CONSTRAINING THE NUCLEAR EQUATION OF STATE WITH HEAVY ION COLLISIONS

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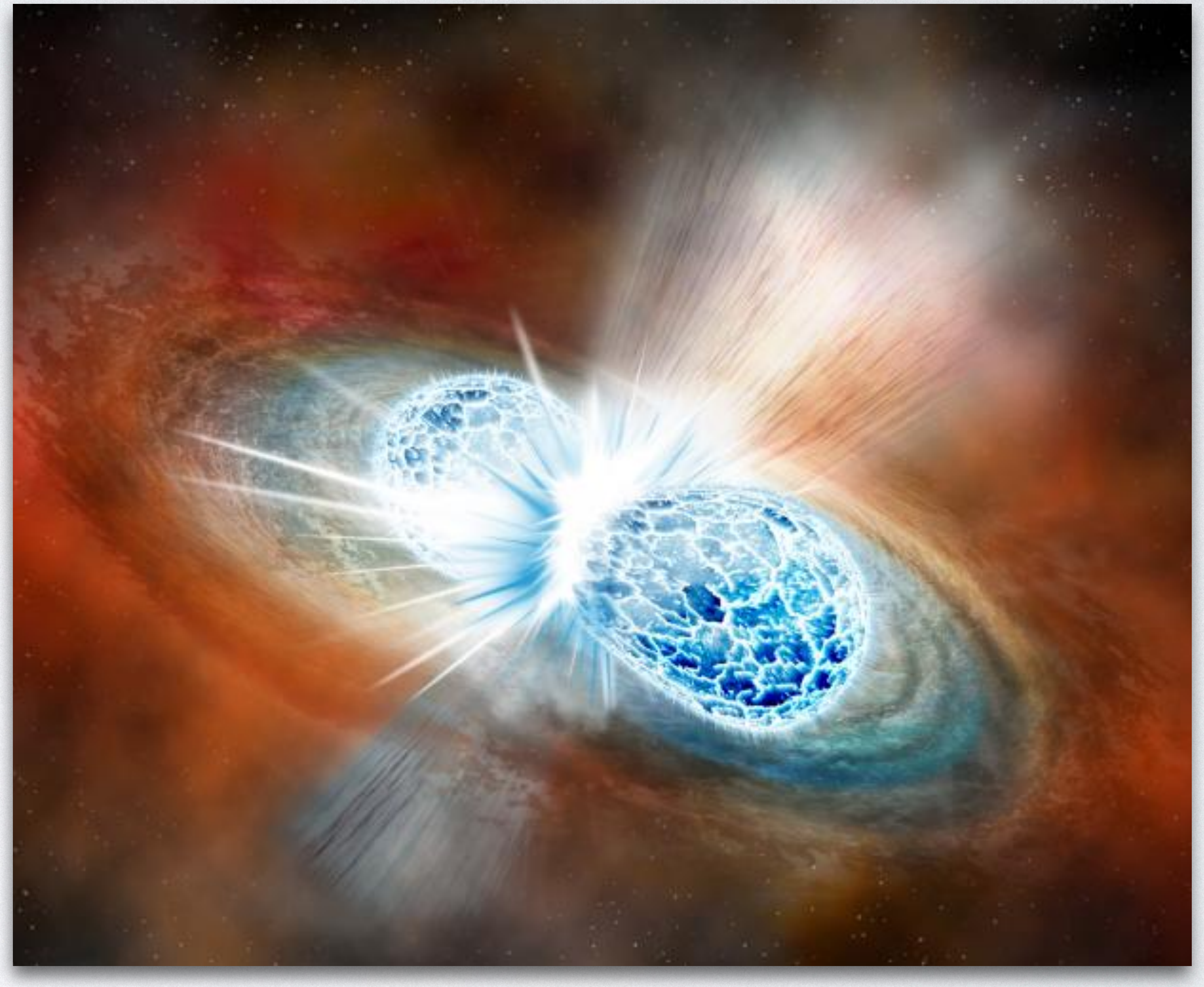
arXiv:2012.11454

MOTIVATION

- Gravitational waves from neutron star mergers renewed interest in equation of state of nuclear matter
- Heavy ion collisions produce nuclear matter under similar conditions as mergers
- Constrain the equation of state from high precision data from heavy ions



carnegiescience.edu

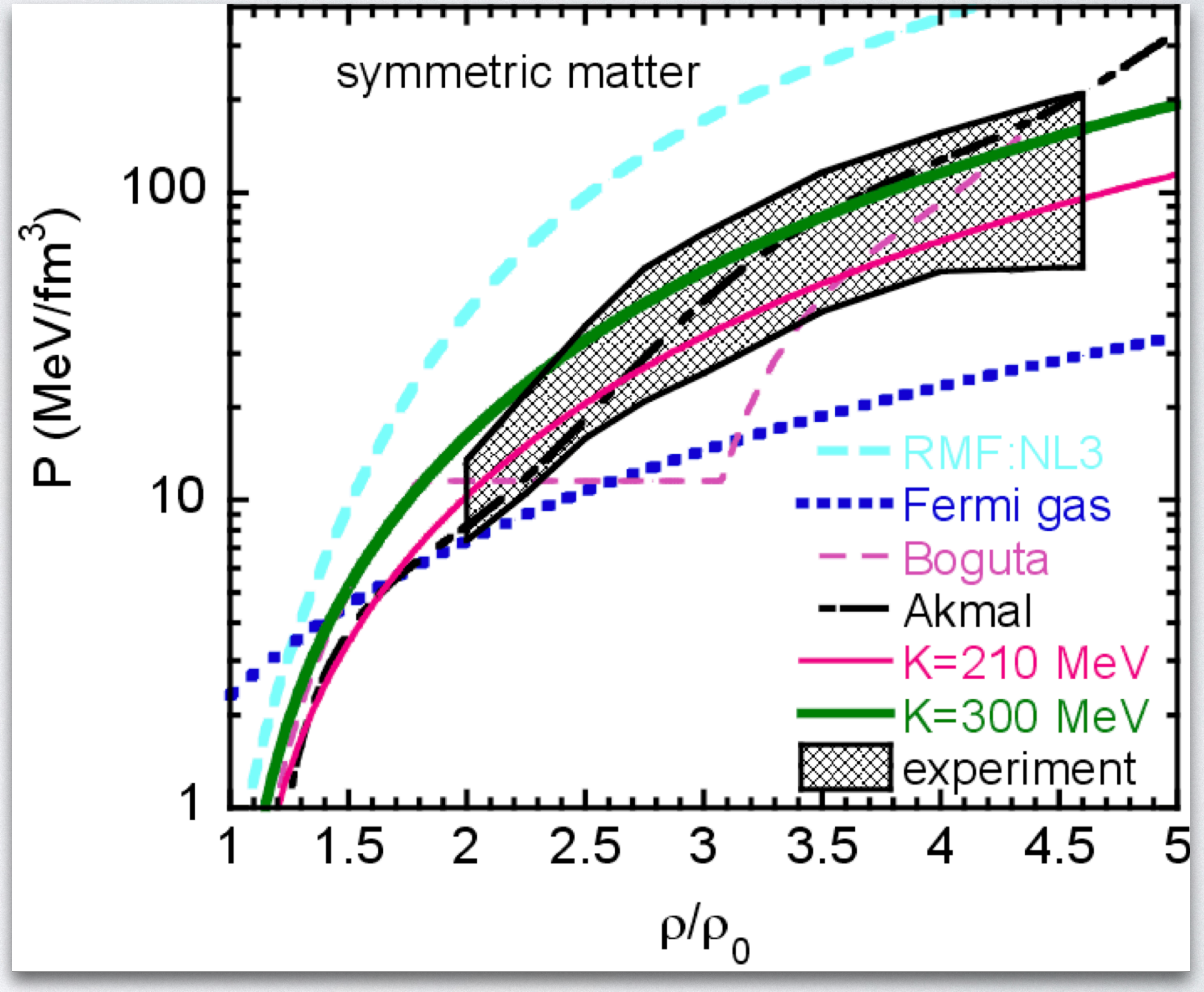
WHAT HAS BEEN DONE SO FAR

- Transport codes are compared with directed and elliptic flow data to extract the stiffness of the EoS

- Models with momentum dependent potentials typically favour a soft EoS
  Aichelin et al. Phys. Rev. Lett. 58, 1926 (1987)
  Fuchs et al. Phys.Rev.Lett. 86 (2001)
  Isse et al. Phys.Rev.C 72 (2005)

- Hard EoS is preferred without momentum dependence

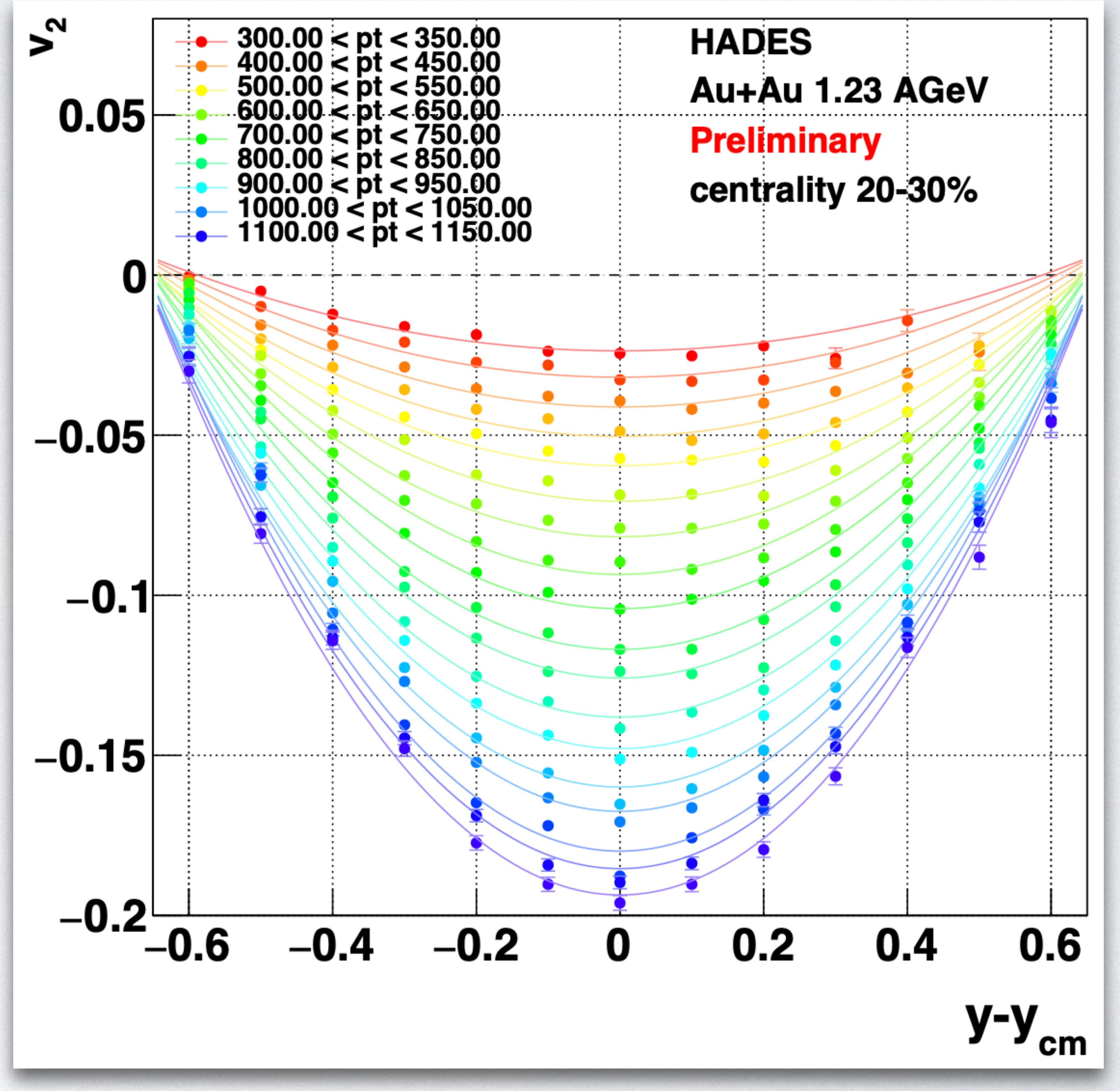
  J. Molitoris, H.Stöcker Phys.Rev.C 32 (1985)
  Hillmann et al. J. Phys. G 45, 085101 (2018)



Danielewicz et al. Science 298 (2002)

WHY DO ANOTHER STUDY?

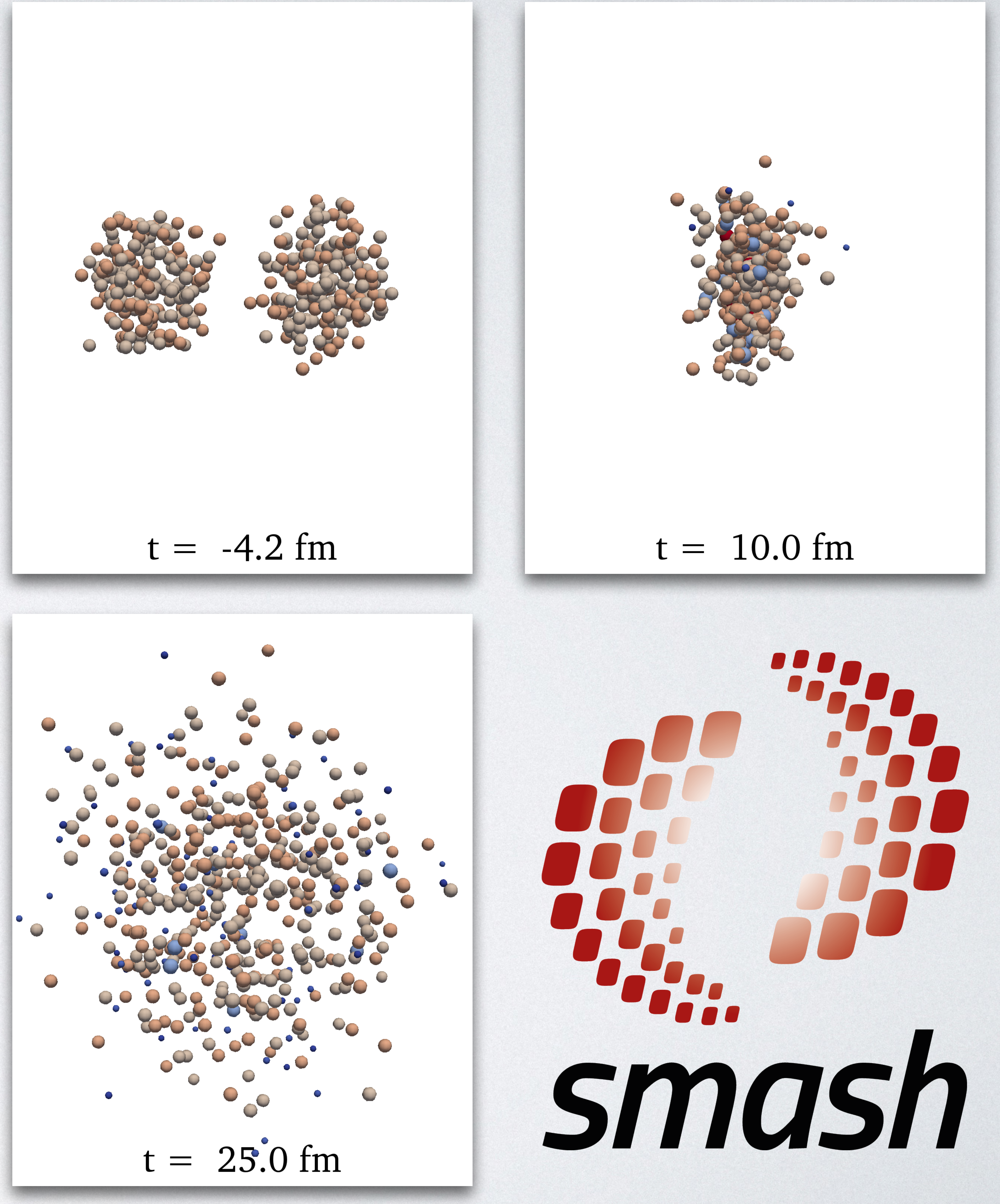
- Many studies on the equation of state available in the literature
- There is new experimental data with very high precision
- The data requires a more systematic comparison to extract information on the EoS



B. Kardan (HADES) Nucl.Phys.A 982 (2019)

SMASH

- Effective solution of the relativistic Boltzmann equation
- Hadron degrees of freedom including resonances from Particle Data Group
- Collisions between hadrons according to geometric collision criterion $d_{\text{trans}} < \sqrt{\sigma/\pi}$
- Use multiple test particles per particle for smoother density calculation
- Publicly available at smash-transport.github.io



POTENTIALS IN SMASH

Calculate densities, gradients and currents by smearing test particles

Oliinychenko et al. Phys.Rev.C 93 (2019)

$$f(r,p) = \frac{1}{N_{\text{test}}} \sum_{i=1}^{N_{\text{test}}} K(\vec{r} - \vec{r}_i)\delta(\vec{p} - \vec{p}_i)$$

$$K(r) = (2\pi\sigma^2)^{-\frac{3}{2}}\gamma \exp\left(-\frac{r^2 + (\vec{r}\cdot\vec{u})^2}{2\sigma^2}\right)$$

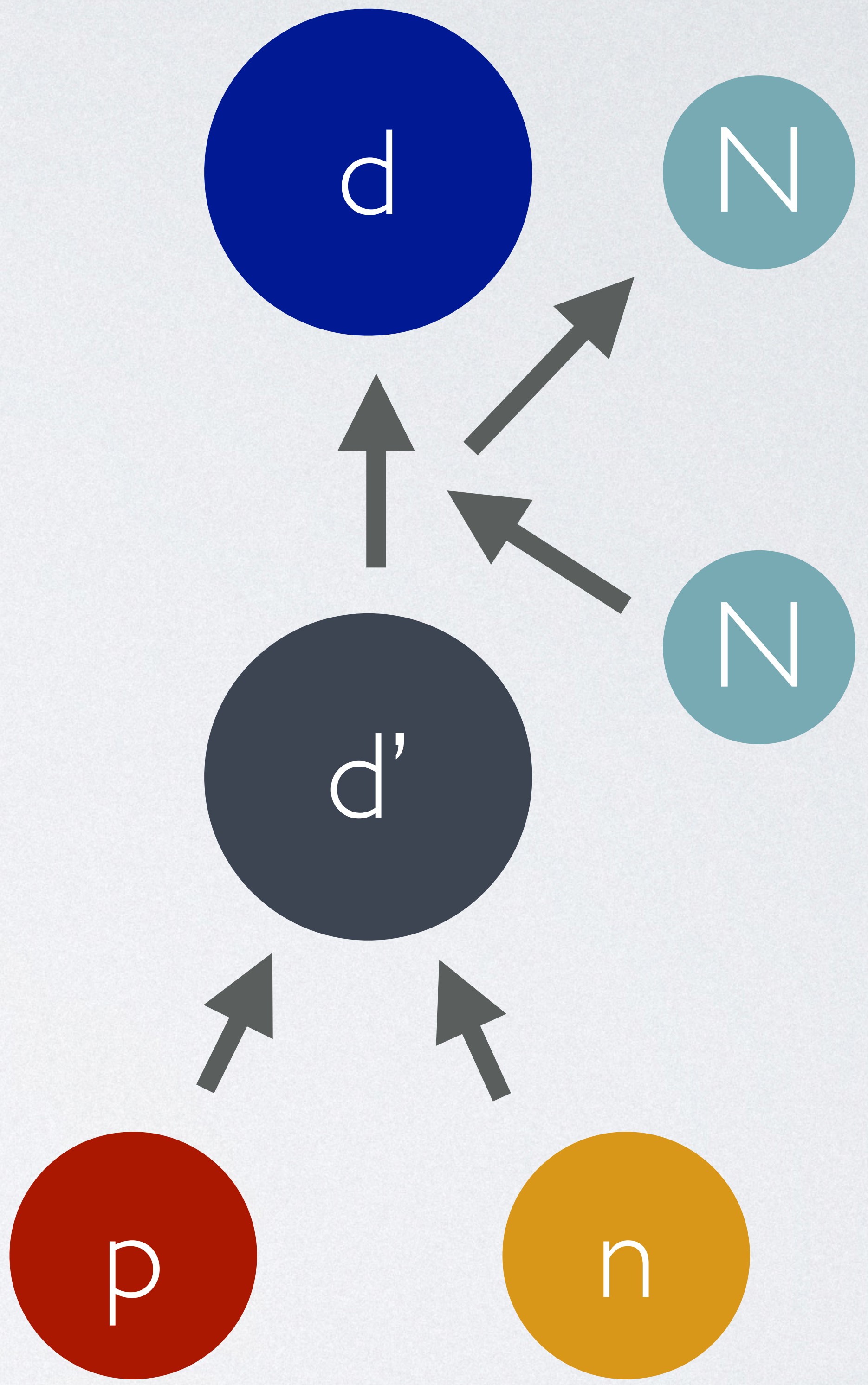
Evaluate equations of motion for simple Skyrme and Symmetry potential

$$\dot{\vec{p}} = \frac{\partial U}{\partial \rho}\left[-\left(\vec{\nabla}\rho + \partial_t \vec{j}\right) + \dot{\vec{x}} \times \left(\vec{\nabla} \times \vec{j}\right)\right]$$

$$U_{\text{Sk}} = A\left(\frac{\rho_B}{\rho_0}\right) + B\left(\frac{\rho_B}{\rho_0}\right)^{\tau} \quad U_{\text{Sym}} = \pm 2S_{\text{pot}}\frac{\rho_{I_3}}{\rho_0}$$

DEUTERONS IN SMASH

- Deuteron represented as a single particle
- Produced in $3 \leftrightarrow 2$ reactions $pnN \leftrightarrow dN$ and $pn\pi \leftrightarrow d\pi$
- Reactions modelled in two steps via "fake" dibaryon resonance $pn \leftrightarrow d'$ and $Nd' \leftrightarrow Nd$
- Deuterons contribute to densities with baryon number 2 and are affected by potentials



Oliinychenko et al. Phys.Rev.C 99 (2019)

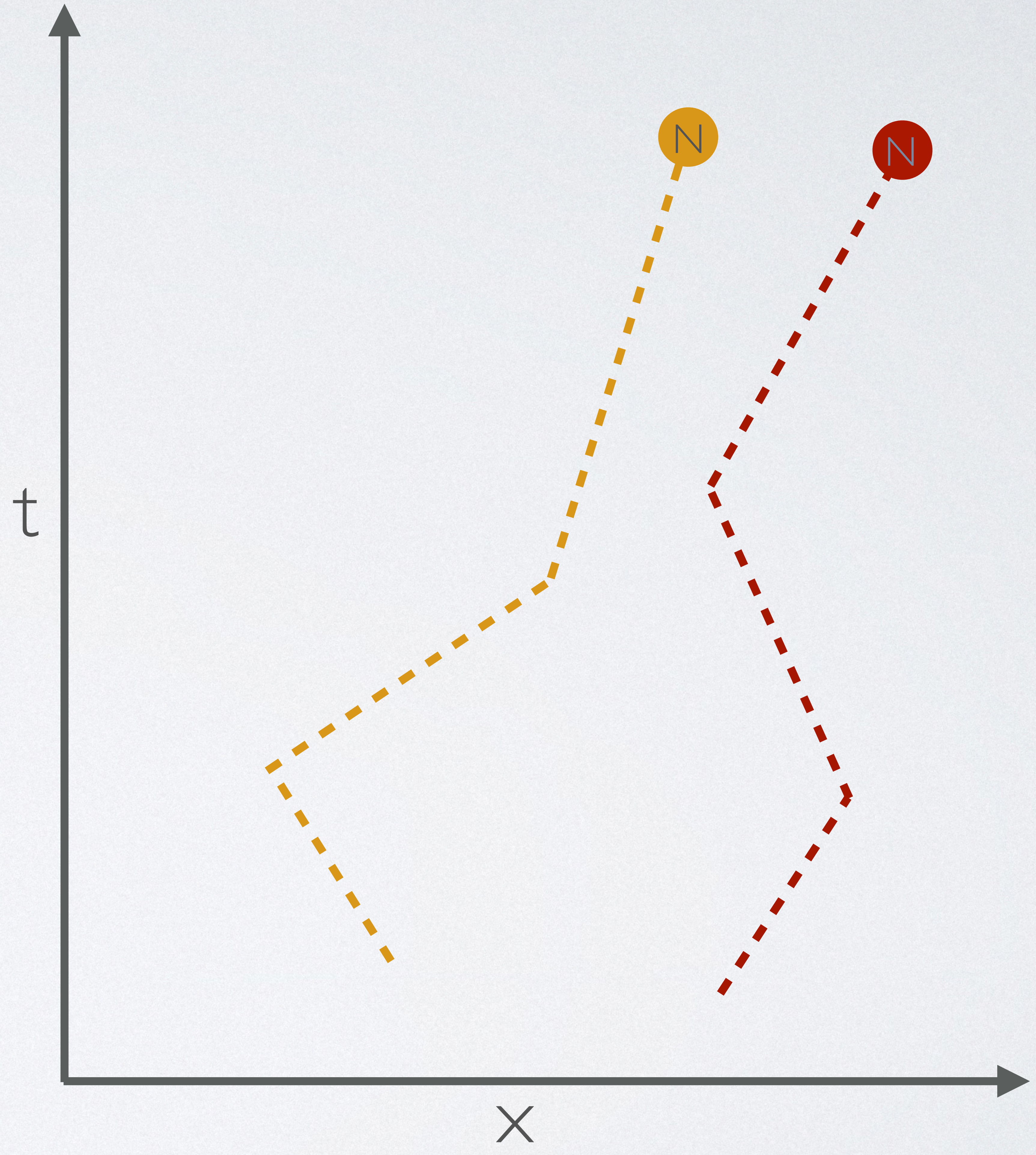
CLUSTERING

- Perform calculation without deuterons and identify light nuclei afterwards

- For each pair of nucleons

  - Look at the distance and momentum difference in their center of mass frame at the time of the latest collision of the two

  - Consider particles as clustered if $\Delta r < r_0$ and $\Delta p < p_0$

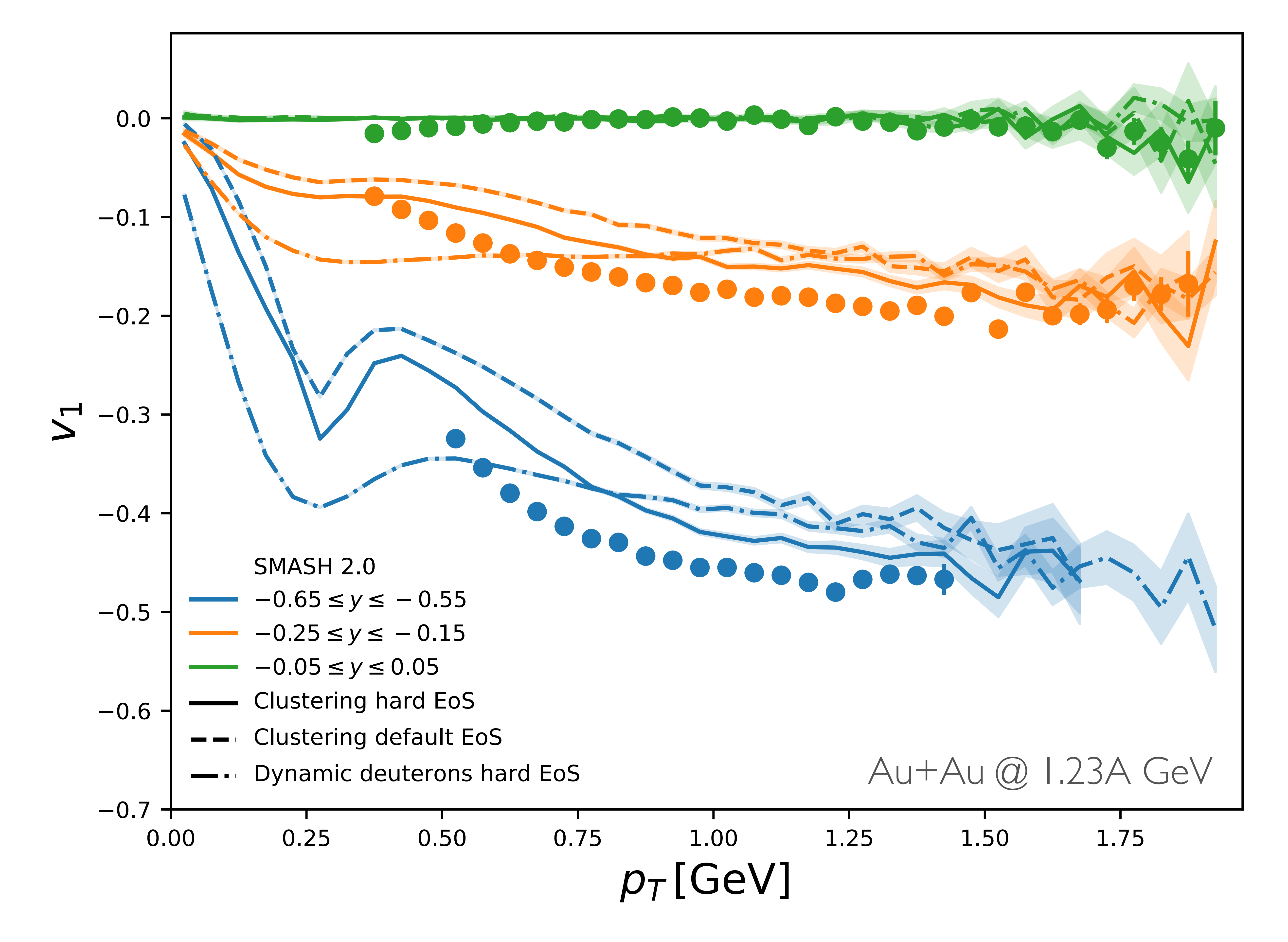


Zhu et al. Phys.Rev.C 92 (2015), Sombun et al. Phys.Rev.C 99 (2019)

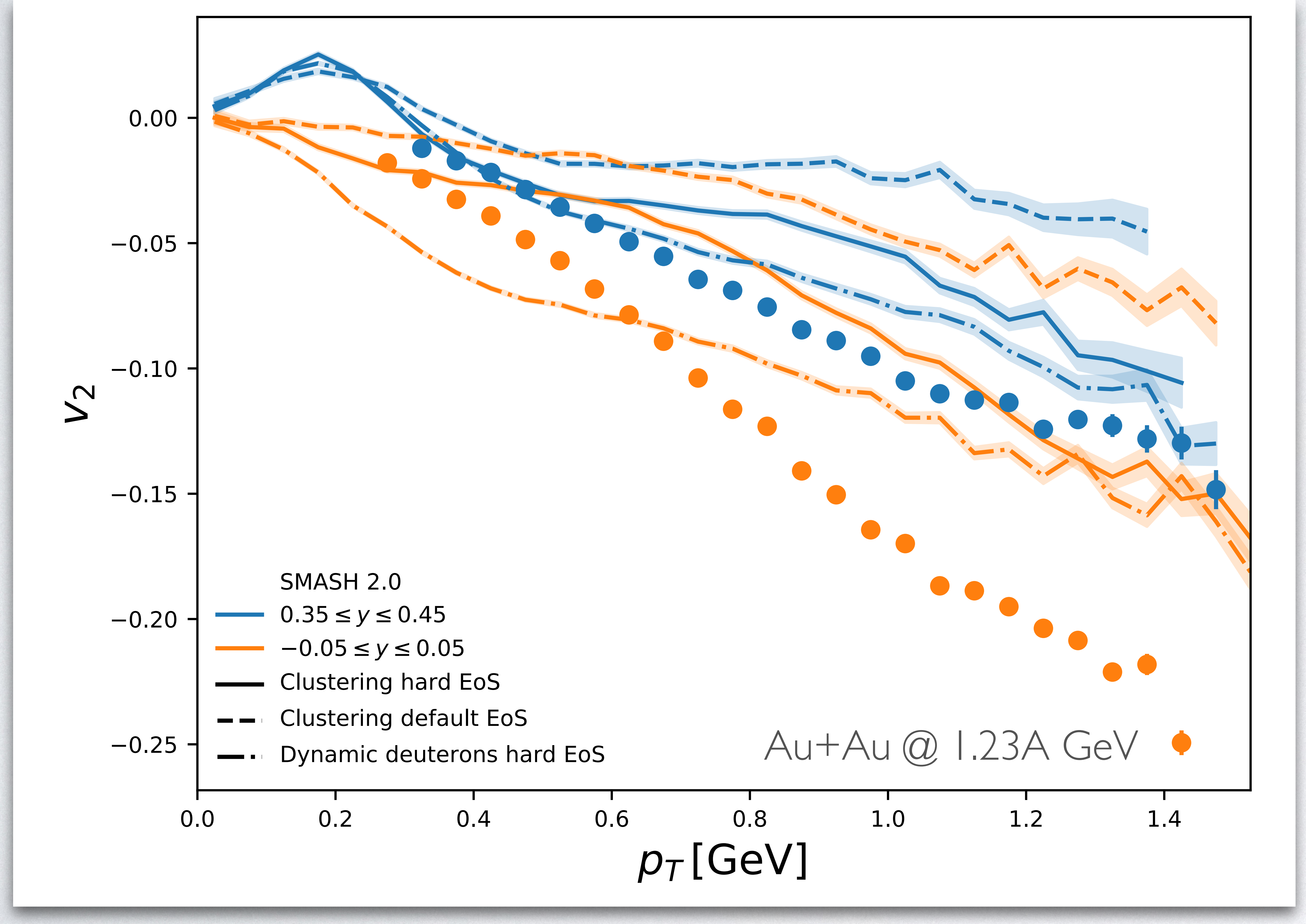
RESULTS - NUCLEON DIRECTED FLOW

- Strongest directed flow signal with hard EoS - fits data best
- Light nuclei formation treatment most important at low transverse momenta
- Overall reasonable description of v_1

	Soft	Default	Hard
A	-356 MeV	-209.2 MeV	-124 MeV
B	303 MeV	156.4 MeV	71 MeV
τ	1.17	1.35	2.0
K	200 MeV	240 MeV	375 MeV

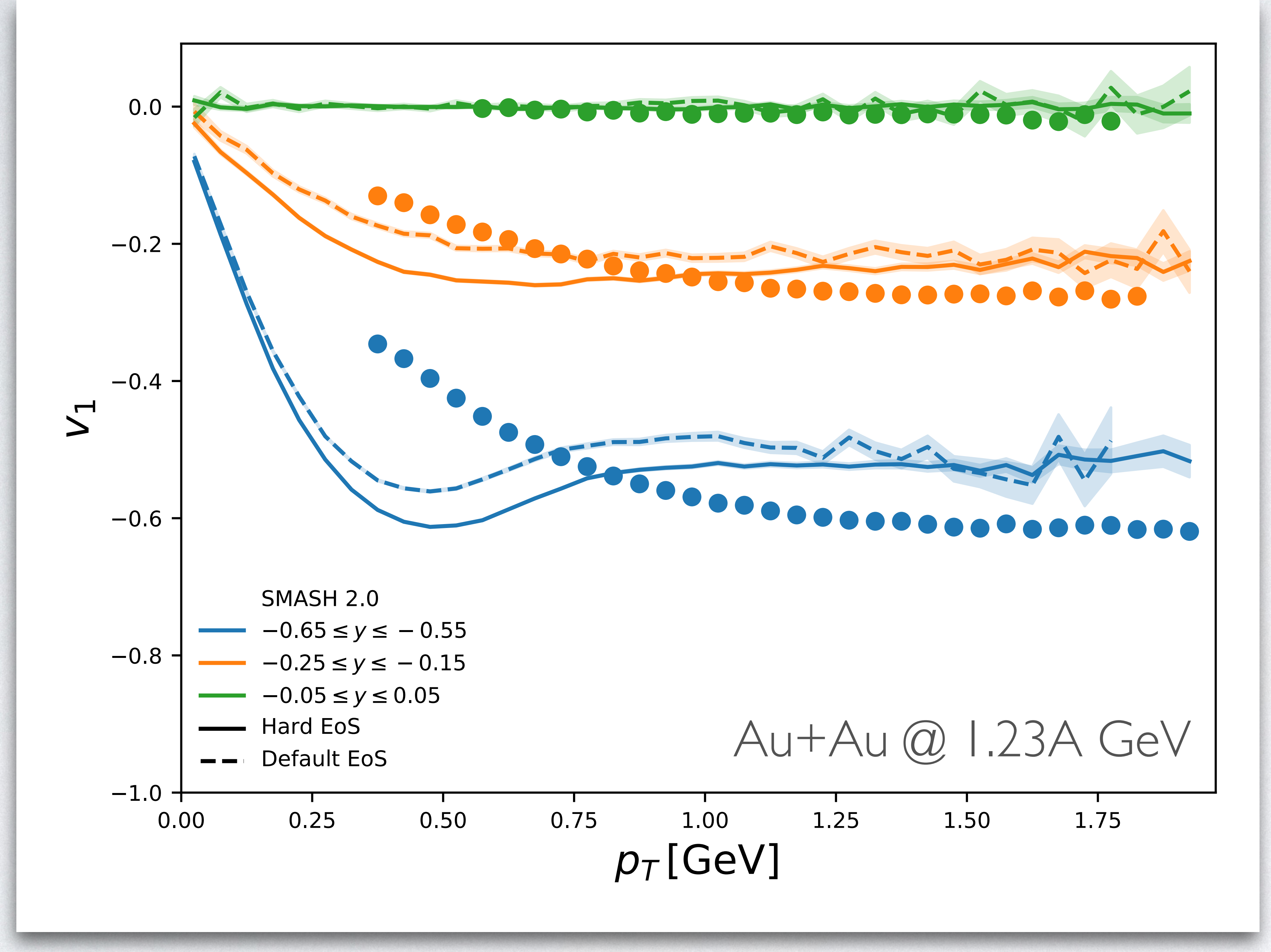


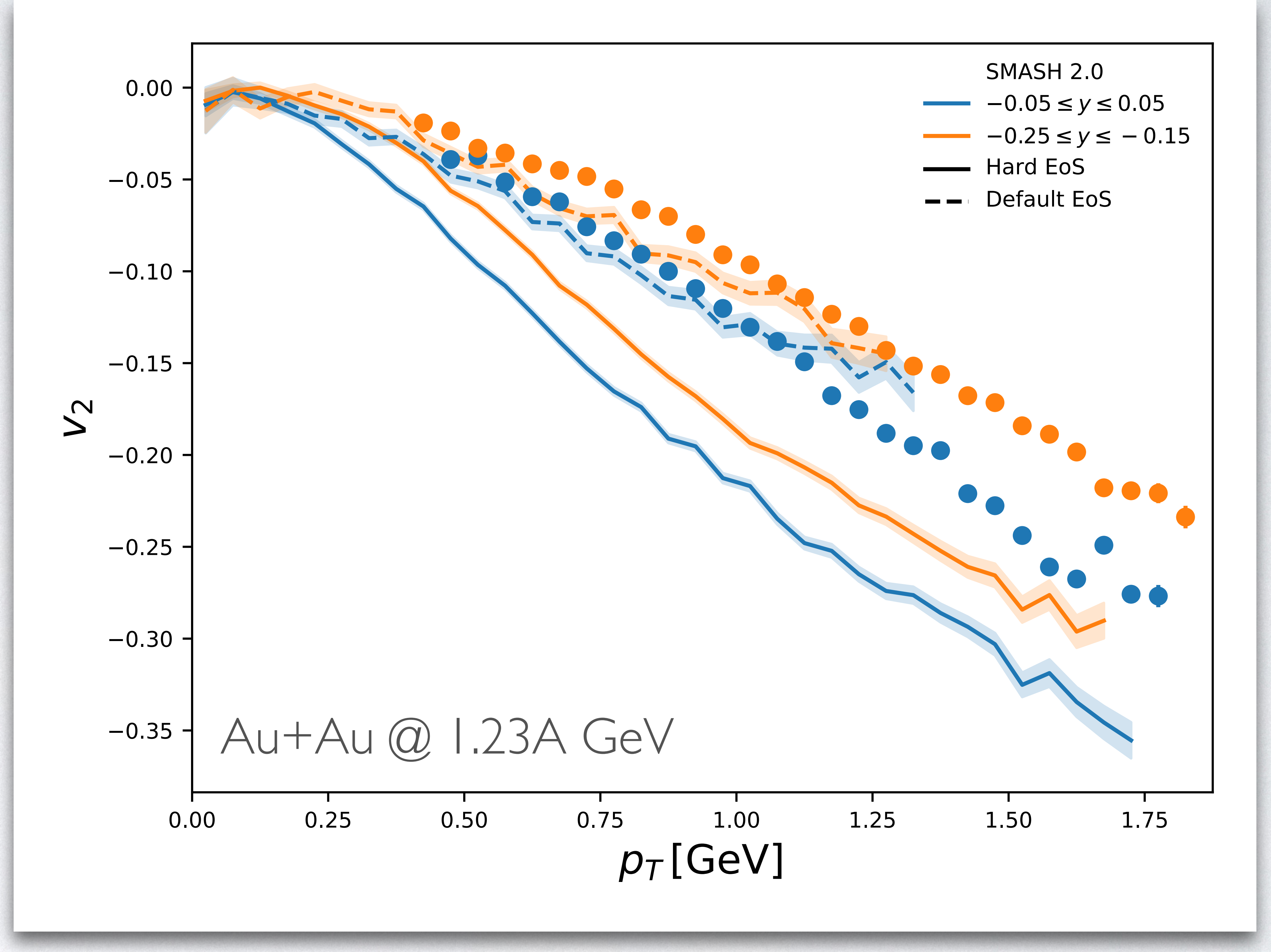
RESULTS - NUCLEON ELLIPTIC FLOW



- Clustering and explicit deuteron formation again differ mostly for low transverse momenta
- Elliptic flow of nucleons at large transverse momenta underestimated → lack of momentum dependence

RESULTS - DEUTERON FLOW





- Directed flow of deuterons relatively well described with hard equation of state
- Elliptic flow of deuterons overestimated for the same equation of state

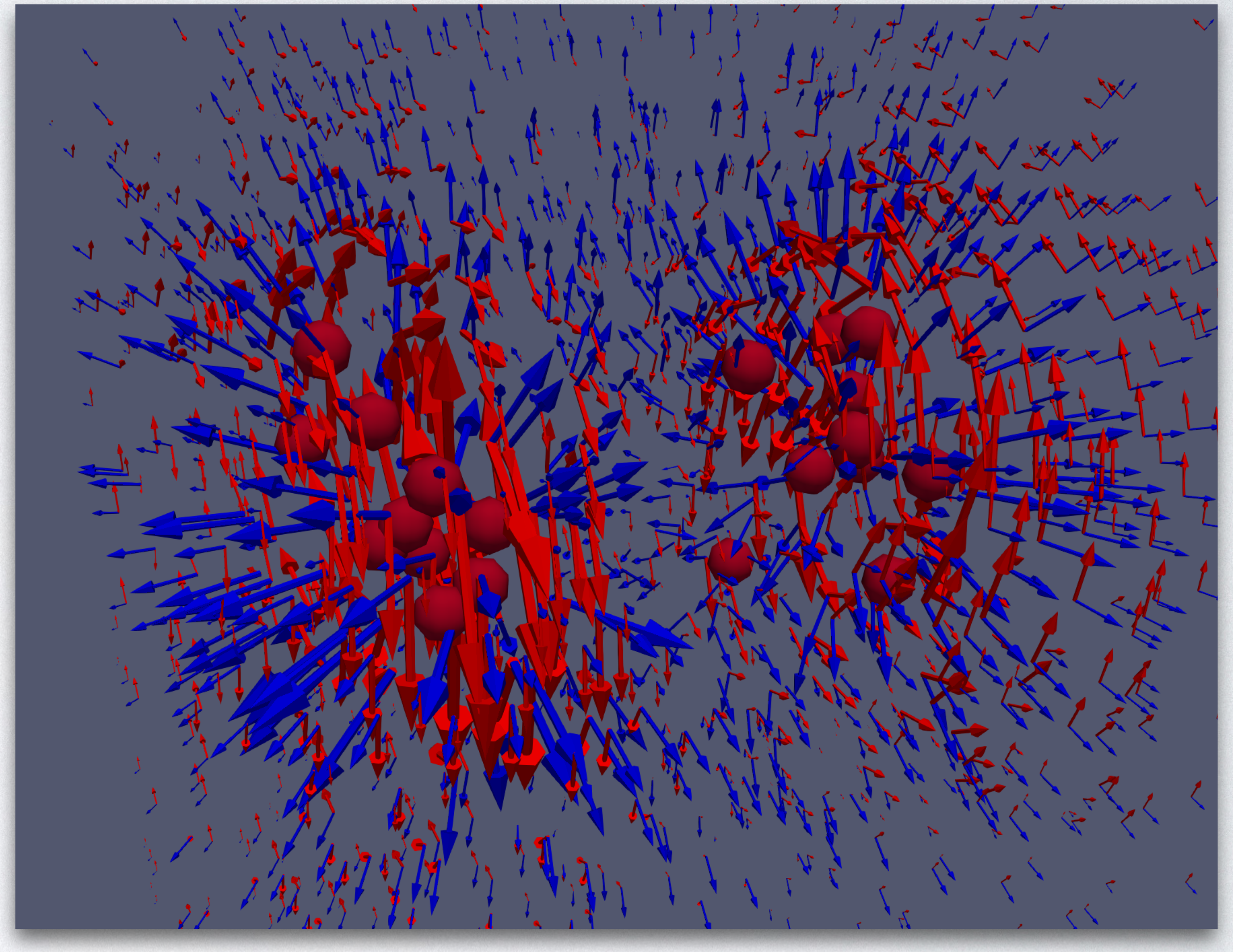
COULOMB POTENTIAL

- Most important for low collision energies where velocities are not very large

- Assume stationary current for simplicity

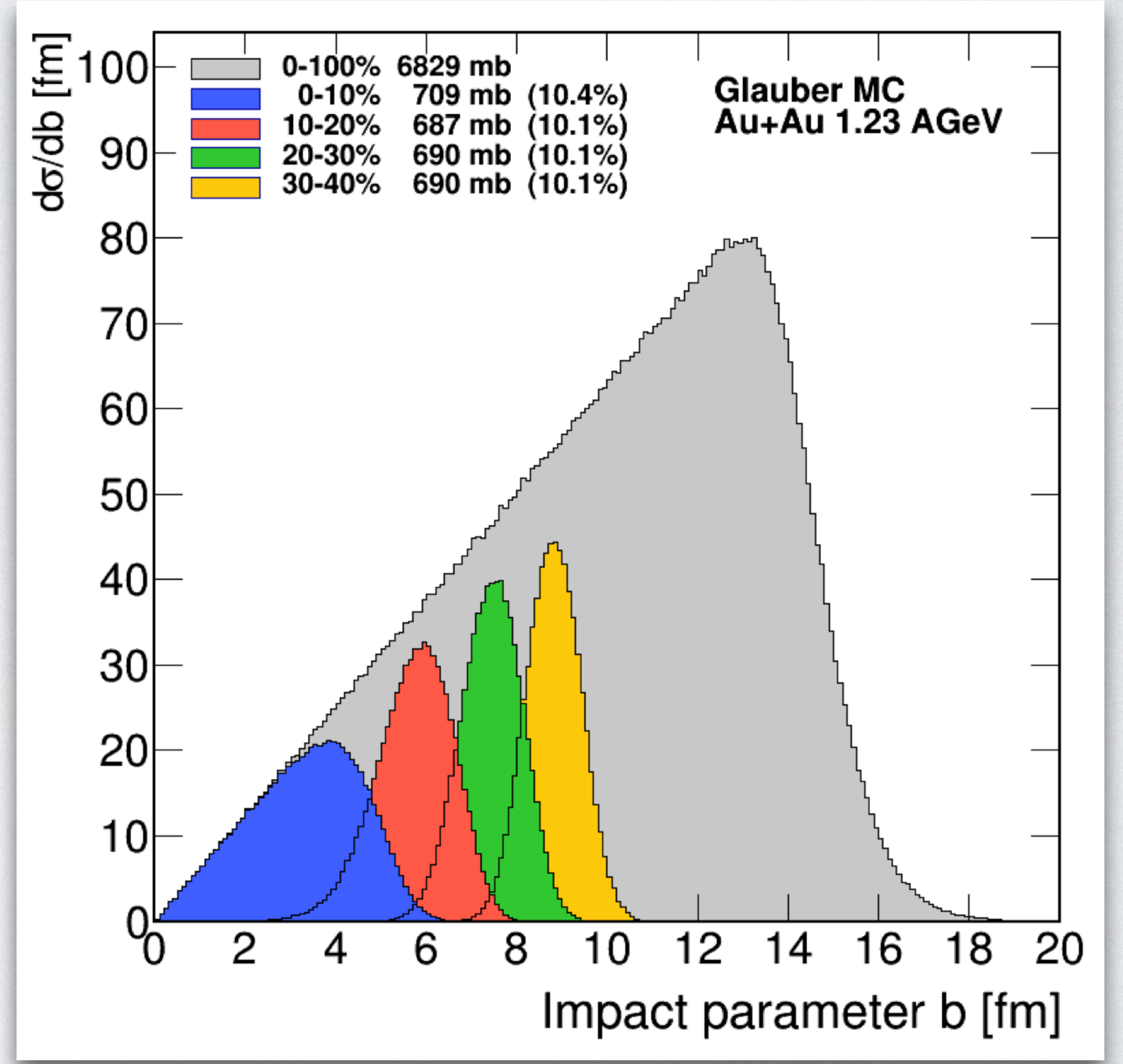
- Calculate fields by integrating over a lattice:
  $\vec{E}(\vec{r}) = \int \frac{\rho(\vec{r}')(\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} dV'$ and $\vec{B}(\vec{r}) = \int \vec{j}(\vec{r}') \times \frac{\vec{r} - \vec{r}'}{|\vec{r} - \vec{r}'|^3} dV'$

- Update momenta using Lorentz force
  $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$



CENTRALITY SELECTION

- Flow coefficients are very sensible to the centrality
- Used impact parameter range from Glauber up to now
- Work with HADES to perform centrality selection as close to experiment as possible including detector simulation



HADES Eur.Phys.J.A 54 (2018)

MOMENTUM DEPENDENT POTENTIALS

- Results suggest that the currently implemented potentials are too simplistic

- The optical potential depends on the momentum relative to surrounding particles

  - Need to improve $U(\rho) \rightarrow U(\rho, \overrightarrow{p})$ but still need to decide on the exact shape

SUMMARY

- Compared results using simple Skyrme and Symmetry potentials to new flow data from HADES
- Hard equations of state works best but potentials need improvement to describe v_1 and v_2 consistently
- Compared different methods of taking light nuclei formation into account and observed a sensitivity mostly in the low p_T region

OUTLOOK

- Plan is to systematically find a constrain on the equation of state given new data
- Improve potentials: add Coulomb and momentum dependence
- Realistic data comparison, especially centrality selection