Quark Recombination and Fragmentation

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In collaboration with

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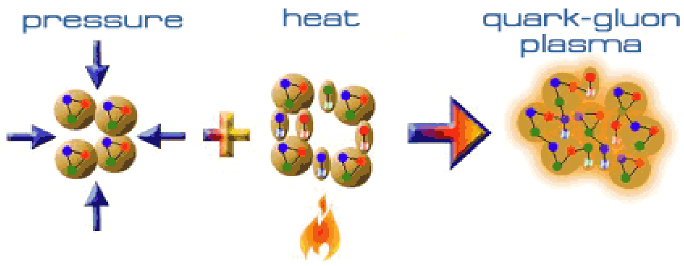
Motivation of HI Collisions

1. Quarks and Gluons exist, but not detected individually at T=0.
   Temperature Dependence of Confinement
   and Chiral Symmetry

2. High-energy nuclear collisions will compress and heat the heavy nuclei so much that their individual protons and neutrons overlap and lots of pions arise, creating the Quark-Gluon Plasma (QGP)

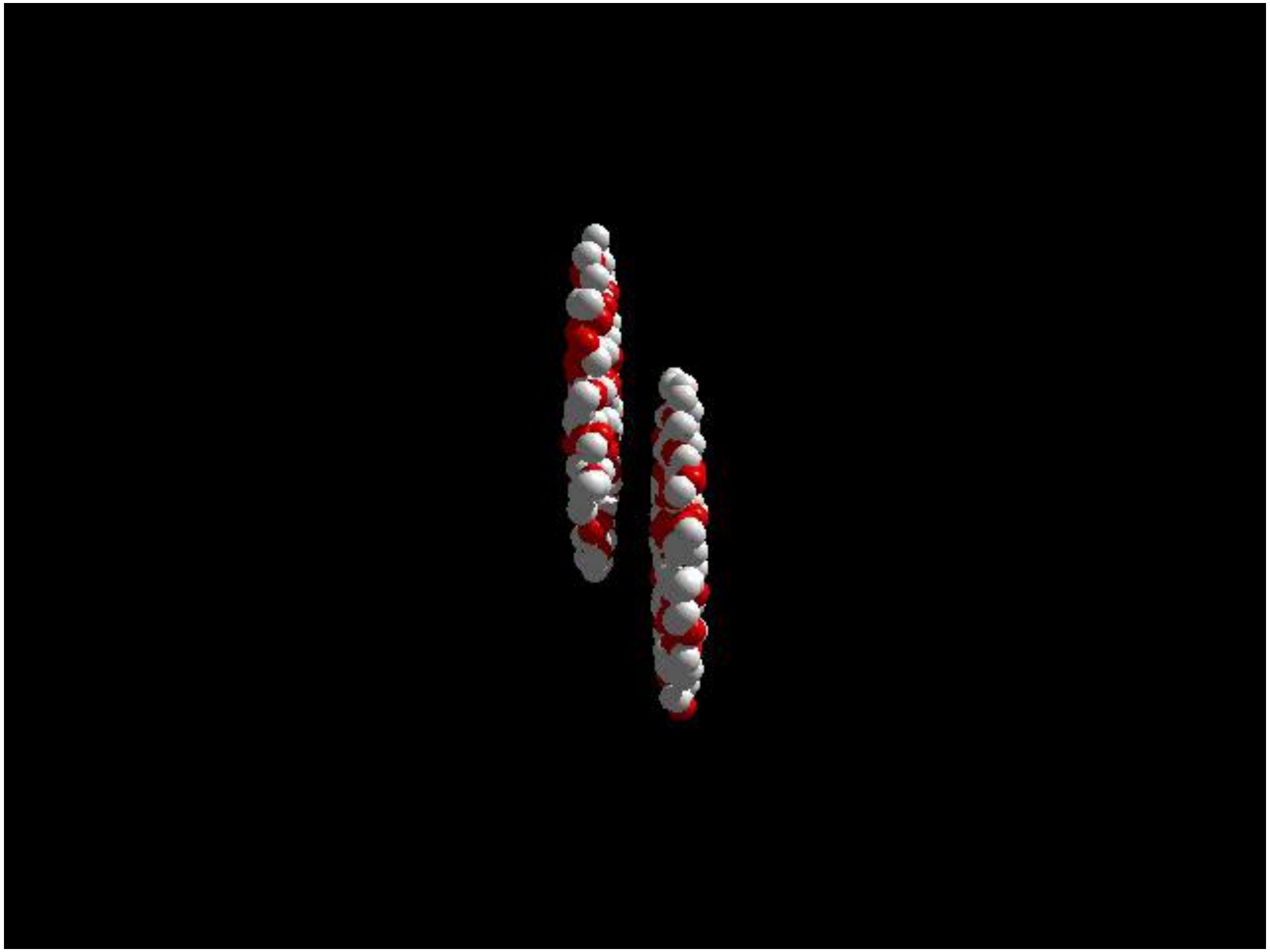


QGP is thought to have existed ten millionths of second after the Big Bang; creating the primordial matter of universe in the laboratory.

3. RHIC obtained distinguished results from CERN SPS.
   - Jet Quenching and Bulk Hadronization (Winner of recent NSAC meeting).
4. LHC ALICE (CMS, ATLAS) would need theoretical predictions at energy 30-fold energy increase from RHIC.

Outline

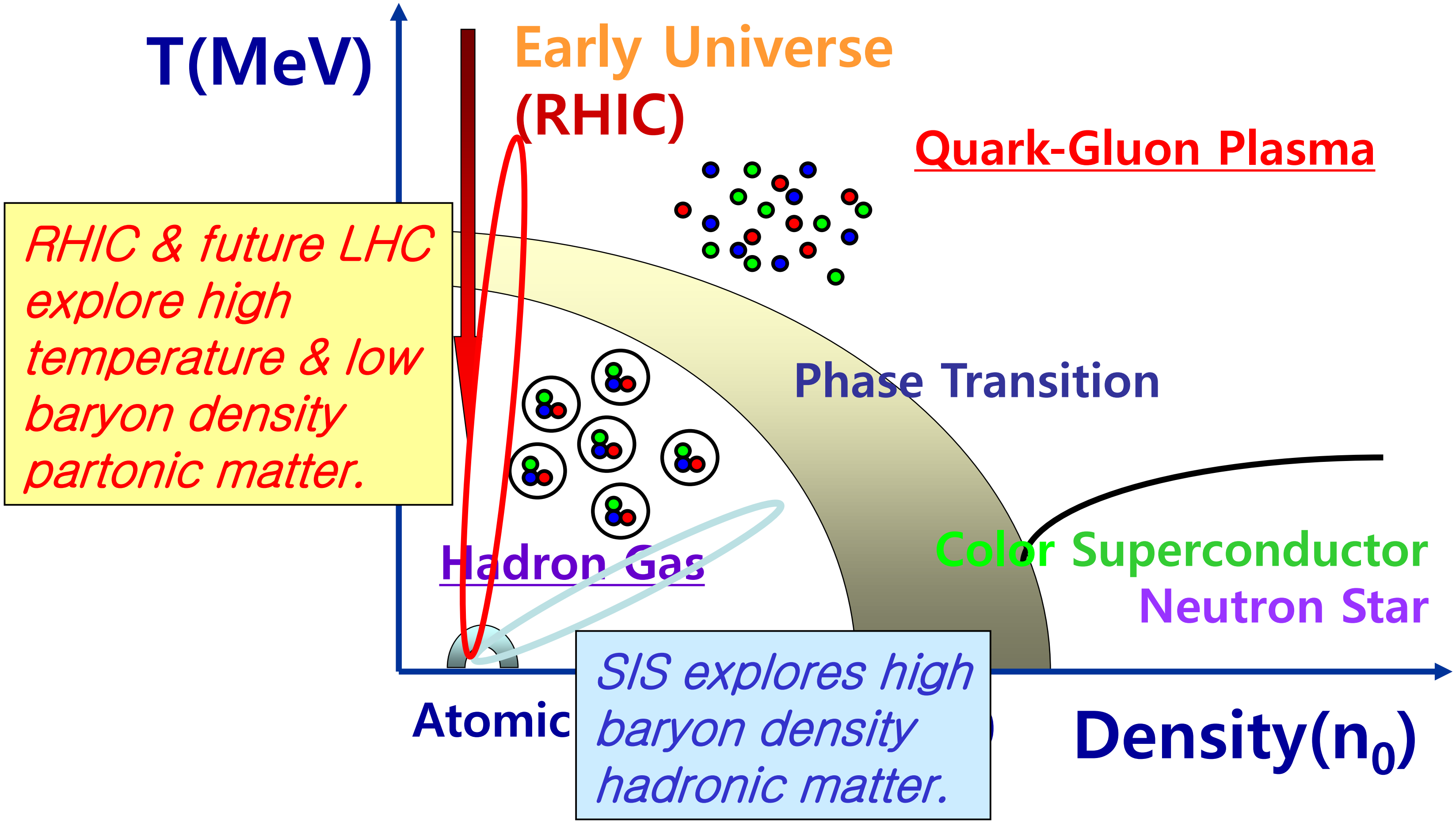
- Brief Overview on State Changes
  - Chemical and Thermal Freeze-outs
- Hadronization Mechanisms
  - Quark Recombination and Fragmentation
- Numerical Results
  - Wavefunction Dependence on P_T Spectra,
  - Ratio between proton and antiproton, etc…
- Discussion and Conclusion
  - BCS-BEC Crossover, Heavy quark systems, etc…



Simulation by the Frankfurt Group

- 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

Nuclear Phase Diagram



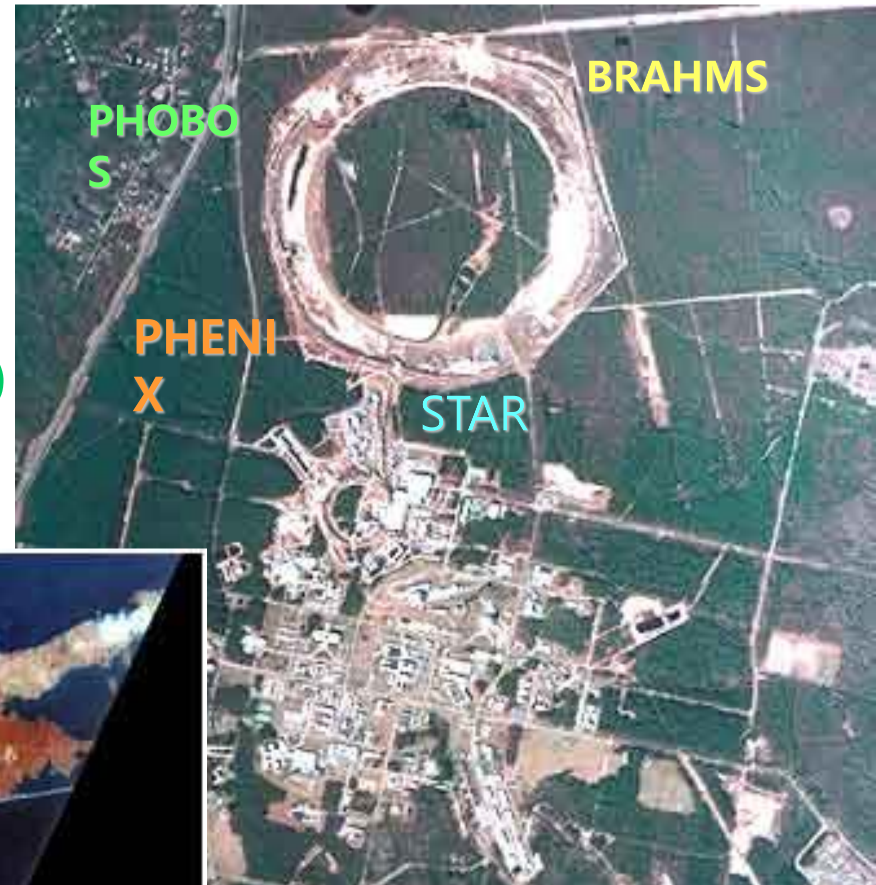
Heavy-Ion Accelerators

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

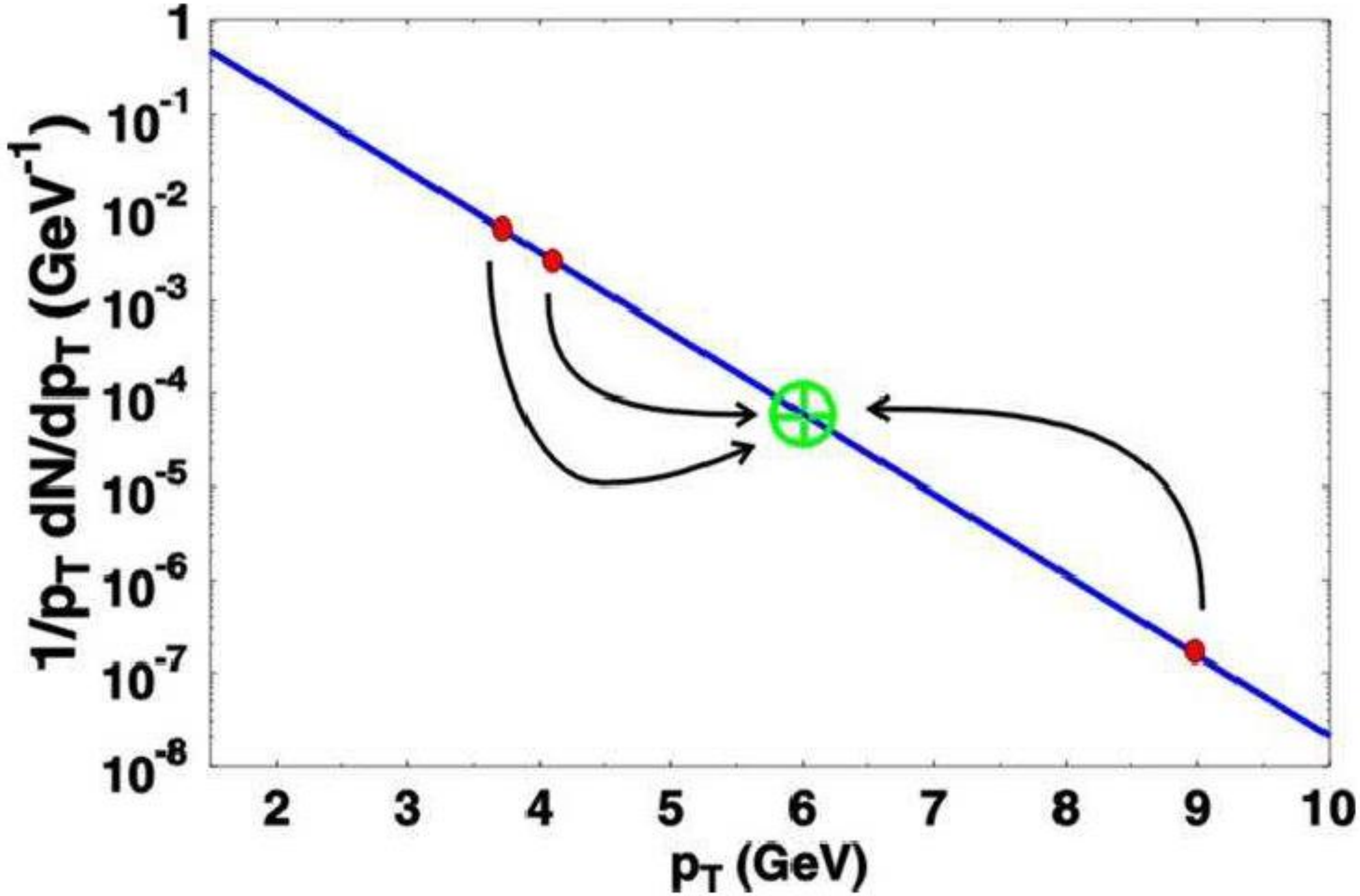
- ***Brookhaven National Lab. in New York***

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



Hadronization Mechanisms

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



Recombination of a Quark-Antiquark Pair

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

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

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

where

$\Phi_M^W(q) = \int d^3r \Phi_M^W(r,q)$ 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

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

where

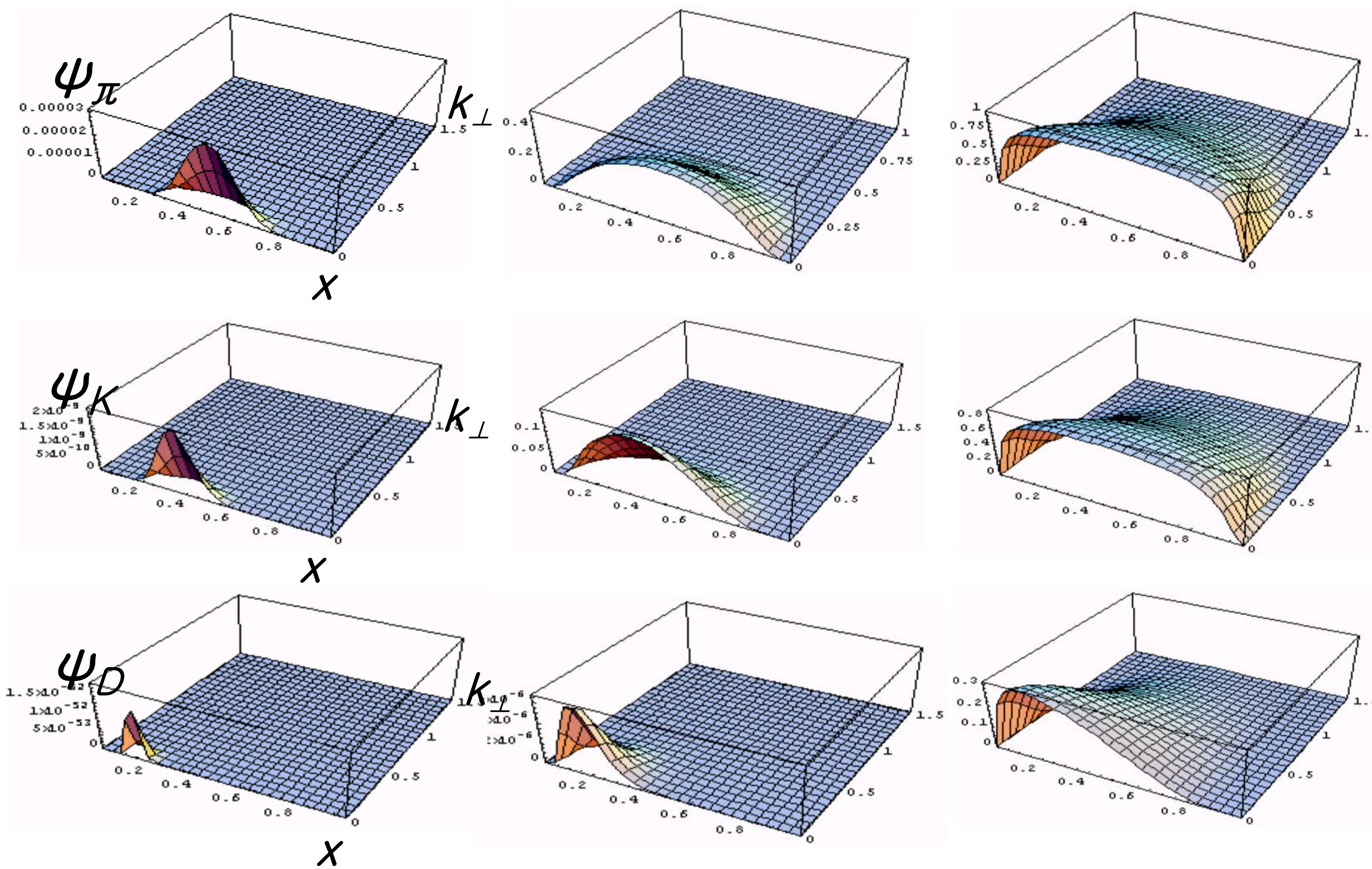
$$k_M(x,k_\perp,P_T) = K_1\left[\frac{\cosh \eta_T}{T}\left[\sqrt{m_a^2 + (xP_T + k_\perp)^2} + \sqrt{m_b^2 + \{(1-x)P_T - k_\perp\}^2}\right]\right]$$

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

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

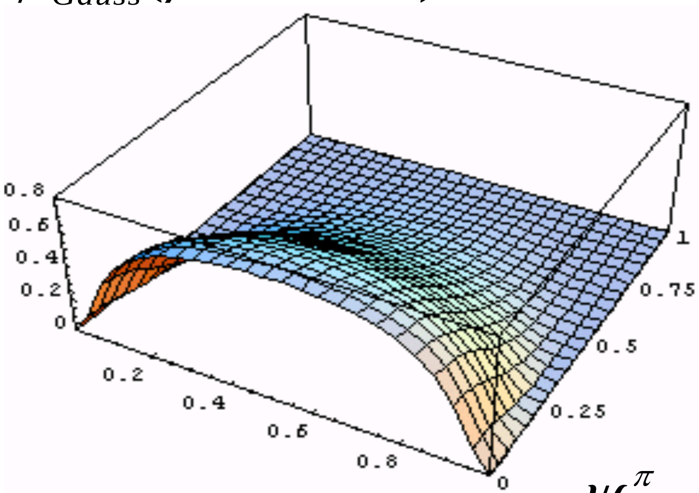
Light-Front Wavefunctions

β^2 (GeV^2) = 0.026 0.26 2.6

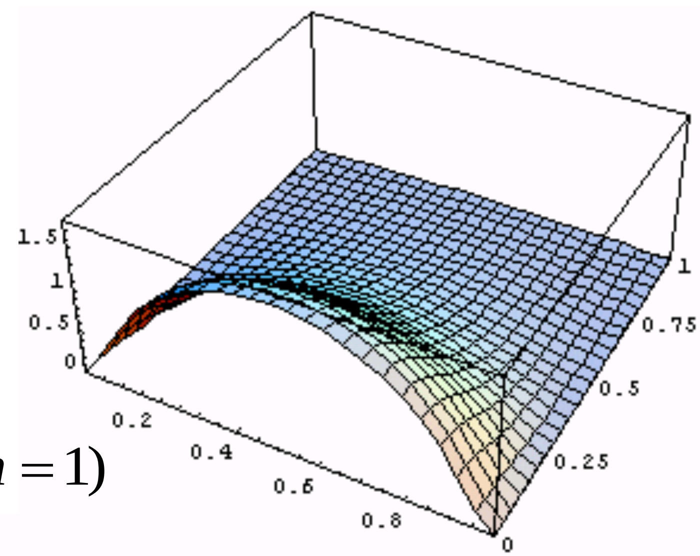


Gaussian vs. Power Law

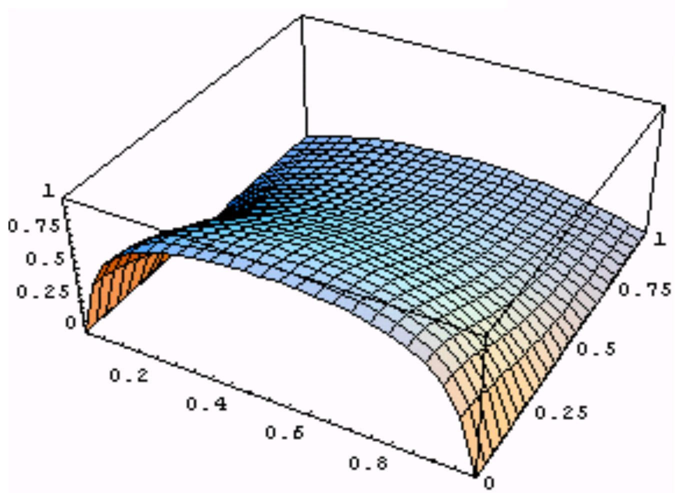
$\psi^{\pi}_{Gauss}(\beta^2 = 0.825)$



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



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



Fragmentation and Jet Quenching

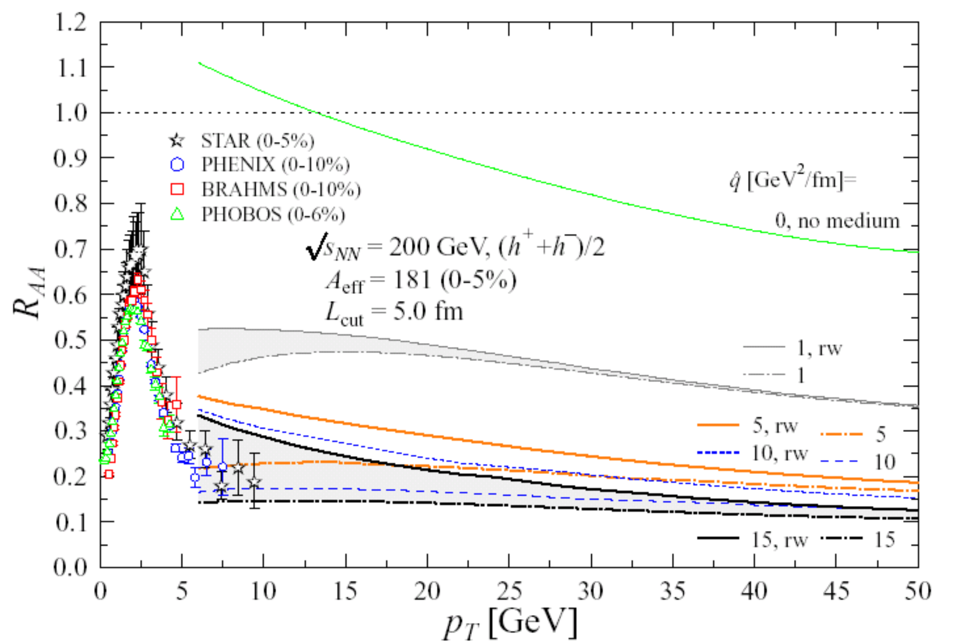
$$E\frac{dN_h}{d^3P} = \sum_a \int_0^1 \frac{dz}{z^2} D_{a\to h}(z) E_a \frac{dN_a}{d^3 p_a}$$

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

- 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)

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

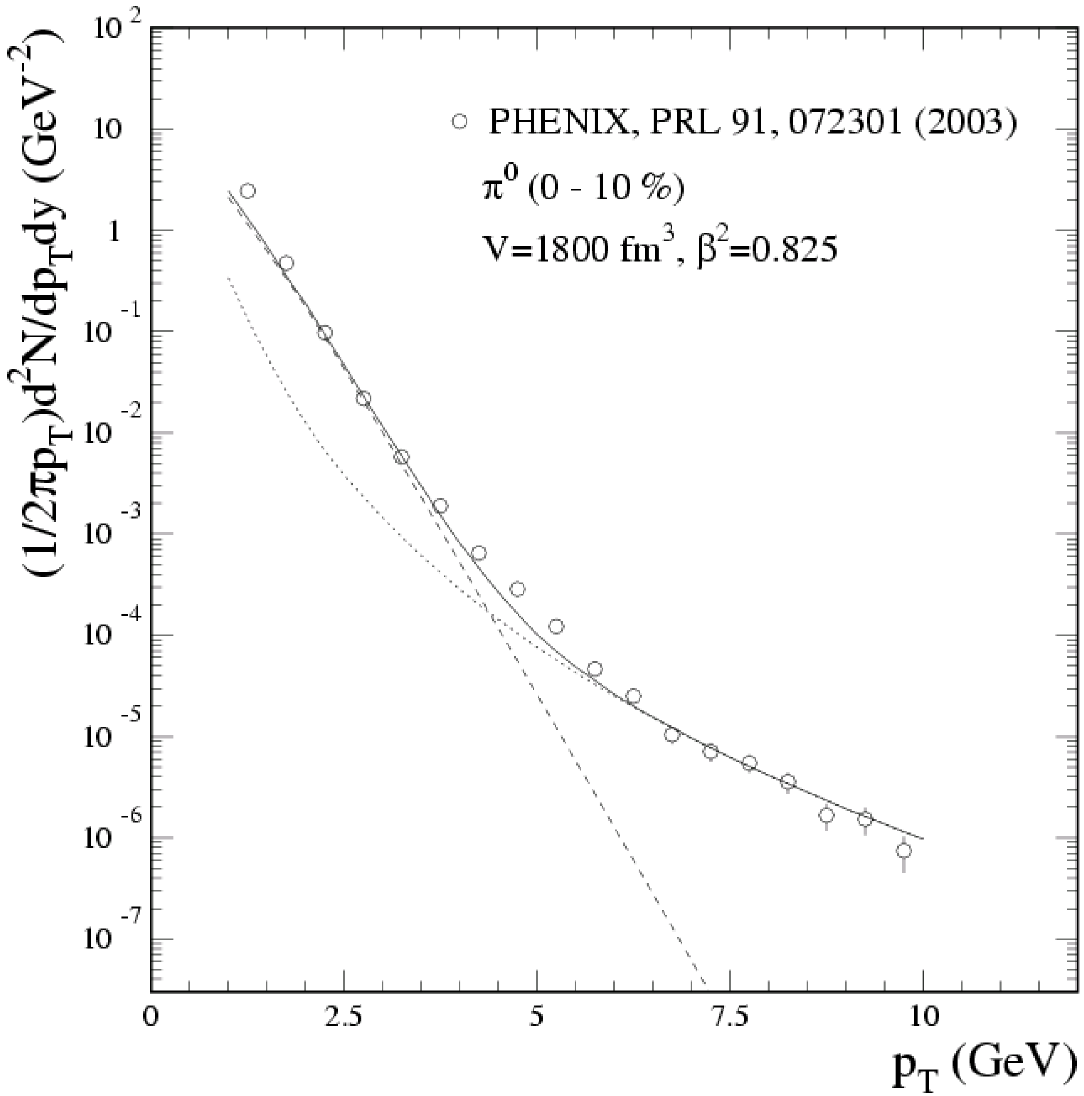
R. Baier, et al., JHEP 0109, 033 (2001)
B. Mueller, PRC 67, 061901 (2003)



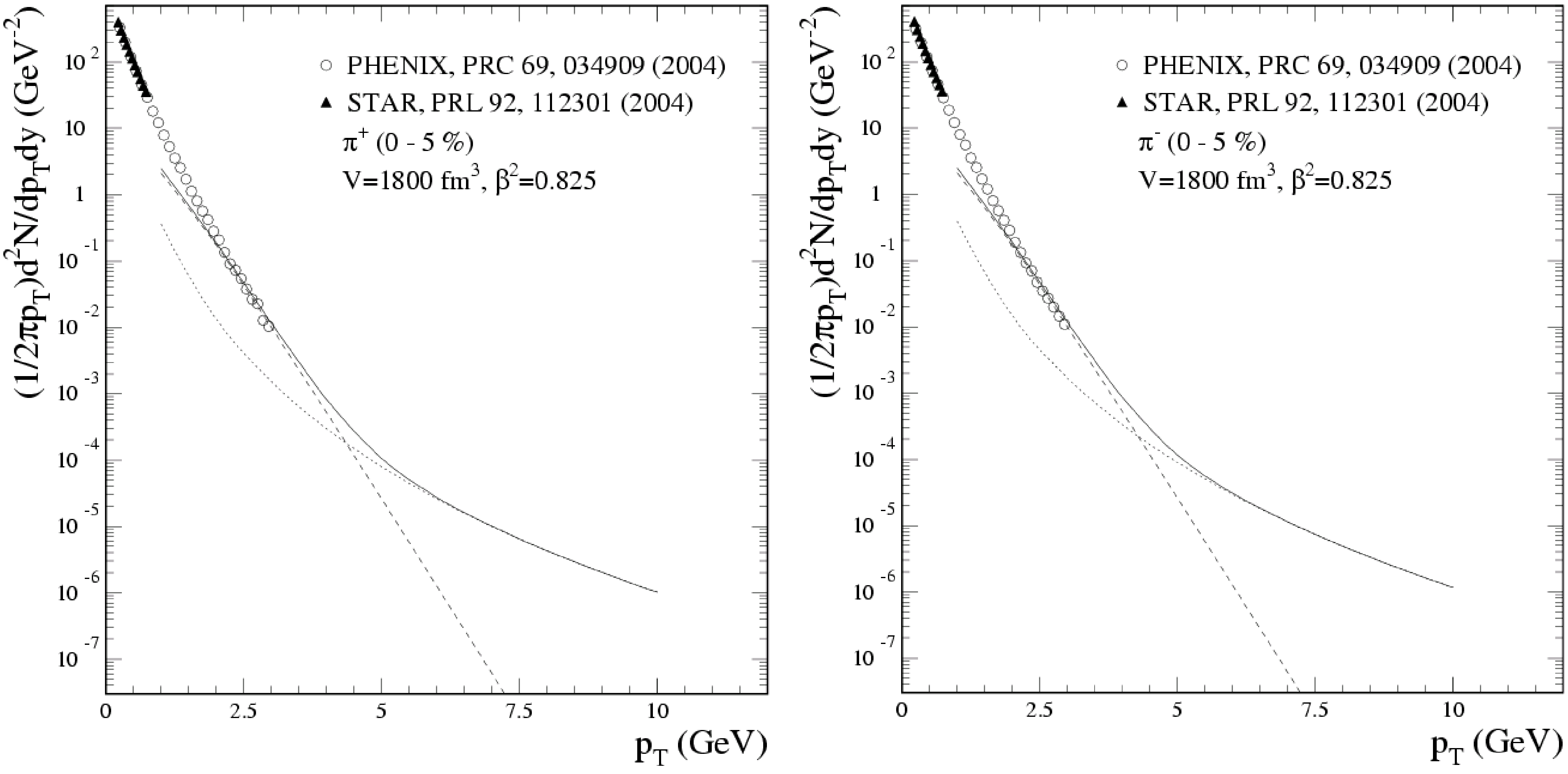
Numerical Results

1. Single Particle Spectra
2. Particle Ratios
3. Nuclear Modification Factor R_{cp}
4. Wave Function Dependence
   - Gaussian vs. Power Law
5. Prediction for D-meson Production at RHIC and LHC

Comparison of Single Spectra



Comparison of Single Spectra



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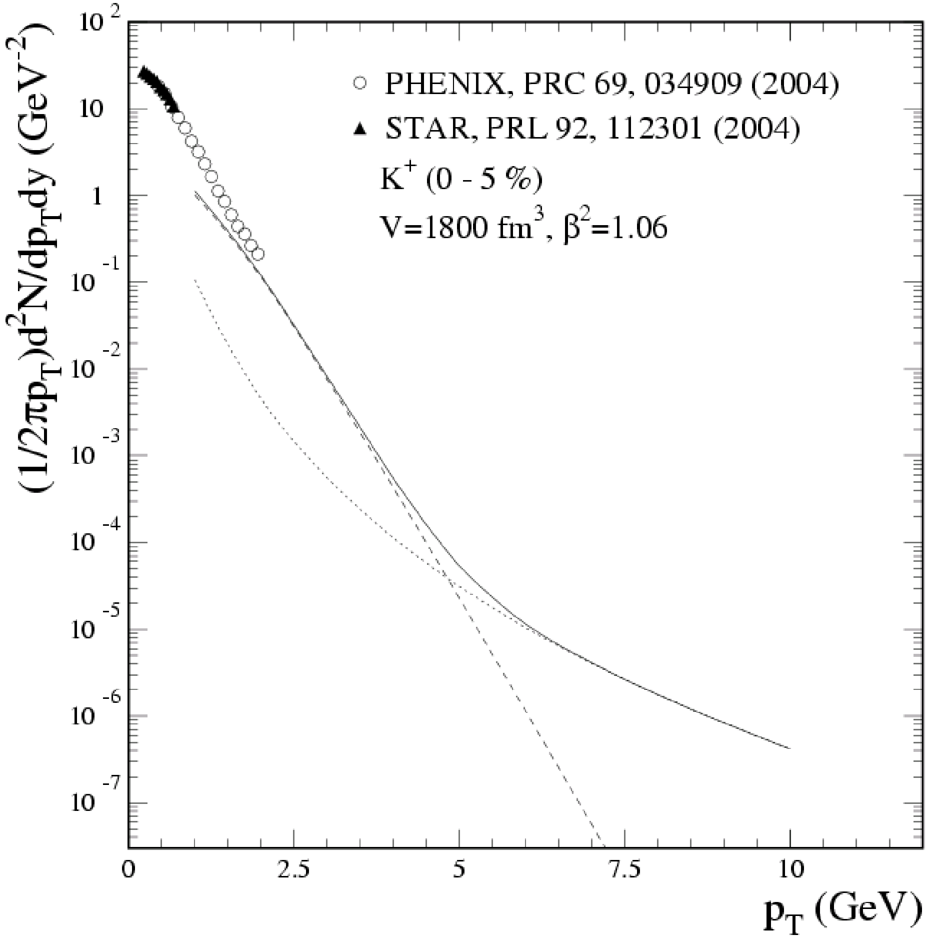

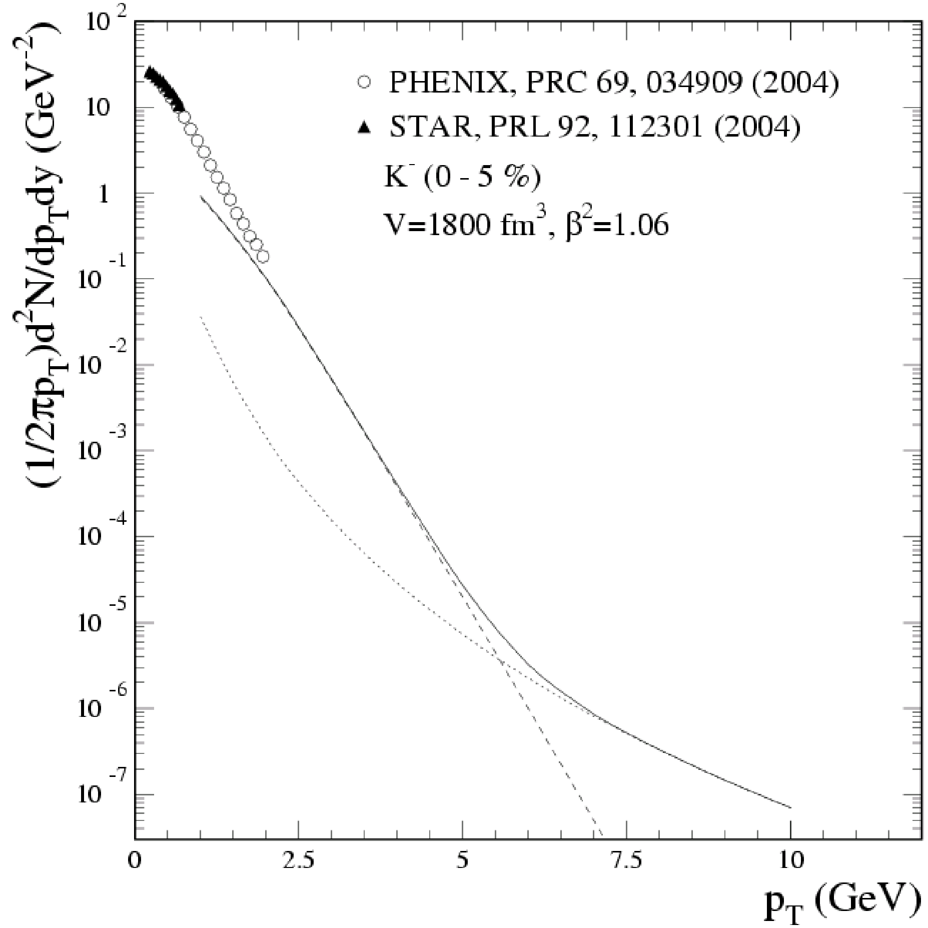

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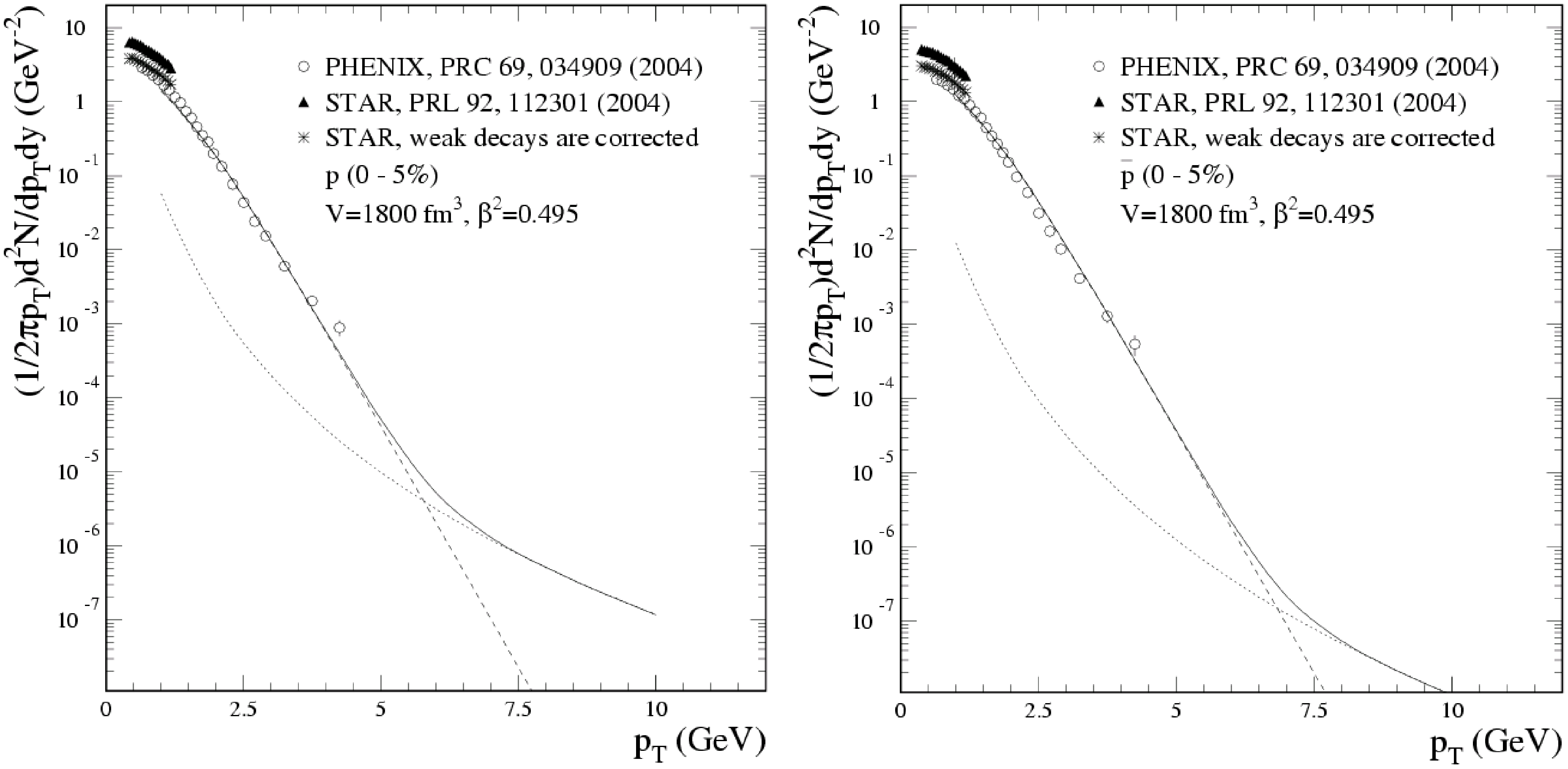

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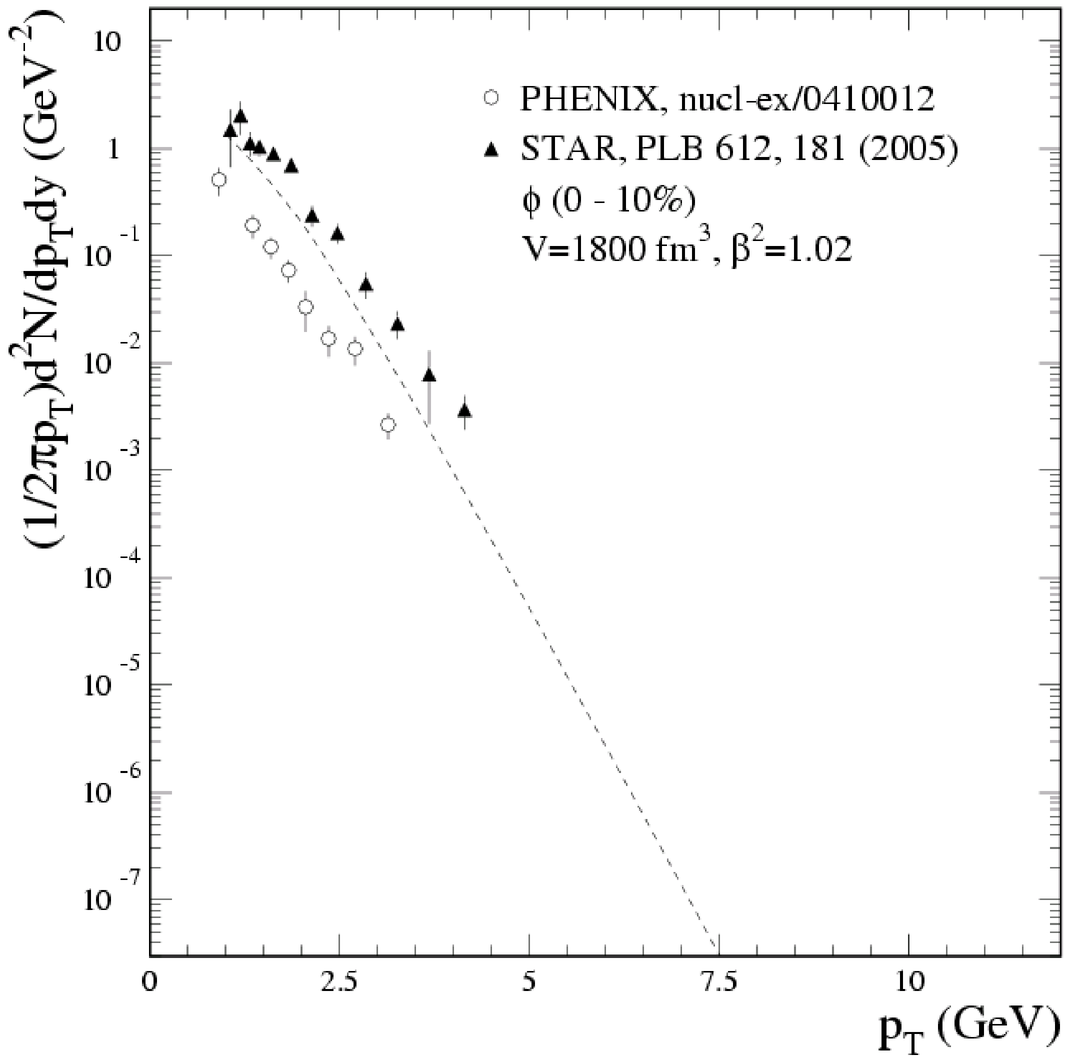

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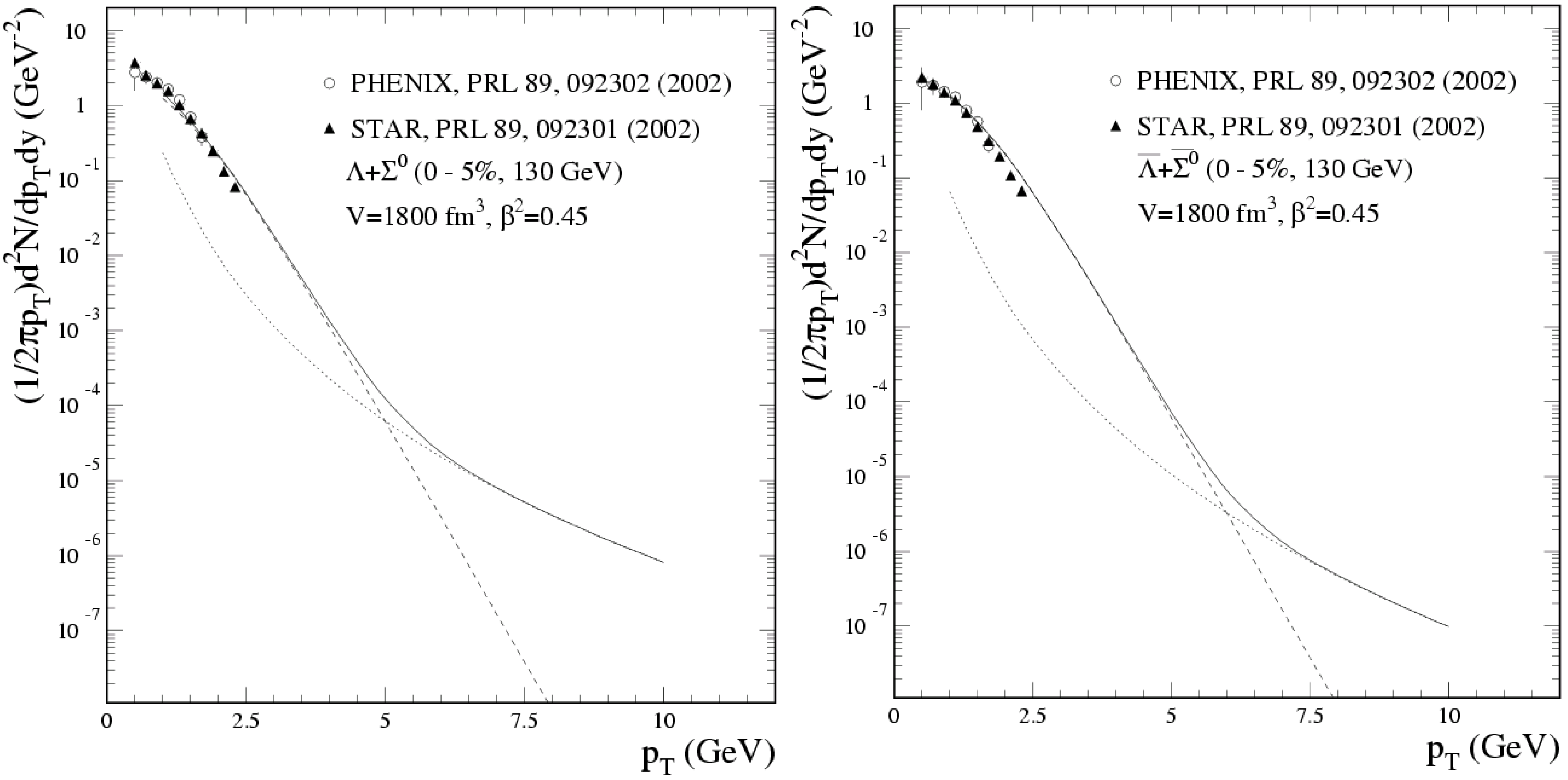

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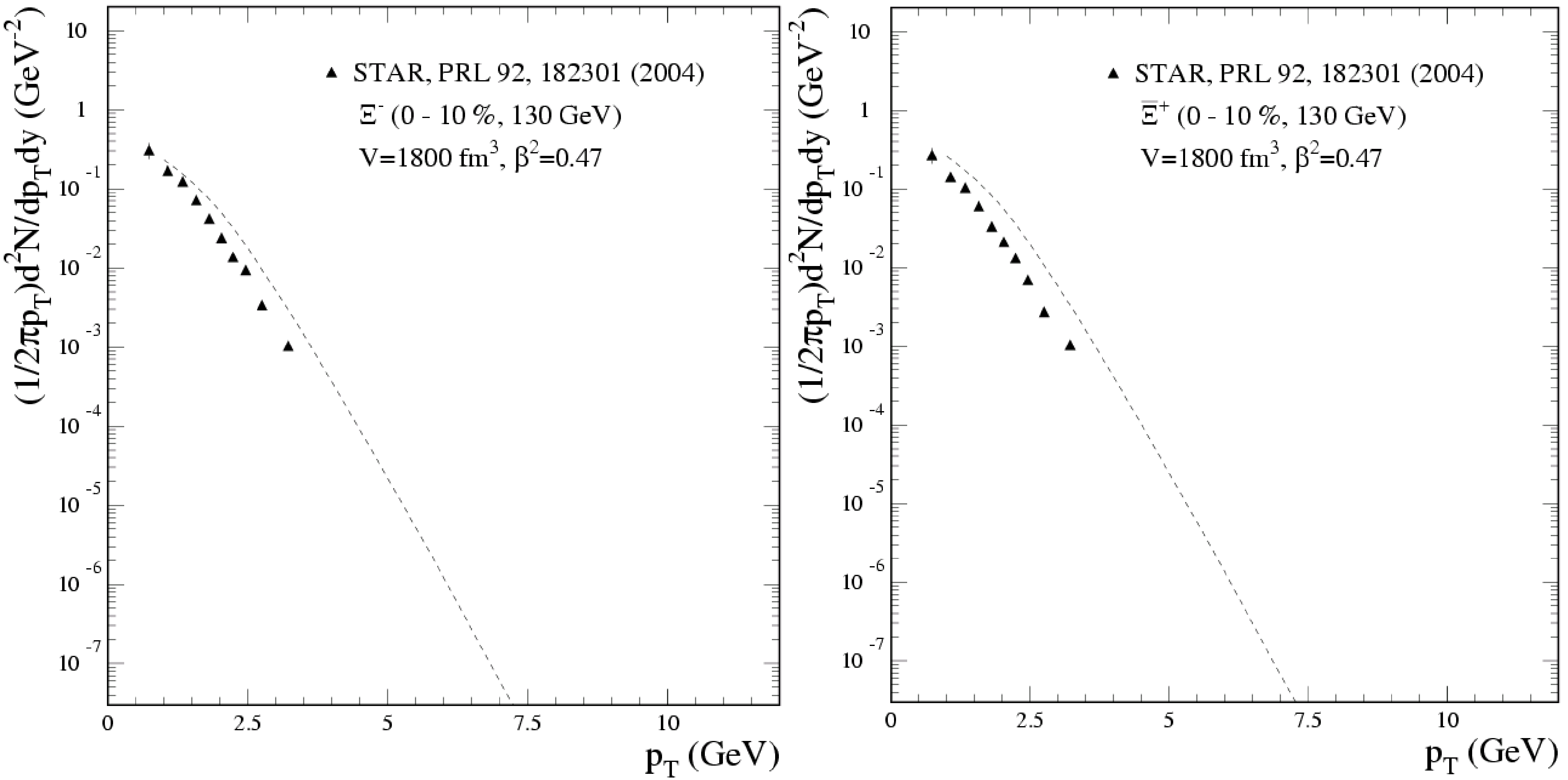

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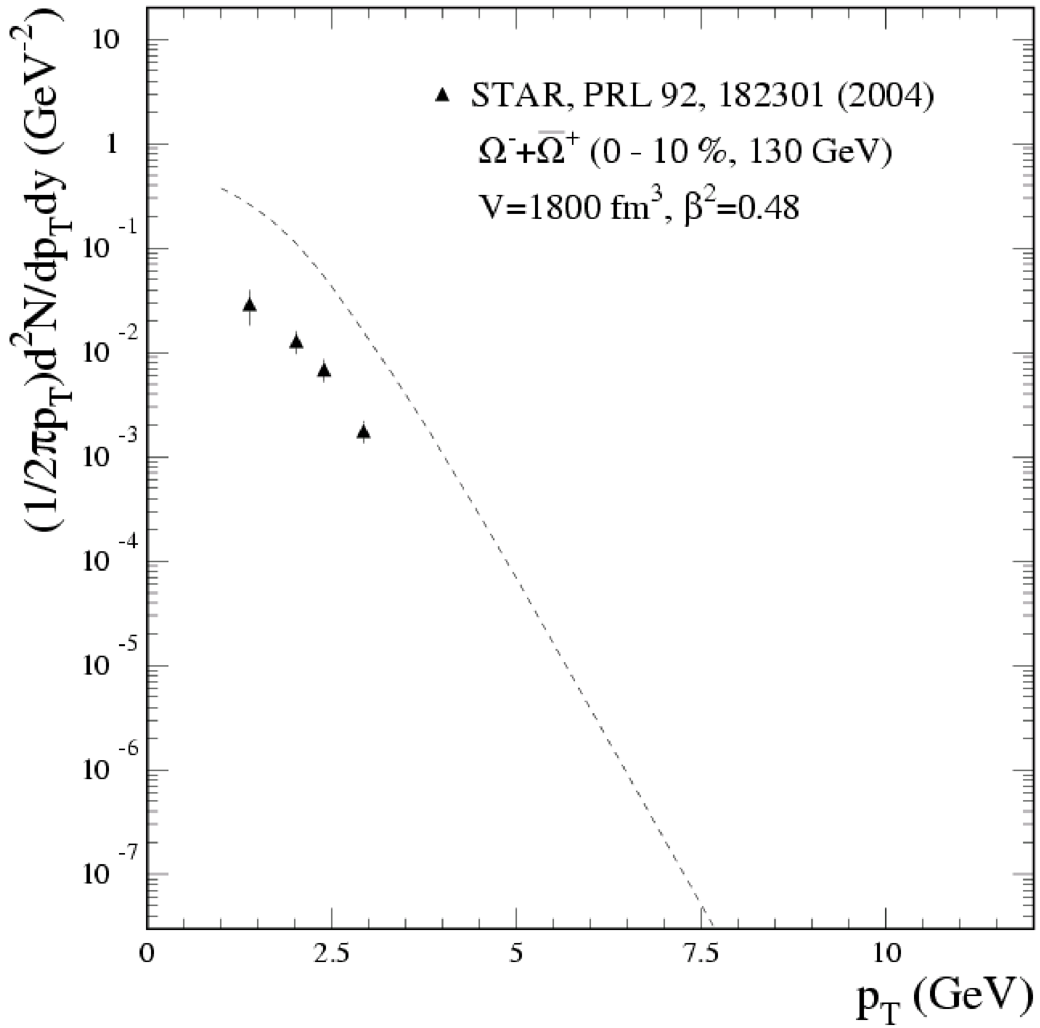
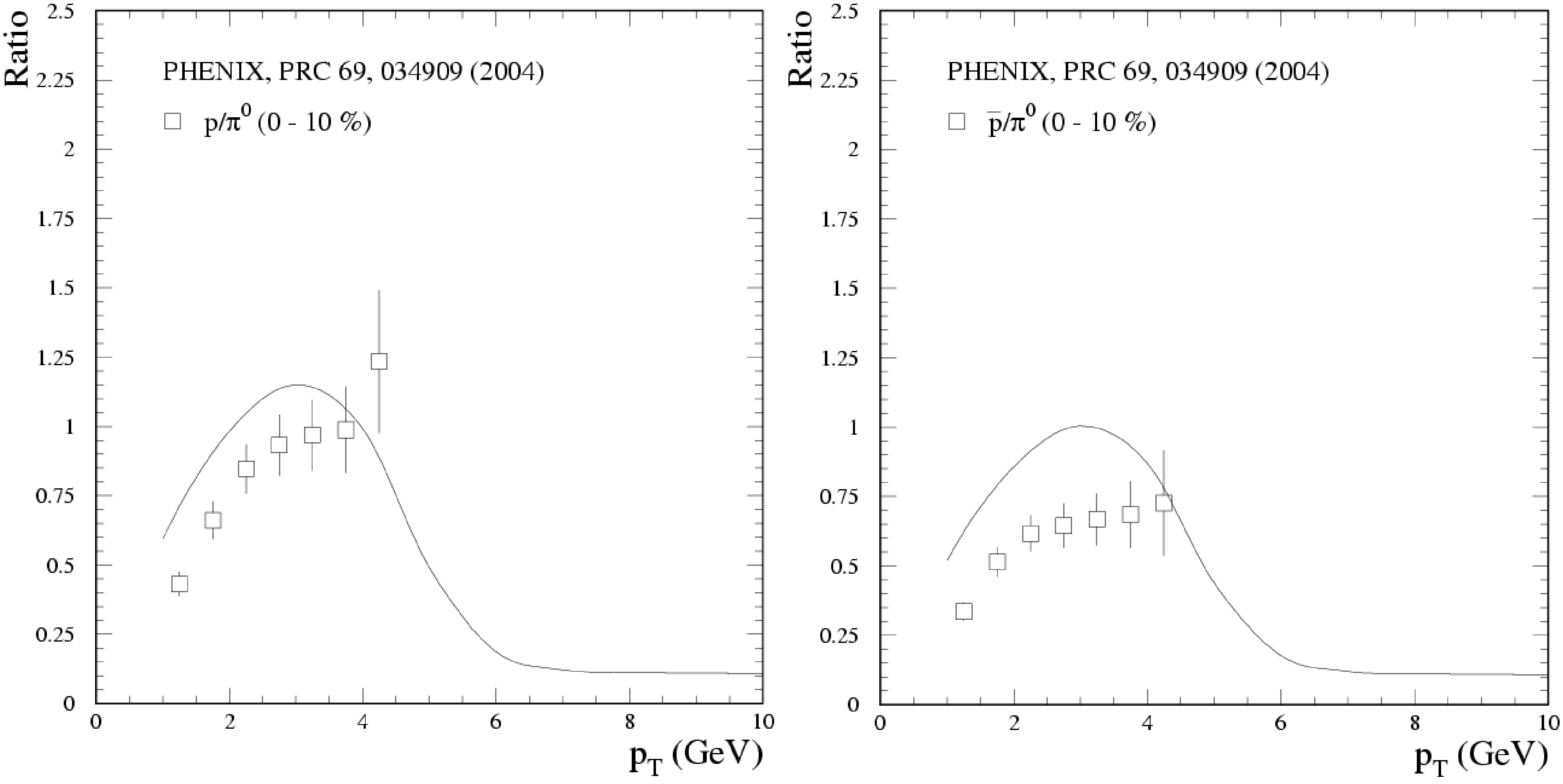


Comparison of Particle Ratios



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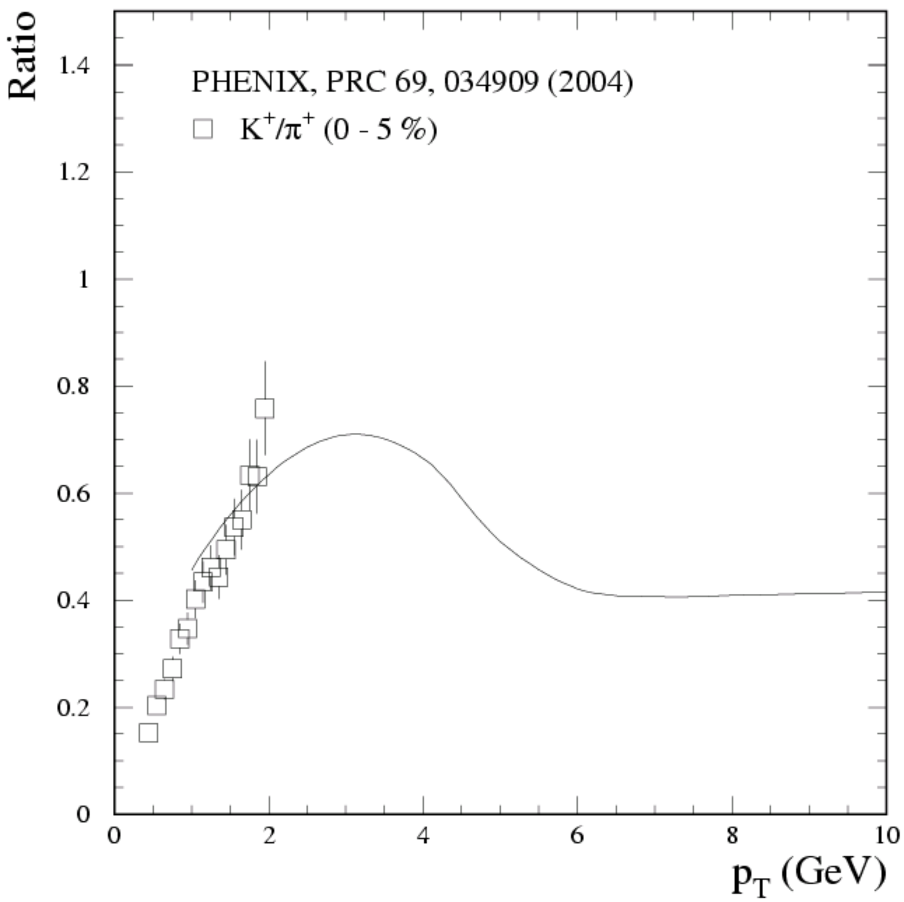

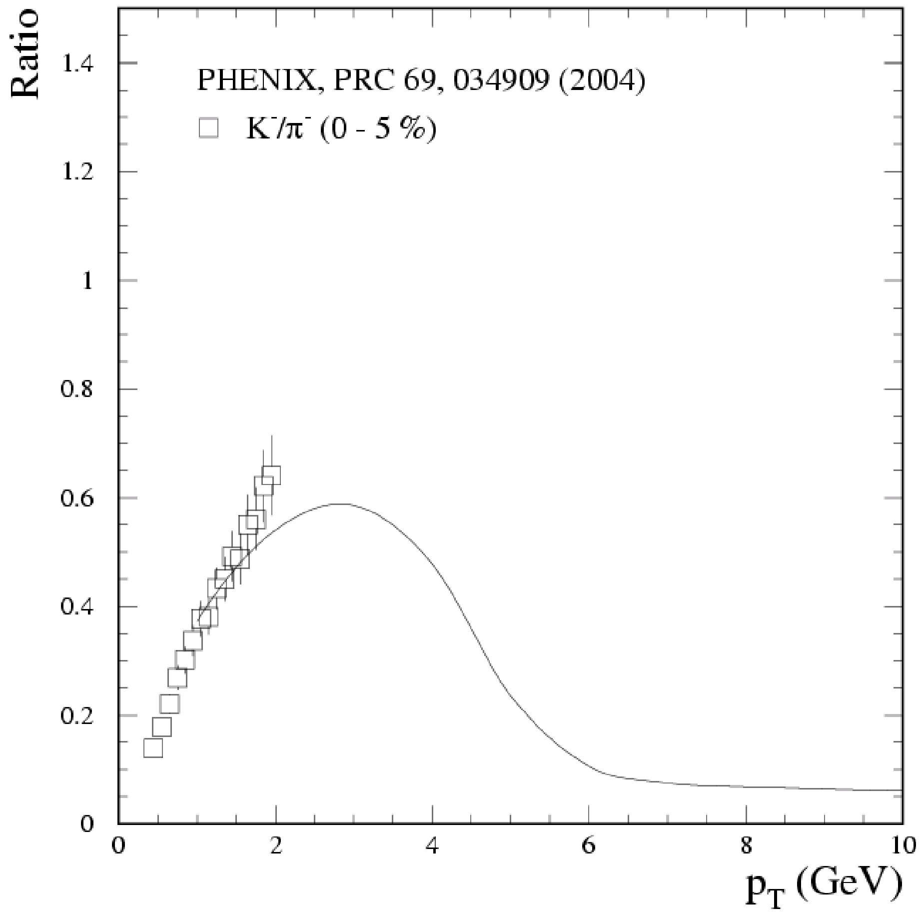

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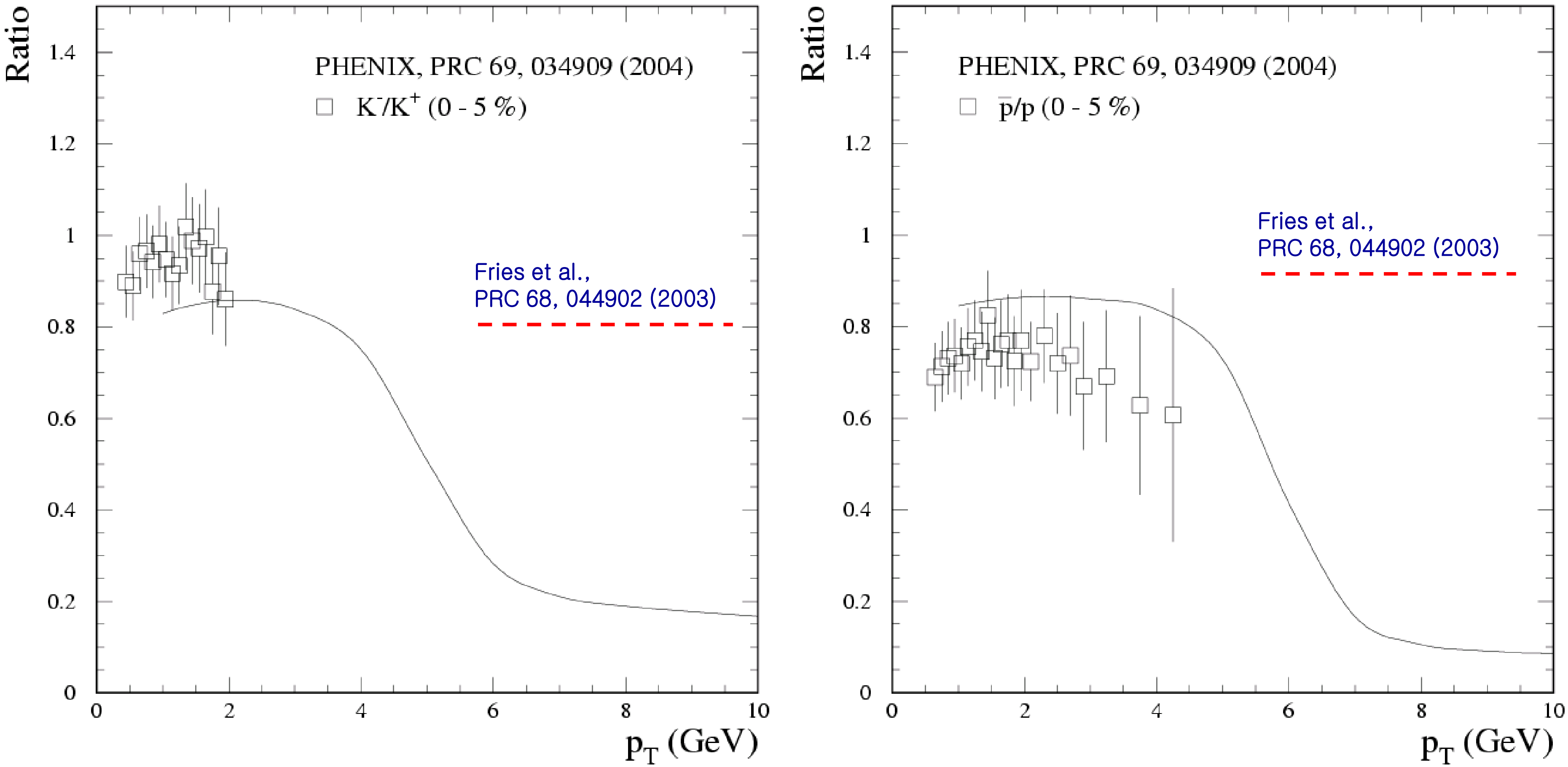
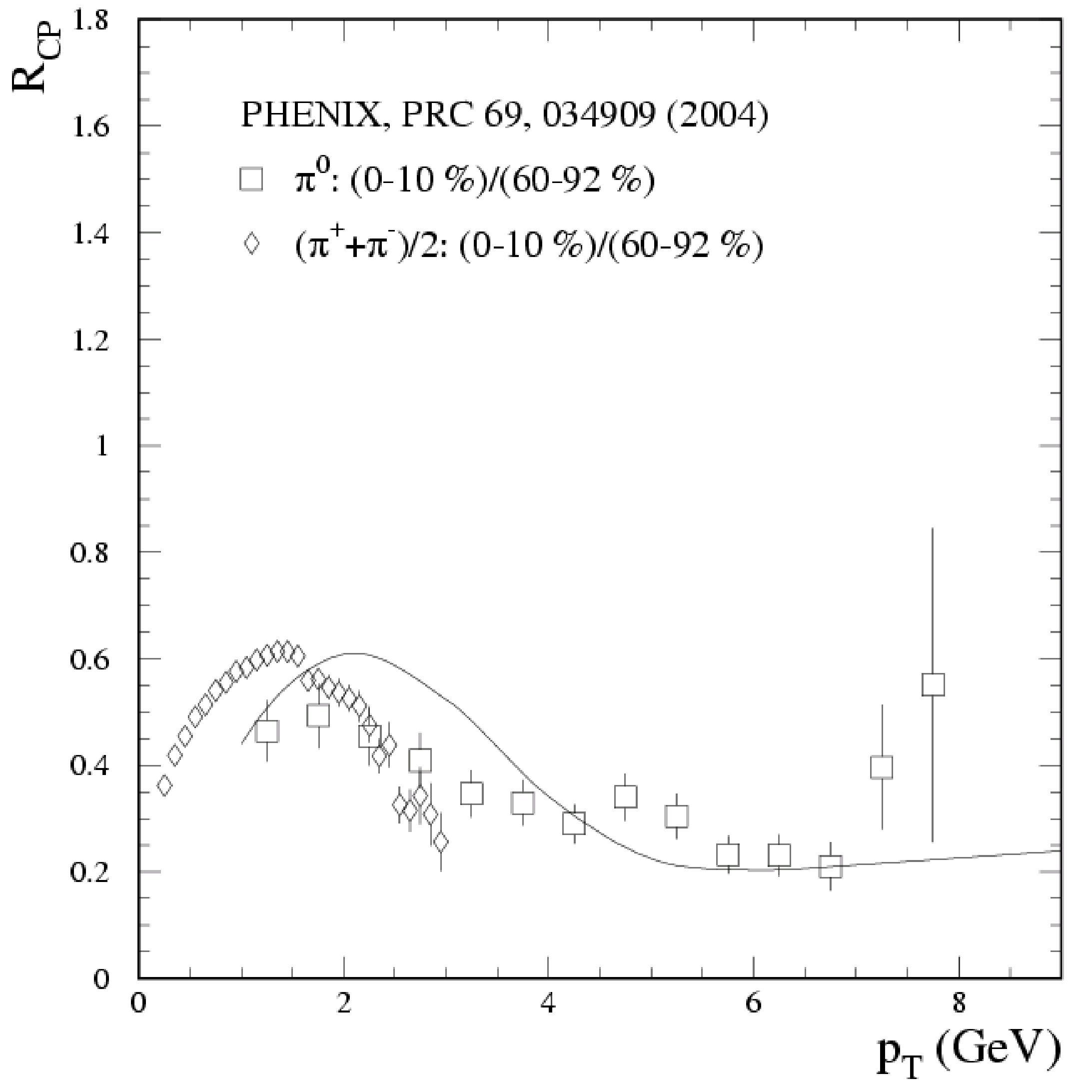


Comparison of Nuclear Modification



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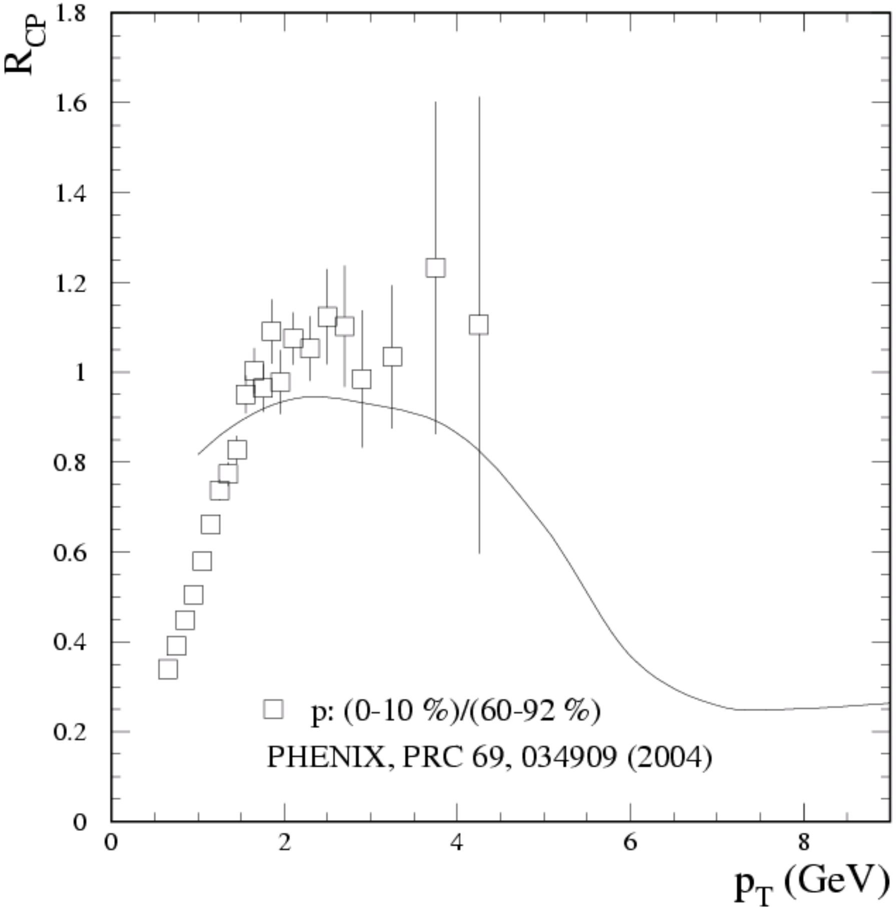
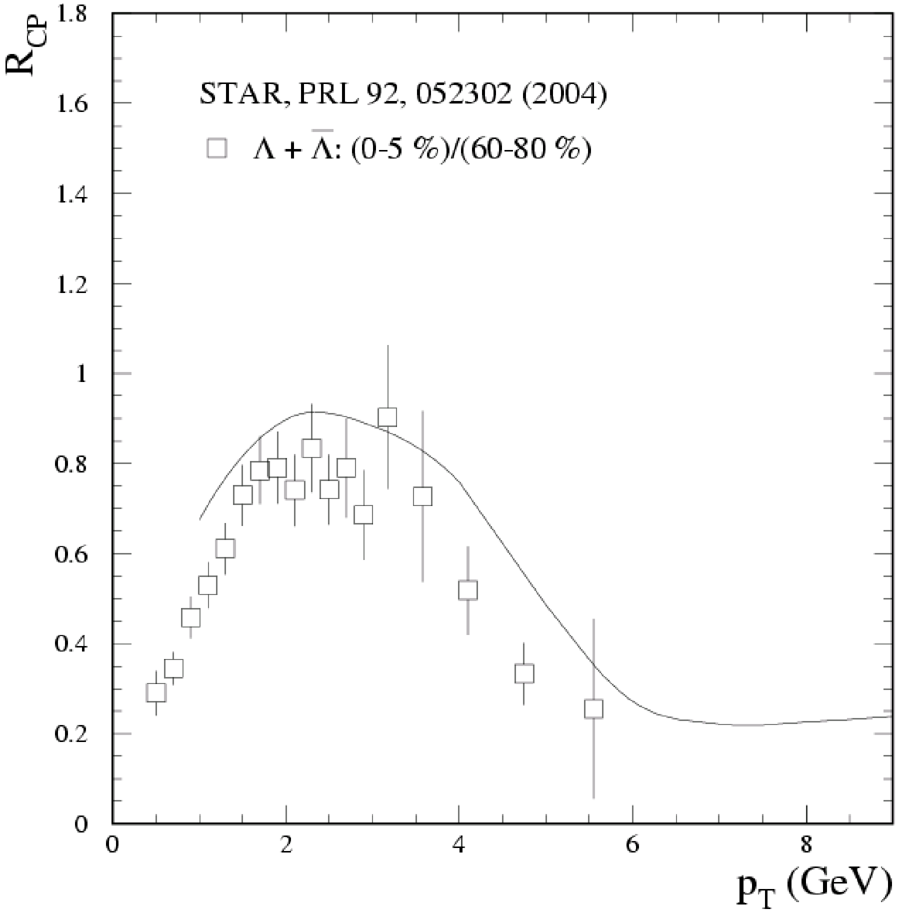
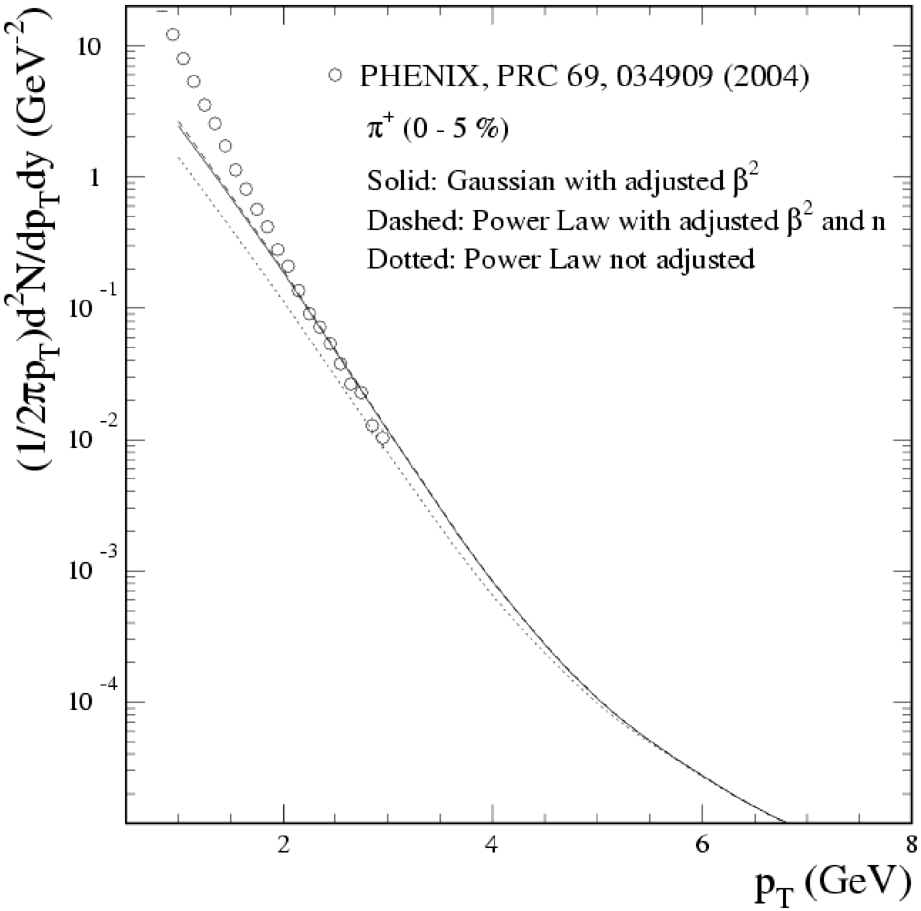
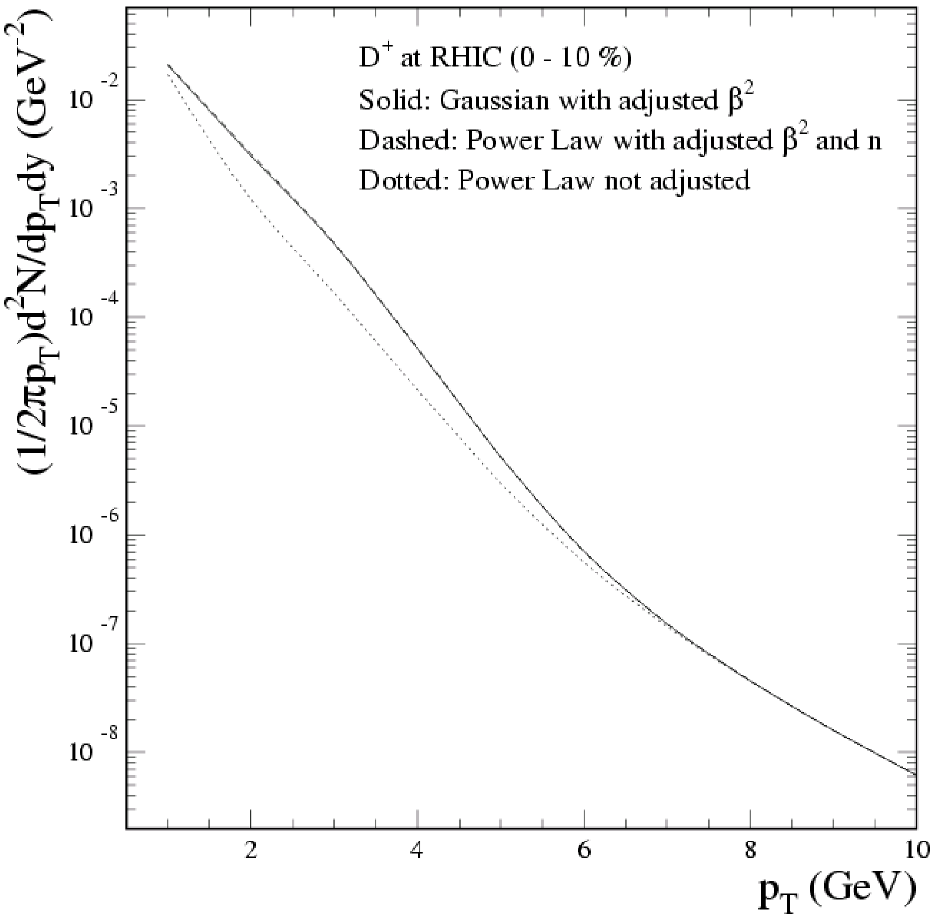




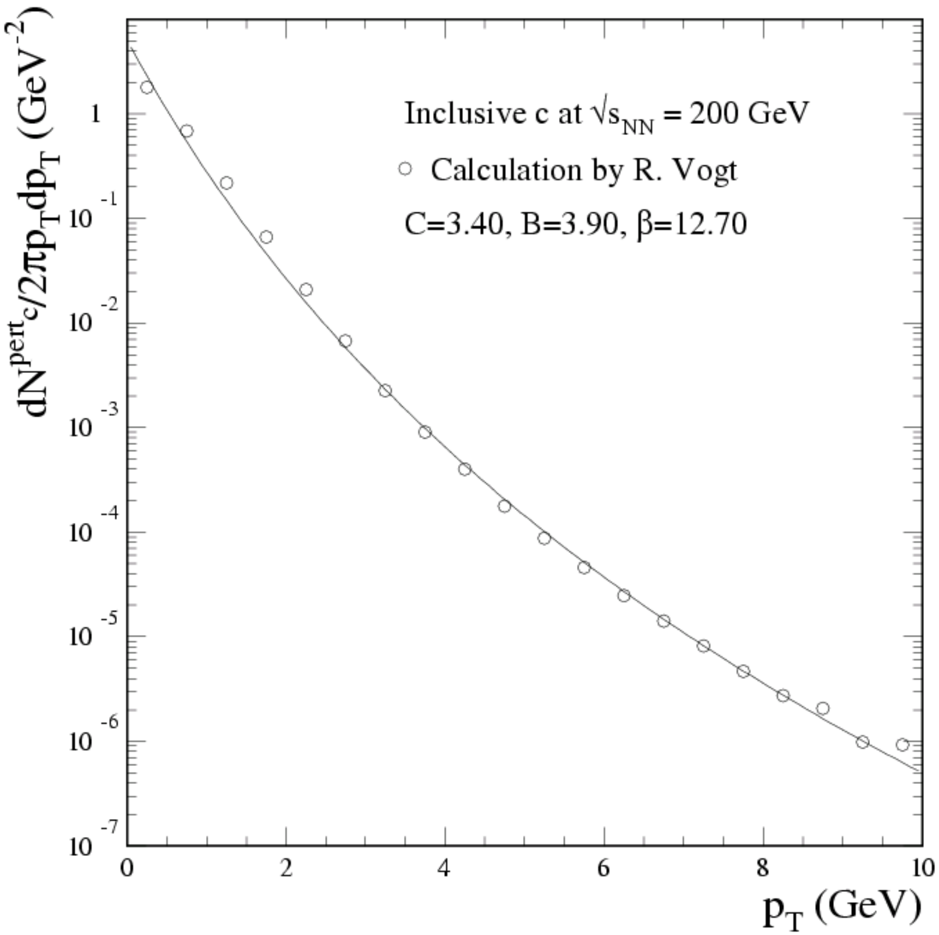
Gaussian vs. Power Law

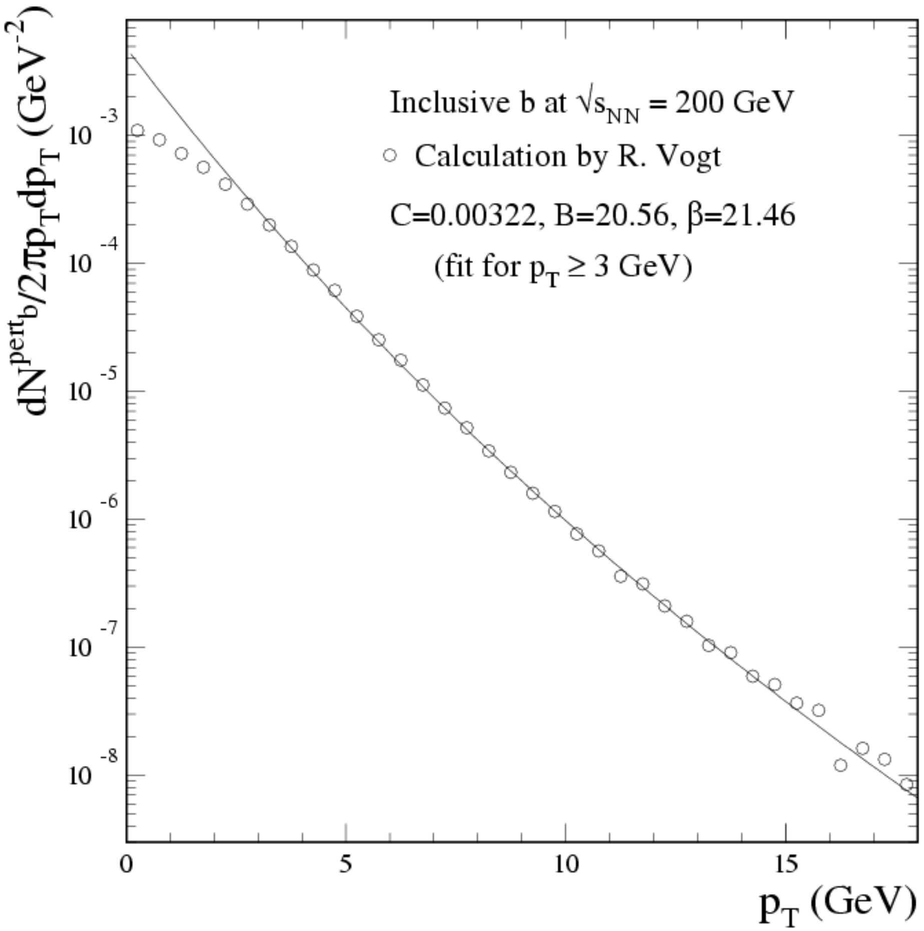




Heavy Quark Distribution Function

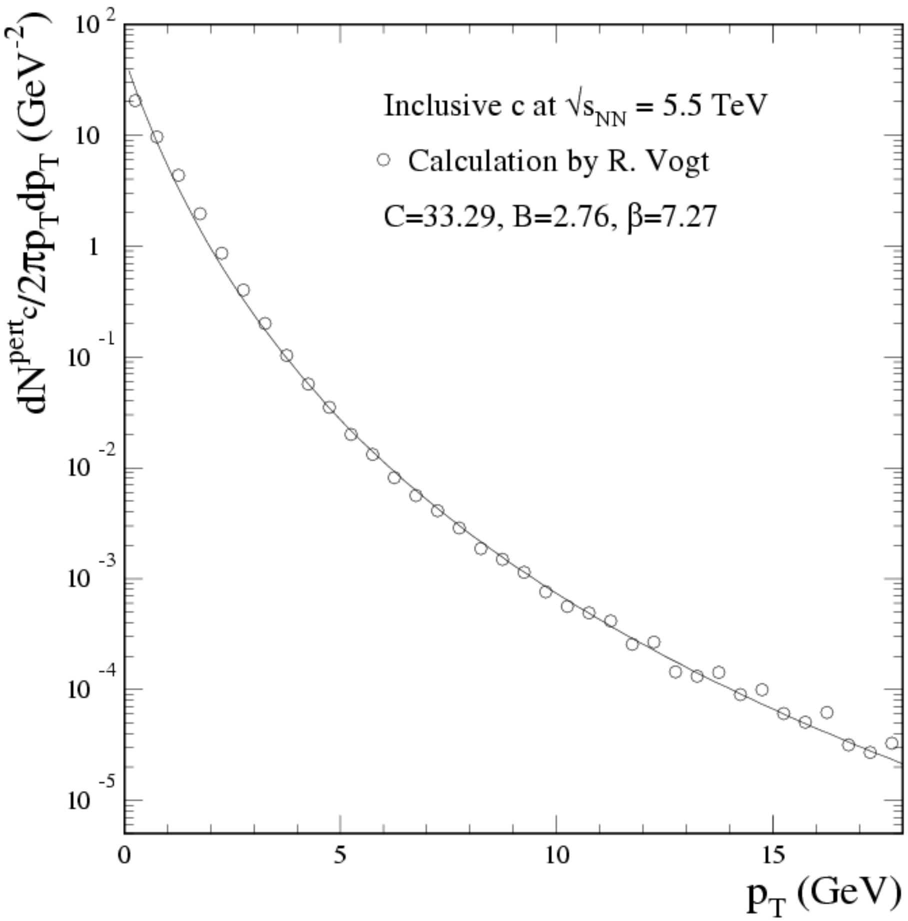
RHIC

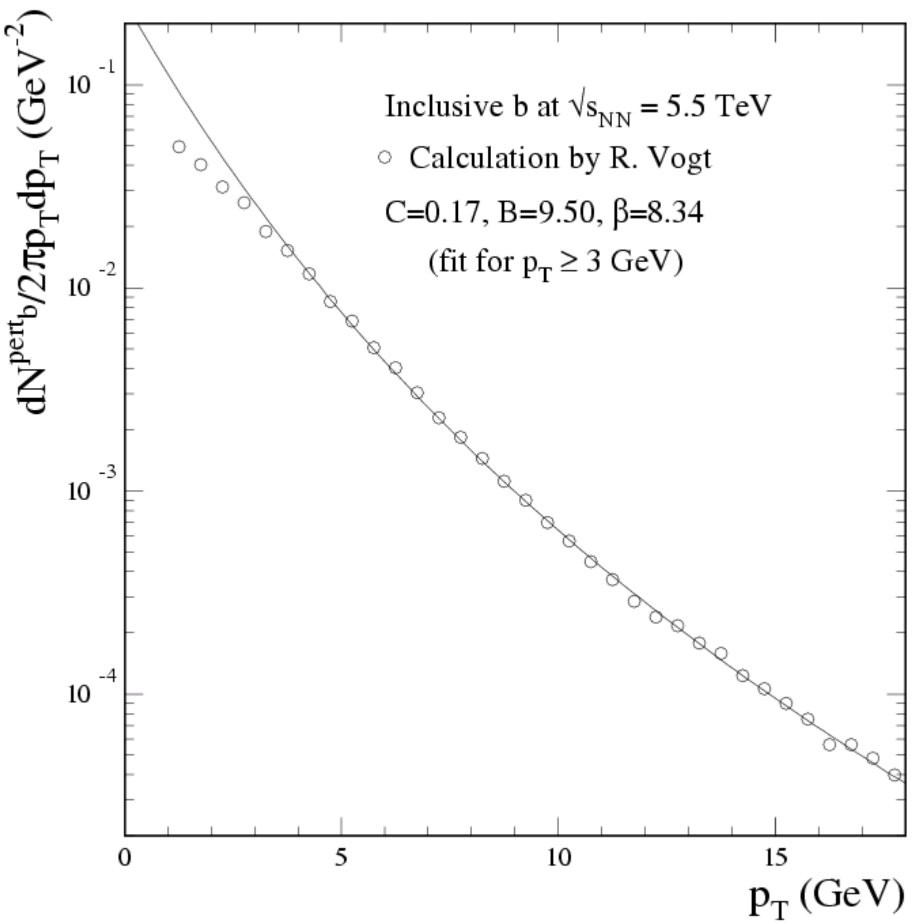




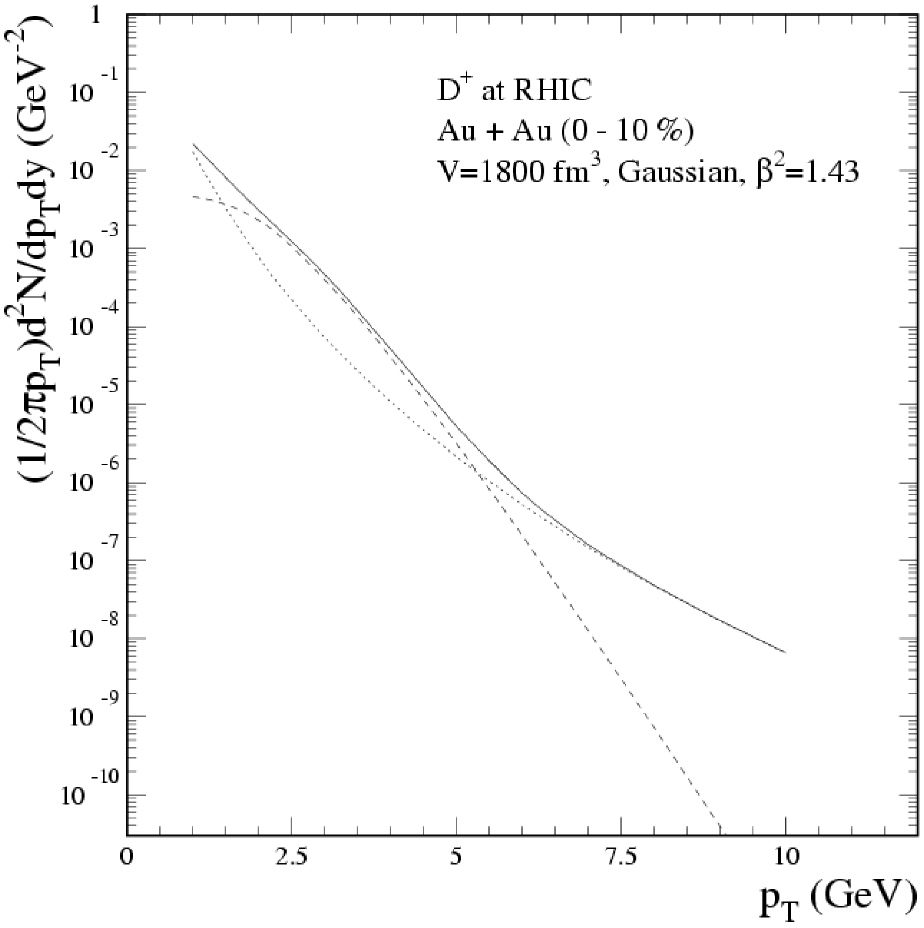
Heavy Quark Distribution Function

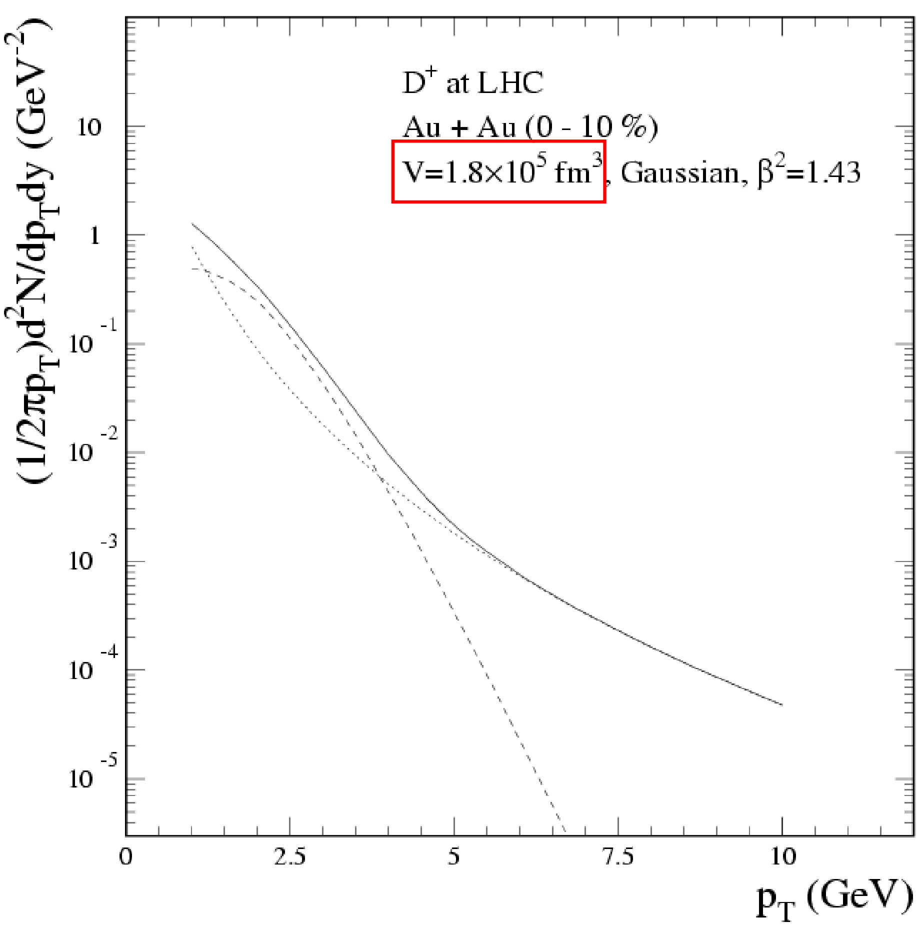
LHC





Prediction of D-Meson Spectra



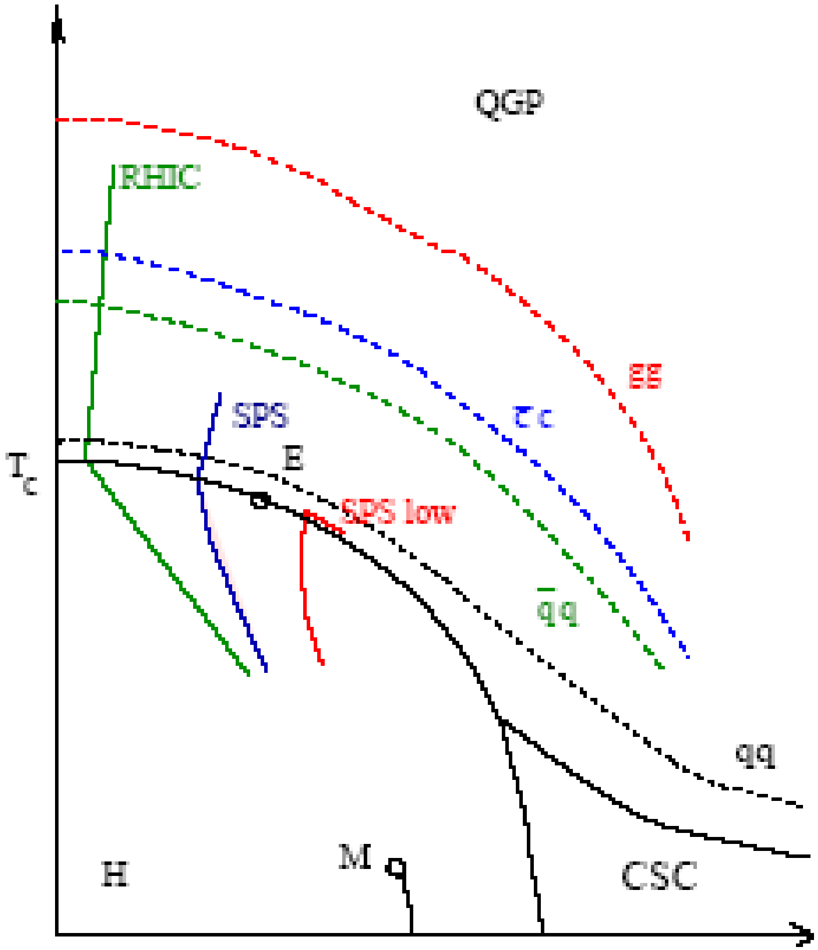


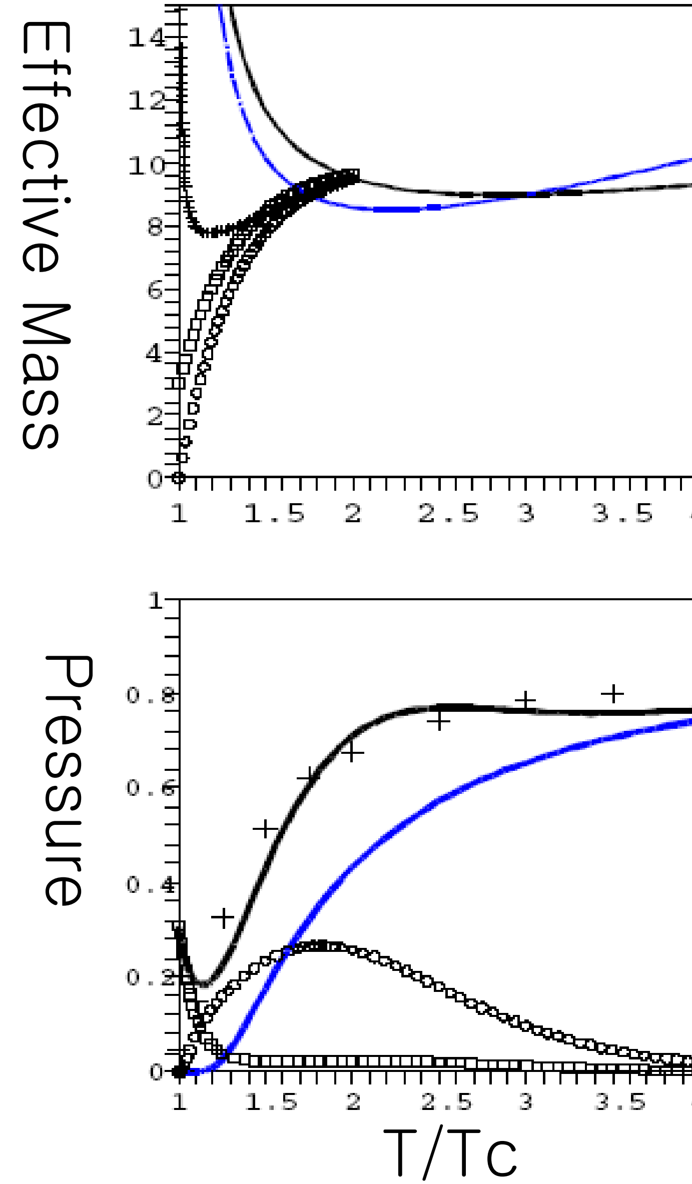
Conclusions and Outlook

- Extended the formulation of the recombination model
  - Intrinsic transverse momentum effect
  - Light-Front wavefunction
    - Gaussian vs. Power Law
- Found the sensitivity of the wavefunction dependence
  - Recombination is favored by the larger size hadrons
- Different results on the yield ratios of K^-/K^+ and pbar/p
  - Jet quenching effect is included
- Our extended formulation may be useful for the analysis of the QGP nature
  - Possible formation of the binary system
  - Crossover between BCS and BEC via Feshbach resonances
- Plan to investigate
  - Heavy hadron production
  - Elliptic flow

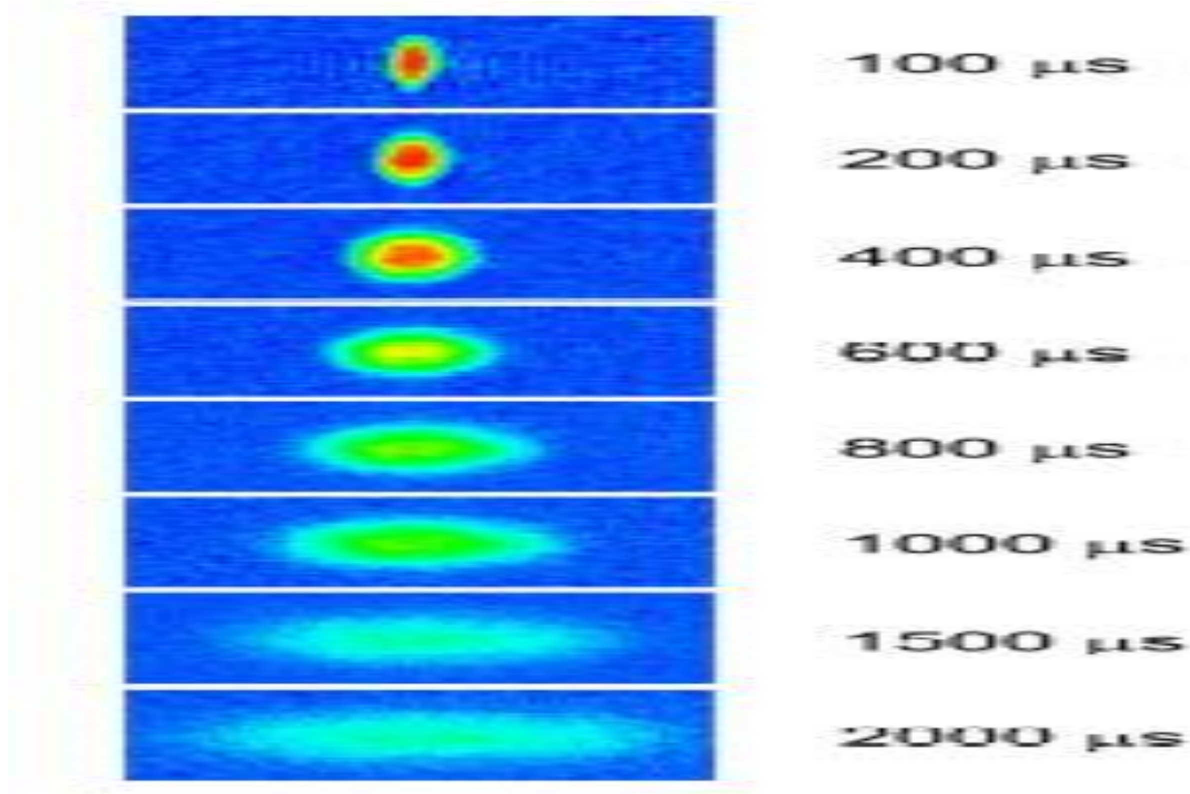
Food for Thoughts: Binary Bound States in QGP

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
SPS
c̄c
E
SPS low
T_c
q̄q
qq
H
M
CSC


Effective Mass
Pressure
T/Tc

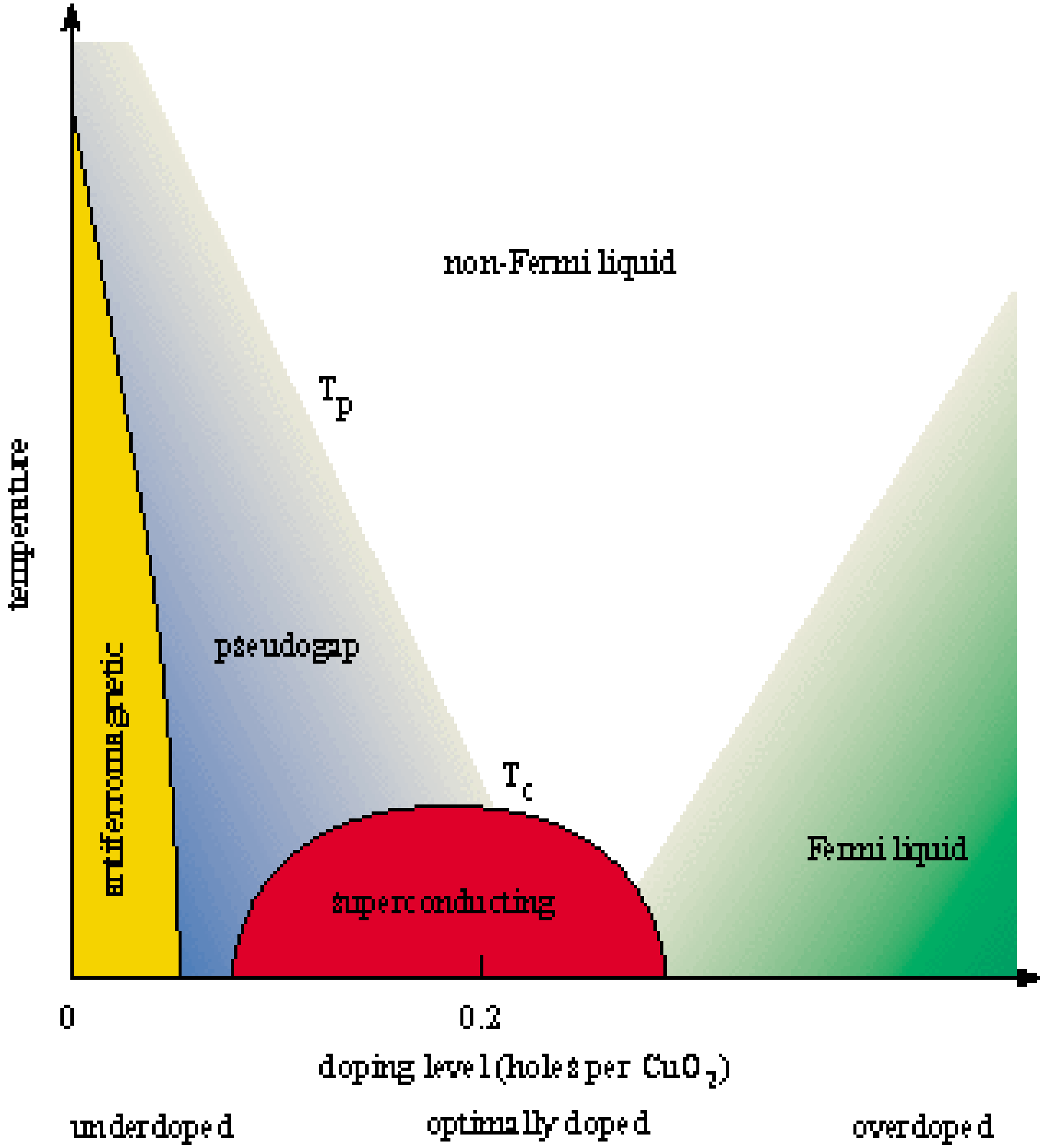
Bose-Einstein Condensation



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.