TOWARDS CONSTRAINTS ON THE EQUATION OF STATE WITH SMASH

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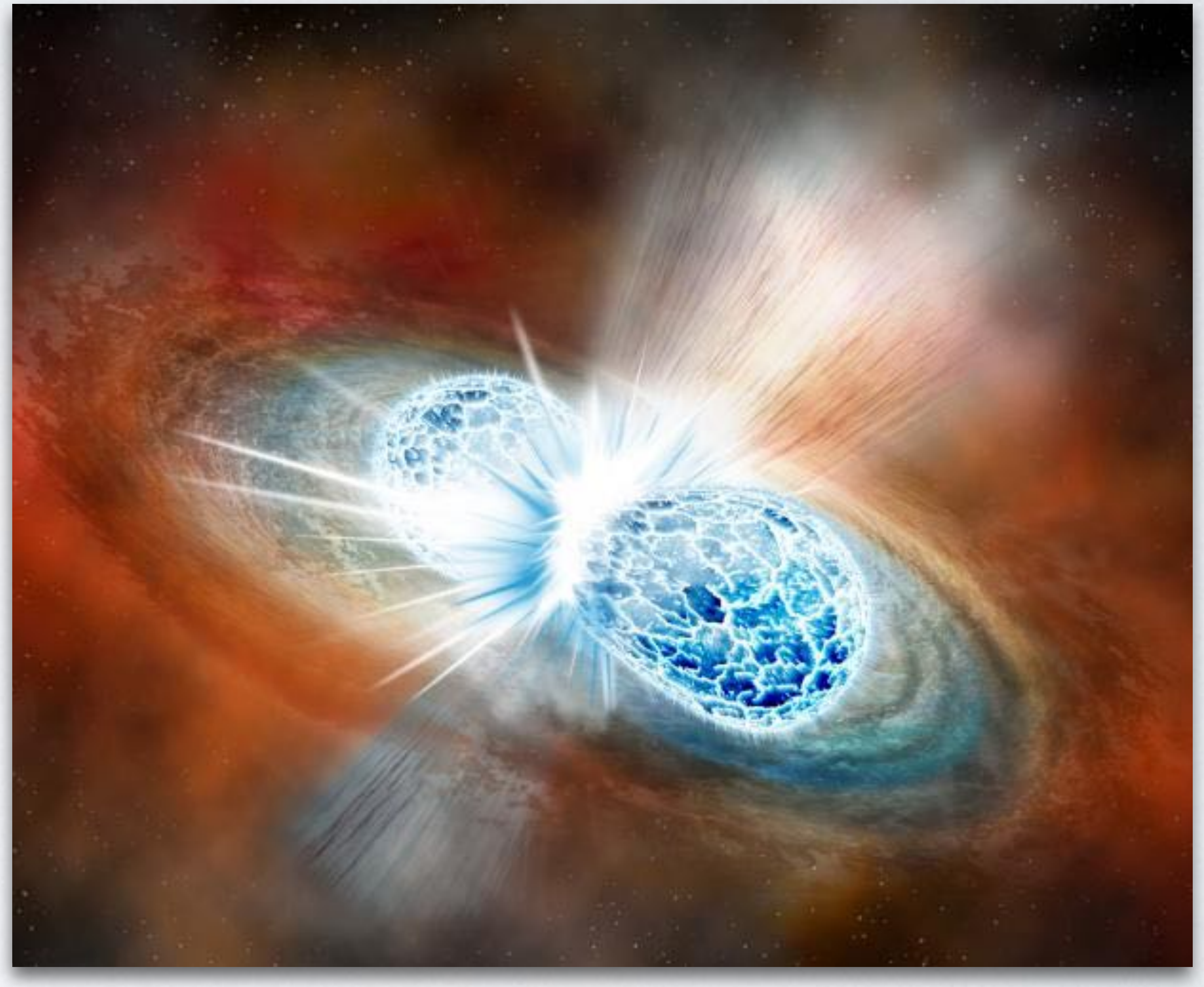
GSI

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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

EQUATION OF STATE FROM TRANSPORT CALCULATIONS

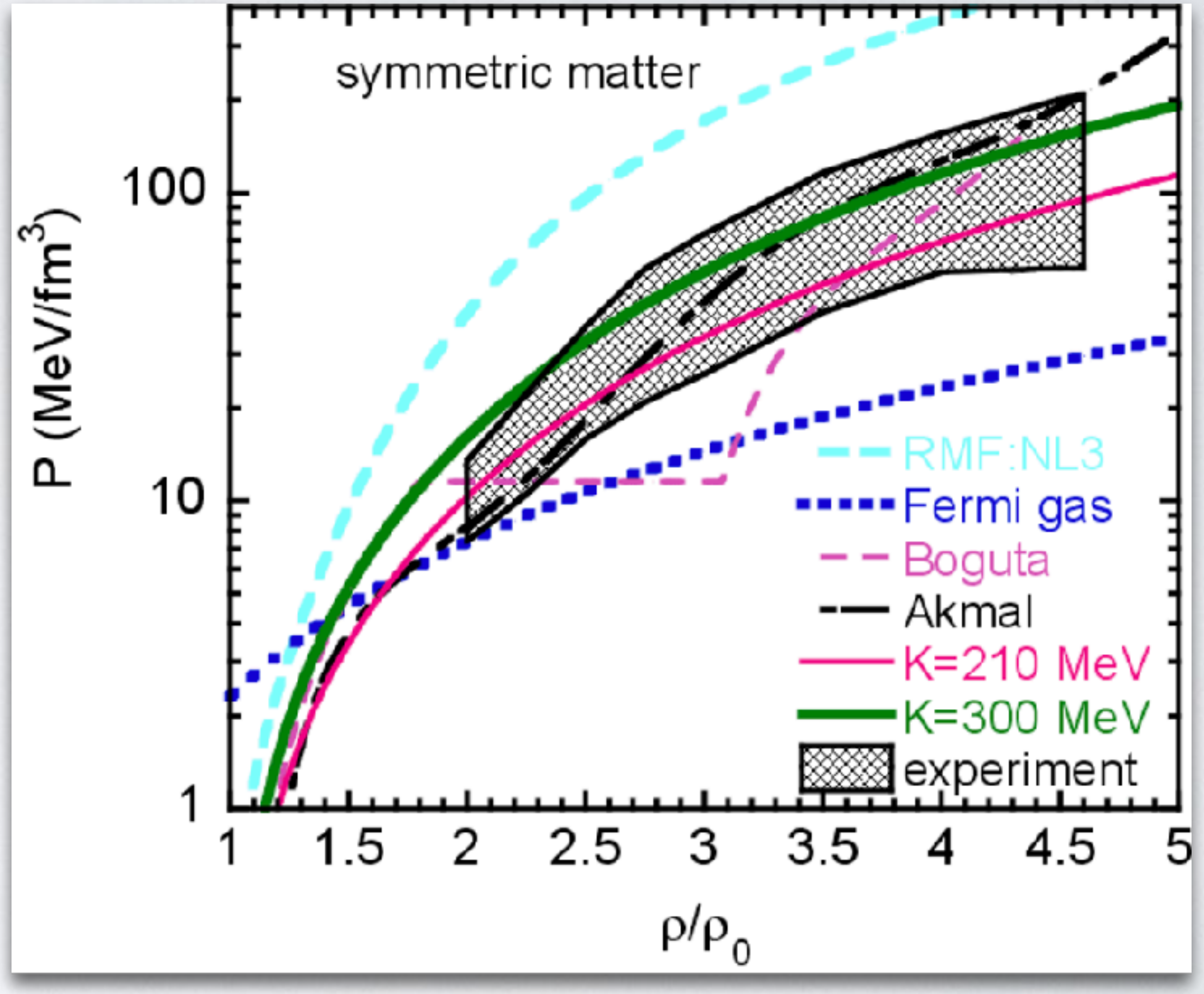
- Transport codes are compared with directed and elliptic flow data to extract the stiffness of the EoS

- 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

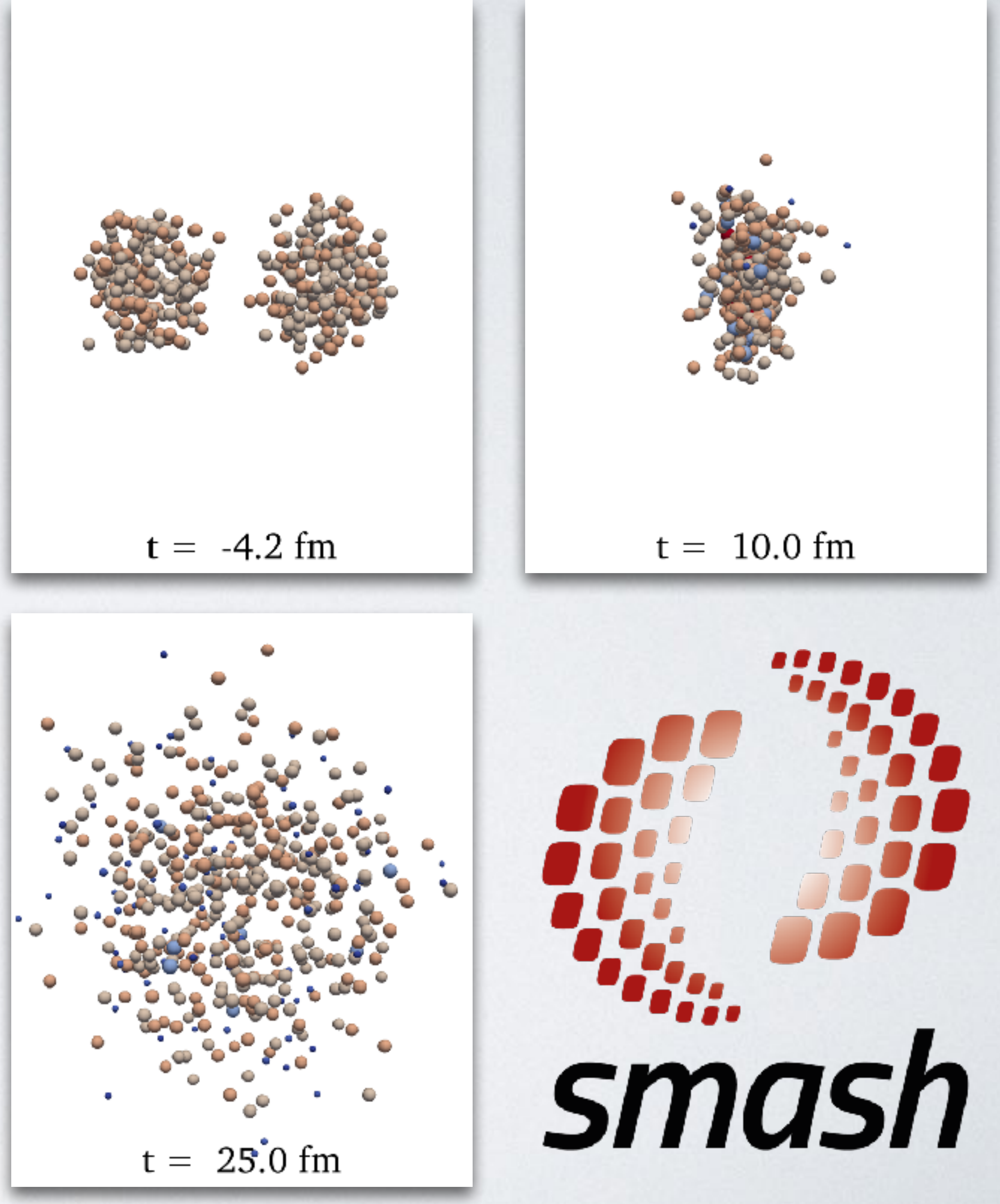
  J. Molitoris, H.Stöcker Phys.Rev.C 32 (1985)
  Hillmann et al. J. Phys. G 45, 085101 (2018)



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 IN SMASH

- Use simple Skyrme and symmetry potential
- Densities and their derivatives are required to evaluate potentials
- Calculate densities using Gaussian smearing kernel

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

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

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

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

MOMENTUM-DEPENDENT POTENTIALS

- Nuclear potential should include a momentum dependence

- Implement the parametrisation by Welke et al.

G. M. Welke et al. Phys.Rev.C 38 (1988)
Used in GiBUU: O. Buss et al. Phys.Rept. 512 (2012)

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

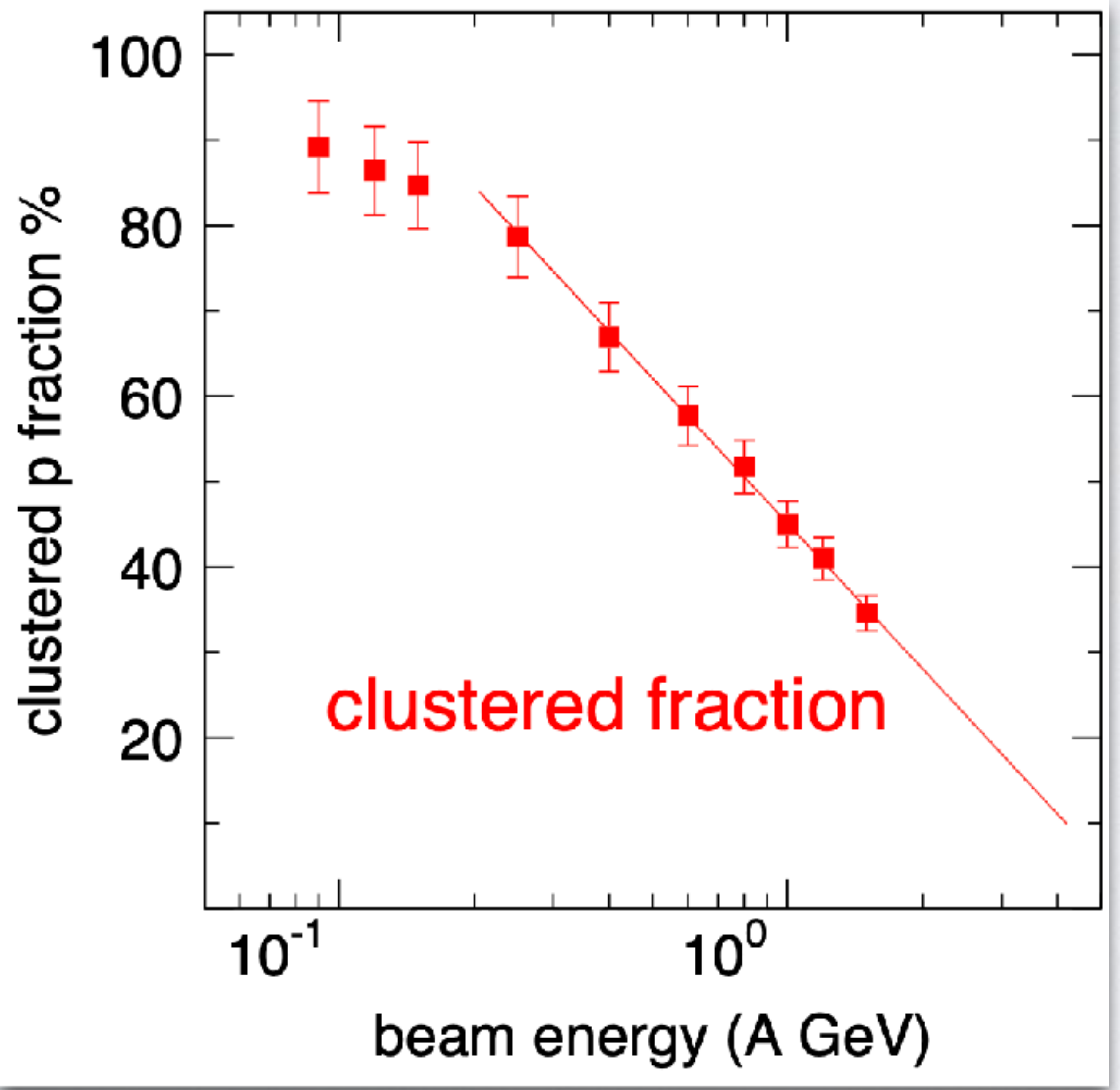
Skyrme Potential

Momentum-dependent part

- Integral is simplified assuming cold nuclear matter: $f(\mathbf{r},\mathbf{p}) = \Theta(p_F - p)$

- Single particle energy evaluated in local rest-frame for equation of motion $\dot{\mathbf{p}} = -\nabla E$

LIGHT NUCLEI FORMATION



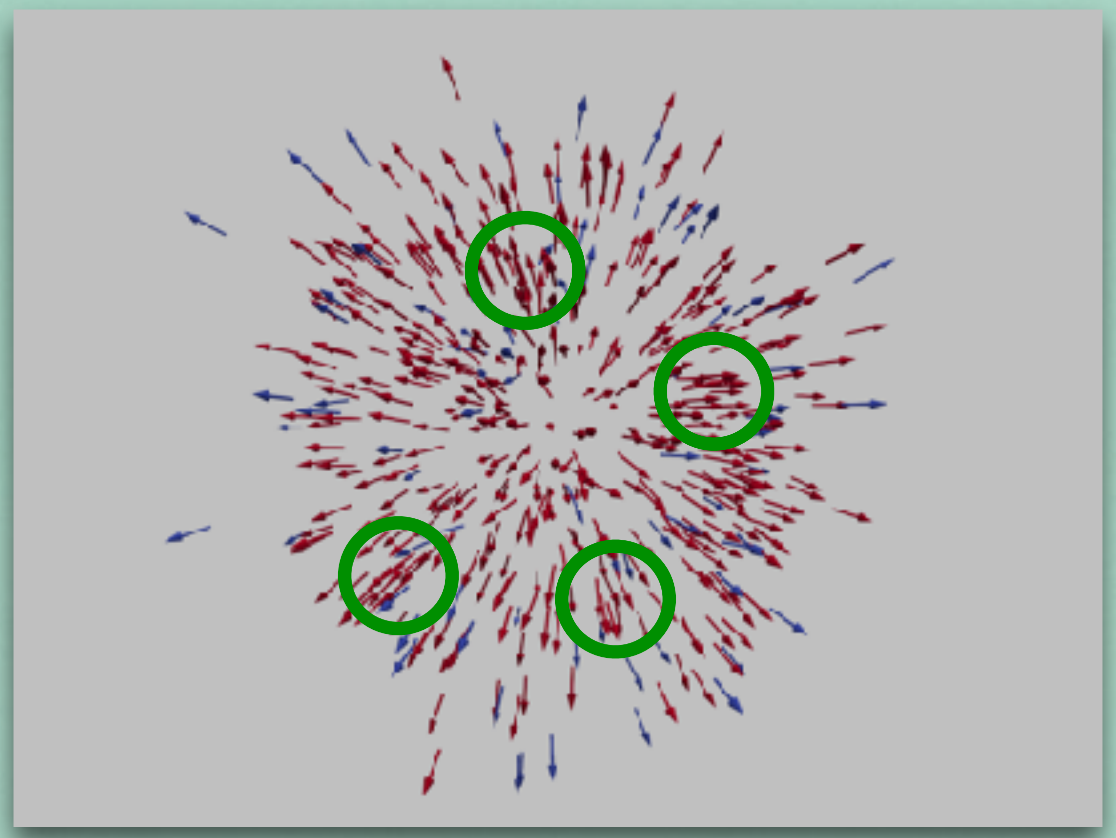
FOPI Nucl.Phys.A 848 (2010)

- 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

LIGHT NUCLEI FORMATION

Clustering

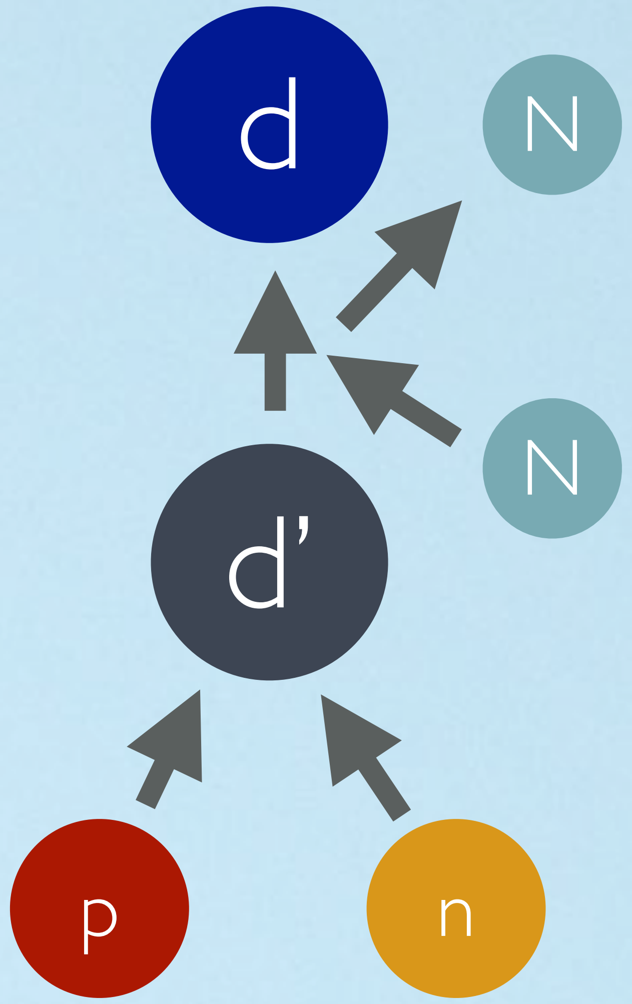
- Identify clusters in the final state



- Phase-space distance as a criterion

Dynamic deuterons

- Deuteron represented as a single particle

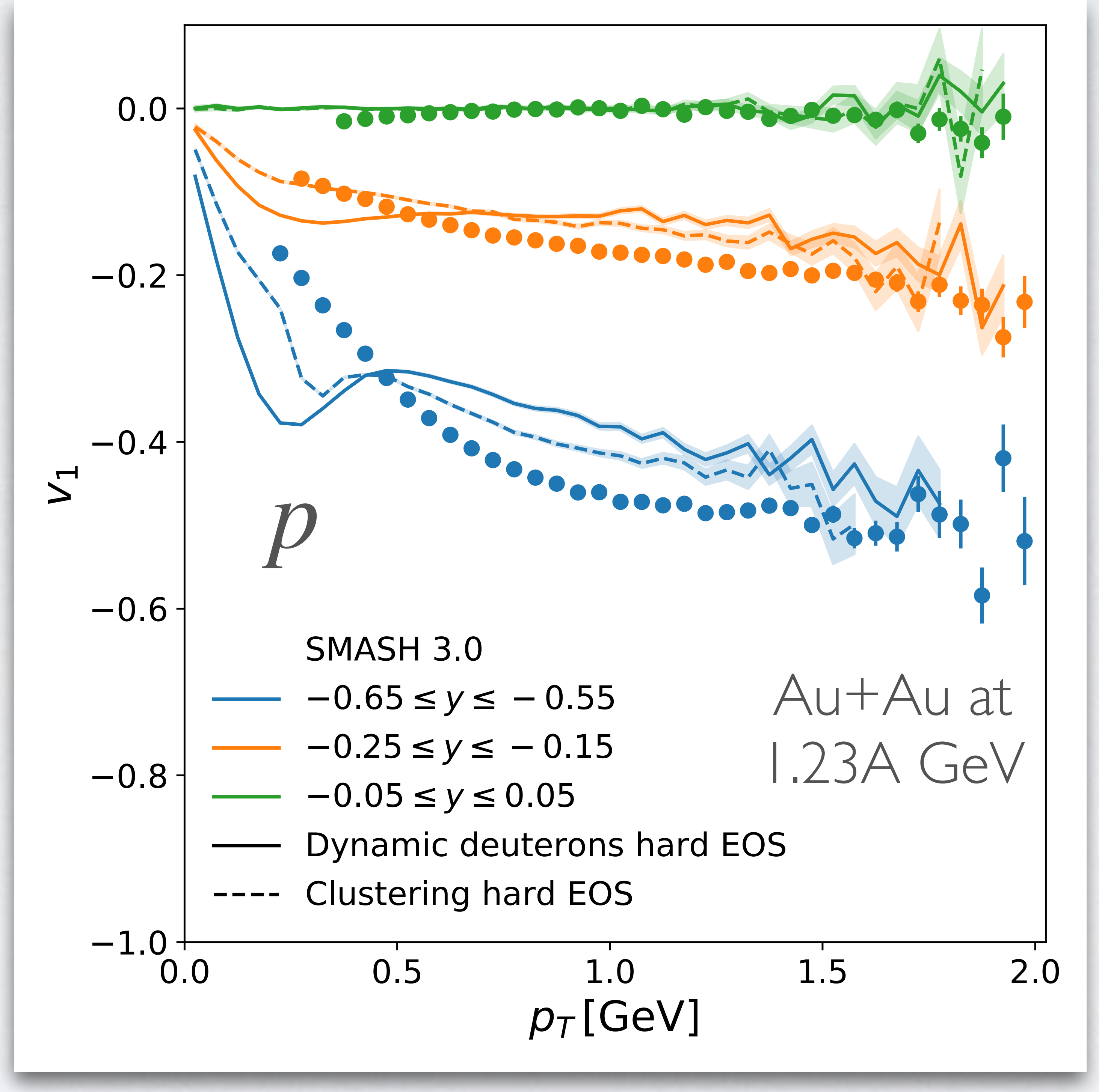


- Dynamically propagated until destroyed

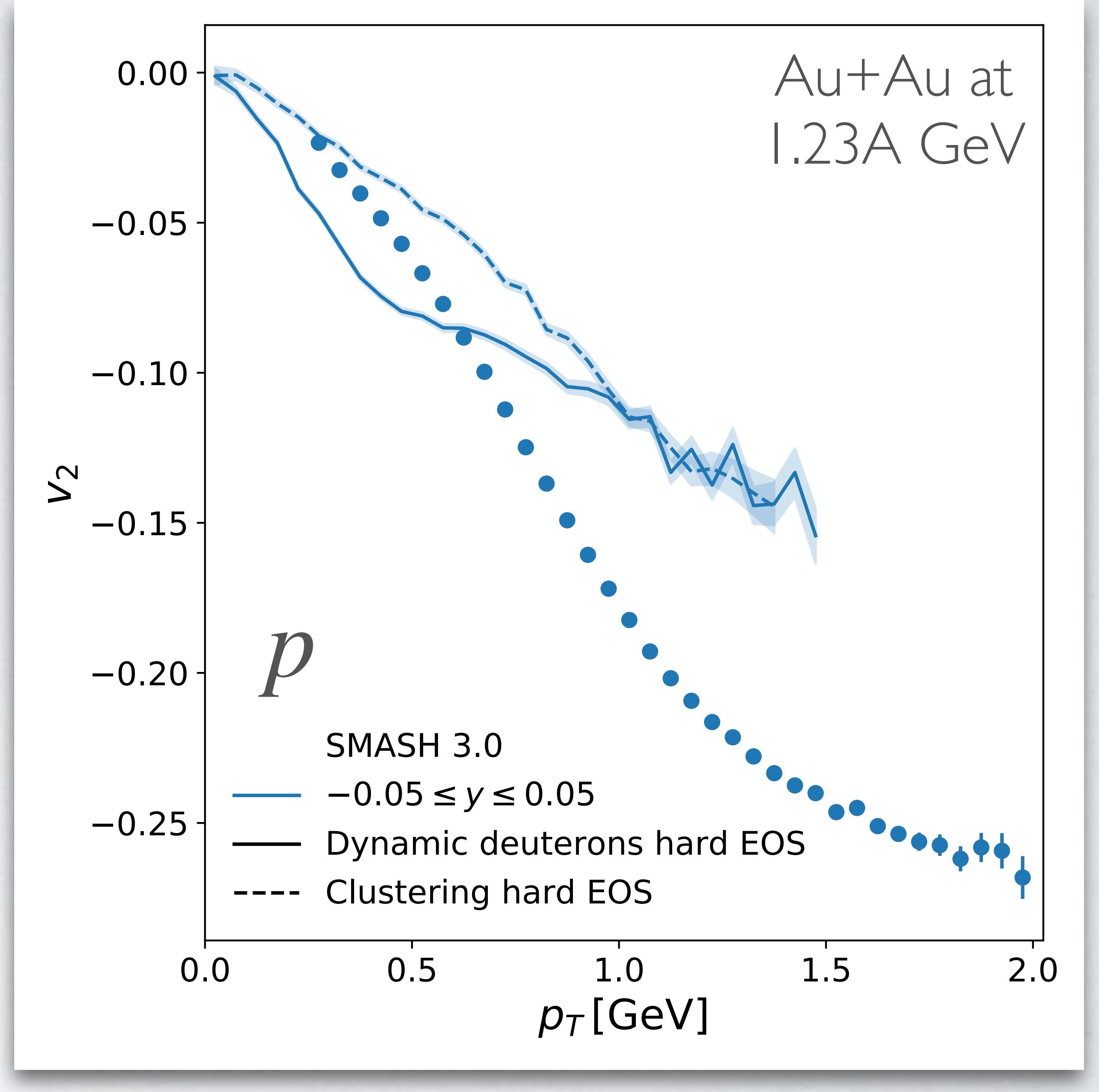
Oliinychenko et al. Phys.Rev.C 99 (2019)

FLOW NUCLEI FORMATION

- Comparing directed and elliptic flow of clustering versus dynamical treatment of deuterons
- Observe strong sensitivity at low transverse momenta
- Flow at larger p_T mainly depends on potentials



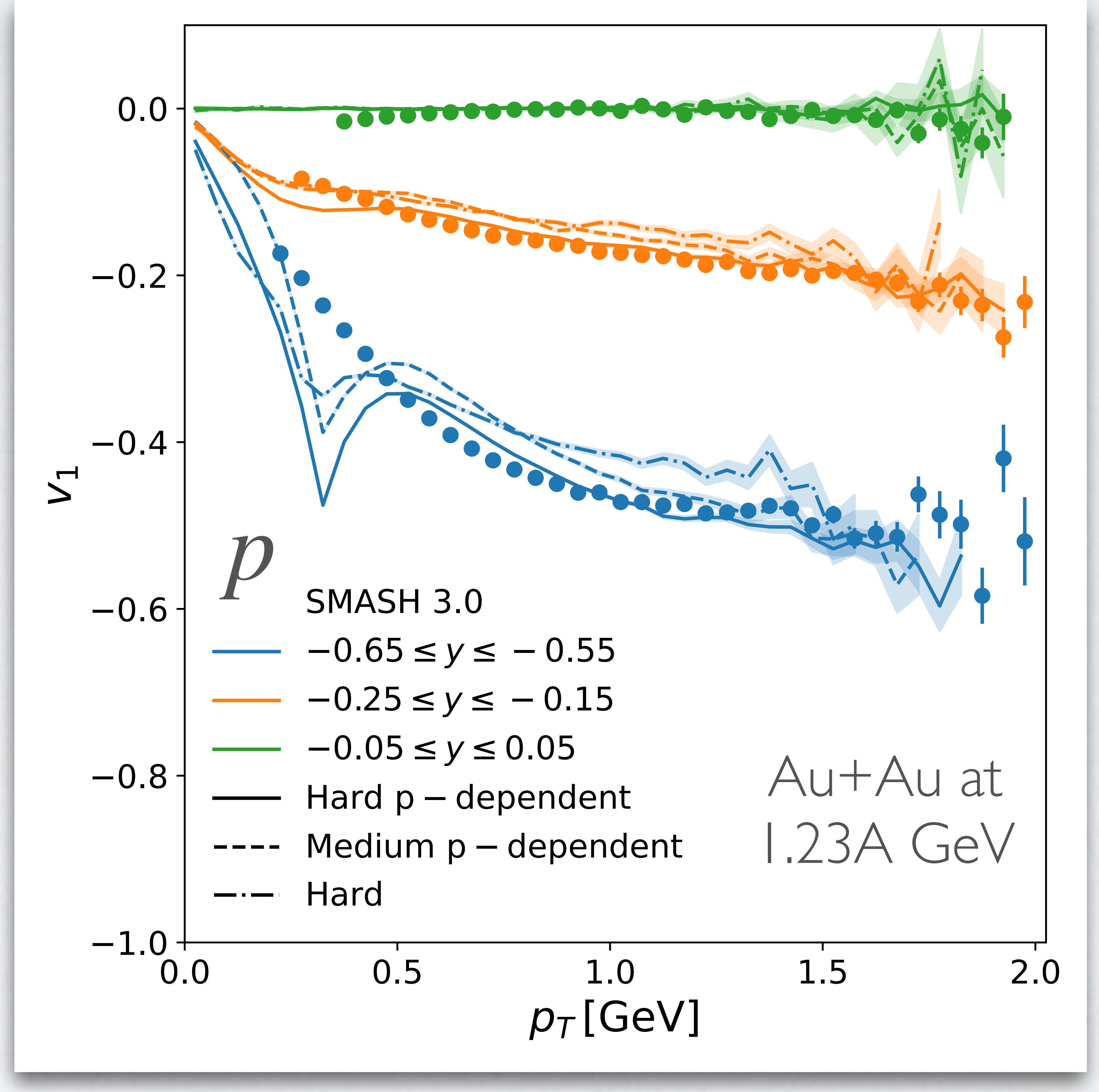
20%-30% centrality
preliminary HADES data
B. Kardan Nucl. Phys. A 967 (2017)



20%-30% centrality
HADES data
Eur. Phys. J. A 59 (2023)

FLOW EOS DEPENDENCE

- Decent description of directed flow for all EOS
- Elliptic flow is enhanced by addition of momentum dependence
- Hard momentum-dependent EOS required to obtain enough elliptic flow



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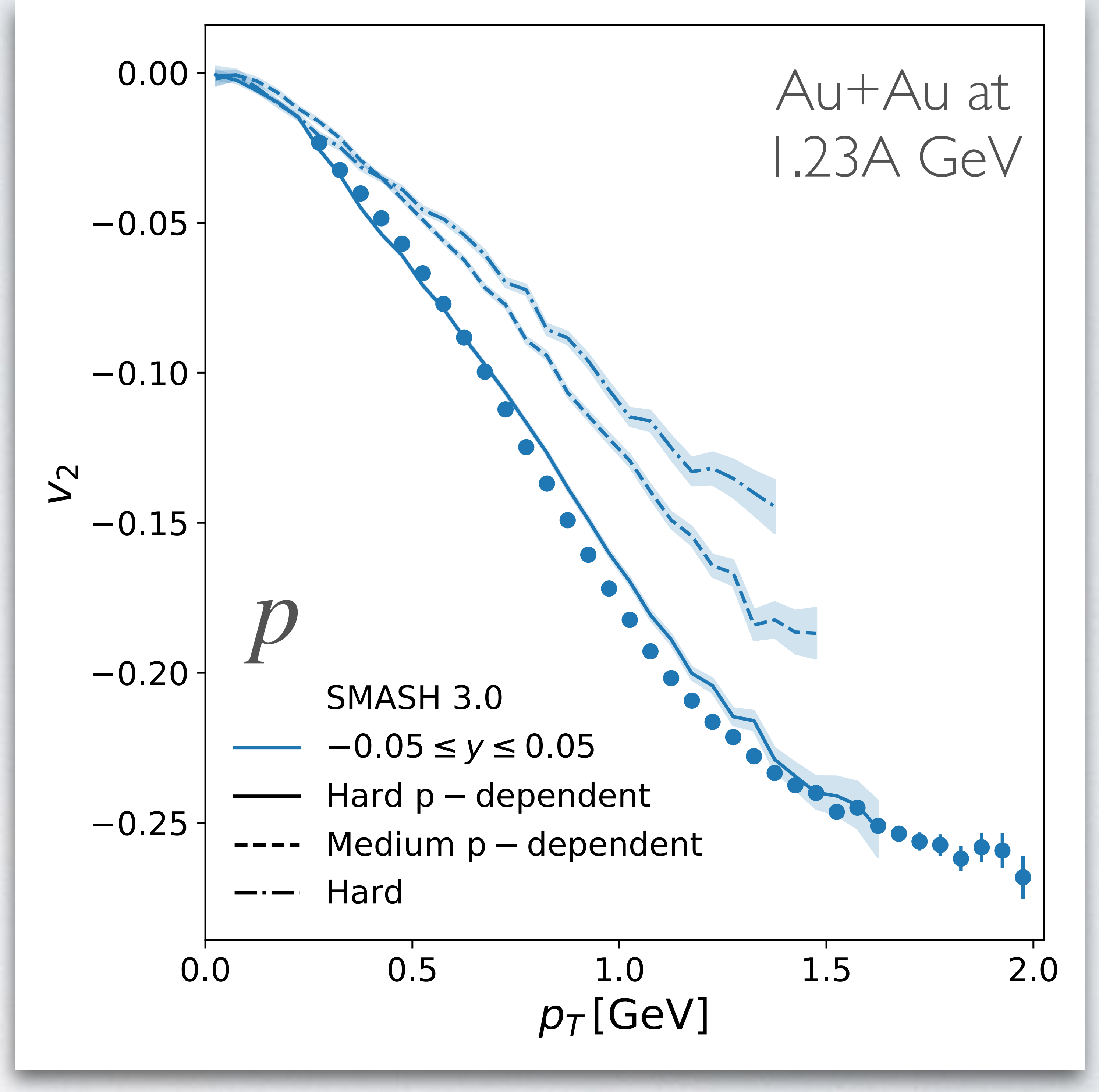
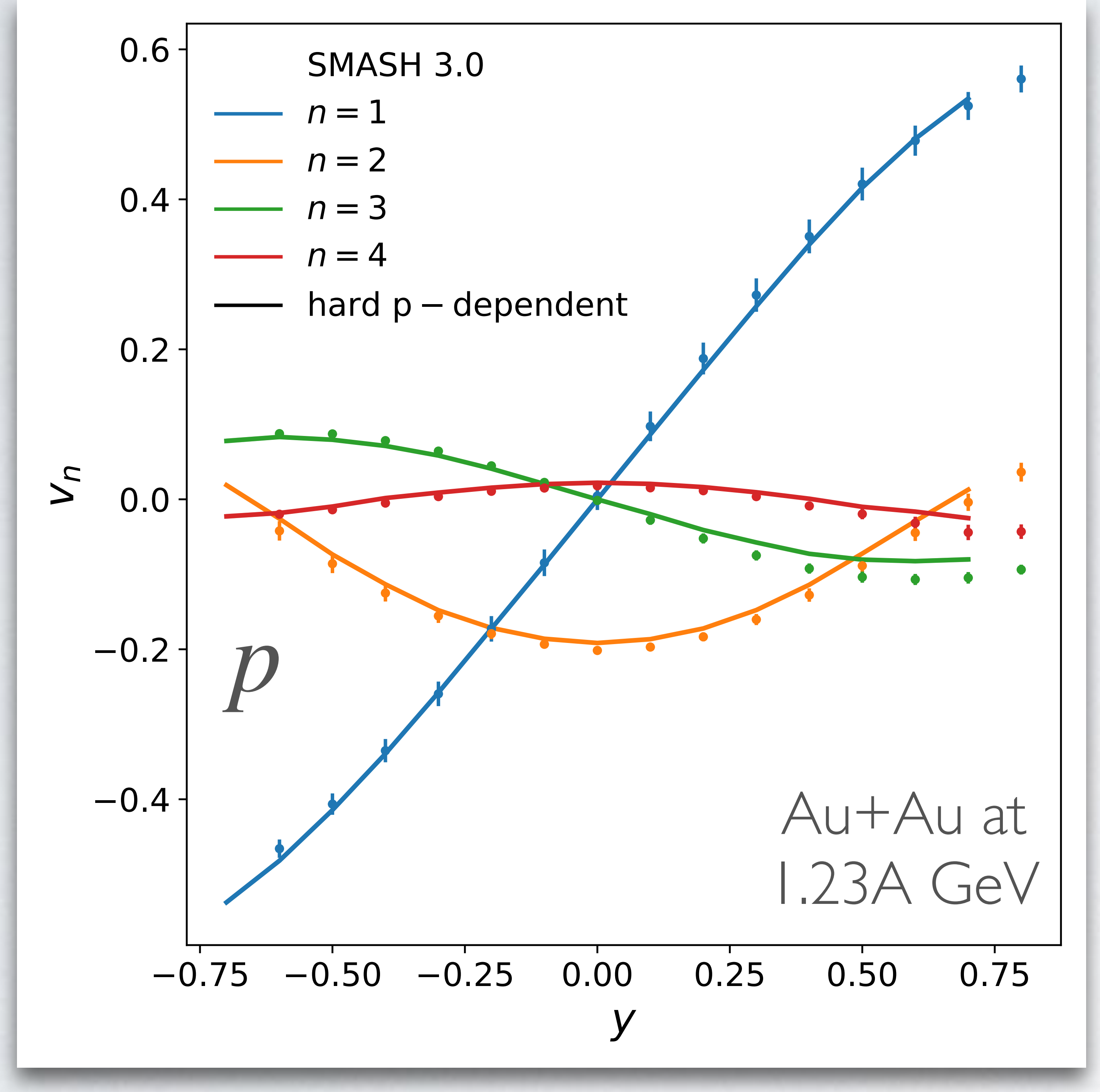
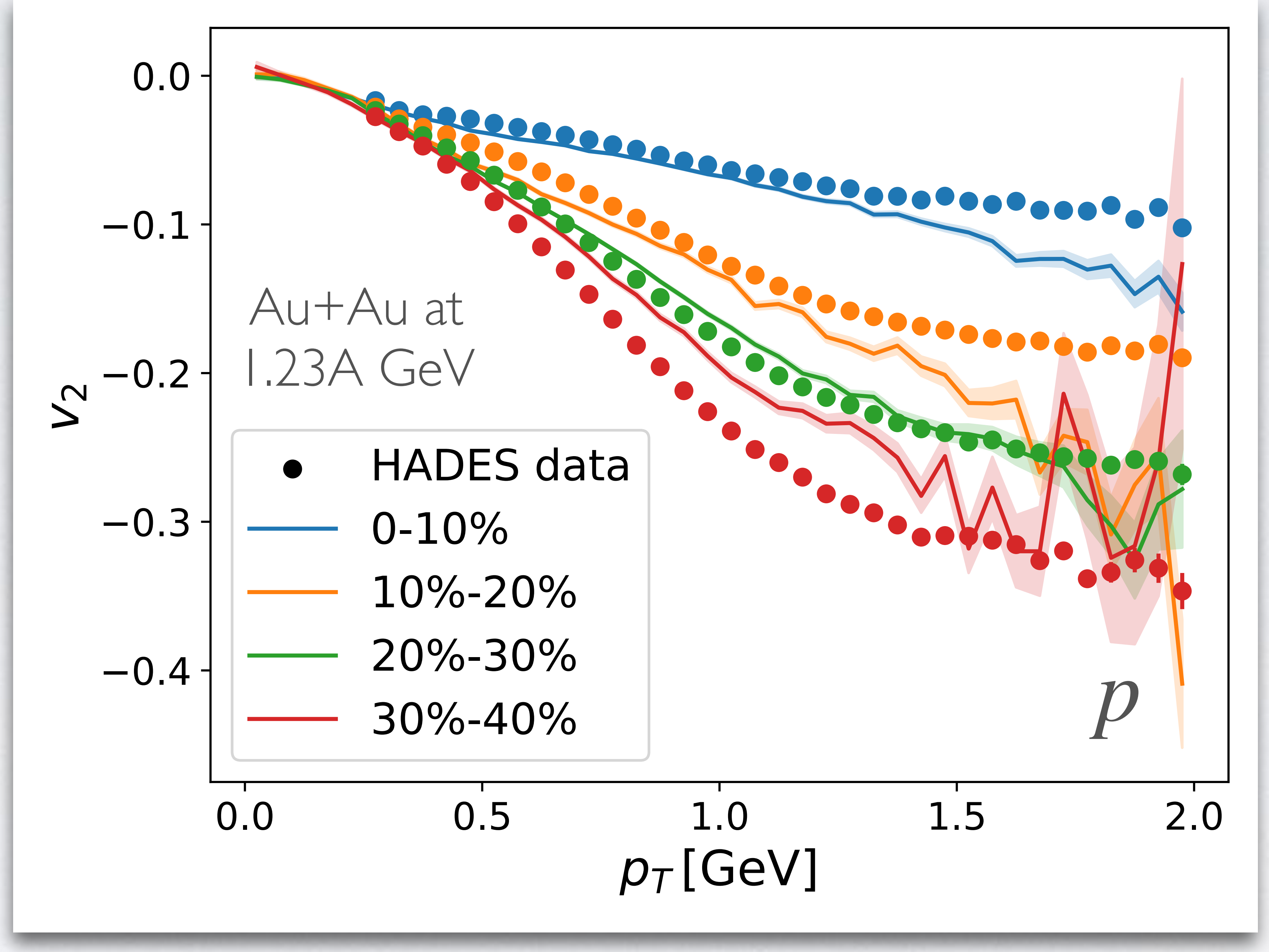


20%-30% centrality
HADES data
Eur. Phys. J. A 59 (2023)

PROTON FLOW OVERVIEW



HADES data
Phys. Rev. Lett. 125 (2020)

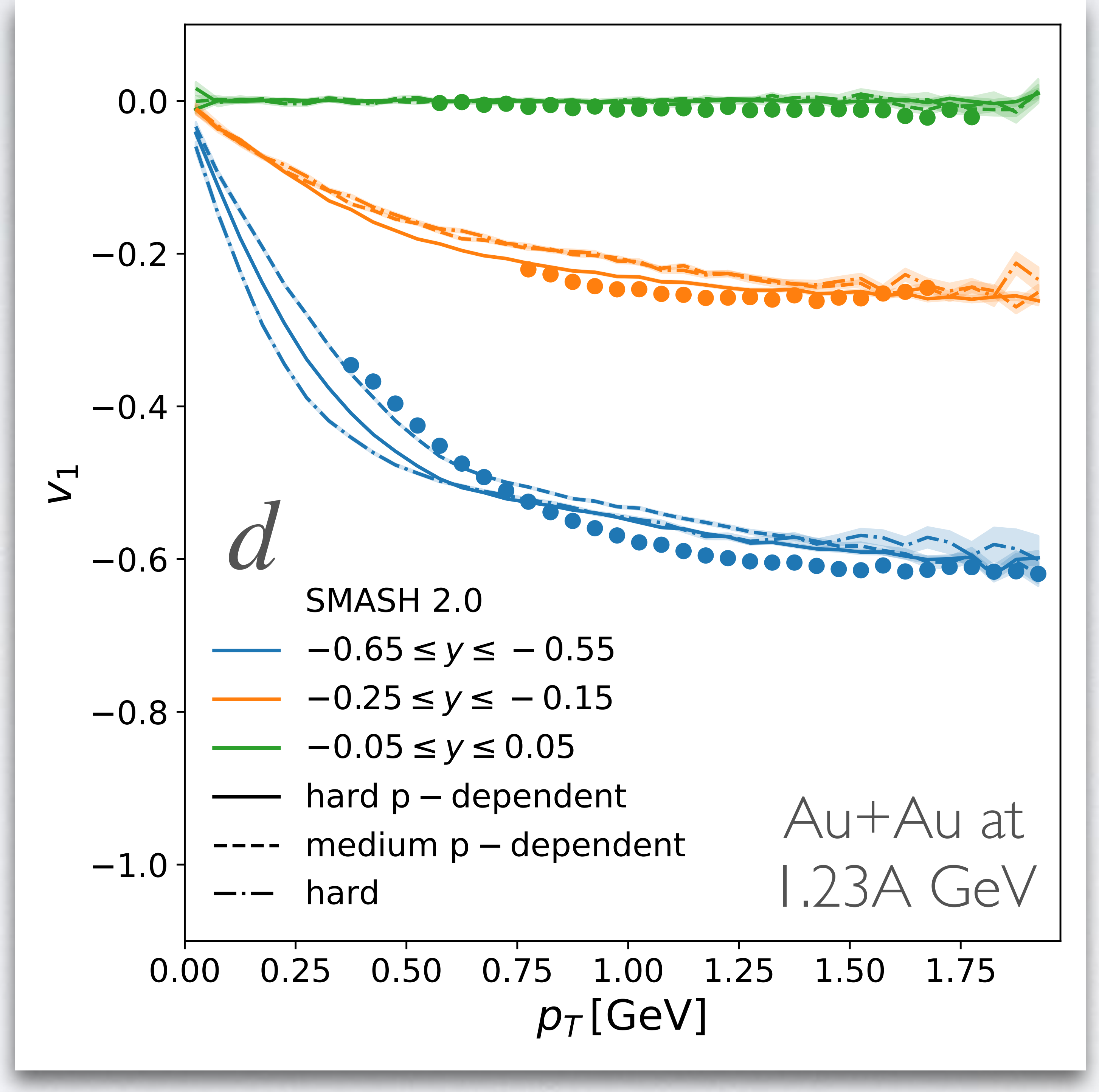


Hard momentum-dependent EOS
HADES data
Eur. Phys. J. A 59 (2023)

- Using hard momentum-dependent EOS
- Centrality dependence reasonable but working on better centrality selection

DEUTERON FLOW

- All EOS give a reasonable description of the directed flow
- Elliptic flow slightly overestimated with hard momentum-dependent EOS



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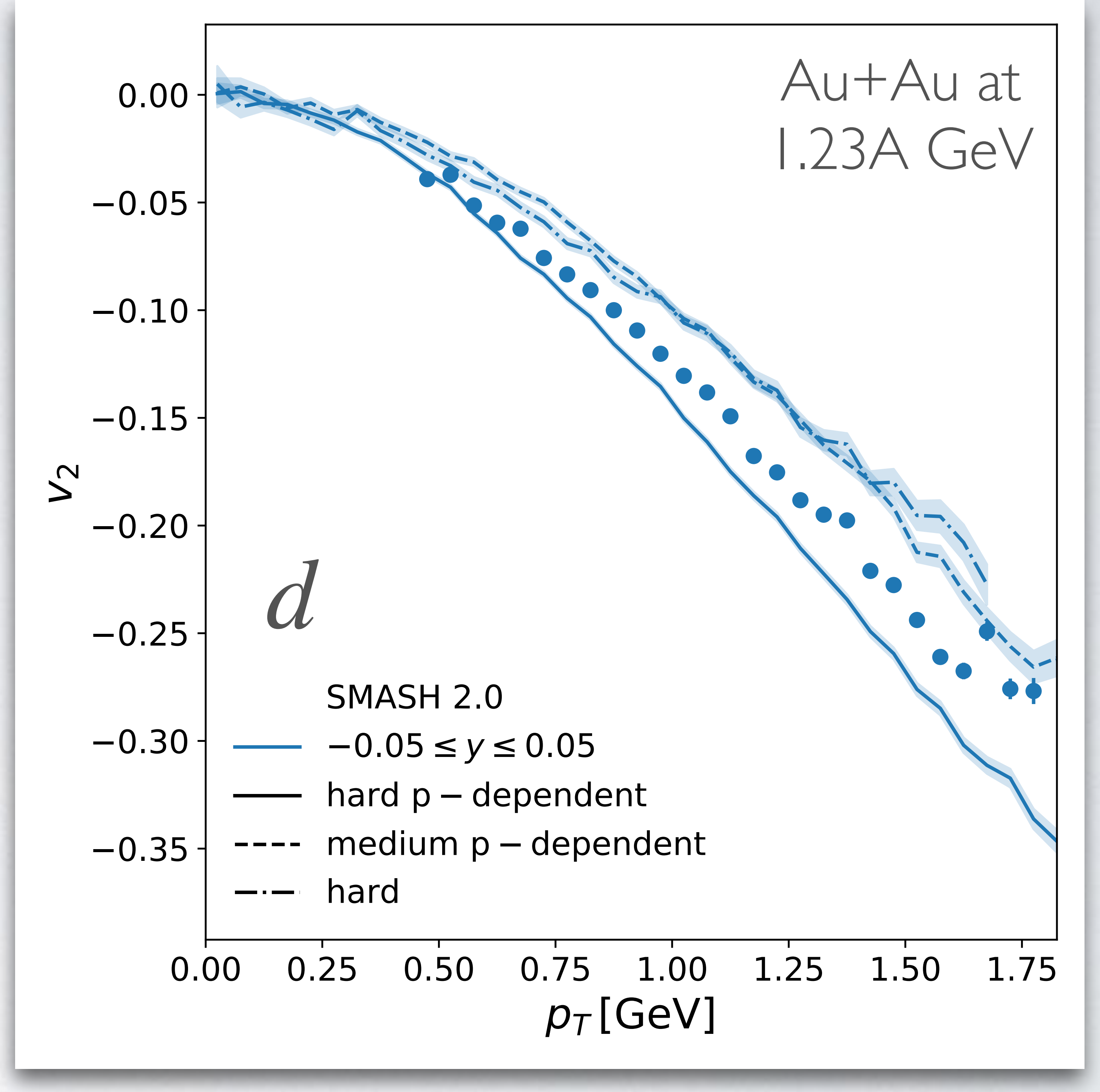
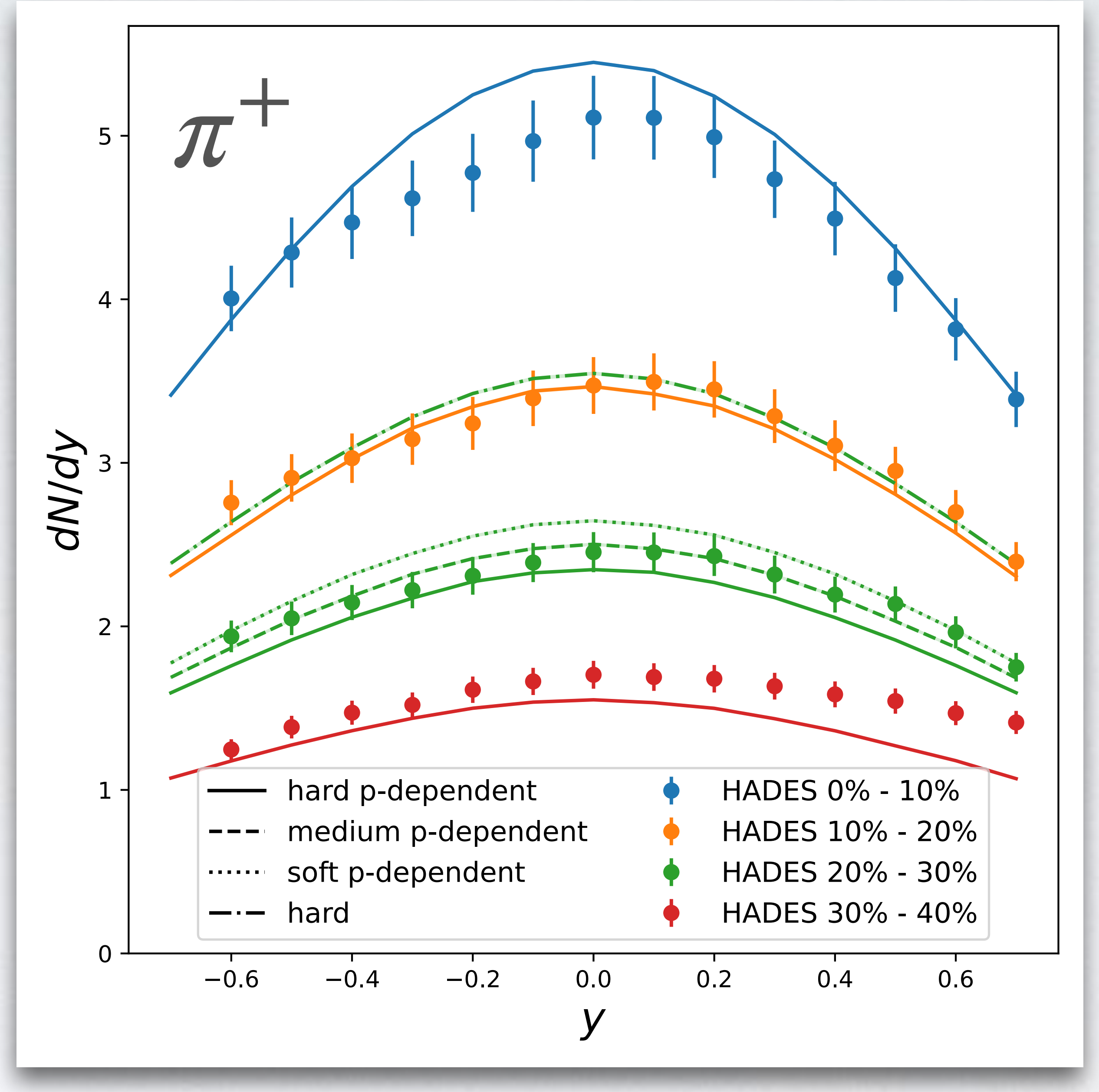
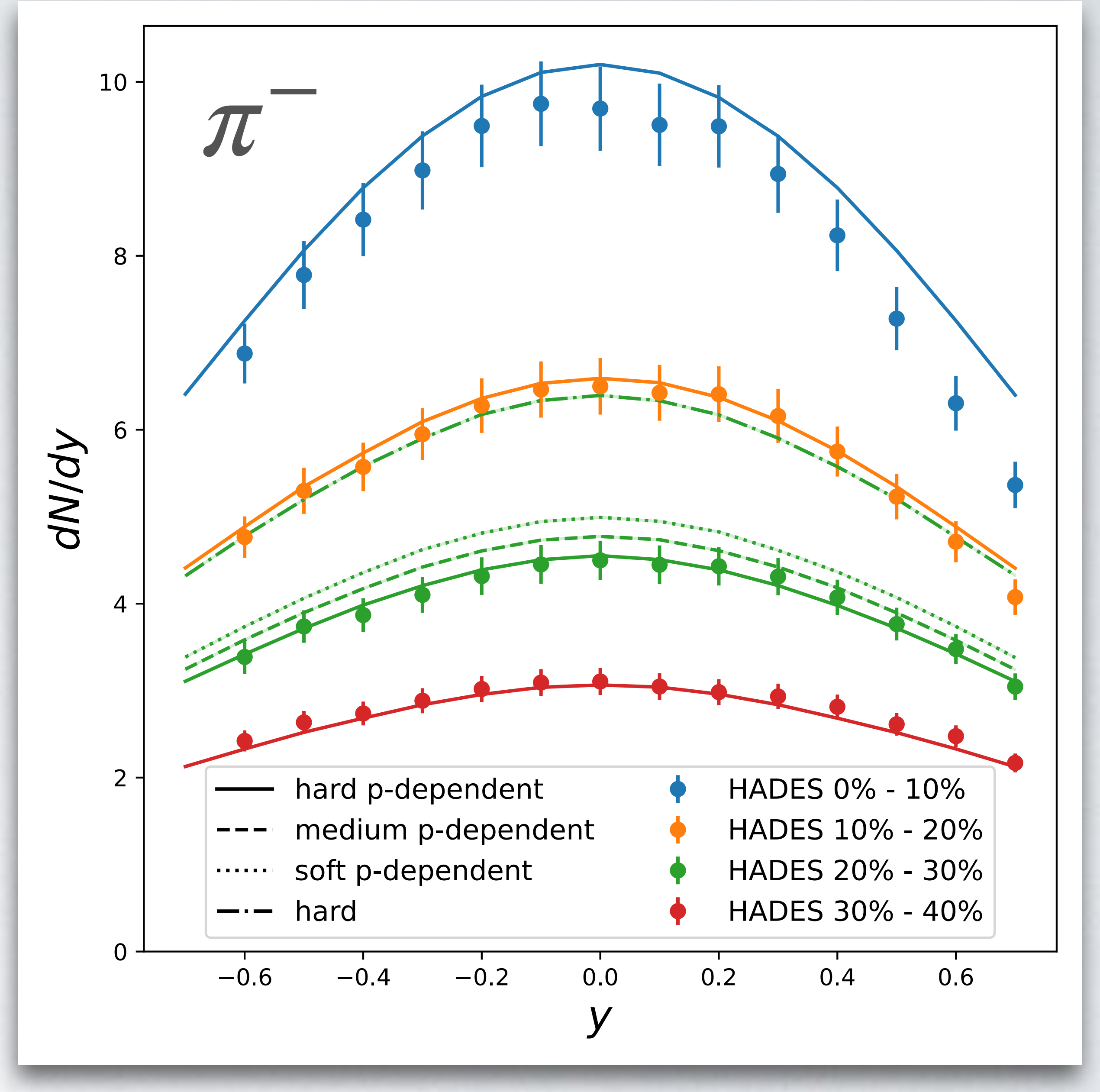


20%-30% centrality
preliminary HADES data
B. Kardan Nucl. Phys. A 967 (2017)

PION PRODUCTION

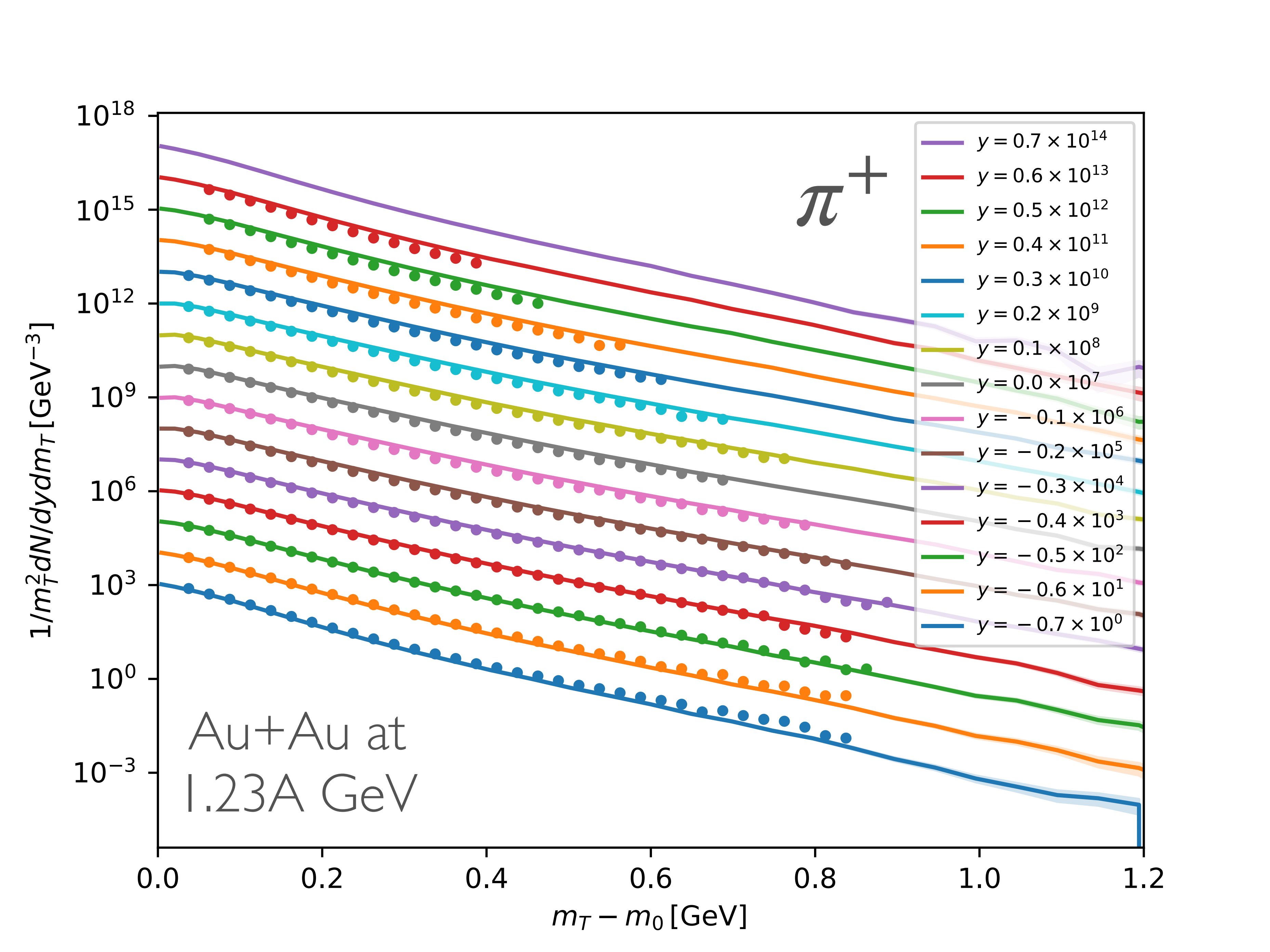
- Pion production compared to HADES data
- Stiffer EOS reduces pion yield
- Including momentum dependence strongly reduces pion yield
- Pion yields are described with the same EOS as proton flow

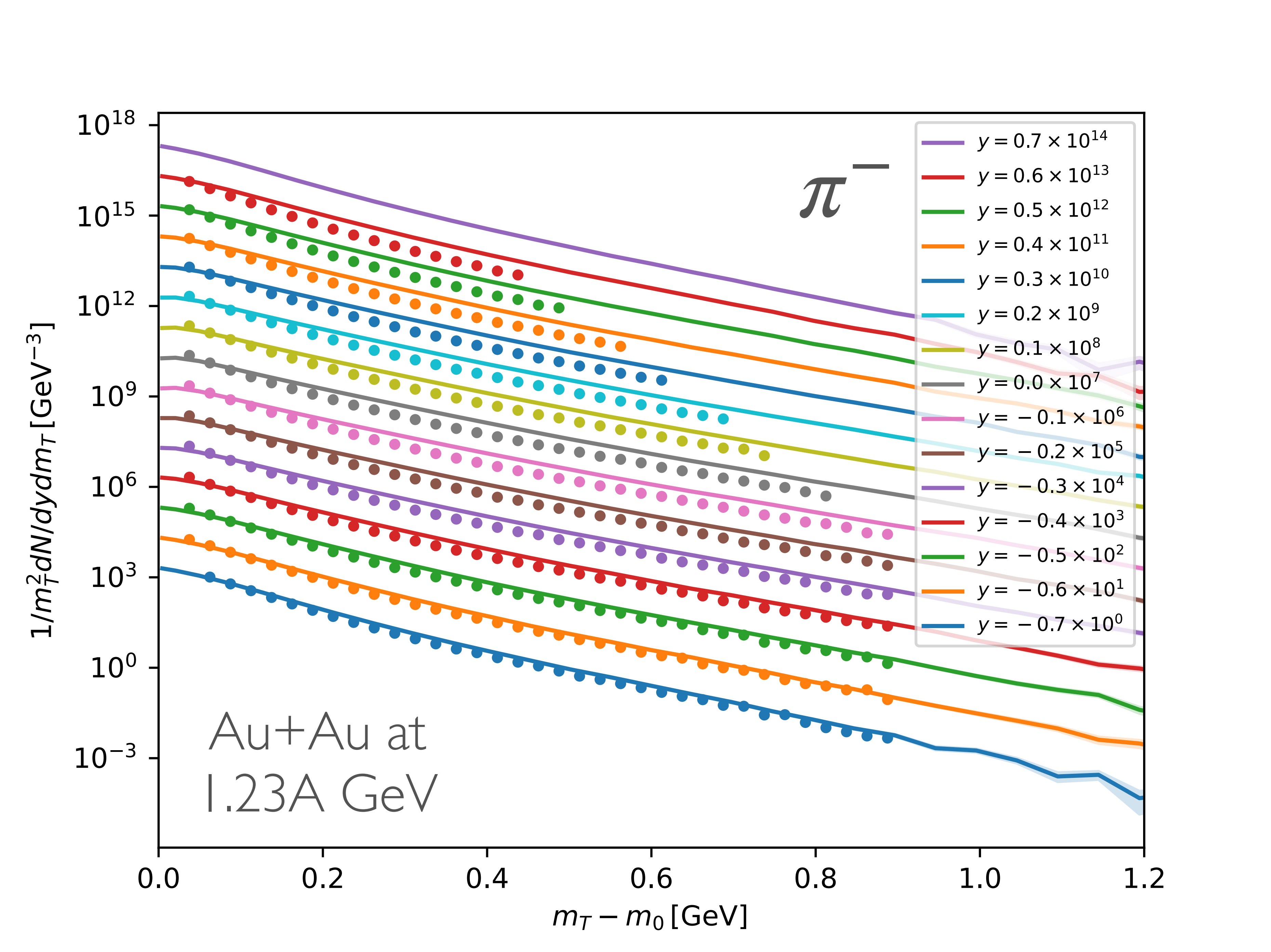




Au+Au at 1.23A GeV
Hades data
Eur. Phys. J. A 56 (2020)

PION PRODUCTION





Comparing hard momentum-dependent potentials to 0-10% centrality Hades data

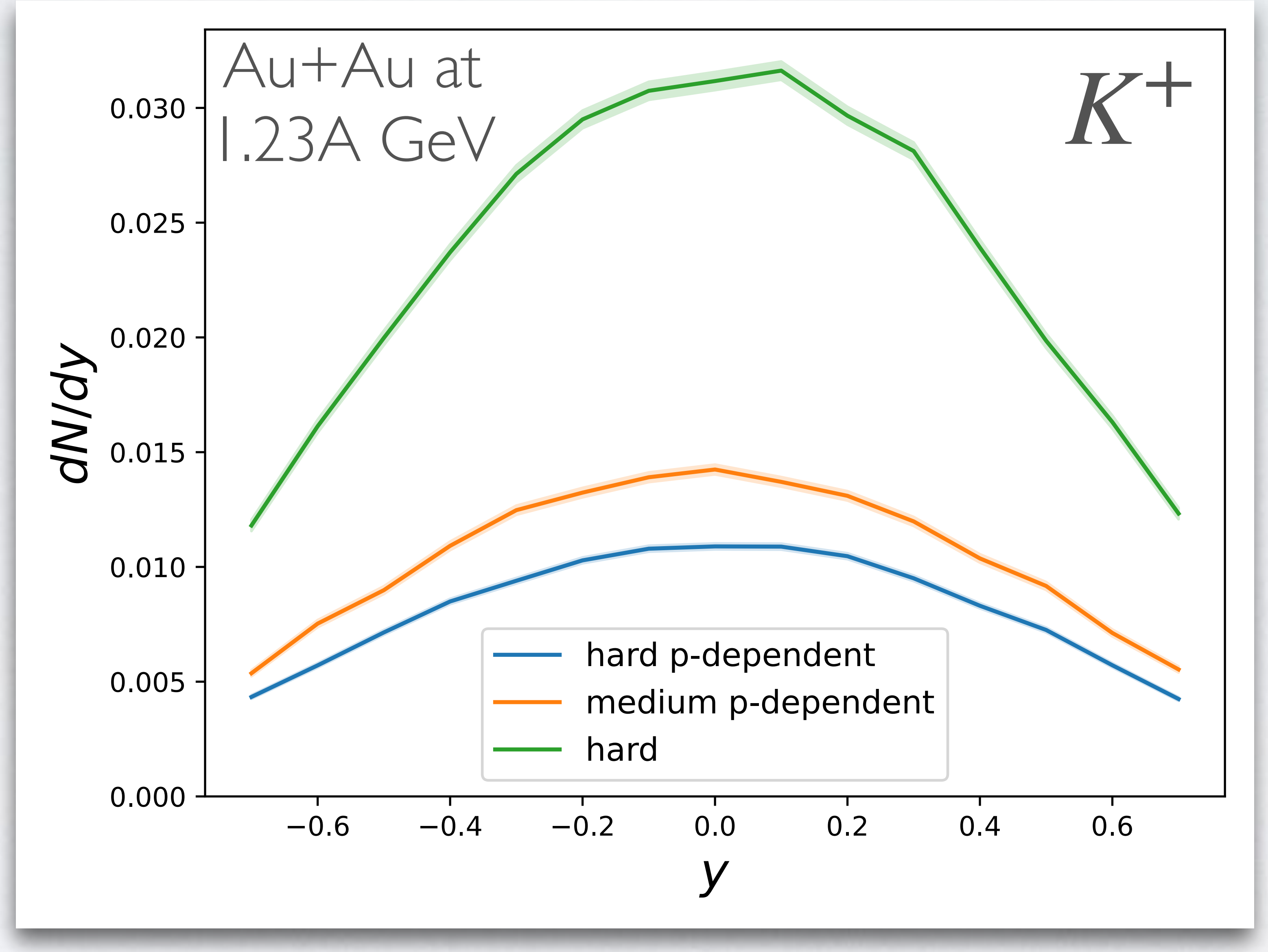
HADES Eur.Phys.J.A 56 (2020)

- Slope and yield of transverse mass spectrum are reasonable

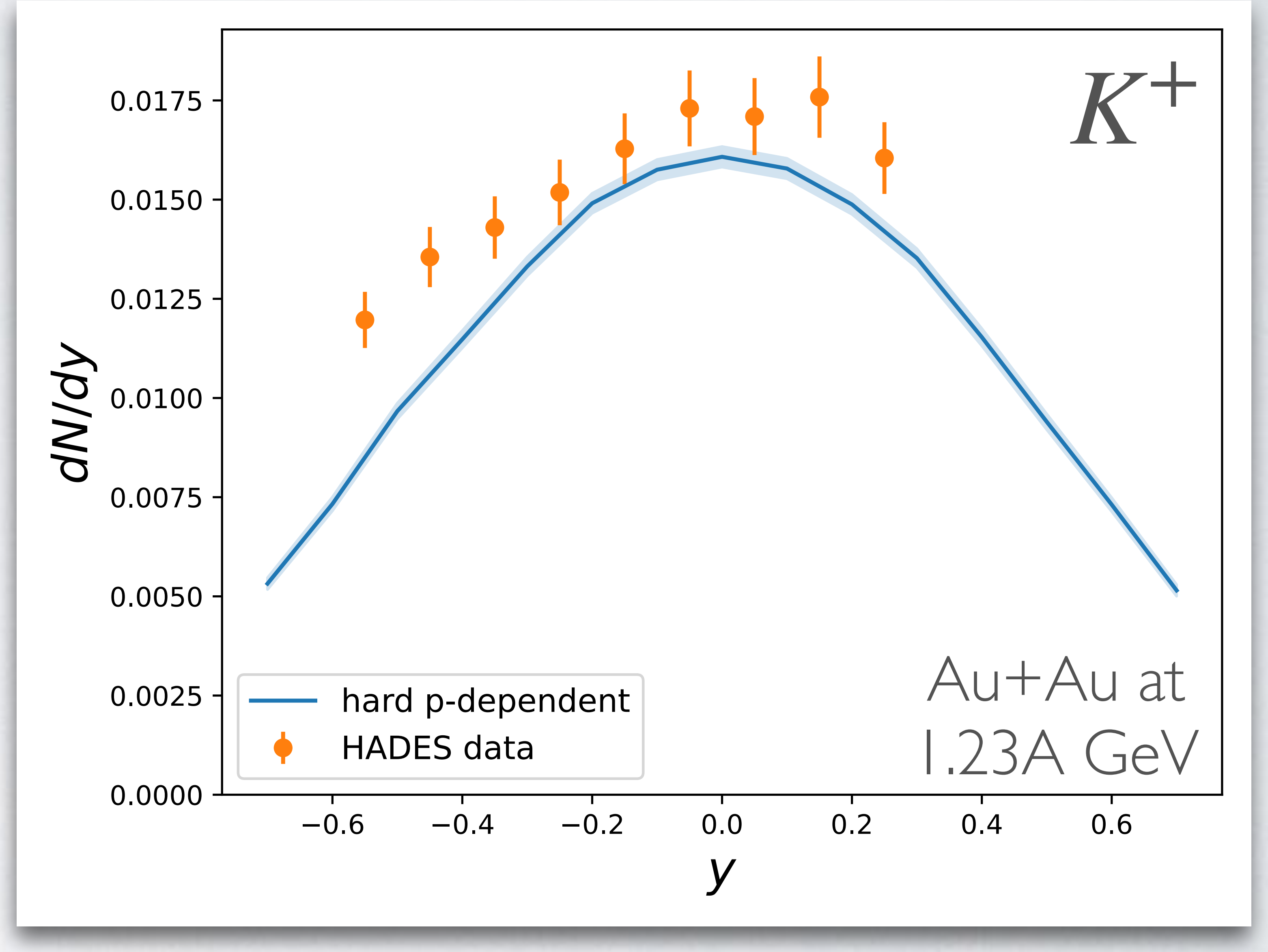
KAON PRODUCTION

- Strong sensitivity to EOS
- No Kaon potentials included
- Kaon yield strongly decreases when including momentum dependence

Hartnack et al. Nucl.Phys.A 580 (1994)



20%-30% centrality



0%-40% centrality
HADES data
Phys. Lett. B 778 (2018)

- Kaon yield described when including momentum-dependence

SUMMARY AND CONCLUSION

- Compared different methods of taking light nuclei formation into account and found sensitivity at low transverse momenta
- Implemented momentum-dependent potentials
- Proton flow is best described by hard EOS with momentum dependence
- Meson spectra improve by adding momentum dependence
- Put systematic constraint on EOS in the future