Does non-monotonic behavior of Directed flow signal the onset of Deconfinment?

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We compute beam energy dependence of the directed flow within a hadronic transport approach:

JAM + hadronic mean field + nuclear cluster + SMD

Quark matter 2015 at Kobe Japan, Sep. 30 2015

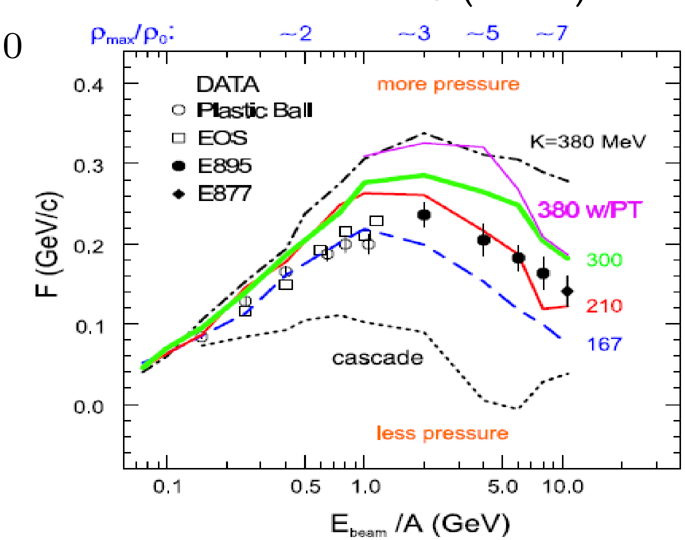
Determination of EOS at high density from an anisotropic flow in heavy ion collisions

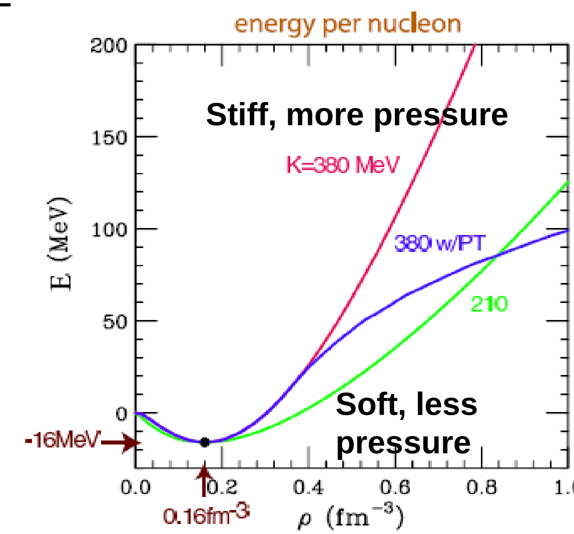
Fourier decomposition of single particle inclusive spectra:

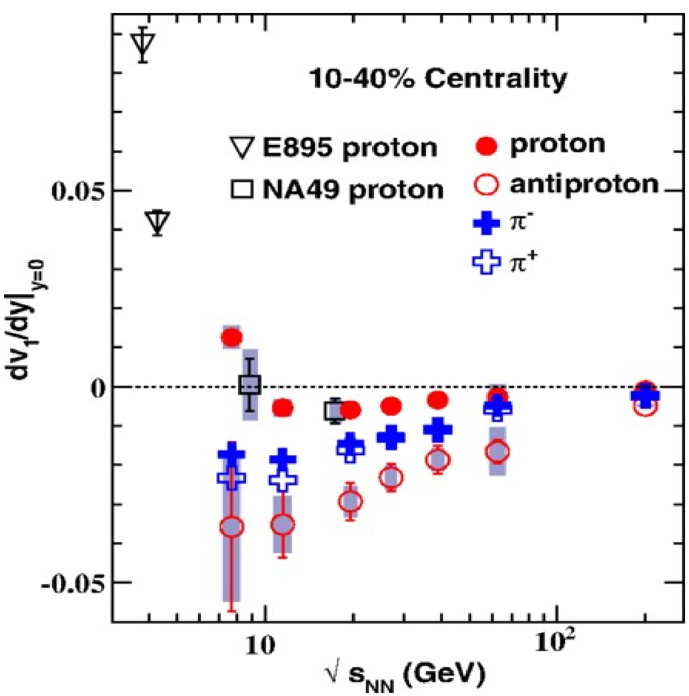
$$\frac{dN}{d^2p_T} = \frac{d^2N}{2\pi dp_T dy}(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots)$$

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad F = \left.\frac{dv_1}{dy}\right|_{y=0}$$

P. Danielewicz, R. Lacey, W.G. Lynch,
Science 298 (2002) 1592



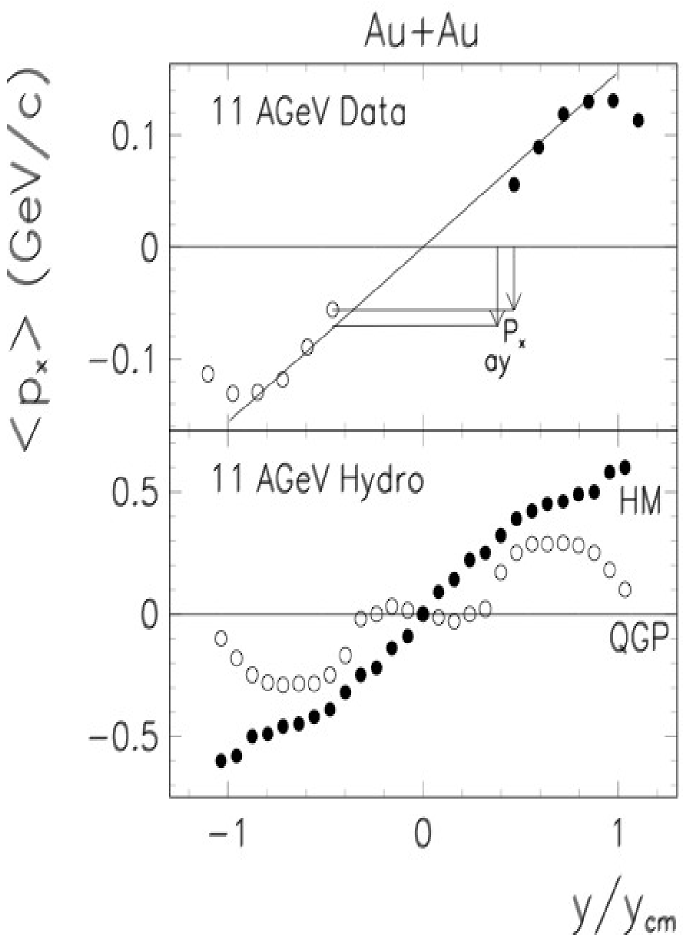




Signal of the phase transition?

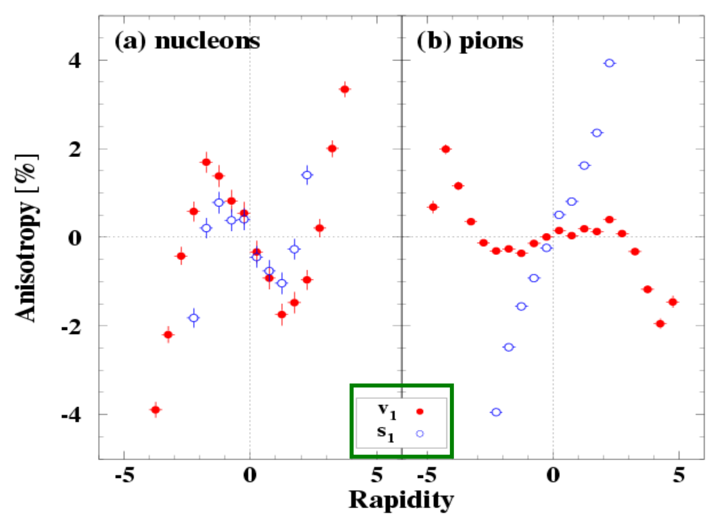
L. Adamczyk et al. (STAR Collaboration)
Phys. Rev. Lett. 112, 162301 – Published 23 April 2014

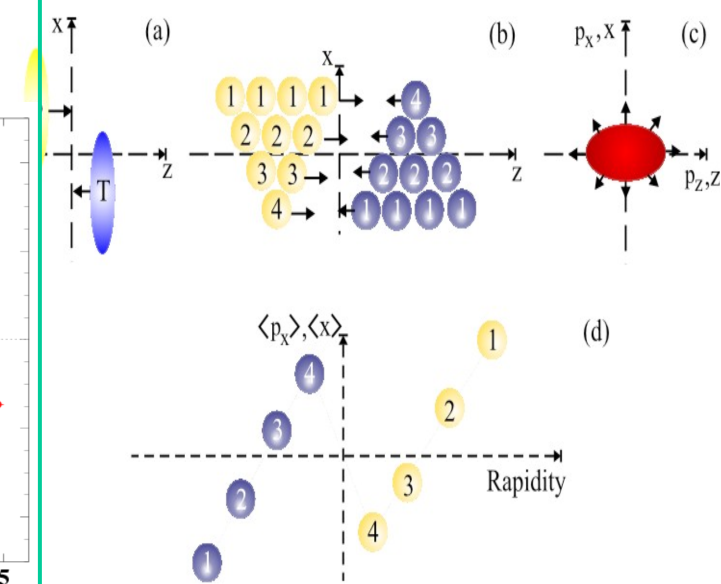
Wiggle: QGP signal in the directed flow?



Baryon stopping + Positive space-momentum correlation leads wiggle (no QGP)

RQMD v2.4





R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.

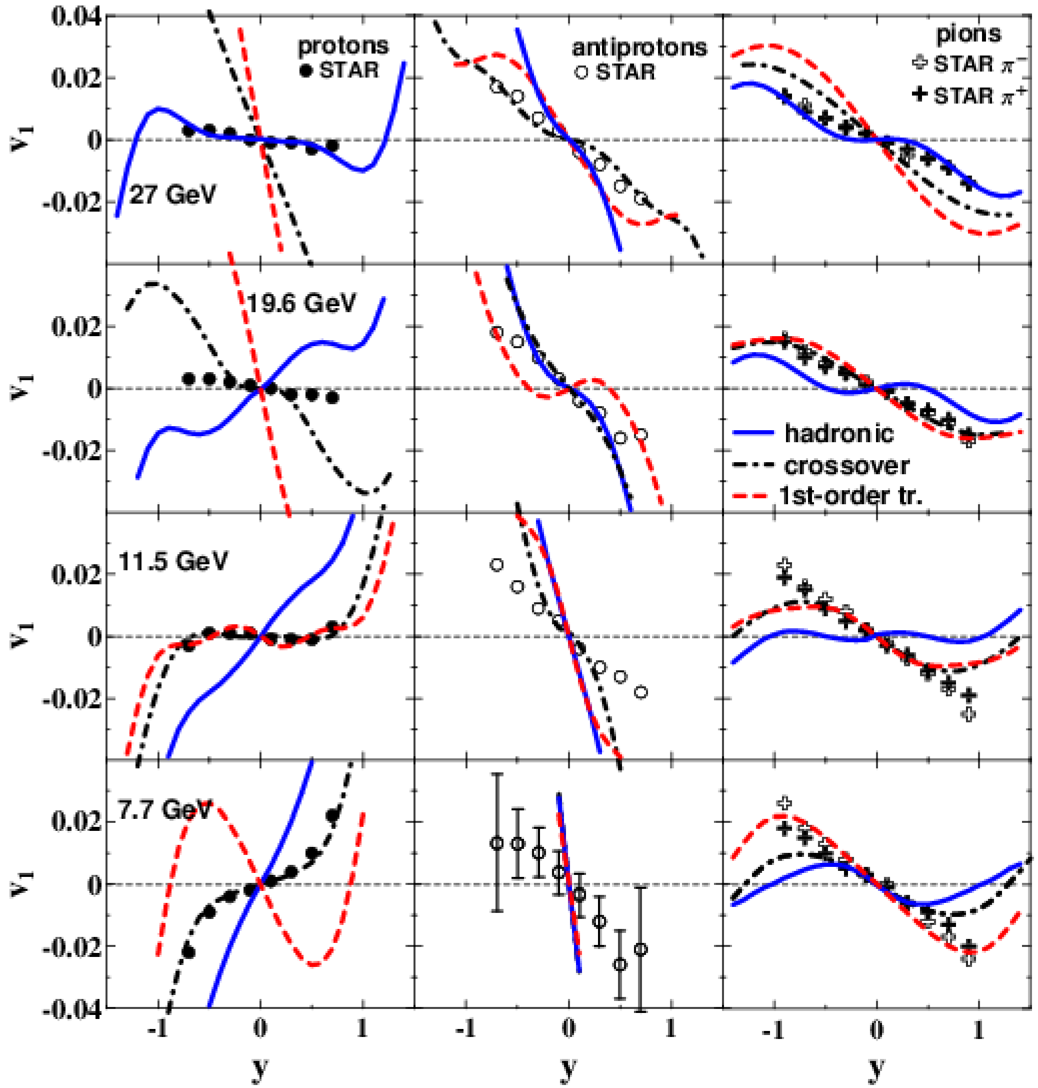
QGP EoS predicts wiggle in hydro

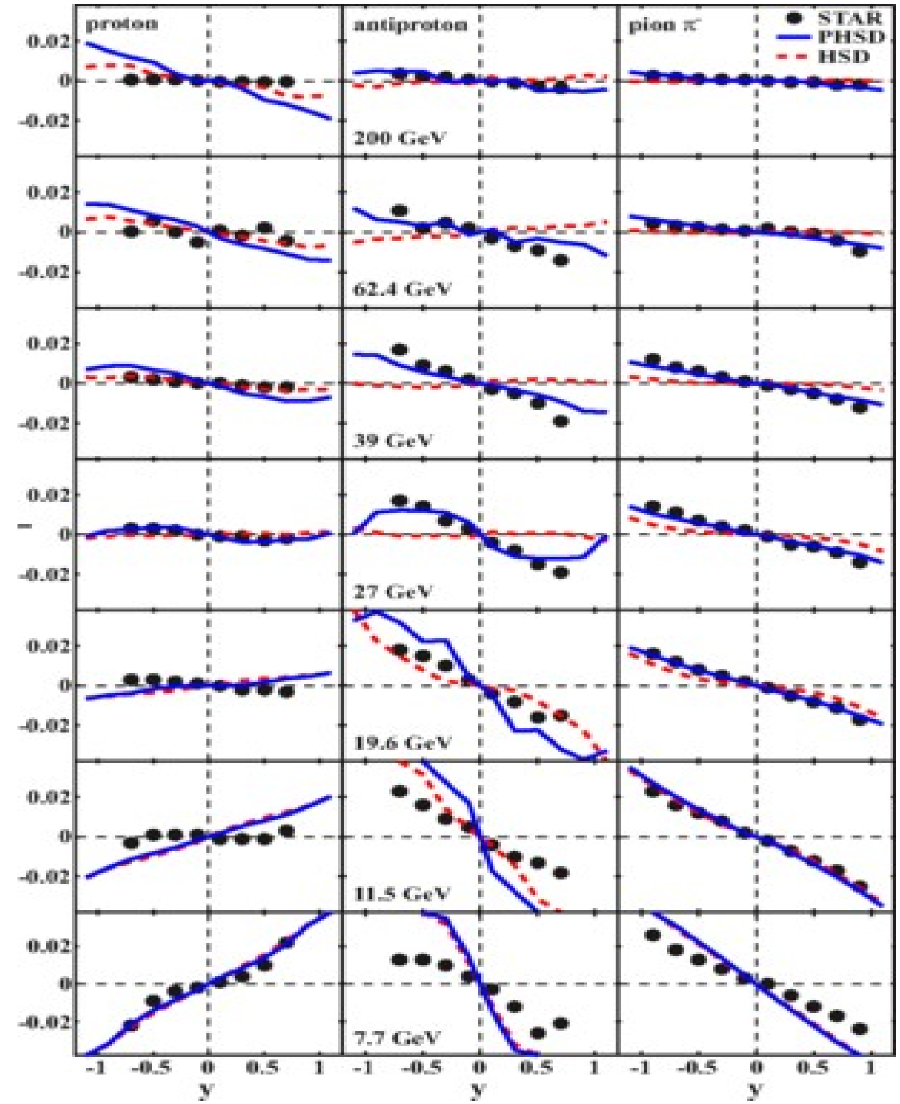
V1 from hydrodynamics

PHSD/HSD predictions

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, no. 2, 024915 (2015)

V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev, **Phys. Rev. C90, no. 1, 014903 (2014)**





Hadronic transport Approach

Purpose：Effects of hadron mean field potential on the directed flow v1

JAM hadronic cascade model : resonance and string excitation

Mean field by the framework of the Relativistic Quantum Molecular Dynamics

Nuclear cluster formation by phase space coalescence.

Statistical decay of nuclear fragment

Relativistic QMD/Simplified (RQMD/S)

RQMD based on Constraint Hamiltonian Dynamcis

Sorge, Stoecker, Greiner, Ann. Phys. 192 (1989), 266.

RQMD/S: Tomoyuki Maruyama, et al. Prog. Theor. Phys. 96(1996),263.

Single particle energy: $$p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2m_iV_i}$$

$$\dot{\boldsymbol{r}}_i = \frac{\boldsymbol{p}_i}{p_i^0} + \sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{p}_i} \qquad \dot{\boldsymbol{p}}_i = -\sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{r}_i}$$

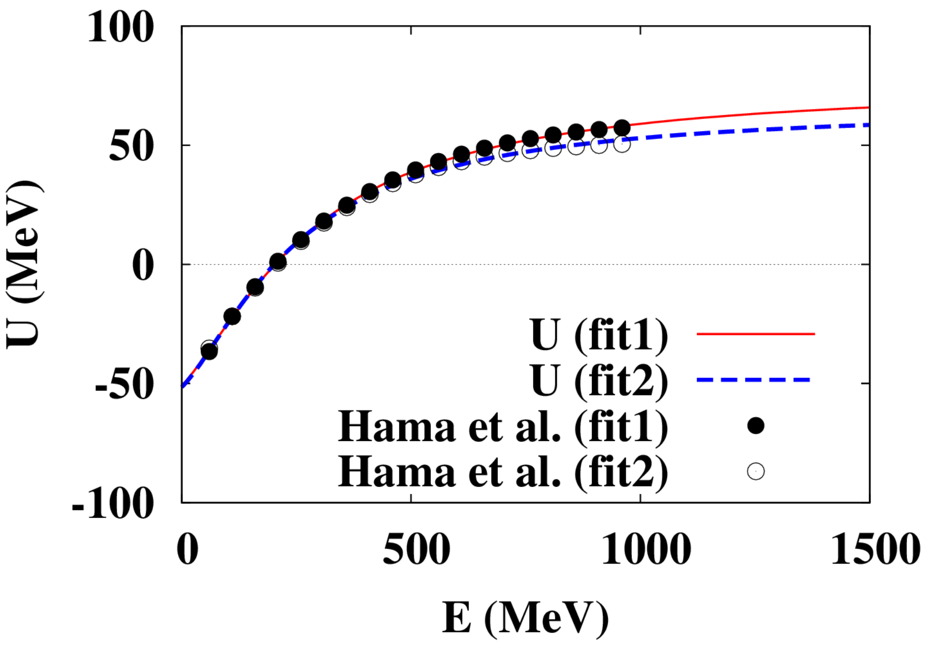
Arguments of potential $\boldsymbol{r}_i - \boldsymbol{r}_j$ and $\boldsymbol{p}_i - \boldsymbol{p}_j$ are replaced by the distances in the two-body c.m.

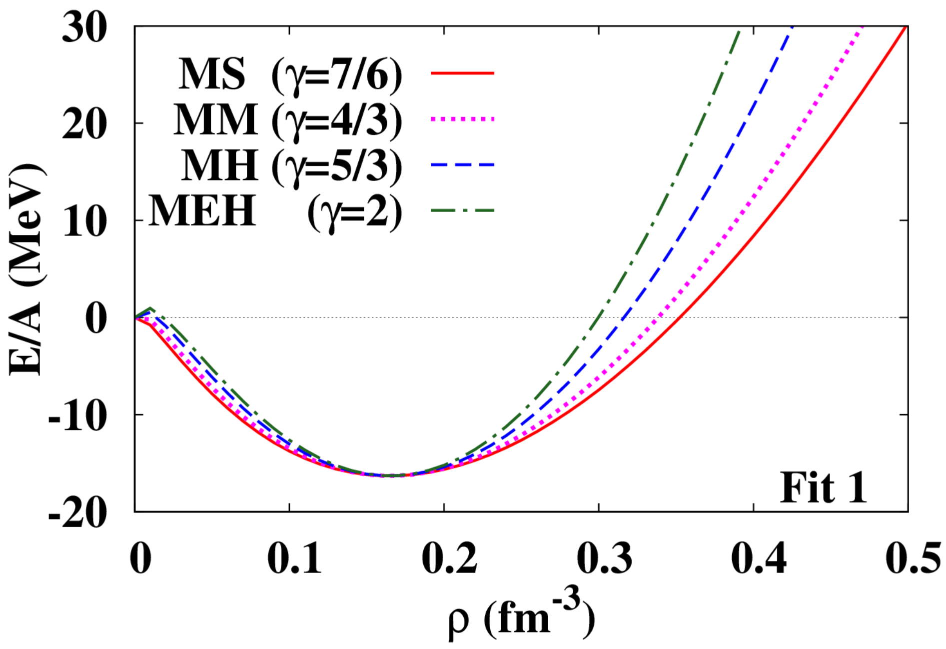
Mean field potential

Skyrme type density dependent + Lorentzian momentum dependent potential

$$V = \sum_i V_i = \int d^3r \left[\frac{\alpha}{2} \left(\frac{\rho}{\rho_0} \right)^2 + \frac{\beta}{\gamma+1} \left(\frac{\rho}{\rho_0} \right)^{\gamma+1} \right] + \sum_k \int d^3\boldsymbol{r} d^3\boldsymbol{p} d^3\boldsymbol{p}' \frac{C_{ex}^{(k)}}{2\rho_0} \frac{f(\boldsymbol{r},\boldsymbol{p}) f(\boldsymbol{r},\boldsymbol{p}')}{1 + (\boldsymbol{p}-\boldsymbol{p}')^2/\mu_k^2}$$

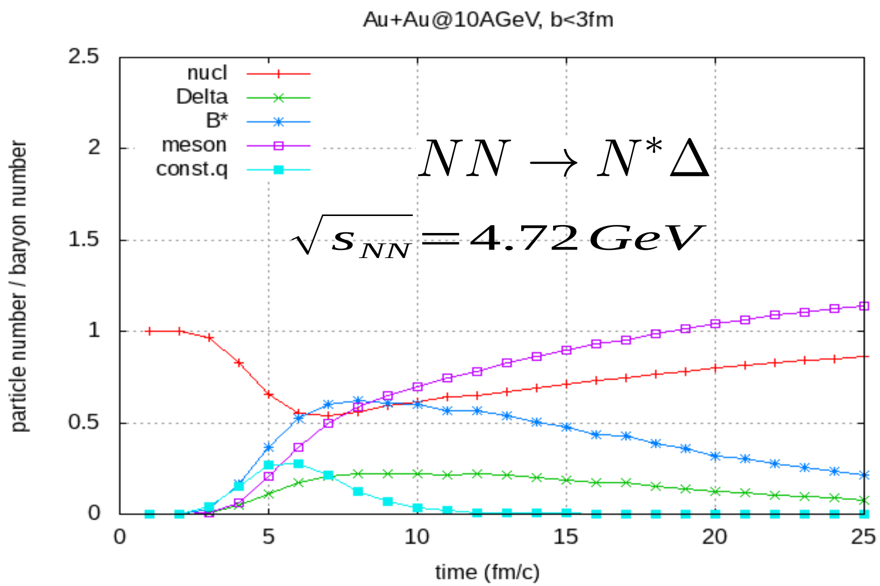
Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 ($\rm fm^{-1}$)	μ_2 ($\rm fm^{-1}$)	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6



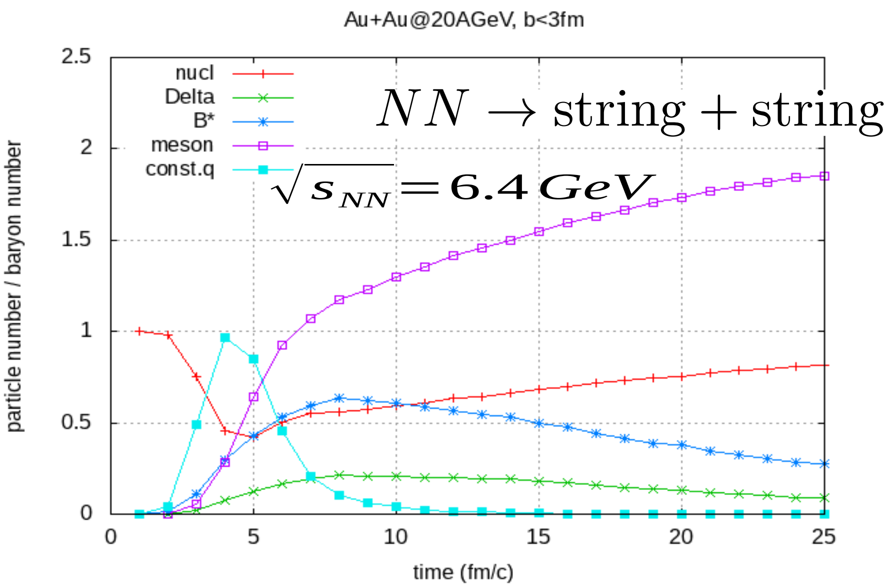


How to treat mean-field for excited matter?

Hadronic resonance dominant



constituent quark dominant due to string



Model 1 JAM/M: potential for all formed baryons

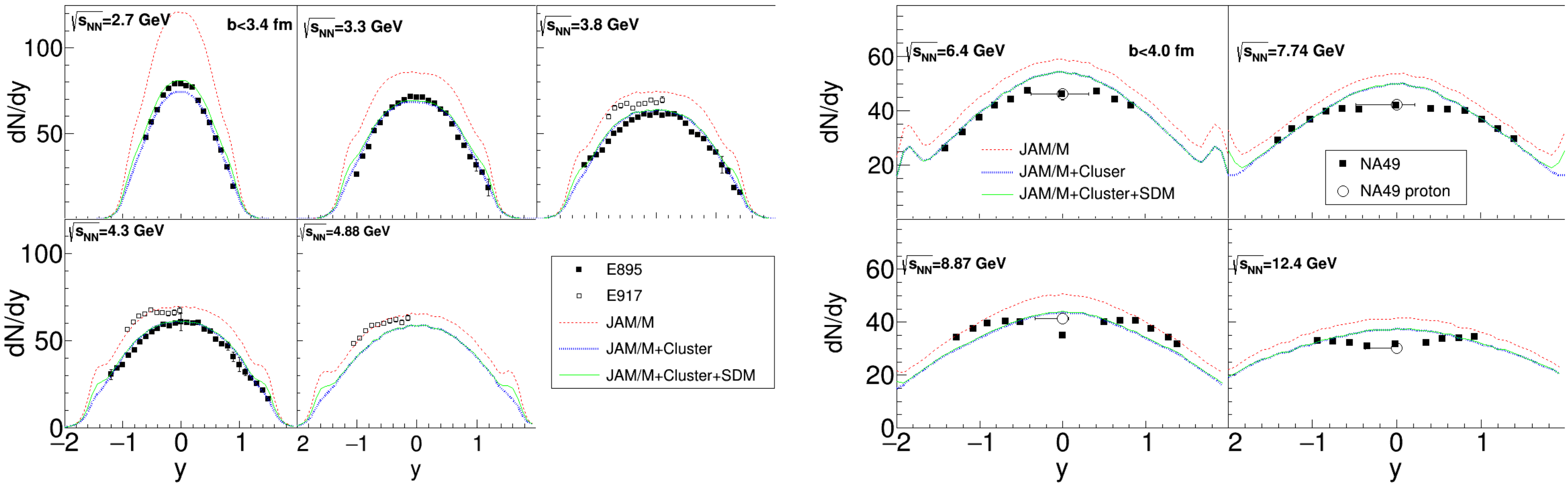
Model 2 JAM/Mq: potentials for quarks inside the pre-formed hadrons

Model 3: JAM/Mf: both formed and pre-formed baryons

Proton rapidity distributions

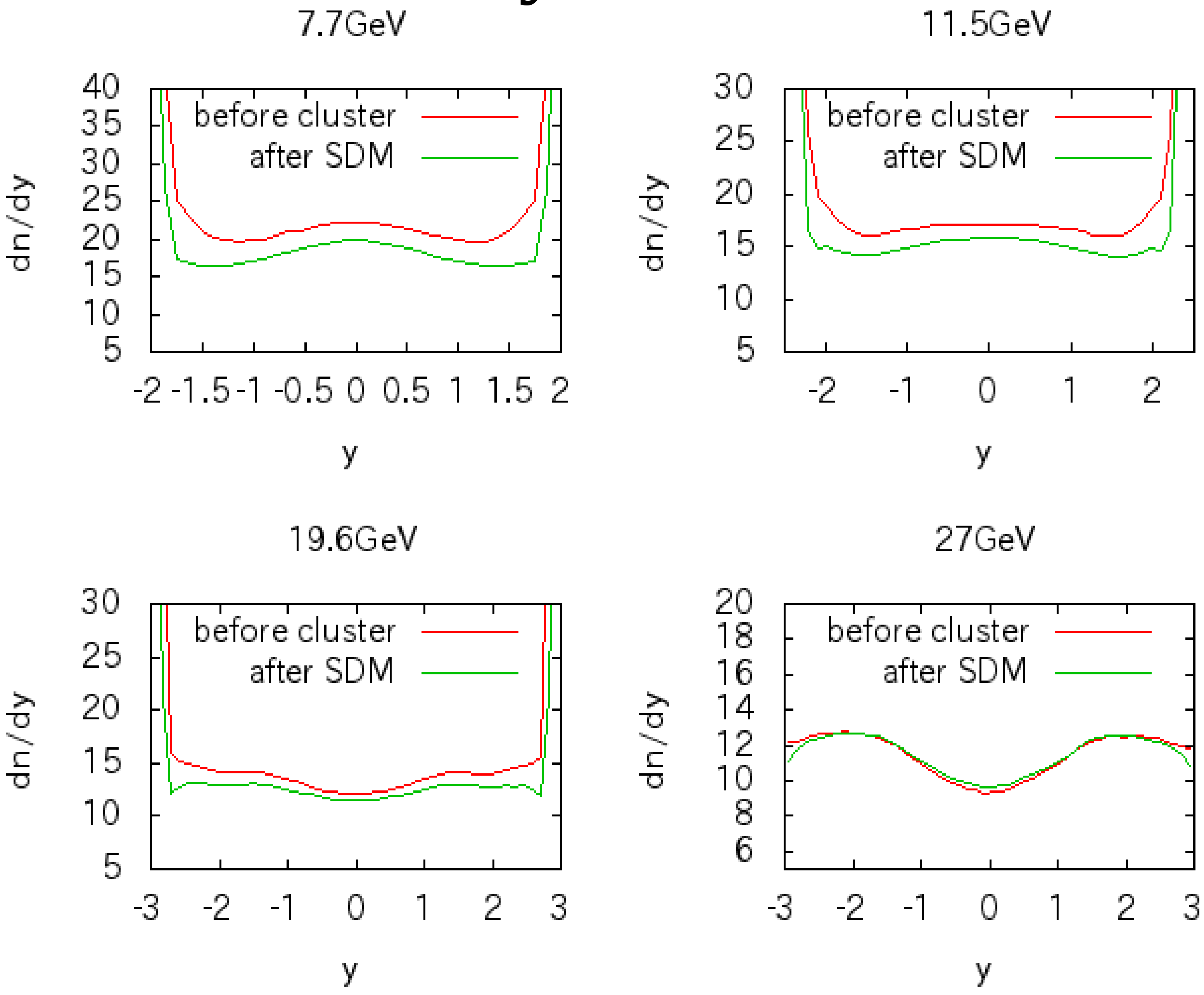
Effect of nuclear clustering on the proton distribution was first pointed out by
Q. Li, Y. Wang, X. Wnag, C Shen and M. Bleicher, hep-ph 1507.06033.
within the UrQMD model.

Coalescence parameter R0=4fm, P0=0.3 GeV/c

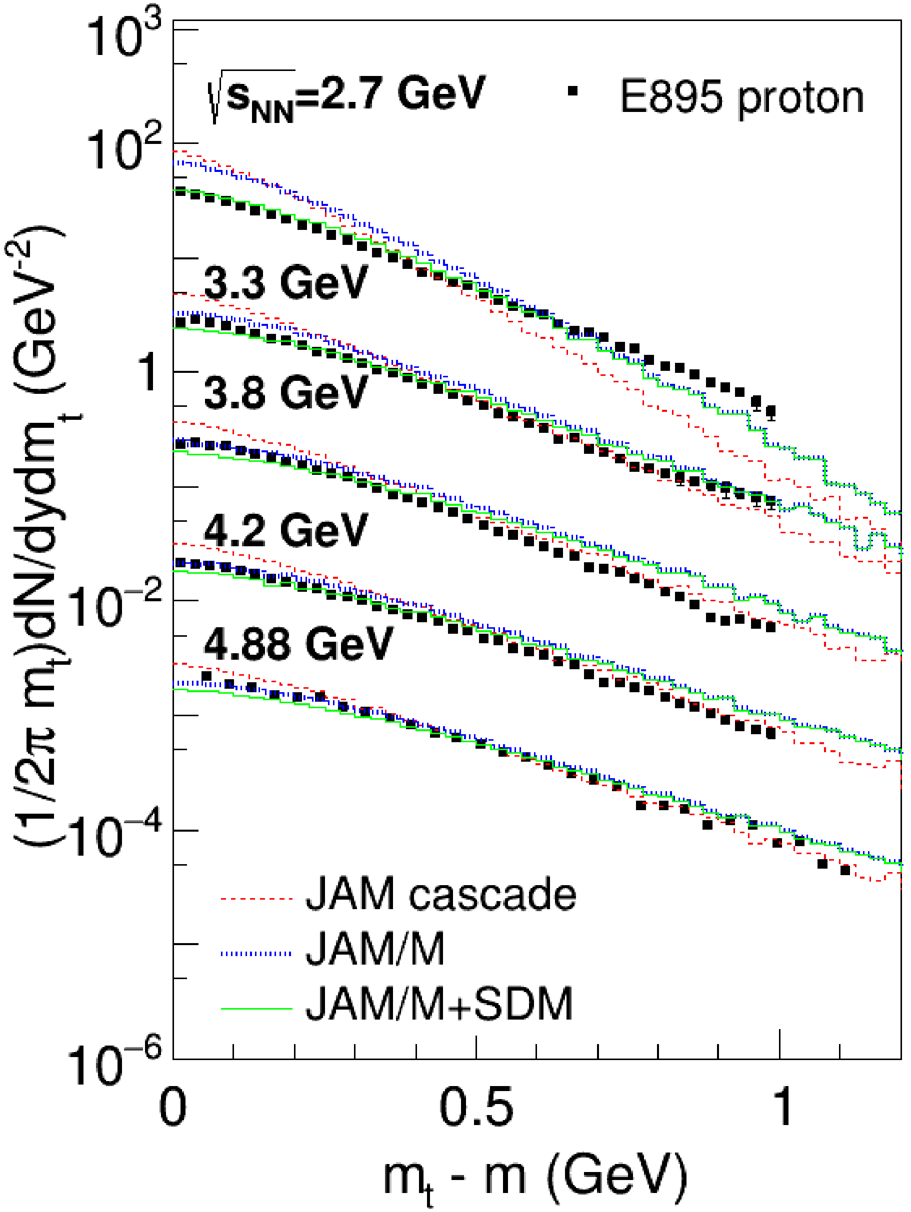


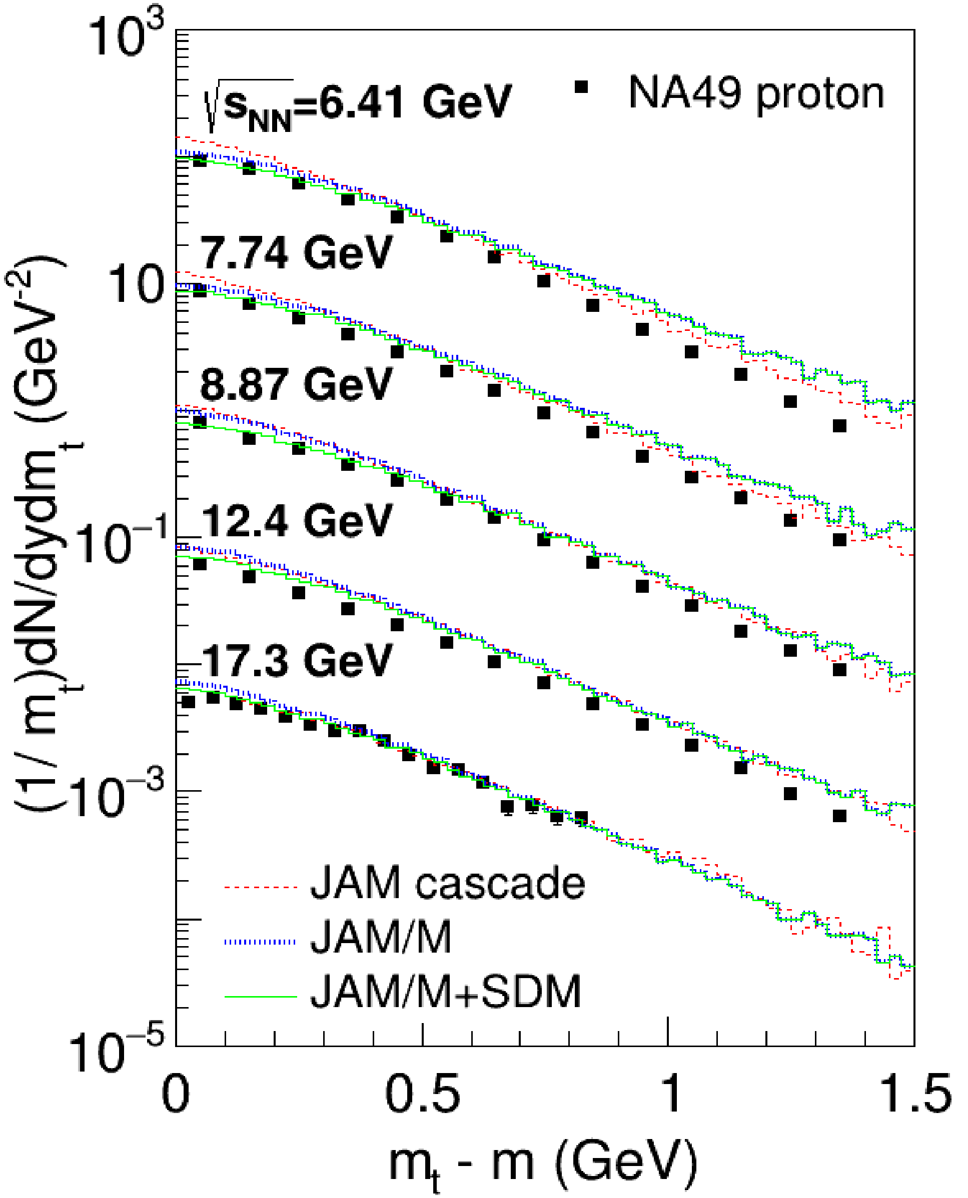
Cluster formation reduces proton dN/dy by around 20%.
Statistical decay of nuclear cluster is important only at Elab= 2AGeV
for the proton rapidity distribution.

Proton dN/dy for semi-central

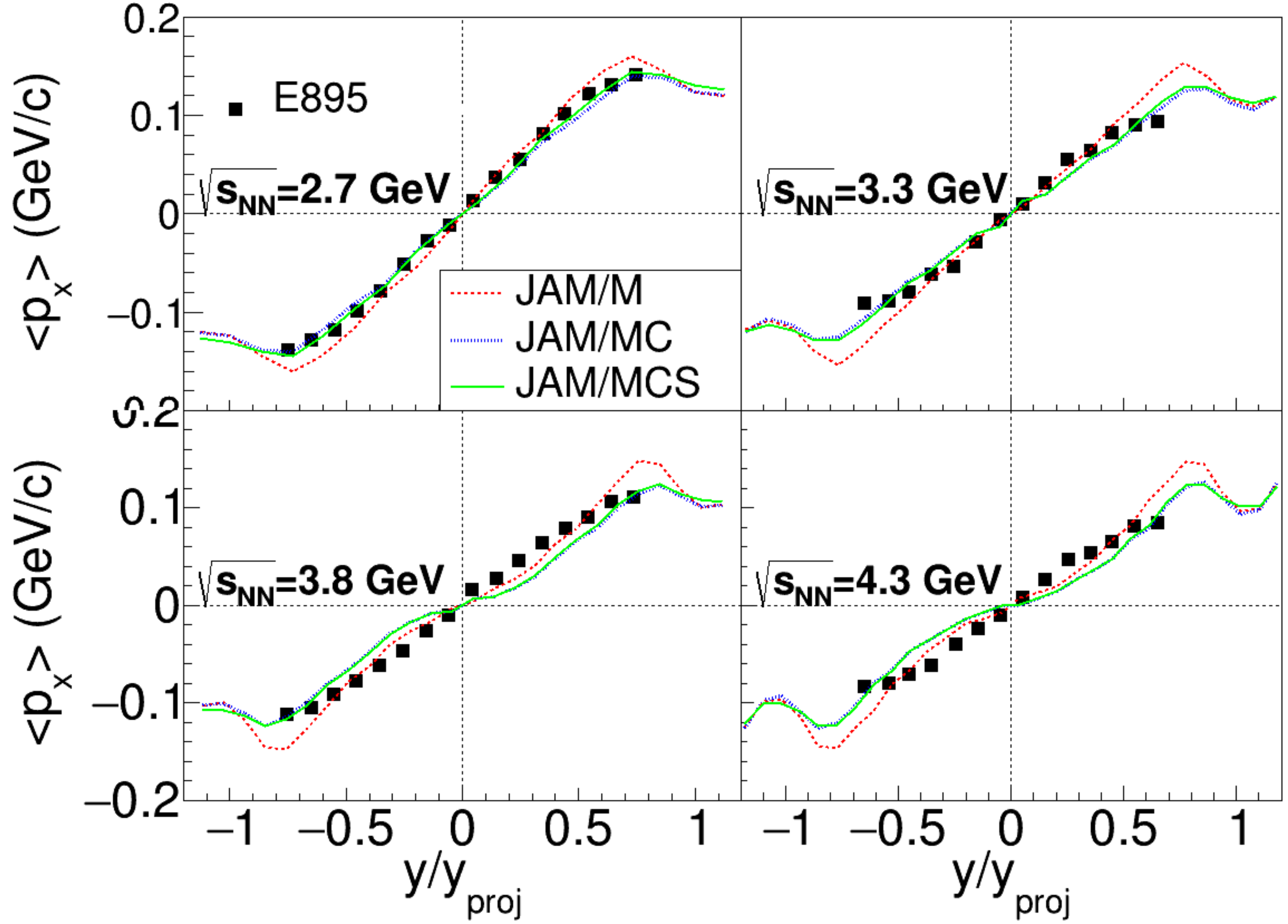


Proton distributions





Effect of cluster and its decay on the directed flow

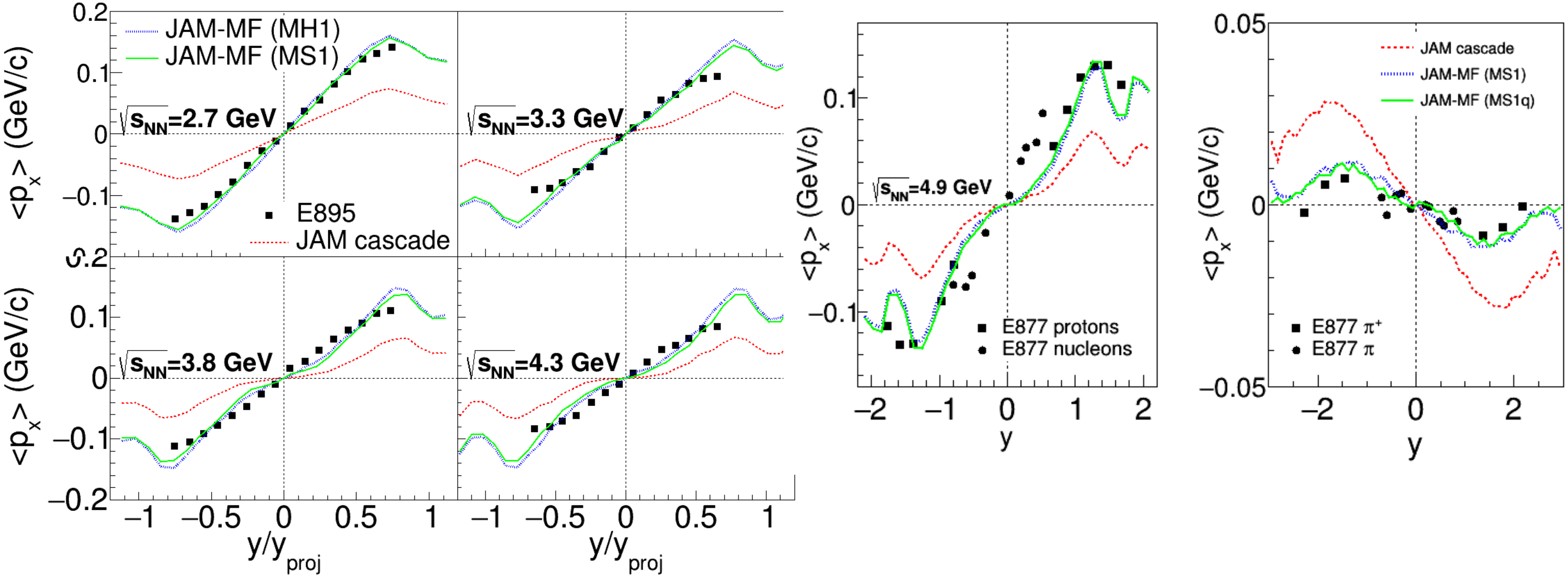


Effect of cluster is 10% on the v1

JAM/RQMD results at AGS energies

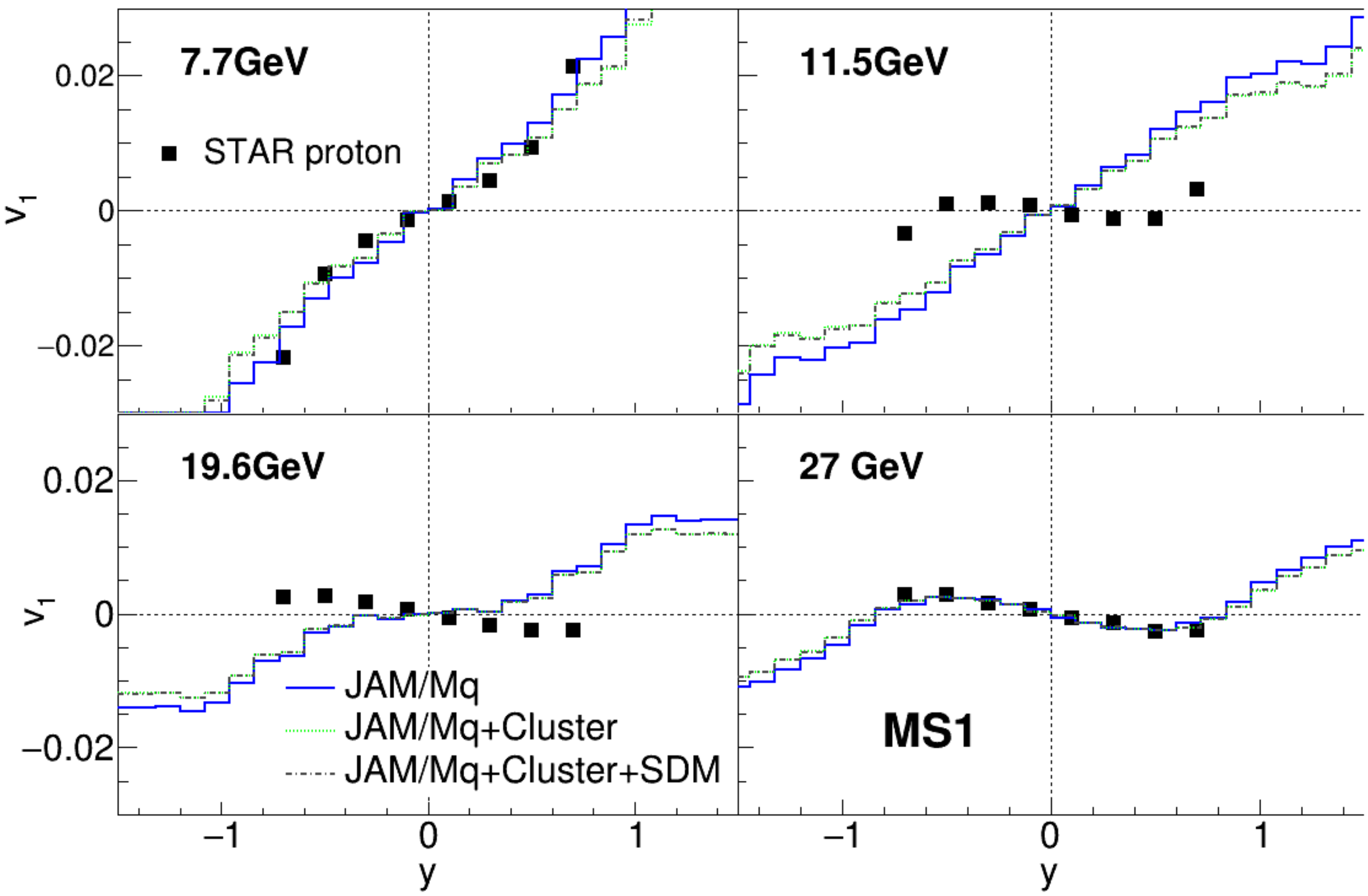
Significant mean-field effect on the directed flow

b=4-8fm



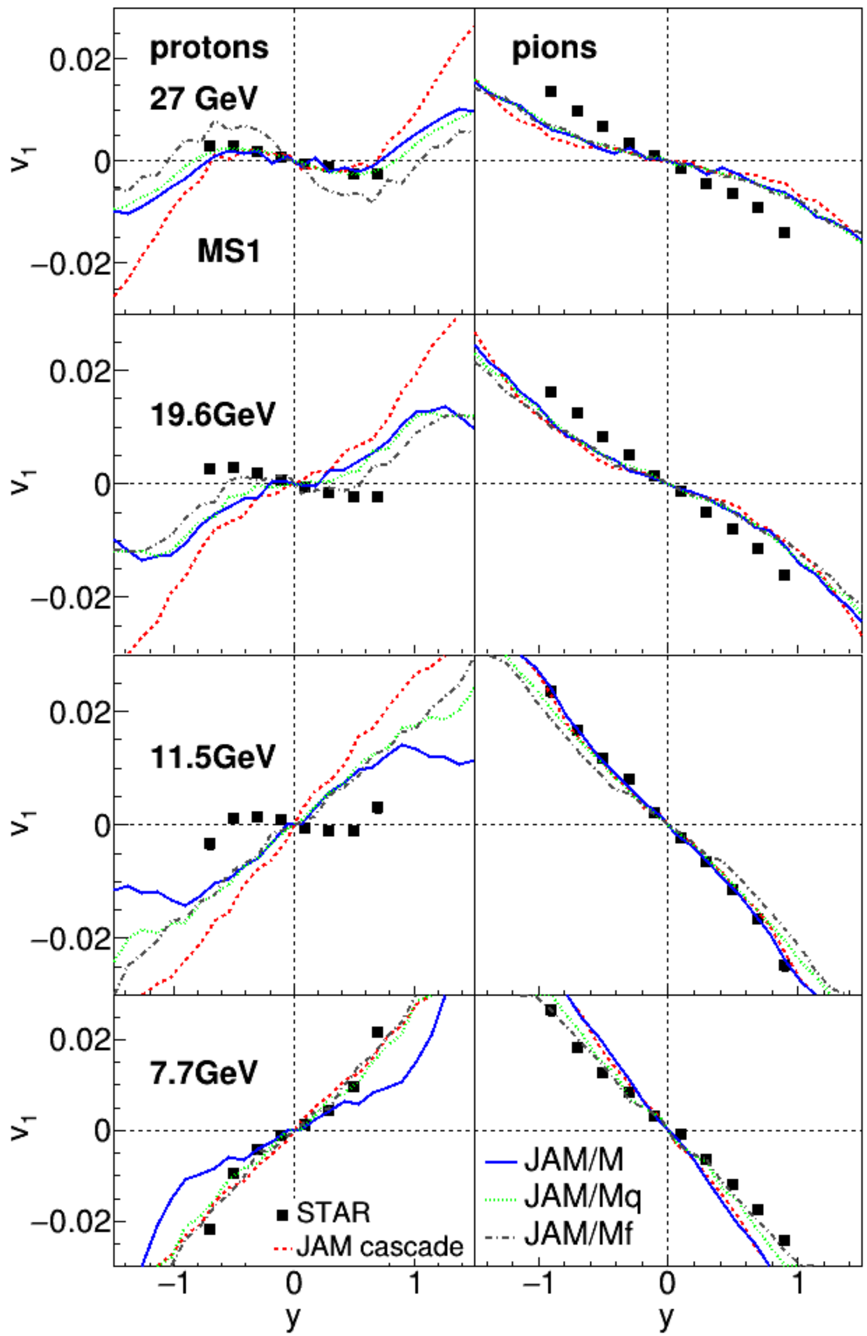
Consistent results with the previous work: M. Isse, et.al PRC72(2005) 064908.

JAM/M at BES energies



Effect of the nuclear cluster formation is about 15%.
No effect of statistical decay of nuclear fragment on v1

Comparison of v1



Effects of potential on the v1 is significant

Hadronic approach does not reproduce the correct beam energy dependence of the directed flow.

Something happens around 10-20GeV?

JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

Summary

- Hadronic transport model JAM with nuclear mean field followed by formation of nuclear cluster and its statistical decay.
  JAM + mean field + nuclear cluster formation + statistical decay

- The proton dN/dy and dN/dmt from 2.7 GeV to 17 GeV are well reproduced in the JAM/M approach.

- JAM/M approach reproduces the observed directed flow up to Ecm=9GeV.

- JAM/M predicts the transition of proton directed flow from positive to negative. However, transition point is inconsistent with the STAR data F<0 at 11.5GeV, but F>0 for JAM/M.

  - Effects of cluster formation on the net-baryon distribution