Heavy Ion Collisions
--- Past, Present, and Future ---

Seminar @ U. Tsukuba, 2007/10/18

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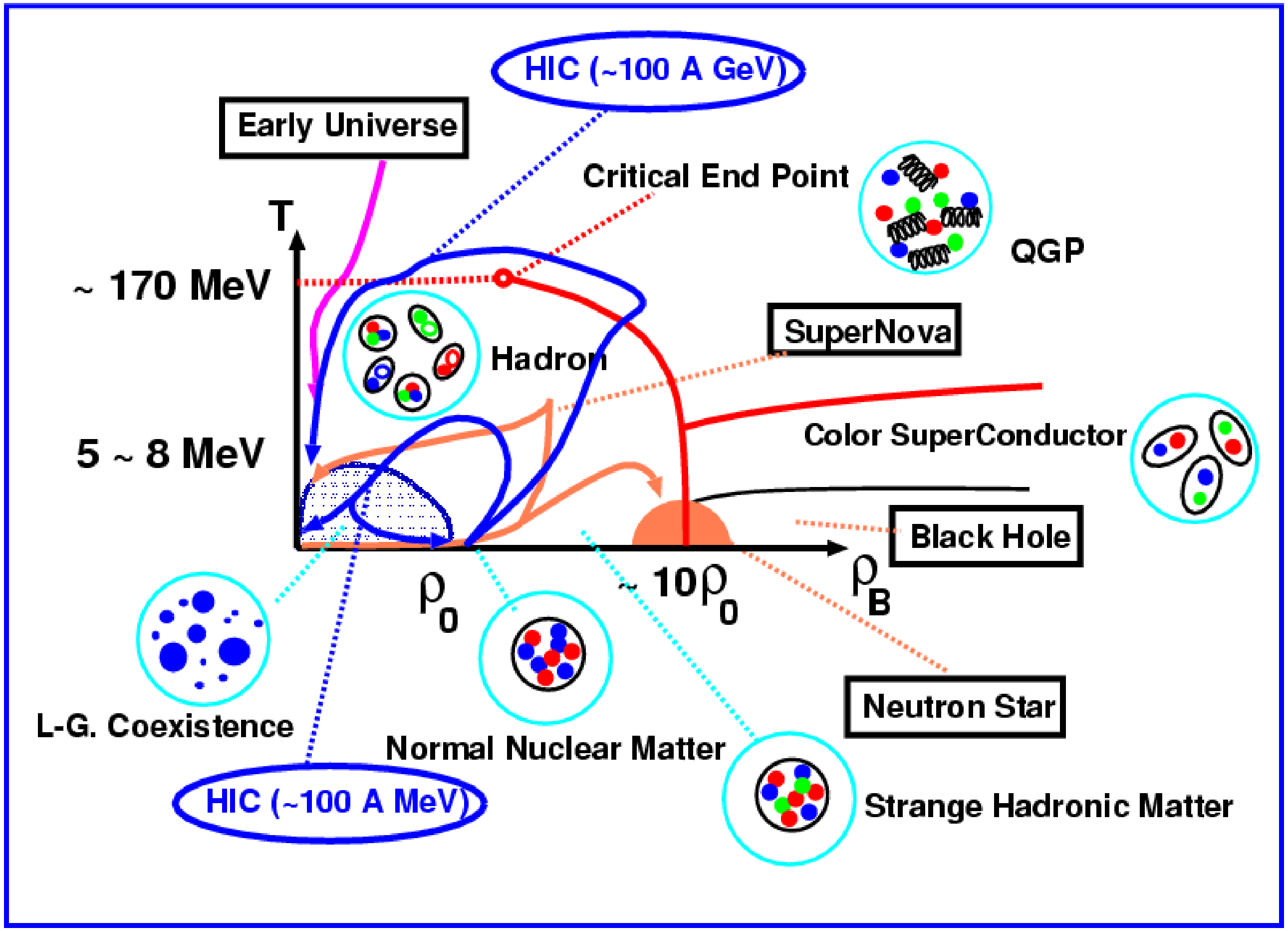
- **Introduction**
- **HIC at E_{inc} ~ 100 MeV/A**
- **HIC at E_{inc} ~ (1-100) GeV/A**
- **HIC at RHIC**
- **Summary**

Hadronic Matter Phase Diagram

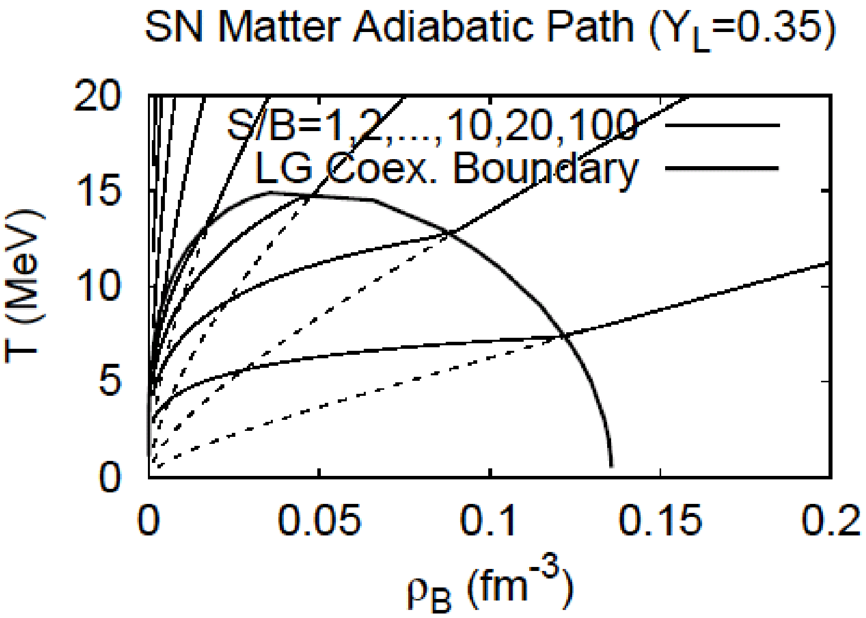


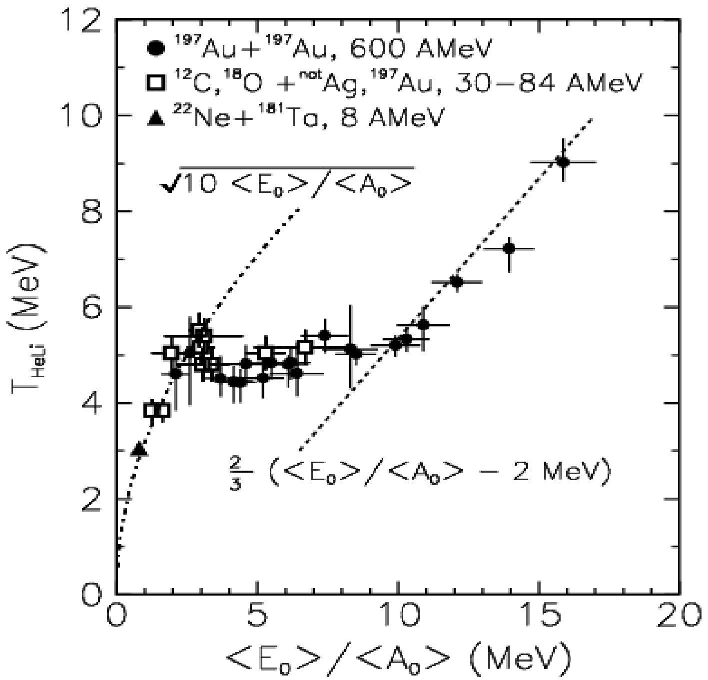
HIC (~ A few 100 A MeV) = Little Supernova
HIC (100+100 A GeV) = Little Big Bang

QCD 相転移=我々の宇宙の最後の真空相転移(菅沼談)

HIC at E_{inc} ~ a few 100 MeV/A

- **Physics of Fragmentation and Liquid-Gas Phase transition**
  - **低温では $\rho_B \sim (0.3\text{-}0.6)\ \rho_0$ において、$dP/d\rho_B < 0$ (spinodal region)**
    → 一様な核物質は不安定となり、液相と気相が共存する。





→ 重イオン反応という
非平衡・非一様な状況で
「相」の情報はみえるのか？

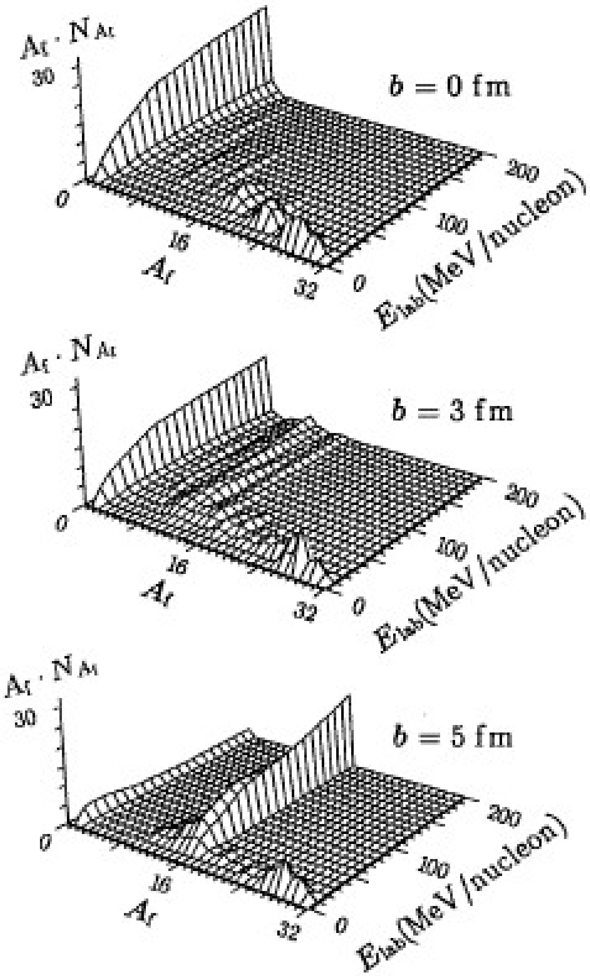
J. Pochadzalla et al (GSI-ALLADIN collab.), PRL 75 (1995) 1040.

$$Y_f \propto g_f \exp((B_f + Z\mu_p + N\mu_n)/T)$$

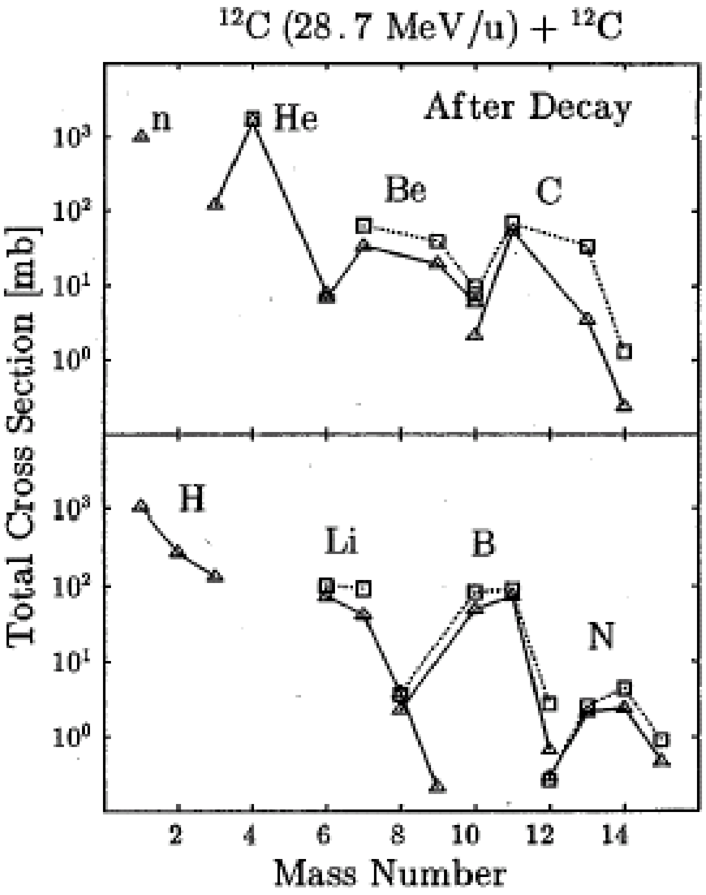
$$\rightarrow \frac{Y(^4He)/Y(^3He)}{Y(^7Li)/Y(^6Li)} \propto \exp(\Delta B/T)$$

Molecular Dynamics Study of Fragmentation

- **Quantum Molecular Dynamics (QMD)**
  & Antisymmetrized Molecular Dynamics (AMD)
  → Reaction Dynamics, Mass & Isotope Dist.



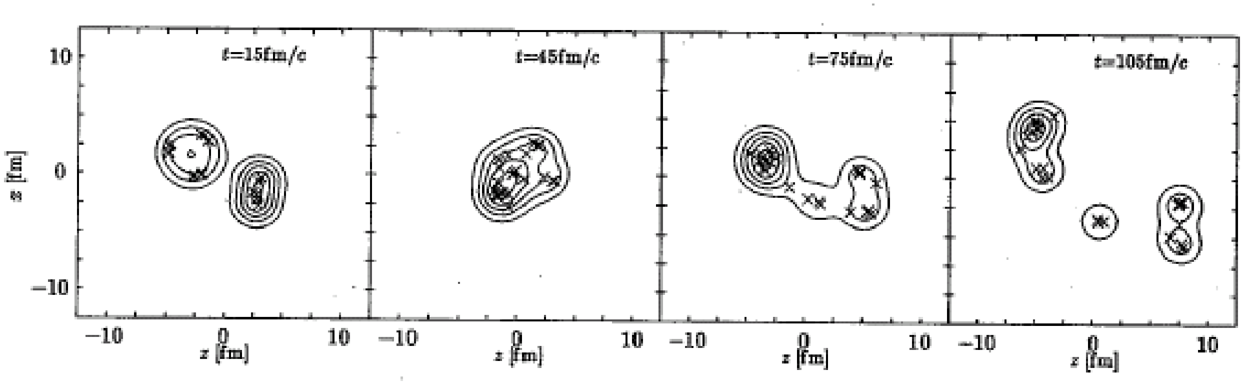
Maruyama, Ohnishi, Horiuchi, PRC45('92)2355

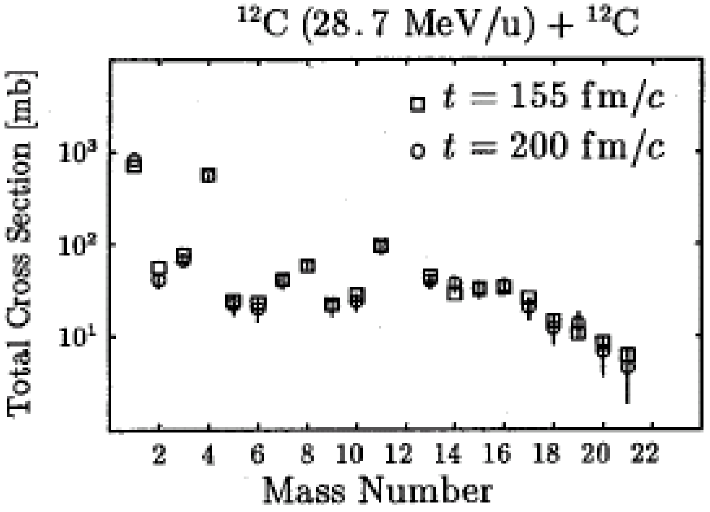


Ono, Horiuchi, Maruyama, Ohnishi, PTP87('92)1185

Molecular Dynamics Study of Fragmentation

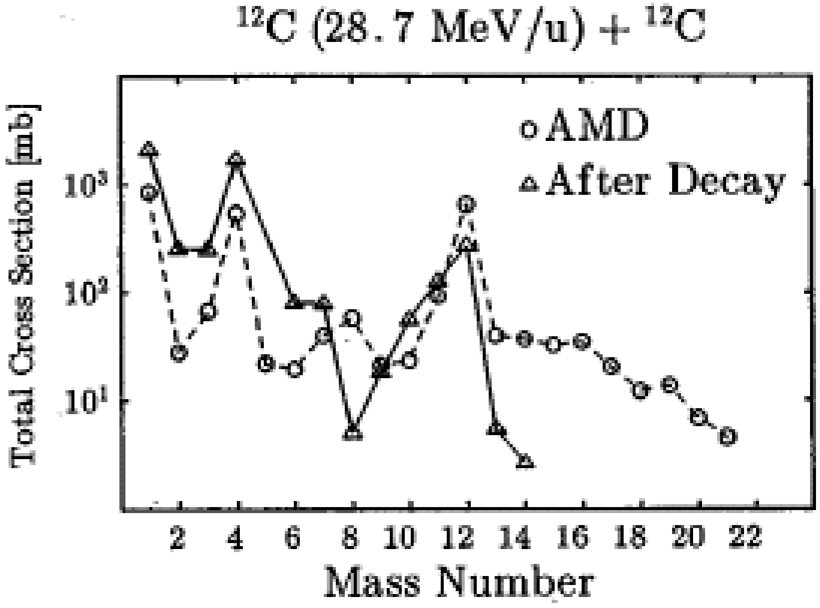
- フラグメント分布を求める手続き
  - Equation of Motion
    Gauss 波束の(反対称化)積波動関数+ 時間依存変分原理
    → (半古典的な)運動方程式
  - クラスター判定
    終状態で位相空間の近い核子の集合を原子核と判定
  - 統計崩壊
    原子核の励起エネルギーと角運動量から統計的に崩壊させる
    (after burner)



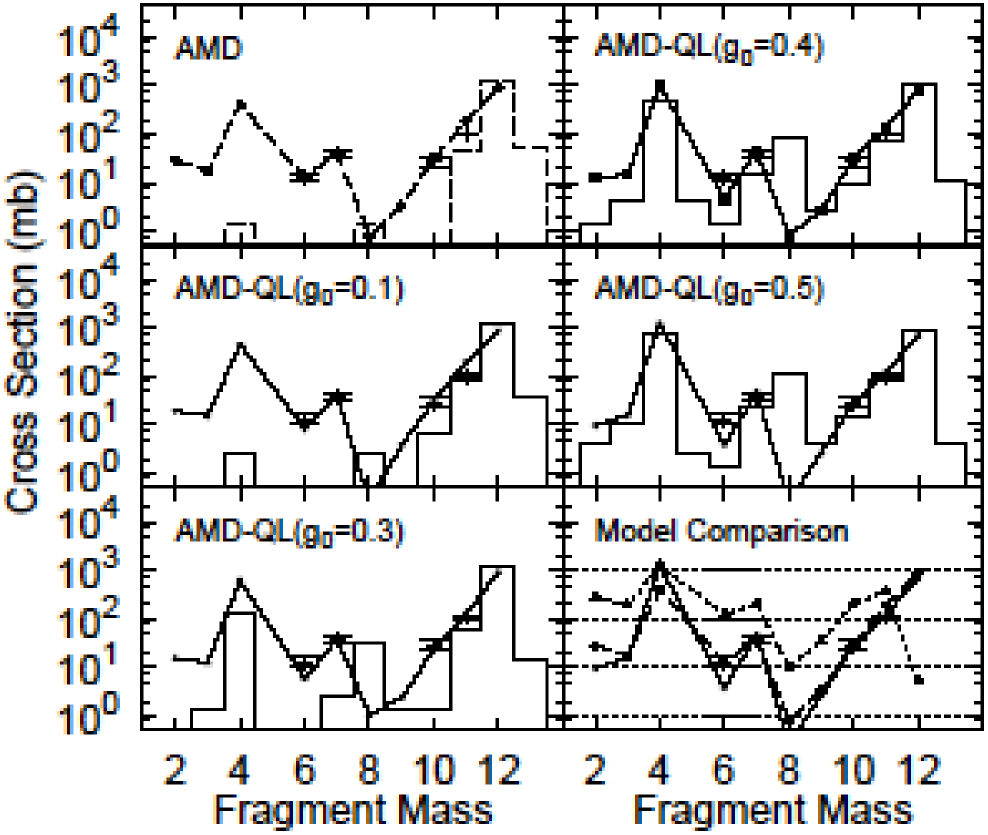


Molecular Dynamics Study of Fragmentation

- **粒子シミュレーションでの時間スケール**
  - **統計崩壊模型で与えられる時間スケールよりも長い**
    → 古典的シミュレーションの問題点



Ono et al., 1992



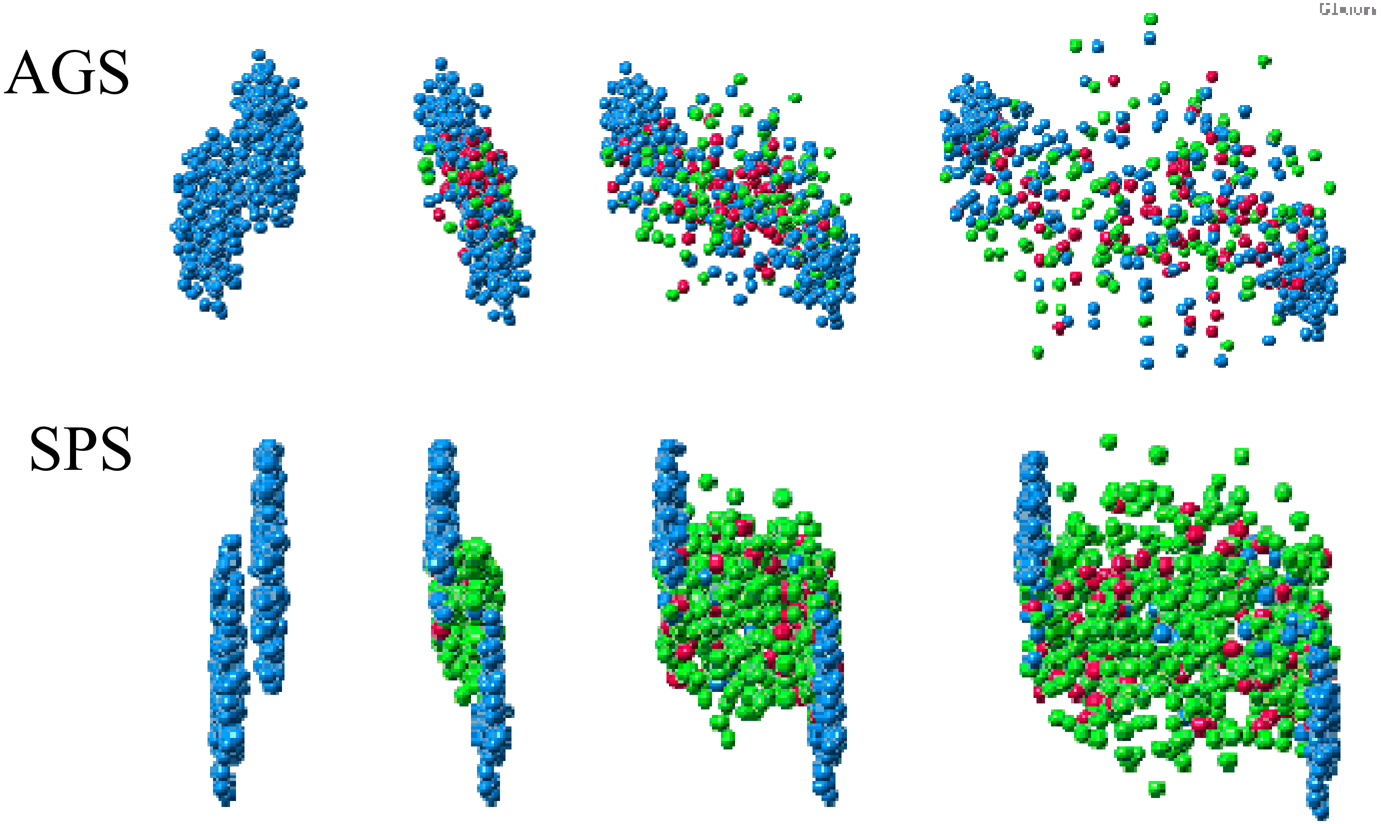
p+12C (45 MeV)
Hirata,Nara,Ohnishi,Harada,Randrup, 1999

Lessons from HIC @ 100 A MeV

- フラグメントの起源
  → まず質量数の大きな励起した原子核が作られ、
  その「統計的」崩壊により多くの原子核が作られる。
  - 「大きな原子核の高い励起状態の状態数 ~ 位相空間」
    → 短い時間スケールでの系の励起エネルギー分布は
    古典的なシミュレーションでよく説明可能であろう。
  - 基底状態フラグメント放出、低エネルギーでの核子放出には、
    エネルギー集中が必要→　統計崩壊模型との組み合わせが必要。
- 反応・崩壊の時間スケールが近い場合の問題点
  - 軽イオン(d, t, 3He, ...)、中間質量片(IMF)生成は
    比較的短時間でおこる
    → 量子揺らぎ、Coalescence 過程、軽イオン自体の輸送等を
    あらわに取り入れる必要がある。
  - 時間スケールをそのまま信頼できないだろう例(東大関連の仕事)
    → Penta Quark の崩壊幅、超新星での Pasta 状態生成時間
    (おそらく古典シミュレーションより短い時間でおこる。結論は問題なし)

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**

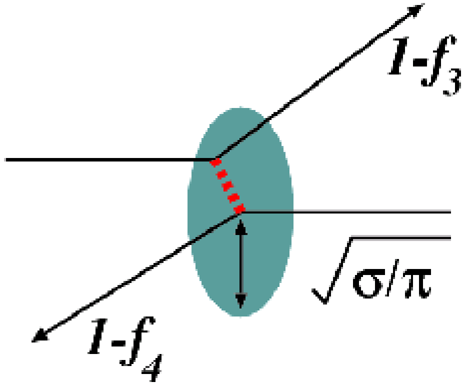
→ 低エネルギーで重要な平均場理論と
高エネルギー(>100 A MeV) で支配的なカスケード過程を統合

→ どのような粒子自由度を導入すべきか？

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

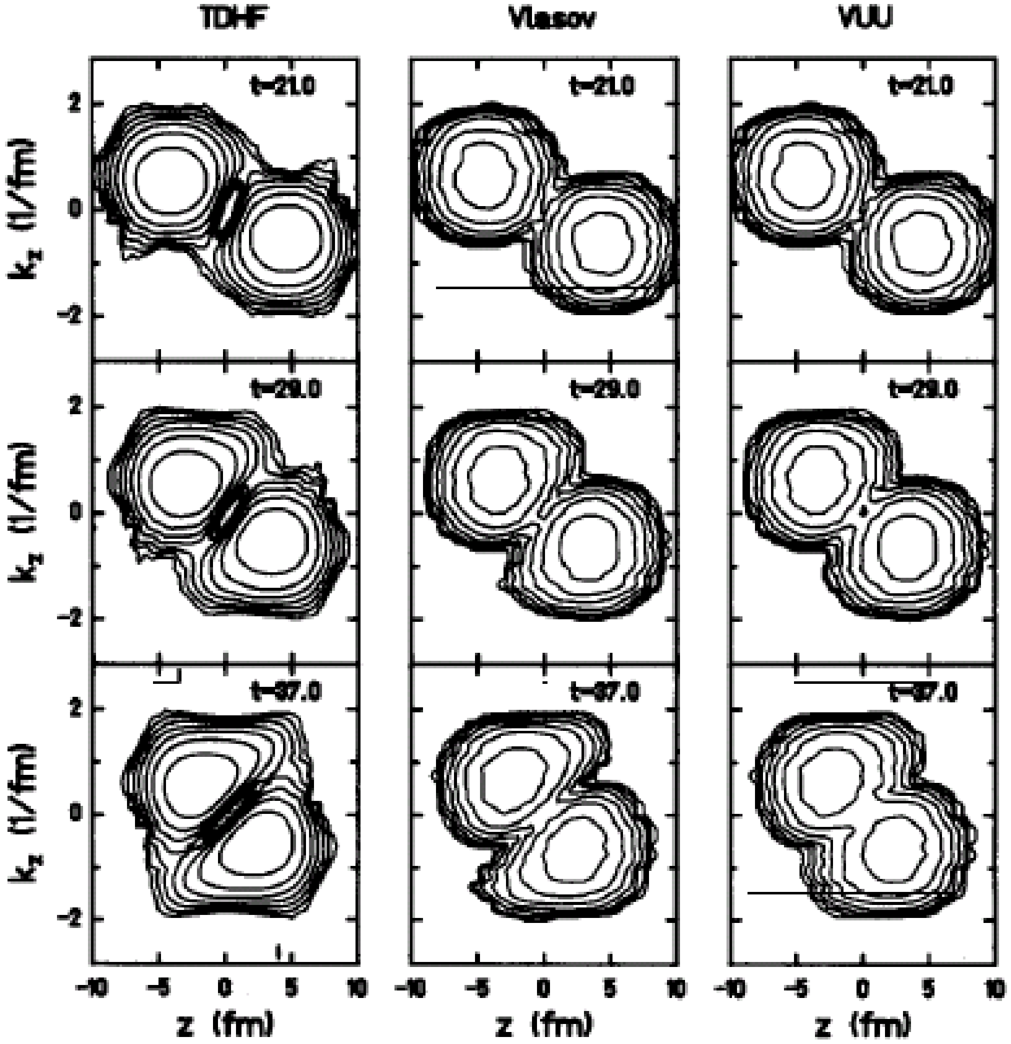
$$I_{coll}[f] = -\frac{1}{2}\int \frac{d^3 p_2\, d\Omega}{(2\pi\hbar)^3} v_{12} \frac{d\sigma}{d\Omega}$$

$$\times \quad [f f_2 (1-f_3)(1-f_4) - f_3 f_4 (1-f)(1-f_2)]$$



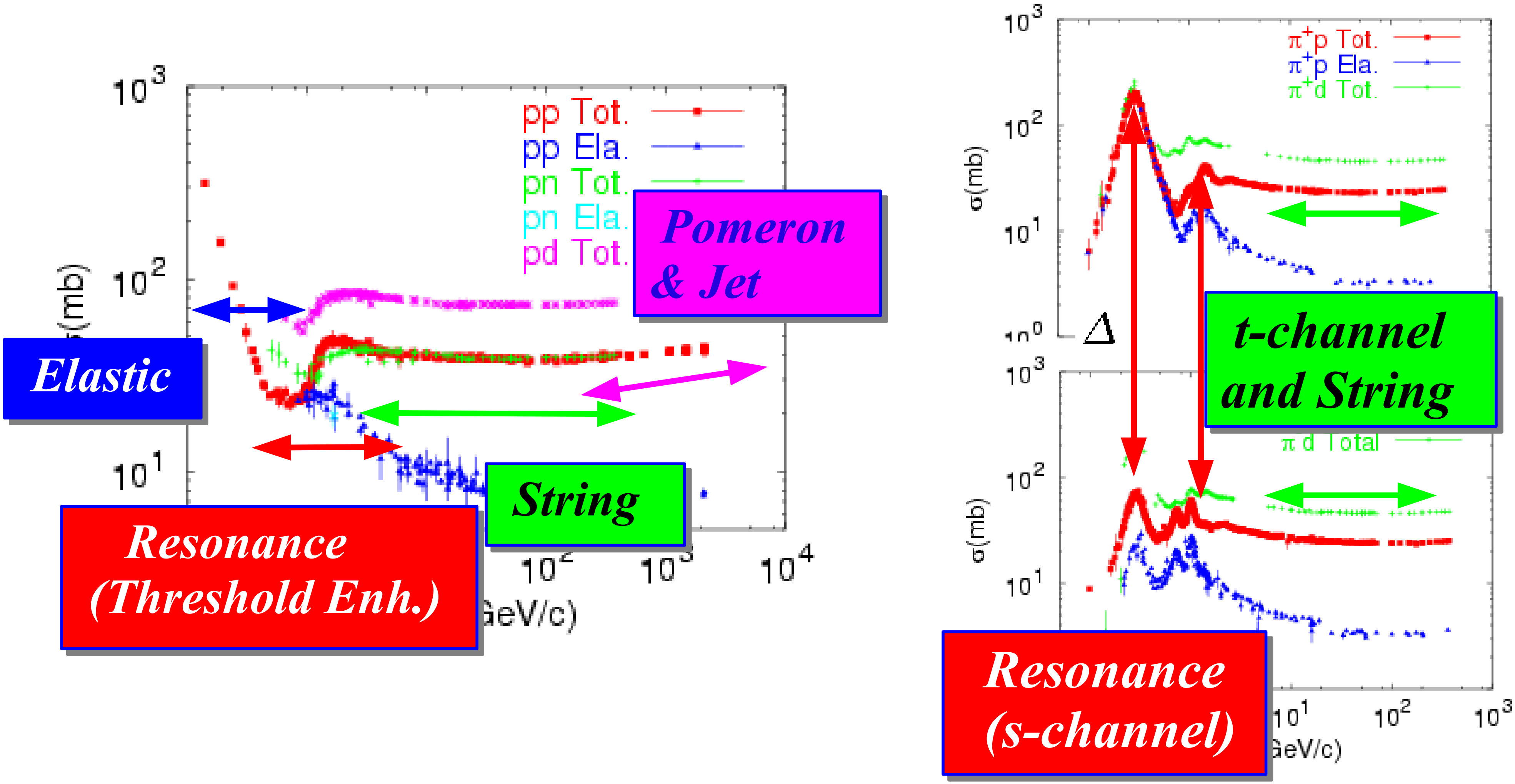
Comarison of TDHF, Vlasov and BUU(VUU)

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



Hadron-Hadron Cross Sections

From Particle Data Group



Elastic

Resonance (Threshold Enh.)

String

Pomeron & Jet

Δ

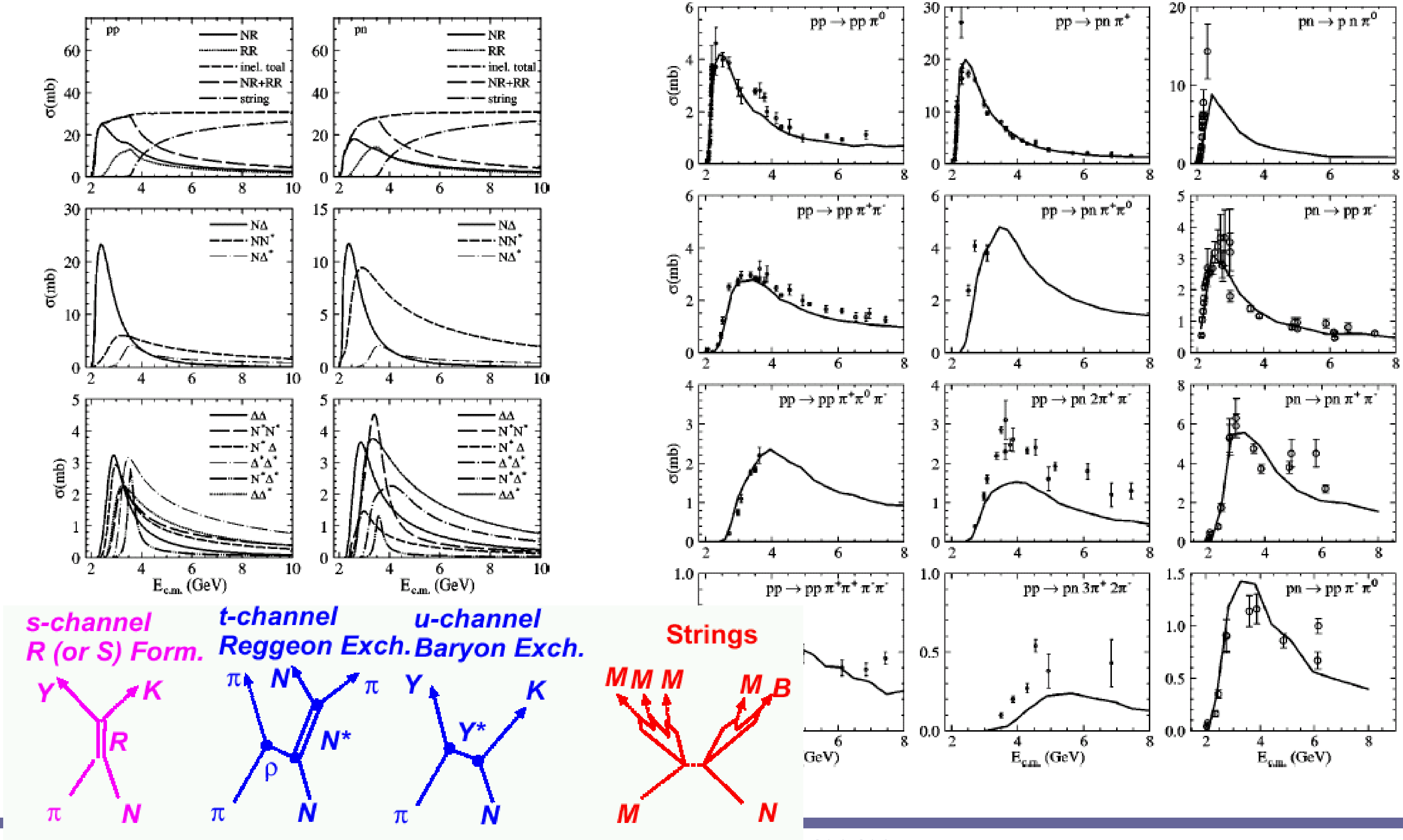
t-channel and String

Resonance (s-channel)

Exclusive Cross Sections in JAM

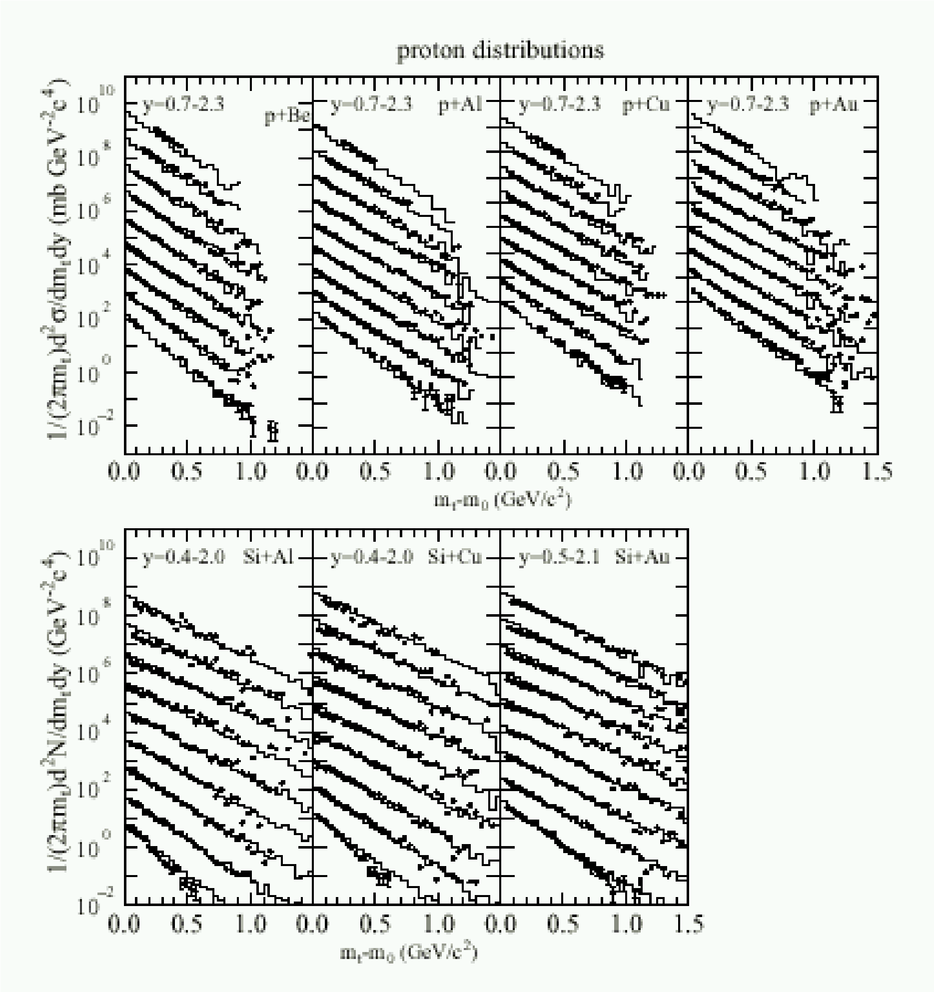
Nara, Otuka, AO, Niita, Chiba (JAM), PRC 61 (2000), 024901.

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

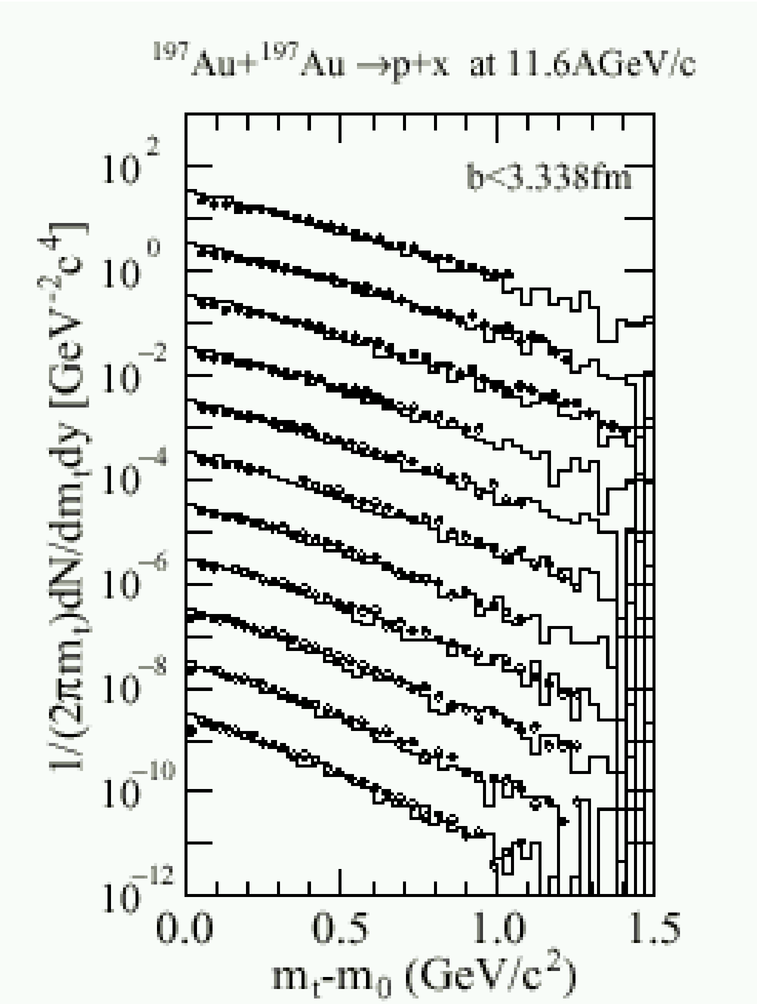


JAM Results @ AGS Energy

- **p-A collisions**



- **Au+Au Collision**



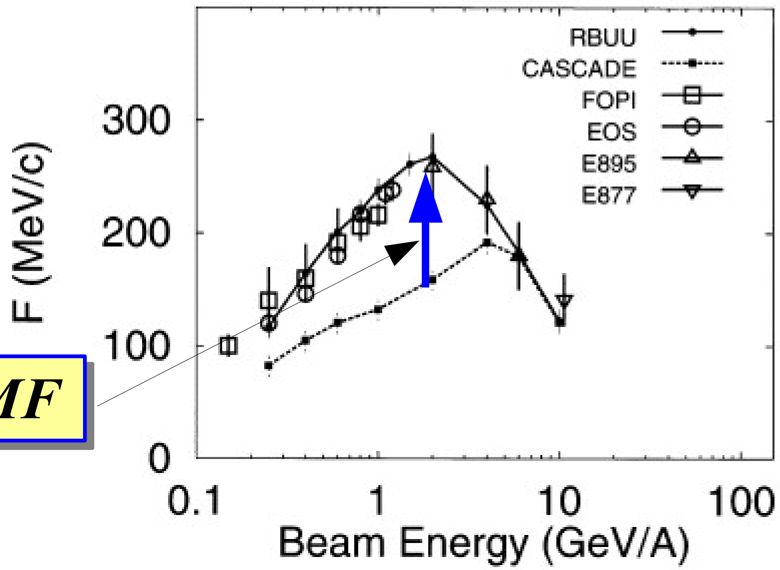
JAM explains AA collisions as well as pA collisions:
→ Good Elementary Cross Sections for MM, MN and NN

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

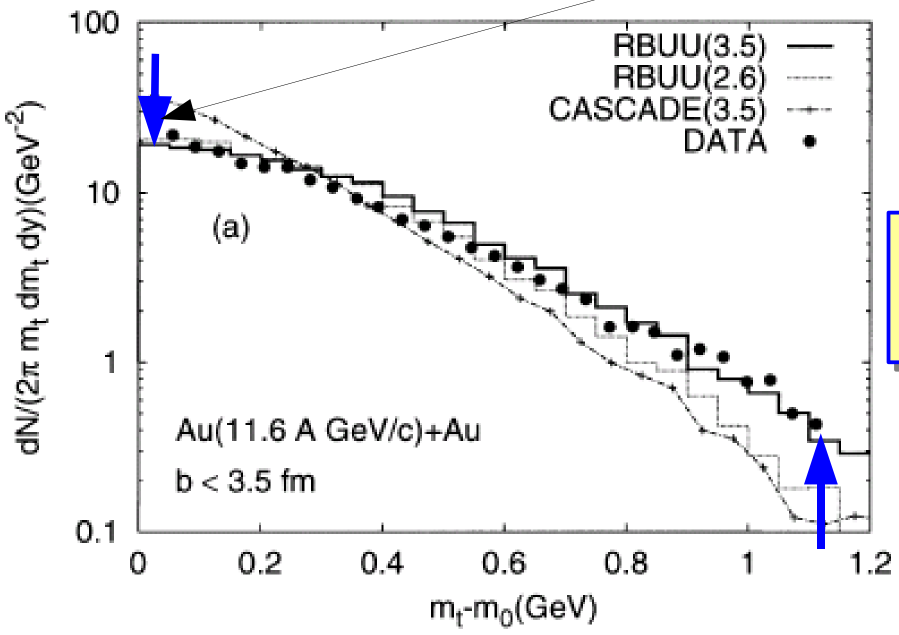
Sahu, Cassing, Mosel, Ohnishi, 2000

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



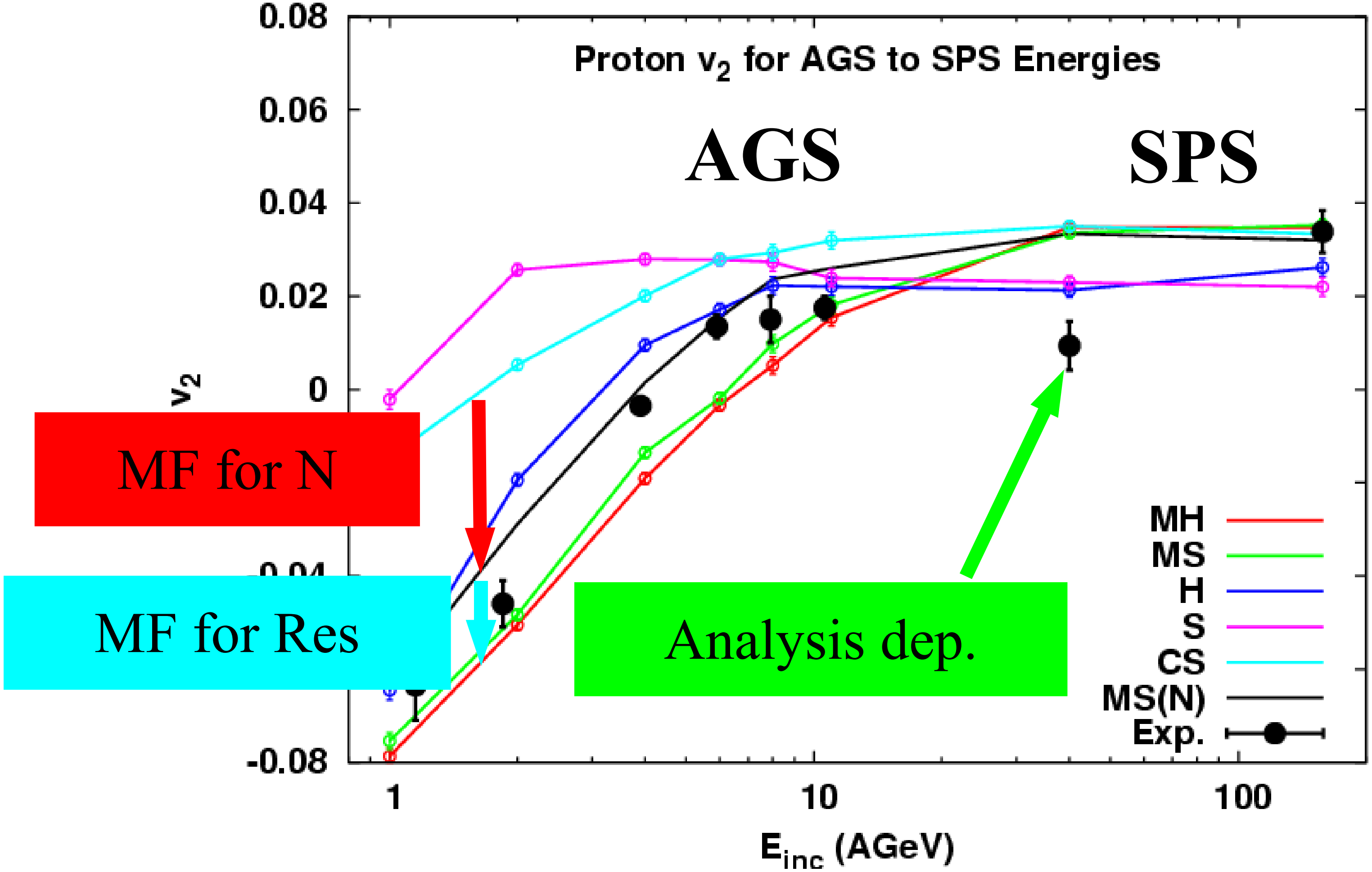
Switching √s = 3.5 GeV
(JAM fit)

Switching √s = 2.6 GeV
(HSD default)

Elliptic Flow from AGS to SPS

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

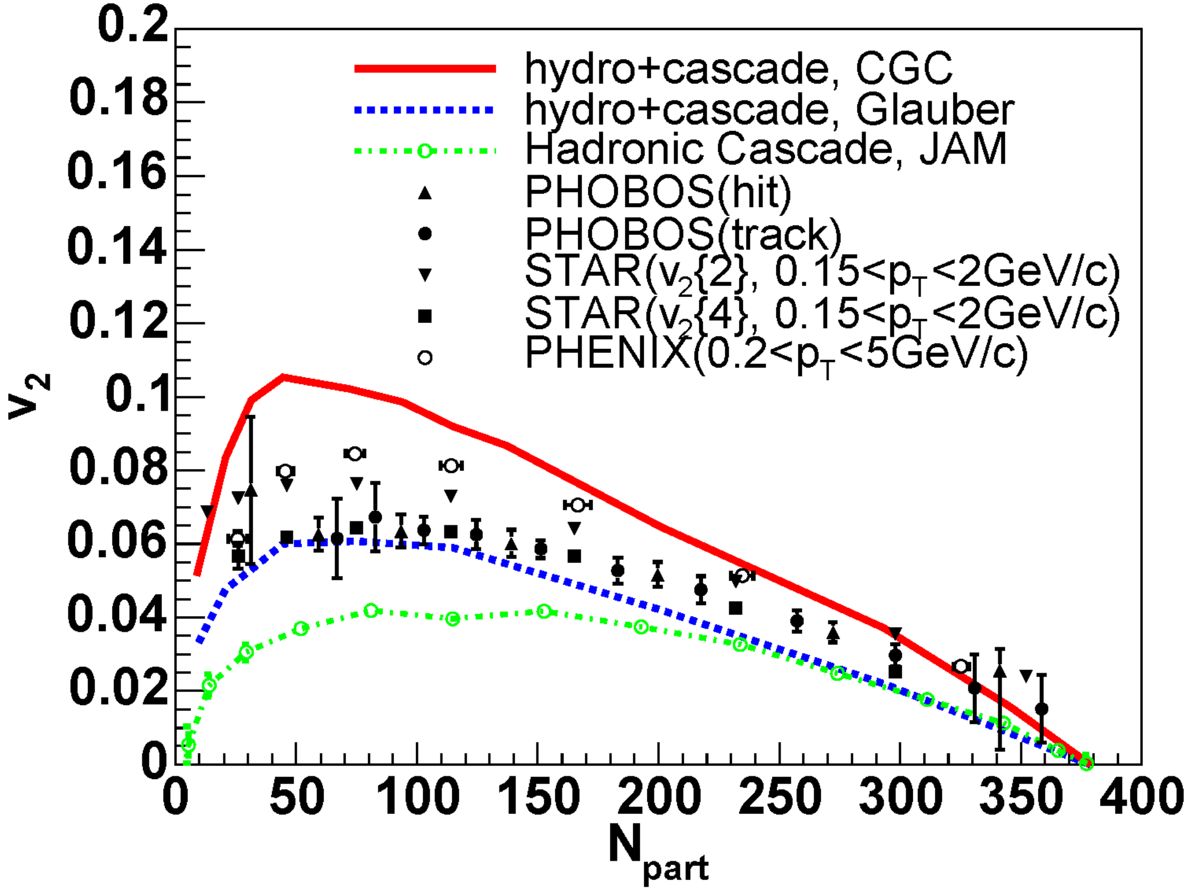
- **JAM-MF with p dep. MF explains proton v2 at 1-158 A GeV**
  - **v2 is not very sensitive to K (incompressibility)**
  - **Data lies between MS(B) and MS(N)**



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.



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)

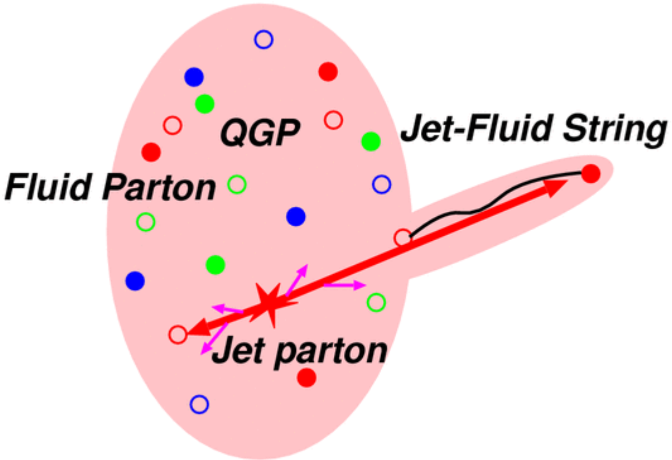
Jet-Fluid String 模型における粒子相関

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)

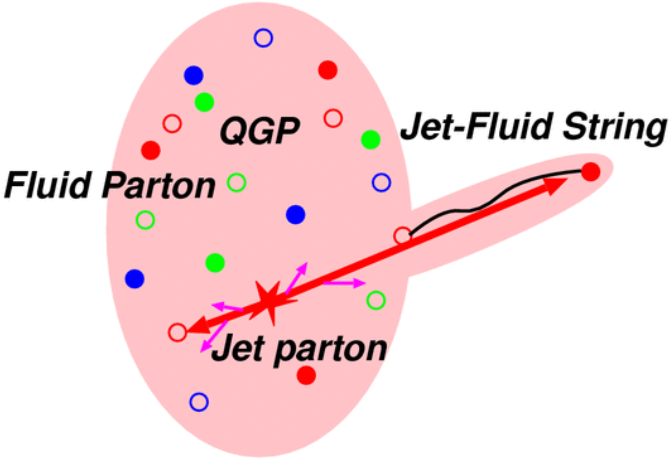
Sahu et al. Pramana 67 ('07)257 (cascade → low p_T data except for v_2)

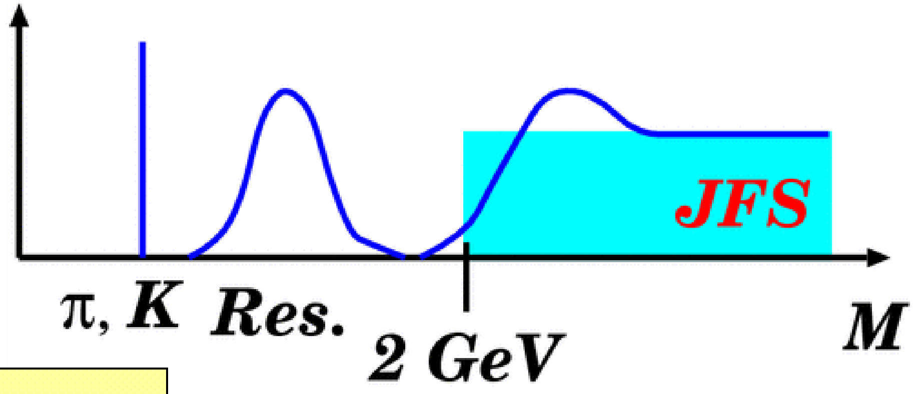
Parton Cascade (Kinder-Geiger) (Parton cluster → hadrons)

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 $\Theta(\sqrt{s} - 2\ \mathrm{GeV})$**



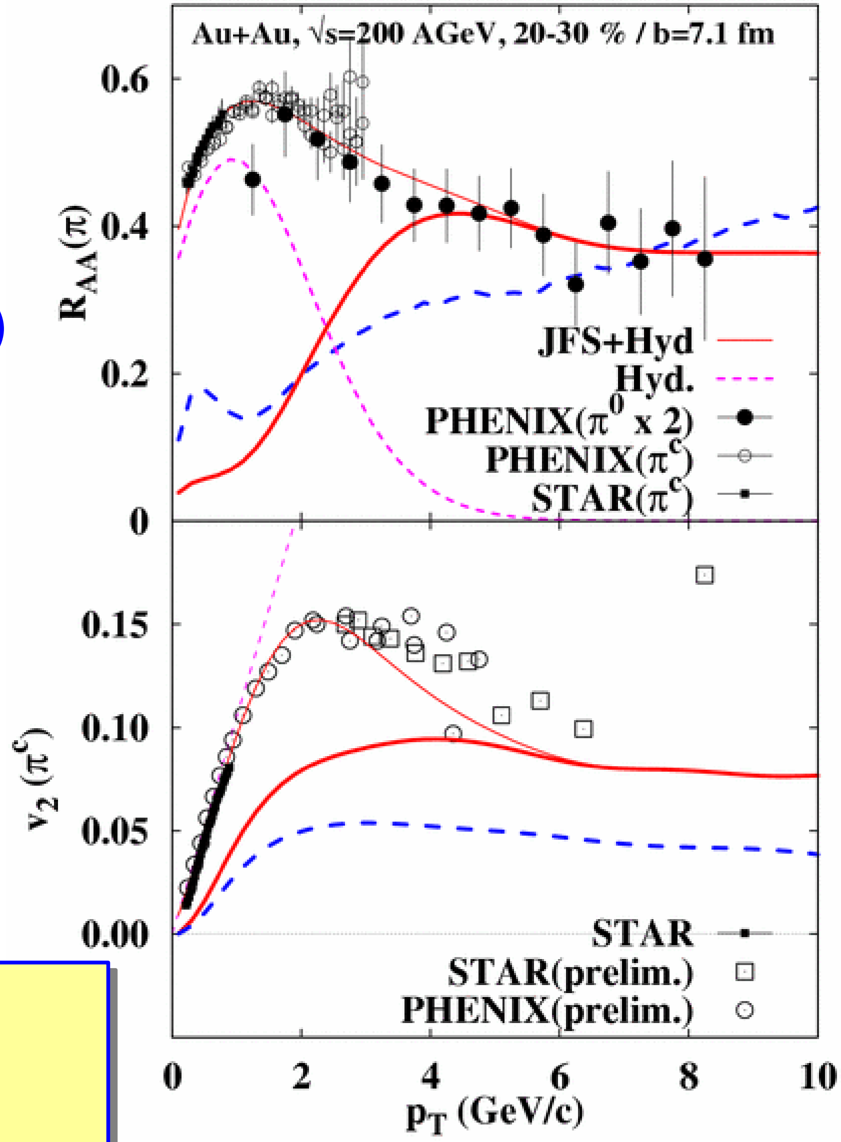


$$D(j\rightarrow h)=\int d^3k_f\, f_f(k_f, T, u_\mu, \boldsymbol{x}(\tau_f))$$
$$\times S(s=(k_j+k_f)^2)\, D(String(\sqrt{s}, k_j, k_f)\rightarrow h)$$

Jet-Fluid String formation and decay: Results

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

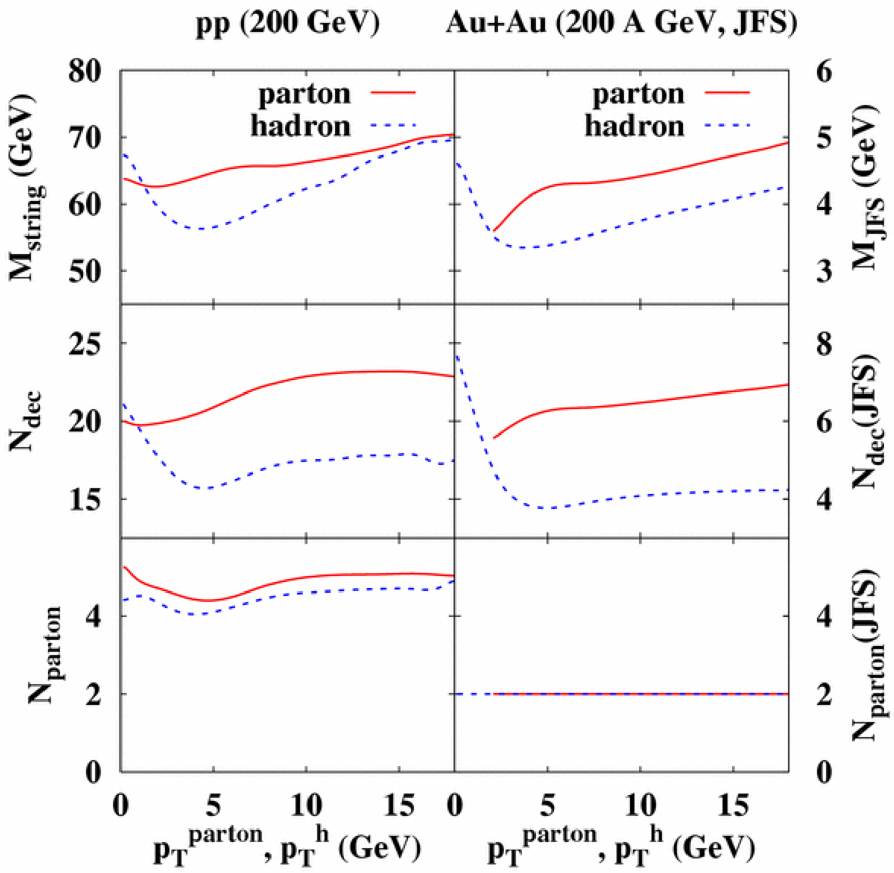
- **高いhigh p_Tハドロン生成率**
  → 大きなエネルギー損失が必要
  - **R_{AA} fit → E-loss fac. C = (6-8)**
    C = (2-3) in Hydro+Jet (Hirano-Nara)
- **大きなエネルギー損失**
  +流体パートンのv_2
  → high p_T での大きな v_2
  - **$v_2 \sim 8$ % @ $p_T > 6$ GeV/c**
    $v_2 \sim$ (3-5) % in Indep. Frag.

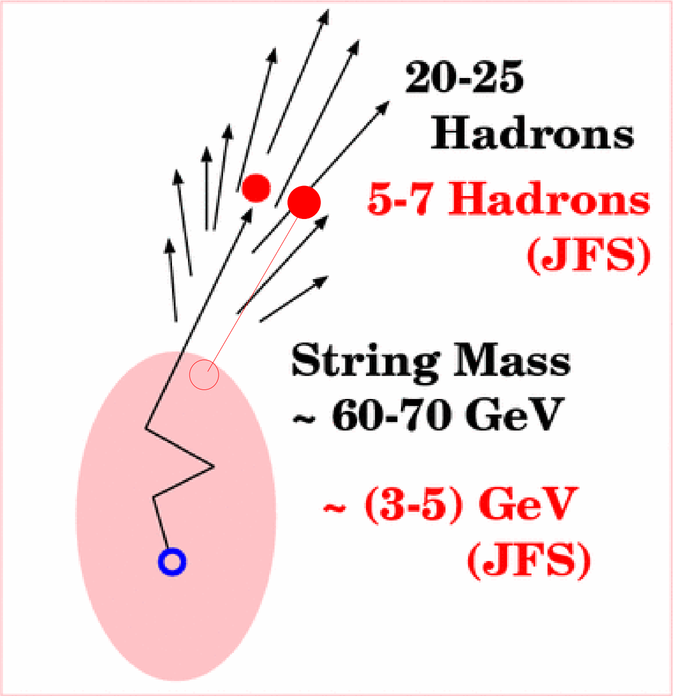


High pTでRAAを説明するE-lossで
v2 データをほぼ説明
→なぜhigh pTハドロンが作られやすい？

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



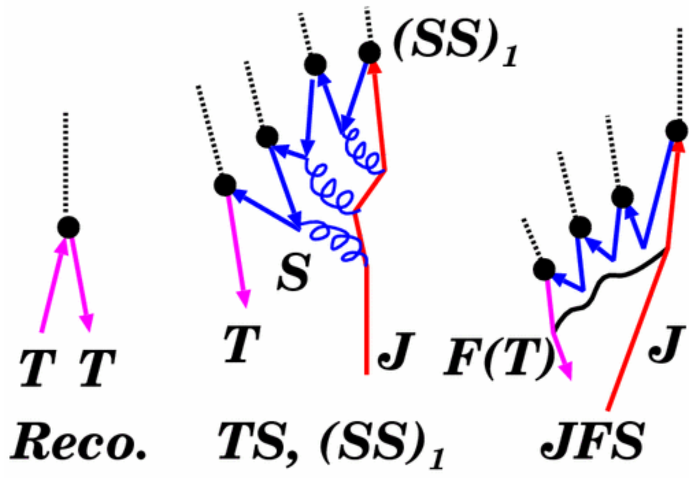


ジェットパートンの独立破砕
~ 重いストリングの崩壊
→ AA衝突のジェット破砕段階で
これほど重いストリングが作られるか？

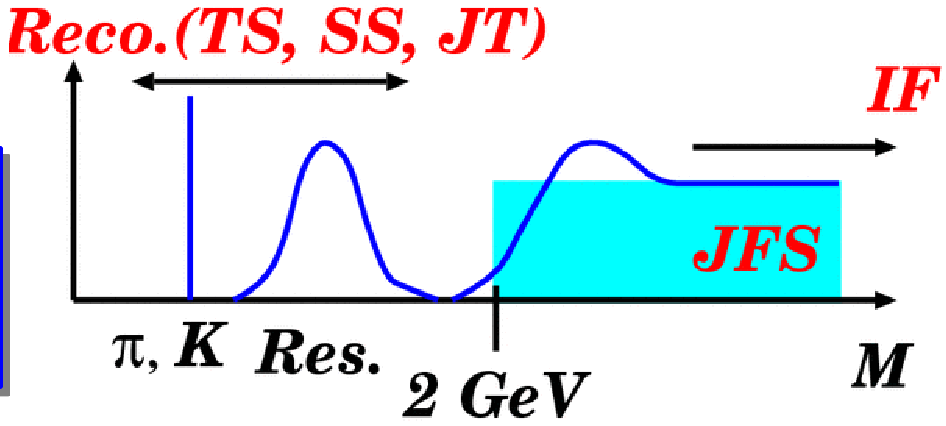
High p_T 領域での再結合模型との比較

- **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

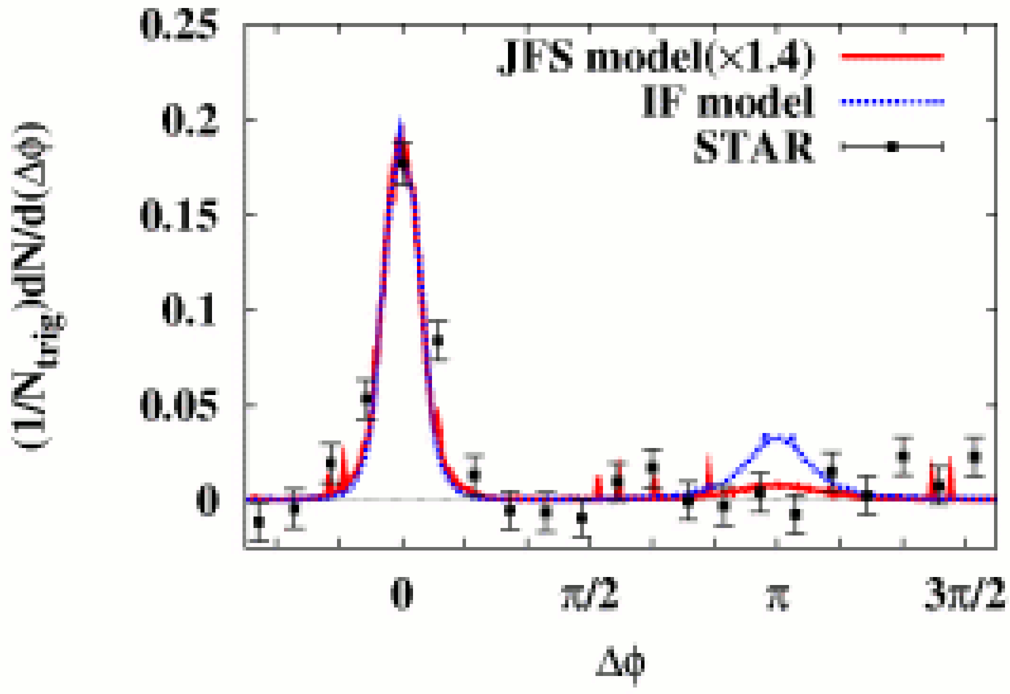


- *T+"part of Jet"によるハドロン生成*
- *π の直接生成より共鳴崩壊が有利*
  → JFSの描像と無矛盾



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

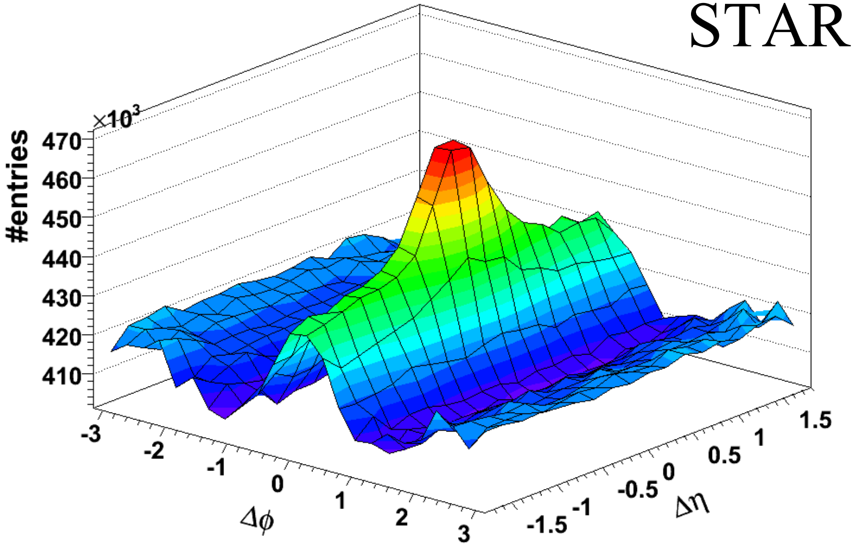


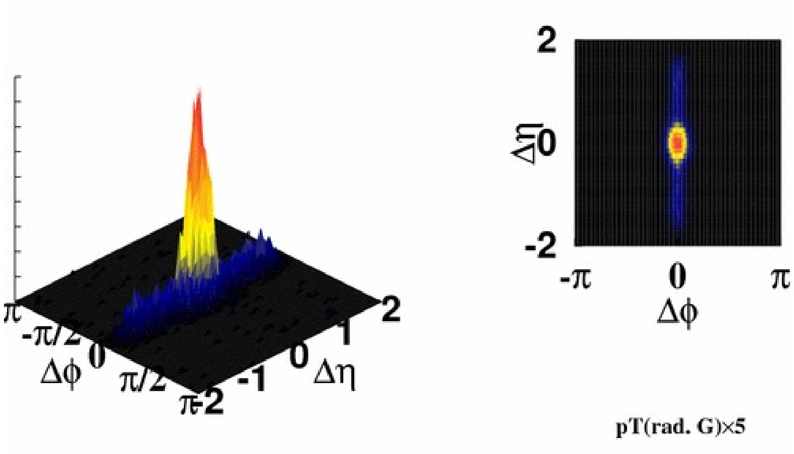
水川、卒論

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....)

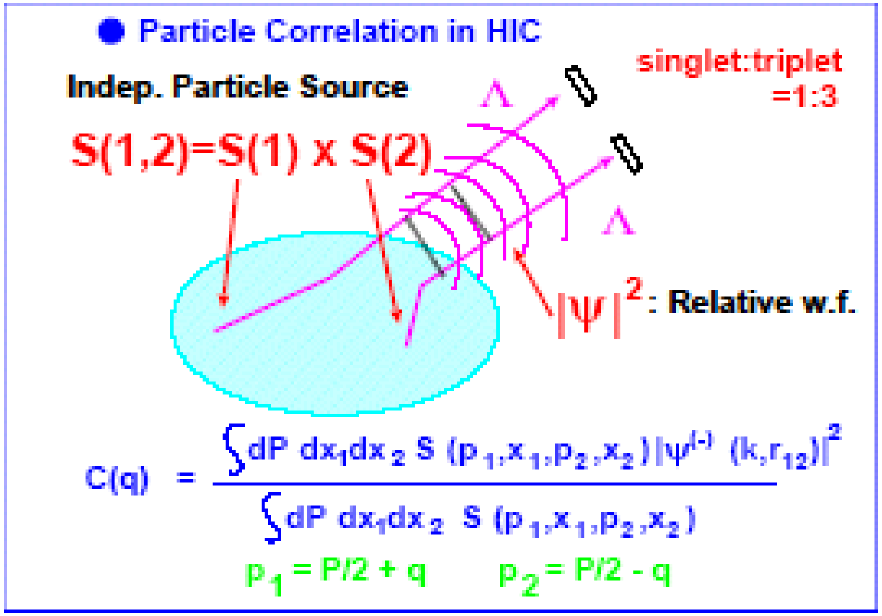
- 分かったこと → jet parton が局所熱平衡に達した bulk quark-gluon matter 中をエネルギーを失いながら伝播し、parton が再結合してハドロンを作る。
  - jet parton は媒質中でエネルギーを失ってからハドロン化
  - bulk 部分が完全流体によりうまく記述できる
    (SPS energy までは、流体模型は「アイデア」を与えるが、定量的には 粒子シミュレーションに勝てなかった。)
  - 中間 pT 領域で baryon が meson より多く、v2 も大きい。
- 分かりつつあること → QCD 物性
  - jet は流体への 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.....

Heavy-Ion Collisions – Past, Present, Future --

- 重イオン反応は相図の広い範囲を実験室で探る唯一の手段
- ただし非平衡・非一様な現象なので輸送現象を扱う動力学が必要
  - SPS まで → ハドロン・ストリング輸送、RHIC → Hydro, Jet, ...
- 正しい自由度での動力学を作らないと現象は記述できない
- 多くの粒子は「崩壊」から作られる
  - 励起した大きな原子核の崩壊 → fragments
  - resonance, string の崩壊 → hadrons
  - jet, fluid の「崩壊」 → hadrons
- 古典的な輸送模型では「時間スケール」が大きな問題
  - (基底状態の) fragment 生成はきわめて「量子論的」な過程
  - Resonance, string 崩壊は、端点の古典力学を追うよりも、量子論的な理論による崩壊を取り入れることが望ましい。
  - fragment 生成で(量子論的) coalescense は比較的重要な役割を持つ

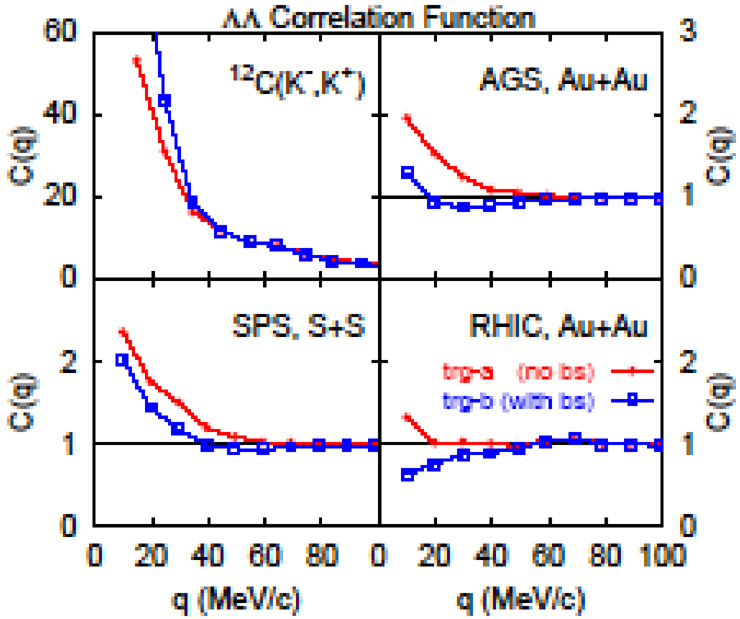
Near Future --- ΛΛ correlation ---

- **Longstanding problem in hadron spectroscopy: Does H (S=-2, B=2) dibaryon below ΛΛ threshold ?**
- **RHIC may solve this problem.**
  - **If ΛΛ bound, continuum w.f. must be orthogonal to b.s.w.f and must have a node around the scattering length.**
  - **Source size at RHIC may be comparable to the scattering length, and w.f. are suppressed in the source, IFF ΛΛ bounds. (Int. between ΛΛ is attractive.)**



$$C(q) = \frac{\int dP\, dx_1 dx_2\, S(p_1,x_1,p_2,x_2)\, |\psi^{(-)}(k,r_{12})|^2}{\int dP\, dx_1 dx_2\, S(p_1,x_1,p_2,x_2)}$$

$p_1 = P/2 + q$ $p_2 = P/2 - q$



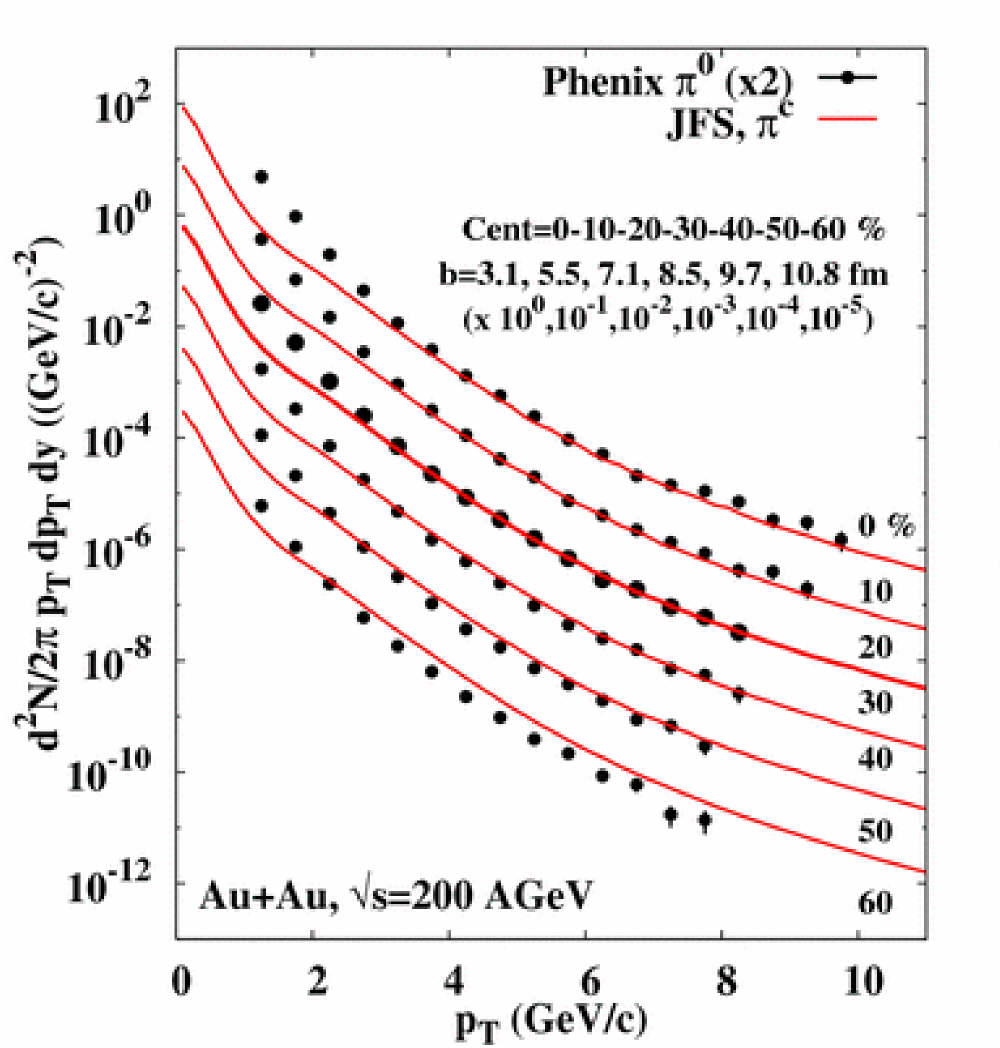
Ohnishi et al., NPA 670 (2000), 297c [arXiv:nucl-th/9903021]

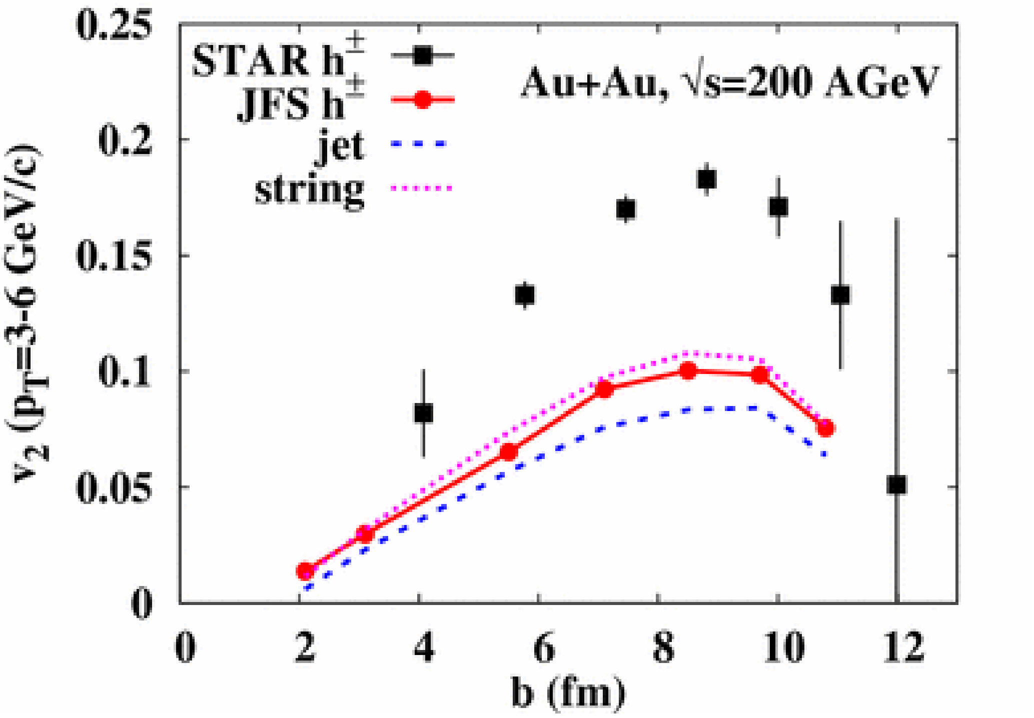
Future HIC Physics

- LHC & RHIC II: High pT Parton DOF becomes more important
  - Viscous Fluid ? (smaller coupling but larger density)
  - Feedback of Jet E-loss to Fluid (c.f. In supernovae, matter is hit by neutrinos and shock may revive.)
  - Jet-Jet interaction
  - Color Glass Condensate would be more clearly seen.
- FAIR: Competition of Hadronic EOS & QCD phase transition
  - 25-30 GeV/A → Highest density matter may be formed.
  - Coex. of hadronic and quark matter → Very small sound velocity
  - Critical End Point search
→ Can we distinguish the first order transition and cross over ?
- RIBF, RIA, ...
  - EOS of neutron rich matter, Fragmentation (Level density, Low E mode, ...),

Backups

Centrality Dependence



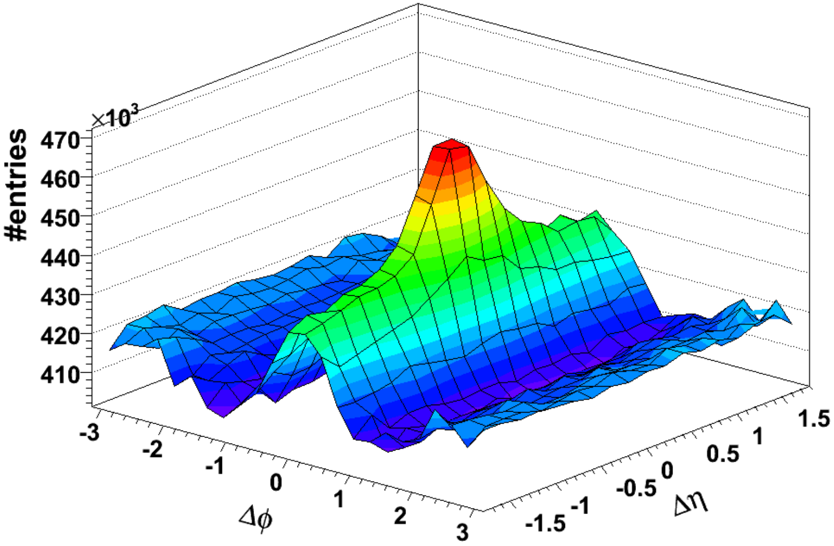


ジェット・リッジ構造

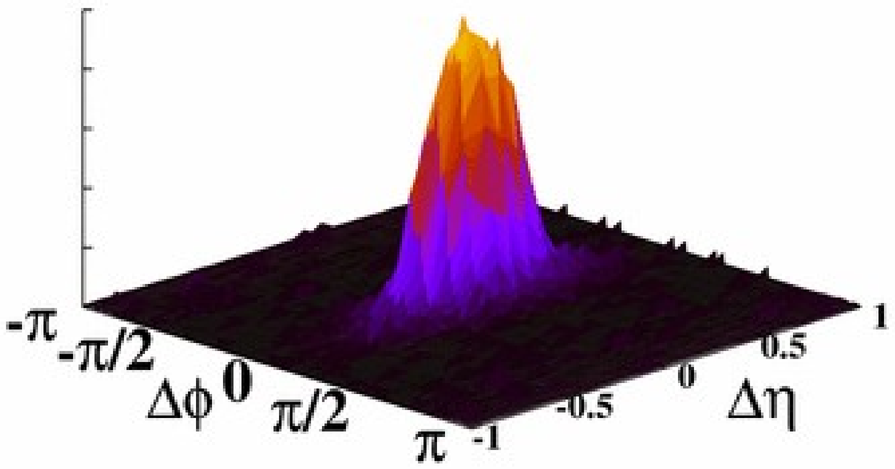
But, ...

- **JFS模型において、リッジ構造は見られていない (理由の分析は今後)**

Data



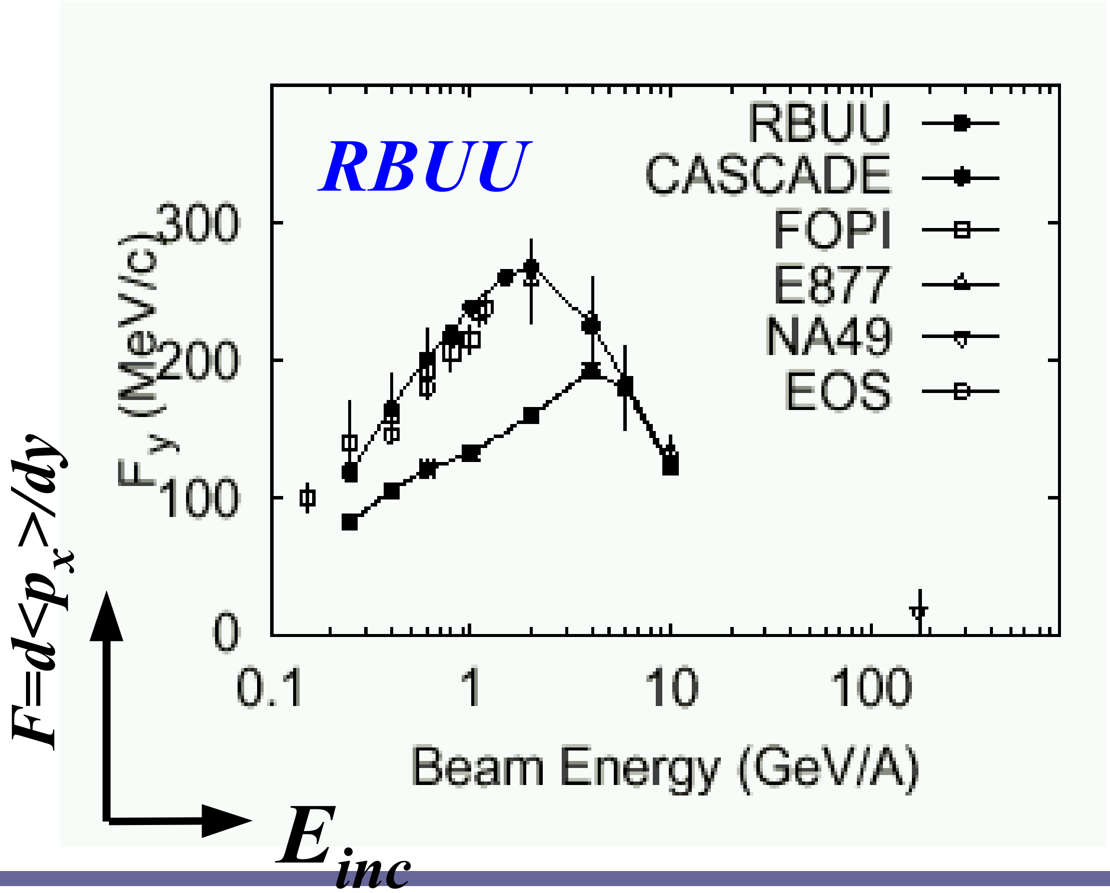
JFS

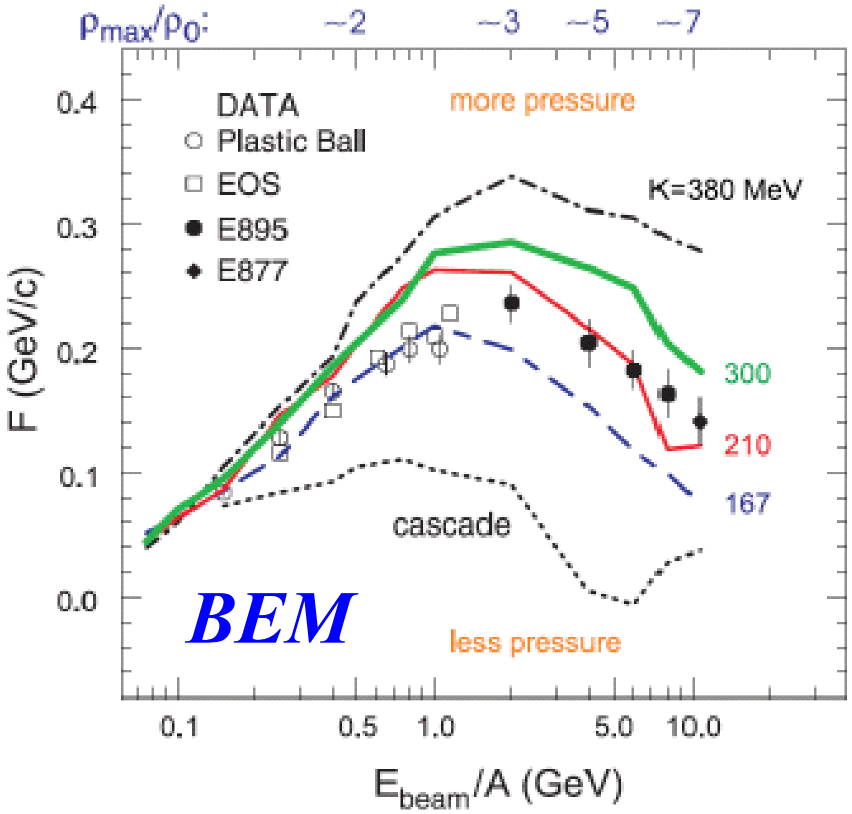


水川、卒論

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.)

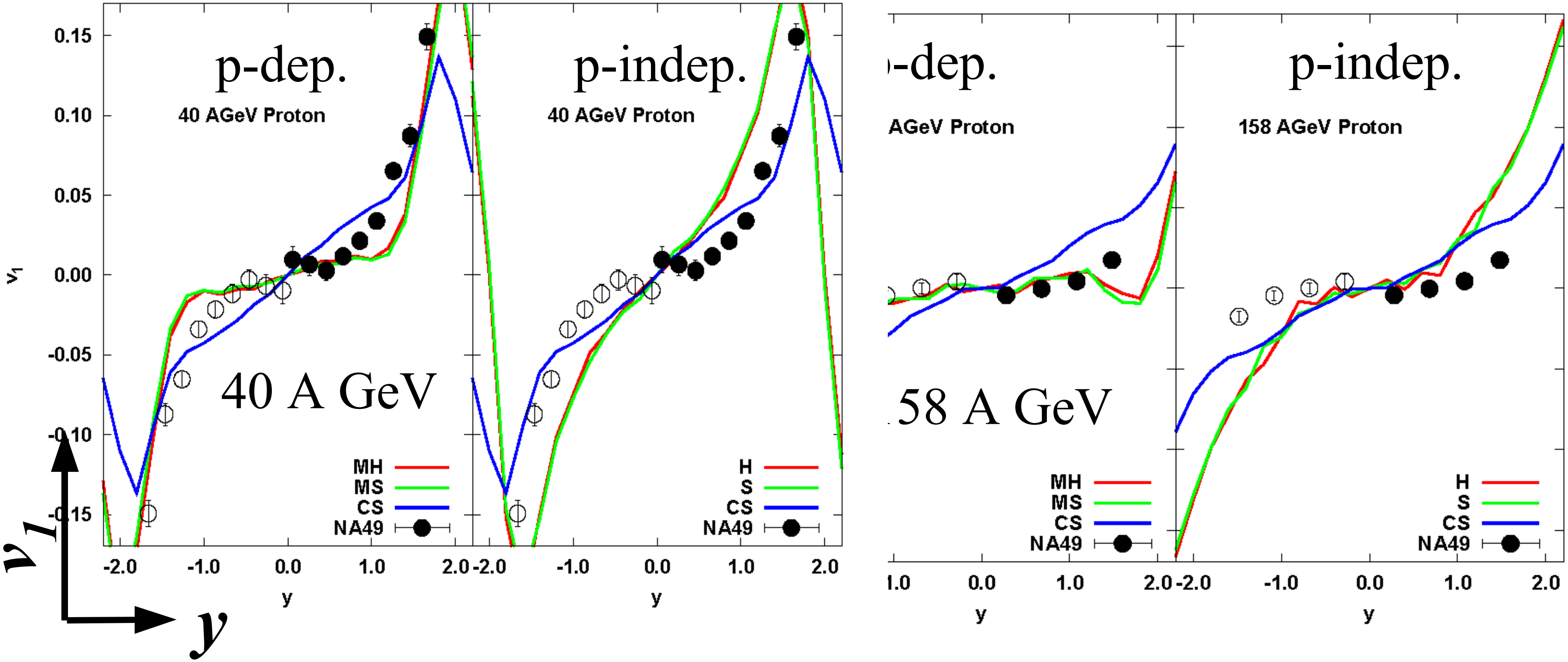




Directed flow v_1 at SPS

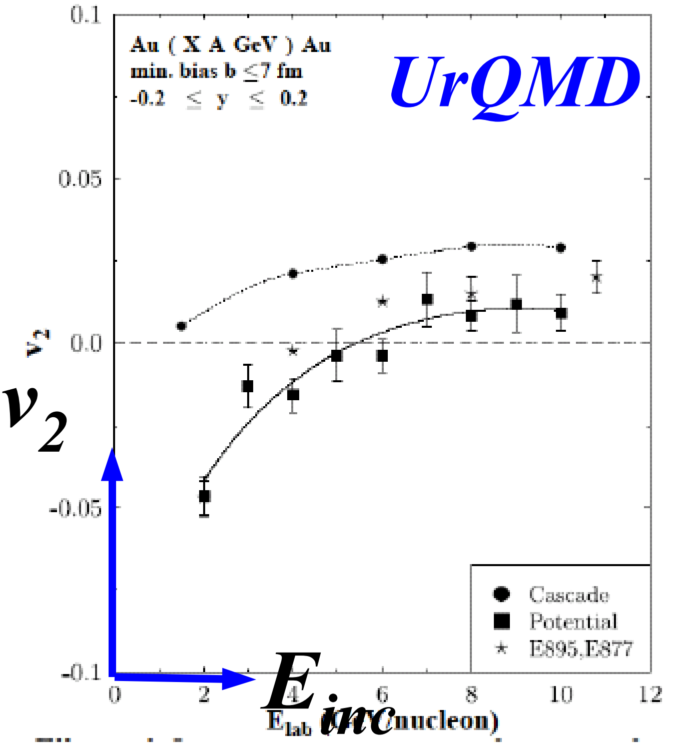
Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908

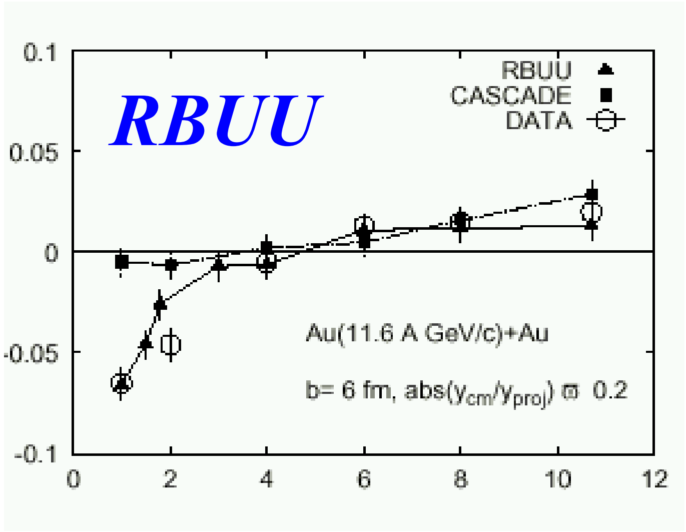
- **JAM-RQMD/S**
  - **p-dep. (indep.) MF suppresses (enhances) v_1.** $v_1 = \langle \cos\phi \rangle = \langle p_x / p_T \rangle$
  - **"Wiggle" behavior appears with p-dep. MF at 158 A GeV.**

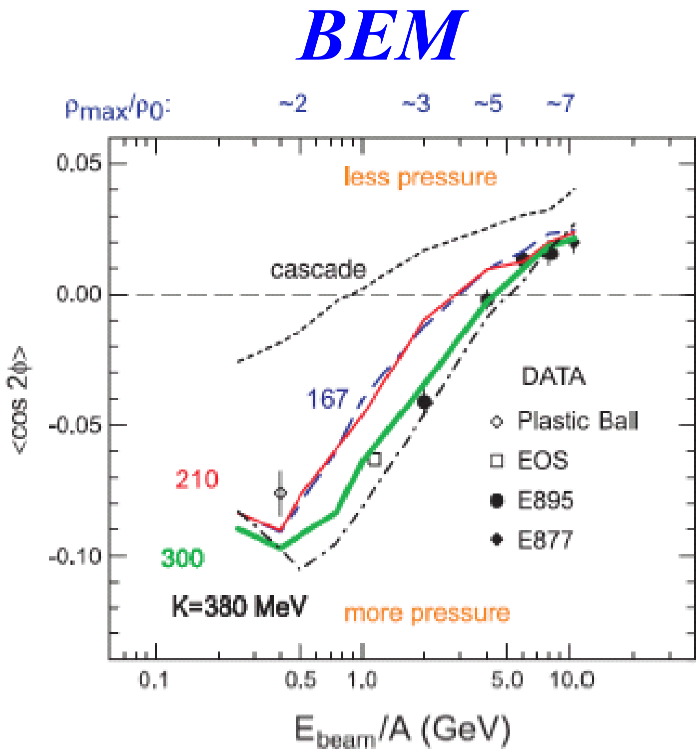


Elliptic Flow at AGS

- 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

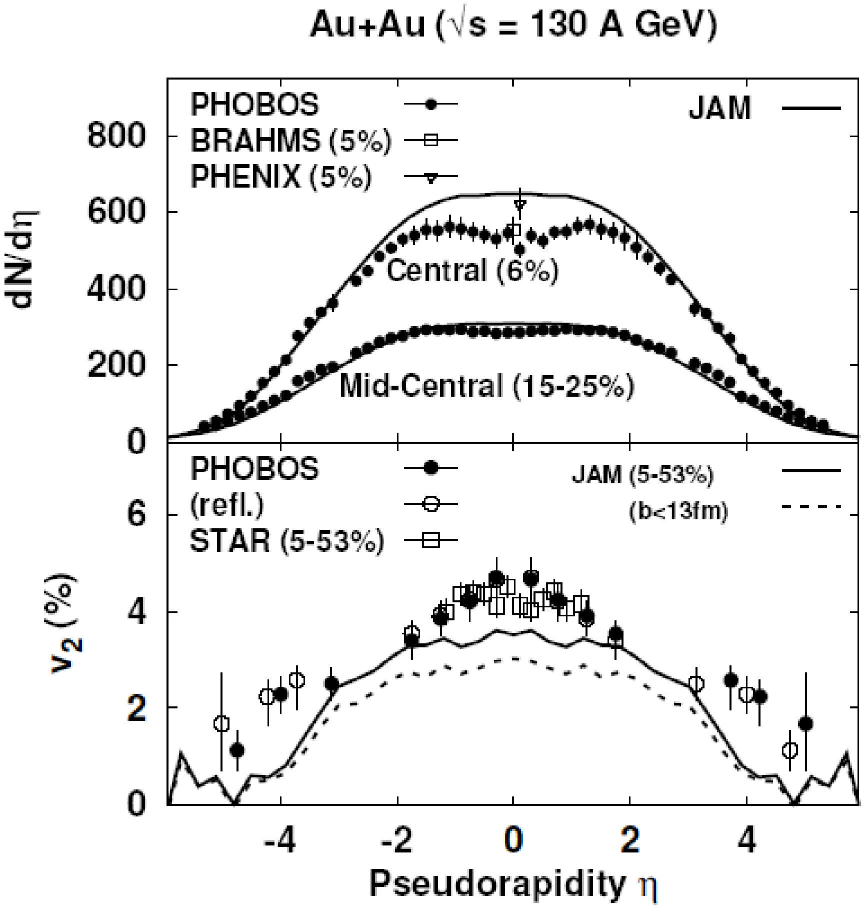


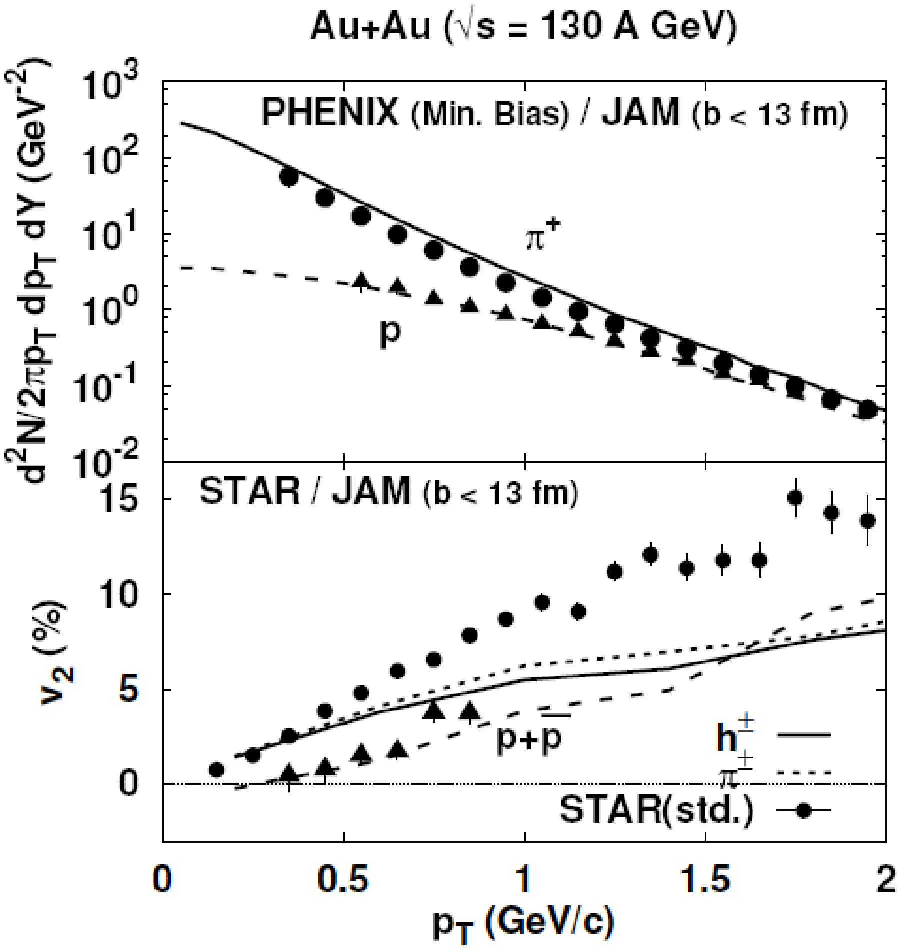




Elliptic Flow in Hadron-String Cascade (I)

- **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)**

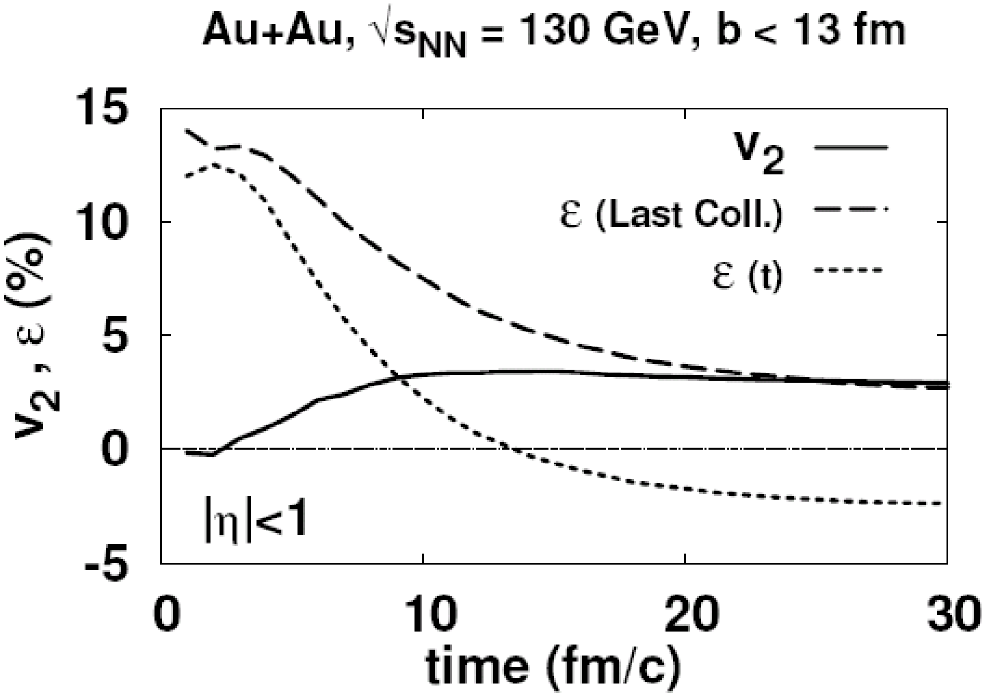


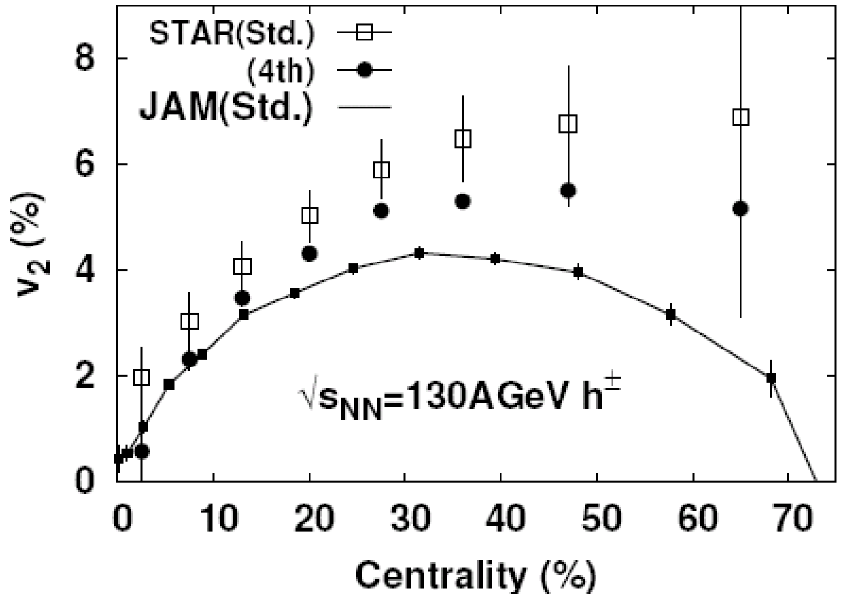


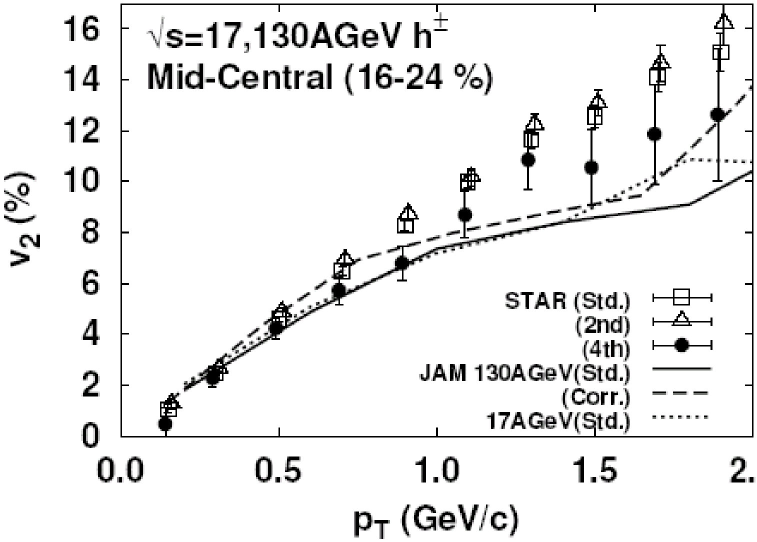
Elliptic Flow in Hadron-String Cascade (II)

- **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

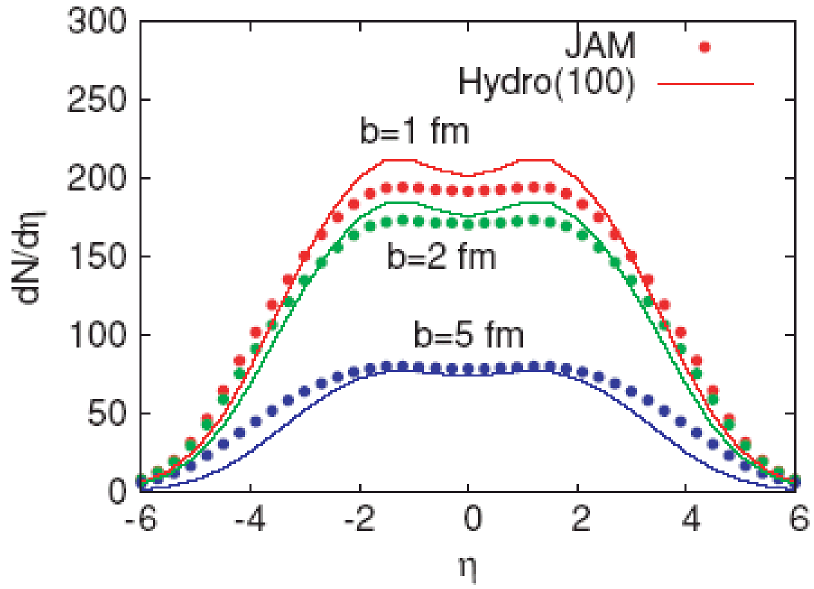


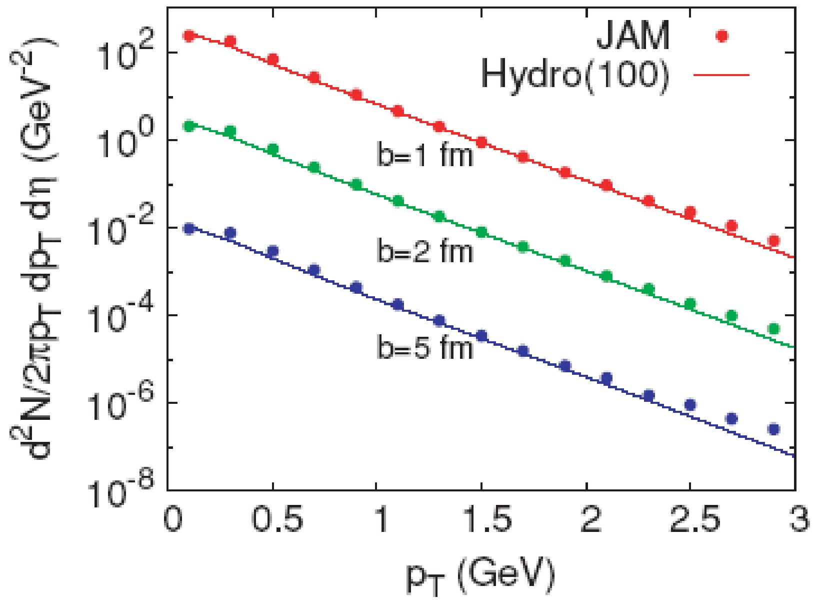




Predictions of Cu+Cu Collisions @ RHIC (I)

- **Single particle spectra**
  - **Cascade (JAM) and Hydro predict almost the same single particle spectra**
    $dN/d\eta$, $d^2N/p_T dp_T d\eta$
- **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





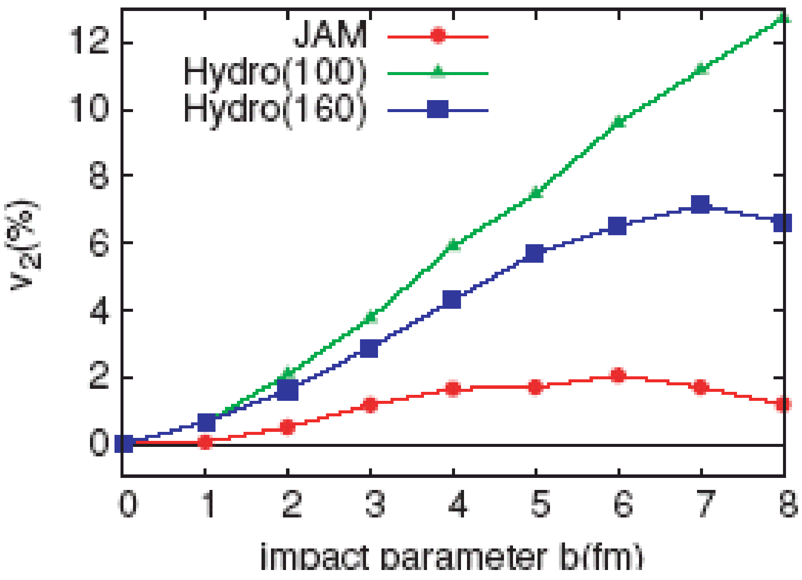
Hirano, Isse, Nara, AO, Yoshino, Phys. Rev. C 72(2005), 041901

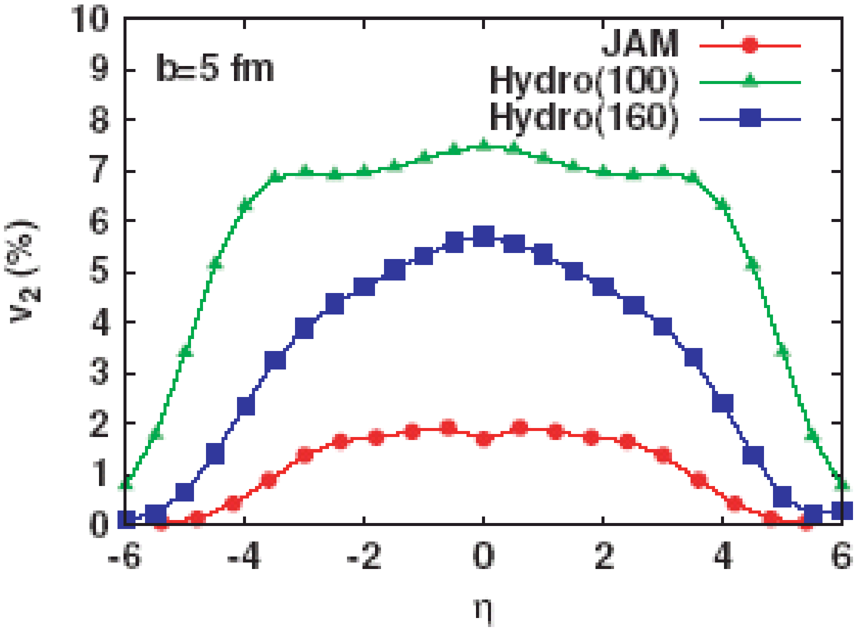
Predictions of Cu+Cu Collisions @ RHIC (II)

- **Calculations were done BEFORE the data are opened to public.**

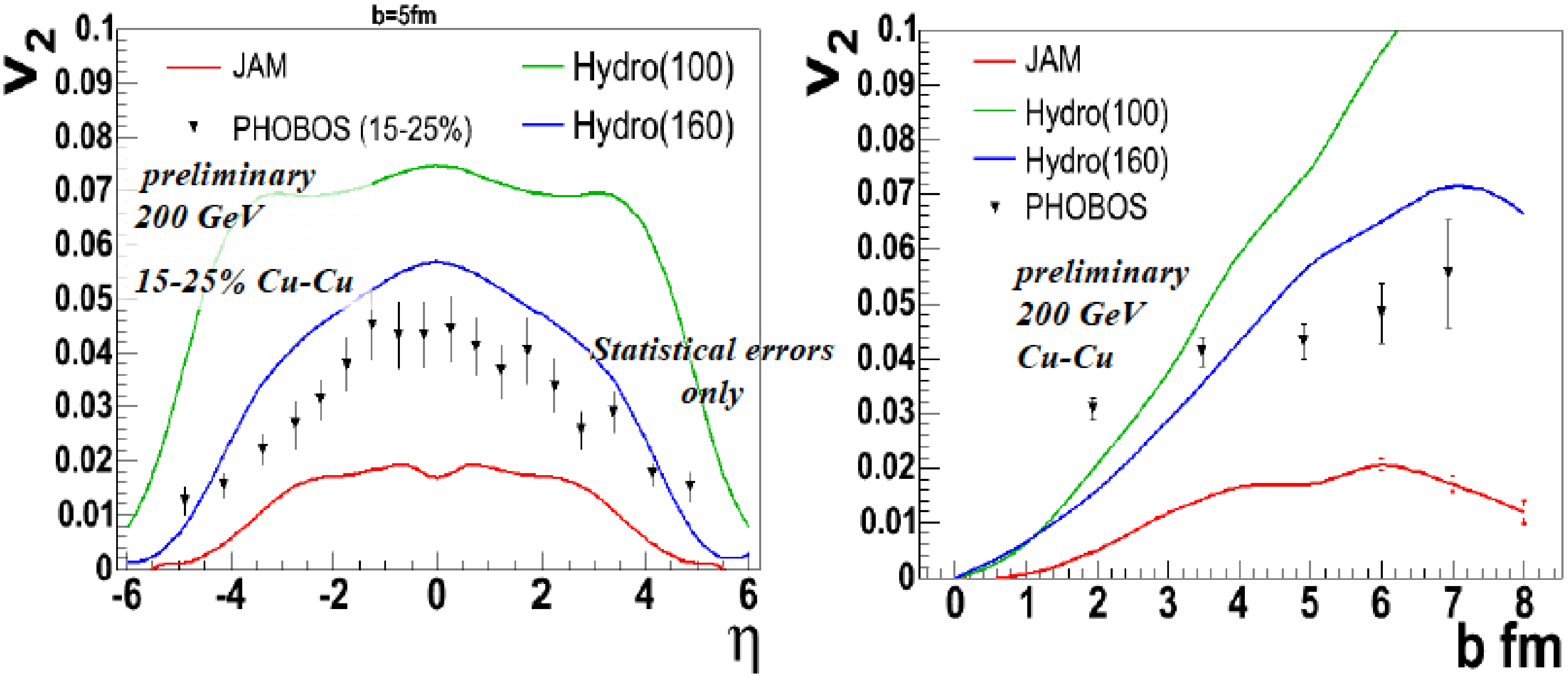
- **Cascade and Hydro predict very different Elliptic Flow !**
    - **Cascade: small v2**
      → Small int. in the early stage
    - **Hydro: large v2**
      → Strong int. after $\tau=\tau_0 \sim 0.6$ fm/c

- **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

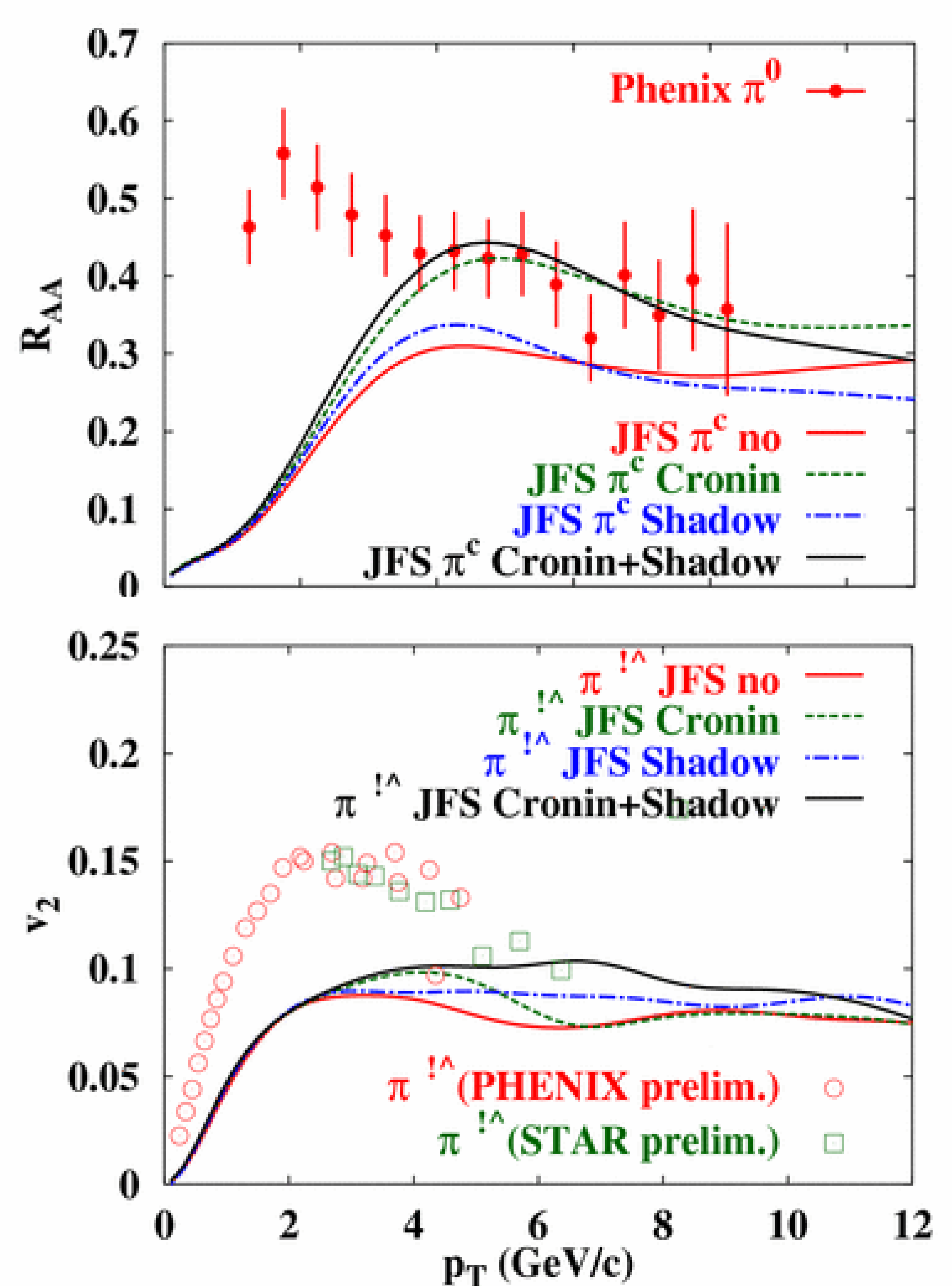


Cu-Cu more like Hydro than JAM hadron string cascade model

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

Cronin and Shadowing Effects

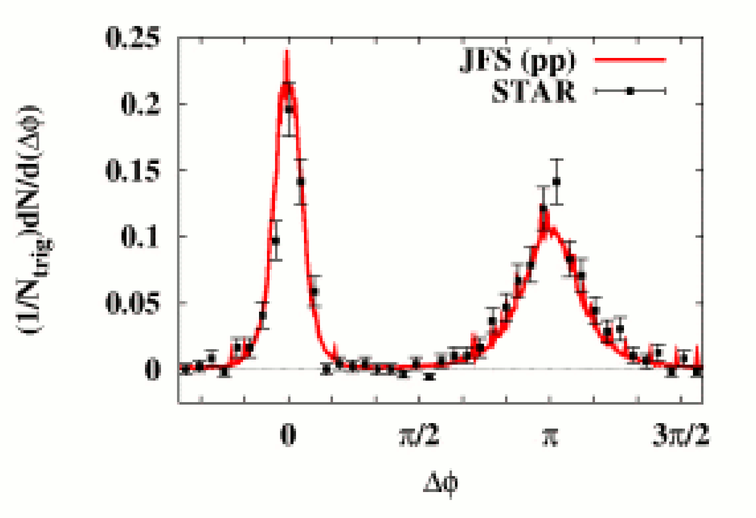
- **Standard (EKS, ...) Cronin+Shadow enh. med. p_T R_{AA} and suppr. high p_T R_{AA}.**

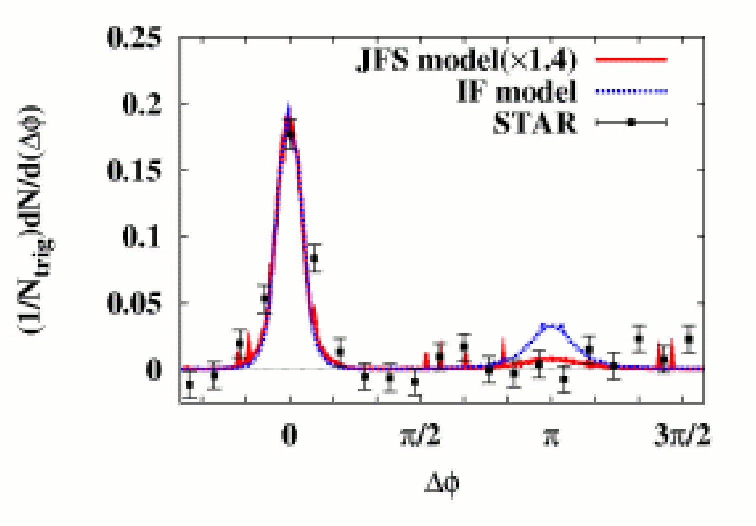


吉野、修論

Two Hadron Correlation

- **pp衝突の correlationは pythia で説明できる**
- **Au+Au衝突を見ると、**
  - **IF modelでは180°相関の消失が不完全**
  - **JFS modelでは180°相関の消失を定性的には再現**





水川、卒論

STAR: J.Adams. *et al.* PRL **91**(2003)072304

AMD (Antisymmetrized Molecular Dynamics)

Ono-Horiuchi-Maruyama-AO, 1992

- **Gaussian Approximation for single particle wave function**

$$|\Psi> = A\prod |\psi_i> \quad , \quad \psi_i = \phi(r;Z_i)\chi(\sigma,\tau) \quad , \quad Z=\sqrt{\nu}D + \frac{i}{2\hbar\sqrt{\nu}}K$$

$$\phi(r;Z) = \left(\frac{2\nu}{\pi}\right)^{3/4} \exp(-\nu(r-Z/\sqrt{\nu})^2 + Z^2/2) \propto \exp(-\nu(r-D)^2 + iK\cdot(r-D)/\hbar)$$

- **Time-dependent Variational Principle → Equations of Motion**

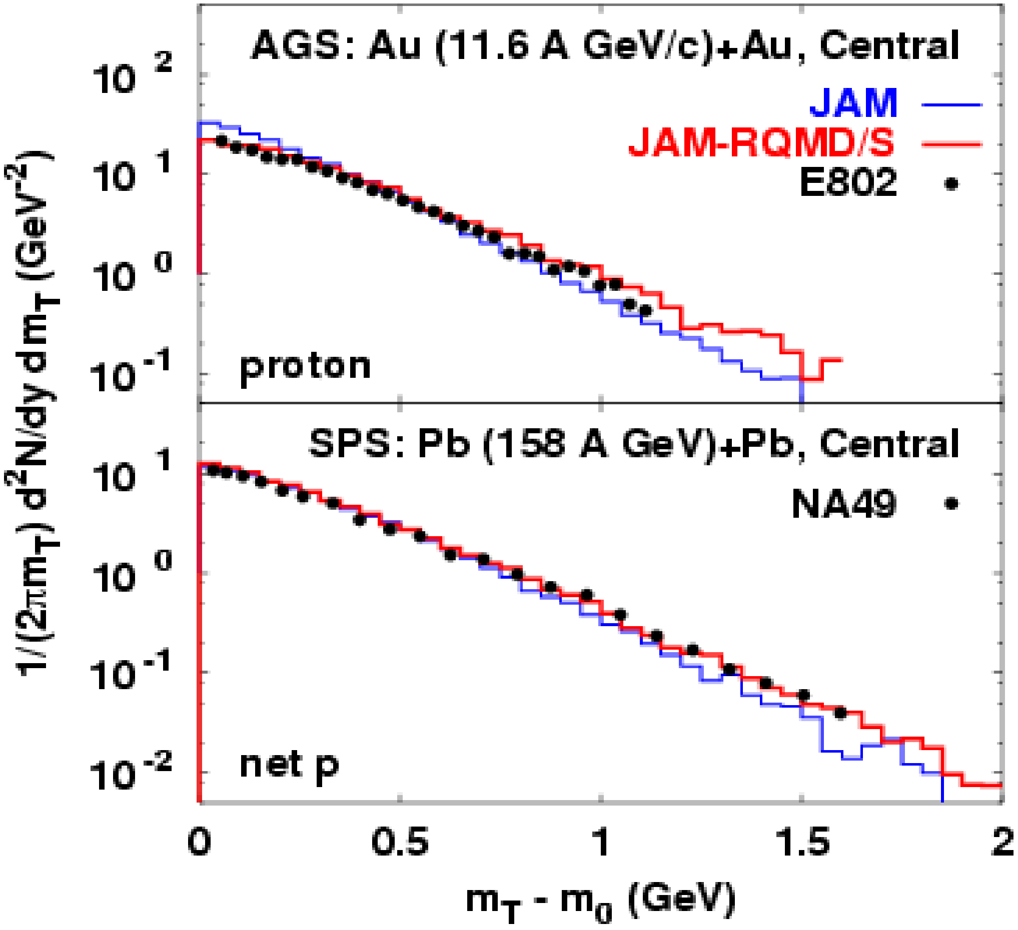
$$L = \frac{\langle\Psi|i\hbar\partial/\partial t - H|\Psi\rangle}{\langle\Psi|\Psi\rangle} \qquad \frac{d}{dt}\frac{\partial L}{\partial(d\bar{Z}_i/dt)} - \frac{\partial L}{\partial \bar{Z}_i} = 0 \quad \rightarrow \quad i\hbar C_{i\alpha,j\beta}\frac{dZ_i}{dt} = \frac{\partial H}{\partial \bar{Z}_i}$$

- **Ignoring Antisymmetrization**
  → Quantum Molecular Dynamics EOM (= Classical EOM)

$$C=\delta \quad \rightarrow \quad \frac{dD_i}{dt} = \frac{\partial H}{\partial K_i} \quad , \quad \frac{dK_i}{dt} = -\frac{\partial H}{\partial D_i}$$

Classical-type EOM is obtained through Gaussian + TDVP

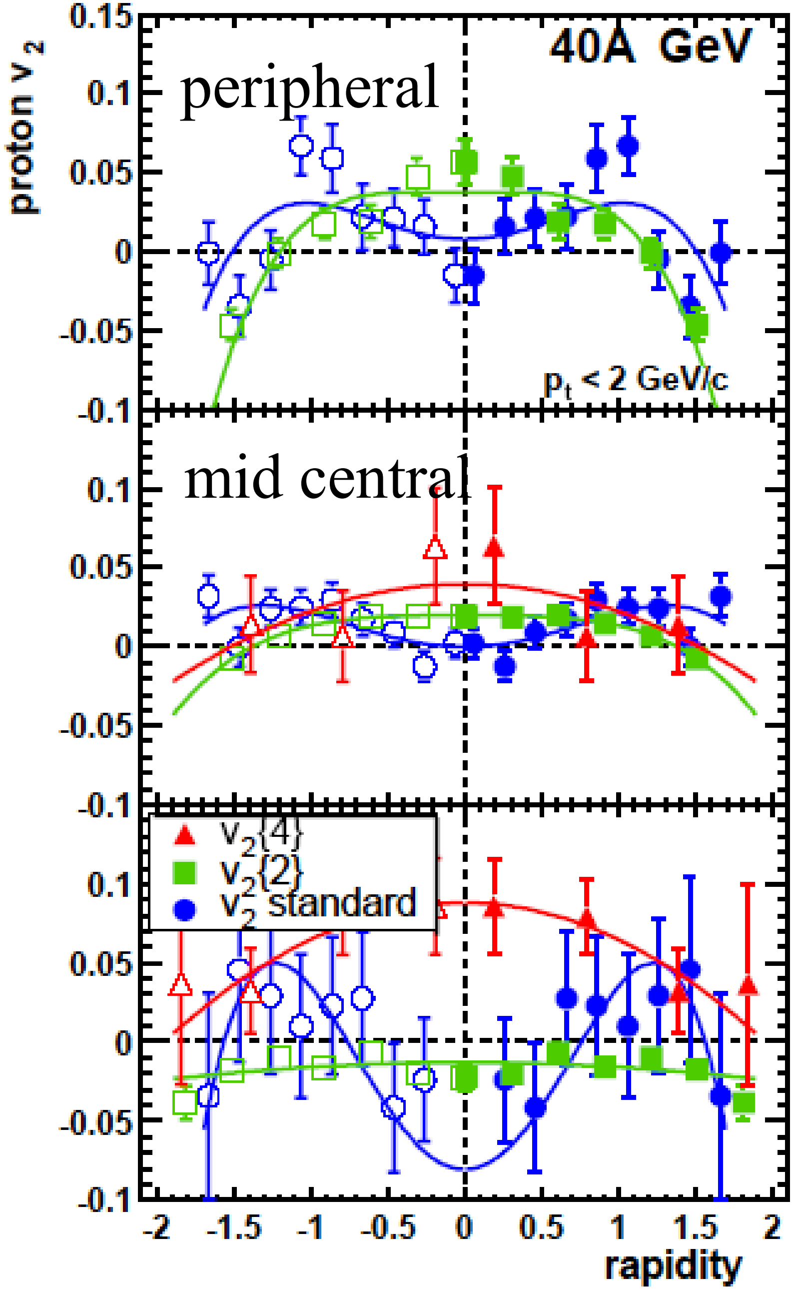
Mean Field Effects in Mt Spectrum



Mean Field affects
the Mt Spectra
even at SPS energy.

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)*

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

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

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

    - **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**

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

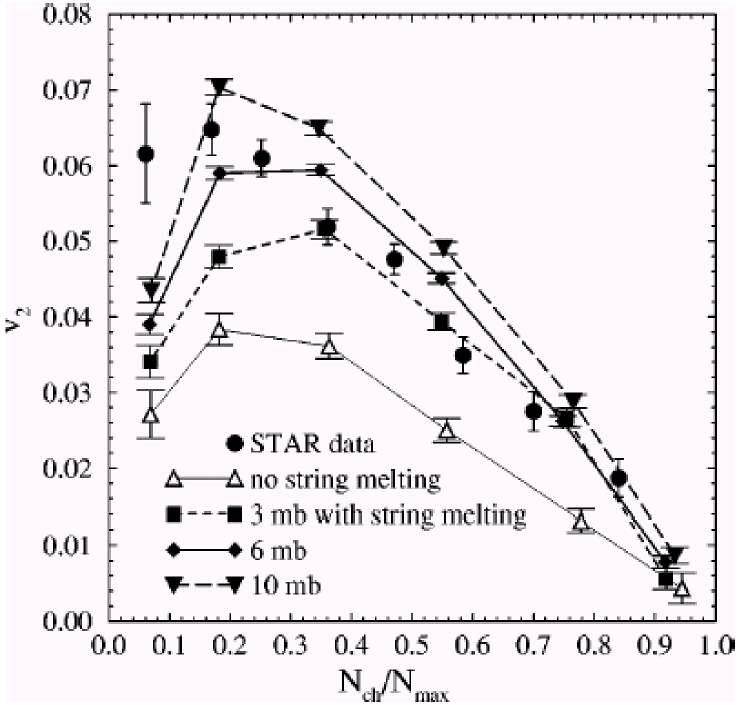


FIG. 3. Impact parameter dependence of elliptic flow at 130 *A* GeV. The data from the STAR collaboration [7] are shown by filled circles, while the theoretical results for different partonic dynamics are given by curves.

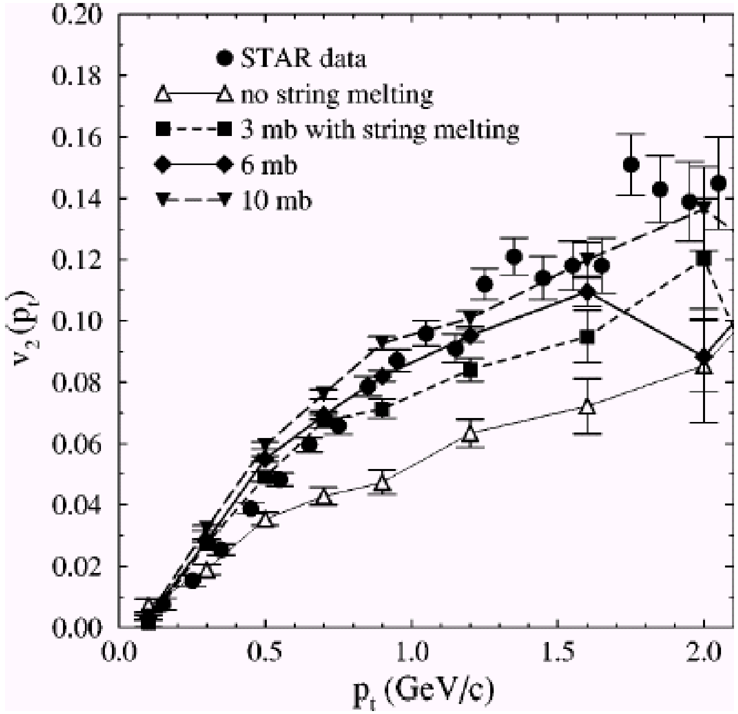


FIG. 4. Transverse momentum dependence of elliptic flow at 130 *A* GeV. Circles are the STAR data for minimum-bias Au+Au collisions [7], and curves represent the minimum-bias results for charged particles within $\eta \in (-1.3,1.3)$ from the AMPT model.

Initial Conditions in Hydro

Glauber-BGK type

[Reference Initial Condition]

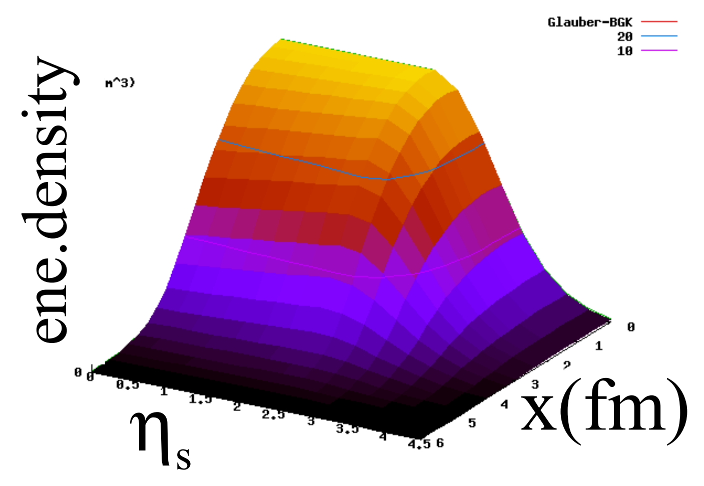
<u>Transverse profile</u>:

Entropy density

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

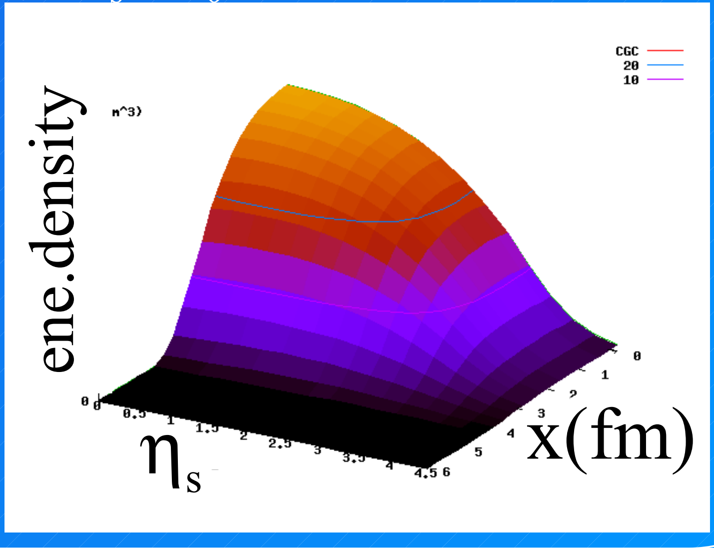
<u>Longitudinal Profile</u>:

Brodsky-Gunion-Kuhn triangle



Color Glass Condensate

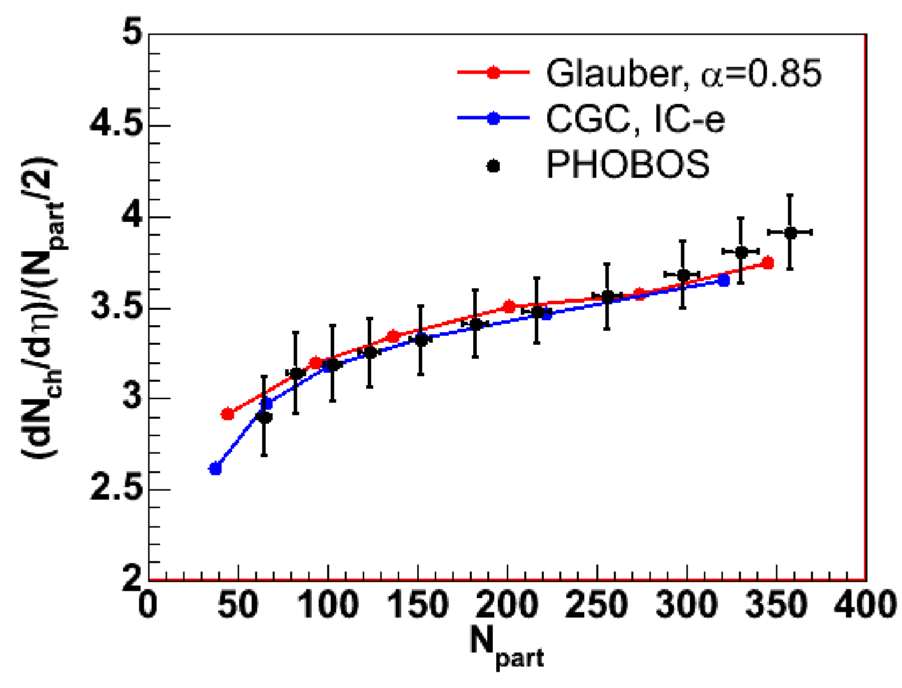
- Unintegrated gluon distribution a.la. Kharzeev, Levin, and Nardi
- Gluon production via k_T factorization formula
- Count deposited energy in dV at (τ_0, x, y, η_s), $\tau_0 = 0.6\mathrm{fm/c}$



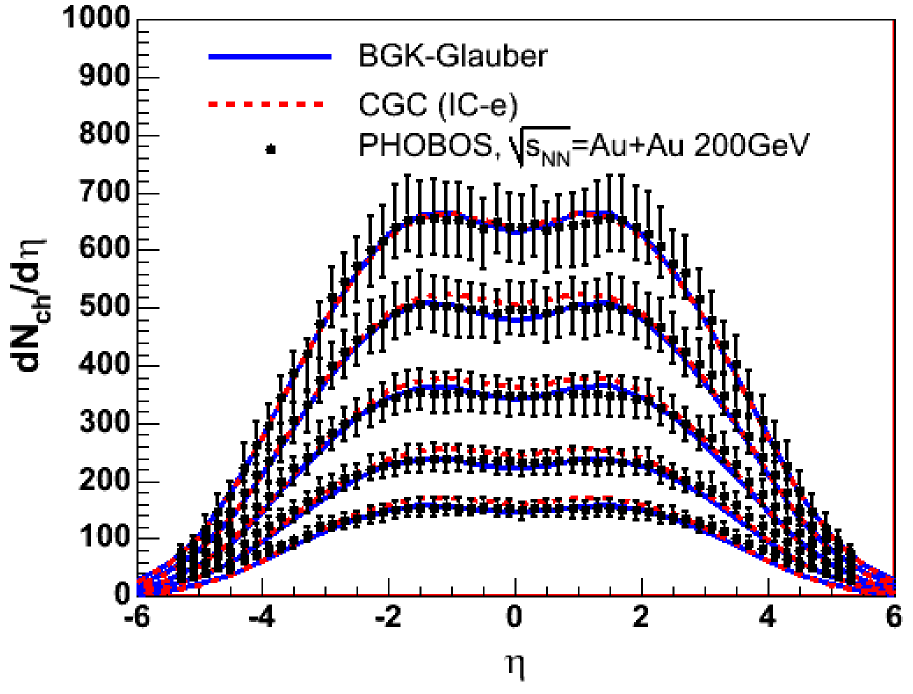
Hirano @ QM2006

Two Hydro Initial Conditions Which Clear the “First Hurdle”

Centrality dependence



Rapidity dependence



1. CGC model

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

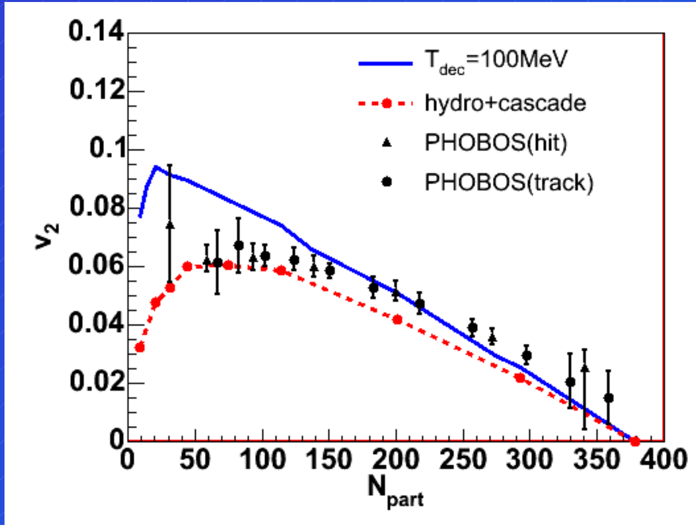
Matching I.C. via $e(x,y,\eta)$

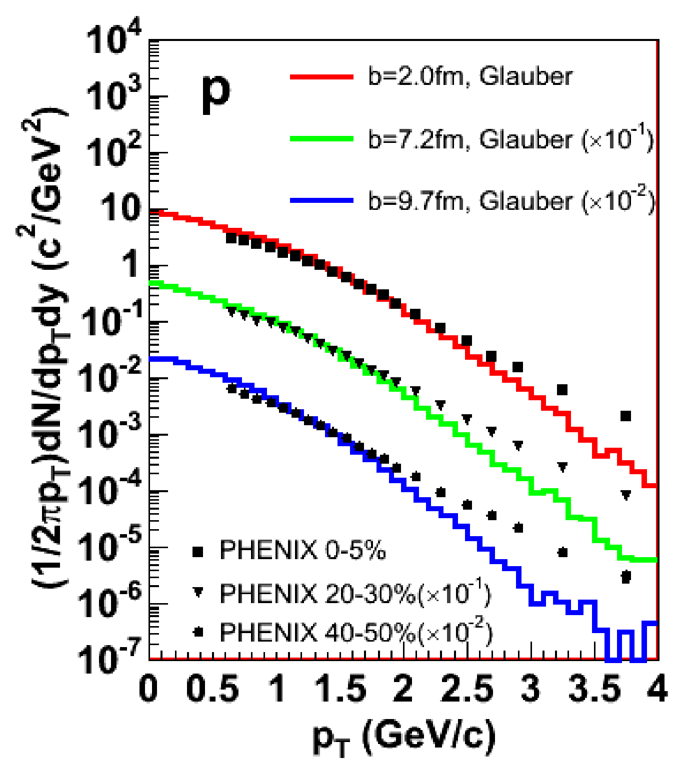
2. Glauber model (as a reference)

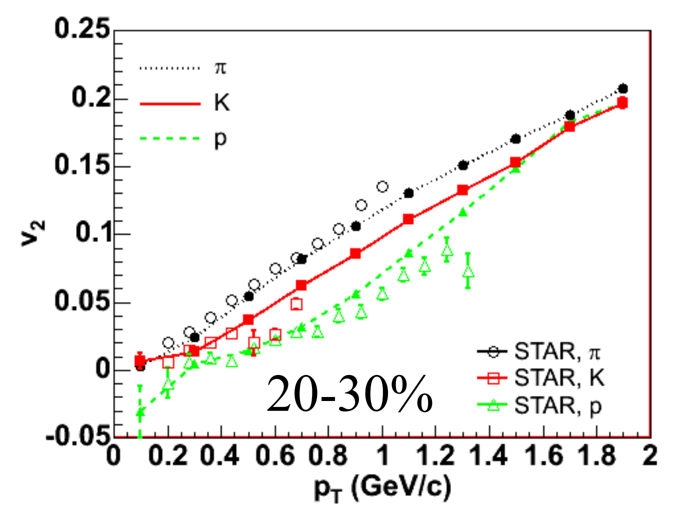
$N_{\mathrm{part}}:N_{\mathrm{coll}} = 85\%:15\%$

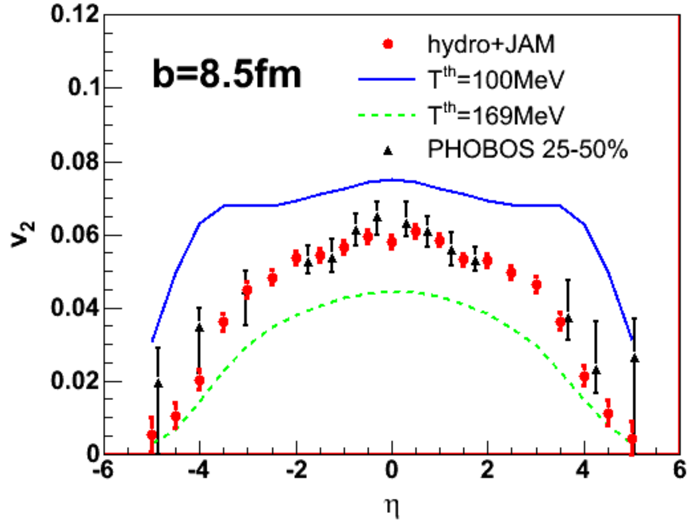
TH et al.('06); in preparation.

Highlights from Glauber + QGP Fluid + Hadron Gas Model









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

→ What happens to the CGC case?

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 .

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

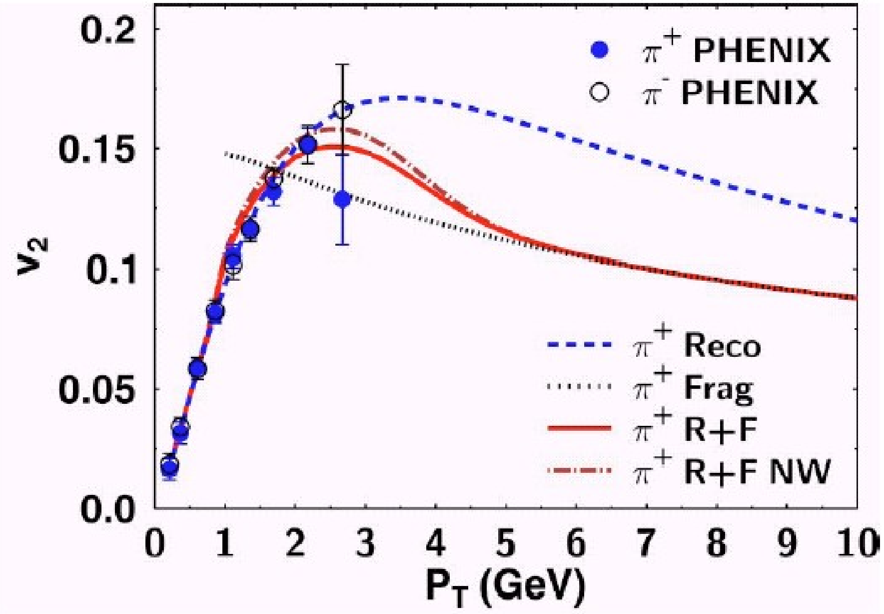
$$\approx 1+2\times 2\,v_2(p/2)\ \cos\varphi$$

- **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.



Unsolved (or NewlyFound) Problems at RHIC

- **Mach Cone / Color Cerenkov**
  - **Many low pT particles are observed along the Quenched Jet (Angle from Jet = 120 deg.)**
- **J/ ψ Production Mechanism**
  - **With the expected absorption ratio at SPS,
J/ψ yield @ RHIC is underestimated.**
- **Baryon(Hyperon)-Hadron azimuthal angle correlation**
  - **Around the high pT baryon angle, many hadrons are observed as in the case of jet production → Baryons are also formed in jets.**
- **High p_T v_2 problem**
  - **With the energy loss explaining p_T spectrum,
elliptic flow is calculated to be too small at high p_T.**
- **And Many....**

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.**