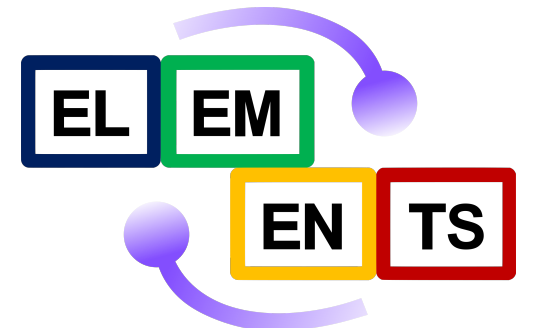# Nuclear Structure in High and Low Energy Collisions

Hannah Elfner

January 26th, 2022, RBRC Workshop, BNL (virtual)

Outline

- High energy heavy-ion collisions
  - Deformation and neutron skin
  - Effects for isobar collisions
  - Nucleon-nucleon correlations
  - Color fluctuations
- Low beam energy collisions
  - SMASH with potentials
  - Collective anisotropic flow
  - Density changes and deformations
- Future plans
  - Short-range correlations in neutron-rich nuclei

SMASH*

- 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, (ROOT)

https://smash-transport.github.io

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

$T_L^{00} [GeV \cdot fm^{-3}]$ v_L
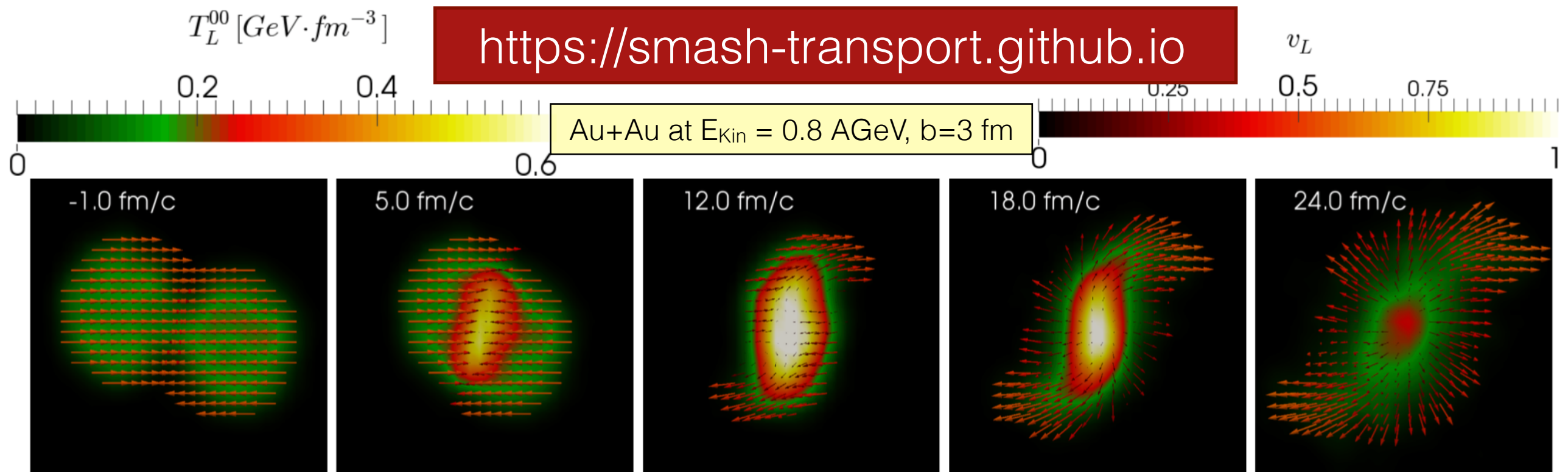
* Simulating Many Accelerated Strongly-Interacting Hadrons

The SMASH Team

- In Frankfurt:
  - Oscar Garcia-Montero
  - Gabriele Inghirami
  - Alessandro Sciarra
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Jan Hammelmann
  - Niklas Götz
  - Renan Hirayama
  - Nils Saß
  - Antonio Bozic
  - Orhan Özel

- In US:
  - Dmytro Oliinychenko
  - Agnieszka Sorensen
  + Damjan Mitrovic

Group excursion in September 2020

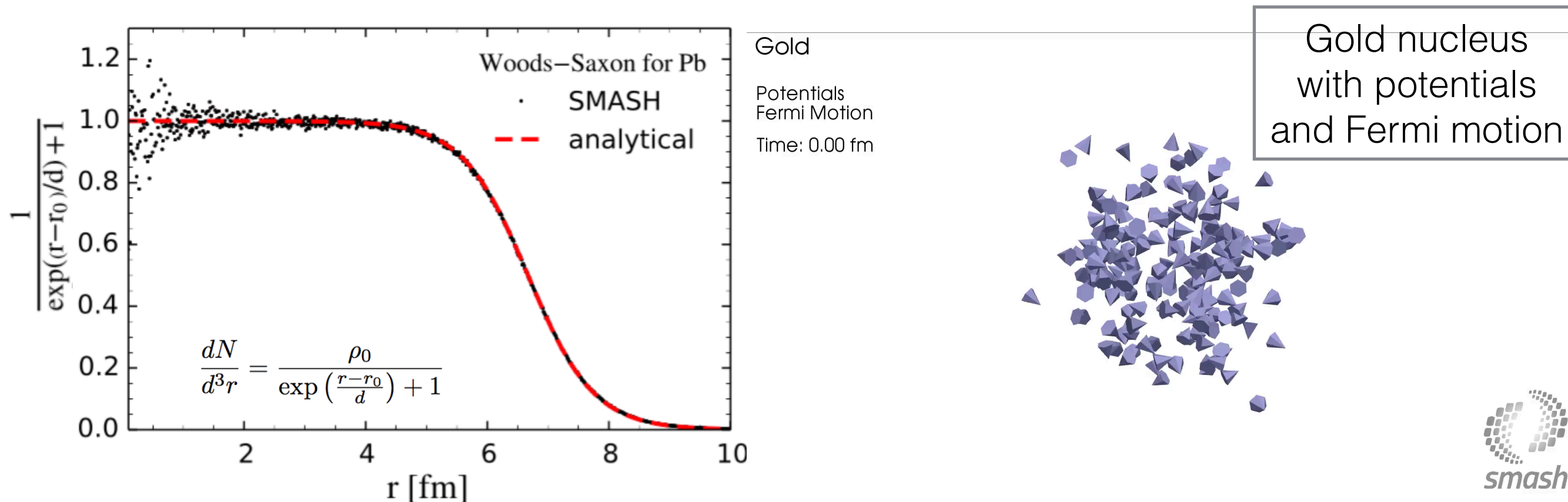# High Energy Collisions

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

Initial Conditions

- ## Nuclear Collisions

  - Woods-Saxon distribution in coordinate space

Woods–Saxon for Pb
· SMASH
-- analytical

$$\frac{dN}{d^3r} = \frac{\rho_0}{\exp\left(\frac{r-r_0}{d}\right) + 1}$$

Gold

Potentials
Fermi Motion

Time: 0.00 fm

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

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)
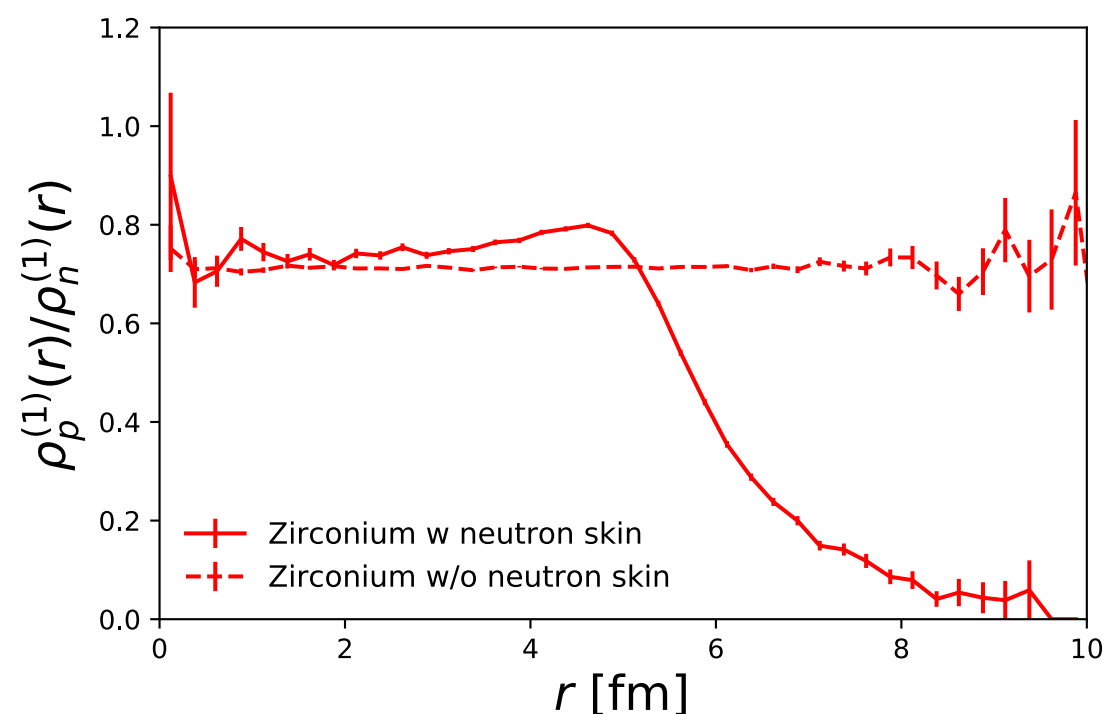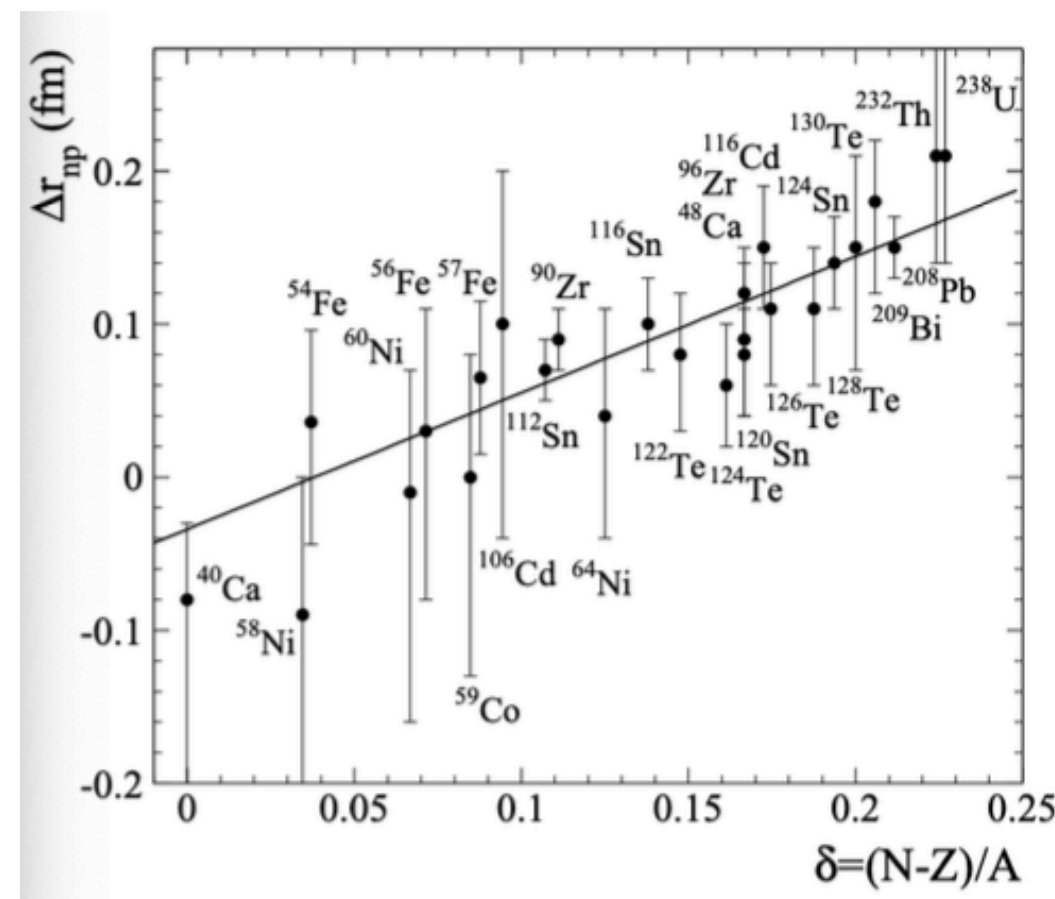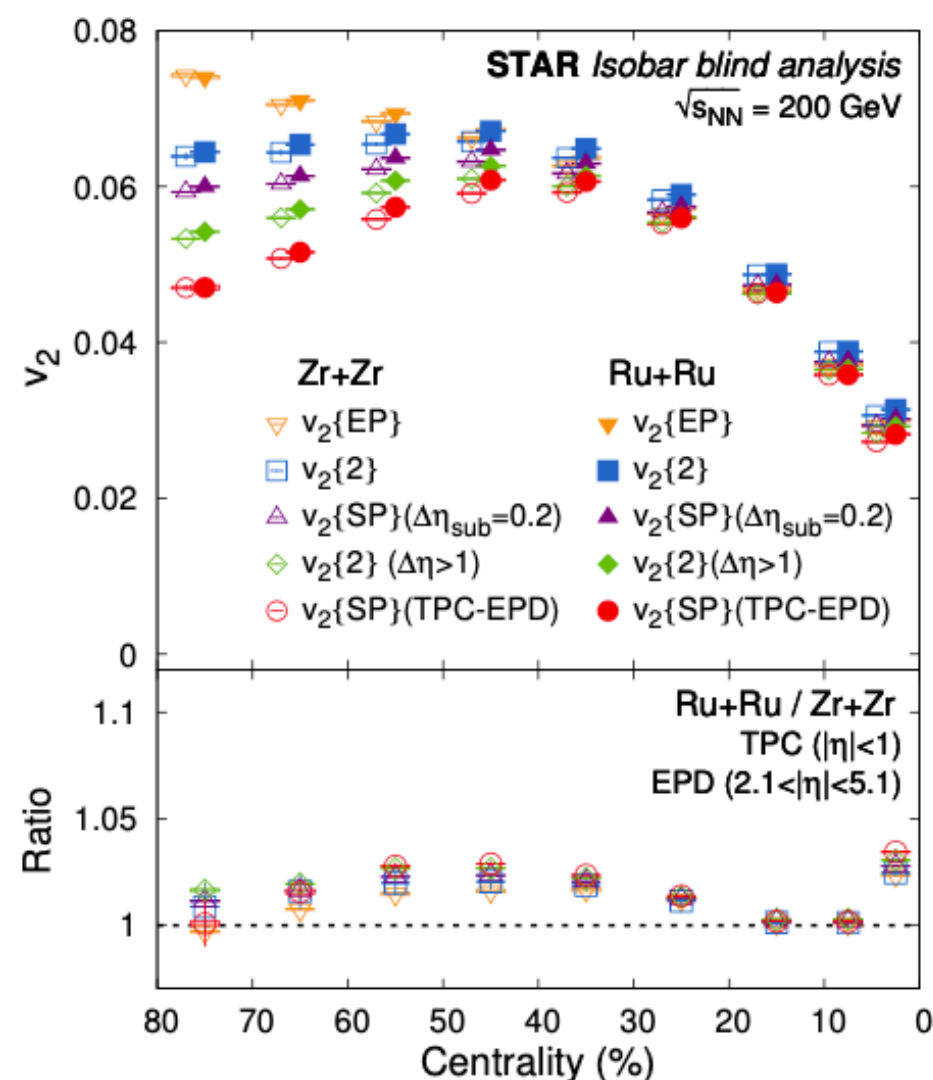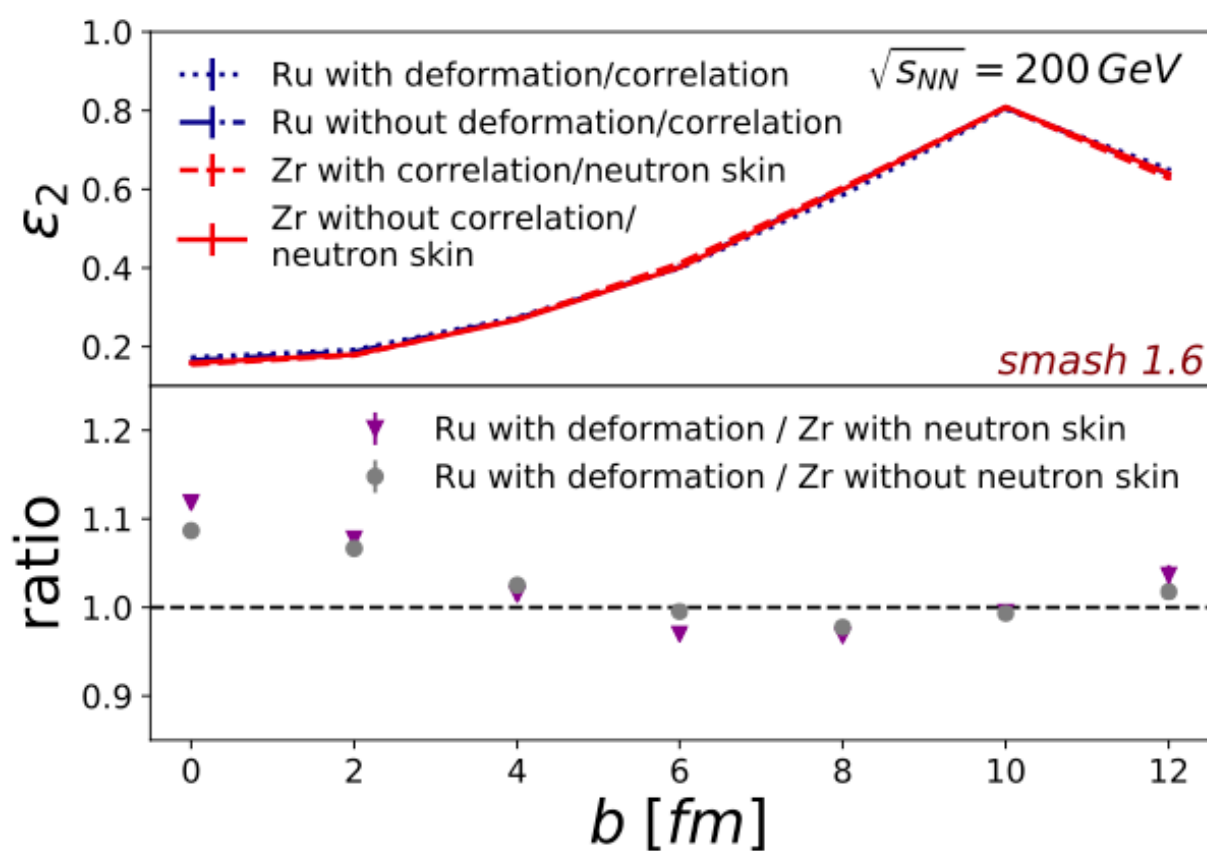
Participant Eccentricity

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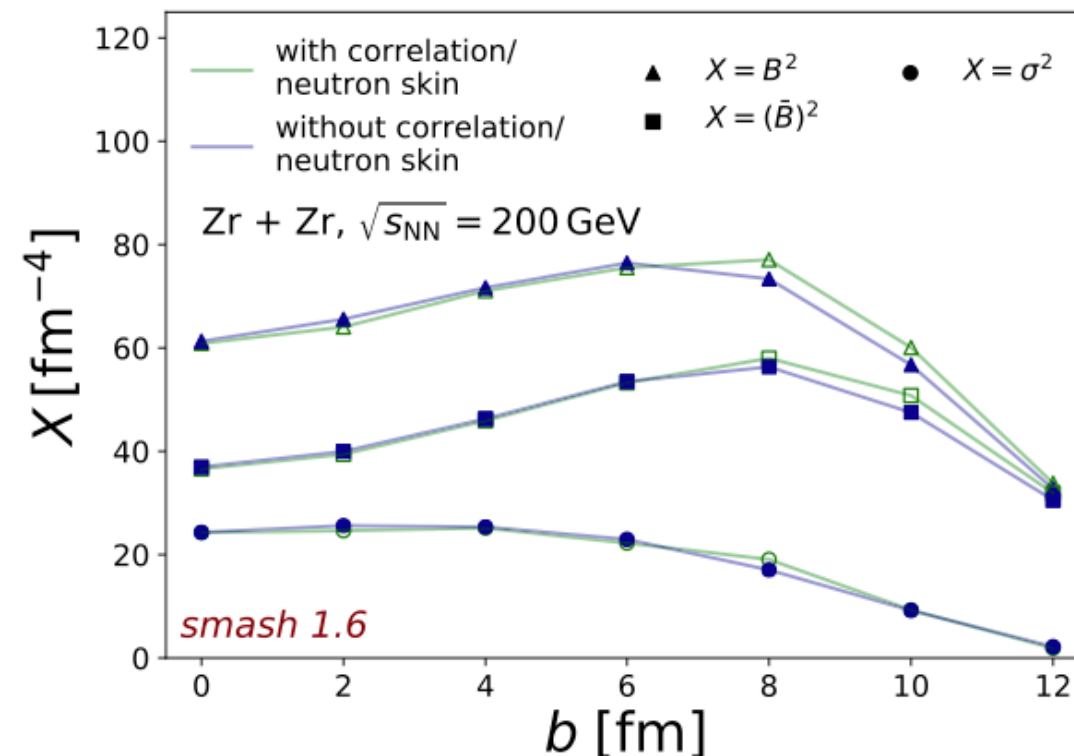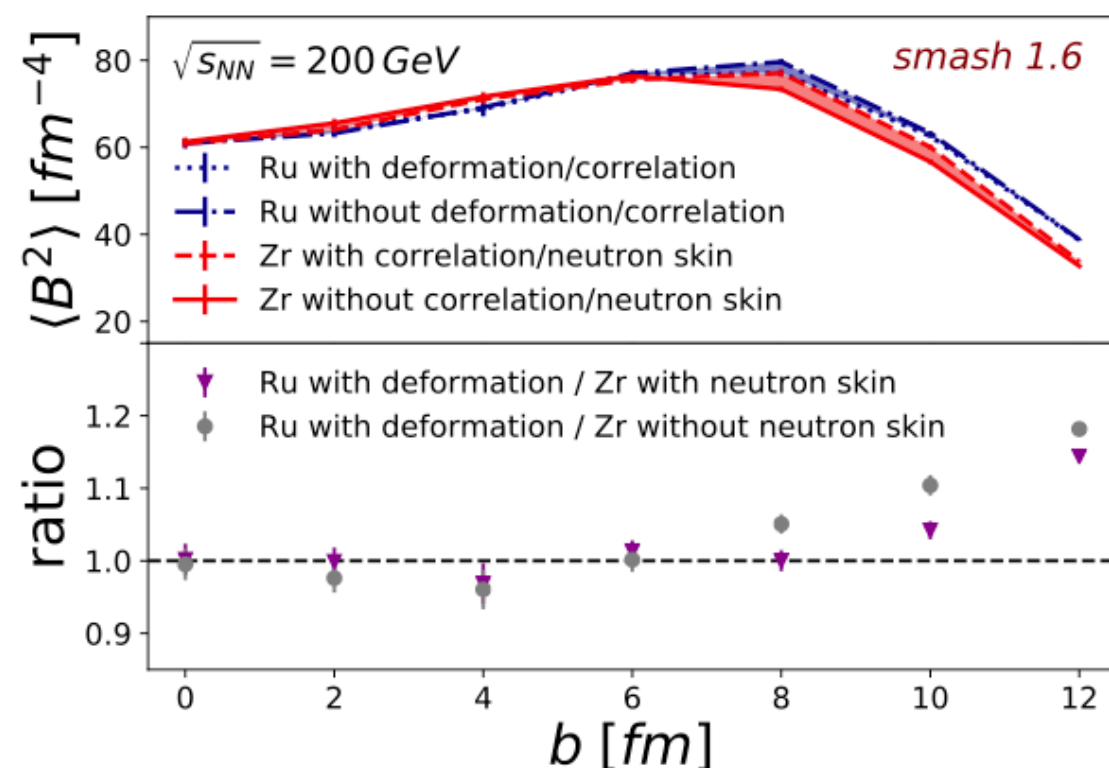
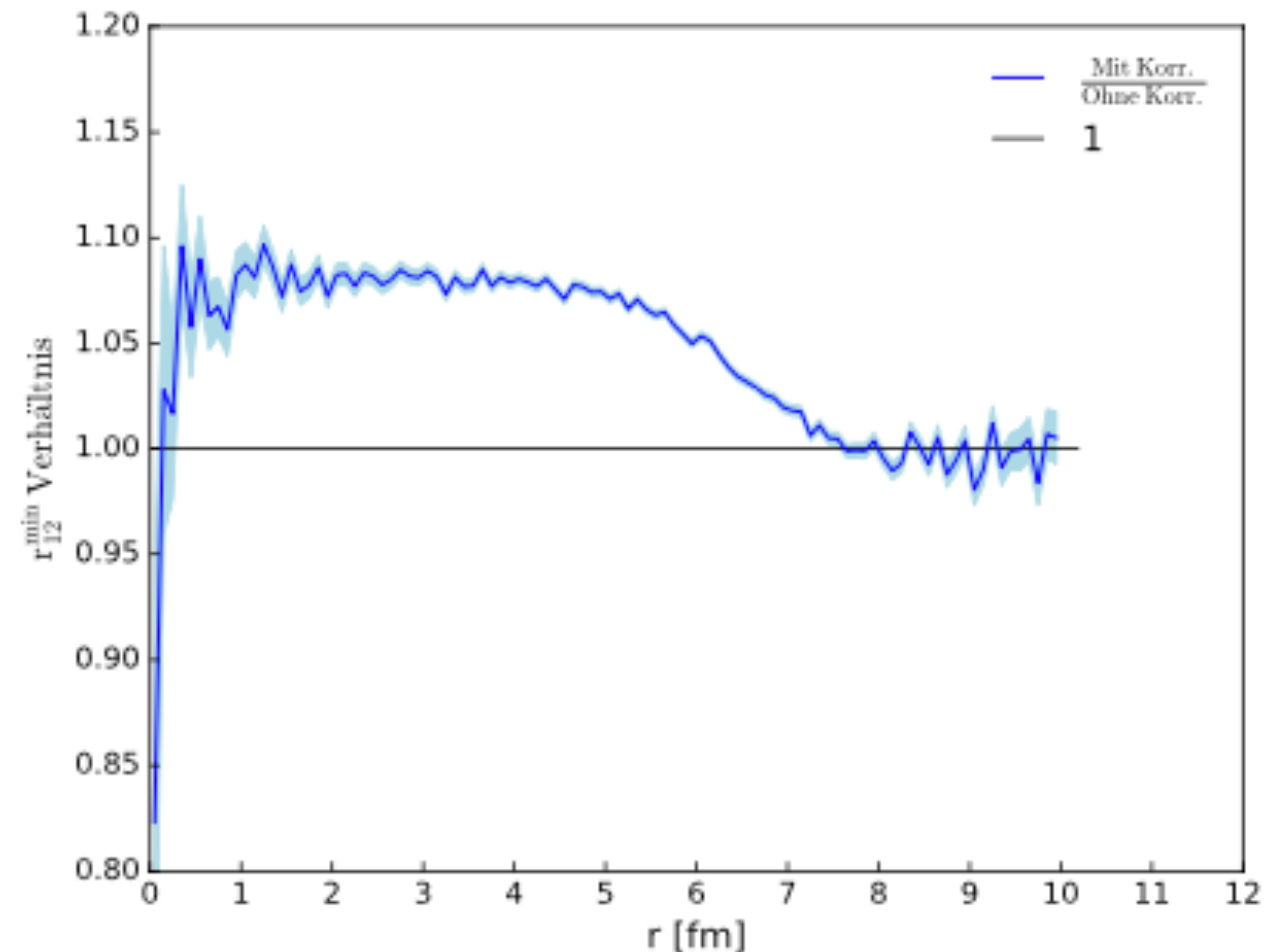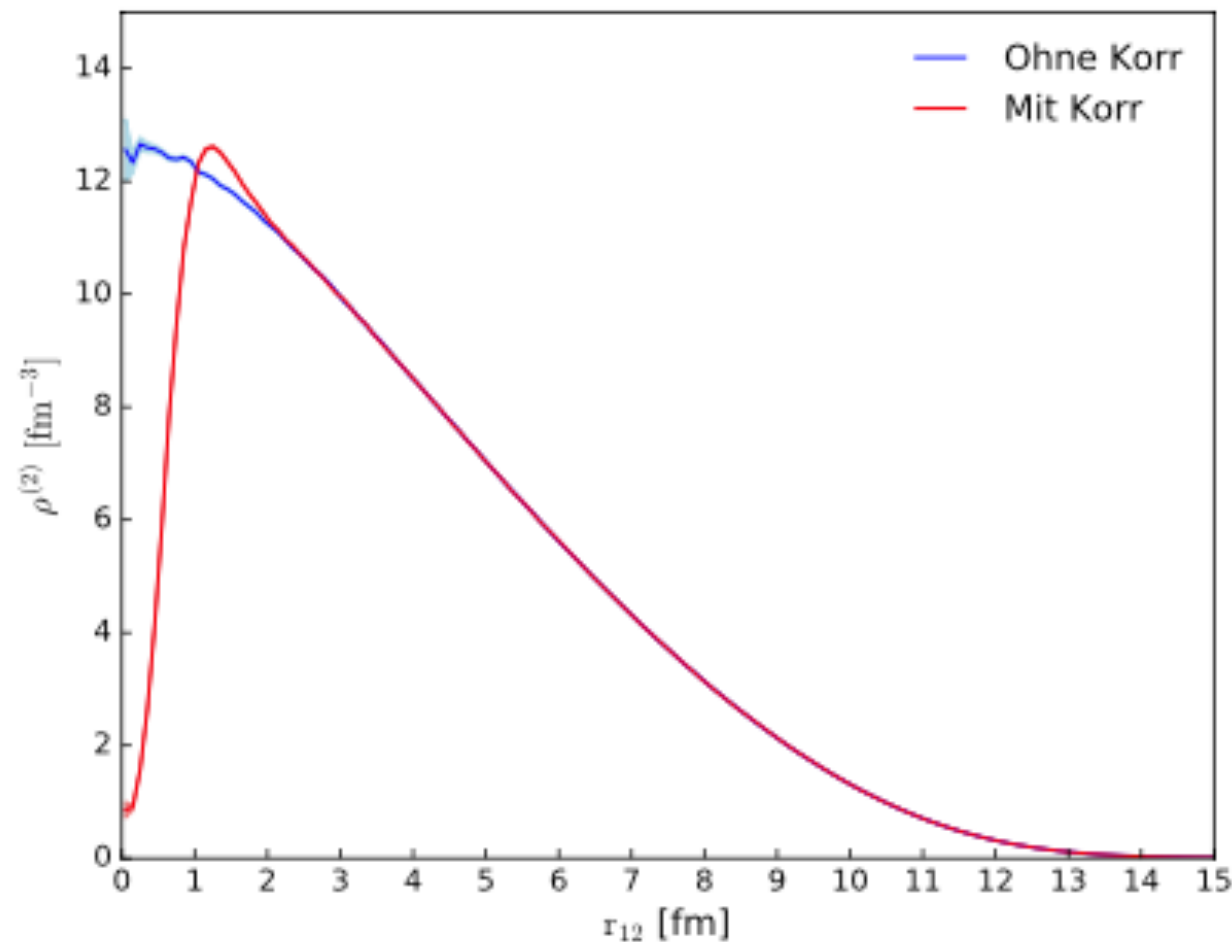J. Hammelmann et al, *Phys.Rev.C* 101 (2020)

- 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
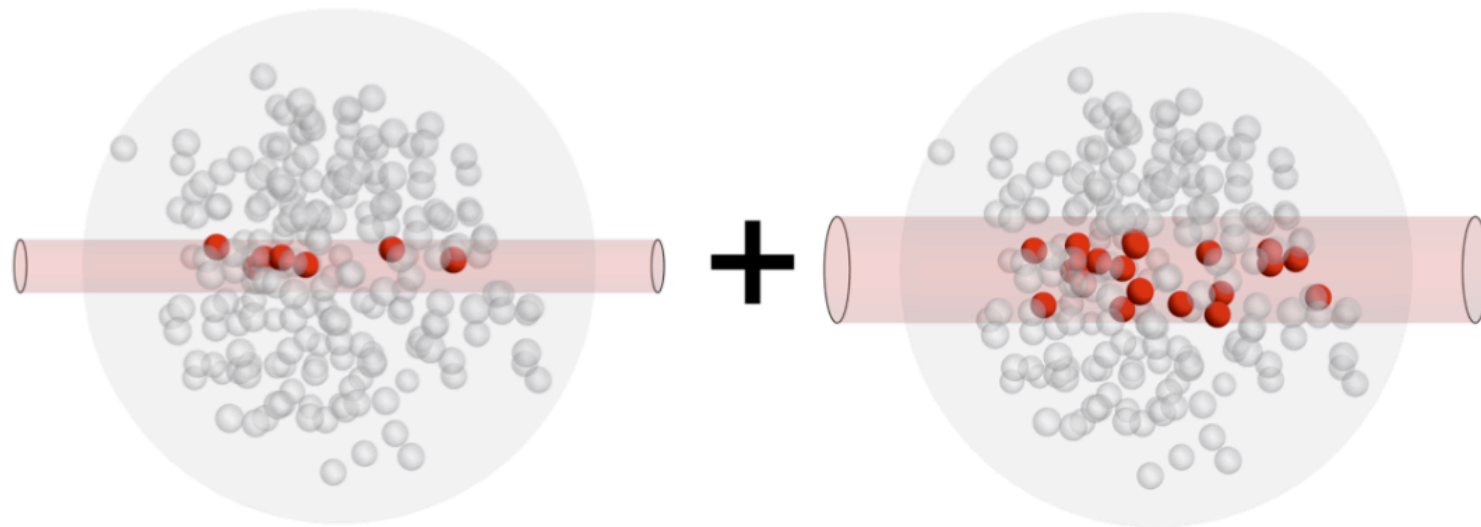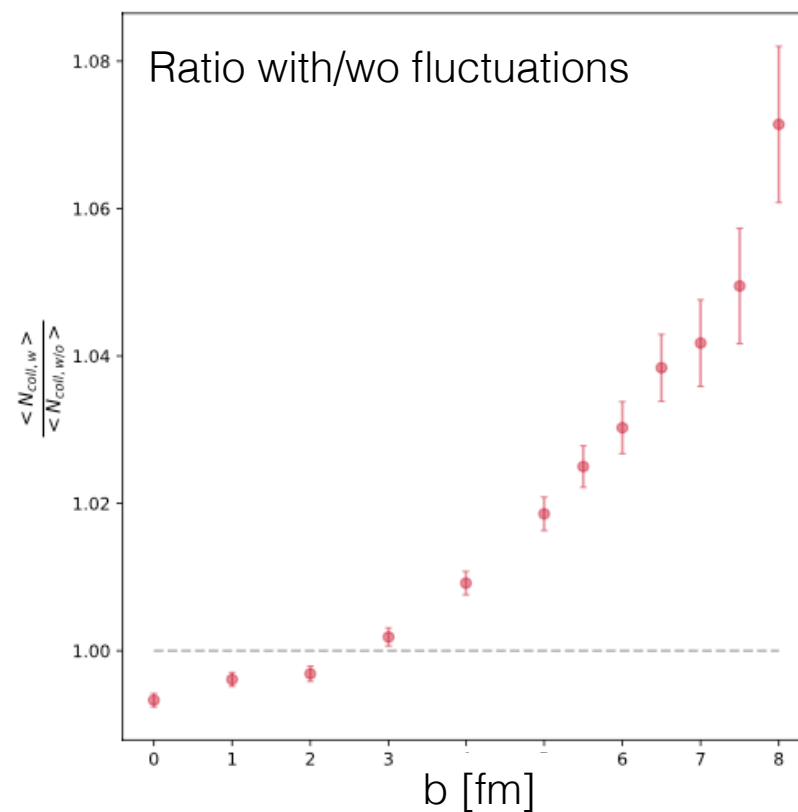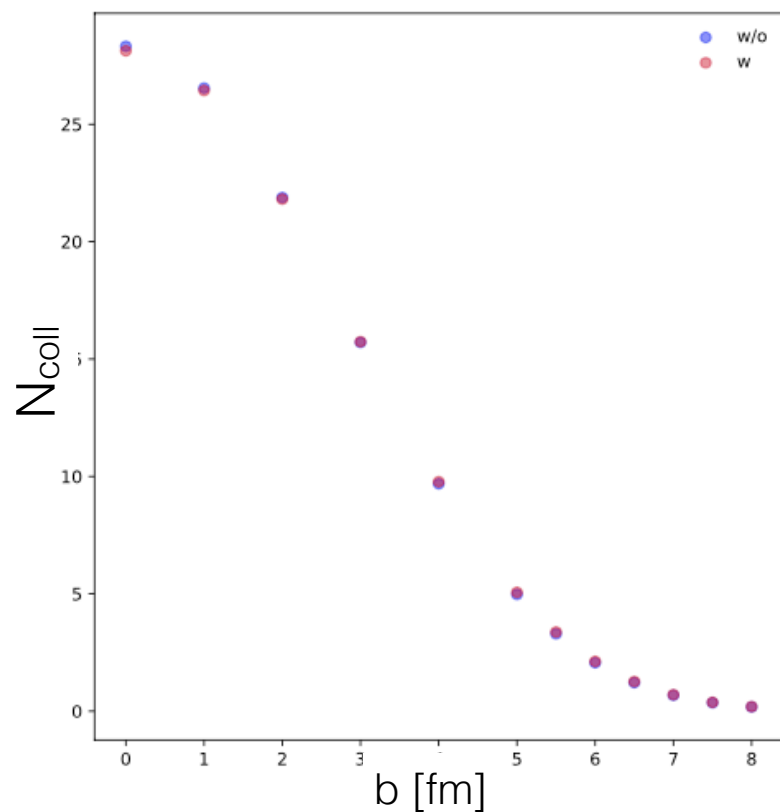
- The 2-particle distribution and the average distance shows the expected behaviour

- Other observables (eccentricities not sensitive)

Color Fluctuations

M. Alvioli et al, PRD 98 (2018)


O+O at sqrts_NN = 200 GeV

BSc thesis, Antonio Bozic, 2021

- Fluctuating first cross-section of NN interactions in SMASH

- Number of collisions in peripheral events is increased for small nuclei

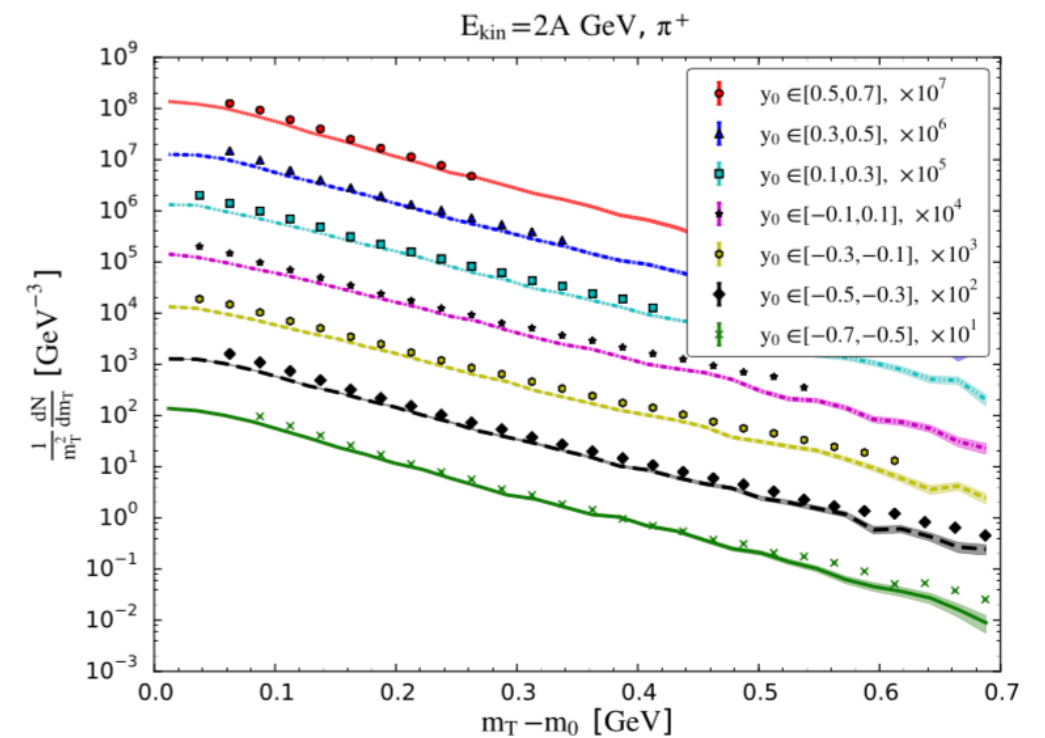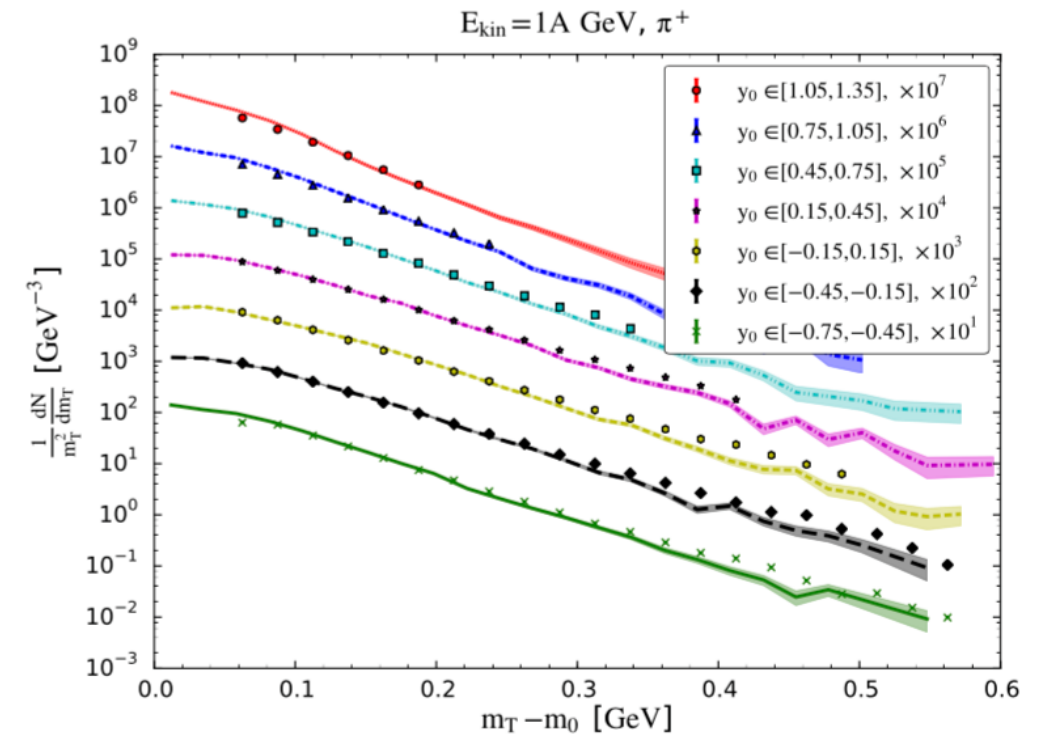- Other bulk observables are not affected

Low Energy Collisions

Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield

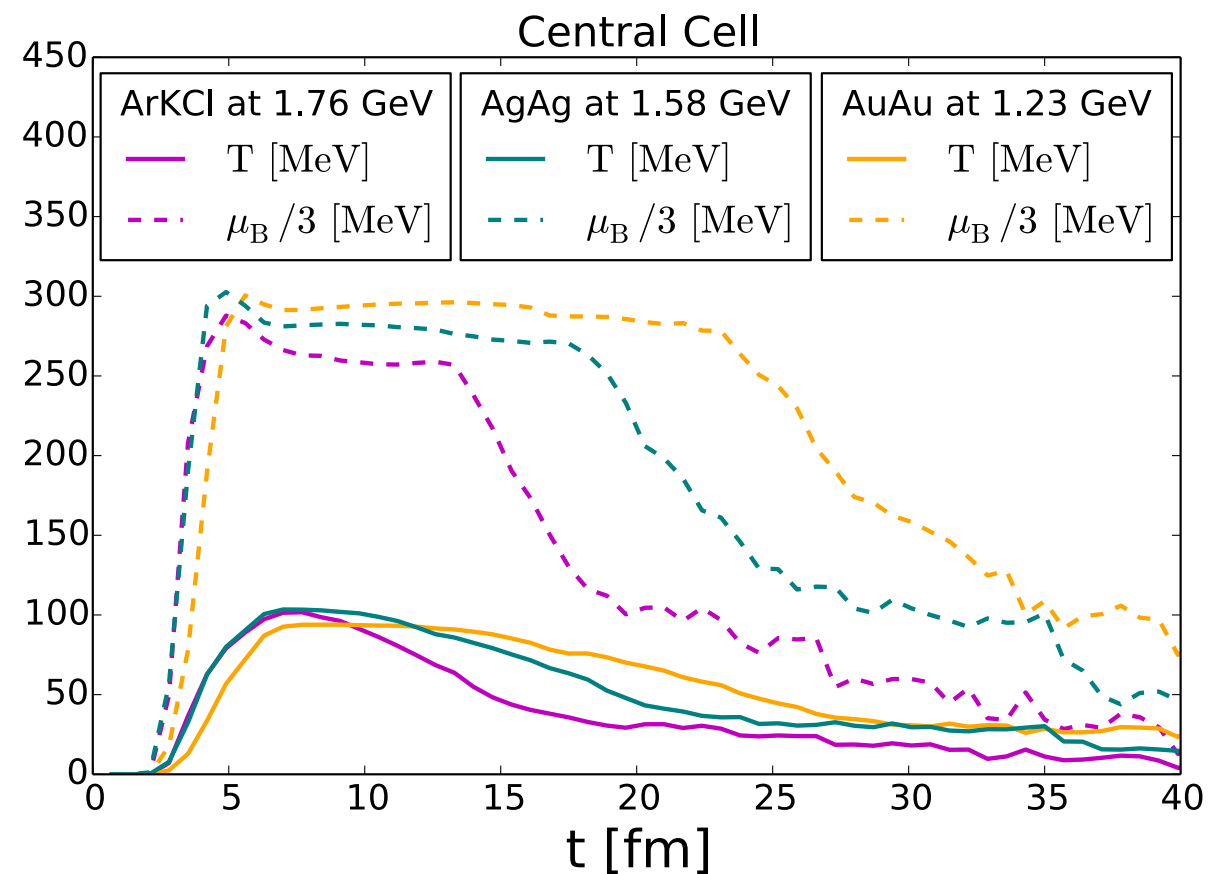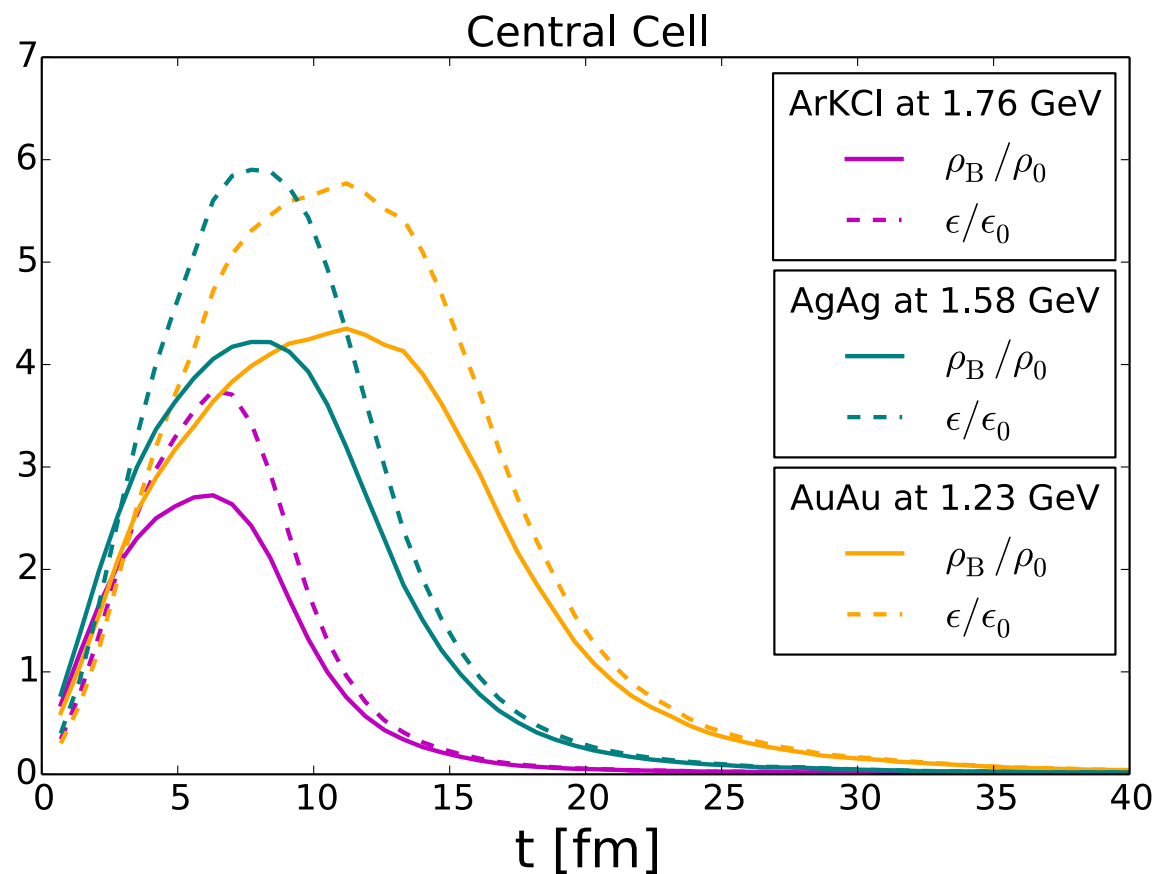- Nice agreement with SIS experimental data
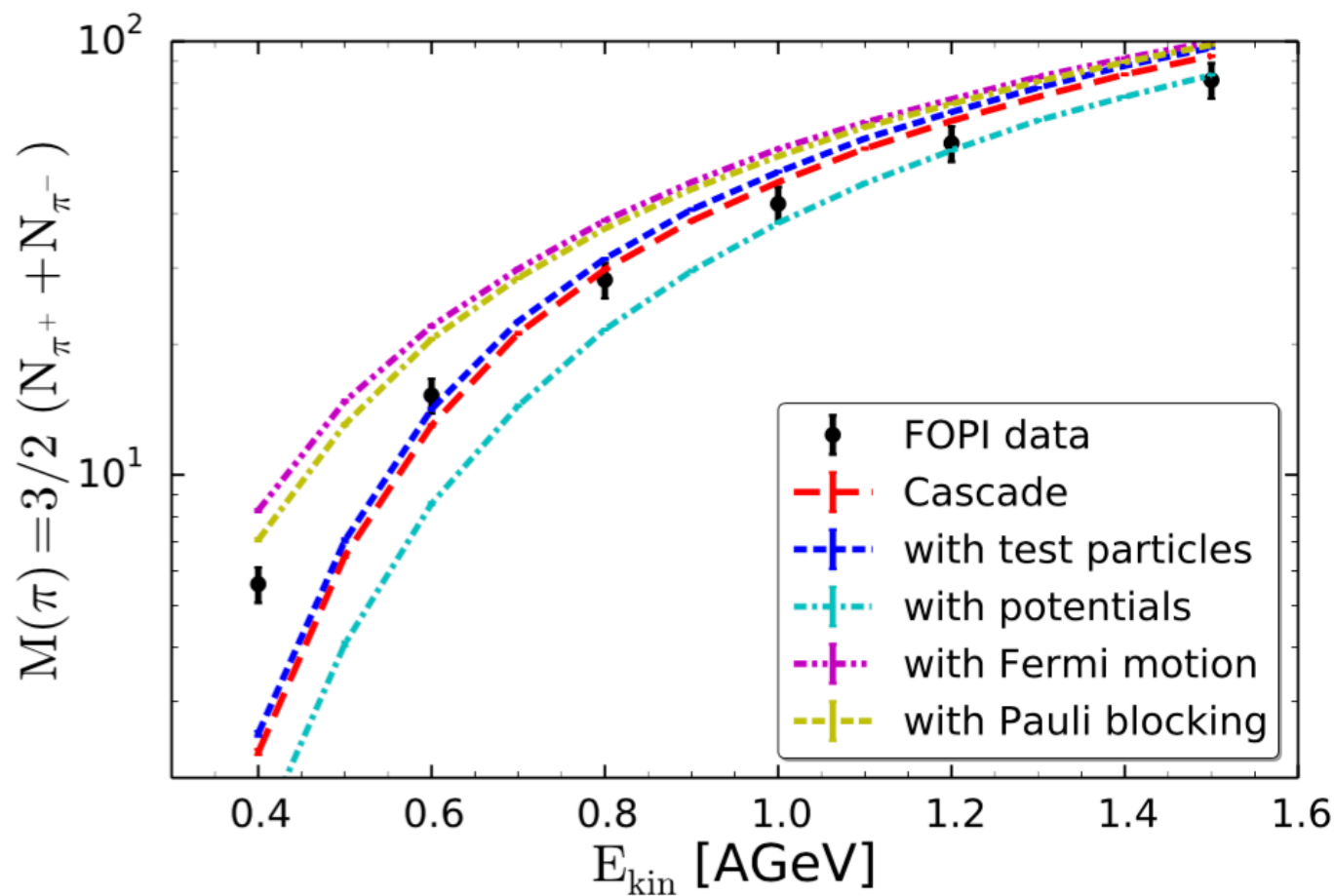
Note: consecutive addition of features

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

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

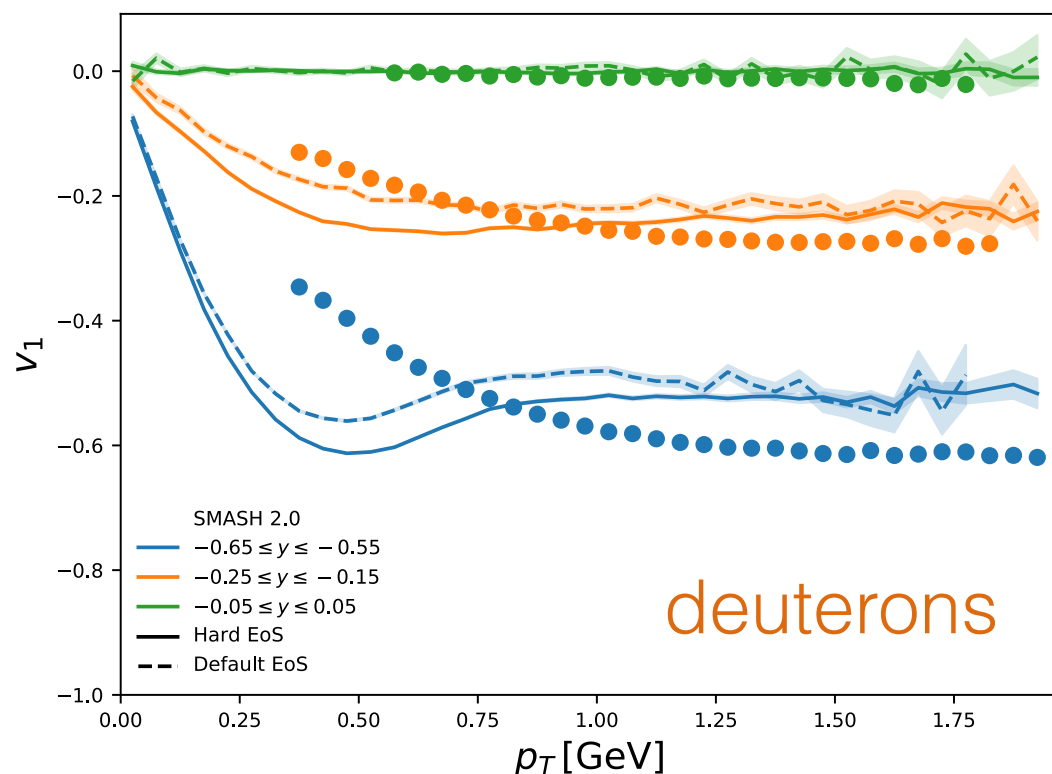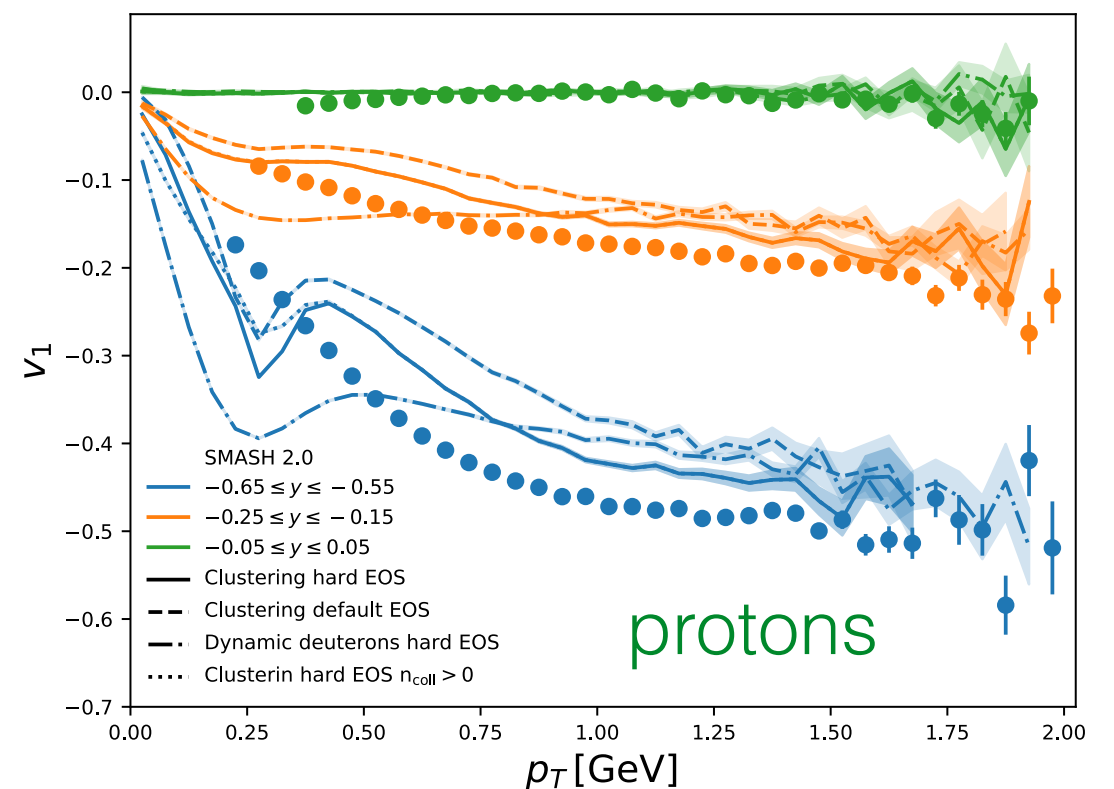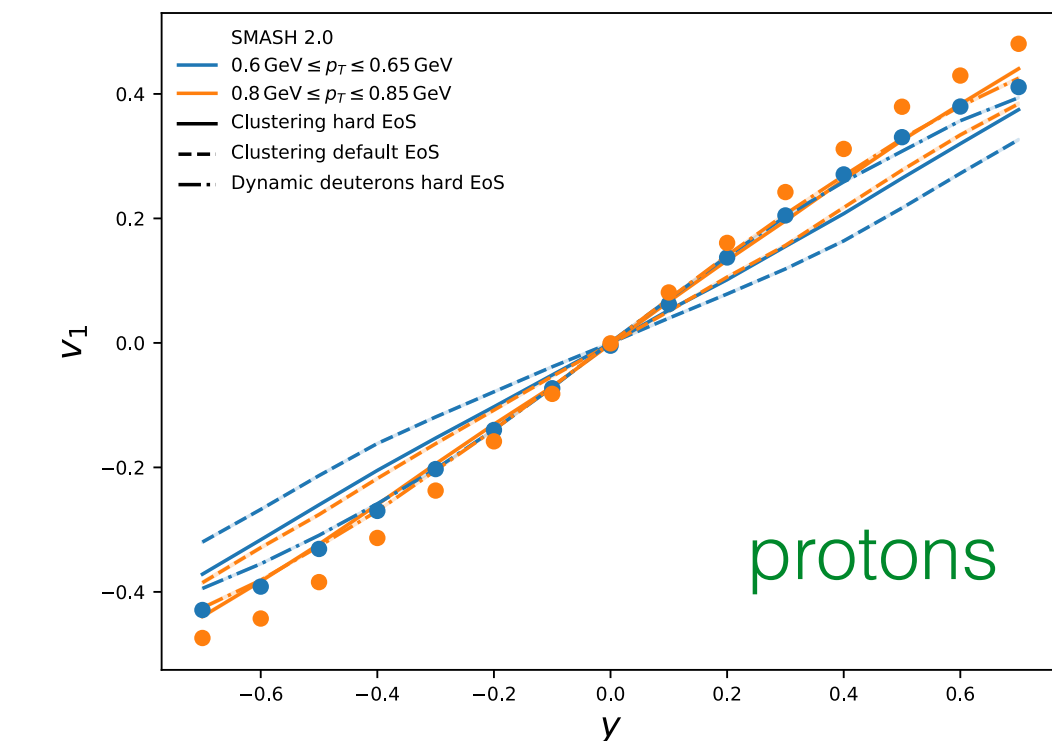 – Describes interactions between nucleons, repulsive at high densities

	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

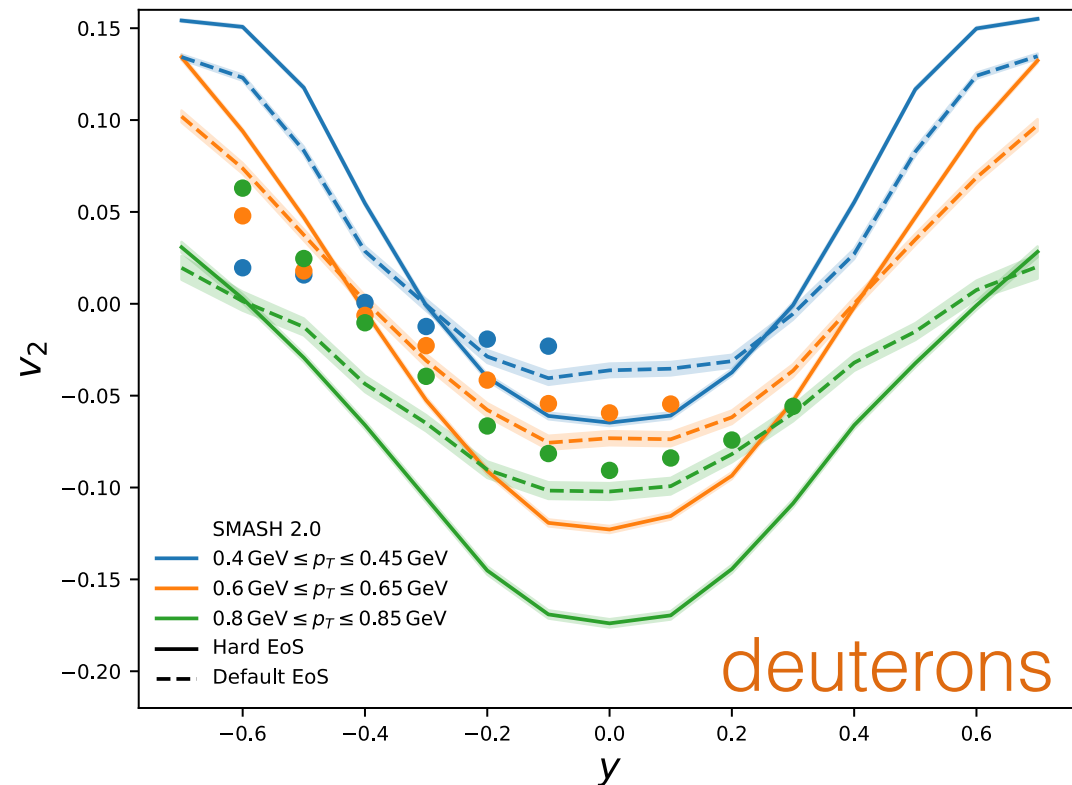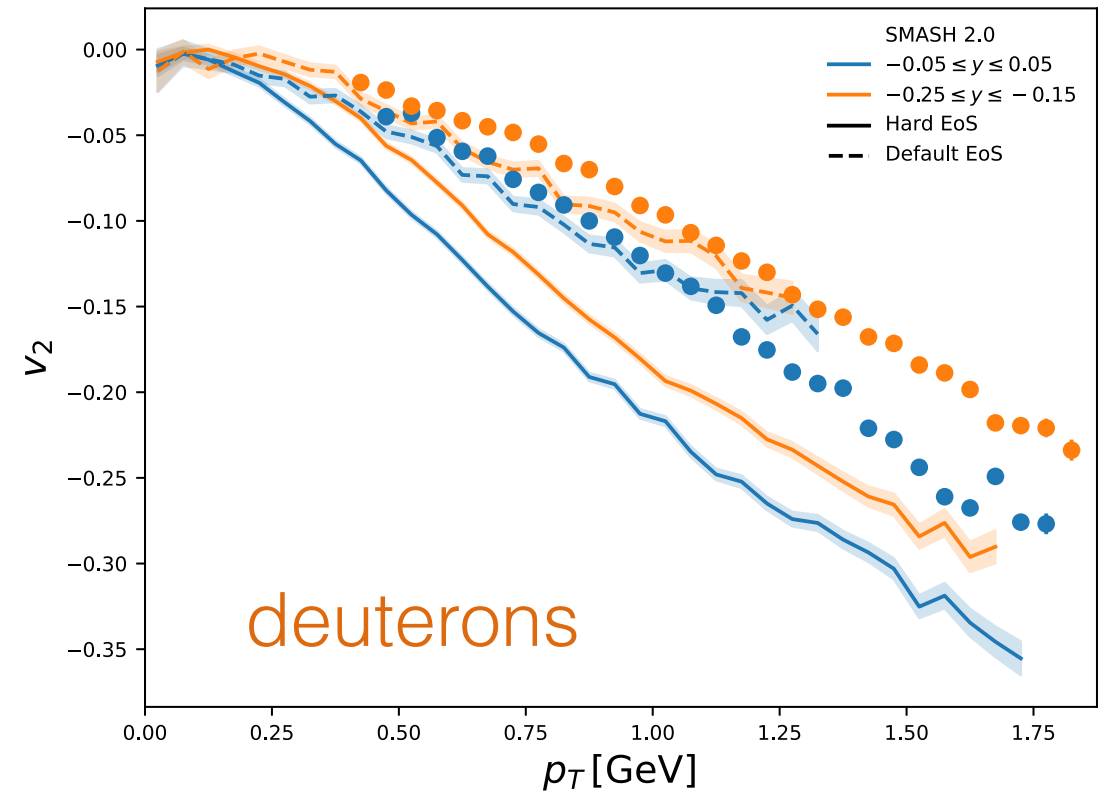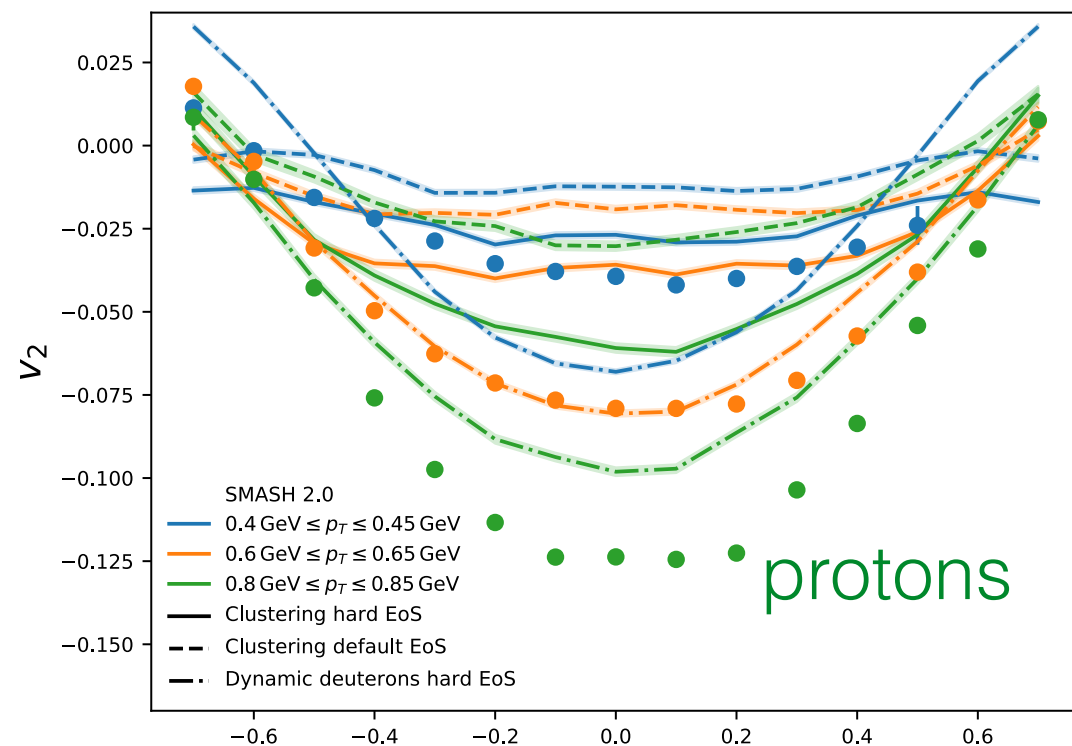 – Default values according to transport code comparison

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
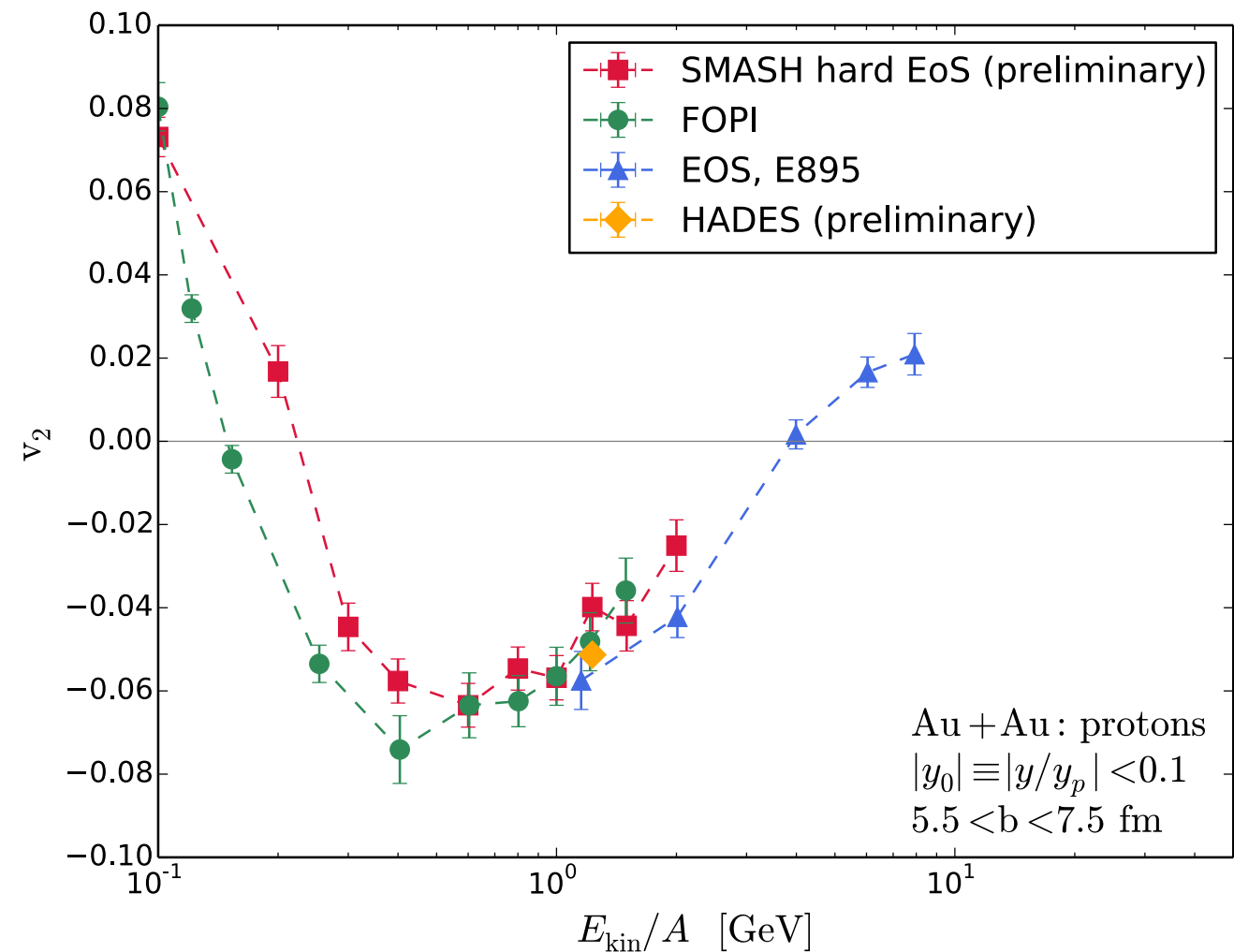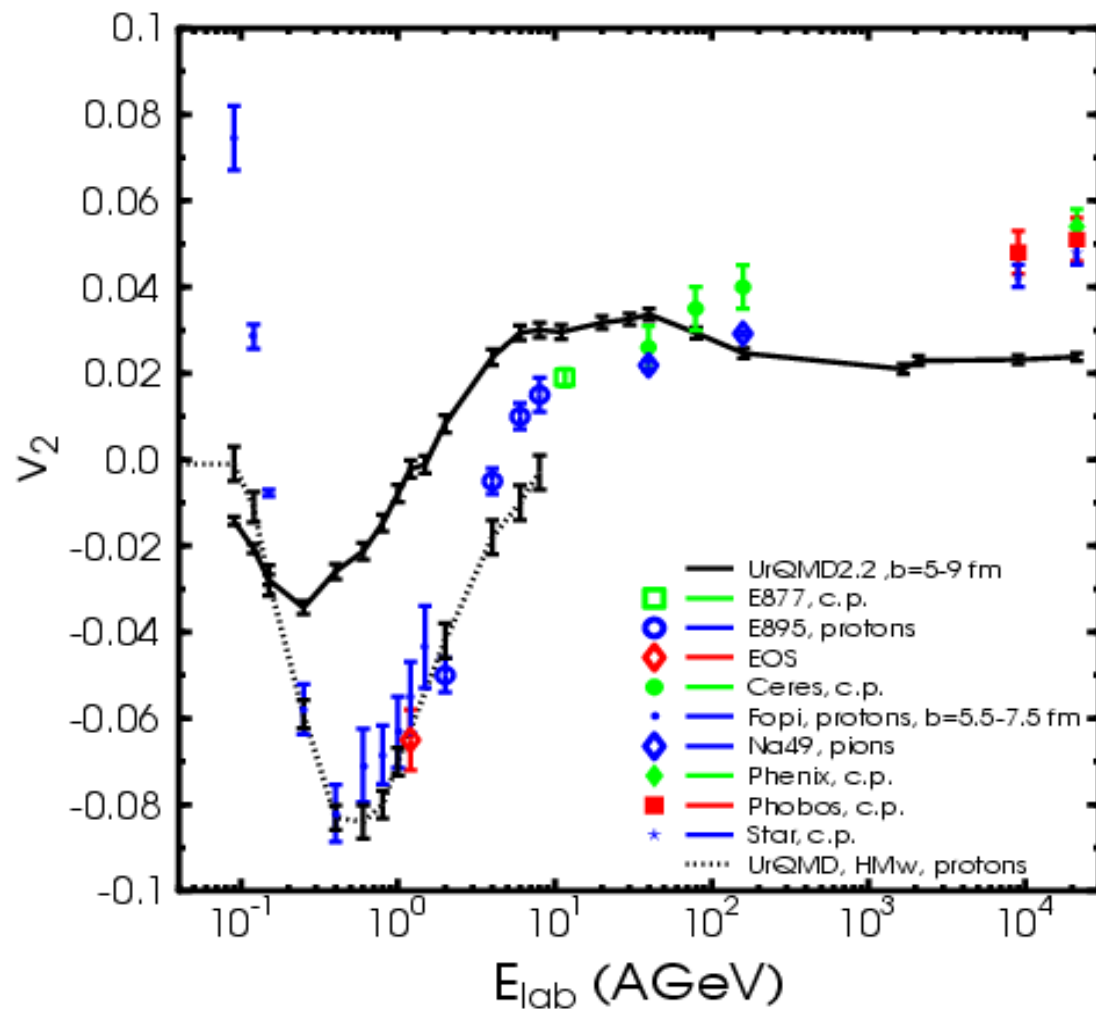
Elliptic Flow in SMASH

- 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

charged particles, |y|<0.1

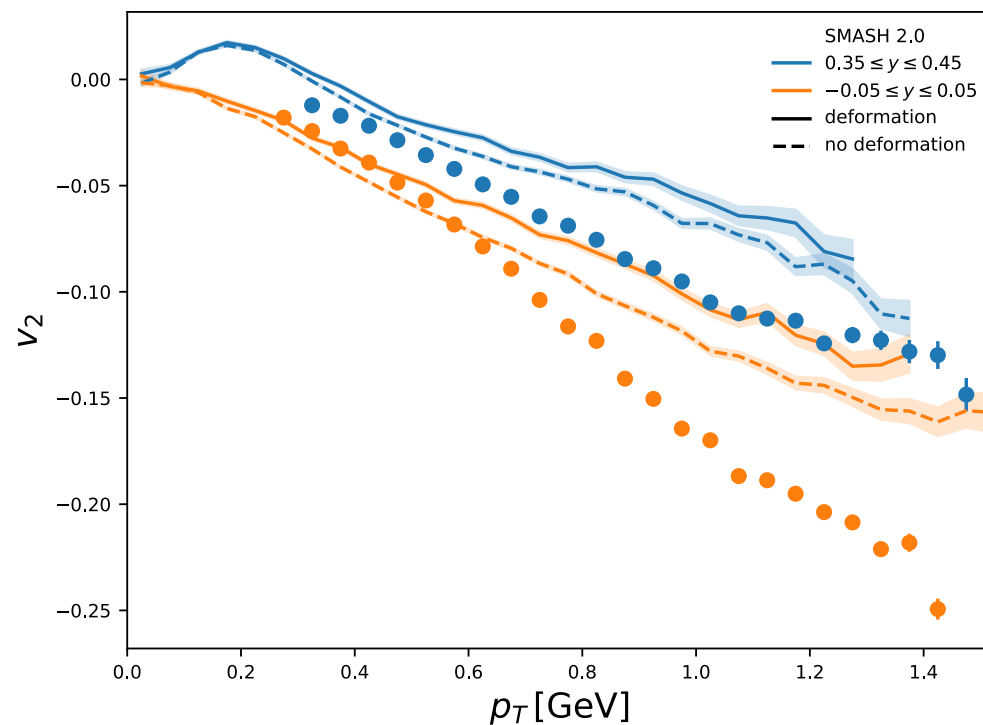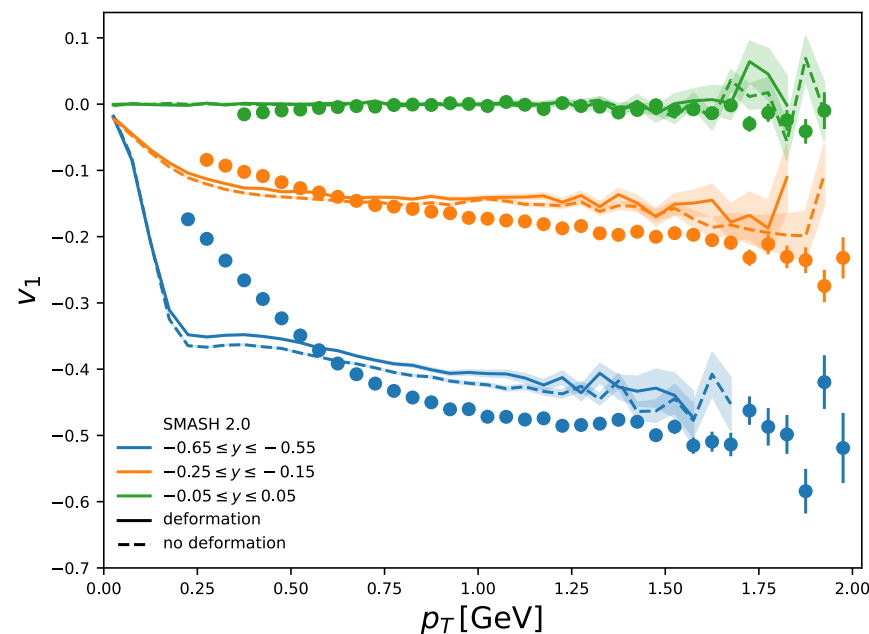H. Petersen et al, Phys.Rev. C74 (2006) 064908

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

Future Plans

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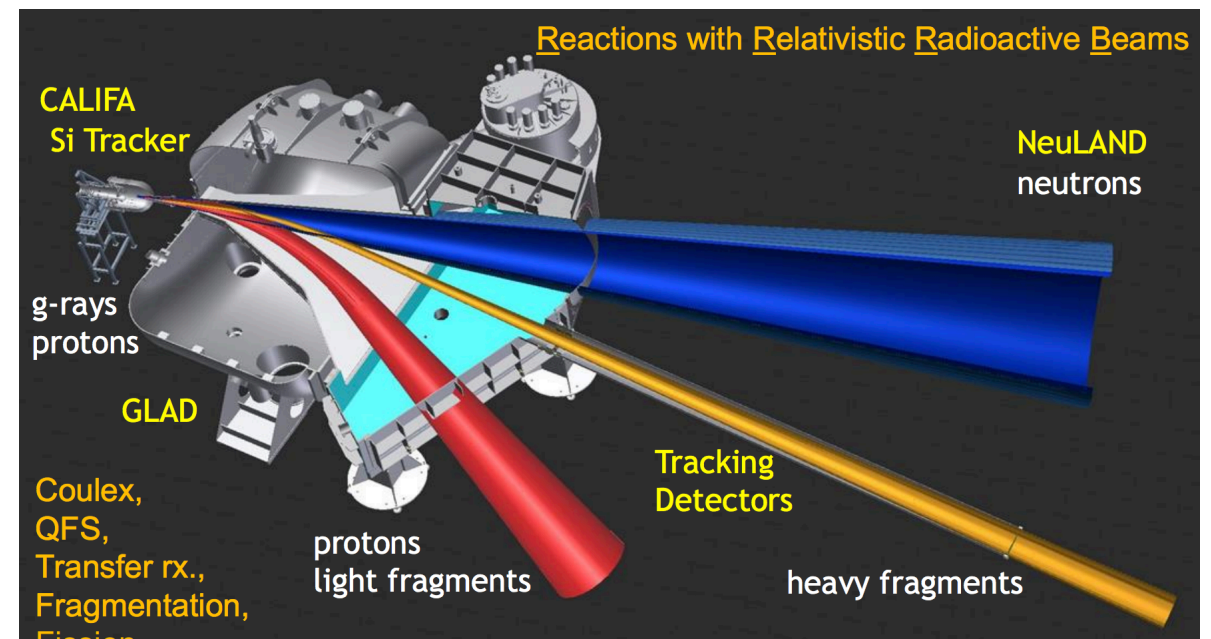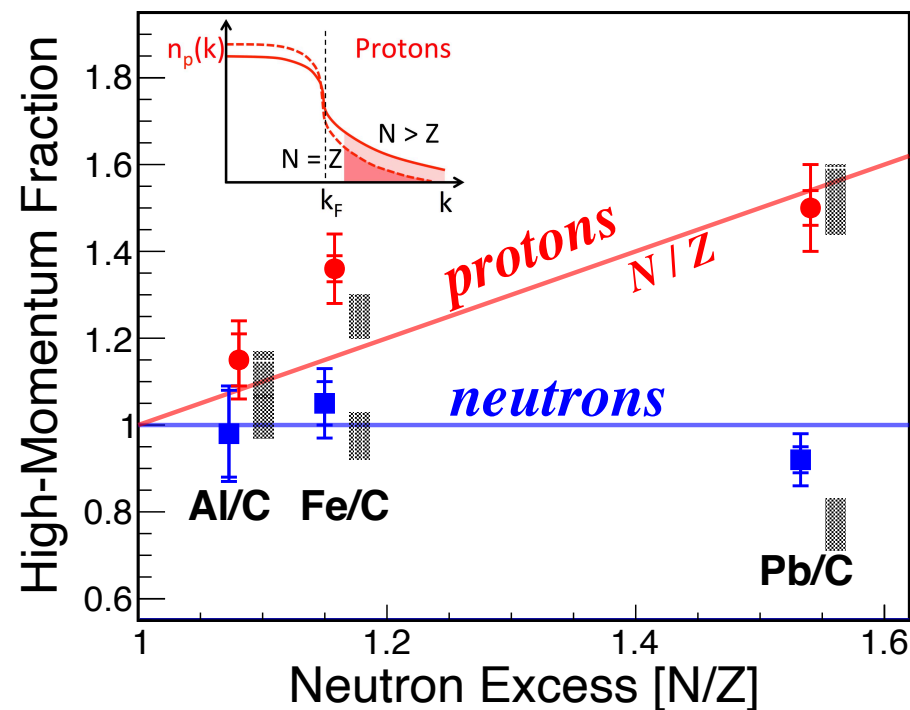
- First experiments 16C+p vs 12C+p in 2022 (ELEMENTS)

Summary

- High energy heavy ion collisions
  - SMASH employed for initial state evolution until full overlap
  - Deformation affects eccentricities in central collisions
  - Neutron skin affects magnetic field in peripheral collisions
  - NN correlations and color fluctuations play only minor role
- Low energy heavy-ion collisions
  - Collective flow is sensitive to nuclear mean field
  - Clustering in light nuclei is crucial
  - Deformation affects flow as well as changes in the density
- Source code is public and possibility to read in external initial state configurations is available
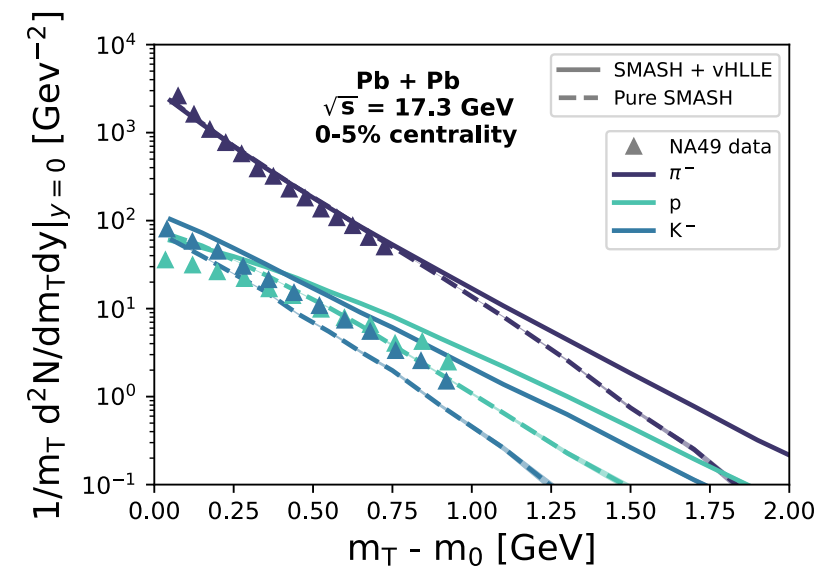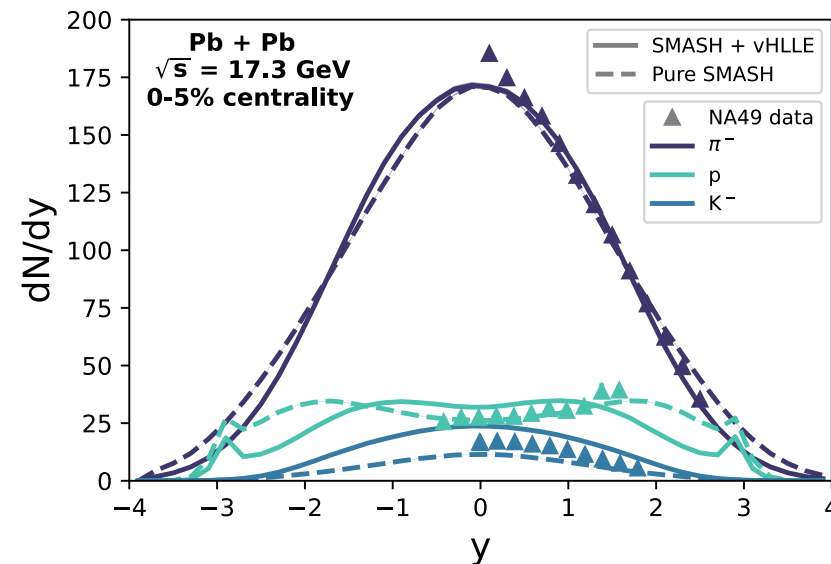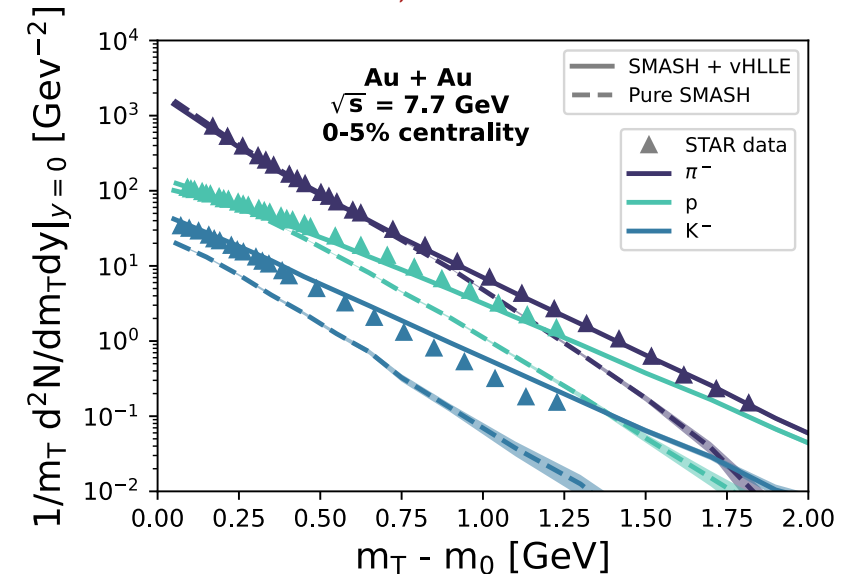- Future: Short-range correlations with multi-GeV rare isotope collisions at FAIR
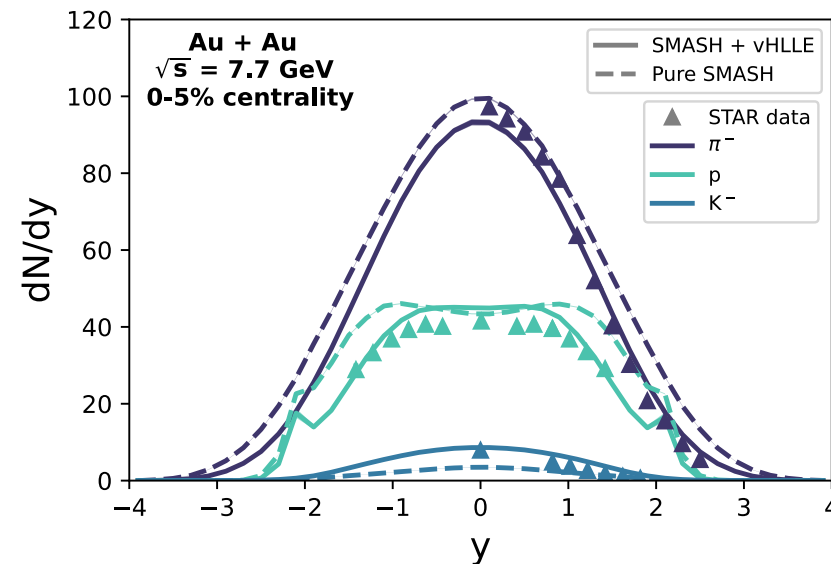
SMASH Hybrid

- ## Full event-by-event SMASH+vHLLE+SMASH hybrid

A. Schäfer et al, arXiv:2112.08724
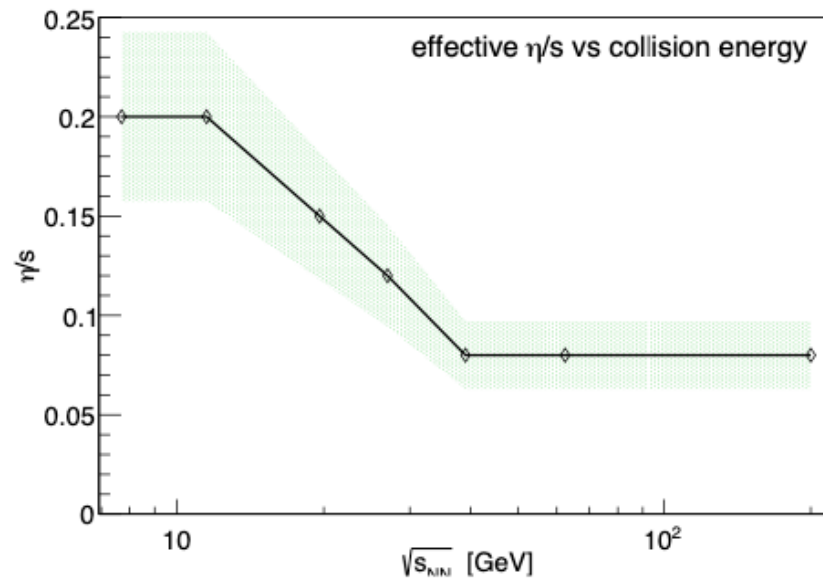
Y. Karpenko et al, Phys.Rev.C 91 (2015)

- ## See talk by A. Schäfer, Thursday, 9.30 AM (EST)

How to Use SMASH?

- Visit the webpage to find publications and link to SMASH-2.1 results
  https://smash-transport.github.io

- Download the code at
  https://github.com/smash-transport/smash

SMASH-2.1 has
HepMC and RIVET

- 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

Backup

General Setup

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

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

- 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

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

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

Degrees of Freedom

| N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^-_{1672}	π_{138}	$f_{0\,980}$	$f_{2\,1275}$	$\pi_{2\,1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^-_{2250}	π_{1300}	$f_{0\,1370}$	$f_2'_{1525}$		K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\,1500}$	$f_{2\,1950}$	$\rho_{3\,1690}$	$K_{1\,1270}$
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\,1710}$	$f_{2\,2010}$		$K_{1\,1400}$
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\,2300}$	$\phi_{3\,1850}$	K^*_{1410}
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\,980}$	$f_{2\,2340}$		$K_0^*_{1430}$
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\,1450}$		$a_{4\,2040}$	$K_2^*_{1430}$
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\,1285}$		K^*_{1680}
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}			η_{1475}	ϕ_{1019}	$f_{1\,1420}$	$f_{4\,2050}$	$K_{2\,1770}$
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_3^*_{1780}$
N_{1875}		Λ_{1890}				σ_{800}		$a_{2\,1320}$		$K_{2\,1820}$
N_{1900}		Λ_{2100}					$h_{1\,1170}$			$K_4^*_{2045}$
N_{1990}		Λ_{2110}				ρ_{776}		$\pi_{1\,1400}$		
N_{2060}		Λ_{2350}				ρ_{1450}	$b_{1\,1235}$	$\pi_{1\,1600}$		
N_{2080}						ρ_{1700}				
N_{2100}							$a_{1\,1260}$	$\eta_{2\,1645}$		
N_{2120}						ω_{783}				
N_{2190}						ω_{1420}		$\omega_{3\,1670}$		
N_{2220}						ω_{1650}				
N_{2250}					As of SMASH-1.7					

- ▸ + 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
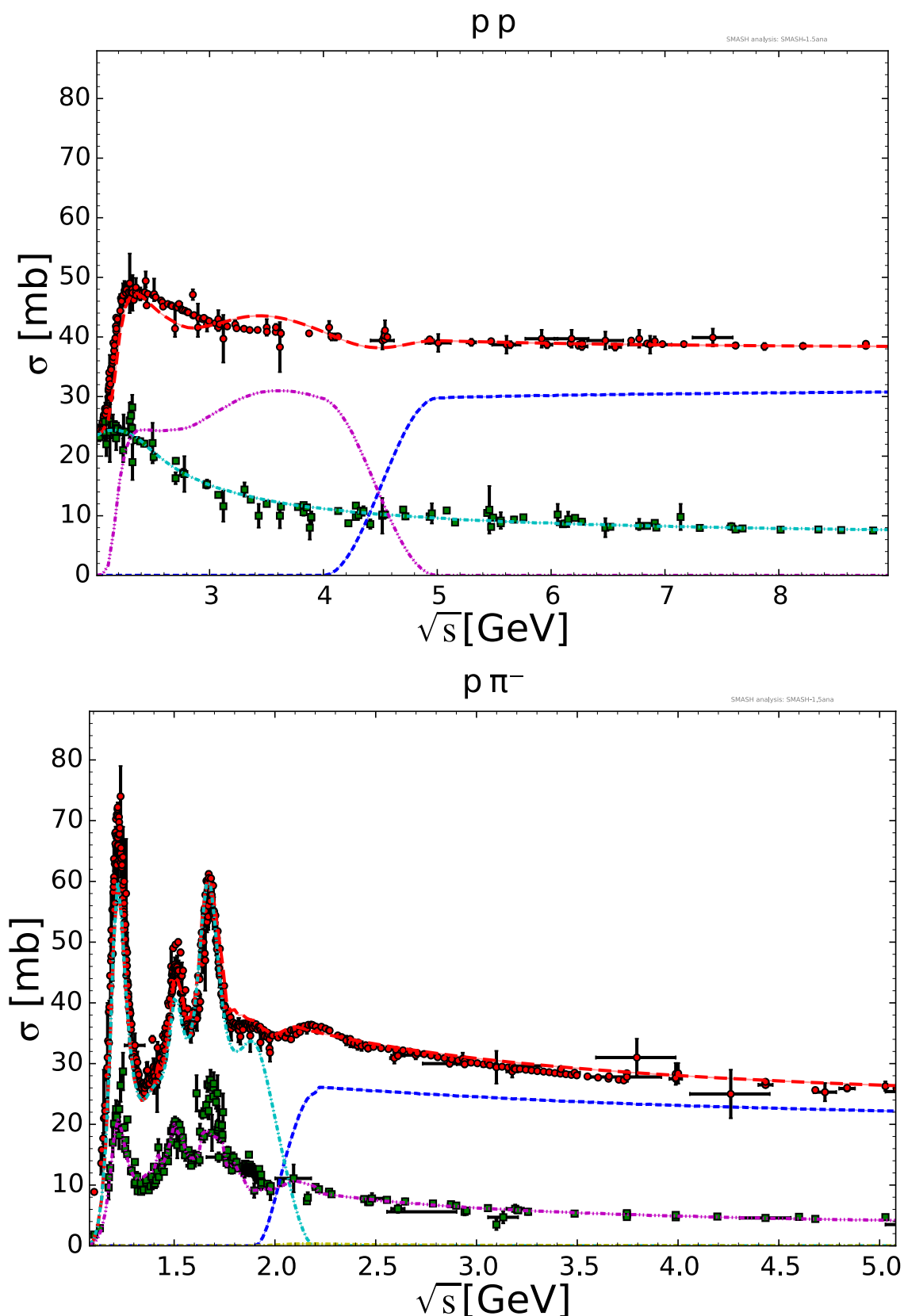
- Total cross section for pp/pπ collisions

- 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-1.5