Flow and EoS at SIS energies: data - SMASH model comparison

Lucia Anna Tarasovičová*, Anton Andronic, Justin Mohns,
Hannah Elfter, Karl-Heinz Kampert
*P.J. Šafárik University, Košice

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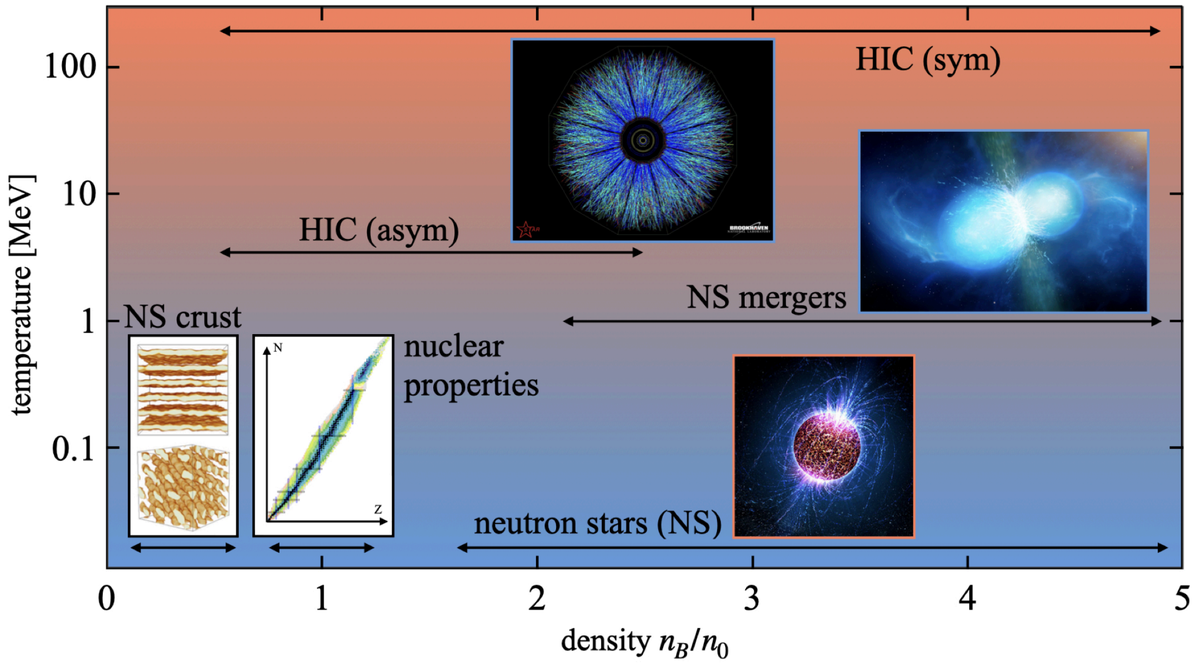
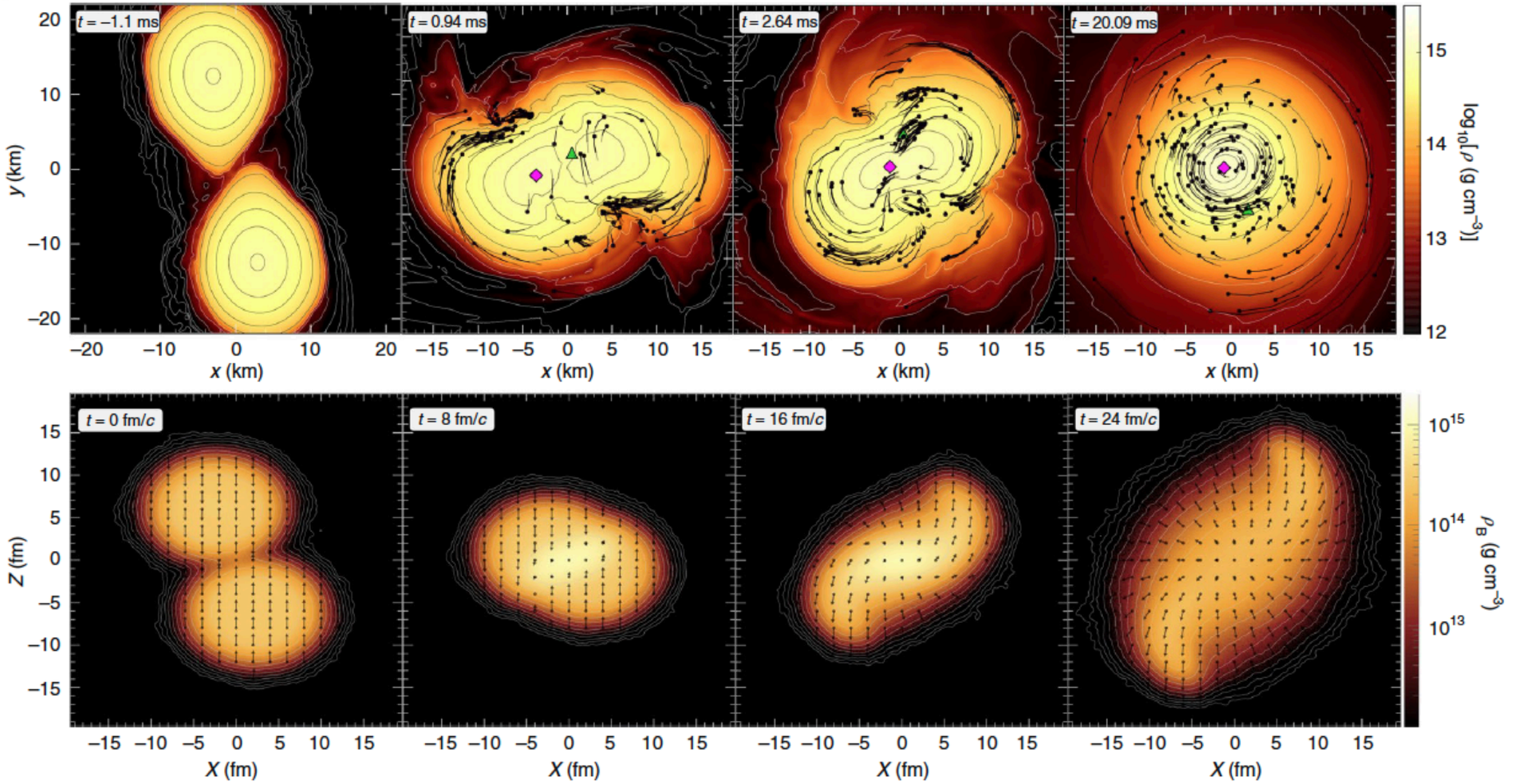
Equation of State

NRW-FAIR Netzwerk

- Fundamental property of nuclear matter
- Controls and determines:
  - Structure of nuclei
  - Neutron-skin thickness in neutron-rich nuclei
  - Properties of nuclear matter at extreme densities and/or temperatures
  - Appearance of new degrees of freedom
- Essential to understand baryonic matter
  - Can be constrained from different observables at different densities and/or temperatures



Analogy small/large scale system

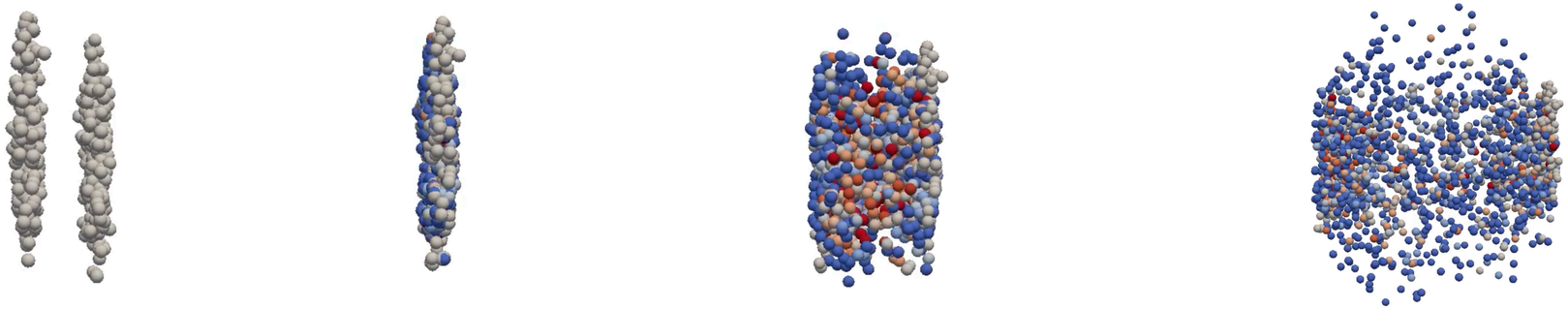


HADES, Nature Phys. 15 (2019) 1040

SMASH

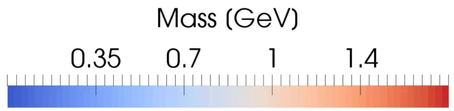
NRW-FAIR Netzwerk

- SMASH = Simulating Many Accelerated Strongly-interacting Hadrons
- Microscopic hadronic transport model
  - Full phase-space information of all particles at all times
  - All well-established hadrons up to a mass of ~ 2 GeV as degrees of freedom



Pb-Pb

$\sqrt{s_{NN}} = 17.3$ GeV



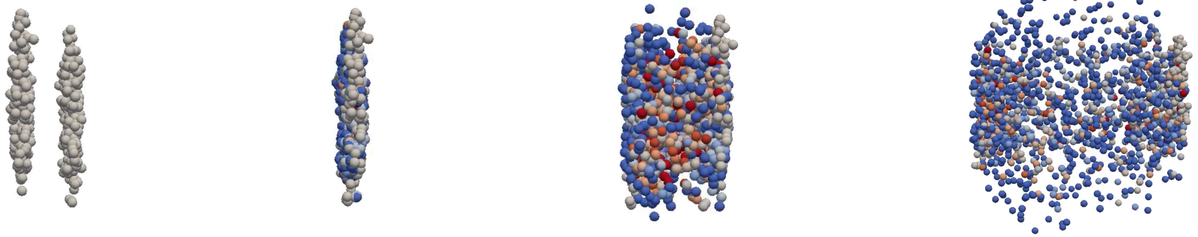
smash

SMASH

- Based on an effective solution of the relativistic Boltzmann equation with binary interactions
- Particles - point-like objects
- Particle interactions
  - Geometric collision criterion
  - Stochastic collision criterion (SS,HS)

$$d_T < d_{int} = \sqrt{\frac{\sigma}{\pi}}$$

$$P_{n\to m} = \frac{\Delta N_{reactions}}{\Pi_{j=1}^{n} \Delta N_j}$$



smash

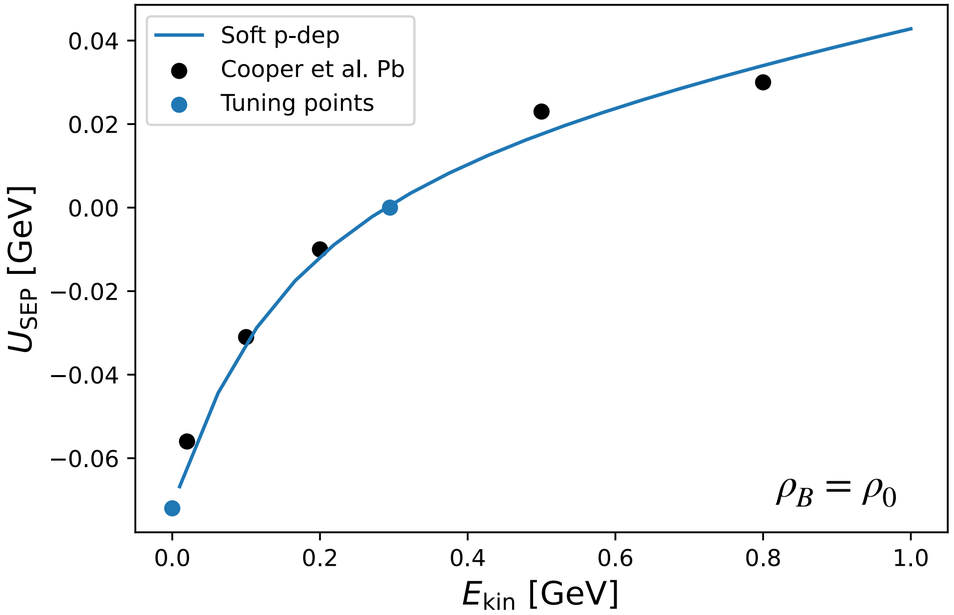
- EoS controlled via potentials (Skyrme)
  - Density dep. potential (M,H)
  - Density + Momentum dep. potential (SP,MP,HP)

$$U_{SK} = A\left(\frac{\rho_B}{\rho_0}\right) + B\left(\frac{\rho_B}{\rho_0}\right)^{\tau}$$

$$U_{\mathrm{sym}} = \pm 2 S_{\mathrm{pot}} \frac{\rho_{I3}}{\rho_0}$$

New in SMASH!

$$U_p = \frac{2C}{\rho_0} g \int \frac{d^3p'}{(2\pi)^3} \frac{f(\mathbf{r},\mathbf{p}')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2}$$



smash

Phase-space coordinates

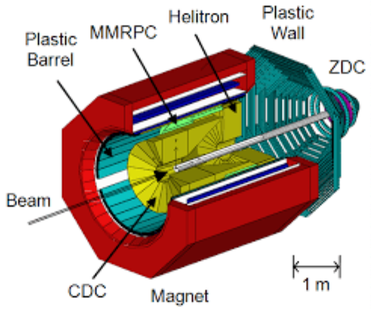
NRW-FAIR Netzwerk

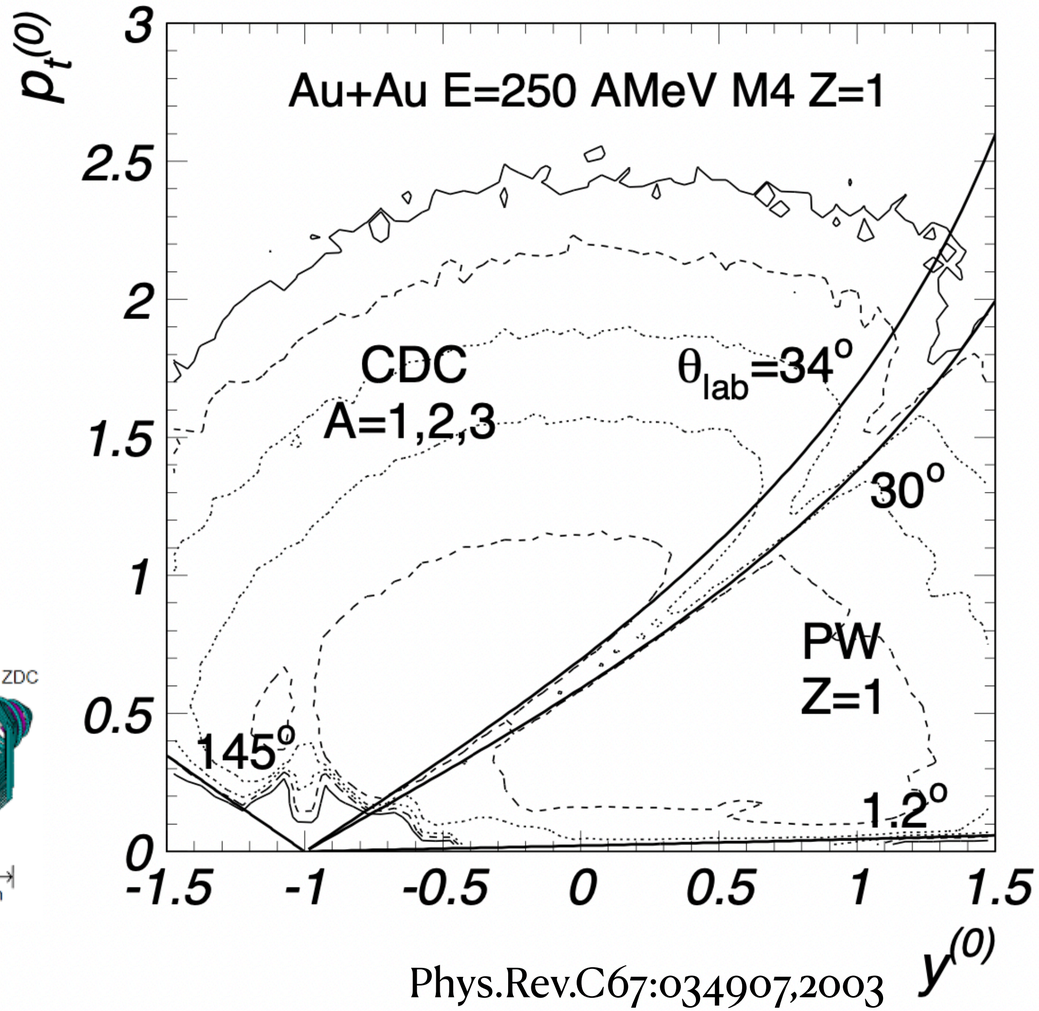
- Normalised center-of-mass (c.m.)
  - Rapidity

$$y^{(0)} = (y/y_P)^{\text{c.m.}}$$

  - Transverse momentum (per nucleon)

$$p_{\text{T}}^{(0)} = (p_{\text{T}}/A)/(p_P^{\text{c.m.}}/A_P)$$





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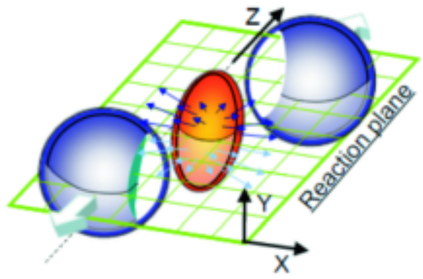
Observables

- Initial conditions create pressure gradients in the expanding medium
- Anisotropy in distribution of final-state particles:

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n cos\ n(\varphi - \psi_{rp})$$

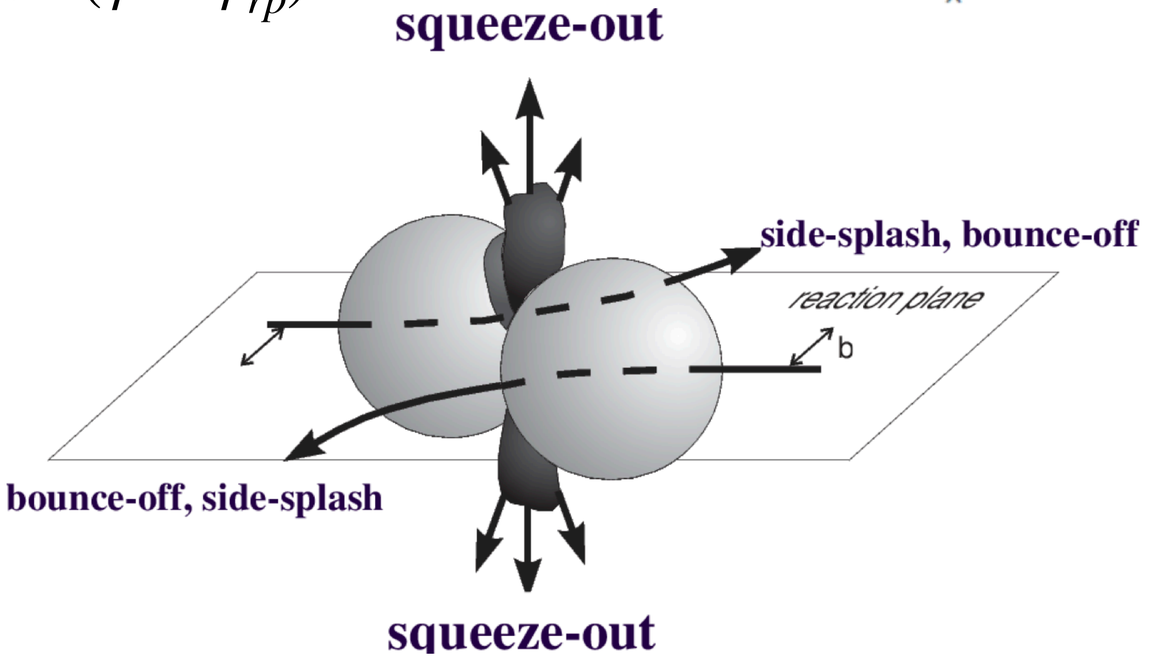


- Directed flow:

$$v_1 = < \cos(\varphi - \psi_{rp}) >$$

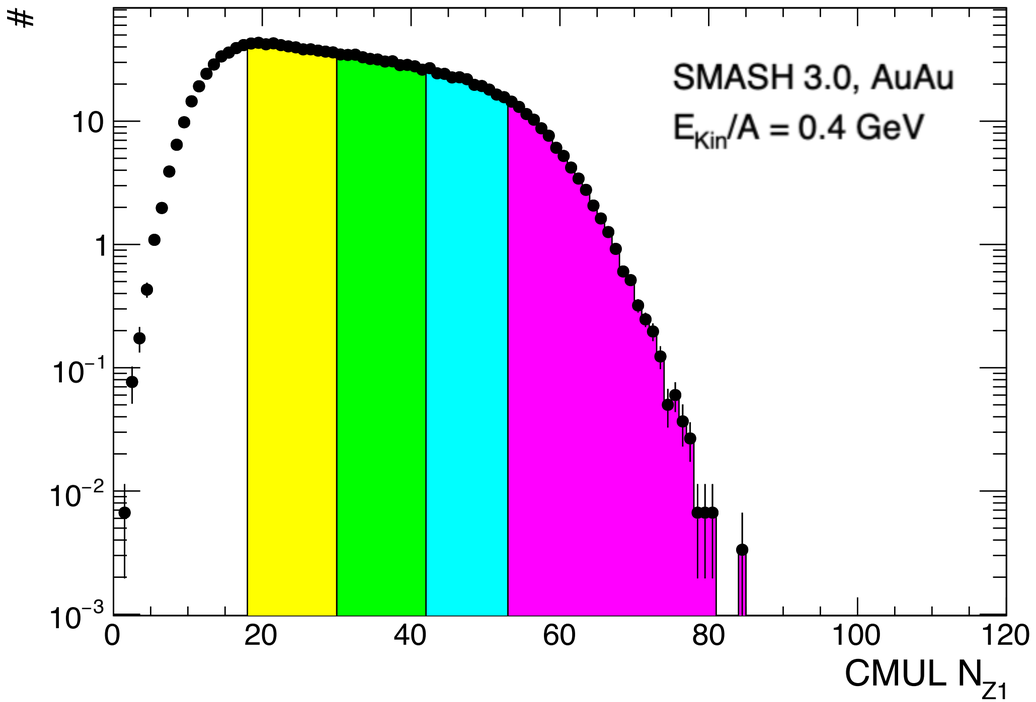
- Elliptic flow:

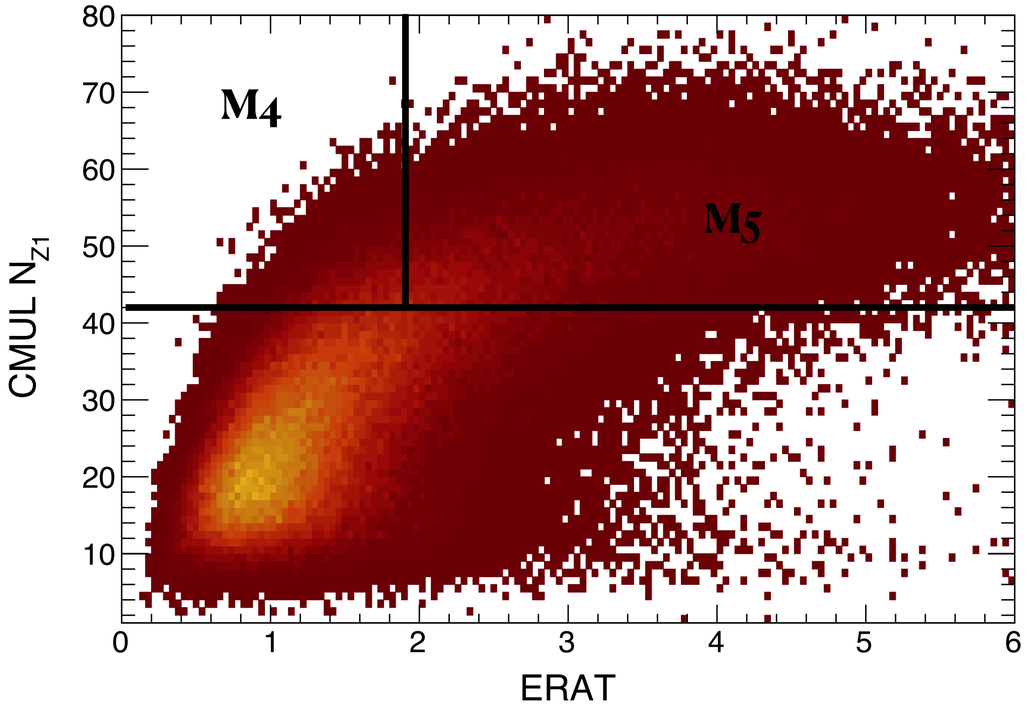
$$v_2 = < \cos(2(\varphi - \psi_{rp})) >$$



Centrality selection

- Impact parameter
- Check with the experimental centrality selection



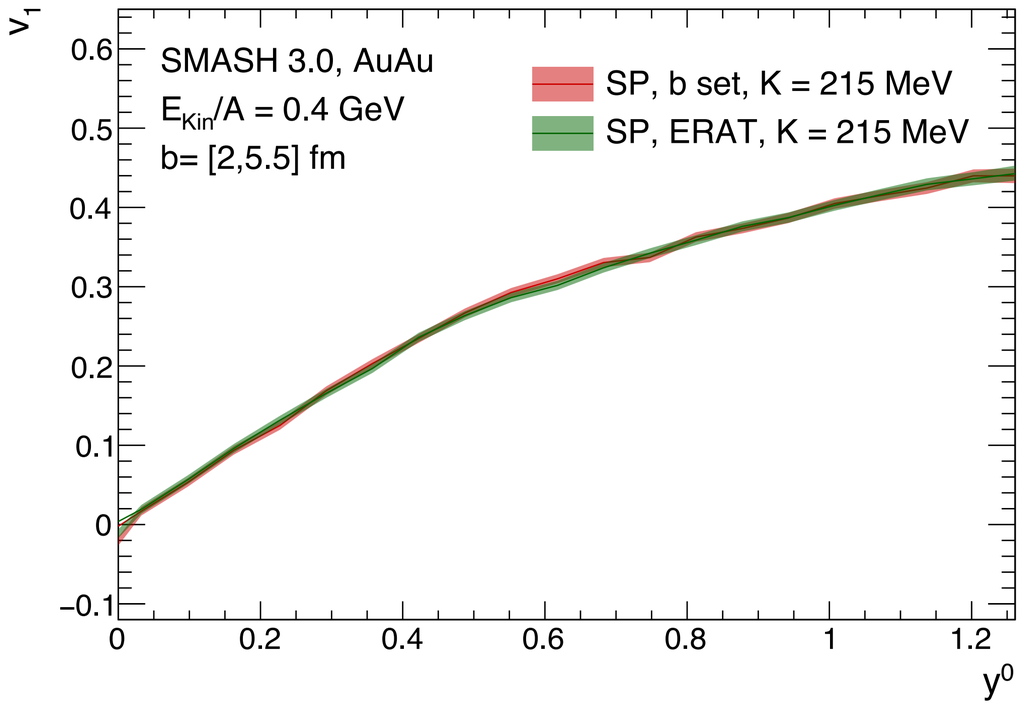


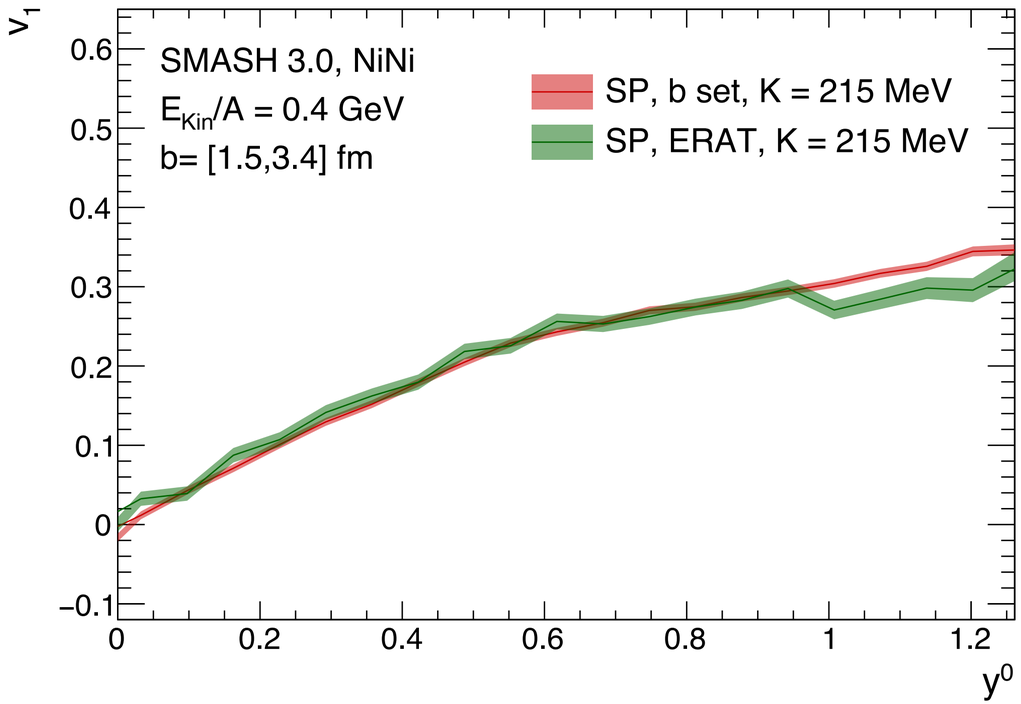
CMUL NZ1 - number of Z1 particles in CDC acceptance, $34^\circ < \theta_{lab} < 145^\circ$

$$Erat = \frac{\sum_i E_{\perp,i}}{\sum_i E_{||,i}}$$

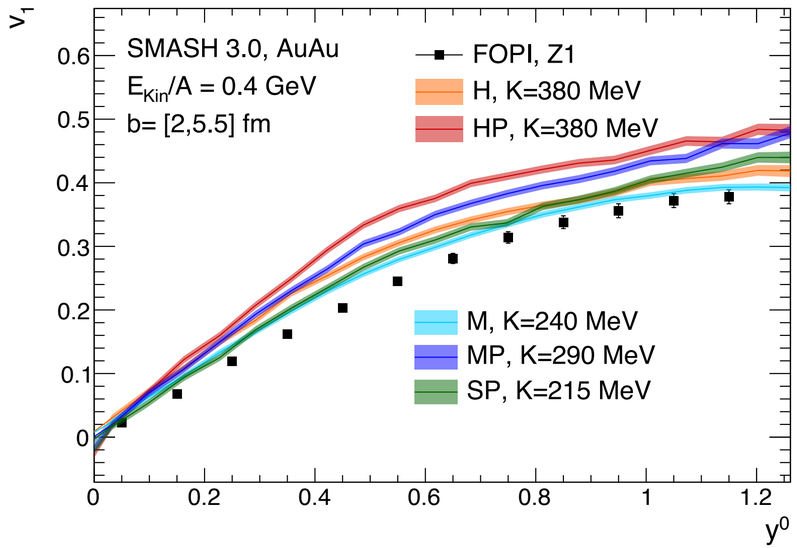
Centrality selection

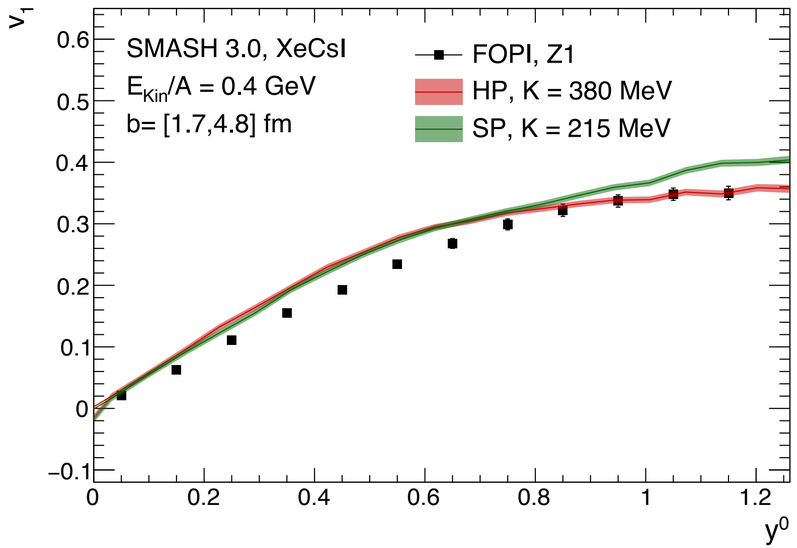
- Impact parameter
- Check with the experimental centrality selection
- Both selections give **identical results** -> impact parameter used

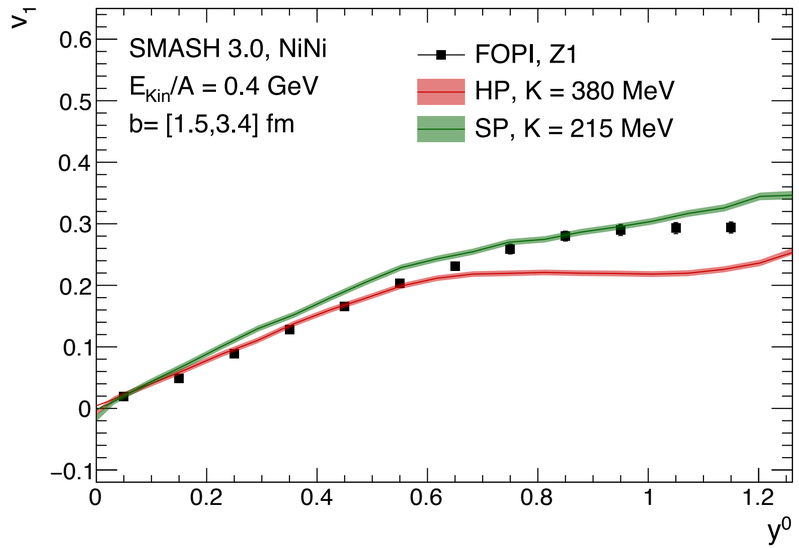




Differential directed flow

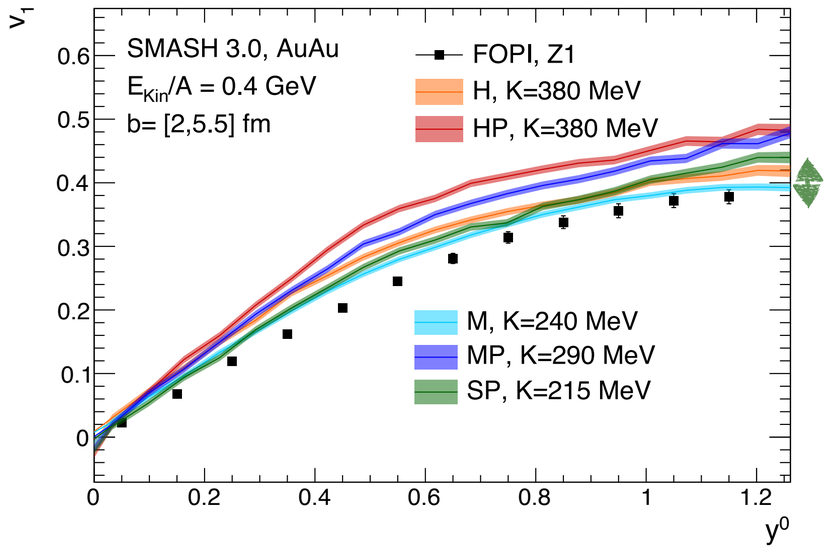


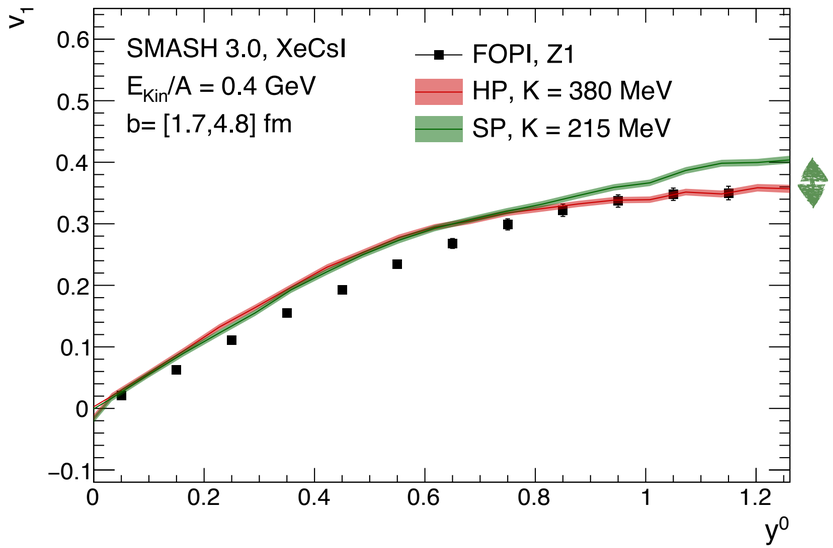


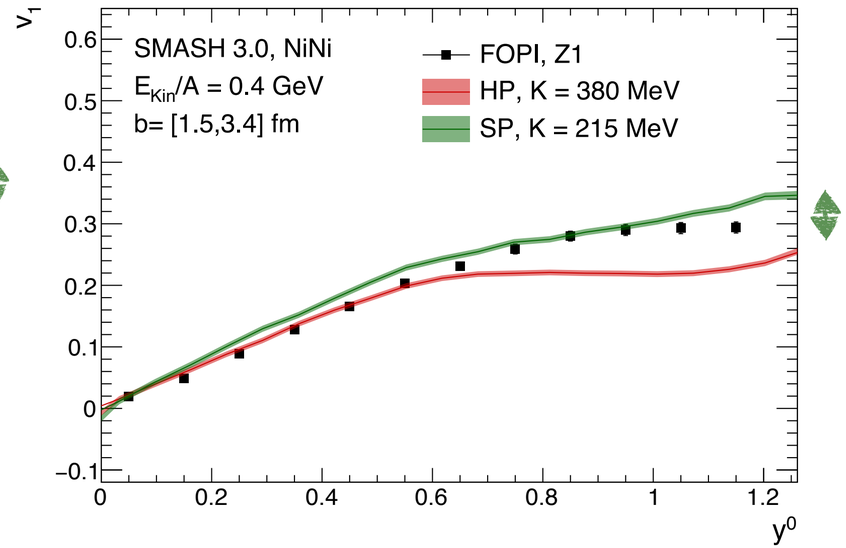


System size

Differential directed flow



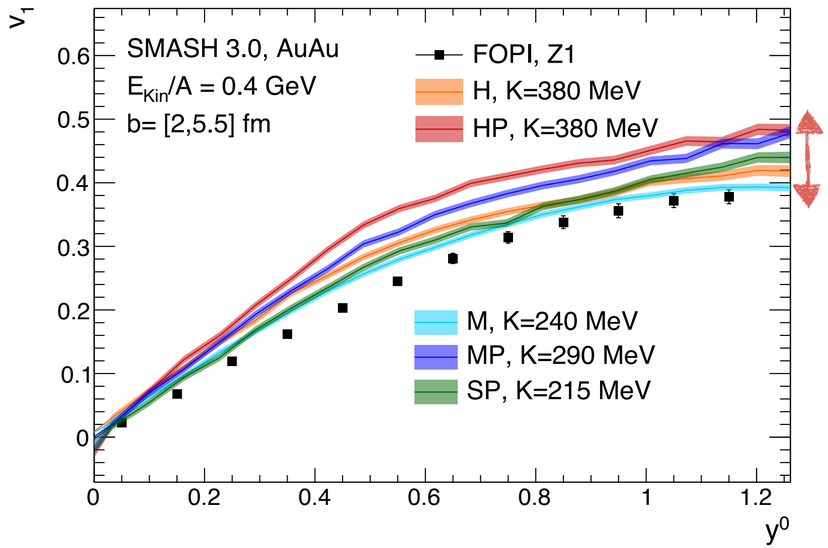


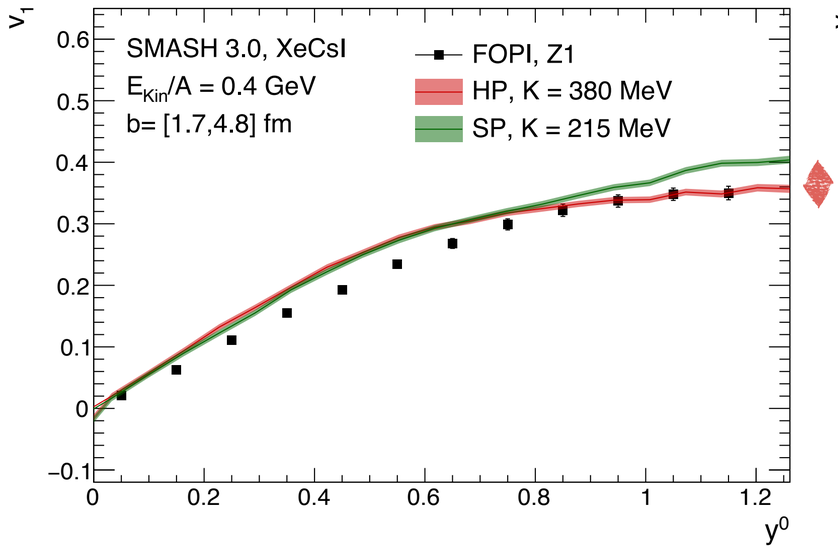


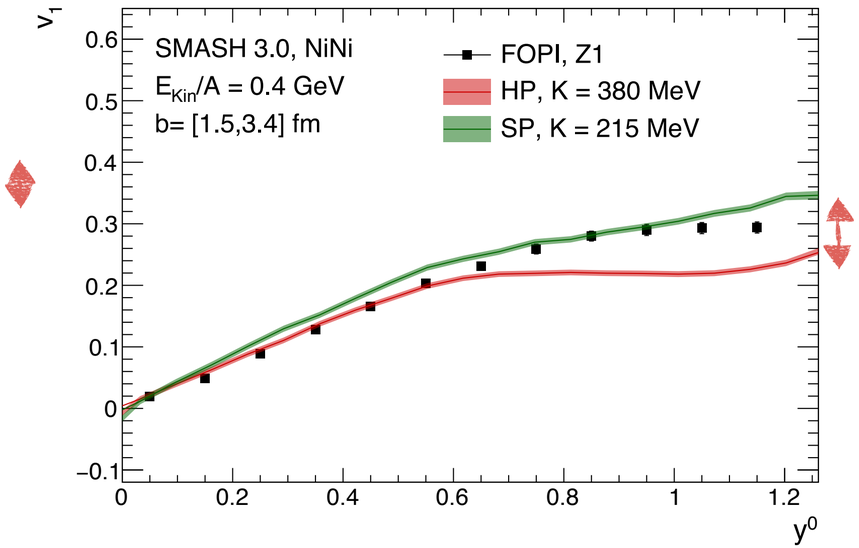
System size

- Soft EoS with momentum dependent potentials
  - Good description in all systems

Differential directed flow







System size

- Soft EoS with momentum dependent potentials
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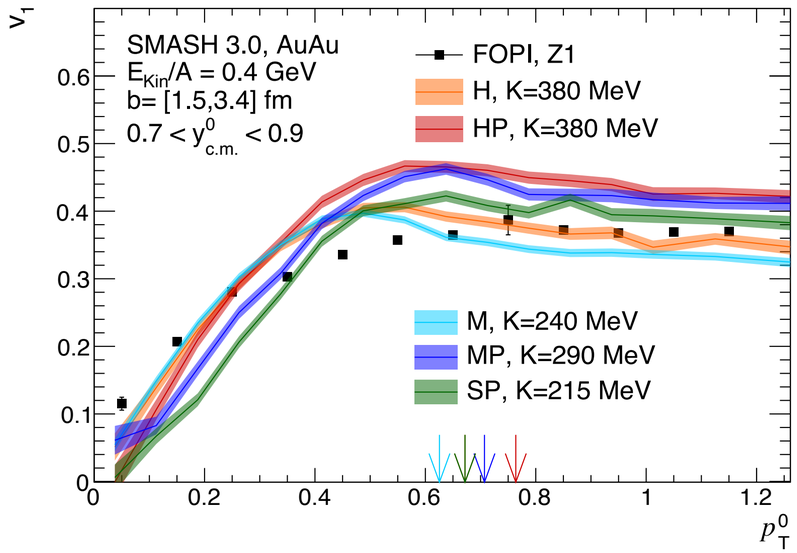
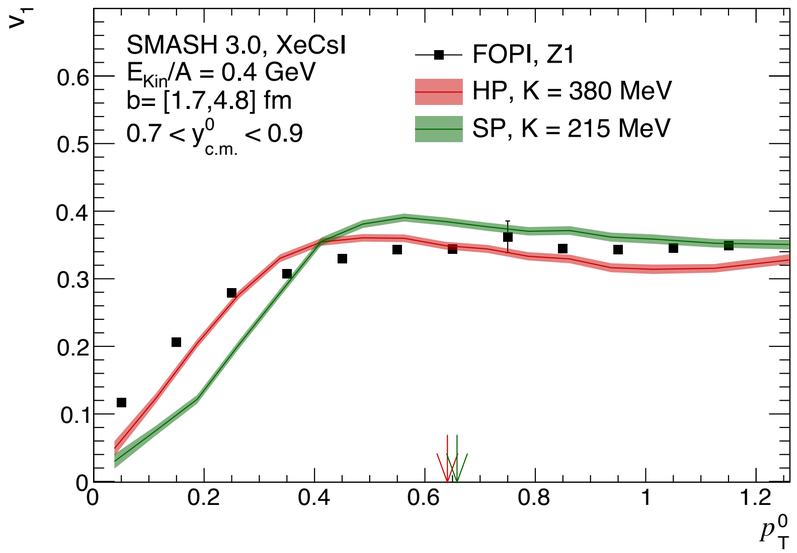
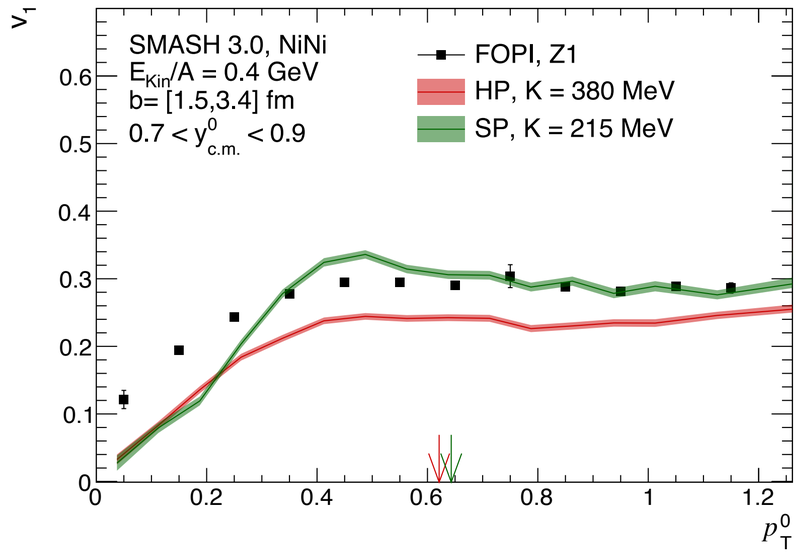
- Hard EoS with momentum dependent potentials
  - HP-SP Inversion from Au-Au to Ni-Ni

Differential directed flow



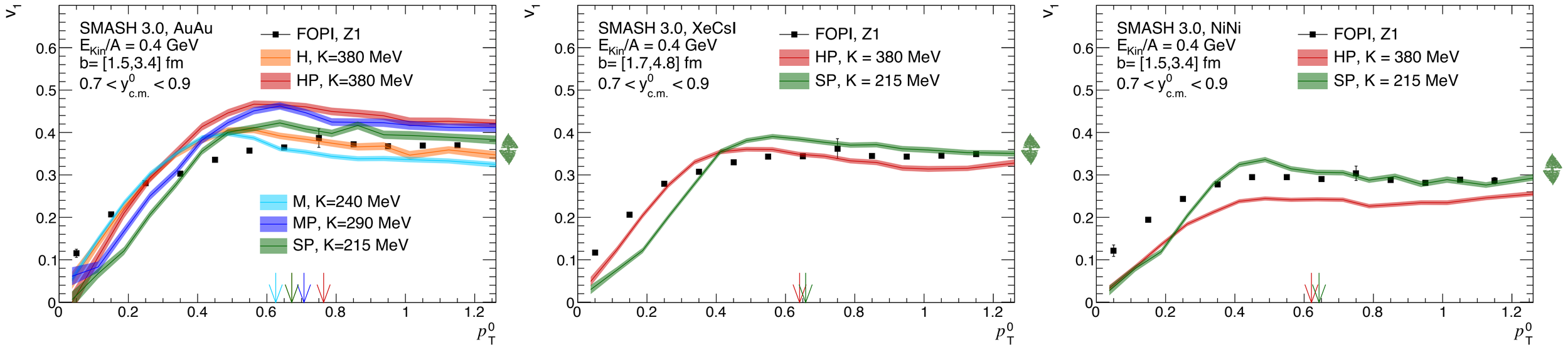




System size

- **Similar** to the momentum integrated case

Differential directed flow



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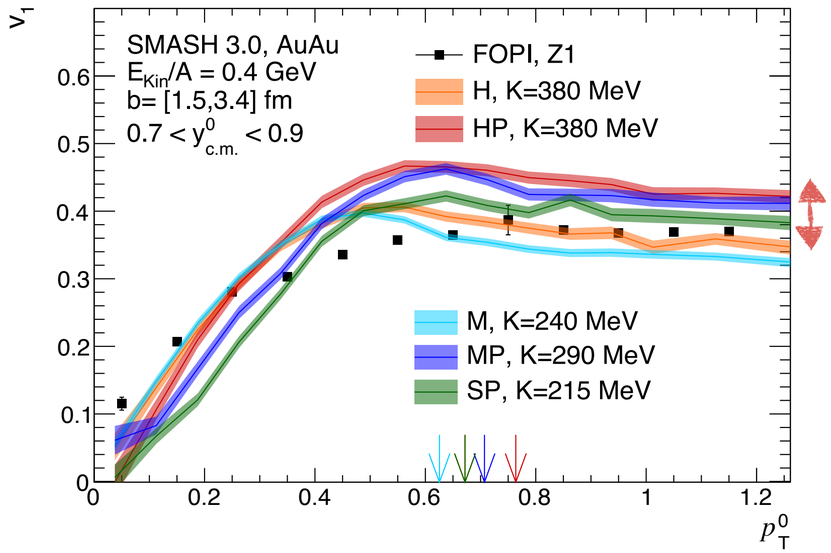

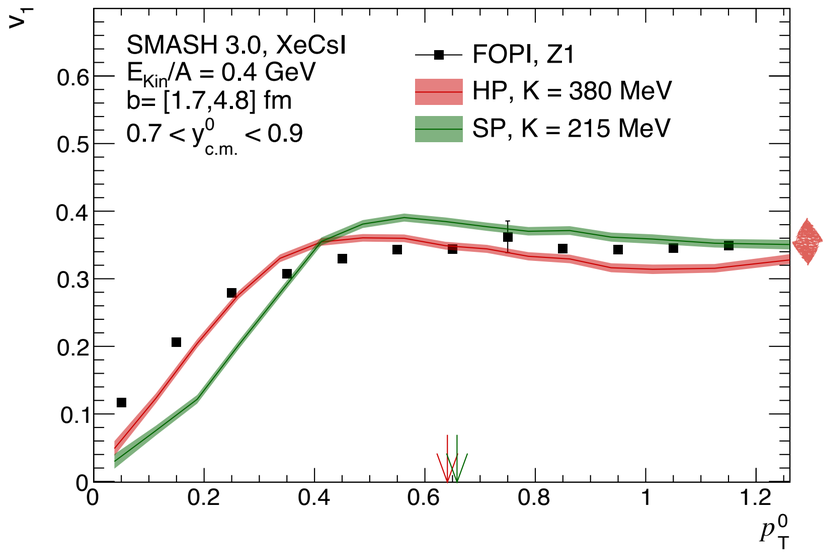

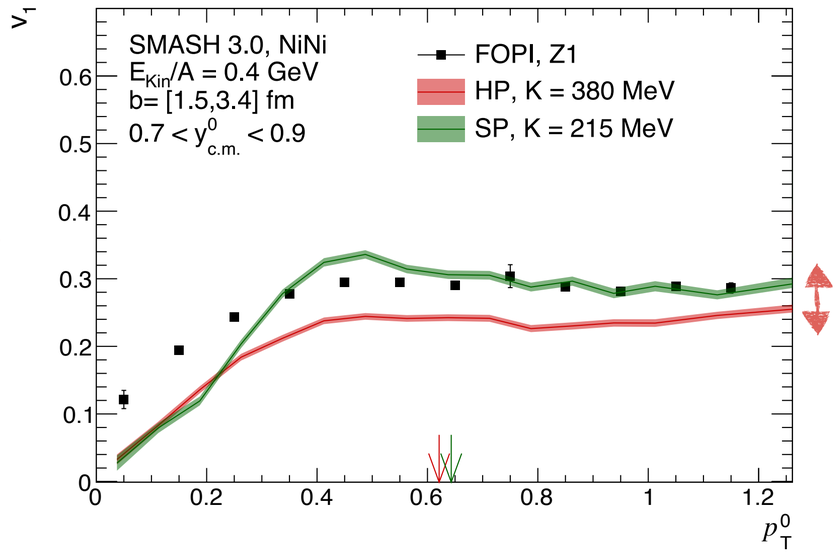

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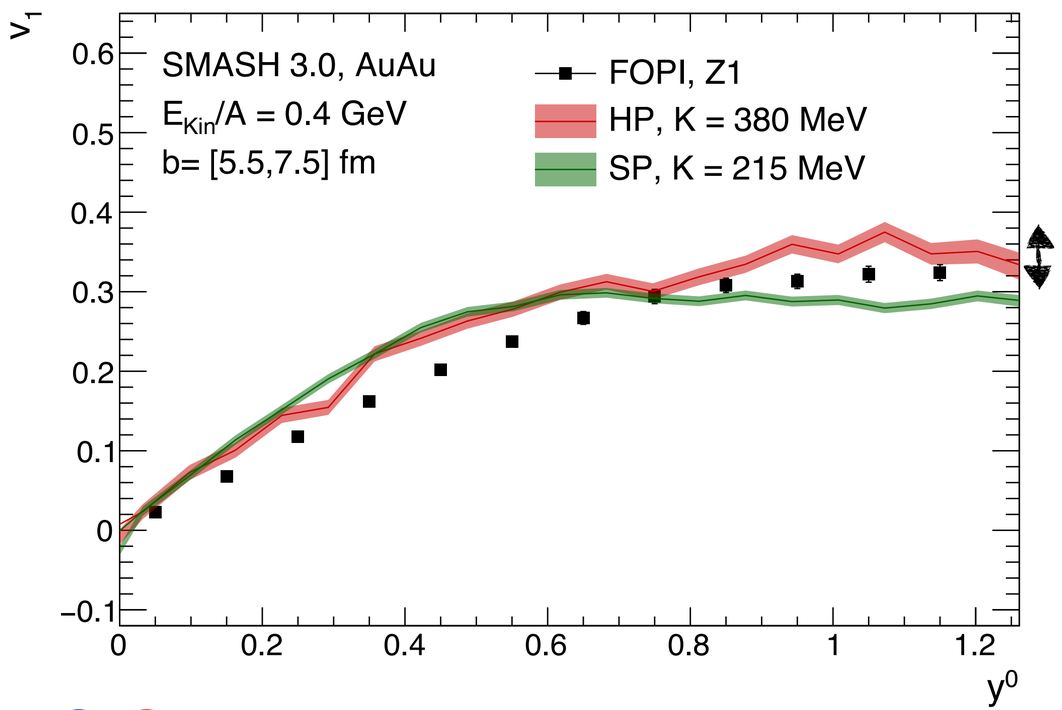
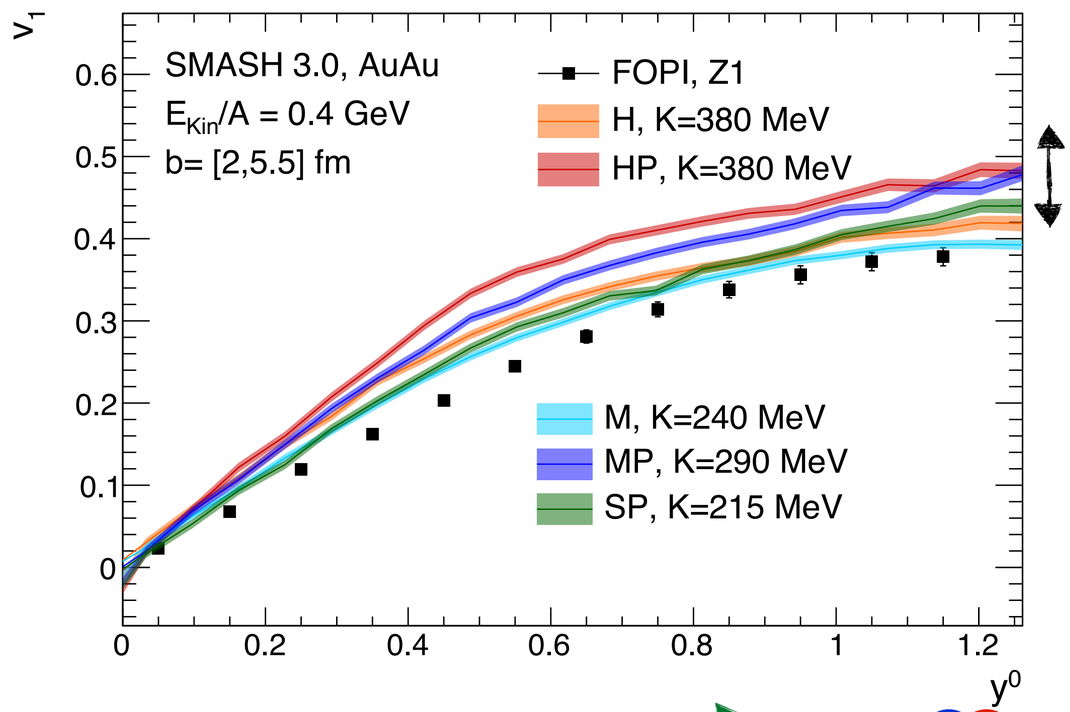
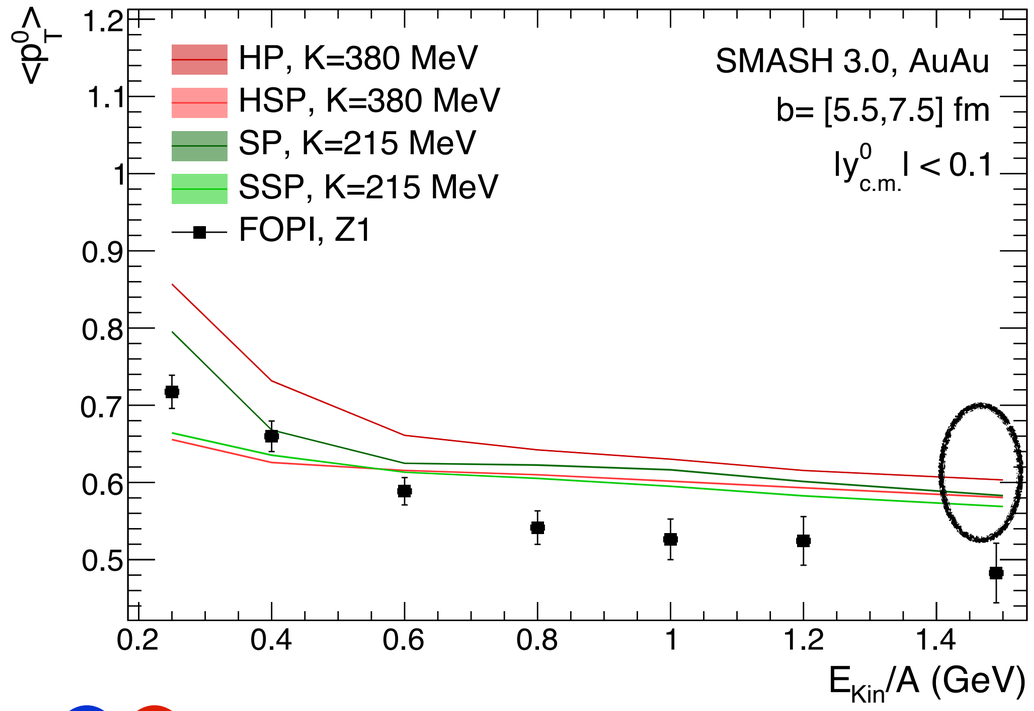
Differential directed flow

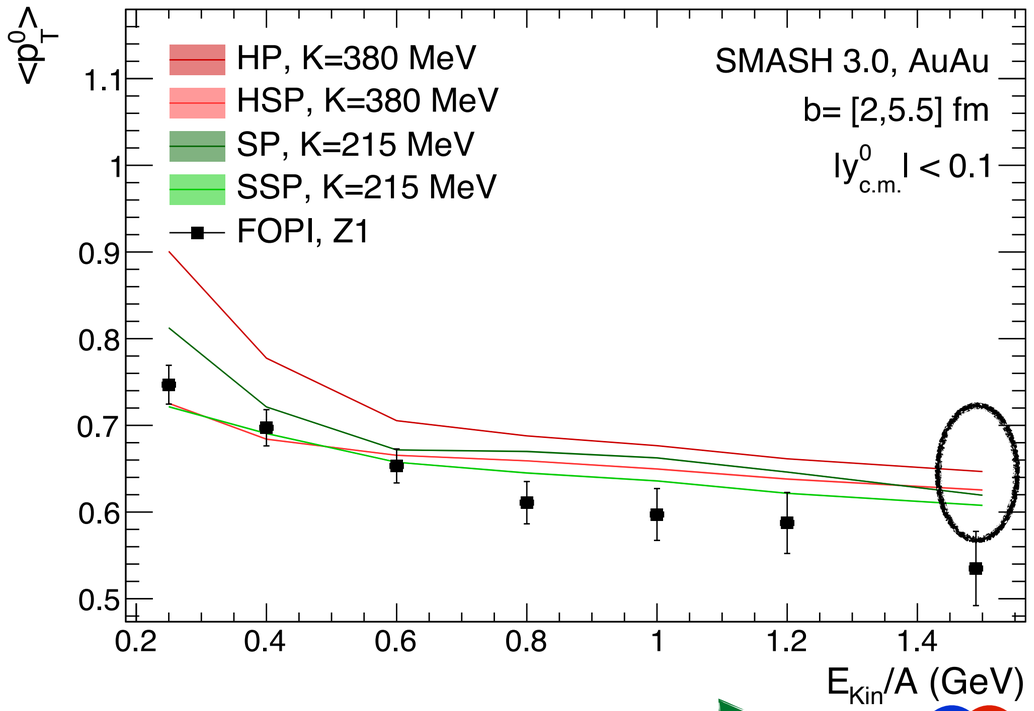




- Similar result for both EoS in peripheral collisions
- For more central collisions hard EoS moves further from data

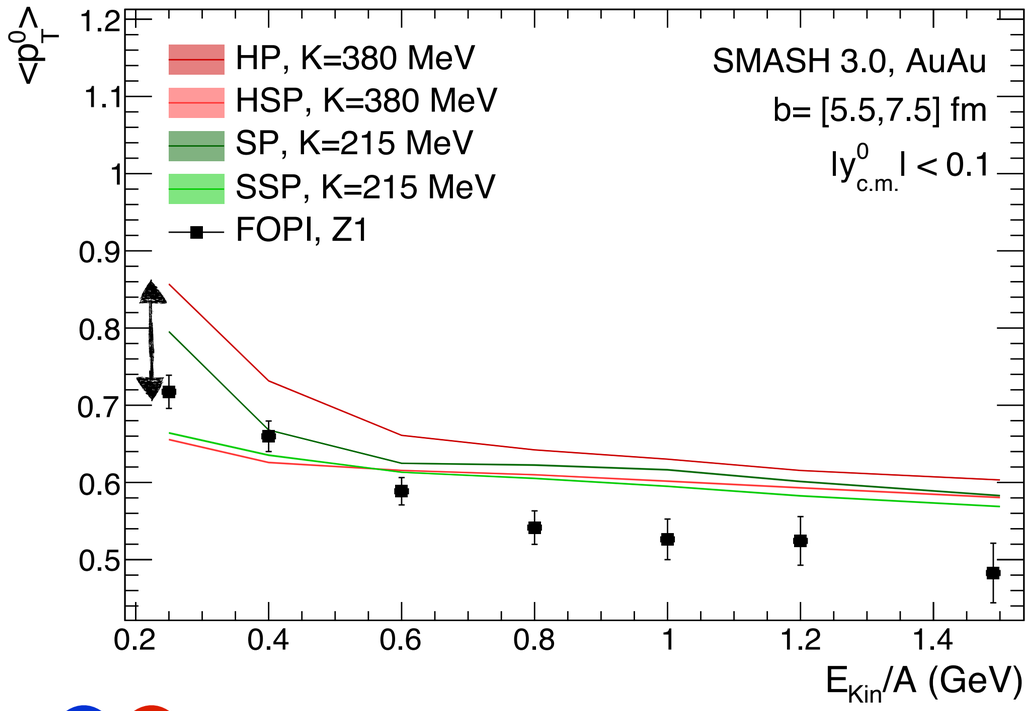
Mean transverse momentum

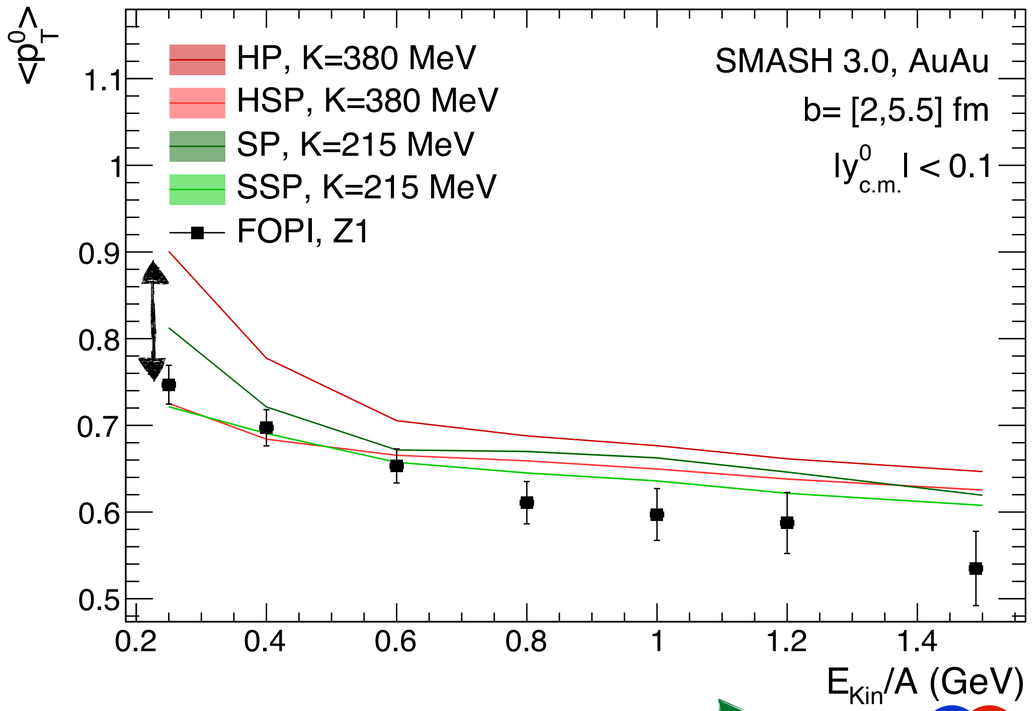




- At higher energies - different EoS converge (overestimating the data)

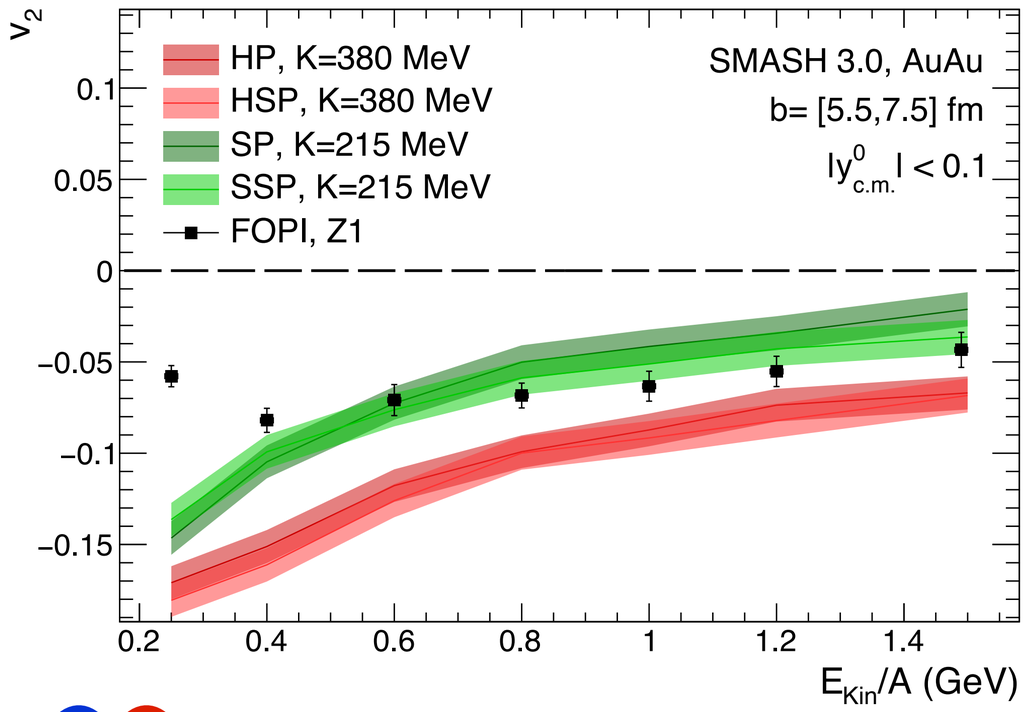
Mean transverse momentum

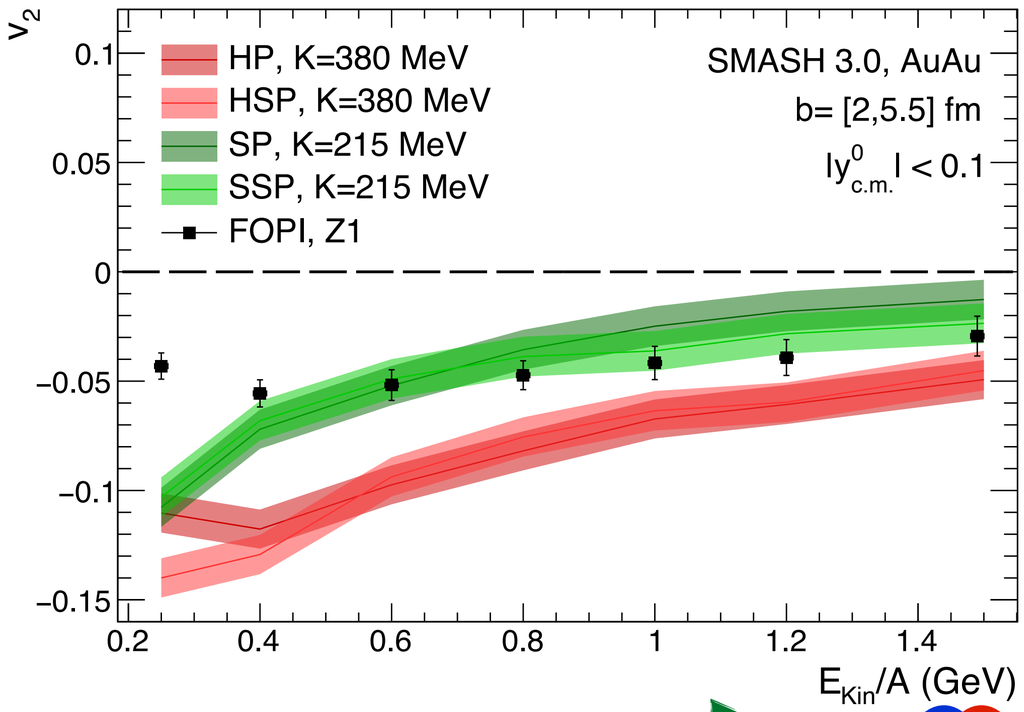




- At higher energies - different EoS converge (overestimating the data)
- Stochastic approach predicts lower mean p_T at lower collision energies

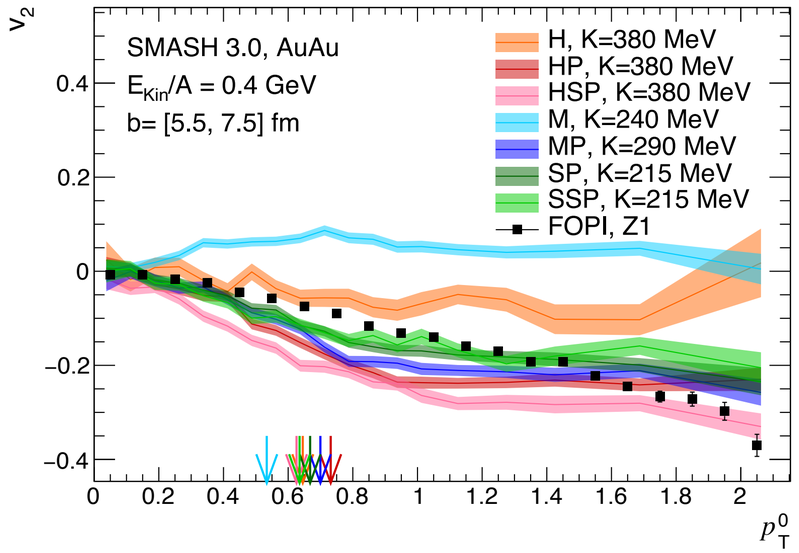
Integrated elliptic flow

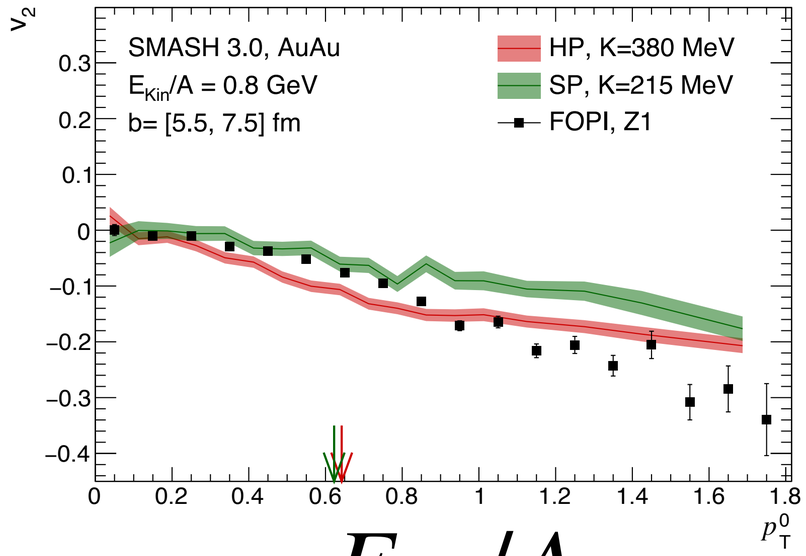


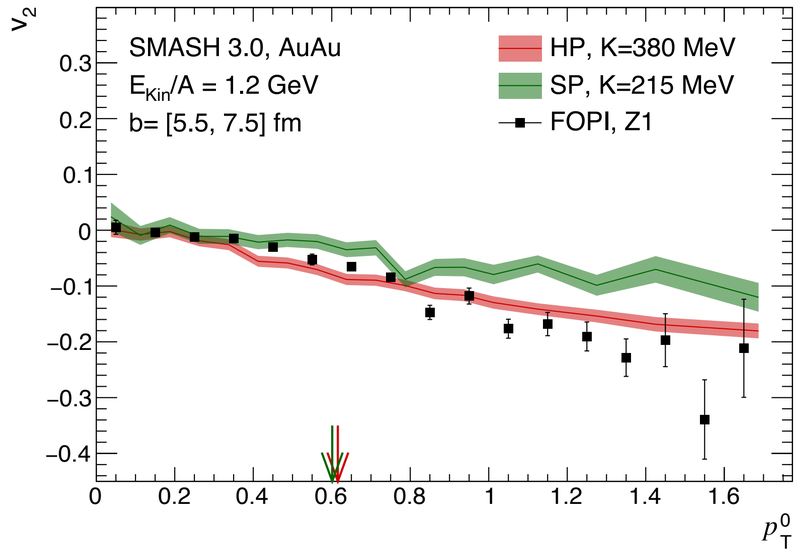


- At higher energies - shift toward hard EoS
- Stochastic approach consistent with the geometric one

Differential elliptic flow

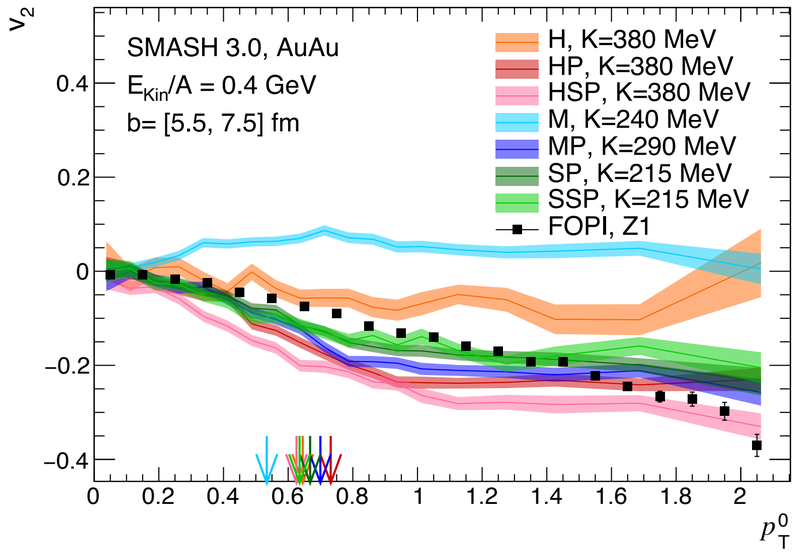


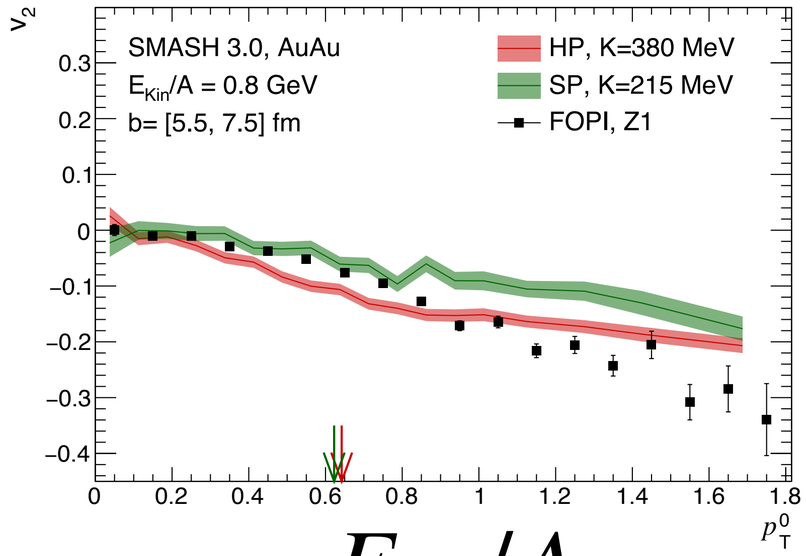


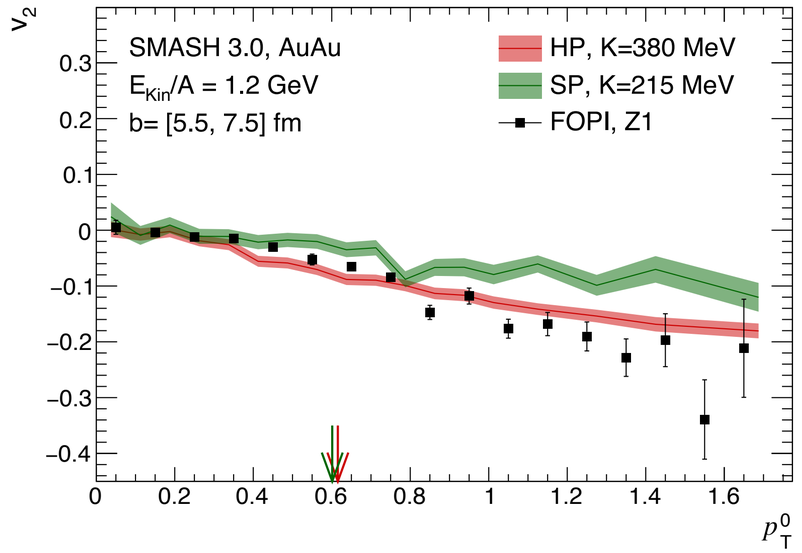


E_{kin}/A

Differential elliptic flow



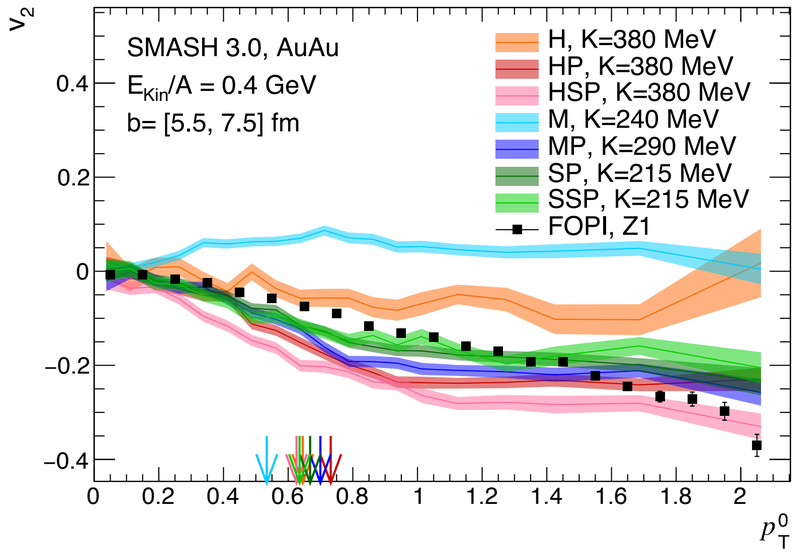


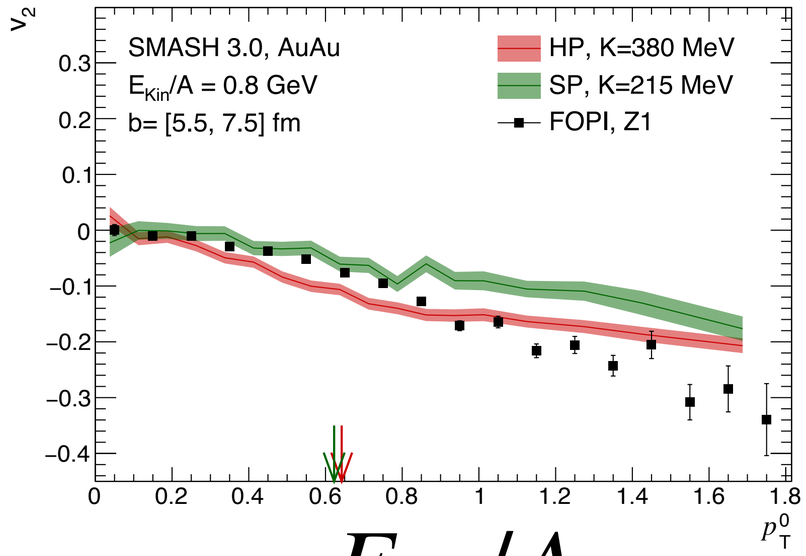


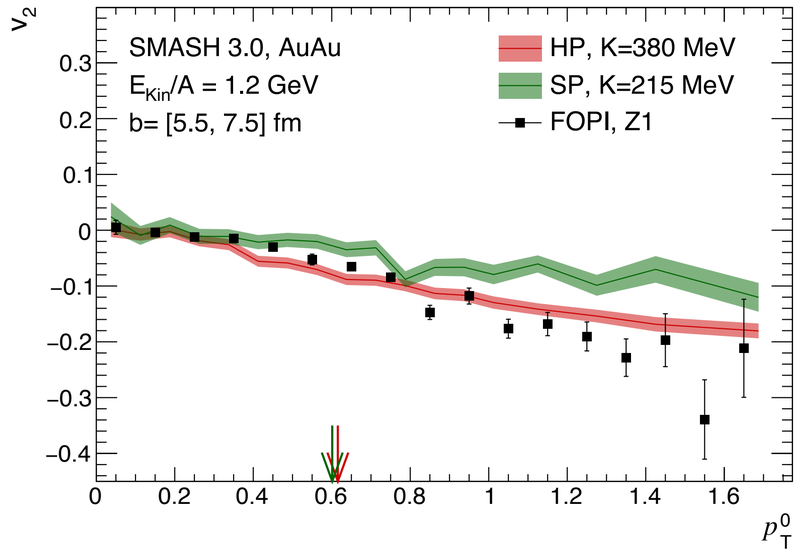
E_{kin}/A

- Soft EoS with momentum dependent potentials
  - Good description at low collision energies
  - Underestimate the data at high energies

Differential elliptic flow



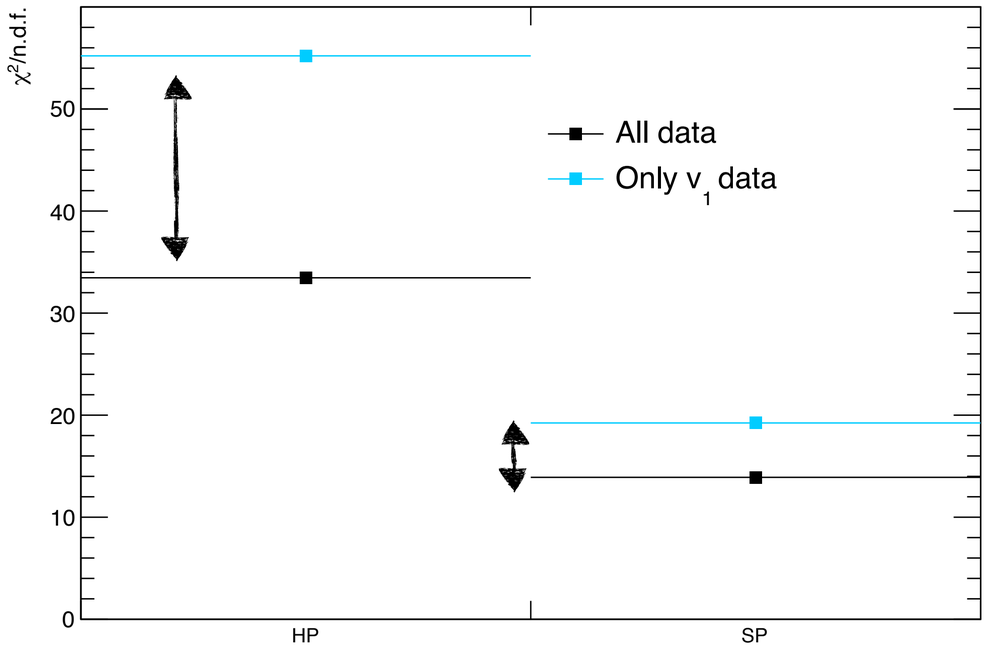


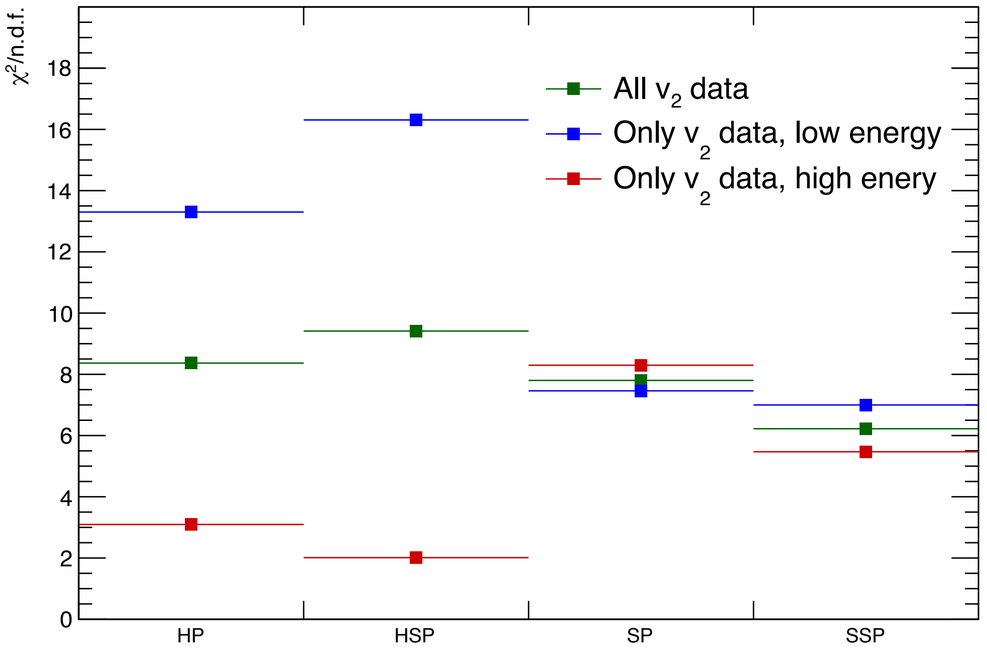


E_{kin}/A

- Soft EoS with momentum dependent potentials
  - Good description at low collision energies
  - Underestimate the data at high energies
- Hard EoS with momentum dependent potentials
  - Overestimate the data at low collision energies
  - Good description at higher energies

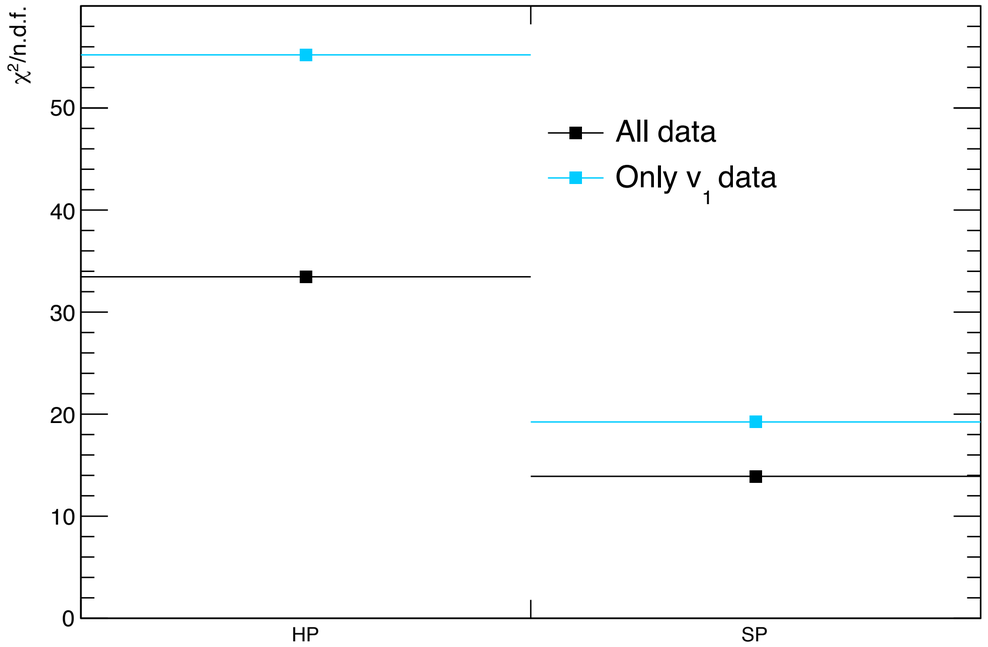
Quantitative EoS comparison

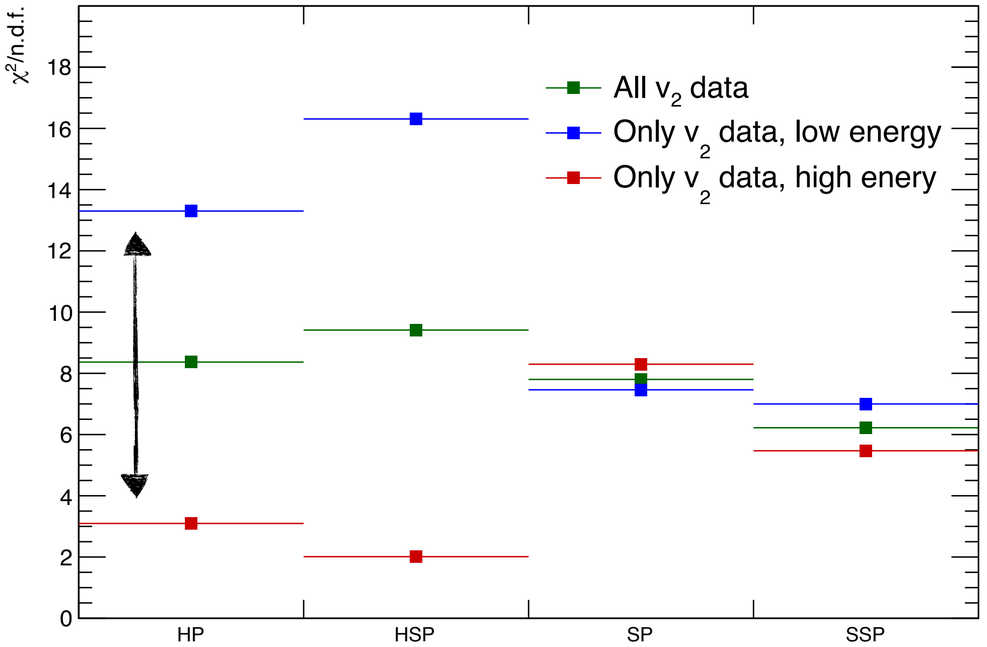




- Overall - soft EoS better
- Exclusion of v_2 data - **big impact** on χ^2 of hard EoS

Quantitative EoS comparison





- Overall - soft EoS better
- Exclusion of v_2 data - **big impact** on χ^2 of hard EoS

- Only v_2 data - Hard and Soft - **comparable**
- Energy dependence for hard Eos
- No energy dependence for soft EoS

Summary and Outlook

NRW-FAIR Netzwerk

- FOPI data compared with SMASH predictions for different EoS stiffness
  - Multi differential comparison
  - First broad test of SMASH down to 400 MeV/A
- Momentum dependent potential improve the data description
- Hard Eos - system size dependent and centrality data description
- Stochastic collision criterion - comparable results to the standard
- Model-data agreement, χ^2
  - Overall - soft EoS better
  - Concerning only high collision energies - Hard EoS

Thank you for your attention!

Questions