

# Probing the Phases of QCD in Ultra-relativistic Nuclear Collisions

**Ivan Vitev**



**DPF 2004, August 26 - August 31, 2004**  
**Riverside, California, USA**

- ▶ The QCD phase transition:
  - QCD is the only theory that invites “easy” phase transitions on a fundamental level
  
- ▶ Observables in heavy ion collisions:

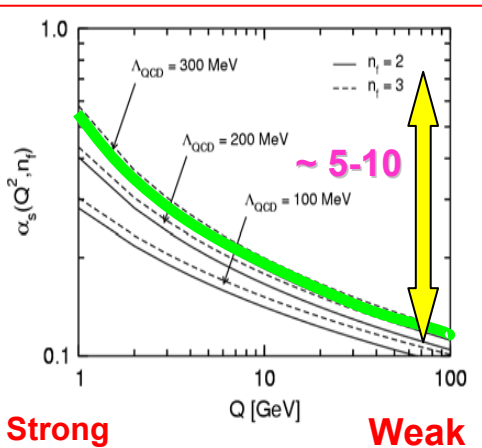
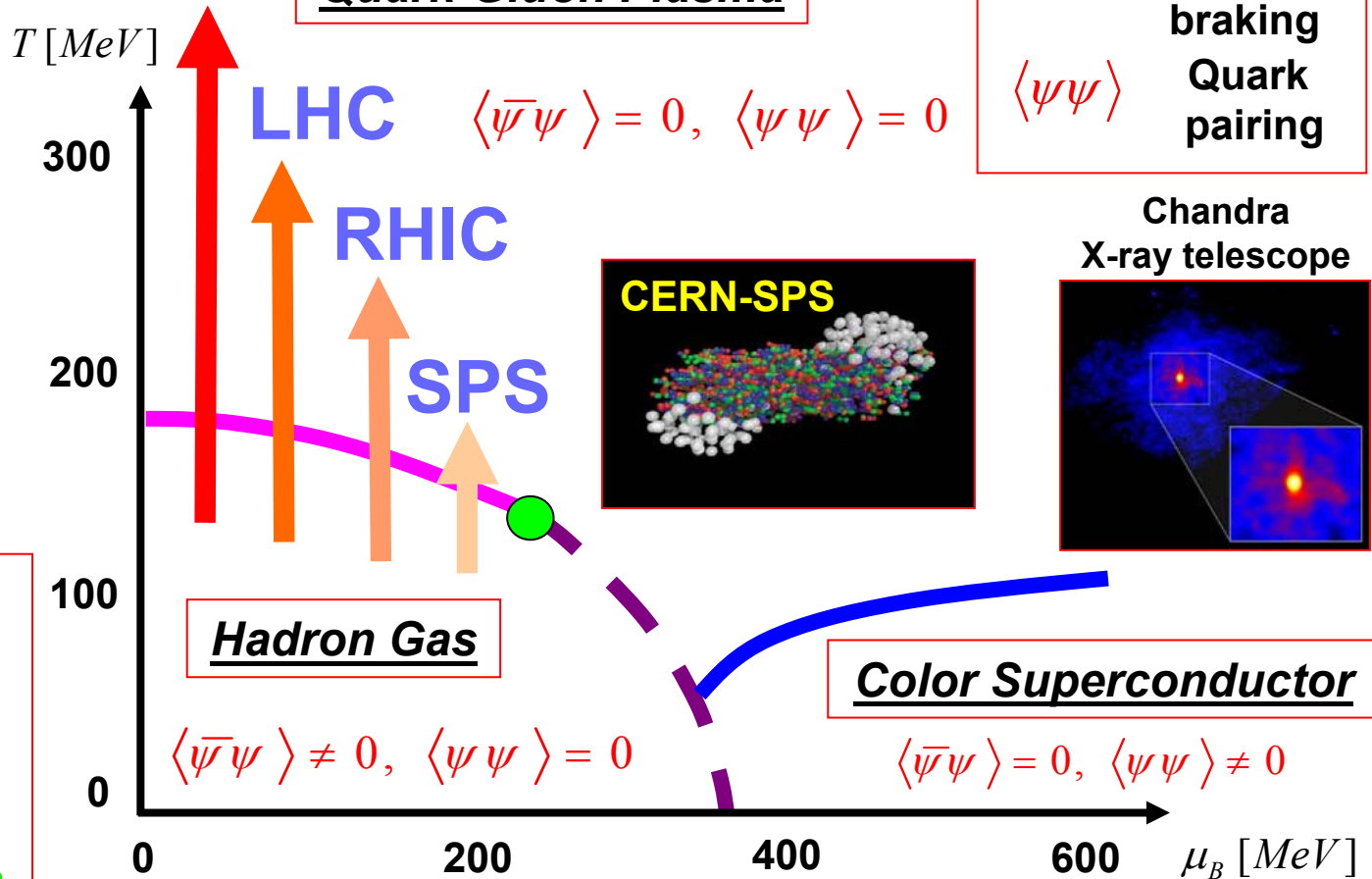
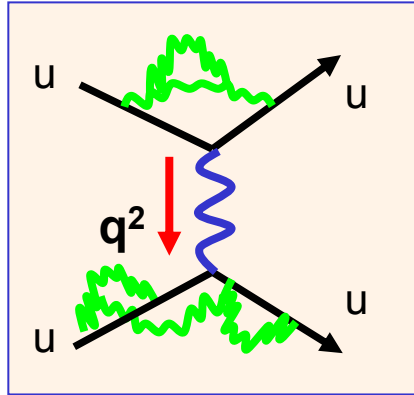
The field of URHIC is generator of novel and exciting physics ideas and possibilities

  - Statistical models and thermodynamic temperature
  - Hydrodynamic models, spectra and elliptic flow
  - Parton saturation models as initial conditions
  - Coalescence models, baryon enhancement and  $v_2$  scaling
  - Charm and charmonium production and shadowing
  - Dynamical parton mass and nuclear power corrections
  - Jet quenching and jet tomography at all HIC energies
  - Jet structure, hadron correlations and tagged jets
  - Comparison to lattice results and recent highlights
  
- ▶ Conclusions:

# The Phase Diagram of QCD



## Big Bang



T.D.Lee, C.G.Wick, Phys.Rev.D 9 (1974)

M.Stephanov, K.Rajagopal, E.Shuryak, Phys.Rev.Lett. 81 (1998)

# Thermodynamic T



- Does the system allow a thermodynamic description?

$$n_i(T, \mu) = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i - \mu_i B_i - \mu_s S_i)/T} \pm 1}$$

Fermions (+)

Bosons (-)

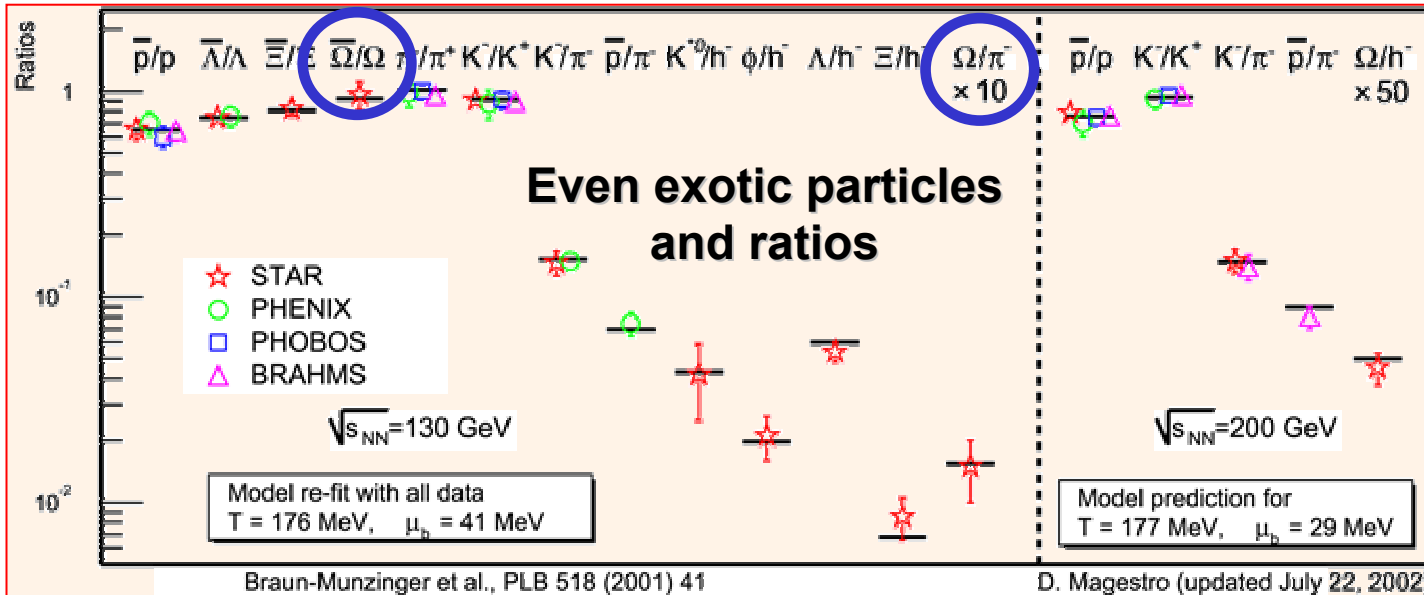


E. Fermi



S. Bose

- Excellent description of particle ratios, Temperature not incompatible with Lattice QCD



$$\bar{p}/p \sim e^{-2\mu/T}$$

$$\pi^+/p \sim \frac{e^{-E_\pi/T}}{e^{-(E_p - \mu)/T}}$$

Determine  $\mu, T$

$T_f = 175 \text{ MeV}$

# $P_T$ - Fluctuations and Thermalization



S.Gavin, Phys.Rev.Lett.92, (2004)

Go beyond the thermal mean  $p_T$  values

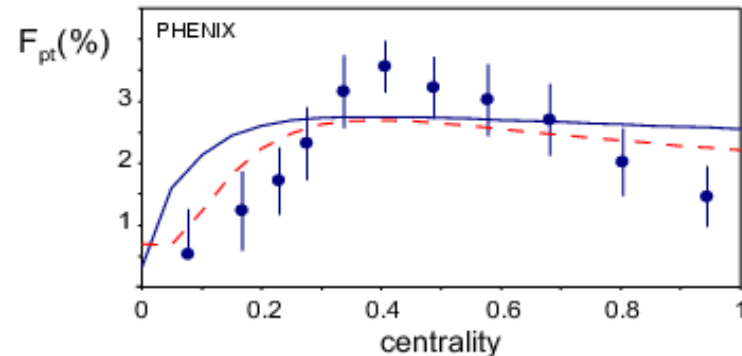
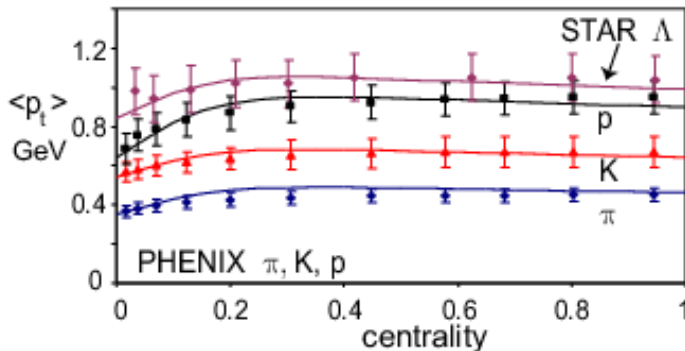
$$r(\mathbf{p}_1, \mathbf{p}_2) = N(\mathbf{p}_1, \mathbf{p}_2) - N(\mathbf{p}_1)N(\mathbf{p}_2)$$

Fluctuations:  $\delta p_{ti} = p_{ti} - \langle p_t \rangle$

Two body correlation  
function

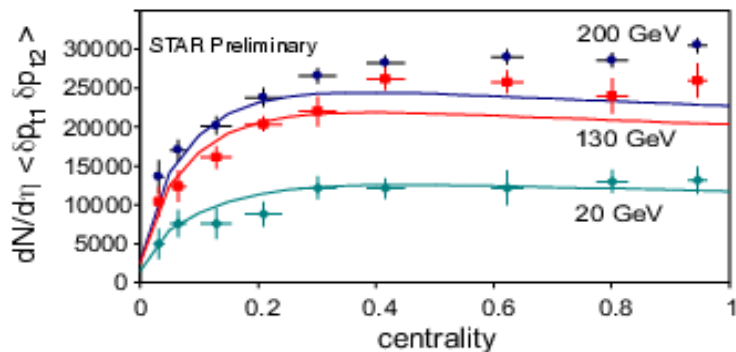
STAR measure:  $\langle \delta p_{t1} \delta p_{t2} \rangle = \int d\mathbf{p}_1 d\mathbf{p}_2 \frac{r(\mathbf{p}_1, \mathbf{p}_2)}{\langle N(N-1) \rangle} \delta p_{t1} \delta p_{t2}$ ,

PHENIX measure:  $F_{pt} \approx N \langle \delta p_{t1} \delta p_{t2} \rangle / 2\sigma^2$



S.Gavin, J.Phys.G30, (2004)

- Given the fits to the mean  $p_T$  one can try and predict the fluctuations
- Not incompatible even at  $\sqrt{s} = 20 \text{ GeV}$



Will learn more from **Mohamed Abdel-Aziz**

$$\partial_\mu T^{\mu\nu}(x) = 0$$

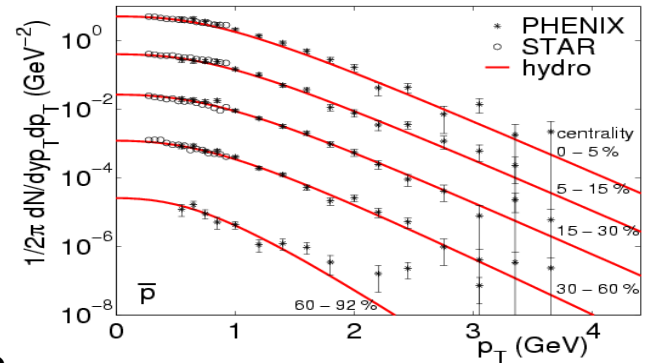
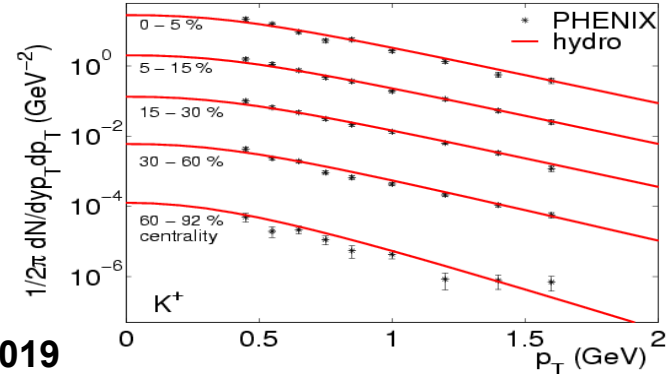
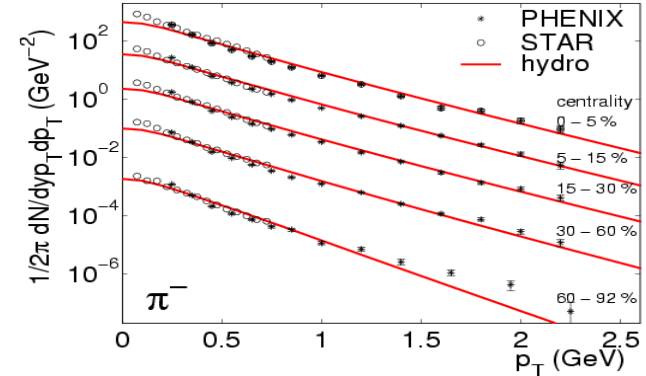
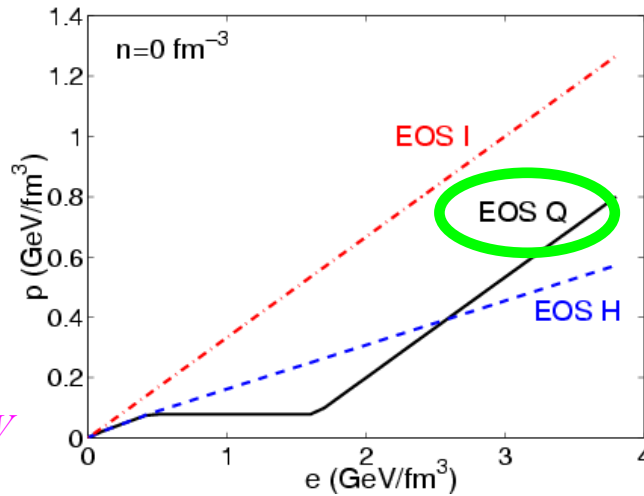
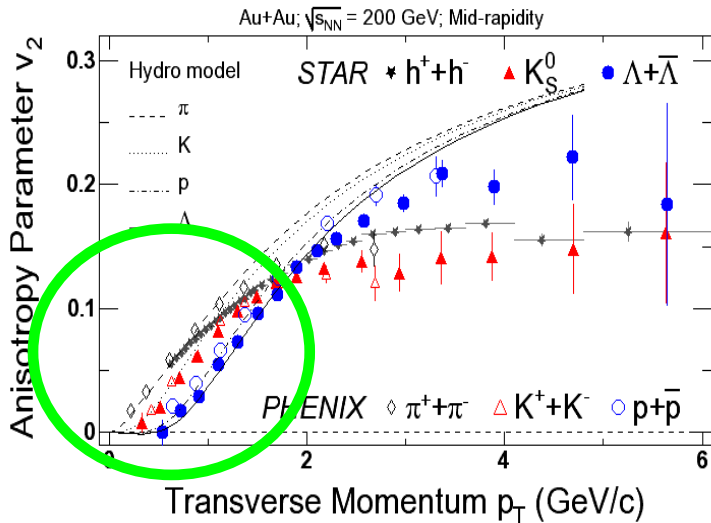
$$\partial_\mu j_\alpha^\mu(x) = 0$$

Get to the EOS

Latent heat:  $\Delta\varepsilon \approx 1 \text{ GeV}$

- Good fits are provided to the spectra but the elliptic flow is more sensitive

$$\frac{dN^h}{dyd^2 p_T d\phi} = \frac{1}{2\pi} \frac{dN^h}{dyd^2 p_T} (1 + 2v_2(\cos 2\phi) + \dots)$$



R.Snellings, nucl-ex/0310019

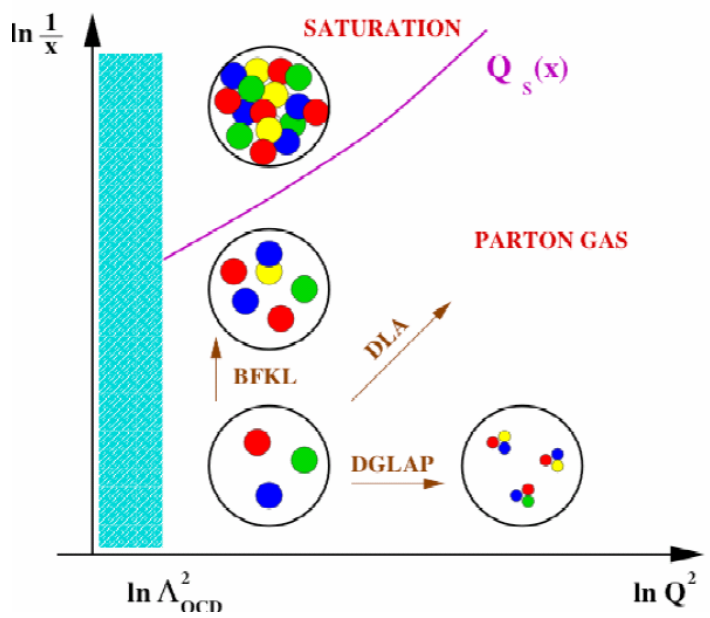
Will learn more from  
Paul Sorensen

To 5 GeV at the LHC?

U.Heinz, P.Kolb, nucl-th/0204061

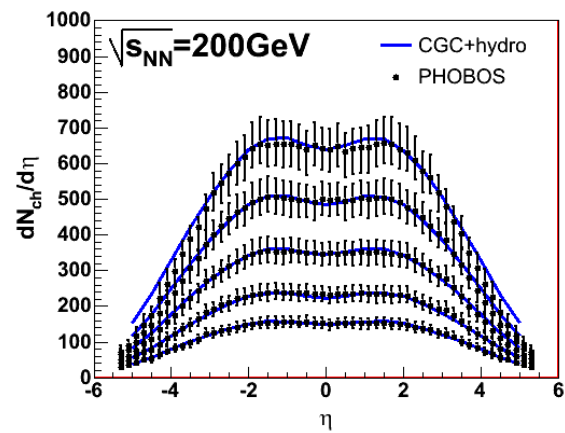
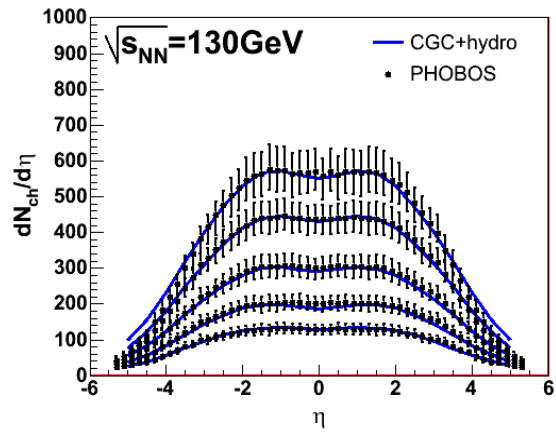
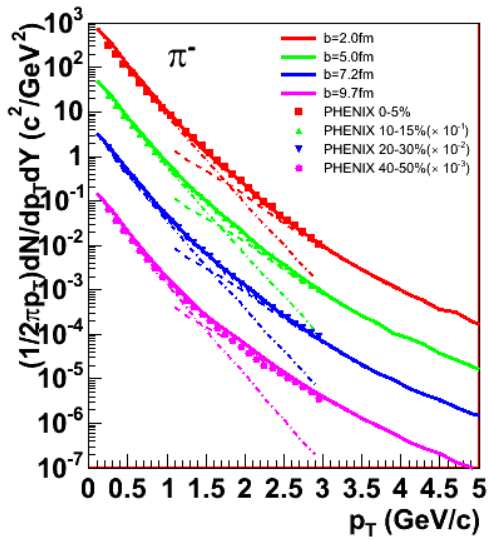
Ivan Vitev, LANL

# Possible Initial Conditions



- If the transverse density of gluons becomes sufficiently high **classical methods** might become applicable
- Has an **incompatibility** with the transverse energy and mean  $p_T$

$$\langle p_T^2 \rangle = Q_s^2, \quad \langle p_T^\pi \rangle = 1-1.5 \text{ GeV}, \quad \frac{dE_T}{dy} = \langle p_T^\pi \rangle \frac{dN}{dy}$$

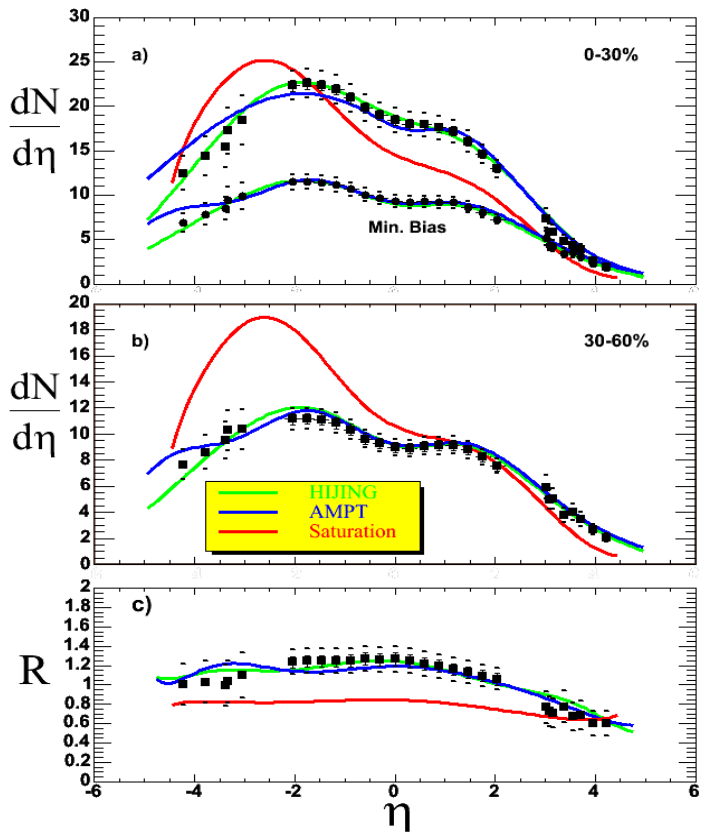


T.Hirano and Y.Nara, nucl-th/0404039

Productive marriage: a) provides motivated initial conditions b) solves the transverse energy problem

Will learn more from **Alexander Krasnitz**

# Transport Models



M.Murray, BRAHMS collaboration, QM 2004

- The same initial conditions do not work in d+A. **Can be improved** but there is no hydro to alleviate the  $E_T$  problem
- Is the gluon shadowing strong?

**Noether's theorem**  $L(x+a) = L(x) \Rightarrow \dot{p}^\mu = 0$

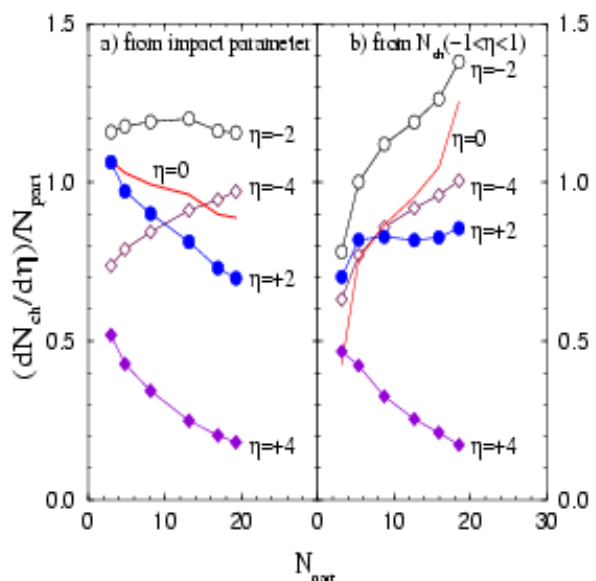
Energy-momentum conservation **dominates** over any exotic dynamics

$$p_1^\mu \partial_\mu f_1 = \iiint_{234} (f_3 f_4 - f_1 f_2) W_{12 \rightarrow 34} \delta^4(p_1 + p_2 - p_3 - p_4) + S(x, \mathbf{p}_1).$$

**Covariant Boltzmann transport**

$$f(x, \mathbf{p}) = \frac{g}{(2\pi)^3} \exp\left[\frac{\mu(x) - p_\mu u^\mu(x)}{T(x)}\right]$$

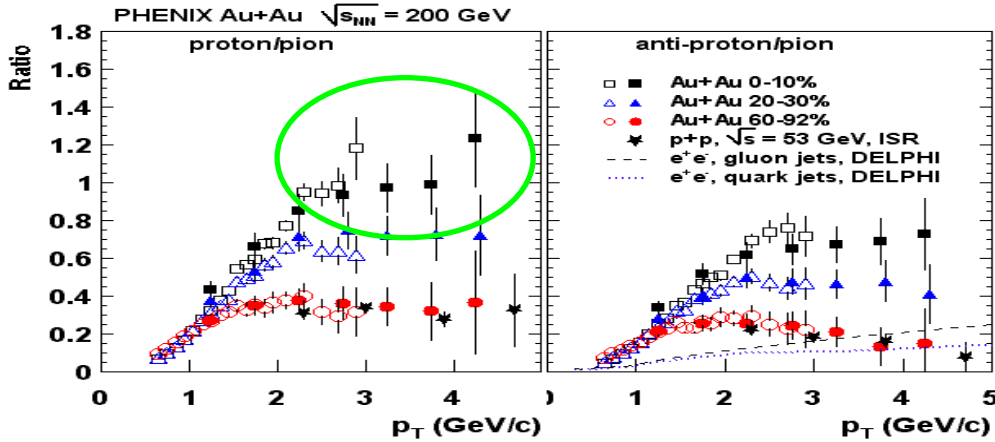
**Phase space density**



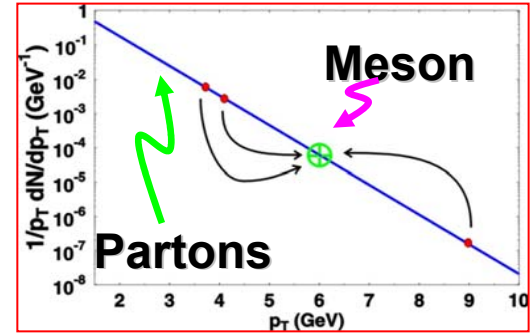
**String and transport Monte Carlo's work very well and **predict** the global d+A**

Z.W. Lin, C.M.Ko, Phys.Rev.C68, (2003)

# Parton Coalescence



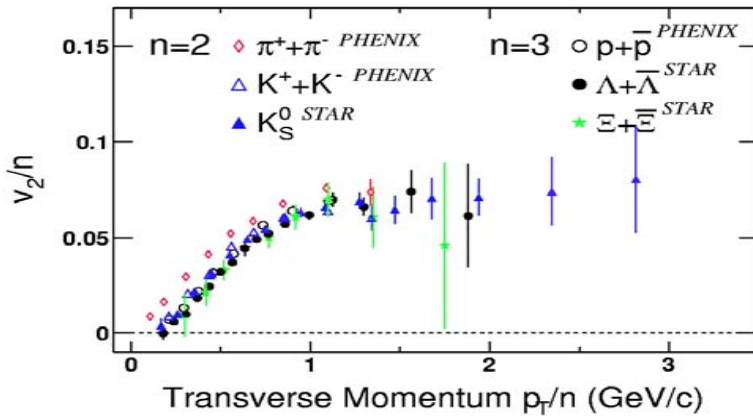
The original motivation  
"Baryon anomaly"



$$E \frac{dN_M}{d^3P} = \int d\sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha, \beta} \int dx w_\alpha(R, xP^+) \bar{w}_\beta(R, (1-x)P^+) |\bar{\phi}_M(x)|^2$$

$$E \frac{dN_B}{d^3p} = \int d\sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha, \beta, \gamma} \int dx dx' w_\alpha(R, xP^+) w_\beta(R, x'P^+) w_\gamma(R, (1-x-x')P^+) |\bar{\phi}_B(x, x')|^2$$

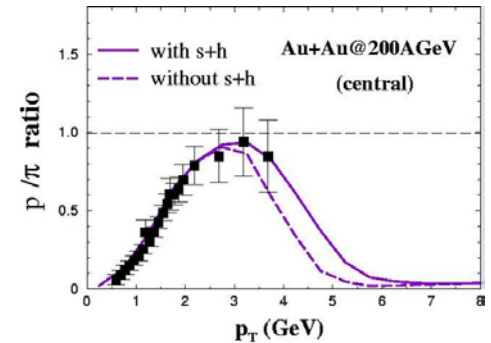
Folding the quark Wigner functions and the meson or baryon wave functions



R.J. Fries et al., Phys.Rev.Lett.90, (2003)

$$v_2^M(p_t) = 2v_2^p \left( \frac{p_t}{2} \right)$$

$$v_2^B(p_t) = 3v_2^p \left( \frac{p_t}{3} \right)$$



Will learn more from: **Paul Sorensen**

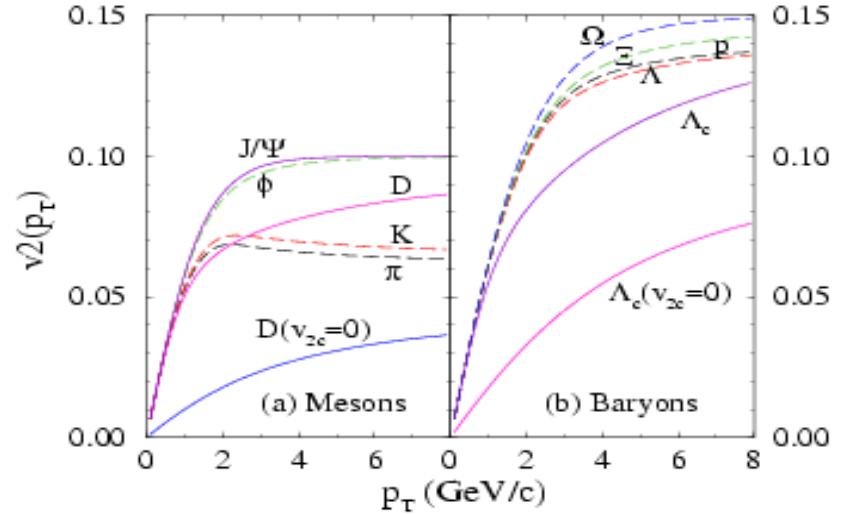
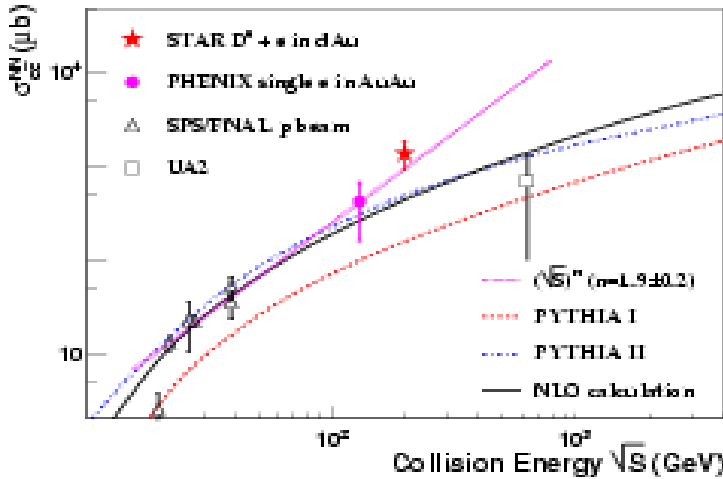
PID at the LHC: **Helio Takai and Jinghua Liu**

# Charm Production



Until recently **charm** and **bottom** production have been exclusive pQCD territory

STAR collab., nucl-ex/0407006



Z.W.Lin and D.Molnar, Phys.Rev.C68, (2003)

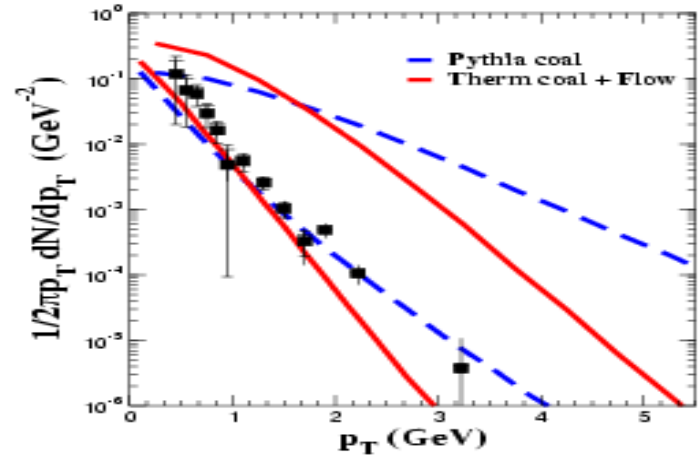
The presence of a large scale  $Q \propto m_T \geq m_c (m_b)$

$$d\sigma^{c\bar{c}} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\sigma^{ab \rightarrow cd}}{dt}$$

R. Vogt, hep-ph/0203151

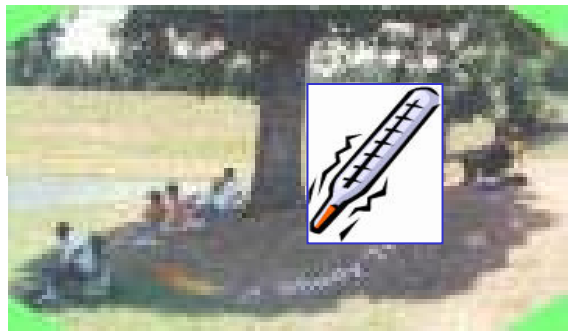
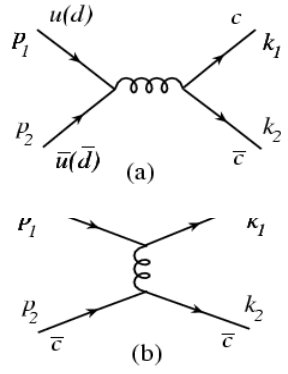
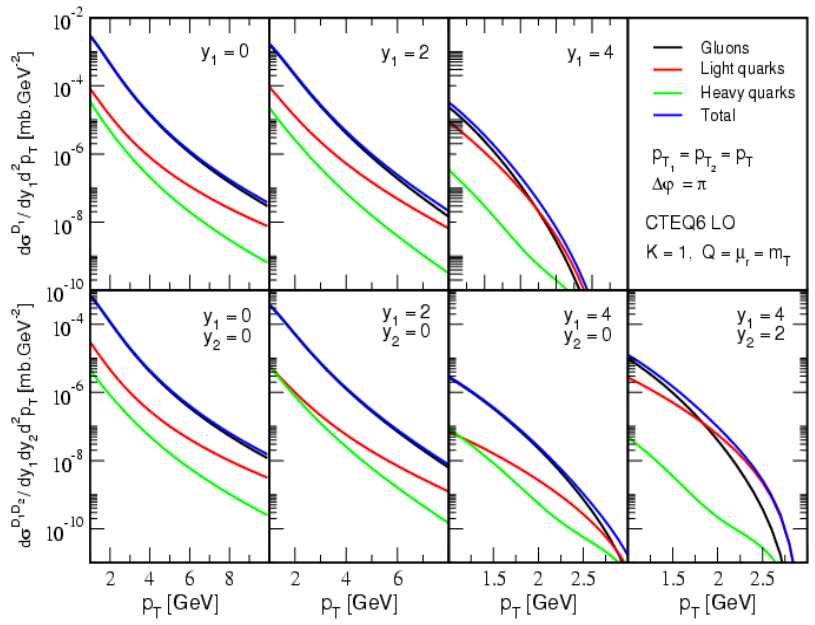
- Coalescence **enhancement** ideas
- If charm **flows** in Au+Au it will be spectacular! (but chances are small)

Quarkonium production at the RHIC: **Ming Liu**



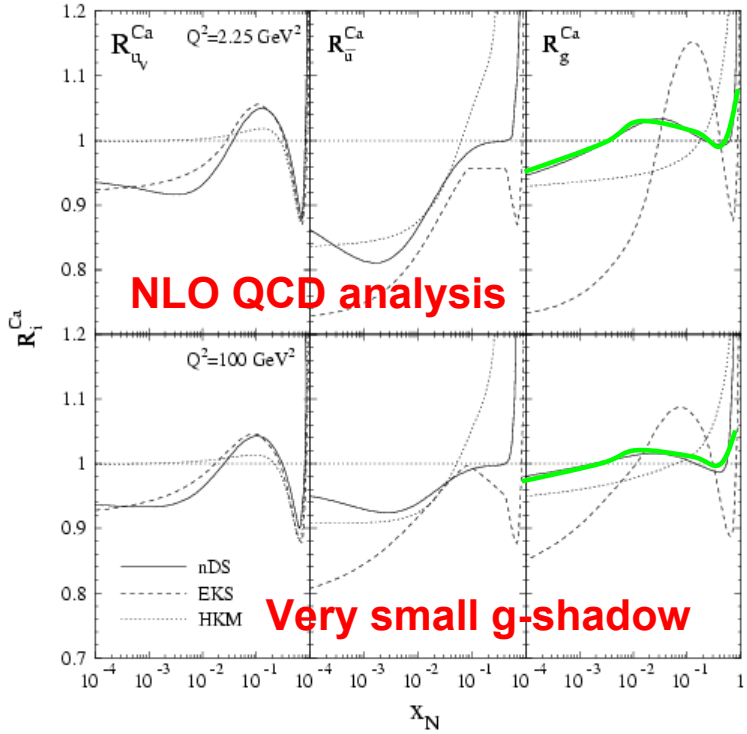
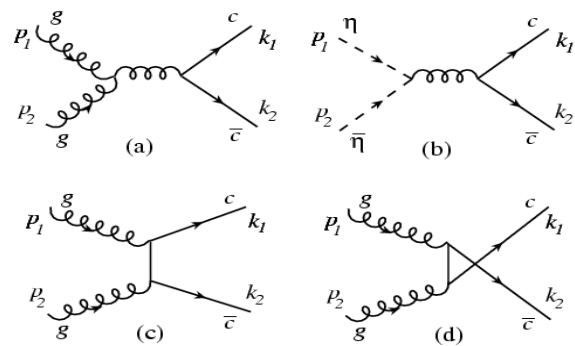
V. Greco, C.M. Ko and R. Rapp Phys.Lett.B 595, (2004)

# Open Charm "Shadow meter"



I.V. et al., in preparation

To LO open charm is dominated by the gluonic initial state



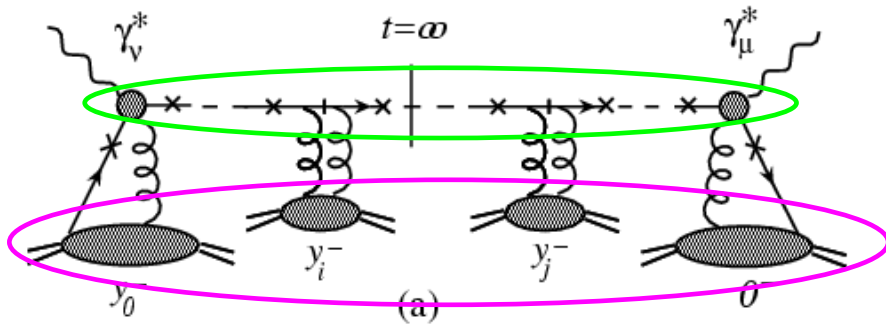
Another possible roadmap

G-saturation → strong g-shadowing → weak g-shadowing



D. de Florian, R. Sassot, Phys.Rev.D69 (2004)

Ivan Vitev, LANL

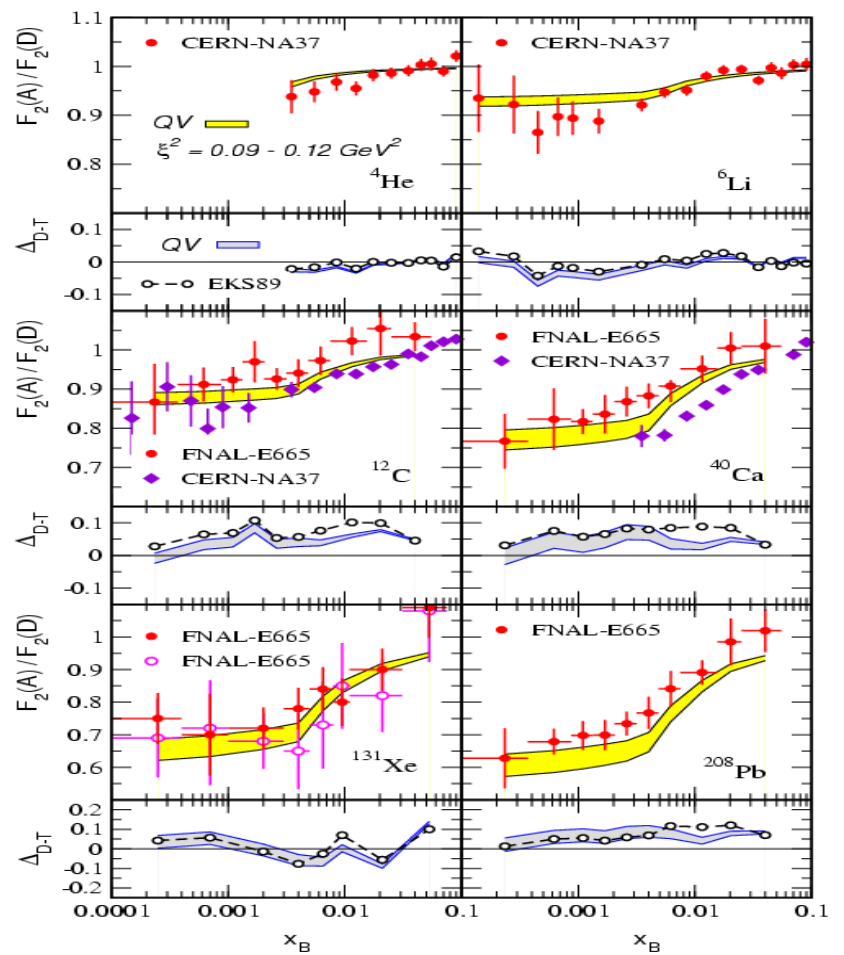
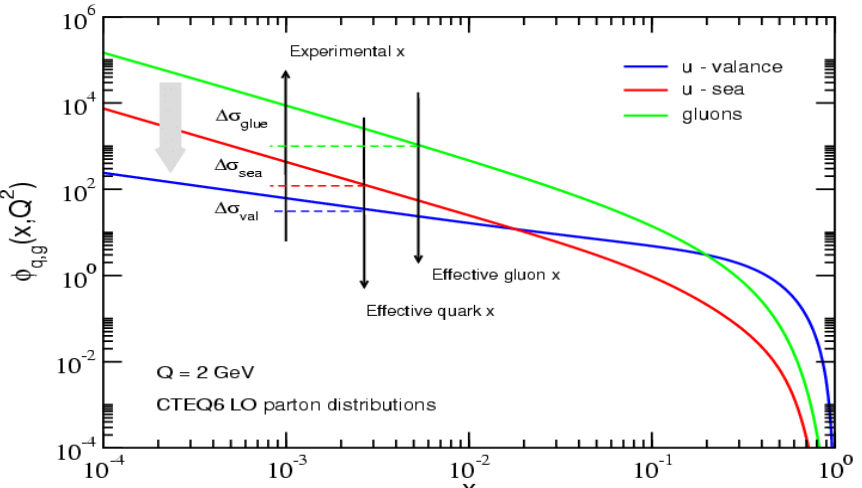


$$\xi^2 = \left( \frac{3\pi\alpha_s(Q^2)}{8r_{0\perp}^2} \right) \langle p | \hat{F}^2(\lambda_i) | p \rangle \frac{1}{2} \lim_{x \rightarrow 0} xG(x, Q^2)$$

$$F_T^A(x, Q^2) \approx A F_T^{(LT)} \left( x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2 \right)$$

$$F_L^A(x, Q^2) \approx A F_L^{(LT)}(x, Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x, Q^2)$$

**Physics:** dynamical generation of the parton's mass



J.W.Qiu and I.V., hep-ph/0309094

In **neutrino-nucleus** - relevant to NuTeV  
(recall the other parallel sessions)

J.W.Qiu, I.V., Phys.Lett.B 587 (2004)

# p+A Collisions



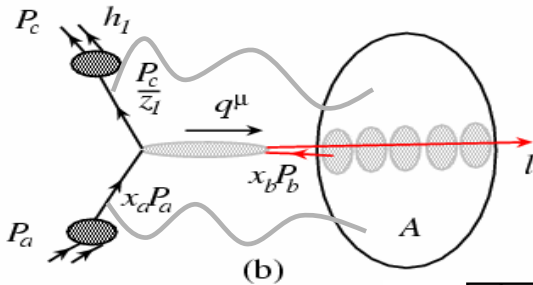
Starting point: LO pQCD

Isolate all the  $x_b$   
dependent function

J.W.Qiu, I.V., hep-ph/0405068

$$F(x_b) = \frac{\phi(x_b)}{x_b} \left| \bar{M}^2_{ab \rightarrow cd} \right|$$

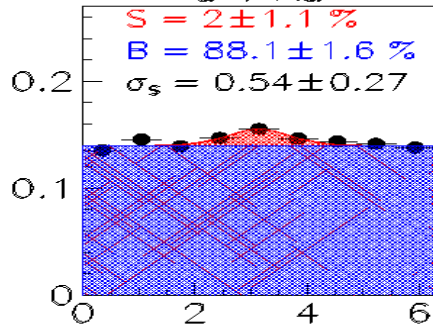
$$F(x_b) \rightarrow F\left(x_b + x_b C_d \frac{\xi^2}{-t} (A^{1/3} - 1)\right)$$



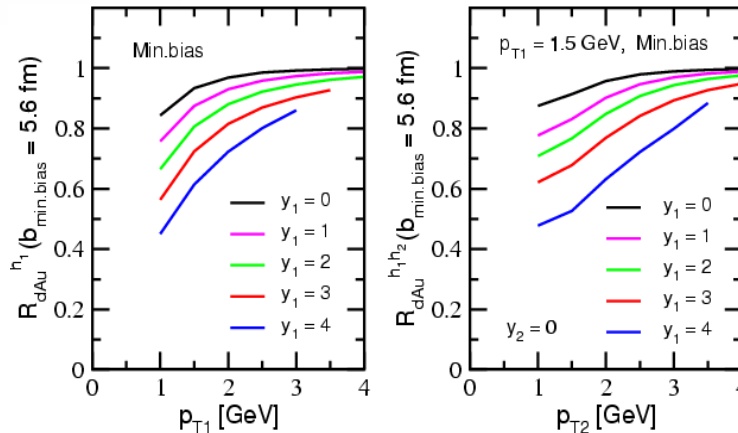
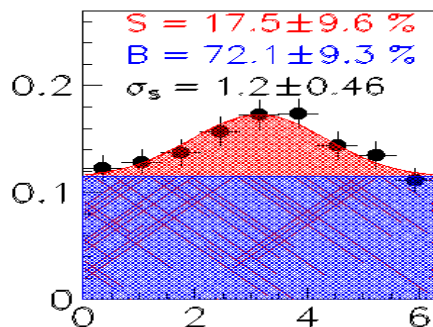
BRAHMS nicely confirm the **power corrections** and the recovery of **QCD factorization**

d + Au

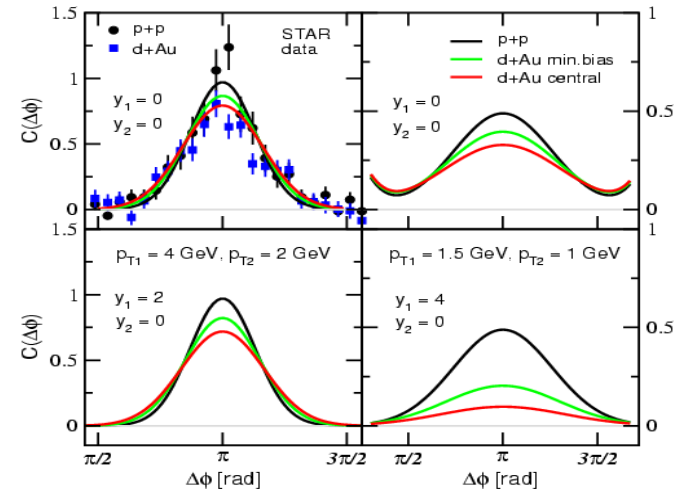
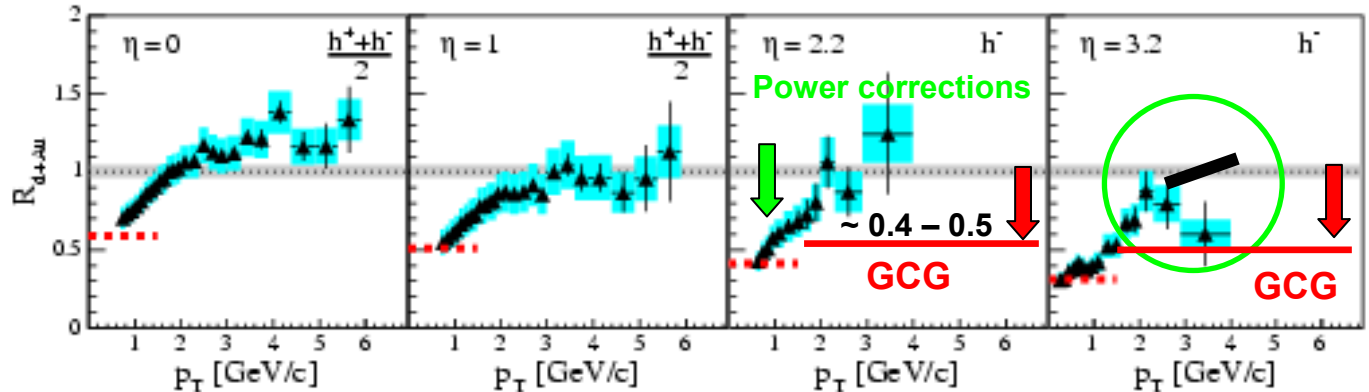
$S = 2 \pm 1.1 \%$   
 $B = 88.1 \pm 1.6 \%$   
 $\sigma_s = 0.54 \pm 0.27$



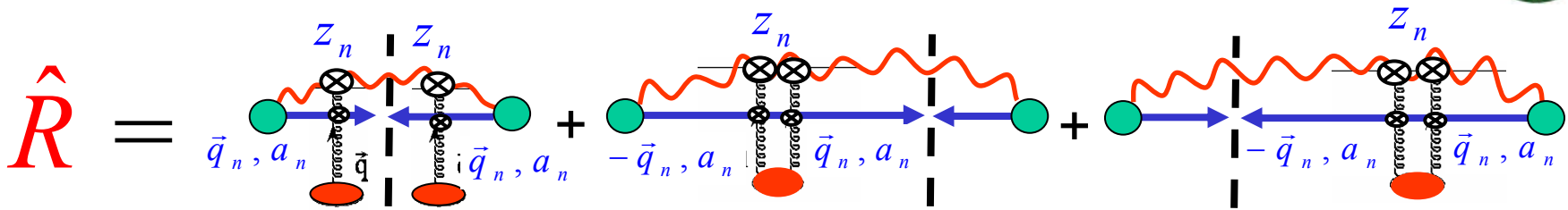
$S = 17.5 \pm 9.6 \%$   
 $B = 72.1 \pm 9.3 \%$   
 $\sigma_s = 1.2 \pm 0.46$



I. Arsene et al., nucl-ex/0403050



# Jet Tomography and A+A



The **GLV** approach: M.Gyulassy *et al.*, Nucl.Phys.B594 (2001); Phys.Rev.Lett.85 (2000)

- The mechanics of the calculation: compare the **size of the medium** to the **formation time**

$$\Delta E \propto E \times \bar{n}_{scat} \times \frac{L}{l_f} \propto E \times \frac{L}{\lambda_g} \times \frac{L}{\frac{2E}{\mu^2}} = \frac{\mu^2}{\lambda_g} L^2$$

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu L^2}{\lambda_g} \text{Log} \frac{2E}{\mu^2(L)L} + \dots,$$

– Static medium

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \text{Log} \frac{2E}{\mu^2(L)L} + \dots,$$

– 1+1D Bjorken

$$\frac{dN^s}{dy} \approx \frac{3}{2} \frac{dN^{ch}}{d\eta} \left| \frac{d\eta}{dy} \right|$$

Isospin symmetry  
Parton-hadron duality

$$\langle \Delta E \rangle \propto I = \int_{t_0}^{\infty} dt t \rho(t, \vec{x}_0 + \hat{v}(t-t_0))$$

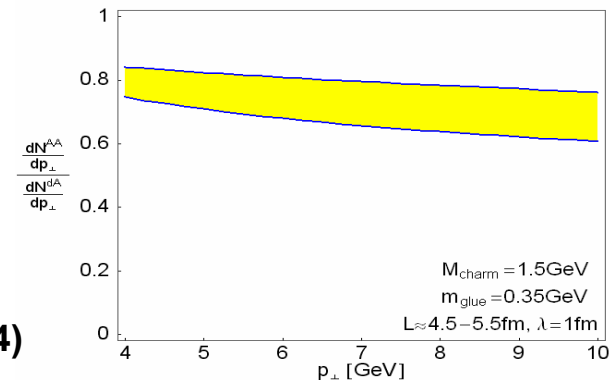
The attenuation analogy:

$$I(r) = I_0 e^{-\int_0^r dr' / \lambda_{abs}(r')} = I_0 e^{-\int_0^r dr' \sigma_{abs}(r') \rho(r')}$$

Basis for jet tomography

Heavy quarks:  
 $\Delta E$  smaller,  
closer to linear

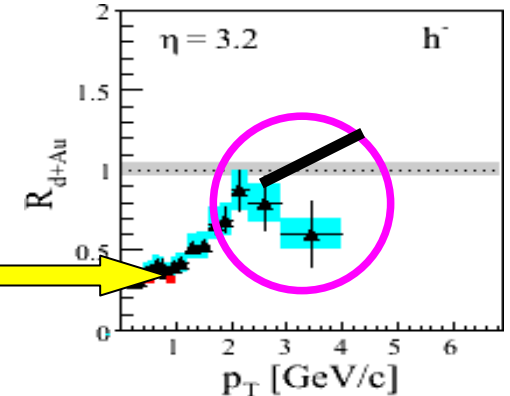
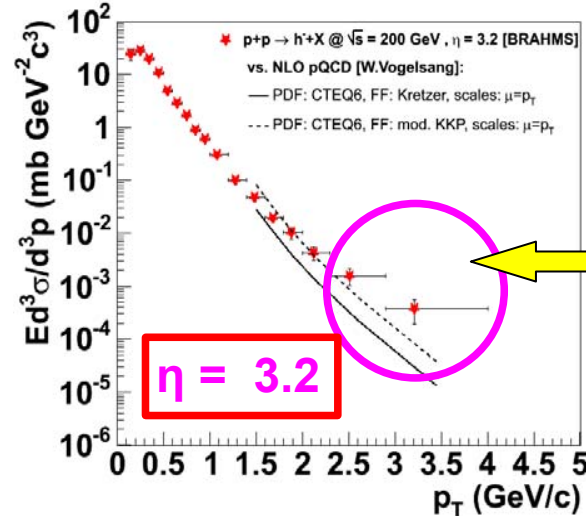
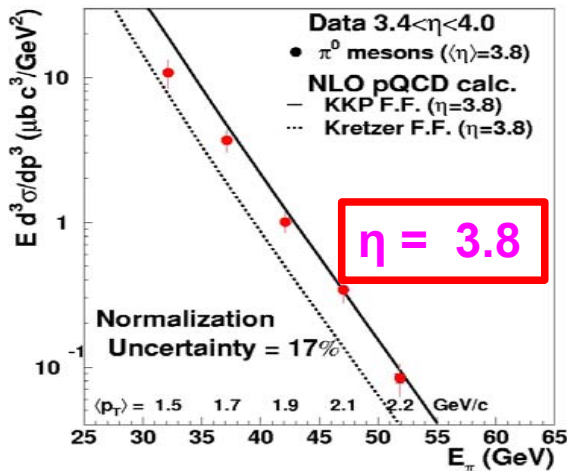
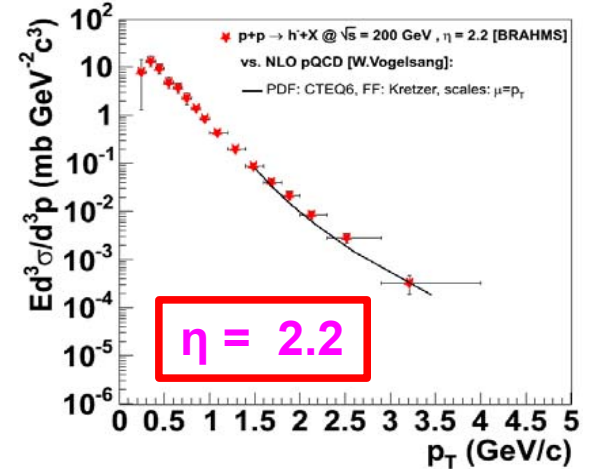
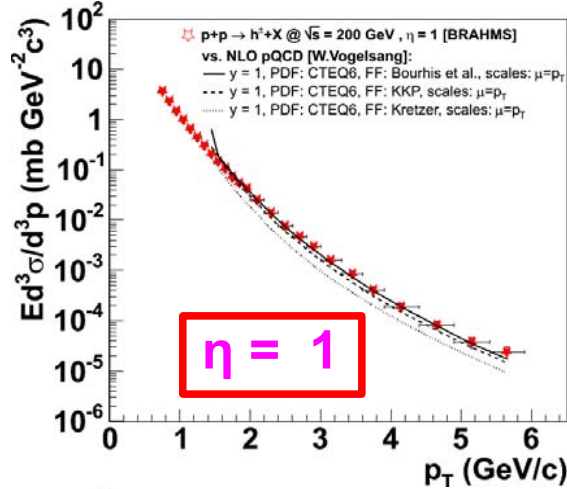
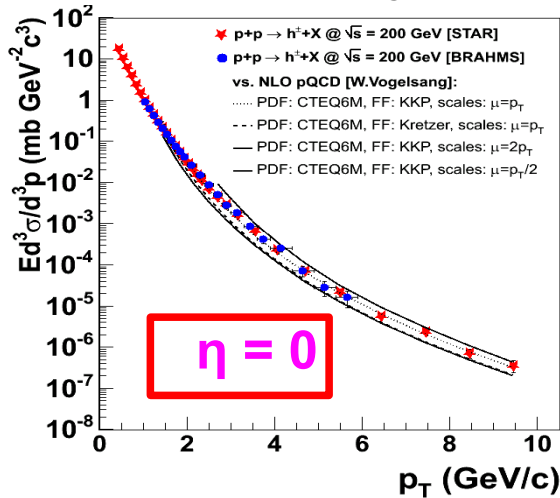
M.Djordjevic *et al.*,  
Nucl.Phys.A733 (2004)



Thanks to D. d'Enterria. "Hot Quarks" 2004

Well understood **baseline** for jet tomography, even versus rapidity

Connection to the **high  $p_T$**  part of the "BRAHMS effect"



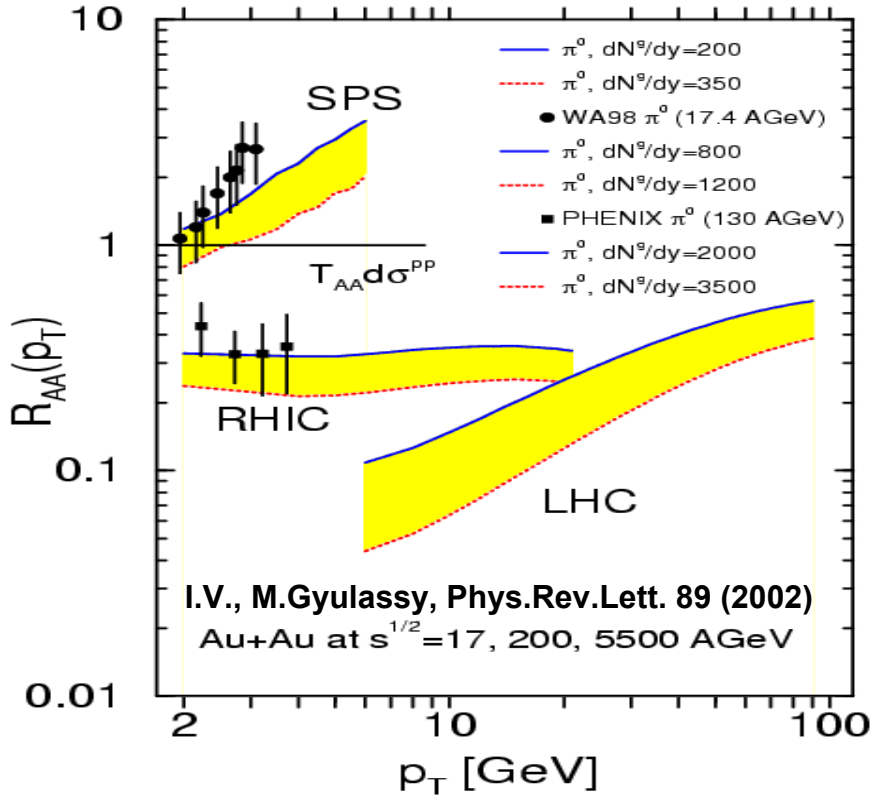
Calculations by W. Vogelsang

See e.g.

B. Jager et al., Phys.Rev.D, (2003)

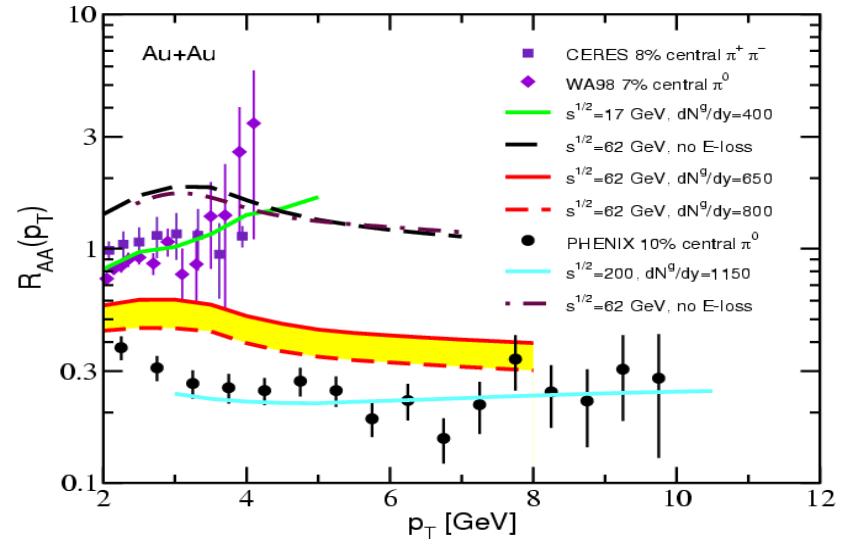
STAR, Phys.Rev.Lett 92, (2004)

The high  $p_T$  hadro-production is the most extensively tested observable at RHIC

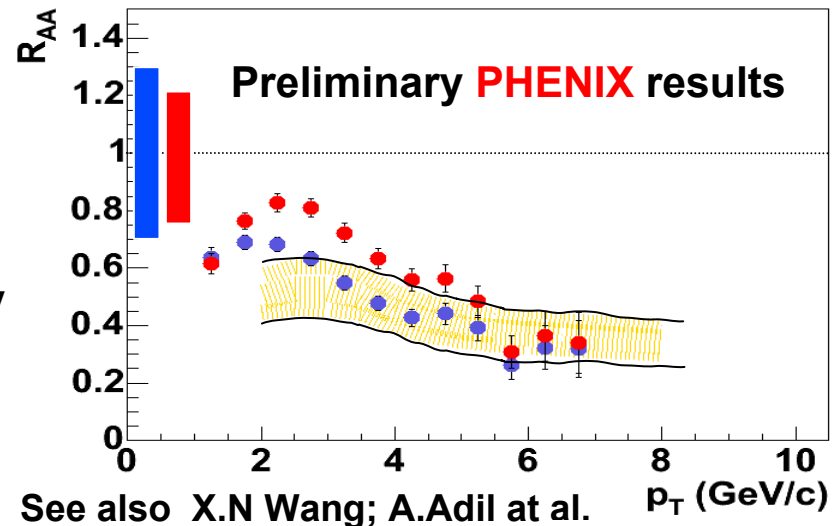


- The **onset of quenching** are among most important measures of the QCD matter density
- Motivator for the 62 GeV Run at RHIC

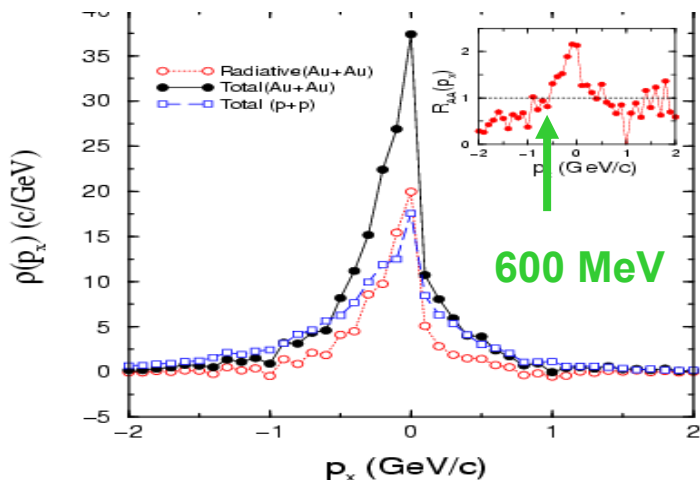
Does it compare to STAR: **Zhangbu Xu**



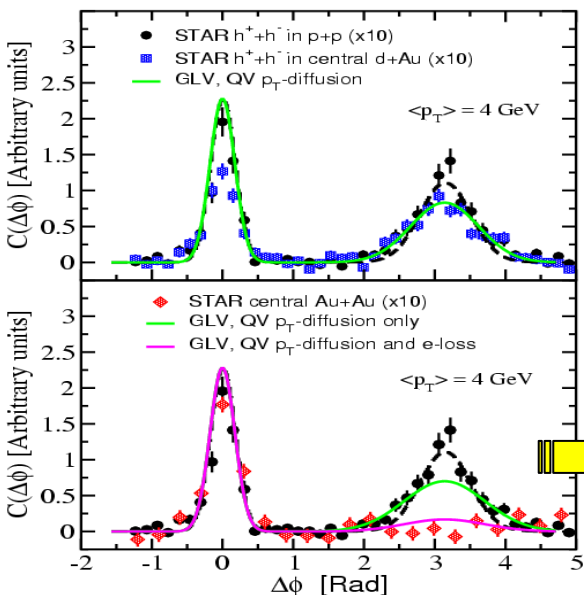
SPS relative to D.d'Enterria, nucl-ex/0403055



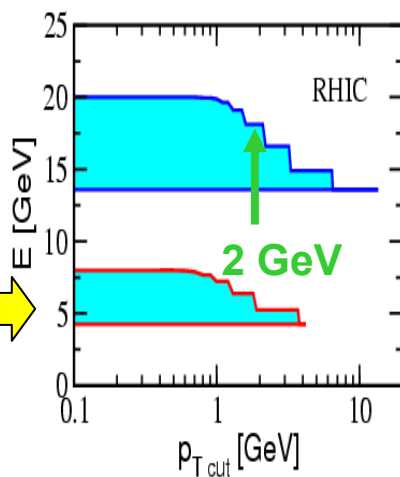
S.Pal, S.Pratt, Phys.Lett.B574 (2003)



I.V., nucl-th/0403089



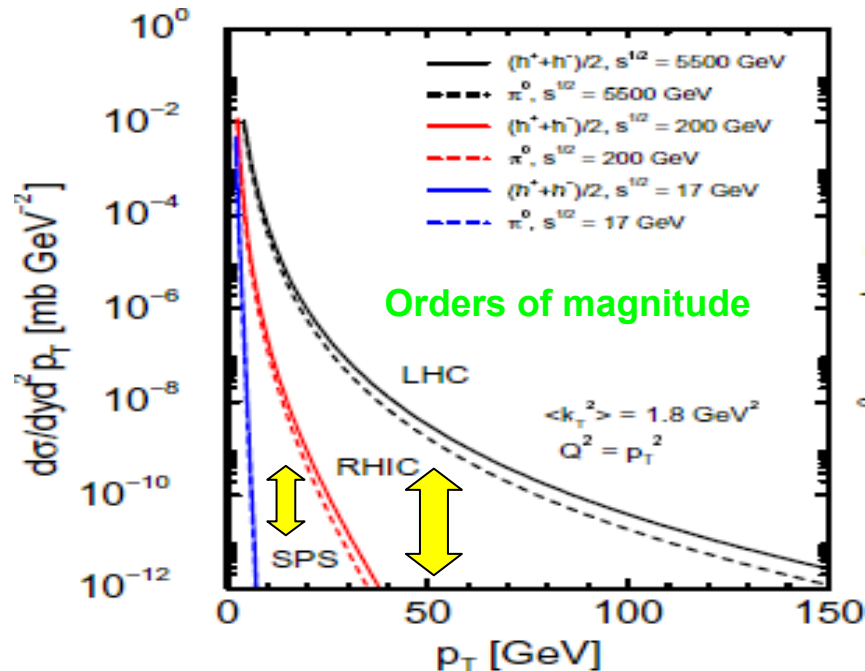
• Energy redistribution



- Attenuation (**disappearance**) of the away-side correlation function
- Dependence relative to the reaction plane  $\Delta E \sim L^n(\phi)$
- **Reappearance** of the lost energy

$$R_{AA}^{h_1 h_2}(p_T) = \frac{d^2\sigma^{AA} / dp_{T1} dp_{T2} d\eta_1 d\eta_2}{\langle N_{bin} \rangle d^2\sigma^{NN} / dp_{T1} dp_{T2} d\eta_1 d\eta_2}$$

$$R^{h_1 h_2} / R^{h_1} \sim 1.5$$



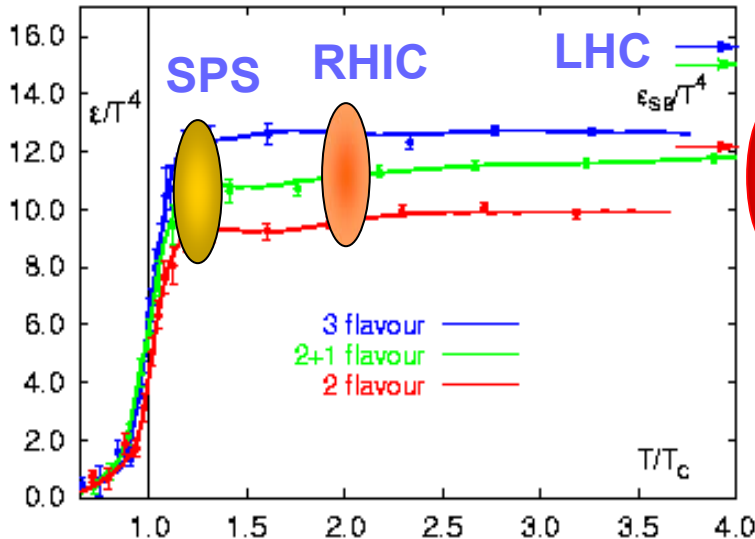
Clearly high  $p_T$  will dominate the LHC

TeV jets: Helio Takai and Jinghua Liu

# Properties of the QGP



	$\langle \frac{dE}{dz} \rangle^* \left[ \frac{GeV}{fm} \right]$	$\tau_0 [fm]$	$T [MeV]$	$\varepsilon [GeV / fm^3]$	$\tau_{tot} [fm]$	$dN^s / dy$
<b>SPS</b>	2-3.5	0.8	210-240	1.5-2.5	1.4-2	200-350
<b>RHIC</b>	7-10	0.6	380-400	14-20	6-7	800-1200
<b>LHC</b>	17-28	0.2	710-850	190-400	18-23	2000-3500



F.Karsch, Nucl.Phys.A698 (2002)

Even SPS seems to have gone above the phase transition

The energy density at RHIC

$$\varepsilon_{RHIC} \approx 100 \varepsilon_0 = 100 \times 0.14 \text{ GeV} / \text{fm}^3$$

- **Strongly coupled** plasma?
- The quarkonium dissociation temperatures **(1.5 – 2 T<sub>c</sub>)**
- Bound states above T<sub>c</sub>

$$R_{Au} = 6.8 \text{ fm}, T_c = 175 \text{ MeV}, \varepsilon_c = 1 \text{ GeV} / \text{fm}^3$$

Latest expectations from lattice:  
**Felix Znatow**

- ▶ The complex dynamics of HIC cannot be approximated within a single approach:
  - There is are **times scales** and **momentum scales** of applicability
  - Every approach pushed beyond its limits of applicability has shown **weaknesses**
- ▶ The combined analysis from all approaches:
  - Suggests the creation of the **deconfined QGP state** of energy density **~ 100 times** normal nuclear matter density
  - Recent theoretical work suggests that the plasma might be **strongly interacting**
- ▶ New and promising directions:
  - Study of **charm and charmonia** (and **bottom**), **direct photons**, **tagged jets** and **multi-hadron correlations**
  - Study of **forward and backward rapidity**, **shadowing/power corrections** and the **Cronin effect**, **leptonic observables**
  - Assess the **LHC** capabilities of testing the dynamical models from RHIC,  $\sqrt{s}$  and  $p_T$  ( $E_T$ ) versus luminosity and running time