THE INFLUENCE OF LIGHT NUCLEI PRODUCTION AND THE EOS ON FLOW IN LOW-ENERGY HEAVY-ION COLLISIONS

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INT Workshop: Dense Nuclear Mater Equation of State from Heavy-Ion Collisions

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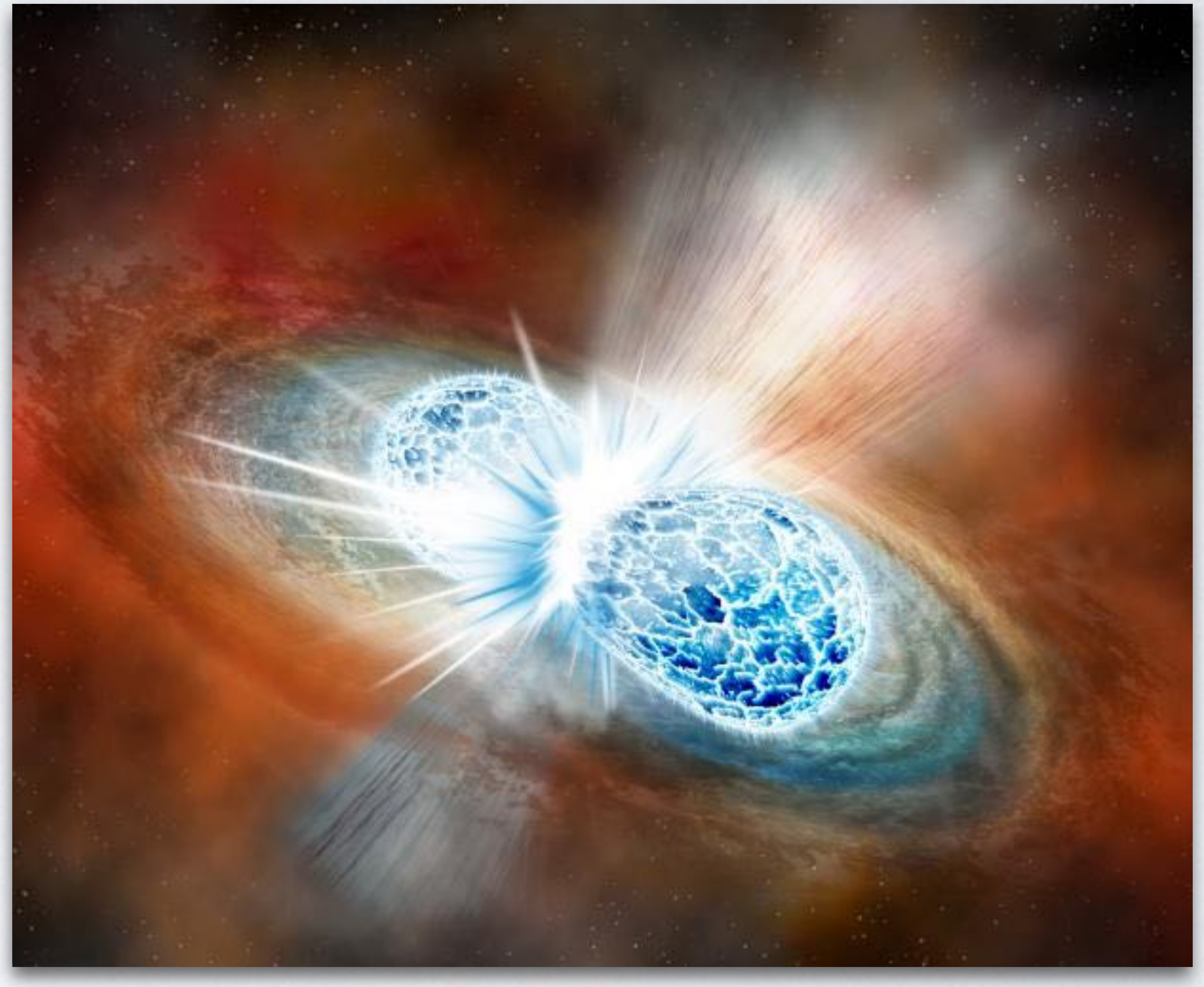
MOTIVATION

- 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



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EQUATION OF STATE FROM TRANSPORT CALCULATIONS

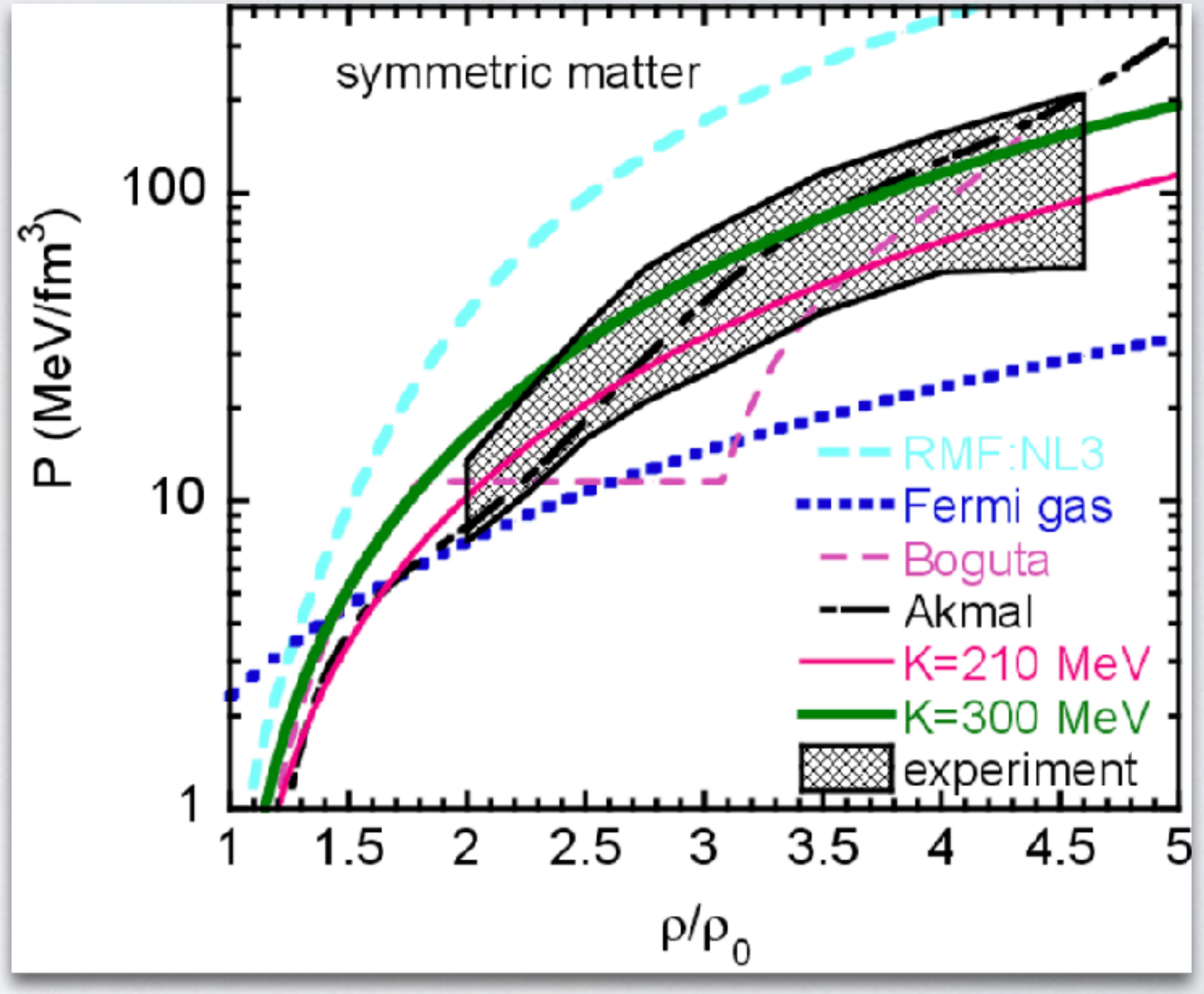
- Transport codes are compared with directed and elliptic flow data to extract the stiffness of the EoS

- 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

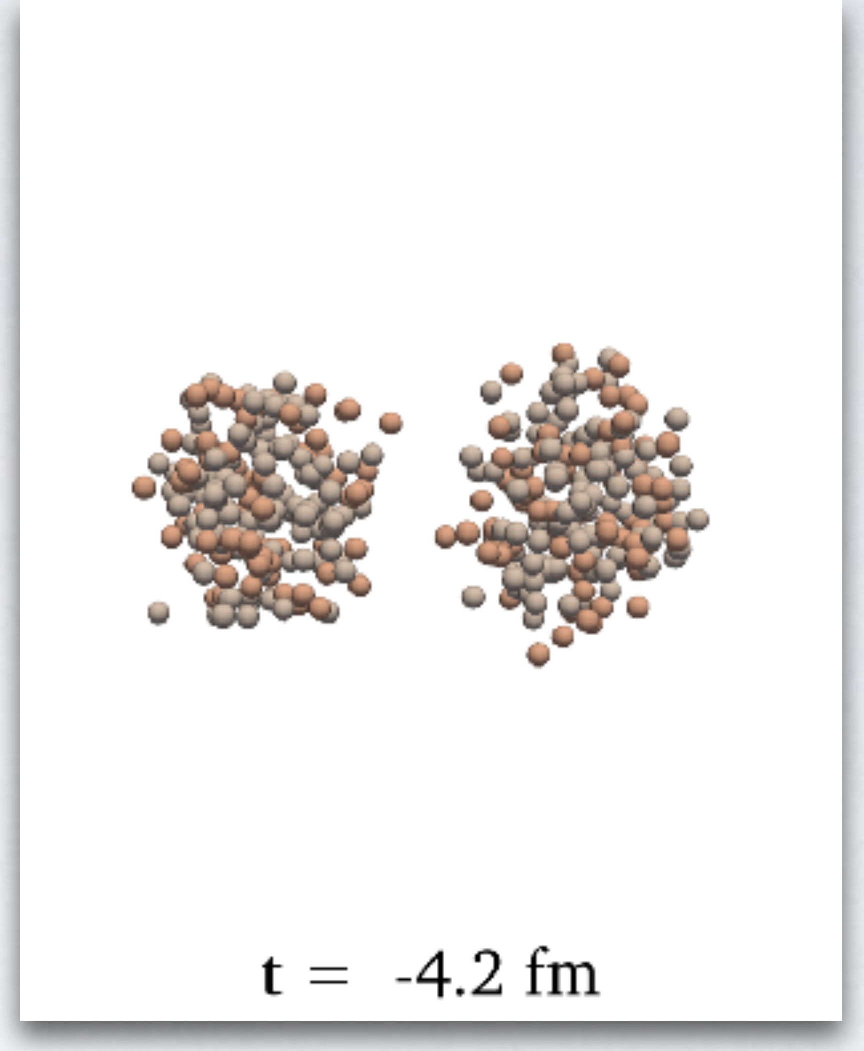
  J. Molitoris, H.Stöcker Phys.Rev.C 32 (1985)
  Hillmann et al. J. Phys. G 45, 085101 (2018)

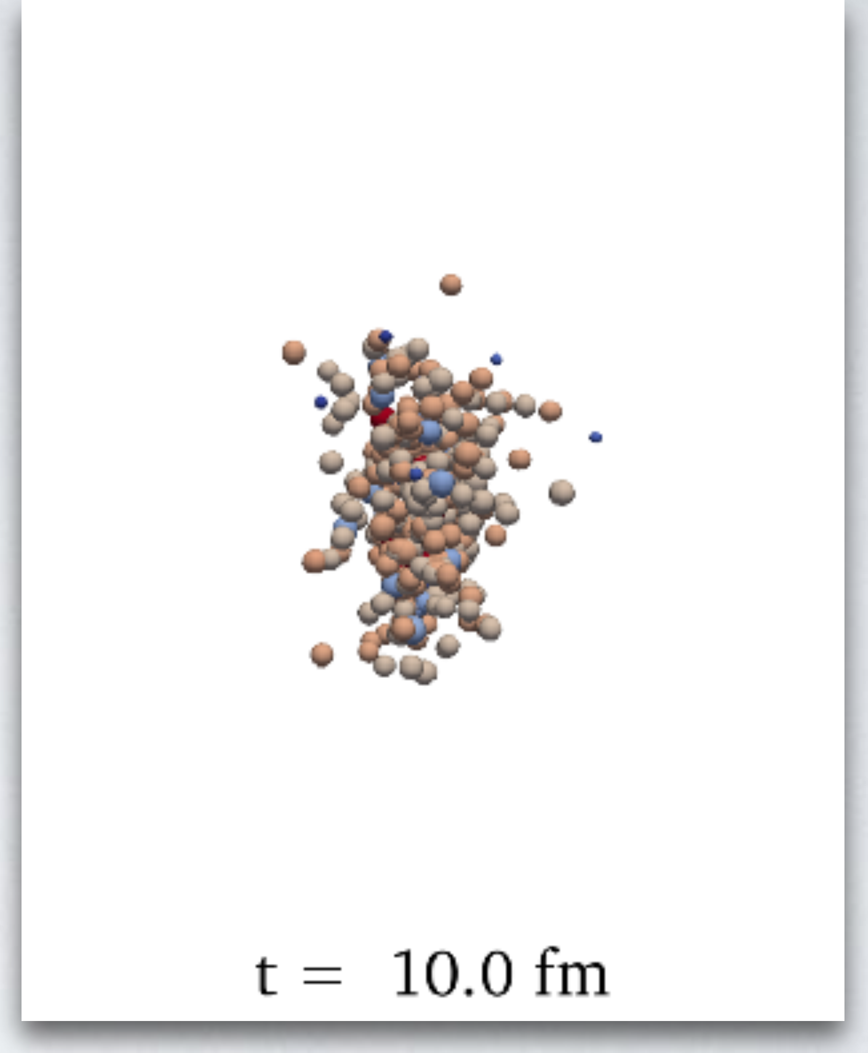


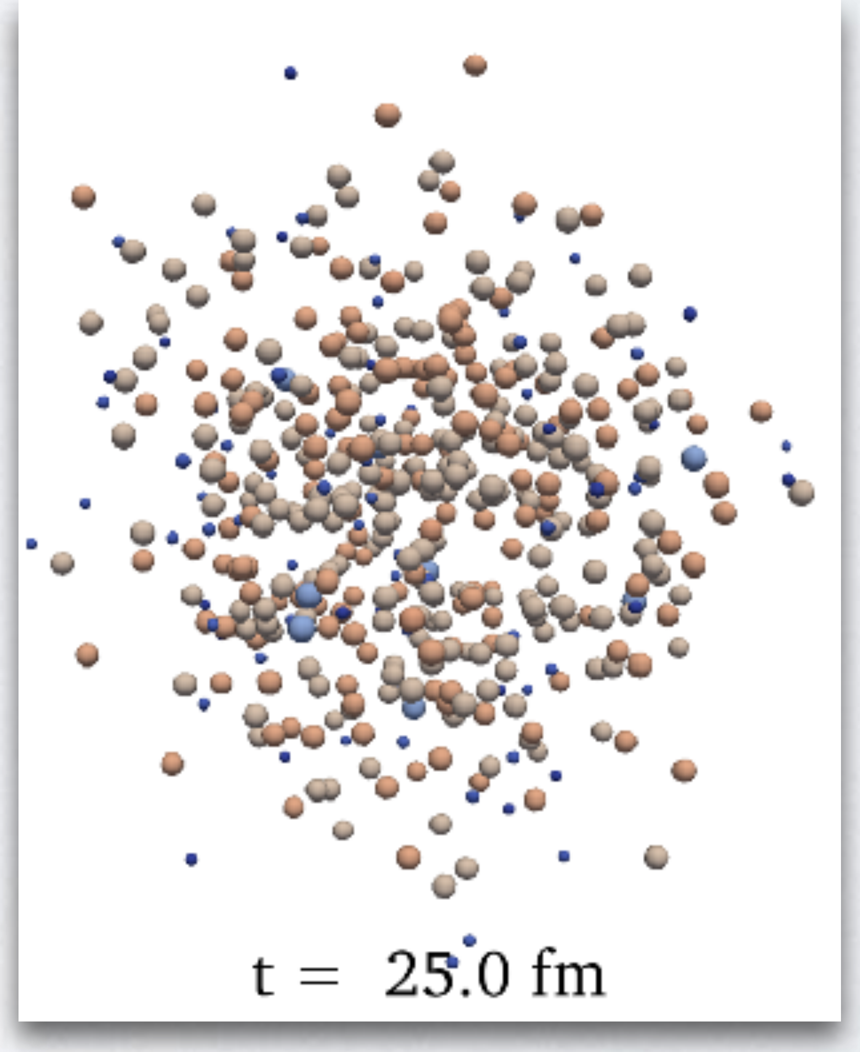
Danielewicz et al. Science 298 (2002)

TRANSPORT MODEL 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 $d_{\text{trans}} < \sqrt{\sigma/\pi}$
- Publicly available at smash-transport.github.io







POTENTIALS AND EQUATION OF MOTION

- Use simple Skyrme and symmetry potential

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

- Equations of motion are expressed in terms of gradients of densities

$$U_{\text{Sym}} = \pm\, 2S_{\text{pot}}\frac{\rho_{I_3}}{\rho_0}$$

- Hamilton's EoM in local rest-frame boosted to calculation frame

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

DENSITY CALCULATION

- Densities and gradients are required to evaluate the equations of motion

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

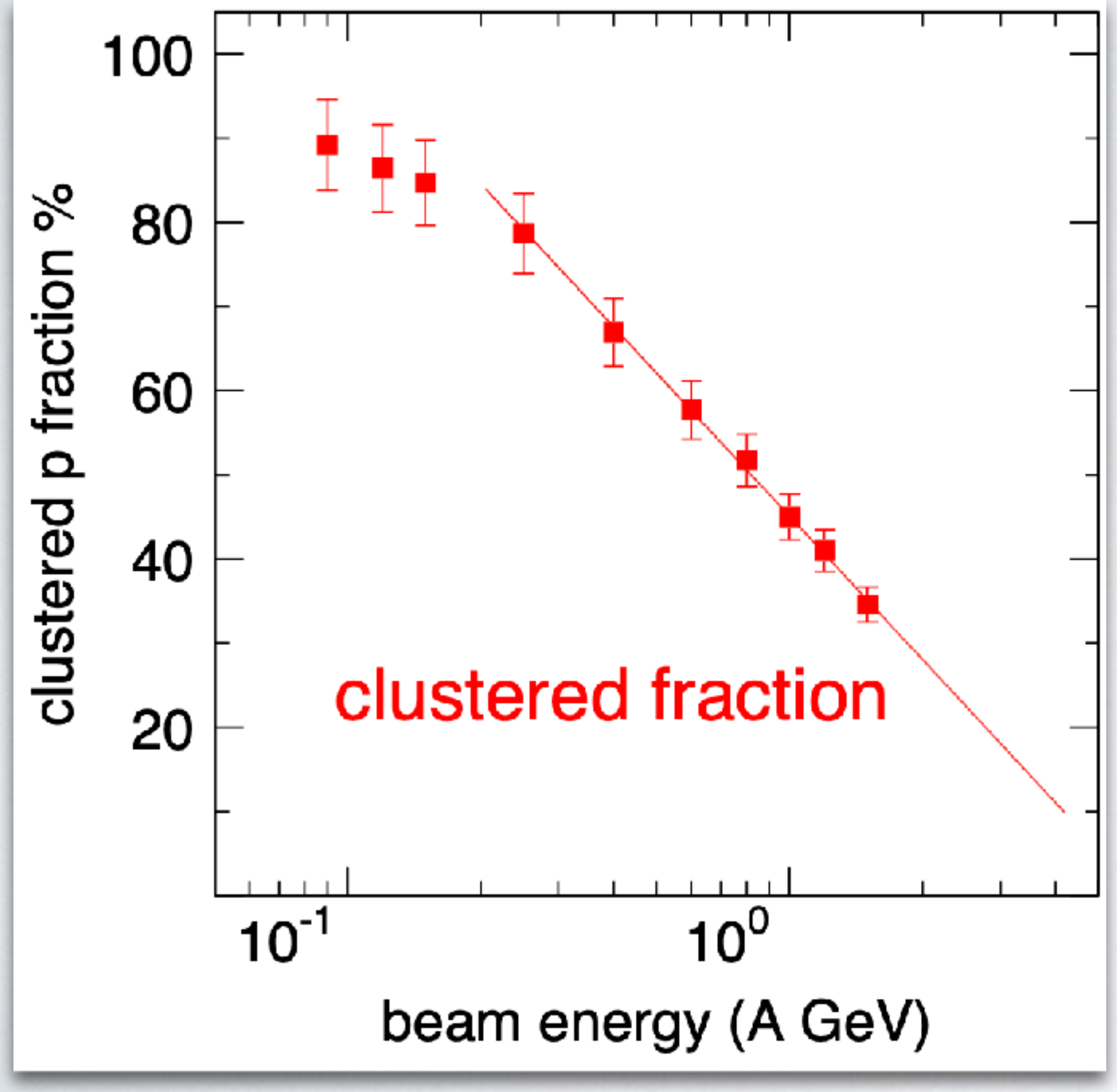
- Apply a smearing kernel $\delta(\mathbf{r} - \mathbf{r}_i) \to K(\mathbf{r} - \mathbf{r}_i)$ to obtain a smooth density profile

- Kernel describes a Gaussian that is Lorentz contracted due to motion of the testparticle

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

- Use a lattice for calculating gradients and time derivatives

LIGHT NUCLEI FORMATION

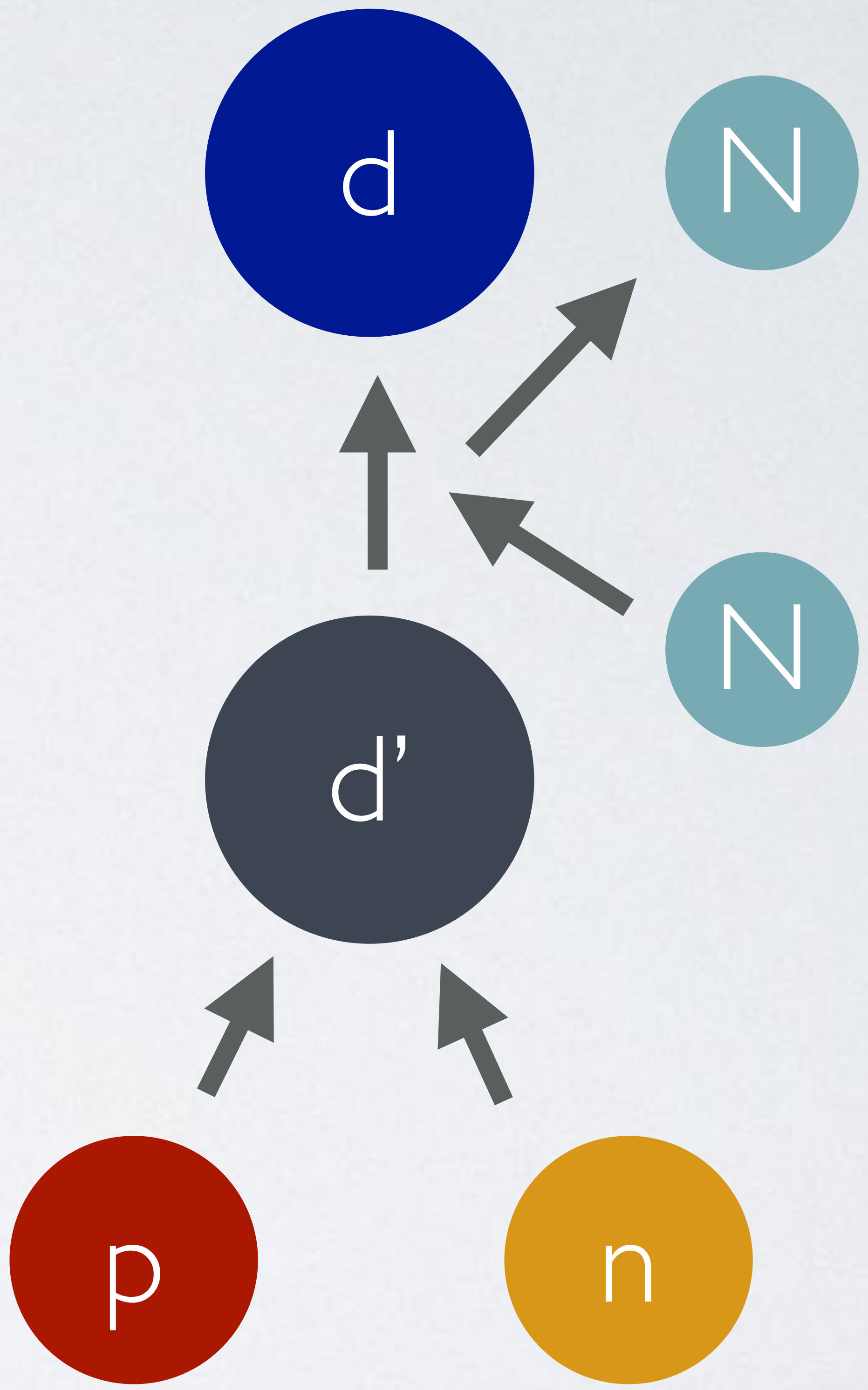


FOPI Nucl.Phys.A 848 (2010)

- Large fraction of protons are bound in light nuclei at low collision energies
- It is important to understand the formation of light nuclei even if one is only interested in protons
- Compare two models of taking deuteron formation into account

DEUTERONS IN SMASH

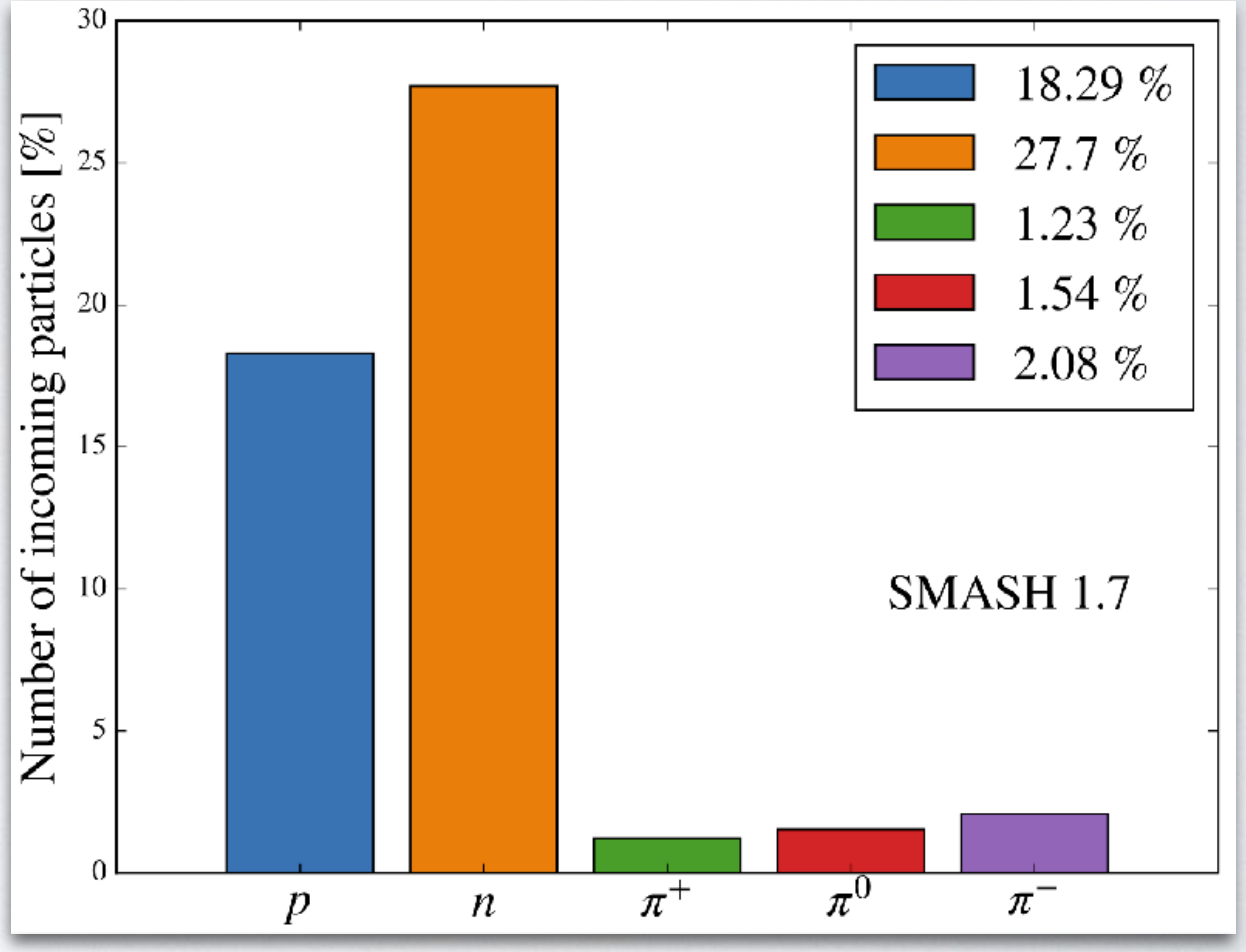
- Deuteron represented as a single particle
- Produced in $3 \leftrightarrow 2$ reactions $pnN \leftrightarrow dN$ and $pn\pi \leftrightarrow d\pi$
- Reactions modelled in two steps via "fake" dibaryon resonance $pn \leftrightarrow d'$ and $Nd' \leftrightarrow Nd$
- Deuterons contribute to densities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



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

REACTIONS PRODUCING DEUTERONS

- Count reaction partners of the intermediate d' resonance
- Deuteron production at low collision energies mainly catalysed by nucleons $pnN \leftrightarrow dN$
- Reaction partners sum up to $\approx 50\,\%$ in the other cases the d' decays to proton and neutron



Reaction partners of d' fake resonance

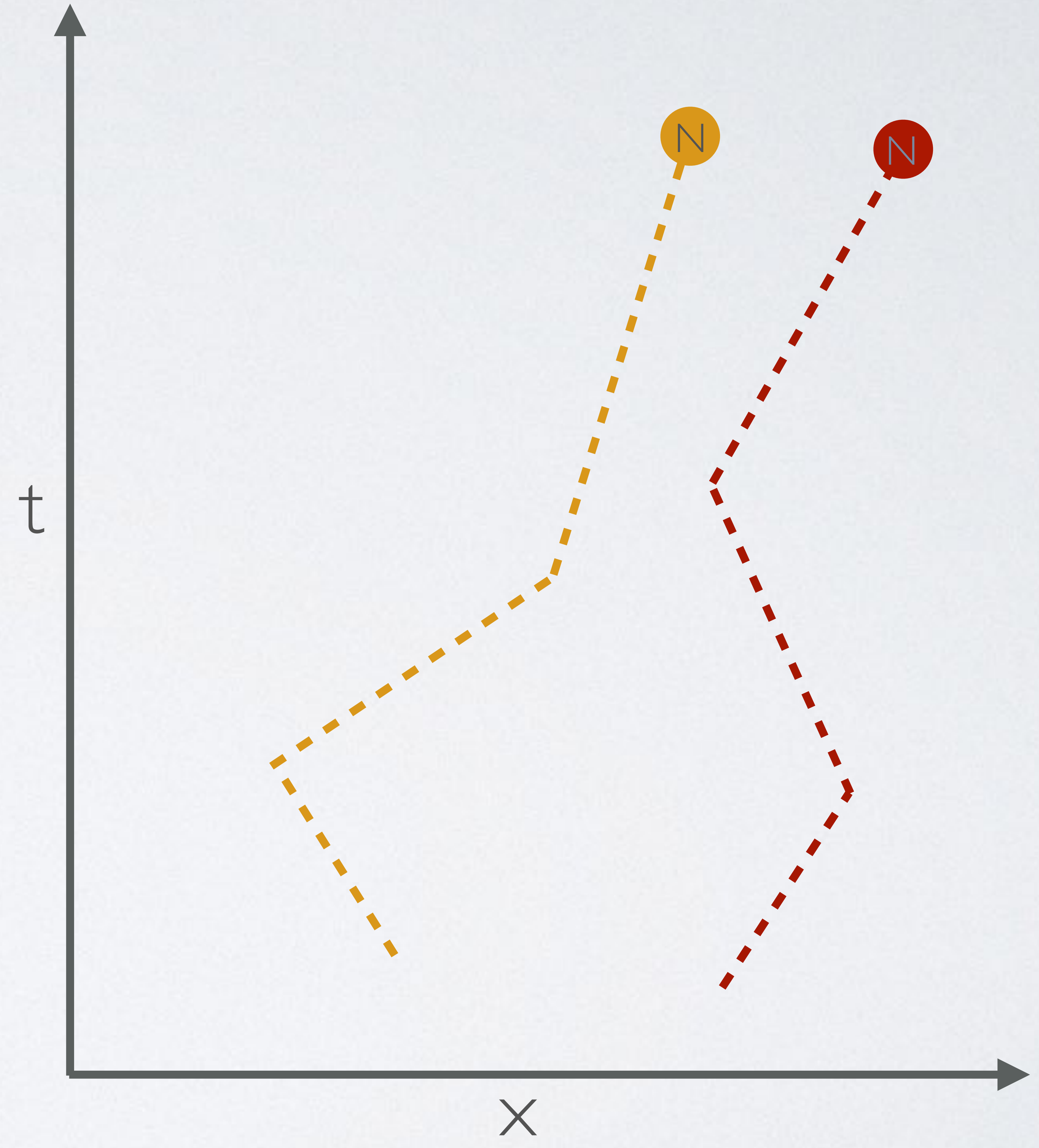
CLUSTERING

- 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 $\Delta p < p_0$



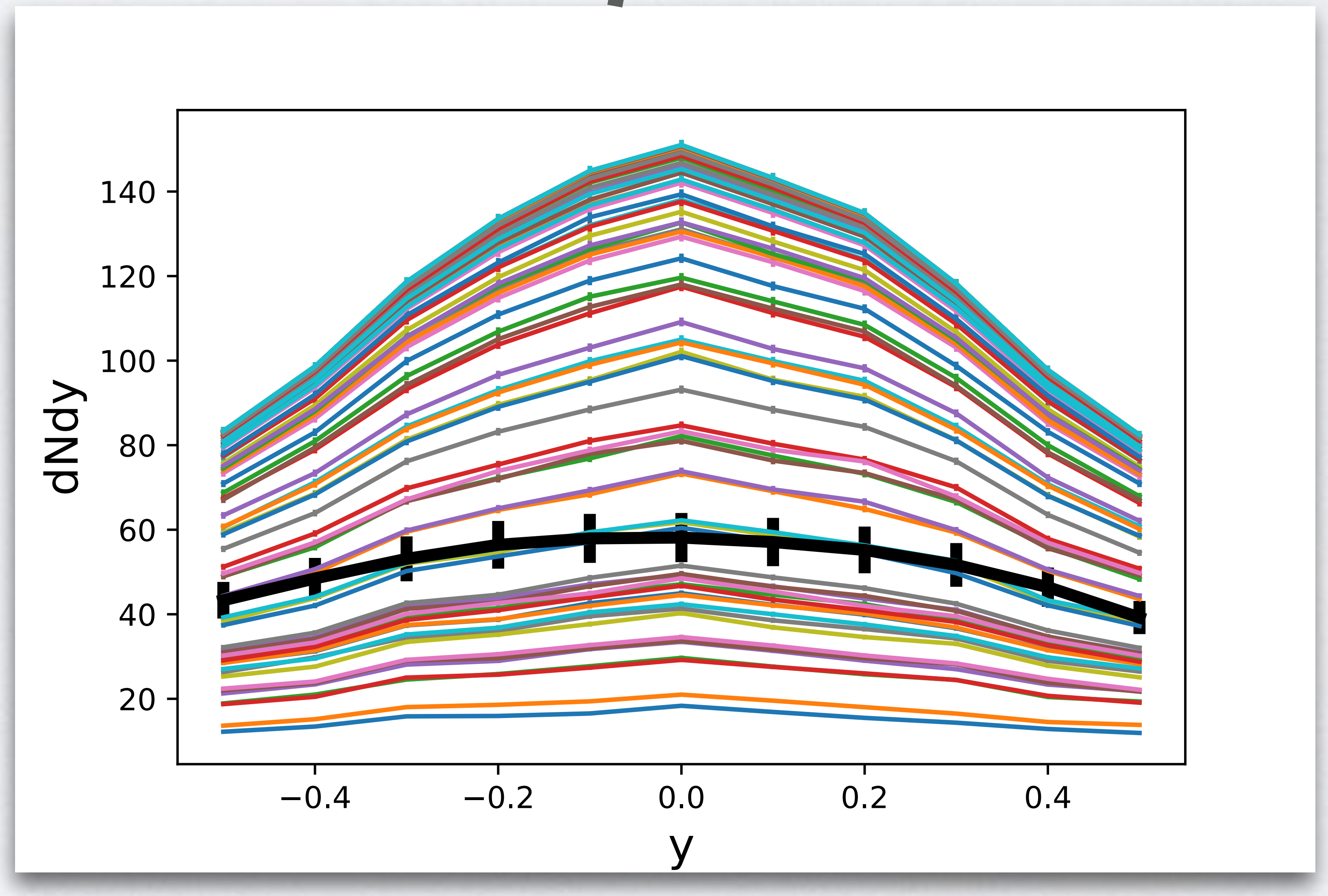
Zhu et al. Phys.Rev.C 92 (2015), Sombun et al. Phys.Rev.C 99 (2019)

CLUSTERING PARAMETERS

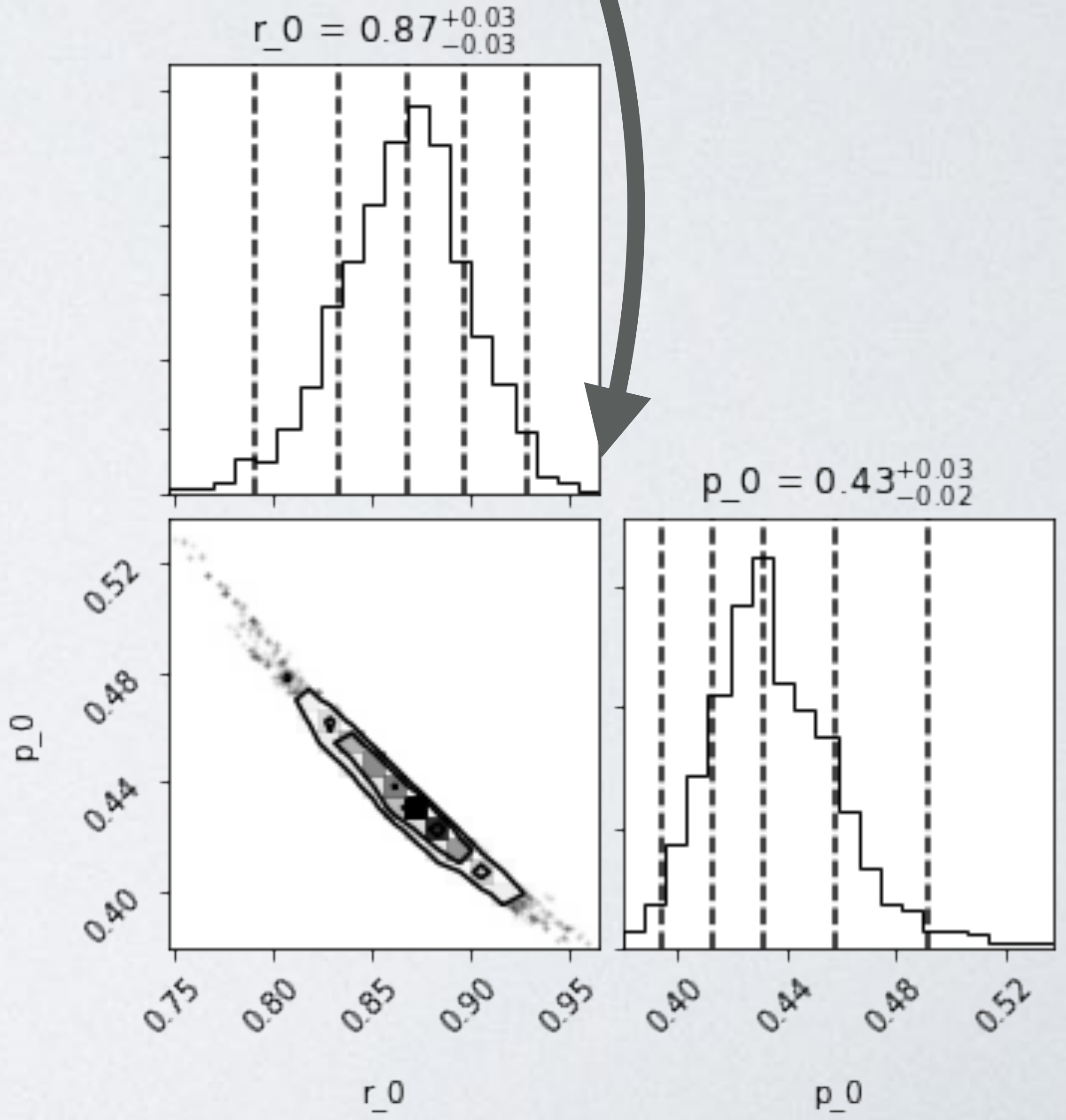
- Calculations in full ensemble: N_{test} times more test particles in an event than real particles
- Need to adapt thresholds p_0 and r_0
- Find $r_0 = 0.87\,\mathrm{fm}$ and $p_0 = 0.43\,\mathrm{GeV}$
- Comparable to $r_0 = 3.58\,\mathrm{fm}$ and $p_0 = 0.285\,\mathrm{GeV}$ from Sombun et al. Phys.Rev.C 99

Train Gaussian process

Bayesian parameter estimation



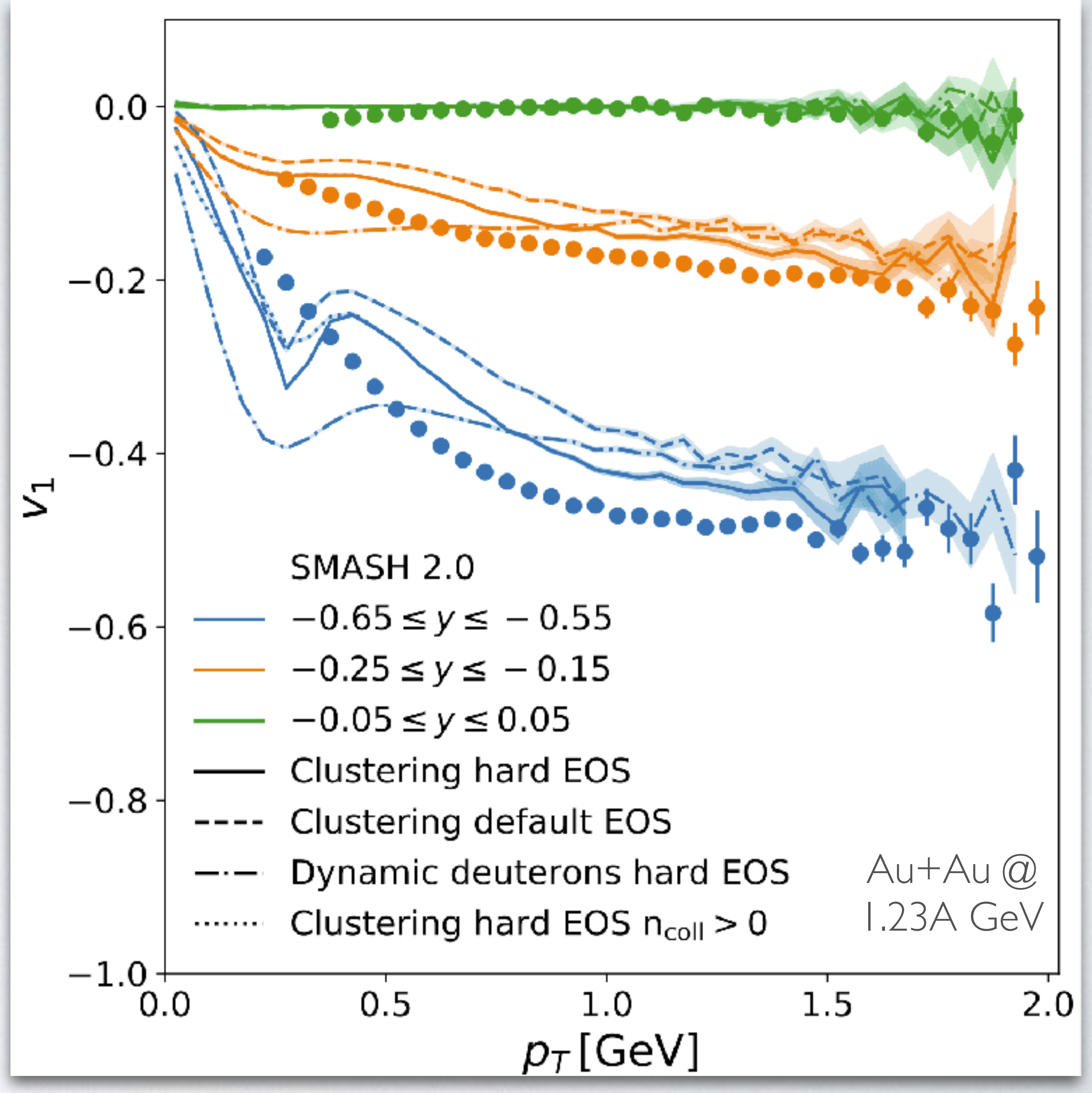
Proton rapidity spectra samples + data(black)



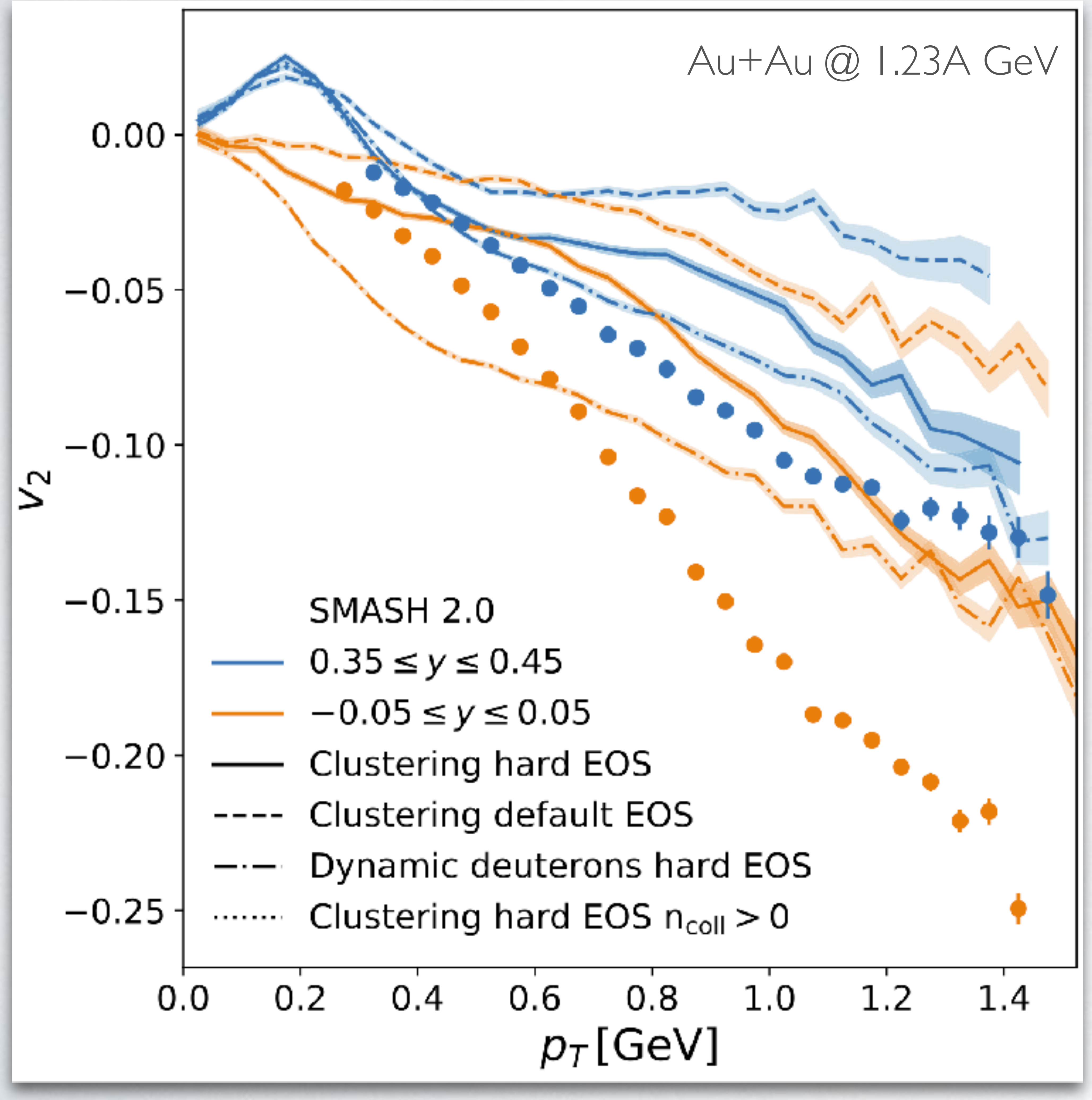
NUCLEON DIRECTED FLOW

- 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



NUCLEON ELLIPTIC FLOW



- Clustering and explicit deuteron formation again differ mostly for low transverse momenta

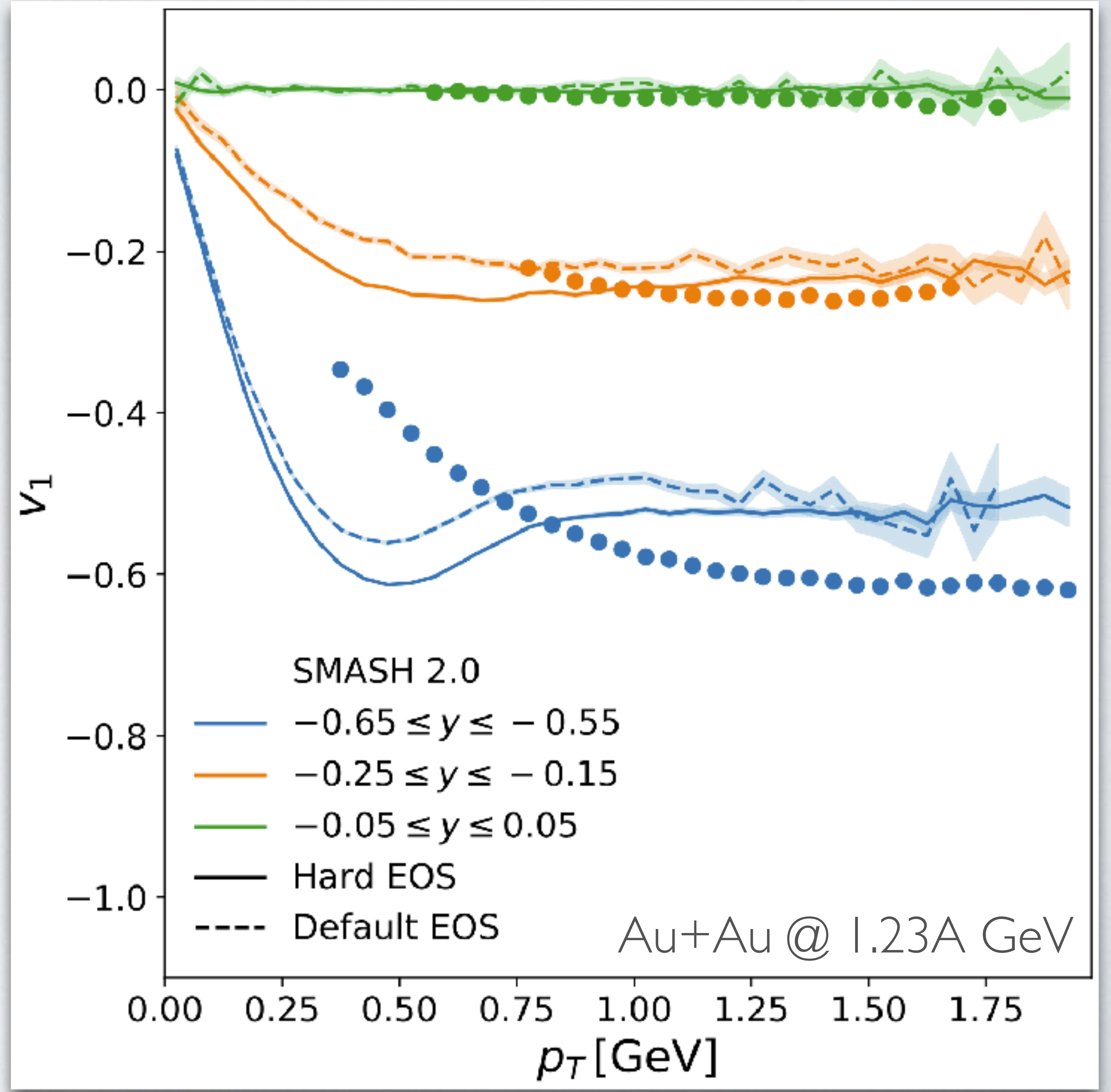
- Elliptic flow of nucleons at large transverse momenta underestimated → Need to improve model and comparison to data

DIRECTED FLOW OF DEUTERONS

- Calculate the directed flow of deuterons in the case where they are dynamically treated as active degrees of freedom

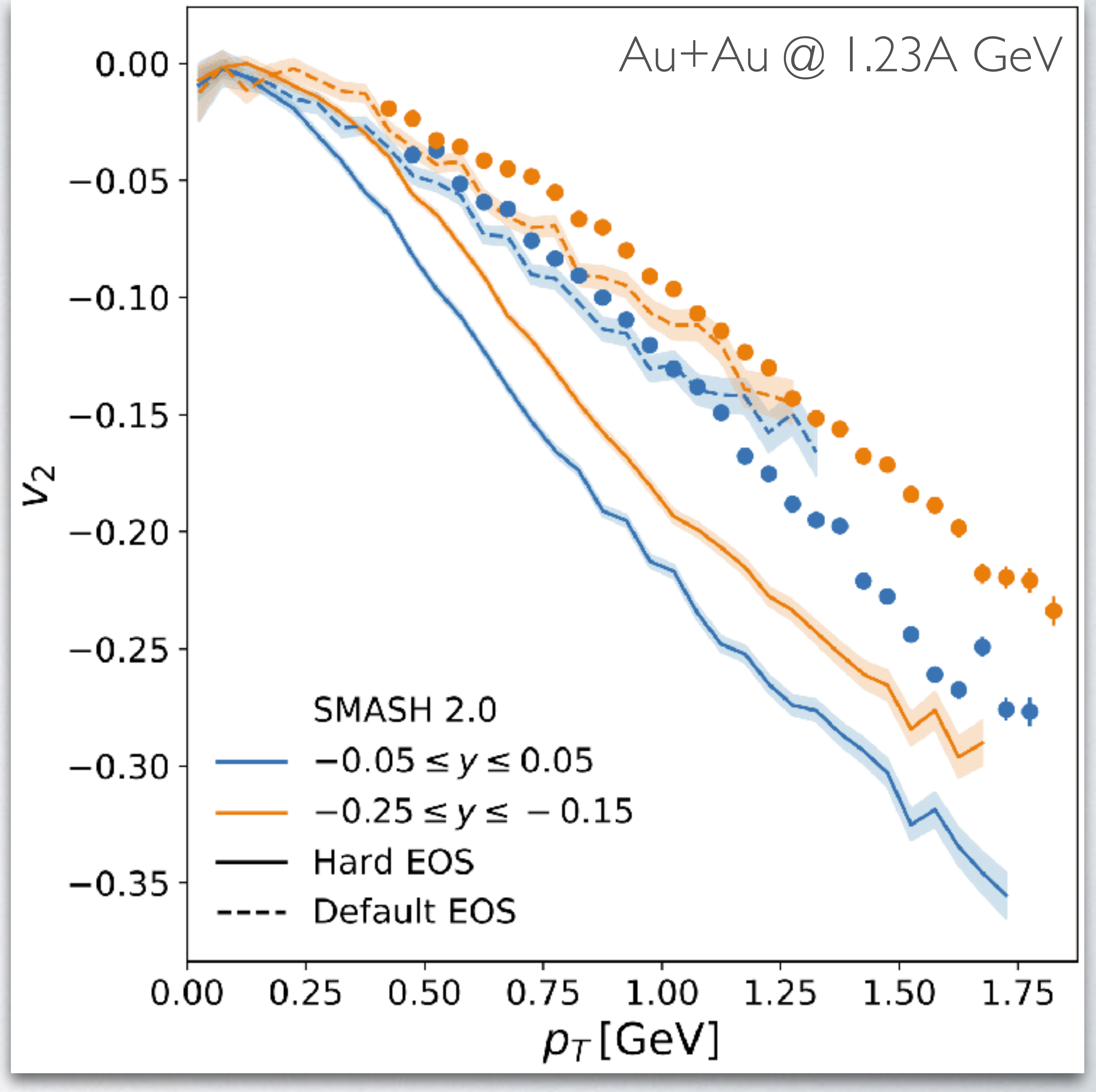
- Describe the data reasonably well but low transverse momentum region at forward rapidity is difficult to reproduce

- No strong dependence on the EoS is observed



ELLIPTIC FLOW OF DEUTERONS

- Elliptic flow of deuterons shows a stronger sensitivity to the EoS
- Data is well described with a softer EoS than the one needed to match the flow of nucleons
- Improve potentials are needed



WHERE CAN WE LEARN ABOUT THE EQUATION OF STATE?

- Flow of light nuclei is sensitive to the EoS and has been measured with high precision

- Allows to constrain EoS but is very challenging to describe

SUMMARY AND CONCLUSIONS

- Calculated directed and elliptic flow of protons and deuterons with simple potentials
- Directed flow is reasonably well described with hard EoS but improvements are needed for elliptic flow
- Compared two ways of taking light nuclei formation into account and observed a strong sensitivity of flow especially at low transverse momenta