

重イオン衝突で生成される最高バリオン密度の 微視的輸送モデルによる解析

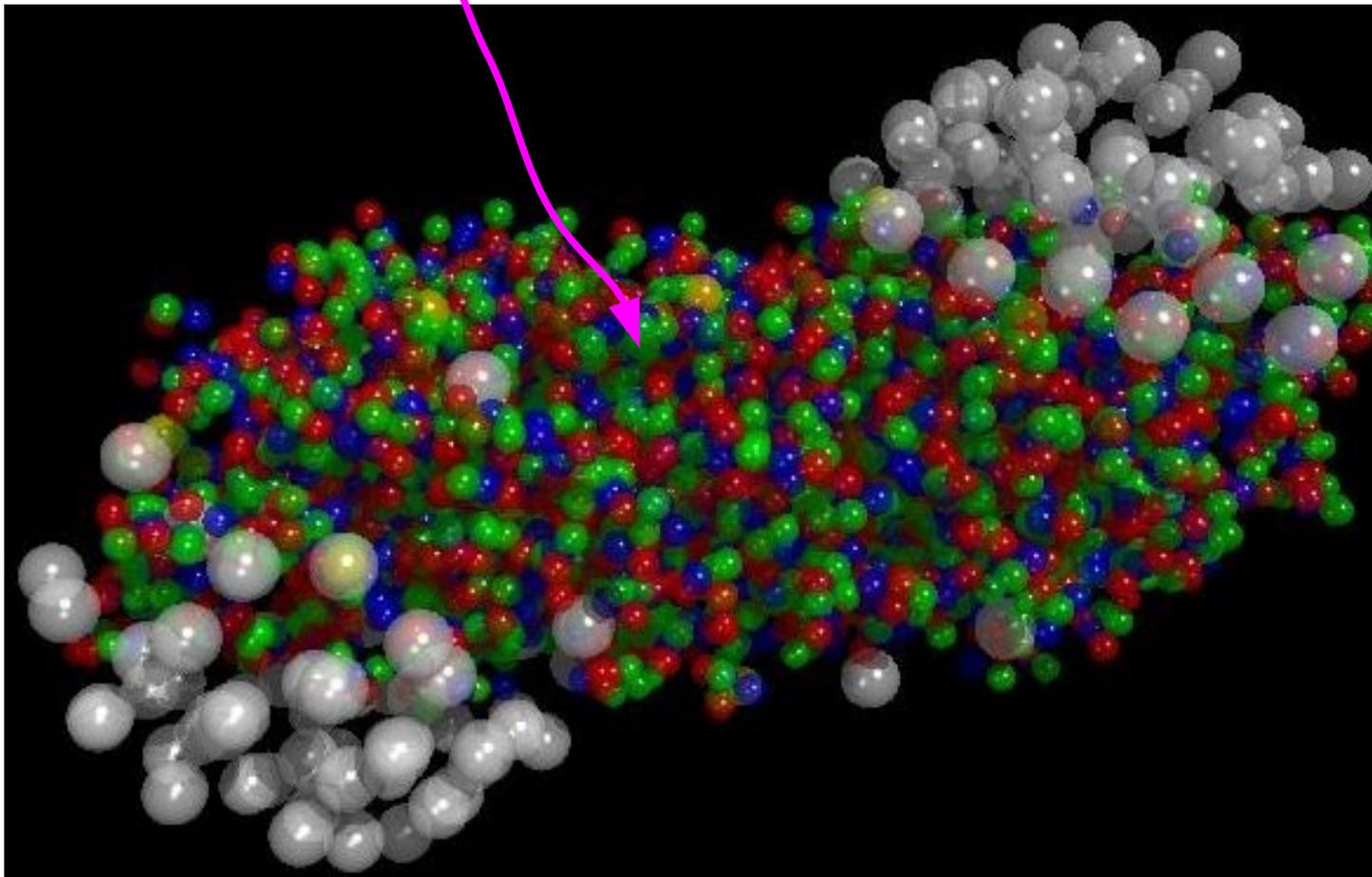
奈良 寧 (国際教養大学)
大西明(京大基研)

- Introduction
- ハドロン輸送模型 JAMと平均場の効果
- Directed flow 入射エネルギー依存性
- まとめ

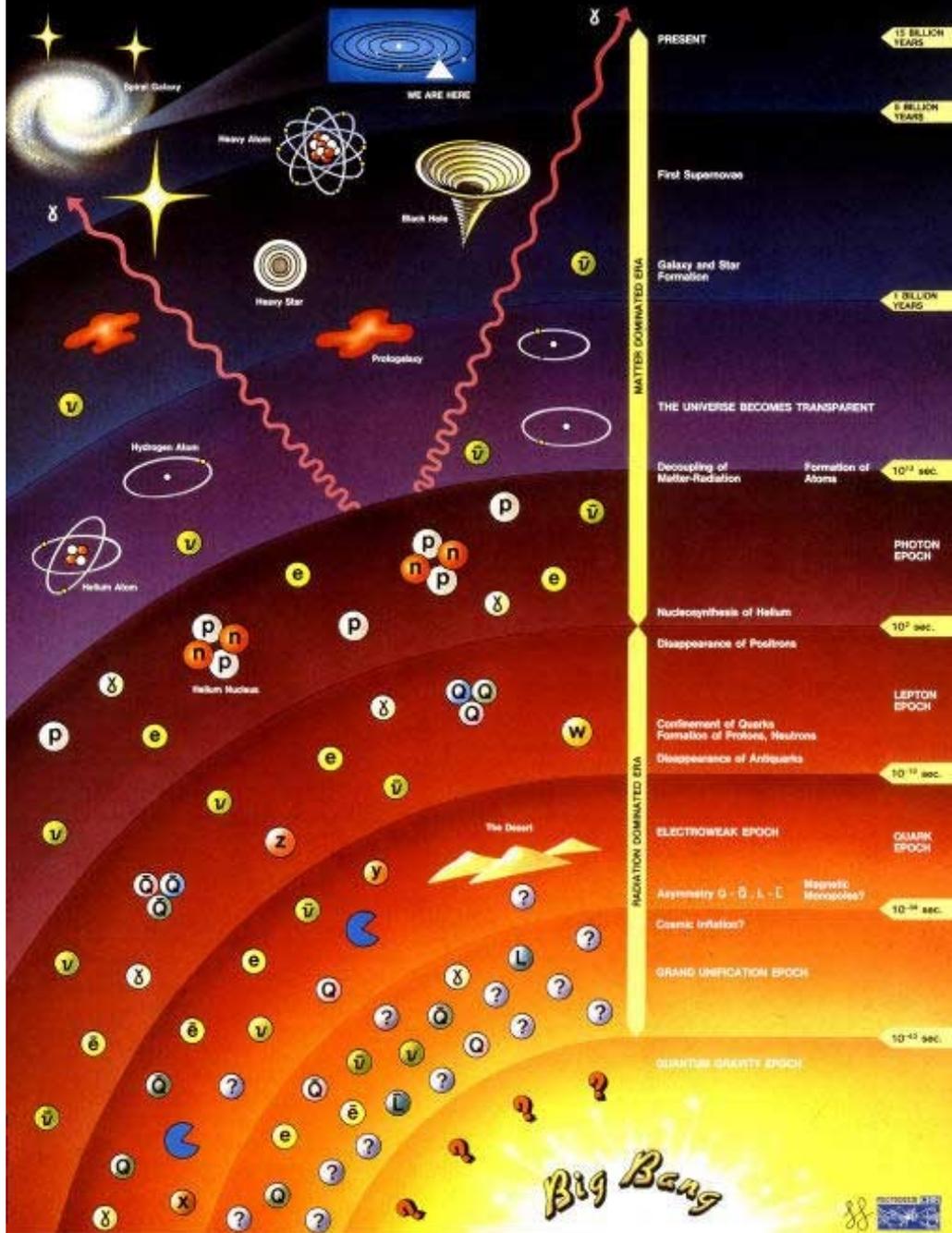
重イオン衝突による高温高密度 QCD物質の研究

UrQMD simulation

Hot and dense matter created!



History of the Universe



380,000 y old, $T=3000K$
formation of atoms

10^2 s old, $R=10^6$ km $T=10^9K$
formation of nuclei

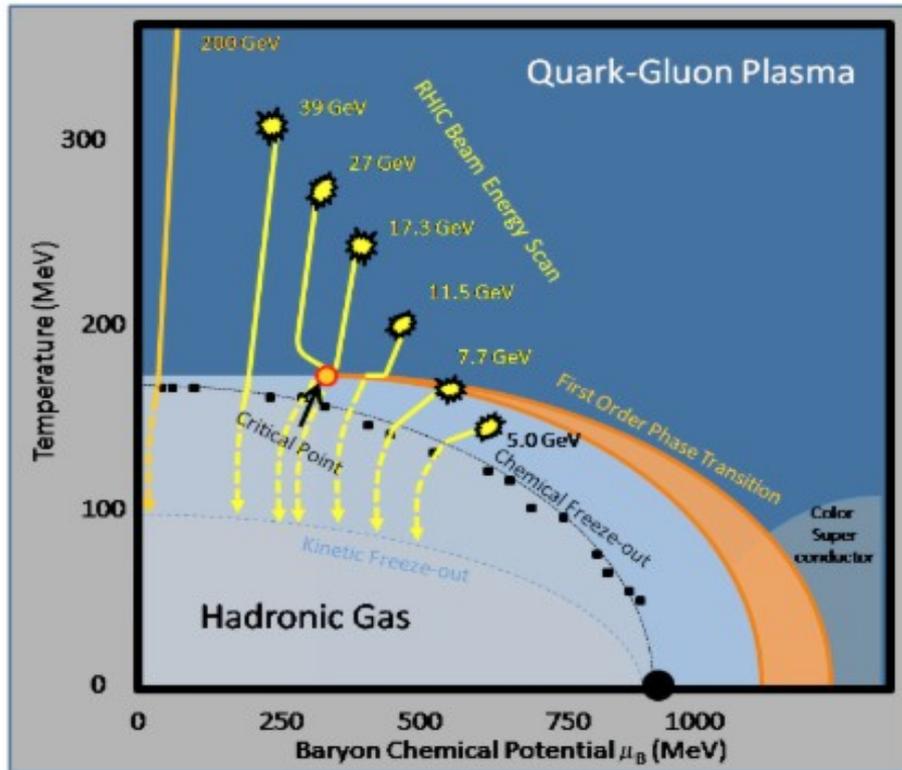
Plasma

10^{-6} s old, $R=3$ km $T=10^{12}K$
quarks formed into protons
and neutrons

Just after the big-bang,
atoms are melted.

Quark gluon plasma (QGP)

QCD Phase Diagram



How do you observe a critical point?

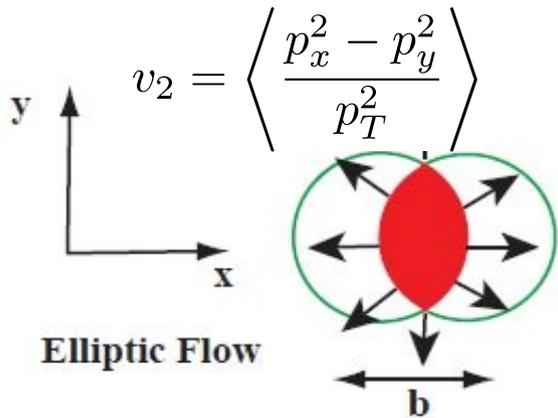
How do you observe a phase transition?

Beam Energy Scan at RHIC
 $E_{cm} = 7.7\text{GeV} - 200\text{GeV}$

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

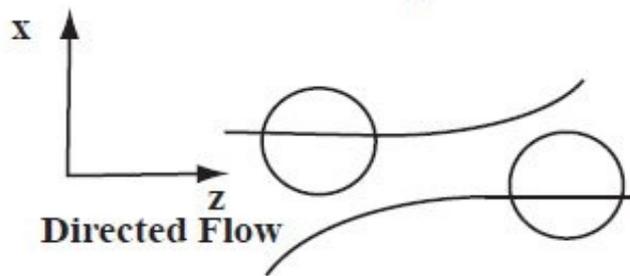
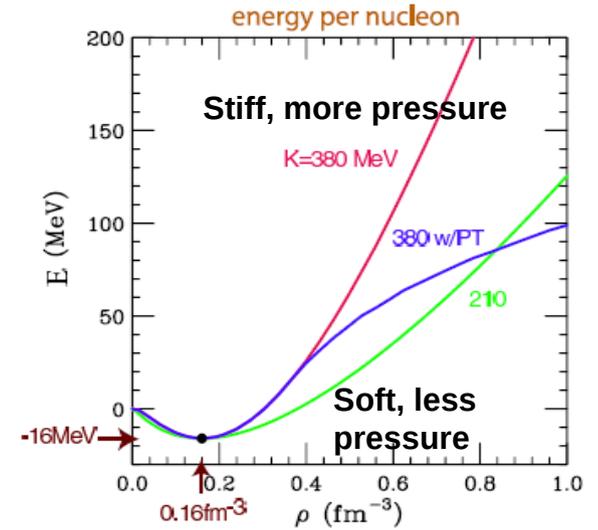
Fourier decomposition of single particle inclusive spectra:

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



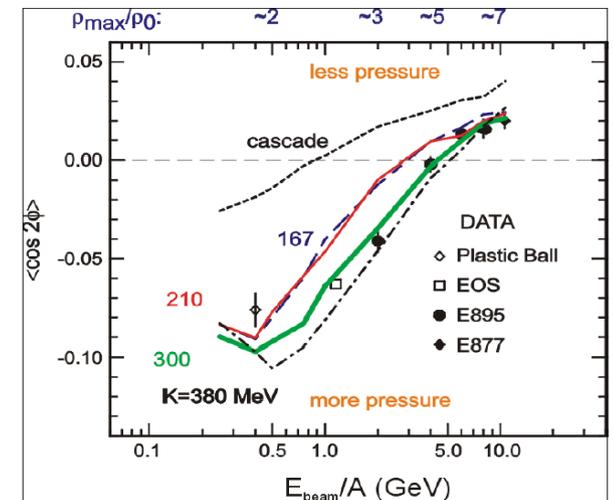
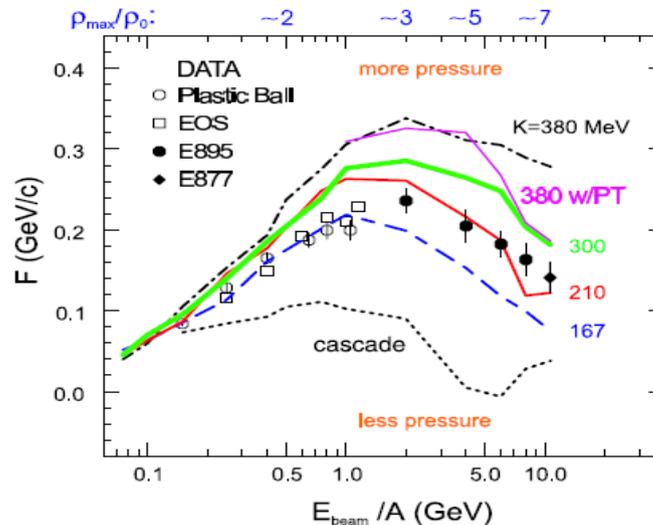
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \quad v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \quad F = \left. \frac{dv_1}{dy} \right|_{y=0}$$

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

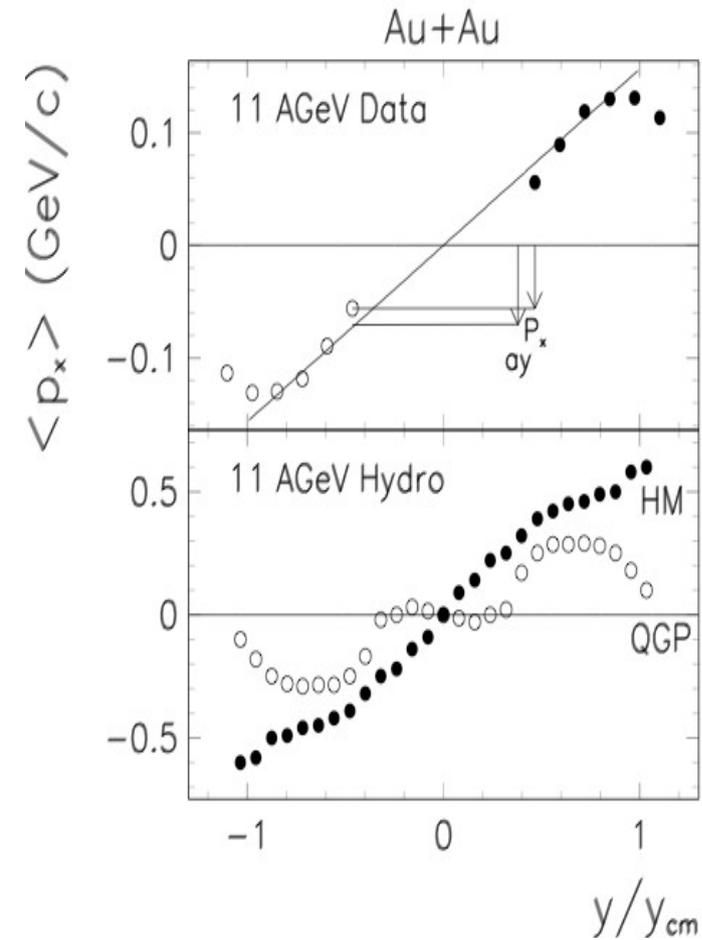


$$F = \left. \frac{\langle p_x/A \rangle}{d(y/y_{cm})} \right|_{y/y_{cm}=1}$$

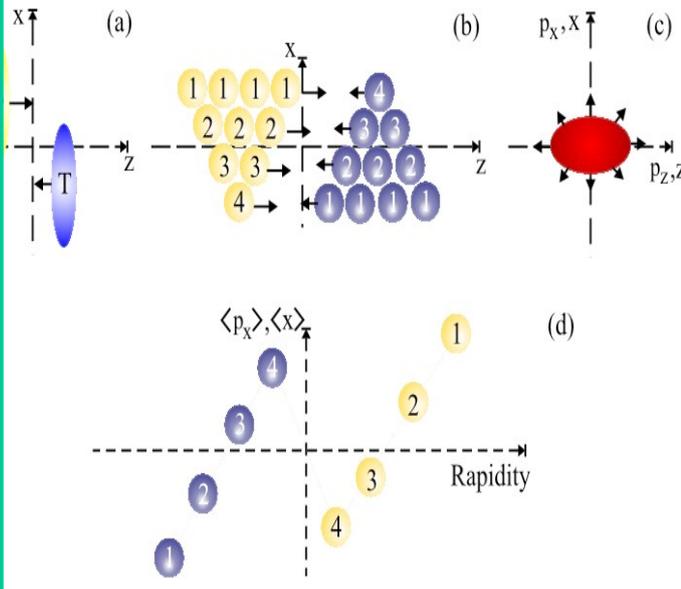
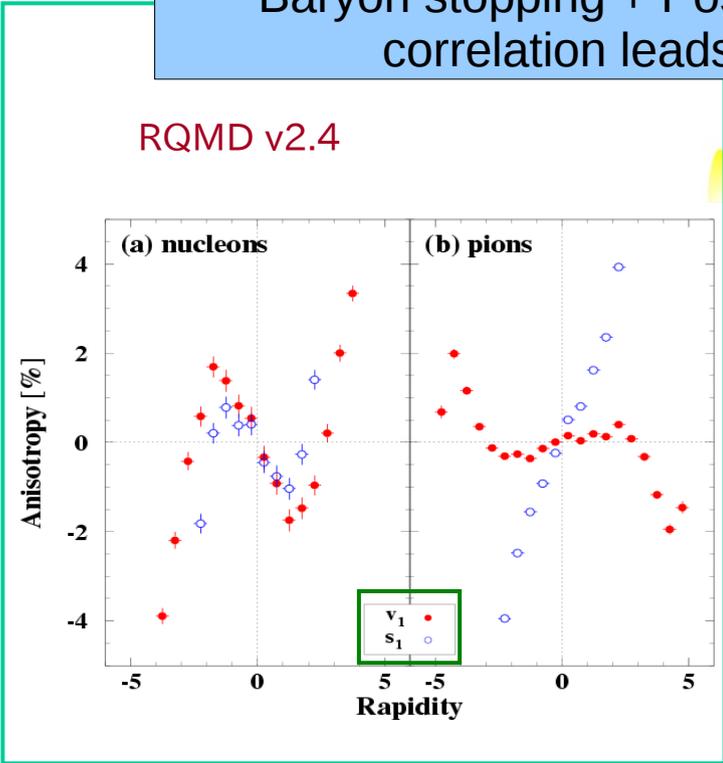
In-plane flow, v_1



Wiggle: QGP signal in the directed flow?



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



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

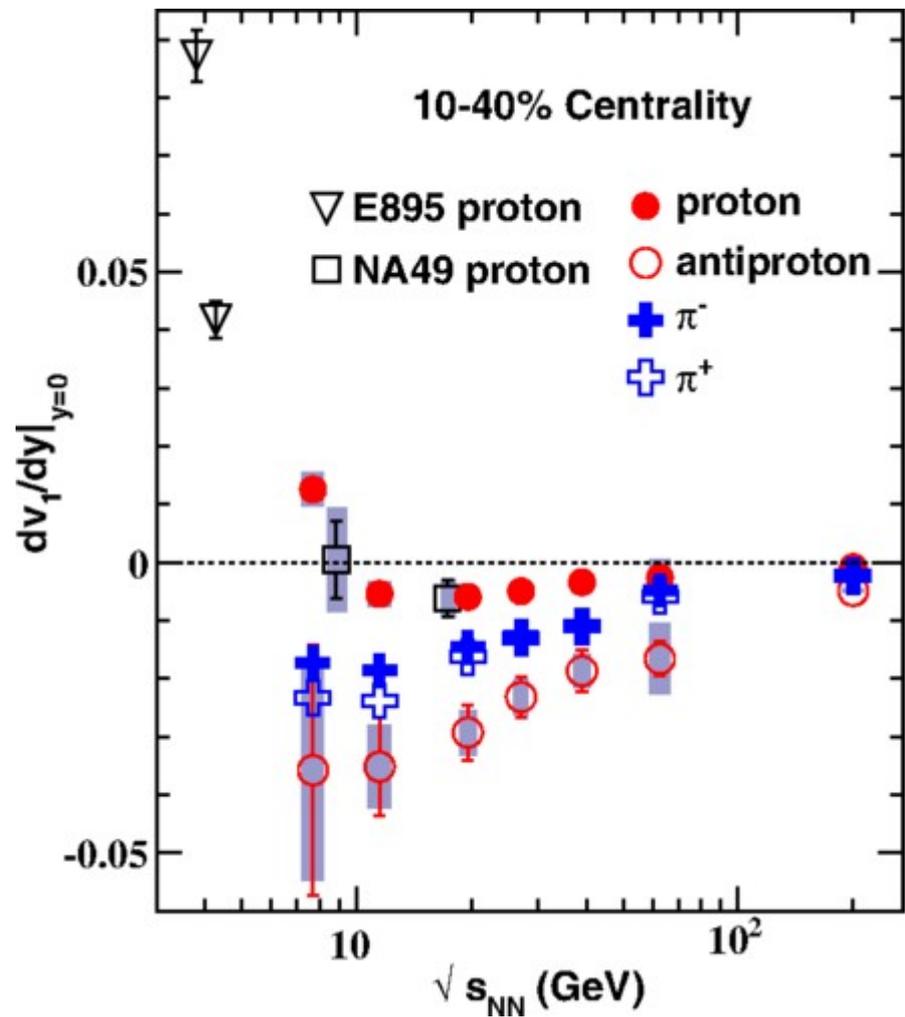
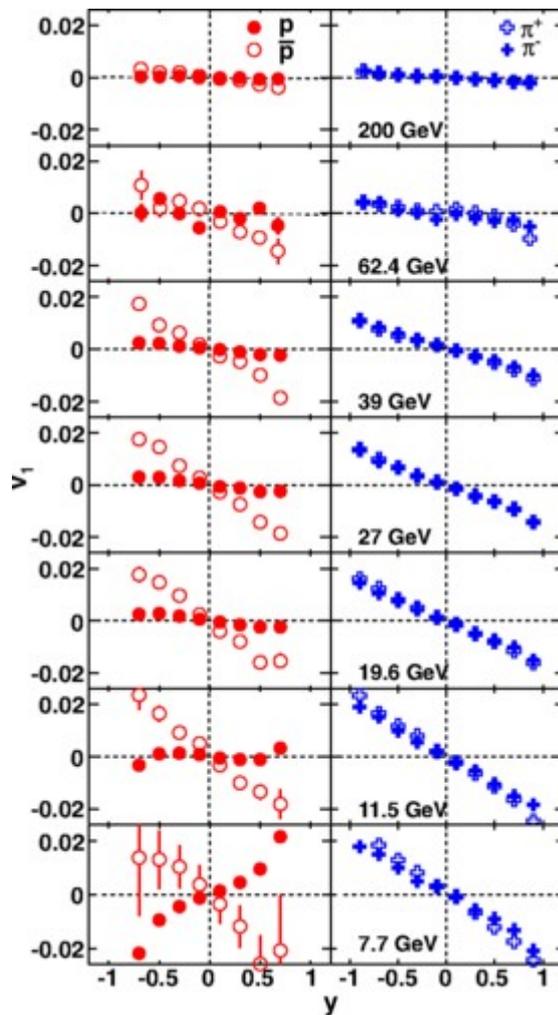
L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.

QGP EoS predicts wiggle in hydro

Beam energy dependence of v_1

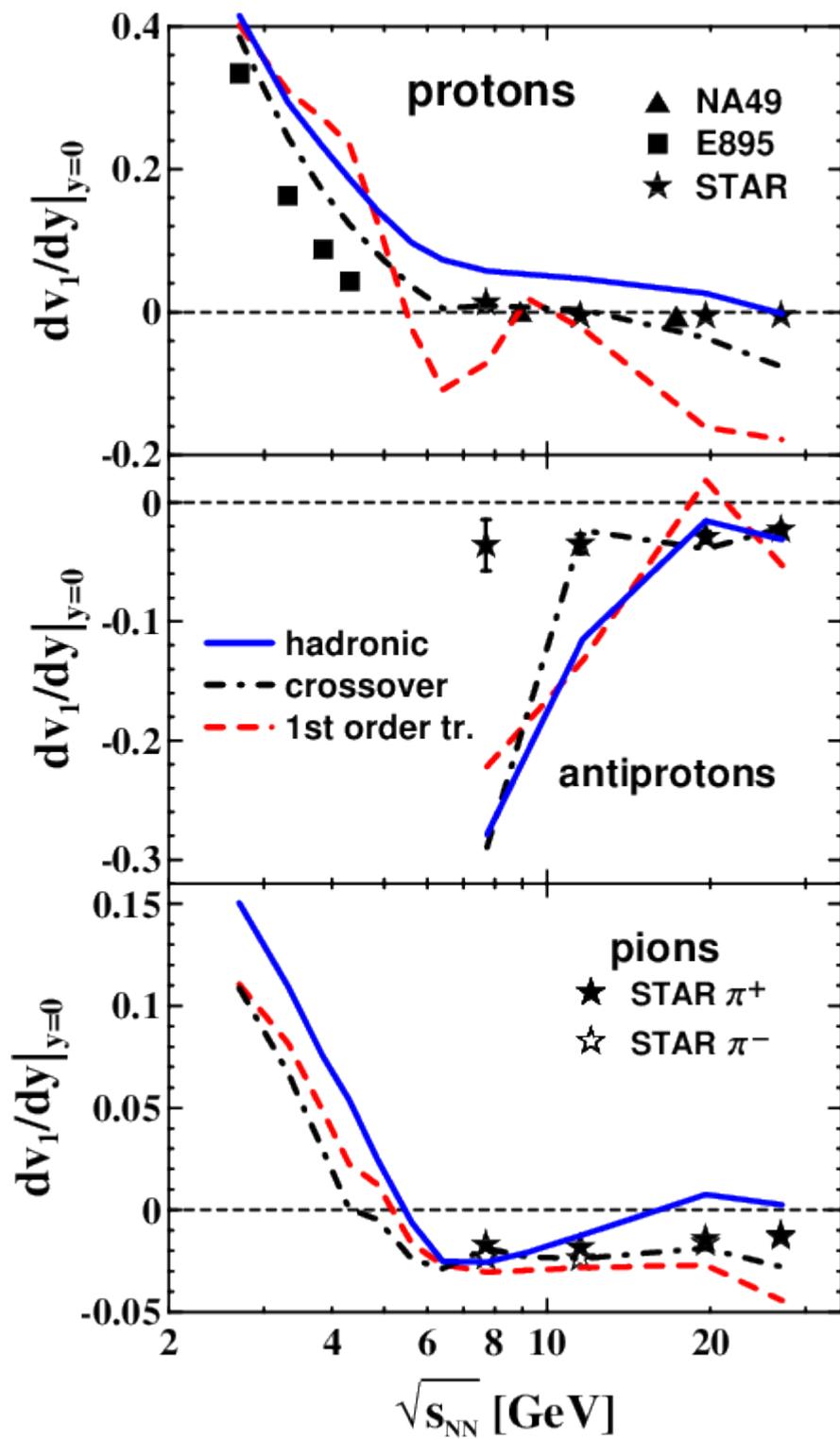
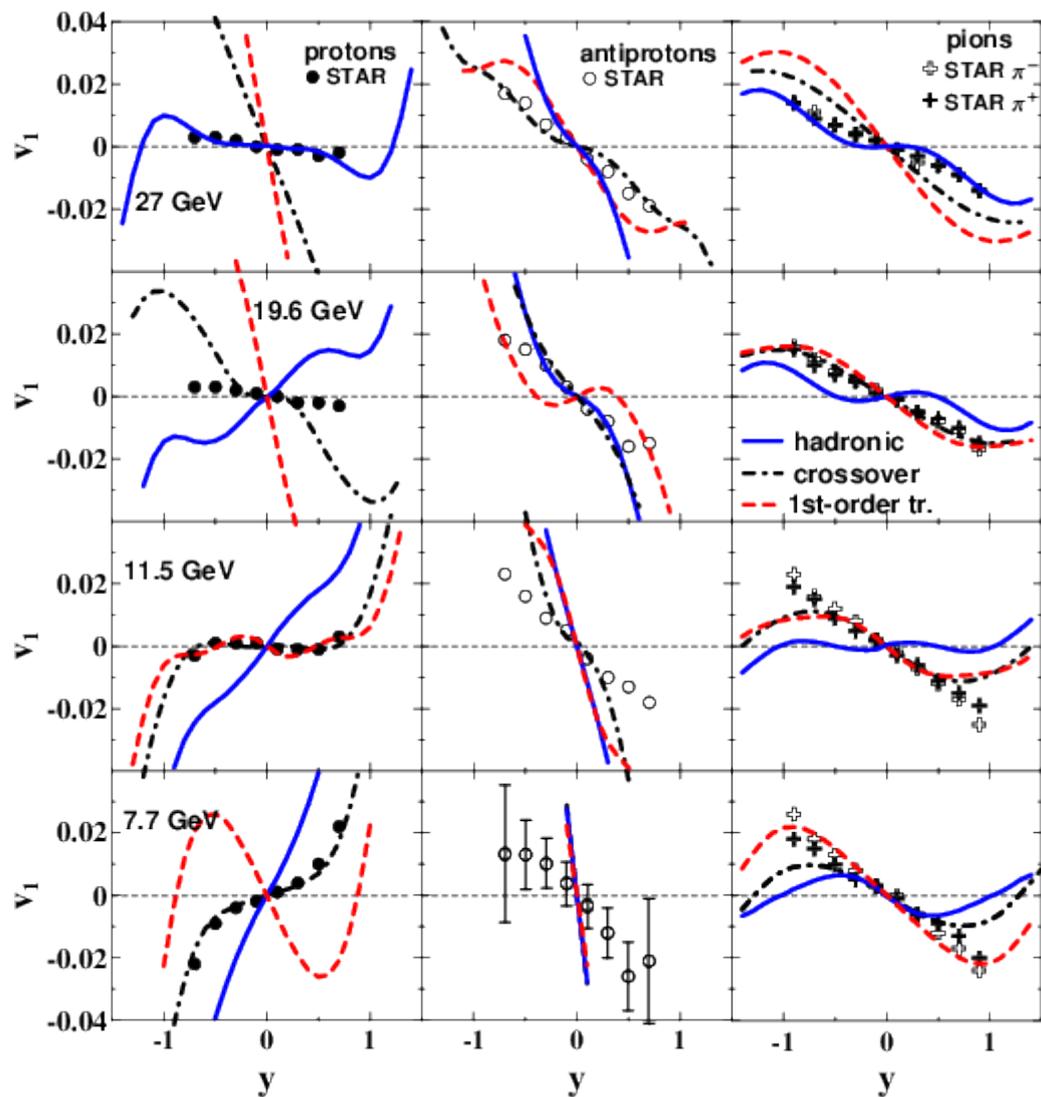
L. Adamczyk et al. (STAR Collaboration)

Phys. Rev. Lett. 112, 162301 – Published 23 April 2014



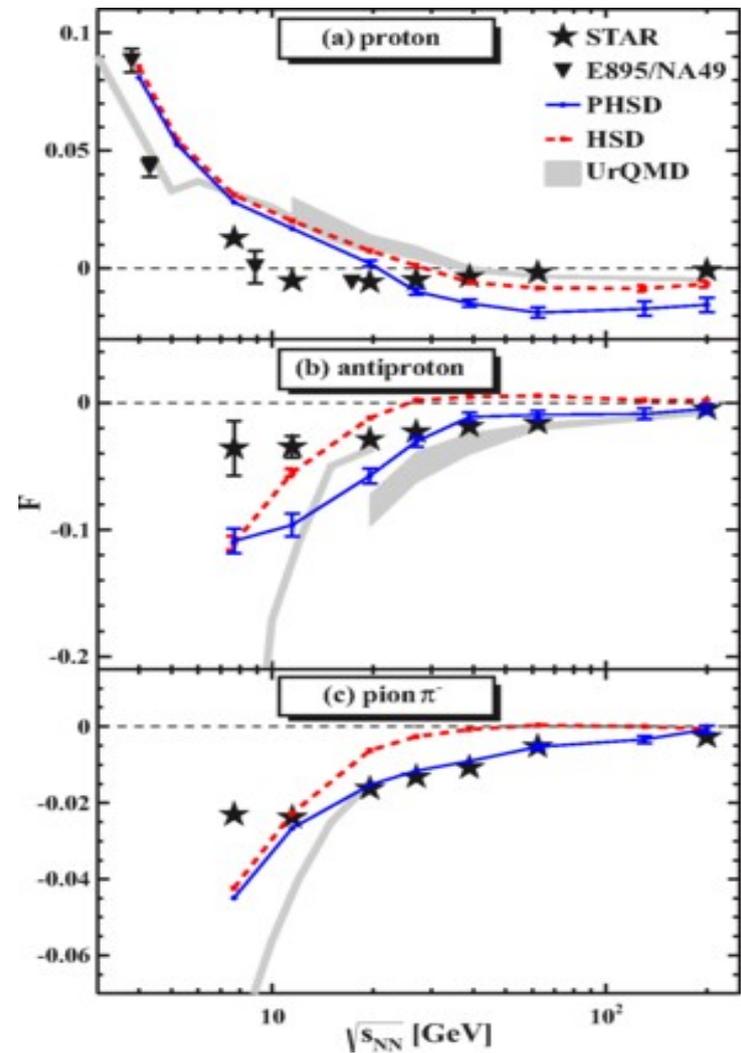
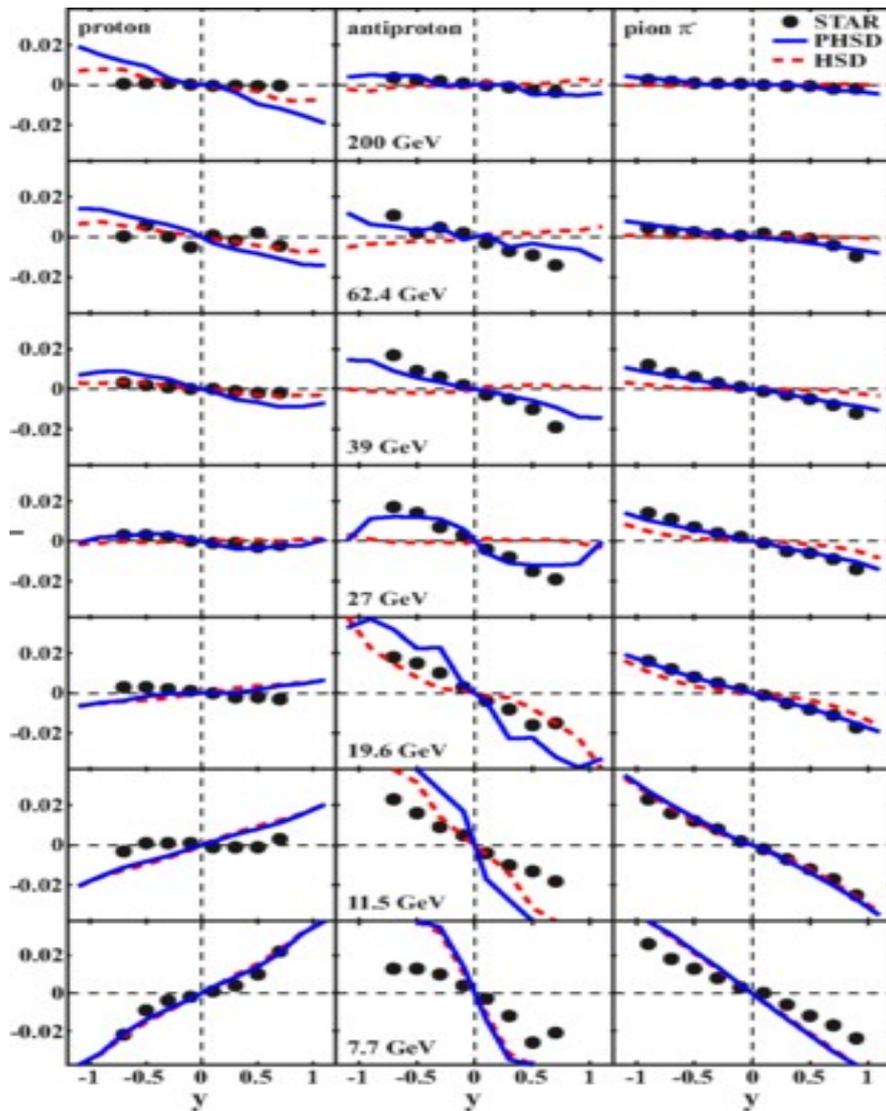
V1 from hydrodynamics

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

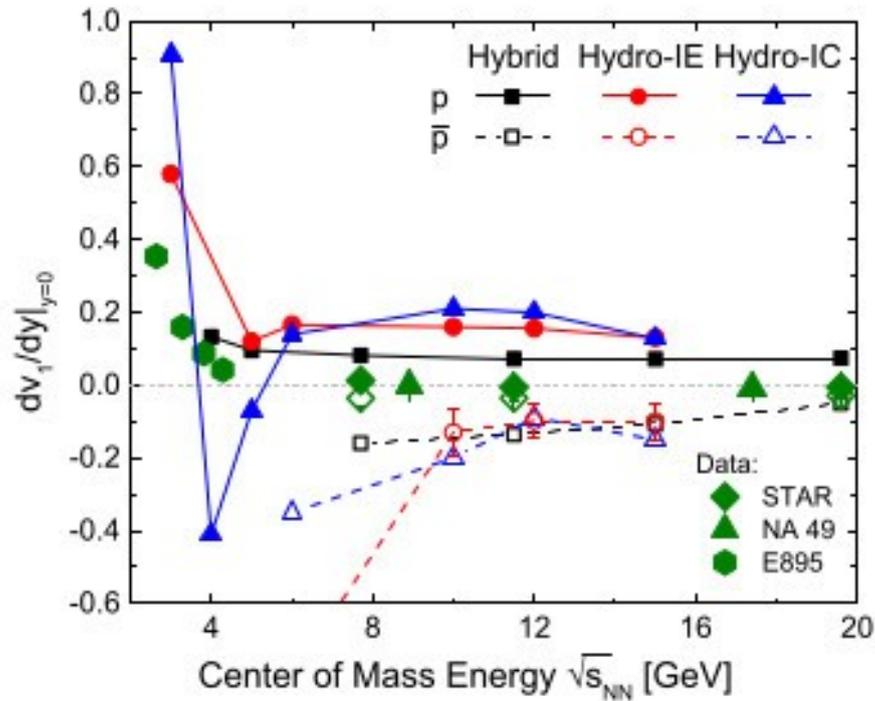


PHSD/HSD predictions

V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev,
*Phys. Rev. C*90, no. 1, 014903 (2014)



UrQMD+hydro+UrQMD results



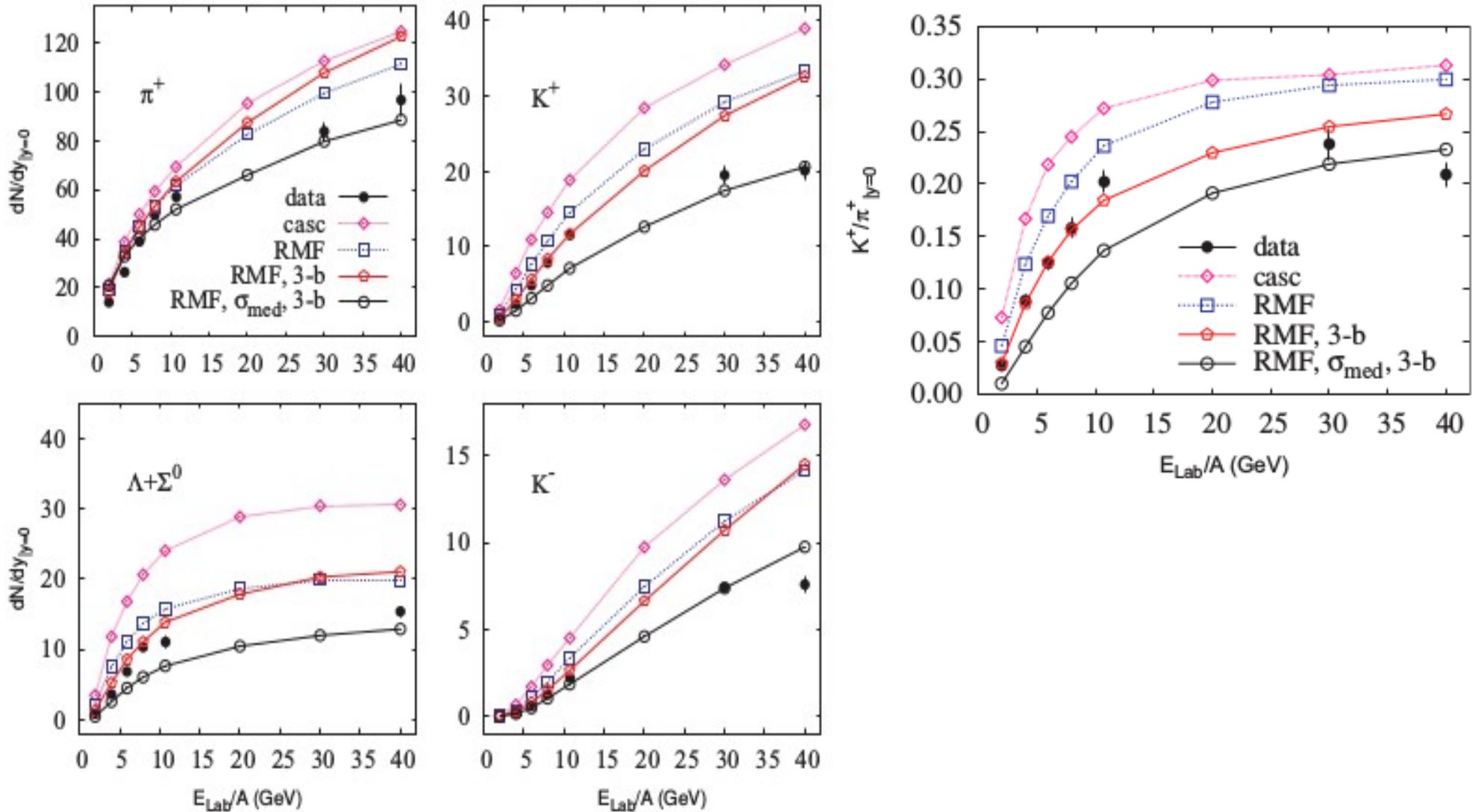
The values of the slopes are always positive.

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

J-PARC エネルギー領域に適用でき るイベントジェネレータ

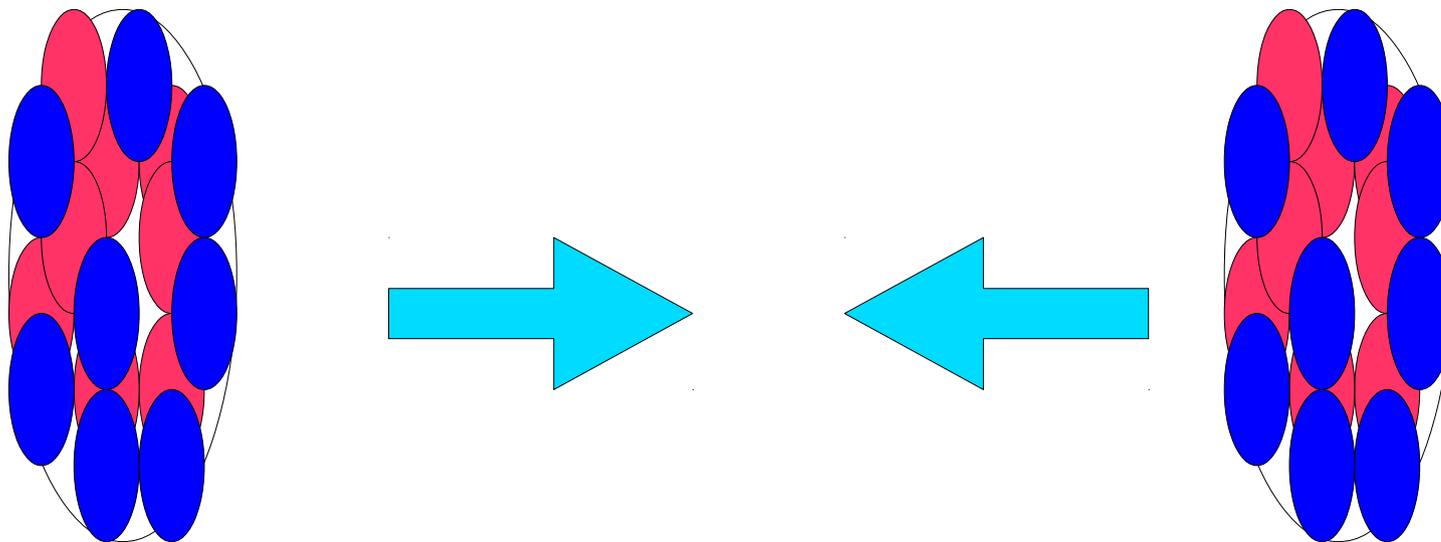
- **UrQMD 3.4** Frankfurt **public**
resonance model N*,D*, string pQCD, PYTHIA6.4
- **PHSD** Giessen (Cassing) **upon request**
D(1232),N(1440),N(1530), string, pQCD, FRITIOF7.02
- **GiBUU 1.6** Giessen (Mosel) **public**
resonance model N*,D*, string, pQCD,PYTHIA6.4
- **AMPT**
HIJING+ZPC+ART
- **JAM public**
resonance model N*,D*, string, pQCD, PYTHIA6.1

GiBUU predictions



Hadron cascade の簡単な説明

Initial state (before collision): Nucleons are sampled according to Woods-Saxon distribution, momentum of each nucleon is sampled by Fermi momentum
,boost two nucleus according to the corresponding incident energy.

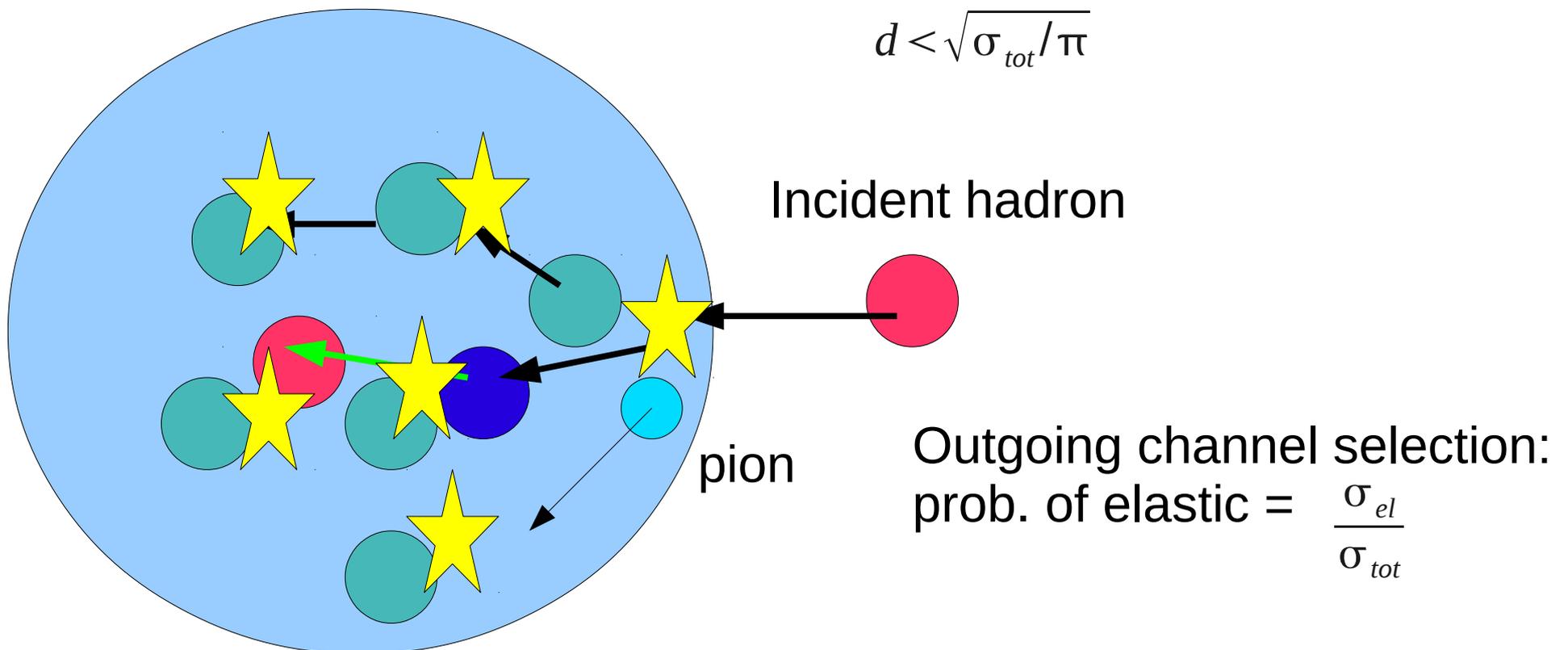


ハドロン-ハドロン散乱の インコヒーレントな重ね合わせ

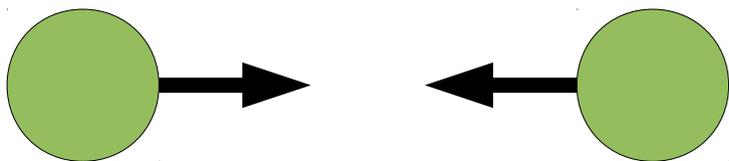
2. Straight line trajectories until particles interact
(Potential can be included)

3. Collision at closest approach

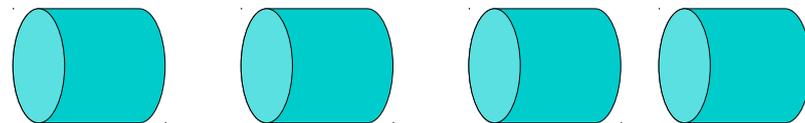
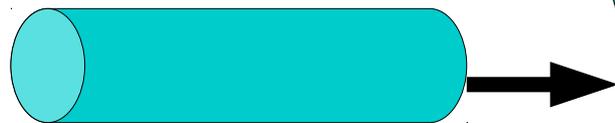
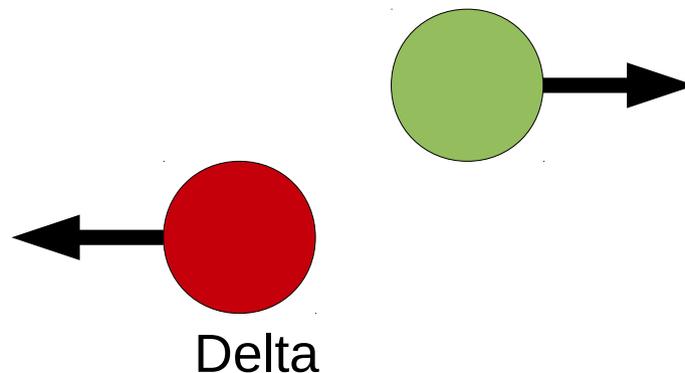
$$d < \sqrt{\sigma_{tot}/\pi}$$



すべての可能な素過程
粒子発生の時空発展



String excitation of hadrons



String decay into hadrons

Hadronic Cross sections in JAM

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

Resonance production (absorption)

$$\sigma_{t-R}(s) : NN \leftrightarrow N\Delta, \quad NN \leftrightarrow N^*\Delta^*, \dots$$

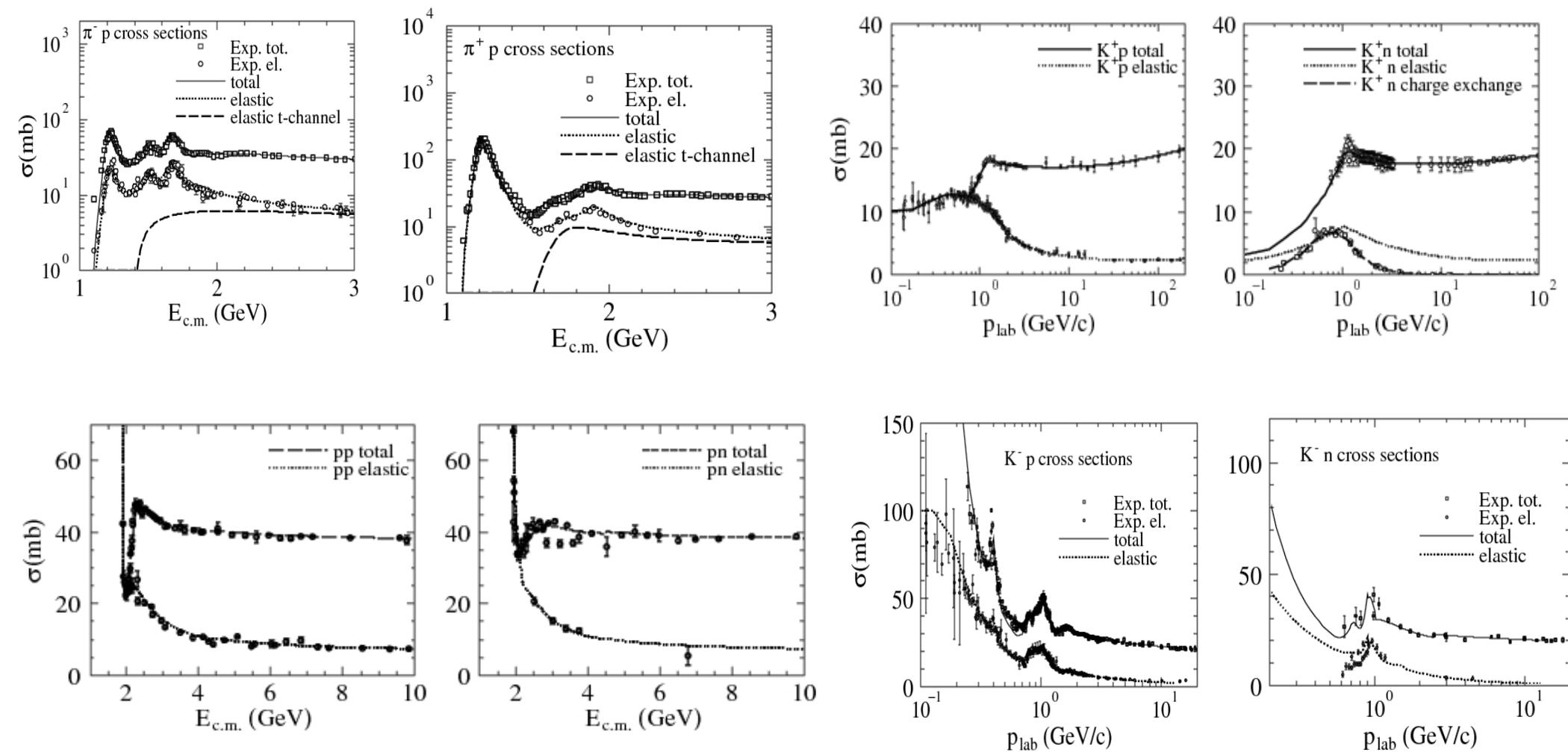
$$\sigma_{s-R}(s) : \pi N \leftrightarrow \Delta, \quad \bar{K}N \leftrightarrow Y^*, \dots$$

String formation

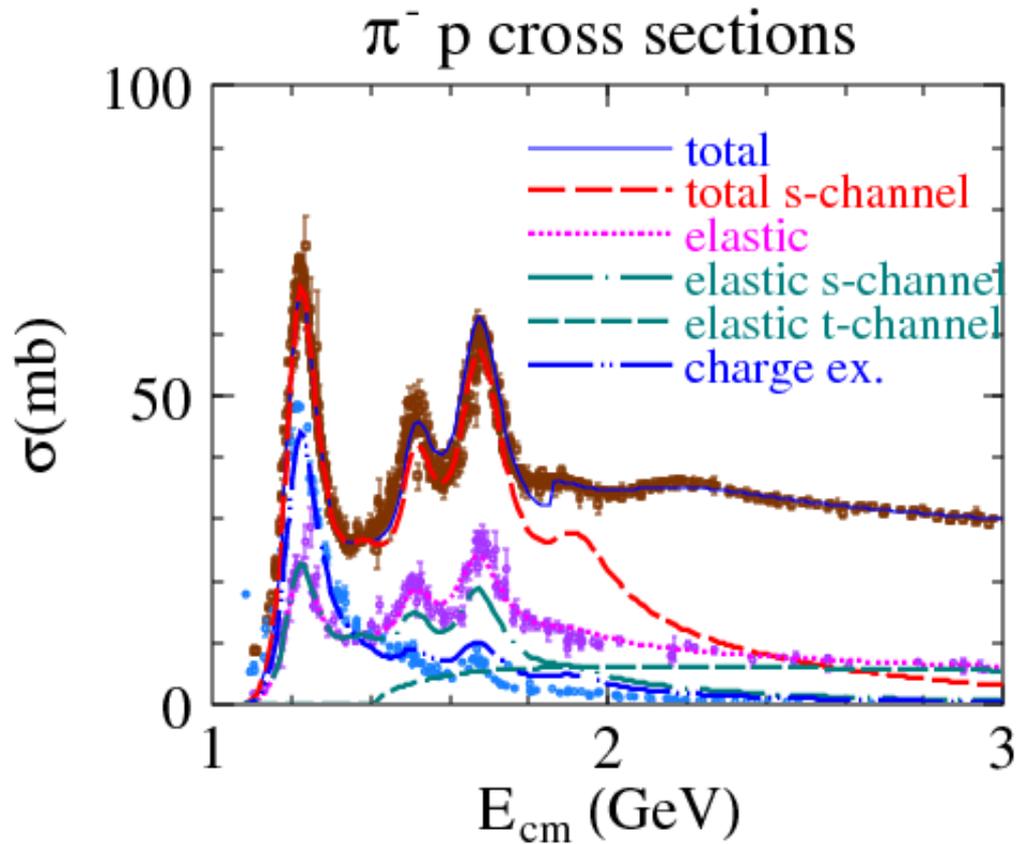
$$\sigma_{t-S}(s) : NN \rightarrow \text{String} + \text{String},$$

$$\sigma_{s-S}(s) : \pi N \rightarrow \text{String}$$

JAM: total cross sections



Modeling low energy π -p cross sections



S-channel inelastic:
 π -p \rightarrow resonance (or string)

T-channel inelastic:
 π -p \rightarrow resonance + resonance

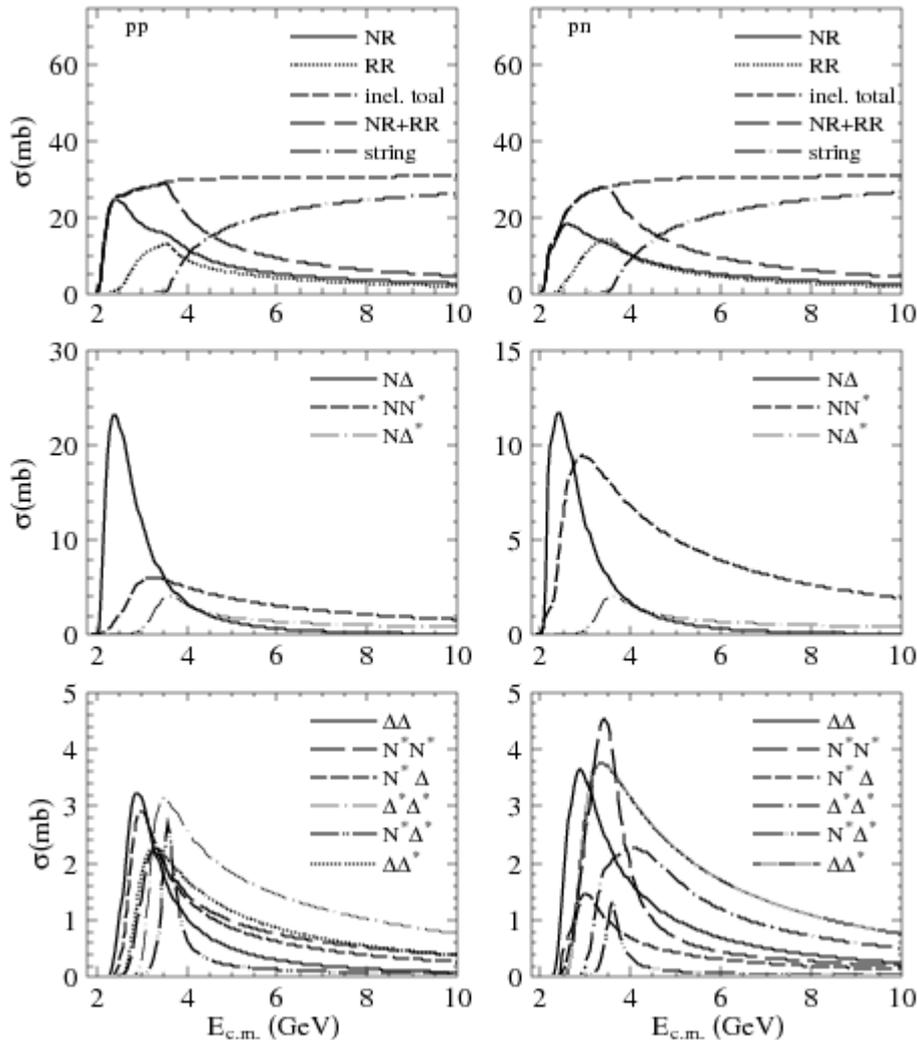
Elastic

Charge exchange: $\pi^- p \rightarrow \pi^0 n$

$$\sigma(MB \rightarrow R) = \frac{\pi(\hbar c)^2}{p_{cm}^2} \sum_R |C(MB, R)|^2 \frac{(2S_R + 1)}{(2S_M + 1)(2S_B + 1)} \frac{\Gamma_R(MB)\Gamma_R(tot)}{(\sqrt{s} - m_R)^2 + \Gamma_R(tot)^2/4}$$

JAM Inelastic cross section in pp

Y.N. et.al Phys. Rev. C61 024901 (2000)



3.5GeVまでは共鳴状態生成

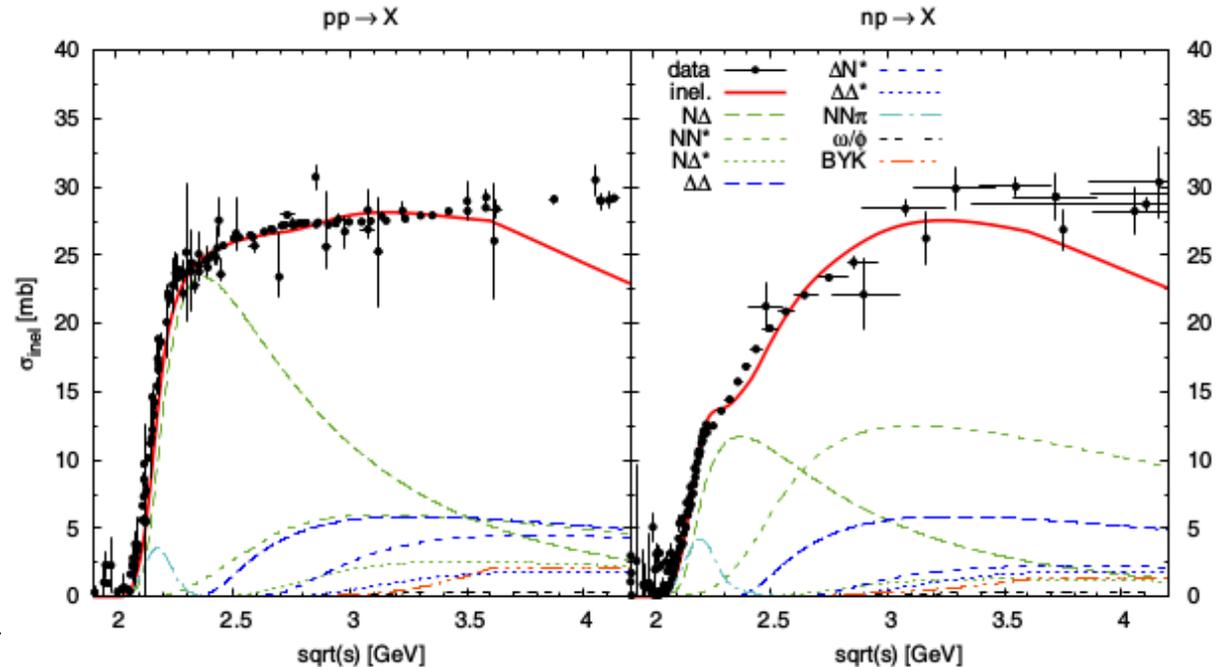
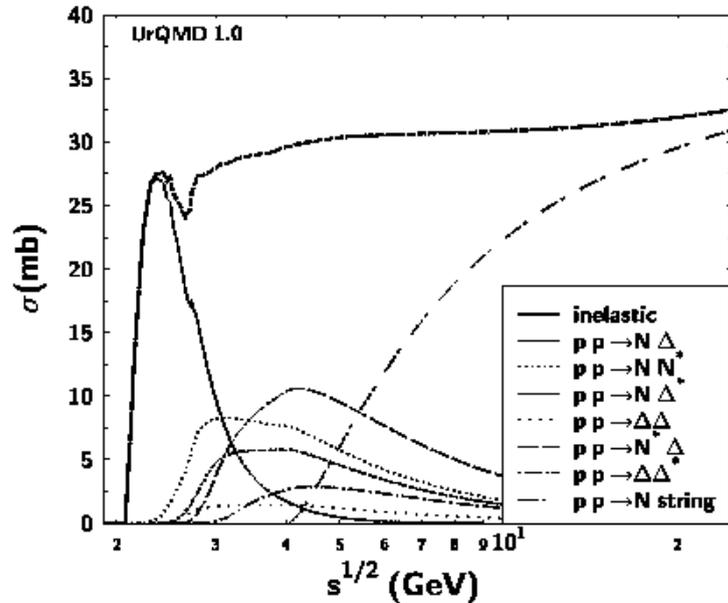
4.5GeV(Elab=10GeV)で
共鳴状態生成とストリング生成が半分ずつ。

6GeV(Elab=20GeV)以上ではストリング

Cross section in pp collision UrQMD and GiBUU

S.A. Bass, et al. Prog.Part.Nucl.Phys. 41(1998)

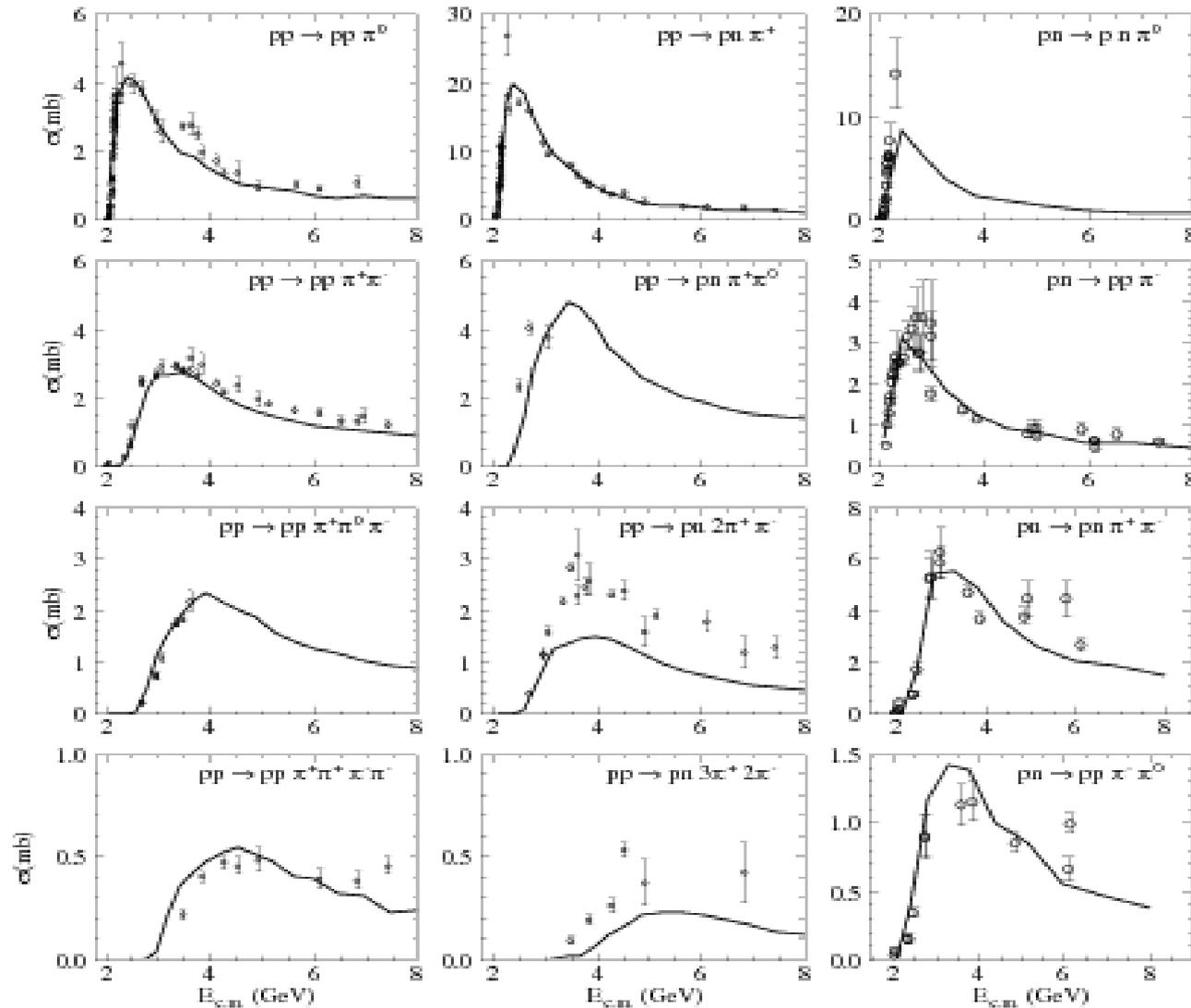
J.Eeil, H.van Hess, U.Mosel, Eur.Phys.J.A(2012)



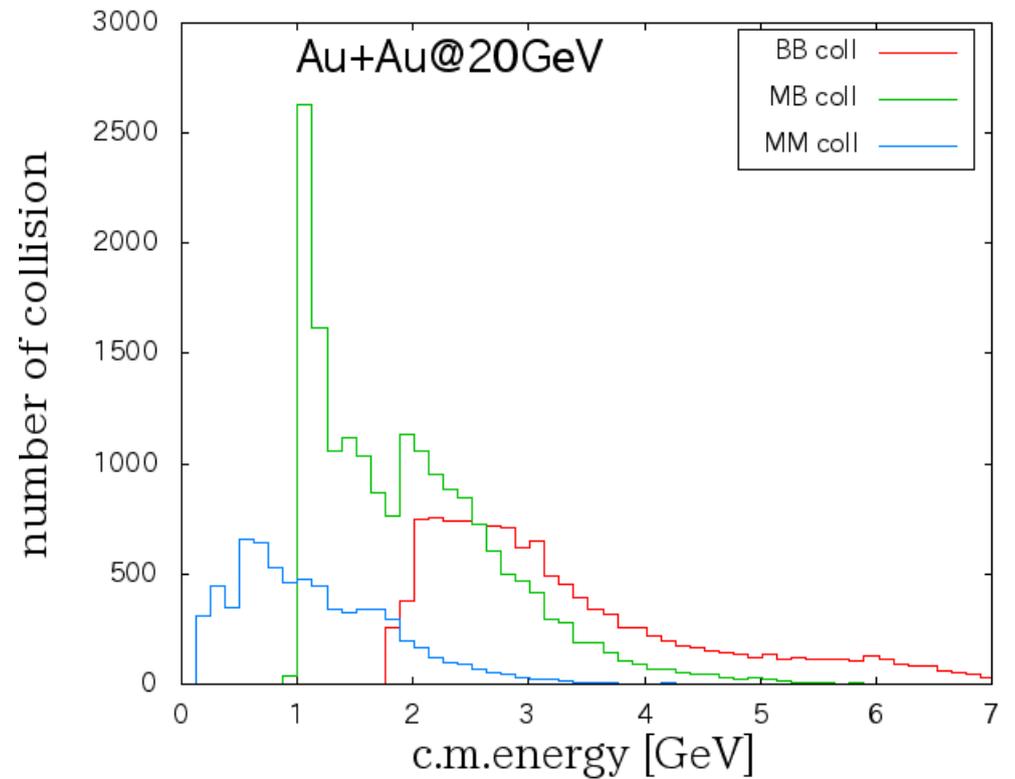
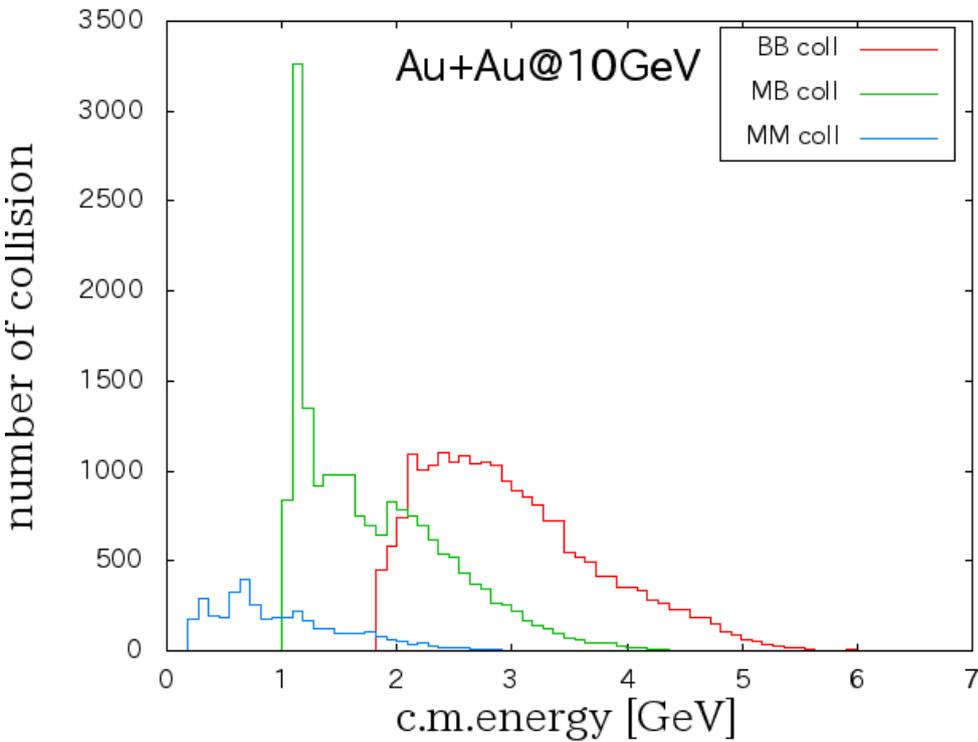
1. $NN \rightarrow N\Delta$
2. $NN \rightarrow NN^*, N\Delta^*$
3. $NN \rightarrow \Delta\Delta$
4. $NN \rightarrow \Delta N^*, \Delta\Delta^*$

$$\sigma_{NN \rightarrow NR} = \frac{C_I}{p_i s} \frac{|\mathcal{M}|^2}{16\pi} \int d\mu \frac{2}{\pi} \frac{\mu^2 \Gamma_R(\mu)}{(\mu^2 - M_R^2)^2 + \mu^2 \Gamma_R^2(\mu)} p_F(\mu)$$

Pion production cross sections in JAM



Collision spectrum



ハドロン間の2次散乱は非常に重要である。

Relativistic QMD/Simplified (RQMD/S)

目的:平均場の効果で陽子v1の入射エネルギー依存性が説明できるか?

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

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

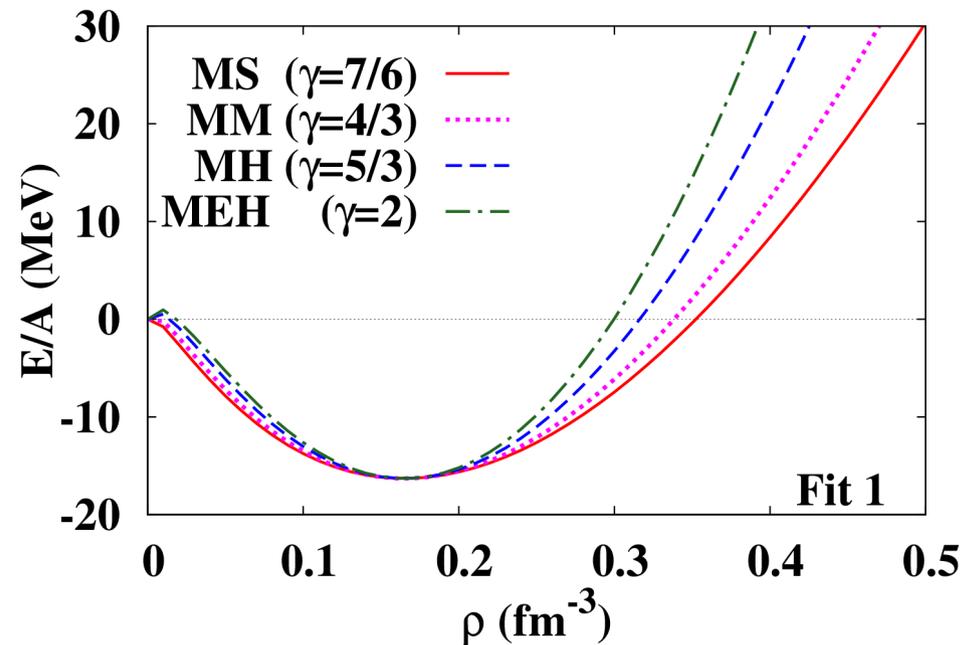
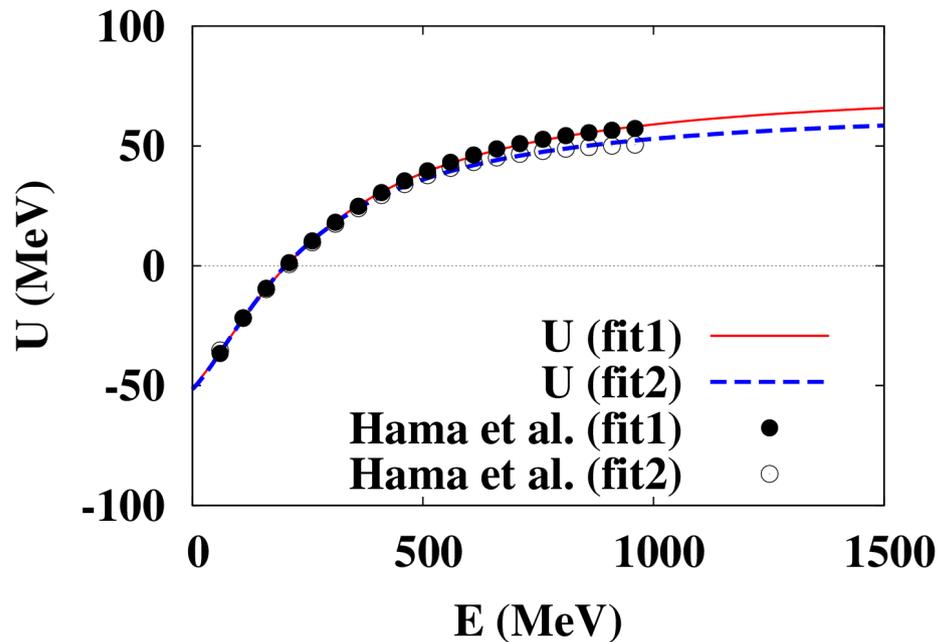
Arguments of potential $\mathbf{r}_i - \mathbf{r}_j$ and $\mathbf{p}_i - \mathbf{p}_j$ are replaced by the distances in the two-body c.m.

Mean field potential

Skyrme type density dependent + Lorentzian momentum dependent potential

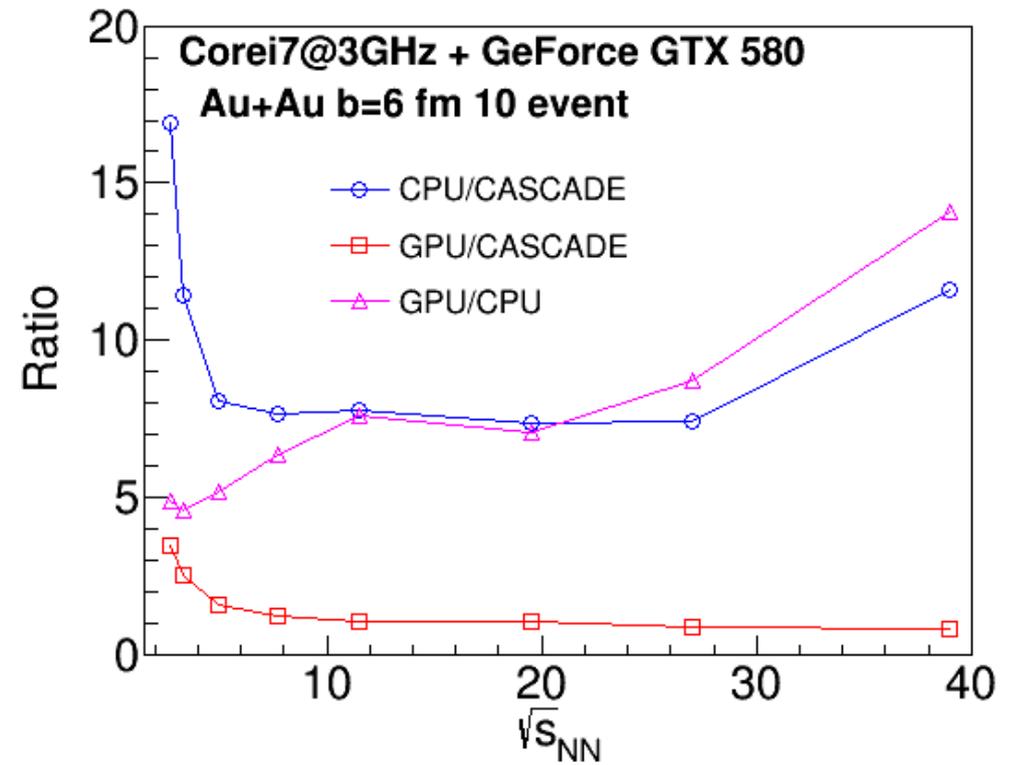
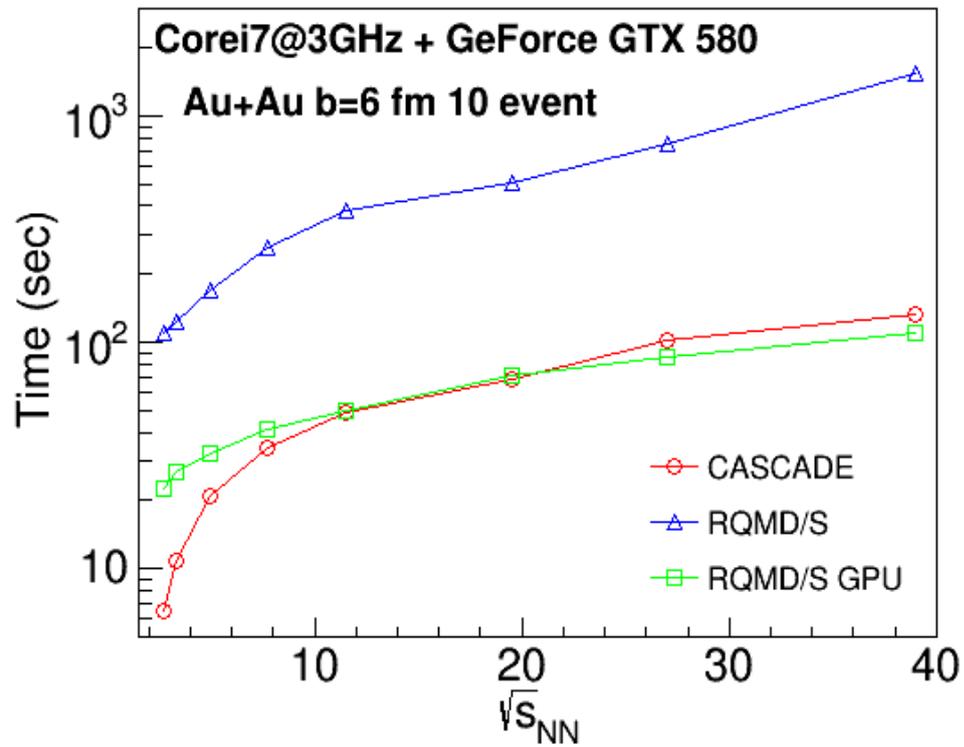
$$V = \sum_i V_i = \int d^3r \left[\frac{\alpha}{2} \left(\frac{\rho}{\rho_0} \right)^2 + \frac{\beta}{\gamma+1} \left(\frac{\rho}{\rho_0} \right)^{\gamma+1} \right] + \sum_k \int d^3r d^3p d^3p' \frac{C_{ex}^{(k)}}{2\rho_0} \frac{f(\mathbf{r}, \mathbf{p}) f(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p}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

Type	α (MeV)	β (MeV)	γ	$C_{ex}^{(1)}$ (MeV)	$C_{ex}^{(2)}$ (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



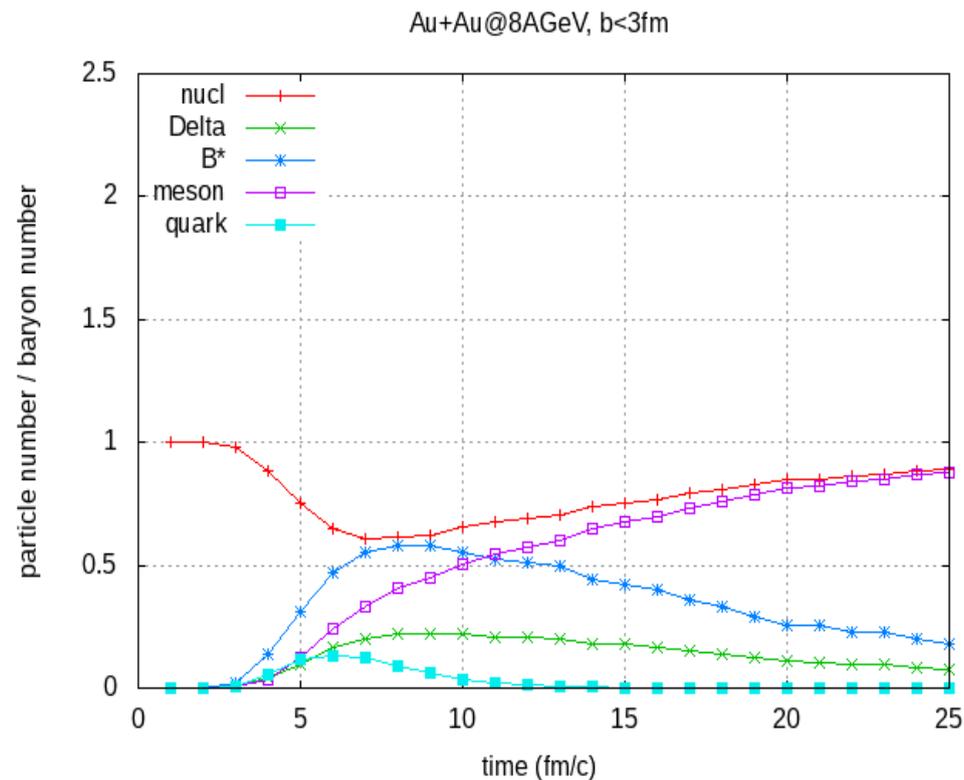
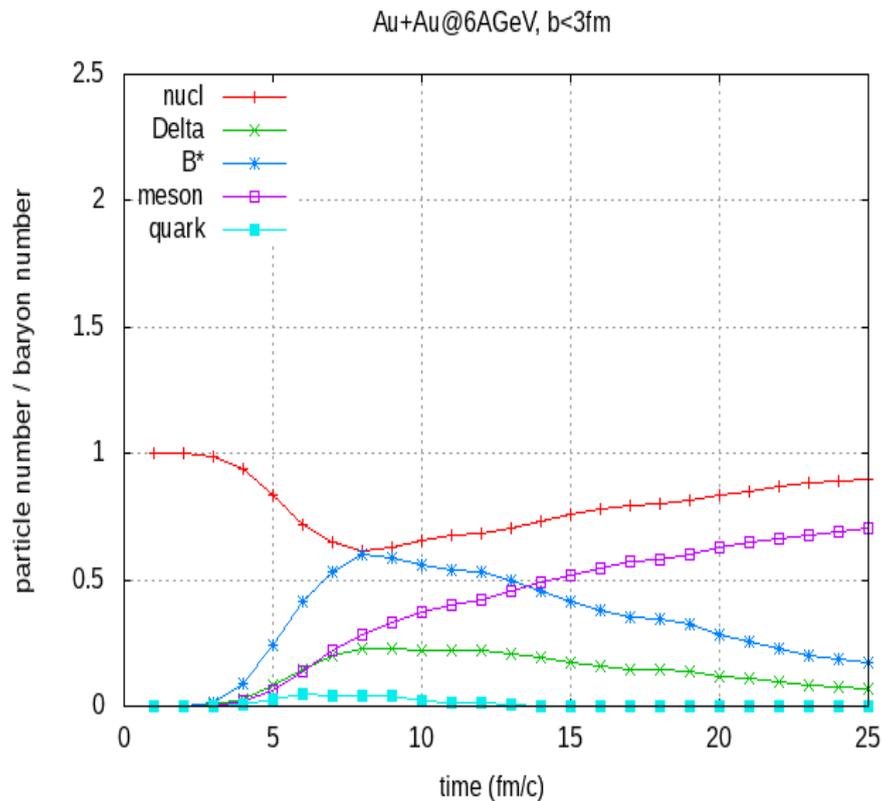
CUDA implementation

Execution time: RQMD/S = CASCADE on GPU



5-14 times faster with GPU

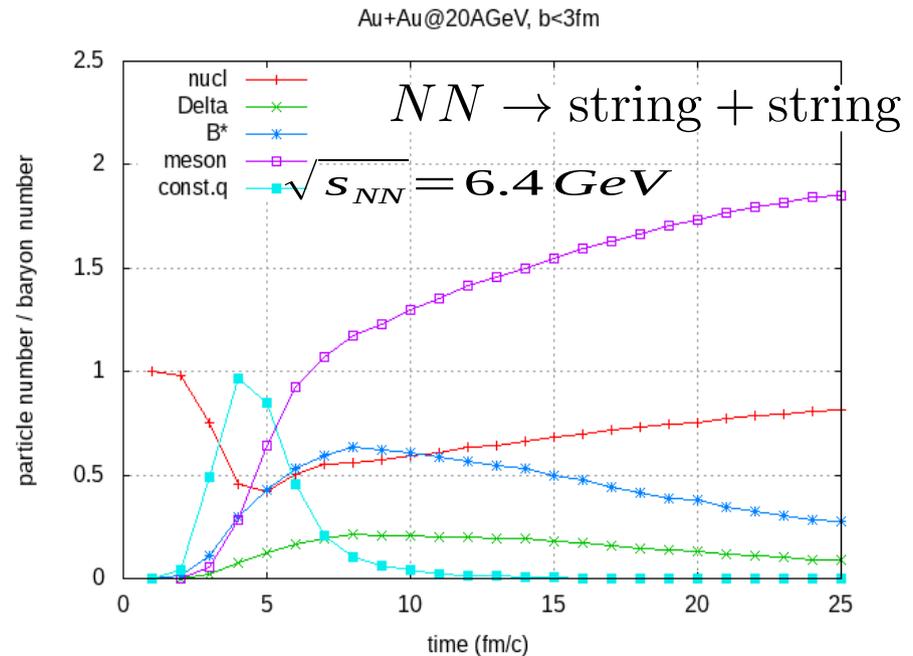
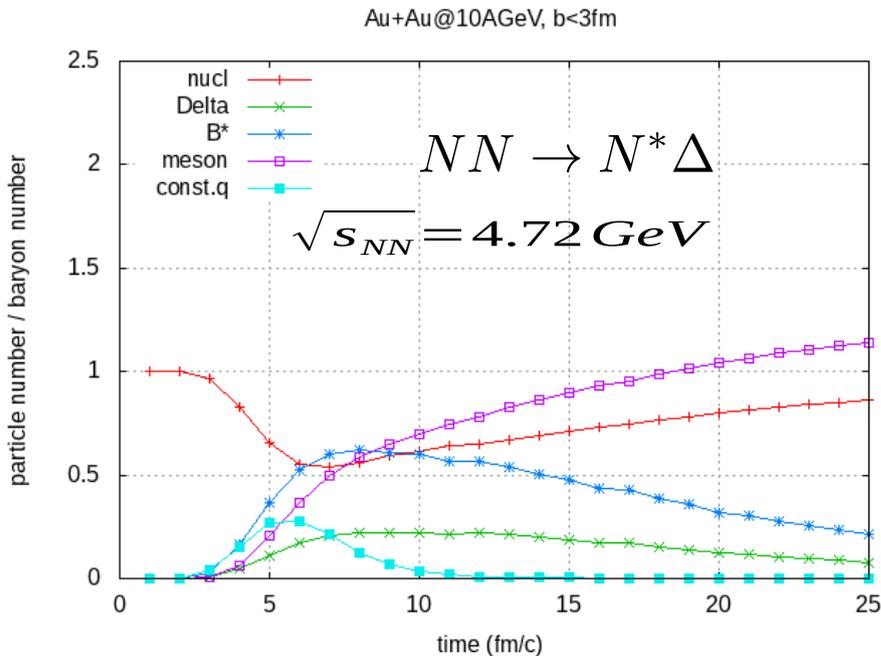
粒子数の時間発展 6GeV,8GeV



How to treat mean-field for excited matter?

粒子数の時間発展: バリオン共鳴状態の数は核子より多くなる。

String 生成により、constituent quark dominant

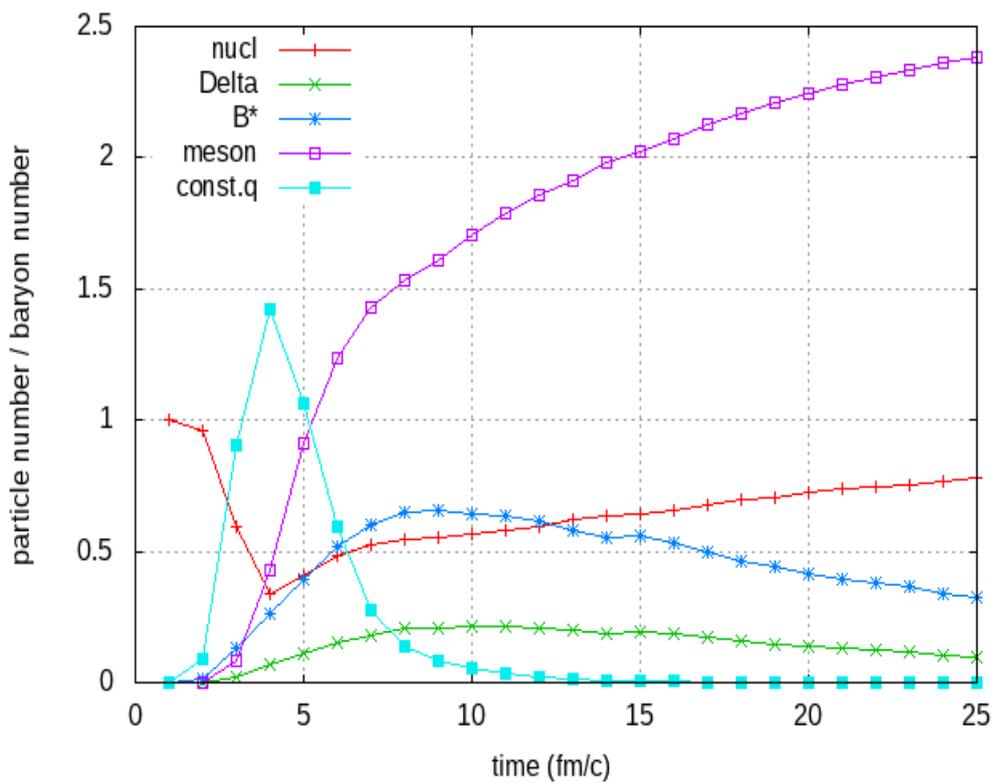


モデル1 JAM-MF: すべての生成されたバリオンが平均場を感じる。

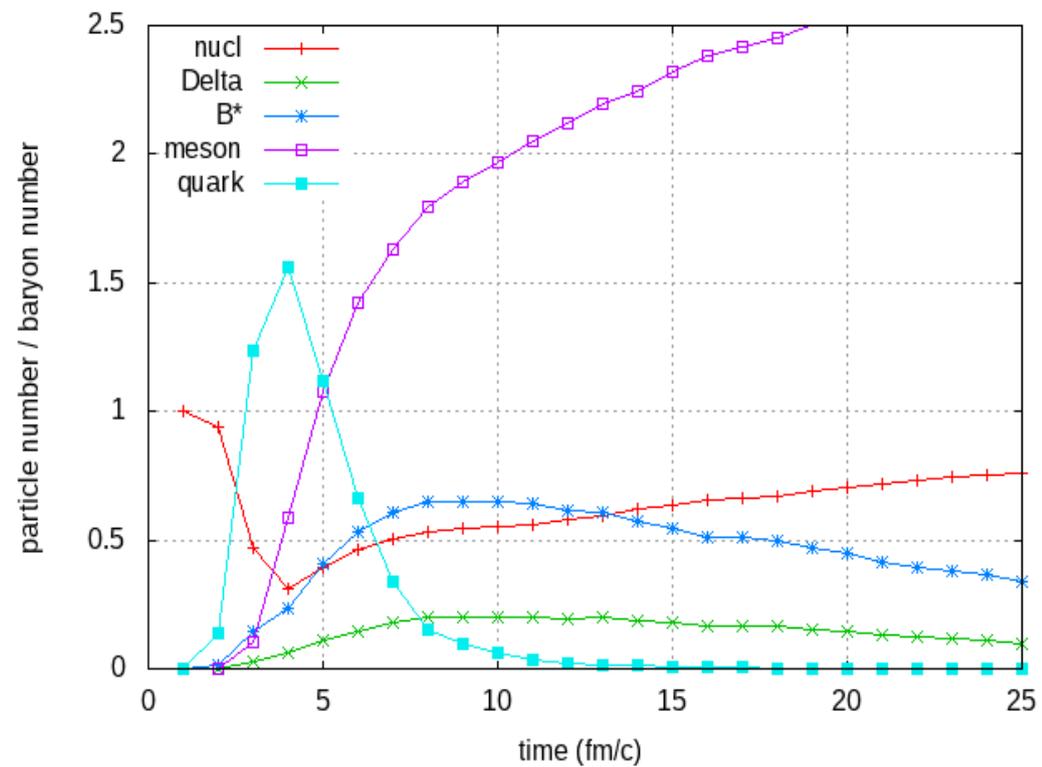
モデル2 JAM-MFq: まだformation time内にあるが、初めにあったconstituent quarkをもっているバリオンは、1/3か2/3の大きさだけ平均場を感じる。

モデル3: JAM-MFf: formation time内にあるバリオンもフルに平均場を感じる。

Au+Au@30GeV, b<3fm



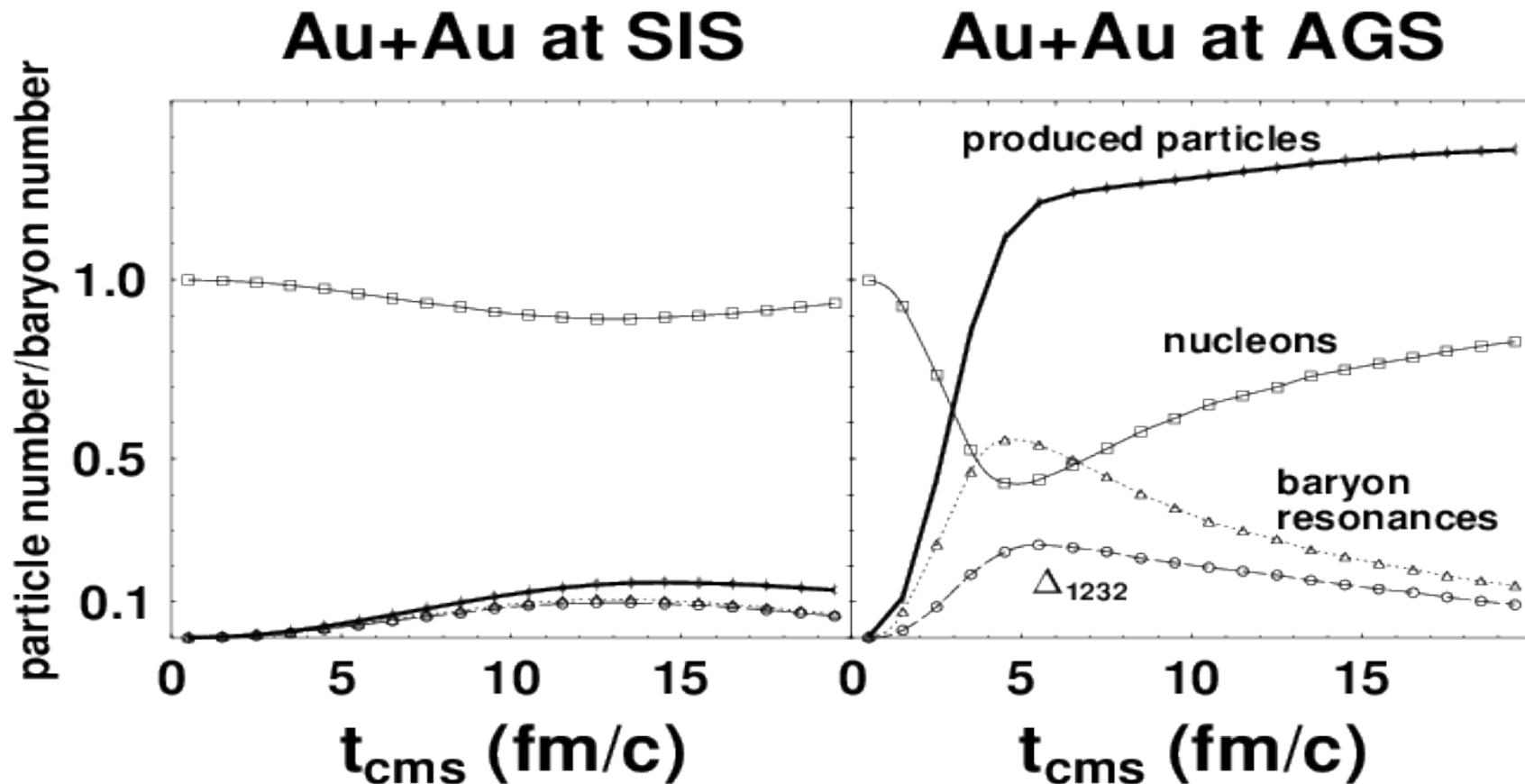
Au+Au@40GeV, b<3fm



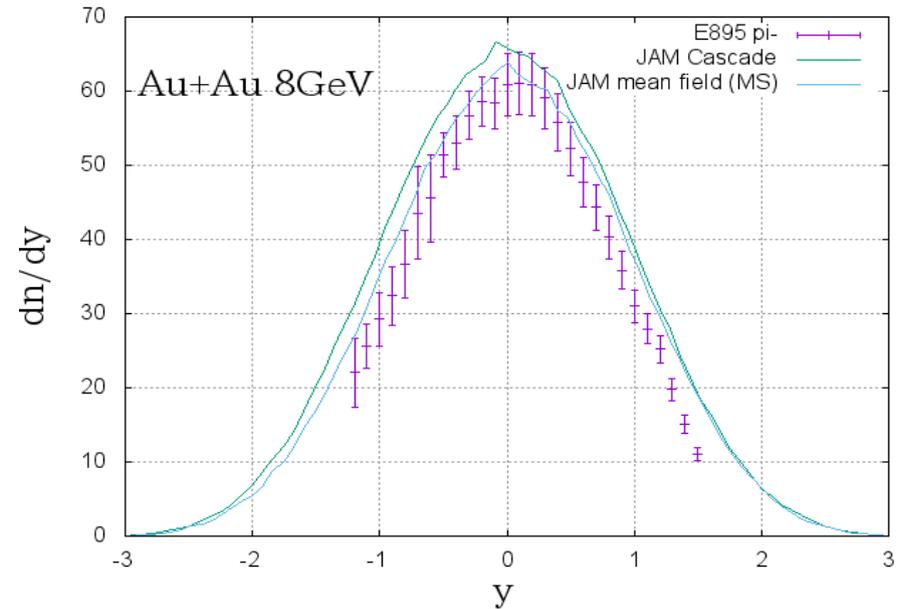
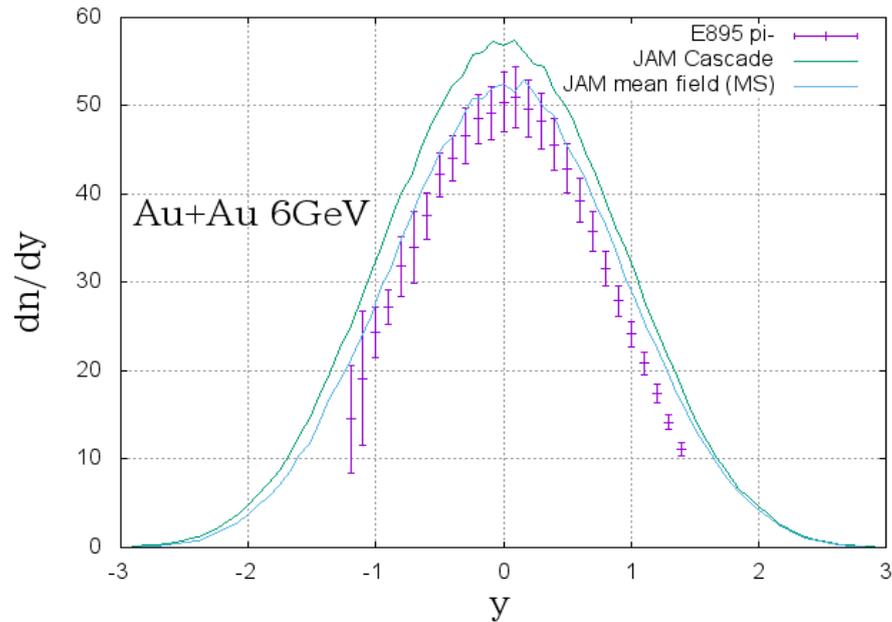
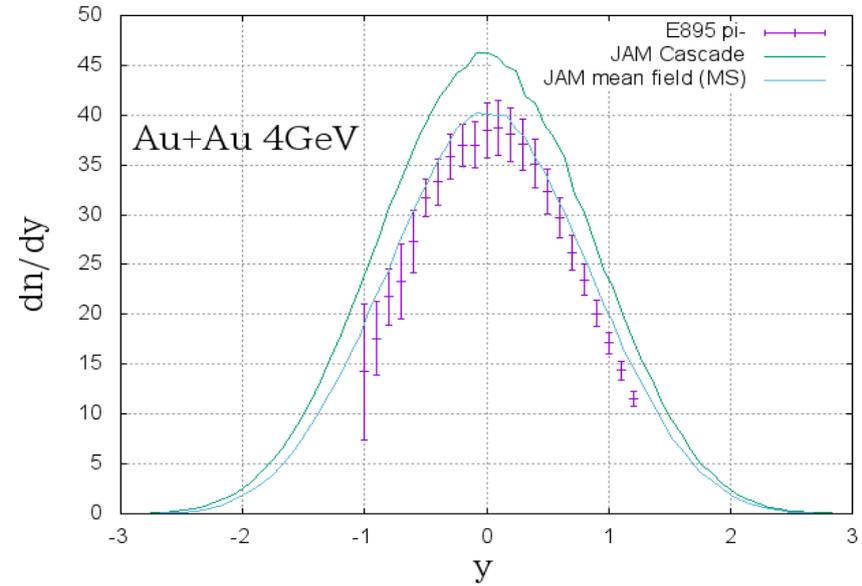
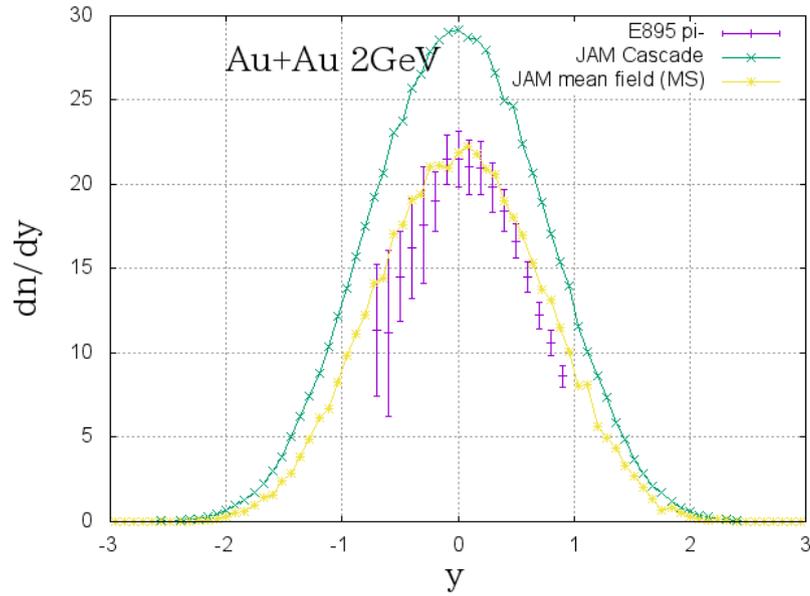
Hadronic resonance matter (デルタ物質)

M. Hofmann, R. Mattiello, H. Sorge, H. Stoecker, W. Greiner,
Phys. Rev. C51,2095 (1995)

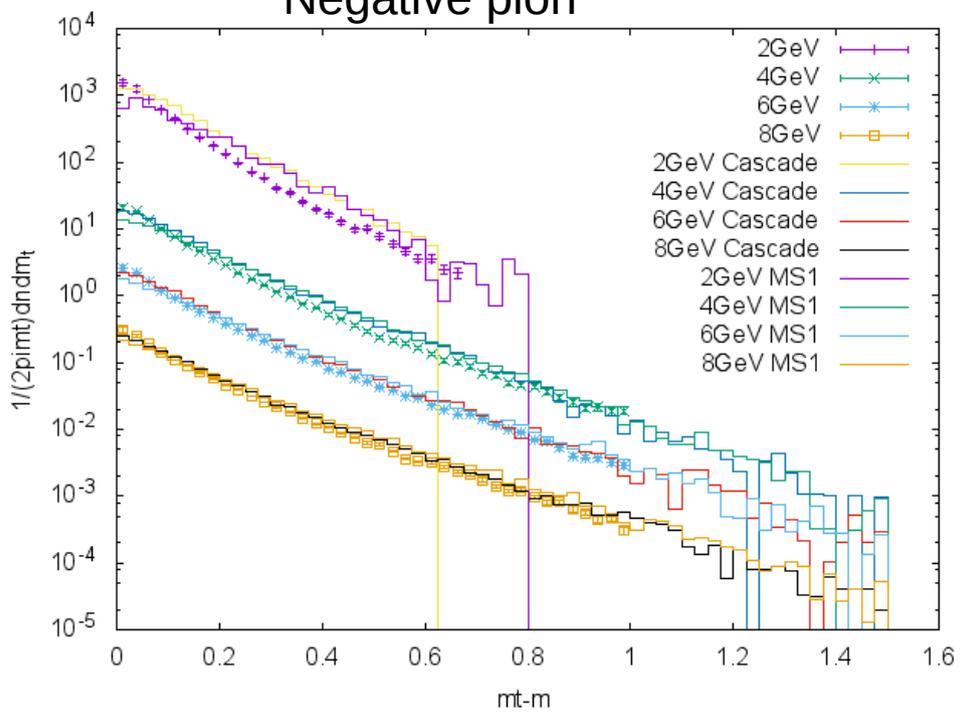
RQMD results



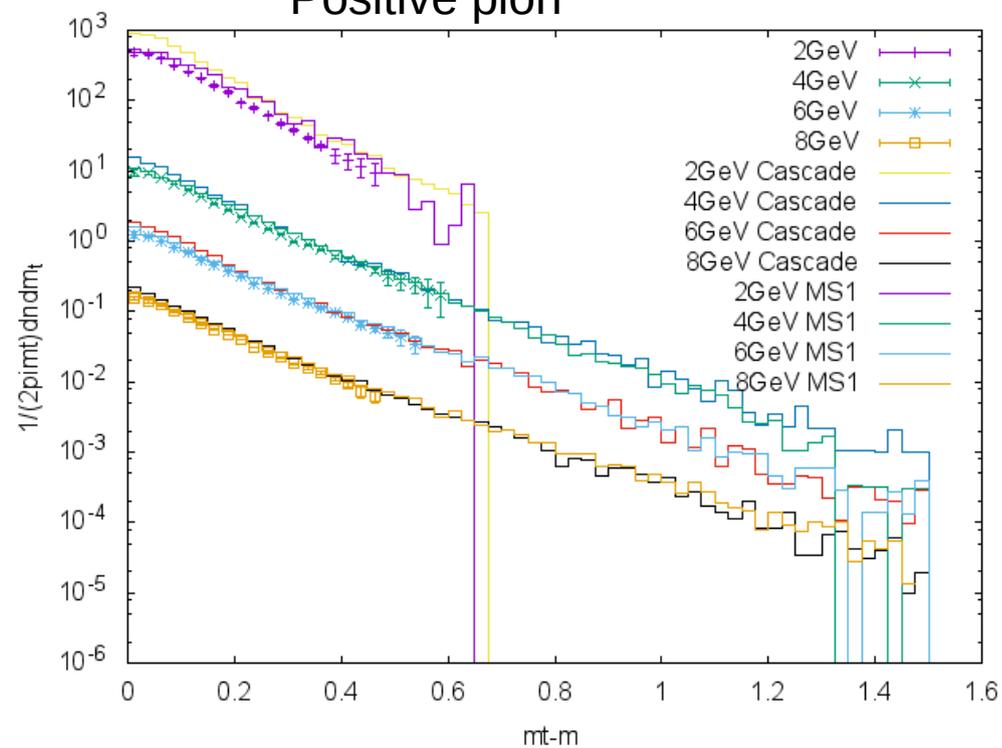
Effect of mean-field on dN/dy



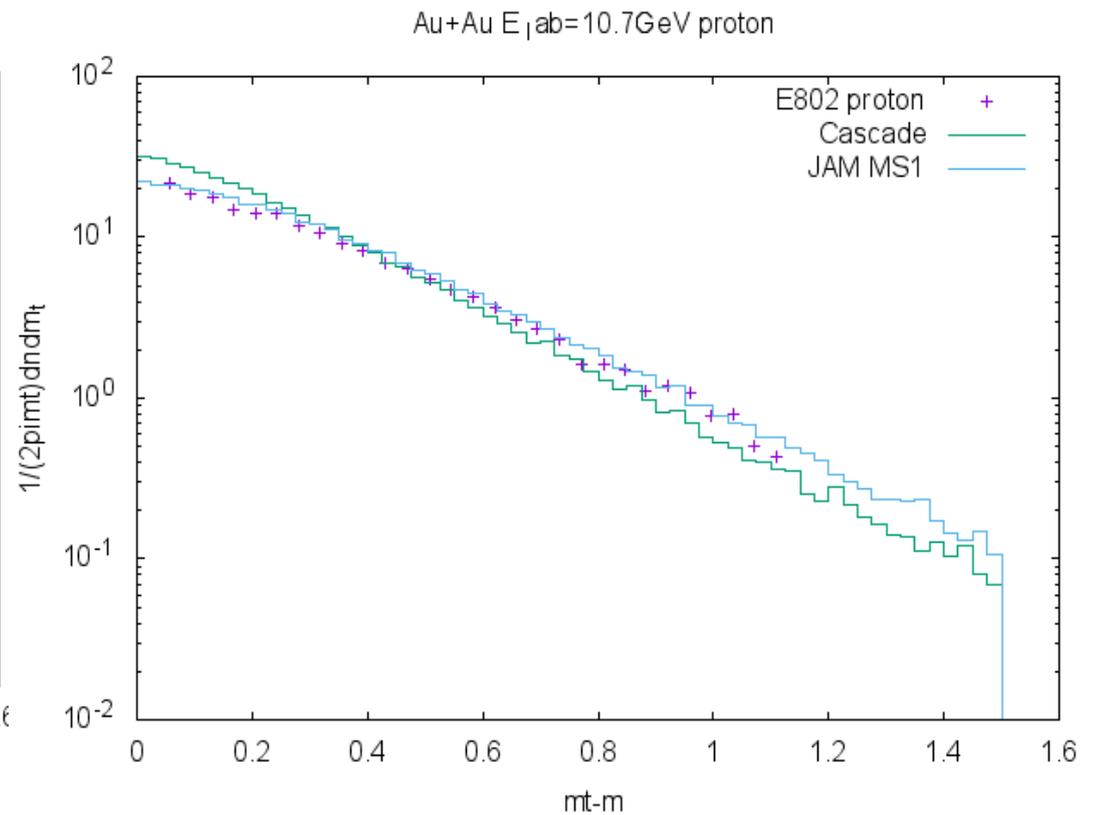
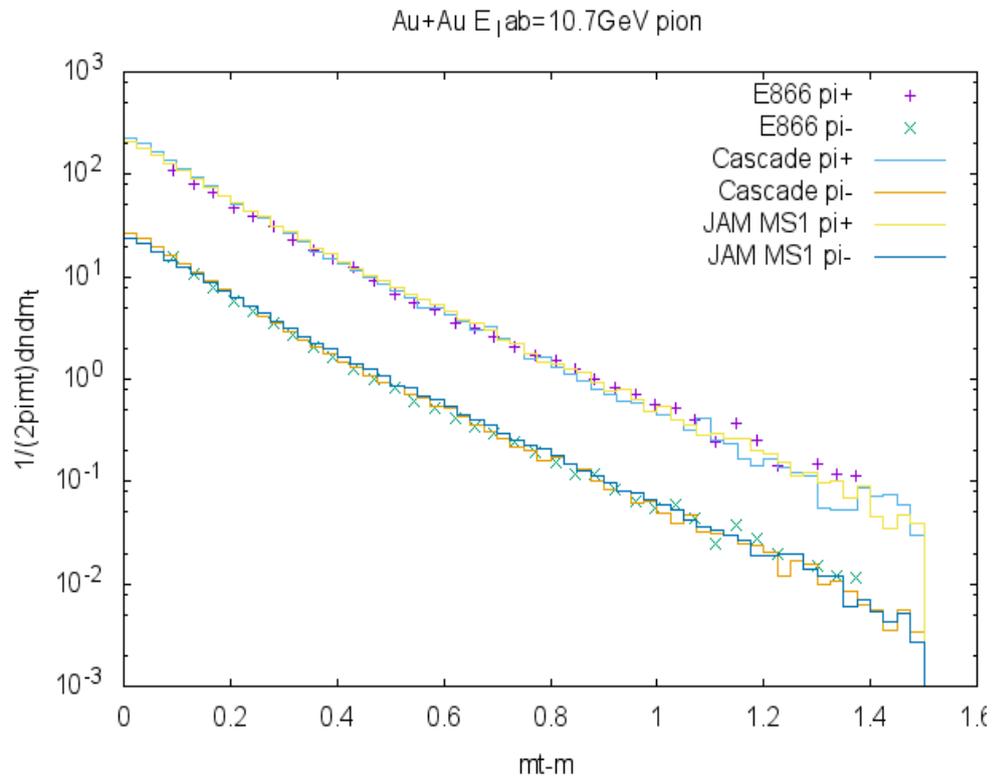
Negative pion



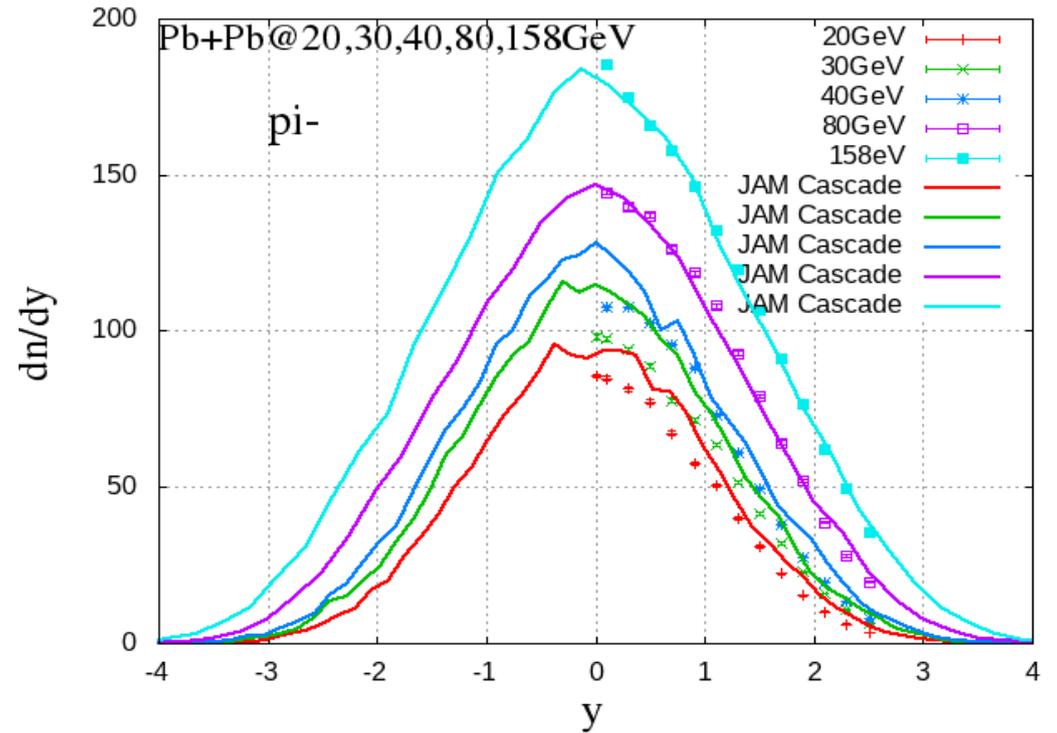
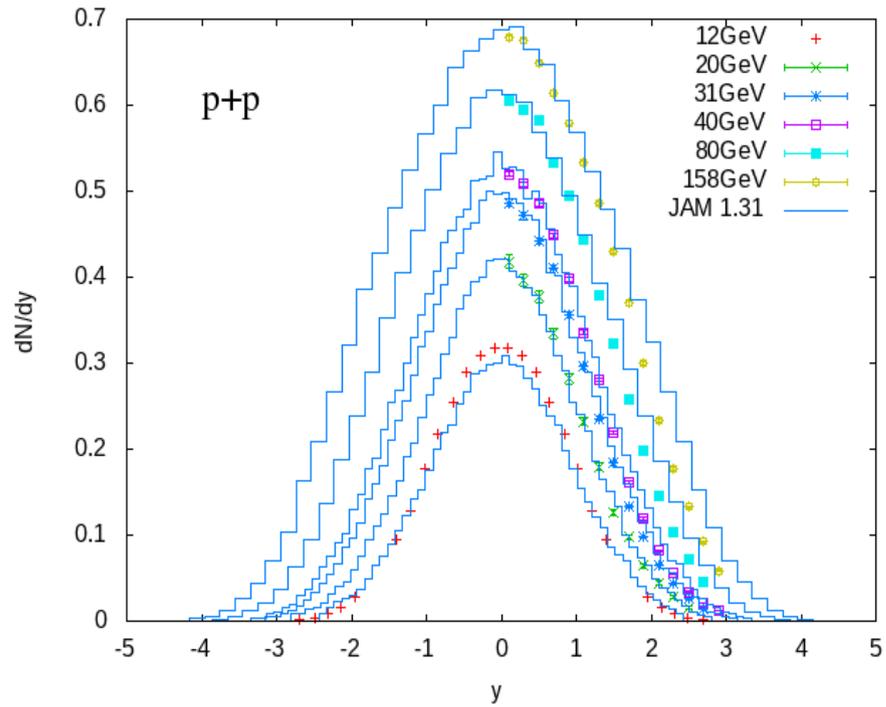
Positive pion



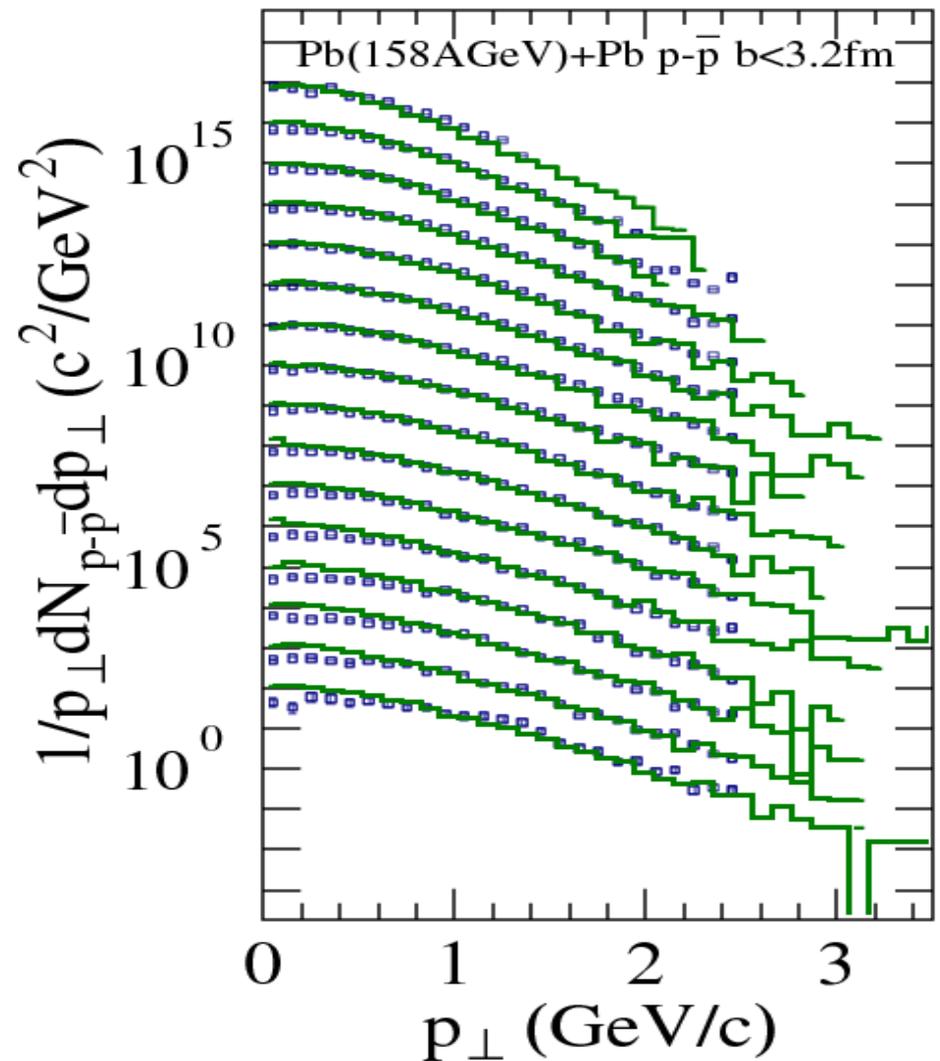
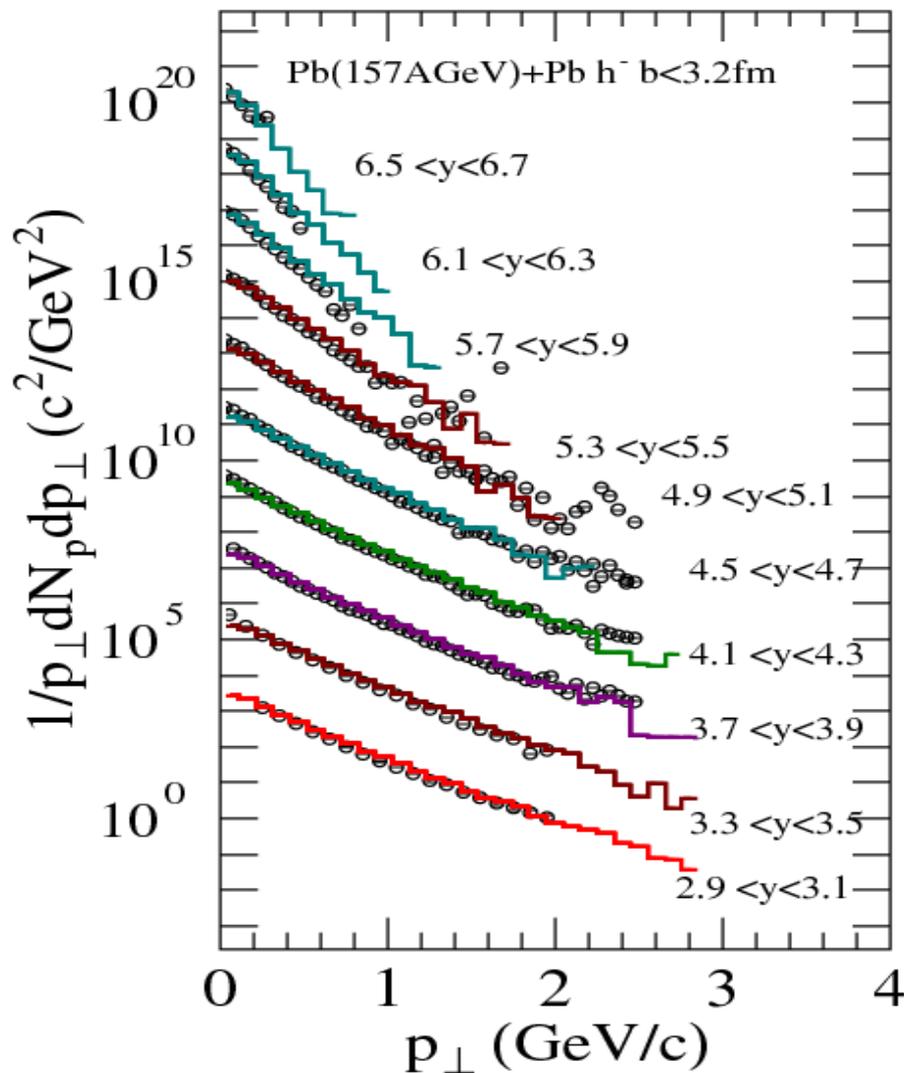
Mean field effect on transverse mom.



JAM predictions



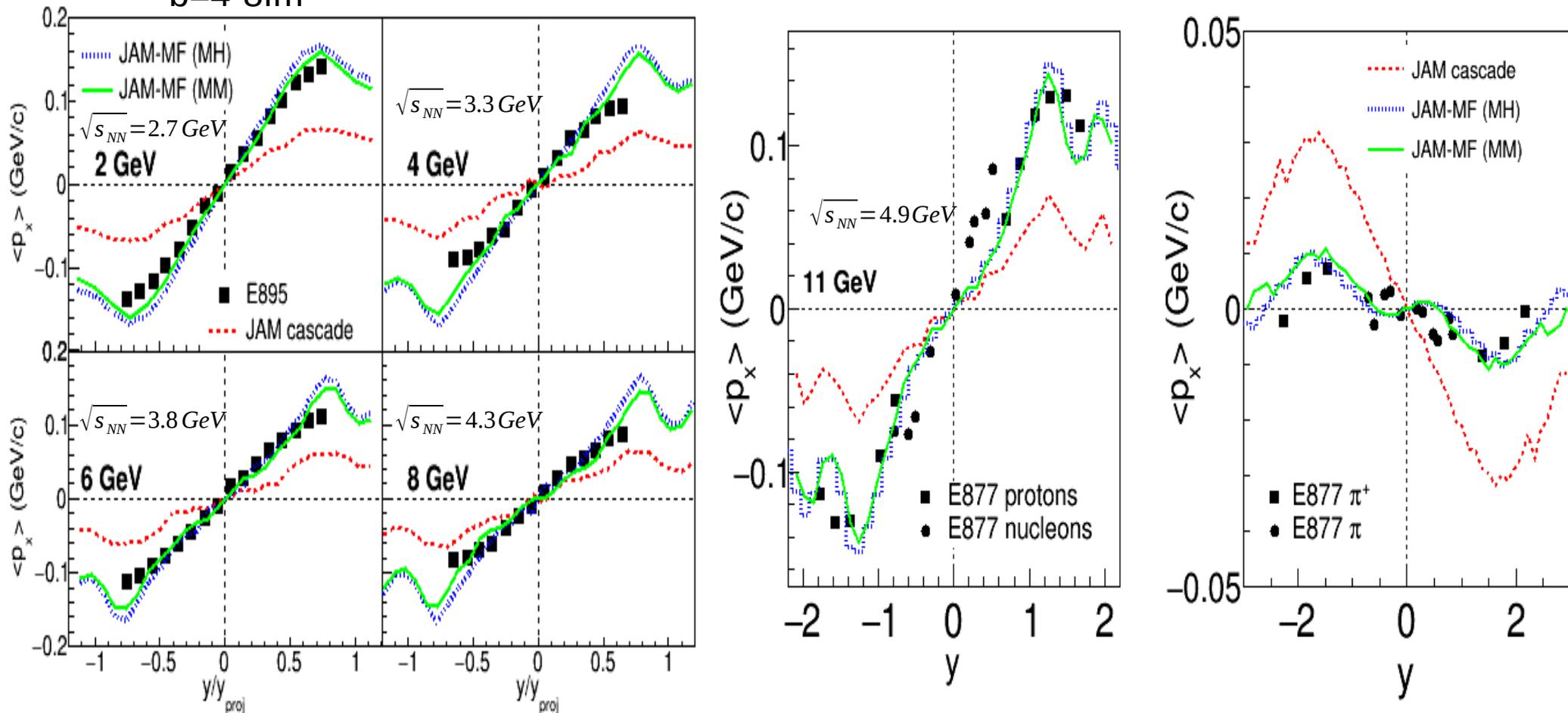
Transverse momentum distribution at SPS energy (160A GeV)



JAM/RQMD results at AGS energies

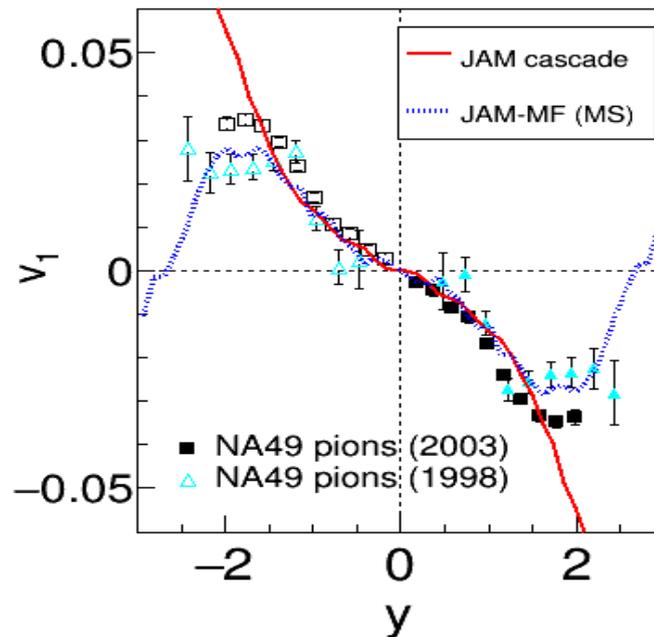
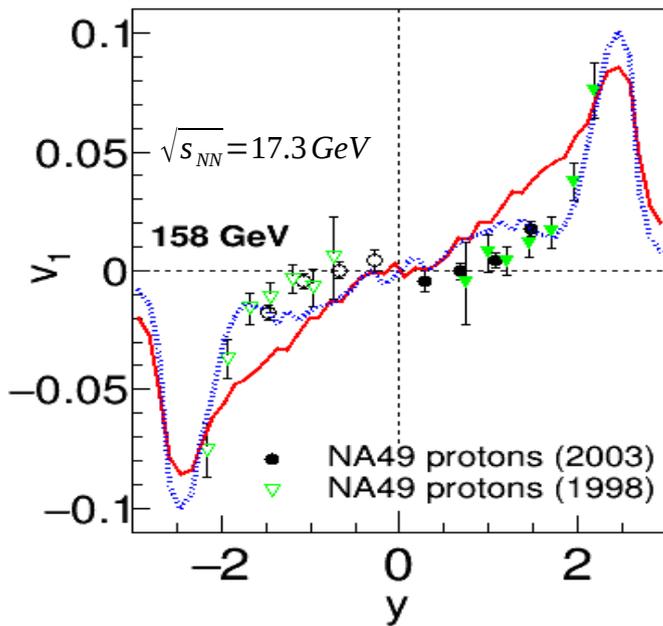
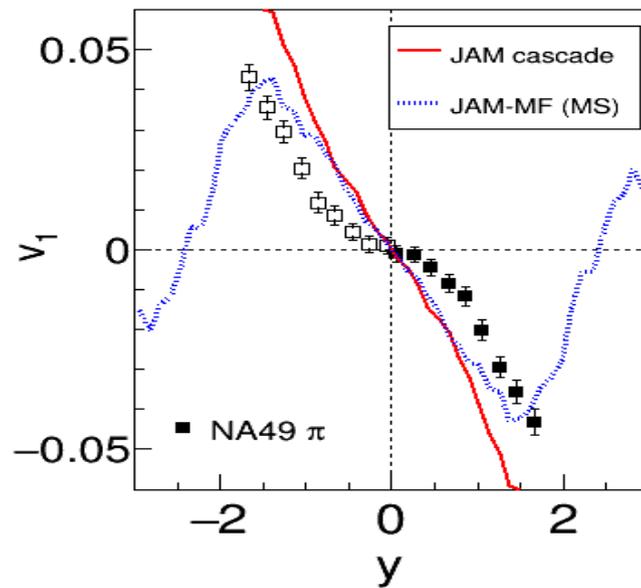
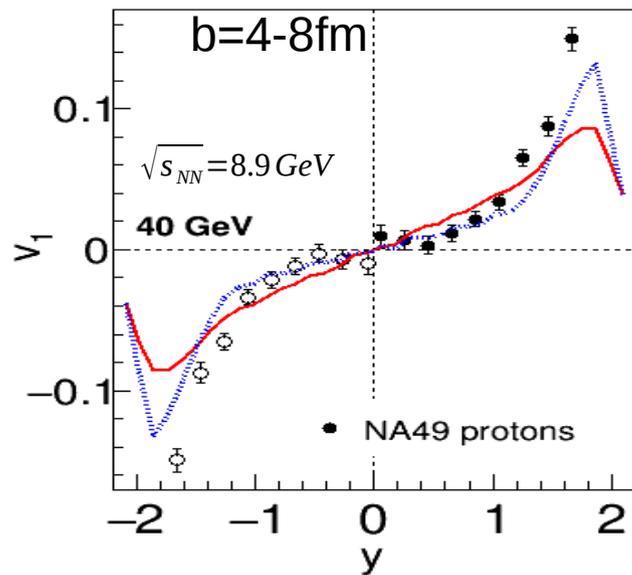
Significant mean-field effect on the directed flow

$b=4-8\text{fm}$

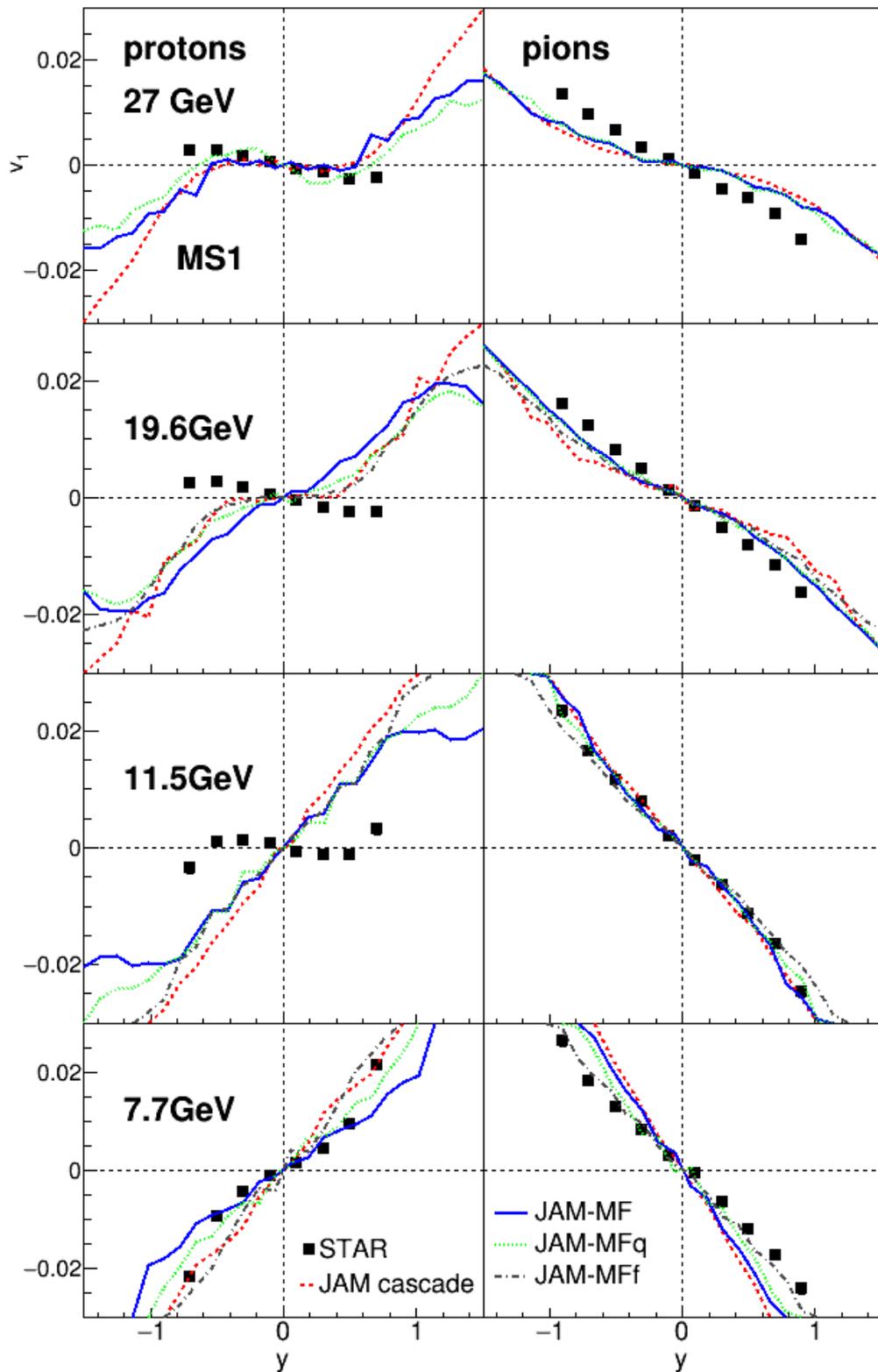


Consistent results with the previous work: M. Isse, et.al PRC72(2005) 064908.

JAM-MF at SPS energies



Comparison of STAR data



JAM-MF: only formed baryons feel potentials
JAM-MFq: constituent quarks feel potentials
JAM-MFf: All non-formed hadrons feel potentials

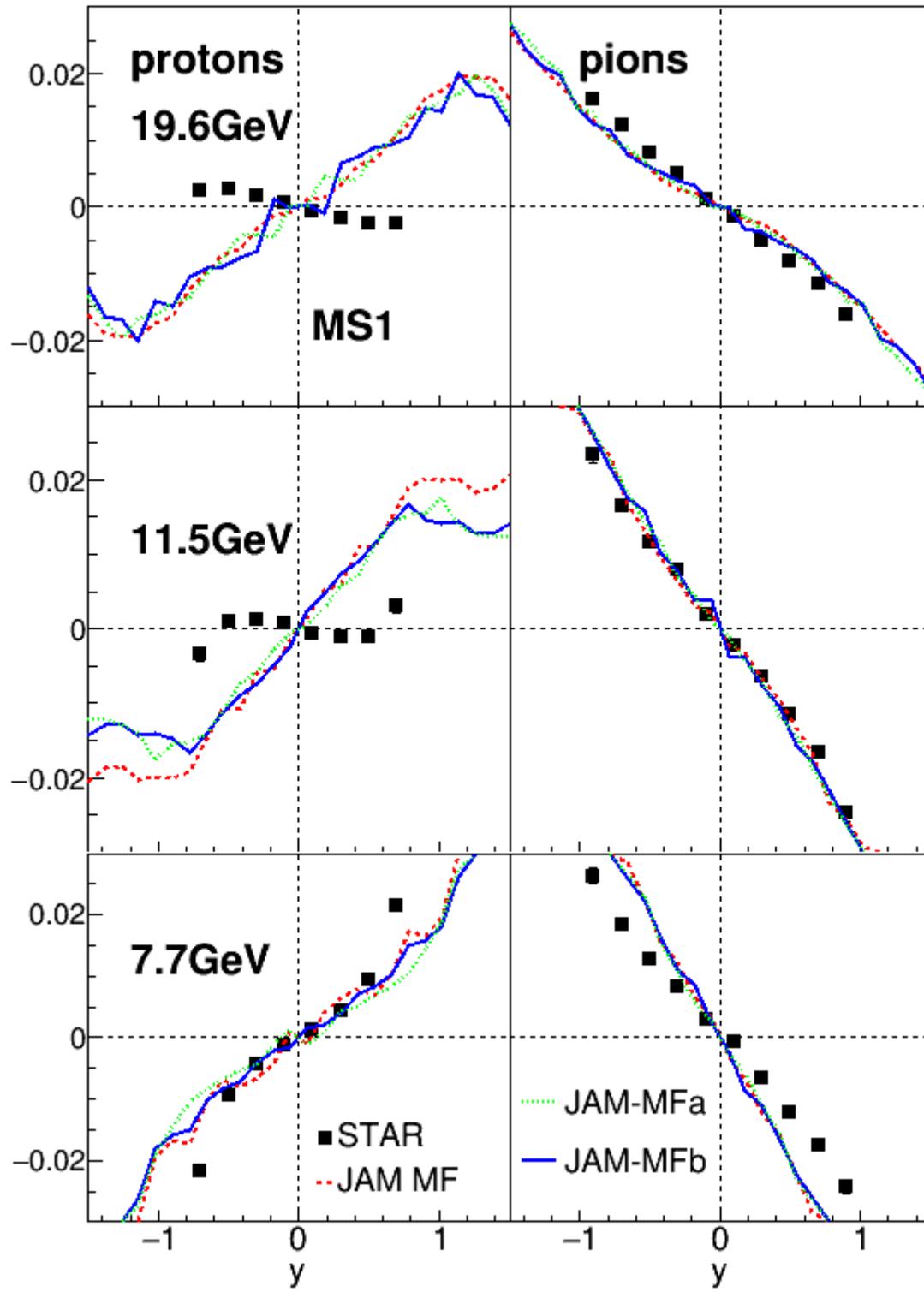
Test delta potential

So far, mean field is assumed to be the same for all baryons. But potentials for resonance may be different from nucleon potential.

To test this effect.

JAM-MFa: reduce the attractive part for the resonance.

JAM-Mfb: increase the repulsive part



まとめ

- ハドロニックカスケードモデルは、重イオン衝突や、ハドロン-原子核反応の時空発展をマイクロに記述するものである。
- 粒子生成は、共鳴状態とそのストリング(連続状態)生成と崩壊で記述される。
- ハドロニックカスケードモデルにRQMD/Sの枠組みを使って、平均場の効果を取り入れた。**JAM-MF approach**

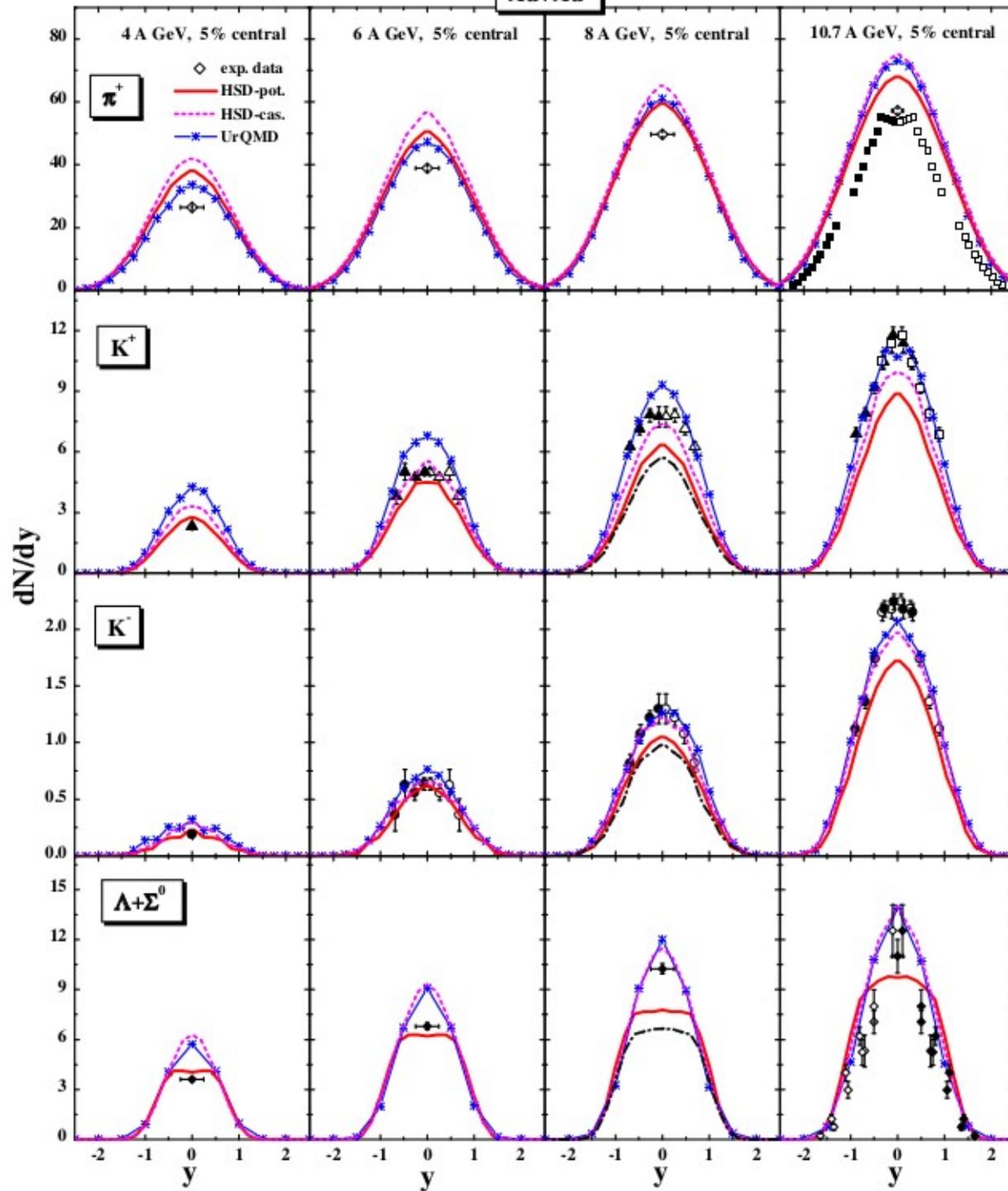
このアプローチは、0.4GeVから200GeVぐらいまでの原子核衝突のバルクな観測量をそこそこ再現できるが、完全ではない。(パイオン生成など)

- JAM-MFは入射エネルギー約40AGeV ($E_{cm}=9\text{GeV}$)までの directed flowをよく再現できる。
- 陽子のDirected flowが正から負になる振る舞いはJAM-MFで説明できるが、 $E_{cm}=11.5\text{GeV}$ で $F < 0$ は平均場の効果で再現できない。

まとめ 2

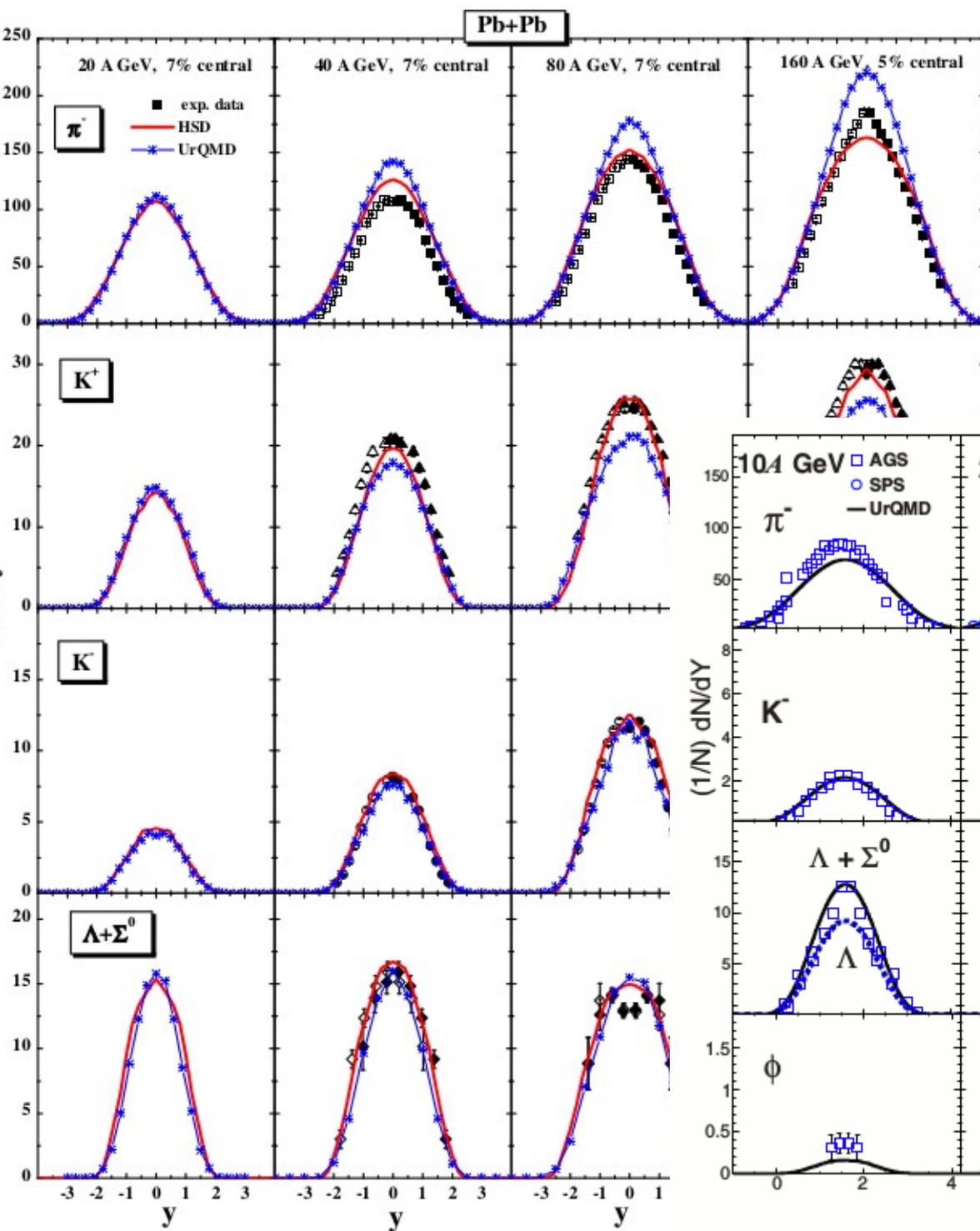
- ★ 共鳴状態の平均場は核子と同じとして計算したが、デルタなどの共鳴状態が核子の数を越える状態が作られる反応においてデルタの平均場の効果は？ Δ のフロー測定による検証の可能性は？
- ★ JAM 2.0 C++ version
- ★ Hydrodynamics + Boltzmann(JAM) + mean field approach?

Au+Au



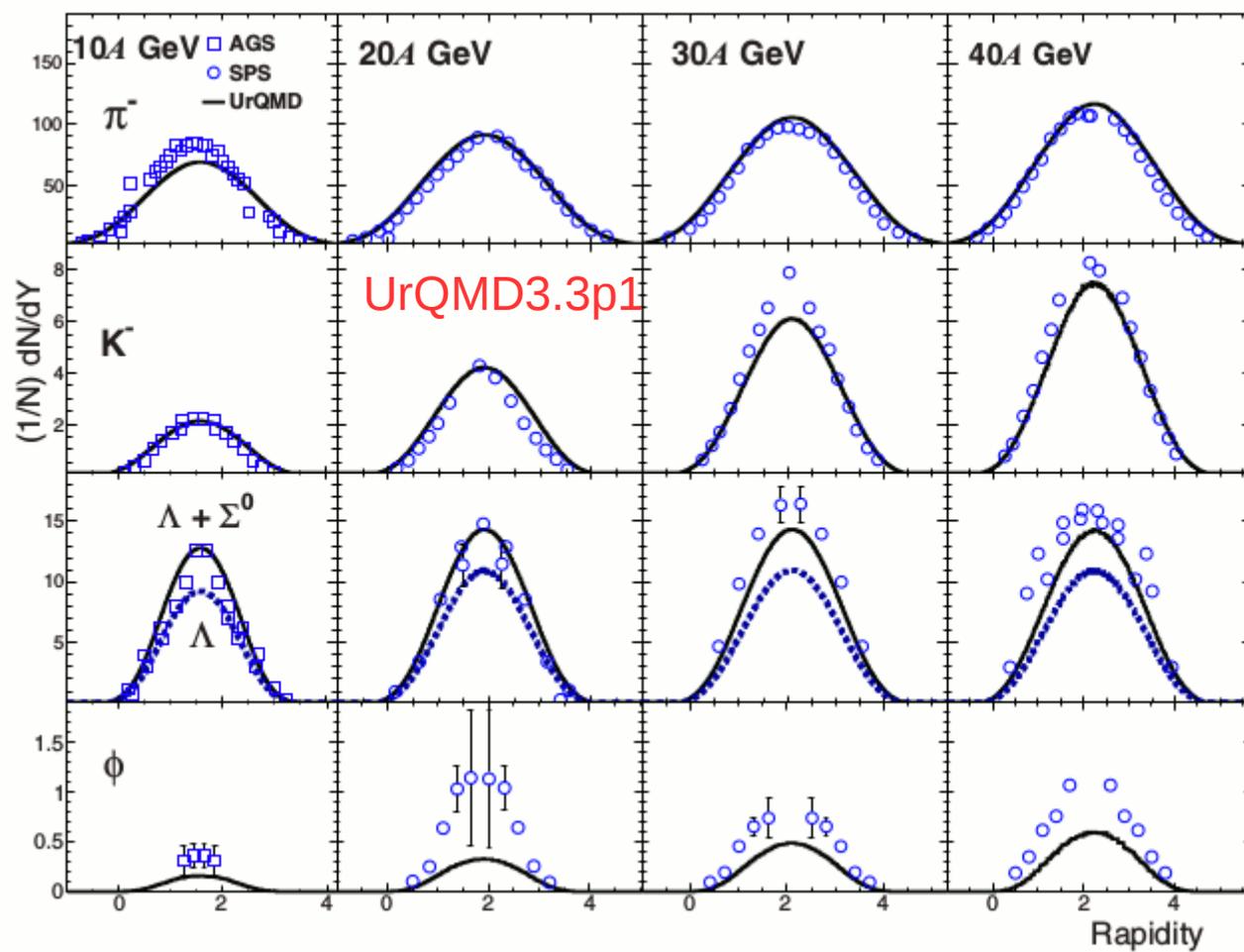
H.Weber, et.al PRC67(2003)014904

モデルの比較



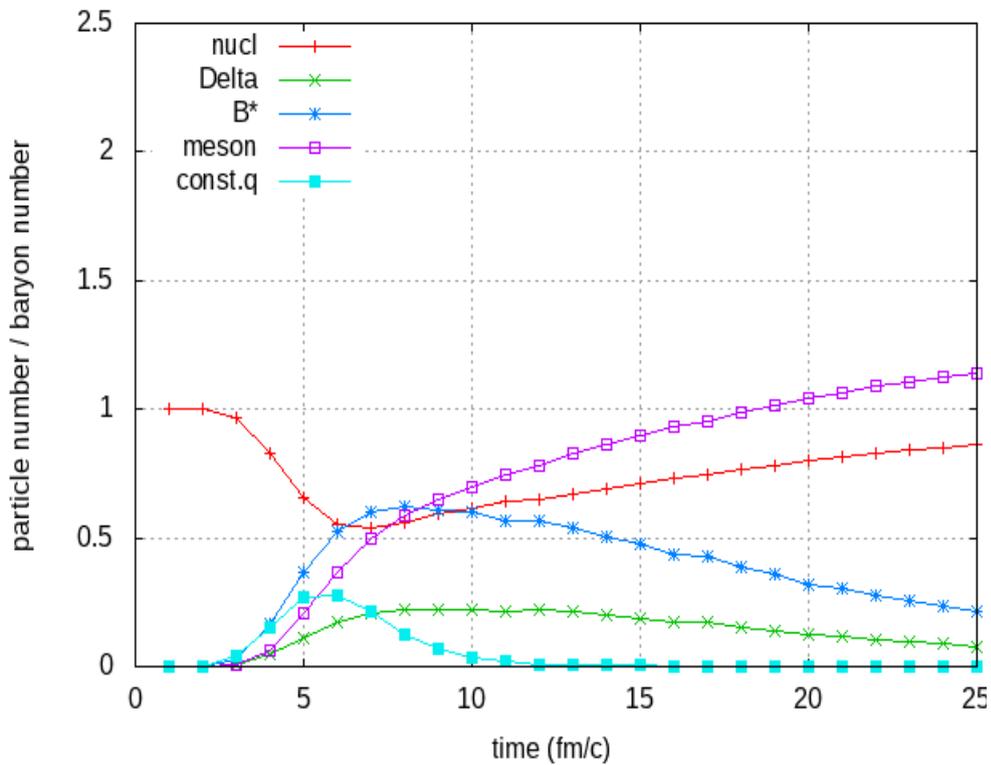
H.Weber, et.al PRC67(2003)014904

Kalyan Dey and B.Bhattacharjee
PRC89,054910(2014)



粒子数の時間発展 10GeV, 20GeV

Au+Au@10GeV, b<3fm



Au+Au@20GeV, b<3fm

