Nov. 5-6, 2002, RHIC/LHC/JHF/GSI Workshop @ CNS

Physics of High Density Matter Formed in Heavy-Ion Collisions at JHF and GSI Energies

Akira Ohnishi, Hokkaido Univ.

1. What We Can Do with JHF/GSI Machine ?
   - ⋆ Hadron Phase Diagram
   - ⋆ JHF $\leftrightarrow$ GSI
2. Towards the Highest Density Matter in Lab.
   - ⋆ (ρ_B, T) Trajectory at JHF
   - ⋆ Collective Flow: Probe of Pressure
   - ⋆ Strangeness Enhancement: Rescattering or Potential ?
   - ⋆ Low-Energy Di-Leptons: Probe of Chiral Symmetry Restoration
3. Towards LTHD (Low T & High ρ) Matter & Baryon Rich QGP Formation
   - ⋆ (ρ_B, T) Fluctuation: Can we make (ρ_B, T)=$(10\rho_0, 50$ MeV) ?
4. Summary

⋆ What We Can Do with JHF/GSI Machine ?

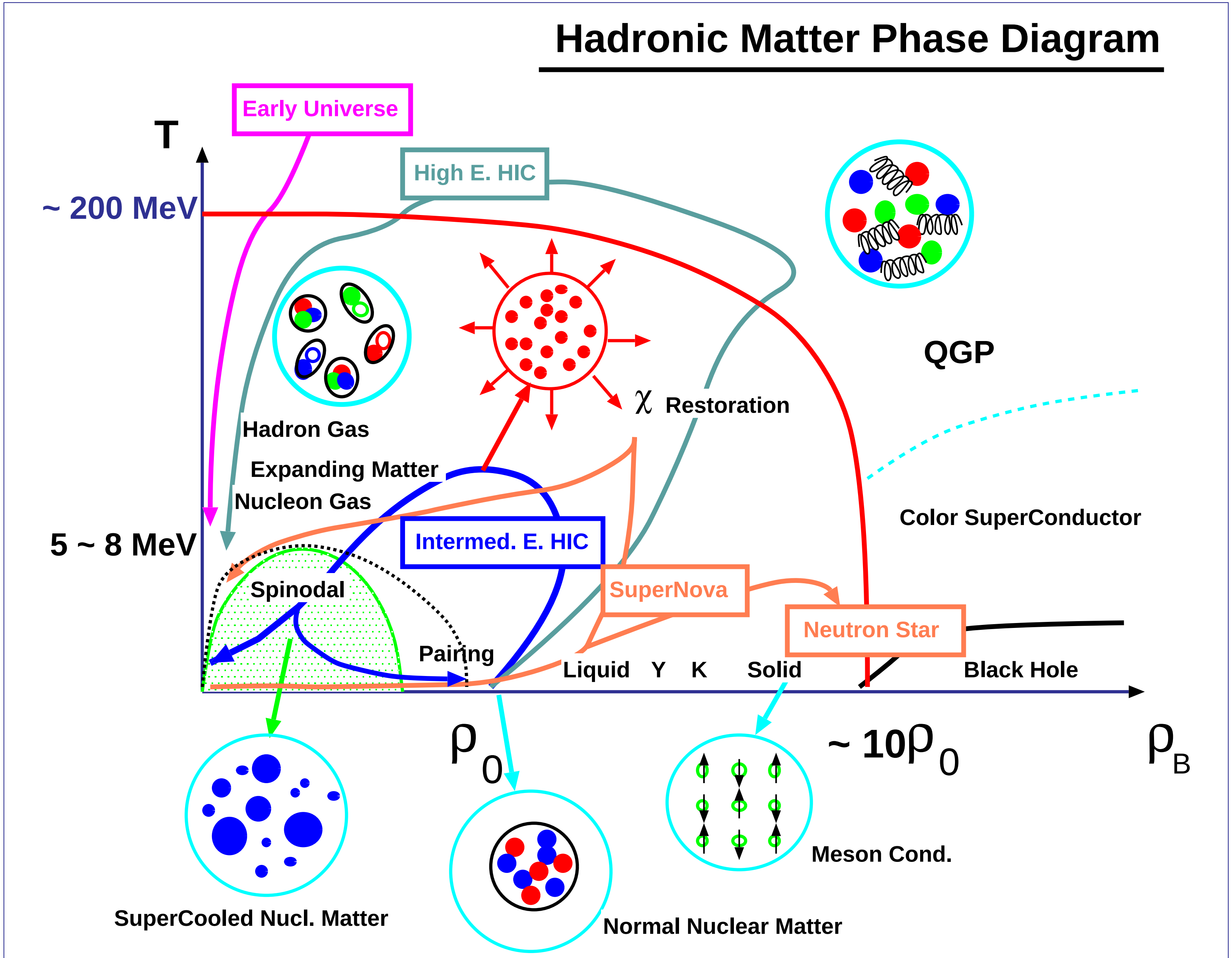
- JHF...

⋆ Proton Beam: 600 MeV ∼ 50 GeV (2 orders Energy Range !)
- Multifragmentation, Particle Production, Hadron Spectroscopy

⋆ Various Intense Secondary Beams (n, μ, ν, $\bar{p}$, K, π, ...)
- Strangeness Nuclear Physics

⋆ HI Beam: ∼ 25 A GeV → Most Dense Hadronic Matter Formation in Lab.
- Hydrodynamical Evol., Caloric Curve, EOS, Hadrons in Dense and Hot Matter

☞ Suitable for studying "Phase Diagram", esp., of "Highly Dense Matter"
- Proton Beam: Elem. Proc., incl. Res., Hadron Property at ρ_0
- HI Beam: EOS of Dense Matter
- Pion/Kaon Beam: Strangeness Production, Y Potentials


Hadronic Matter Phase Diagram
Early Universe
T
High E. HIC
~ 200 MeV
QGP
χ Restoration
Hadron Gas
Expanding Matter
Nucleon Gas
5 ~ 8 MeV
Intermed. E. HIC
Color SuperConductor
SuperNova
Spinodal
Neutron Star
Pairing
Liquid Y K Solid
Black Hole
ρ0
~ 10ρ0
ρB
Meson Cond.
SuperCooled Nucl. Matter
Normal Nuclear Matter

⋆ Why and How is Dense Matter Study @ JHF/GSI Interesting ?

⋆ Essential in Understanding Compact Steller Objects.
$\cdots$ EOS, Particle Ratio, Pairing, ...
$\leftrightarrow$ Neutron Stars, Supernovae, Black Hole, Neutron Star Merger

⋆ In addition to Particle Degrees of Freedom (hadron $\leftrightarrow$ quark & gluon), Interaction plays vital roles.
$\cdots$ *FREE* models fail in many ways.

⋆ Hadron Natures (sometimes) become clear in medium

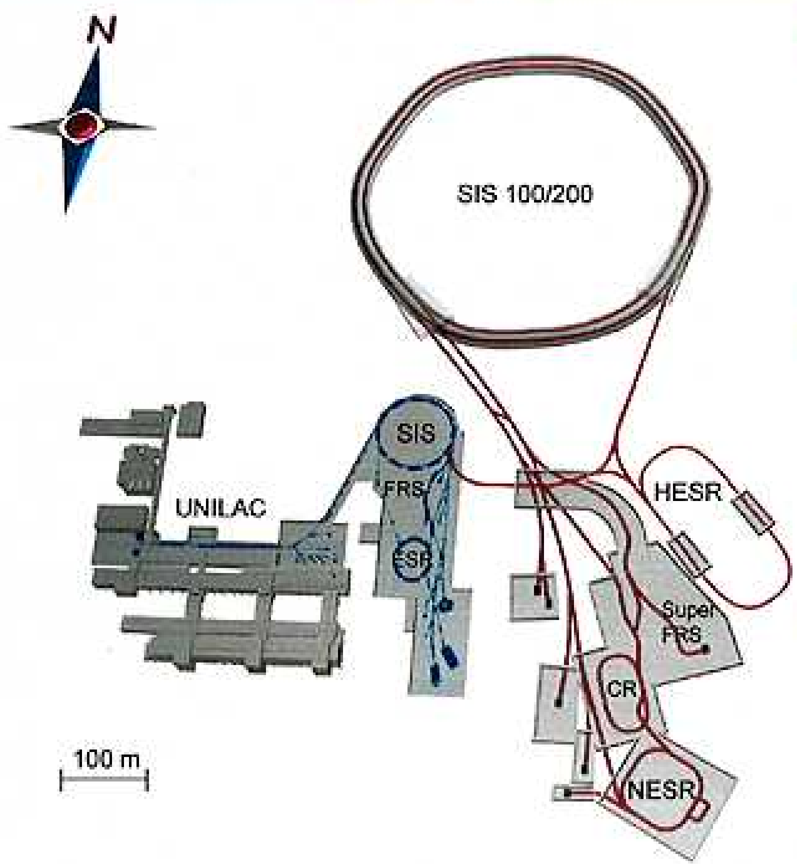
$\cdots$ ρ, σ, K, η, N^*, Λ^*, Σ^*

⋆ Baryon Rich QGP may be formed at JHF/GSI.

Two Projects are Competing !
JHF (Second Stage, 25 A GeV)
$\leftrightarrow$ GSI Future Project (SIS 100/200) ($\sim$ 30 A GeV)

Henning (http://www.gsi.de/cbm2002/)

GSI Future Project



Gain Factors

- Primary beam intensity: Factor 100 – 1000
- Secondary beam intensities for radioactive nuclei: up to factor 10,000
- Beam energy: Factor 15

Special Properties

- Intense, fast cooled energetic beams of exotic nuclei
- Cooled antiproton beams up to15 GeV
- Internal targets for high-luminosity in-ring experiments

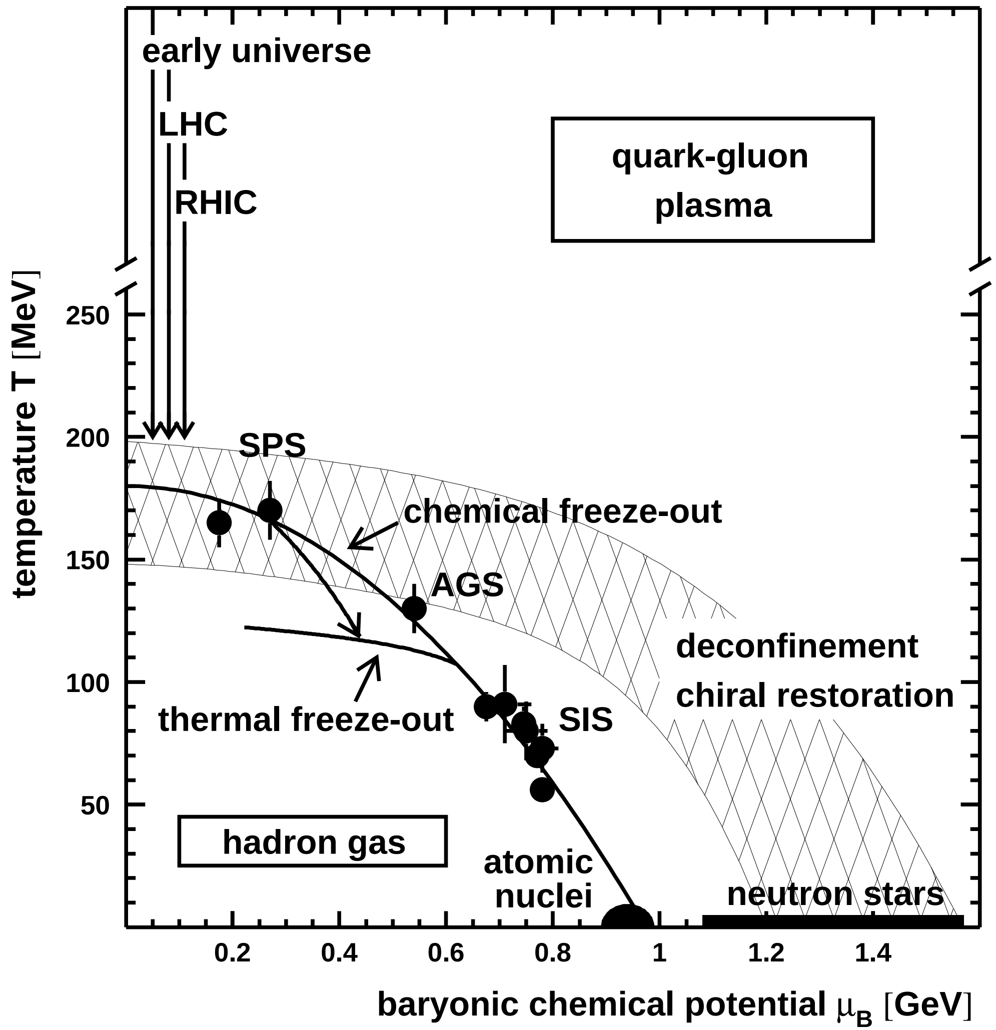
New Technologies

- Fast cycling superconducting magnets
- Electron cooling at high ion intensities and energies
- Fast stochastic cooling

GSI

⋆ Towards the Highest Density Matter in Lab.

- Freeze-Out Point at SIS, AGS, and SPS

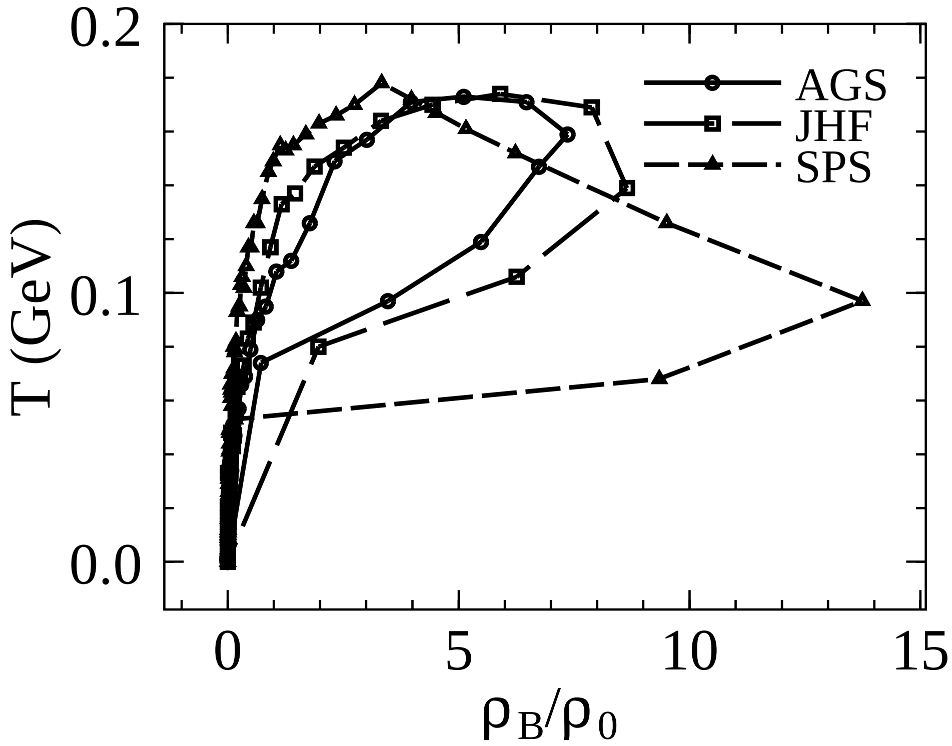


(Stachel)

Freeze-out point seems to evolve *SMOOTHLY* as a function of Incident Energy
→ How about Trajectory ?

- HI Collision at 25 A GeV

$\cdots$ would make the Highest Density Hadronic Matter under Approximate Equilibrium



AGS (11 A GeV), JHF (25 A GeV):
→ Smooth Evolution in (ρ_B, T)
$\rho_B(\max) > 2\gamma_{cm}\rho_0$

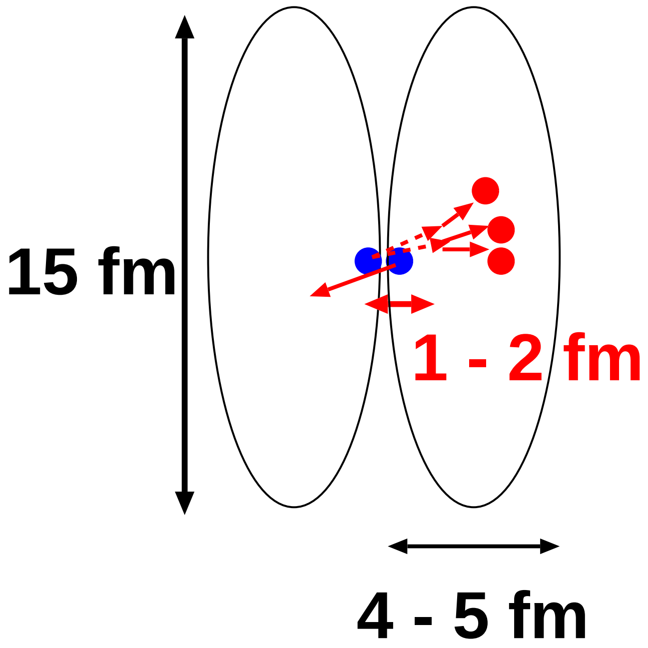
SPS (158 A GeV), RHIC:
→ Sudden Jump to (Low ρ_B, High T)
$\rho_B(\max) < 2\gamma_{cm}\rho_0$

IF we can make high ρ_B QGP,
it is at JHF.

(JAM Calc., Y. Nara,FRONP99, 8/2-4, 1999 at JAERI)

JHF Energies

$\gamma_{cm} \simeq 3.5, \quad \tau \simeq 0.5 - 1$ fm/c

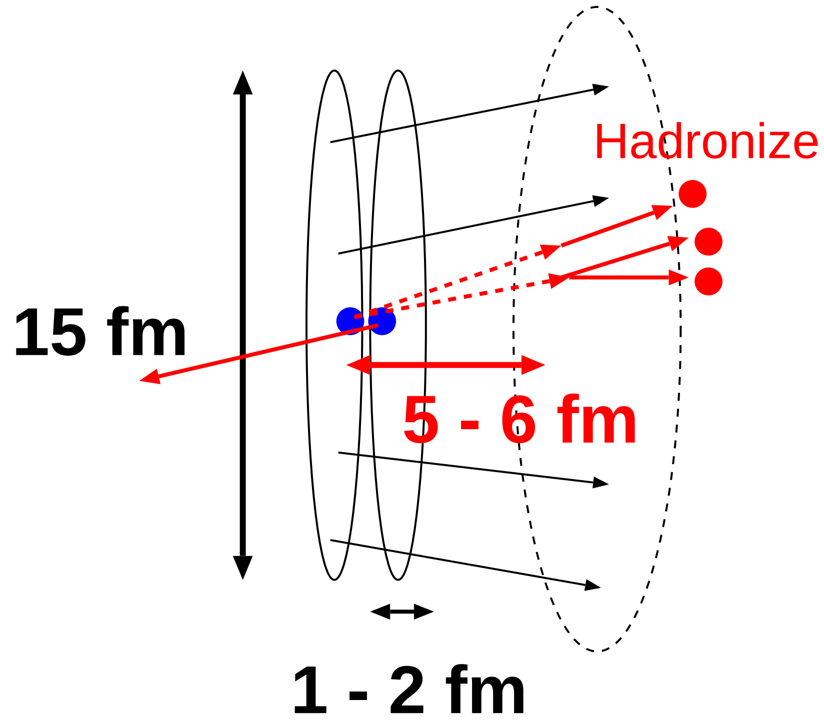


Multiple Hadron-Hadron Collisions

☞ (Approx.) Thermalized Hadron Gas

SPS Energies

$\gamma_{cm} \simeq 10, \quad \tau \simeq 0.5 - 1$ fm/c



String-String, String-Hadron Int.

+ Int. within Co-Movers

- Major Topics in HEHI
  - ⋆ Collective Flow: EOS at High Density
  - ⋆ Low-Mass Lepton Pair: Hadron Masses at High Density
  - ⋆ High-Mass Lepton Pair: J/ψ Suppresion at High Temperature
  - ⋆ Jet Energy Loss: Parton Dynamics at High Gluon Density
  - ⋆ Strangeness Enhancement: Potential at High Density

☞ Study of Highly Dense Hadronic Matter is NECESSARY
and it's difficult to make at SPS and RHIC Energies

⋆ Collective Flows: Probe of Pressure

(Directed) Flow (dP_X/dY)

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

Elliptic Flow (V_2)

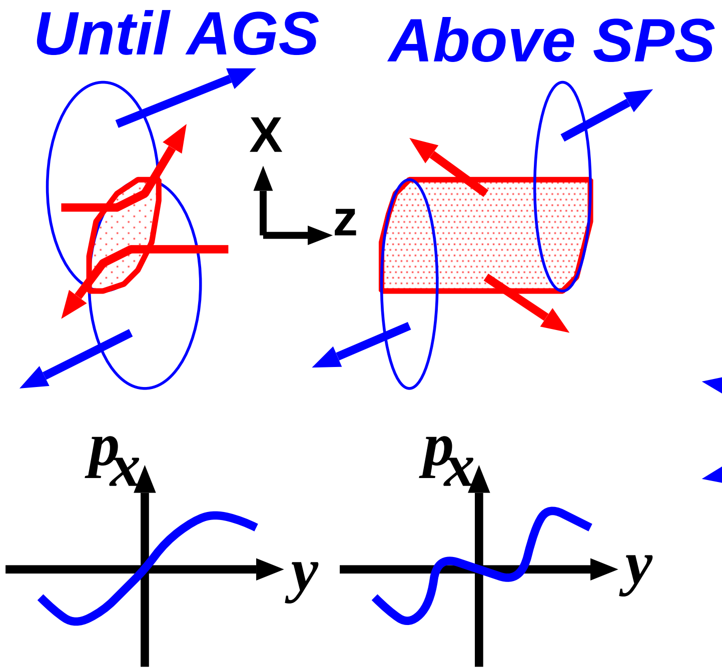
Thermalization
& Pressure Gradient

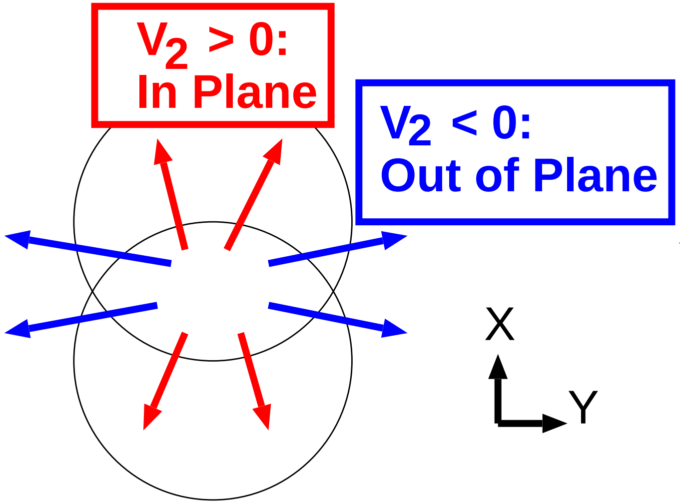
Radial Flow (β_T)

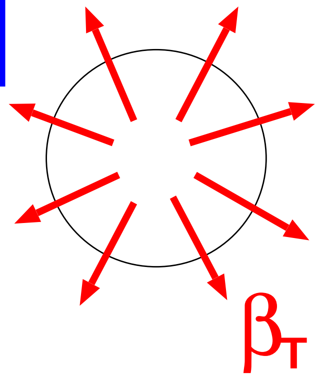
Pressure History

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

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







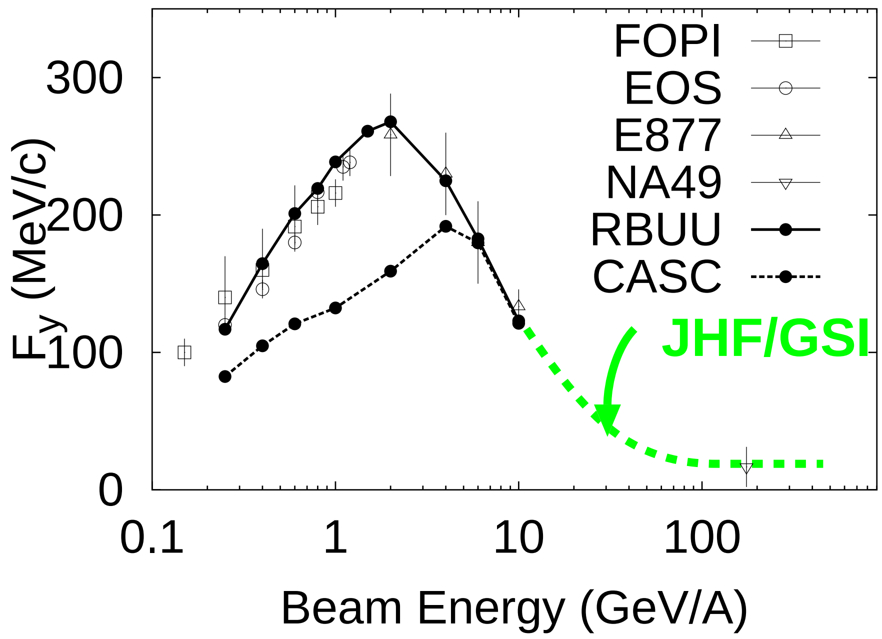
- Incident Energy Dependence

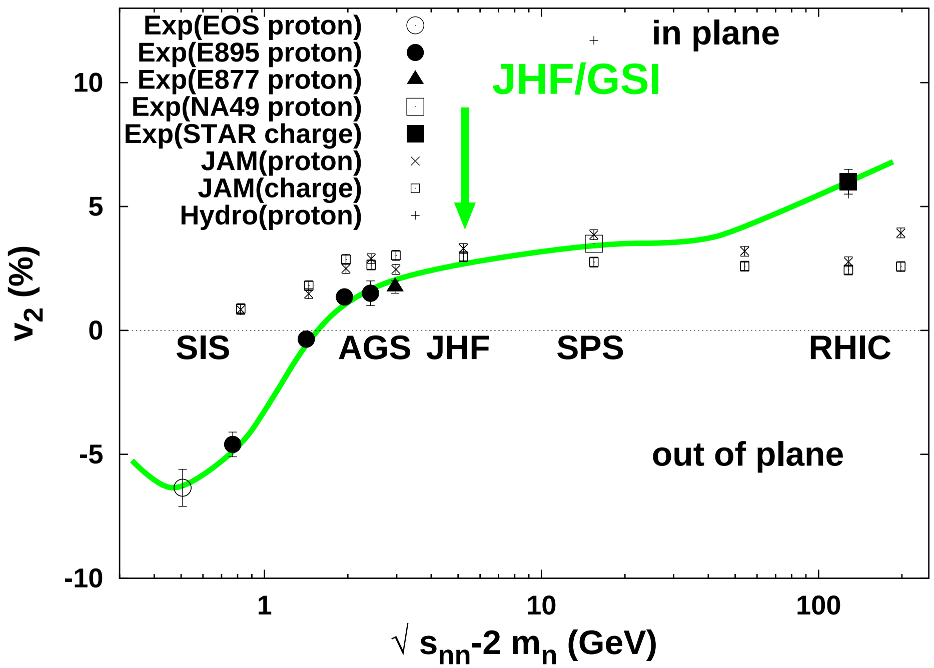
(Directed) Flow (dP_X/dY)

Sahu,Cassing,Mosel,AO, NPA(2000))

Elliptic Flow (V_2)

Sahu,Otuka,AO, (nucl-th/0206010)



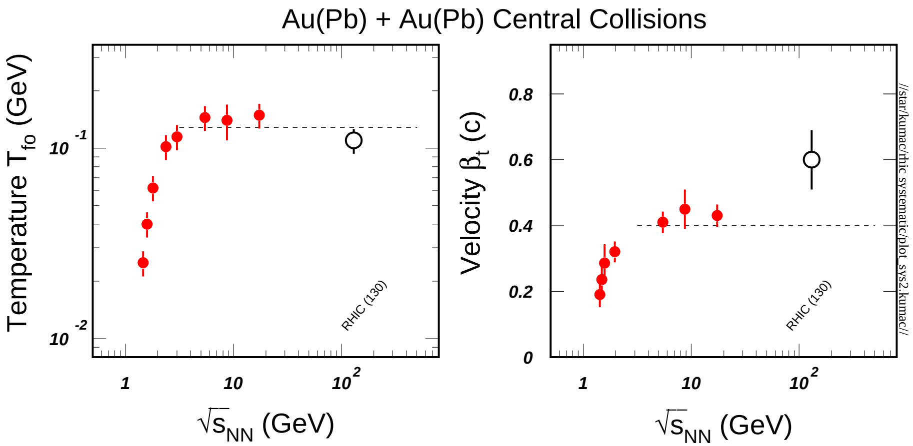


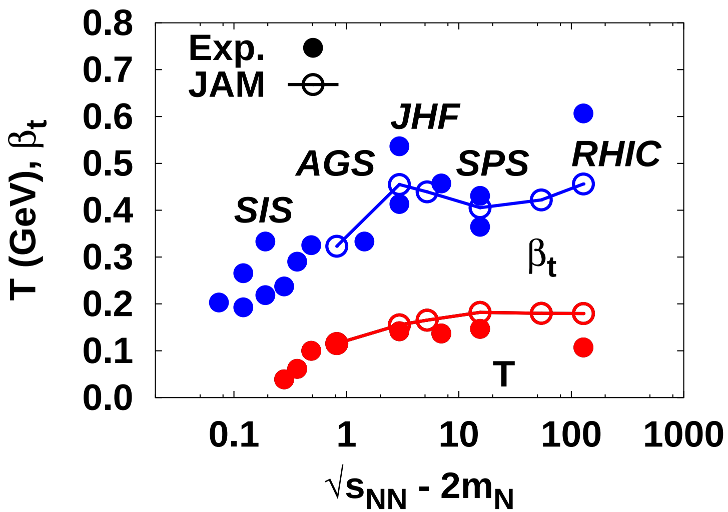
☞ $dP_X/dY \sim 0$, $V_2 \sim$ Saturating Value @ JHF

Radial Flow (β_t)

Exp: Nu Xu and M. Kaneta (STAR)

Otuka,Sahu,Isse,Nara,AO (nucl-th/0102051)





Local Max. of β_t@ JHF

Characteristics of Flow @ JHF

⋆ Smaller Spectator-Participant Interaction → Clear Participant Dynamics

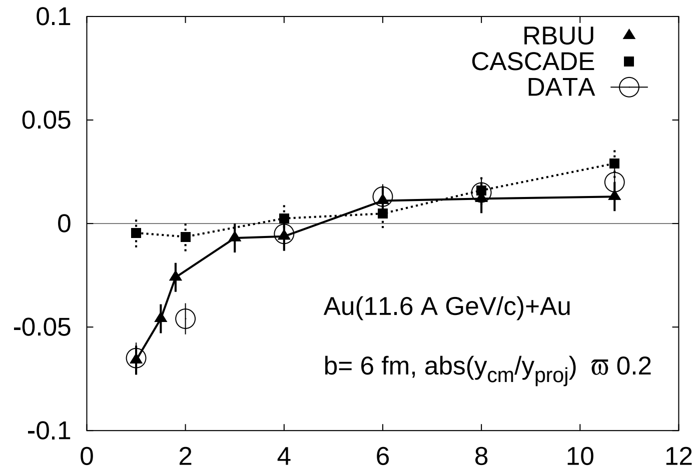
⋆ Large Radial Flow → Expansion for Long Time

→ Approximately Equilibrated Dense (Baryon Rich) Matter

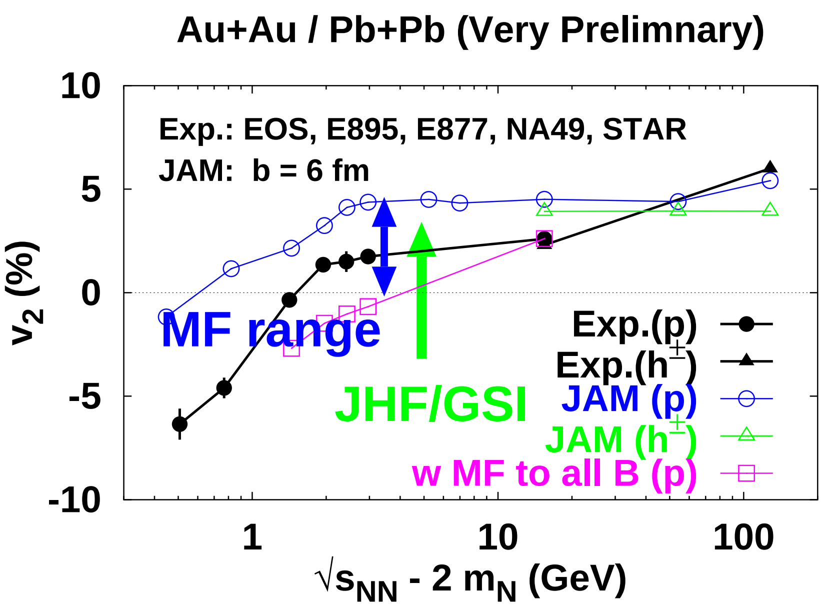
⋆ Elliptic Flow from SIS to RHIC

- Mean Field Effects

RBUU (Sahu-Cassing-Mosel-AO, 2000)



JAM-RQMD/S (Isse et al.)

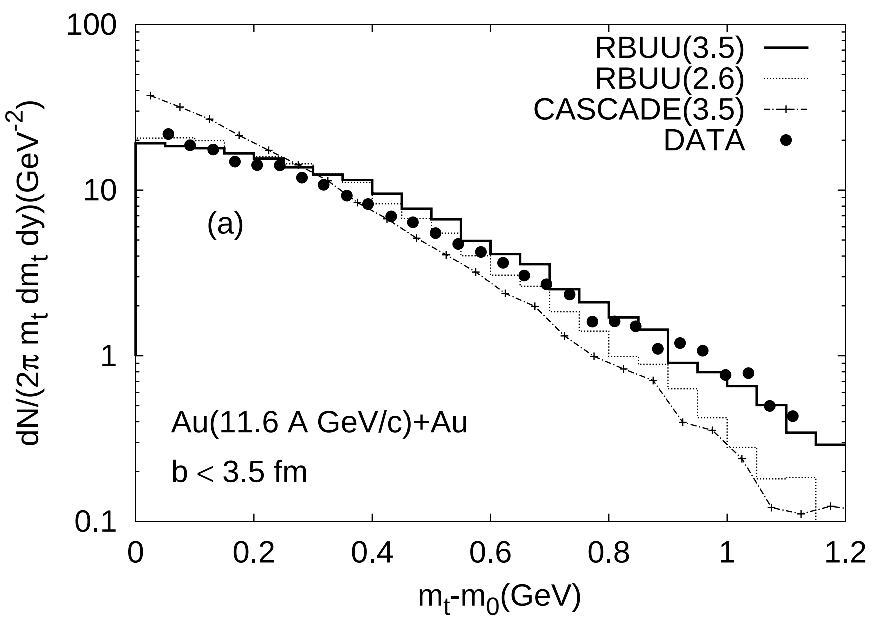


☞ Mean Field Shifts V_2 Downwards

→ Upward Shift at RHIC cannot be explained by Hadronic Mean Field

- Radial Flow

RBUU (Sahu-Cassing-Mosel-AO, 2000)



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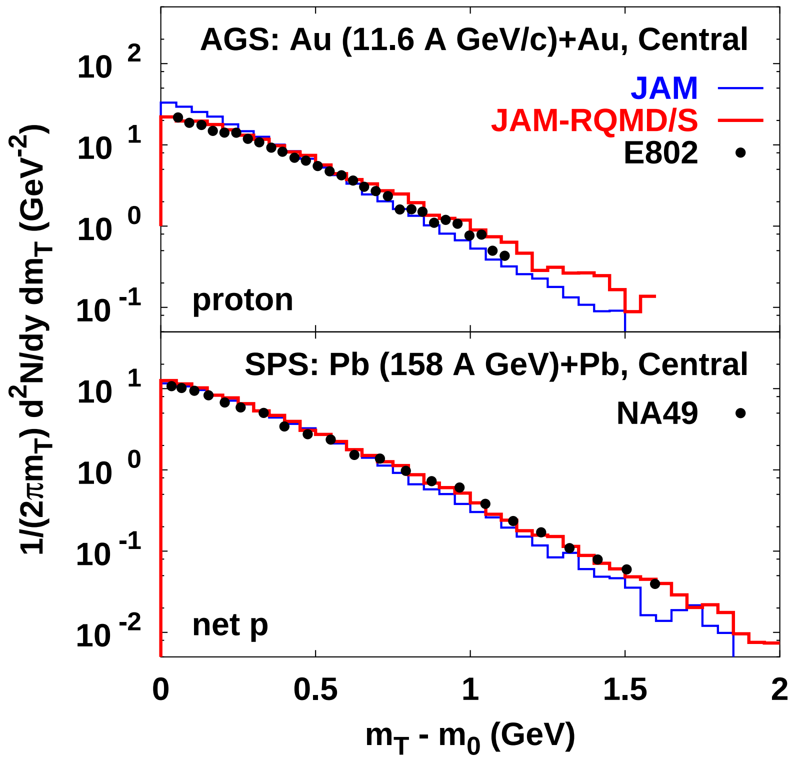
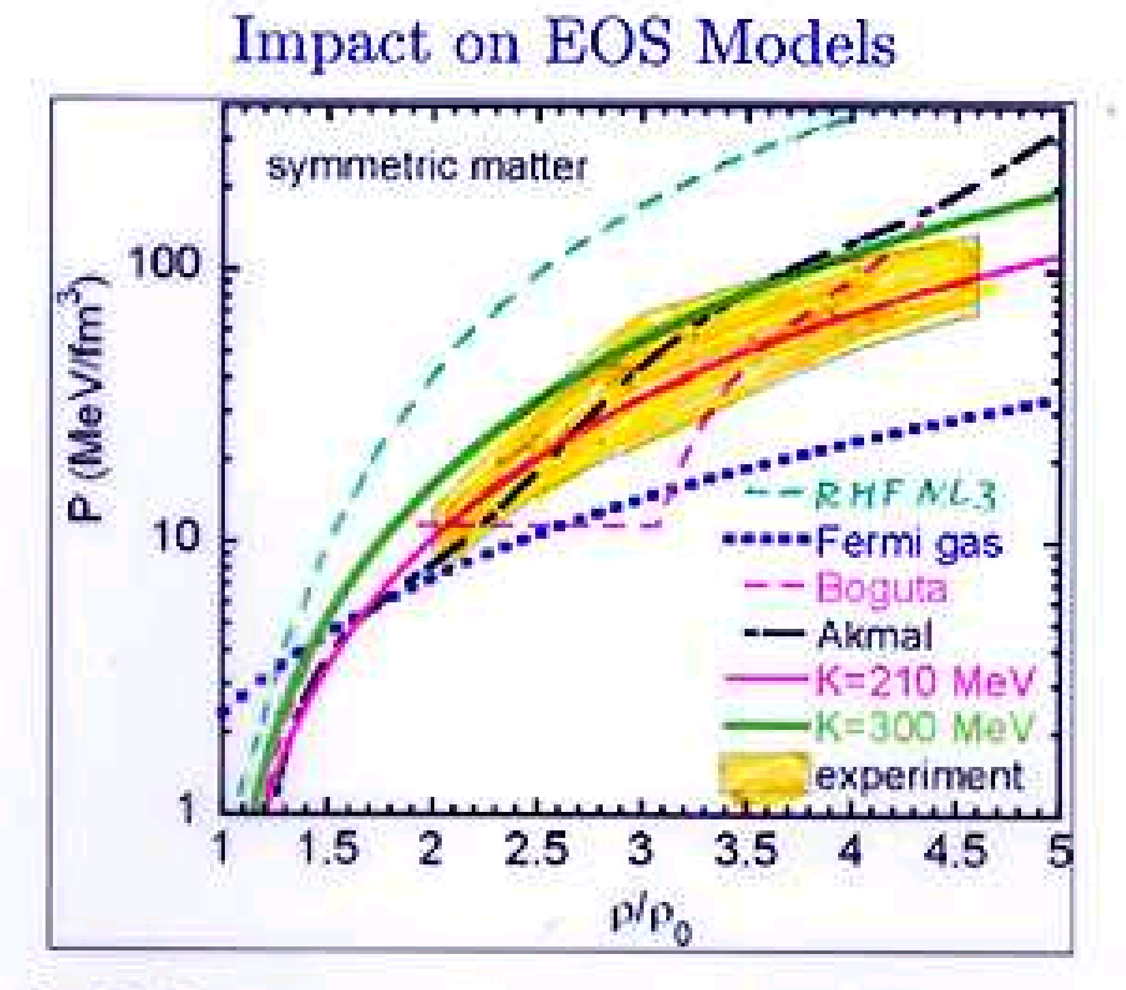


☞ Mean Field Modifies Low P_t (= Dominant part in Yield) Shape

• Probed (ρ,T) Region

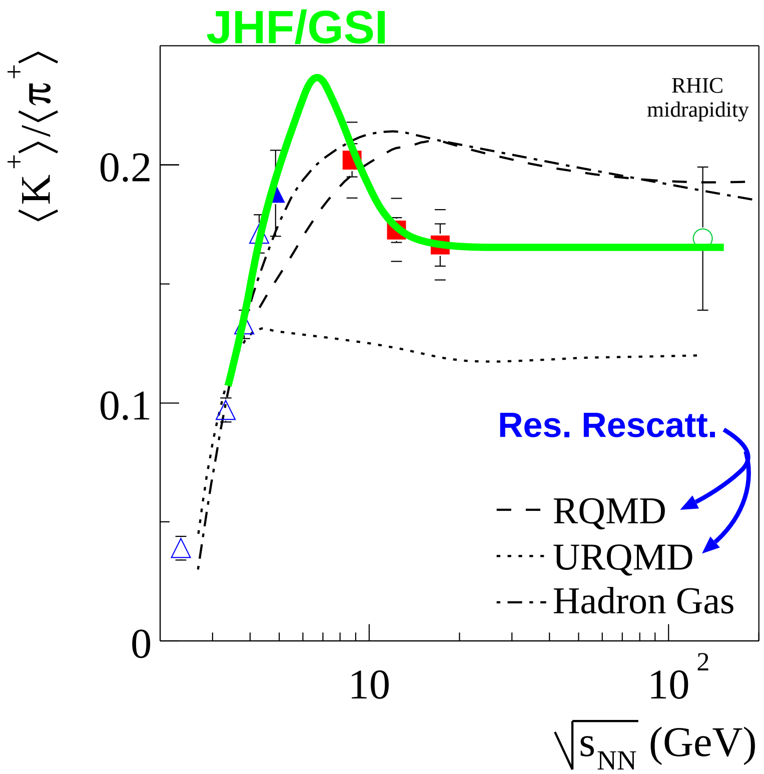
P. Danielewicz (GSI workshop, 2002)

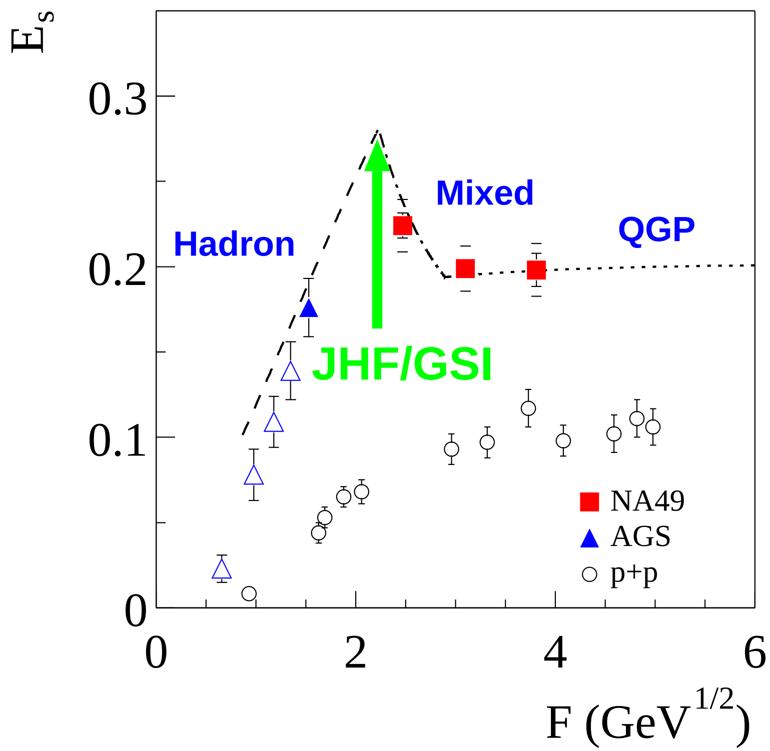


⋆ Strangeness Enhancement: Rescattering or Potential ?

Strangeness is Enhanced Sharply at $E_{inc} = 10 - 40$ GeV/A !

NA49 (nucl-ex/0205002)



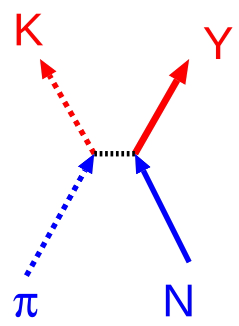


Hadron → Mix → QGP

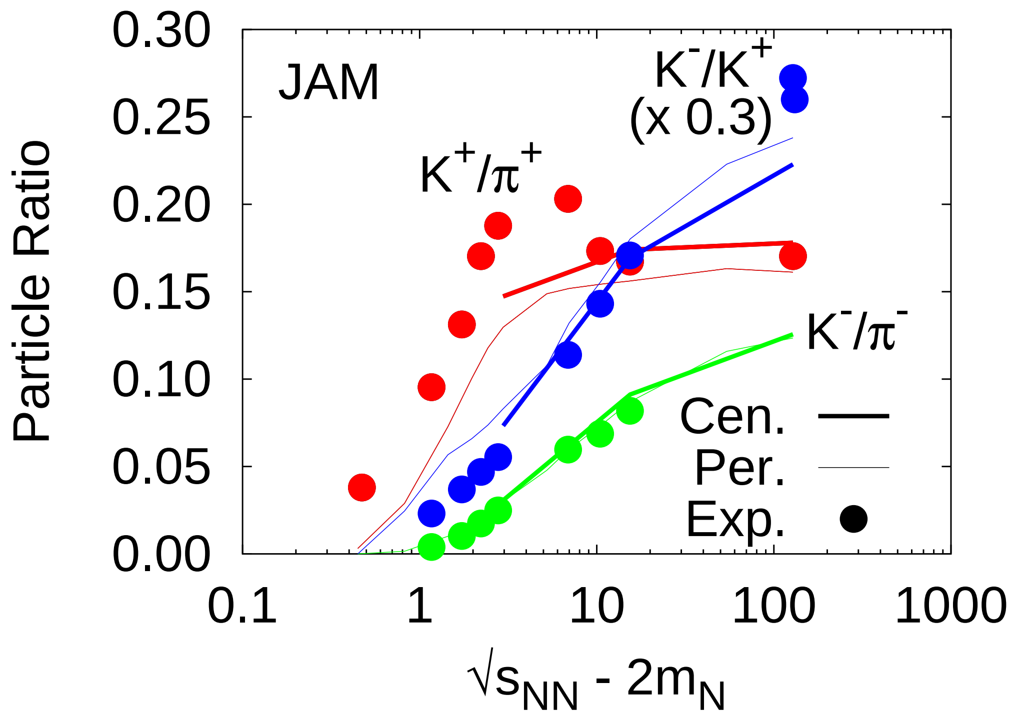
JHF Energy: ∼ Maximum K/π ratio

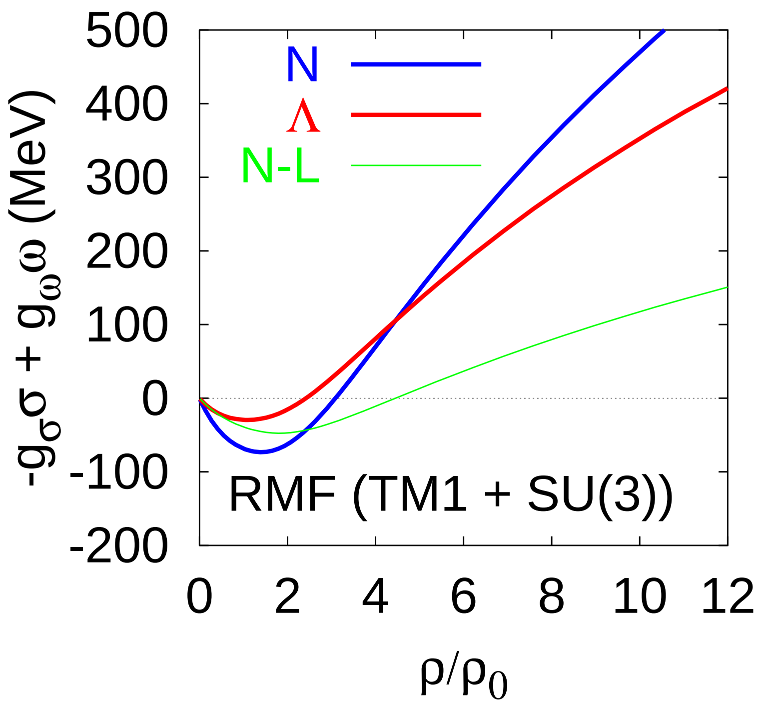
Possible Explanations

- ⋆ Rescattering of Resonances/Strings (RQMD)
- ⋆ Baryon Rich QGP Formation (Right Fig.)
- ⋆ High Baryon Density Effect (Associated Prod. of Y)



K^+ is enhanced ! → Mean Field Effects for Y ?



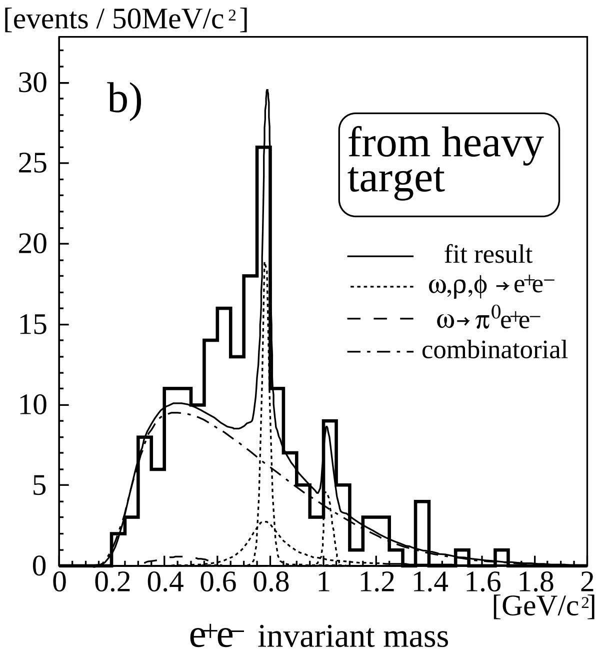


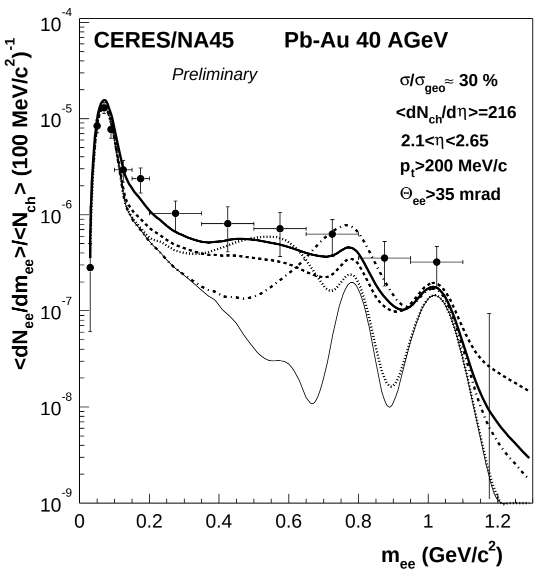
⋆ Low-Energy Di-Leptons: Probe of Chiral Symmetry Restoration

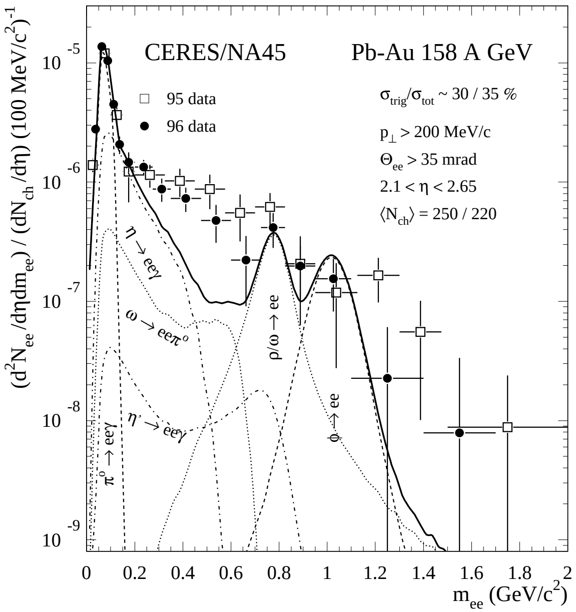
KEK-PS-E325
pA ($T \simeq 0$, $\rho_B \simeq \rho_0$)

CERN-SPS-CERES/NA45
Pb+Au (40 A GeV)

CERN-SPS-CERES
Pb+Au (158 A GeV)







Possible Explanations:

$\sim$ In-Medium Partial Chiral Symmetry Restoration Effects !

$\cdots$ Spectral function mod. (mass shift, broadening),
π-π Amplitude mod., σ-ω mixing

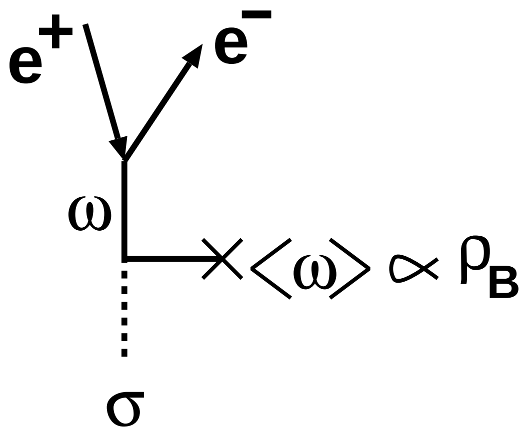
ρ_B Effects are more direct than those of T !

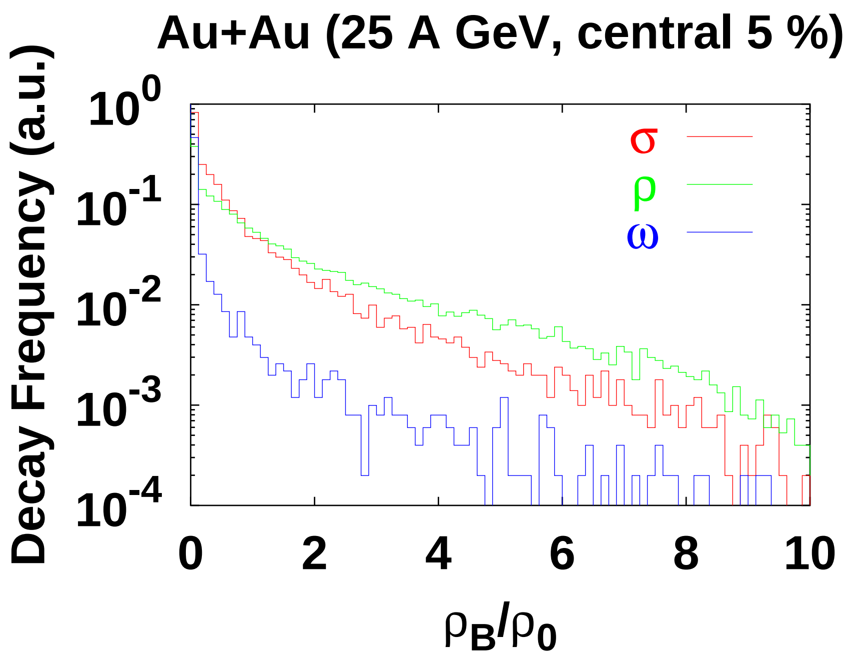
- ⋆ Rho meson mass shift

$$m_\rho^* = m_\rho \,(1 - C\rho_B/\rho_0)\,(1 - (T/T_c^\chi)^4)^a$$

$$(C \sim 0.15, T_c^\chi \sim 200\mathrm{MeV}, a \sim 0.3)$$

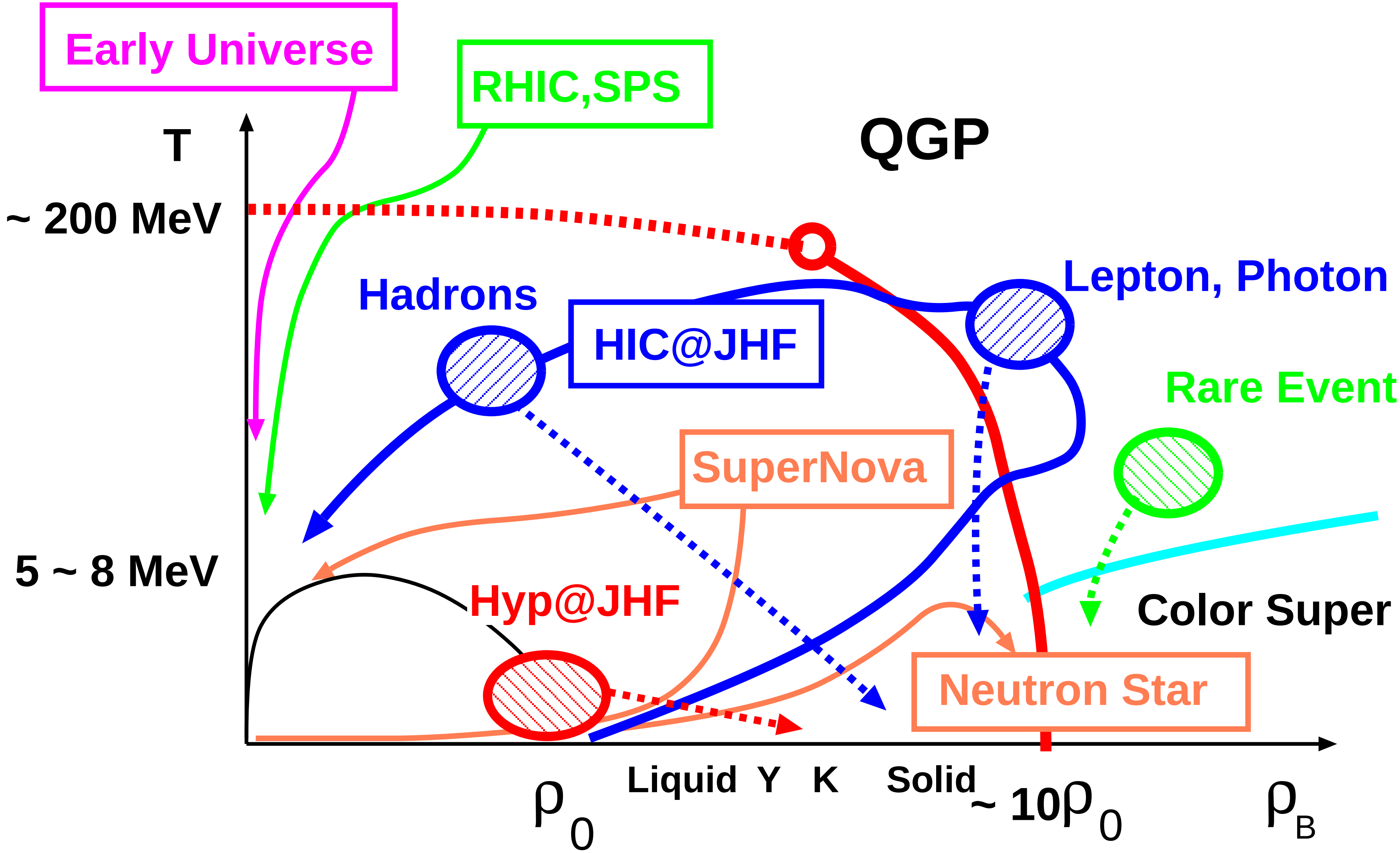
- ⋆ σ-ω Mixing: $\sigma\omega\omega \longrightarrow \sigma\delta\omega < \omega >, < \omega > \propto \rho_B$



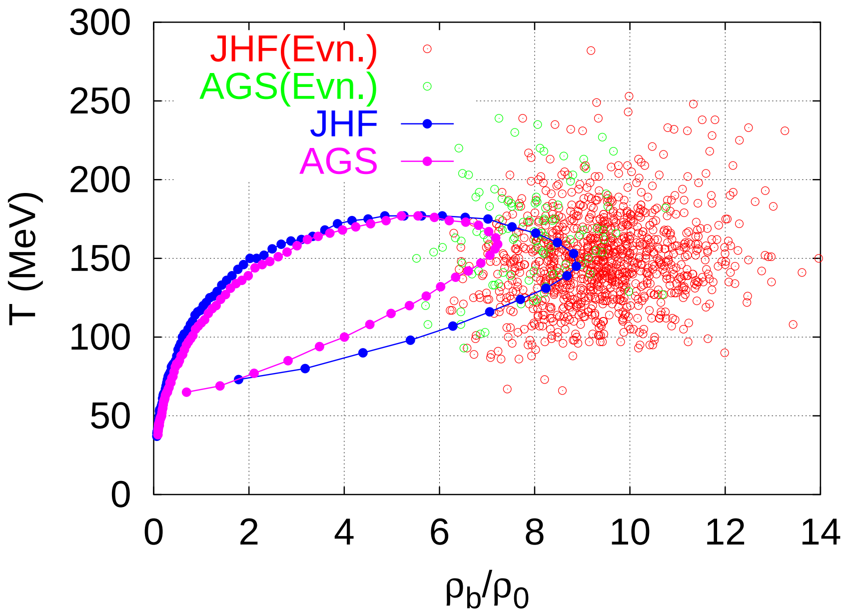


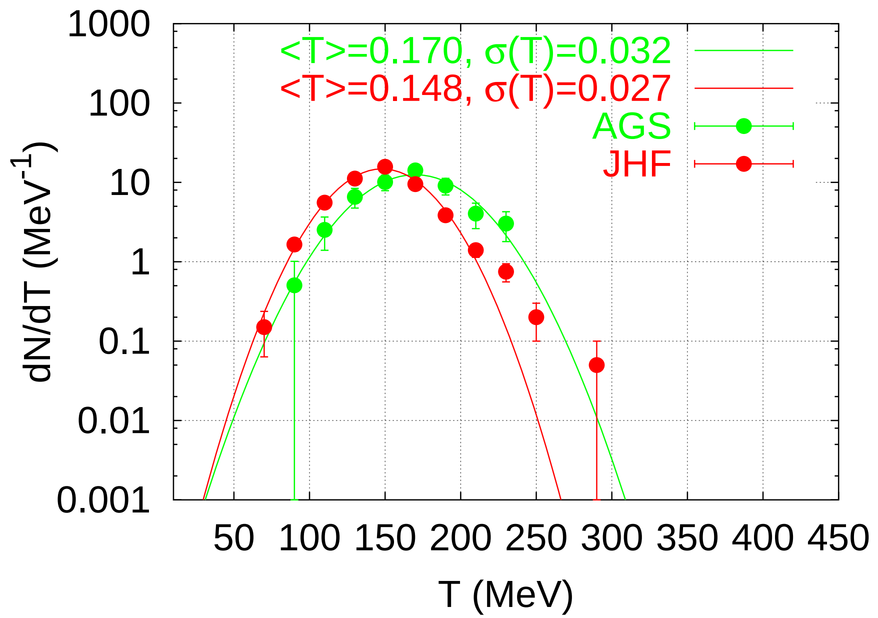
☞ Dilepton Mass Spectrum may show *No Peak* Structure

⋆ Towards LTHD (Low T & High ρ) Matter & Baryon Rich QGP Formation



- How Cold Matter we can make at JHF ?





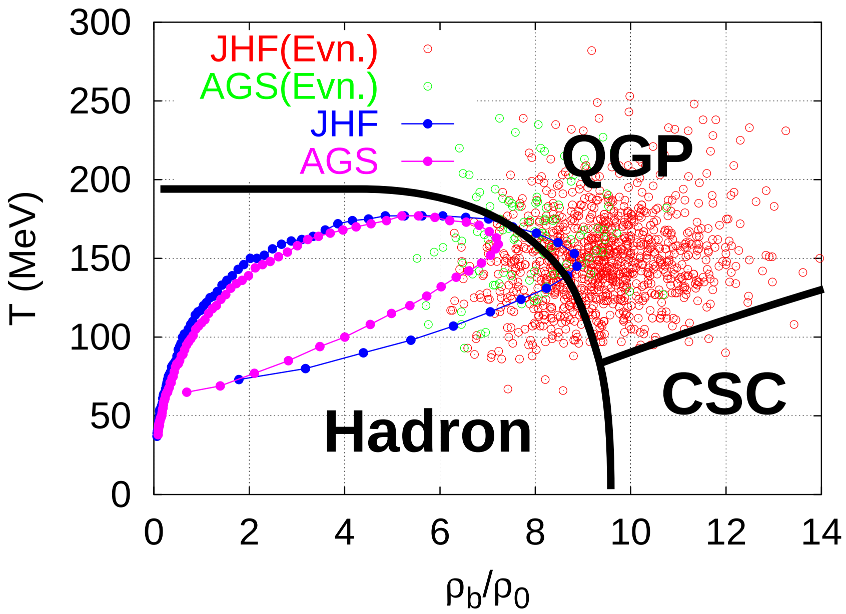
Finite System Has Fluctuation !

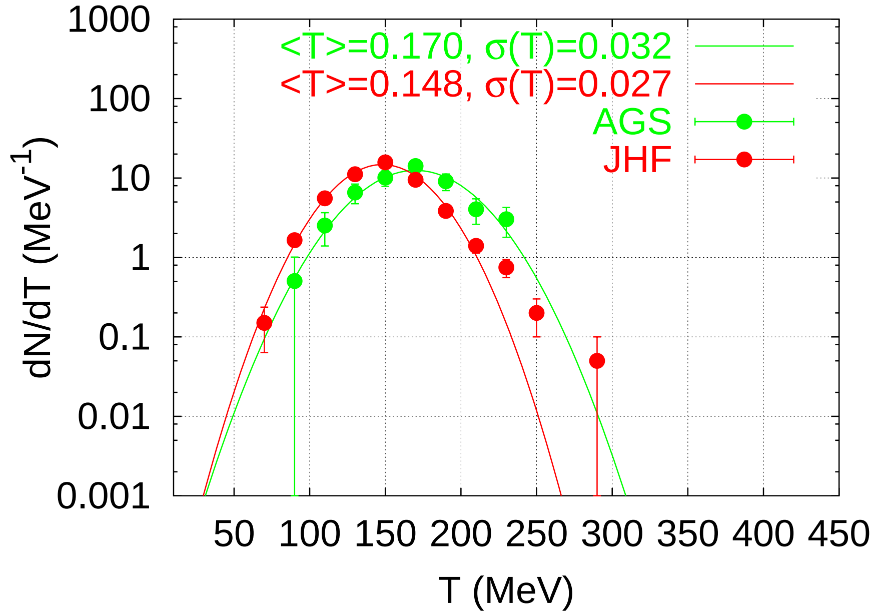
Average: $(\rho_B, T) \sim (9\rho_0, 150MeV) \to$ Event Fluctuation: $\sigma(T) \sim 27$MeV (JAM)

Events with $T < 50$ MeV at $\rho_B > 5\rho_0 \longrightarrow 1/1000 \sim 1/10000$

$\to$ Precursor Signal of CSC ? (Kitazawa, Koide, Kunihiro, Nemoto, 2002)

- How Cold Matter we can make at JHF ?





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⋆ Summary

- ⋆ Heavy-Ion Collision Experiment at JHF/GSI Energies is Suitable for Exploring "Highly Dense Matter".
  - ∘ Formation Time and γ Factor limit the Incident Energy Region to form Baryon Rich Matter.
  - ∘ EoS of Cold & Dense Matter
    → Supernova, NStar, Color Super
  - ∘ Hadron Properties in Dense Matter may be very different....
    → Chiral Sym., Interaction, Phase Transition, ...
- ⋆ We can probe "Dense Matter" in Three Ways at JHF/GSI
  - ∘ Strangenss Nuclear Physics ($\Lambda, \Sigma, \Xi, K, ... \rightarrow$ Yield, Spectra, Flow)
  - ∘ Heavy-Ion Physics (High ρ_B and High T)
  - ∘ Rare Event Search in Heavy-Ion Physics (High ρ_B and Low T)

→ We NEED PROBES !

"High Baryon Density" Physics at RHIC

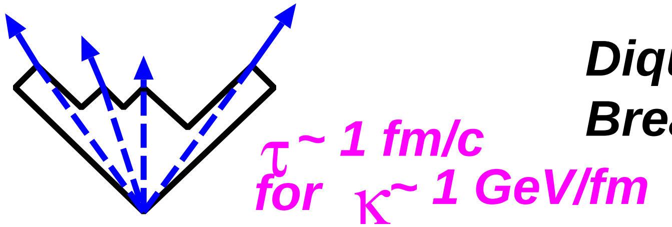
⋆ Hadron-String Cascade Model from SIS to RHIC

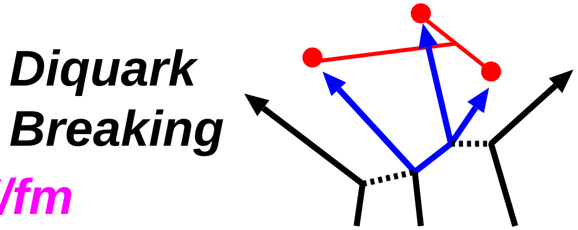
JAM (Jet Aa Microscopic transport model)

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

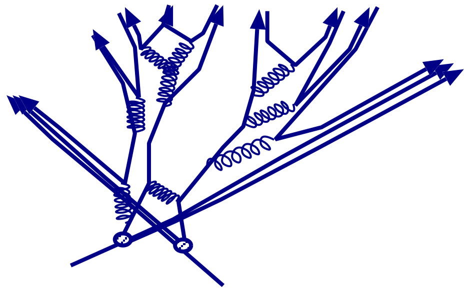
DOF: h(B, B*, M, M* (m $\leq$ 2 GeV)) + s(Strings) + Mini-Jet Partons

σ: Hadronic ($hh \leftrightarrow hh$, $hh \leftrightarrow h$) + Soft [1,2] + Hard [3]





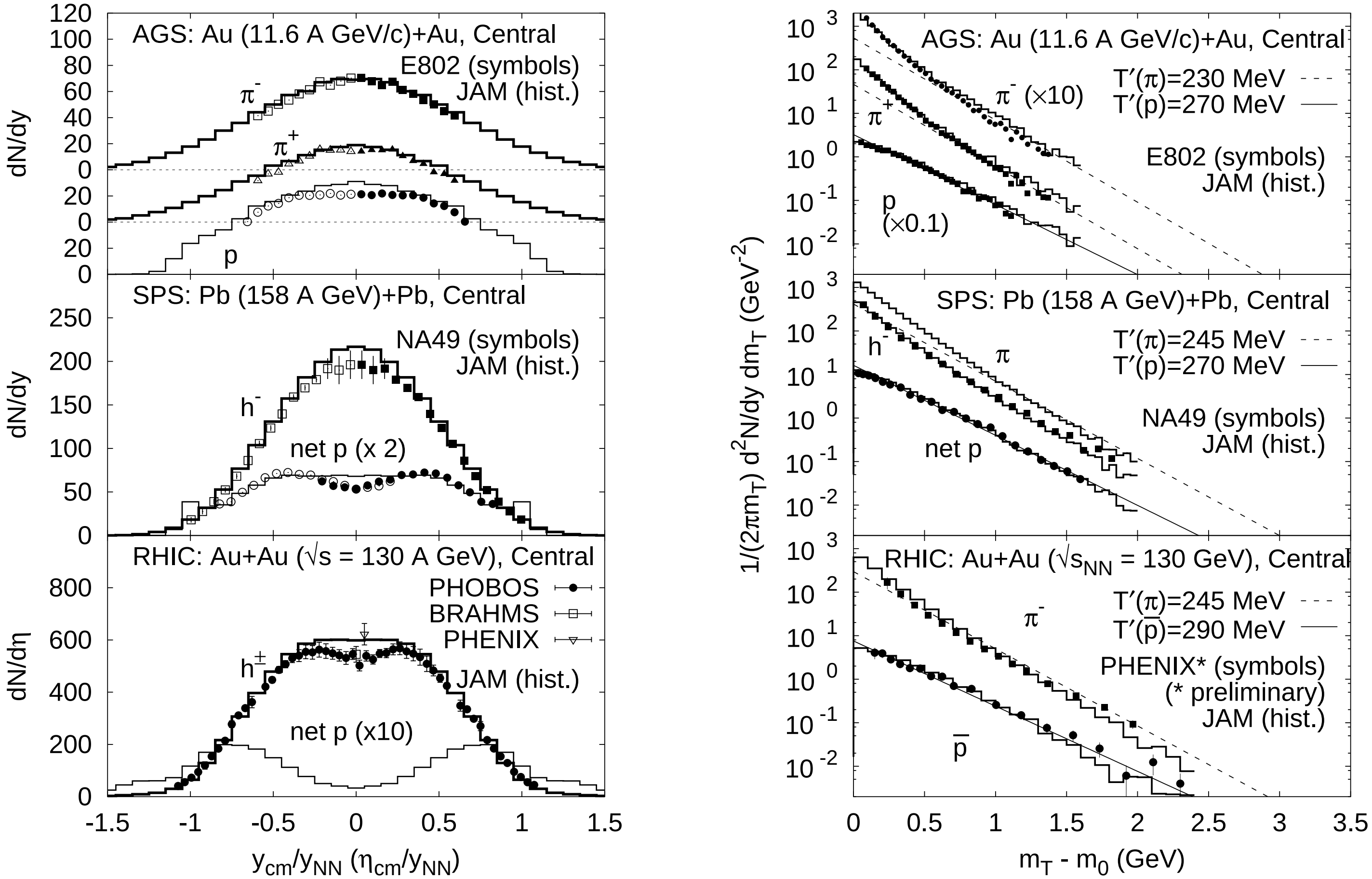
Resonance
+ String
+ Jet



[1] "DPM + Lund" (∼ HIJING) + Phase Space (hh↔s, hh→hs, hh→ss, s→hhh...)
[2] Consituent Rescattering (∼ RQMD)
(c= (qq), q, q̄ ch↔ ch, ch→ cs (c= (qq), q, q̄))
[3] Jetset: Pythia (Mini-Jet Production)

⋆ Hadronic Spectra from SIS to RHIC

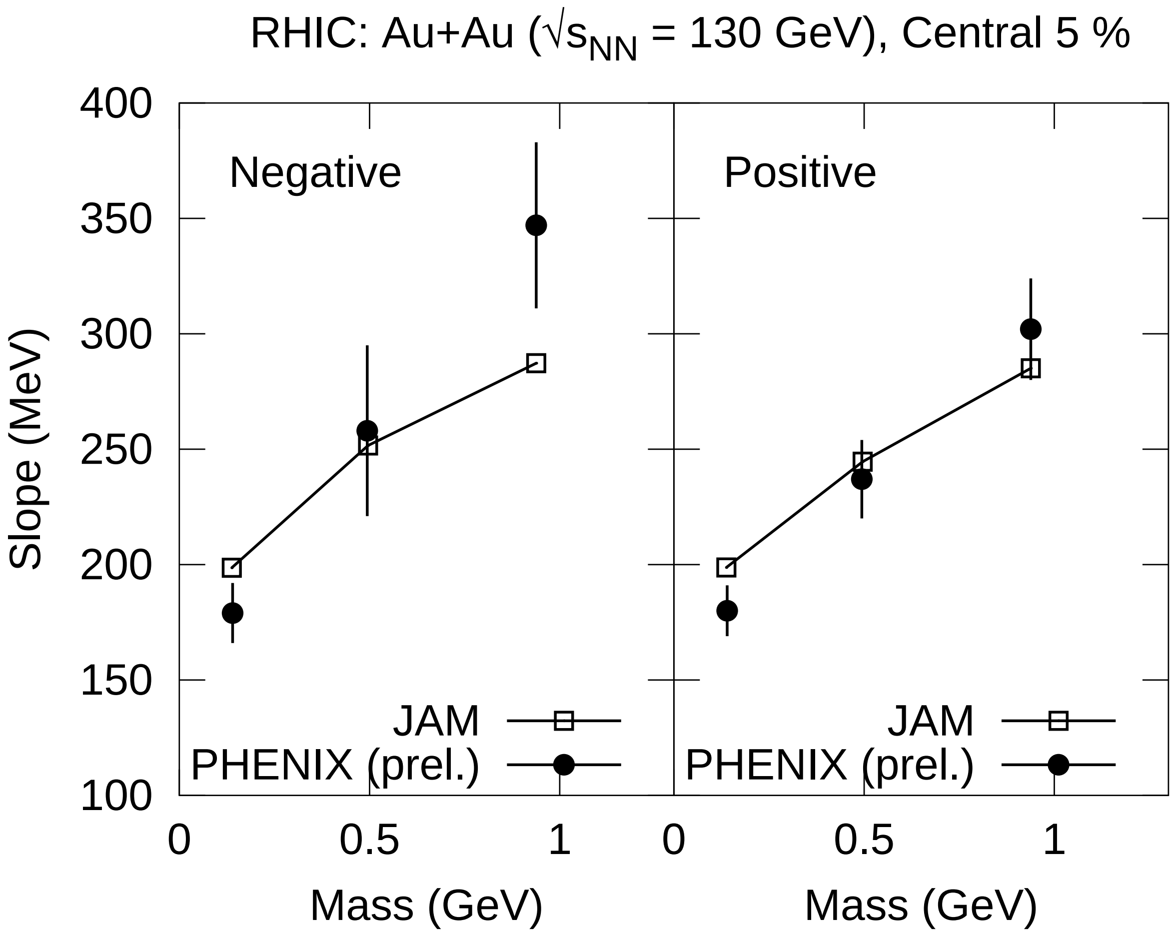
- Rapidity and m_T Distributions (N. Otuka et al. nucl-th/0102051, M. Isse et al., in preparation)



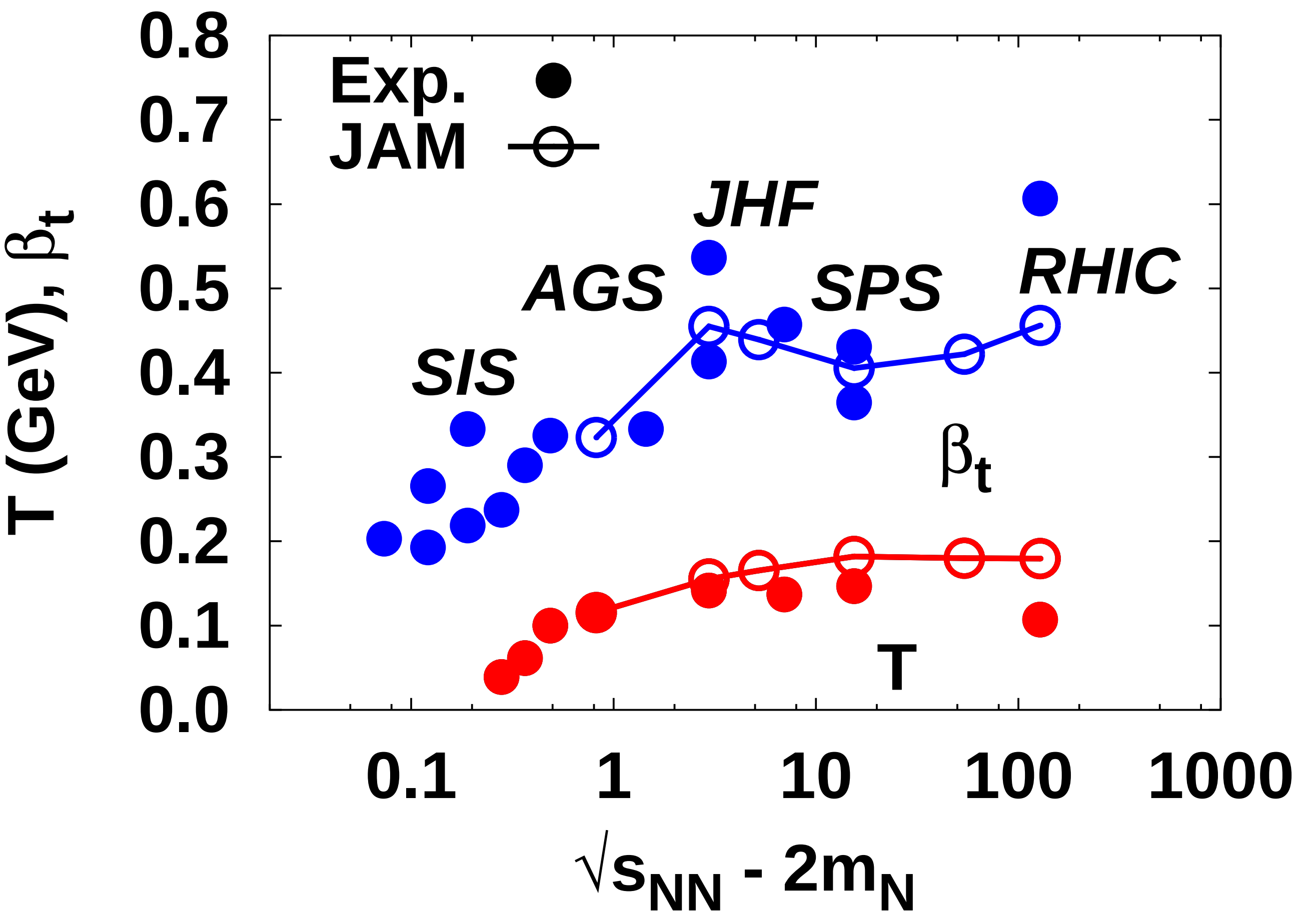
Good EXCEPT FOR anti-proton (and proton) m_T spectra at RHIC

- Decomposition to T and β

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



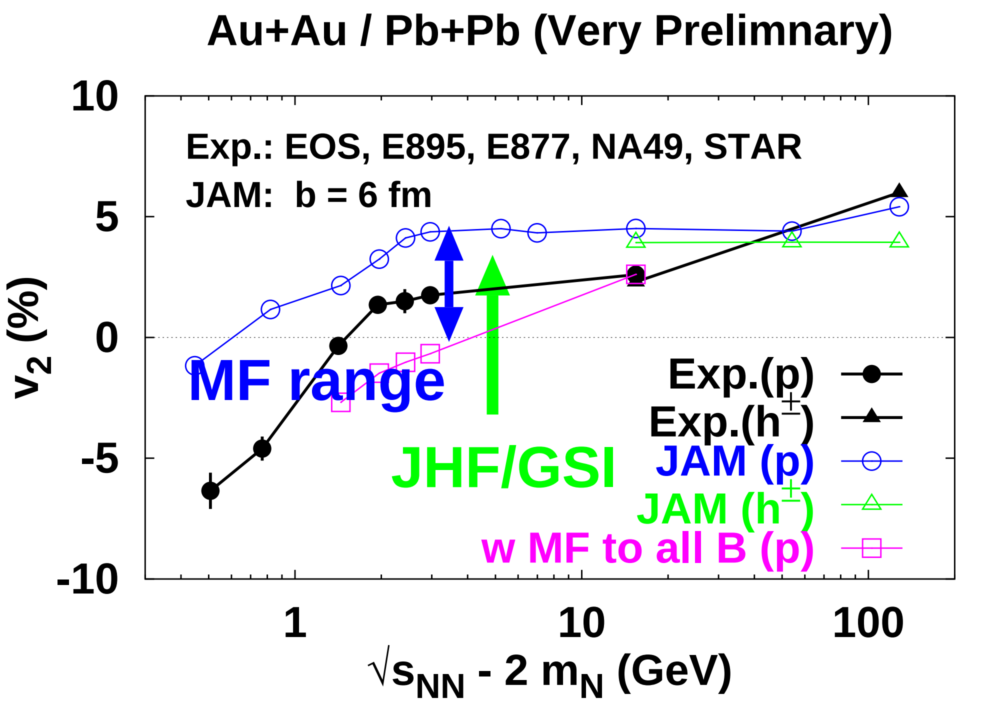
- Temperature and Radial Flow from SIS to RHIC



Re-Hardening in JAM is Too WEAK.

⋆ Elliptic Flow from SIS to RHIC

- Mean Field Effects (M. Isse et al.)

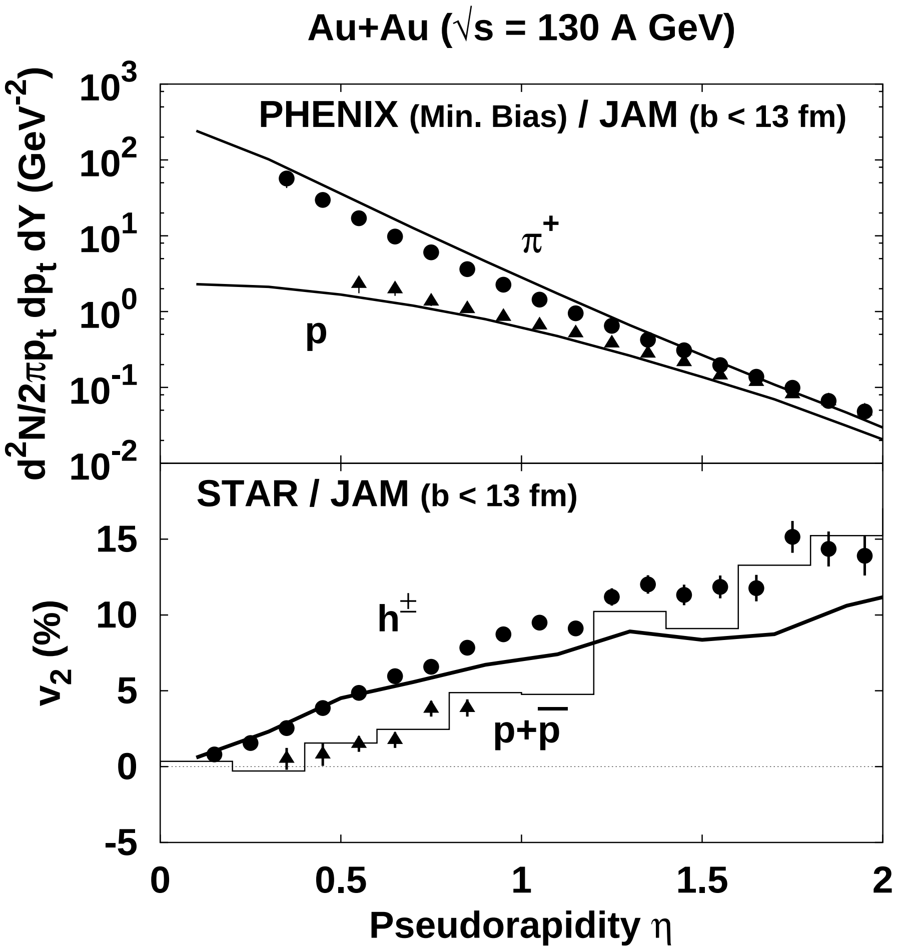


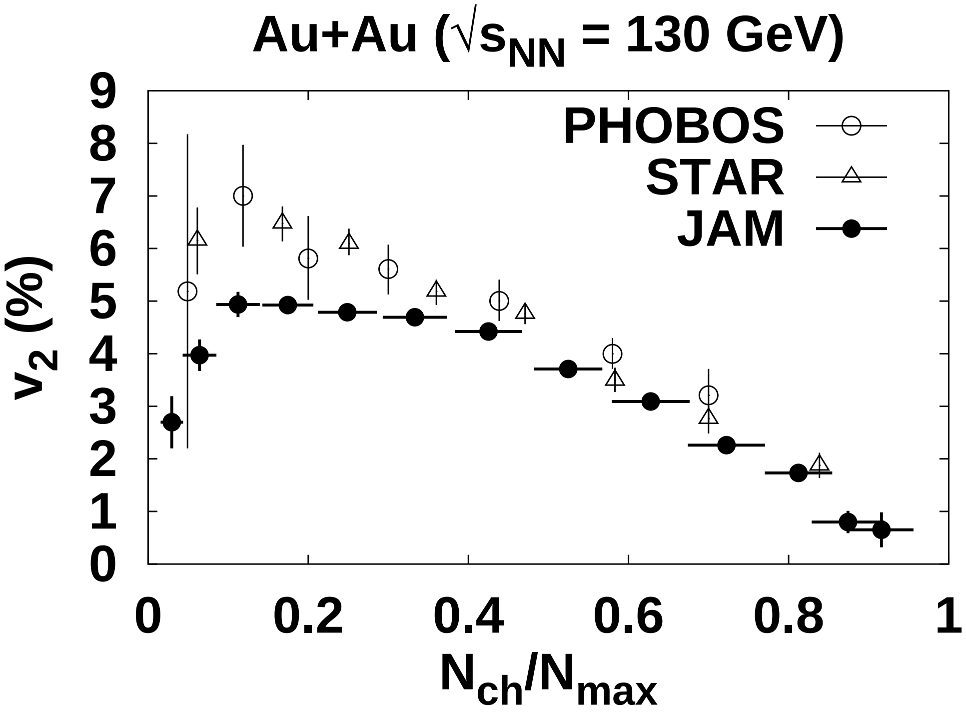
(* Stronger P_t are introduced)

☞ Mean Field Shifts V_2 Downwards

→ Upward Shift at RHIC cannot be explained by Hadronic Mean Field

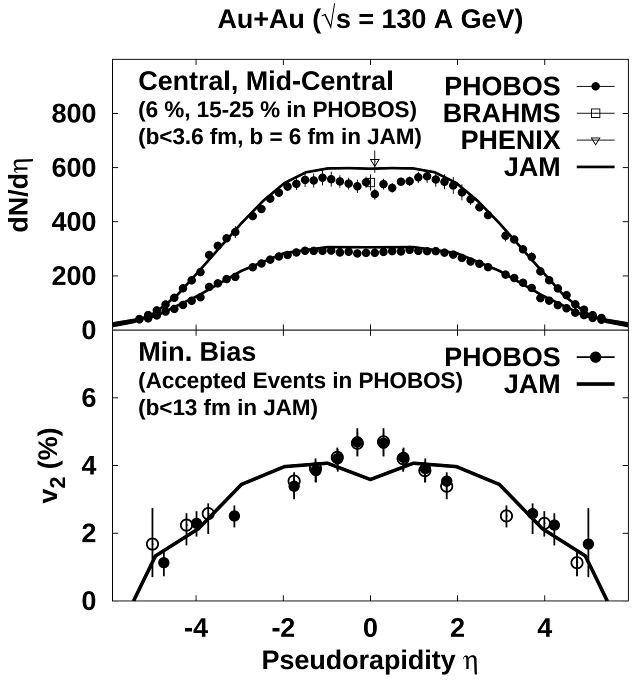
- P_T and Impact Parameter Dependence (P.K.Sahu et al.)



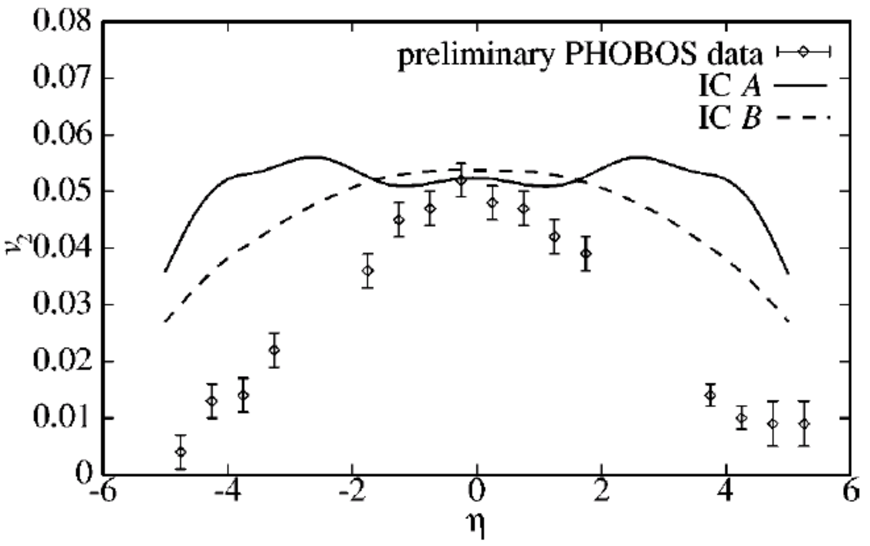


• Where Do We Underestimate V_2 ? : Pseudo-Rapidity Dependence

Cascade Sahu-Otuka-AO

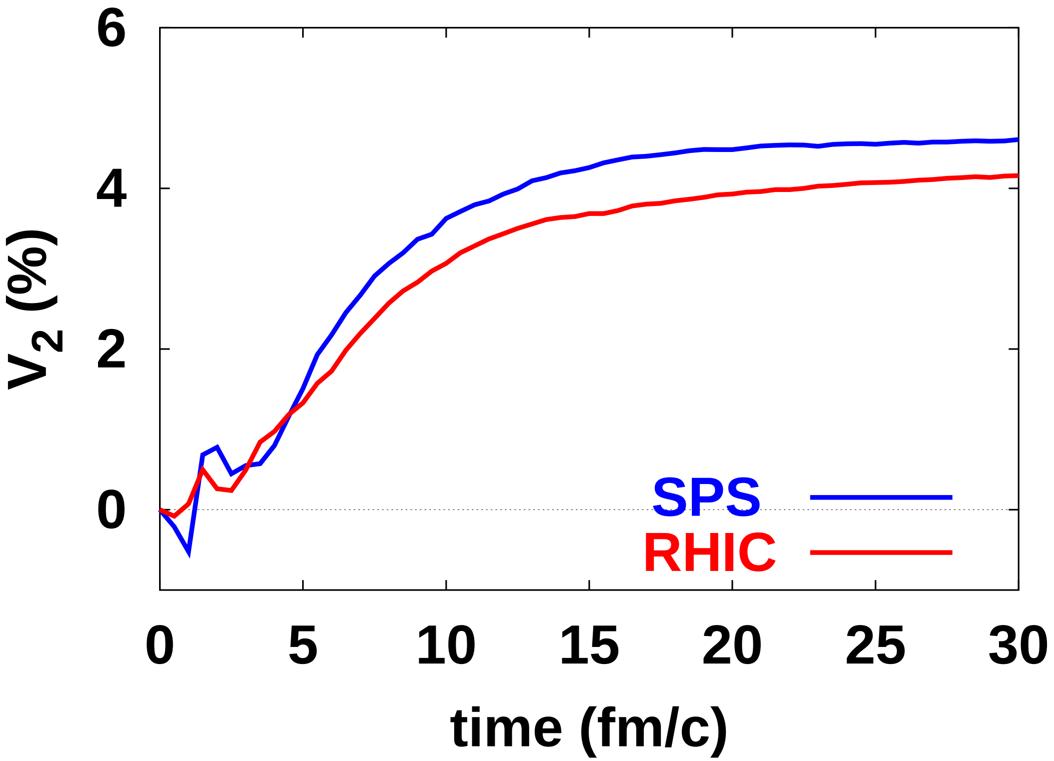


Hydro Hirano, 2001



MID-RAPIDITY V_2 is Underestimated in Hadron-String Cascade!

- Why Do We Underestimate V_2 ? : Time Dependence



In Hadron-String Scenario,
Formation Time and Interaction Suppression before String Decay
Make V_2 to Grow Later !
→ Almond Shape is Already Obscured due to Large γ !

- Large Rapidity Region

  It is not Baryon Free at $|Y| > 3$!