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

Heavy-Ion Cafe @ U-Tokyo, 2007/09/15

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Introduction

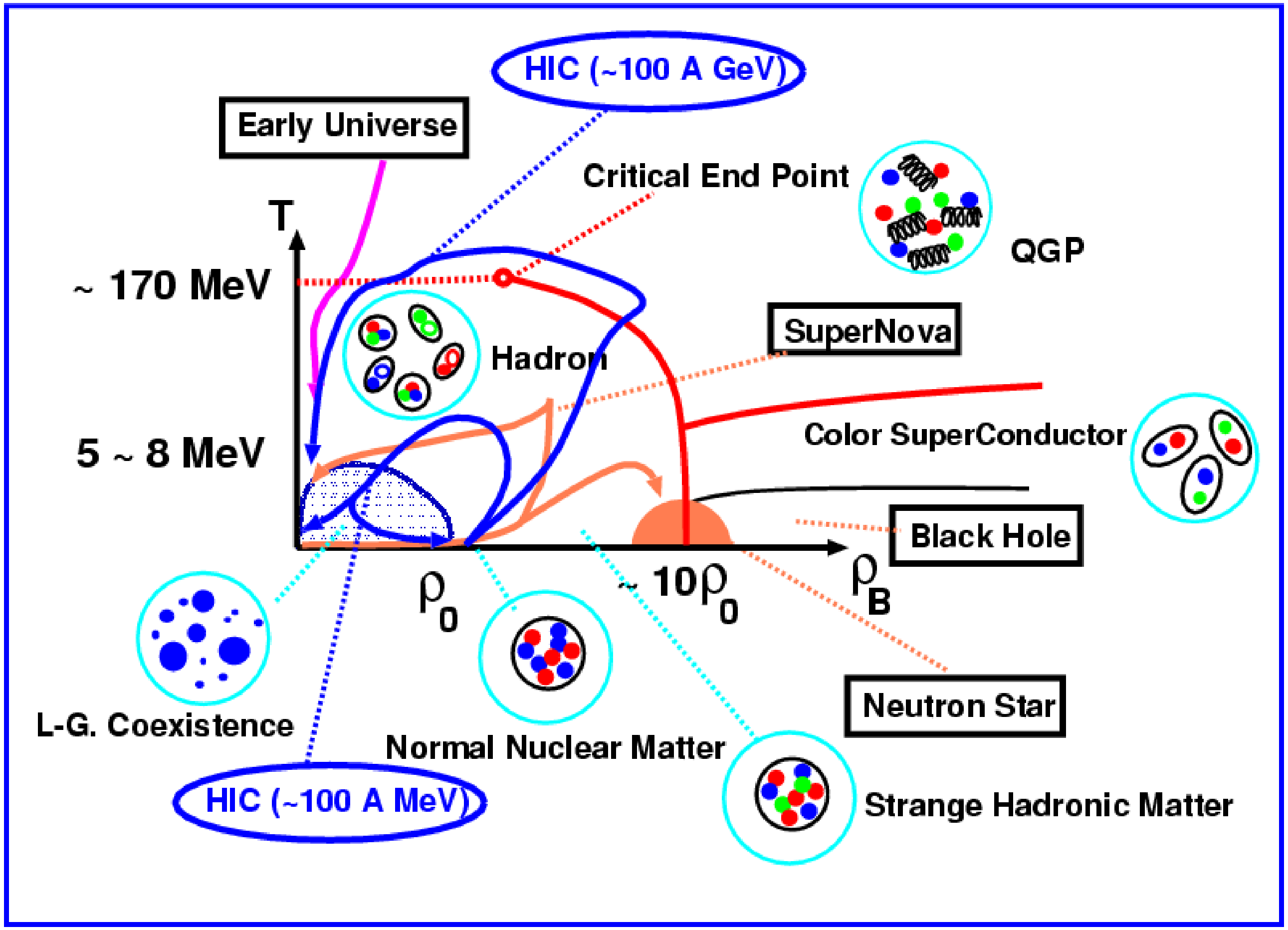
HIC at E_{inc} ~ 100 MeV/A

HIC at E_{inc} ~ (1-100) GeV/A

HIC at RHIC

Summary

Hadronic Matter Phase Diagram



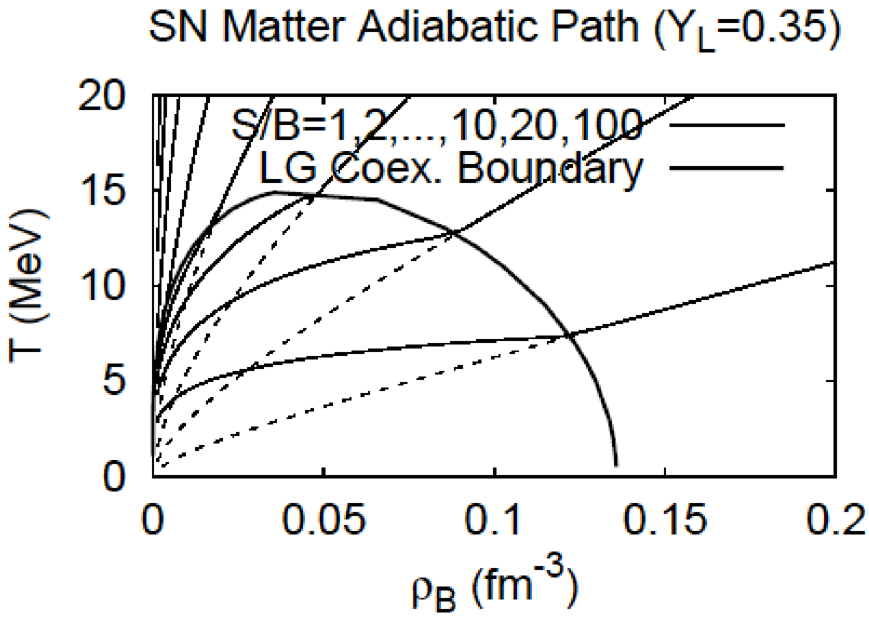
HIC (~ A few 100 A MeV) = Little Supernova
HIC (100+100 A GeV) = Little Big Bang

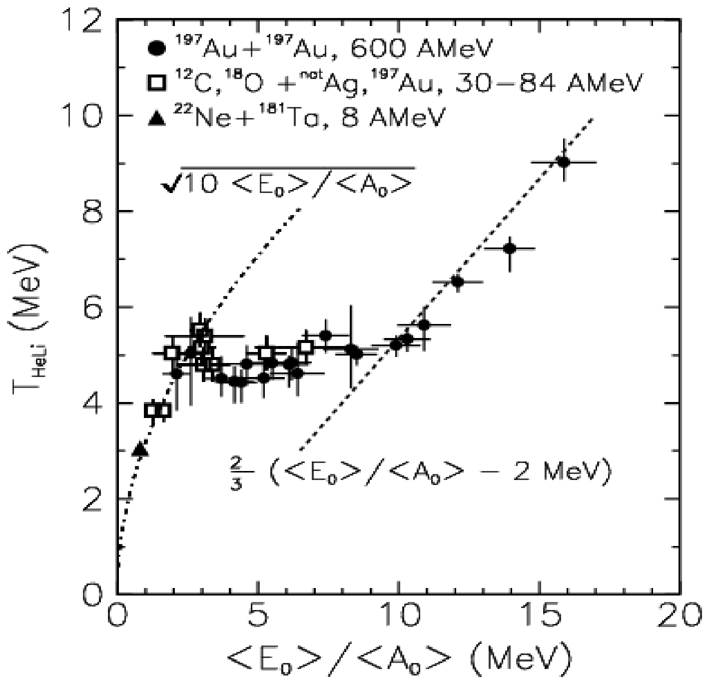
QCD 相転移=我々の宇宙の最後の真空相転移(菅沼談)

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。





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

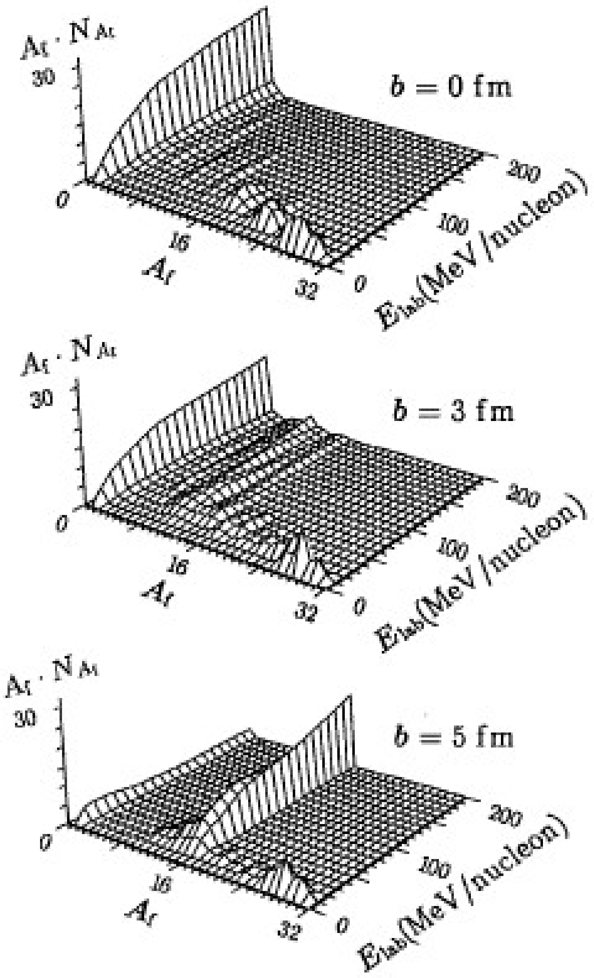
→ 重イオン反応という
非平衡・非一様な状況で
「相」の情報はみえるのか？

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

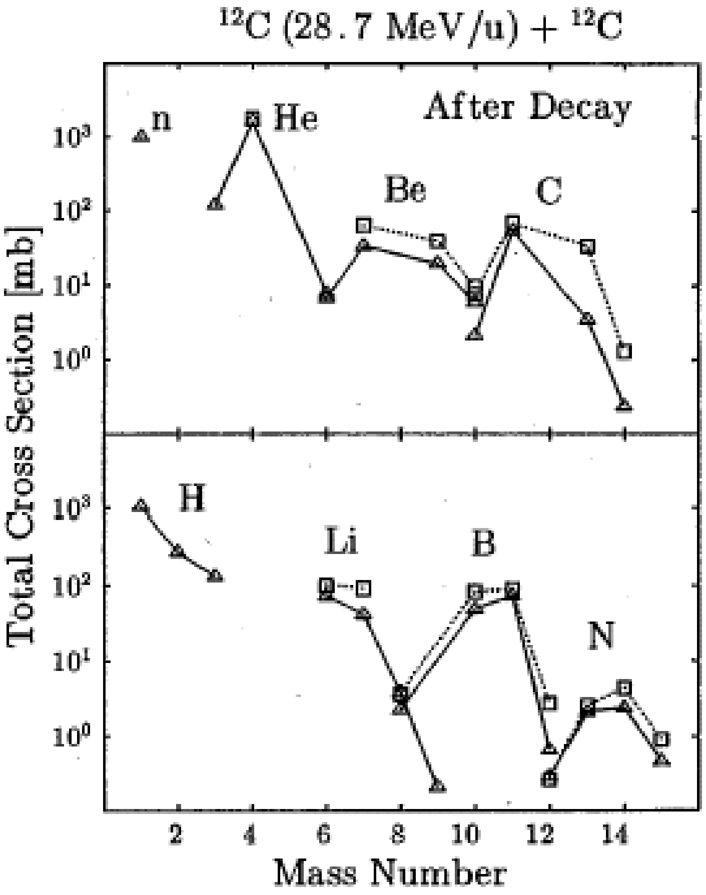
$$\rightarrow \frac{Y(^4He)/Y(^3He)}{Y(^7Li)/Y(^6Li)} \propto \exp(\Delta B/T)$$

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

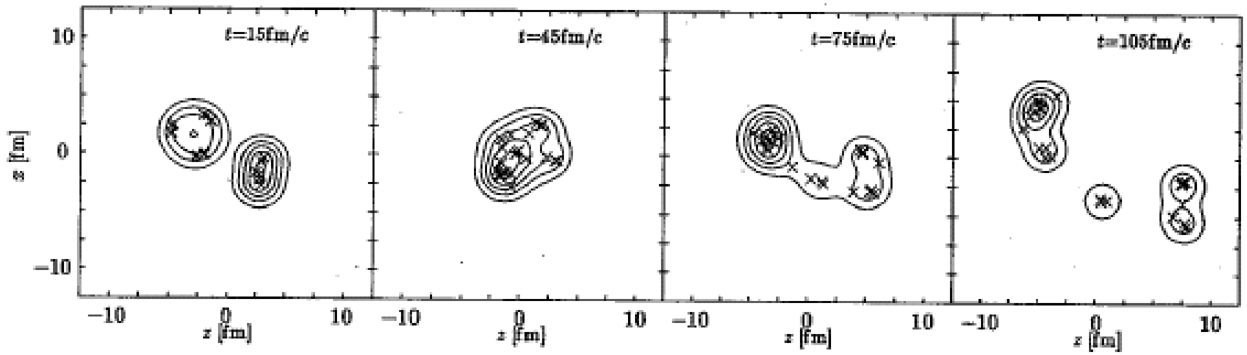
クラスター判定

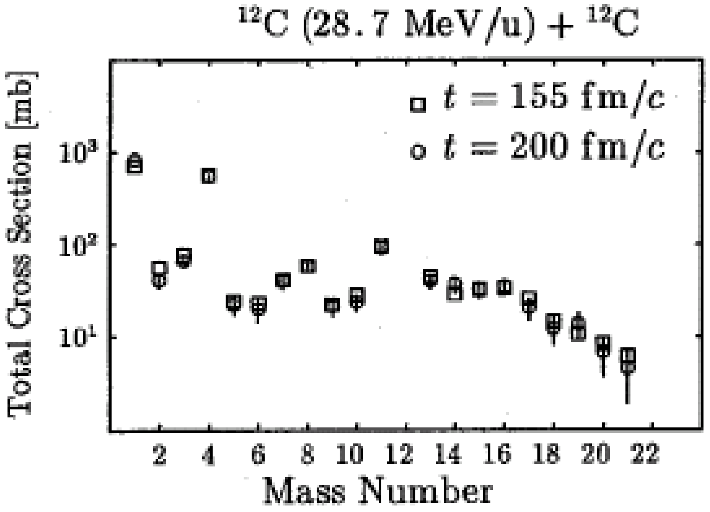
終状態で位相空間の近い核子の集合を原子核と判定

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)

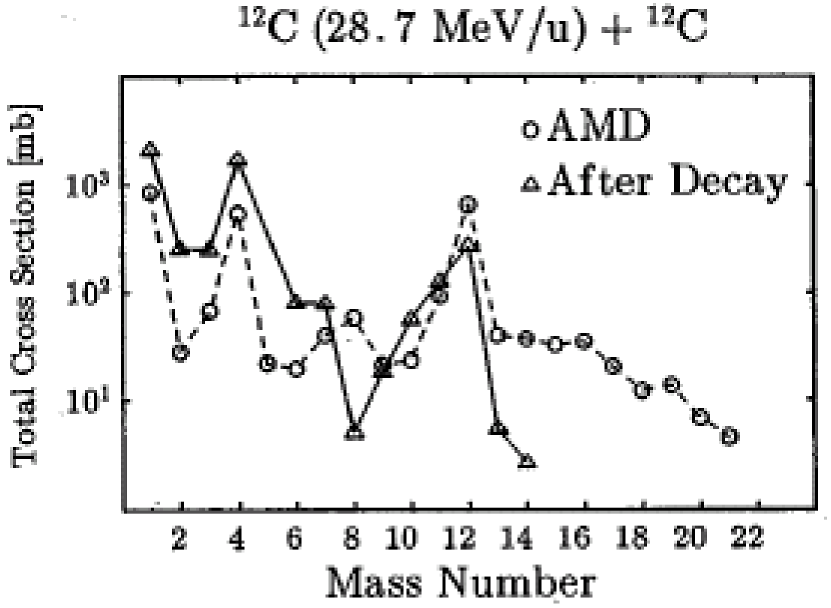




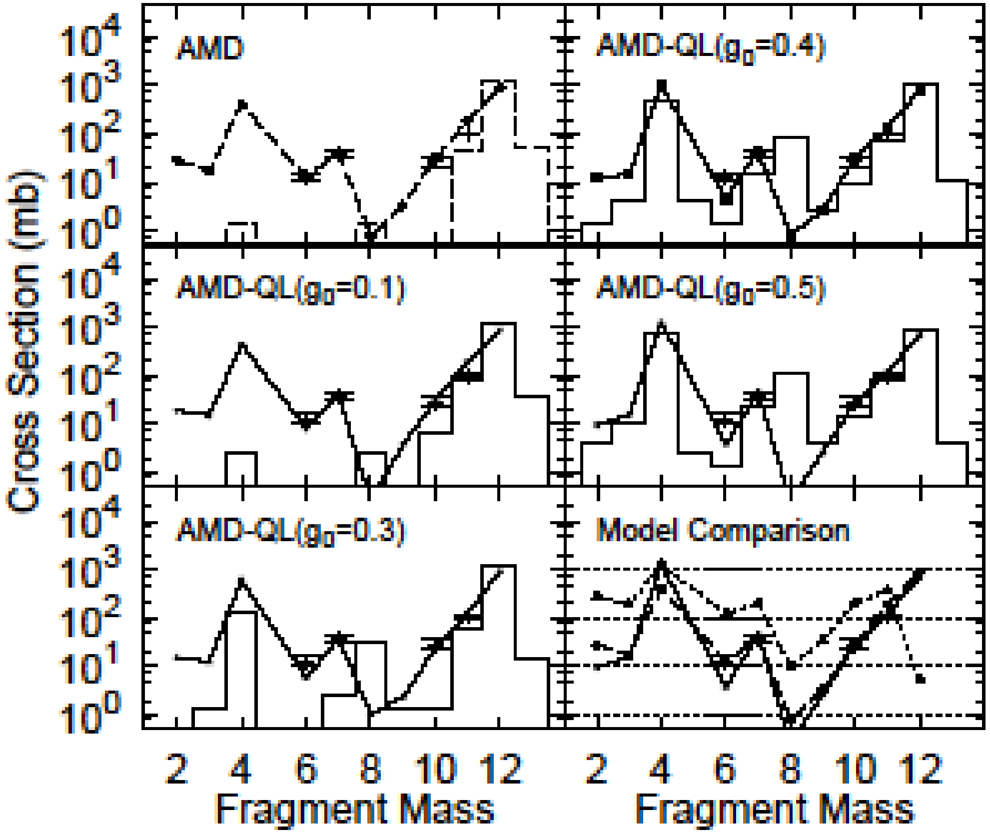
Molecular Dynamics Study of Fragmentation

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

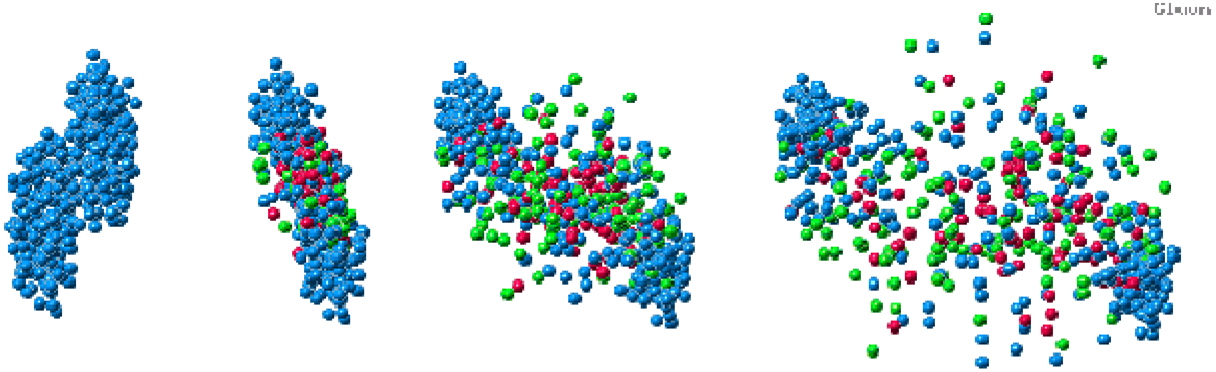
軽イオン(d, t, 3He, ...)、中間質量片(IMF)生成は
　比較的短時間でおこる
　→ 量子揺らぎ、Coalescence 過程、軽イオン自体の輸送等を
　　あらわに取り入れる必要がある。

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)

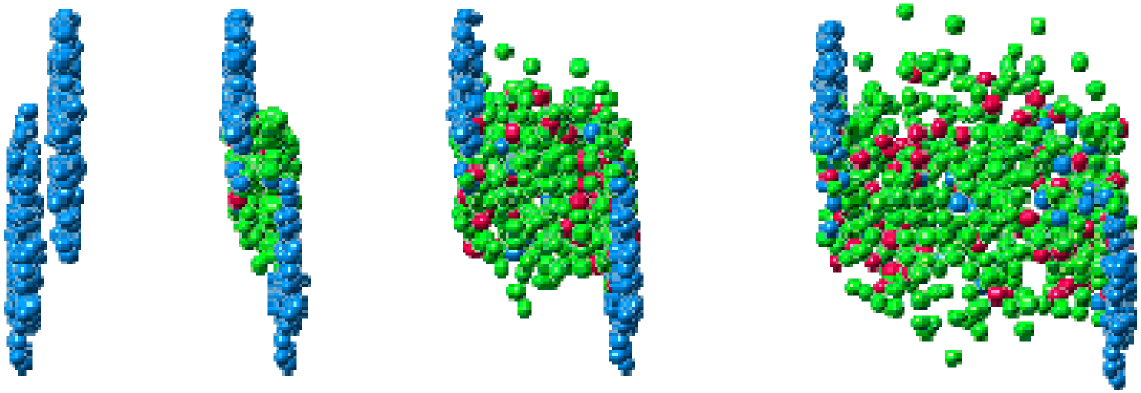
Heavy-Ion Collisions at Einc ~ (1-100) A GeV

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

AGS



SPS



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

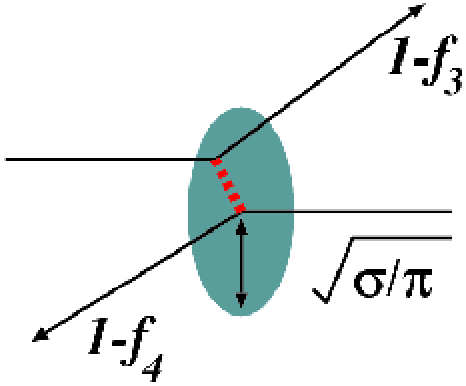
→ 低エネルギーで重要な平均場理論と
高エネルギー(>100 A MeV) で支配的なカスケード過程を統合

→ どのような粒子自由度を導入すべきか？

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

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

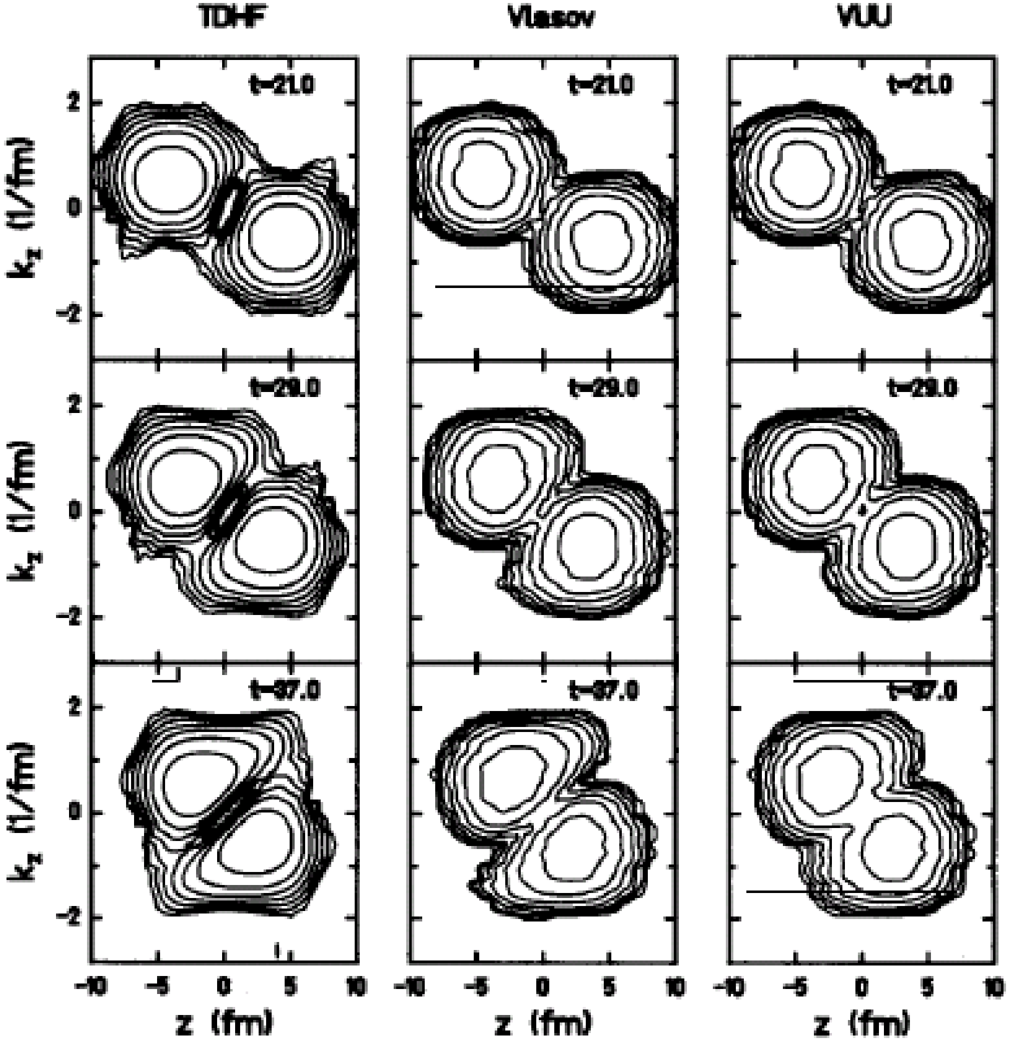
$$\times \quad [f f_2 (1-f_3)(1-f_4) - f_3 f_4 (1-f)(1-f_2)]$$



Comarison of TDHF, Vlasov and BUU(VUU)

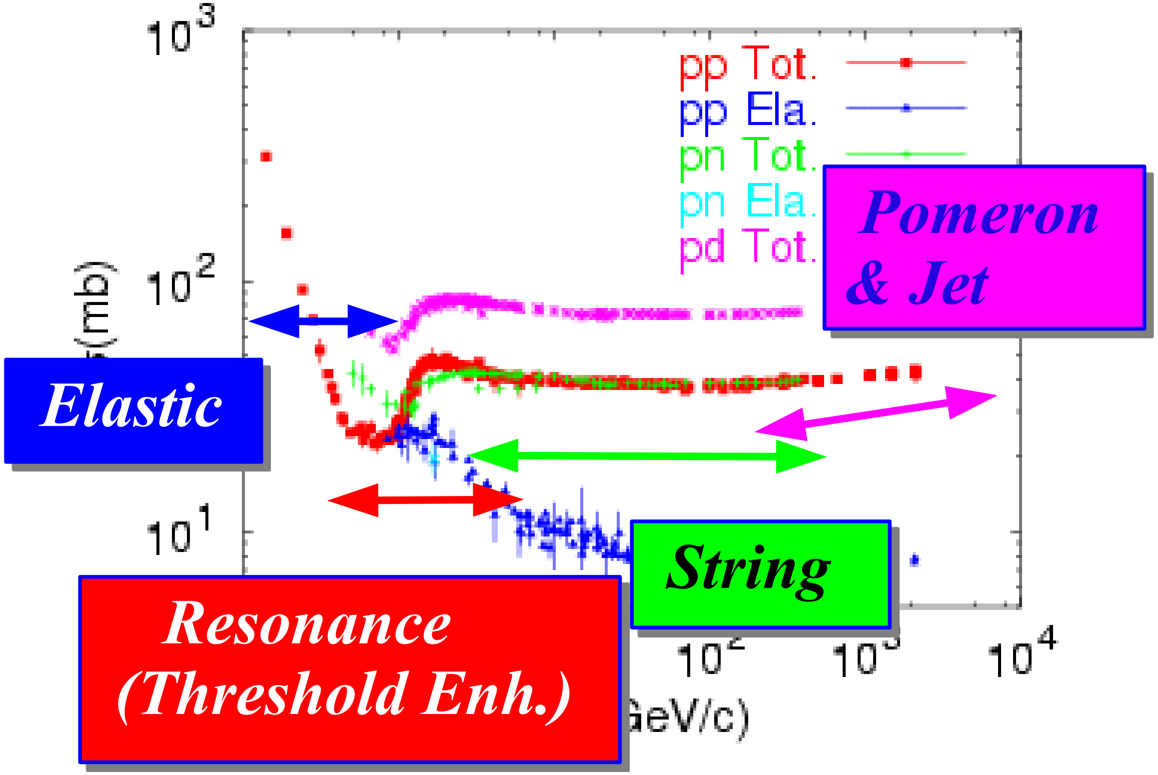
Ca+Ca, 40 A MeV

(Cassing-Metag-Mosel-Niita, Phys. Rep. 188 (1990) 363).



Hadron-Hadron Cross Sections

From Particle Data Group

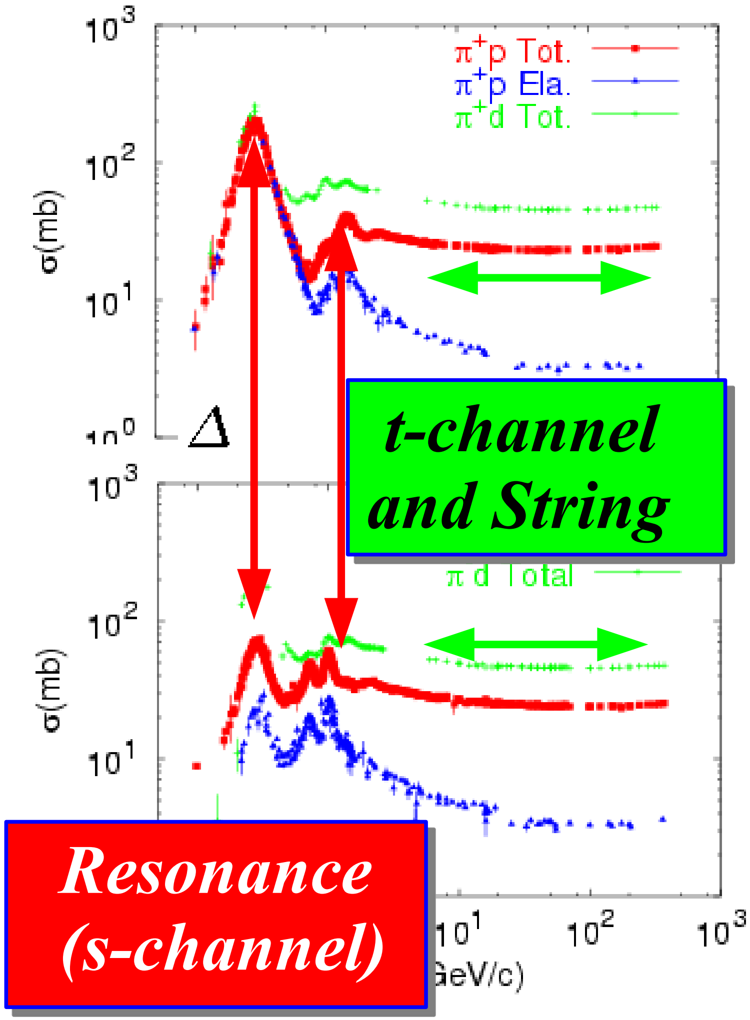


Pomeron & Jet

Elastic

String

Resonance (Threshold Enh.)



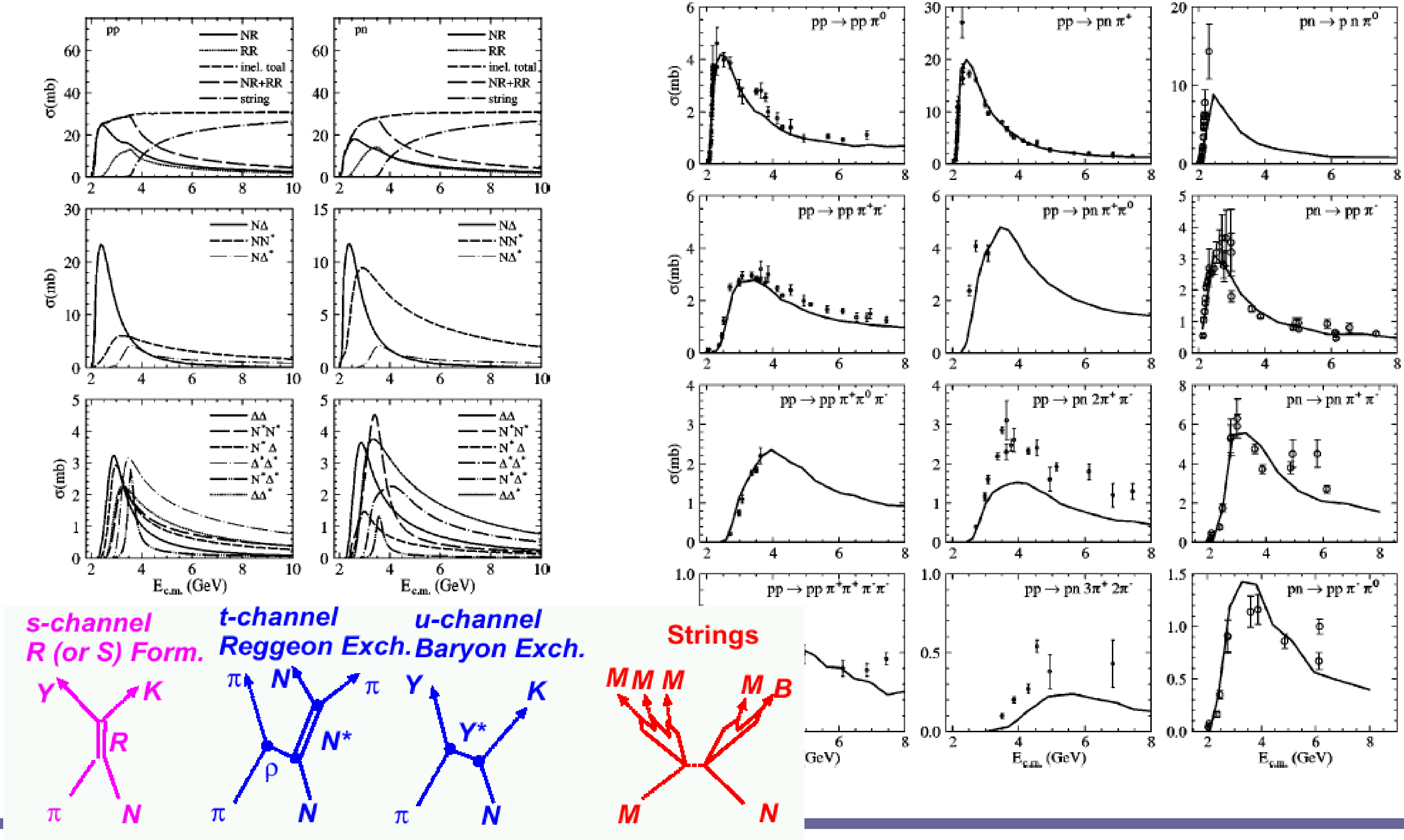
t-channel and String

Resonance (s-channel)

Exclusive Cross Sections in JAM

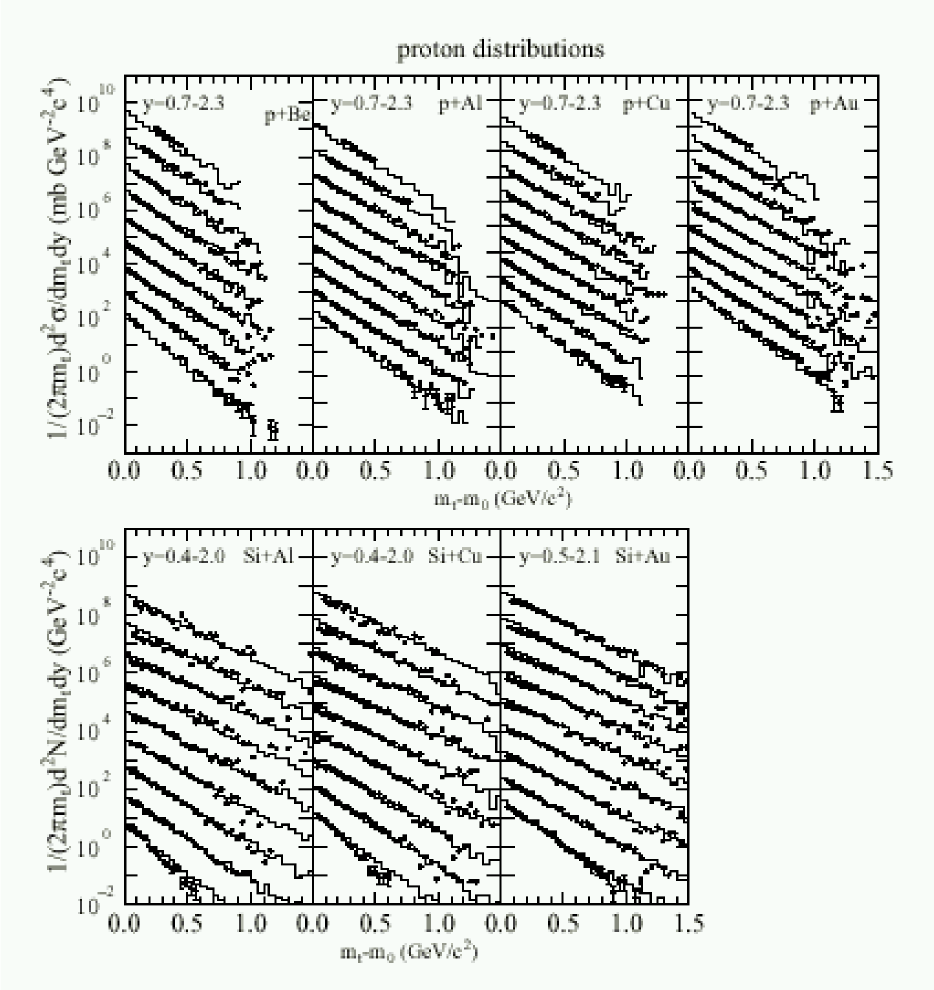
Nara, Otuka, AO, Niita, Chiba (JAM), PRC 61 (2000), 024901.

Ground State Hadrons, Resonances, and Strings

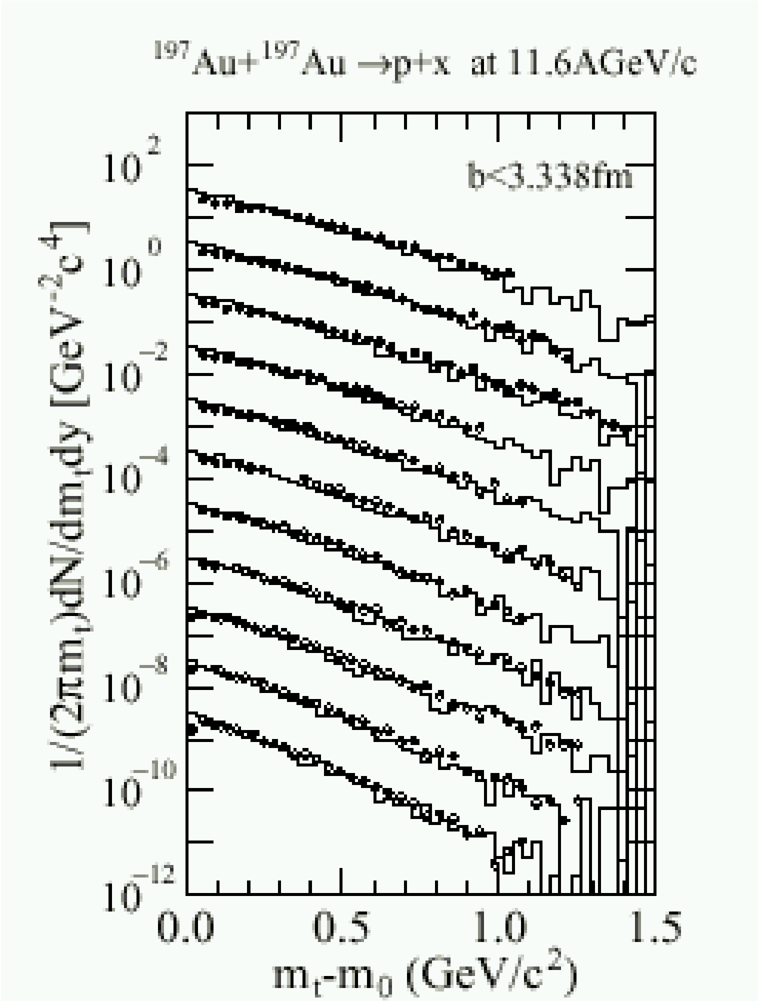


JAM Results @ AGS Energy

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**

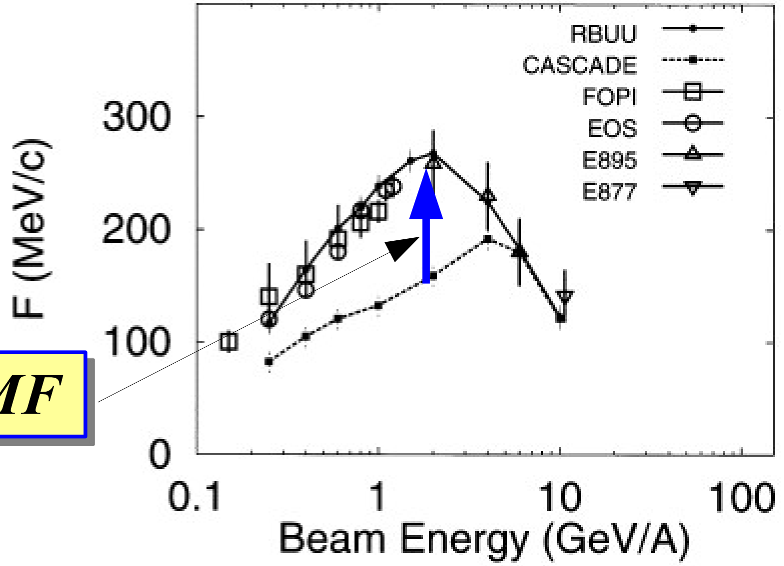
Essential for Flow

Particle DOF Effects

→ **Seen at high p_T**

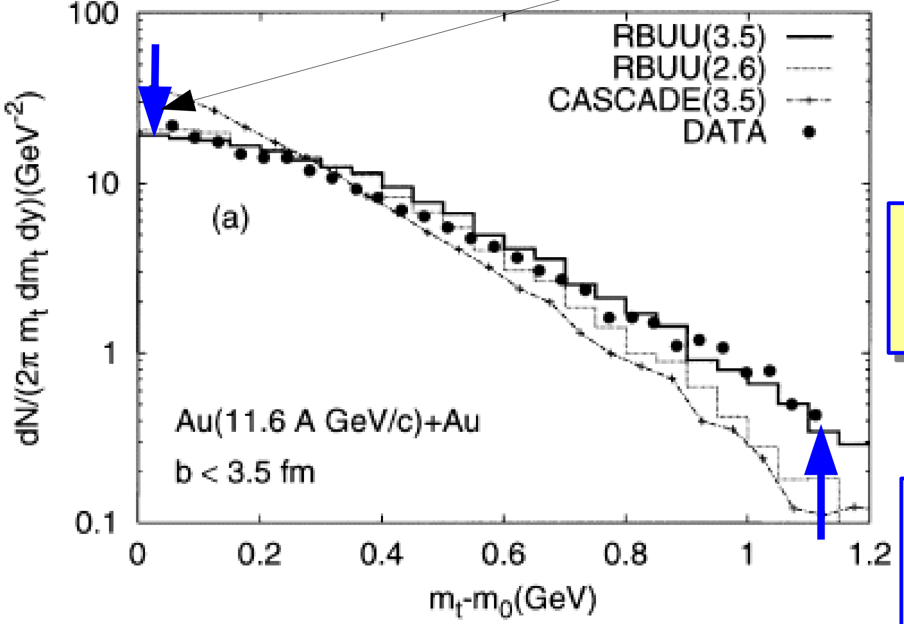
Sahu, Cassing, Mosel, Ohnishi, 2000

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 √s = 3.5 GeV (JAM fit)

Switching √s = 2.6 GeV (HSD default)

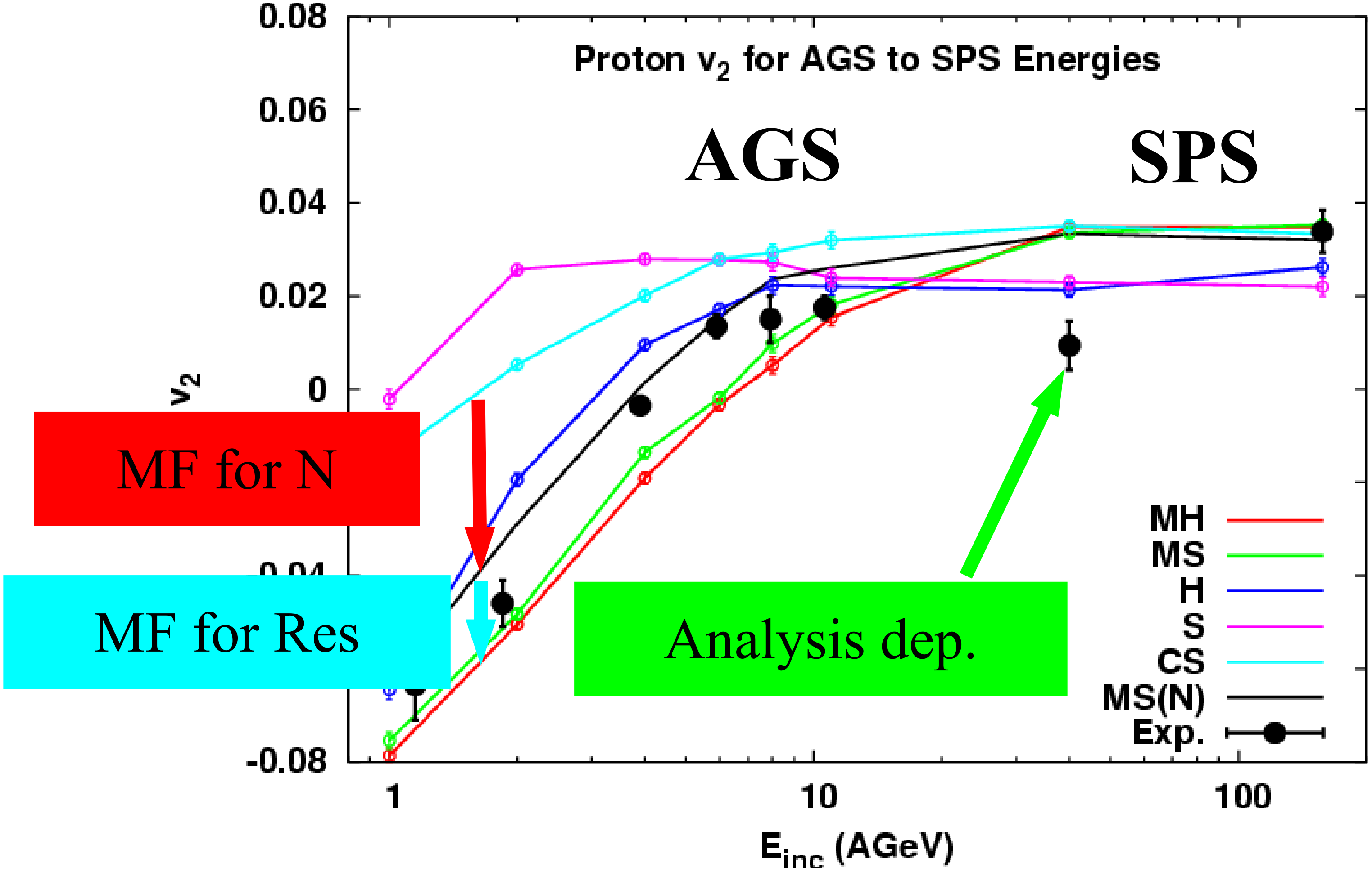
Elliptic Flow from AGS to SPS

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)



MF for N

MF for Res

Analysis dep.

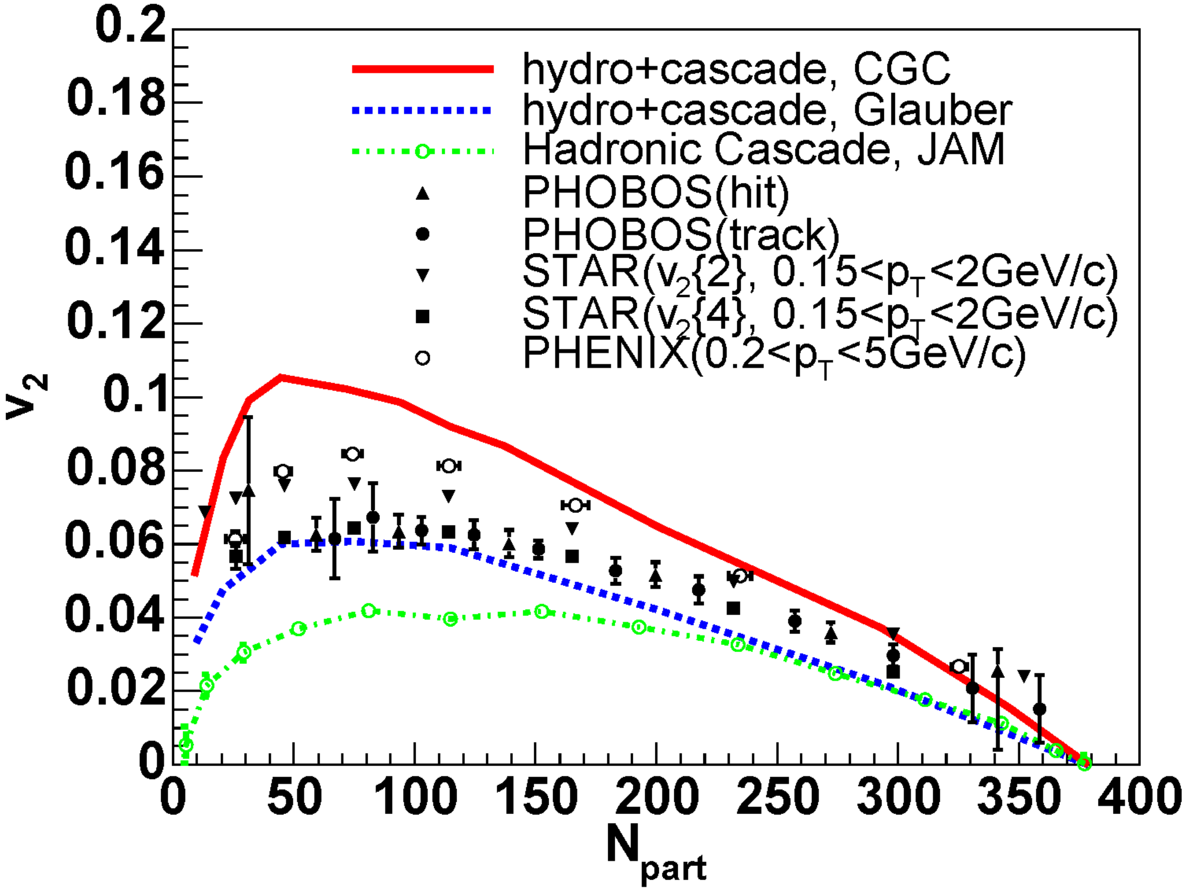
Cascade vs Hydro @ RHIC: Au+Au

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

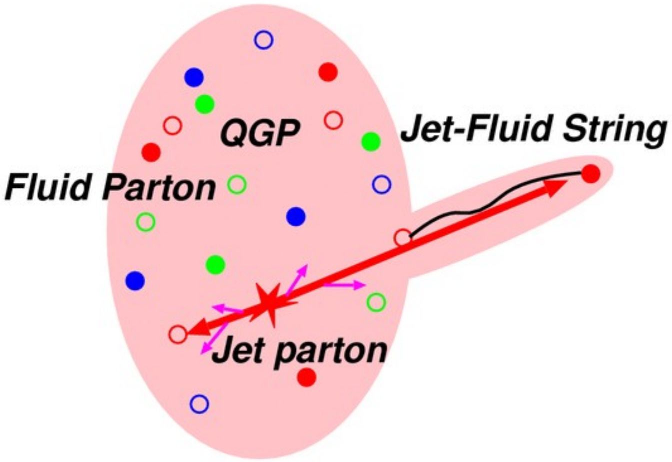
T.Hirano, M.Isse^A, R. Mizukawa^B, Y.Nara^C, A. Ohnishi^B, K.Yoshino^B
U. Tokyo, Osaka U.^{A}, Hokkaido U.^{B}, Frankfurt U.^{C}

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)

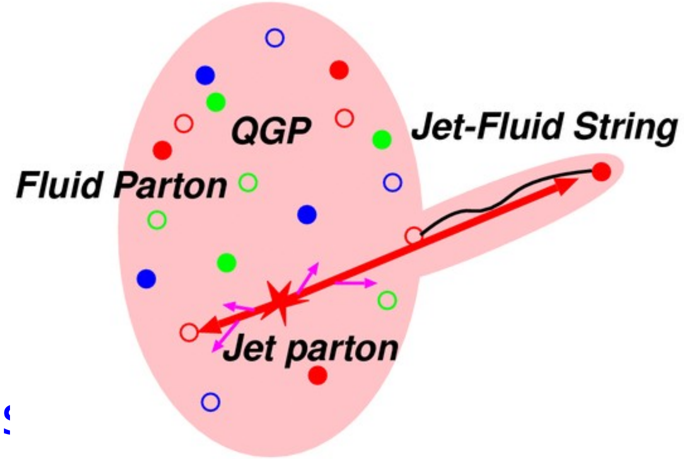
QGP中のパートン伝播

3次元流体模型

Hirano-Nara, PRL91('03), 082301;
PRC69('04),034908
Hirano,Tsuda, PRC66('02),054905

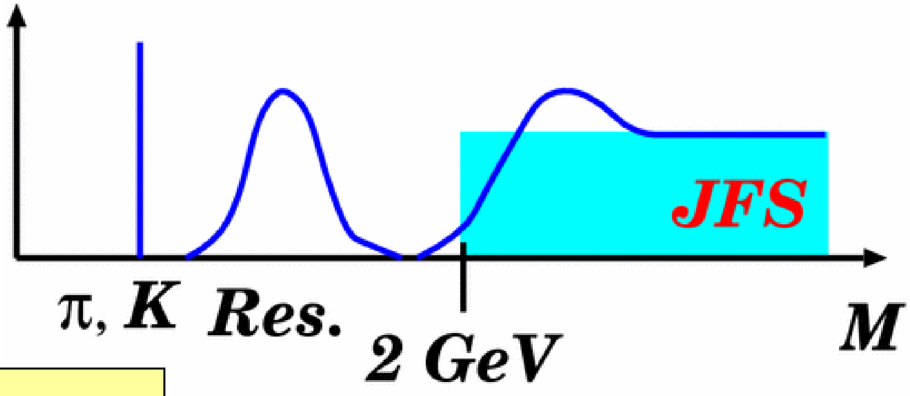
GLV エネルギー損失× factor (*C*) Gyulas

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)

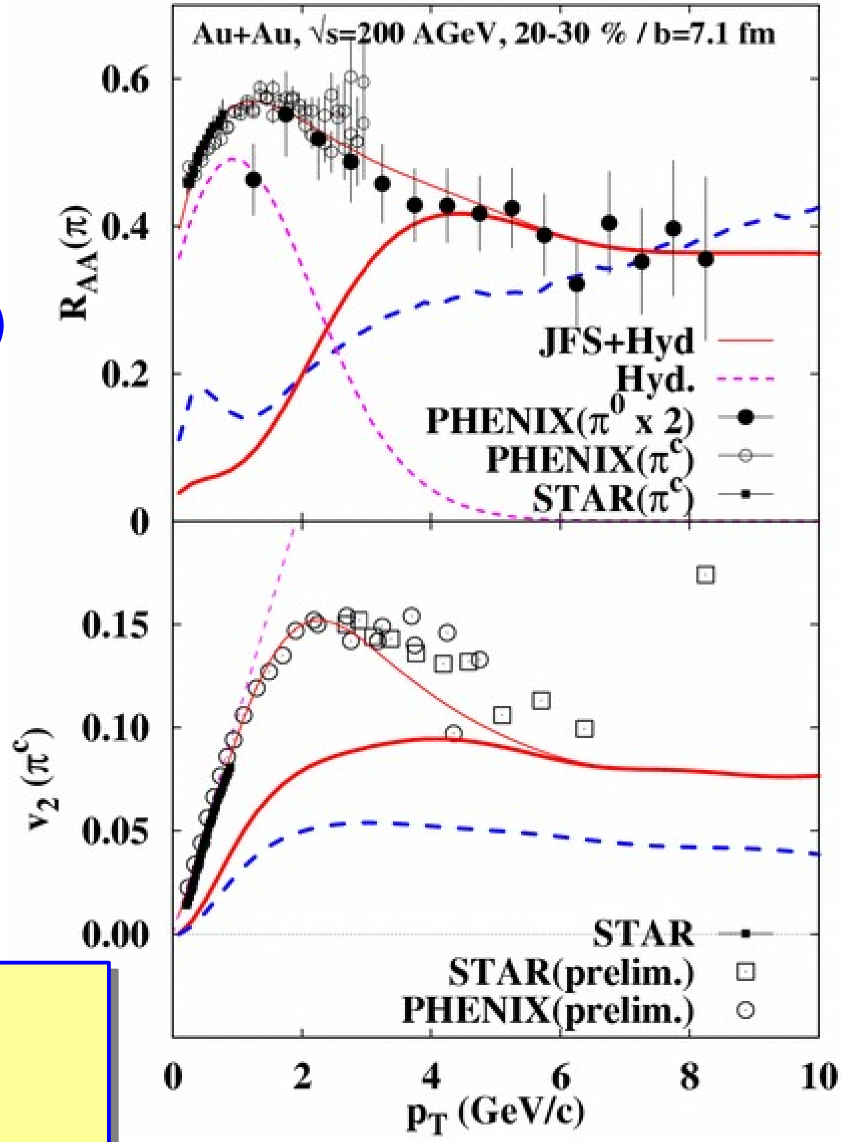
大きなエネルギー損失

+流体パートンのv_2

→ high p_T での大きな v_2

v_2 ~ 8 % @ p_T > 6 GeV/c

v_2 ~ (3-5) % in Indep. Frag.



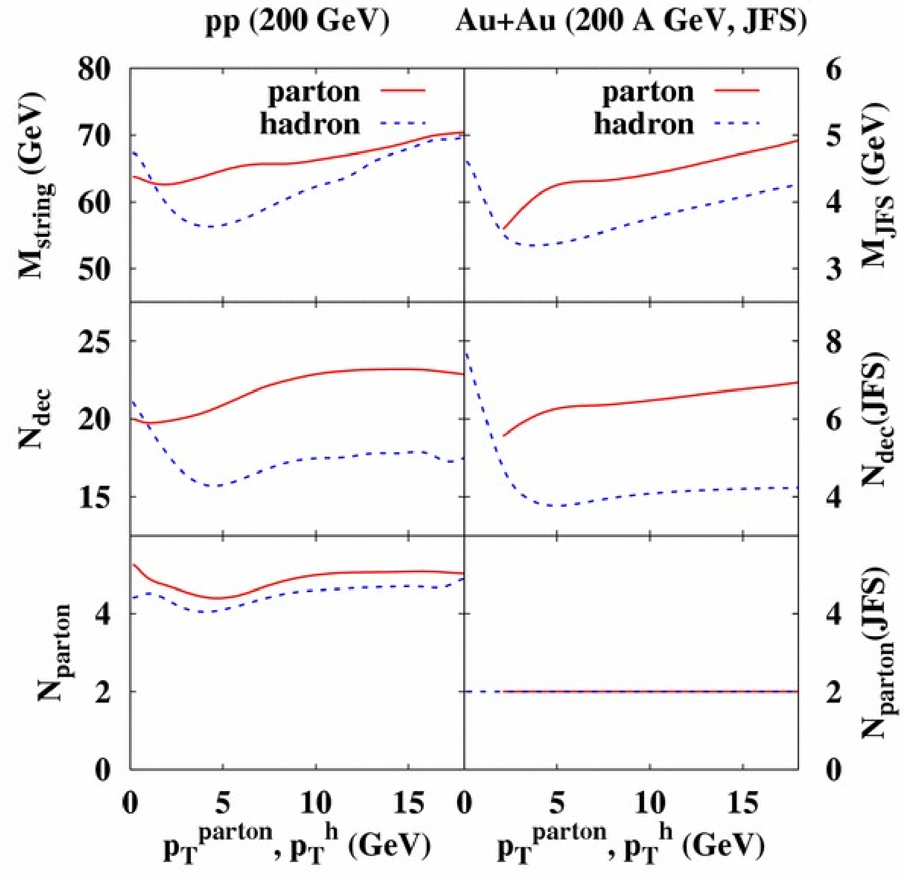
High pTでRAAを説明するE-lossで
v2 データをほぼ説明
→なぜhigh pTハドロンが作られやすい？

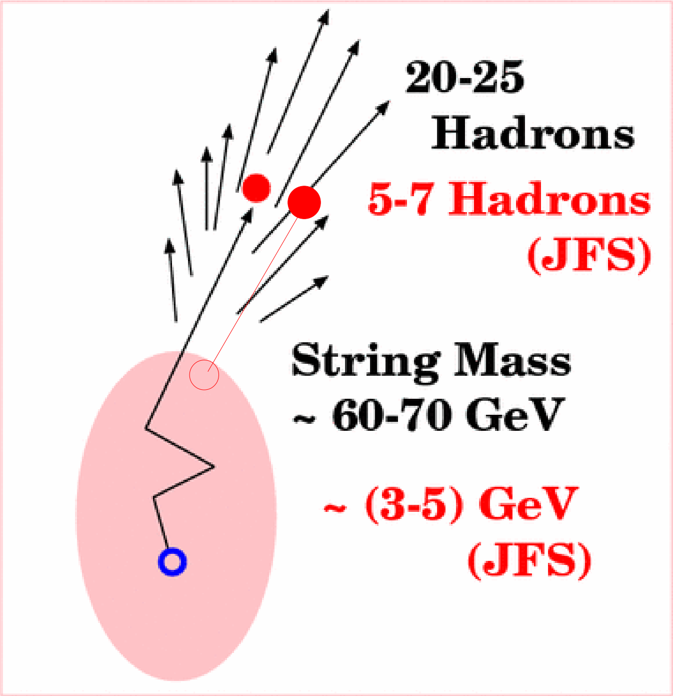
独立破砕模型との比較

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

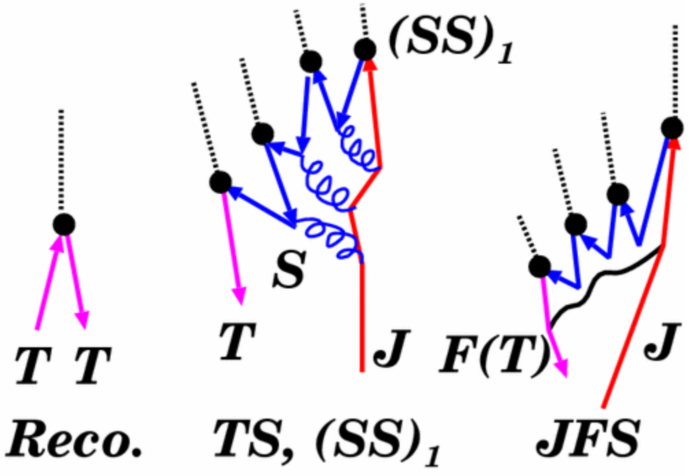
TS → med. pT, (SS)$_1$ → high pT

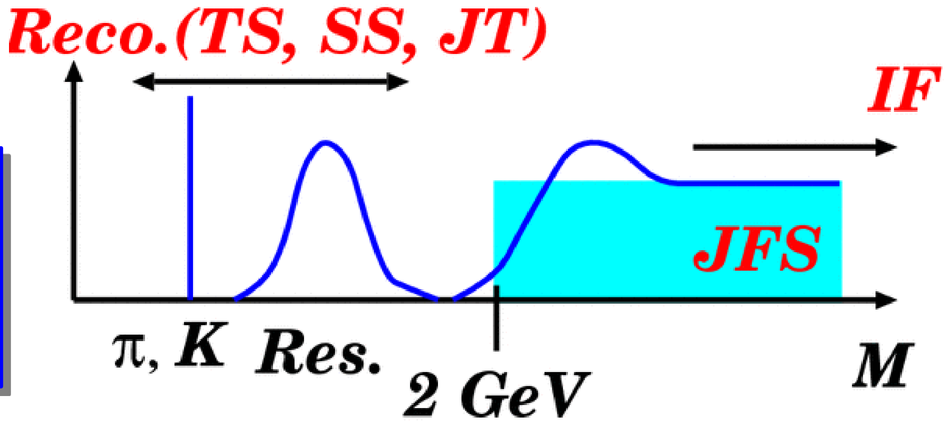
Hwa-Yang, PRC70('04)024905

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)

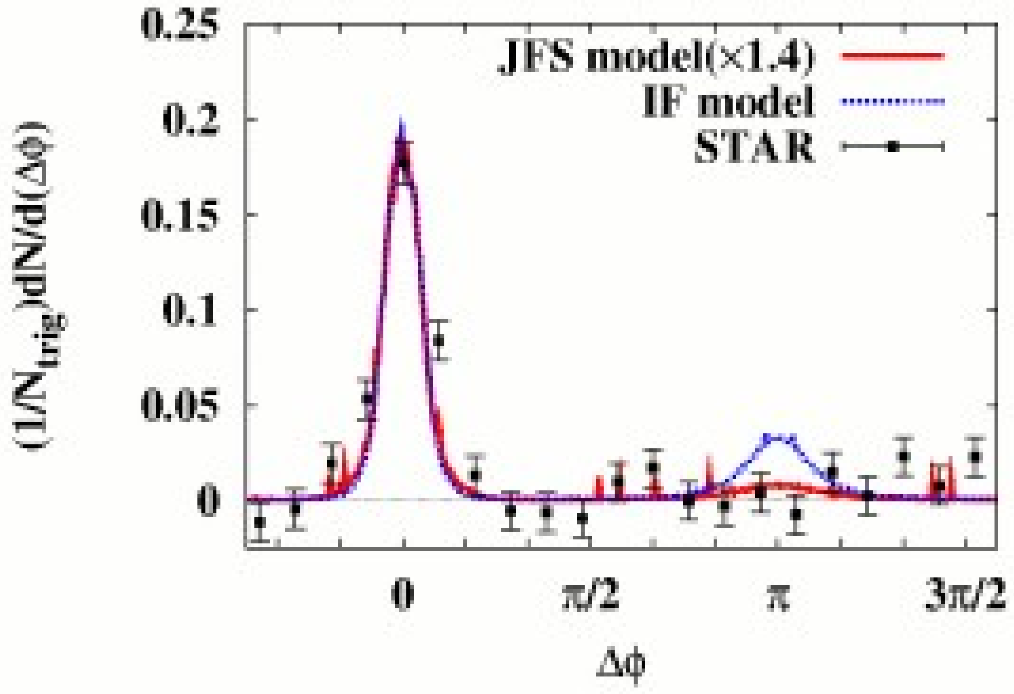
- R_{AA} を説明する E-loss では後方相関の抑制が十分でない
- ジェットの方向を変える散乱効果を取り入れると説明可能

Jet “absorption” model Drees, Feng,Jia, PRC71('05),034909

- ジェットパートンが $\exp(-\alpha L)$ 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.)

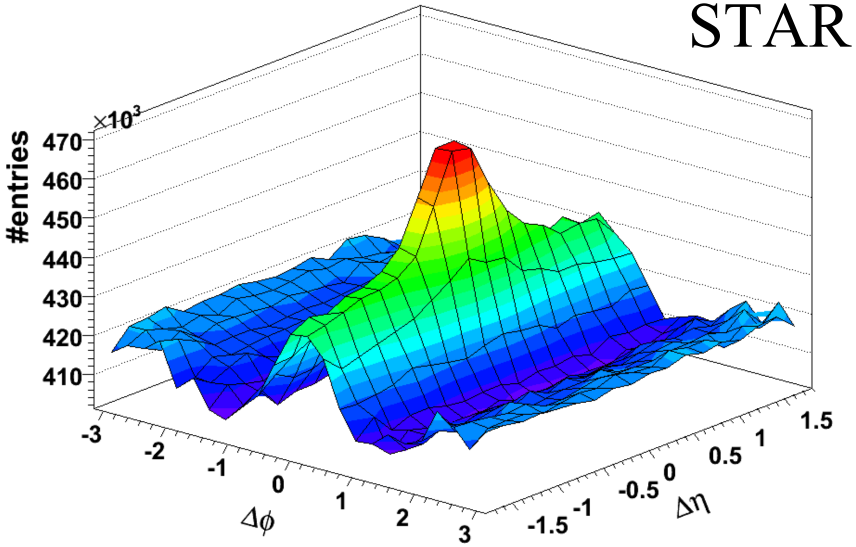
JFS では見えない

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

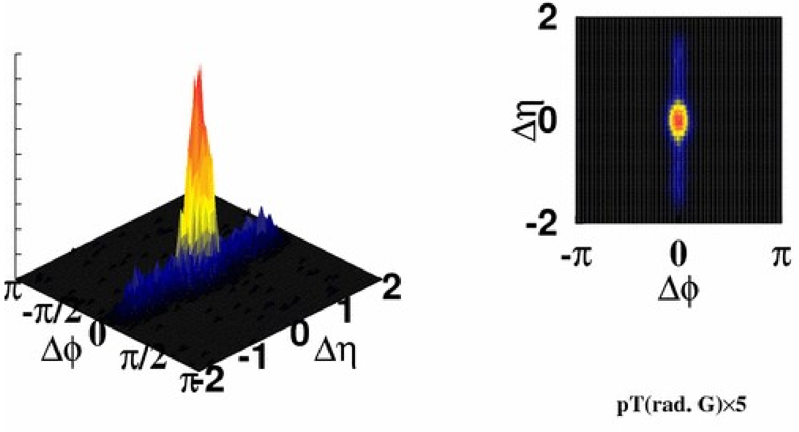
Shuryak: エネルギーを失った jet parton が流体中の「非平衡成分」として現れる

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

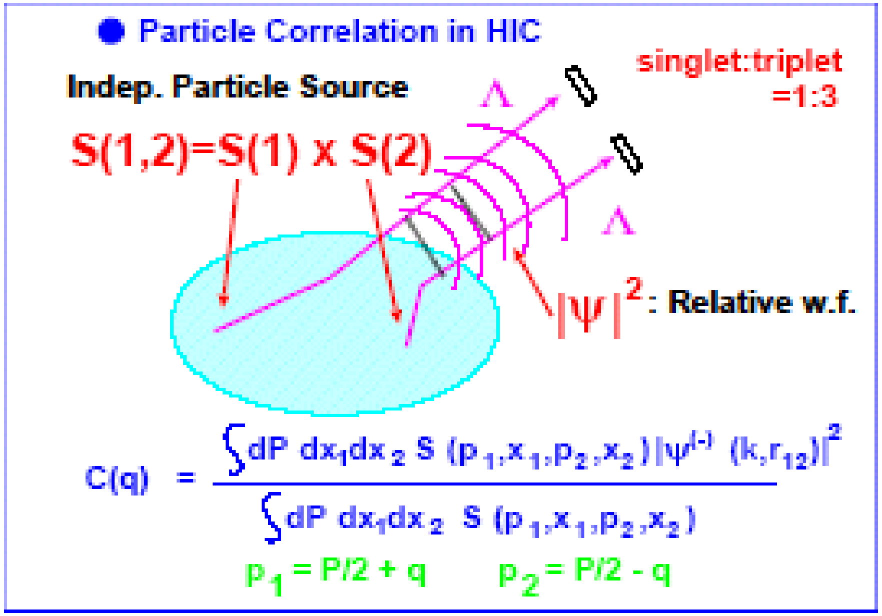
Near Future --- ΛΛ correlation ---

Longstanding problem in hadron spectroscopy:
Does H (S=-2, B=2) dibaryon below ΛΛ threshold ?

RHIC may solve this problem.

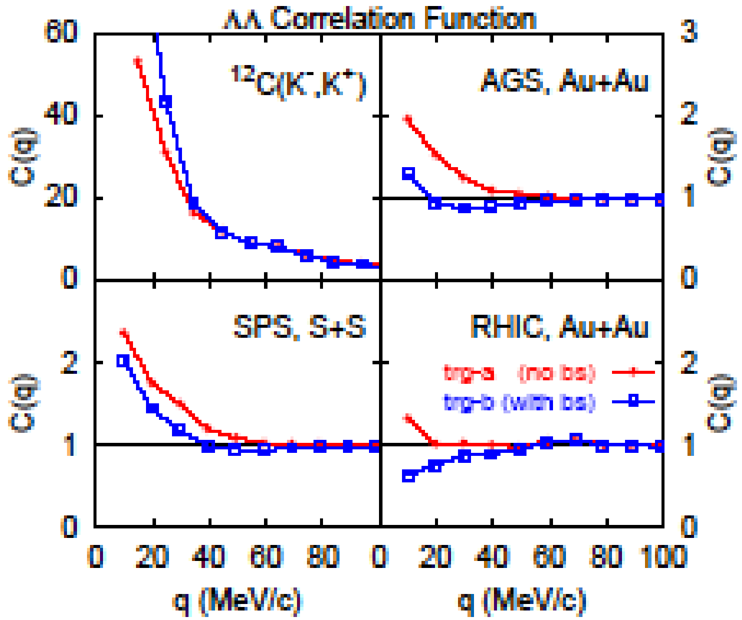
If ΛΛ bound, continuum w.f. must be orthogonal to b.s.w.f and must have a node around the scattering length.

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.)



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

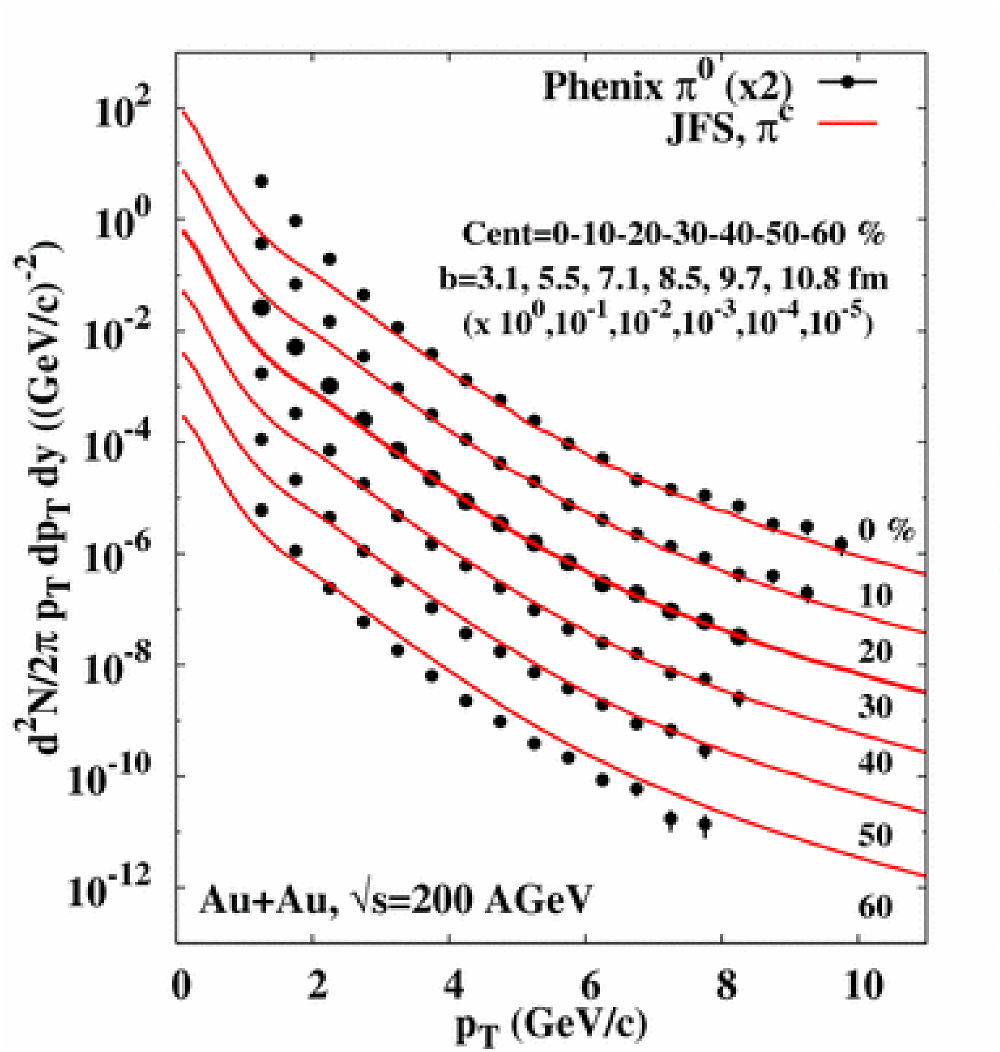
$p_1 = P/2 + q \qquad p_2 = P/2 - q$

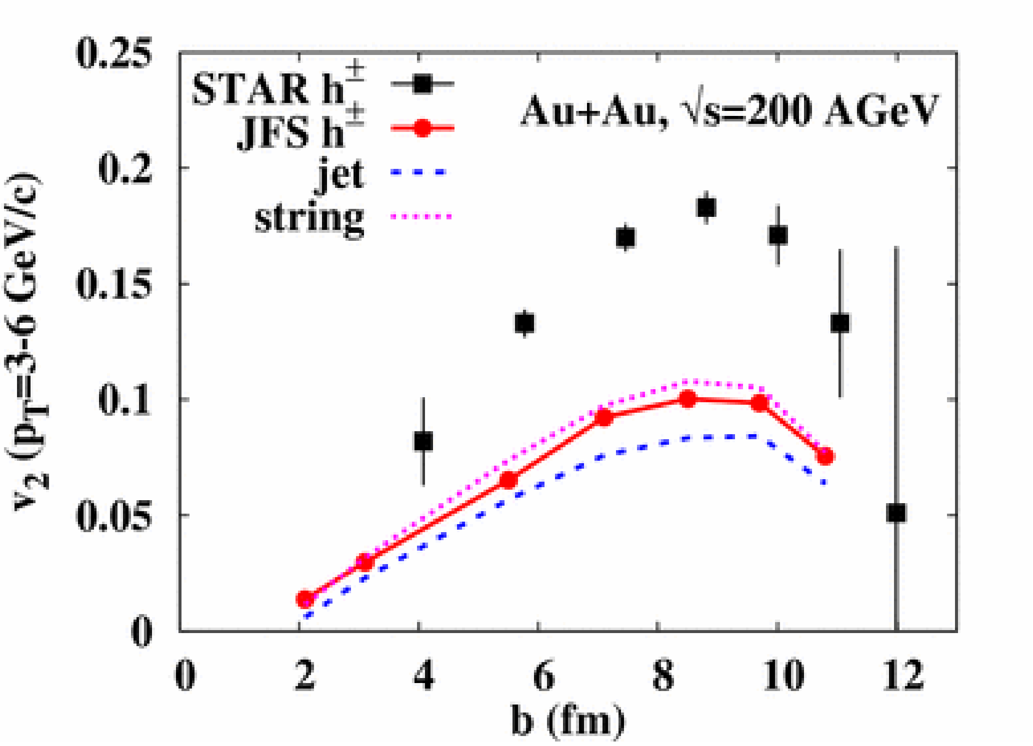


Ohnishi et al., NPA 670 (2000), 297c [arXiv:nucl-th/9903021]

Backups

Centrality Dependence



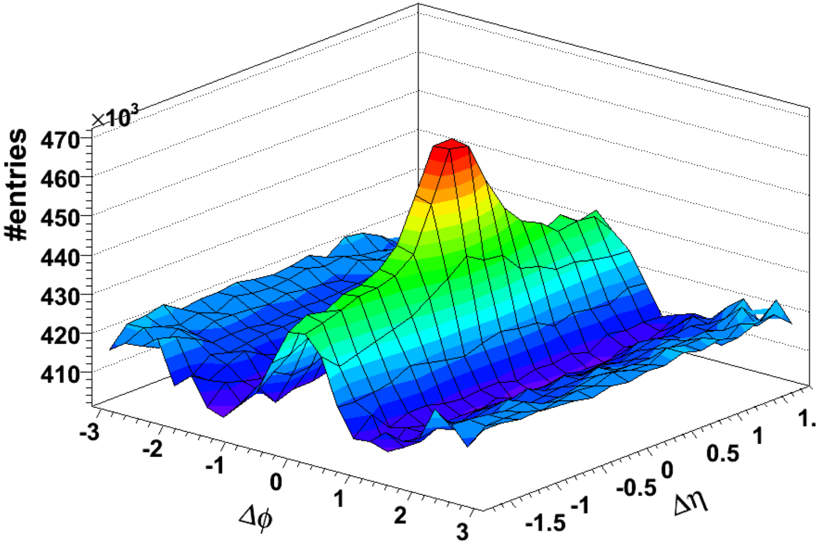


ジェット・リッジ構造

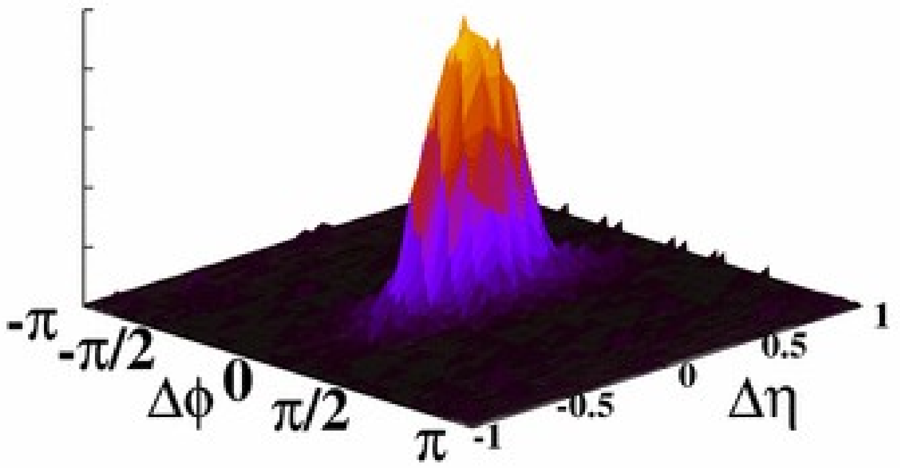
But, ...

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

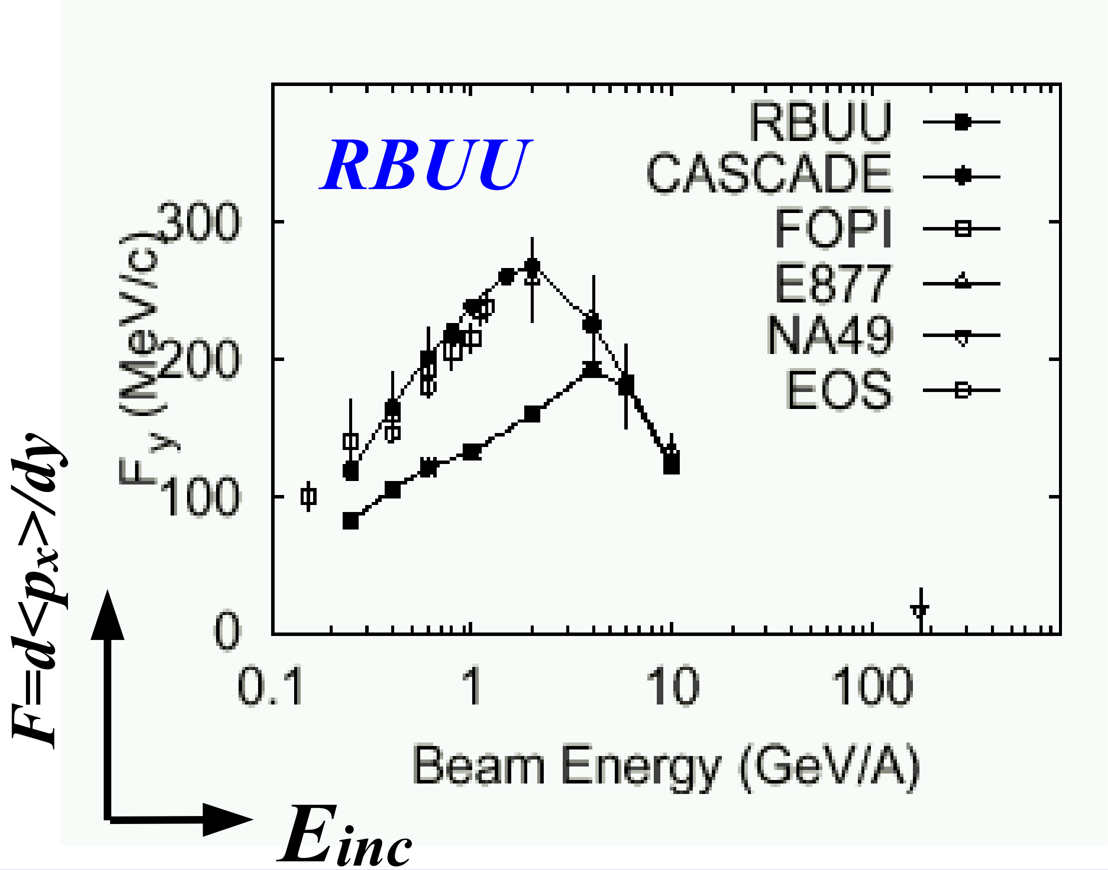


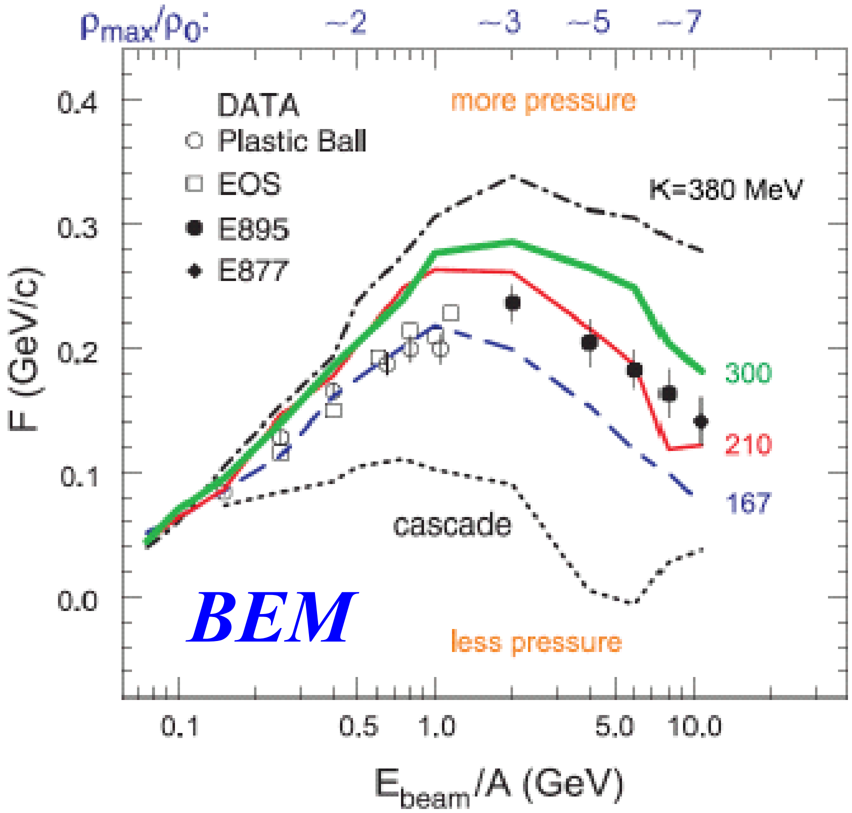
水川、卒論

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.)





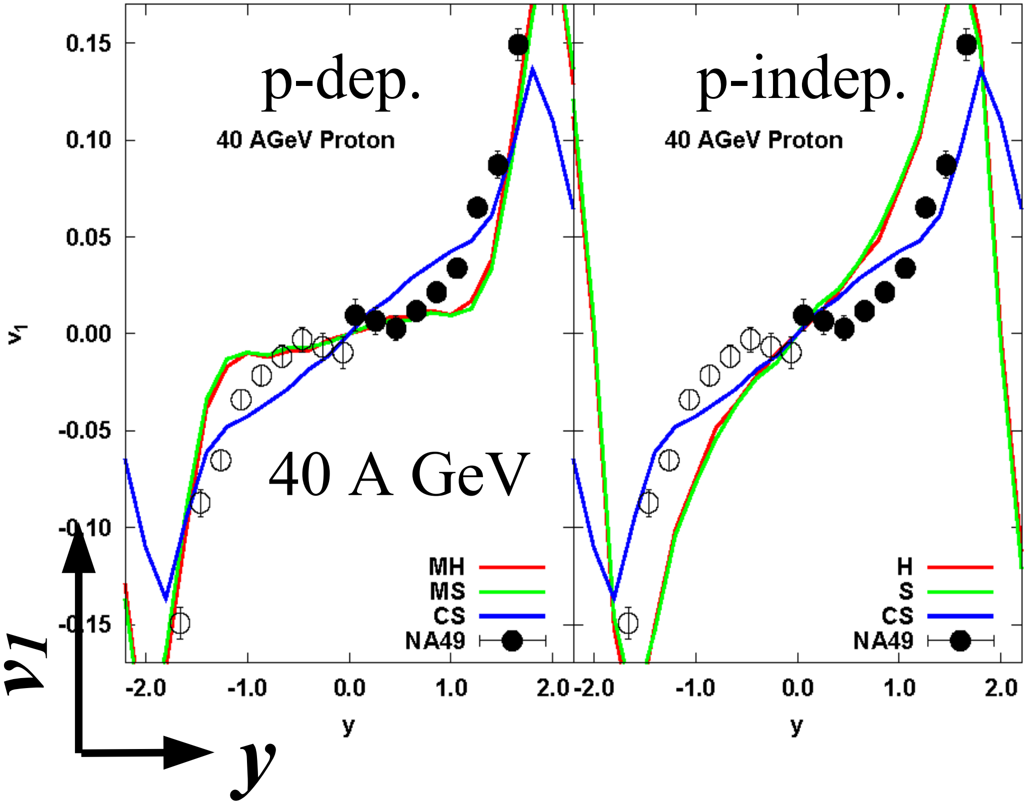
Directed flow v1 at SPS

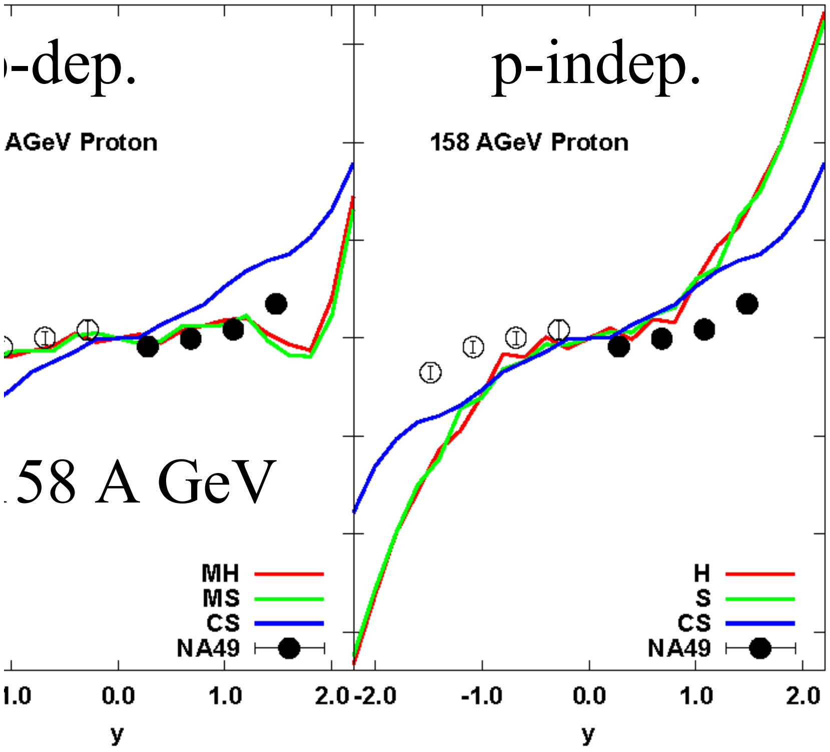
Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908

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.

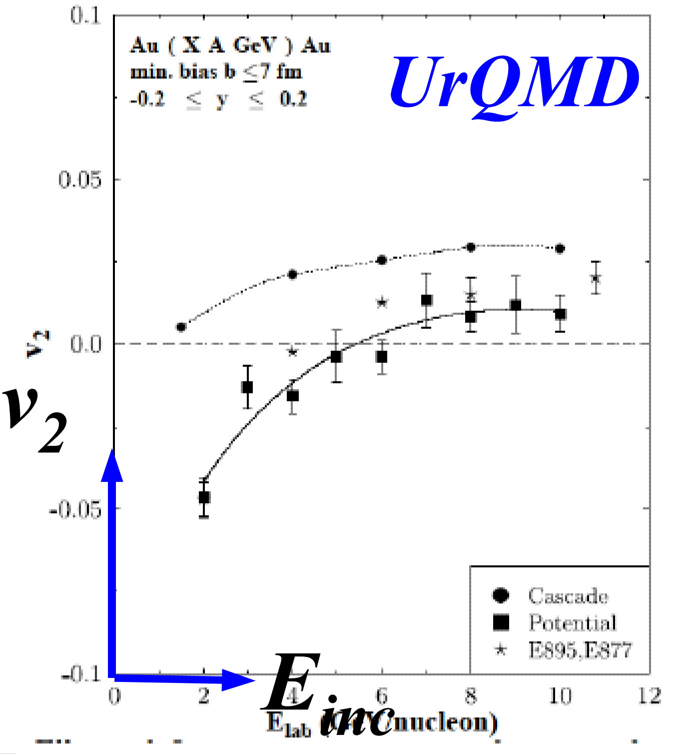


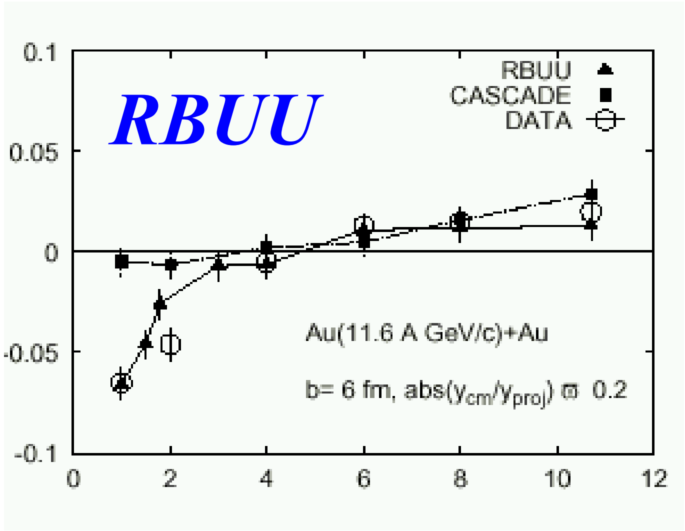


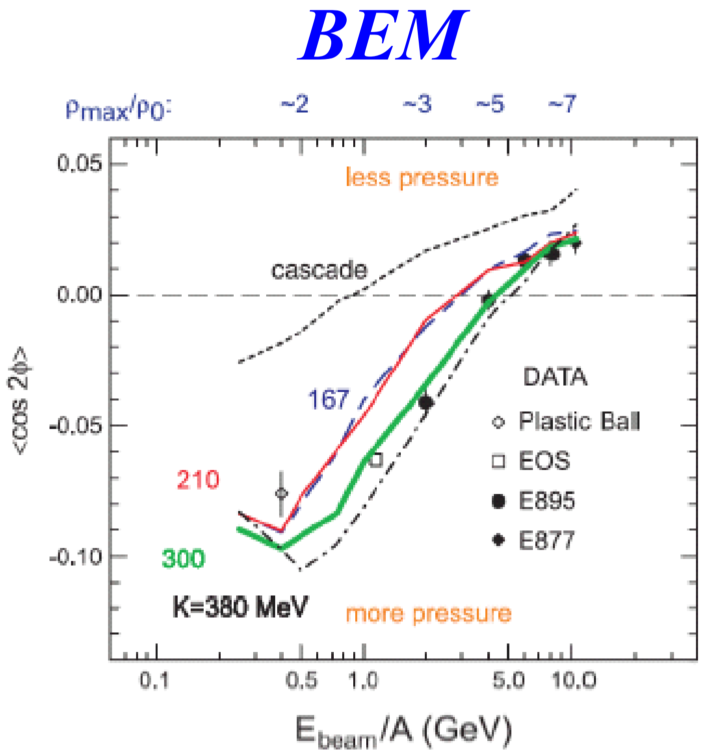
Elliptic Flow at AGS

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**





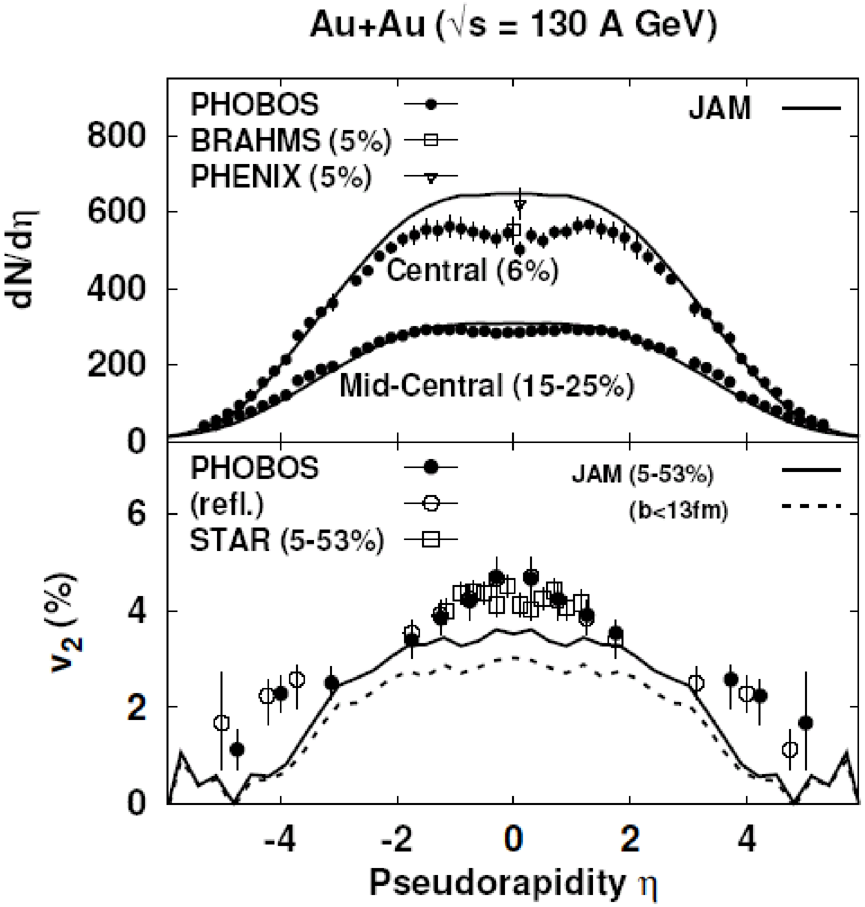


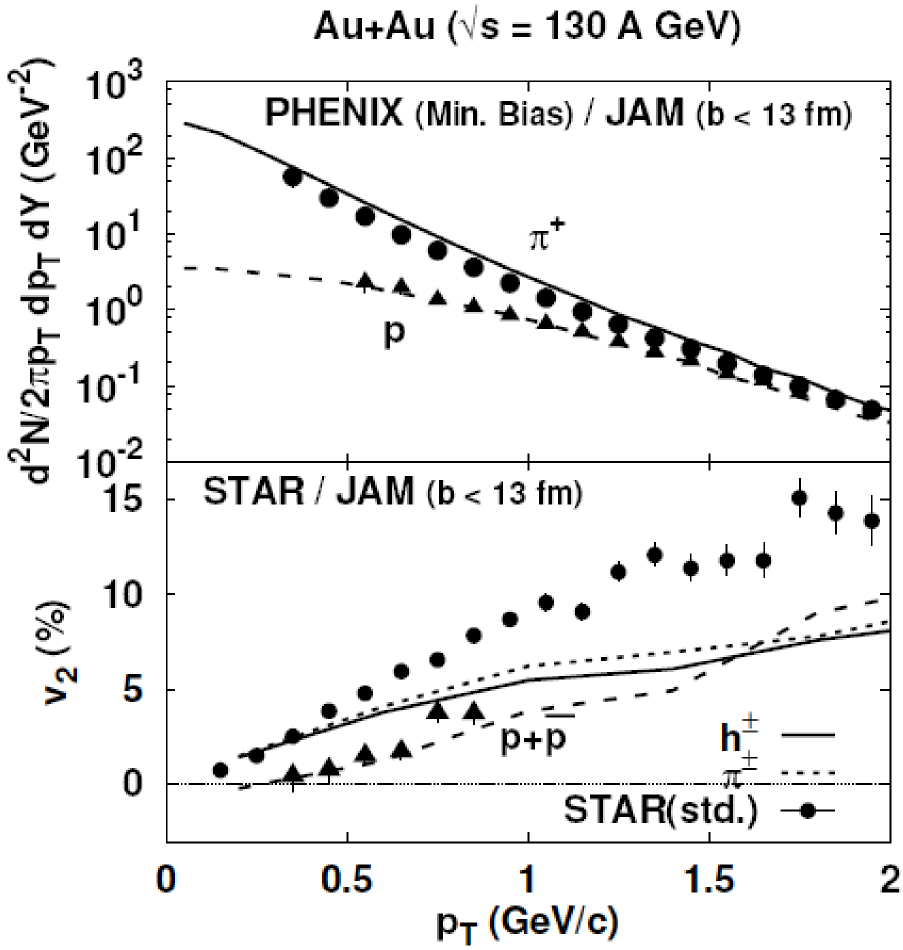
Elliptic Flow in Hadron-String Cascade (I)

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)



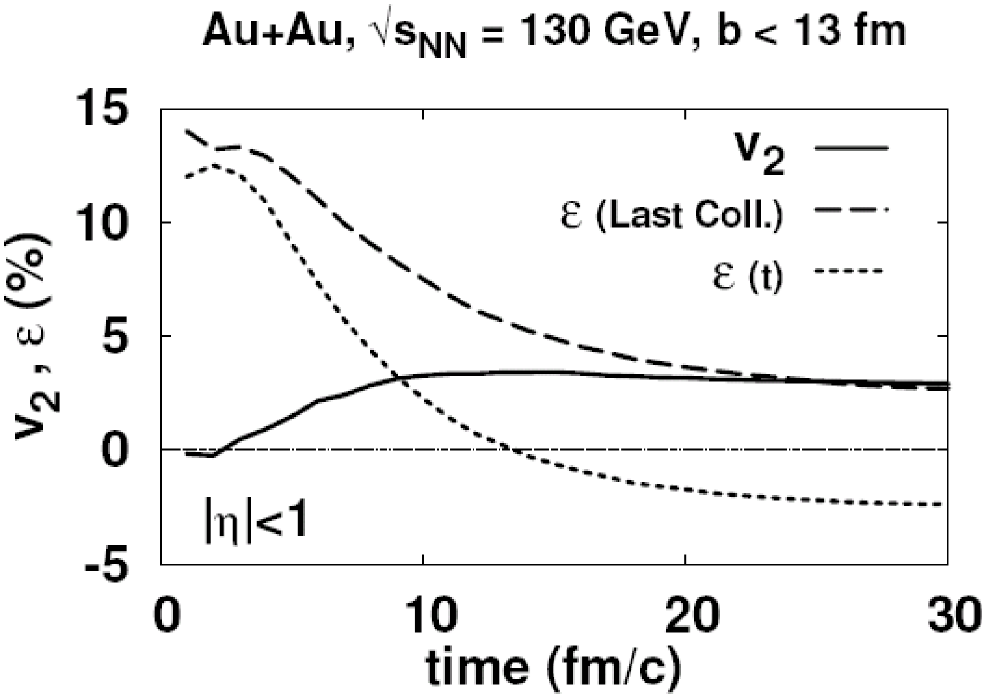


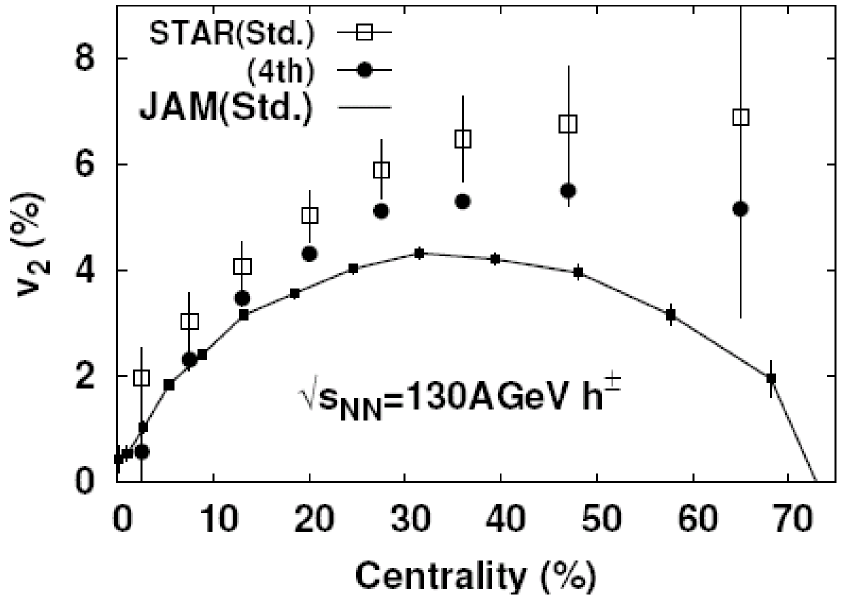
Elliptic Flow in Hadron-String Cascade (II)

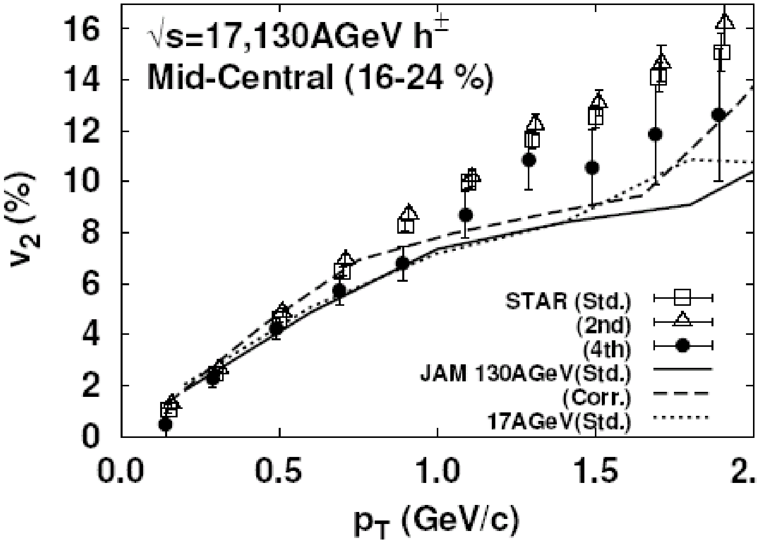
Why do we underestimate v2 in Hadron-String Cascade ?

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







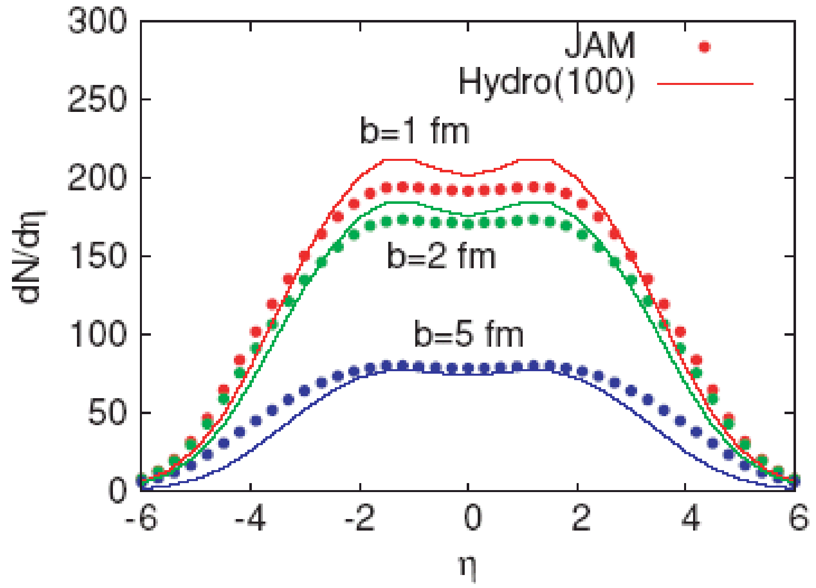
Predictions of Cu+Cu Collisions @ RHIC (I)

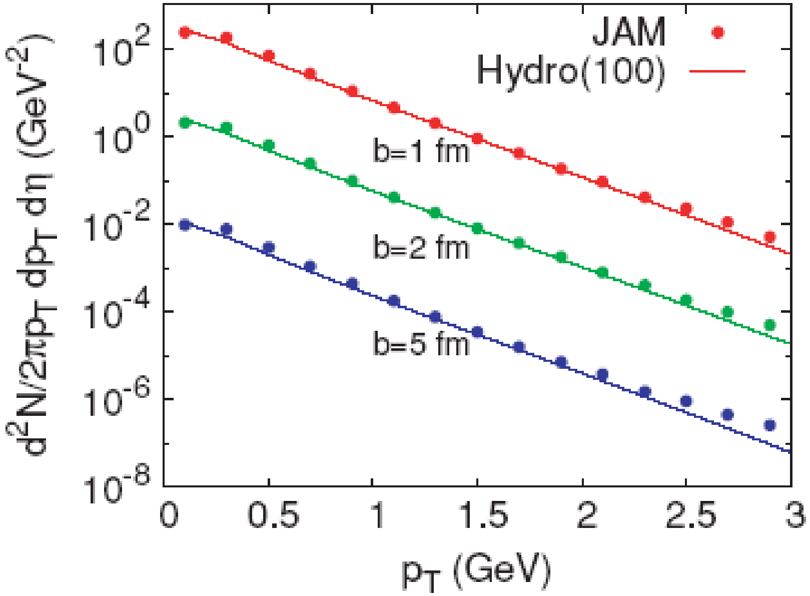
Single particle spectra

- **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)

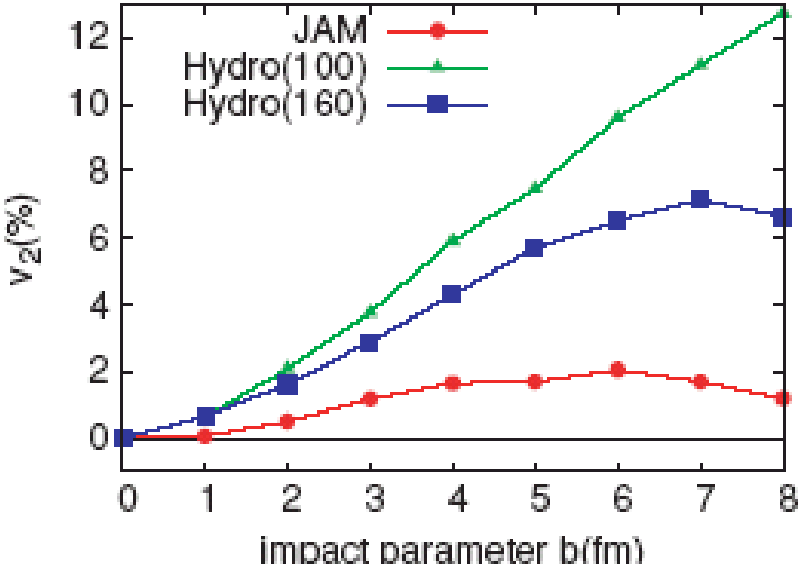
Calculations were done BEFORE the data are opened to public.

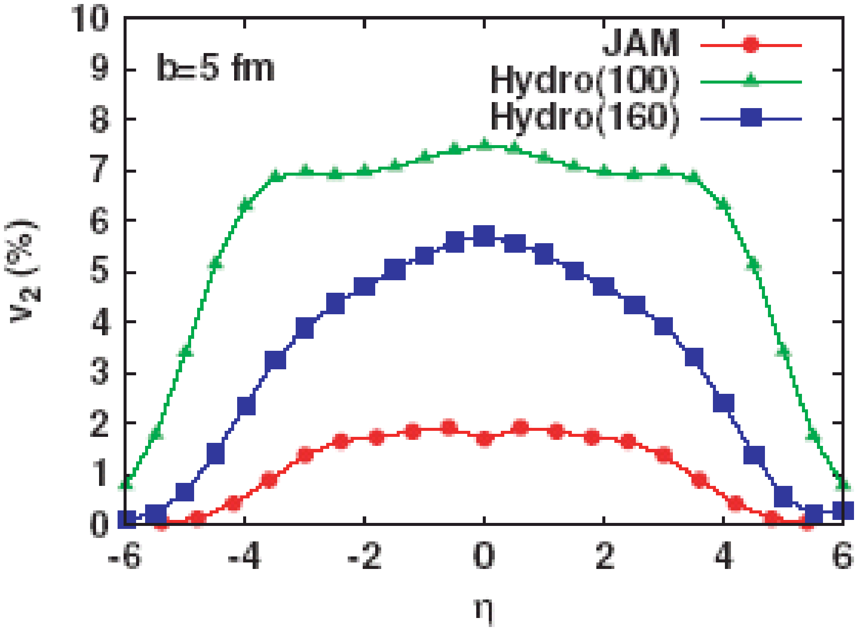
Cascade and Hydro predict very different Elliptic Flow !

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

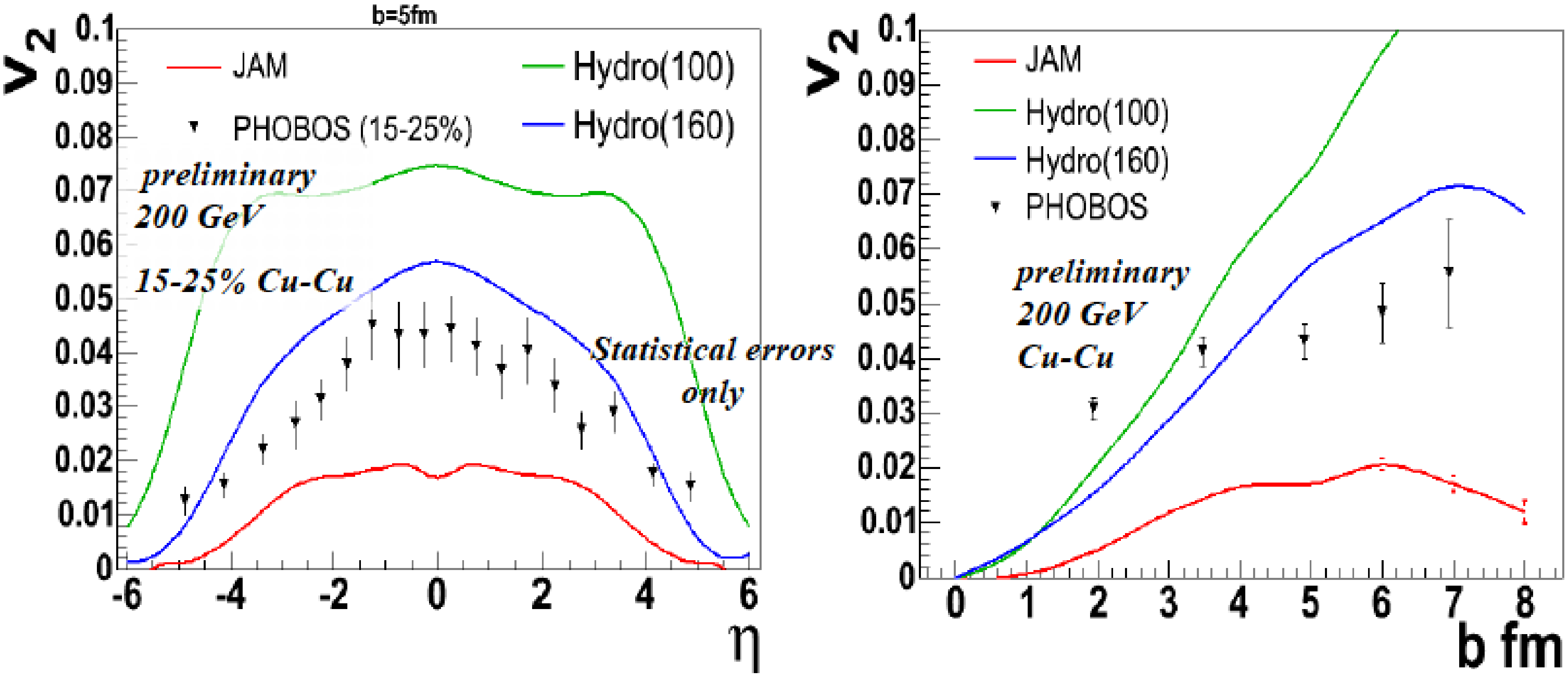
T^{th} dependence

- **$T^{th} = 160$ 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



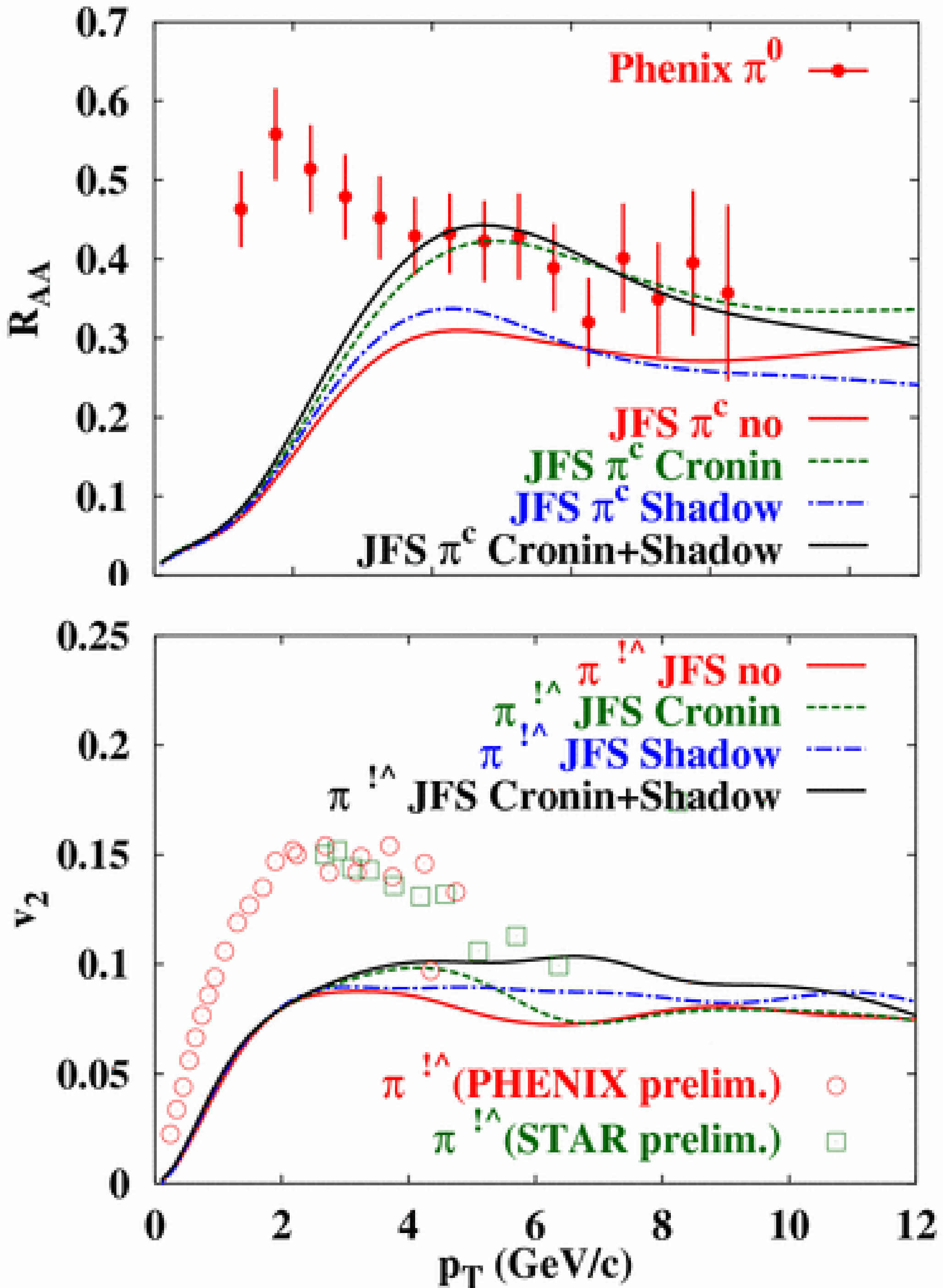
Cu-Cu more like Hydro than JAM hadron string cascade model

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}.**



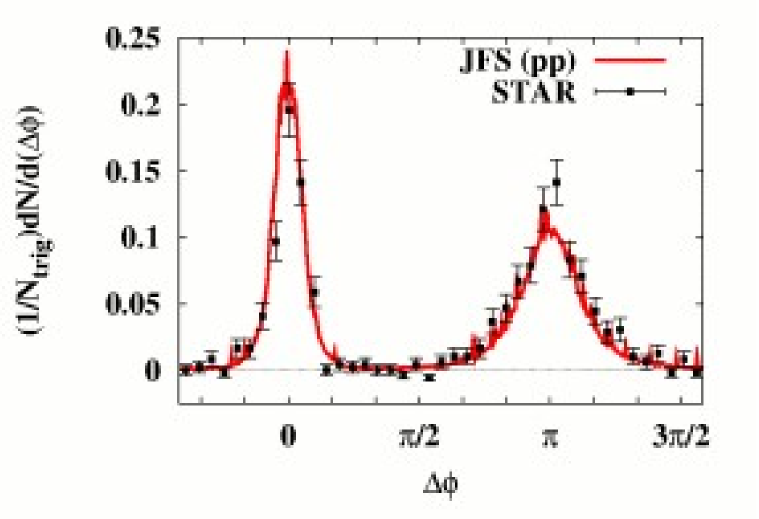
吉野、修論

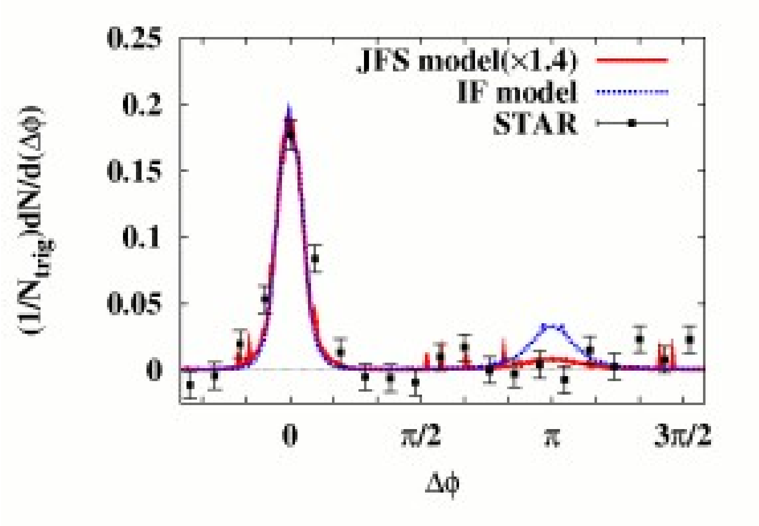
Two Hadron Correlation

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

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

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

Time-dependent Variational Principle → Equations of Motion

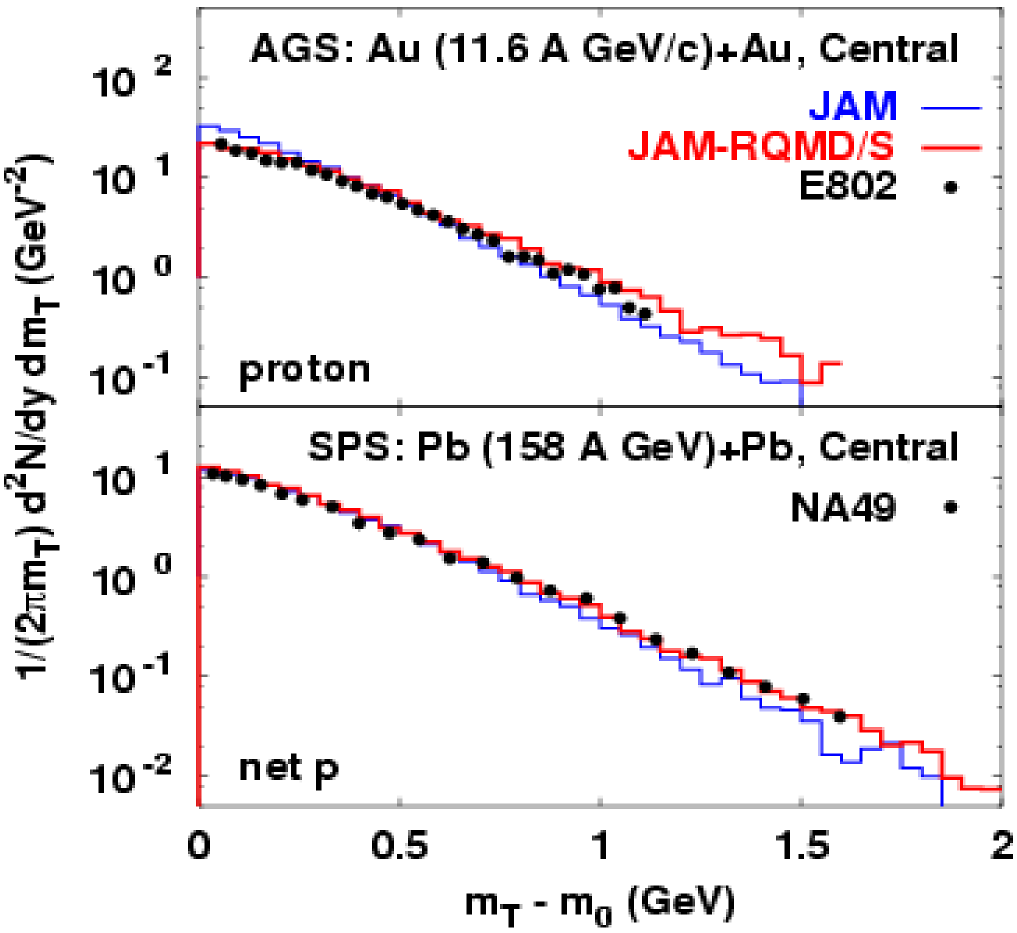
$$L = \frac{\langle\Psi|i\hbar\partial/\partial t - H|\Psi\rangle}{\langle\Psi|\Psi\rangle} \qquad \frac{d}{dt}\frac{\partial L}{\partial(d\overline{Z}_i/dt)} - \frac{\partial L}{\partial\overline{Z}_i} = 0 \quad \rightarrow \quad i\hbar C_{i\alpha,j\beta}\frac{dZ_i}{dt} = \frac{\partial H}{\partial\overline{Z}_i}$$

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



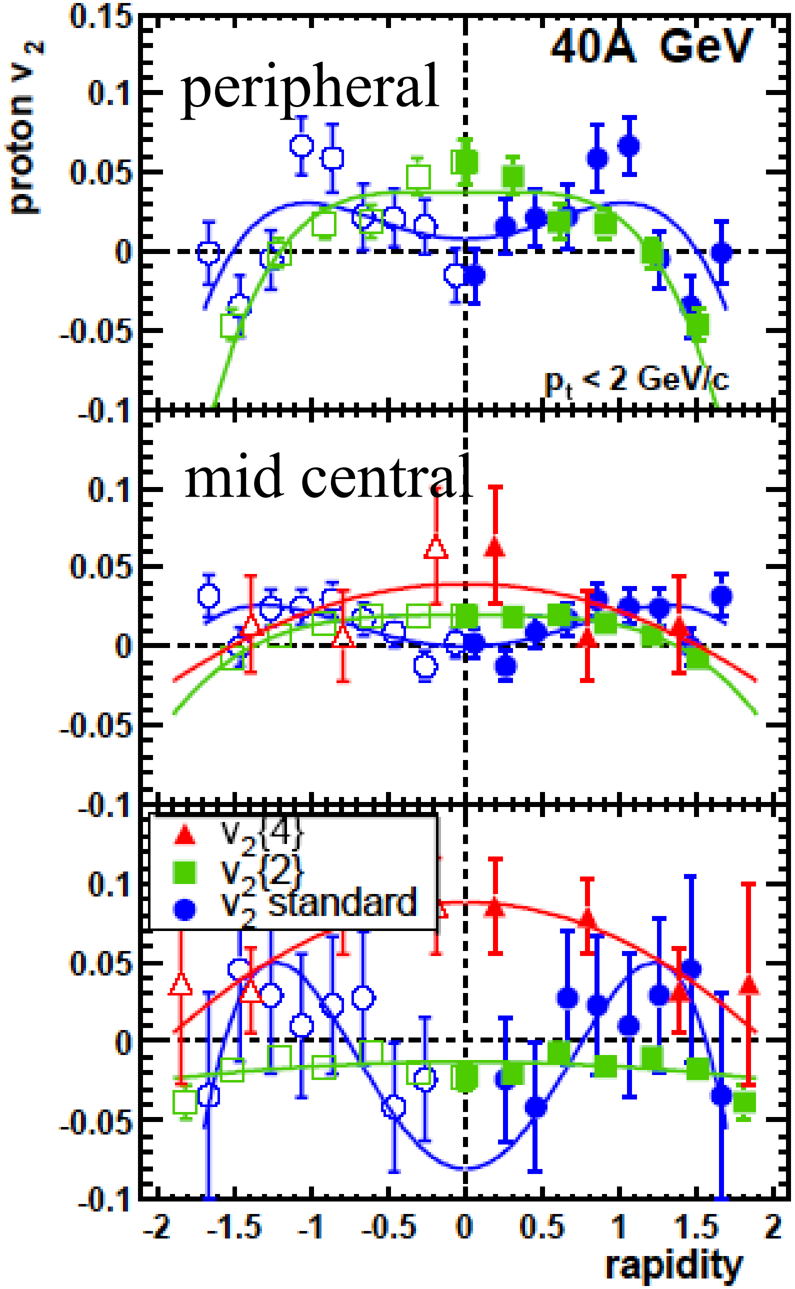
Mean Field affects
the Mt Spectra
even at SPS energy.

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)

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

Due to the Scalar potential nature, EOS dependence is smaller.

Scalar/Vector Combination *Danielewicz, Lacey, Lynch, Science 298('02), 1592*

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

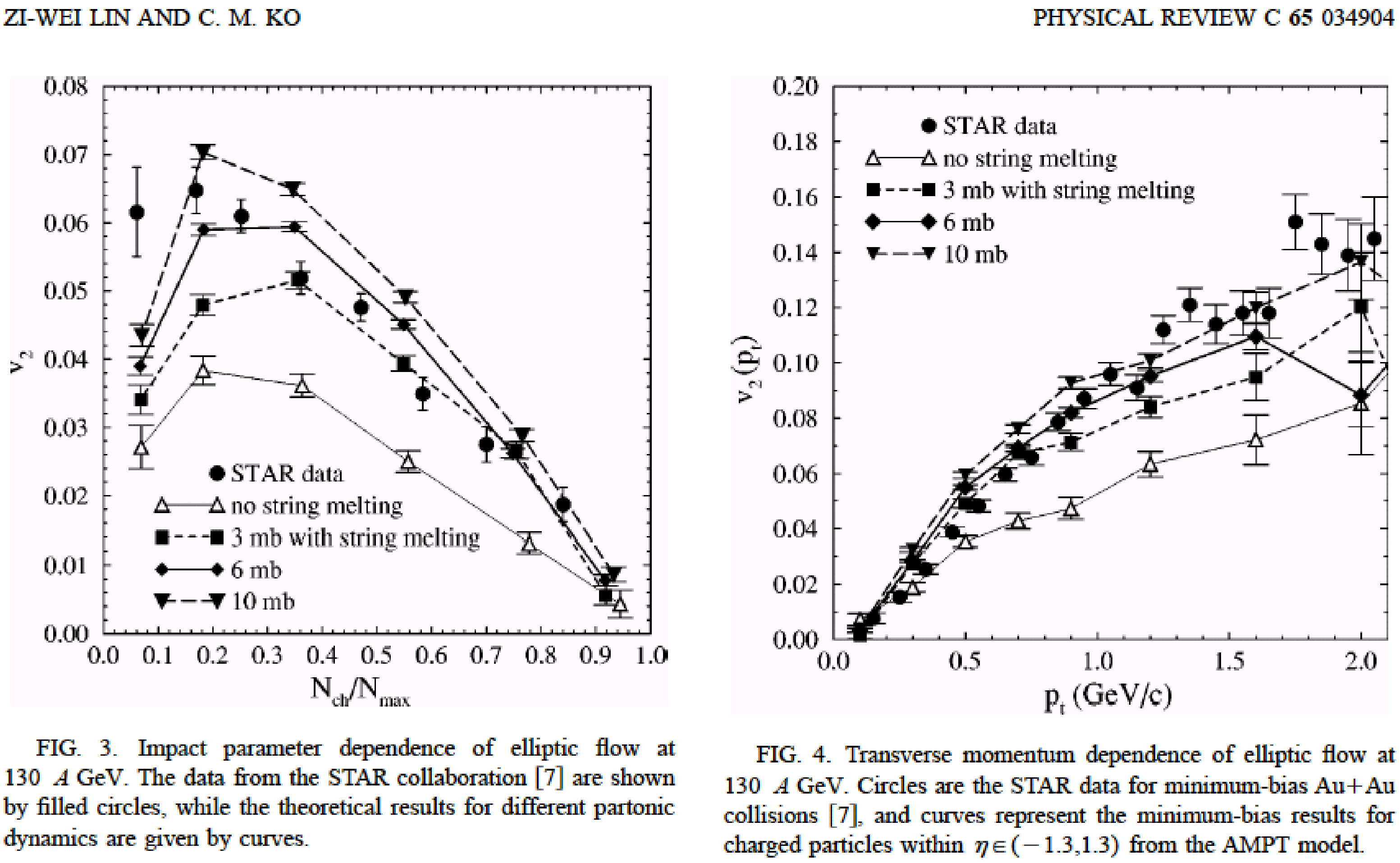
Relatively Strong EOS dependence even at high energy

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]

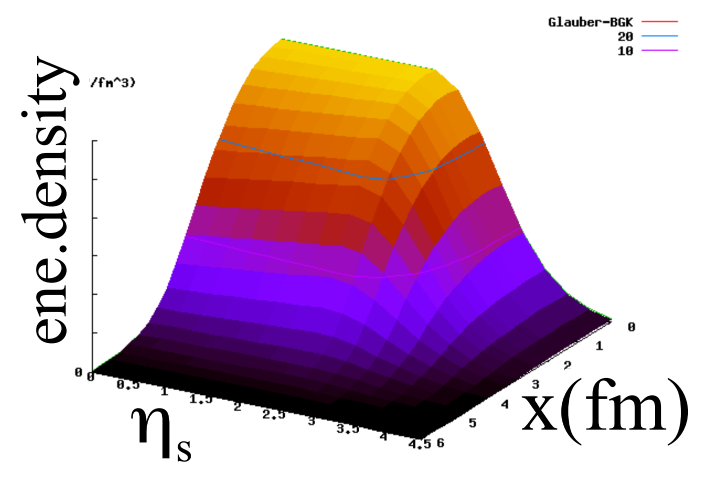
<u>Transverse profile</u>:

Entropy density

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

<u>Longitudinal Profile</u>:

Brodsky-Gunion-Kuhn triangle

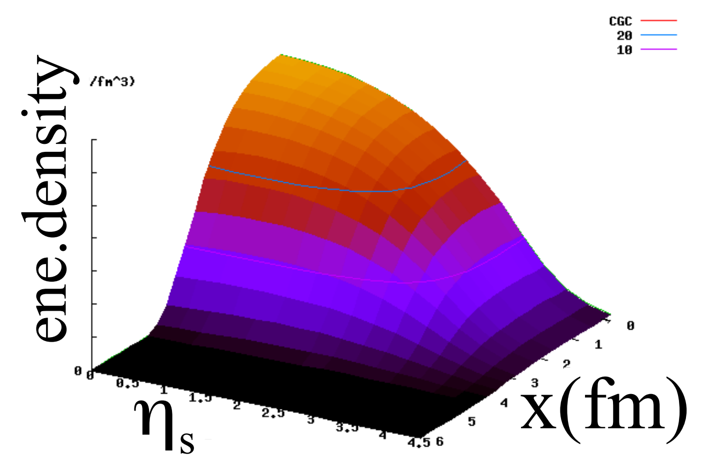


Color Glass Condensate

Unintegrated gluon distribution a.la. Kharzeev, Levin, and Nardi

Gluon production via k_T factorization formula

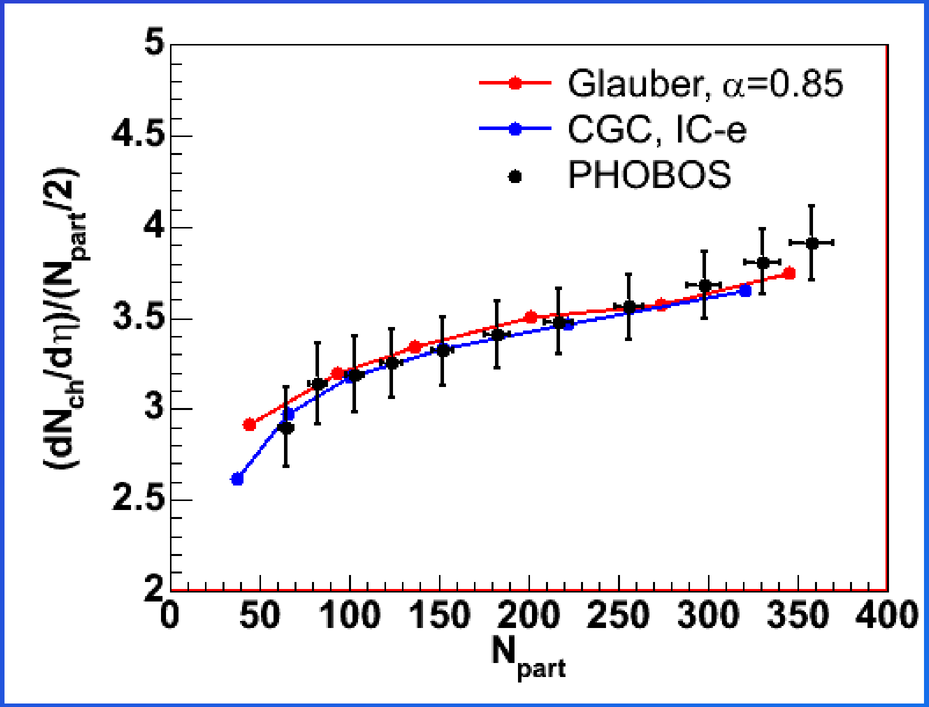
Count deposited energy in dV at (τ_0, x, y, η_s), $\tau_0 = 0.6\mathrm{fm/c}$



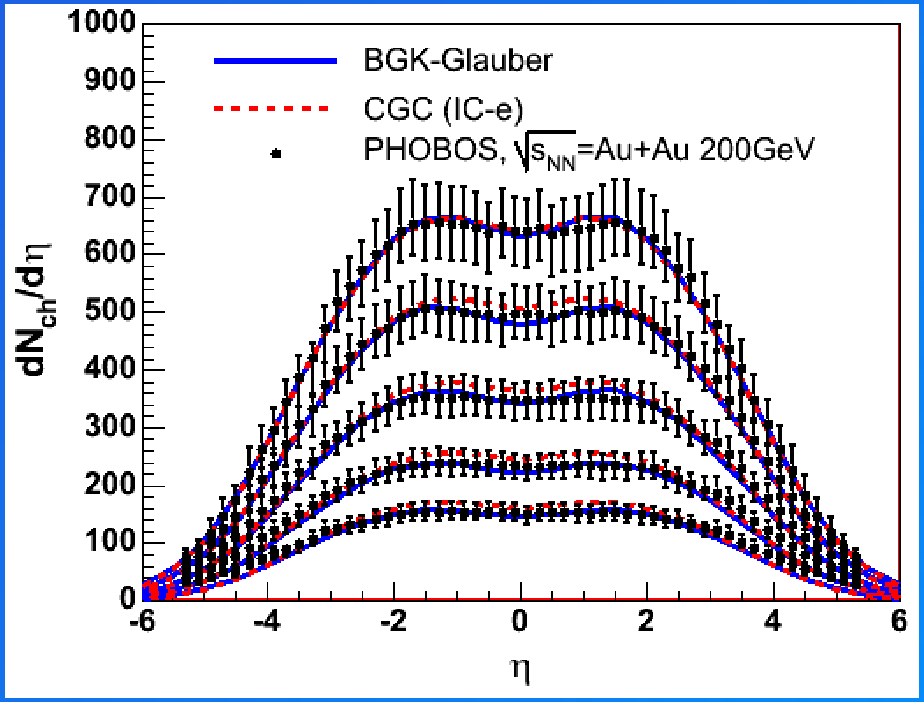
Hirano @ QM2006

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 $e(x,y,\eta)$

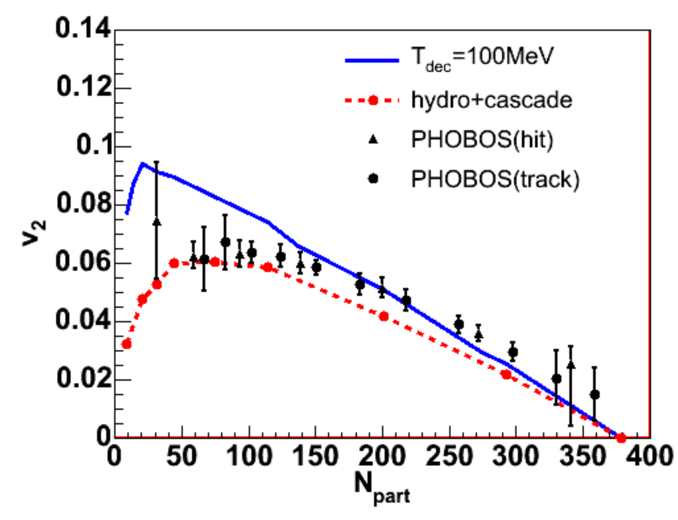
2.Glauber model (as a reference)

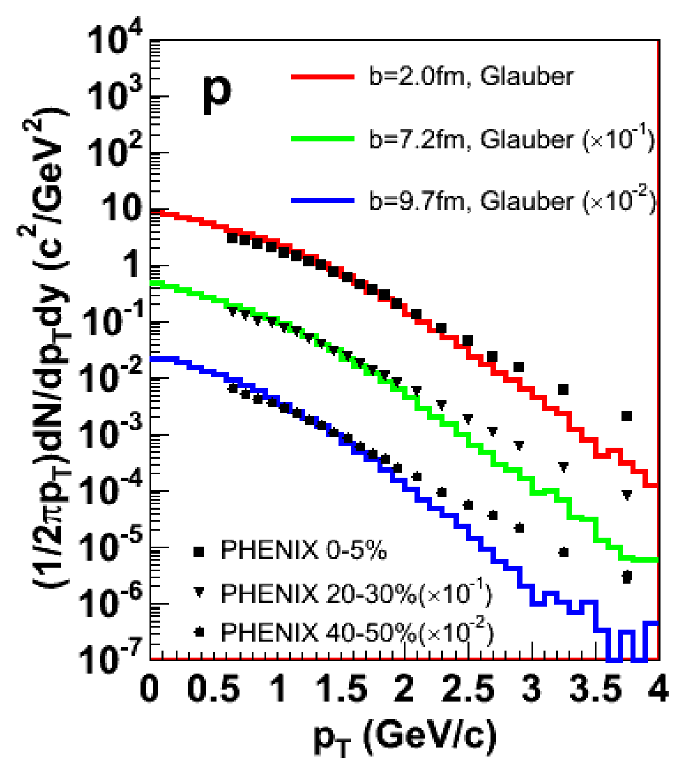
$N_{part}:N_{coll} = 85\%:15\%$

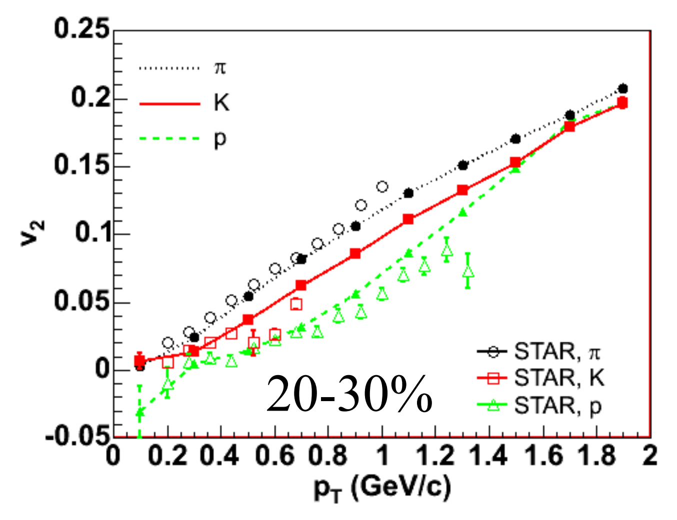
Hirano @ QM2006

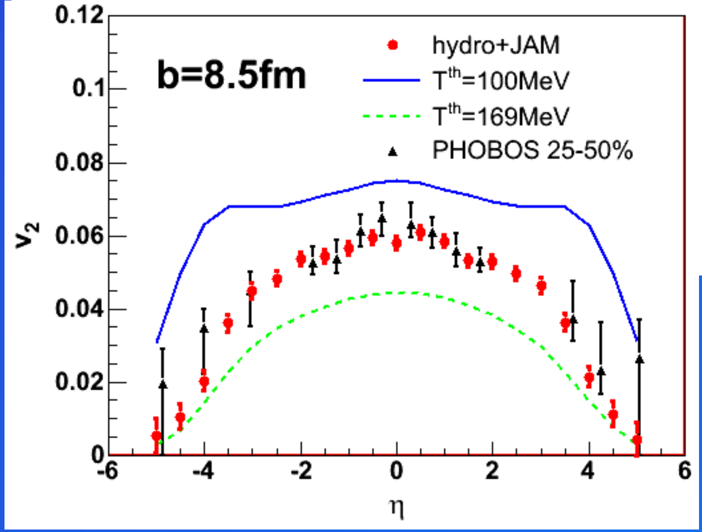
TH et al.('06); in preparation.

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 .

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

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

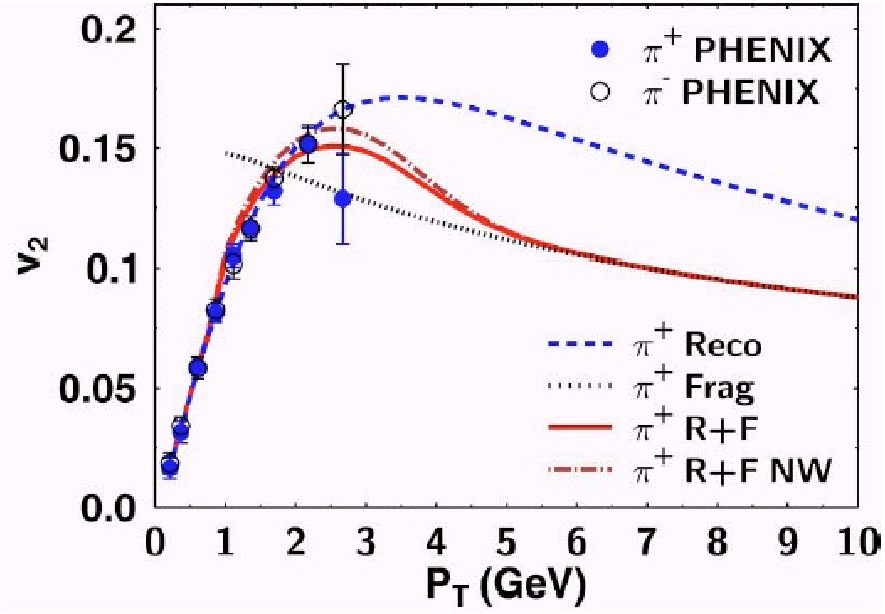
Problems: Sharply edged density dist. (Hard Sphere)

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

→ 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.