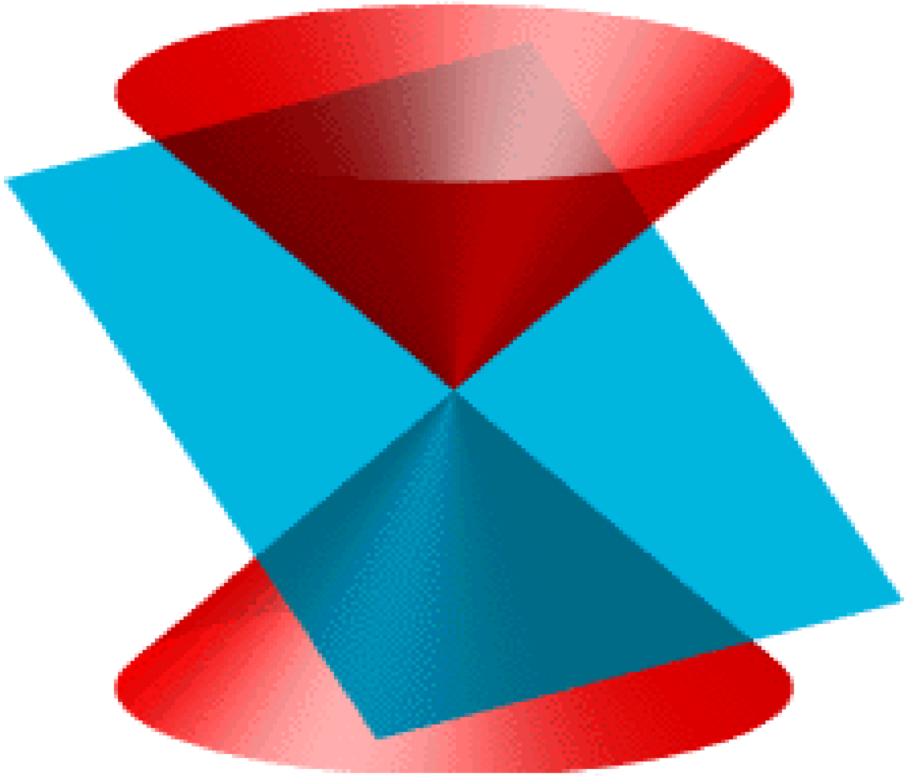
Light-Front Dynamic Application to the RHIC Physics

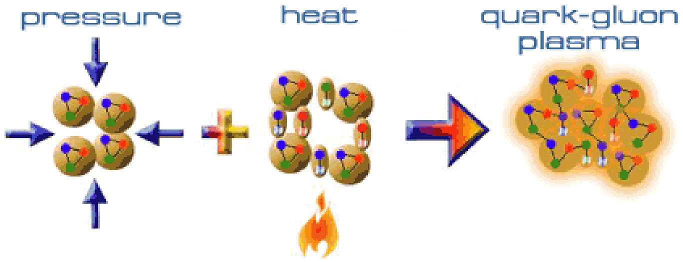


In collaboration with Prof. Byungsik Hong

Korea University, June 16, 2007

Motivation

- QGP is thought to have existed ten millionths of second after the Big Bang; creating the primordial matter of universe in the laboratory.



- RHIC obtained distinguished results from CERN SPS.
  – Jet Quenching and Bulk Hadronization (BARYONS07)

- LHC ALICE (CMS, ATLAS) would need theoretical predictions at energy 30-fold energy increase from RHIC.

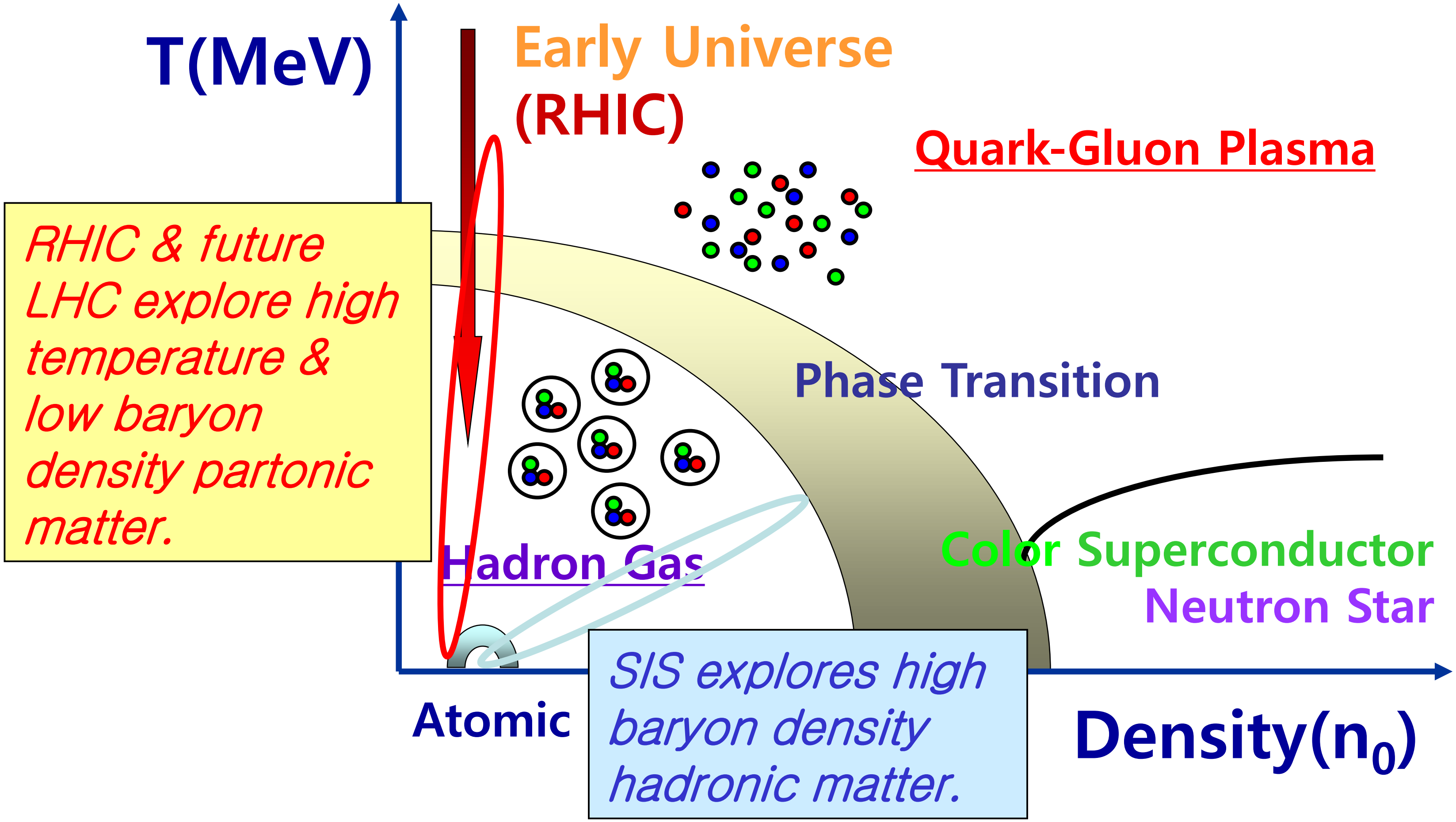
- LFD has progressed last several years.
  – Trecherous points exist and correct use is required.

Time to investigate the application and make a progress….

Outline

- Brief Overview on State Changes
  - Chemical and Thermal Freeze-outs
- Hadronization Mechanisms
  - Quark Recombination and Fragmentation
- Numerical Results
  - Wavefunction Dependence on P_T Spectra,
  - Ratio between proton and antiproton, etc...
- Elliptic Flow
  - Preliminary V_2 calculation
- Conclusion

Nuclear Phase Diagram



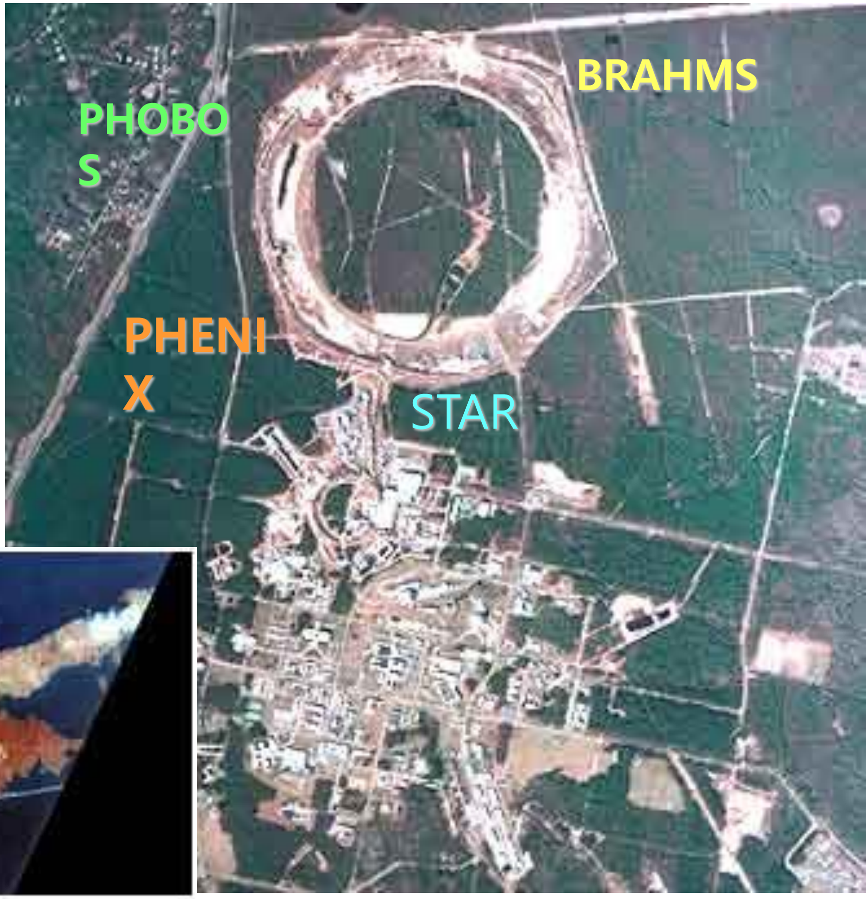
Heavy-Ion Accelerators

Accelerator	c.m. Energy (GeV)	Status
SIS 18 (GSI, Germany)	**2A (A=mass number)**	Running
AGS (BNL, USA)	**5A**	Finished
SIS 300 (GSI, Germany)	**8A**	Plan to run from ~2014
SPS (CERN, Switzerland)	**20A**	Finish soon
RHIC (BNL, USA)	**200A**	Running
LHC (CERN, Switzerland)	**5500A**	Plan to run from ~2007

Relativistic Heavy Ion Collider

- ***Brookhaven National Lab. in New York***

✓**Circumference: 3.83 km**
✓**First collision: 2000**
✓**100A GeV Au+Au($2X10^{26}/cm^2/s$)**
✓**250 GeV $\vec{p}$ + $\vec{p}$ ($2X10^{32}/cm^2/s$)**

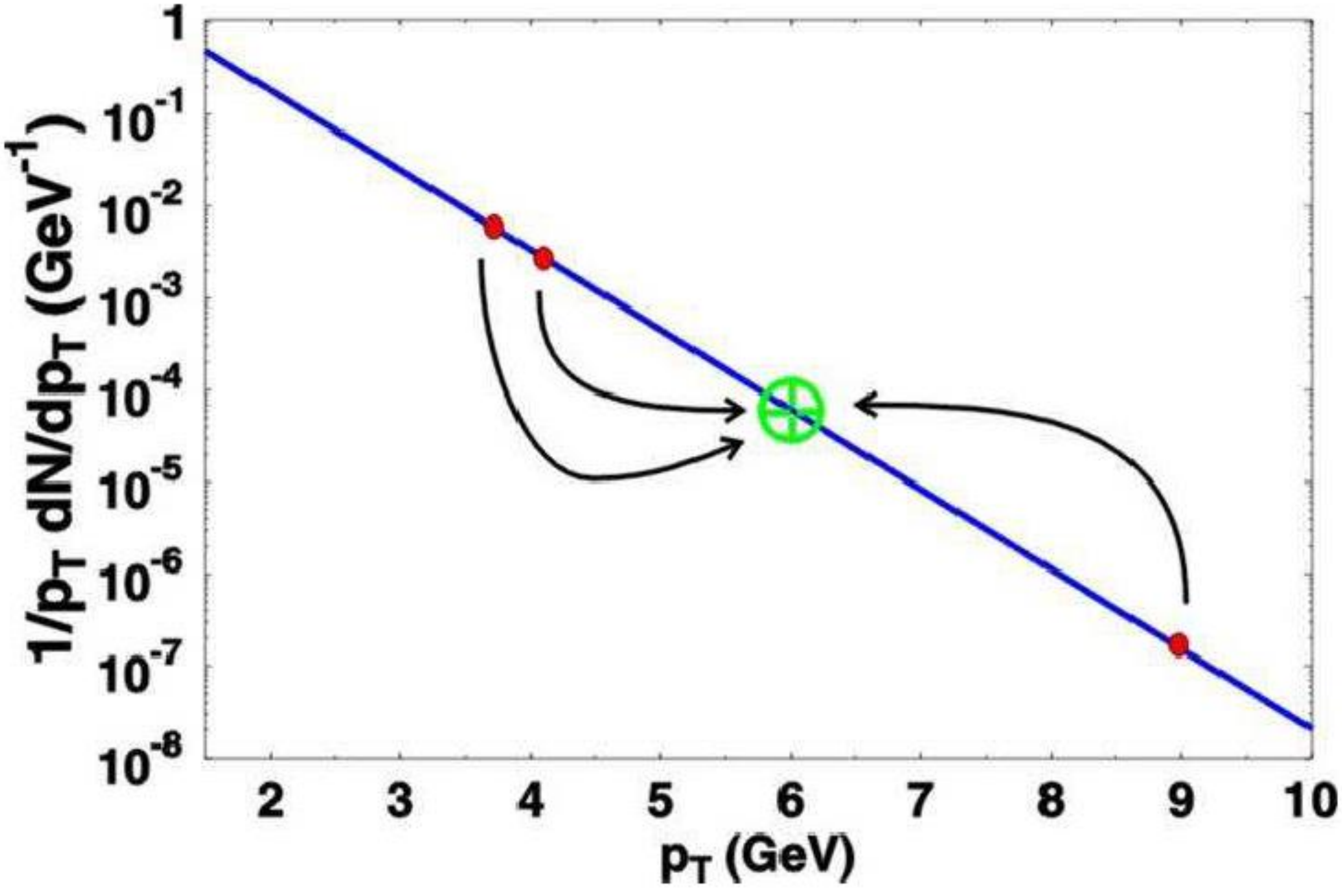


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- Heavy Ion Collision
  - Hard Scattering and High P_T Fragmentation
- Formation of QGP
  - $T \gg T_C \approx 175$ MeV
- Expansion and Cooling
  - $T \rightarrow T_C$
- Hadronization from QGP
  - Intermediate P_T (2–5 GeV)
  - Recombination
- Chemical Equilibrium and Freeze-out ($T_C \approx 175$ MeV)
  - Inelastic Channels (e.g. $\Delta \leftrightarrow p\pi$)
  - Number of each hadron species doesn't change
- Thermal Equilibrium
  - Elastic Scatterings Dominant
  - Interaction still exists (MFP > DBP)
- Continued Expansion and Thermal Freeze-out
  - Particle distance gets larger (DBP > MFP)
  - No further elastic collisions but still heavy particles can decay into light particles (e.g. $\Delta \rightarrow P\pi$): $T_{freeze-out} \approx 120$ MeV

Hadronization Mechanisms

R.J. Fries, nucl-th/0403036, PRC 68, 044902 (2003)



Recombination of a Quark-Antiquark Pair

R.Fries,B.Muller,C.Nonaka and S.Bass,
PRC68, 044902(2003); PRL90, 202303(2003)

$$N_M = \sum_{ab} \int \frac{d^3P}{(2\pi)^3} < M; P | \hat{\rho}_{ab} | M; P >$$

$$E\frac{dN_M}{d^3P} = C_M \int_\Sigma \frac{d^3 R P \cdot u(R)}{(2\pi)^3} \int \frac{d^3 q}{(2\pi)^3} w_a(R; \frac{P}{2} - q) \Phi_M^W(q) w_b(R; \frac{P}{2} + q)$$

$$= C_M \int_\Sigma \frac{d^3 R P \cdot u(R)}{(2\pi)^3} \int \frac{dx P^+ d^2 k_\perp}{(2\pi)^3} w_a(R; xP^+, k_\perp) |\psi_M(x, k_\perp)|^2 \; w_b(R; (1-x)P^+, -k_\perp)$$

where

$\Phi_M^W(q) = \int d^3 r \Phi_M^W(r, q)$ in Wigner Function Formalism

$$w_a(R; p) = \gamma_a e^{-p \cdot v(R)/T} e^{-\eta^2/2\Delta^2} f(\rho, \phi)$$

$$f(\rho, \phi) \approx \Theta(\rho_0 - \rho)$$

Extended Recombination Formalism

B.Hong, C.Ji, D.-P.Min, PRC73, 054901 (2006)

$$\left.\frac{dN_M}{d^2P_T dy}\right|_{y=0} = C_M M_T \frac{V}{(2\pi)^3} 2\gamma_a\gamma_b I_0\left[\frac{P_T \sinh \eta_T}{T}\right]\int_0^1 dx\int_0^\infty d^2k_\perp \left|\psi(x,k_\perp)\right|^2 k_M(x,k_\perp,P_T)$$

where

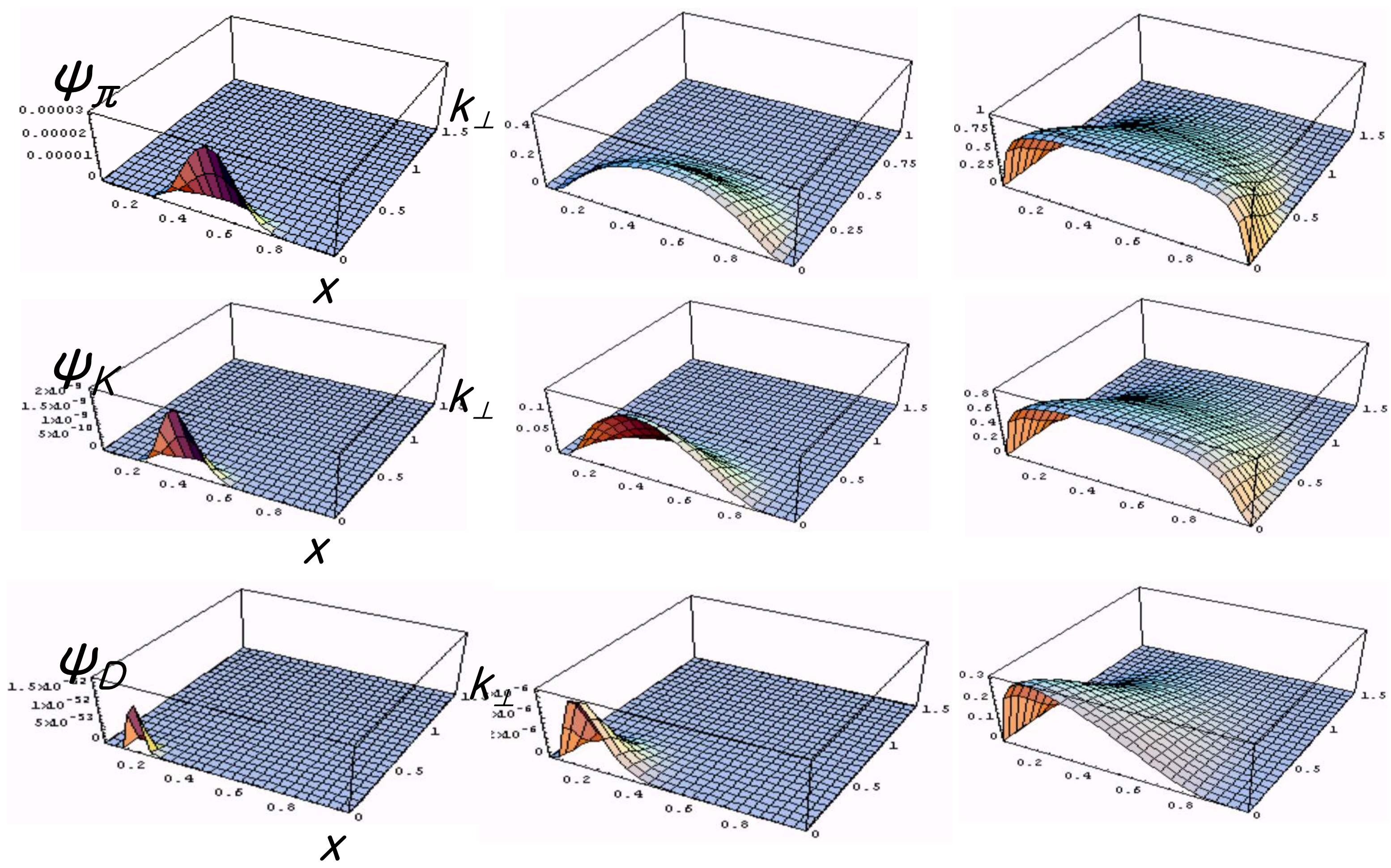
$$k_M(x,k_\perp,P_T) = K_1\left[\frac{\cosh\eta_T}{T}\left[\sqrt{m_a^2+(xP_T+k_\perp)^2}+\sqrt{m_b^2+\{(1-x)P_T-k_\perp\}^2}\right]\right]$$

$$\psi_{Gauss}(x,k_\perp) = \mathrm{Exp}[-(\frac{m_a^2+k_\perp^2}{x}+\frac{m_b^2+k_\perp^2}{1-x})/\beta^2]$$

$$\psi_{Power}(x,k_\perp) = 1/(\frac{m_a^2+k_\perp^2}{x}+\frac{m_b^2+k_\perp^2}{1-x}+\alpha^2)^n$$

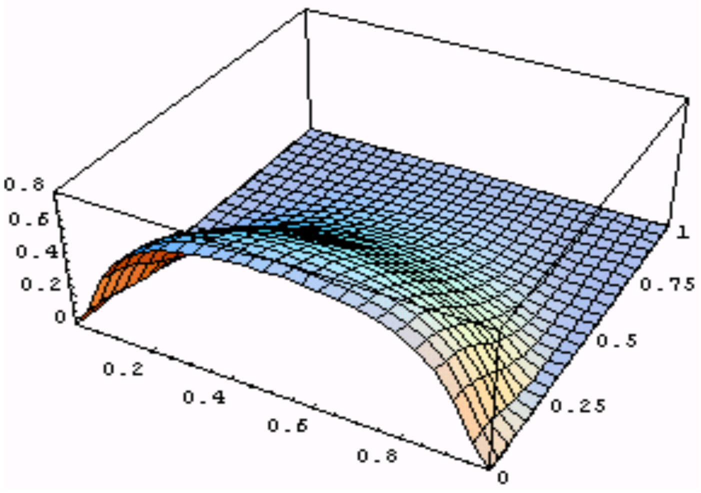
Light-Front Wavefunctions

β^2 (GeV^2) = 0.026 0.26 2.6

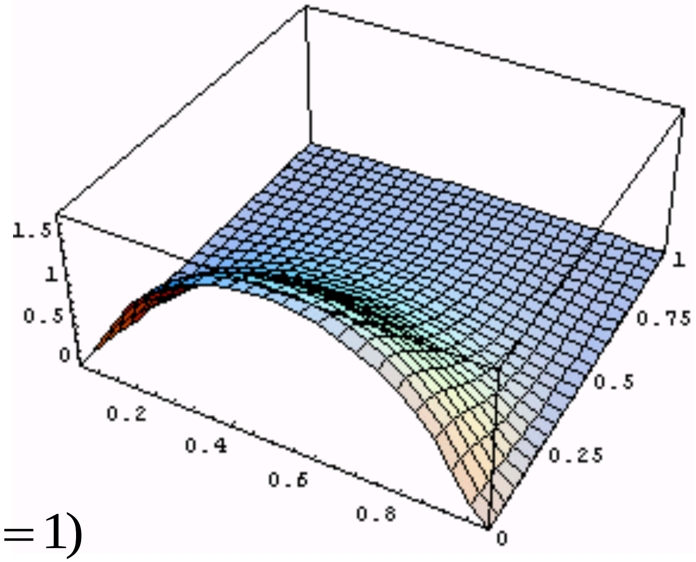


Gaussian vs. Power Law

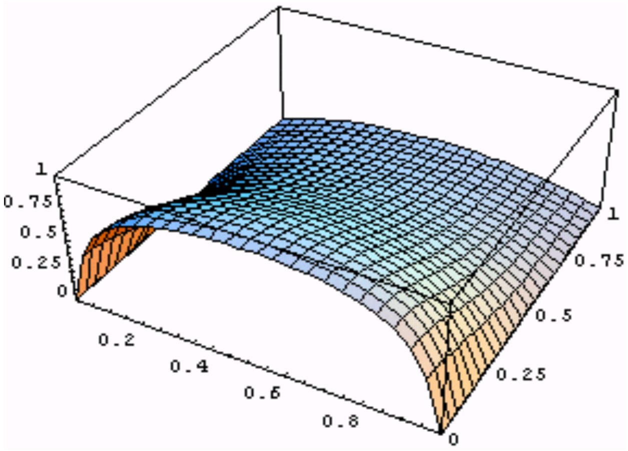
$\psi^{\pi}_{Gauss}(\beta^2 = 0.825)$

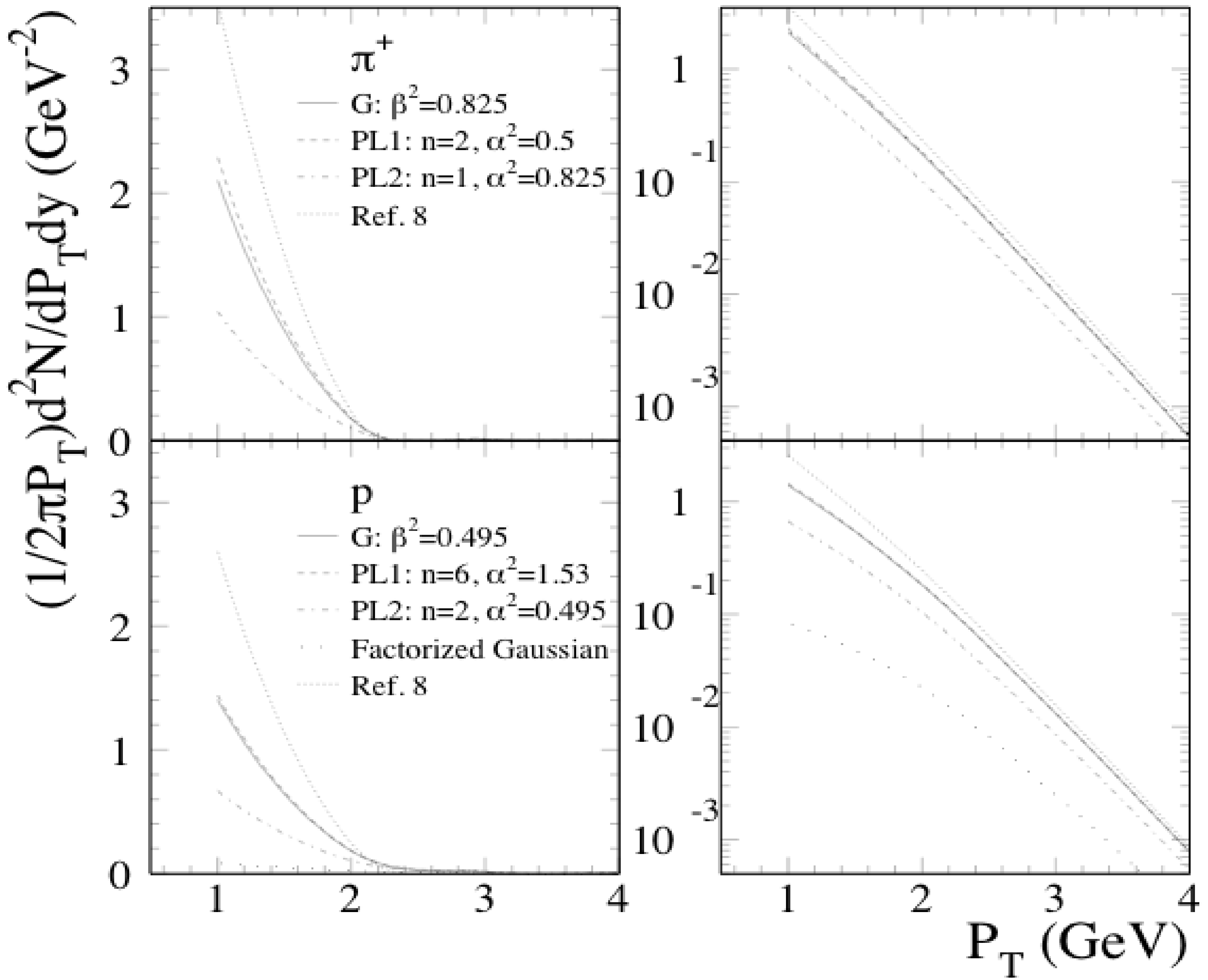


$\psi^{\pi}_{Power}(\alpha^2 = 0.5, n = 2)$



$\psi^{\pi}_{Power}(\alpha^2 = 0.825, n = 1)$





Ref.8: R.Fries,B.Muller,C.Nonaka,S.Bass,PRC68,044902(2003)

Fragmentation and Jet Quenching

$$E\frac{dN_h}{d^3P} = \sum_a \int_0^1 \frac{dz}{z^2} D_{a\to h}(z) E_a \frac{dN_a}{d^3p_a}$$

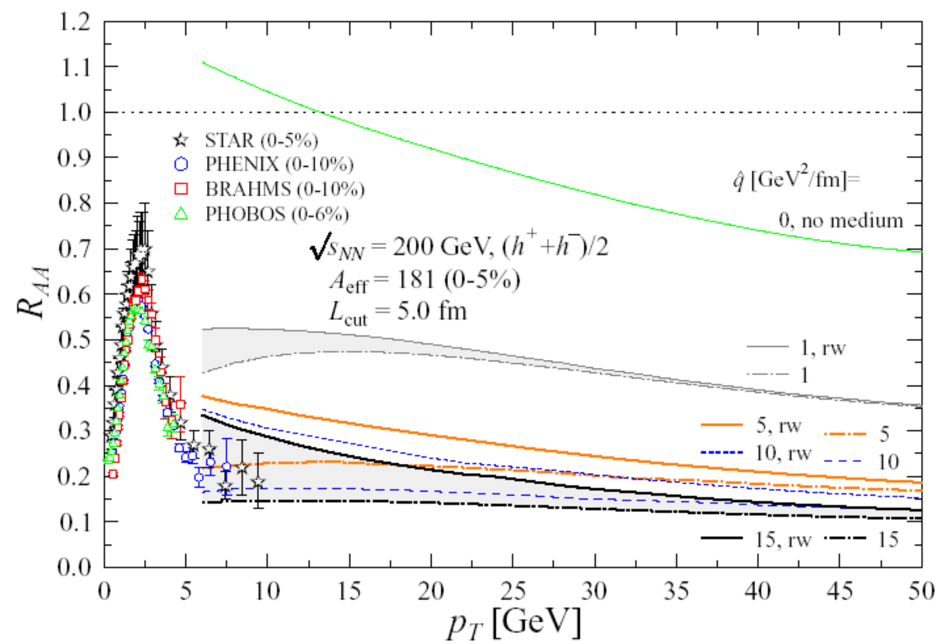
$$\left.\frac{dN_a^{pert}}{d^2p_T dy}\right|_{y=0} = K\frac{C}{(1+p_T/B)^\kappa}$$

- Parameters of the parton distribution function
  D.K. Srivastava, et al., PRC 67, 034903 (2003)
- Parameters of the Fragmentation function
  B.A. Kniel, et al., NPB 582, 514 (2000)
  D. De Florian, et al., PRD 57, 5811 (1998)

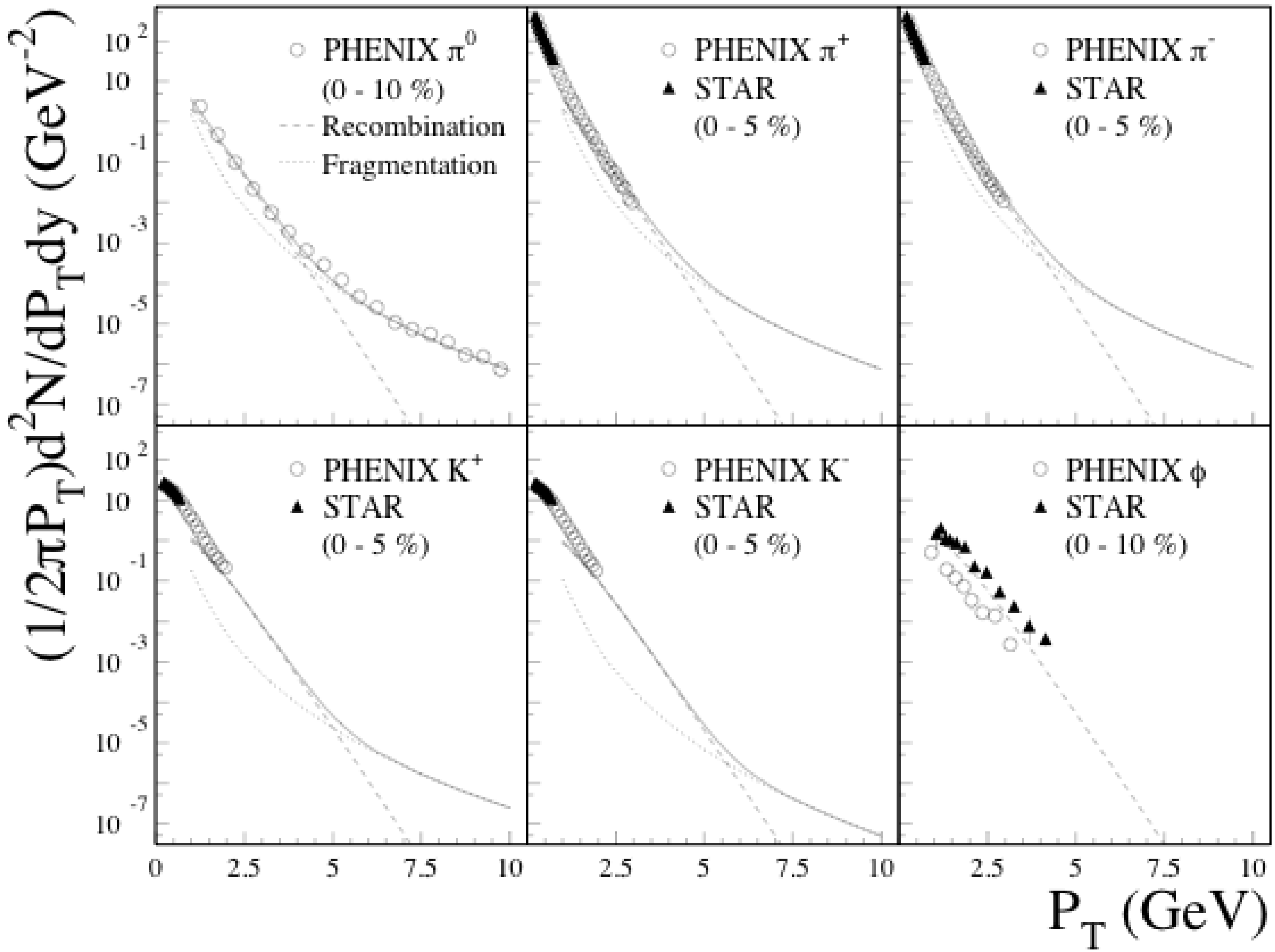
$$\Delta p_T(b, p_T) = \varepsilon(b)\sqrt{p_T}\frac{<L>}{R_A}$$

R. Baier, et al., JHEP 0109, 033 (2001)
B. Mueller, PRC 67, 061901 (2003)

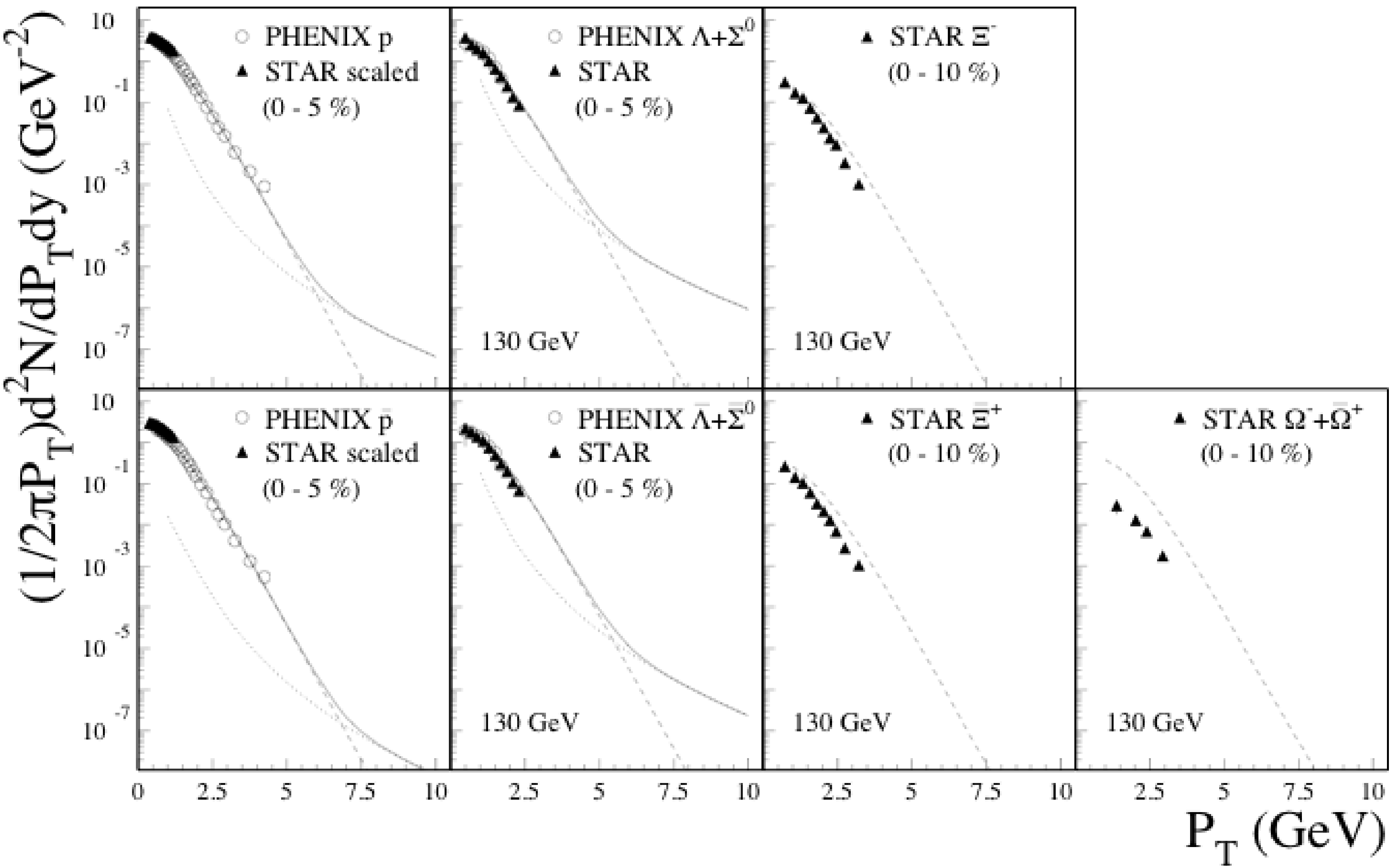
Striking results from STAR:
BARYONS07



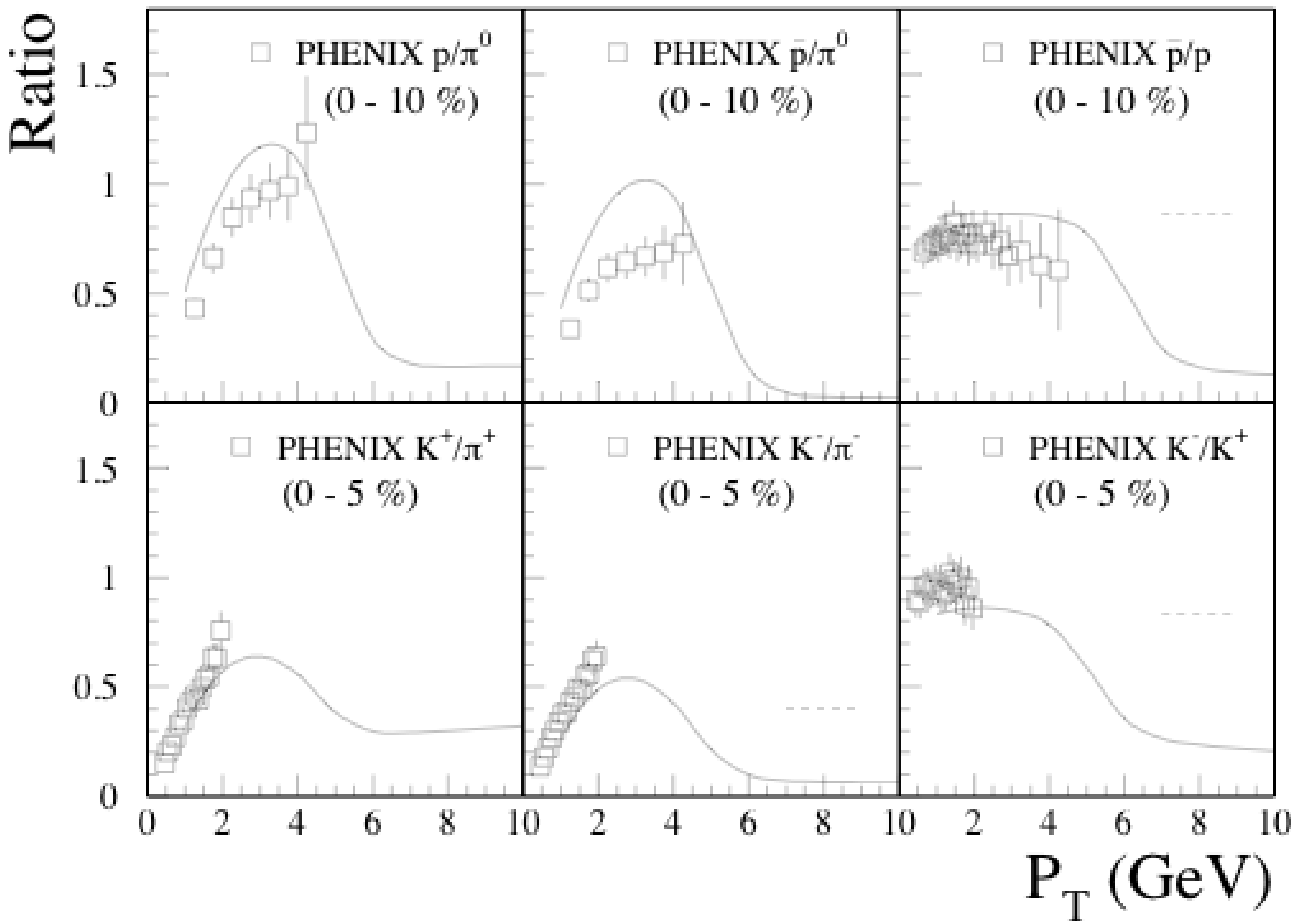
Single Spectra of Mesons



Single Spectra of Baryons



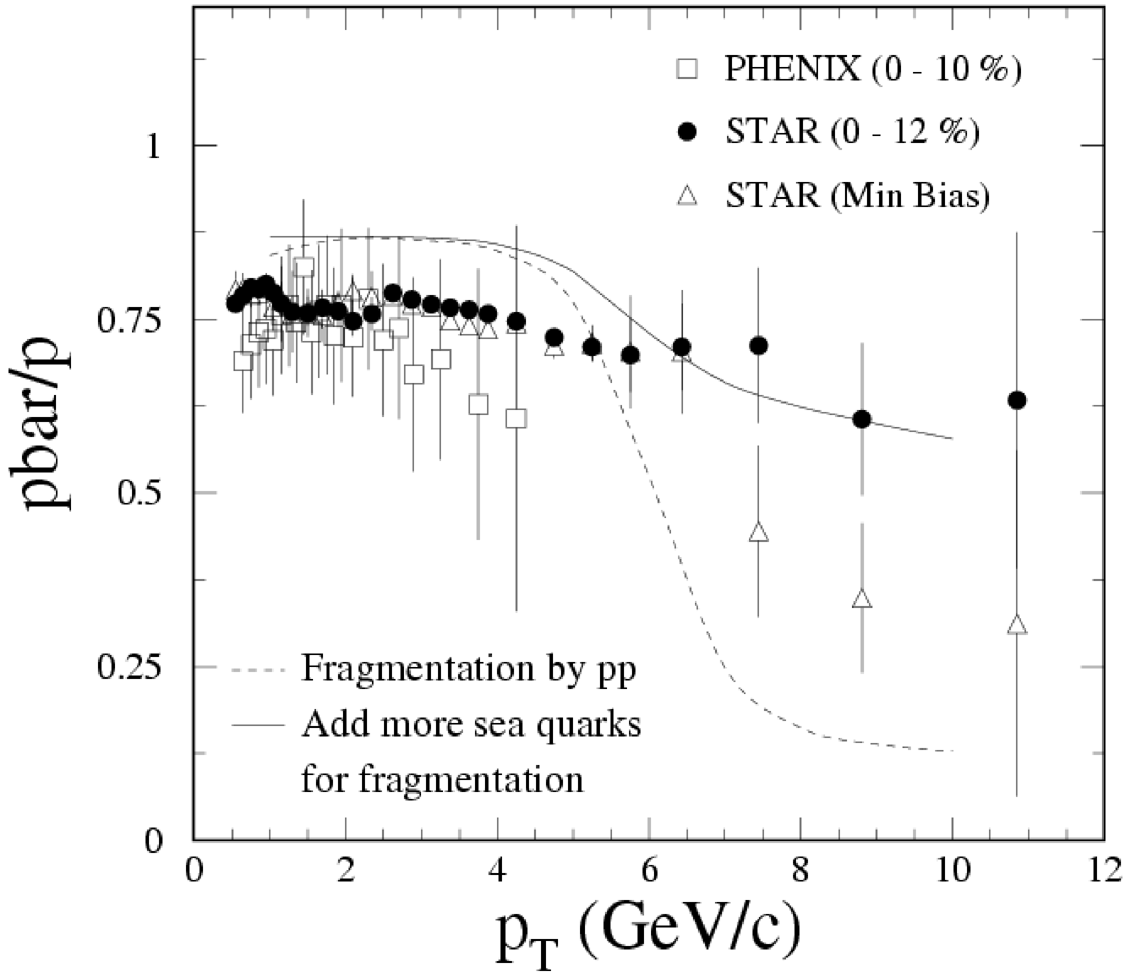
Comparison of Particle Ratios



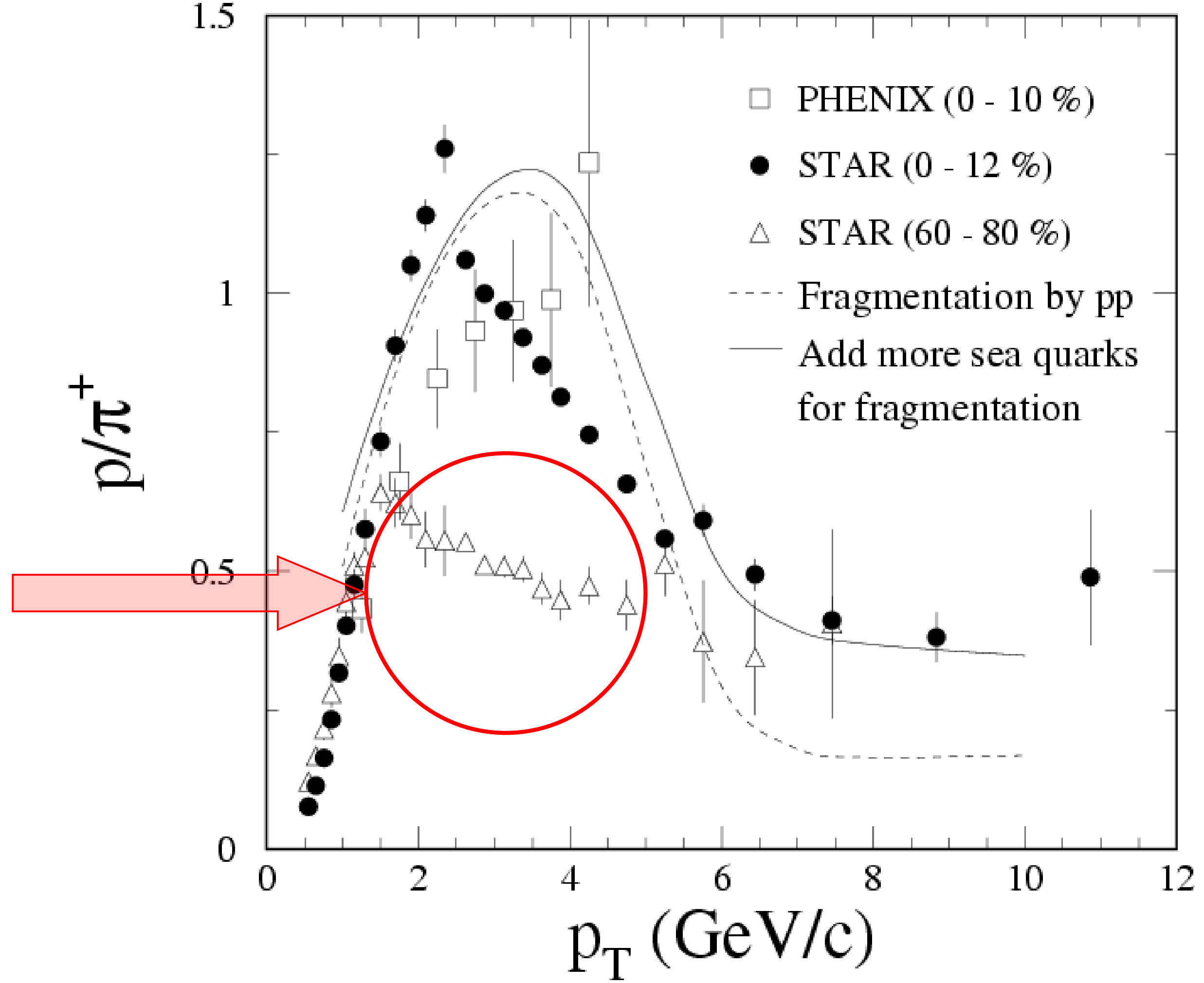
--- R.Fries,B.Muller,C.Nonaka,S.Bass,PRC68,044902(2003)

— B.Hong,C.Ji,D.-P.Min,PRC74,054901(2006)

Enhanced sea quark contribution to the fragmentation of p and pbar.



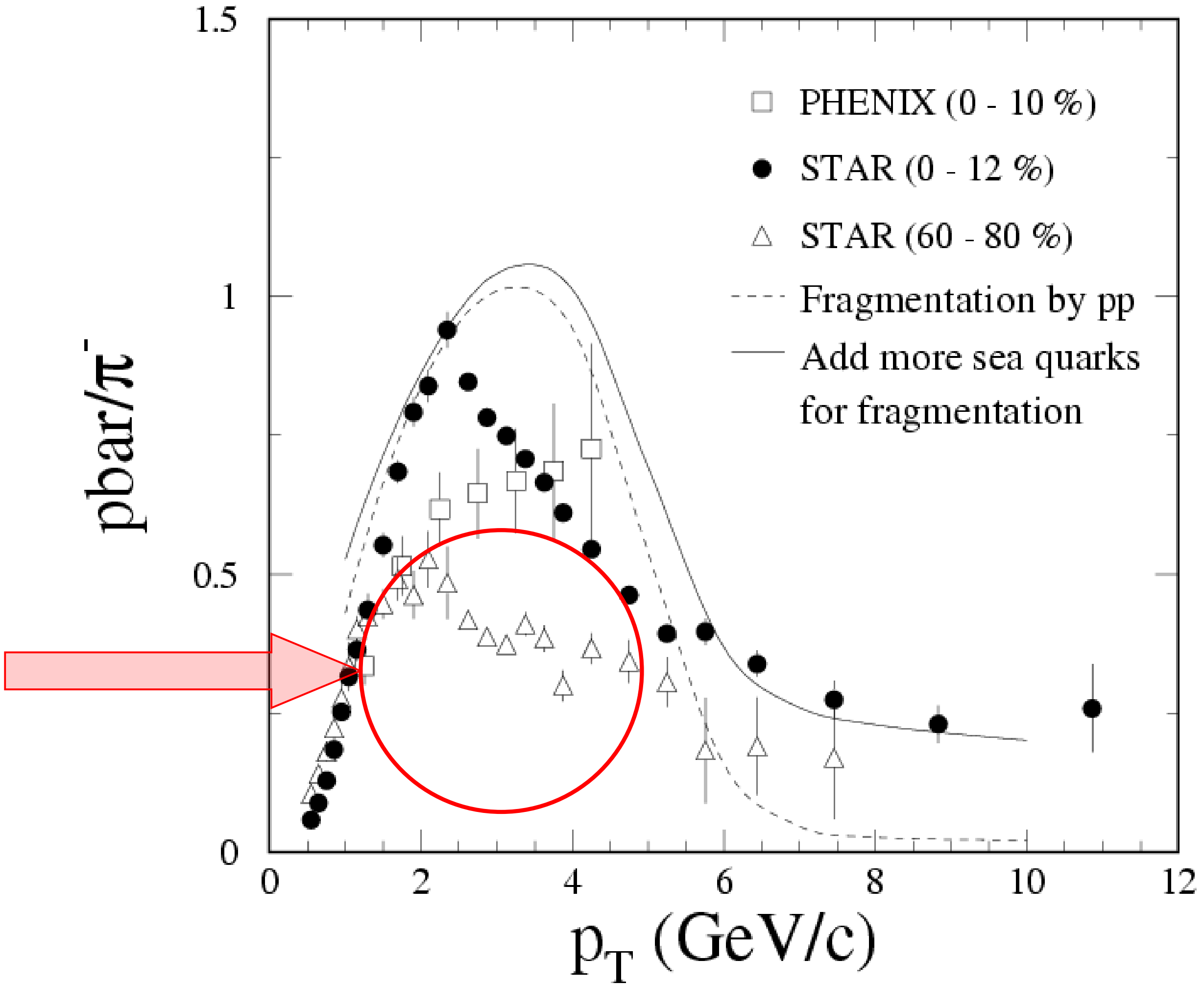
Enhanced sea quark contribution to the fragmentation of p.



We do not expect for the recombination model to work for peripheral collisions.

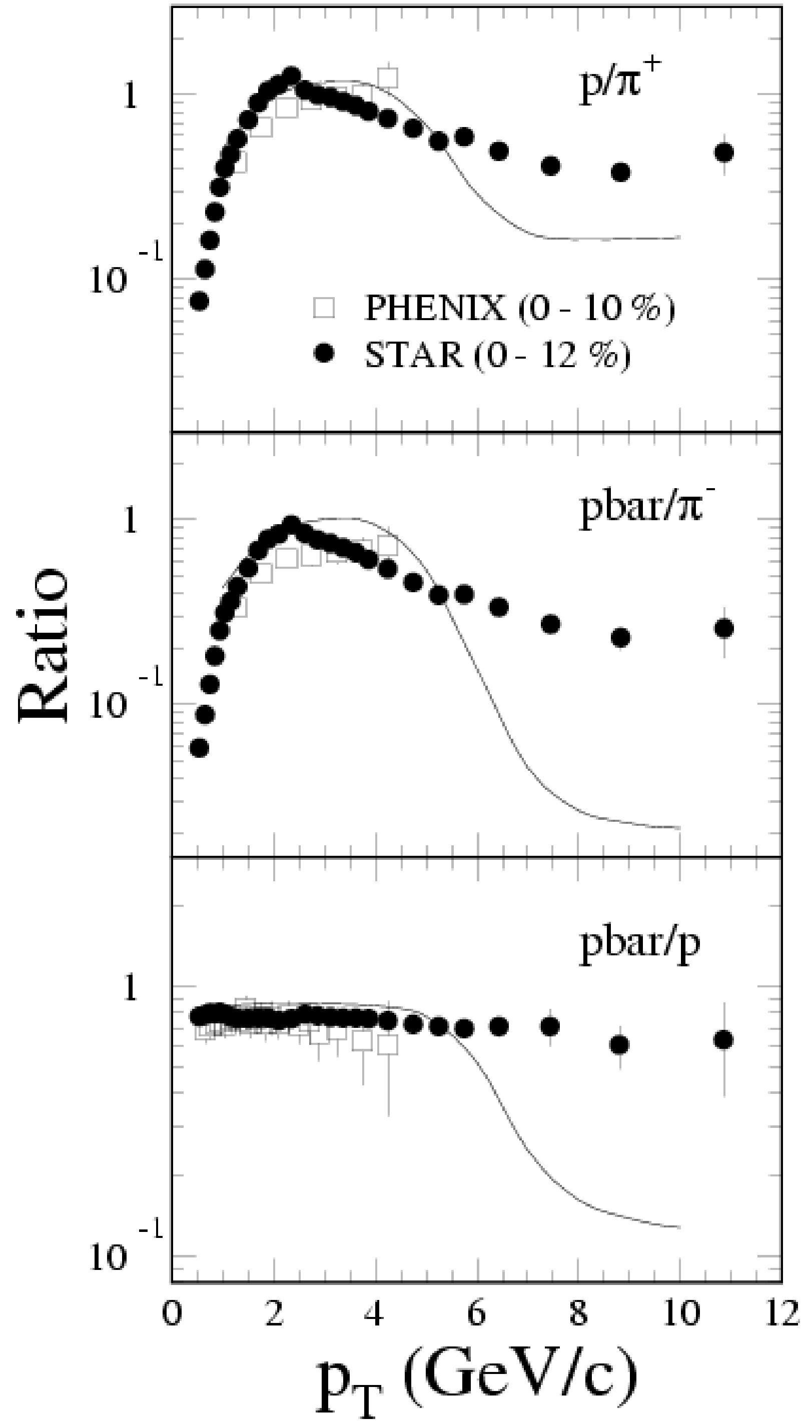
Enhanced sea quark contribution to the fragmentation of pbar.

We do not expect for the recombination model to work for peripheral collisions.



Particle Ratios

- Data for central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Open Squares: PHENIX Data
  -Phys. Rev. C 69, 034909 (2004)
- Solid Circles: STAR Data
  -Phys. Rev. Lett. 97, 152301 (2006)
- Solid Lines: Predictions by the present recombination model by using the fragmentation function determined by the pp collisions data

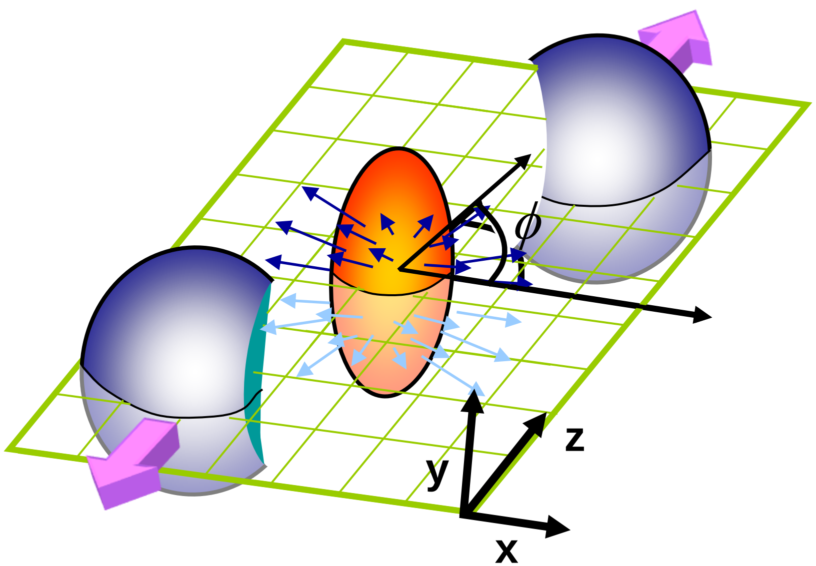


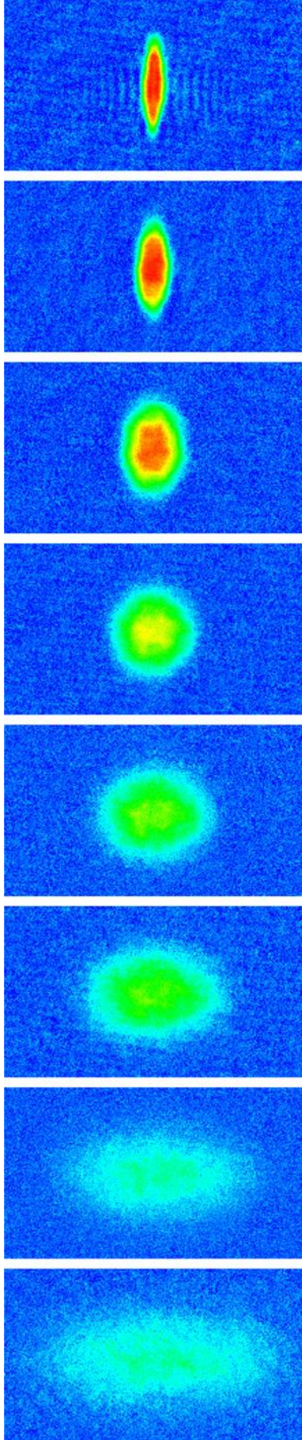
Anisotropy Parameter v_2

Elliptic flow = v_2 = 2nd Fourier coefficient of momentum anisotropy

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$

Initial spatial anisotropy is converted into momentum anisotropy.
Efficiency of the conversion depends on the properties of the medium





Elliptic Flow Calculation

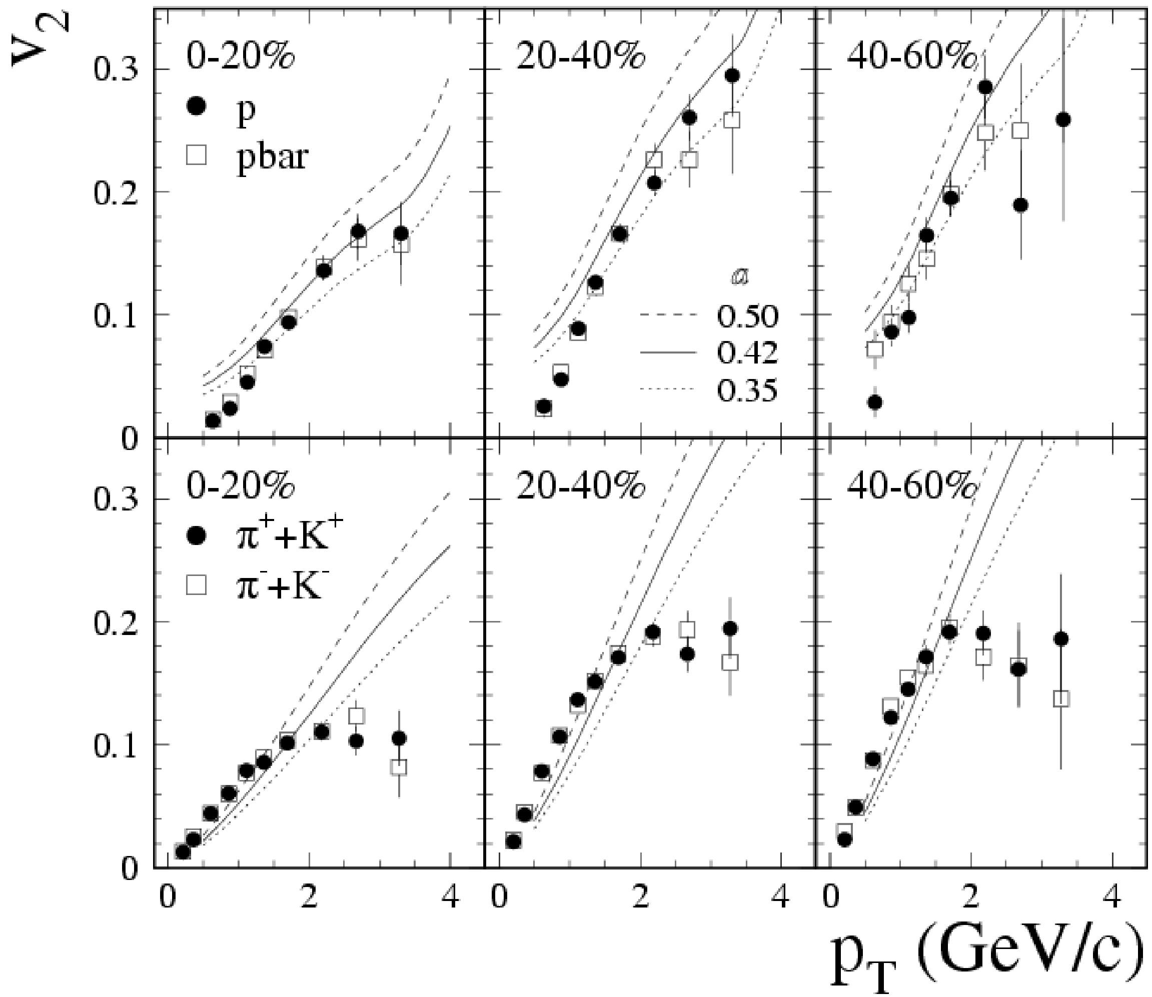
$$v_2^M(P_T) = \frac{\int dx d^2k_\perp \,|\psi(x,k_\perp)|^2 \{v_2^a(xP_T + k_\perp) + v_2^b[(1-x)P_T - k_\perp]\} k_M(x,k_\perp,P_T)}{\int dx d^2k_\perp \,|\psi(x,k_\perp)|^2 \{1 + 2v_2^a(xP_T + k_\perp) v_2^b[(1-x)P_T - k_\perp]\} k_M(x,k_\perp,P_T)}$$

$$\xrightarrow{NR} \frac{v_2^a(\frac{1}{2}P_T) + v_2^b(\frac{1}{2}P_T)}{1 + 2v_2^a(\frac{1}{2}P_T) v_2^b(\frac{1}{2}P_T)}$$

$$v_2^a(p_T) = \left\langle \cos(2\phi) \right\rangle = \frac{\int d\phi \cos(2\phi)\, I_2[p_T \sinh \eta_T(\phi)/T]\, K_1[m_T \cosh \eta_T(\phi)/T]}{\int d\phi\, I_0[p_T \sinh \eta_T(\phi)/T]\, K_1[m_T \cosh \eta_T(\phi)/T]}$$

$$\eta_T(\phi) = \eta_T^0[1 - f(p_T)\cos(2\phi)]\,;\; f(p_T) = \frac{\alpha^n}{1 + (p_T/p_0)^m}\,;\, \alpha = \frac{w(b) - l(b)}{w(b) + l(b)}$$

Anisotropy Parameter v_2



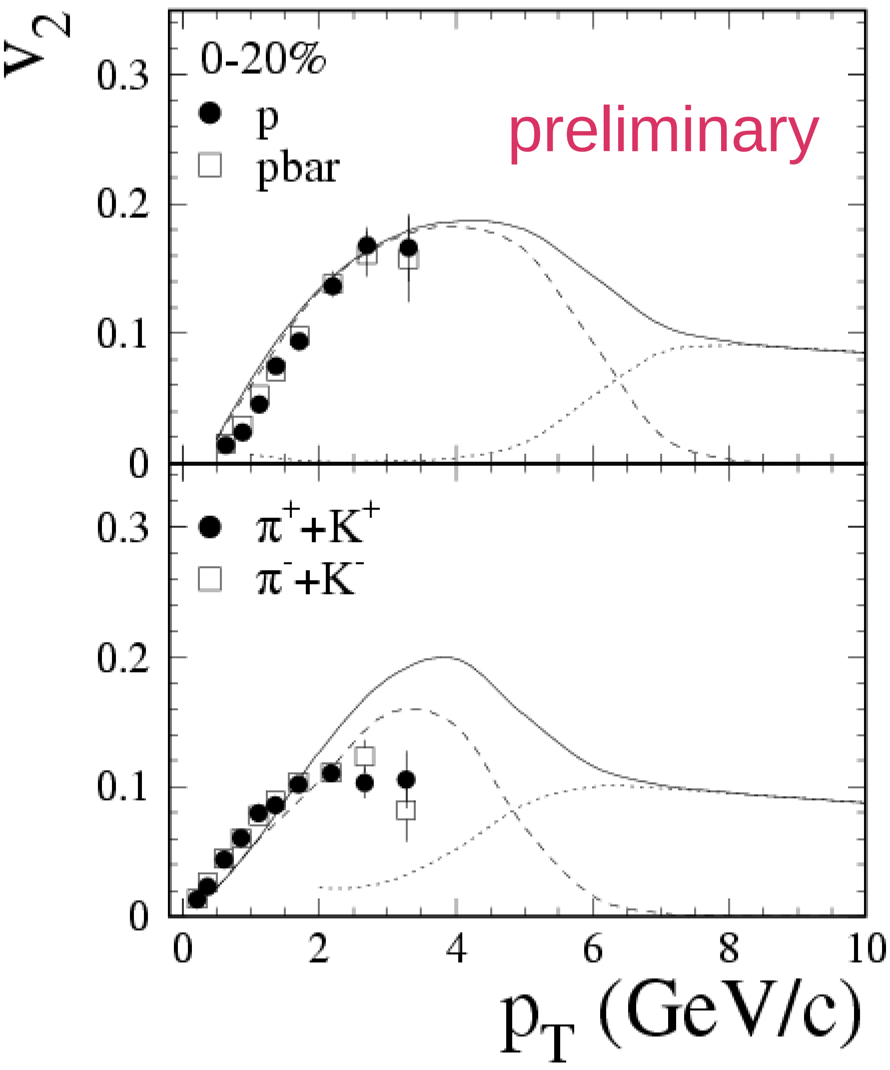
- Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
- Data
  - Open Symbols for negatives
  - Solid Symbols for positives
- Recombination model
  - No fragmentation
  - Dashed lines: α=0.50
  - Solid lines: α=0.42
  - Dotted lines: α=0.35

Anisotropy Parameter v_2

- Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

- Data
  - Open Symbols for negatives
  - Solid Symbols for positives

- Recombination model
  -Explicit model calculation for protons by the recombination for p_T>4 GeV/c is still underway.
  -For preliminary result here, we assumed the simple quark number scaling for now.
  -Including the fragmentation part
  -Dashed lines: Recombination
  -Dotted lines: Fragmentation
  -Solid lines: Sum



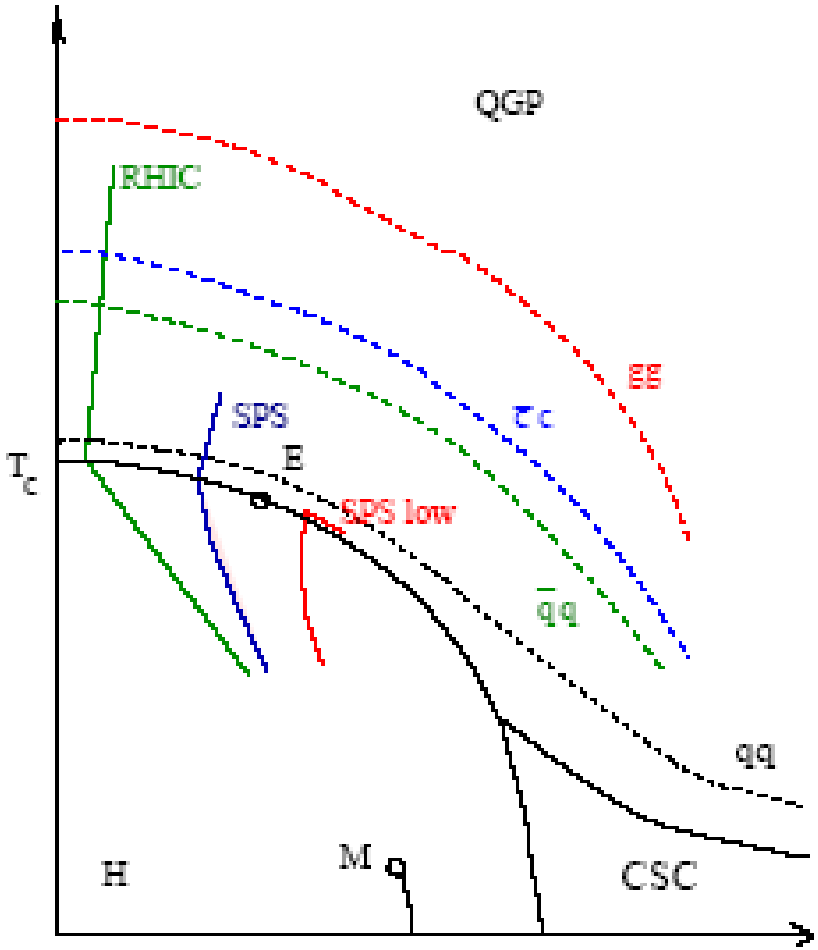
Conclusions and Outlook

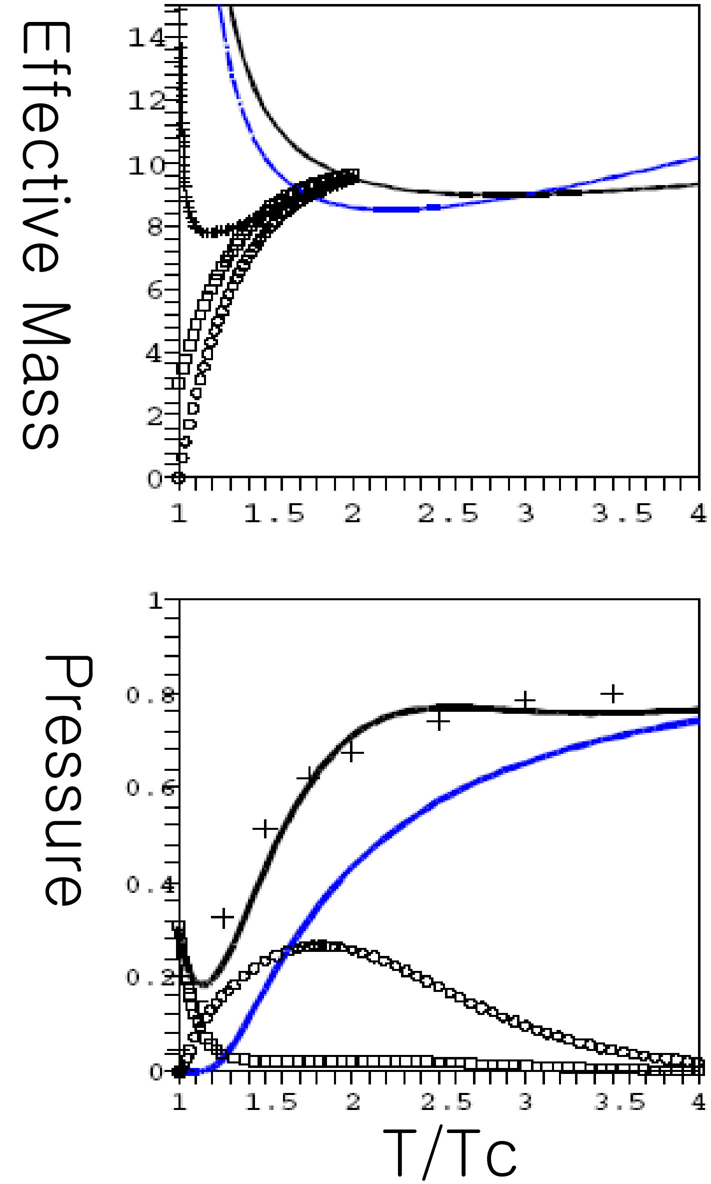
- Extended the formulation of recombination model
  - Intrinsic Transverse Momentum Effect
  - Light-Front Wavefunction
    - Gaussian vs. Power Law
- Found the sensitivity of wavefunction dependence
  - Recombination favored by the larger size hadrons
- New results on yield ratios of K^-/K^+ and pbar/p
  - Jet Quenching Effect included
- Elliptic flow

  Extension possible and preliminary results obtained
- Maybe useful for the analysis of other QGP nature
  - Possible Formation of the Binary Systems
  - Crossover between BCS and BEC
    - Feshbach Resonances
  - Heavy Hadron Production

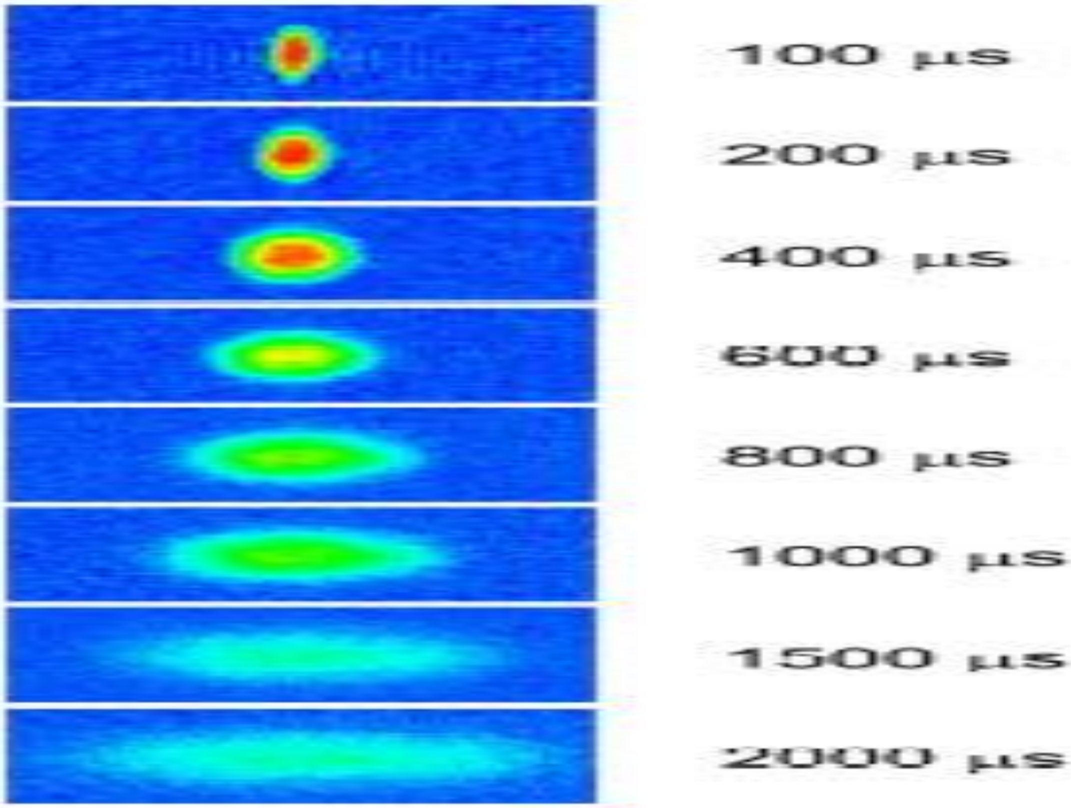
Food for Thoughts:
Binary Bound States in QGP

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$


QGP
RHIC
EE
c̄c
SPS
T
c
E
SPS low
q̄q
qq
H
M
CSC


Effective Mass
Pressure
T/Tc

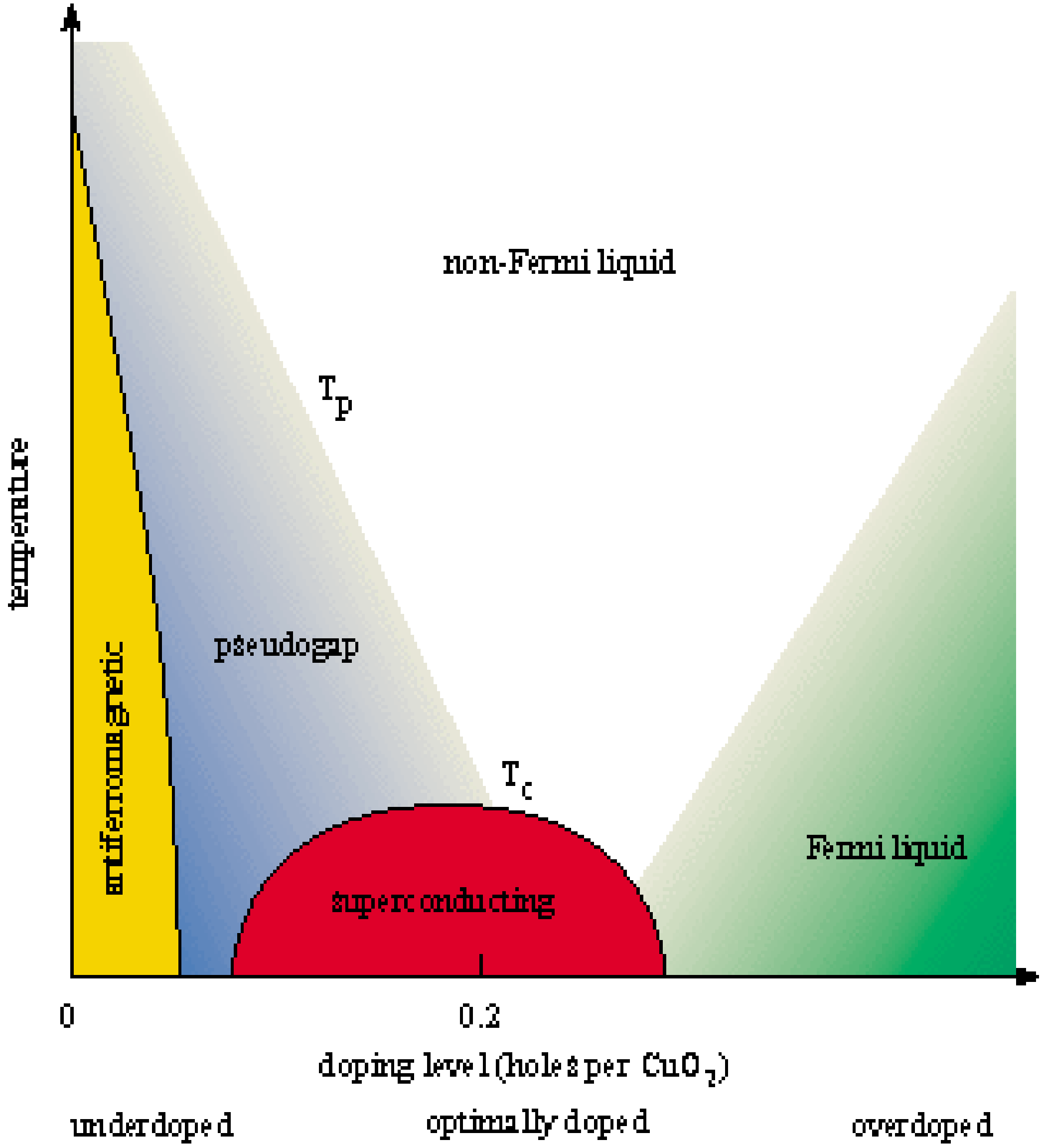
Bose-Einstein Condensation



Hydrodynamical Expansion of Trapped Atoms

Analogous to Elliptic Flows in RHIC Data

Crossover between BCS and BEC



Controlling Parameters

- High Tc Superconductors:
  Doping Holes
- Ultracold Trapped Atoms:
  Applying Magnetic Fields
- RHIC:
  Changing s_{NN} and Projectiles, etc.