Numerical simulations in high energy nuclear collisions

Yasushi Nara (Akita International Univ.)

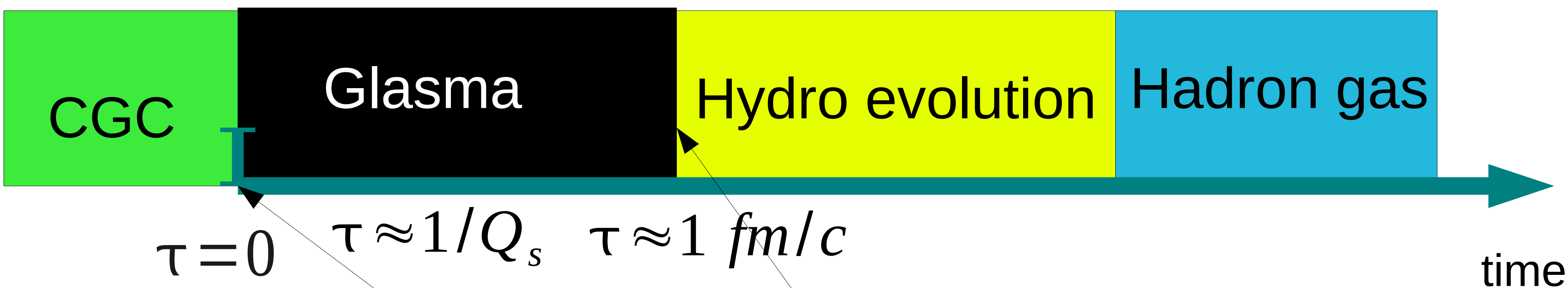
- Event generators for high energy nuclear collisions
- Recent development for hadronic transport model for phase transition region (with Akira Ohnishi (YITP,Kyoto U.)
- Results for directed flow.

CANHP 2015 at YITP Kyoto U., Japan, Oct. 5th 2015

High energy heavy ion collisions

Initial state interactions

Final state interactions



Initial condition for hydro

DGLAP,BFKLevolution
JIMWLK,BK evolution

Initial condition for non-equilibrium evolution

KB equation
Classical YM
Boltzmann equation

Hydro simulations

Hadronic transport models

Numerical approaches are essential tools for nuclear collisions

Gluon production based on CGC

- x-evolution + Solving classical Yang-Mills equation

CYM + IP-sat model, Schenke, Tribedy, Venugopalan
CYM+JIMWLK evolution, Lappi, Phys.Lett.B703(2011)325

- rcBK evolution + Based on kt-factorization formula

Albacete, Armesto,Mihano, Salgado 2009 for HERA fit

$$\frac{dN_g}{d^2 x_t\, dy} = \frac{4\pi N_c}{N_c^2 - 1} \int \frac{d^2 p_t}{p_t^2} \int d^2 k_t\, \alpha_s\, \varphi(x_{1,} k_t^2)\, \varphi(x_{2,} (p_t - k_t)^2)$$

Forward particle production: Dumitru Hayashigaki Jalilian-Marian (DHJ)

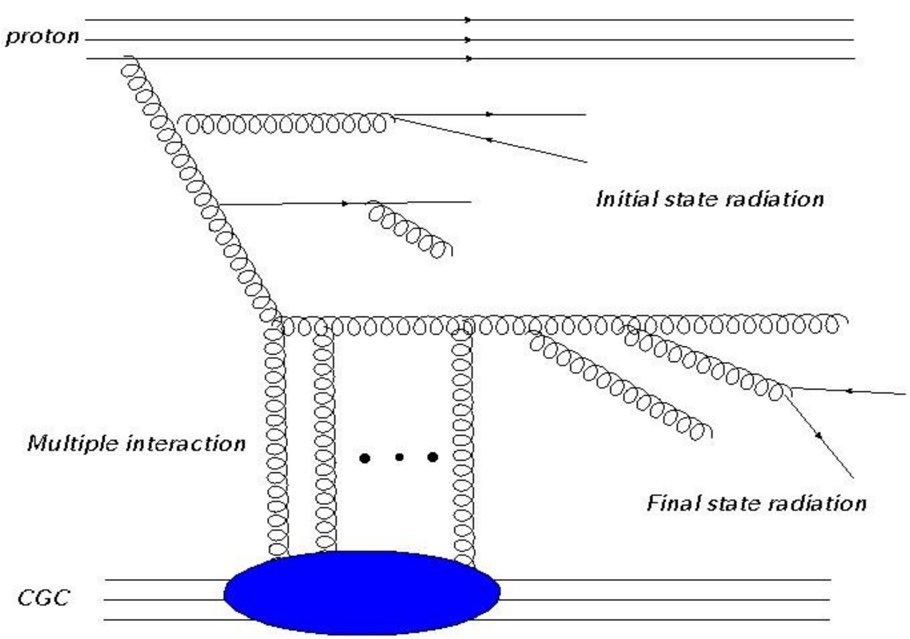
$$\frac{dN}{dy_h d^2 p_\perp} = \frac{K}{(2\pi)^2} \sum_{i=q,g} \int_{x_F}^{1} \frac{dz}{z^2} x_1 f_{i/p}(x_1, p_\perp^2) N_i(p_\perp / z, x_2) D_{h/i}(z, p_\perp^2)$$

RcBK integro- differential equation: 50-170 times faster on GPU

Monte-Carlo Event Generator for DHJ approach

Phys.Rev.D91,014006(2015)

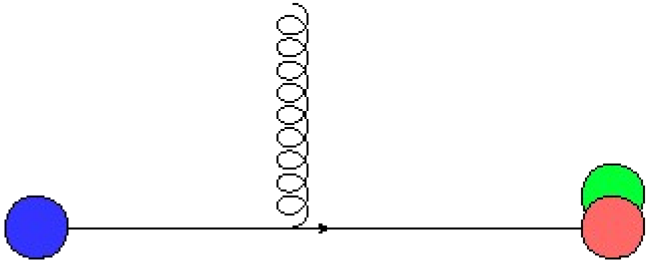
$gg \to g, \;\; gq \to q$ with initial and final state radiations



Gluons and quarks are generated according to the DHJ formula.

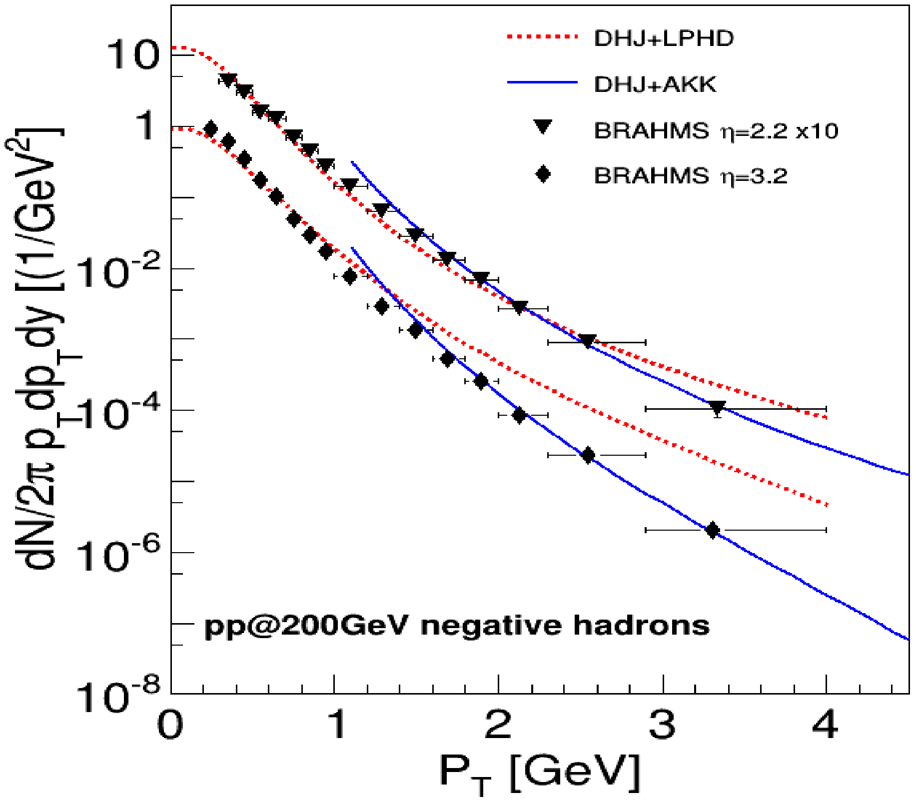
$$\frac{dN}{dyd^2p_\perp} = \frac{K}{(2\pi)^2} f_{i/p}(x_1, p_\perp^2) N_i(p_\perp, x_2)$$

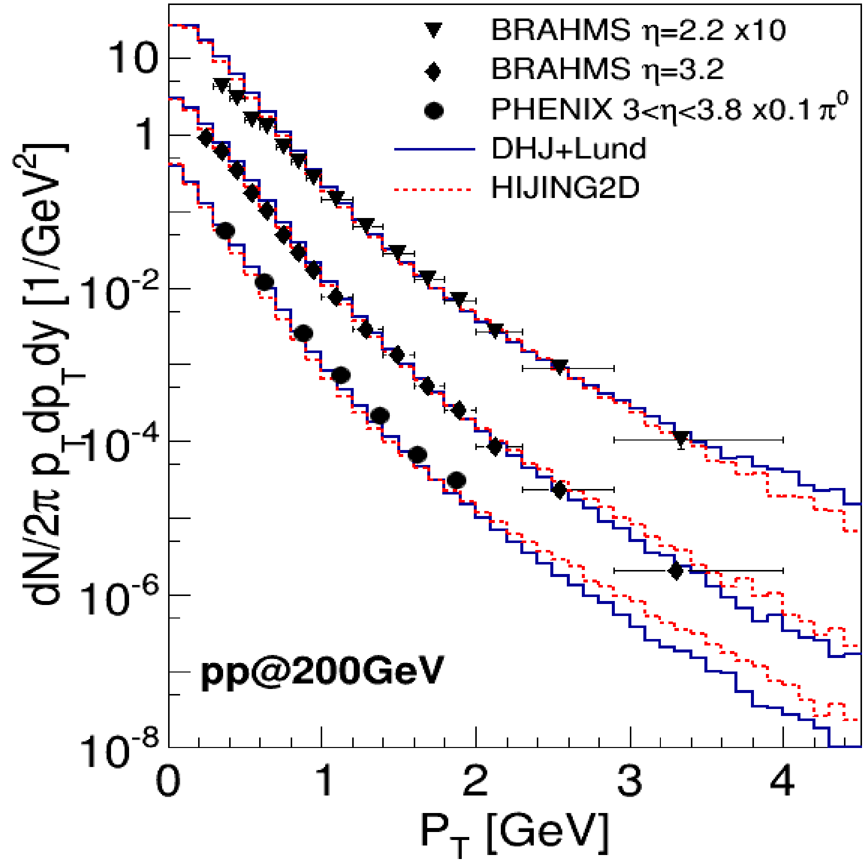
Hadrons are produced by
the Lund string fragmentation model



How do you simulate x-evolution in MC?
SMALLX (CCFM),RAPGAP
CASCADE (CCFM evolution)
LDC(Linked Dipole Chain), DIPSY

DHJ+LPHD or FF v.s. MC-DHJ





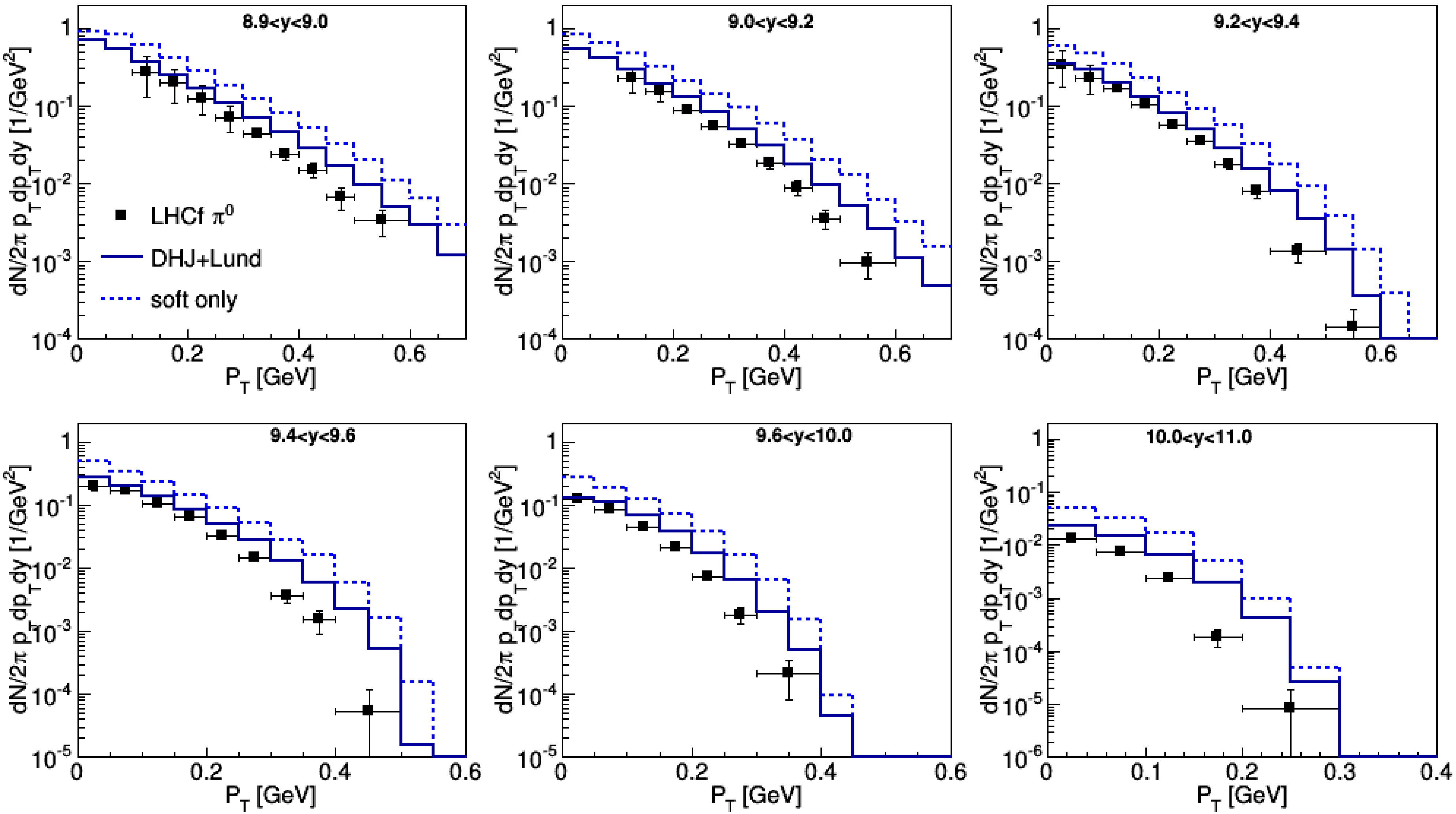
Within kt-factrizaton approach,
High pt hadrons are well described by
the Fragmentation function,

Low pt hadrons including multiplicity are well described by the parton-padron duality.

More realistic model:
event generator version of DHJ describes the data in a unified way.

Phys.Rev.D91,014006(2015)

Comparison of LHCf data



Phys.Rev.D91,014006(2015)

Event generators in high energy physics

HepForge: development environment for high energy physics software

https://www.hepforge.org/

PYTHIA, HERWIG++, SHERPA and so on

OSCAR: Open Standard Codes and Routines

https://karman.physics.purdue.edu/OSCAR/index.php/Main_Page

Event generators mainly for cosmic ray physics

DPMJET 3
QGSJET II
SIBYLL 2.1
EPOS3

Microscopic transport models (event generator for nuclear collisions)

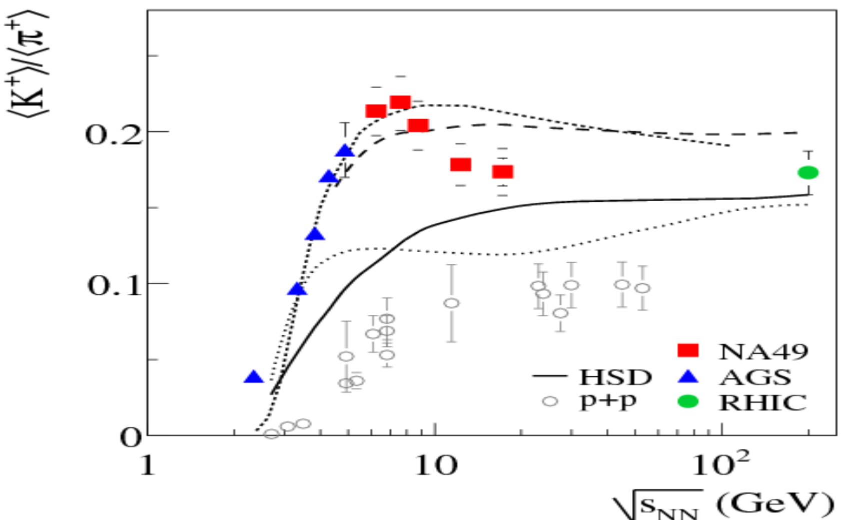
- UrQMD 3.4 Frankfurt public
  resonance model N*,D*, string pQCD, PYTHIA6.4

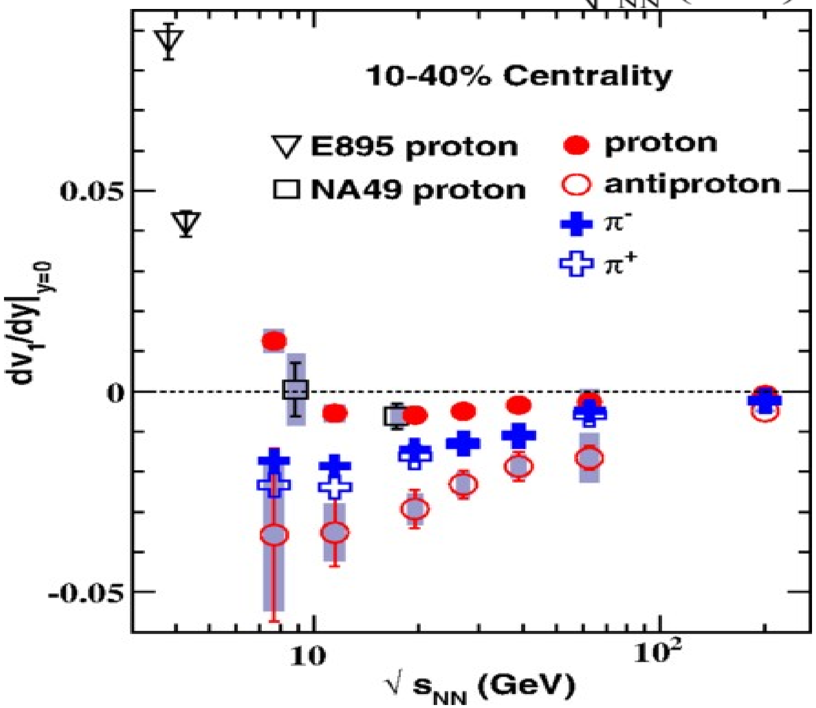
- PHSD Giessen (Cassing) upon request
  D(1232),N(1440),N(1530), string, pQCD, FRITIOF7.02

- GiBUU 1.6 Giessen (Mosel) public
  resonance model N*,D*, string, pQCD,PYTHIA6.4
- AMPT public
  HIJING+ZPC+ART

- JAM public
  resonance model N*,D*, string, pQCD, PYTHIA6.1

Search for phase transition



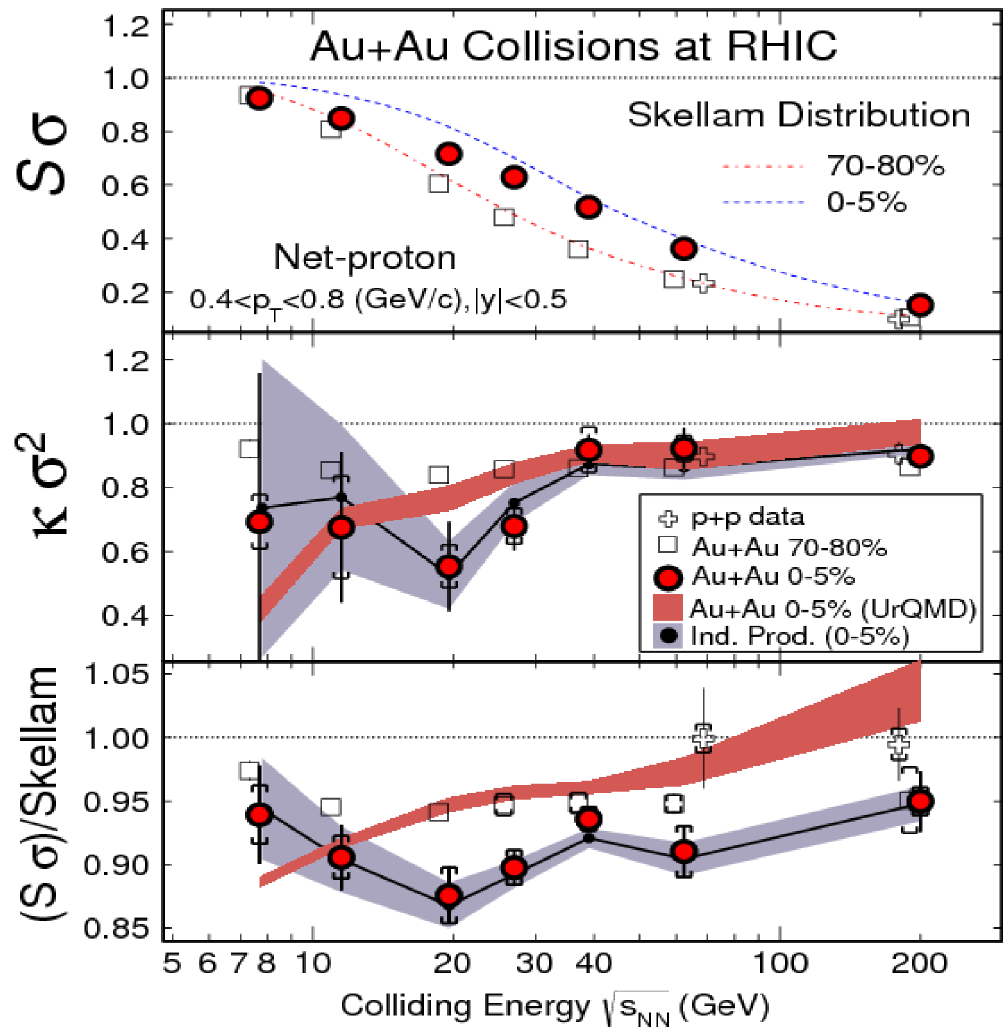


RHIC beam scan, FAIR, NICA, J-PARC

STAR, PRL 112, 032302 (2014)

$$\sigma=\langle\delta N^2\rangle, S\sigma=\langle\delta N^3\rangle/\sigma^2, K\sigma^2=\langle\delta N^4\rangle/\sigma^2-3\sigma^2$$

Event-by-event fluctuations

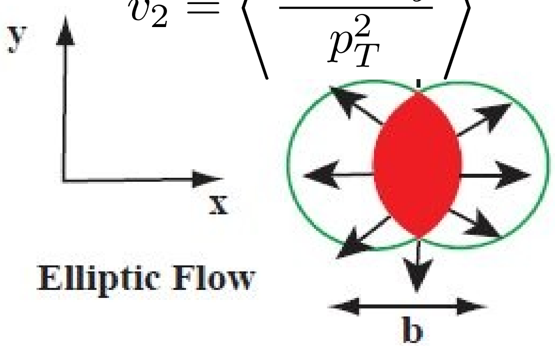


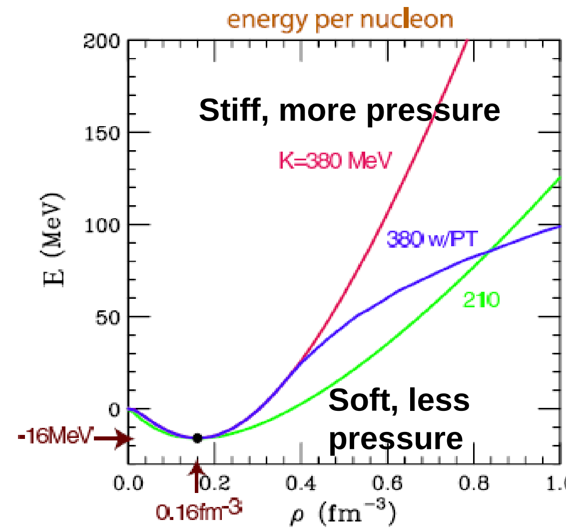
Determination of EOS at high density from an anisotropic flow in heavy ion collisions

Fourier decomposition of single particle inclusive spectra:

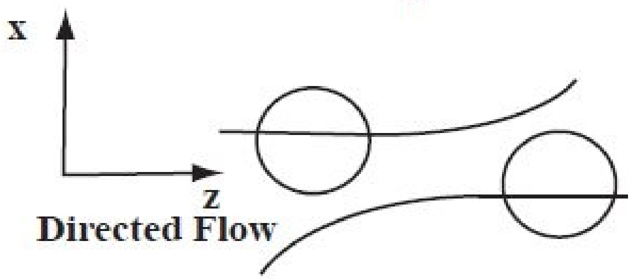
$$\frac{dN}{d^2p_T} = \frac{d^2N}{2\pi dp_T dy}\left(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots\right)$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \qquad v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad F = \left.\frac{dv_1}{dy}\right|_{y=0}$$



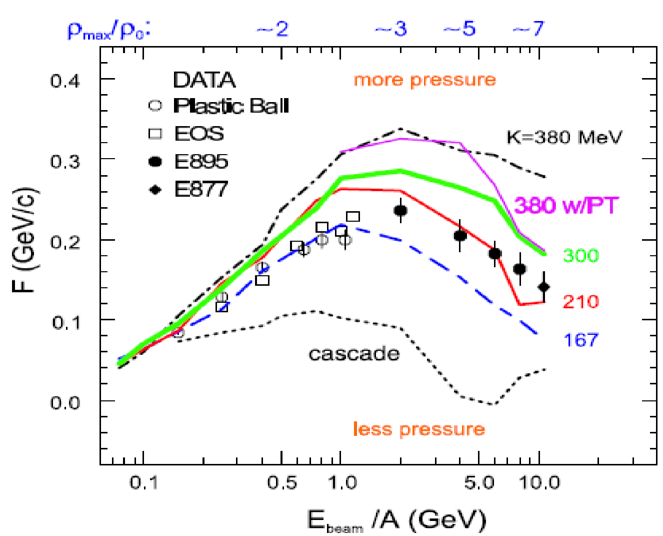


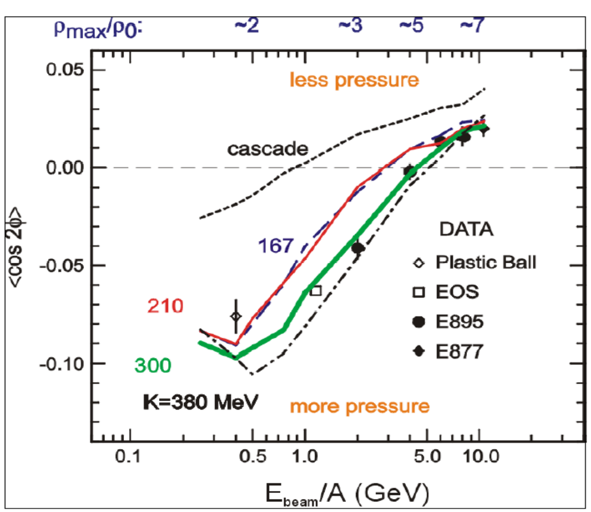
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



$$F = \left.\frac{\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1}$$

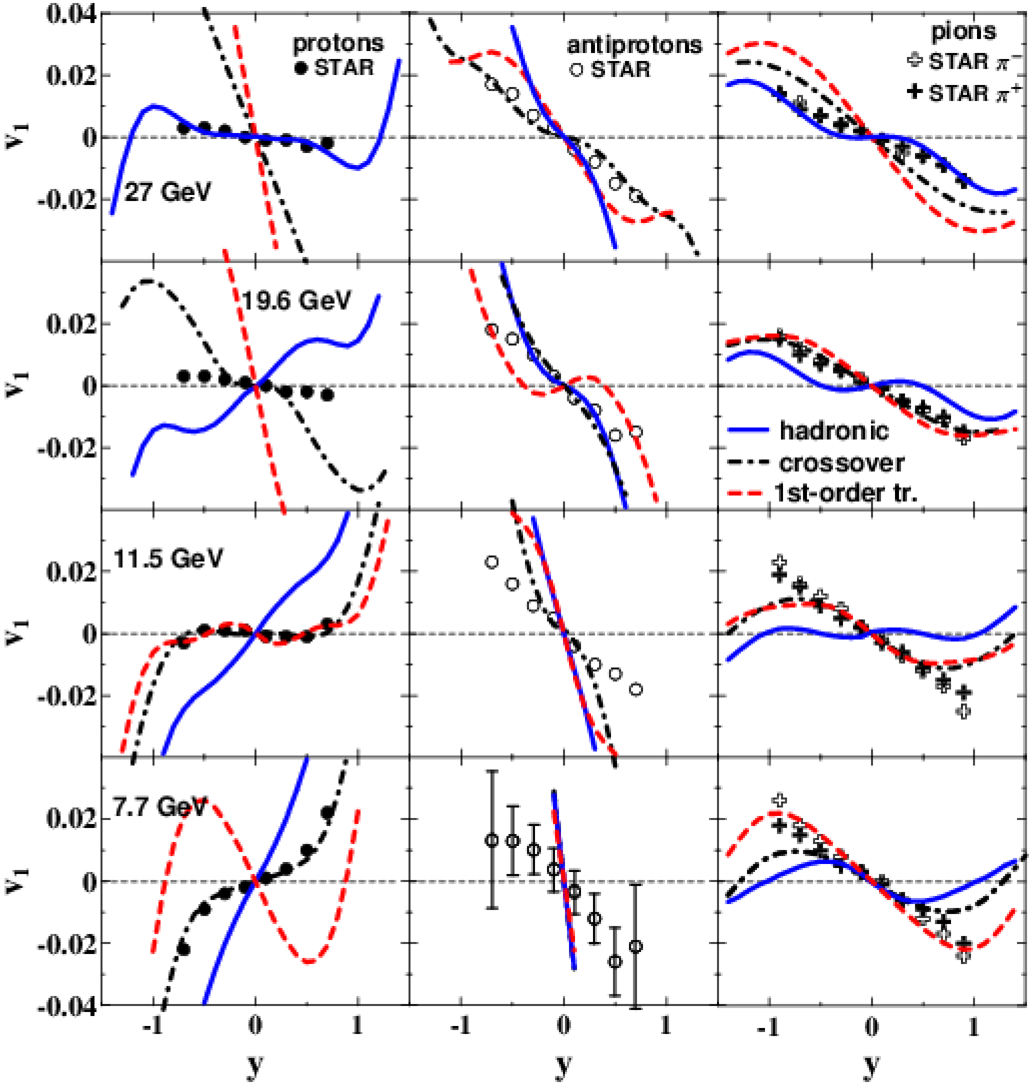
In-plane flow, v1

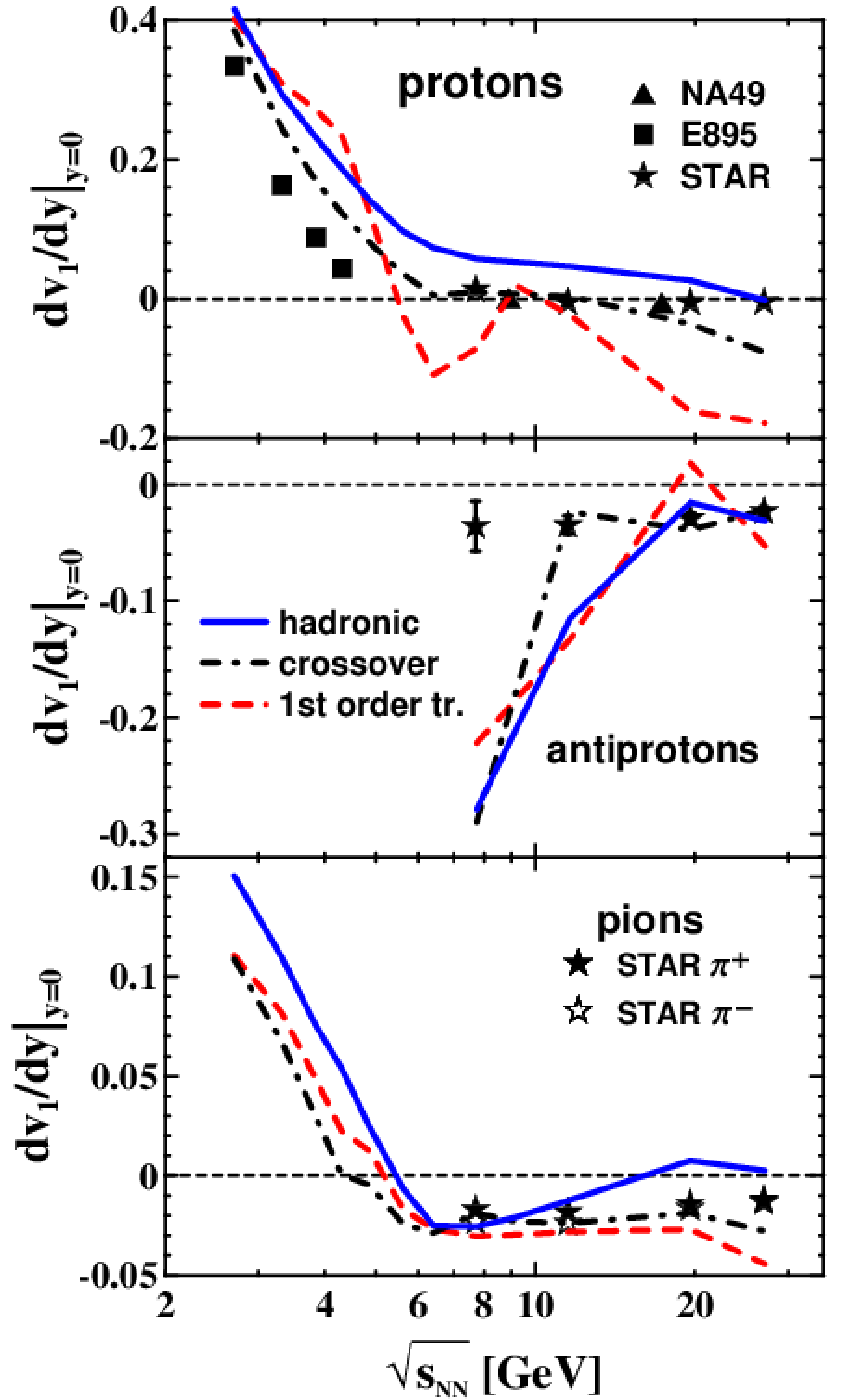




V1 from hydrodynamics

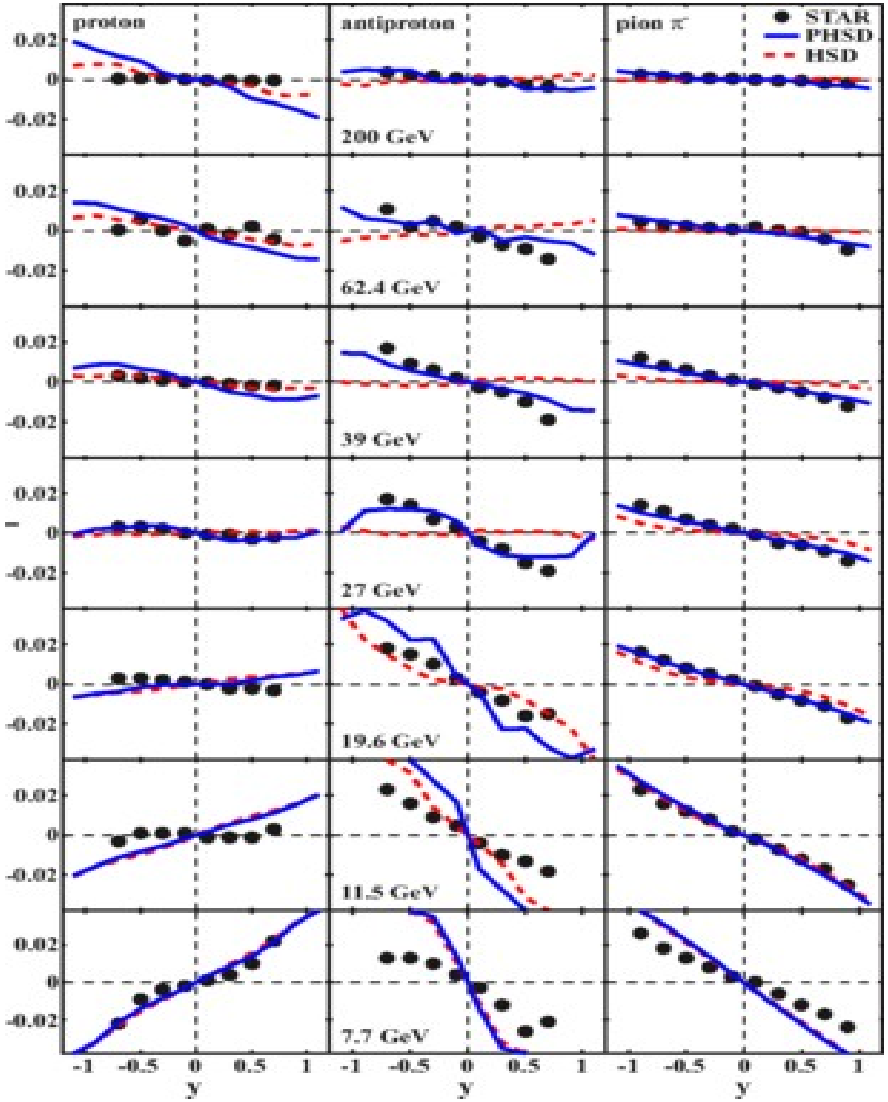
Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, no. 2, 024915 (2015)

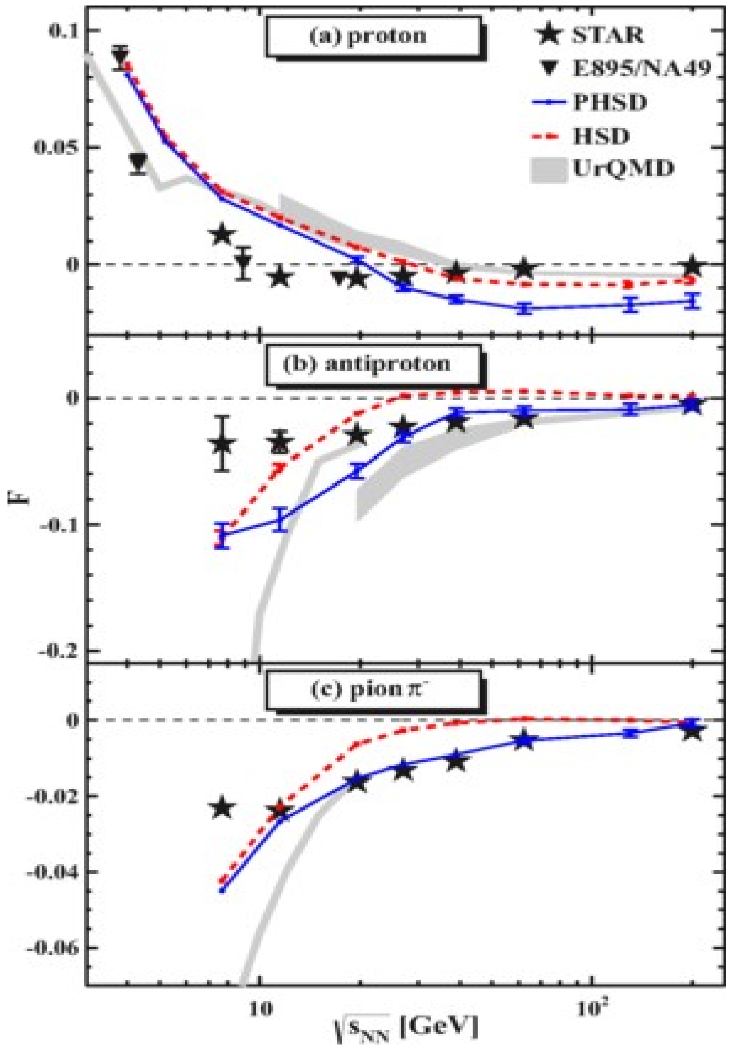




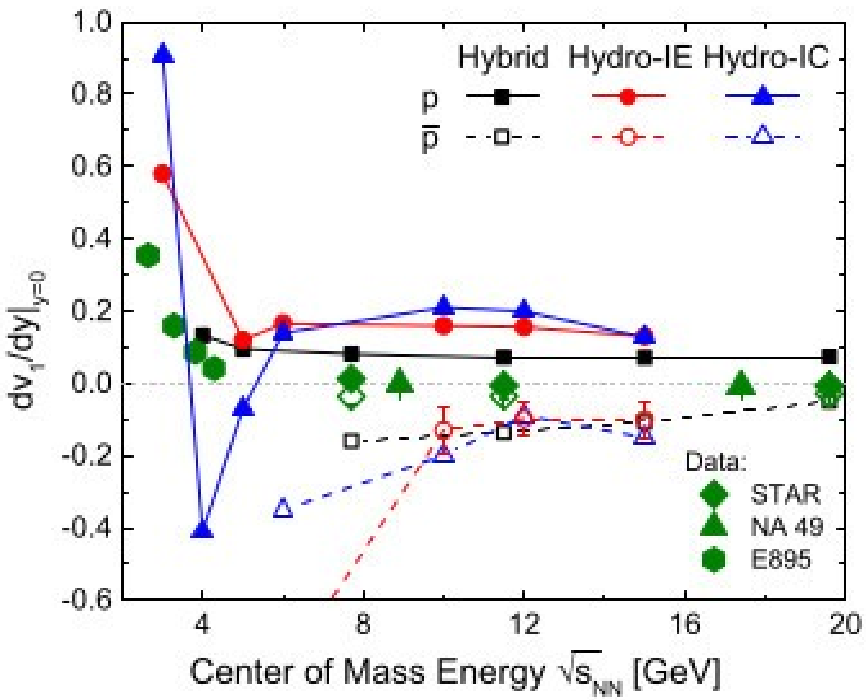
PHSD/HSD predictions

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





UrQMD+hydro+UrQMD results



The values of the slopes are always positive.

J. Steinheimer et al. PRC89, 054913(2014)

Hadronic taransport 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: $p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2m_i V_i}$

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

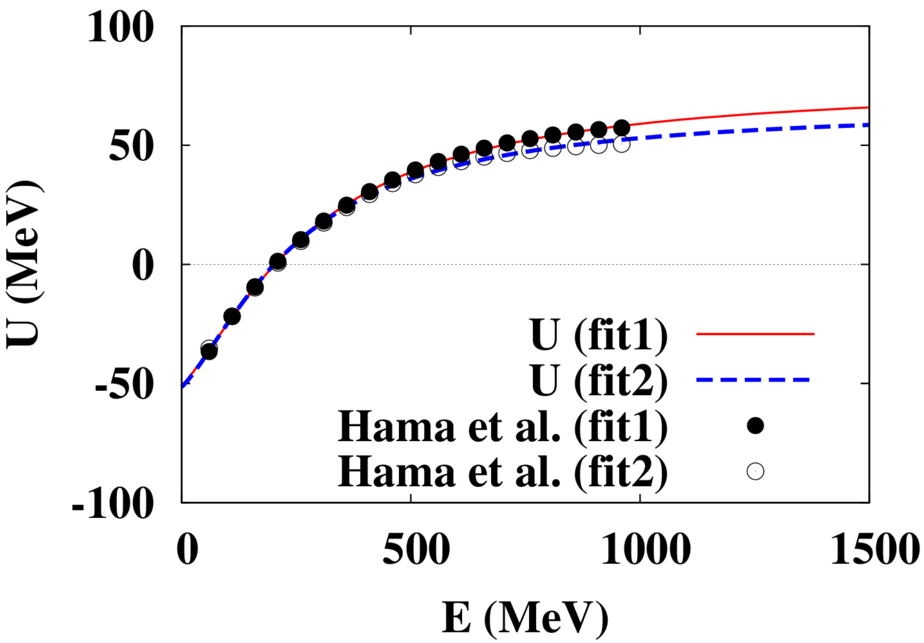
Arguments of potential $\boldsymbol{r}_i - \boldsymbol{r}_j$ and $\boldsymbol{p}_i - \boldsymbol{p}_j$ are replaced by the distances in the two-body c.m.

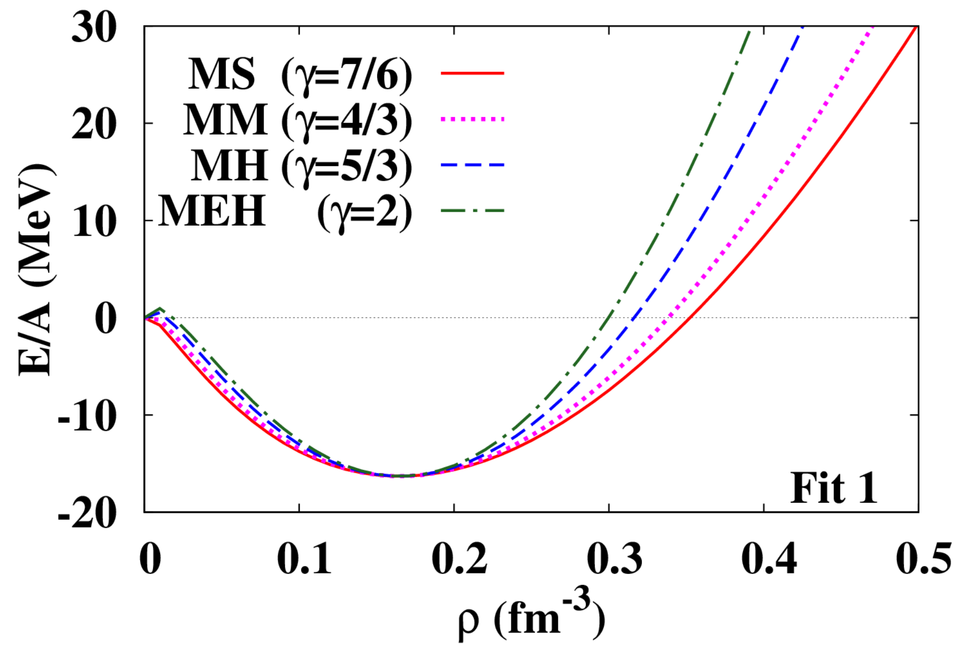
Mean field potential

Skyrme type density dependent + Lorentzian momentum dependent potential

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

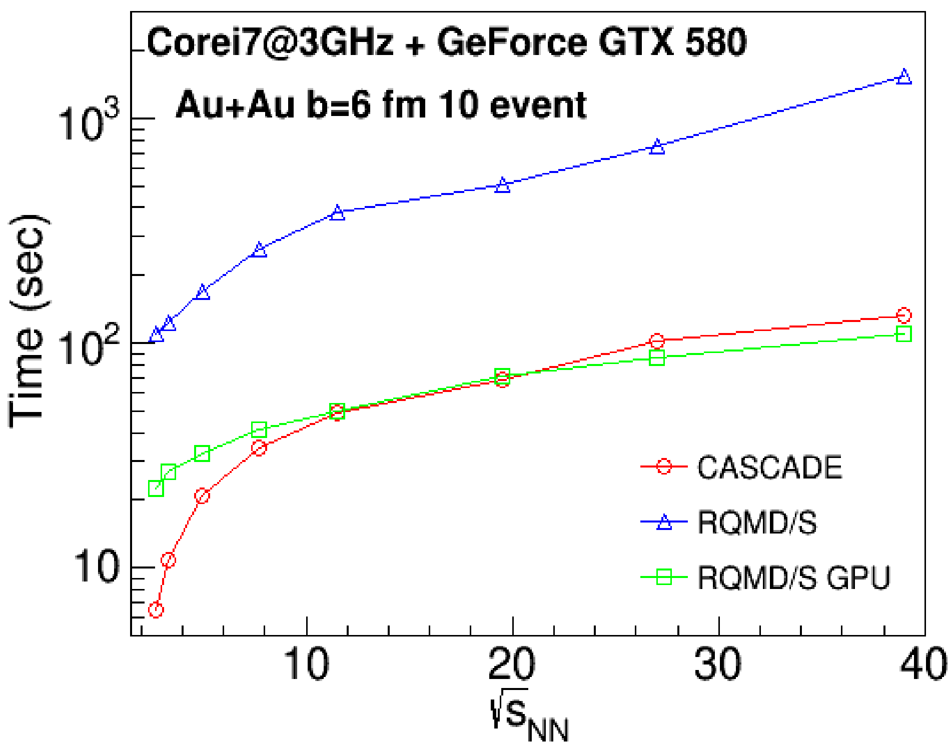
Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 (fm^{-1})	μ_2 (fm^{-1})	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6

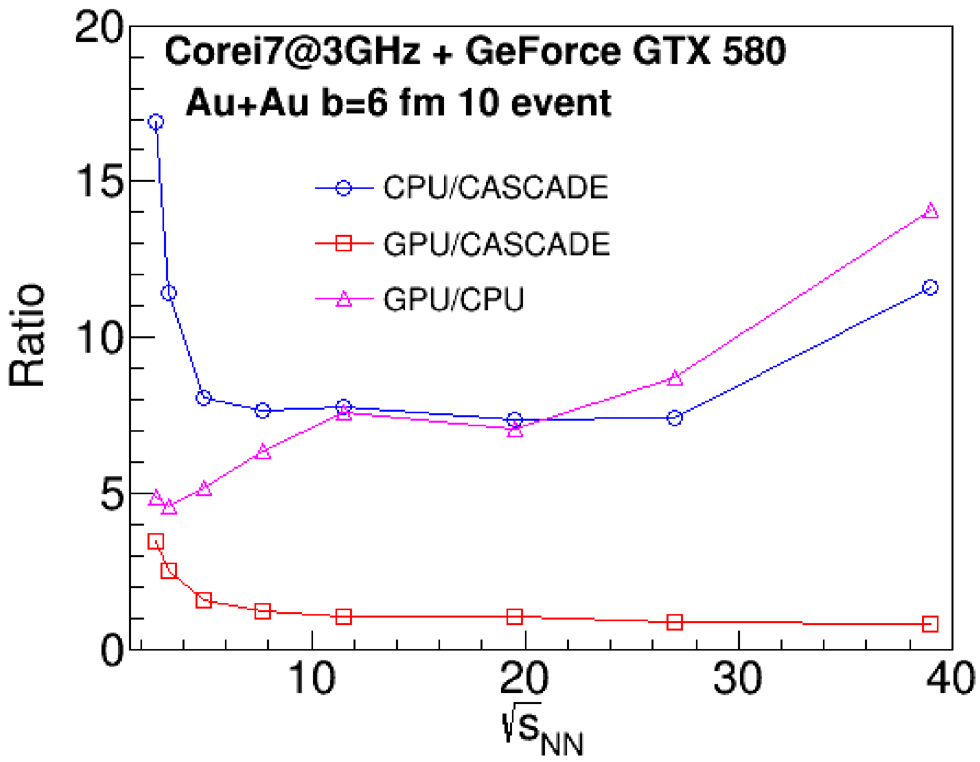




CUDA implementation

Execution time: RQMD/S = CASCADE on GPU

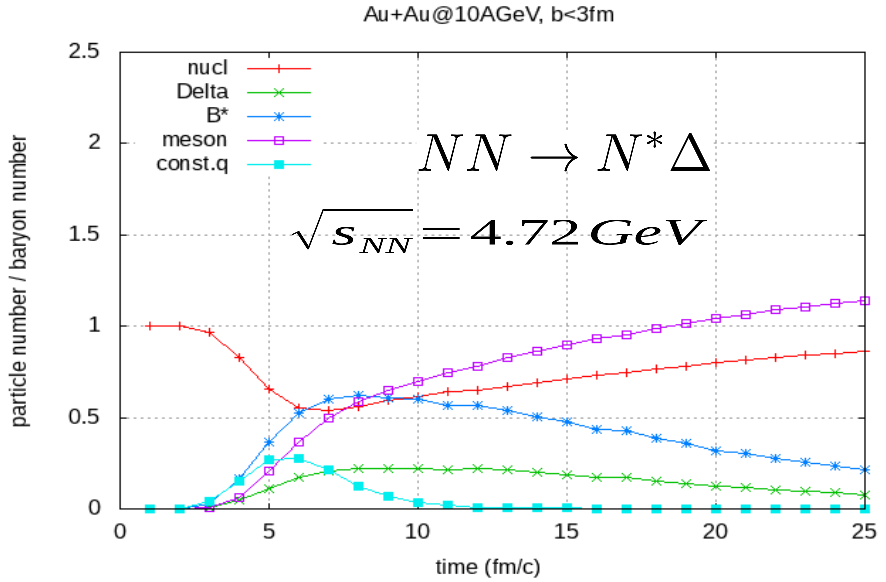




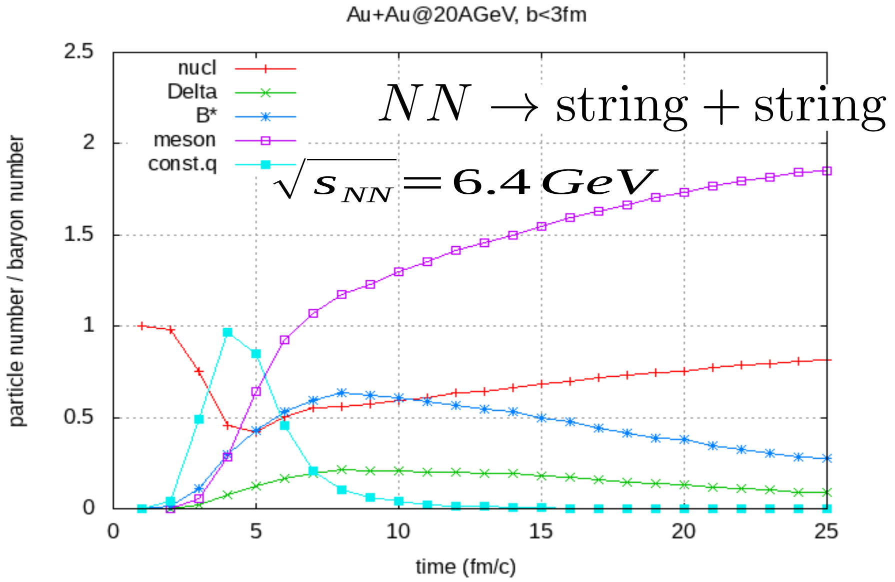
5-14 times faster with GPU

How to treat mean-field for excited matter?

Hadronic resonance dominant



constituent quark dominant due to string

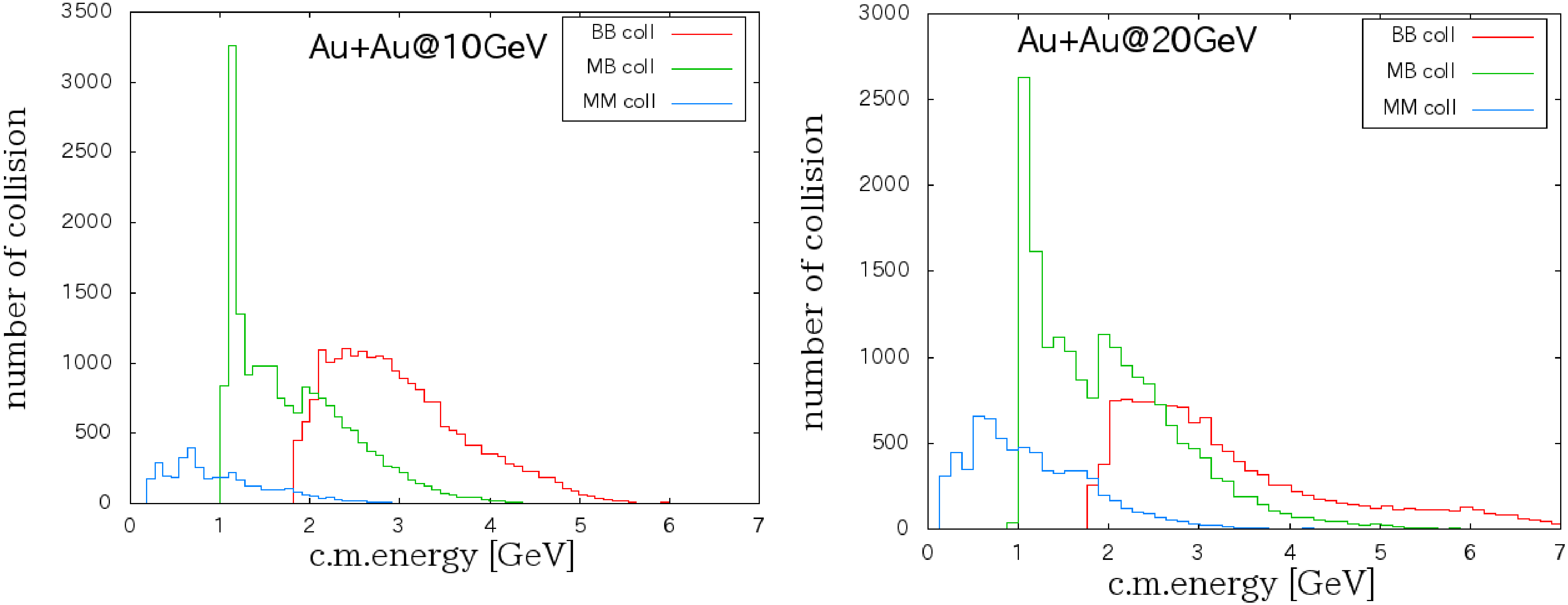


Model 1 JAM/M: potential for all formed baryon

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

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

Collision spectrum

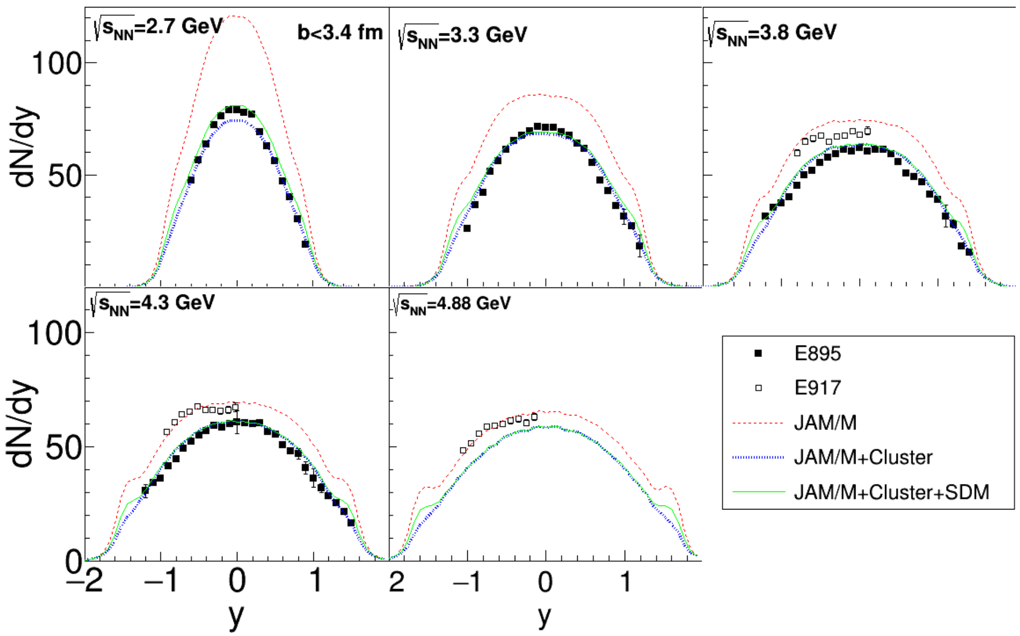


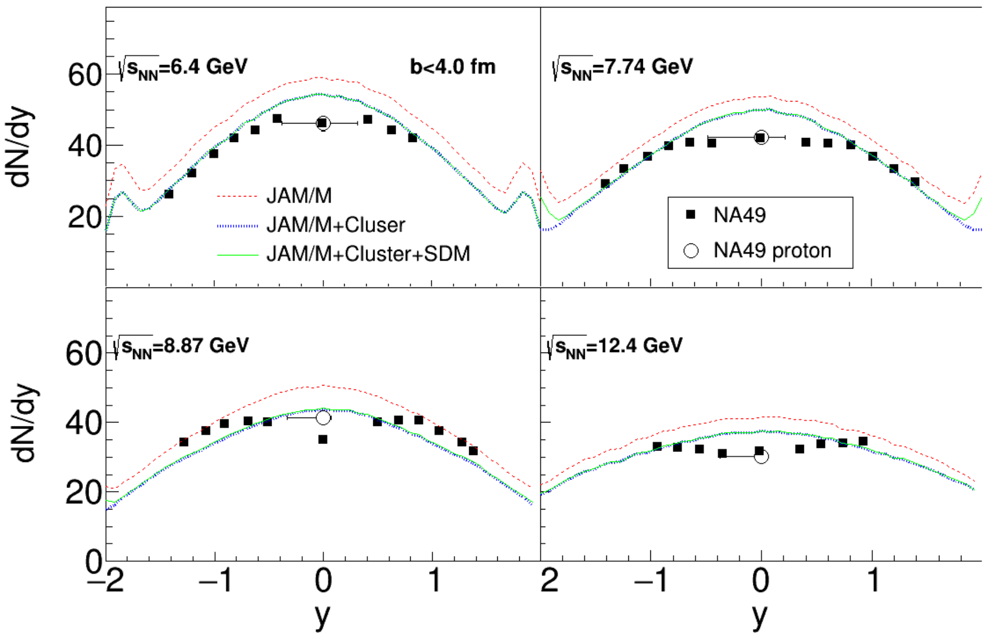
Re-scattering among produced particle is very important

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.

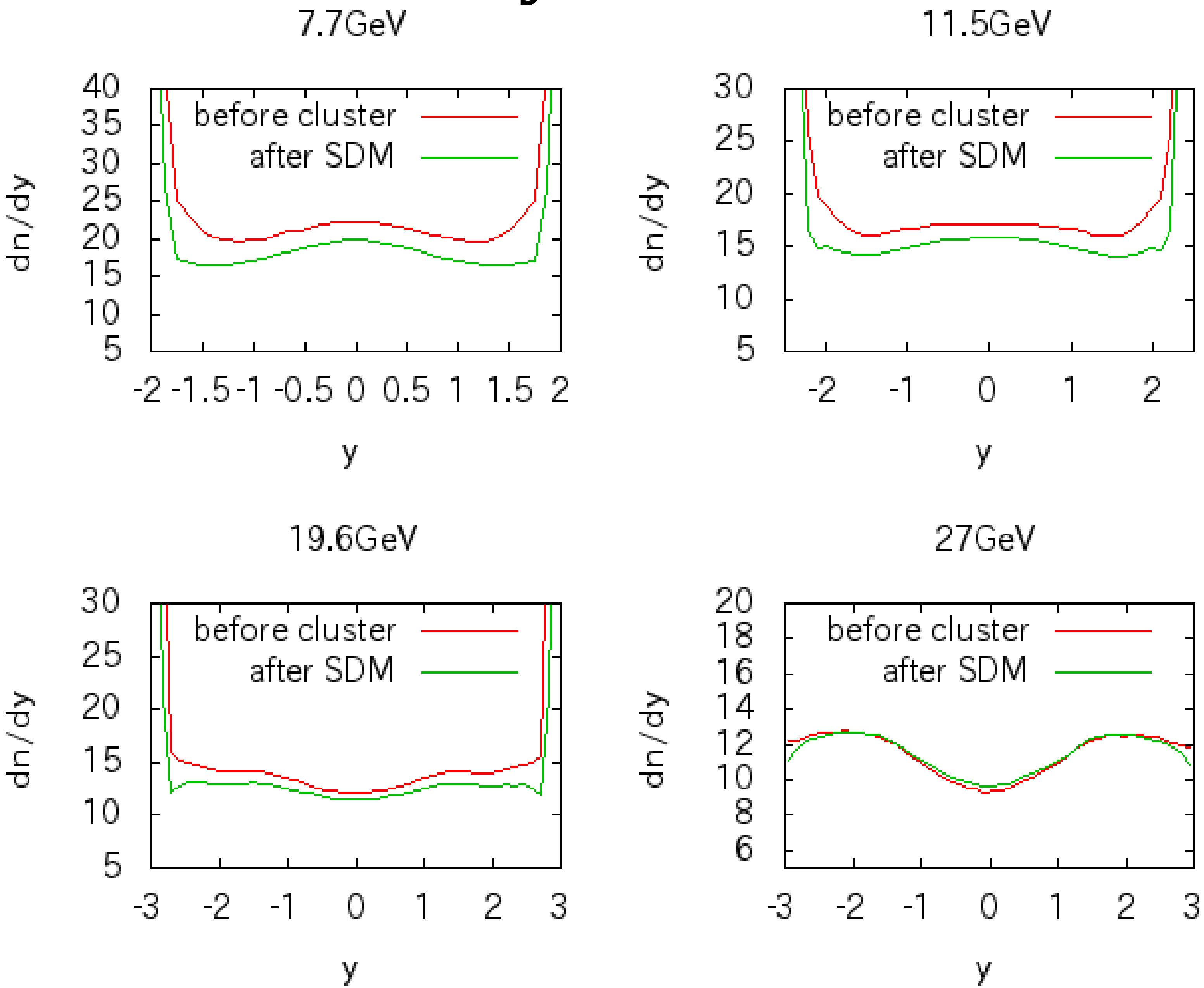
Coalescence parameter R0=4fm, P0=0.3 GeV/c



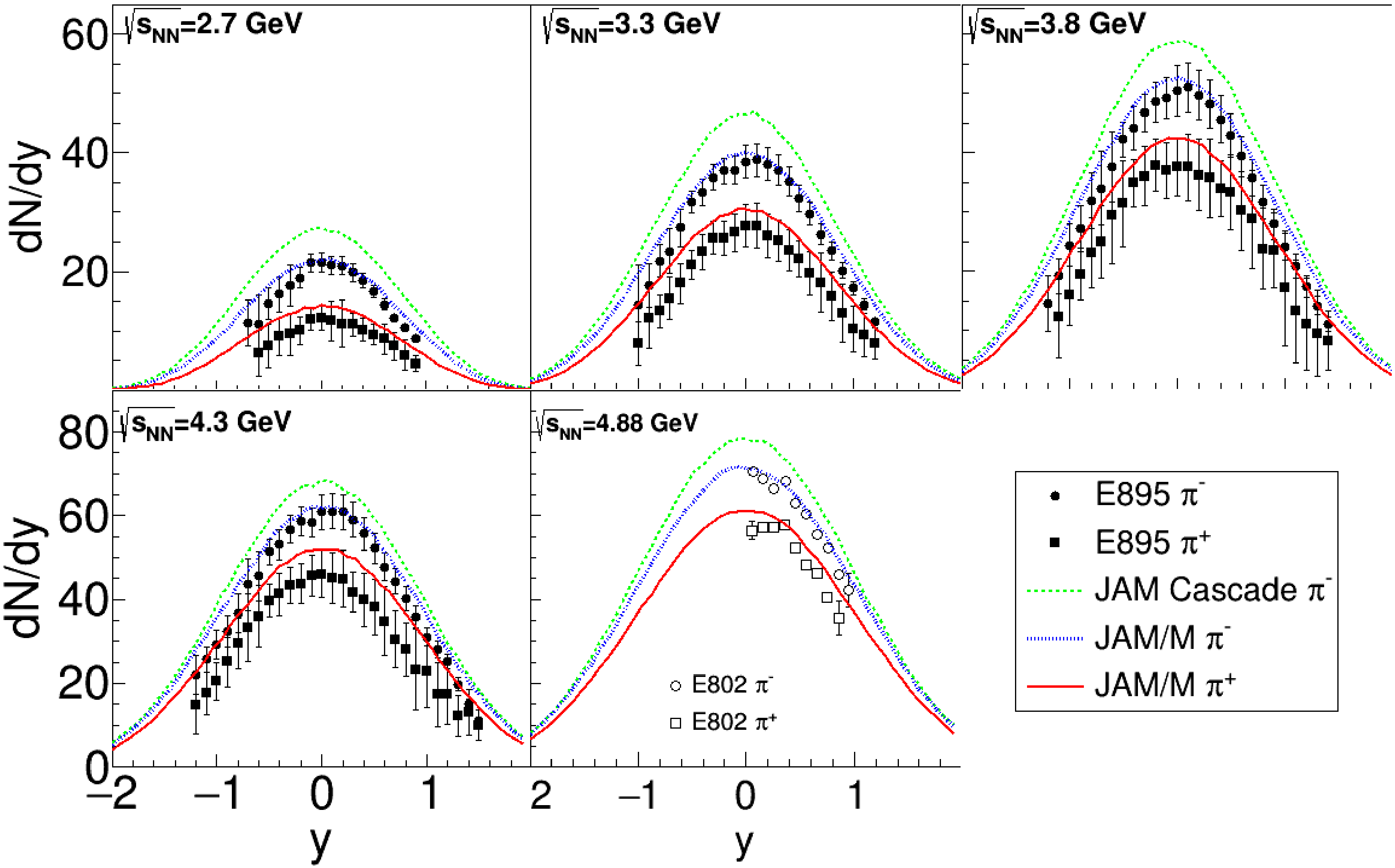


Cluster formation reduces proton dN/dy by around 20%.
Statistical decay of nuclear cluster is important only at Elab= 2AGeV
for the proton rapidity distribution.

Proton dN/dy for semi-central

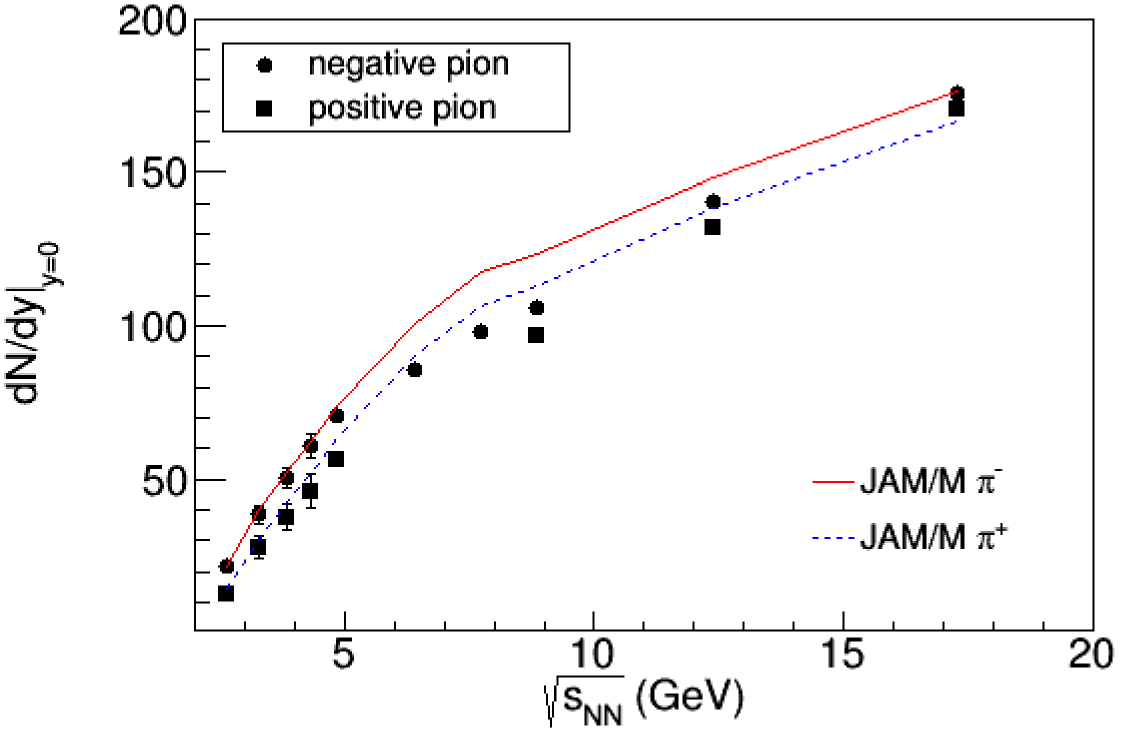


Pion rapidity distributions

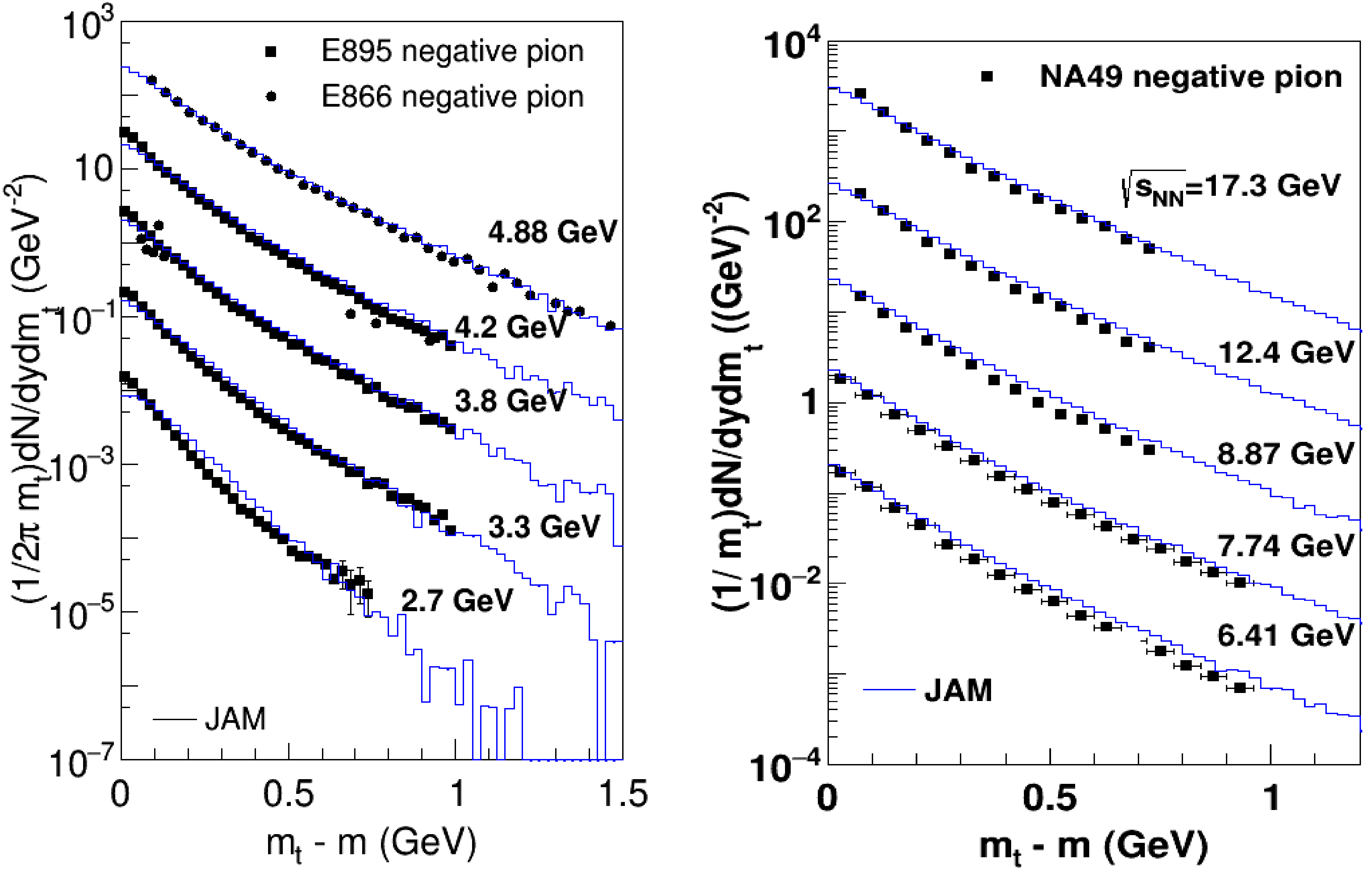


Nuclear mean field reduces the pion yield.

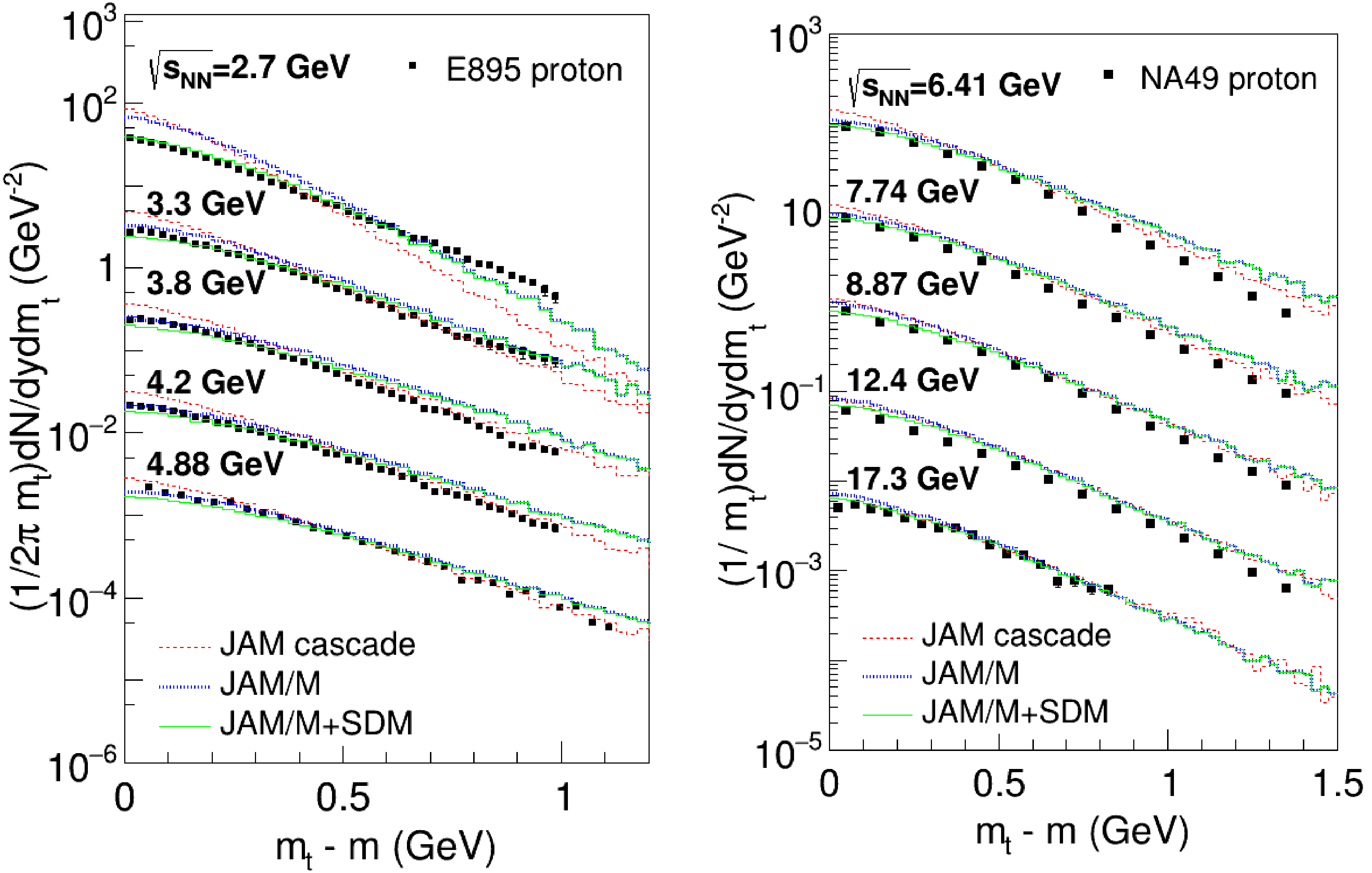
Pion yield at mid-rapitiy



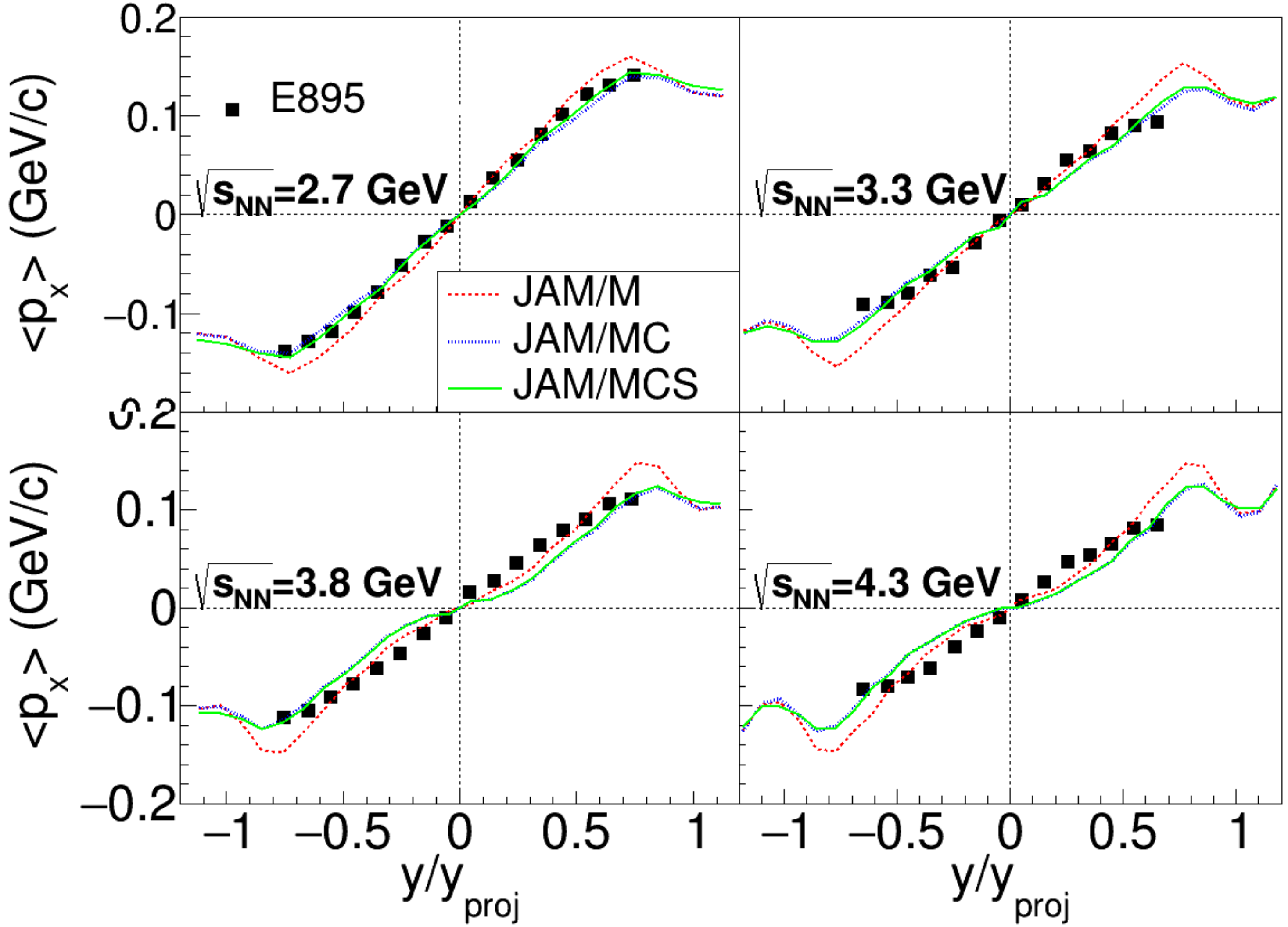
Pion transverse mas distribution



Proton distributions



Effect of cluster and its decay on the directed flow

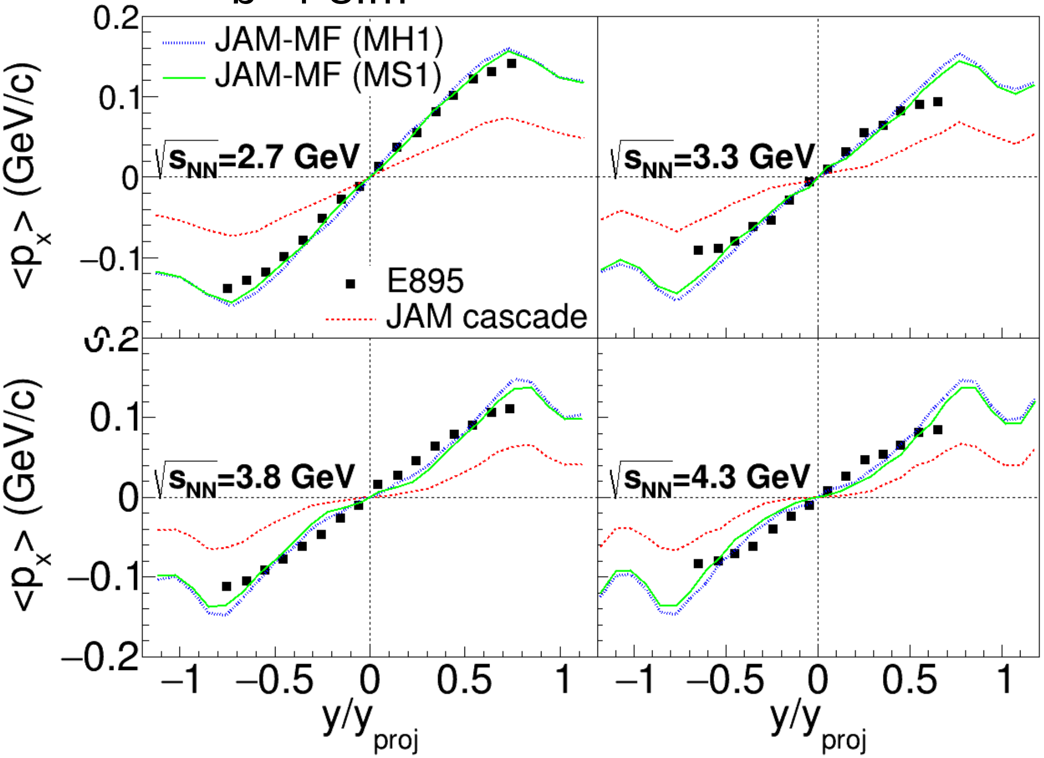


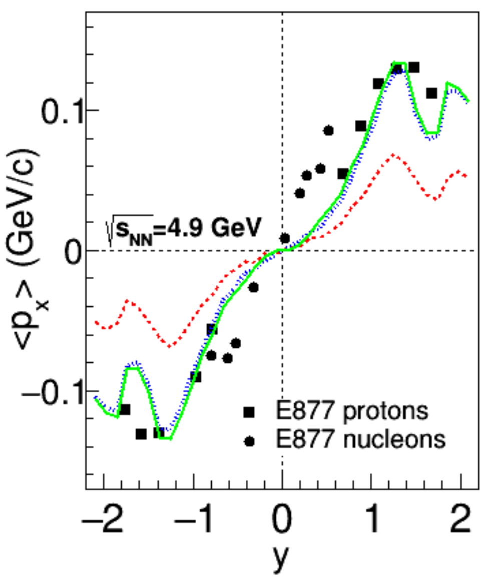
Effect of cluster is 10% on the v1

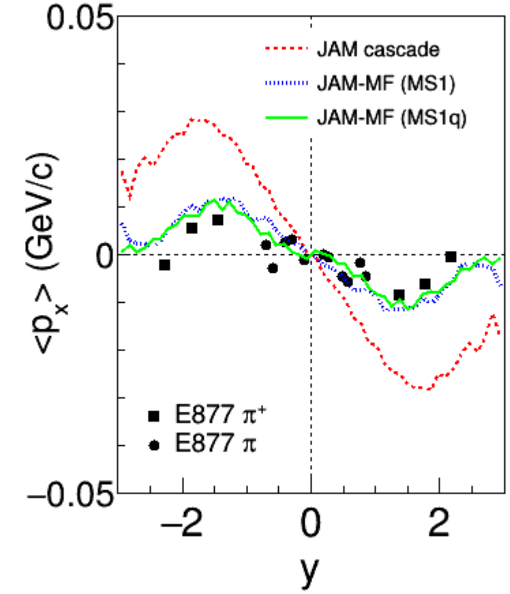
JAM/RQMD results at AGS energies

Significant mean-field effect on the directed flow

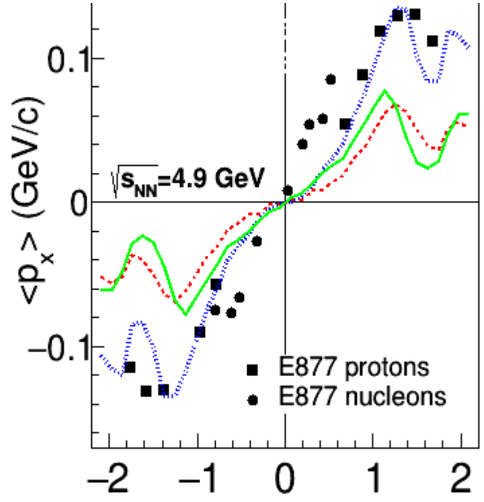
b=4-8fm

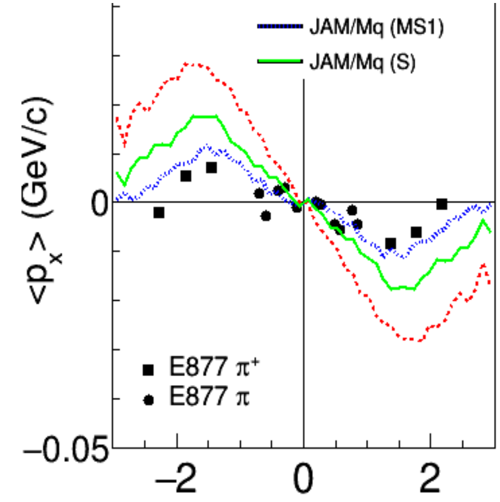






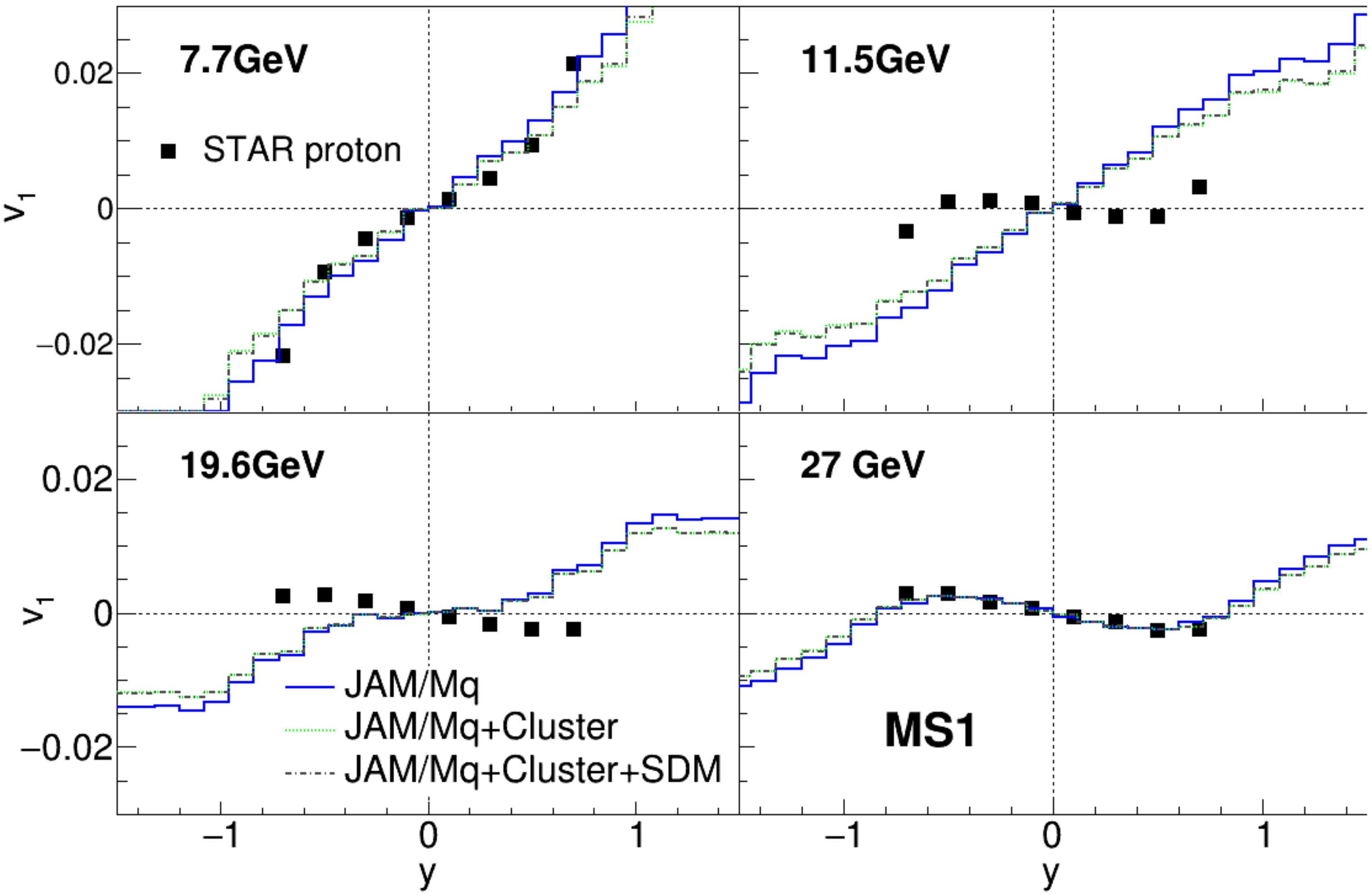
Momentum dependence of the potential is important.





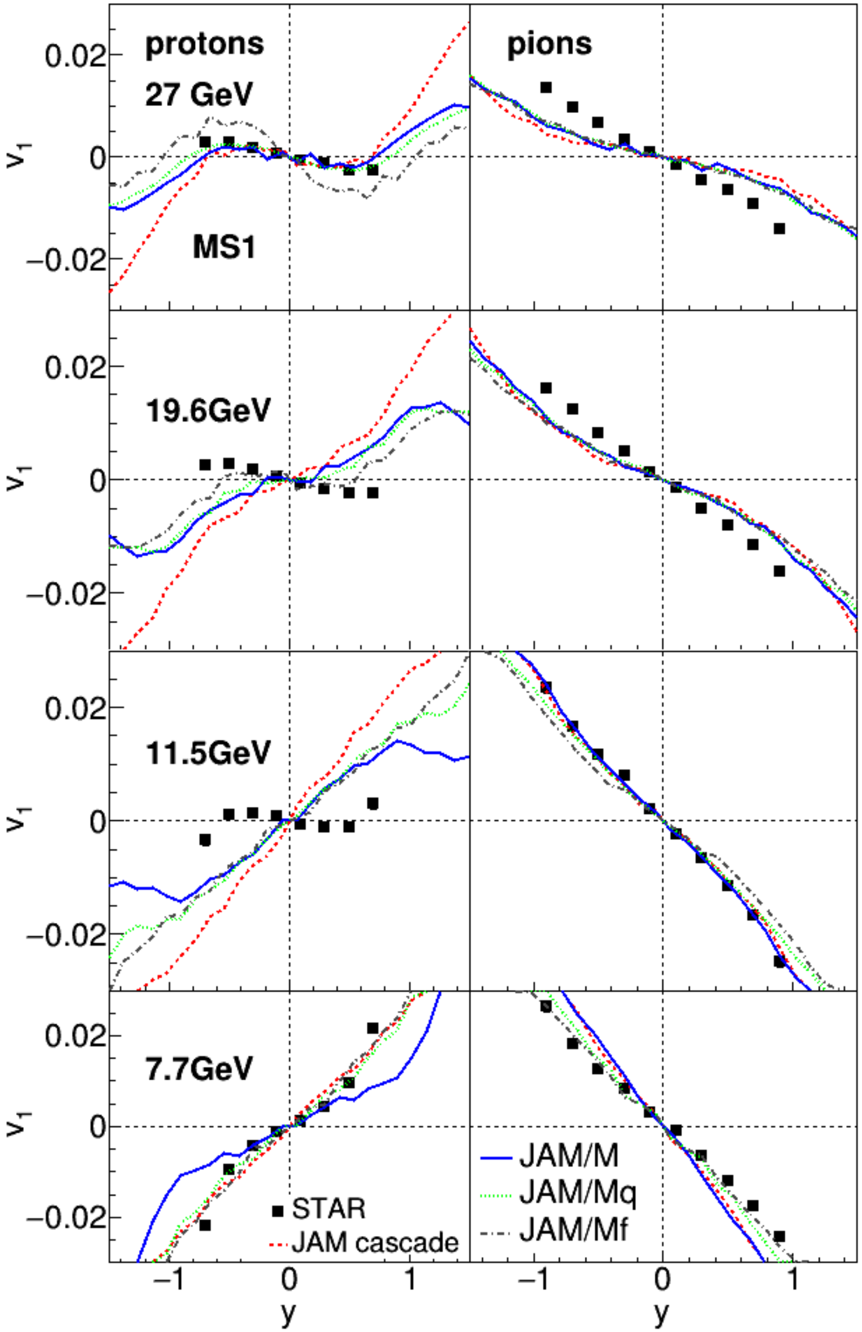
Consistent results with the previous work: M. Isse, et.al PRC72(2005) 064908.

JAM/M at STAR 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

- Remarkable progress of the models for numerical simulation of high energy nuclear collisions such as
  CGC + hydro + Boltzmann approach.

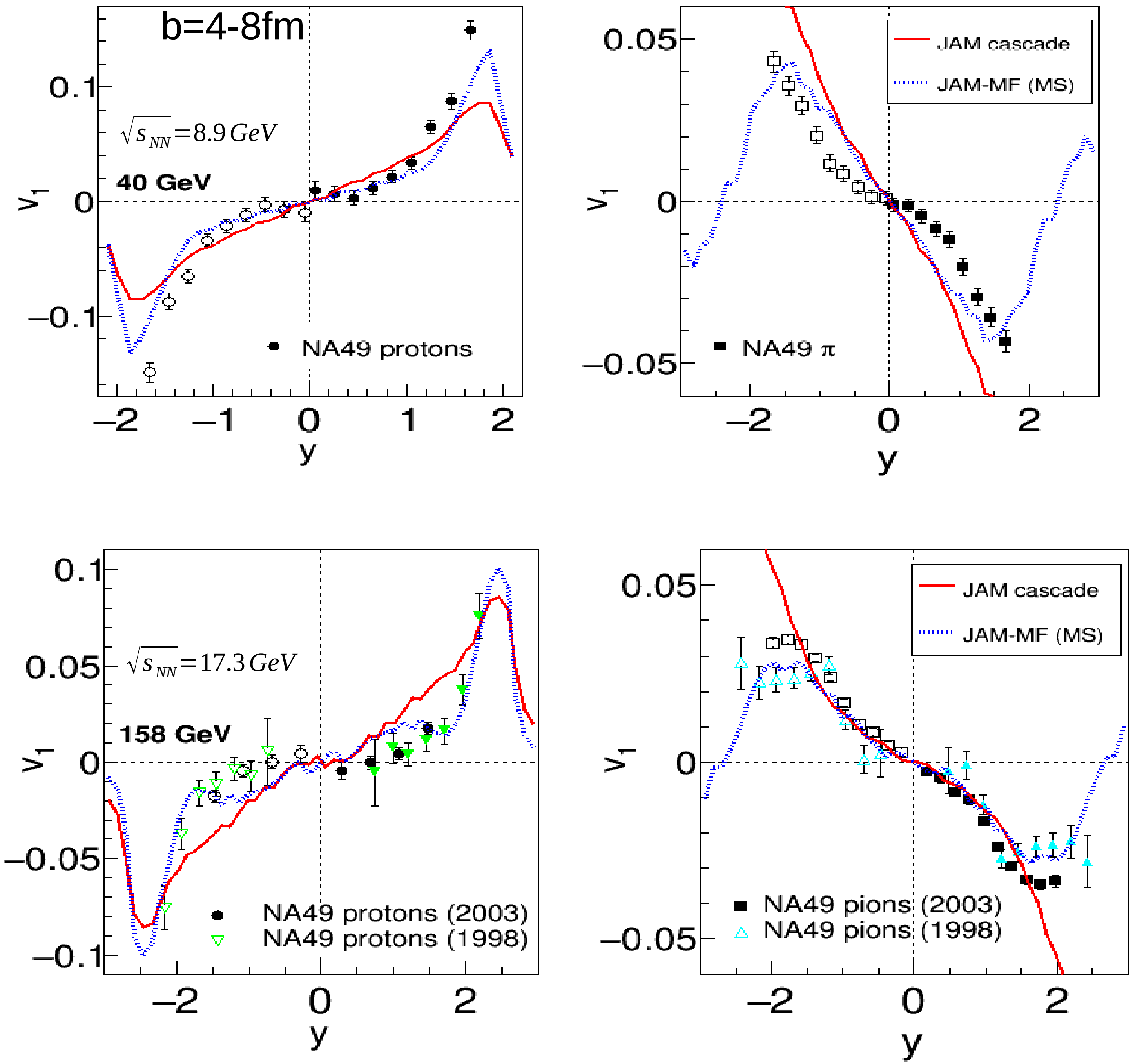
- Reliable models for phase transition region must be developed.

- 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

- 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
★ Hydrodynamics + Boltzmann(JAM) + mean field approach?

JAM-MF at SPS energies



Hadronic Cross sections in JAM

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{ch}(s) + \sigma_{ann}(s)$$
$$+ \sigma_{t-R}(s) + \sigma_{s-R}(s) \quad : \text{Resonance}$$
$$+ \sigma_{t-S}(s) + \sigma_{s-S}(s) \quad : \text{String}$$

Resonance production (absorption)

$$\sigma_{t-R}(s) : NN \leftrightarrow N\Delta, \quad NN \leftrightarrow N^*\Delta^*, \cdots$$
$$\sigma_{s-R}(s) : \pi N \leftrightarrow \Delta, \quad \bar{K}N \leftrightarrow Y^*, \cdots$$

String formation

$$\sigma_{t-S}(s) : NN \to \text{String} + \text{String},$$
$$\sigma_{s-S}(s) : \pi N \to \text{String}$$