Re-Hardening of Hadron Transverse Mass Spectra in Relativistic Heavy-Ion Collisions

Akira Ohnishi[a]
in collaboration with
N. Otuka[ab], P.K. Sahu[a], M. Isse[a], Y. Nara[c]
a. Hokkaido U., b. JAERI, c. BNL

Abstract

We analyze the spectra of pions and protons in heavy-ion collisions at relativistic energies from 2 A GeV to 65+65 A GeV by using a jet-implemented hadron-string cascade model, JAM. In this energy region, hadron transverse mass spectra first show softening until SPS energies, and re-hardening may emerge at RHIC energies. Since hadronic matter is expected to show only softening at higher energy densities, this re-hardening of spectra can be a good signature of the quark-gluon plasma formation.

⋆ QGP Signals

⋆ Anomalous J/ψ supression
- ◯ : Deconf. phase → No Bound State (Matsui & Satz)
- △ : $\sigma(J/\psi\text{-}h)$ = constant (?) ($h = N, \pi, \rho, N^*$, strings, ...)

⋆ Strangeness Enhancement
- ◯ : QGP → Fast Chem. Equilibrium
- △ : Rope formation (Sorge),
- × : multi-π → Strange particles (C. Greiner)

⋆ Low-E Dilepton Enh.
- △ : Partial χ-rest. rather than Deconf. (Hatsuda & Lee)

⋆ Softening of particle spectra
- ◯ : Decrease of Directed Flow (SIS-AGS)
- × : It can be explained in Hadron-String Scenario (Hadronic DOF + Mean Field, Sahu et al.; Otuka Thesis)

• Possible Explanation

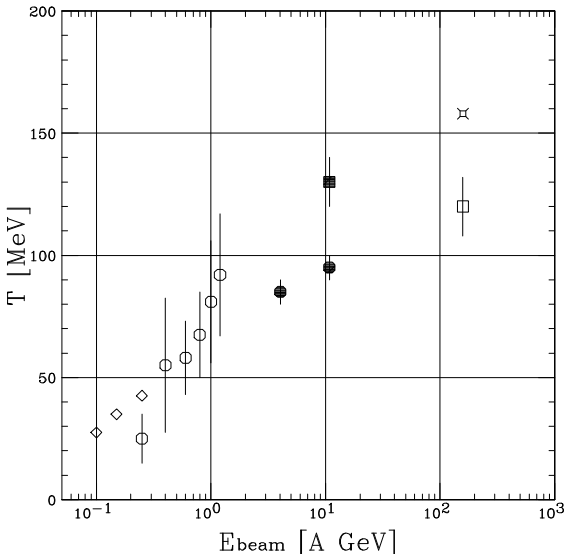
1. QGP is formed at SPS energy Pb+Pb Collisions.
2. Hot and Dense (Heavy-)Resonance-String Gas (Approximate Hagedorn Gas) is formed.
   - ⋆ $J/\psi + N^* \to D\bar{D}$
   - ⋆ string + string → Rope → $Y\bar{Y}$
   - ⋆ Large Mass Energy ↔ Smaller Pressure

Key Logic: Hadron Gas becomes Softer and Softer at High Energy Density. (Hagedorn, 1965)

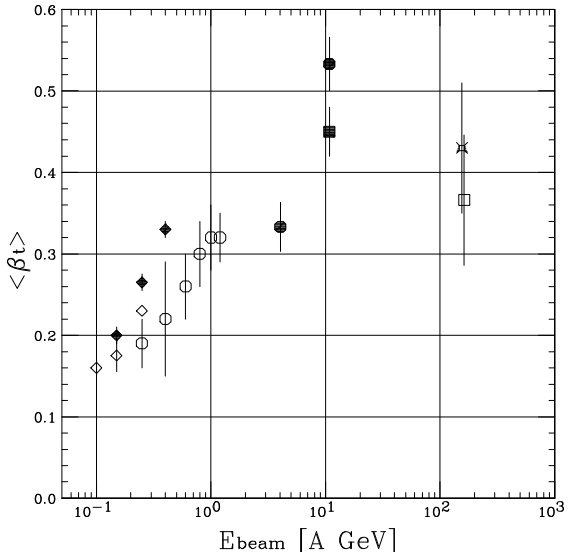
⋆ Softening at SIS-AGS-SPS

Chujo, Thesis.

Temperature

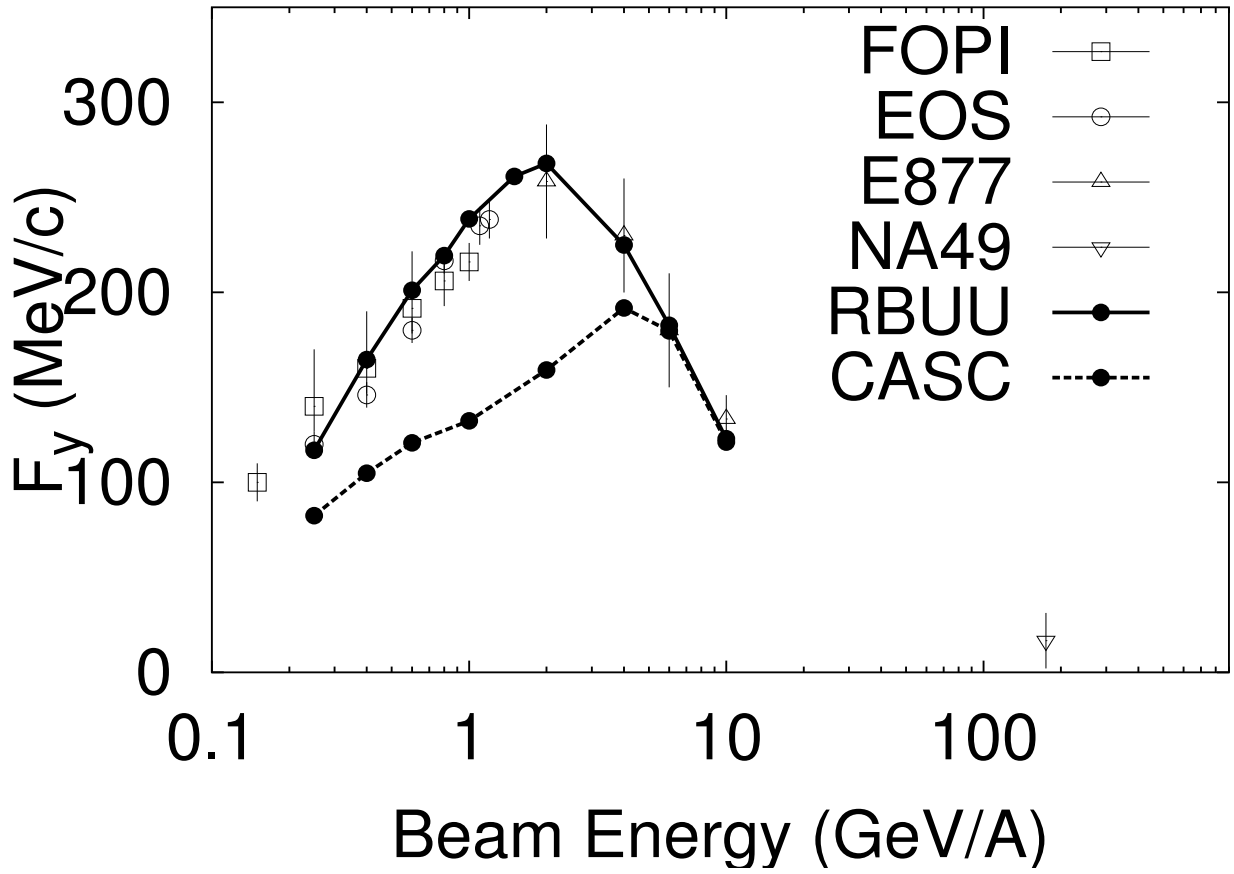


Radial Flow



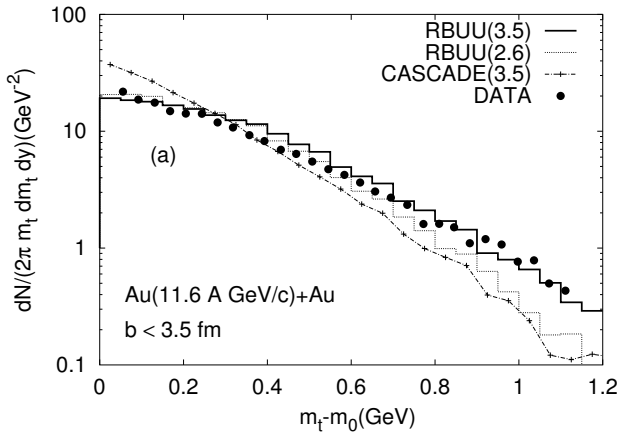
Collective Flow

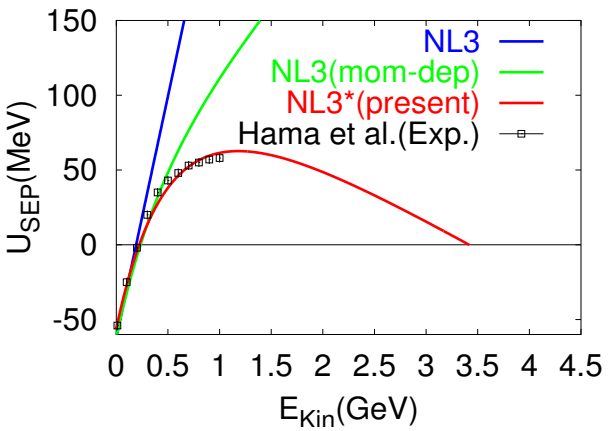
P.K.Sahu et al., NPA672(2000)376



Why does it become soft ?

Hadronic DOFs + Reduction of MF





Y.Nara et al., PTP Suppl. 129(1997)33, N.Otuka, Thesis; to be submitted.

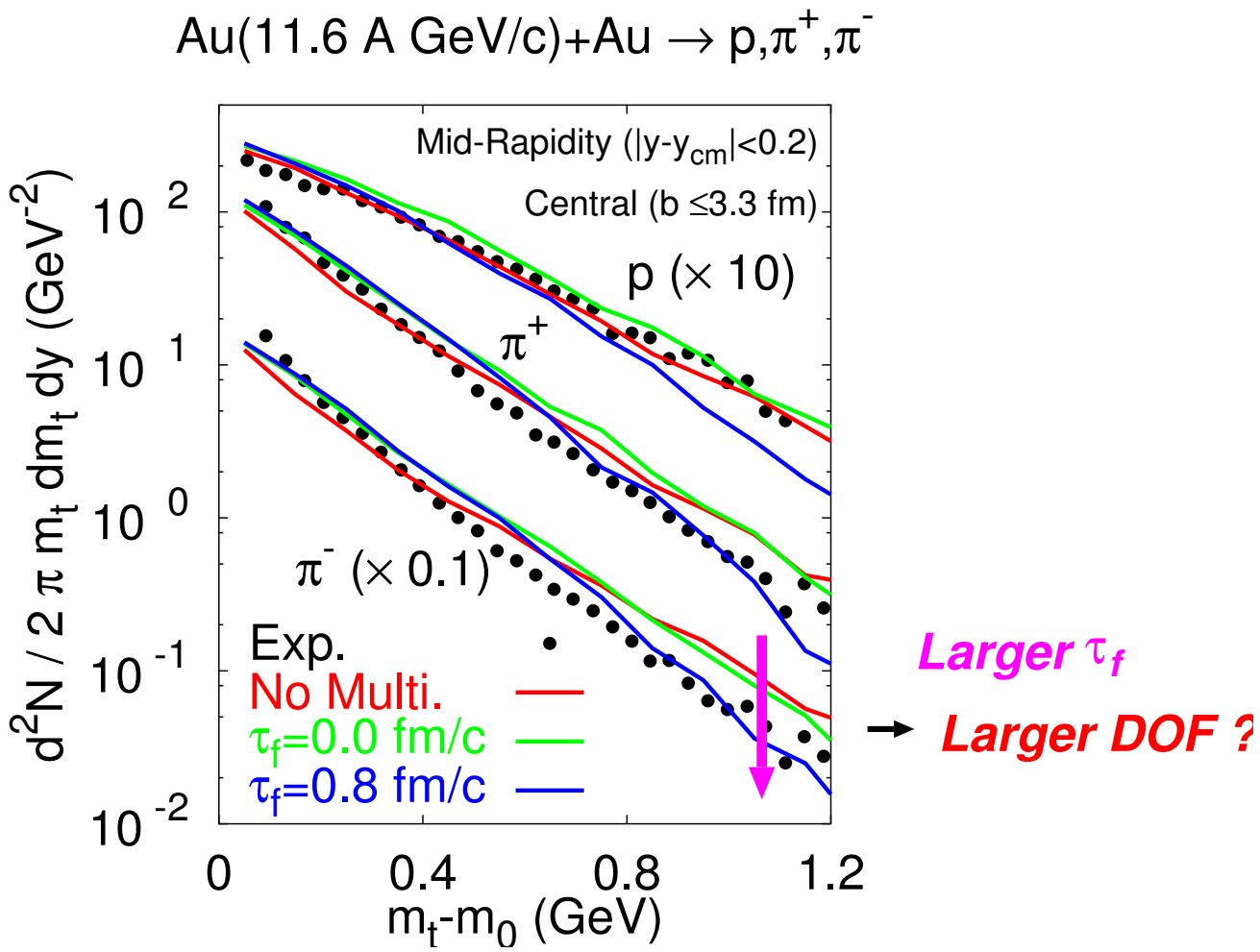
⋆ Thermal Properties of Hadronic Cascade

Small DOF models may give Too Stiff Spectra
… Why do ARC and ART Explain Data ?

Answer: Multiparticle Prod. with finite Formation Time Generates Effective Large DOFs.

ARC: Y.Pang et al. PRL68('92)2743,
ART: B.A.Li & C.M.Ko, PRC52('95)2037; PRC57('98)2065.

M_t Spectra with Multi. Prod. (HANDEL)

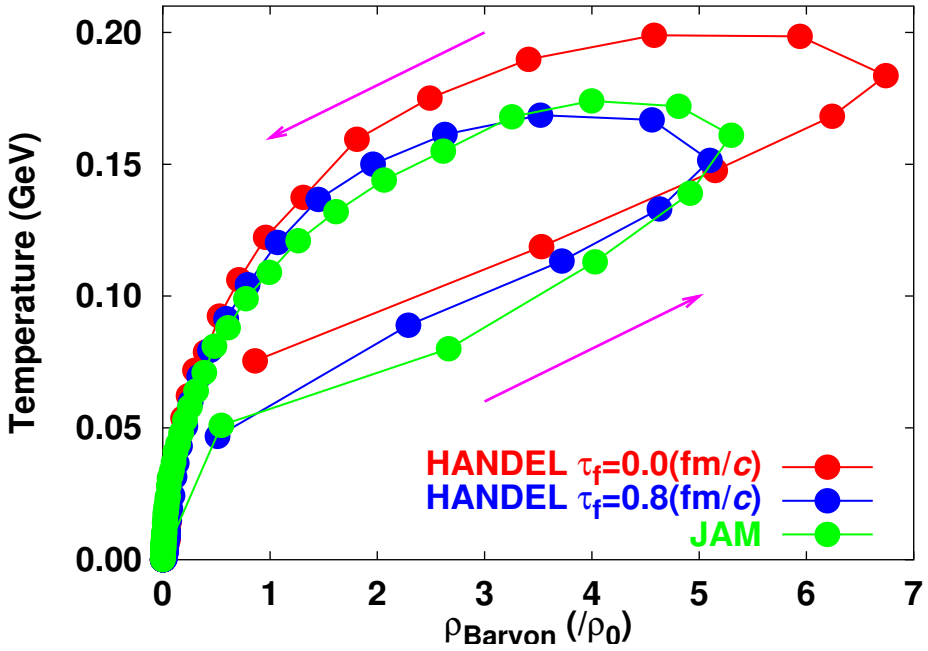


Thermal Evolution of Matter (JAM and HANDEL)

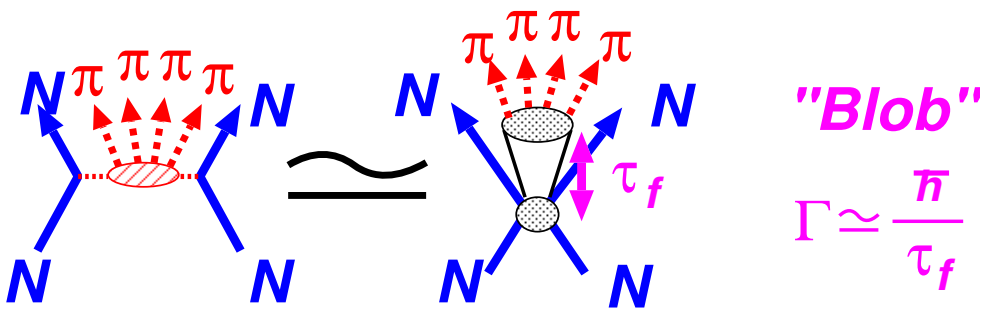
Temperature during HIC

$$T \simeq P/\rho \quad \text{(Ideal Gas EOS)}$$

ρ= Total Hadron Number Density



Why Multi Pion Production Reduces P (and thus T)?
→ "Blob" may play a role of Massive (Continuum) DOF.



How about Re-Hardening ?

- Preliminary RHIC data
  - ⋆ Pion Slope Parameter = 291 MeV (Phenix)
  - ⋆ Proton Slope Parameter $\simeq$ (400-500) MeV (H.Ohnishi for Phenix @ JPS)

⋯ Very Hard Spectra compared to those at SPS
Very Hard to explain in Hadronic Scenario

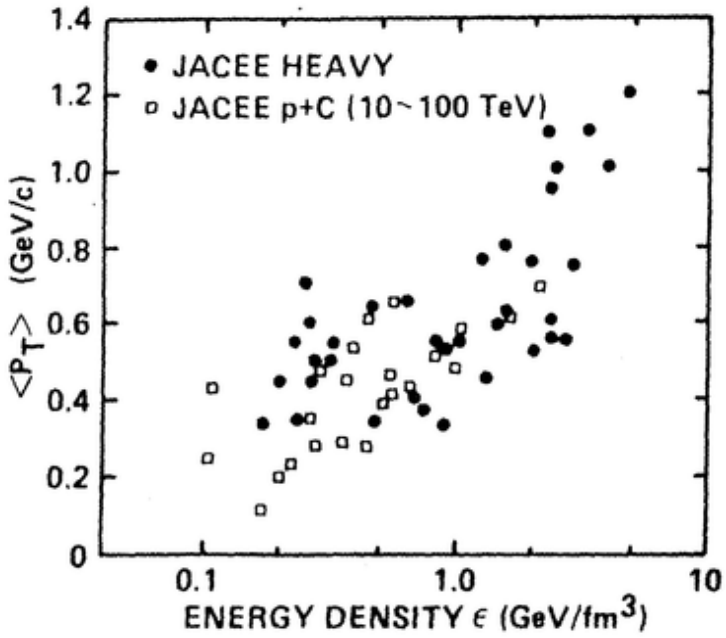
- Earlier Suggestions of Hardening
  - ⋆ JACEE observation ($< P_t >$ grows quickly)
  - ⋆ Hydro + UrQMD ($< P_t >$ grows quickly)
  - ⋆ Nu Xu @ QM2001 (β(RHIC) $>$ β(SPS))

... In this work,

- ⋆ We study proton and pion M_t spectrum in SIS-AGS-JHF-SPS-RHIC energy region systematically, by using a jet-implemented hadron-string cascade (JAM),
- ⋆ and demonstrate that the "Re-Hardening" is actually expeced in the calculation.

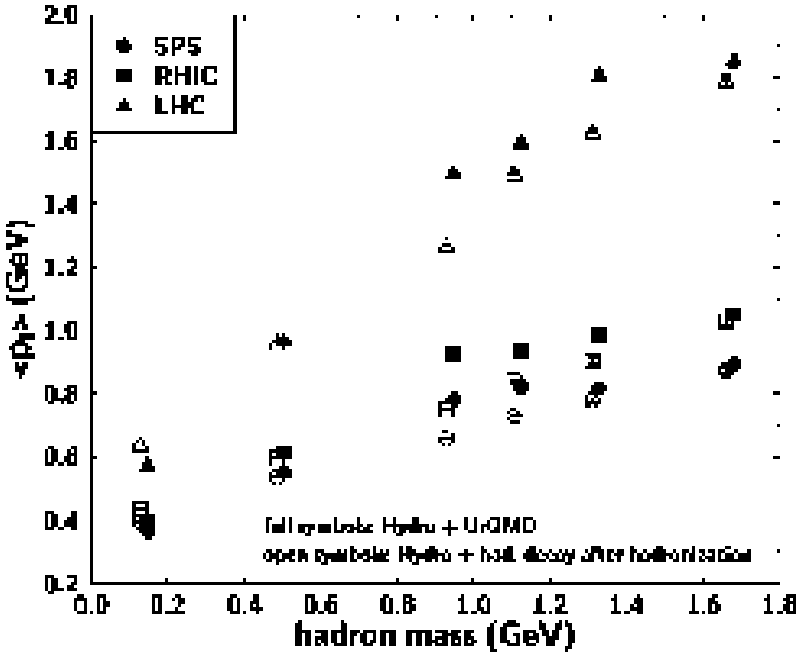
JACEE results

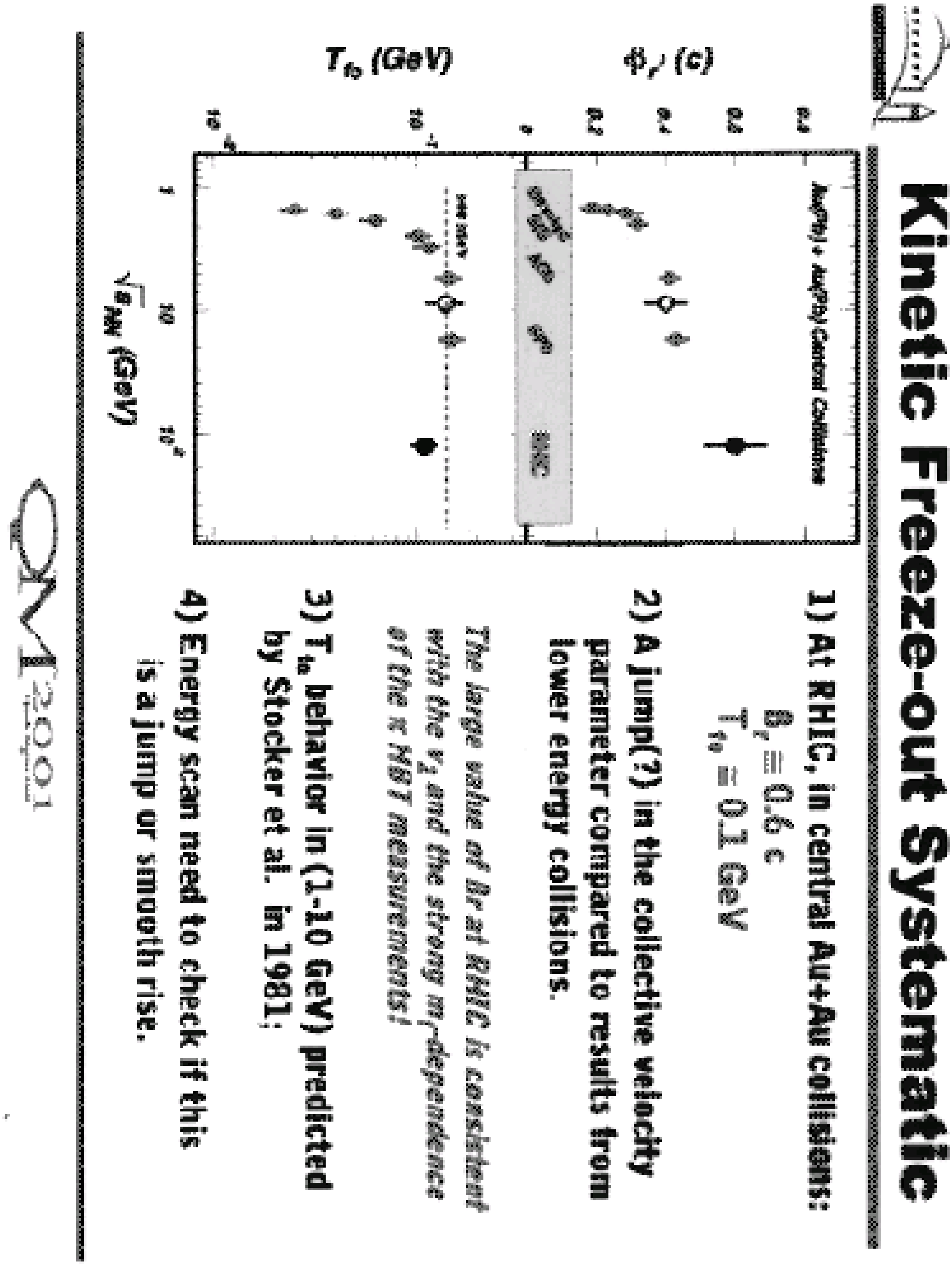
(Y.Takahashi et al., NPA461(1987)263c)



Hydro + UrQMD results

(Bass et al., PRC61(2000)064909)





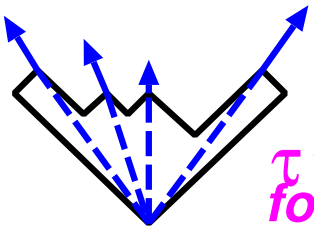
Nu Xu, Presentation at QM2001.

JAM (Jet Aa Microscopic transport model)

Y. Nara et al., PRC61('00), 024901.

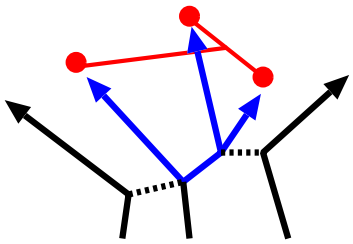
⋆ DOF: h(B, B*, M, M* (m $\leq$ 2 GeV)) + s(Strings)
+ Partons (at higher energies)

⋆ σ: Hadronic ($hh \leftrightarrow hh$, $hh \leftrightarrow h$)
+ Soft ($hh \leftrightarrow s$, $hh \rightarrow hs$, $hh \rightarrow ss$, $s \rightarrow hhh$... [1]
$ch \leftrightarrow ch$, $ch \rightarrow cs$ (c= (qq), q, $\bar{q}$) [2])

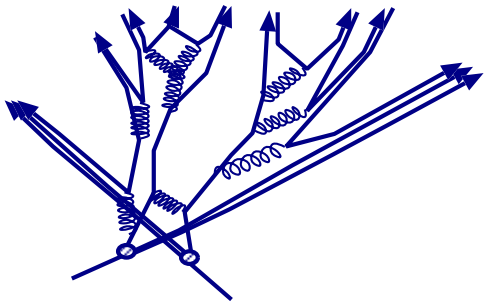


τ ~ 1 fm/c
for κ ~ 1 GeV/fm

Diquark Breaking



Resonance
+ String
+ Jet



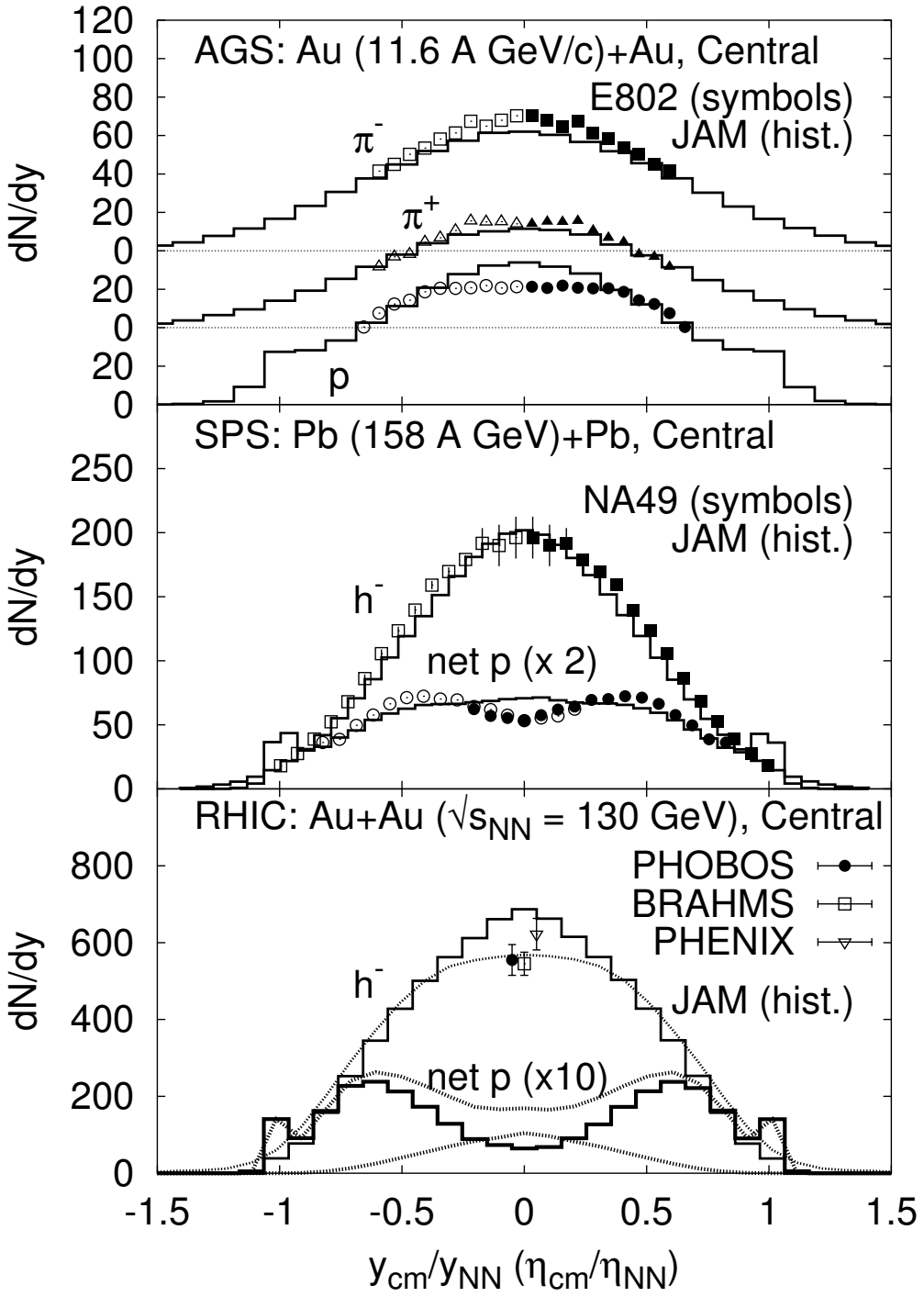
+ Hard (Jet Production, at higher energies) [3]

⋆ No Mean Field (in progress), No Medium Modification

[1] "DPM + Lund" (~ HIJING) + Phase Space
[2] Consituent Rescattering (~ RQMD), c= (qq), q, $\bar{q}$
[3] Jetset (Pythia)

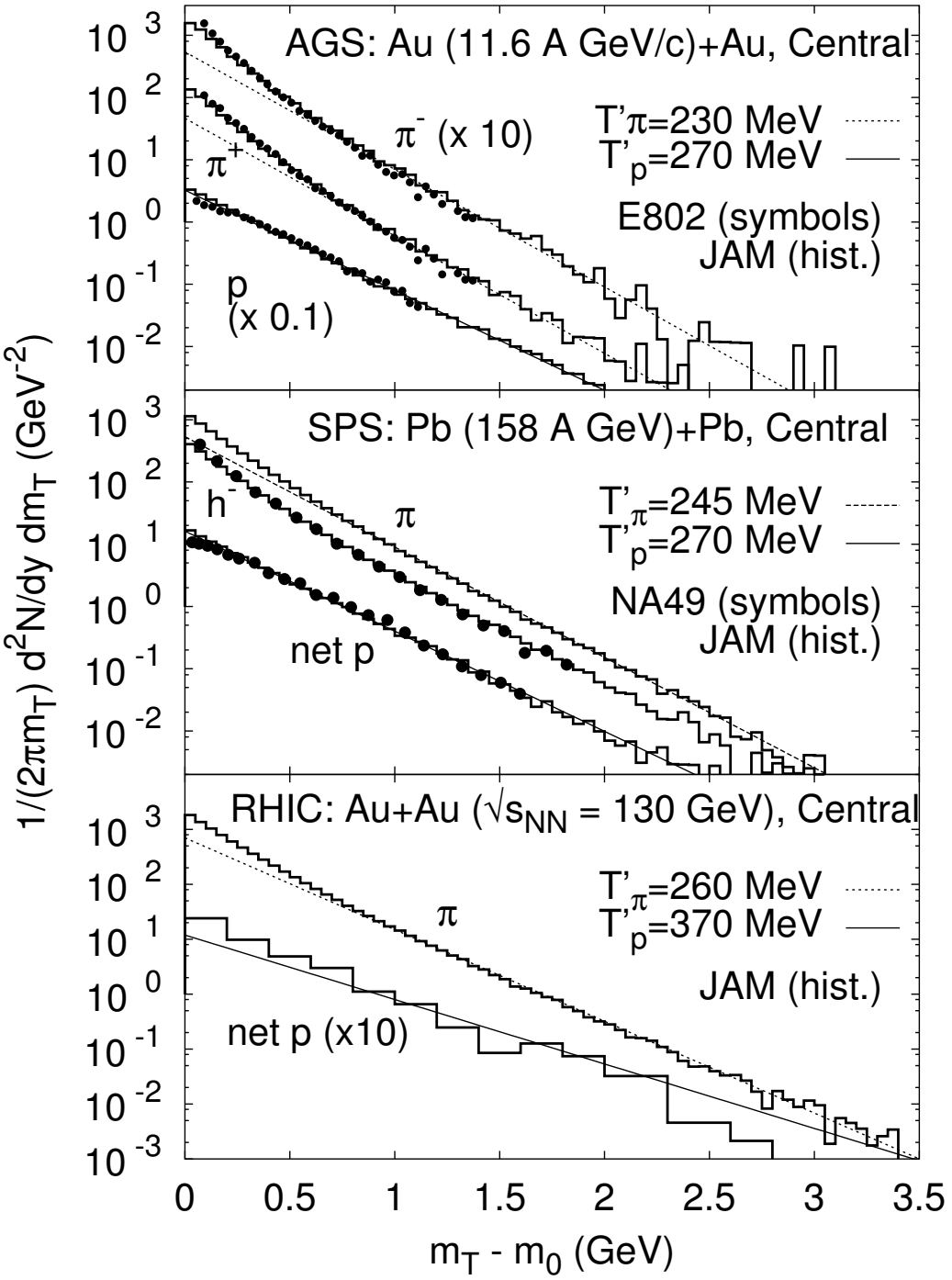
Version: JAM1.009.27 (April 2000 Version)

⋆ Rapidity Distributions: Hadron Yields



⋆ Globally Good, except for
Systematically Larger Stopping Power of Protons.

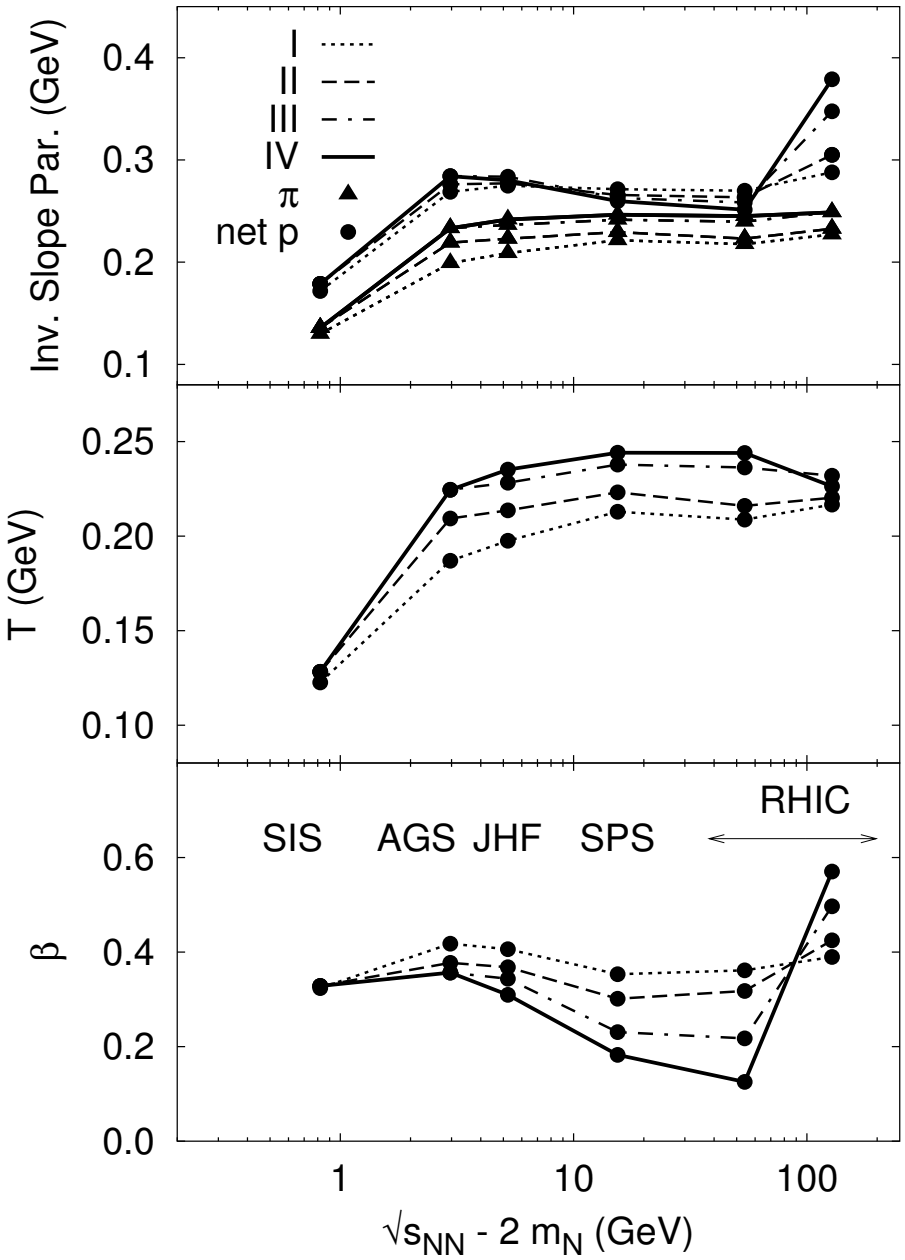
⋆ M_t Spectra: Measure of Generated Pressure



Nicely Reproduced, except for
Low Energy Protons (No Mean Field)

⋆ Decomposition to T and β

$$\frac{d^2N}{M_t dM_t dY d\phi} \propto \exp(-M_t/T'), \qquad T'(M) = T + \frac{1}{2} M \beta^2$$



Re-Hardening emerges
between SPS and RHIC energies

⋆ Summary and Conclusion

- **Re-Hardening of Hadron Spectra**

  is very hard to explain in Hadronic Scenario since more and more hadronic heavy DOFs are activated, (Otuka, Thesis)

  then it can be a good signature of BULK QGP formation.

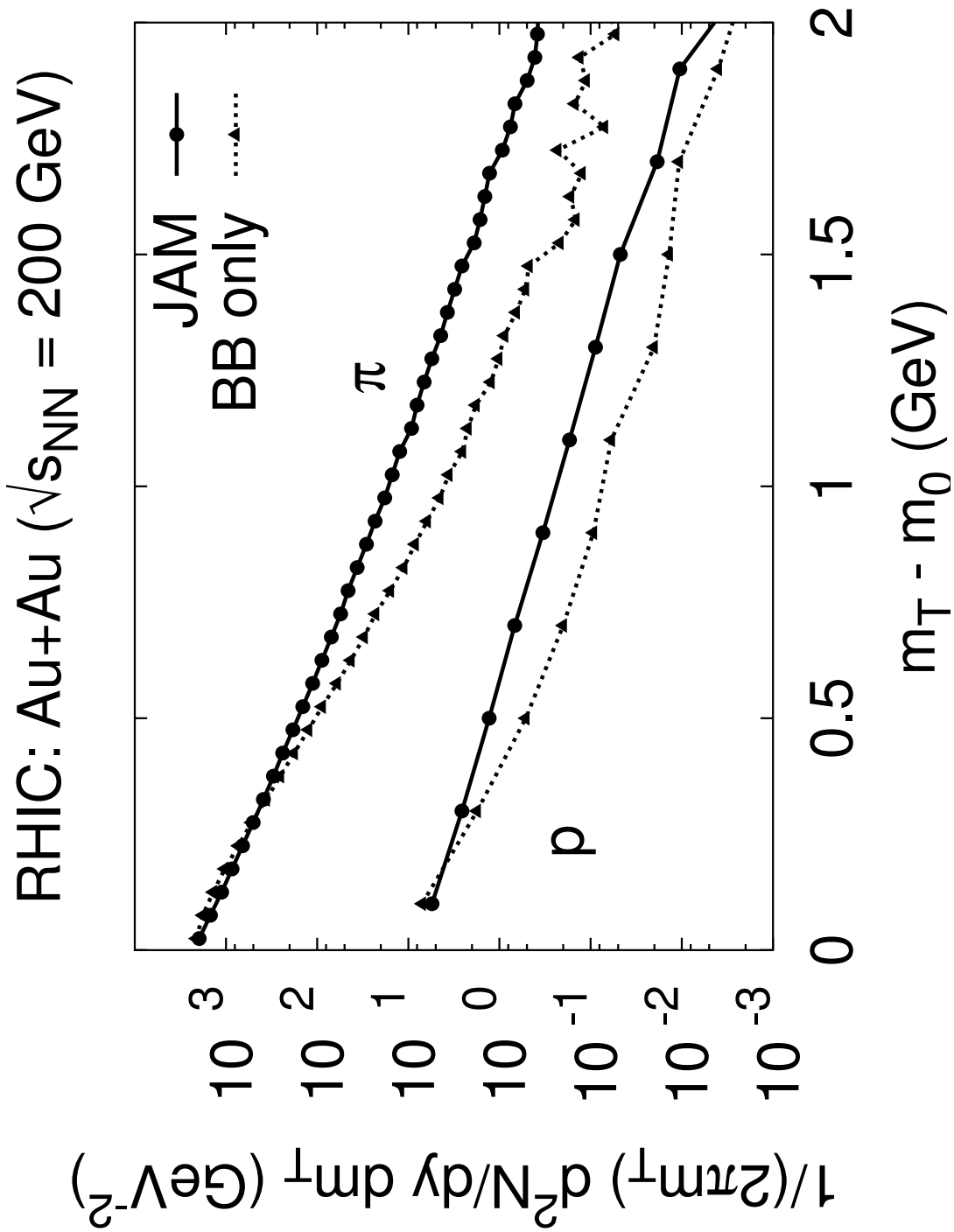
- **RHIC preliminary results and JAM cal.**

  show re-hardening between SPS and RHIC energies.

⋆ JAM results systematically reproduces AGS-SPS-RHIC energy heavy-ion collisions.

- $dN/d\eta(\text{charged}) \simeq 570$
- $\bar{p}/p \simeq 0.63$
- Slopes: a little softer than data

⋆ Local Maximum of β may appear at around JHF-NSP energies. It can be a consequence of "the highest baryon density".


RHIC: Au+Au ($\sqrt{s_{NN}}$ = 200 GeV)
JAM
BB only
π
p
$1/(2\pi m_T)\ d^2N/dy\ dm_T$ (GeV^{-2})
$m_T - m_0$ (GeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.5
1
1.5
2