Collective flows in heavy-ion collisions from AGS to RHIC

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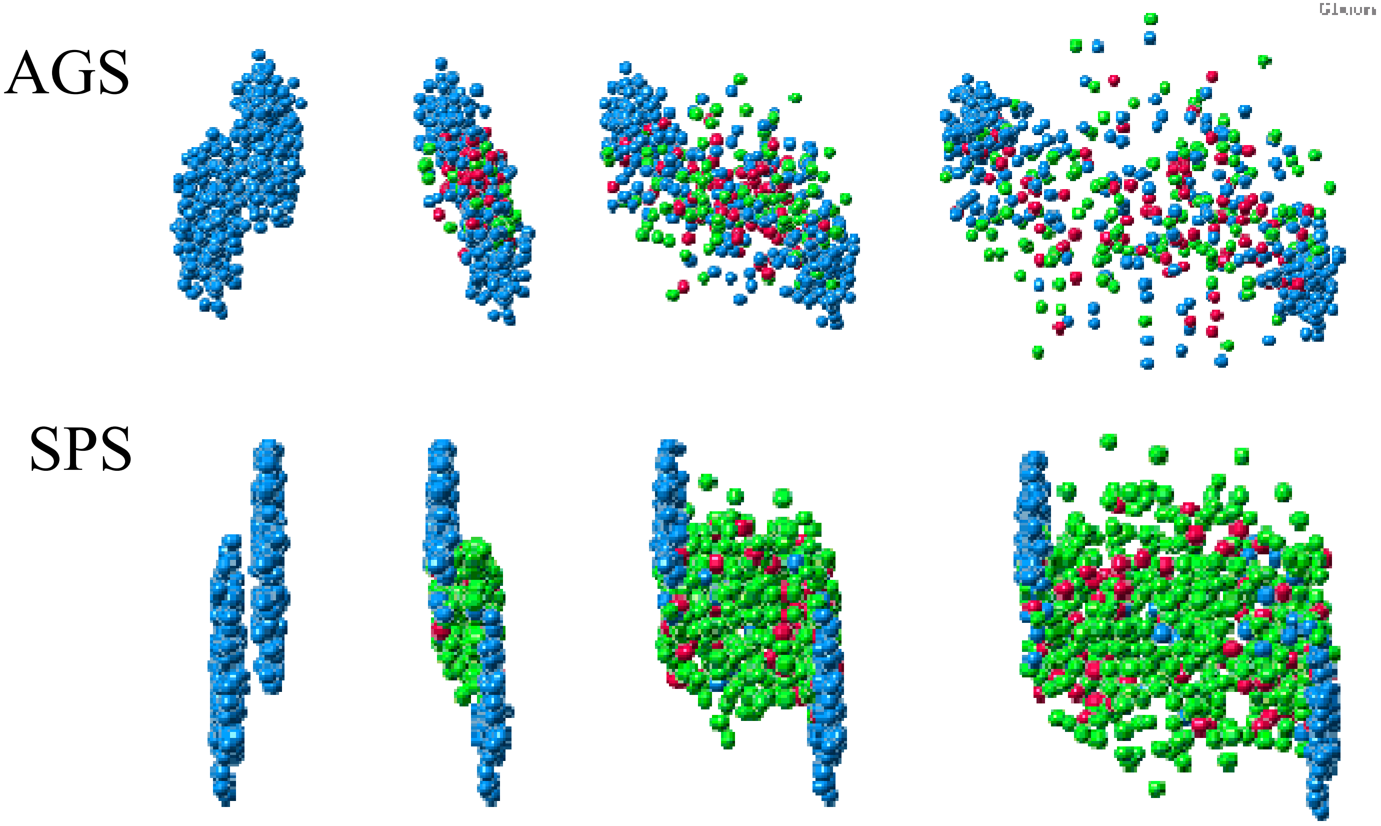
- **Collective Flows from AGS to SPS Energies**
  Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908
- **Hydro. vs Cascade Comparison at RHIC**
  Hirano, Isse, Nara, AO, Yoshino, Phys. Rev. C 72(2005), 041901
  Sahu, Isse, Otuka, AO, Pramana, 2006.
  Isse, Ph.D Thesis
- **Jet Fluid-String formation and decay at RHIC**
  Isse, Hirano, Mizukawa, Nara, AO, 2007.

Heavy-Ion Collisions at Einc ~ (1-100) A GeV

- **Study of Hot and Dense Hadronic Matter**
  → Particle Yield, Collective Dynamics (Flow), EOS, ...



JAMming on the Web, linked from http://www.jcprg.org/

Collective Flow and EOS: Old Problem ?

- **1970's-1980's: First Suggestions and Measurement**
  - **Hydrodynamics suggested the Exsitence of Flow.**
  - **Strong Collective Flow suggests Hard EOS**
- **1980's-1990's: Deeper Discussions in Wider E_{inc} Range**
  - **Momentum Dep. Pot. can generate Strong Flows.**
  - **Einc deps. implies the importance of Momentum Deps.**
  - **Flow Measurement up to AGS Energies.**
- **2000's: Extention to SPS and RHIC Energies**
  - **EOS is determined with Mom. AND Density Dep. Pot. ?**

Old but New (Continuing) Problem !

Mean Field Dynamics + Two-Body Collision

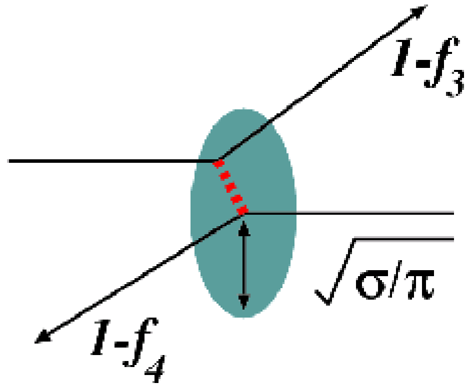
- **BUU Equation (Bertsch and Das Gupta, Phys. Rept. 160(88), 190)**
  - **Time-Dependent Hartree-Fock Eq. を Wigner 変換→ Vlasov Eq.**
  - **Pauli blocking を導入した Boltzmann 方程式の衝突項を導入**

→ 低エネルギーで重要な平均場理論と
高エネルギー(>100 A MeV) で支配的なカスケード過程を統合

→ どのような粒子自由度を導入すべきか？

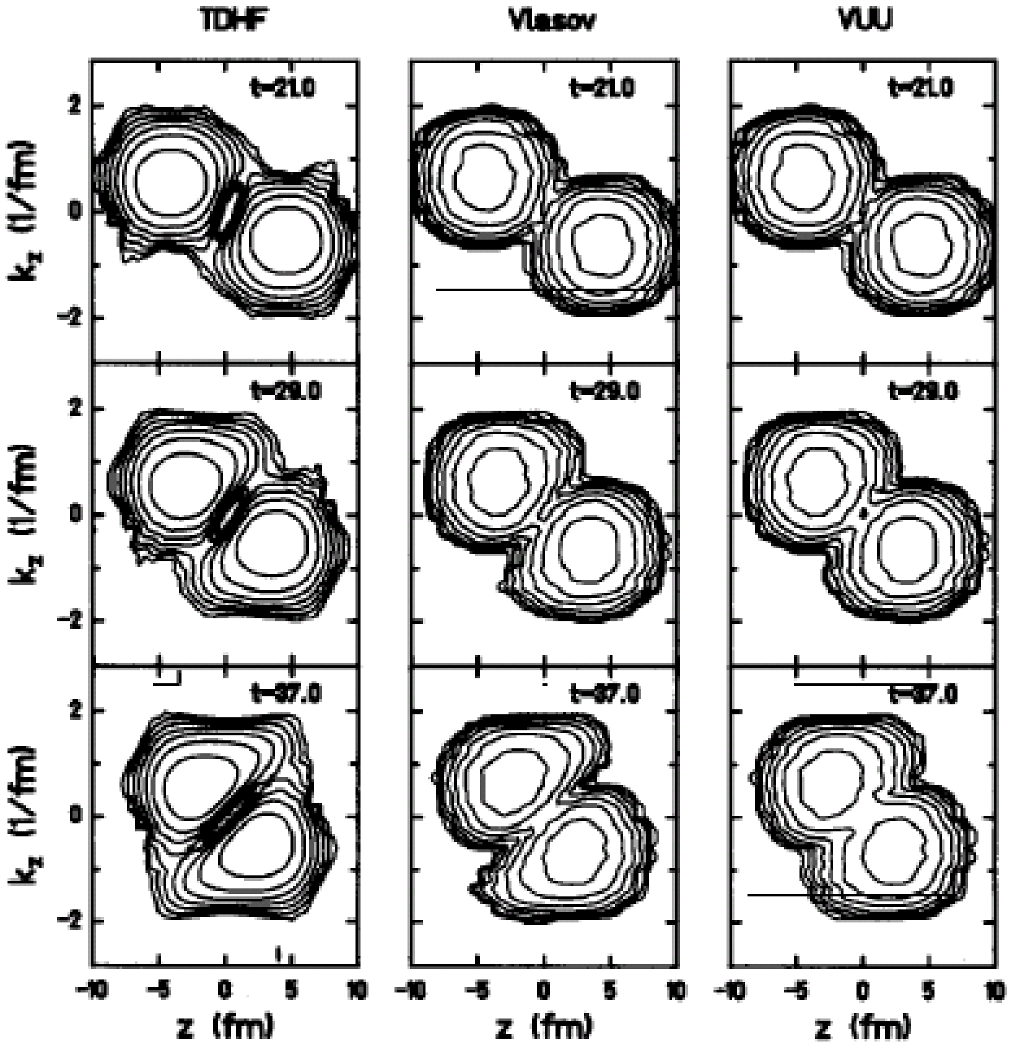
$$\frac{\partial f}{\partial t} + v\cdot\nabla_r f - \nabla U\cdot\nabla_p f = I_{coll}[f]$$

$$I_{coll}[f] = -\frac{1}{2}\int \frac{d^3 p_2\, d\Omega}{(2\pi\hbar)^3}\, v_{12}\, \frac{d\sigma}{d\Omega} \times \left[f f_2(1-f_3)(1-f_4) - f_3 f_4(1-f)(1-f_2)\right]$$



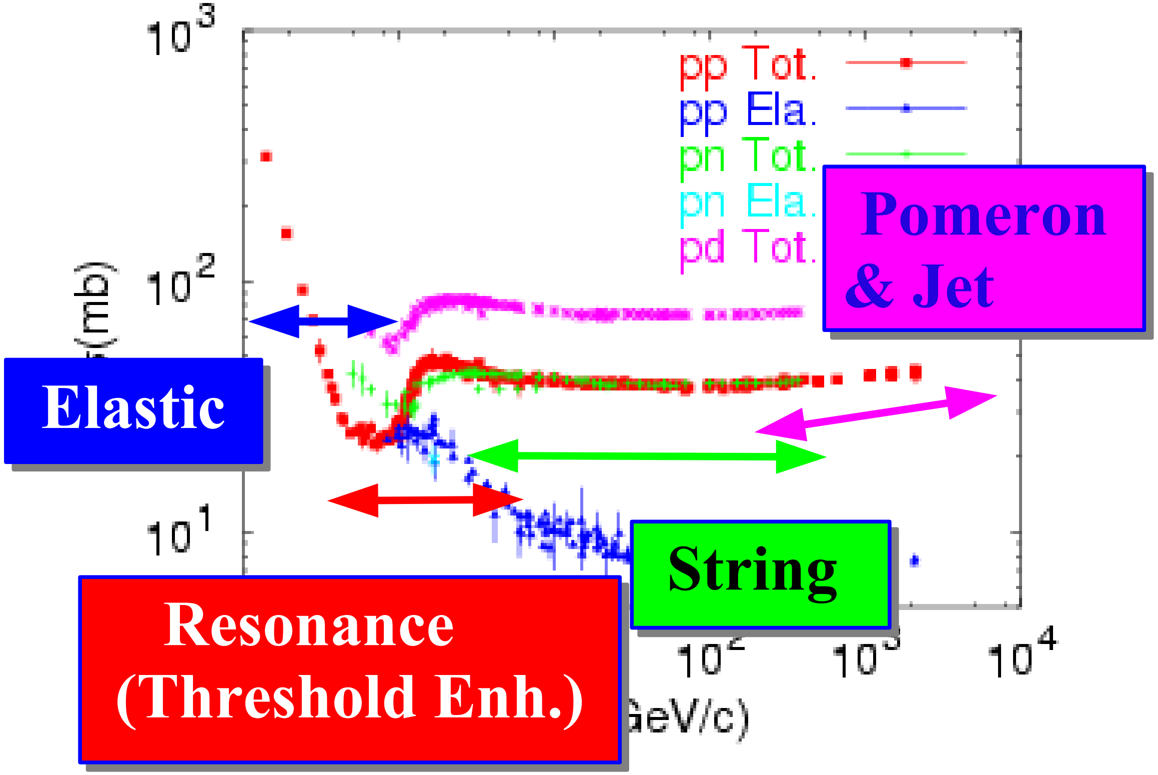
Comarison of TDHF, Vlasov and BUU(VUU)

- **Ca+Ca, 40 A MeV**
  (Cassing-Metag-Mosel-Niita, Phys. Rep. 188 (1990) 363).



Hadron-Hadron Cross Sections

From Particle Data Group

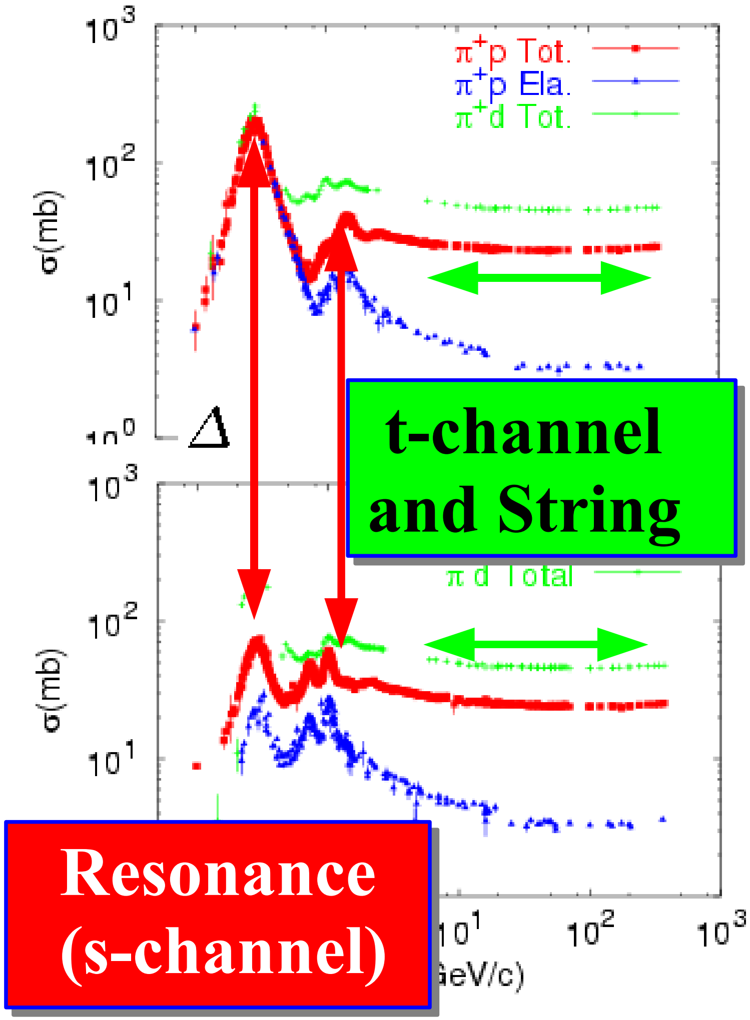


Pomeron & Jet

Elastic

String

Resonance (Threshold Enh.)



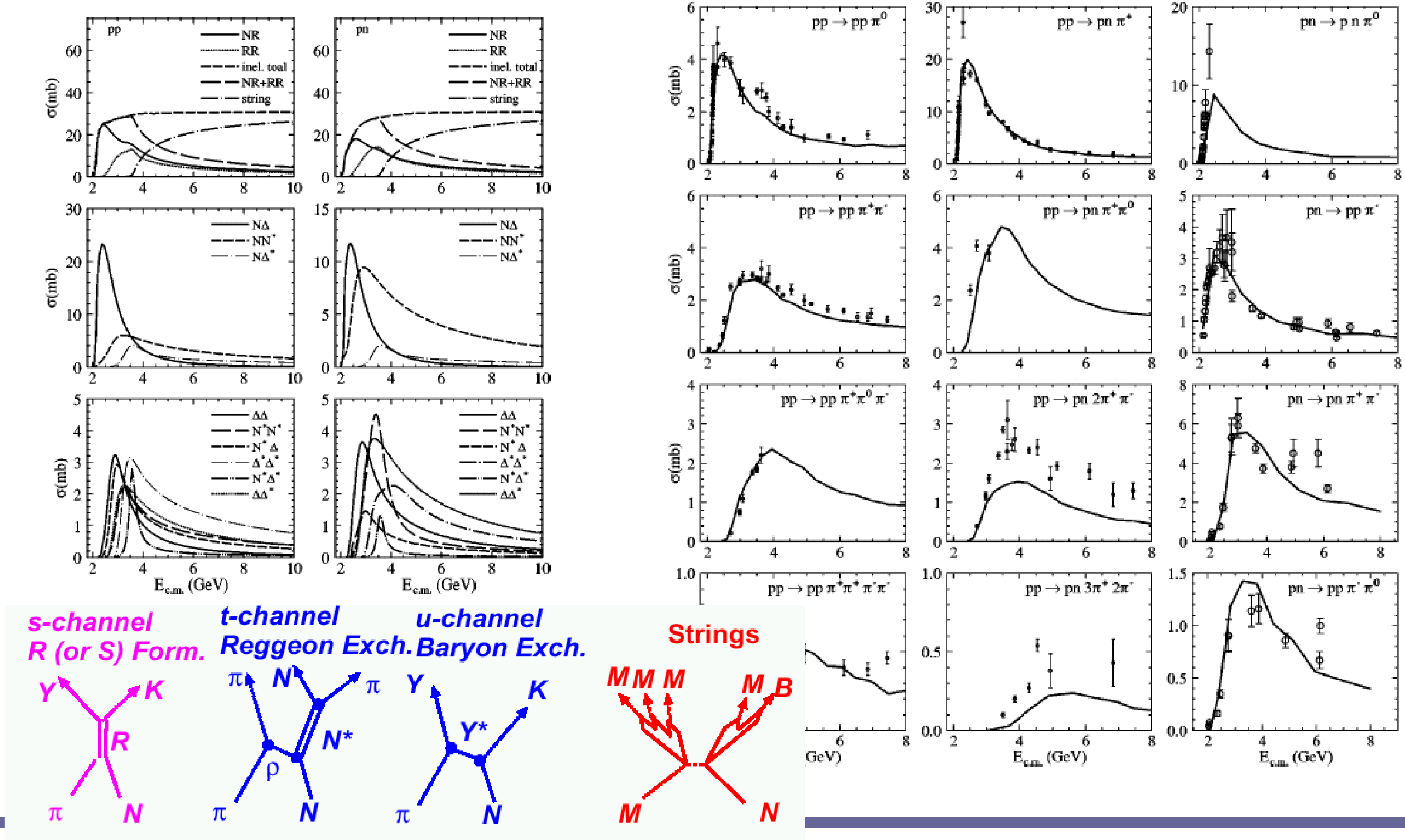
t-channel and String

Resonance (s-channel)

Exclusive Cross Sections in JAM

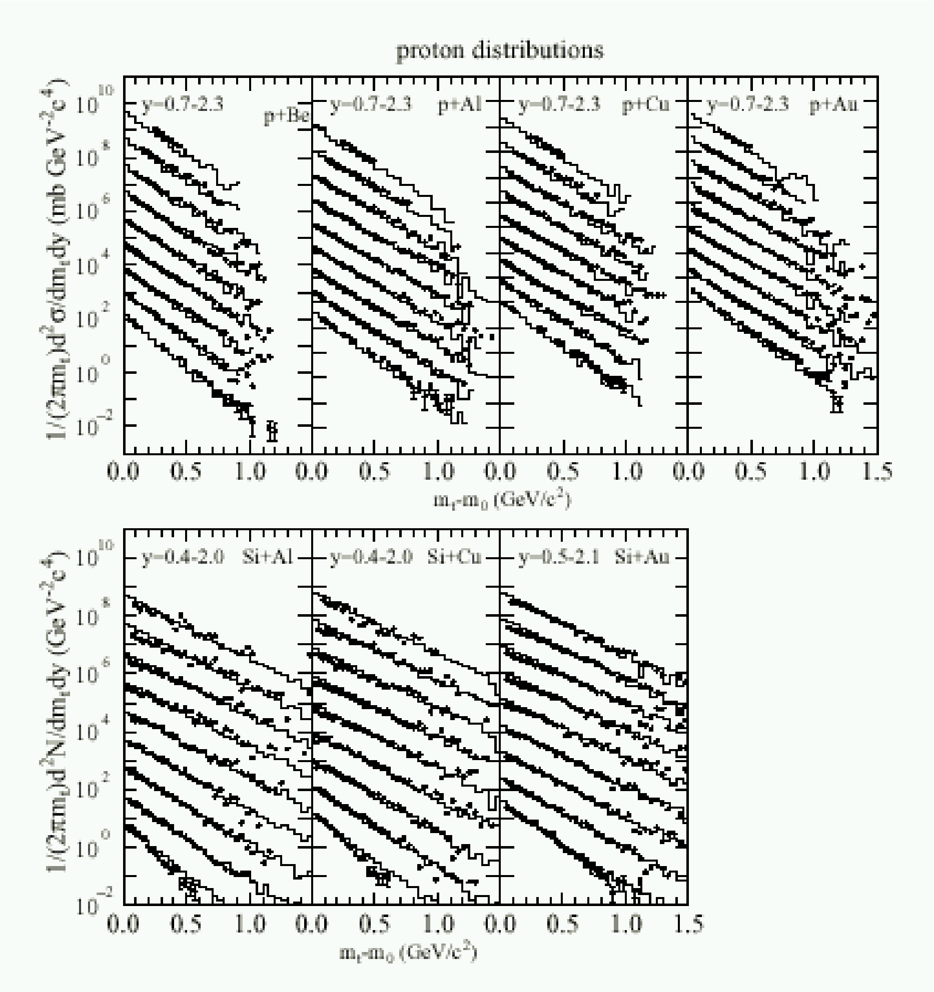
Nara, Otuka, AO, Niita, Chiba (JAM), PRC 61 (2000), 024901.

- **Ground State Hadrons, Resonances, and Strings**

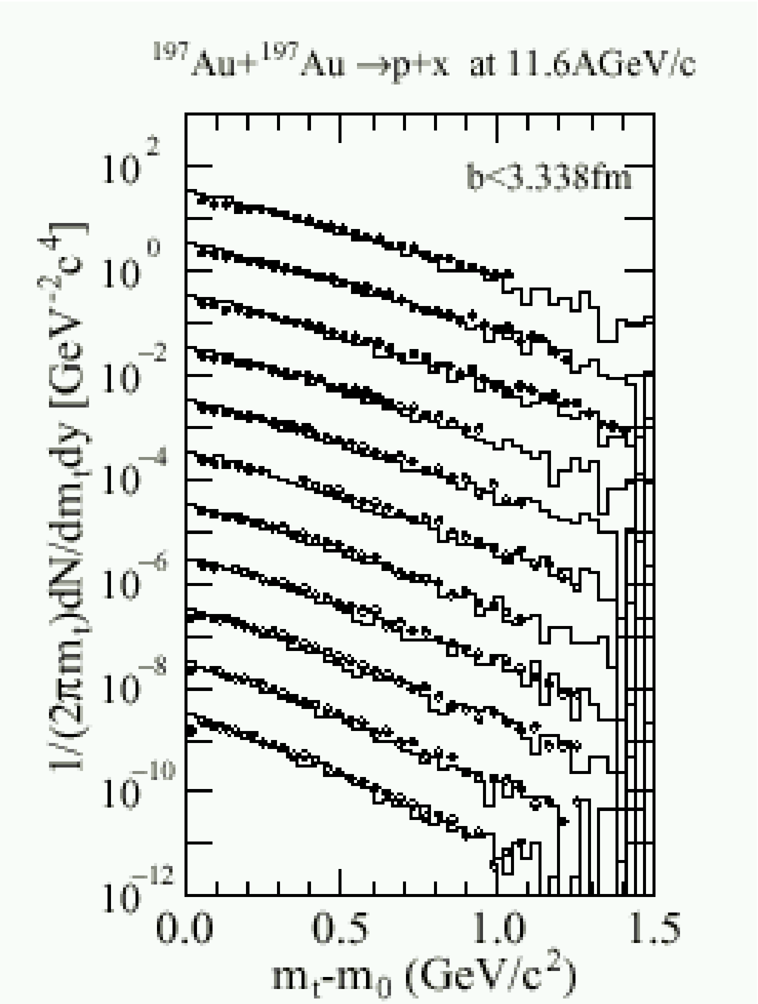


JAM Results @ AGS Energy

- **p-A collisions**



- **Au+Au Collision**



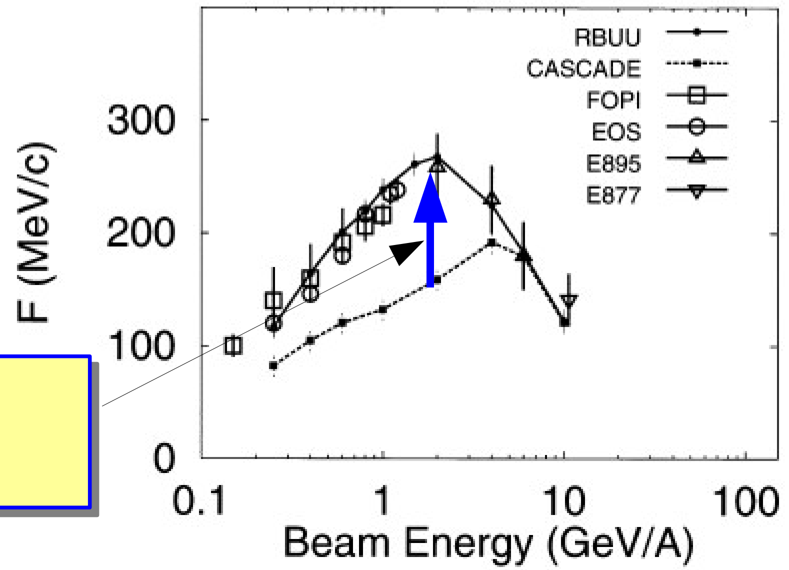
JAM explains AA collisions as well as pA collisions:
→ Good Elementary Cross Sections for MM, MN and NN

Mean Field and Particle DOF Effects @ AGS

- **Mean Field Effects at AGS**
  → Visible but small for p_T spectrum
  Essential for Flow
- **Particle DOF Effects**
  → Seen at high p_T

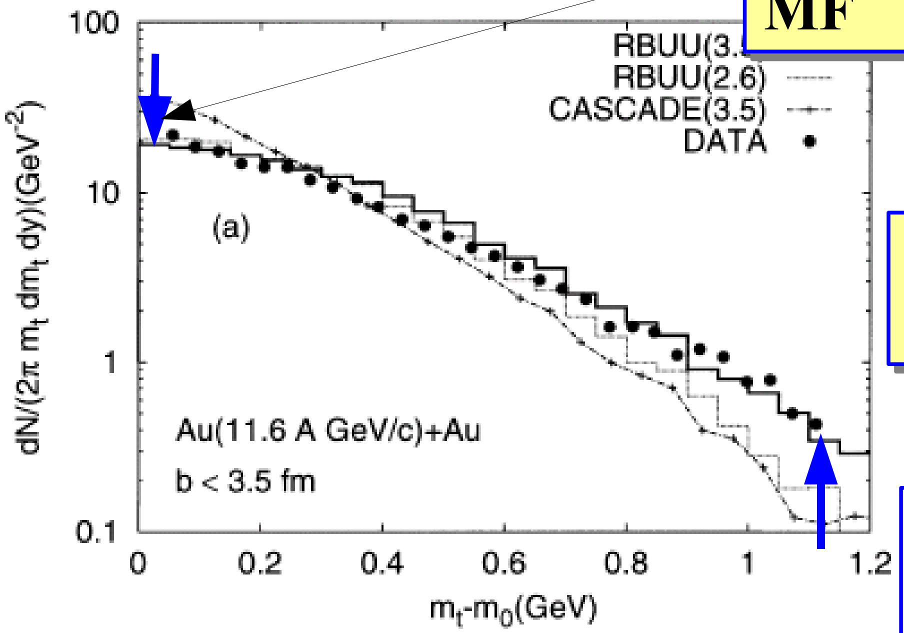
Sahu, Cassing, Mosel, Ohnishi, 2000

P.K. Sahu et al. / Nuclear Physics A 672 (2000) 376–386



Repulsive MF

P.K. Sahu et al. / Nuclear Physics A 672 (2000) 376–386



Switching $\sqrt{s}$ = 3.5 GeV (JAM fit)

Switching $\sqrt{s}$ = 2.6 GeV (HSD default)

Relativistic Quantum Molecular Dynamics (RQMD)
-- Tool to attack collective flows at high E. --

Relativistic QMD/Simplified (RQMD/S)

- **RQMD = Constraint Hamiltonian Dynamics**

  (Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.)

- **Constraints: φ ≈ 0 (Satisfied on the realized trajectory, by Dirac)**
  - **Variables in Covariant Dynamics = 8N phase space:** q_μ , p_μ
  - **Variables in EOM = 6N phase space**
    → We need 2N constraints to get EOM

- **On Mass-Shell Constraints**

$$H_i \equiv p_i^2 - m_i^2 - 2m_i V_i \approx 0$$

- **Time-Fixation in RQMD/S**

$$\chi_i \equiv \hat{a} \cdot (q_i - q_N) \approx 0 \, (i = 1, \sim N-1) \quad , \quad \chi_N \equiv \hat{a} \cdot q_N - \tau \approx 0$$

$$\hat{a} = \mathit{Time{-}like\ unit\ vector\ in\ the\ Calculation\ Frame}$$

(Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.)

RQMD/S (cont.)

- **Hamiltonian is made of constraints**

$$H = \sum_i u_i \phi_i \quad (\phi_i = H_i (i=1 \sim N), \chi_{i-N} (i=N+1 \sim 2N))$$

- **Time Development** $\frac{d f}{d \tau} = \frac{\partial f}{\partial \tau} + \{ f, H \}$, $\{ q_\mu, p_\nu \} = g_{\mu\nu}$

- **Lagrange multipliers are determined to keep constraints**
  → ***We can solve obtain the multipliers analytically in RQMD/S***

$$\frac{d \phi_i}{d \tau} \approx 0 \quad \to \quad \delta_{i,2\mathrm{N}} + \sum_j u_j \{ \phi_i, \phi_j \} \approx 0$$

- **Equations of Motion**

$$H = \sum_i (p_i^2 - m_i^2 - 2 m_i V_i) / 2 p_i^0 \quad , \quad p_i^0 = E_i = \sqrt{\vec{p}_i^{\,2} + m_i^2 + 2 m_i V_i}$$

$$\frac{d \vec{r}_i}{d \tau} \approx - \frac{\partial H}{\partial \vec{p}_i} = \frac{\vec{p}}{p_i^0} + \sum_j \frac{m_j}{p_j^0} \frac{\partial V_j}{\partial \vec{p}_i} \quad , \quad \frac{d \vec{p}_i}{d \tau} \approx \frac{\partial H}{\partial \vec{r}_i} = - \sum_j \frac{m_j}{p_j^0} \frac{\partial V_j}{\partial \vec{r}_i}$$

We can include MF in an almost covariant way in molecular dynamics

Particle “DISTANCE”

$$r_{Tij}{}^{2} \equiv r_{\mu} r^{\mu} - \left(r_{\mu} P_{ij}^{\mu}\right)^{2} / P_{ij}^{2} = \vec{r}^{\,2} \qquad (in\ CM)$$

$$P_{ij} \equiv p_i + p_j \quad , \qquad r \equiv r_i - r_j$$

Particle “Momentum Difference”

$$p_{Tij}{}^{2} \equiv p_{\mu} p^{\mu} - \left(p_{\mu} P_{ij}^{\mu}\right)^{2} / P_{ij}^{2} = \vec{p}^{\,2} \qquad (in\ CM)$$

$$p \equiv p_i - p_j$$

Lorentz Invariant, and Becomes Normal Distance in CM !

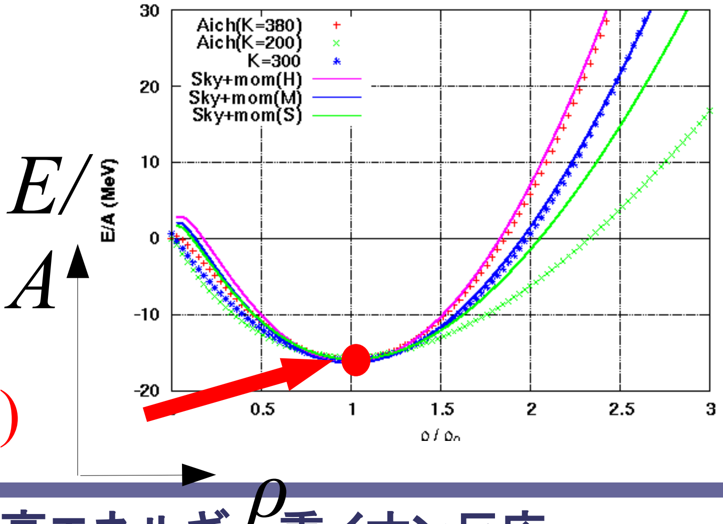
Nuclear Mean Field for HIC
--- Density and Momentum Deps. ---

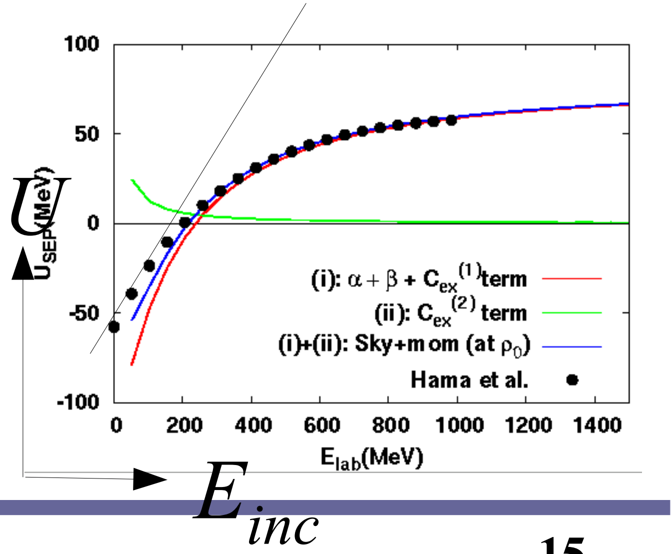
Nuclear Mean Field

- **MF has on both of ρ and p-deps.**
  - **ρ dep.: (ρ_0, *E/A*) = (0.15 fm^{-3}, -16.3 MeV) is known**
    Stiffness is not known well
  - **p dep.: Global potential up to E=1 GeV is known from pA scattering**
    $U(\rho_0, E) = U(\rho_0, E{=}0) + 0.3\,E$
- **Ab initio Approach; LQCD, GFMC, DBHF, G-matrix, ...**
  → Not easy to handle, Not satisfactory for phen. purposes
- **Effective Interactions (or Energy Functionals):**
  Skyrme HF, RMF, ...

$U(E)=U(0)+0.3E$

$(\rho_0\,, E/A)$
$=(0.15\ \mathrm{fm}^{-3}\,, -16.3\ \mathrm{MeV})$





Skyrme Hartree-Fock

See Ring-Schuck for details

- **Zero-Range Two- and Three-Body Interaction**

$$v_{ij}=t_0\delta(r_i-r_j)+\frac{1}{2}\left[\delta(r_i-r_j)k^2+k^2\delta(r_i-r_j)\right]$$

$$+t_2 k\,\delta(r_i-r_j)k+iW_0\left[\sigma_i+\sigma_j\right]\times\delta(r_i-r_j)k$$

$$k=\frac{1}{2\mathrm{i}}\left(\nabla_i-\nabla_j\right)$$

$$v_{ijk}=t_3\delta(r_i-r_j)\delta(r_j-r_k)$$

- **Energy Density (Even-Even, N=Z)**

$$H(r)=\frac{\hbar^2}{2\mathrm{m}^*(\rho)}\tau+\frac{3}{8}t_0\rho^2+\frac{1}{16}t_3\rho^3+\mathit{Deriv.\ terms}\rightarrow\rho\left[\frac{3}{5}\ \frac{\hbar^2k_F^2}{2m^*(\rho)}+\frac{3}{8}t_0\rho+\frac{1}{16}t_3\rho^2\right]$$

$$\tau=\sum_i|\nabla\phi_i|^2\ ,\quad \frac{\hbar^2}{2\mathrm{m}^*(\rho)}=\frac{\hbar^2}{2\mathrm{m}}+\frac{1}{16}(3t_1+5t_2)\rho$$

Problems in Skyrme HF (in Dense Nuclear Matter/High Energy)
Repulsive Zero-Range 3-body Int.: → Ferromagnetism
Energy Dep. = Linear (m term) → Too Repulsive at High E*

Relativistic Mean Field (I)

Serot-Walecka, Walecka text book.

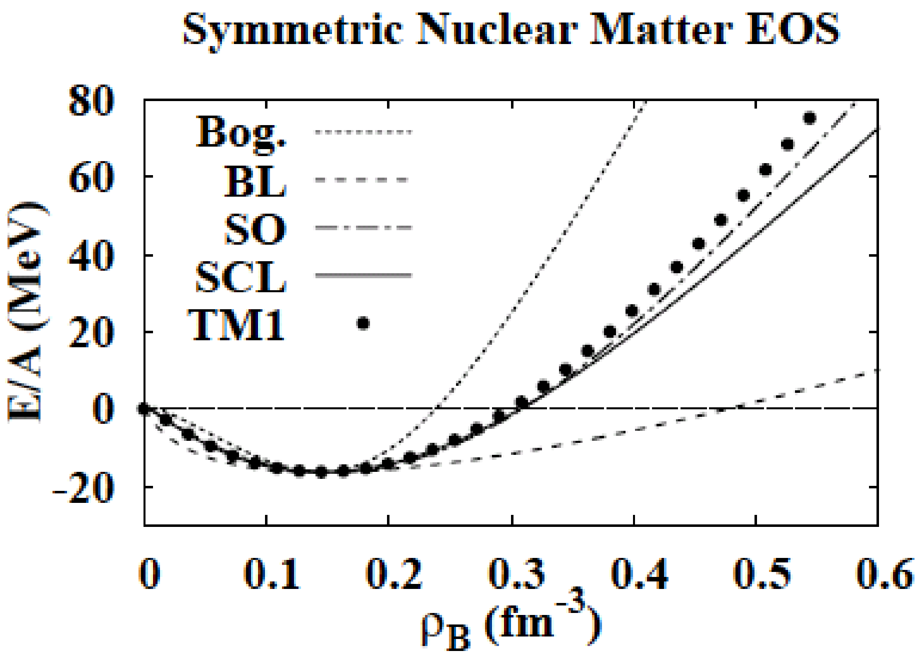
- **Describe nuclear energy functional in meson and baryon fields**
  - **Fit B.E. of Stable as well as Unstable (n-rich) Nuclei**
  - **Has been successfully applied to Supernova Explosion**
  - **Three Mesons (σ,ω,ρ) are included**
  - **Meson Self-Energy Term (σ,ω)**

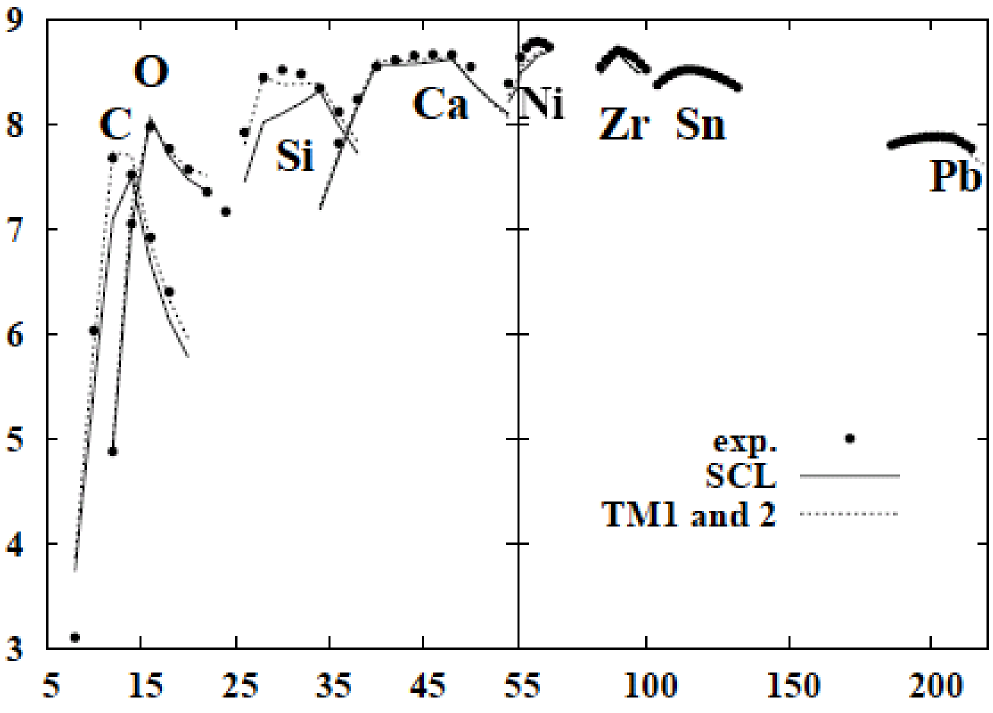
$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}_N \left(i\not{\partial} - M - g_\sigma \sigma - g_\omega \not{\omega} - g_\rho \tau^a \not{\rho}^a \right) \psi_N \\
&+ \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 \\
&- \frac{1}{4} W^{\mu\nu} W_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} R^{a\mu\nu} R^a_{\mu\nu} + \frac{1}{2} m_\rho^2 \rho^{a\mu} \rho^a_\mu + \frac{1}{4} c_3 \left(\omega_\mu \omega^\mu \right)^2 \\
&+ \bar{\psi}_e \left(i\not{\partial} - m_e \right) \psi_e + \bar{\psi}_\nu i\not{\partial} \psi_\nu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \ , \\
W_{\mu\nu} =& \partial_\mu \omega_\nu - \partial_\nu \omega_\mu \ , \\
R^a_{\mu\nu} =& \partial_\mu \rho^a_\nu - \partial_\nu \rho^a_\mu + g_\rho \epsilon^{abc} \rho^{b\mu} \rho^{c\nu} \ , \\
F_{\mu\nu} =& \partial_\mu A_\nu - \partial_\nu A_\mu \ . \qquad (2)
\end{aligned}
$$

Nuclear Matter EOS and Nuclear Binding E in TM

Sugahara-Toki, NPA579 (1994), 557.

- **Example: TM1 parameter set**
  - **Nuclear Matter: σ4 and ω4 terms soften EOS (K ~ 280 MeV)**
  - **Finite nuclei: Explains B.E. from C to Pb isotopes**





c.f. SCL=Chiral RMF with log σ term.

(K. Tsubakihara and AO, 2007)

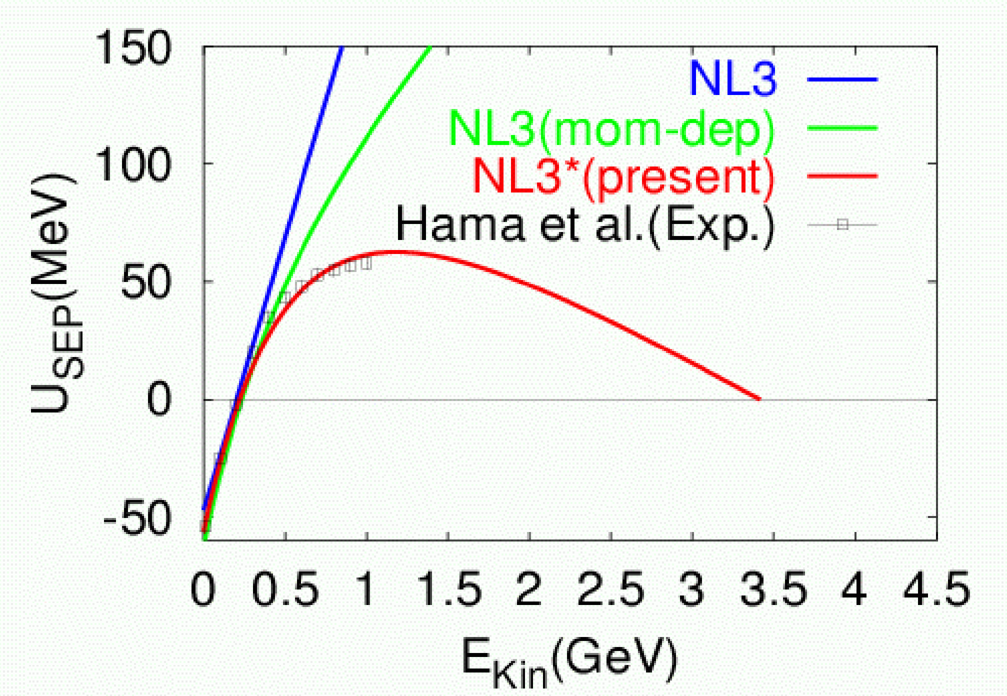
Relativistic Mean Field (II)

- **Dirac Equation** $\left(i\gamma\partial-\gamma^0 U_v-M-U_s\right)\psi=0\ ,\quad U_v=g_\omega\omega\ ,\quad U_s=-g_\sigma\sigma$
- **Schroedinger Equivalent Potential**

$$\begin{pmatrix} E-U_v-M-U_s & -i\sigma\cdot\nabla \\ i\sigma\cdot\nabla & -E+U_v-M-U_s \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix}=0$$

$$U_{sep}\sim U_S+\frac{E}{m}U_V=-g_\sigma\sigma+\frac{E}{m}g_\omega\omega$$

$$=-\frac{g_\sigma^2}{m_\sigma^2}\rho_s+\frac{E}{m}\frac{g_\omega^2}{m_\omega^2}\rho_B$$



Saturation: -Scalar+Baryon Density
Linear Energy Dependence: Good at Low Energies,
Bad at High Energies (We need cut off !)

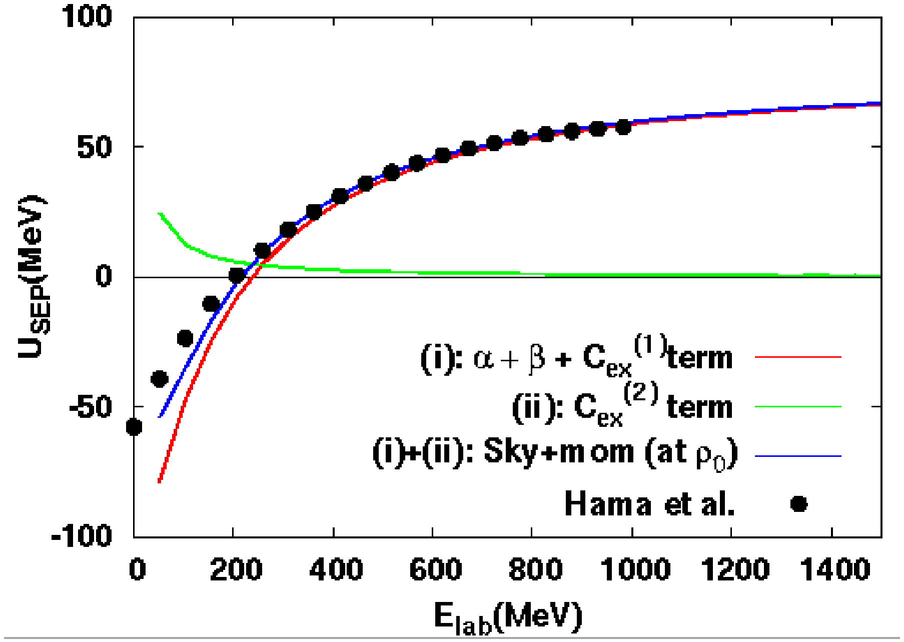
(Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)

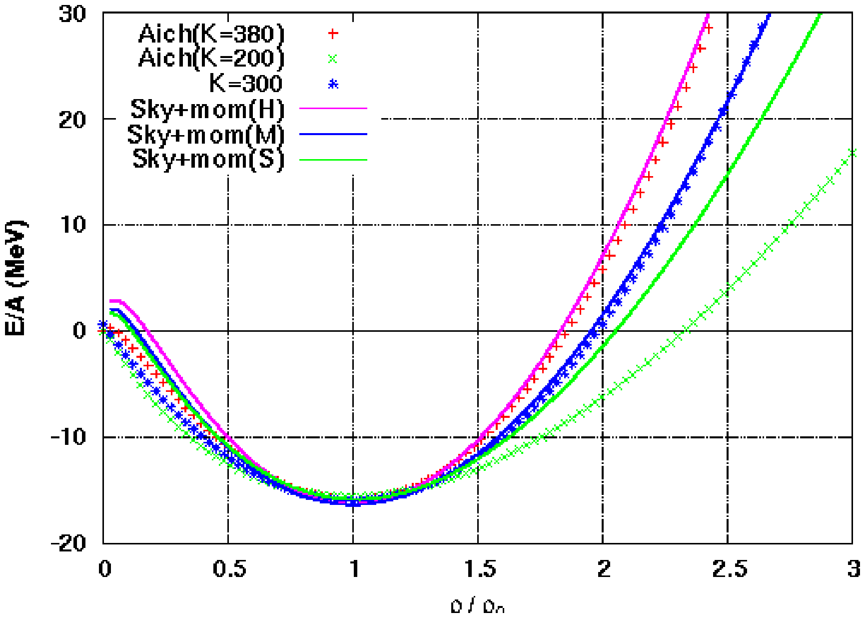
Phenomenological Mean Field

- **Skyrme type ρ-Dep. + Lorentzian p-Dep. Potential**

$$V=\sum_i V_i=\int d^3r\left[\frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{\beta}{\gamma+1}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}\right]$$

$$+\sum_k\int d^3r\,d^3p\,d^3p'\,\frac{C_{ex}^{(k)}}{2\rho_0}\,\frac{f(r,p)\,f(r,p')}{1+(p-p')^2/\mu_k^2}$$





Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908

Exercise (4)

- **Prove that the single particle potential with Skyrme interaction has a linear dependence on energy. From NA elastic scattering, the energy dependence is found to be**

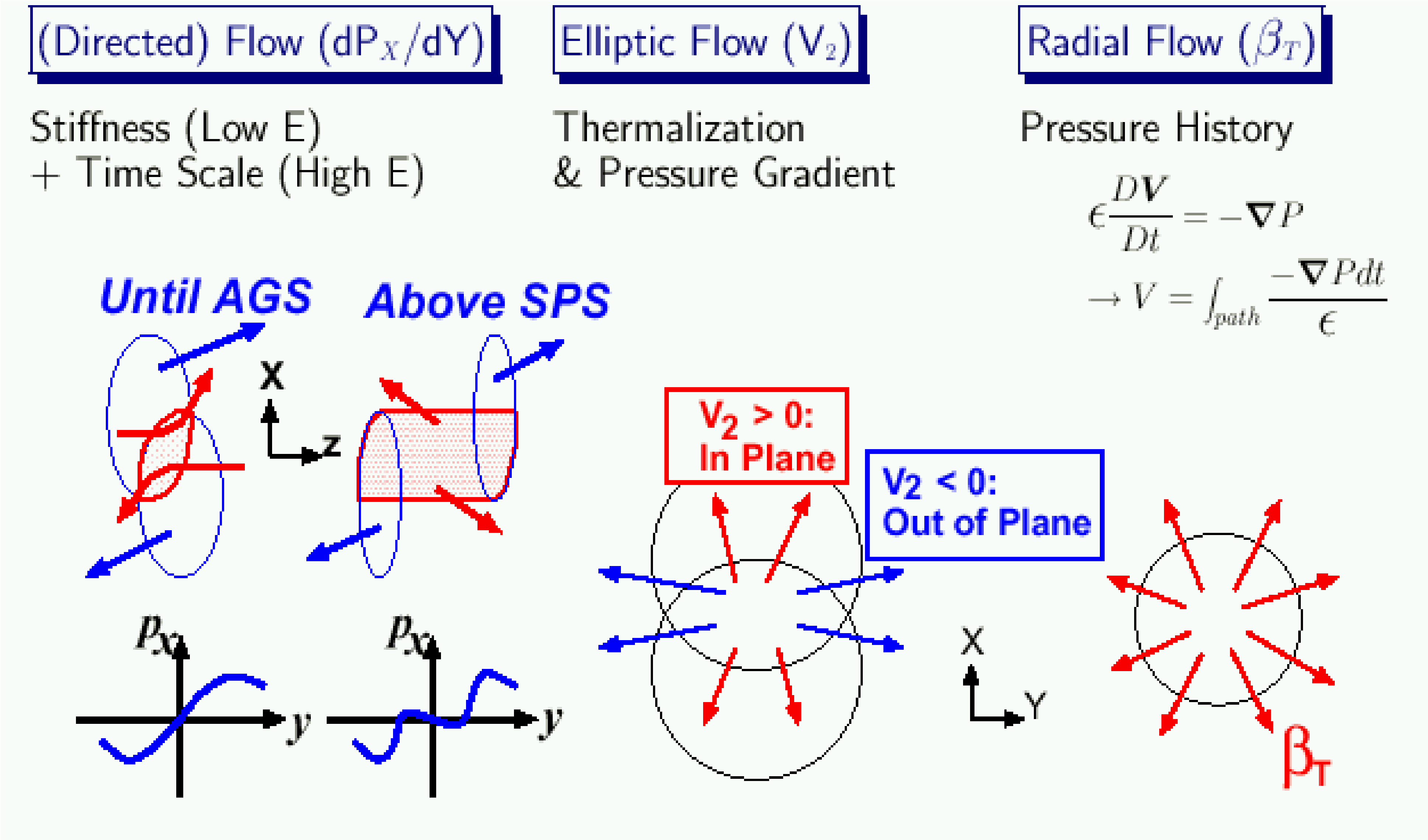
  $$U(\rho_0, E) \sim U(\rho_0, E=0) + 0.3\,E$$

  at low energies. Obtain the value of m*/m which explains the above energy dependence.

- **Obtain the form of the Schrodinger equivalent potential in RMF. You will find that the spin-orbit potential appears as a sum of scalar and vector potential.**

Collective Flows at AGS and SPS Energies

What is Collective Flow ?



(Directed) Flow (dP_X/dY)

Stiffness (Low E)
+ Time Scale (High E)

Elliptic Flow (V_2)

Thermalization
& Pressure Gradient

Radial Flow (β_T)

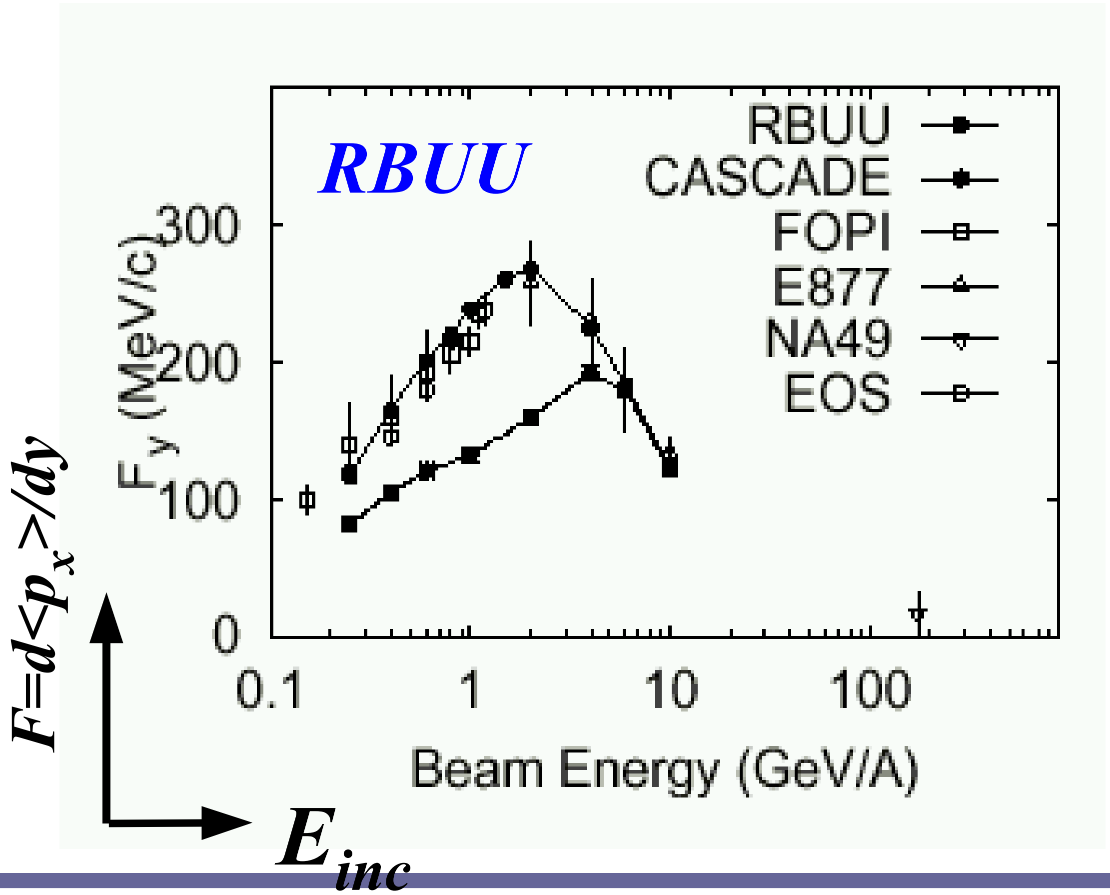
Pressure History

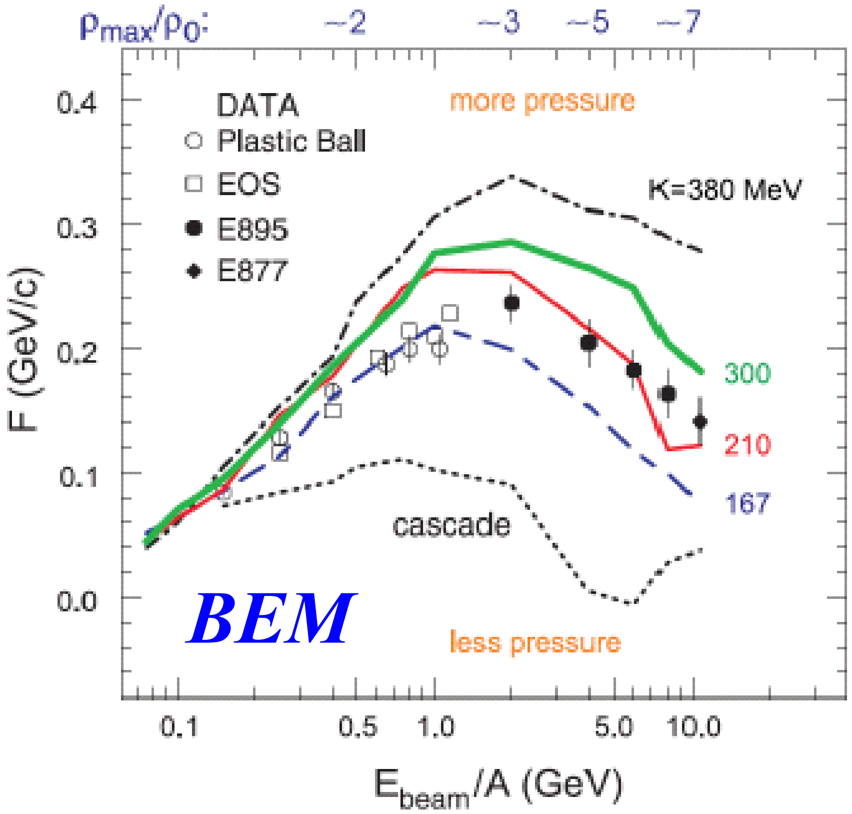
$$\epsilon \frac{D\mathbf{V}}{Dt} = -\nabla P$$

$$\to V = \int_{path} \frac{-\nabla P dt}{\epsilon}$$

Side Flow at AGS Energies

- **Relativistic BUU (RBUU) model: *K ~ 300 MeV***
  (Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)
- **Boltzmann Equation Model (BEM): *K=167~210 MeV***
  (P. Danielewicz, R. Lacey, W.G. Lynch, Science 298(2002), 1592.)

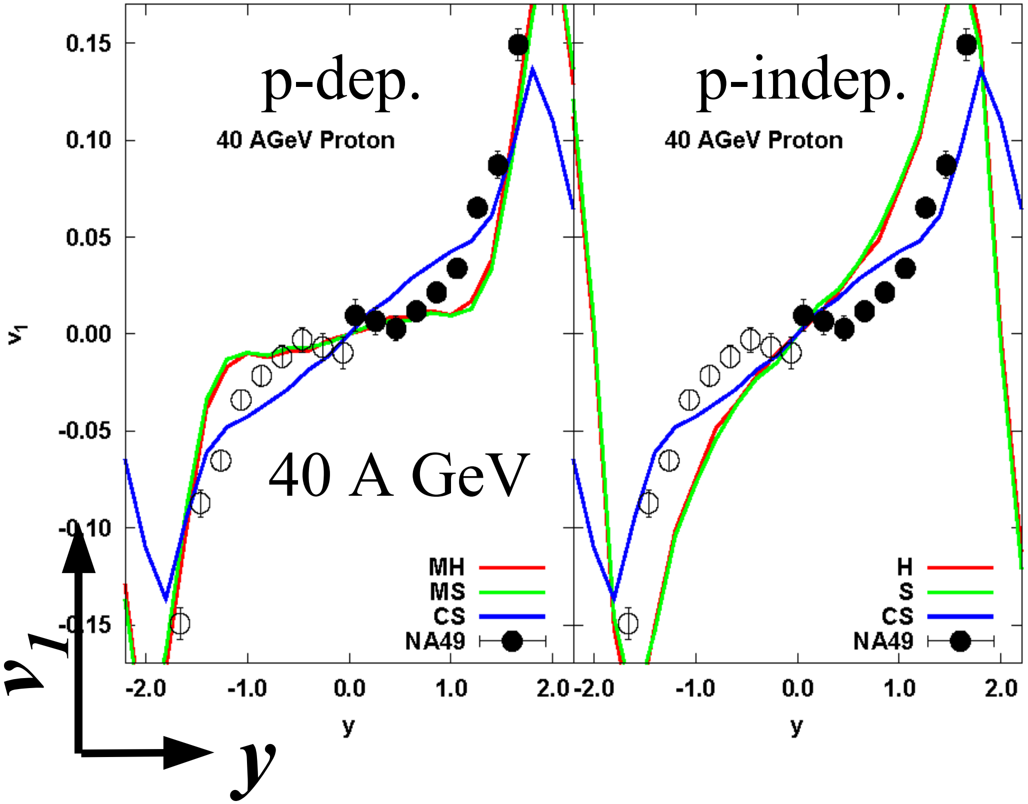


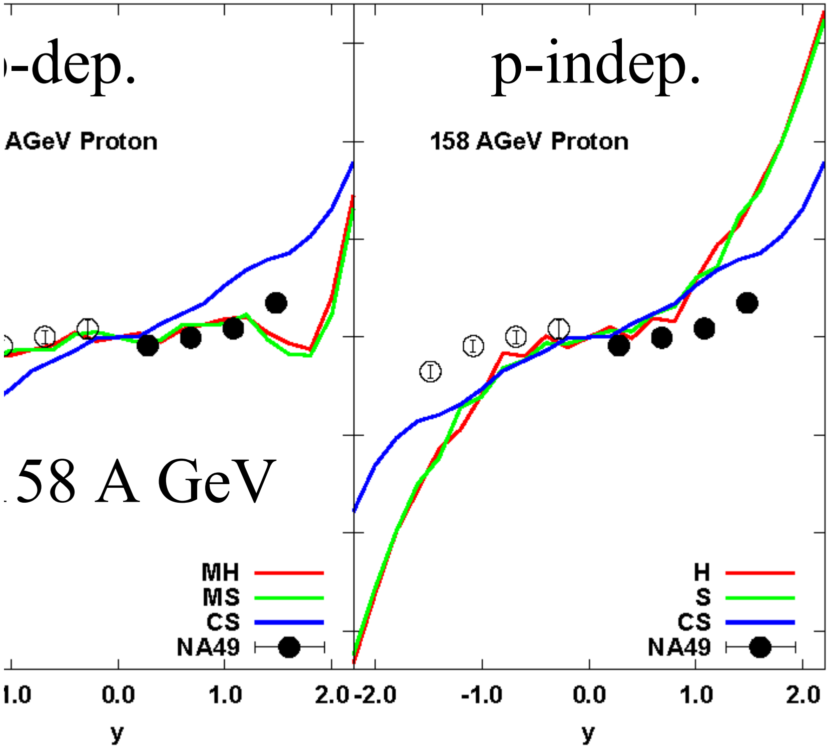


Directed flow v_1 at SPS

Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908

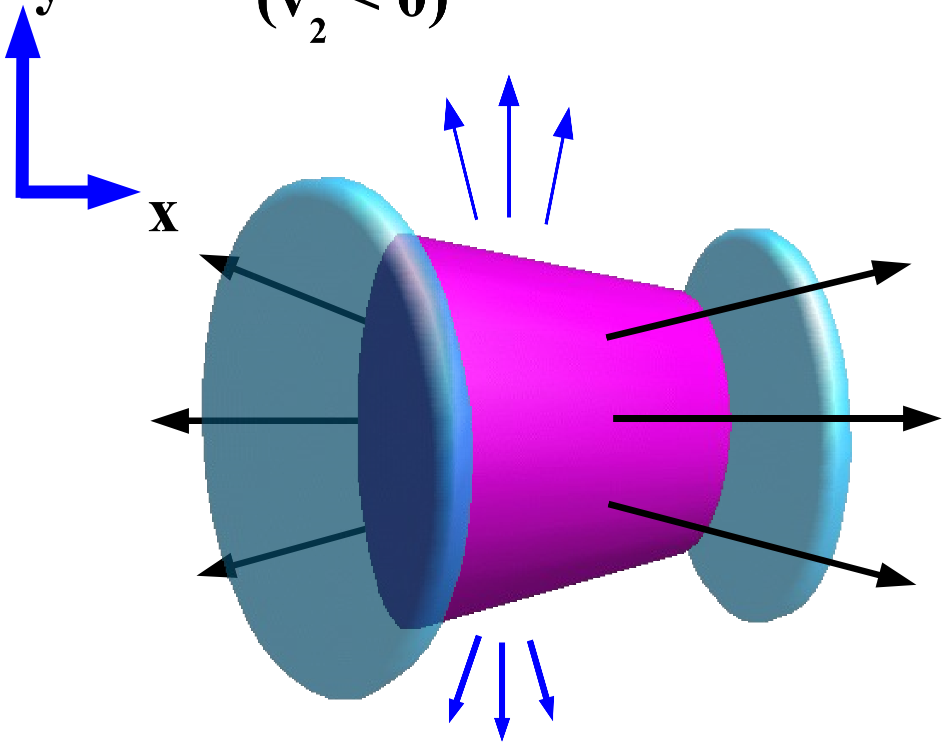
- **JAM-RQMD/S**
  - **p-dep. (indep.) MF suppresses (enhances) v_1.** $v_1 = \langle \cos\phi \rangle = \langle p_x / p_T \rangle$
  - **“Wiggle” behavior appears with p-dep. MF at 158 A GeV.**





Elliptic Flow

- **What is Elliptic Flow ? → Anisotropy in P space**
- **Hydrodynamical Picture**
  - **Sensitive to the Pressure Anisotropy in the Early Stage**
  - **Early Thermalization is Required for Large V2**



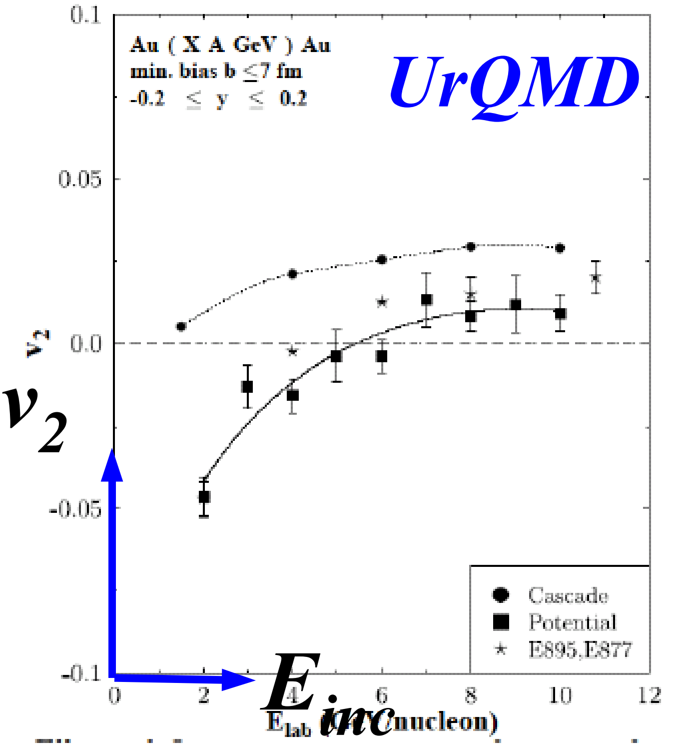
Out-of-Plane Flow
($v_2 < 0$)

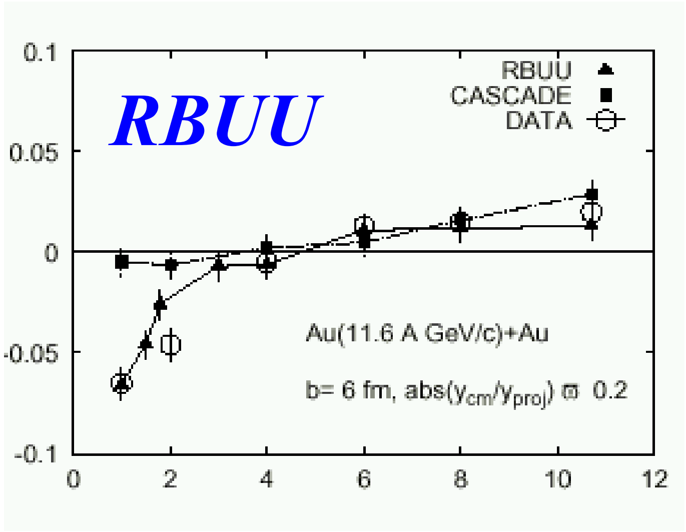
In-Plane Flow
($v_2 > 0$)

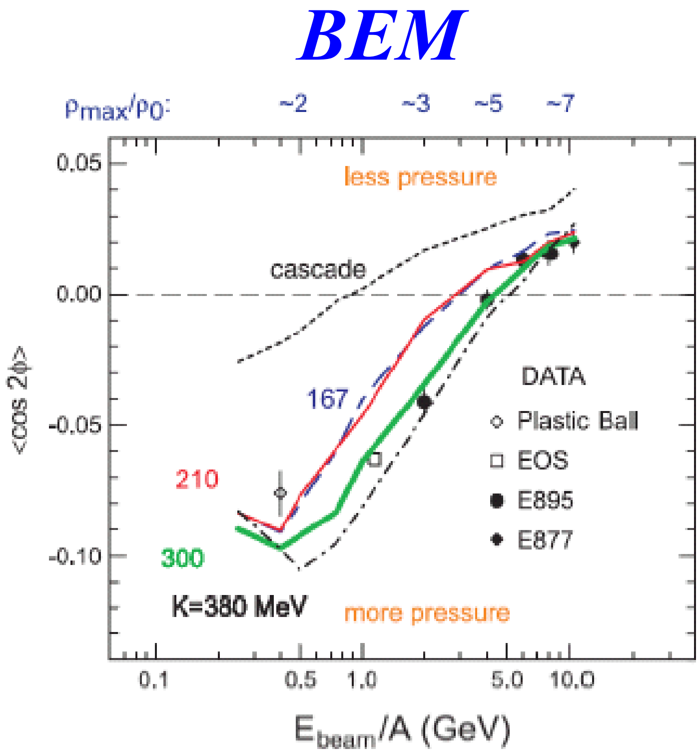
$$v_2 \equiv \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\phi \rangle$$

Elliptic Flow at AGS

- **Strong Squeezing Effects at low E (2-4 A GeV)**
  - **UrQMD: Hard EOS (S.Soff et al., nucl-th/9903061)**
  - **RBUU (Sahu-Cassing-Mosel-AO, 2000): K ~ 300 MeV**
  - **BEM(Danielewicz2002):   K = 167 → 300 MeV**

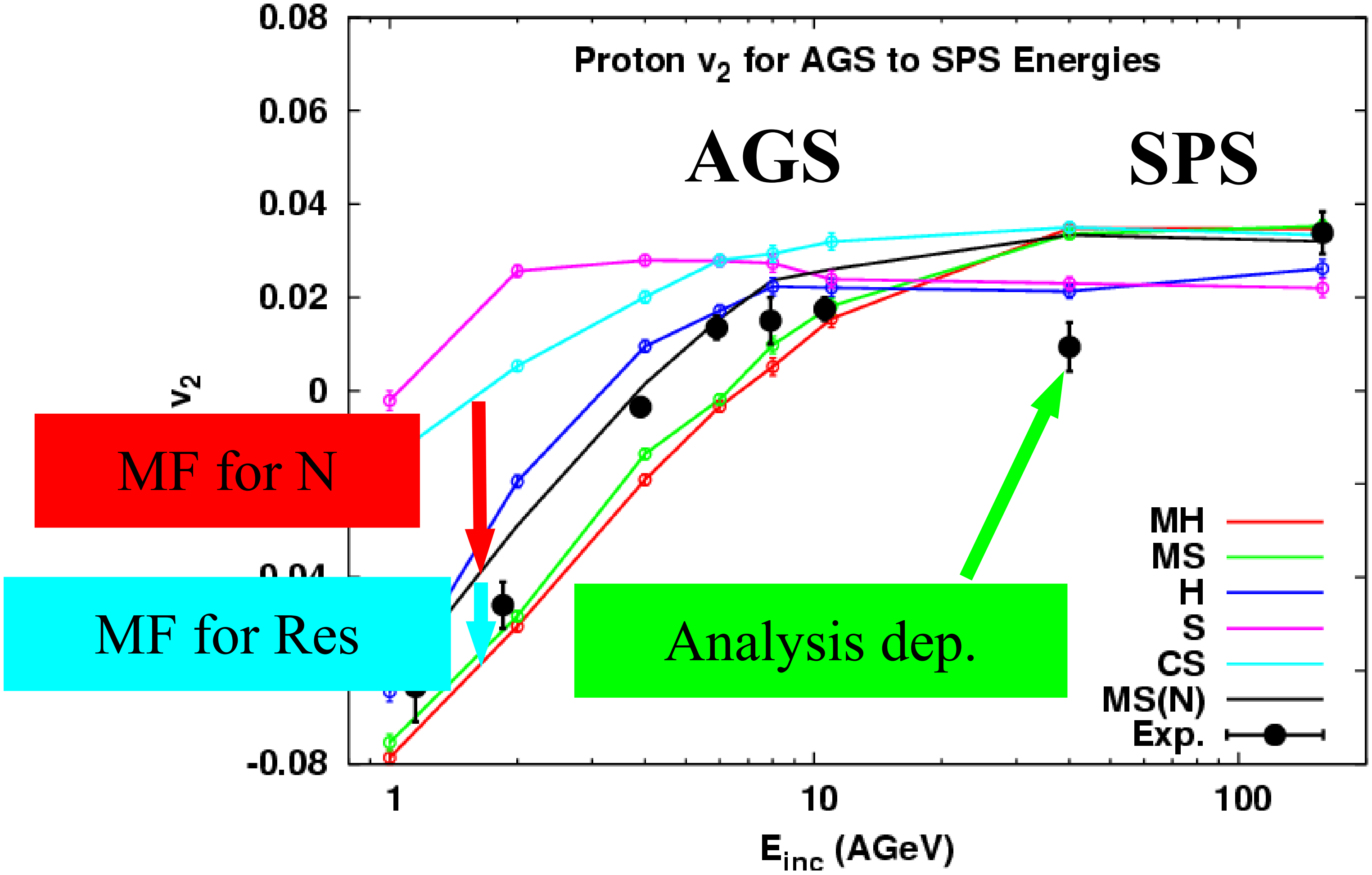






Elliptic Flow from AGS to SPS

- **JAM-MF with p dep. MF explains proton v2 at 1-158 A GeV**
  - **v2 is not very sensitive to K (incompressibility)**
  - **Data lies between MS(B) and MS(N)**



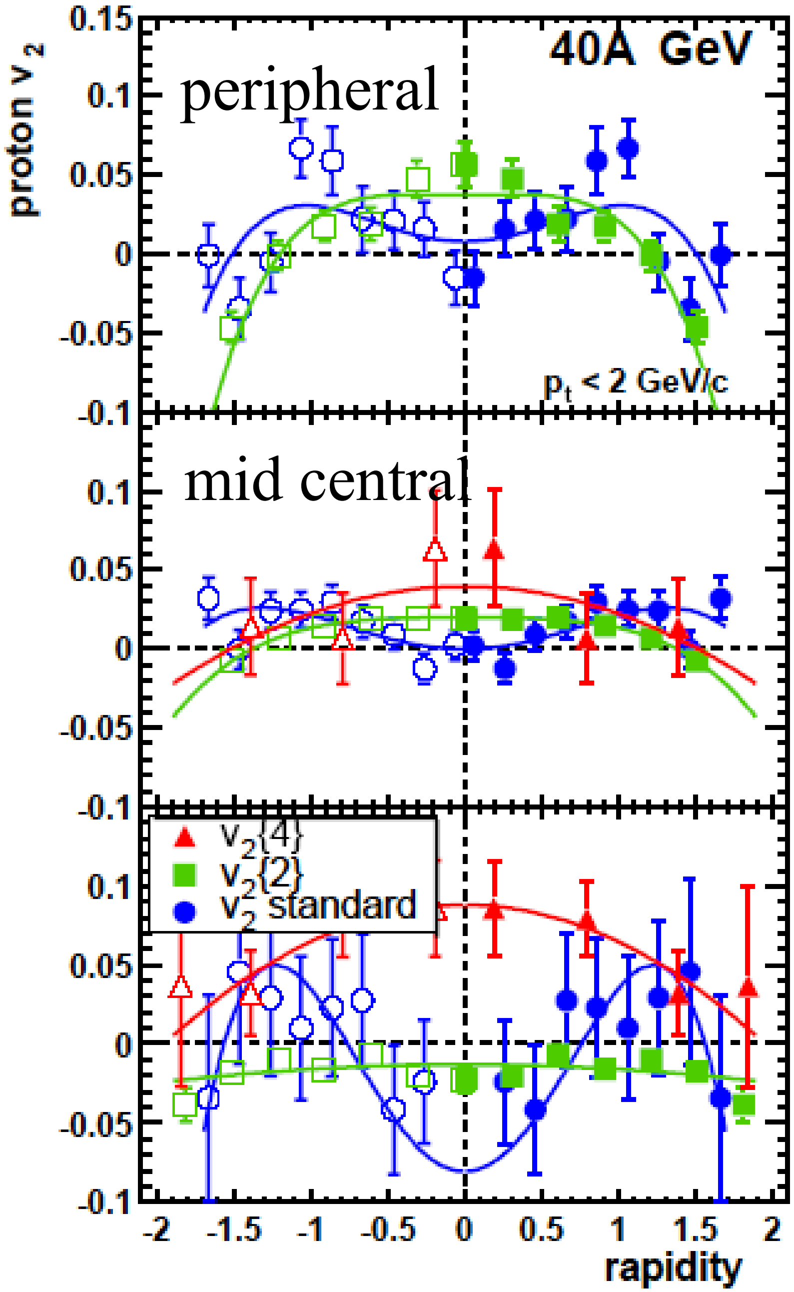
MF for N

MF for Res

Analysis dep.

Dip of V_2 at 40 A GeV: Phase Transition ?

- **Dip of V_2 at 40 A GeV may be a signal of QCD phase transition at high baryon density. (Cassing et al.)**
- **However, the data is too sensitive to the way of the analysis (reaction plane/two particle correlation).**
  - **We have to wait for better data.**



Flow and EOS; to be continued

- **In addition to the ambiguities in in-medium cross sections, Res.-Res. cross sections, we have model dependence.**
  - **RBUU** *(e.g. Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)*
    - **In RMF, Strong cut-off for meson-N coupling in RMF → Smaller EOS dep.**
  - **Scalar potential interpretation in BUU** *Larionov,Cassing,Greiner,Mosel, PRC62,064611('00), Danielewicz, NPA673,375('00)*

$$\varepsilon(\boldsymbol{p},\rho)=\sqrt{[m+U_s(\boldsymbol{p},\rho)]^2+\boldsymbol{p}^2}\quad=\sqrt{m^2+\boldsymbol{p}^2}+U(\boldsymbol{p},\rho)$$

    - **Due to the Scalar potential nature, EOS dependence is smaller.**
  - **Scalar/Vector Combination** *Danielewicz, Lacey, Lynch, Science 298('02), 1592*

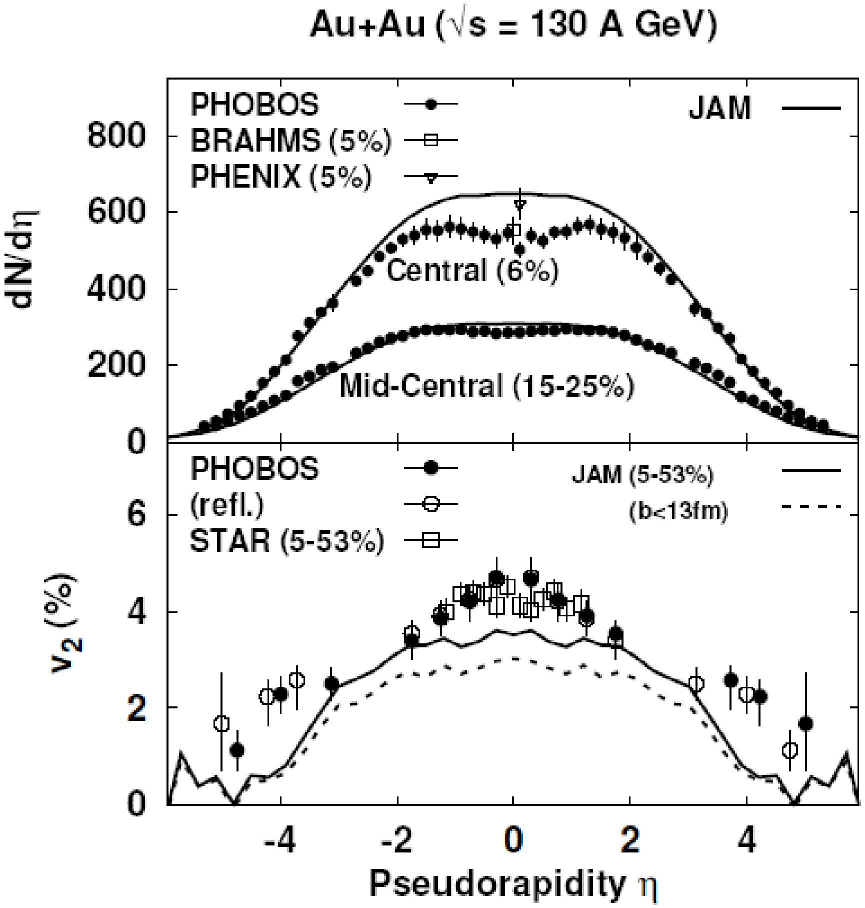
$$\varepsilon(p,\rho)=m+\int_0^p dp'v^*(p',\rho)+\tilde{U}(\rho),\quad v^*(p,\rho)=\frac{p}{\sqrt{p^2+[m^*(p,\rho)]^2}}.$$

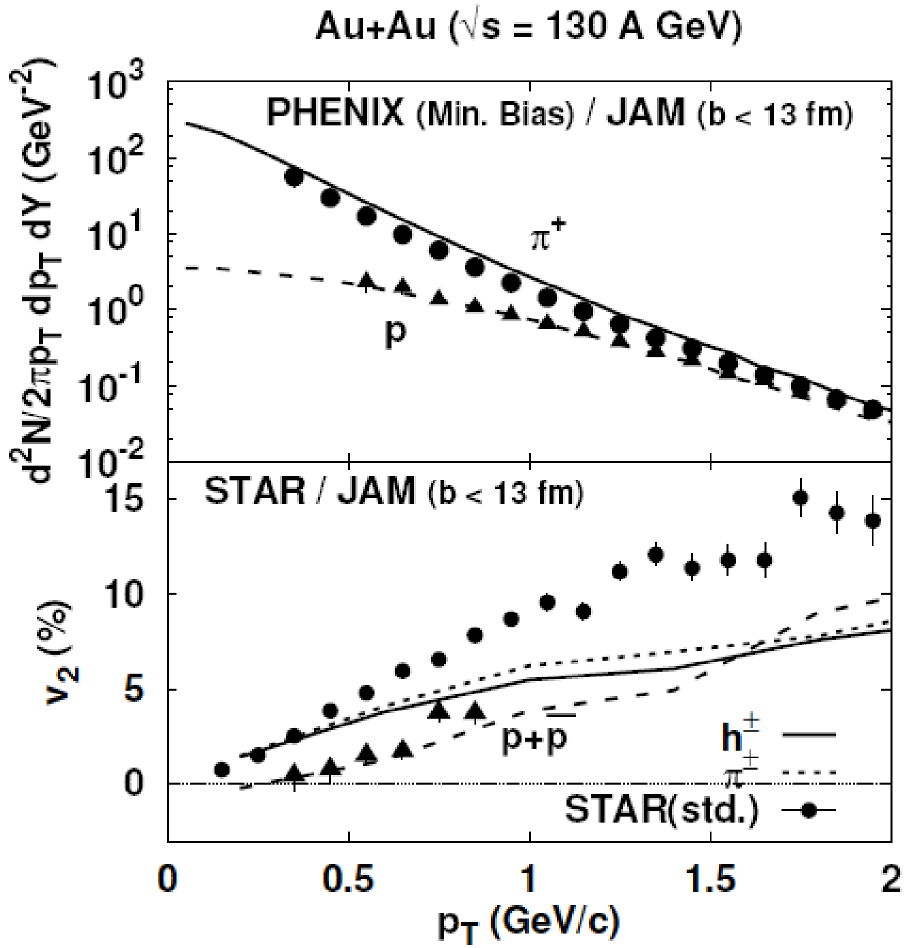
    - **Relatively Strong EOS dependence even at high energy**
  - **JAM-RQMD/S** *Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908*
    - **Similar to the Scalar model BUU**

Elliptic Flow @ RHIC

Elliptic Flow in Hadron-String Cascade (I)

- **Hadron-String Cascade (JAM) @ RHIC**
  - **Hadron Yield is reasonably explained up to 2 GeV/c (10-20 % error)**
  - **v2 is underestimated (20-30 % (integrated), 50 % (p_T > 1 GeV)**

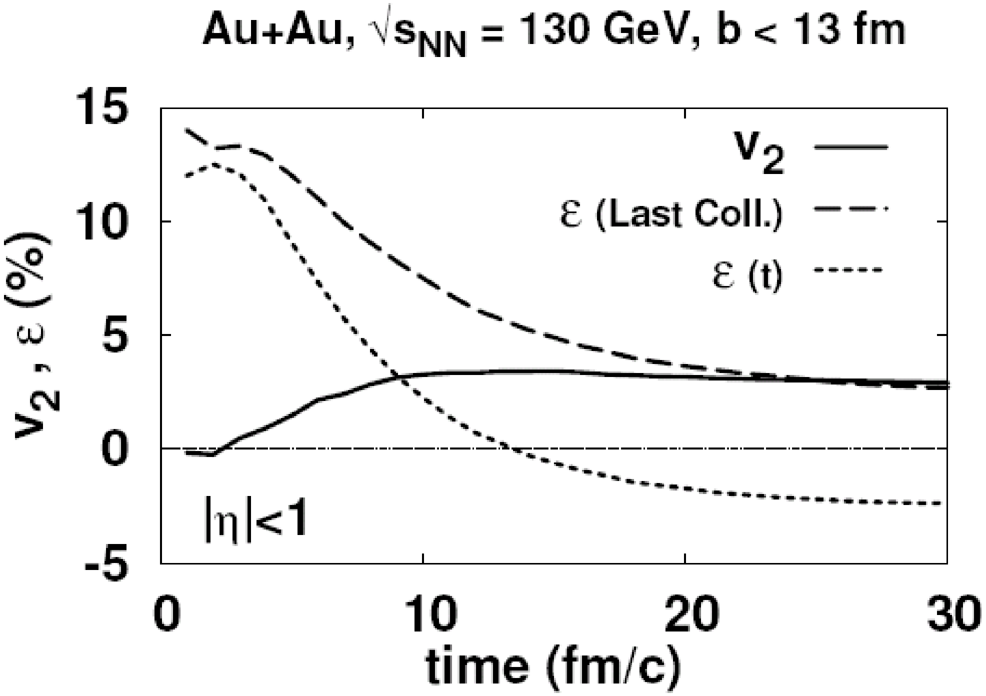


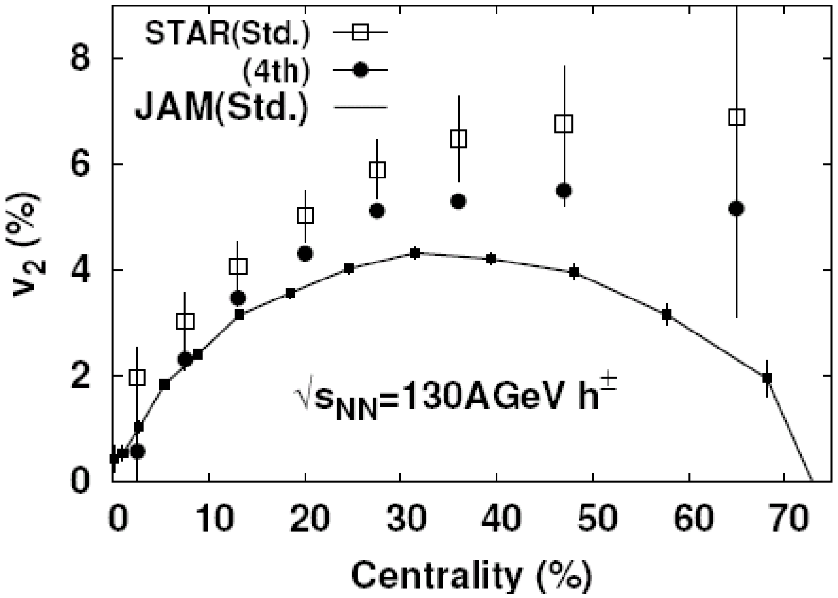


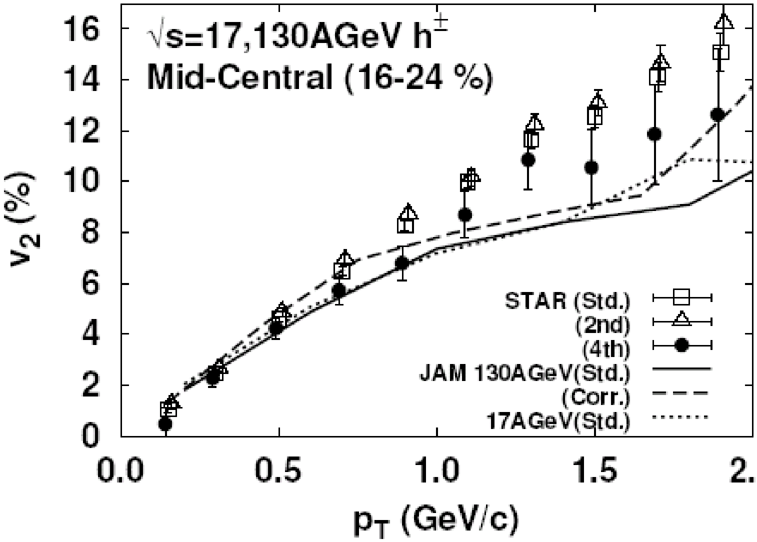
Elliptic Flow in Hadron-String Cascade (II)

- **Why do we underestimate v2 in Hadron-String Cascade ?**
  - **v2 growth time is long (~ 10 fm/c), due to hadron formation time (τ~ 1 fm/c).**
    → much longer than hydro

Sahu-Isse-AO-Otuka-Phatak 2006







Results of Parton Cascade

- **Unexpectedly high parton cross sections of σ =5-6 mb have to be assumed in parton cascades in order to reproduce the elliptic flow.**

ZI-WEI LIN AND C. M. KO PHYSICAL REVIEW C **65** 034904

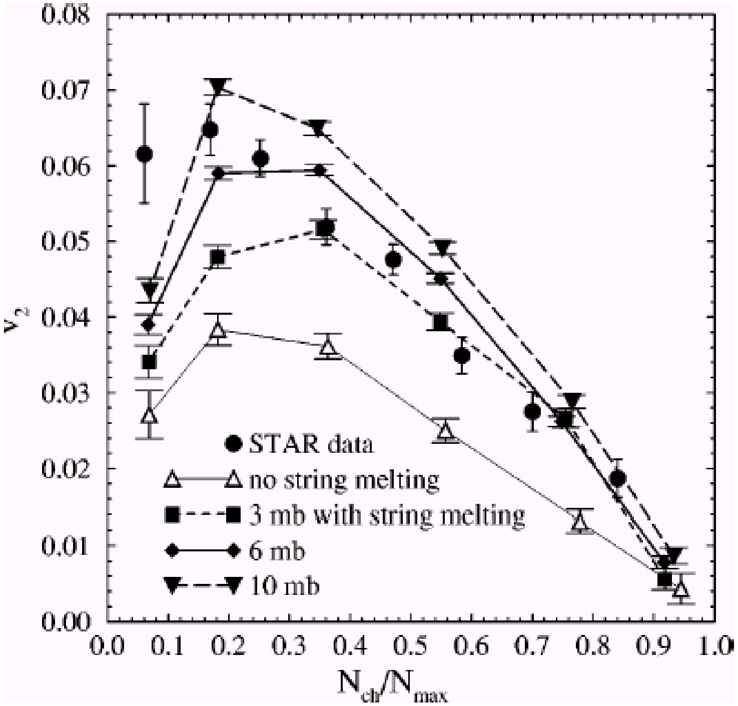


FIG. 3. Impact parameter dependence of elliptic flow at 130 *A* GeV. The data from the STAR collaboration [7] are shown by filled circles, while the theoretical results for different partonic dynamics are given by curves.

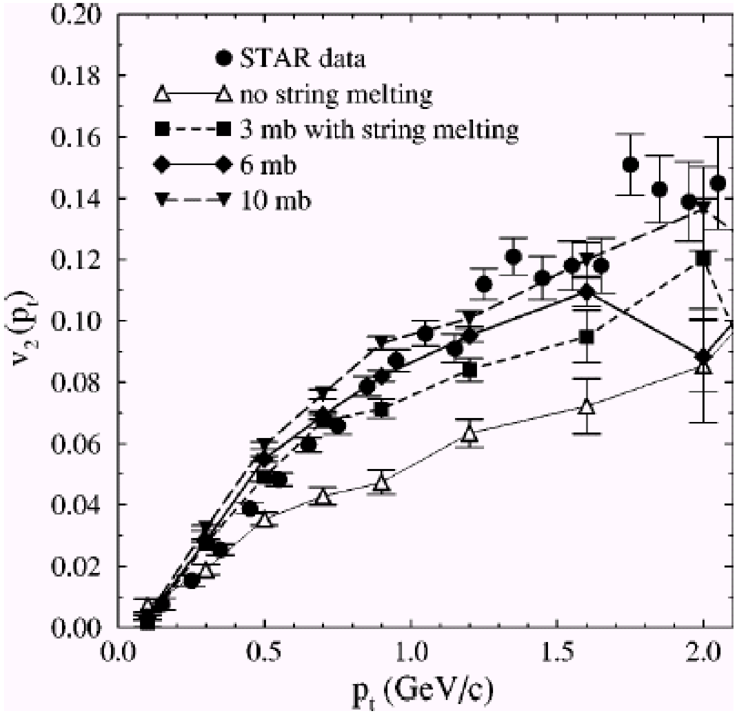


FIG. 4. Transverse momentum dependence of elliptic flow at 130 *A* GeV. Circles are the STAR data for minimum-bias Au+Au collisions [7], and curves represent the minimum-bias results for charged particles within $\eta \in (-1.3,1.3)$ from the AMPT model.

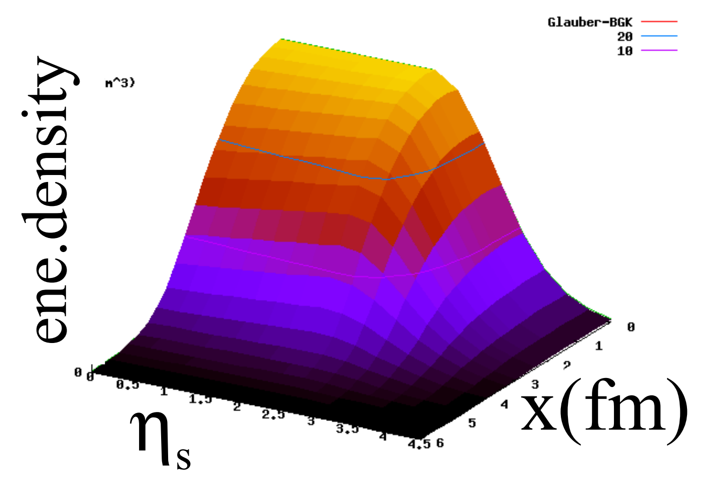
Initial Conditions in Hydro

Glauber-BGK type

[Reference Initial Condition]
<u>Transverse profile</u>:
Entropy density

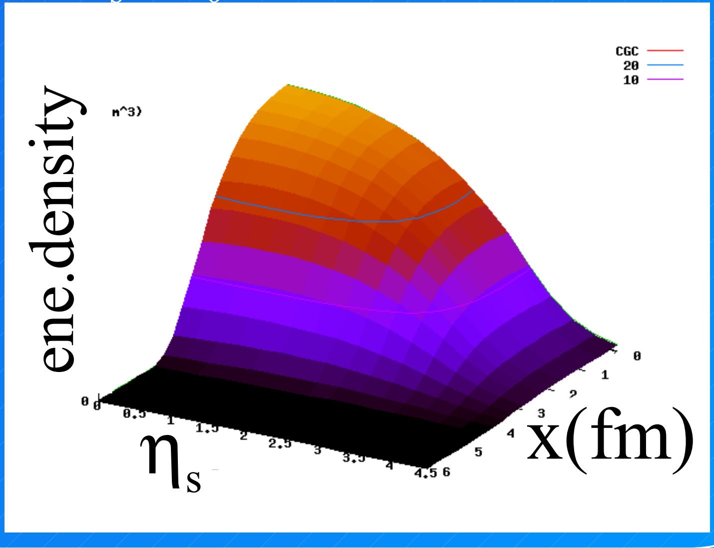
$$\propto a\rho_{\text{part}} + b\rho_{\text{coll}}$$

<u>Longitudinal Profile</u>:
Brodsky-Gunion-Kuhn triangle



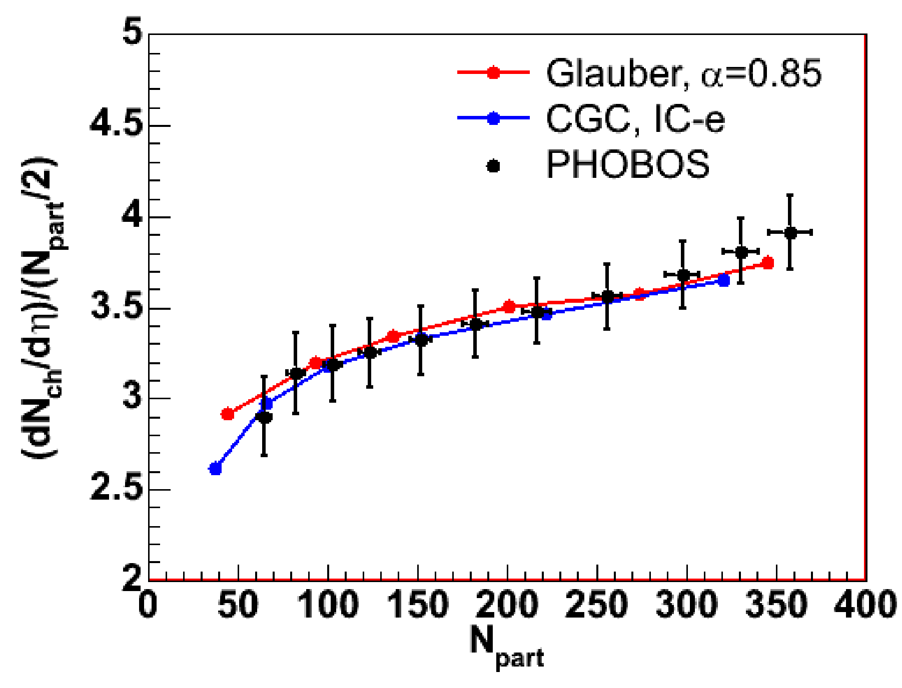
Color Glass Condensate

- Unintegrated gluon distribution a.la. Kharzeev, Levin, and Nardi
- Gluon production via k_T factorization formula
- Count deposited energy in dV at (τ_0, x, y, η_s), $\tau_0 = 0.6$fm/c

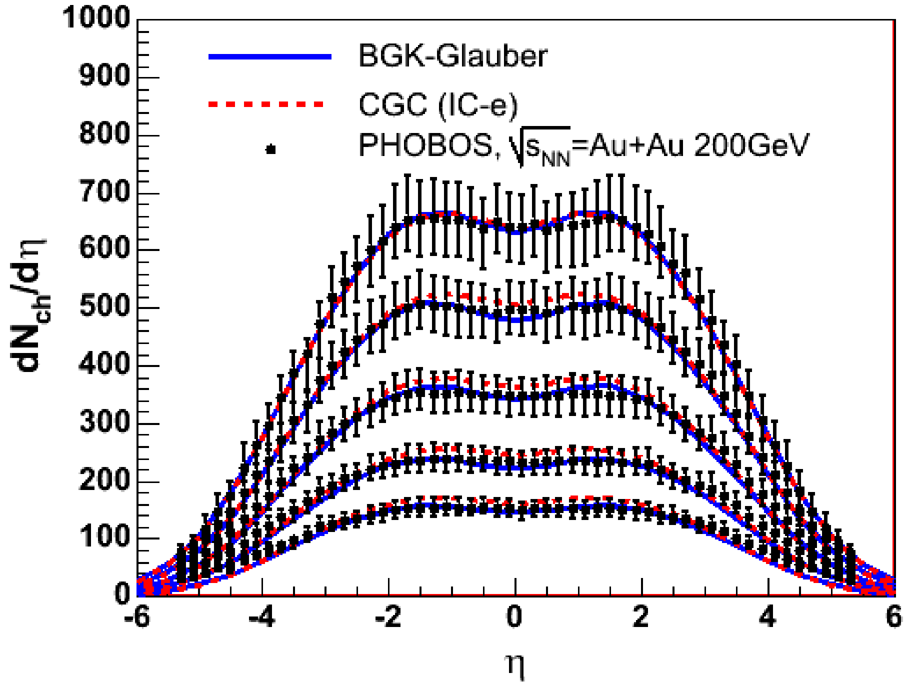


Two Hydro Initial Conditions Which Clear the “First Hurdle”

Centrality dependence



Rapidity dependence

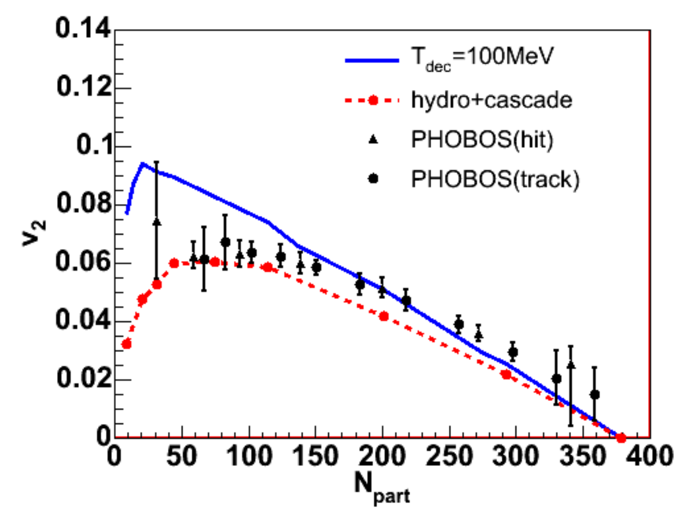


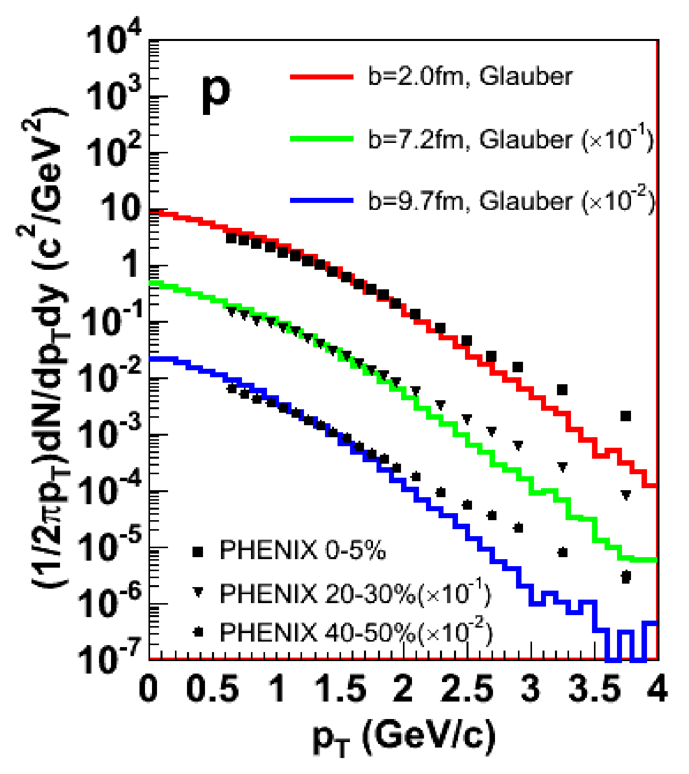
1. CGC model
   Matching I.C. via $e(x,y,\eta)$
2. Glauber model (as a reference)
   $N_{part}:N_{coll} = 85\%:15\%$

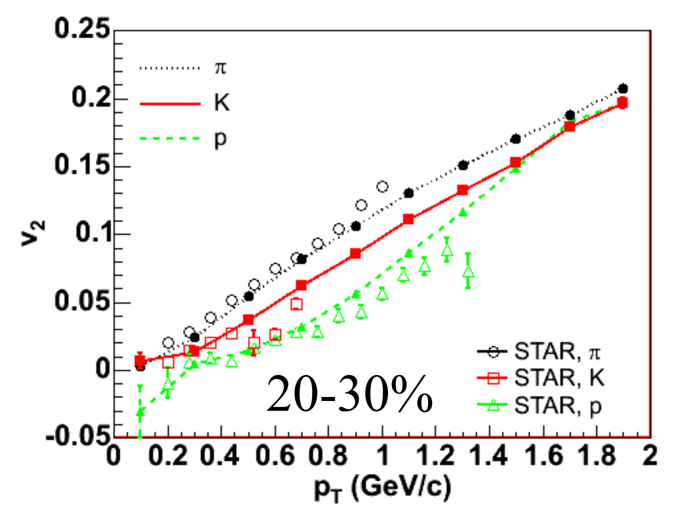
Kharzeev,Levin, and Nardi
Implemented in hydro by TH and Nara

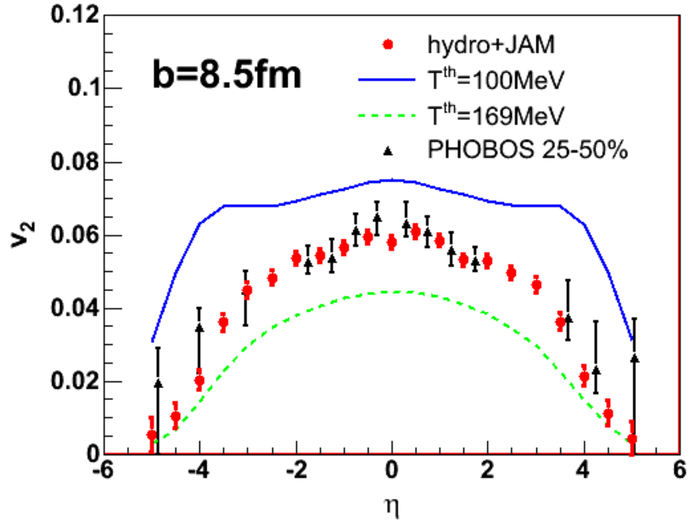
TH et al.('06); in preparation.

Highlights from Glauber + QGP Fluid + Hadron Gas Model









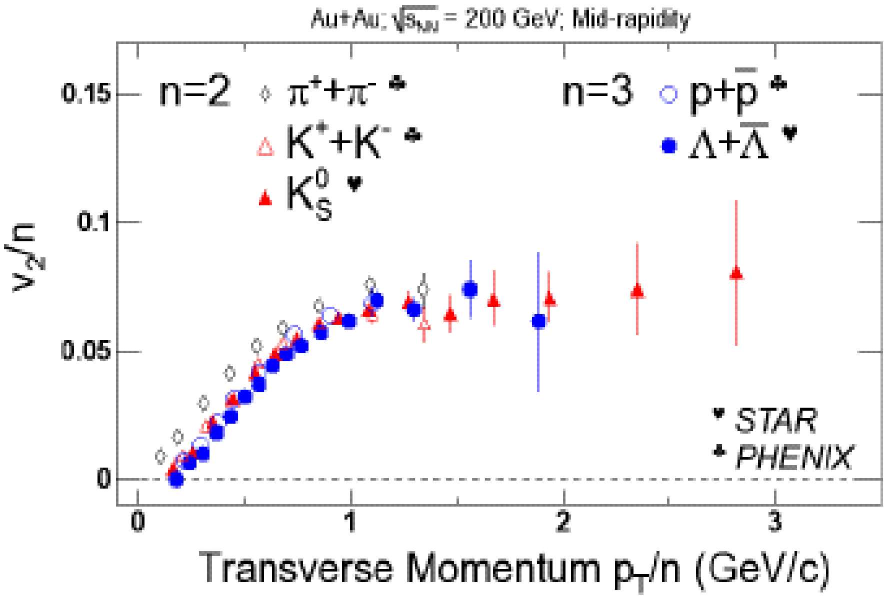
Good agreement for bulk (p_T<~1.5GeV/c)

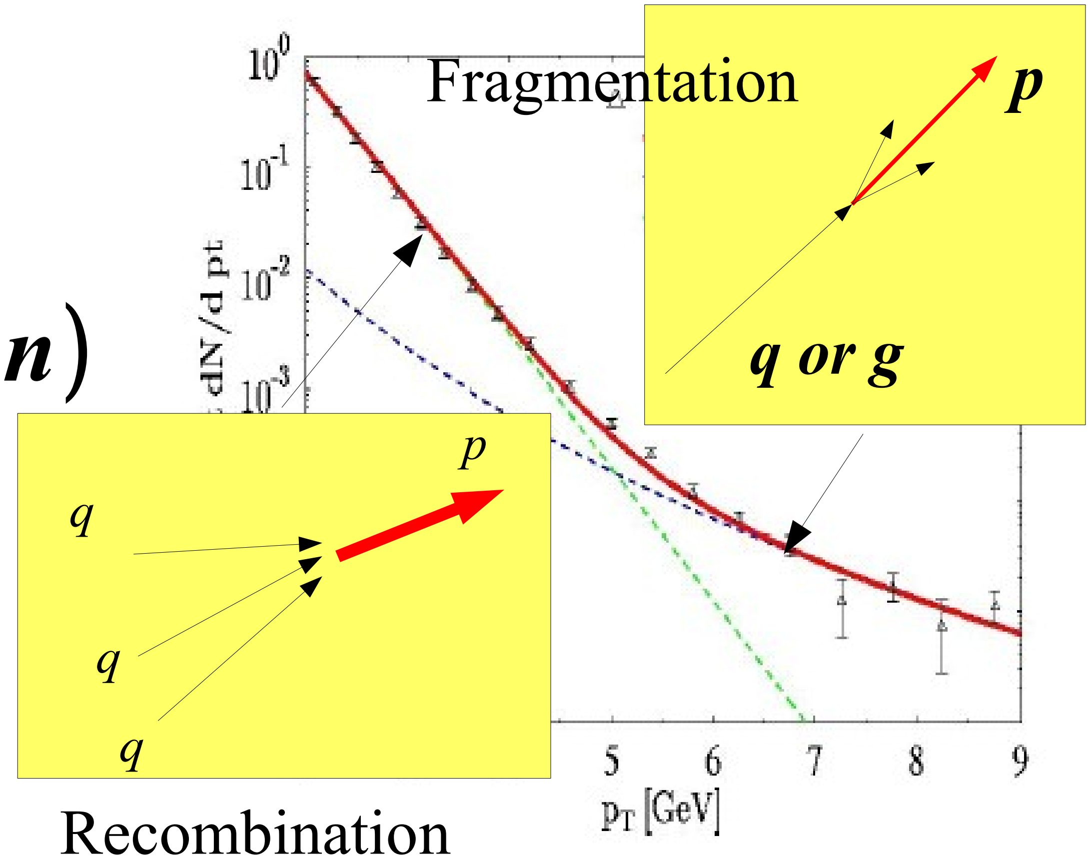
→ What happens to the CGC case?

QGP Signals: Quark Number Scaling

- **When *n* quarks recombines to a hadron, v2 is enhanced by *n* times.**

$$v_2^{Hadron}(P_T) = n\, v_2^{Parton}(P_T/n)$$





Fries et al. PRL 90 (2003), 202303
Nonaka et al., nucl-th/0308051

Recombination Picture seems to work well
... Parton Elliptic Flow

Recombination and Fragmentation

Fries,Muller,Nonaka,Bass, PRL90, 202303(2003); PRC68,044902 (2003)

- **Successes: quark number scaling, baryon/meson ratio**
  → $v_2 \sim 0.10$ at high-pT .

$$f(p,\varphi)=(1+2\,v_2(p/2)\cos\varphi)\times(1+2\,v_2(p/2)\cos\varphi)$$

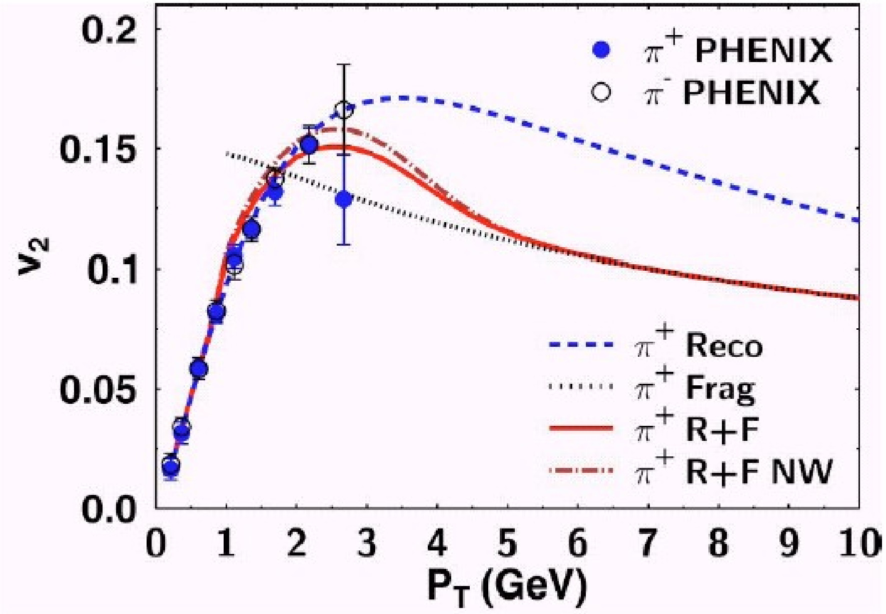
$$\approx 1+2\times \mathbf{2\,v_2(p/2)}\ \cos\varphi$$

- **Problems: Sharply edged density dist. (Hard Sphere)**

$$\ell(b)=\sqrt{R_A^{\,2}-(b/2)^2}$$

→ E-loss ∝ ℓ → v2 ~ 0.10

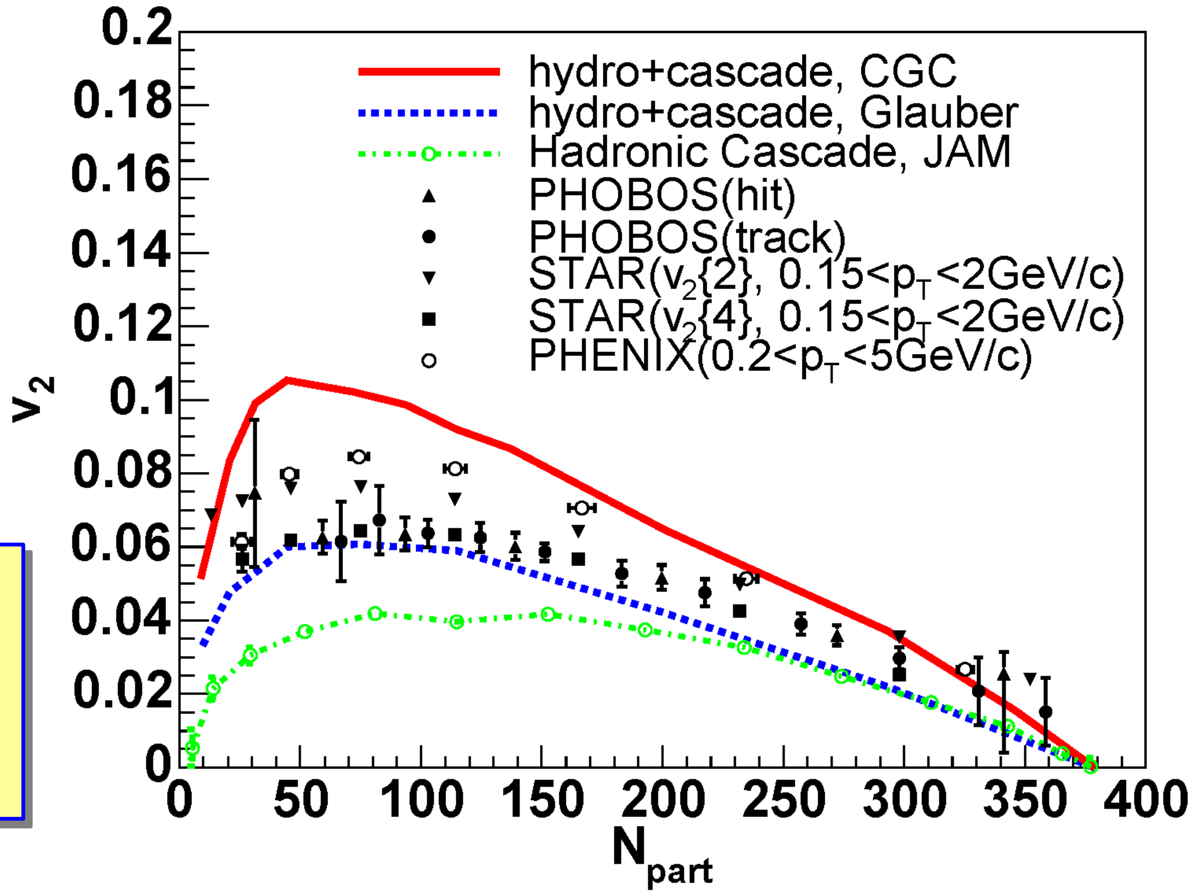
  - **Woods-Saxon density distribution**
    → v2 ~ 0.05 : Half of H.S.



Cascade vs Hydro @ RHIC: Au+Au

- **Comparison of v2 as a function of N_{part}**
  - **Cascade predict smaller v2 in peripheral collisions**
  - **Data lies between hydro results with two different initial condition CGC (Color Glass Condensate) and Glauber type initial condition.**

Hydro is better,
CGC may be realized
in central collisions.



When and where is QGP formed ?

- **Incident Energy**
  - **AGS: Strangeness Enh. (High baryon ρ effect ?)**
  - **SPS:**

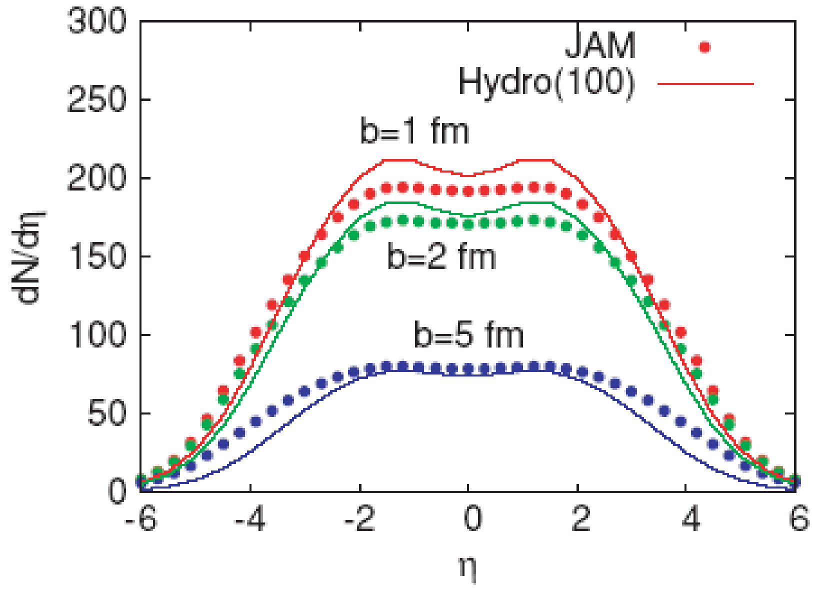
    J/ψ suppression (QGP?), Low mass dilepton enh. (chiral sym.)
    Hydro overestimate v_2 data
  - **RHIC:**

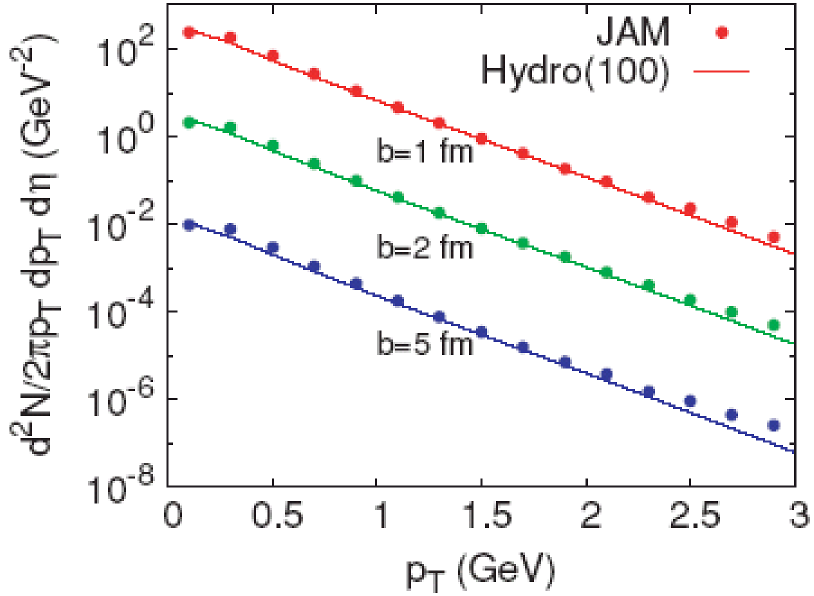
    Jet quenching, Strong v_2, Quark number scaling of v_2, ...
    Hadronic Cascade underestimate v_2 data

  → Bulk QGP formation seems to start between SPS and RHIC
- **Proj./Targ. Mass dependence**
  - **Au+Au: v_2(Casc.) < v_2(hydro) ~ v_2(data)**
  - **Cu+Cu: Recently Measured**

Predictions of Cu+Cu Collisions @ RHIC (I)

- **Single particle spectra**
  - **Cascade (JAM) and Hydro predict almost the same single particle spectra**
    $dN/d\eta$, $d^2N/p_Tdp_Td\eta$
- **Surprising ?**
  - **Initial Cond. of Hydro is tuned to fit *$dN/d\eta$* (~ Energy per rapidity)**
  - **Cascade use fitted σ_{NN}**
  - **Themailzation is expected at Low p_T (long time before particle production)**
    → Coincidence may not be surprising

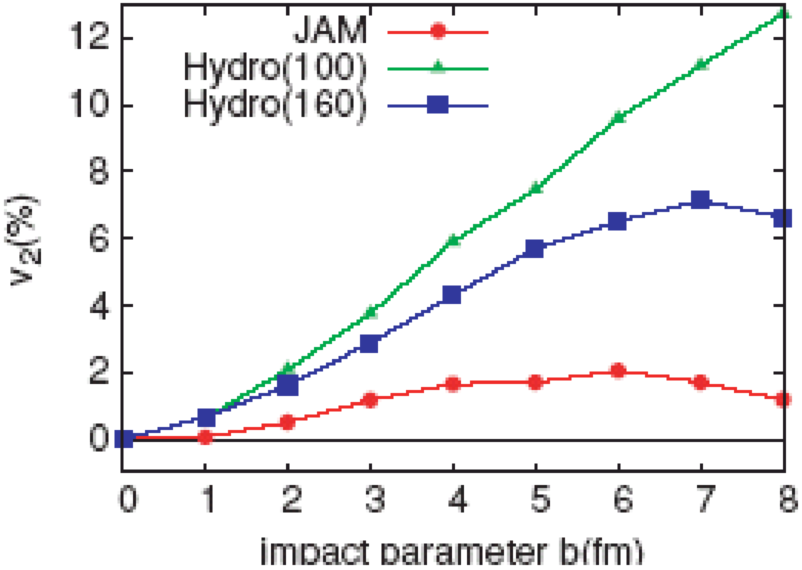


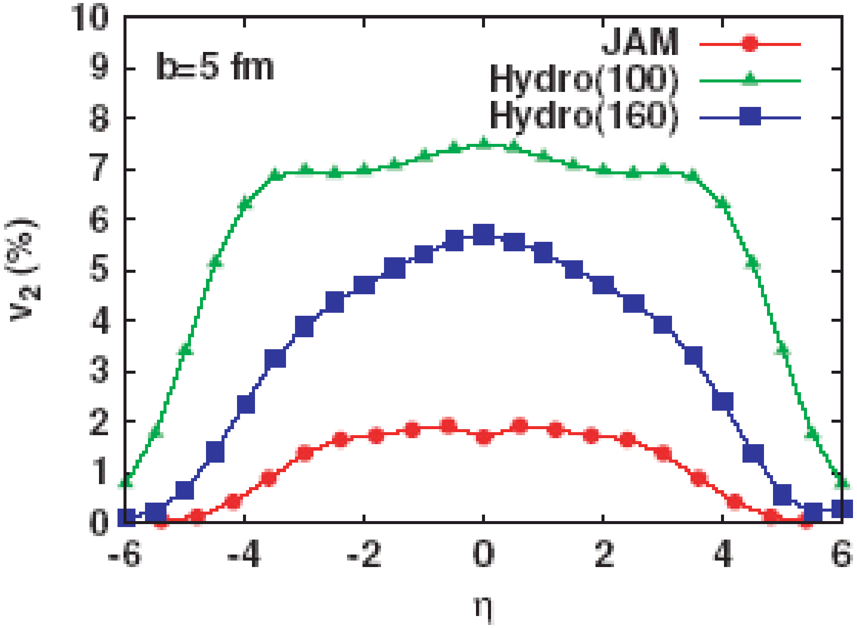


Hirano, Isse, Nara, AO, Yoshino, Phys. Rev. C 72(2005), 041901

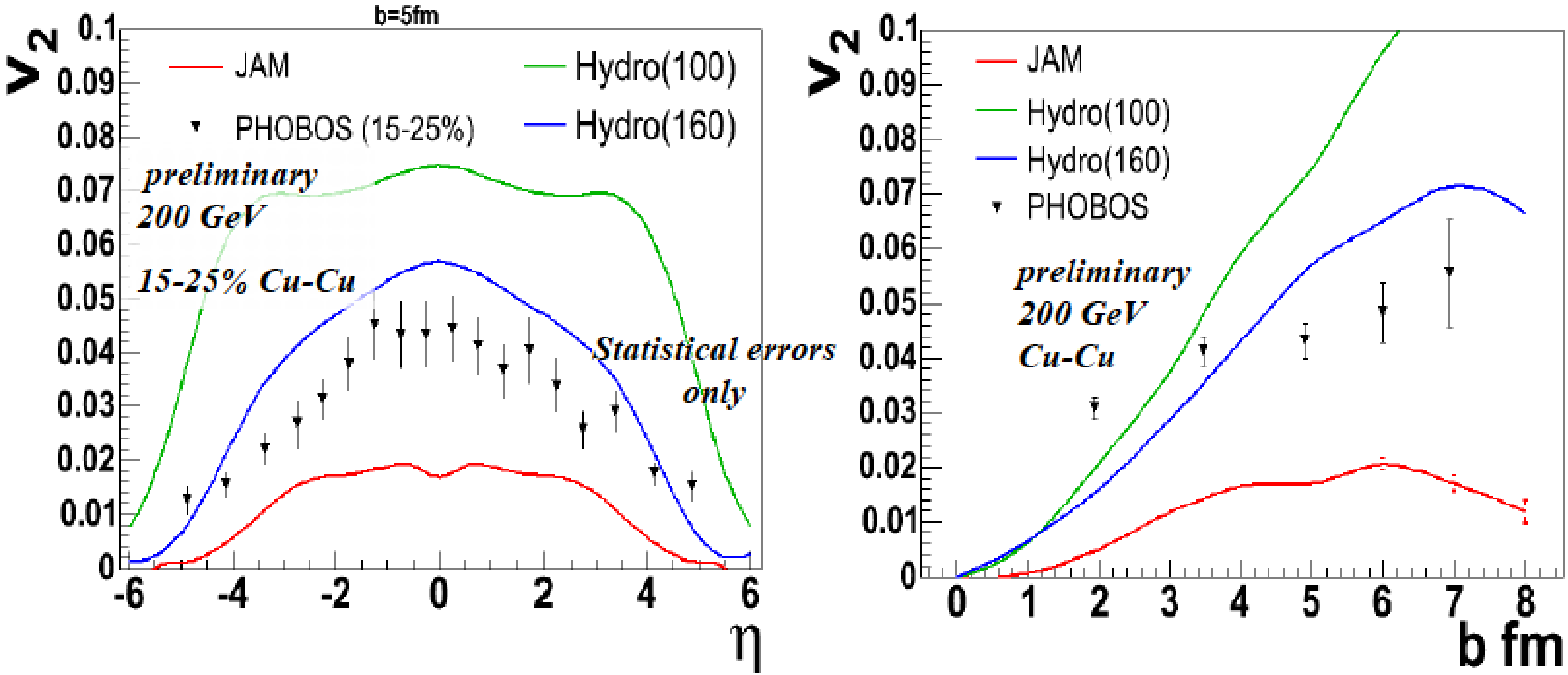
Predictions of Cu+Cu Collisions @ RHIC (II)

- **Calculations were done BEFORE the data are opened to public.**
- **Cascade and Hydro predict very different Elliptic Flow !**
  - **Cascade: small v2**
    → Small int. in the early stage
  - **Hydro: large v2**
    → Strong int. after $\tau=\tau_0 \sim 0.6$ fm/c
- **T^{th} dependence**
  - **T^{th} = 160 MeV ~ Tc = 170 MeV**
    → short time of expansion
    in the hadron phase
  - **T^{th} = 100 MeV < Tc = 170 MeV**
    → long time of expansion





Compared to JAM Model

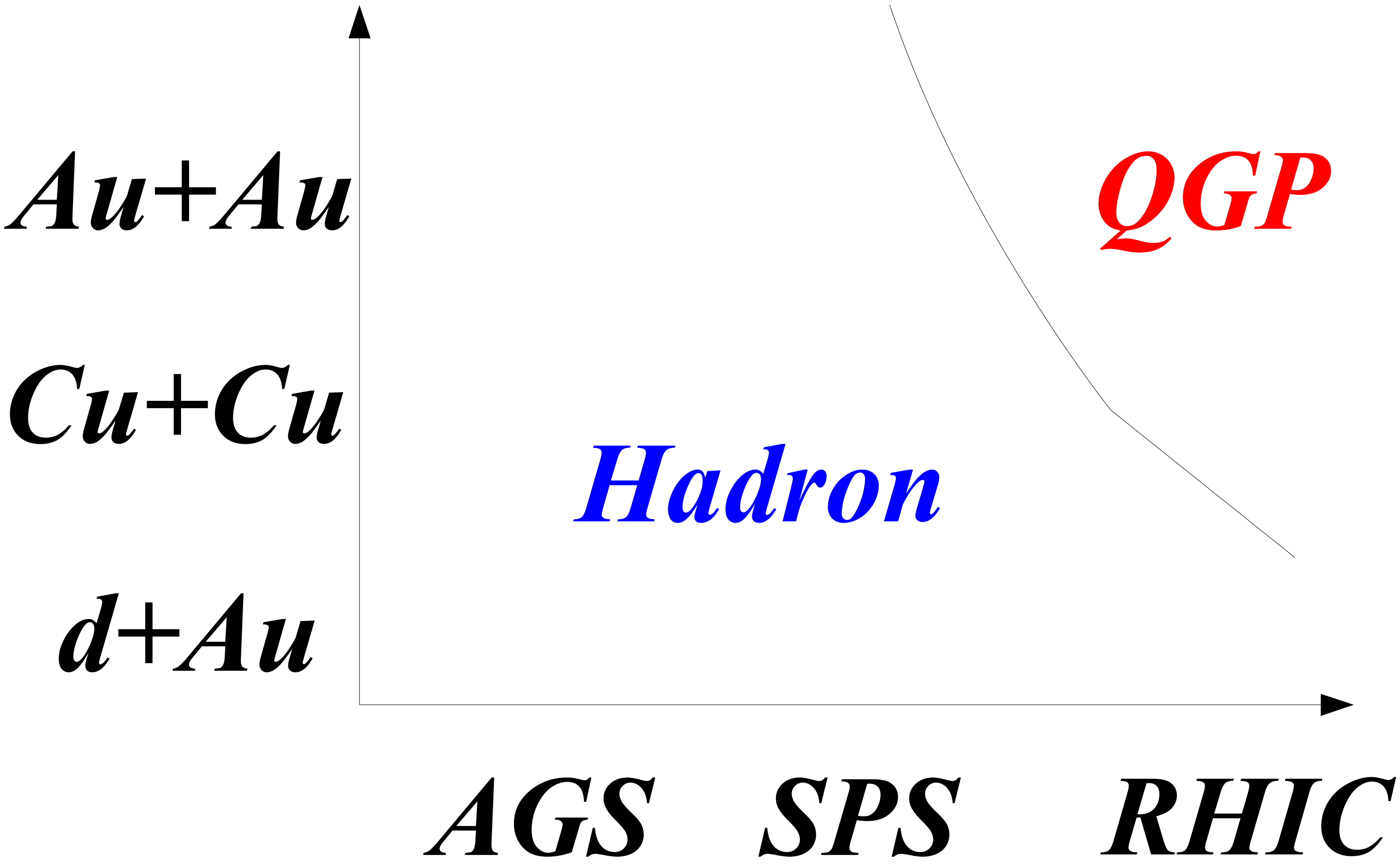


Cu-Cu more like Hydro than JAM hadron string cascade model

Here JAM uses a 1 fm/c formation time. Hydro (160) has kinetic freezeout temperature at 160 MeV

After Data are opened, ...

- **Hydro wins Cascade at RHIC even for Cu+Cu collisions in the initial stage evolution.....**
- **“Reaction Phase Diagram” seems to be .....**



Lessons from AGS and SPS Energy HIC

- 粒子生成の主要過程
  - 1 A GeV Energy → 共鳴粒子生成 + 共鳴崩壊
  - 10 A GeV Energy (AGS) → 2共鳴ハドロン生成、ストリング生成+崩壊
  - 100 A GeV Energy (SPS) → ストリング生成+崩壊
- 必要な自由度の輸送を取り入れる必要性
  - pT スペクトルに直接的に影響を与える。
  - あらわな自由度を取り入れない場合
    → formation time 等を導入して相互作用の強さ(圧力)を調整
    (量子論的な「漸近領域に達する時間」だけではないだろう)
- RHICエネルギーでのハドロン輸送模型の失敗
  - SPS エネルギーまでで成功している formation time を使うと、
    反応初期での相互作用が小さすぎる
    → 遅い熱平衡化時間、小さな楕円フロー(特に high pT)

Hadron Correlation at RHIC in Jet-Fluid String Model

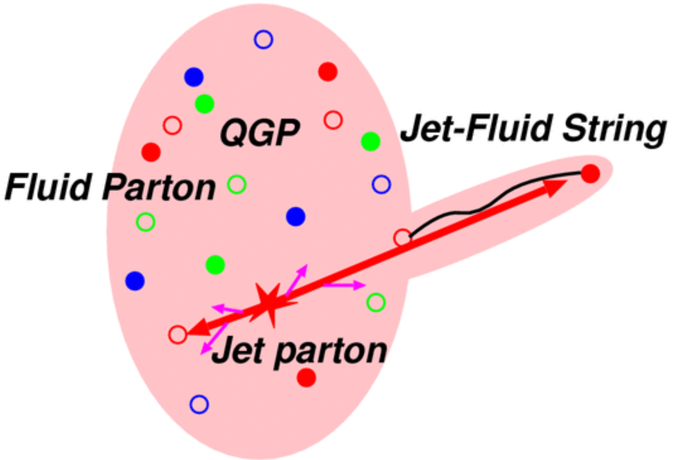
Jet-Fluid String 模型における粒子相関

東大理、阪大理^{A}、北大理^{B}、フランクフルト大^{C}
平野哲文、一瀬昌嗣^{A}、水川零^{B}、奈良寧^{C}、大西明^{B}、吉野公二^{B}

Hadron correlations in Jet-Fluid String model

T.Hirano, M.Isse^{A}, R. Mizukawa^{B}, Y.Nara^{C}, A. Ohnishi^{B}, K.Yoshino^{B}
U. Tokyo, Osaka U.^{A}, Hokkaido U.^{B}, Frankfurt U.^{C}

- **Introduction**
- **High p_T でのハドロン化模型**
- **JFSでのハドロン相関**
- **まとめ**



Isse, Hirano, Mizukawa, AO, Yoshino, Nara, nucl-th/0702068

High p_T ハドロン生成

- **GSI, AGS, SPS → 共鳴ハドロン、ストリング生成と破砕**
  Nara et al., PRC61('00),024901; Isse et al., PRC72('05),064908.

- **RHICでの標準描像= pQCD+E-loss+独立破砕**

$$\frac{dN^{AA}(b)}{dy\,d^2p_T} = \int d\boldsymbol{r}_T\, t_A(\boldsymbol{r}_T - \boldsymbol{b}/2)\, t_B(\boldsymbol{r}_T + \boldsymbol{b}/2)$$

Geometry

$$\times K \sum_{abcd} \int dx_a\, dx_b\, d^2k_a\, d^2k_b\, f_{a/A}\, f_{b/B} \frac{d\sigma^{ab\to cd}}{d\hat{t}}$$

pQCD × K-fac.

$$\times D(E_c - \Delta E_c(\boldsymbol{r}_T); c \to h)$$

E-loss + Indep. Frag.

→ しかし問題は残っている (high p_T での v_2 など)

→ RHICではストリング破砕は必要ないのか？

Hirano et al., PLB636('06)299 (afterburner improves v_2 in Hydro+Jet)

Sahu et al. Pramana 67 ('07)257 (cascade → low p_T data except for v_2)

Parton Cascade (Kinder-Geiger) (Parton cluster → hadrons)

Hadronization Mechanism at RHIC

- ***High p_T: Indep. Frag. of Jet Partons*** ***(E.g. Hirano-Nara)***

  O Explains pT spectrum when E-loss is included.

  X Elliptic Flow v_2 is small at high p_T ←*This Talk*

- ***Medium p_T: Recombination*** ***(E.g. Duke-Osaka-Nagoya)***

  O Explains Baryon Puzzle and Quark Number Scaling of v_2

  X Hard sphere density profile is implicitly assumed

- ***Low p_T: Equil. Fluid Hadronization*** ***(E.g. Hirano-Gyulassy)***

  O Explains p_T spec. and v_2 at low p_T

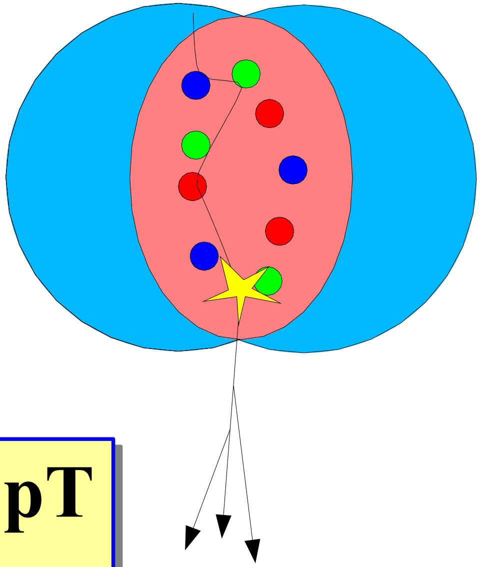
  X Results depends on the Freeze-Out Conditions

QGP Signals are understood separately,
and they are not necessarily consistent.
→ Further Ideas are required !

How can we get large v_2 at high p_T ?

- **Quark Recombination → Combined Objects have larger v2**

$$f(p, \varphi) = (1 + 2\, v_2(p/2) \cos\varphi) \times (1 + 2\, v_2(p/2) \cos\varphi)$$
$$\approx 1 + 2 \times \color{red}{2\, v_2(p/2)}\ \cos\varphi$$



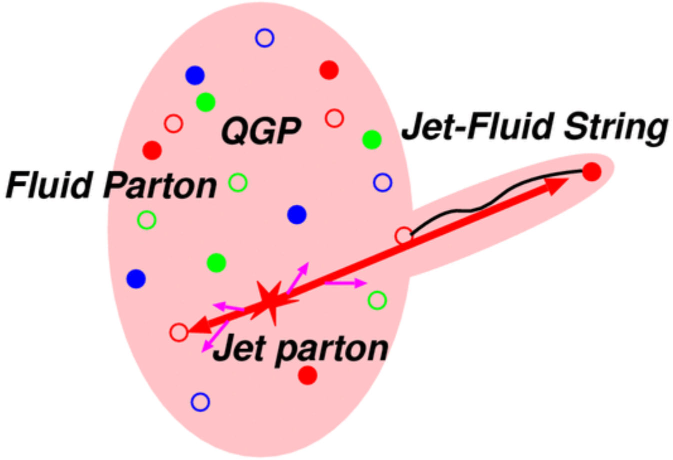
- **Energy Loss in QGP generates v2**
  - **Large/Small suppression in y/x directions**

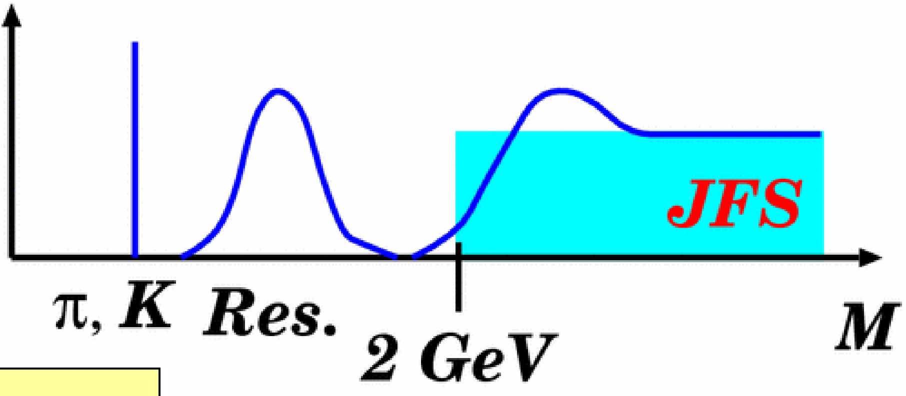
Plausible Hadronization giving large v2 at high pT
- **Combination of several partons**
- **Large Energy Loss**
  → Jet parton picks up Fluid parton
  and forms a string (Jet-Fluid String)

Jet-Fluid String formation and decay: Model

Isse, Hirano, Mizukawa, AO, Yoshino, Nara, nucl-th/0702068

- **ミニジェット生成=pQCD** (PYTHIA 6.4)
- **QGP中のパートン伝播**
  - **3次元流体模型**
    Hirano-Nara, PRL91('03), 082301;
    PRC69('04),034908
    Hirano,Tsuda, PRC66('02),054905
  - **GLV エネルギー損失× factor (*C*)**
    Gyulassy-Levai-Vitev, PRL85('00), 5535.
- **ストリング生成・破砕**
  - **”スペクトル”関数 $\Theta(\sqrt{s}-2\ \mathrm{GeV})$**



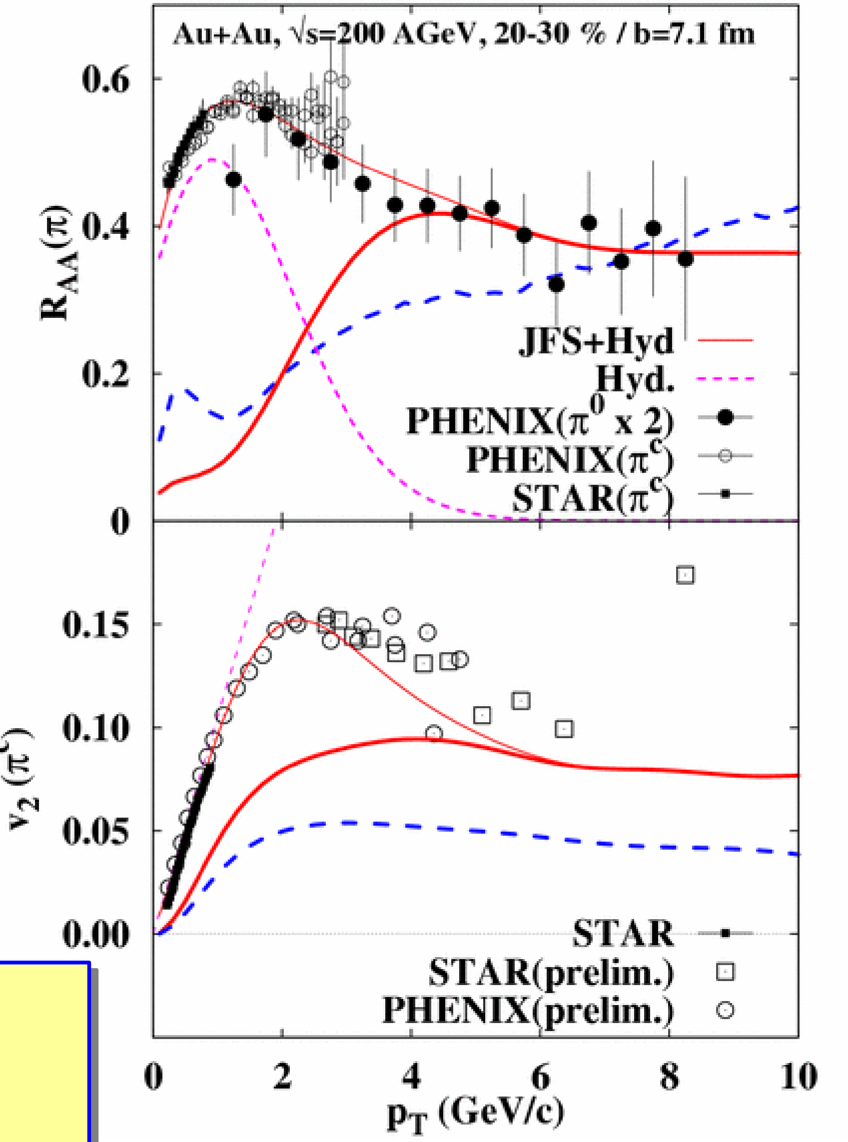


$$D(j\to h)=\int d^3k_f\, f_f(k_f,T,u_\mu,\boldsymbol{x}(\tau_f))$$
$$\times S(s=(k_j+k_f)^2)\, D(String(\sqrt{s},k_j,k_f)\to h)$$

Jet-Fluid String formation and decay: Results

Isse, Hirano, Mizukawa, AO, Yoshino, Nara, nucl-th/0702068

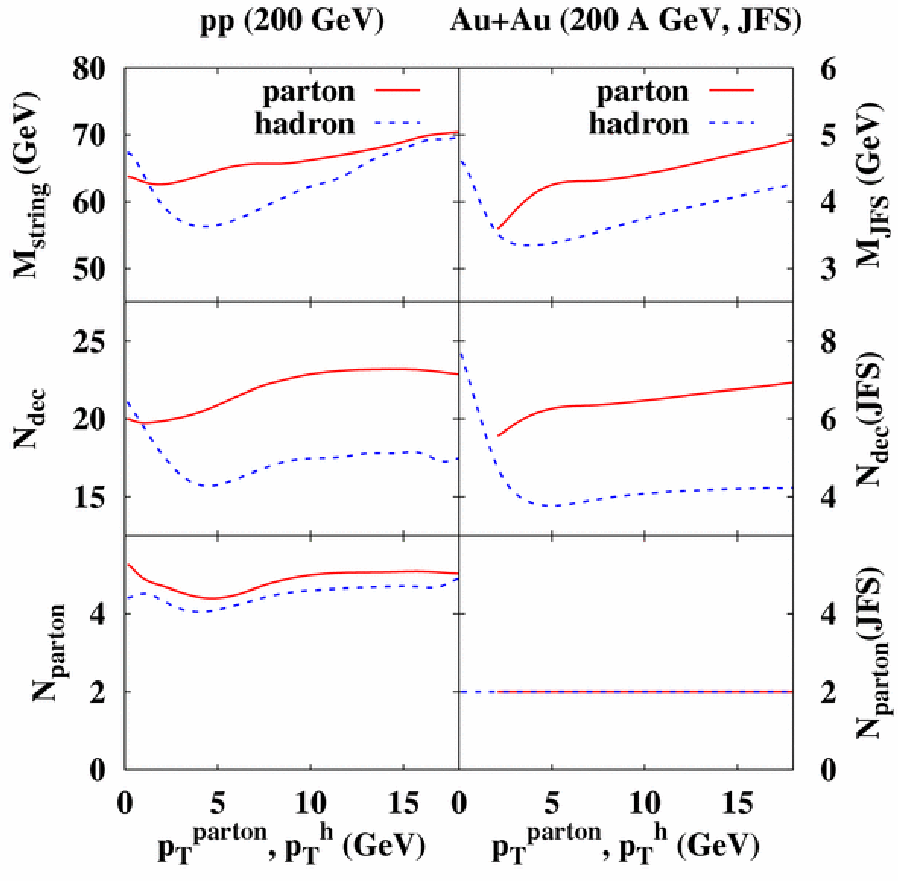
- 高いhigh p_Tハドロン生成率
  → 大きなエネルギー損失が必要
  - R_{AA} fit → E-loss fac. C = (6-8)
    C = (2-3) in Hydro+Jet (Hirano-Nara)
- 大きなエネルギー損失
  +流体パートンのv_2
  → high p_T での大きな v_2
  - $v_2 \sim 8$ % @ $p_T > 6$ GeV/c
    $v_2 \sim$ (3-5) % in Indep. Frag.

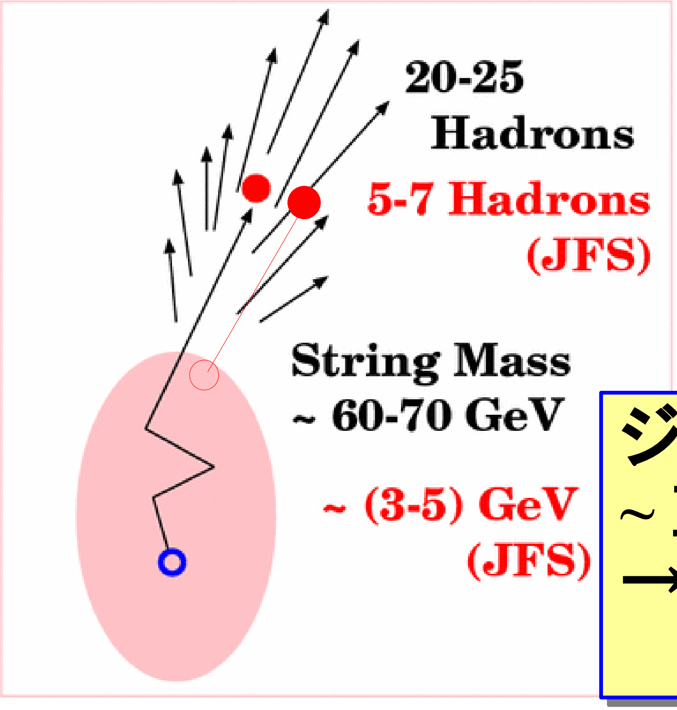


High pTでRAAを説明するE-lossで
v2 データをほぼ説明
→なぜhigh pTハドロンが作られやすい？

独立破砕模型との比較

- **独立破砕模型(IF)**
  - ppでは IF ~ストリング破砕
    → 重いストリング(60-70 GeV)が
    多くのハドロン(20-25) に崩壊
  - AAでの IF @ pT (After E-loss)
    ~ pp でのストリング破砕@ p_T



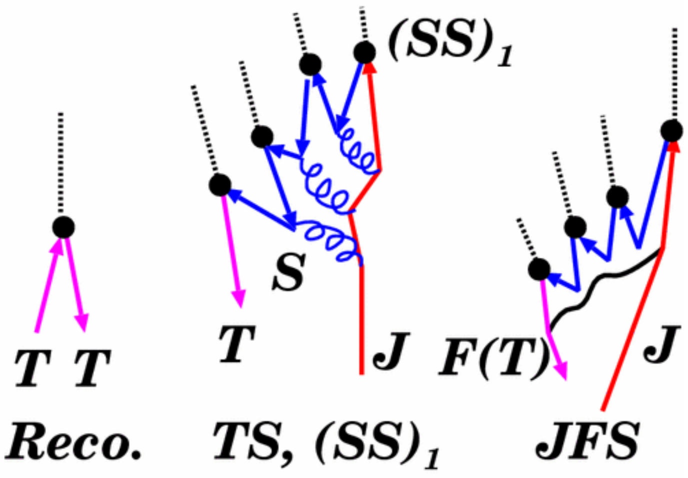


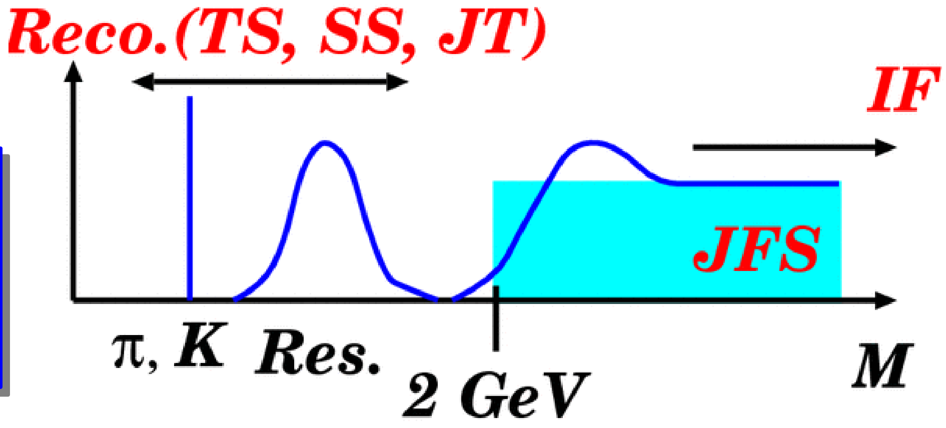
ジェットパートンの独立破砕
~ 重いストリングの崩壊
→ AA衝突のジェット破砕段階で
これほど重いストリングが作られるか？

High p_T 領域での再結合模型との比較

- **TT(T) → med. pT**
  Nonaka et al., PRC69('04),031902
- **JT → med. pT (soft-hard)**
  Greco-Ko-Levai, PRC68('03),034904
- **TS → med. pT, $(SS)_1$ → high pT**
  Hwa-Yang, PRC70('04)024905
- **TT(T)→ Res. → med./low pT**
  Greco-Ko, PRC70('04)024901

T: Thermal (Fluid) parton
J: Jet parton
S: Shower parton

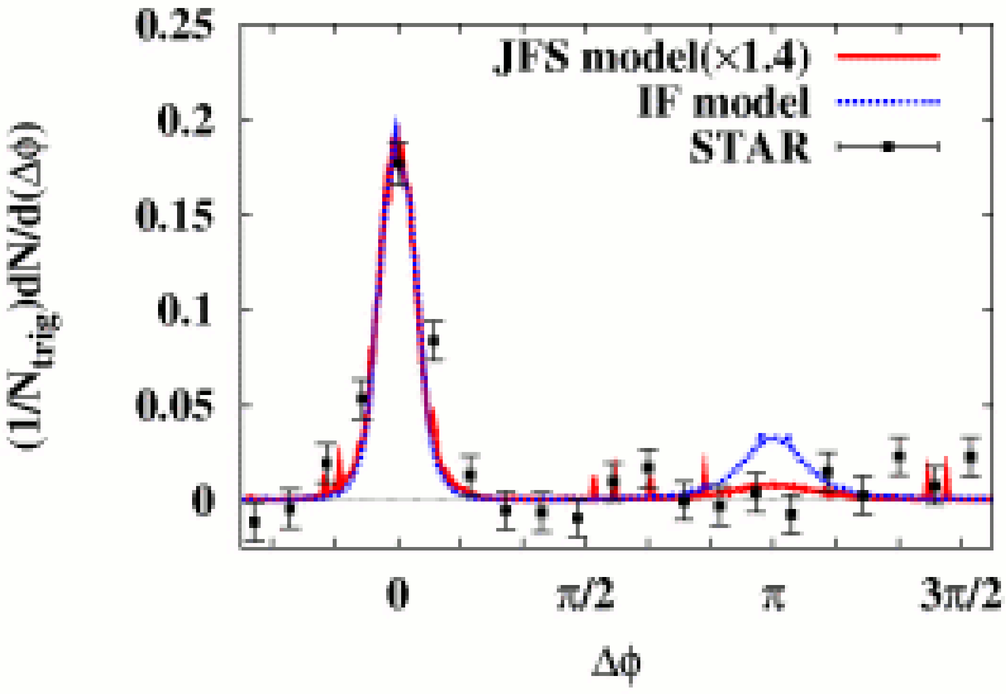




- **T+"part of Jet"によるハドロン生成**
- **π の直接生成より共鳴崩壊が有利**
  → JFSの描像と無矛盾

ハドロンの方位角相関

- Au+Au衝突での後方相関の消失＝QGP生成の強いシグナル
  - Hydro + Jet model Hirano & Nara, PRL (2003)
    - R_{AA} を説明する E-loss では後方相関の抑制が十分でない
    - ジェットの方向を変える散乱効果を取り入れると説明可能
  - Jet “absorption” model Drees, Feng,Jia, PRC71('05),034909
    - ジェットパートンが exp(-αL) の確率で「吸収」
    - エネルギー損失との関係は？
  - JFS
    → R_{AA} を説明するE-loss により、後方相関は消失

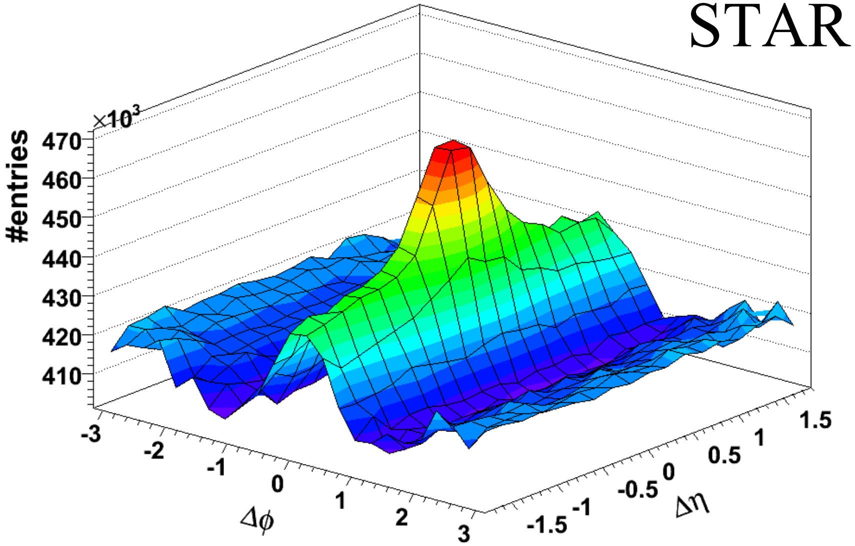


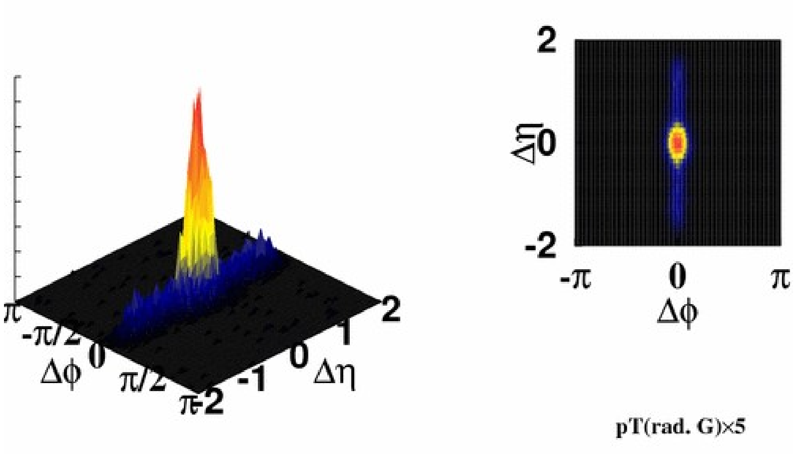
水川、卒論

リッジ構造

- **Jet-Ridge structure**
  → 横に狭く、縦に広い相関
  (narrow Δφ +wide Δη corr.)
  - **JFS では見えない**
  - **Chiu and Hwa：早い時点で Jet により熱せられた広い η の範囲の流体 parton が coalescense**
  - **Shuryak: エネルギーを失った jet parton が流体中の「非平衡成分」として現れる**
  - **Wong: Jet のエネルギー損失時に放出された radiation が平衡に達する前の広い η 分布を持つ bulk parton に大きな pT を与えてハドロン化**
    → radiation の pT を拡大すると、弱いが ridge 構造を出す

STAR





水川

Lessons from RHIC physics (until now....)

- 分かったこと → jet parton が局所熱平衡に達した bulk quark-gluon matter 中をエネルギーを失いながら伝播し、parton が再結合してハドロンを作る。
  - jet parton は媒質中でエネルギーを失ってからハドロン化
  - bulk 部分が完全流体によりうまく記述できる
    (SPS energy までは、流体模型は「アイデア」を与えるが、
    定量的には粒子シミュレーションに勝てなかった。)
  - 中間 pT 領域で baryon が meson より多く、v2 も大きい。
- 分かりつつあること → QCD 物性
  - jet は流体への feed back や流体 parton との再結合により、より低い pT ハドロンの分布にも影響を与える。
- よく分かっていないこと
  - 初期条件、速い熱平衡化、jet の失われたエネルギーの行き先、jet 起源で十分な量の baryon を作る方法, viscous hydro の輸送係数.....

Summary

- Heavy-ion collisions up to SPS energies seems to be reasonably described by using hadron-string cascade such as JAM model, while HIC at RHIC requires earlier thermalization (larger anisotropic pressure) even in lighter nuclear collisions such as Cu+Cu collisions.

- There are many things to do in high-energy heavy-ion collision physics.
  - AGS-FAIR-SPS energies
    Nuclear matter EOS, Baryon rich QGP, Strangeness enh., ...
  - RHIC-LHC energies
    Detailed studies of QGP properties have just started
    → Consistent understandings are not yet achieved,
    and we still have many puzzles

Backups

Jet-Fluid String Formation and Decay at RHIC

Hirano, Isse, Mizukawa, Nara, AO, Yoshino, in preparation

Jet-Fluid String Formation and Decay

Jet production: pQCD(LO) x K-factor (PYTHIA6.3, K=1.8, *pp* fit)

$$\sigma_{jet} = K \sigma_{jet}^{pQCD(LO)}$$

Jet propagation in QGP

3D Hydro + Simplified GLV 1st order formula x *C*

(Hirano-Nara, NPA743('04)305, Hirano-Tsuda, PRC 66('02)054905. Web version!

Gylassy-Levai-Vitev, PRL85('00)5535)

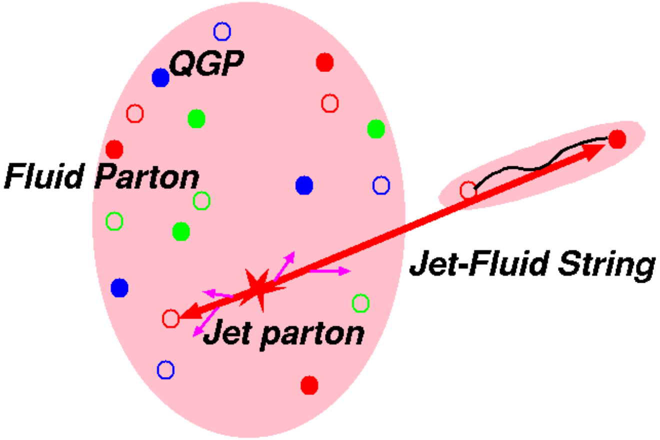
$$\Delta E = \mathbf{C} \times 9\pi \frac{\alpha_s^3}{4} C_R \int d\tau (\tau - \tau_0) \rho_{\mathrm{eff}} \log\left(\frac{2E_0}{\mu^2 L}\right)$$

Jet-Fluid String formation

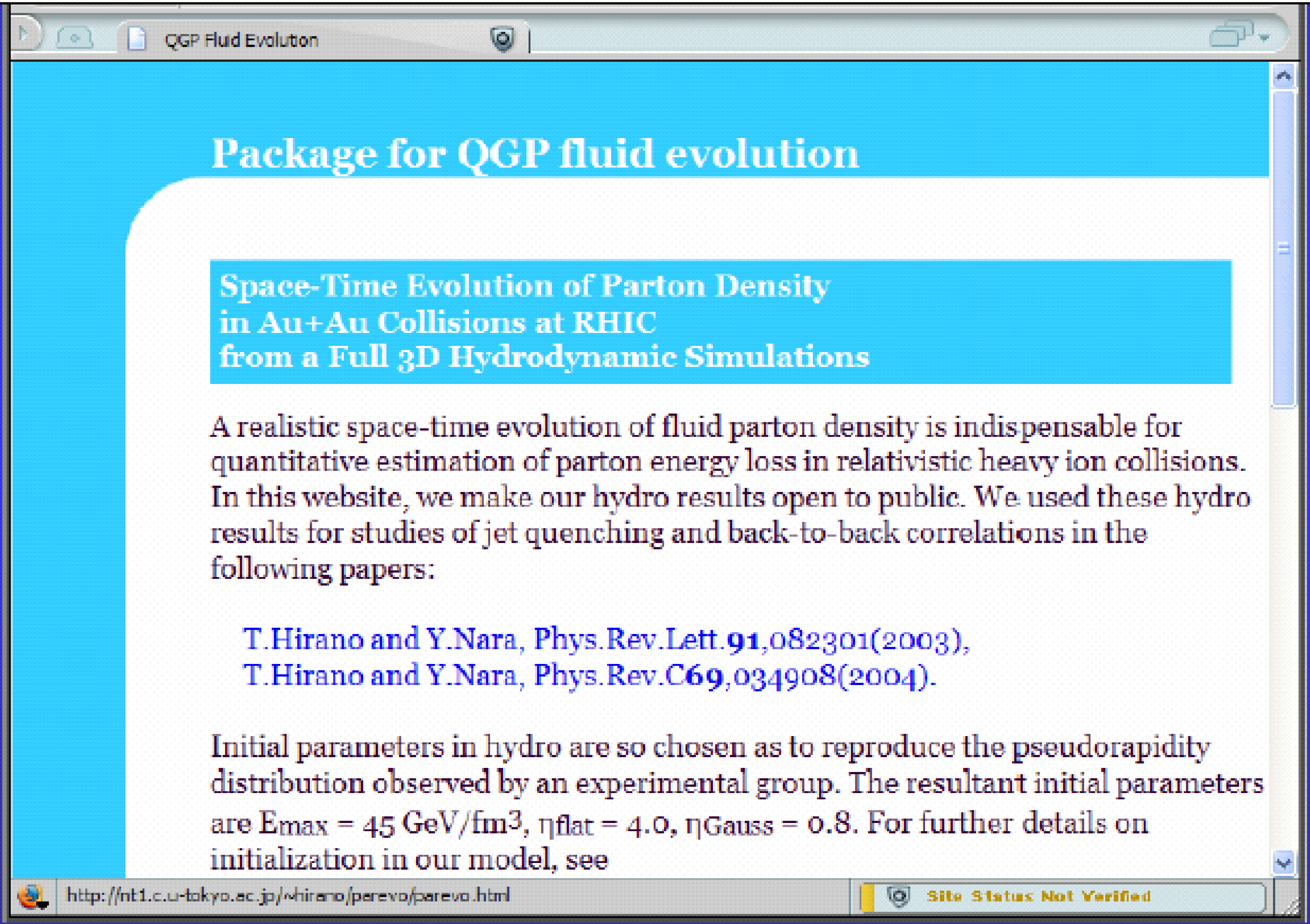
Fluid parton breaks color flux, according to string spectral func.

$$P(\sqrt{s}) \propto \Theta(\sqrt{s} - \sqrt{s_0}) \quad (\sqrt{s_0} = 2\,\mathrm{GeV})$$

Only g and light q (qbar) are considered.



http://nt1.c.u-tokyo.ac.jp/~hirano/parevo/parevo.html



Package for QGP fluid evolution

Space-Time Evolution of Parton Density in Au+Au Collisions at RHIC from a Full 3D Hydrodynamic Simulations

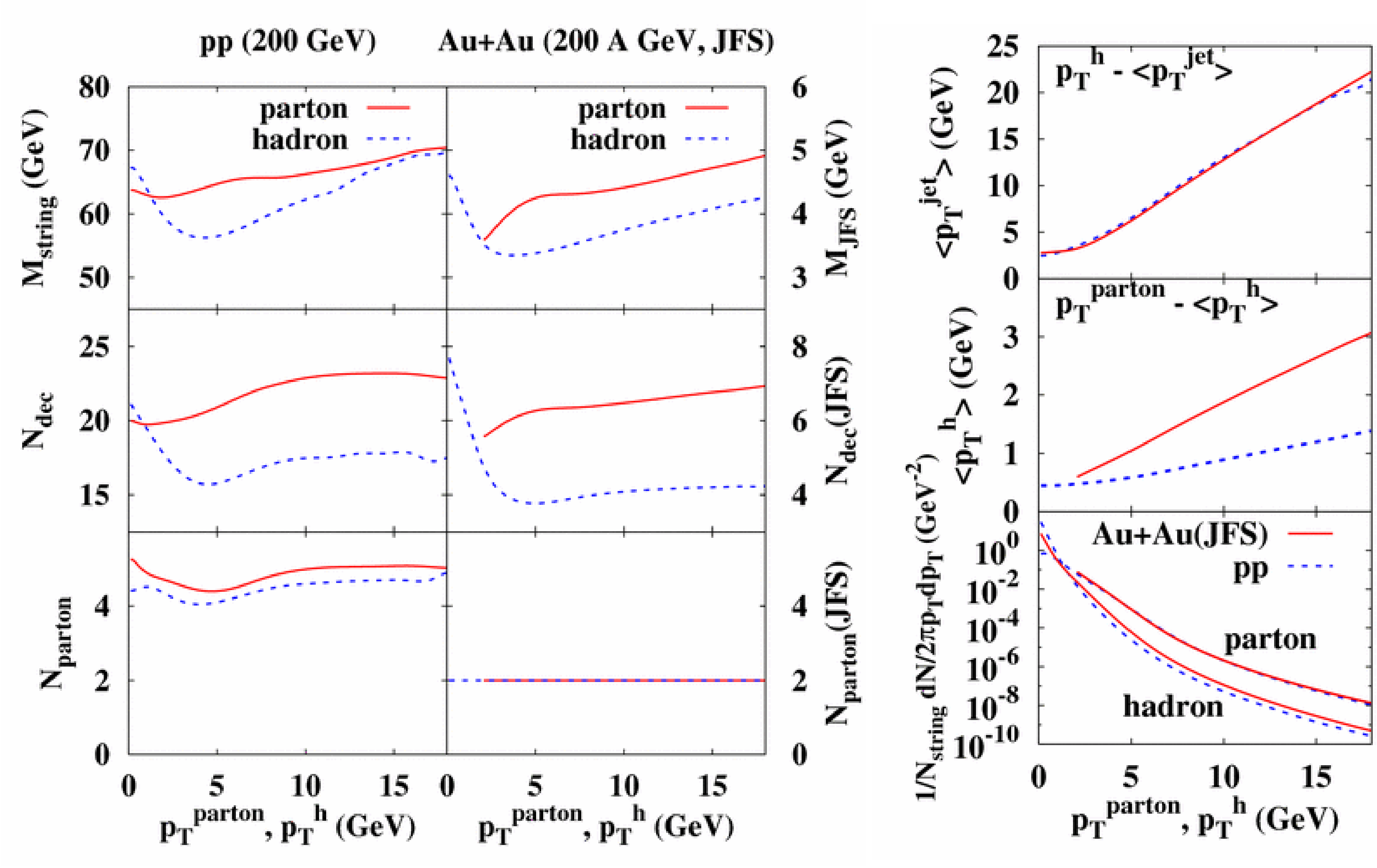
A realistic space-time evolution of fluid parton density is indispensable for quantitative estimation of parton energy loss in relativistic heavy ion collisions. In this website, we make our hydro results open to public. We used these hydro results for studies of jet quenching and back-to-back correlations in the following papers:

T.Hirano and Y.Nara, Phys.Rev.Lett.**91**,082301(2003),
T.Hirano and Y.Nara, Phys.Rev.C**69**,034908(2004).

Initial parameters in hydro are so chosen as to reproduce the pseudorapidity distribution observed by an experimental group. The resultant initial parameters are Emax = 45 GeV/fm^3, ηflat = 4.0, ηGauss = 0.8. For further details on initialization in our model, see

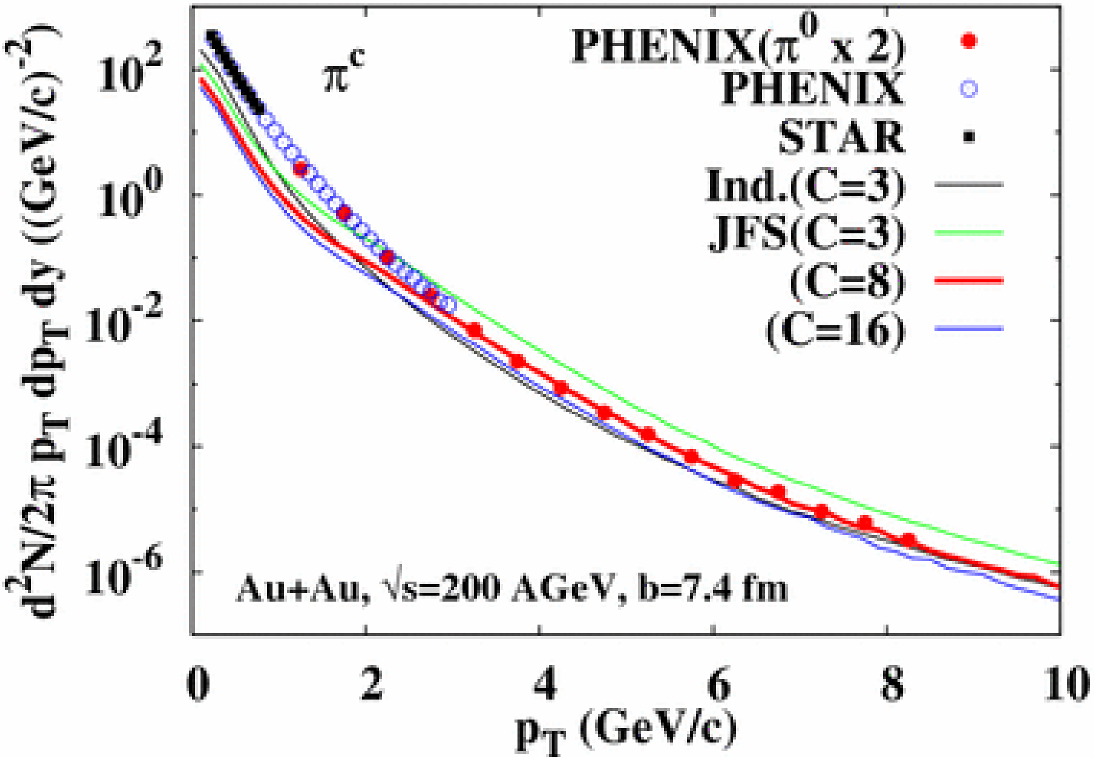
String Mass and p_T in JFS

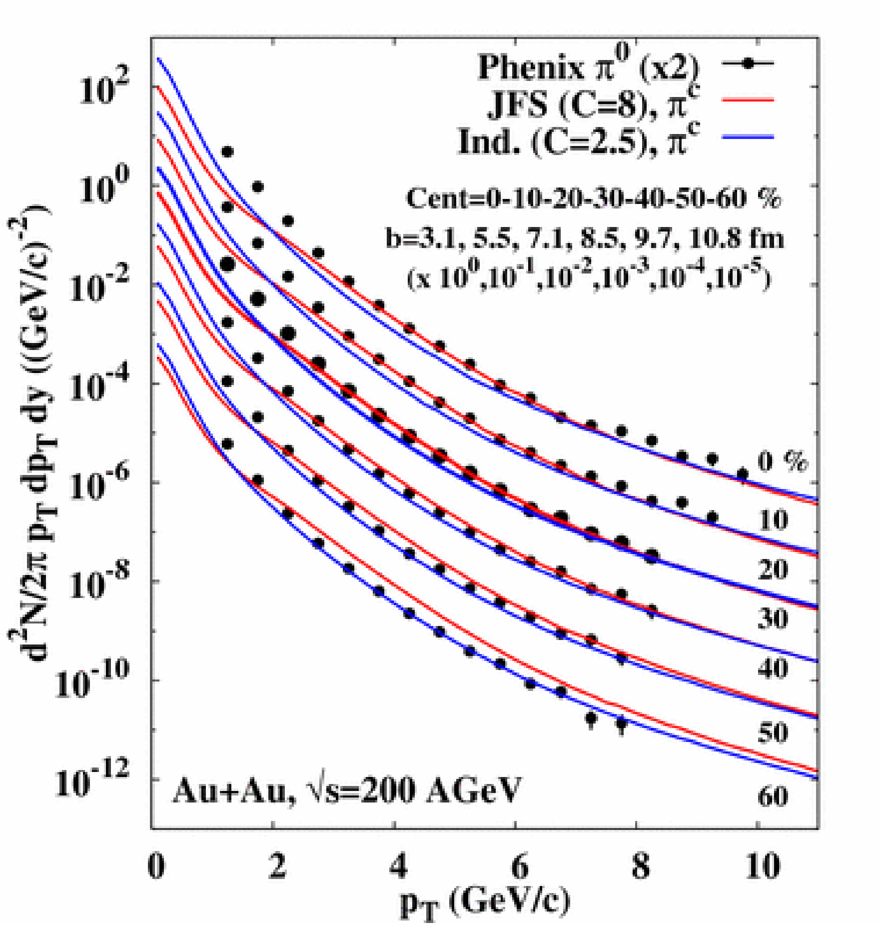
- **Compared to pp collisions (and thus to Ind. Frag.), JFS has much smaller mass and decays into fewer hadrons.**
  → high pT hadrons are enhanced → Larger E-loss is required



Energy Loss Factor C : p_T Spectrum Fit

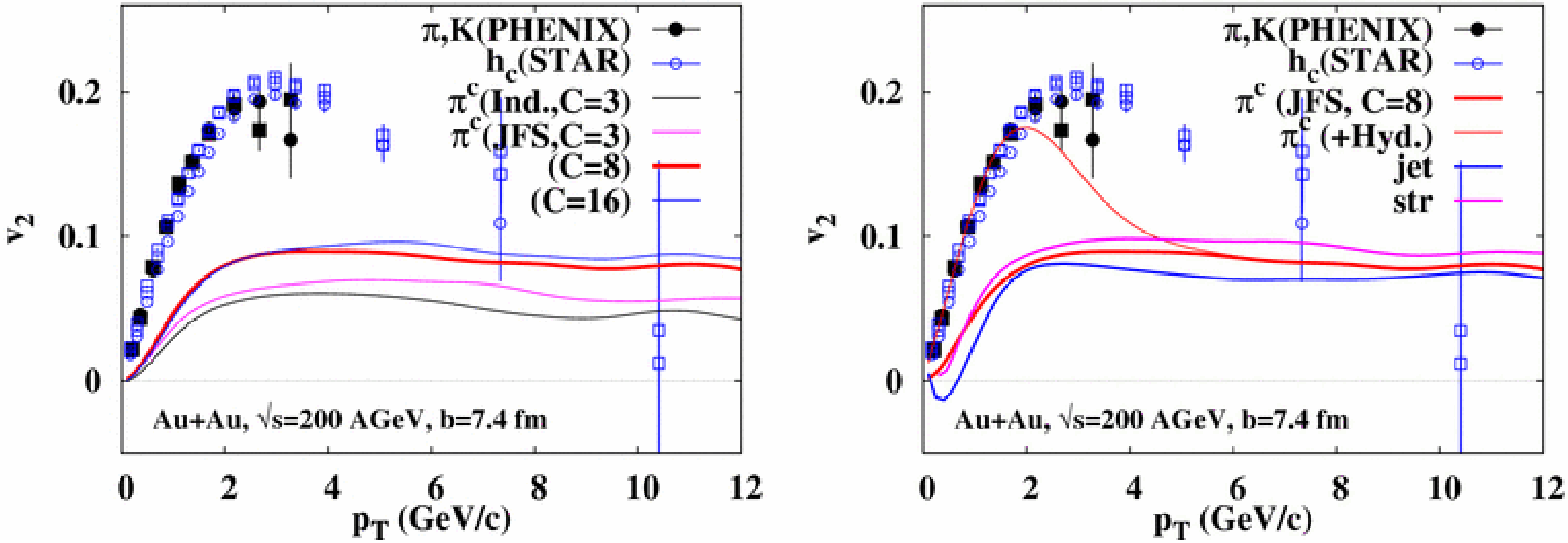
- **For the same C →** $dN_{JFS}(high\ p_T) > dN_{Ind}(high\ p_T)$
- p_T **spec. fit → Ind. Frag.:** *C ≈ (2.5-3)*, **JFS:** ***C ≈ 8***
  → ***Large Energy Loss is necessary / allowed in JFS***





Elliptic Flow: p_T Deps.

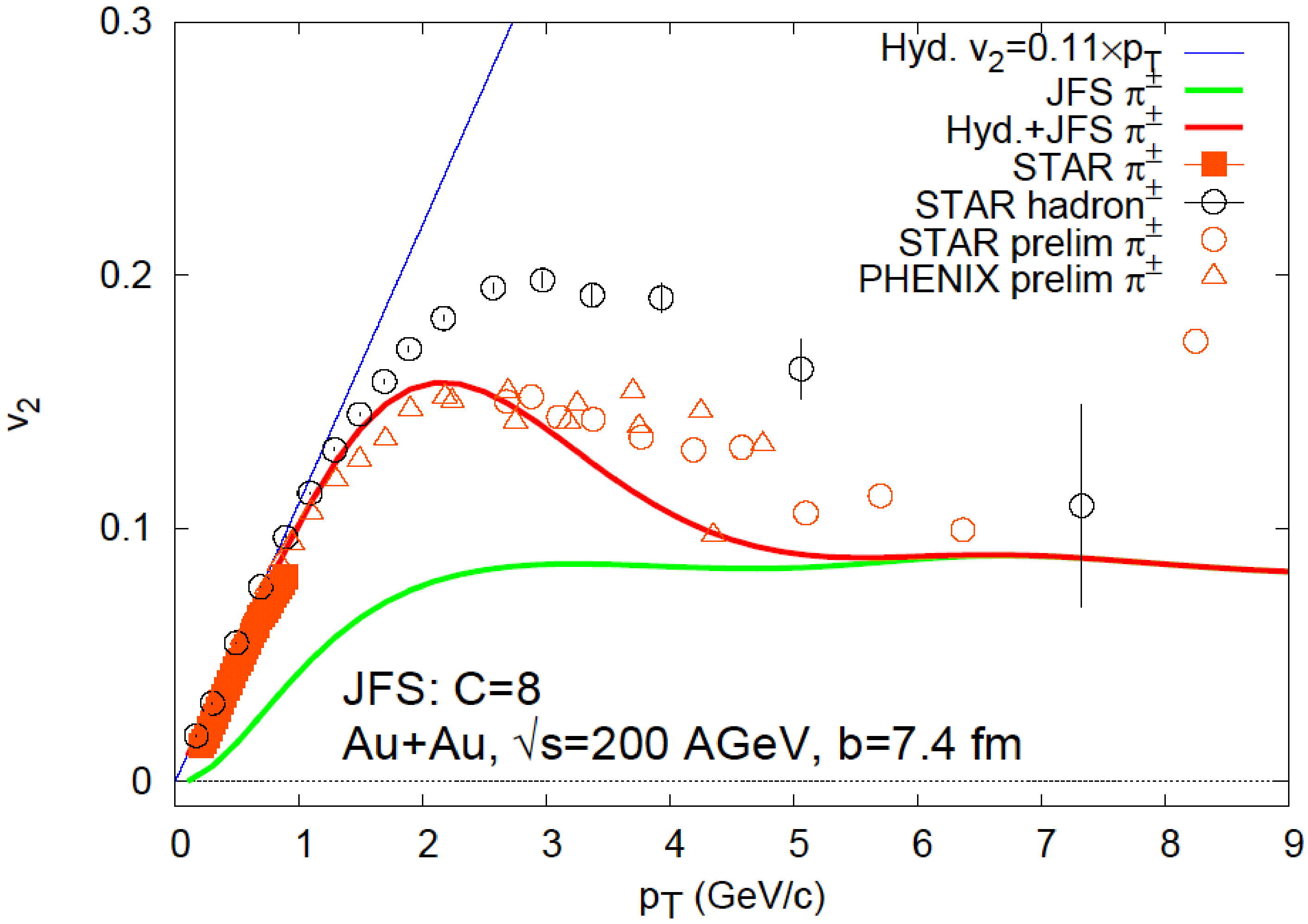
- **High pT v_2 : ~ 5 % in Ind. ($C = 3$) ↔ ~ 8 % in JFS ($C = 8$)**



Origin of Large v_2 = Large E-loss factor C + Fluid parton v_2

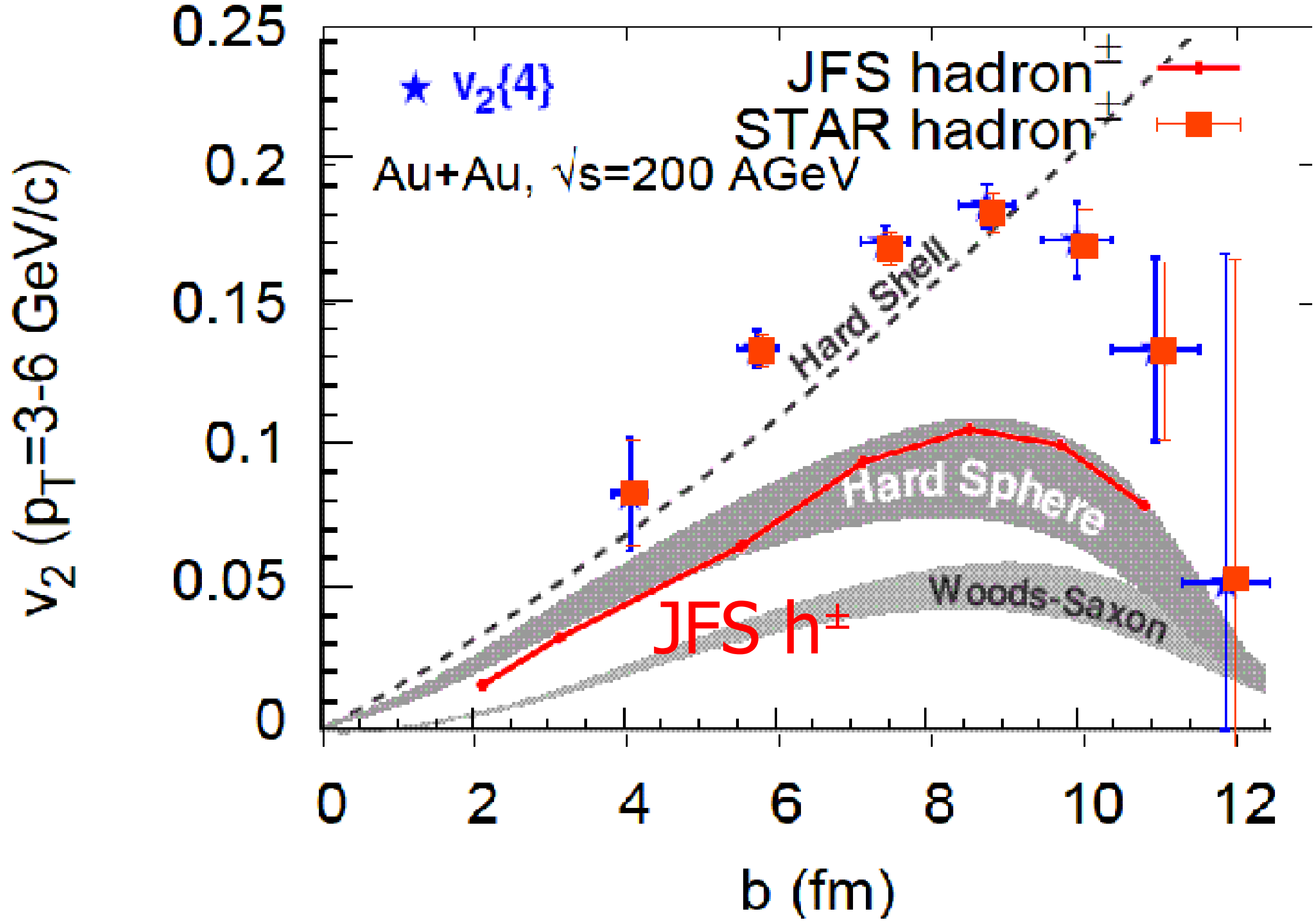
Elliptic Flow of pions

- **Observed pion v_2 at $p_T > 5$ GeV/c ~ 10 %**
  ↔ v2(JFS, $p_T > 5$ GeV/c) ~ 8 %



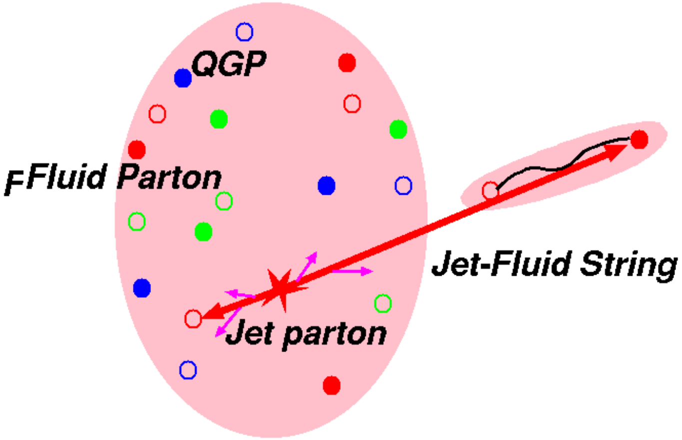
Impact Parameter Dependence

- **Mid-p_T v_2 ($3 < p_T < 6$ GeV/c) in JFS is larger than the "Strong E-loss Limit" with Woods-Saxon profile in Independent Fragmentation, but still smaller than Data.**



JFS Summary

- ***Jet-Fluid String (JFS) formation and decay*** **is proposed as a mechanism to produce high p_T hadrons.**
  - **Effecitve to produce high p_T hadrons**
  - **Event-by-Event Energy-Mom. conservation ↔ Ind. Frag.**
  - **Simple and small mass strings decaying into a few hadrons ↔ Ind. Frag.**
- **When we FIT p_T spectrum,** ***large v_2 emerges at high p_T***
  - **Large E-loss+fluid parton v_2**
- **Problems and Homeworks**
  - **Mechanism of large E-loss**
  - **d+Au fit → Cronin Effects**
  - **s-quarks, string spectral func.**



Backups

Comparison with Previous Works

- J. Casalderrey-Solana, E.V. Shuryak, hep-ph/0305160
  - Quarks, diquarks and gluons in QGP cut color flux (~ JFS).
  - Large E-loss is generated by "phaleron"
  - *Large E-loss leads "surface emission" → large v_2*
- Recombination (Duke-Osaka-(Minesota)-Nagoya)
  - Predicts large v_2 (~ 10 %) at high-pT
    - Sharply edged density dist. → E-loss $\propto L \rightarrow v_2 \approx 10$ %
    - Woods-Saxon density dist. $\rightarrow v_2 \approx 5$ %
  - Entropy problem: S(QGP) ≈ S(H) requires Res. and Strings
  - *Spectral Func.: δ func. ↔ θ func. in JFS*

K-factor

- K-factor → absolute value of σ_{jet}
- Experimental Data: pp → π^0 @ $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)

$$\frac{1}{\sigma^{exp}}\frac{d^2\sigma^{exp}}{2\pi p_T dp_T dy} = K \frac{\sigma^{pQCD(1st)}}{\sigma^{exp}}\frac{d^2N^{pQCD(1st)}}{2\pi p_T dp_T dy} \qquad A = K\frac{\sigma^{pQCD(1st)}}{\sigma^{exp}}$$

$\sigma^{Exp.}$ = 21.8 mb (trigger)

$\sigma^{pQCD(1st)}$ = 9.9 mb

- pythia6.3 fit:

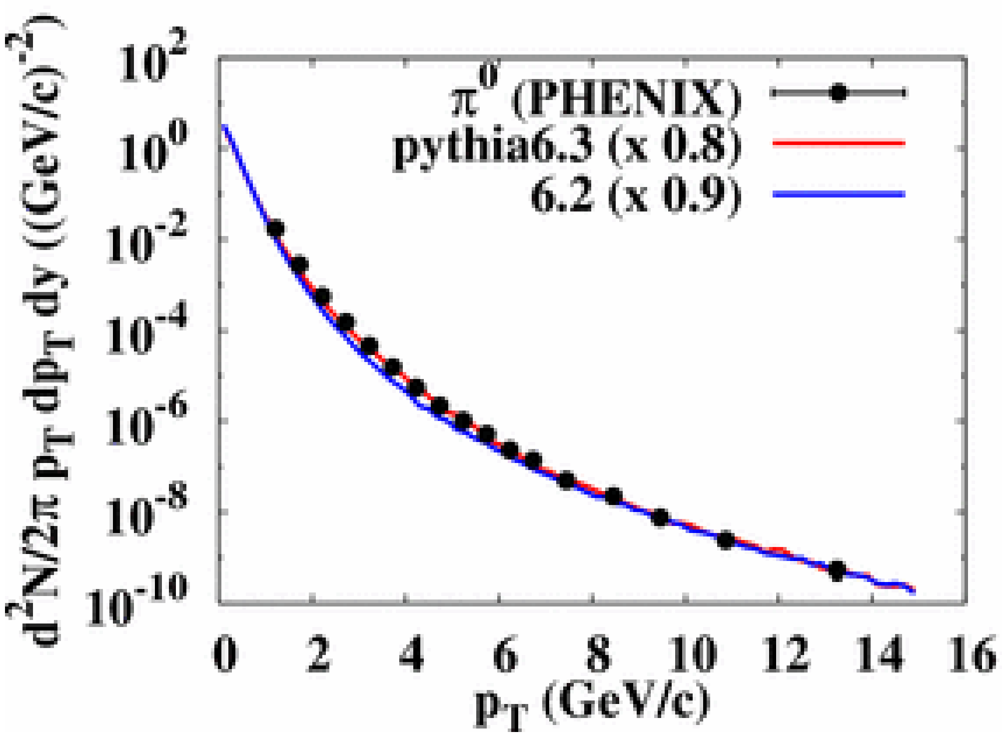
  A ≈ 0.8 → K = 1.8

  (σ_{jet} (p_T^{hard}>2Gev/c)≈ 17.5 mb)

- pythia6.2 fit:

  A ≈ 0.9 → K= 2.0

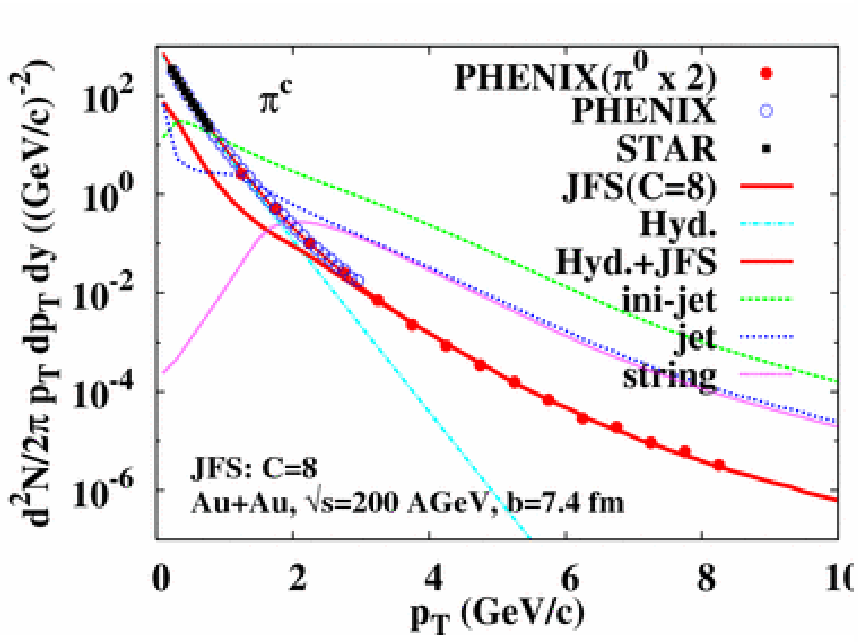
  (σ_{jet} ≈ 19.6 mb)

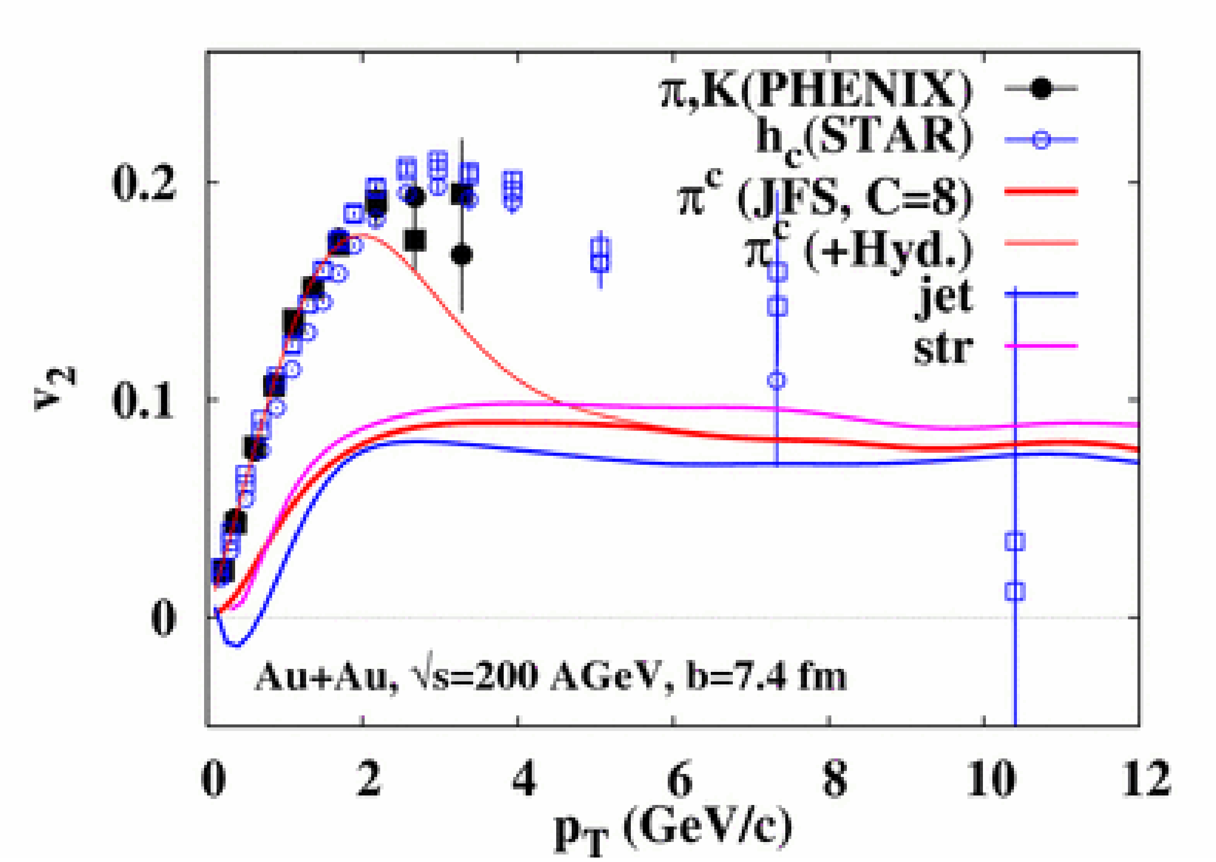


Combined with Low p_T spectrum

- **Low pT spectrum is assumed and combined.**

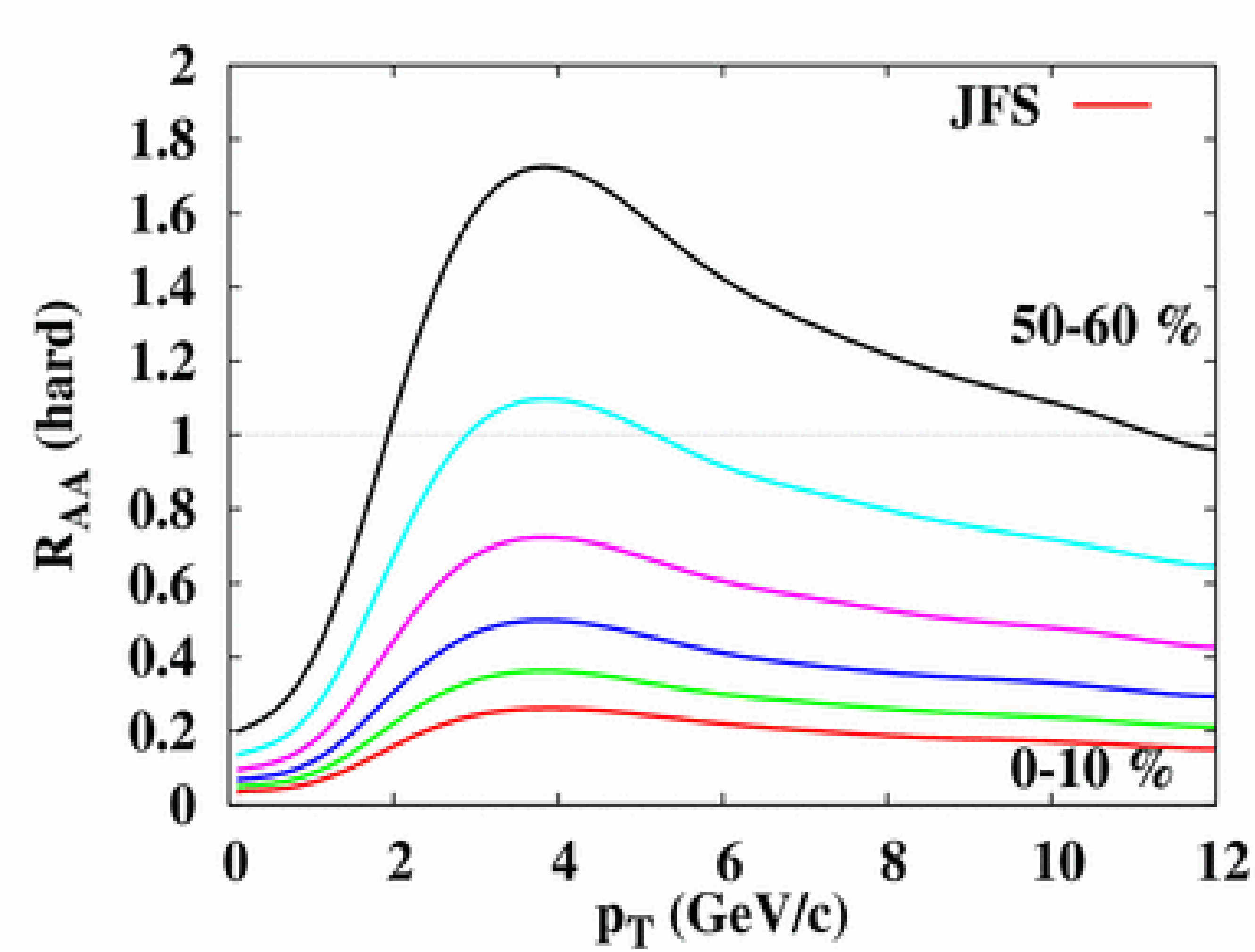
$$E\frac{d^3N_{Hyd}}{dp^3}(p_T)=A\exp(-p_T/T)(1+B/(1+(p_T/p_0)^8)) \qquad v_2^{Hyd}(p_T)=0.14\,p_T$$





Nuclear Modification Factor

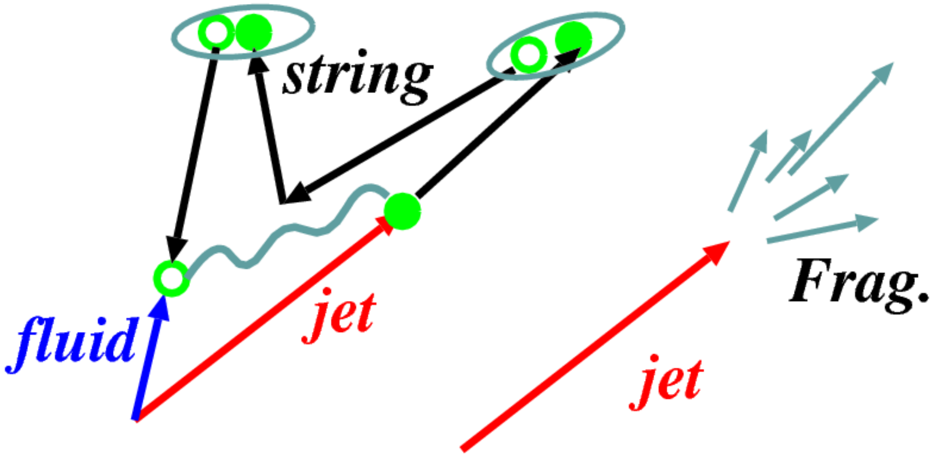
- p_T Deps.



Discussion

- Mechanism to produce high p_T hadrons in JFS
  - String Decay from Lorenz boosted fluid
  - Relative momentum is relatively small
    → Smaller number of hadrons with high p_T are formed

↔ Independent Frag. (Large no. of Low p_T hadrons)



Energy Loss Factor

- Additional Factor for Energy Loss → High p_T hadron yield
- Exp. Data: p_T spectra of π in Au+Au (PHENIX,STAR)

$$\frac{d^2 N^{Exp.}}{2\pi\, p_T\, d\, p_T\, dy} = N_{jet} \frac{1}{N_{jet}} \frac{d^2 N^{JFS}(C)}{2\pi\, p_T\, d\, p_T\, dy}$$

→ Determining N_{jet} is important !

Ncoll = 373 @ b=7.4 fm (PHENIX estimate)

σ^{NN}_{jet} = 17.5 mb (pp fit pythia 6.3), σ^{NN}_{tot} = 47. 4 mb (JAM)

$$N_{jet} = \sigma^{NN}_{jet} \int d_T^{2r}\, T_A(r_T + b/2)\, T_B(r_T - b/2) = \frac{\sigma^{NN}_{jet}}{\sigma^{NN}_{tot}} N_{coll}$$

$$T_A(r_T) = \int dz\, \rho(r_T, z)$$

Further Problems

- Very large energy loss is required to explain p_T spectrum.
  - C ≈ 8 in JFS ↔ C ≈ 2.7 in Hydro+Jet model (Hirano-Nara)

  Is it possible to justify this large energy loss ?
- Elliptic flow at medium pT is underestimated.
  → Fluid-Fluid String would be necessary to consider.
- Large baryon yield at medium pT may not be explained.
  → Three parton string ? (Jet-Fluid-Fluid, Fluid-Fluid-Fluid)
- String formation probability should be evaluated
  in pQCD matrix element + string level density.
- Strange hadrons