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

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

1. Introduction: Re-Hardening as a QGP signal
2. Jet implemented Hadron-String Cascade (JAM)
3. Pion and Proton Spectra at RHIC energies
4. Re-Hardening
5. Summary

∗ Submitted:
N. Otuka, P.K. Sahu, M. Isse, Y. Nara and A. Ohnishi
"Re-Hardening of Hadron Transverse Mass Spectra in Relativistic Heavy-Ion Collisions"
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⋆ Proposed and Observed QGP Signals up to SPS

⋆ Anomalous J/ψ supression
◯ : Deconf. phase → No Bound State
(Matsui & Satz, Miyamura et al.)
△ : $\sigma(J/\psi\text{-}h) =$ 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, Otuka/Sahu)

- 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.

⋆ $J/\psi + N^* \to D\bar{D} + N$

⋆ string + string → Rope → $Y\bar{Y}$

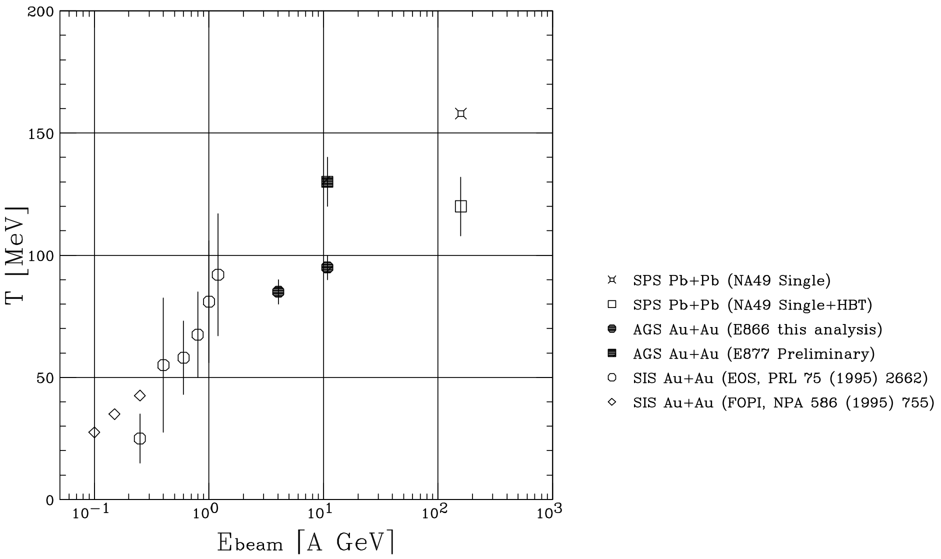
⋆ Large Mass Energy ↔ Smaller Pressure

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

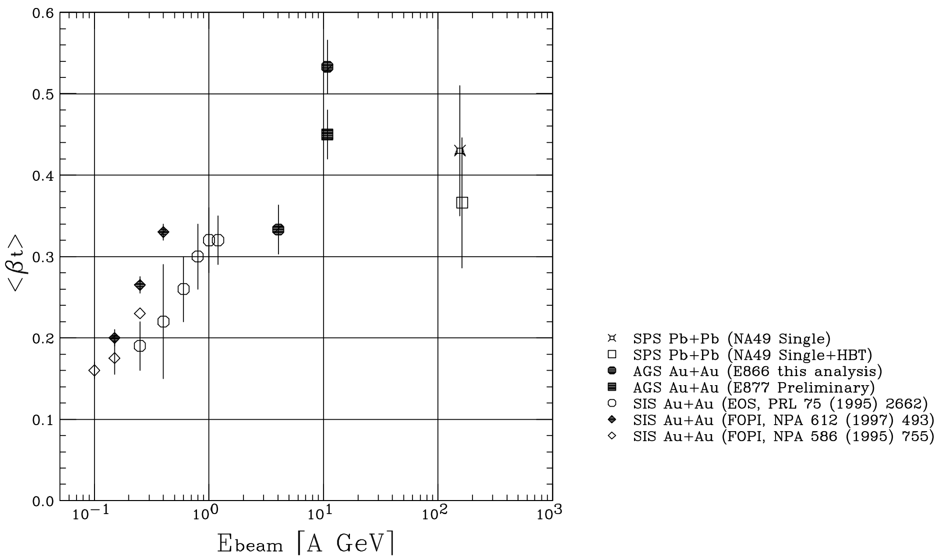
⋆ Softening at SIS-AGS-SPS

Chujo, Thesis.

Temperature

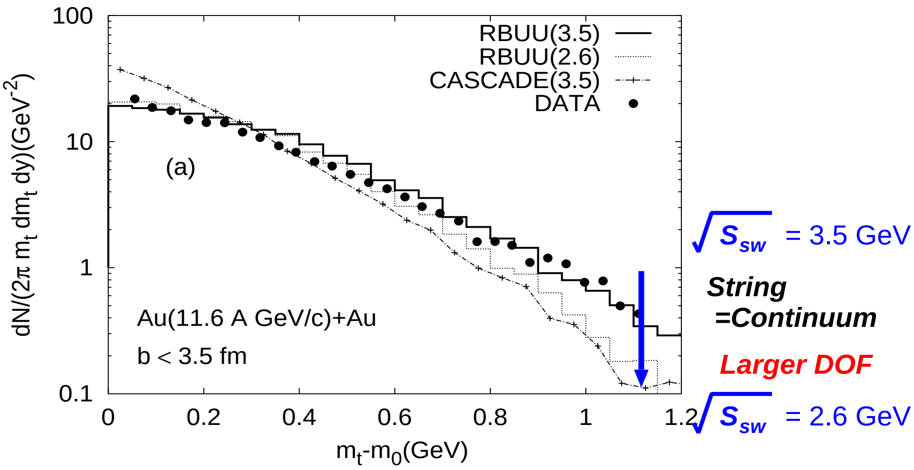


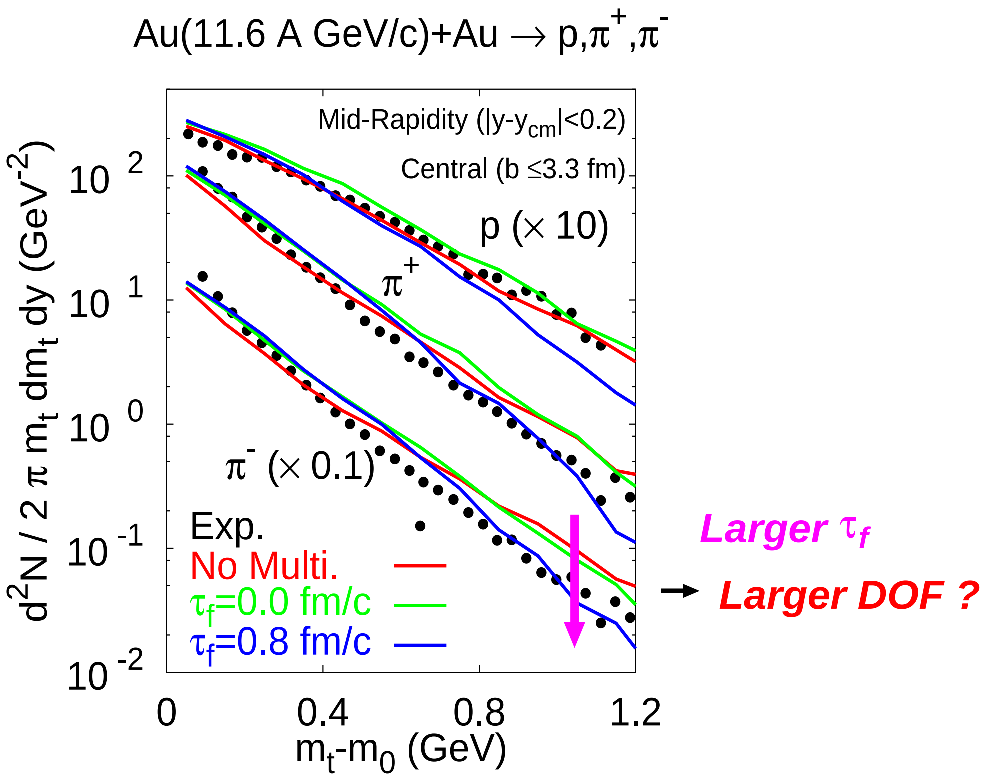
Radial Flow



⋆ Increase of Hadronic DOF → Softening

Y.Nara et al., PTP Suppl. 129(1997)33; P.K.Sahu et al., NPA672(2000)376; N.Otuka, Thesis; to be submitted.

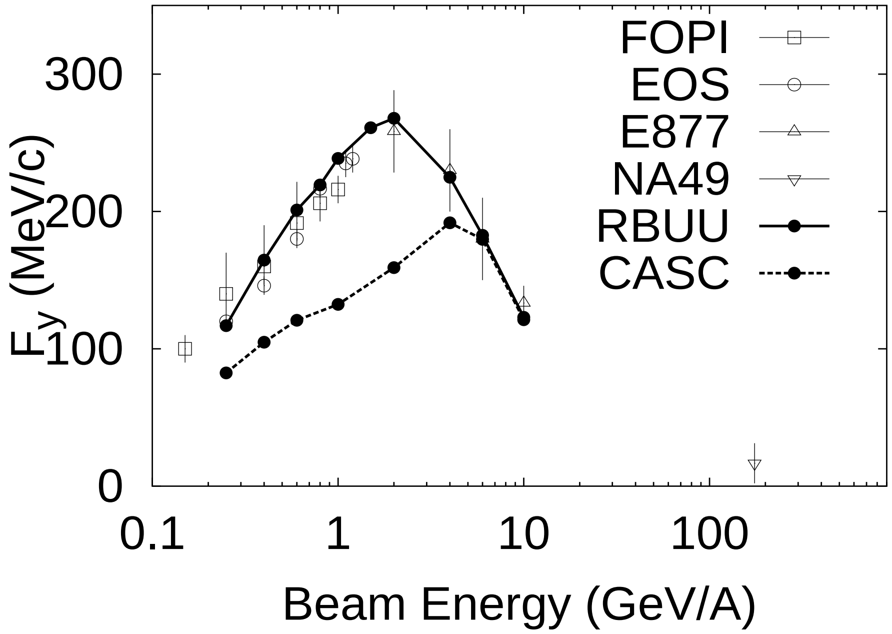


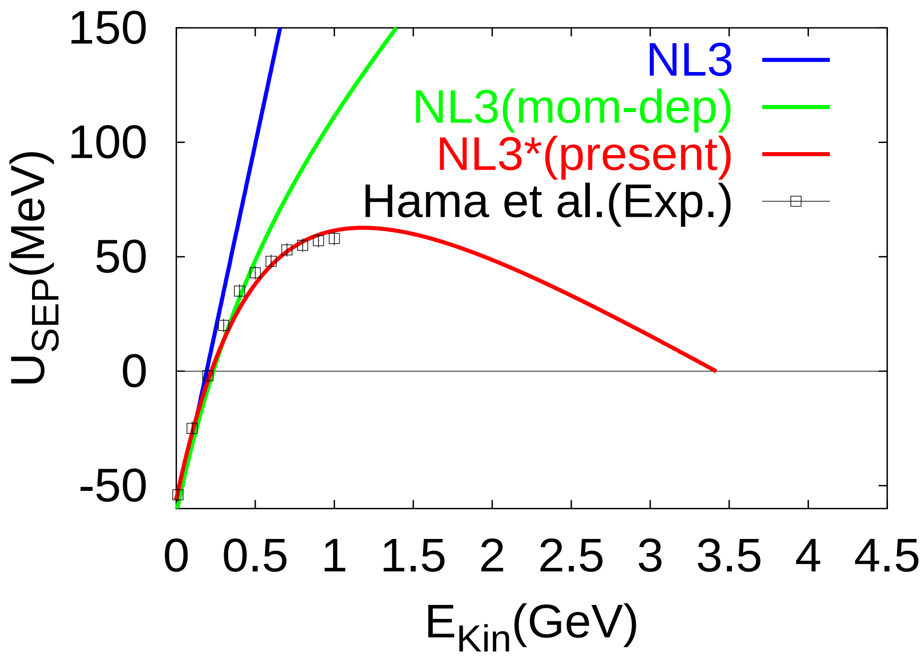


Large Hadronic DOFs are necessary, either

- ⋆ Explicitly (RQMD, RBUU, URASiMA, JAM, ...)
- ⋆ or Implicitly (ARC, ART, HANDEL) through Multiparticle Prod. with Finite τ

⋆ Reduction of Repulsive Int. → Softening





Repulsive Nuclear Interaction Should be Supperssed at Higher Momentum

How about Re-Hardening ?

- Preliminary RHIC data

  ⋆ Pion Slope Parameter = 291 MeV (Phenix)

  ⋆ Proton Slope Parameter ≃ (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))

- Problems of Re-Hardening as a QGP signal

  ⋆ Thermally Equilibrated ?

  ⋆ Initial Mini-Jet Effects ?

... 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,

⋆ but the Re-Hardening signature is
WEAKER than the data.

⋆ Simple Model

⋆ Hadron Gas = Massless Pion Gas

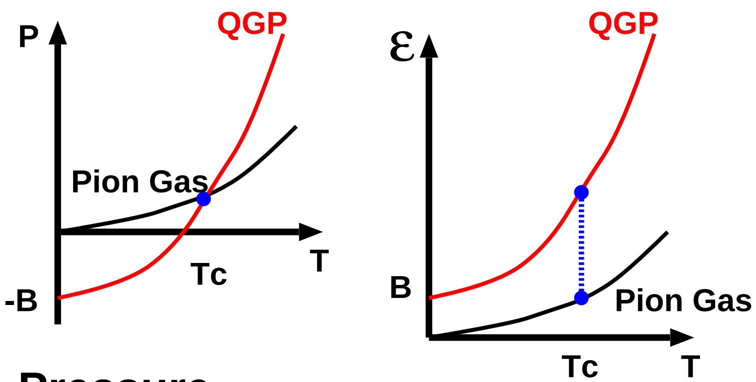
$$P = \frac{\pi^2}{90} g_\pi T^4 \ , \epsilon = \frac{\pi^2}{30} g_\pi T^4 \ (g_\pi = 3) \rightarrow P = \epsilon/3 \ .$$

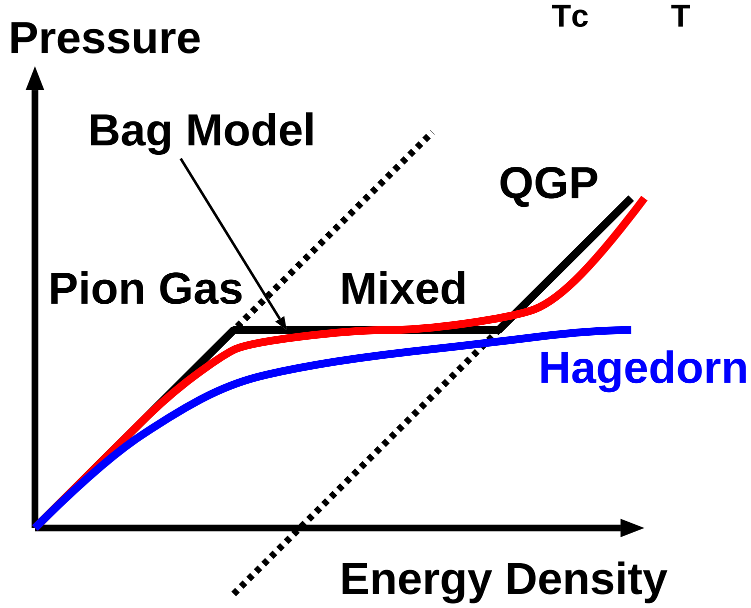
⋆ QGP = Bag model

$$\begin{aligned} P &= \frac{\pi^2}{90} g_{qgp} T^4 - B \ , \epsilon = \frac{\pi^2}{30} g_{qgp} T^4 + B \rightarrow P = (\epsilon - 4B)/3 \ , \\ g_{qgp} &= 2 \times 8(\text{gluon}) \\ &+ \frac{7}{8}(2 \times 2 \times 3 \times 3)(\text{quark, spin, } q, \bar{q}, \text{ color, flavor}) \end{aligned}$$

⋆ Hydrodynamics

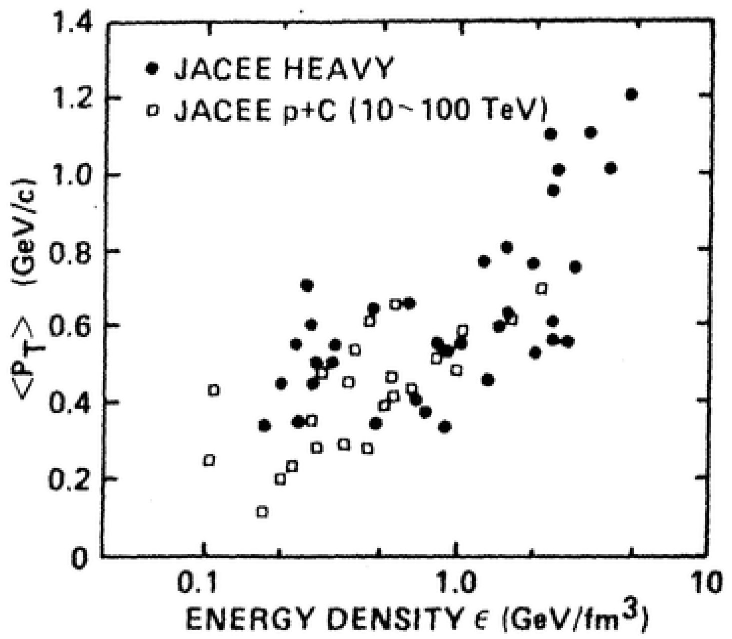
$$\epsilon \frac{D\boldsymbol{V}}{Dt} = -\boldsymbol{\nabla} P \rightarrow V = \int_{path} \boldsymbol{\nabla} P \cdot d\boldsymbol{r}/\epsilon$$





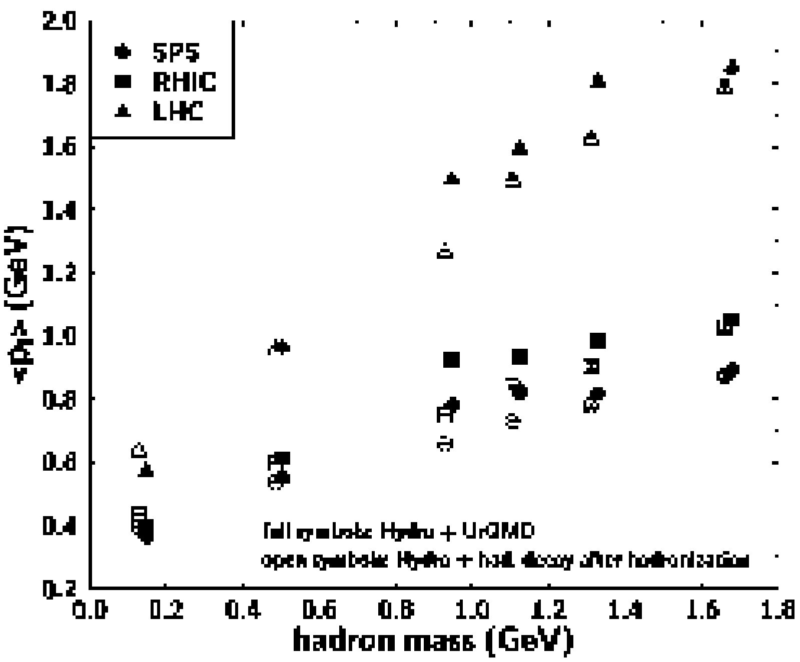
JACEE results

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



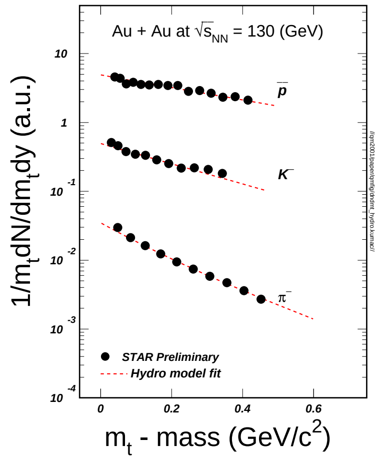
Hydro + UrQMD results

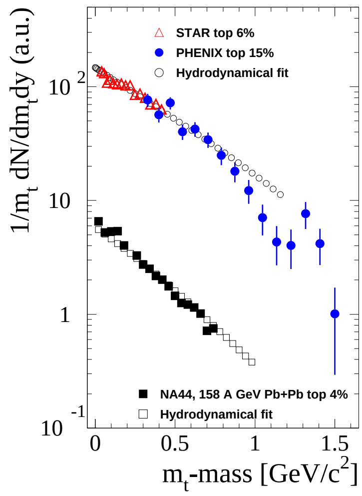
(Bass et al., PRC61(2000)064909)

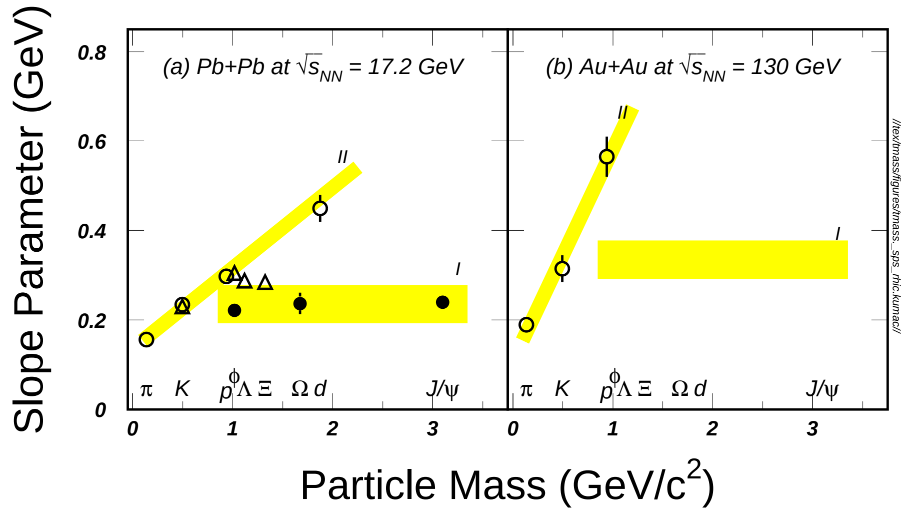


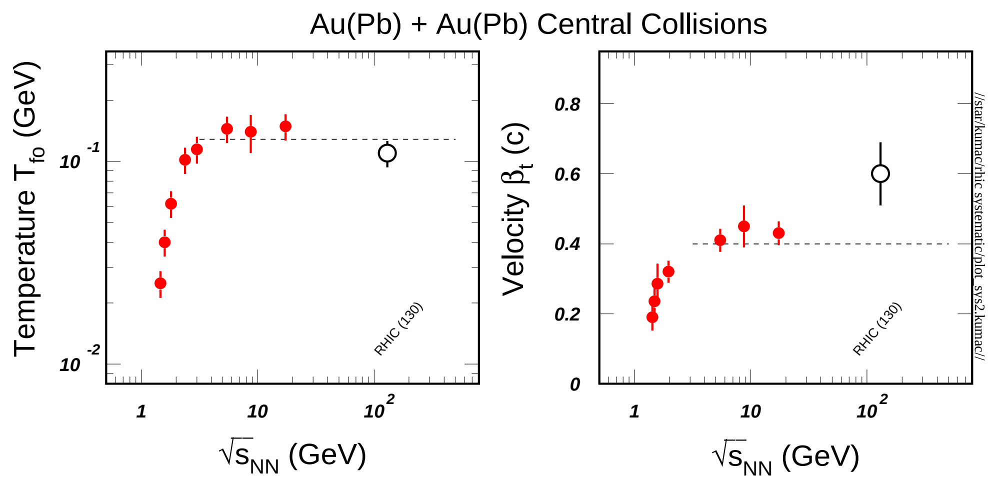
• Recent RHIC data

Nu Xu and M. Kaneta, nucl-ex/0104021









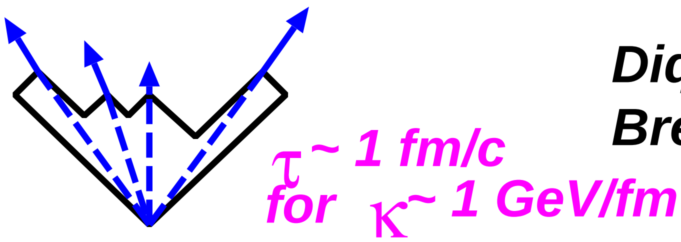
Clear Re-Hardening is seen !

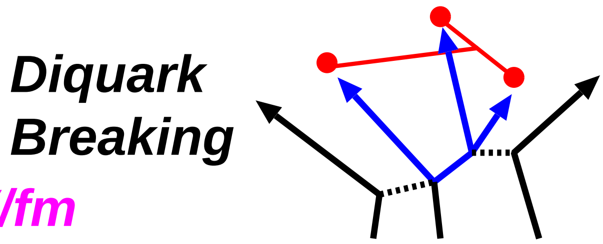
JAM (Jet Aa Microscopic transport model)

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

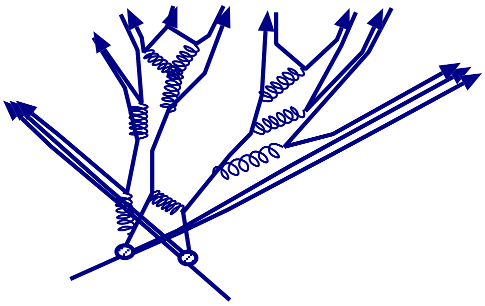
⋆ DOF: h(B, B*, M, M* (m $\leq$ 2 GeV)) $+$ s(Strings)
  $+$ Partons (at higher energies)

⋆ 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, $\bar{\text{q}}$) [2])





Resonance
+ String
+ Jet



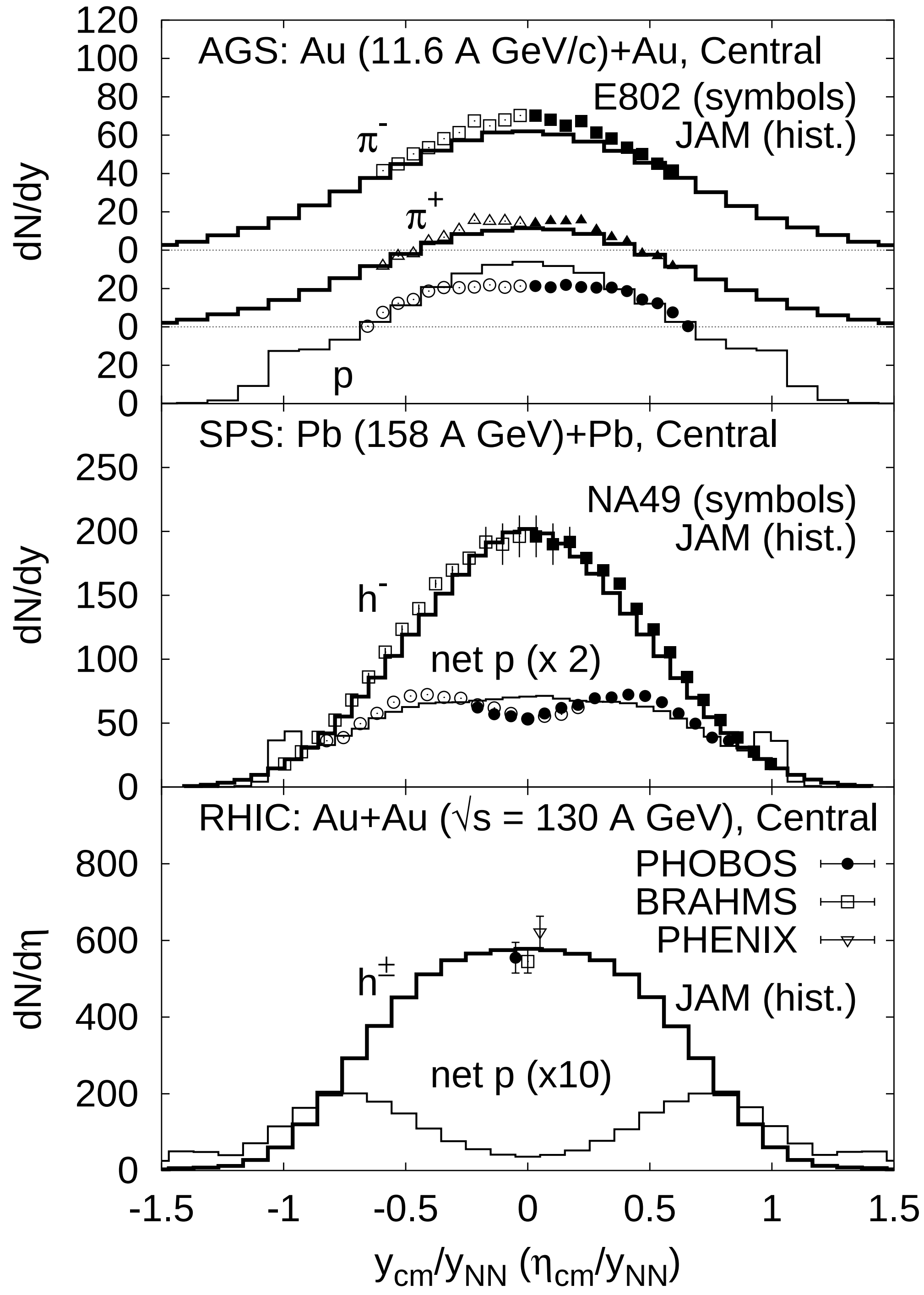
$+$ Hard (Jet Production, at higher energies) [3]

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

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

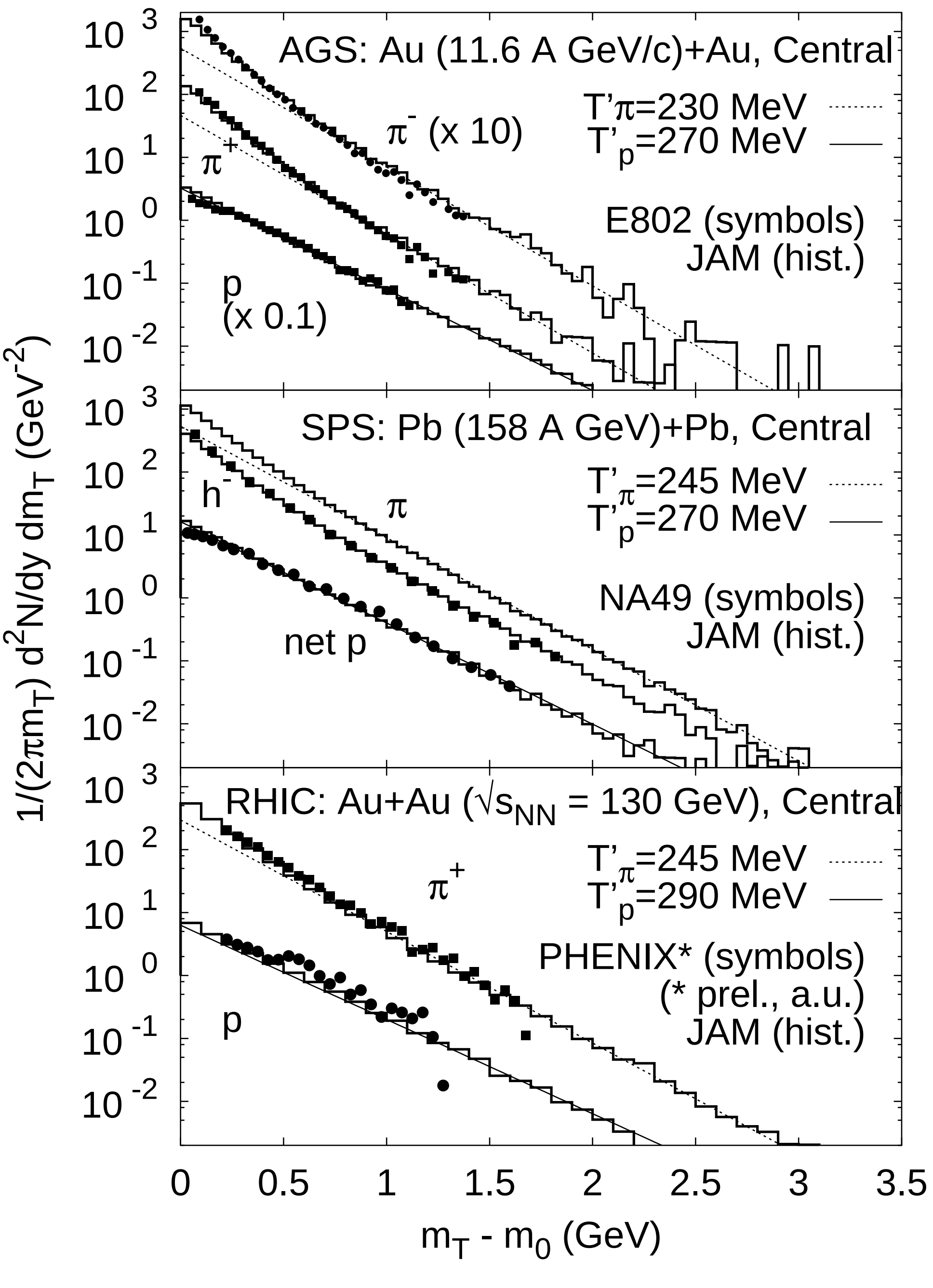
Version: JAM1.009.27 (April 2000 Version)

⋆ Rapidity Distributions: Hadron Yields



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

$\star$ M_t Spectra: Measure of Generated Pressure



Nicely Reproduced at AGS and SPS, except for Low Energy Protons (No Mean Field).

At RHIC, JAM underestimates High Energy Protons (No Parton Cascade).

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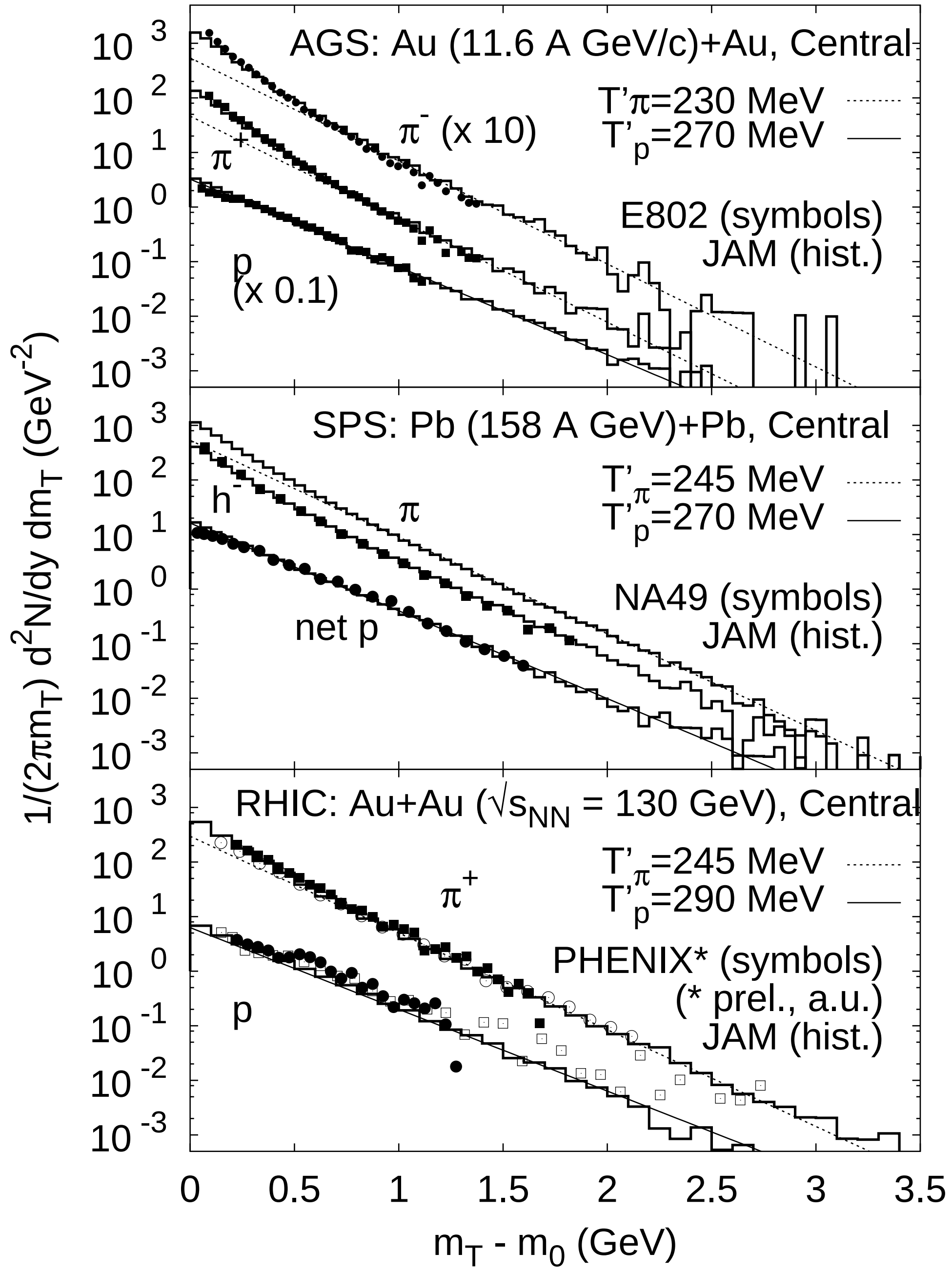

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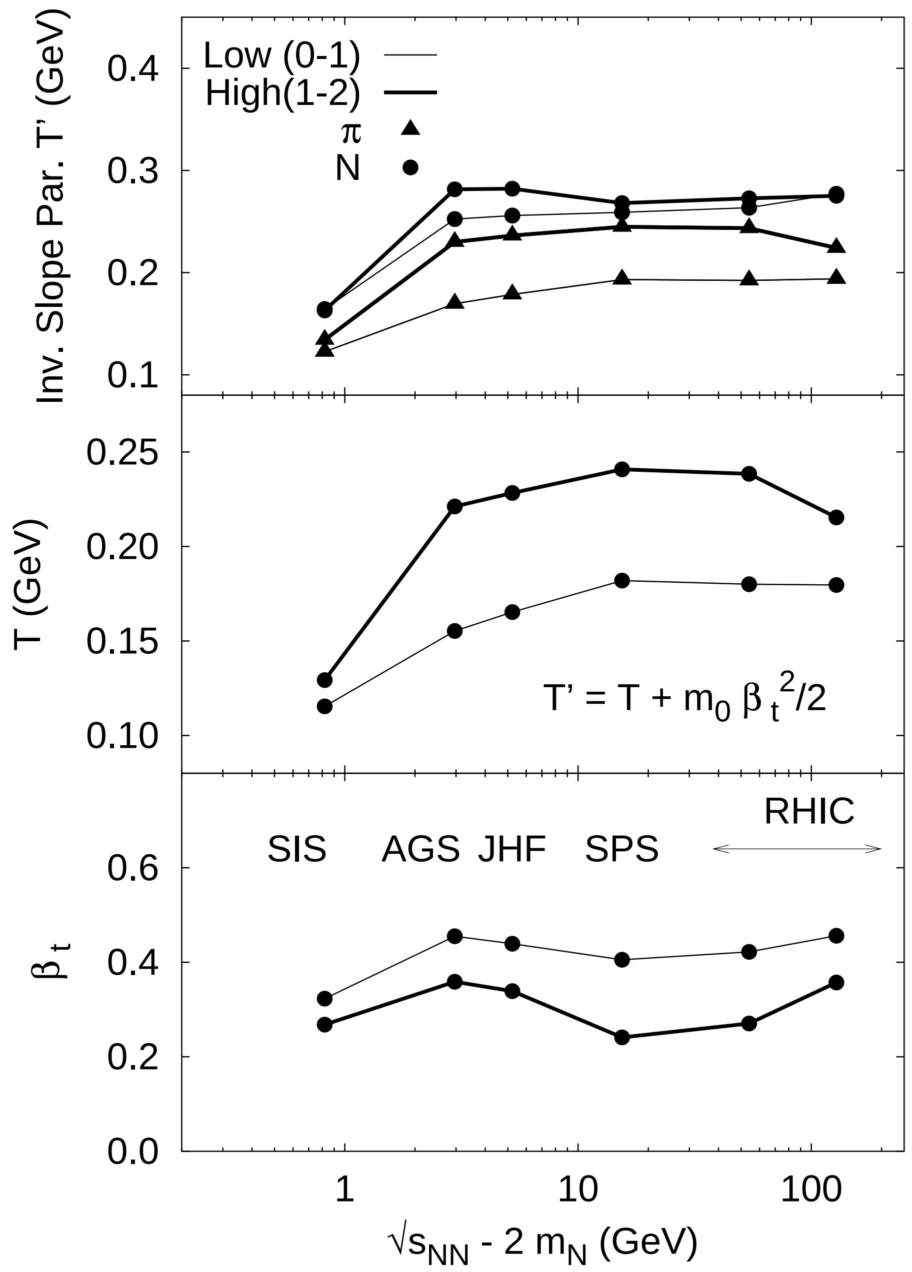
⋆ Decomposition to T and β

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



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

  Increase of Hadronic DOFs

  and Reduction of Repul. Int.

  make it softer and softer at high Energy density then it can be a good signature of bulk QGP formation, provided that the system is equilibrated to a large extent.

- ⋆ RHIC preliminary results show re-hardening between SPS and RHIC energies.
- ⋆ JAM (with Mini-jet productions) results also show re-hardening behavior, but this signature is weaker than the prelimnary data (not confirmed yet).
- ⋆ The difference would be due to the Parton Cascade Processes, which are not incorportated in JAM, and play an essential role in early thermalization.

- ⋆ 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".