_\sigma$$

- Idea: Structure of proton allows for fluctuations in intermediate states
- Different configurations are realised by different cross-sections
- Fluctuating first cross-section of NN interactions in SMASH

Number of Collisions

M. Alvioli et al, PRD 98 (2018)

- Color fluctuations can influence centrality selection
- Probability distribution of number of collisions is affected

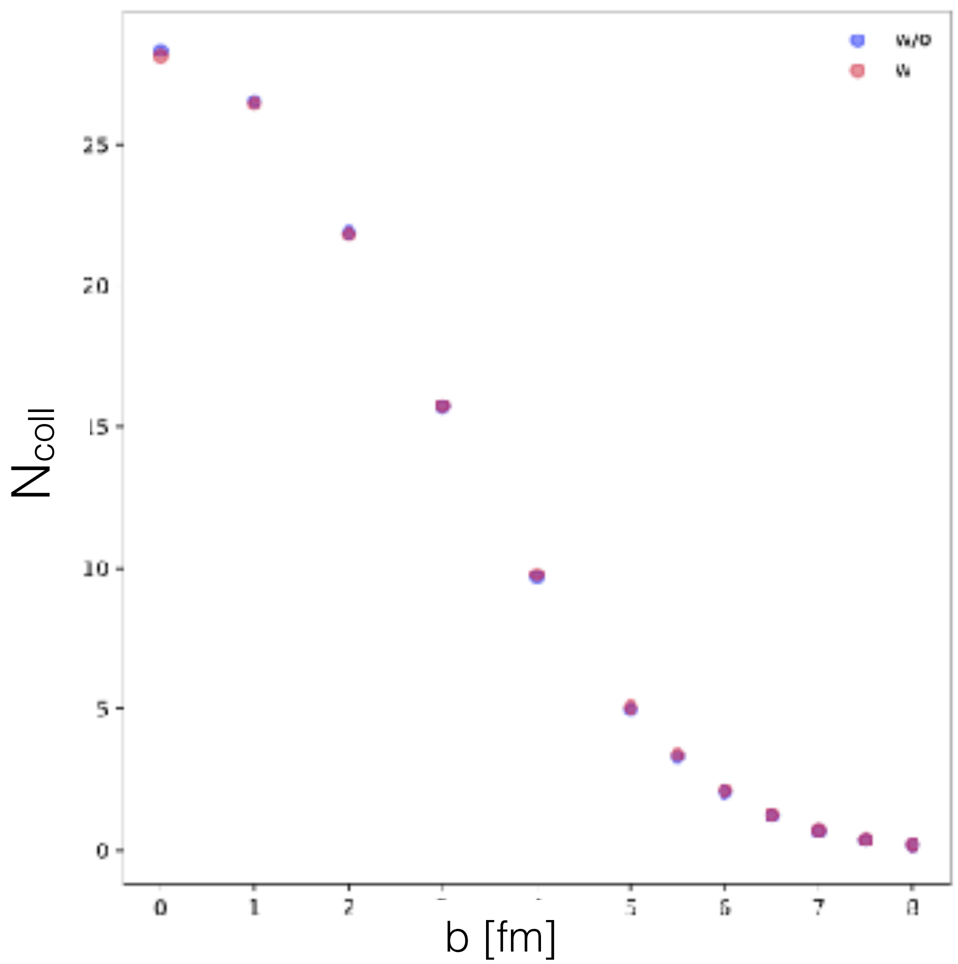


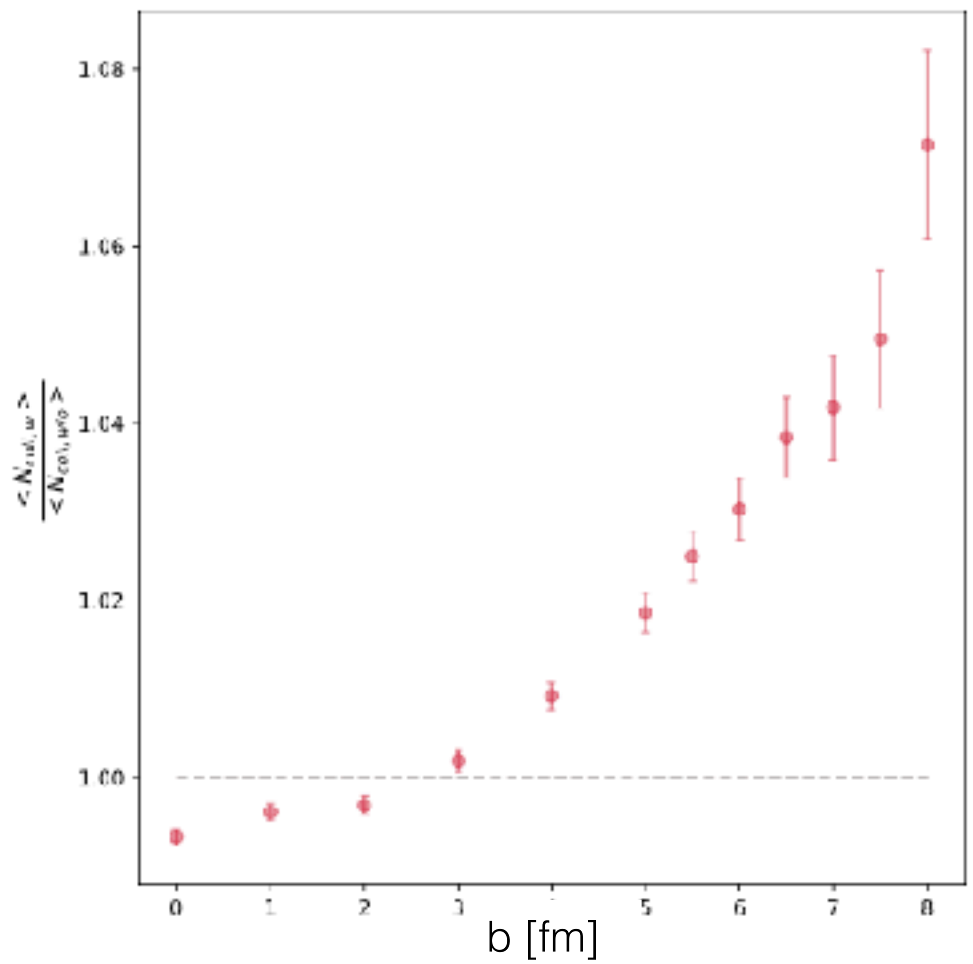
M. Alvioli, RBRC Workshop, January 2022

- Effects are more significant for pA and small systems

Oxygen-Oxygen in SMASH

O+O at $\sqrt{s_{NN}}$= 200 GeV





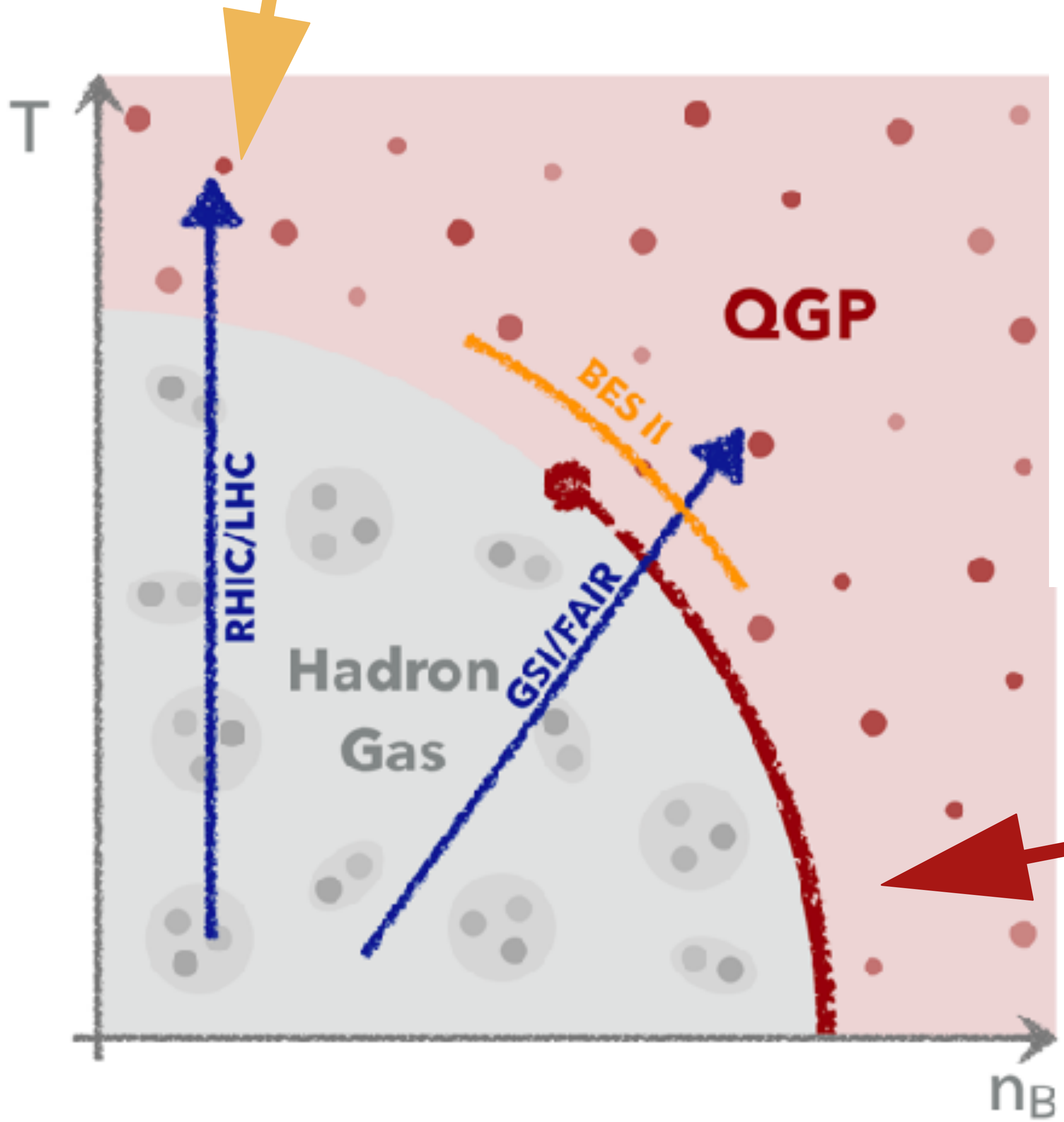
- Number of collisions in peripheral events is increased for small nuclei
- Other bulk observables are not affected

BSc thesis, Antonio Bozic, 2021

Low Energy Collisions

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

smash

FAIR Construction Site

- Rare probes (hyper-nuclei, polarization and dileptons)
- Phase-0 research program started in 2019 and producing exciting results
- Impact of war in Ukraine is assessed
- All future collaboration with Russian institutions suspended -> challenges, but no show-stoppers
- Scientific review in progress

FAIR Control Center ground-breaking ceremony with 3 ministers on March 29, 2022

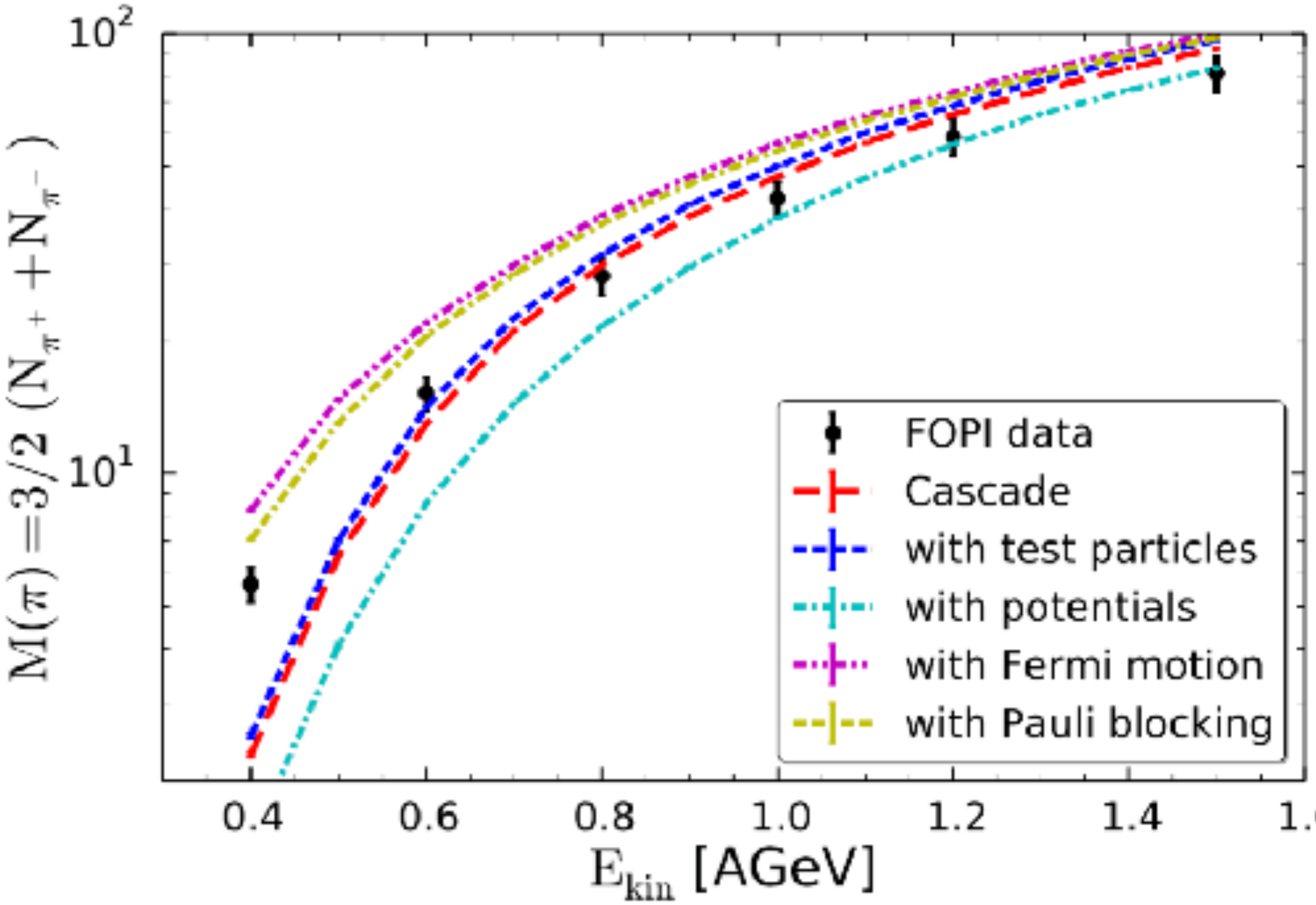
FAIR Phase 0 Research Program

Visualization of FAIR,
GSI Helmholtzzentrum für Schwerionenforschung, ion42

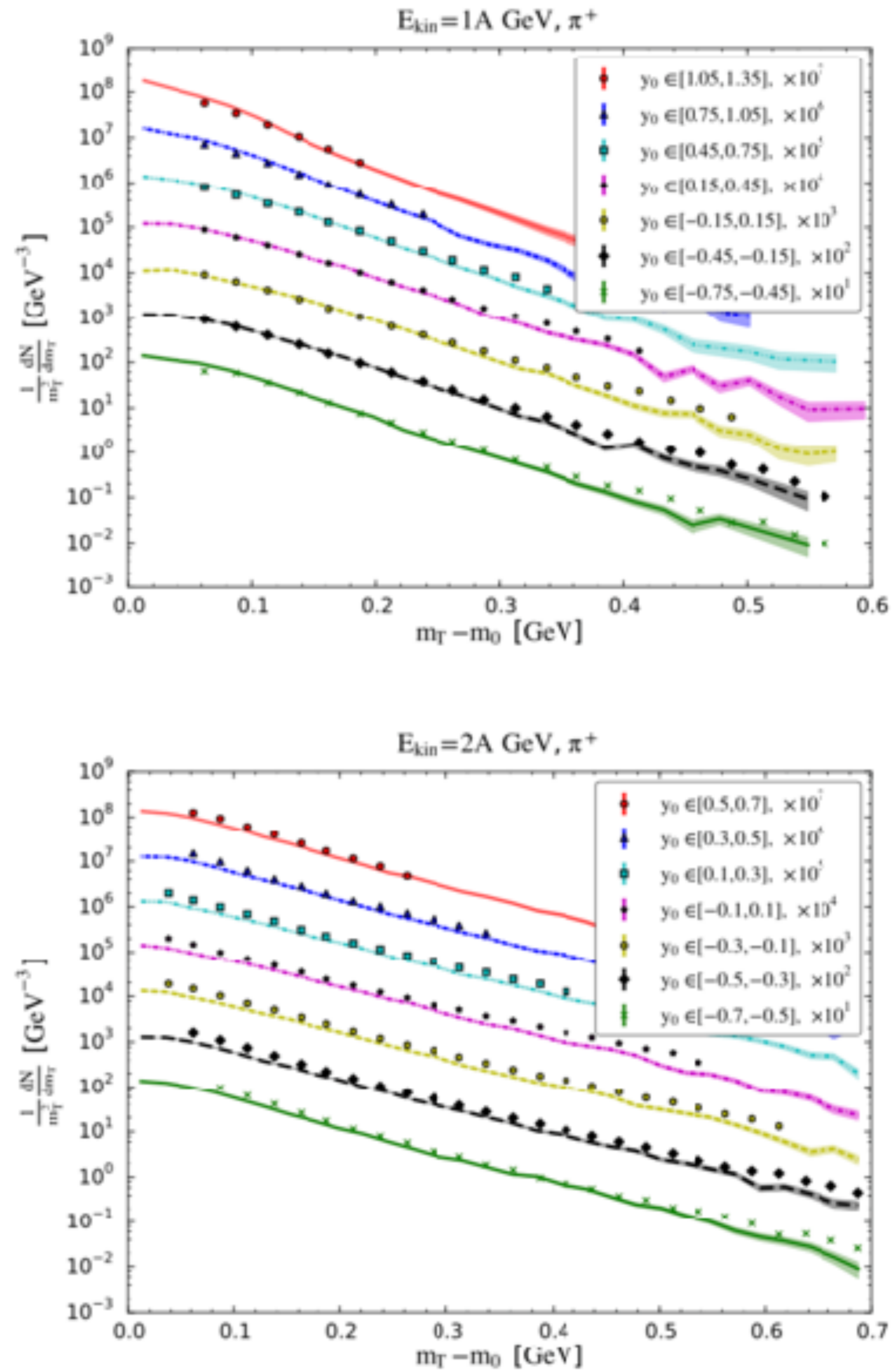
D. Fehrenz/GSI/FAIR

Pion Production in Au+Au

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



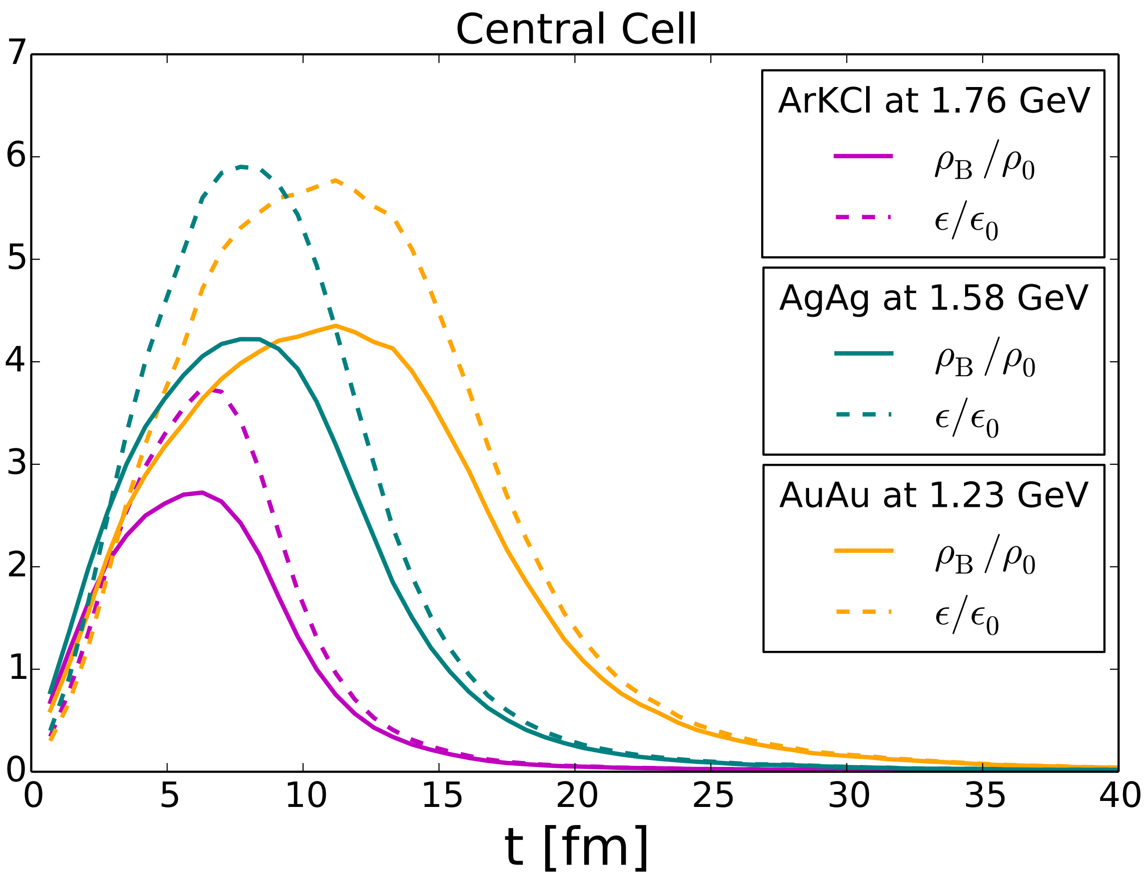
Note: consecutive addition of features

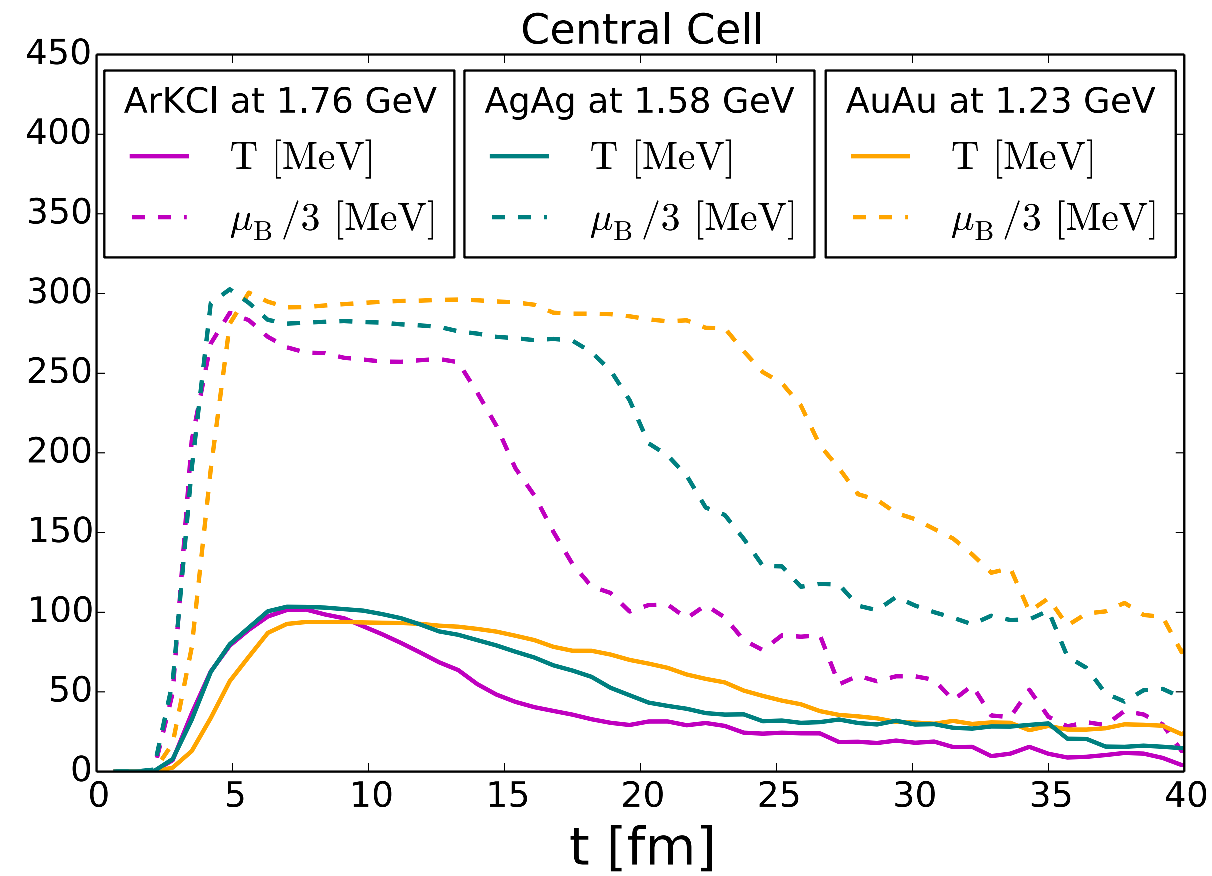


J. Weil et al, PRC 94 (2016)

Time Evolution

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





J. Staudenmaier, N. Kübler and HE, arXiv:2008.05813

- 2-4 times nuclear ground state density reached

Collective Behaviour

- Potentials in SMASH
  - Basic Skyrme and symmetry potential

$$U_{\text{Skyrme}} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\tau \qquad U_{\text{Symmetry}} = \pm 2 S_{\text{Pot}} \frac{\rho_{I_3}}{\rho_0}$$

  - Describes interactions between nucleons, repulsive at high densities

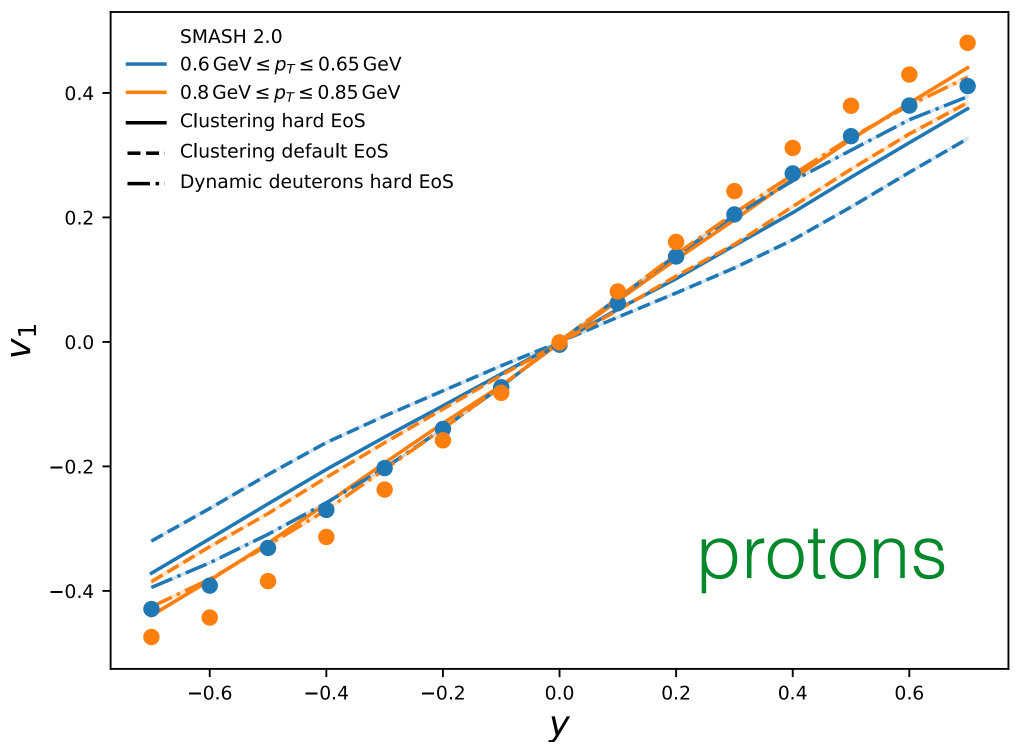
	soft EoS	default EoS	hard EoS
α	-356.0 MeV	-209.2 MeV	-124.0 MeV
β	303.0 MeV	156.4 MeV	71.0 MeV
τ	1.17	1.35	2.00
κ	200 MeV	240 MeV	380 MeV

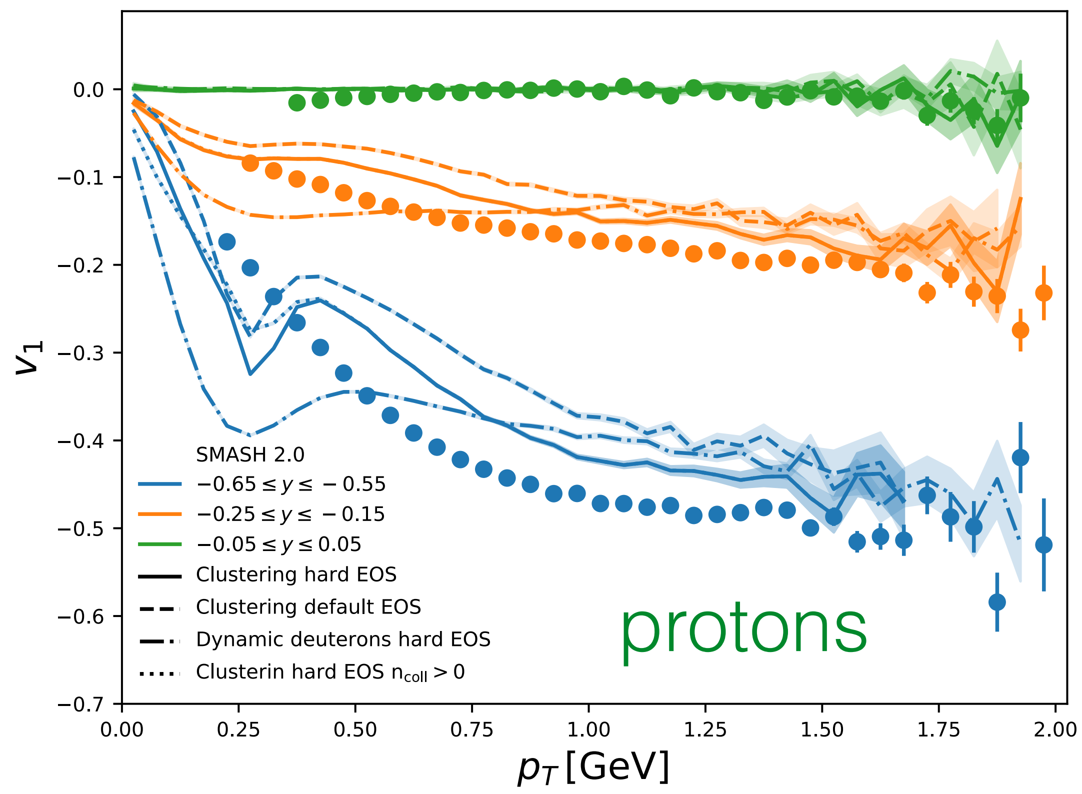
  - Default values according to transport code comparison

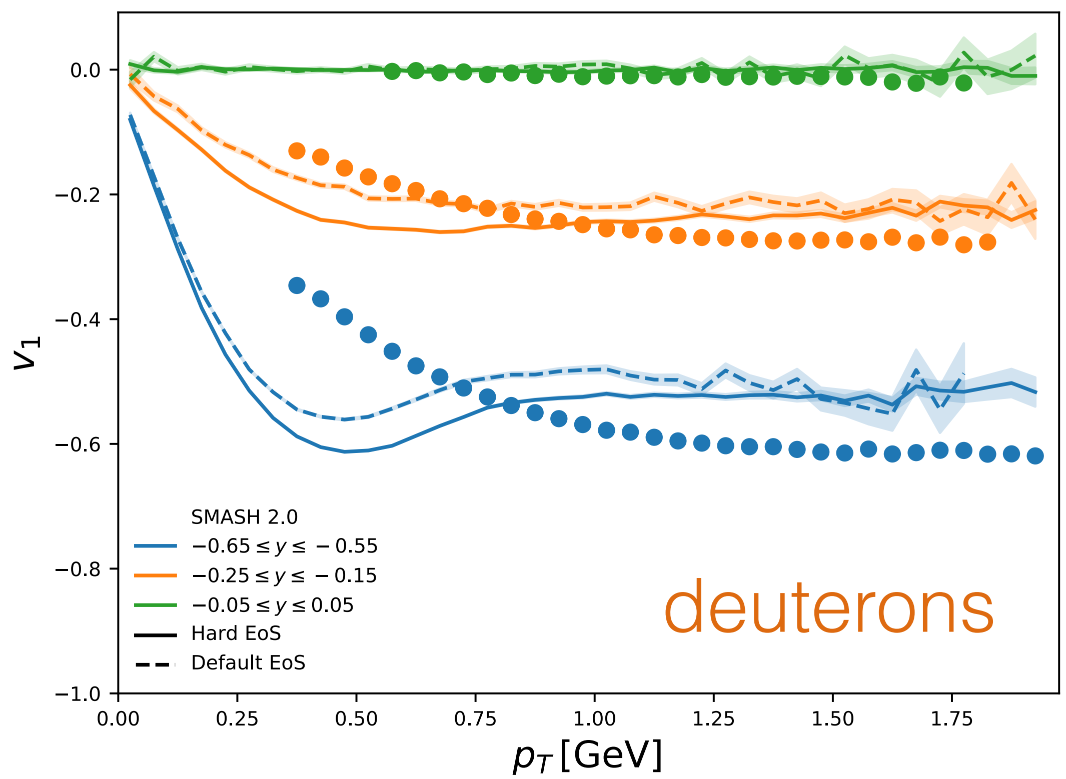
J. Xu et al., PRC 93 (2016)

Directed Flow in SMASH

J. Mohs, M. Ege, H. Elfner and M. Mayer, arXiv: 2012.11454

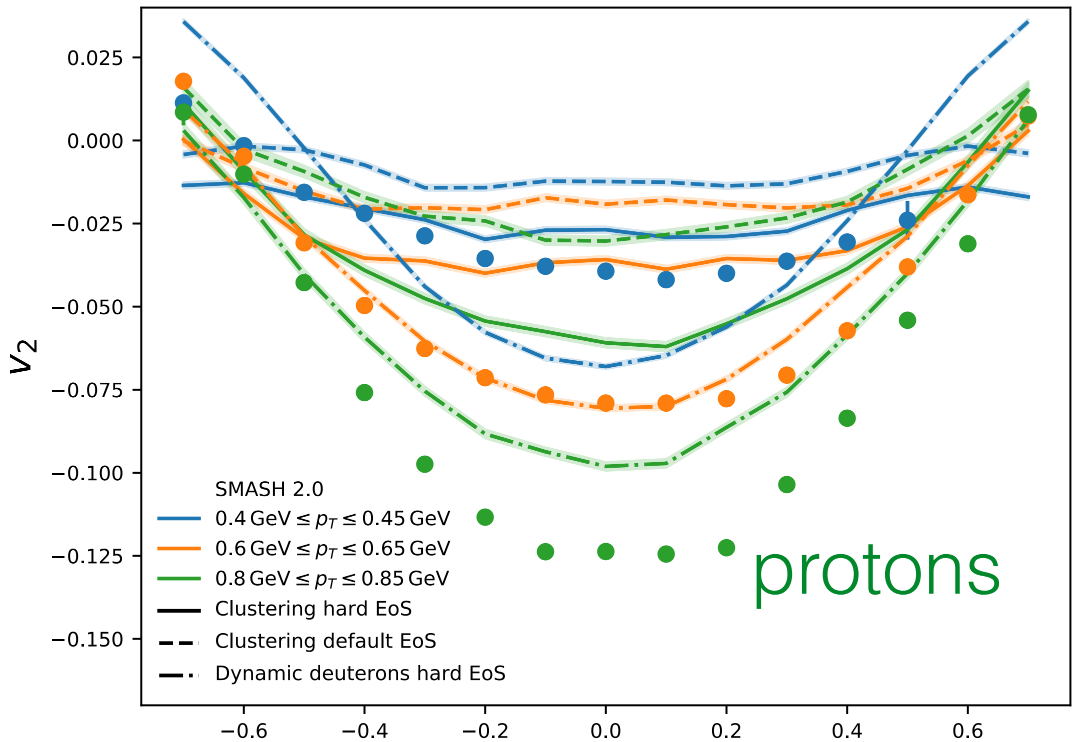


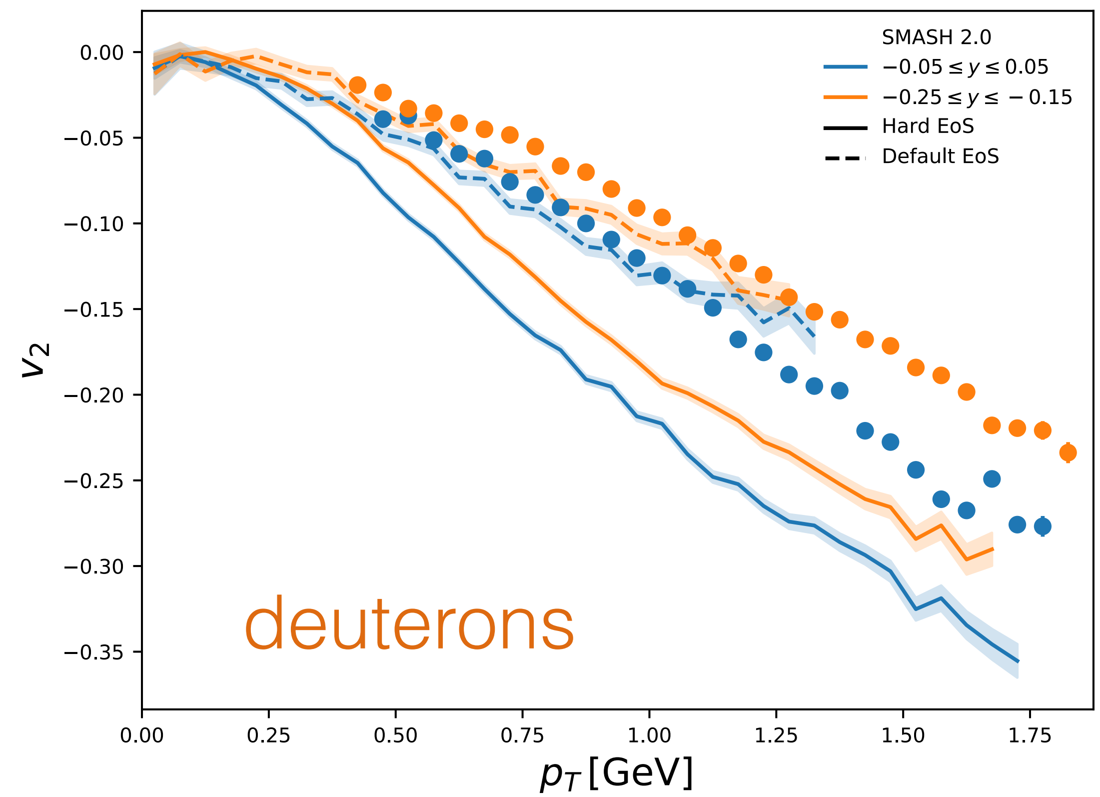


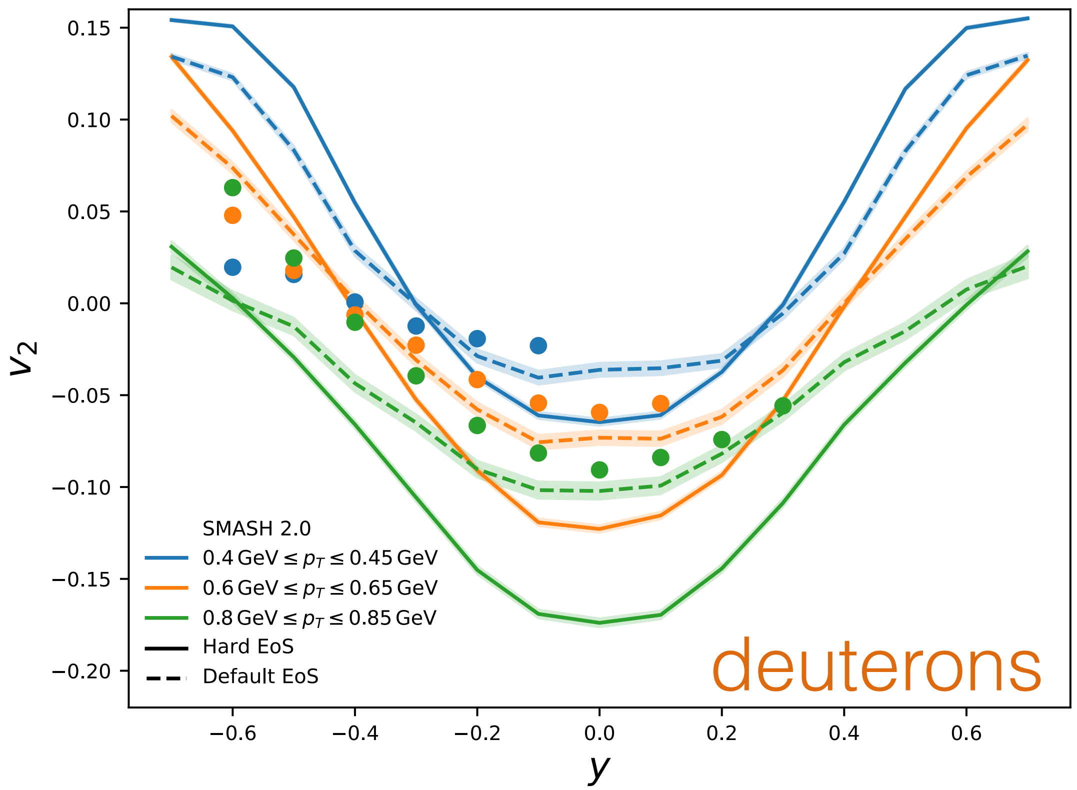


- Protons and deuterons fit better with hard EoS
- No momentum dependence of potential yet
- Clustering effect has similar magnitude as influence of potential

Elliptic Flow in SMASH







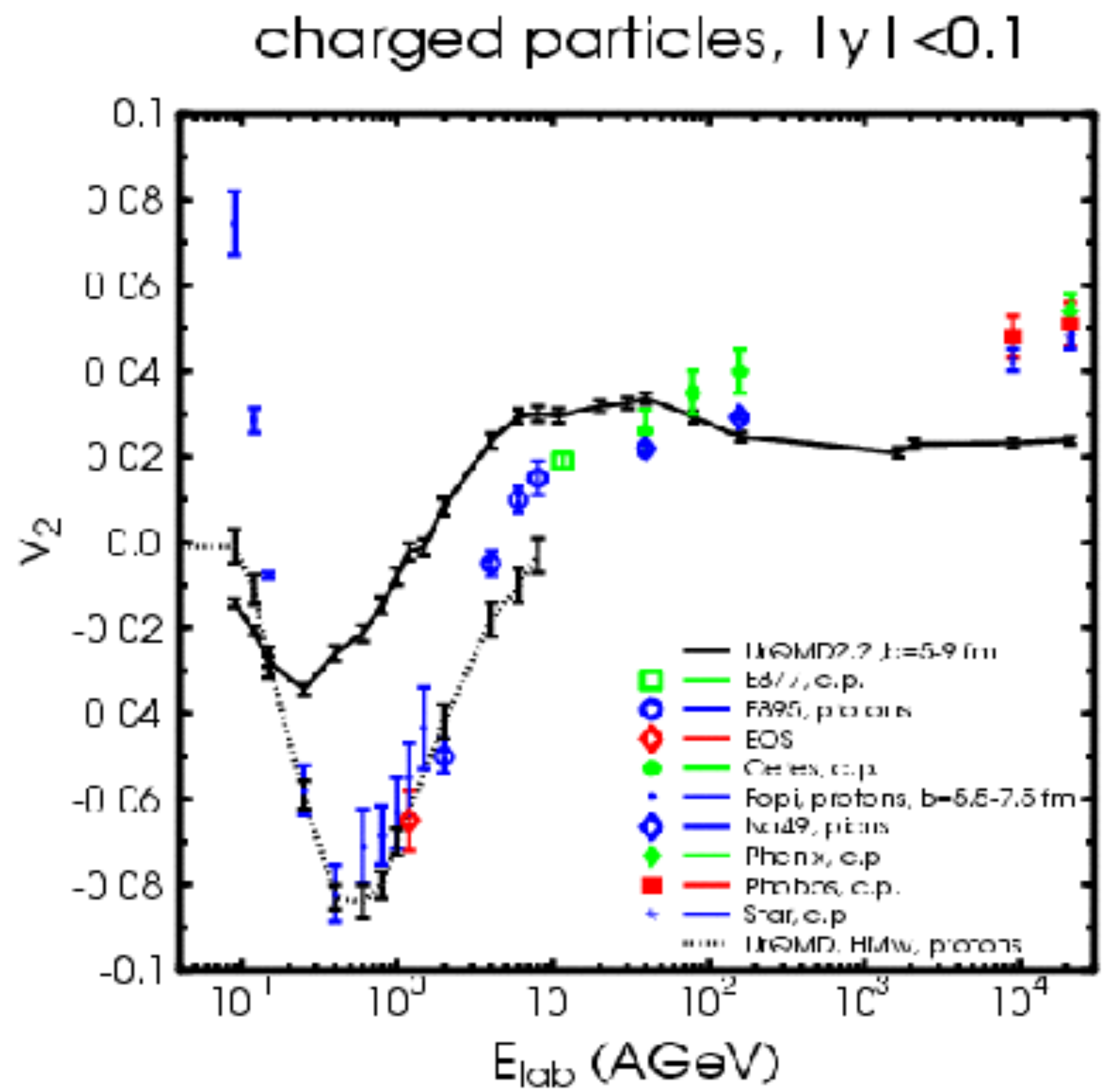
- Deuterons look better than protons (with default EoS)
- Again light clusters play a role and dependence on EoS is clearly visible

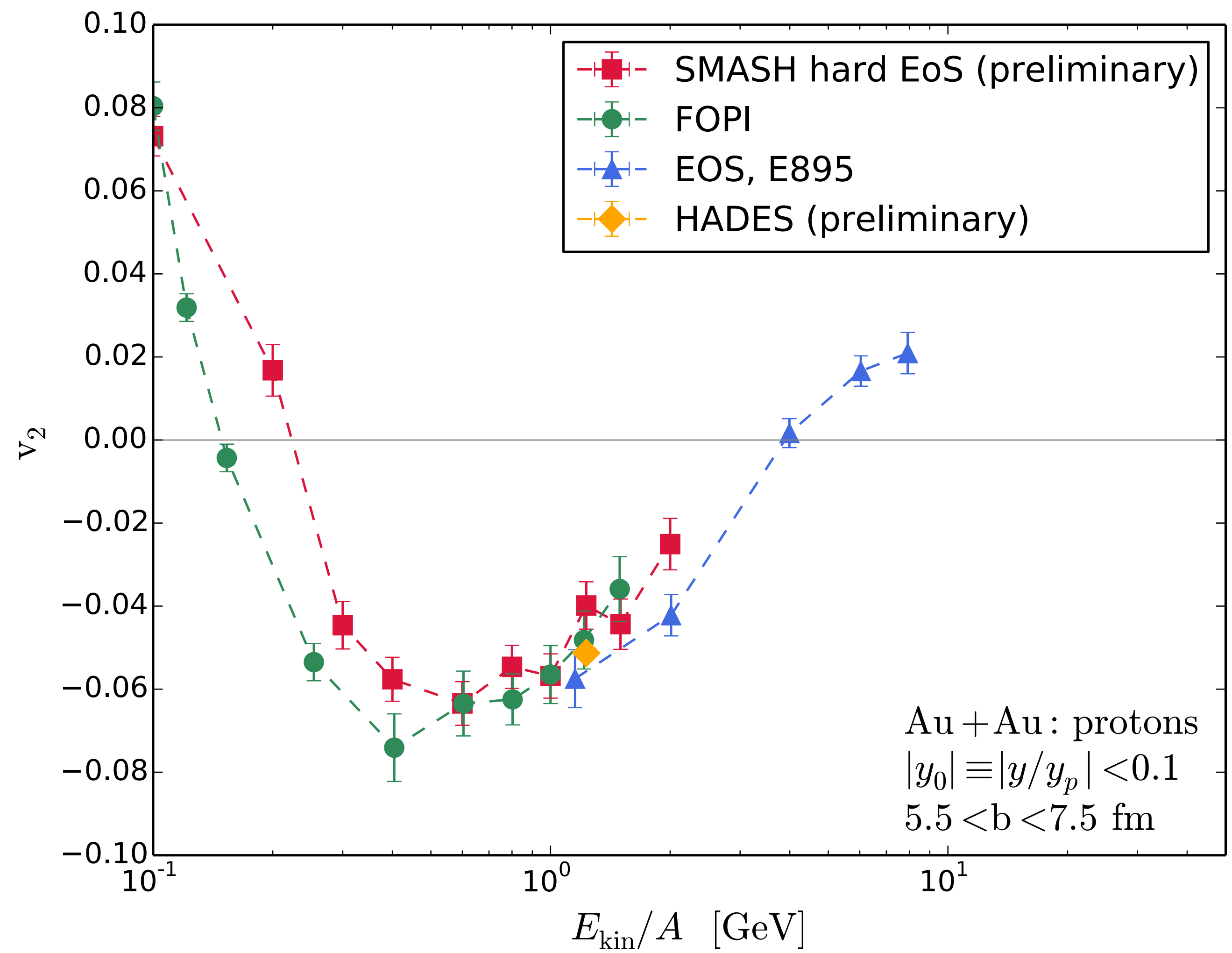
J. Mohs, M. Ege, H. Elfner and M. Mayer, arXiv: 2012.11454

Excitation Function

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

H. Petersen et al, Phys.Rev. C74 (2006) 064908



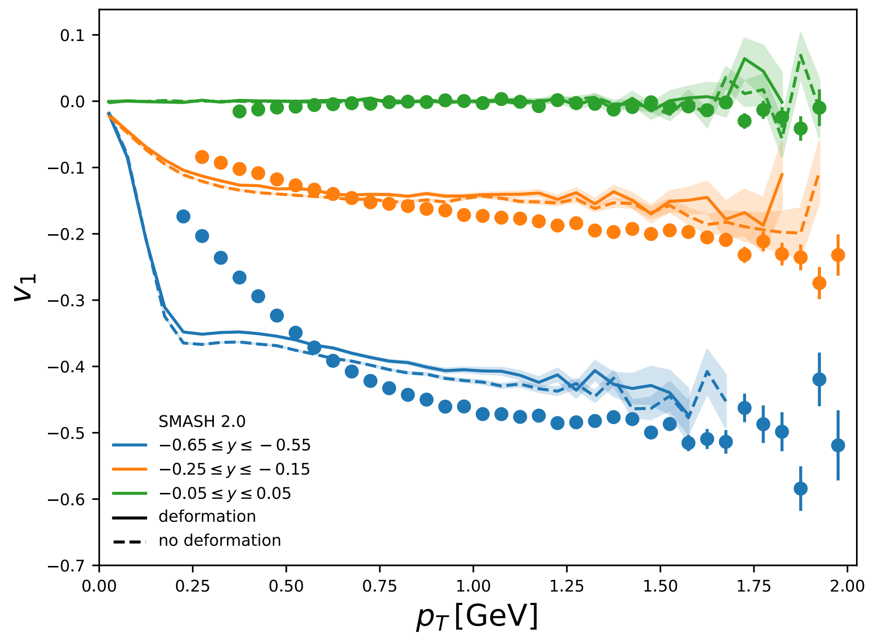


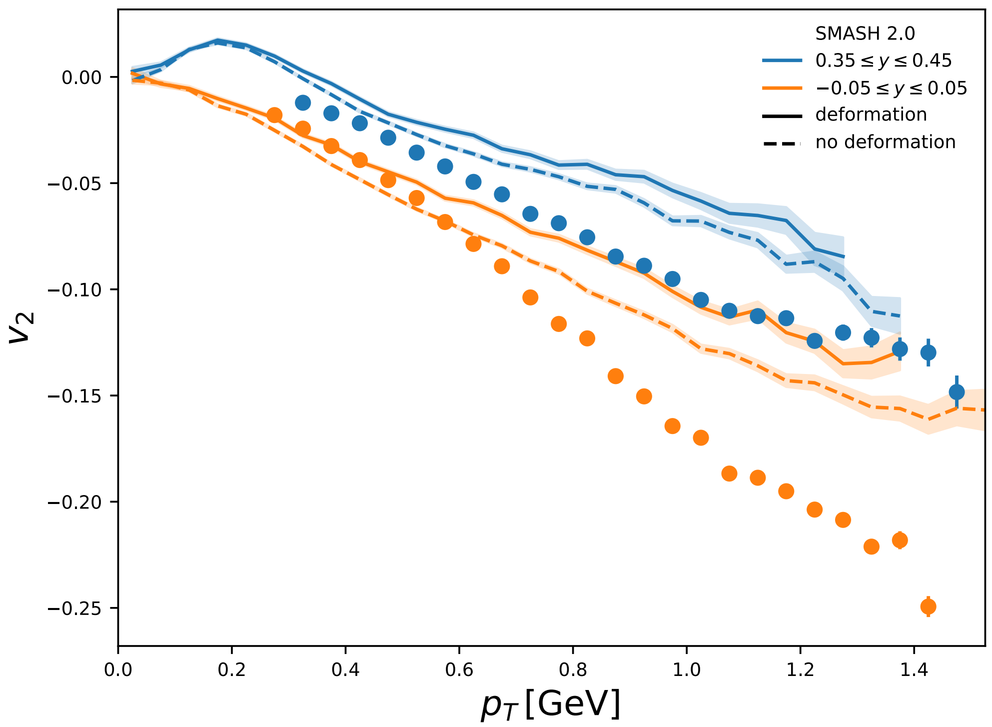
H.Petersen (now Elfner) et al, NPA 982, 2019

- SMASH agrees well with previous UrQMD calculation

Deformations and Density Effects

- Deformations at low energy have some effect:
  - Artificially deformed Au nucleus to see qualitative difference

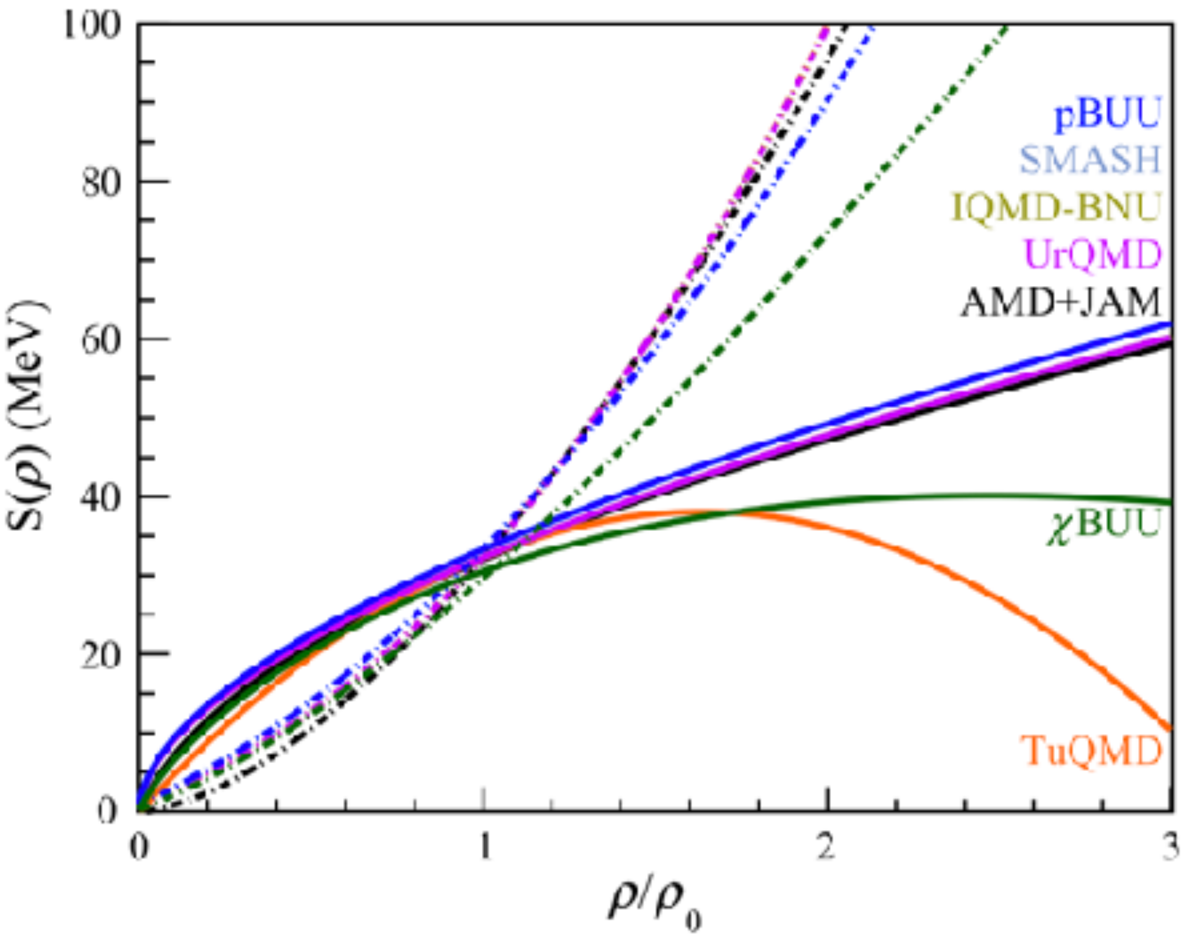


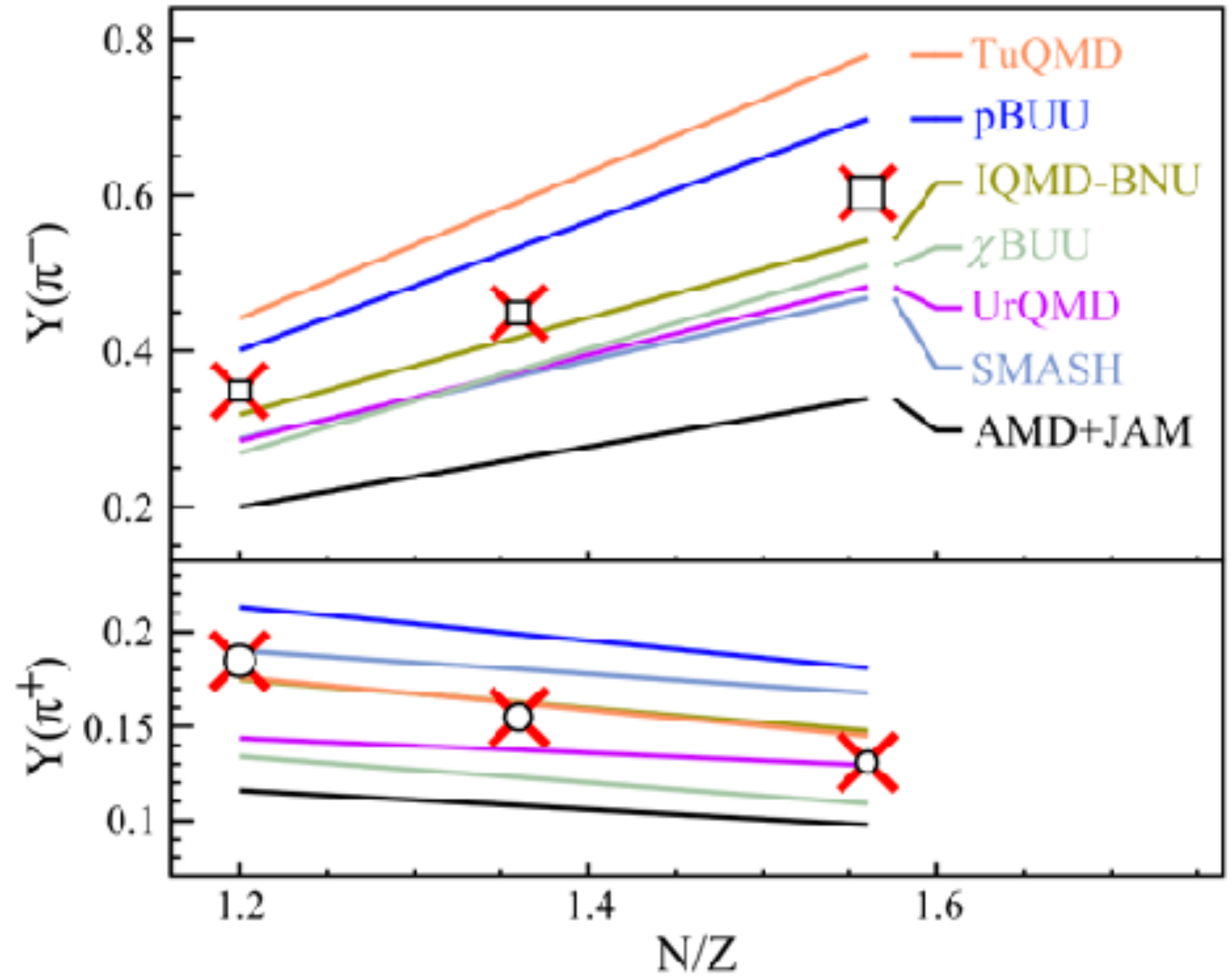


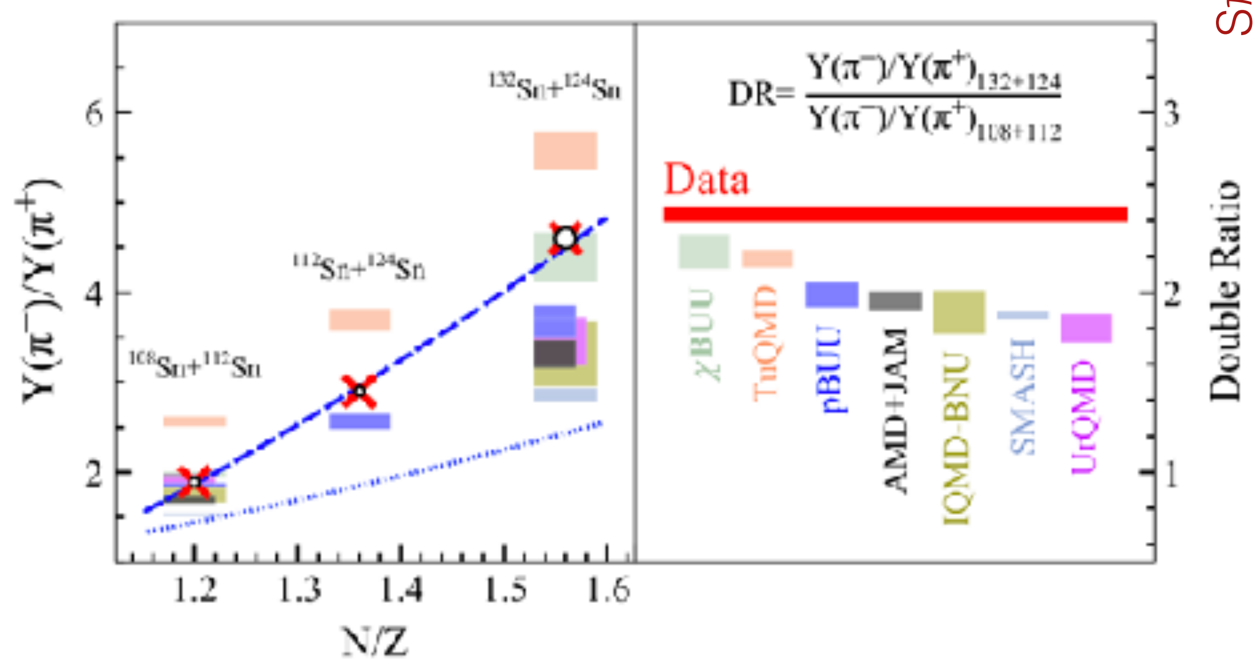
- Neutron skin has no effect on dilepton production in AuAu collisions at 1.23 AGeV
- Slight error in radius calculation within SMASH resulted in significant differences in the density calculation
  - Nuclear structure is important in low energy reactions

Symmetry Energy

- The symmetry energy is crucial when moving from heavy ions to neutron stars





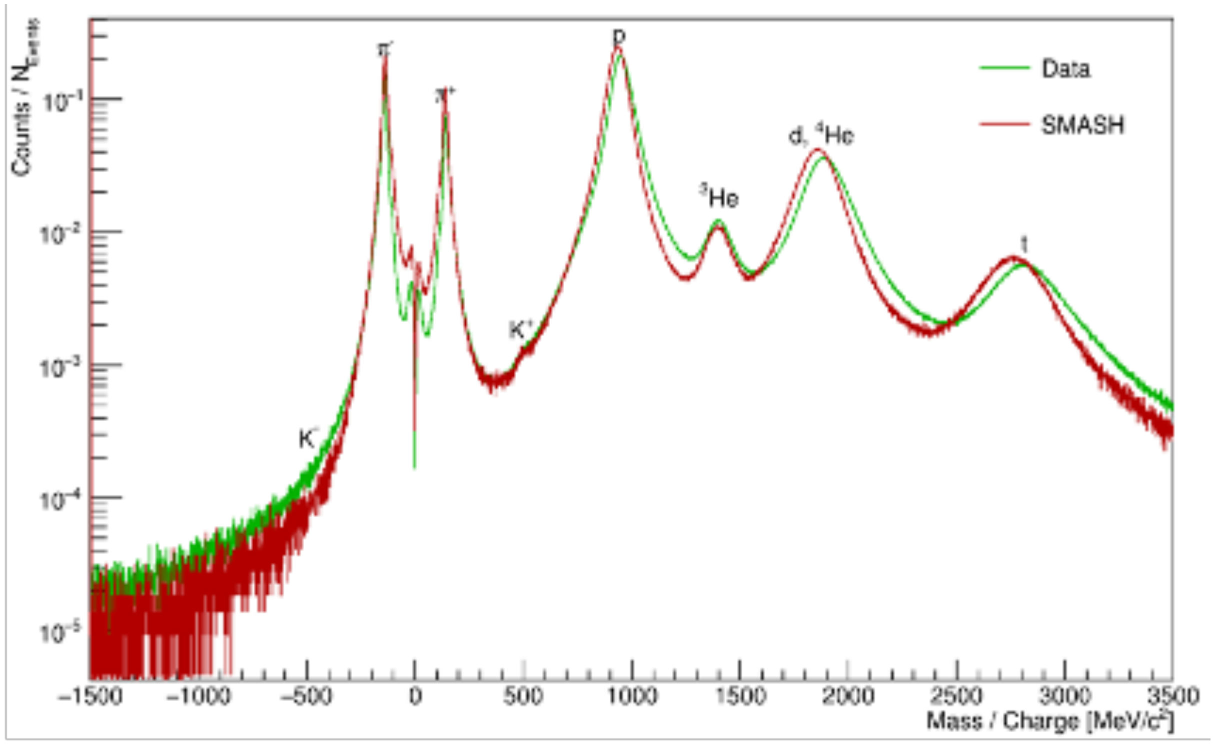


SπRIT and TMEP collaboration, PLB, 813 (2021)

- Pion production in tin isotopes indicates large model dependence

Light Nuclei Formation and Centrality

- Goal is to perform centrality selection as similar to experiment as possible
- In experiment centrality is defined by number of hits in a specific detector
- Need to perform clustering to obtain realistic number of particles
- Find an observable that can be directly mapped to the number of tracks to determine centrality

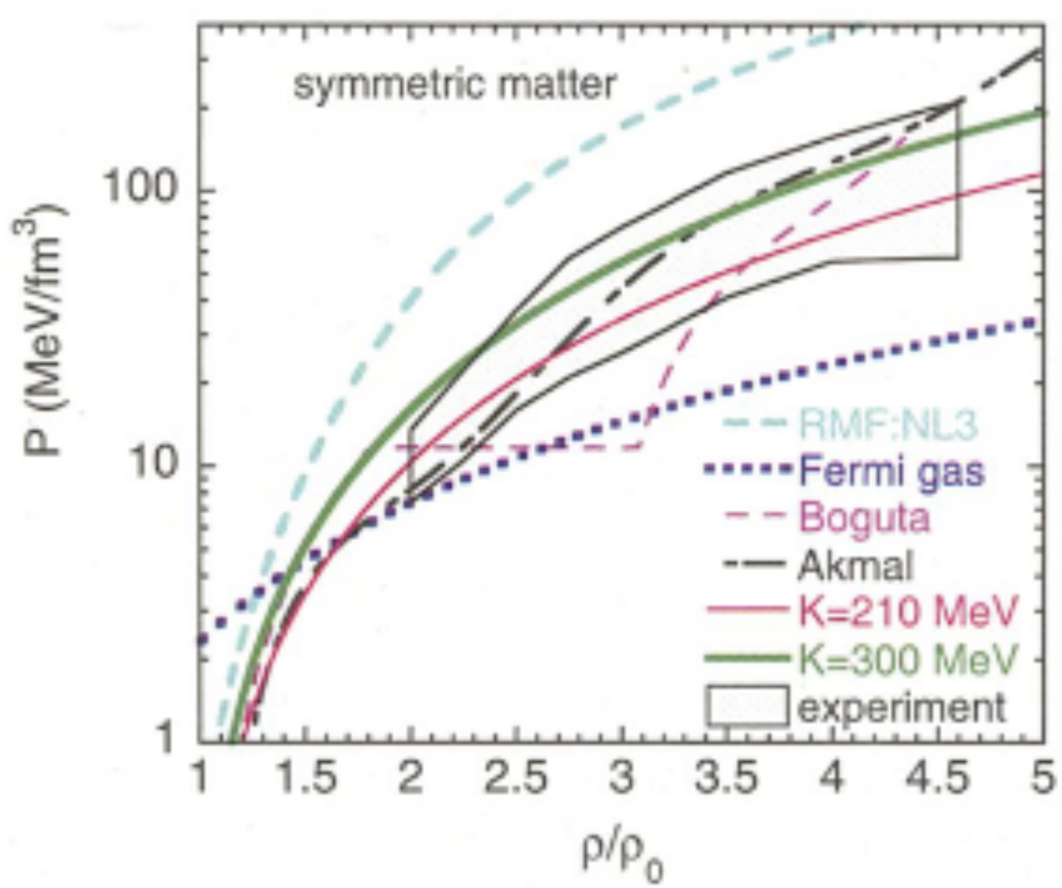


Au+Au at 1.23A GeV, 0-10% most central

J. Mohs and S. Spies, work in progress

Bayesian Analysis

- Constraining the equation of state of nuclear matter at high density with a multi-parameter study
- Understand model dependence of results



P.Danielewicz et al., Science, 298, 1592-1596 (2002)

Differential flow measurements of protons and light clusters

+

State-of-the-art dynamical models

+

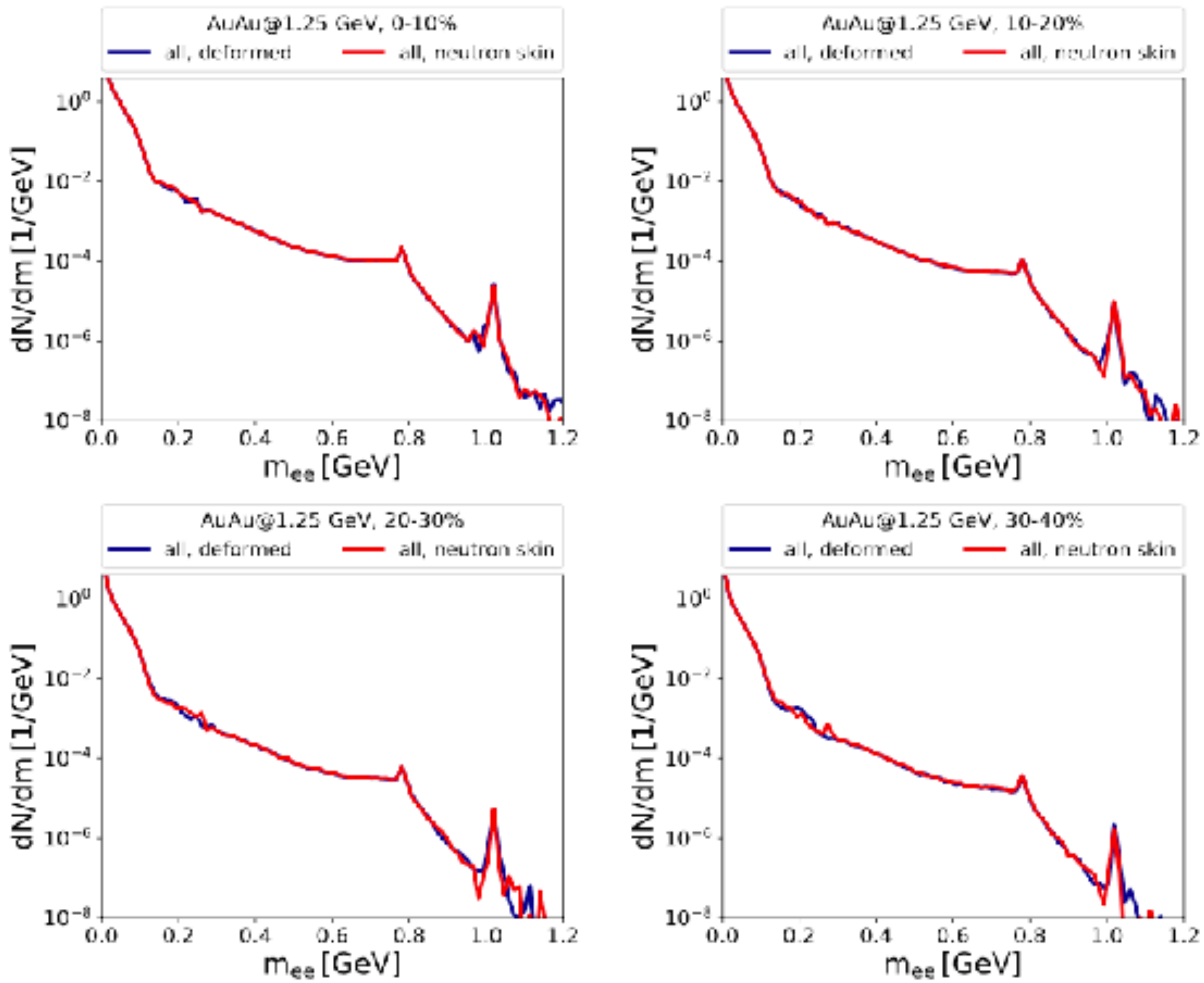
Bayesian multi-parameter techniques

=

Constraints on **EOS at high density** including uncertainty for symmetry energy

Electromagnetic Emission

- Due to the different isospin configurations, one might expect difference in dilepton spectra due to neutron skin



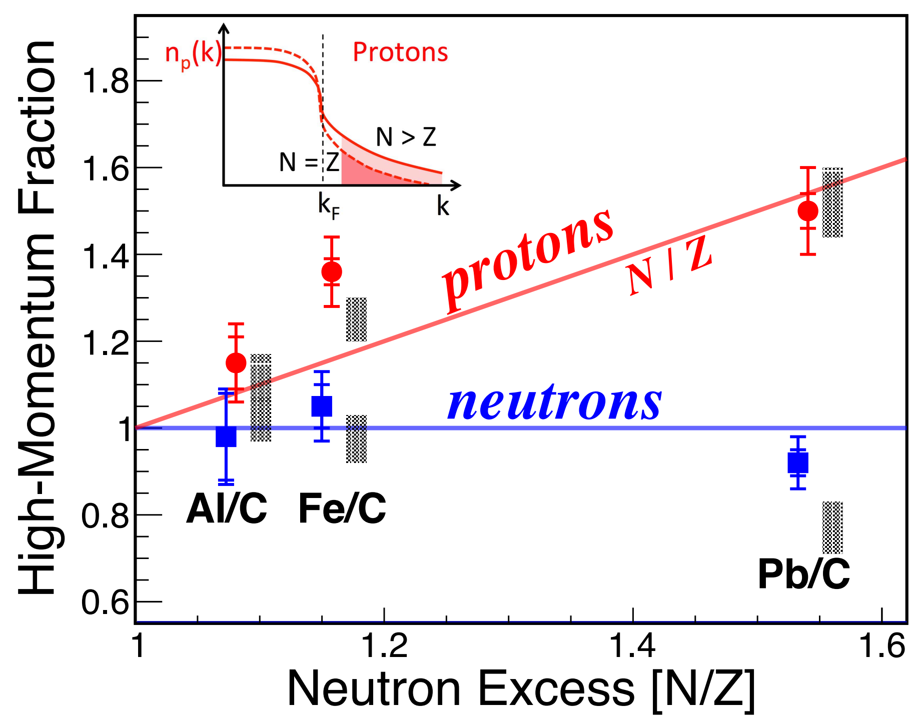
- Not observed in SMASH calculation

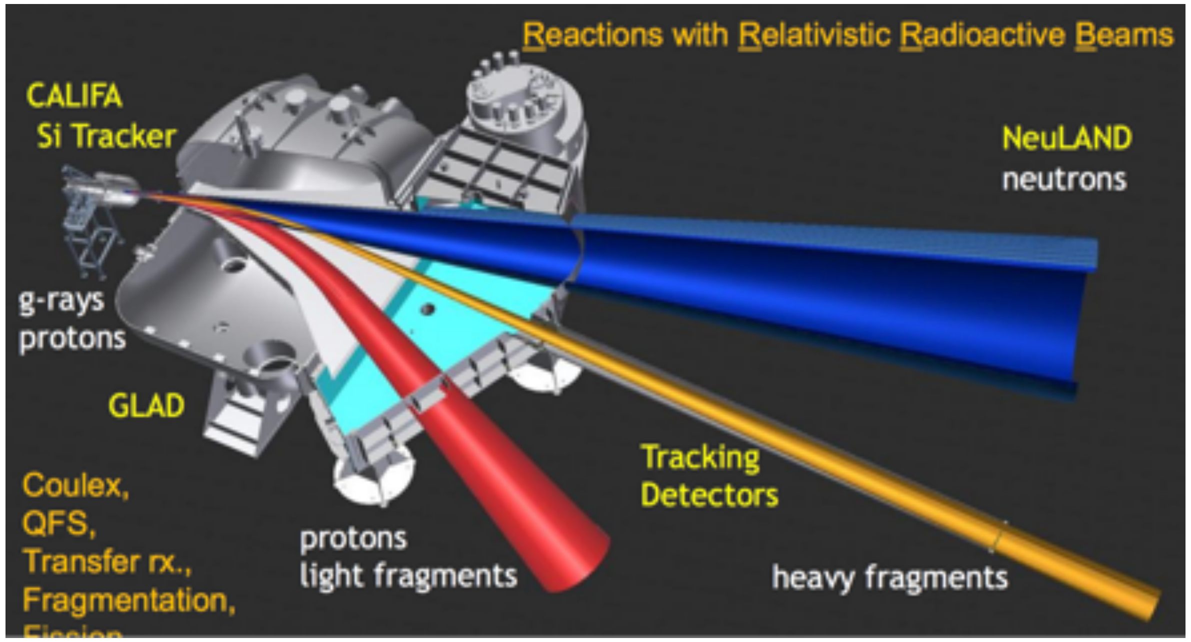
J. Hammelmann, MSc thesis, 2019

Short-Range Correlations

- Short-range correlations result in fluctuations to high momentum
- Develop a link between SRC observables and dense nuclear matter
- Identification of SRC in neutron-rich unstable nucleus at GSI with radioactive-ion beams

M. Duer et al, Nature (2018)

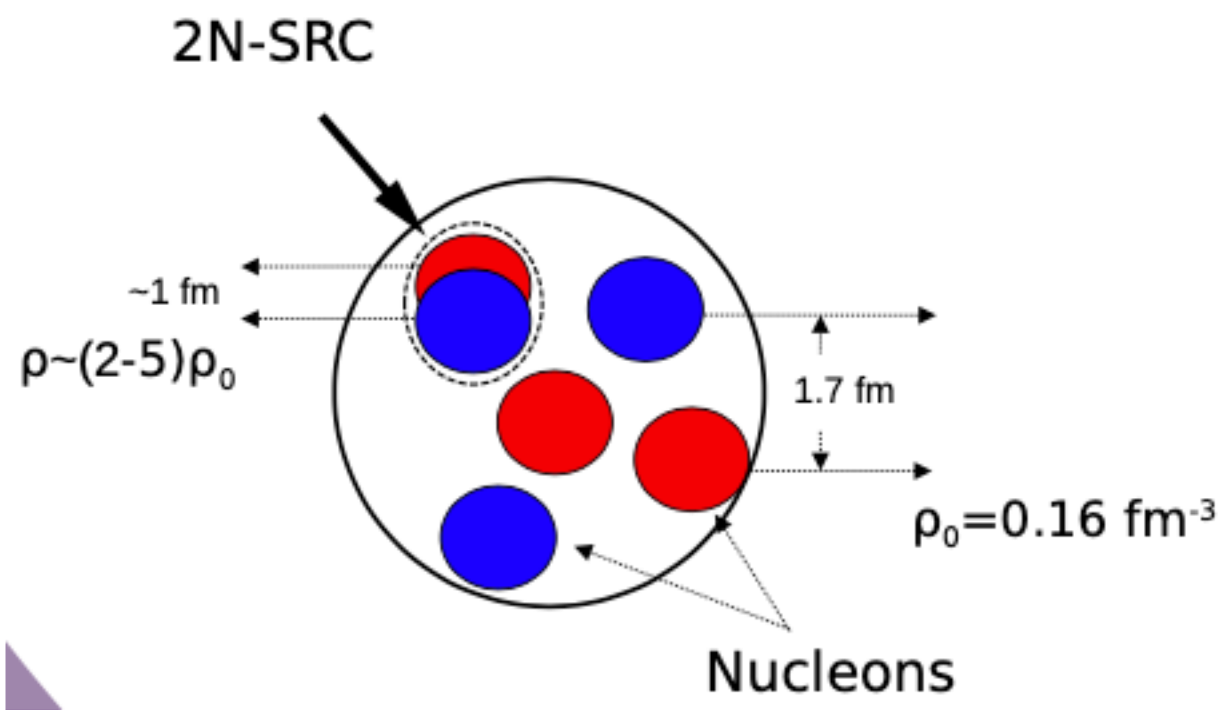


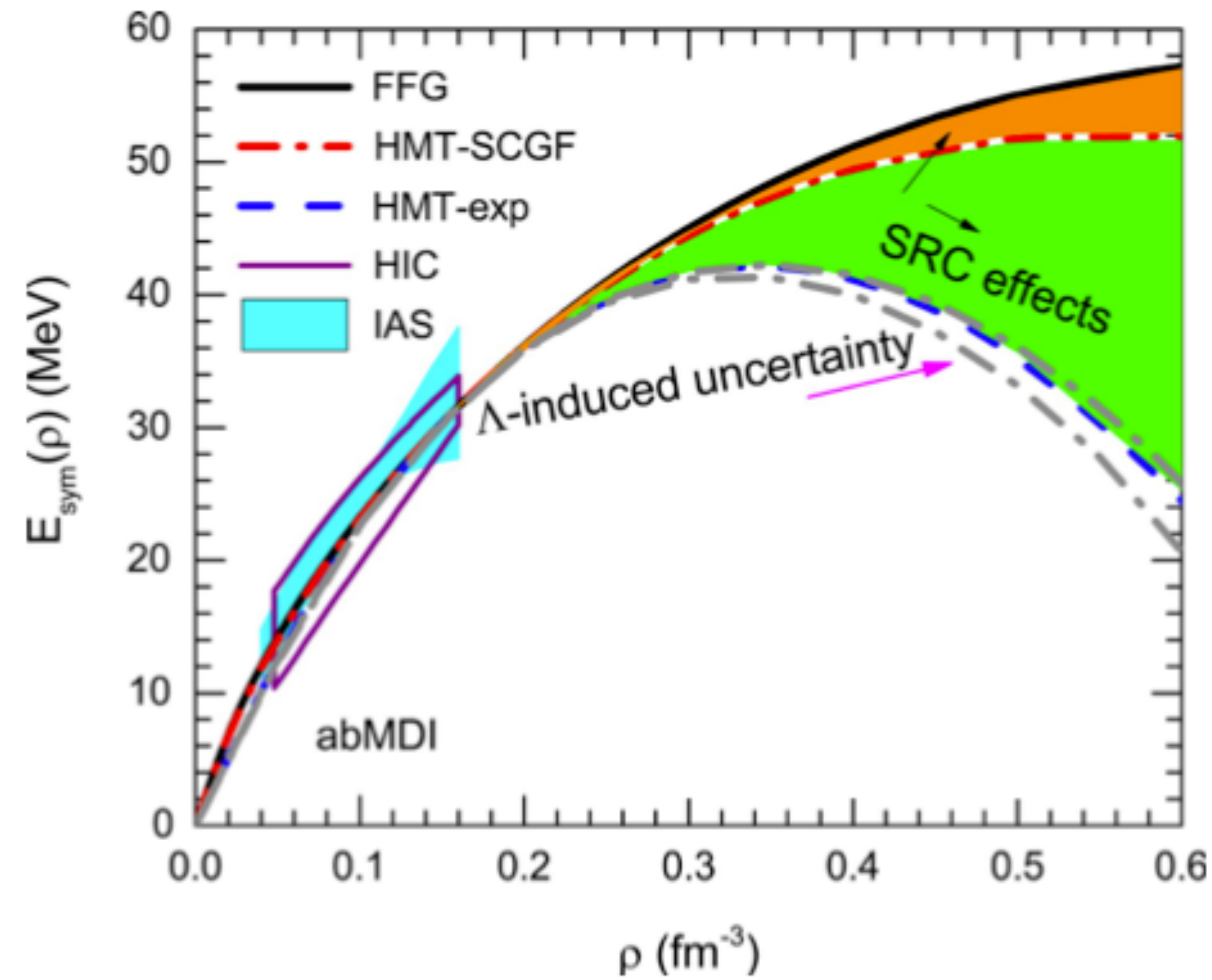


- First experiments 16C+p vs 12C+p in 2022 (ELEMENTS)

High Density Region

- Studying NN correlations provides insights about high density regions

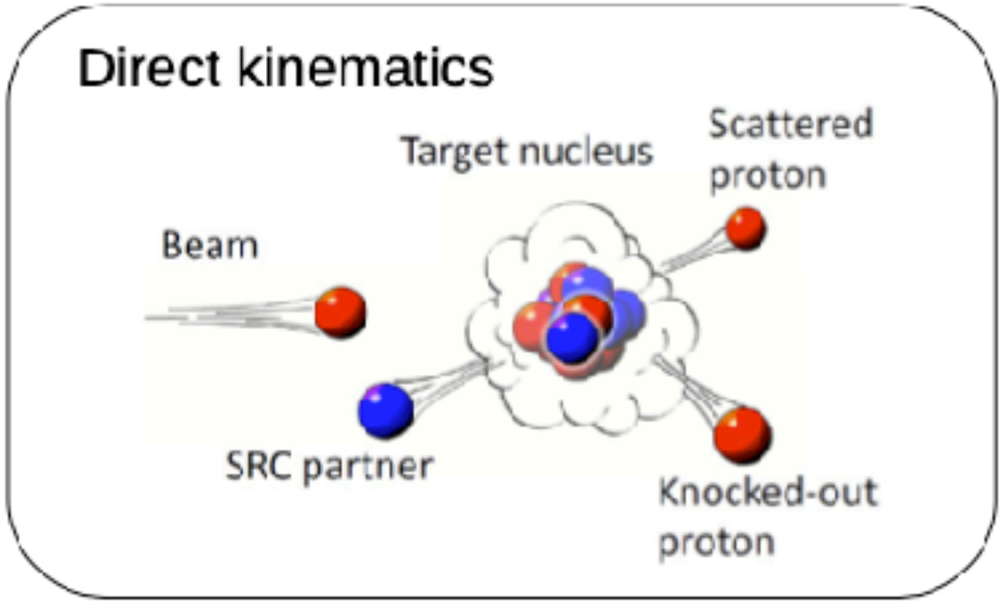


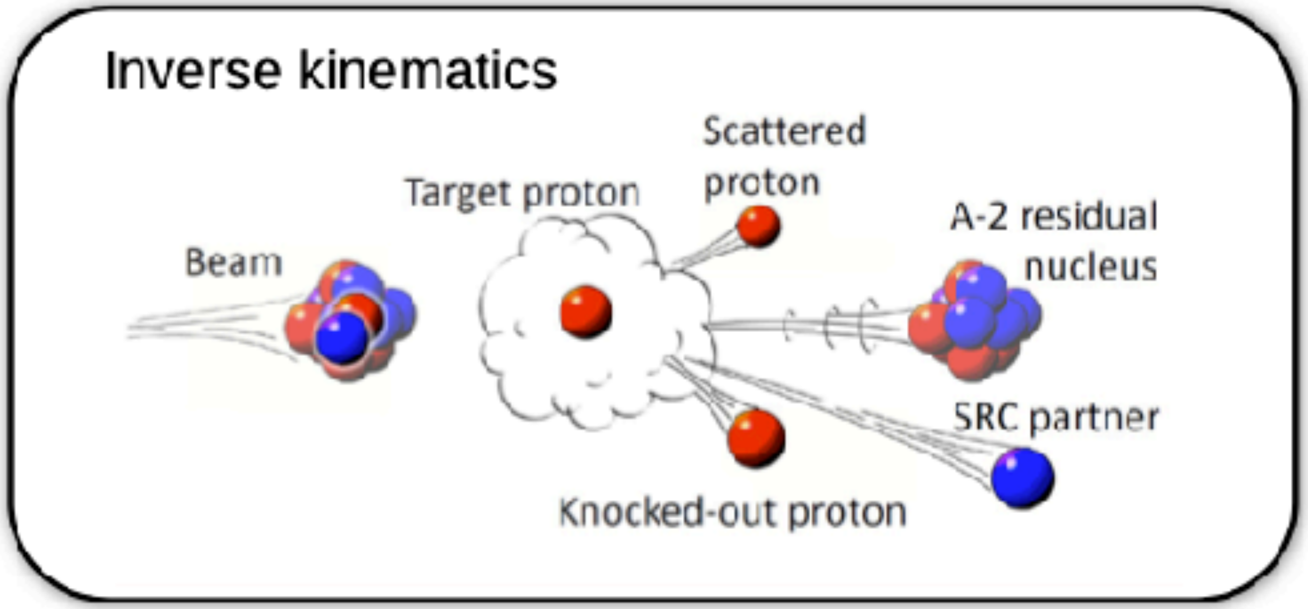


- Most experimental insights from electron scattering (JLab)
- Theory suggests softening of symmetry energy at high densities due to SRC

M. Dürr, ELEMENTS conference 2022

Neutron-Rich Nuclei





- Inverse kinematics allows to access unstable nuclei
  - Larger N/Z difference
  - Systematics of isospin dependence
- Kinematically complete measurement A(p,2pN) A-2
- First experiment running now (May 2022) at GSI R3B

M. Dürr, ELEMENTS conference 2022

Theory Developments

- To provide predictions for short-range correlations a proper treatment of momentum space is required
  – Any insights on how to treat the high momentum tail in a Monte Carlo model?

- Dynamic production of light (hyper)nuclei via multi-particle reactions and stochastic rates within SMASH
  – Experimental interest in studying hypernuclei production (HYDRA experiment)
  – This might again provide insights into high density equation of state of nuclear matter

Summary

- Hybrid approach for RRTF isobar calculations
  - SMASH initial state with charge distribution and deformations/ neutron skin/external input
  - Viscous hydrodynamics (event-by-event, 2+1D)
  - Cooper-Frye and rescattering with conservation laws
- Nuclear structure input
  - Neutron skin, deformation, NN correlations and color fluctuations have been studied
  - Neutrin skin has a significant effect on magnetic field
- Low energy heavy-ion collisions
  - Light nuclei production is important
  - Insights on equation of state of nuclear matter at high density
  - Experiment on short-range correlations in neutron-rich nuclei

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