Heavy Ions - Prospects at LHC

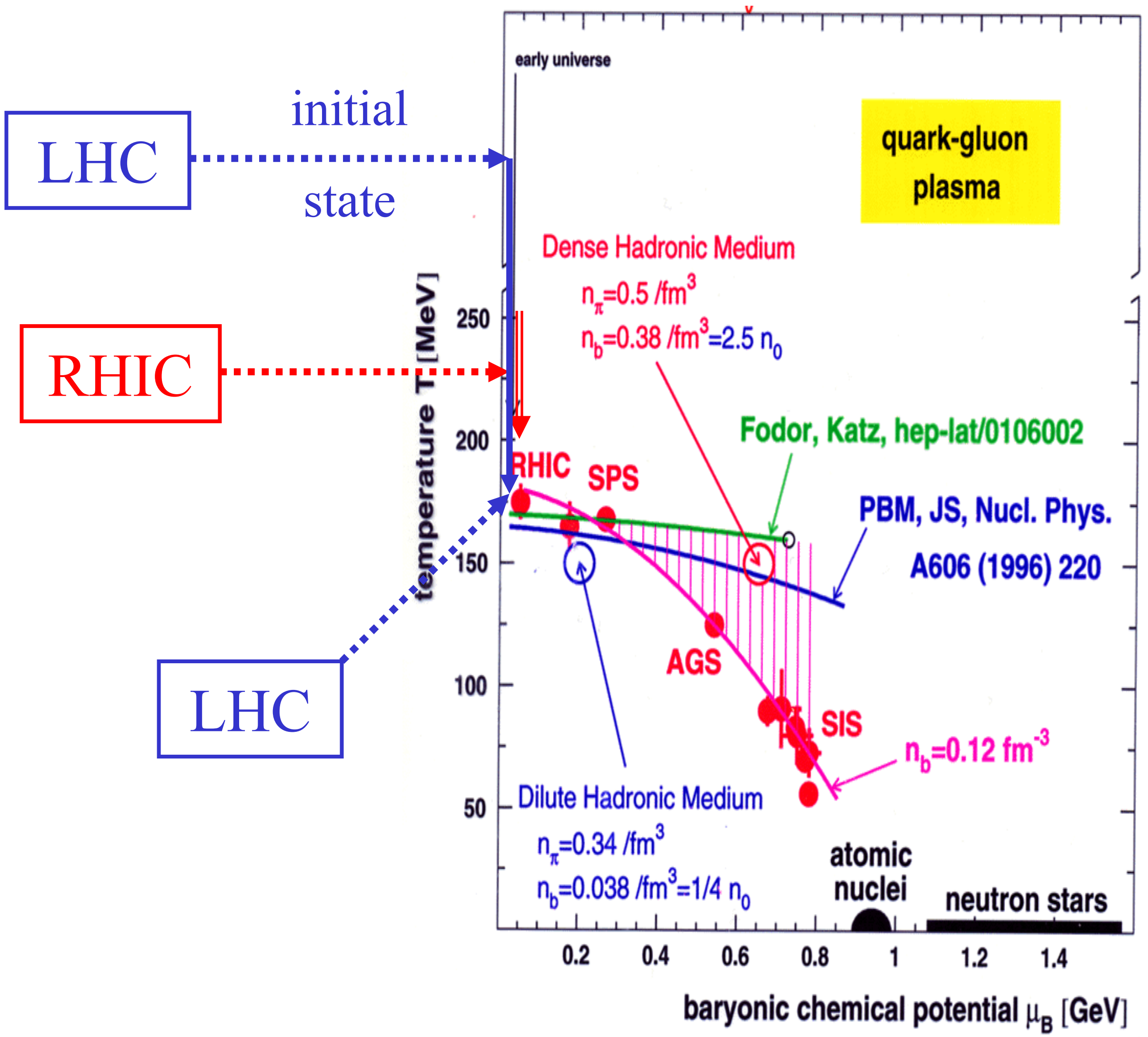
Physics at LHC

Vienna, Austria   13-17 July, 2004

- Super-hot QCD matter
- What have we learned from RHIC & SPS
- What is different at the LHC ?
- Goals of HI experiments at the LHC

HPC reports hep-ph/0310274, 0311048 for survey of hard probes at LHC

QCD phase diagram

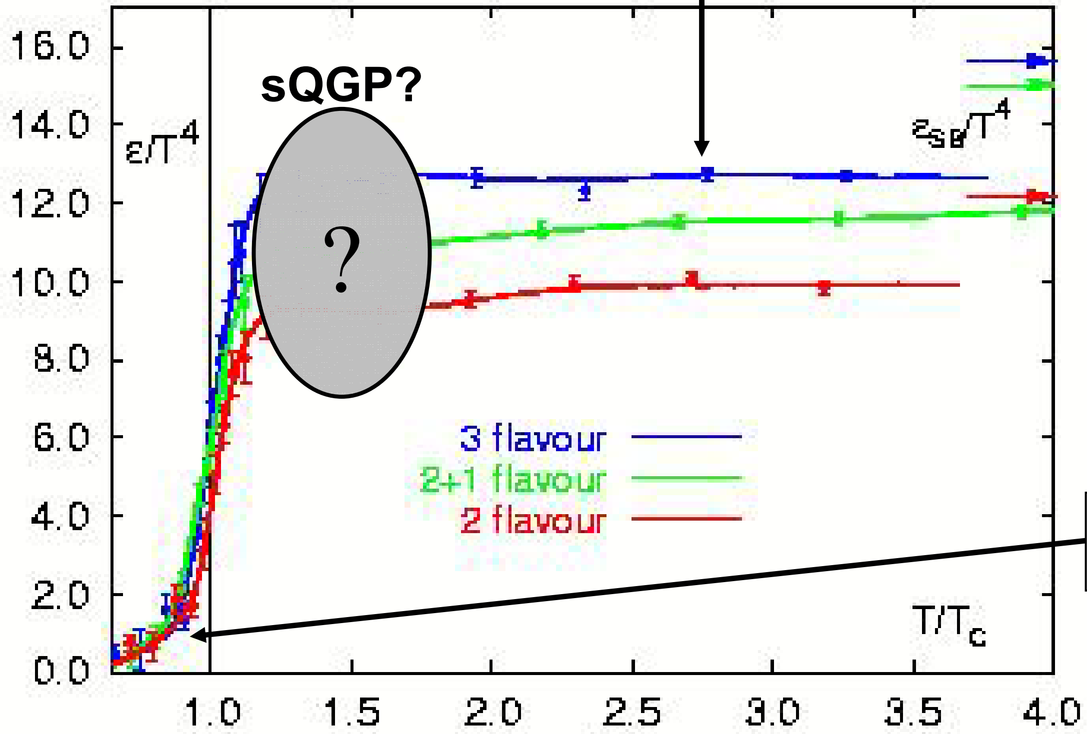


From hadrons to QGP

$$\varepsilon = \frac{\pi^2}{30} g_{\mathrm{DOF}} T^4$$

QGP = quark-gluon plasma

$$\langle \bar{\psi}\psi \rangle \approx 0$$



QCD equation of state from lattice QCD

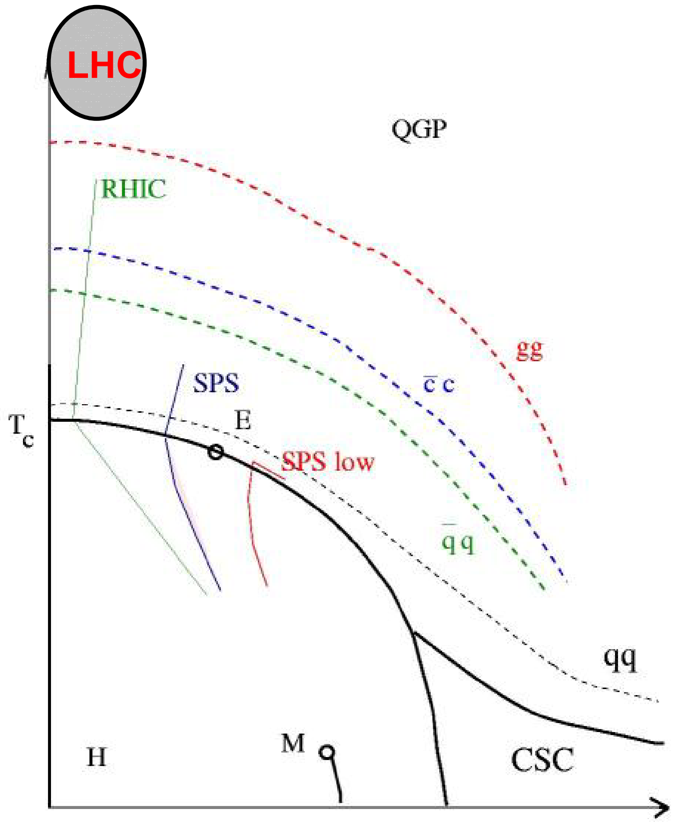
Hadron gas

$$\langle \bar{\psi}\psi \rangle_0$$

Is the QGP at RHIC a "sQGP" ?

- Very large energy loss
- Almost ideal fluid = very low viscosity
- require $\alpha_s^{eff} \approx 0.5$.

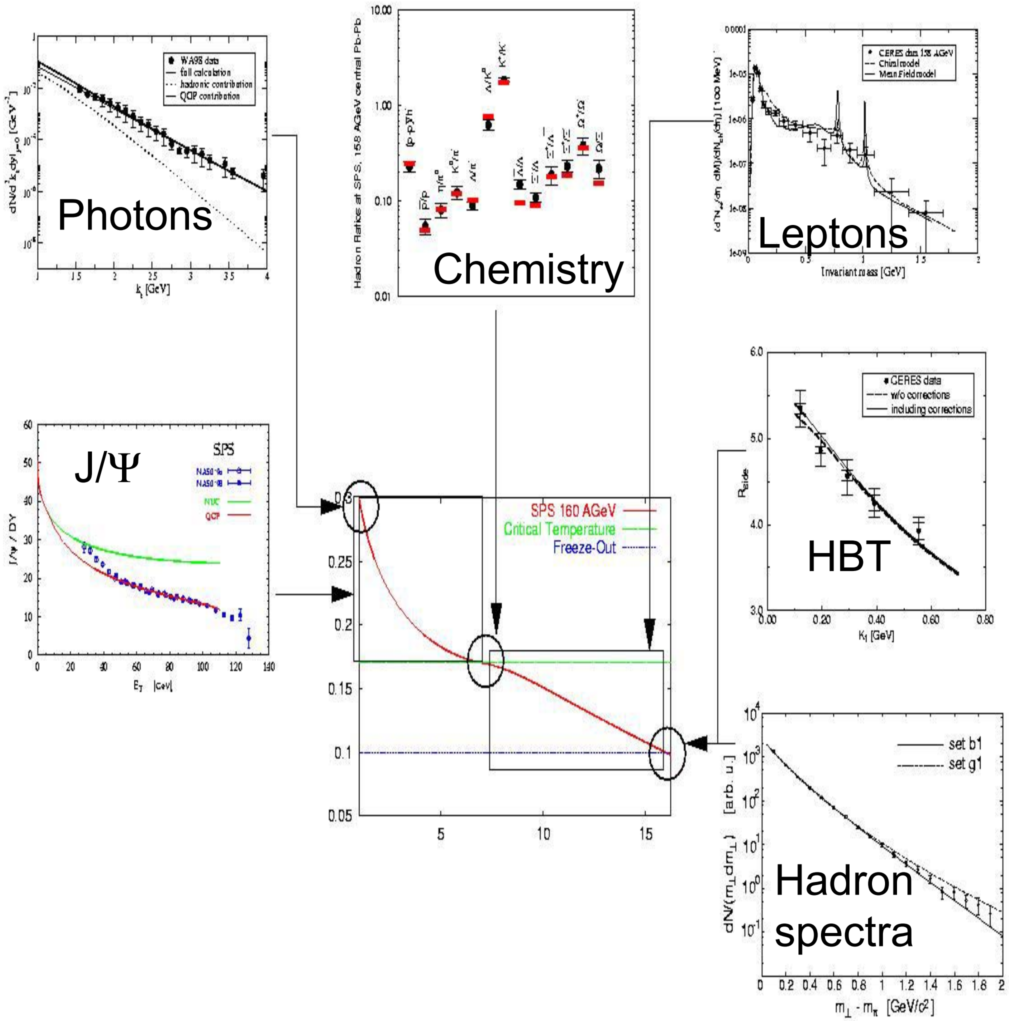
- Strong coupling ($g \approx 2.5!$) gives quasiparticles large effective masses and may even favor color octet and singlet bound states.



Signatures of a QCD phase change

- Effects of "latent heat" in (E, T) relation
- Enhancement of s-quark production
- Disappearance of light hadrons (ρ^0)
- Thermal l^+l^- and γ radiation
- Hadronization = quark recombination
- Critical fluctuations (momentum, baryon number)
- Collective vacuum excitations (DCC, etc.)
- Disappearance of Ψ, ✝ bound states
- Large energy loss of fast partons (jet quenching)

SPS: Panorama for Pb+Pb (158 GeV)



Parametrized hydrodynamical evolution (Thorsten Renk).

Accelerated radial re-expansion of a compressed fireball.

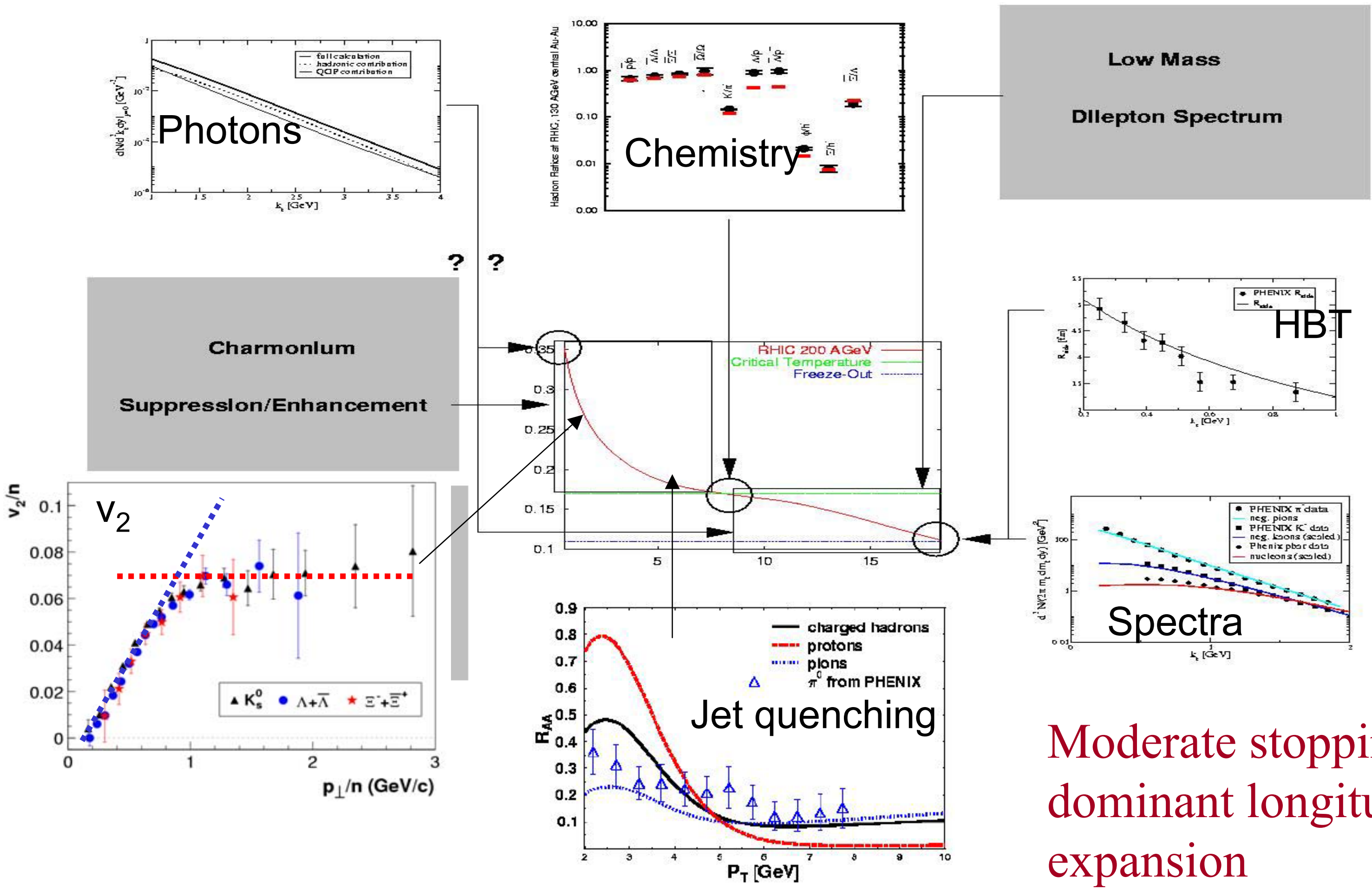
Provides comprehensive view of different probes:

Photons and J/Ψ are probes of the QGP phase;

Hadrochemistry probes T_c;

Lepton pairs, hadron spectra, HBT mostly probe hadron gas phase.

RHIC: Panorama for Au+Au (200 GeV)



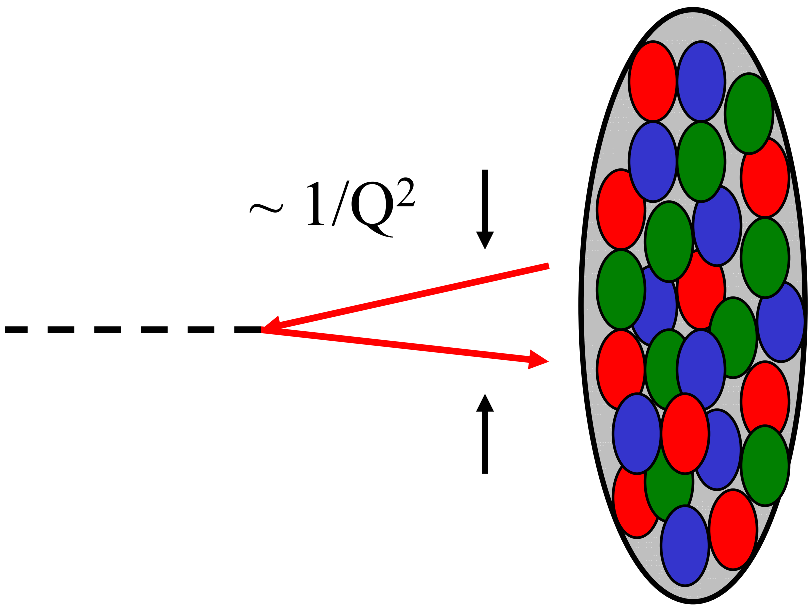
Moderate stopping and dominant longitudinal expansion

What's different (better) at the LHC ?

Much larger "dynamic range" compared to RHIC

- Higher energy density ε_0 at earlier time τ_0: "sQGP" $\rightarrow$ QGP ?
- Jet physics can be probed to $p_T > 100$ GeV.
- *b, c* quarks are plentiful, good probes.
- Increased lifetime of QGP phase (10-15 fm/c) $\rightarrow$ Initial state effects less important.
- QGP even more dominant compared with final-state hadron interactions.

Parton saturation at small x



Gribov, Levin, Ryskin ’83:

$$\Rightarrow Q^2_{\text{sat}}(x, A)$$

“color glass condensate”

$$\text{parton density} \times \text{area} = \frac{xG_A(x,Q^2)}{\pi R_A^2} \times \frac{\alpha_s}{Q^2} \sim \frac{A^{1/3}x^{-\lambda}}{Q^2} \sim 1$$

After “liberation”, partons equilibrate and screen color force

$E_{\rm CM}$ dependence of dN/dy

Geometric scaling à la Golec-Biernat & Wüsthoff

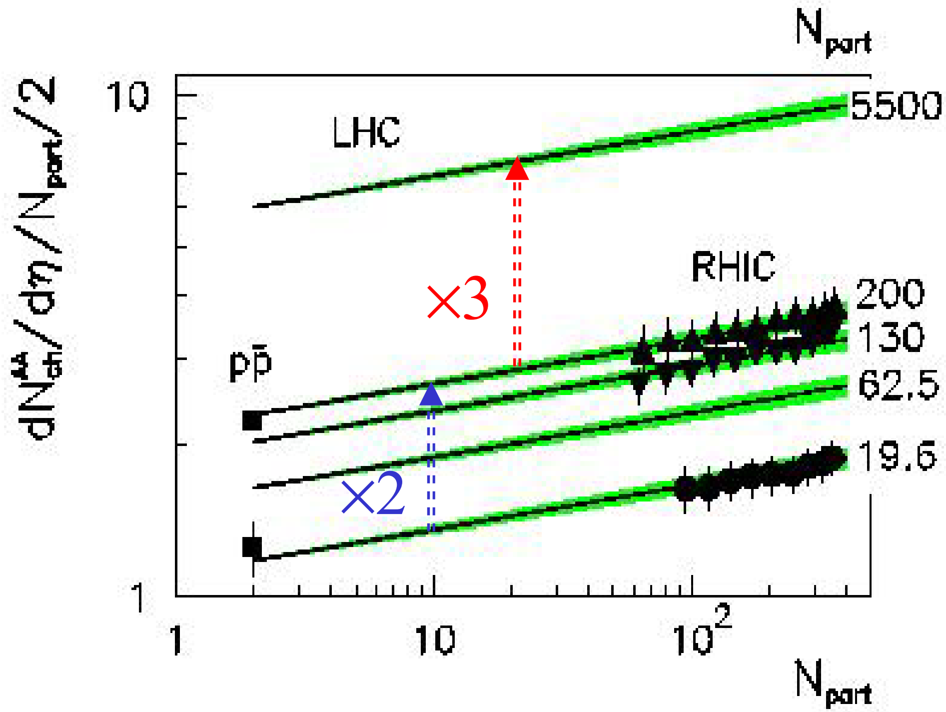
$$Q_{\rm sat}^2(x,A) = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda}\left(\frac{A}{R_A^2}\right)^{1/\delta}$$

with $\lambda = 0.288, \delta = 0.79$

(Armesto et al. hep-ph/0407018)

From fit to HERA e-p and NMC nuclear photoabsorption data.

$$dN/dy \propto Q_{{\rm sat},A}^2 \pi R_A^2$$

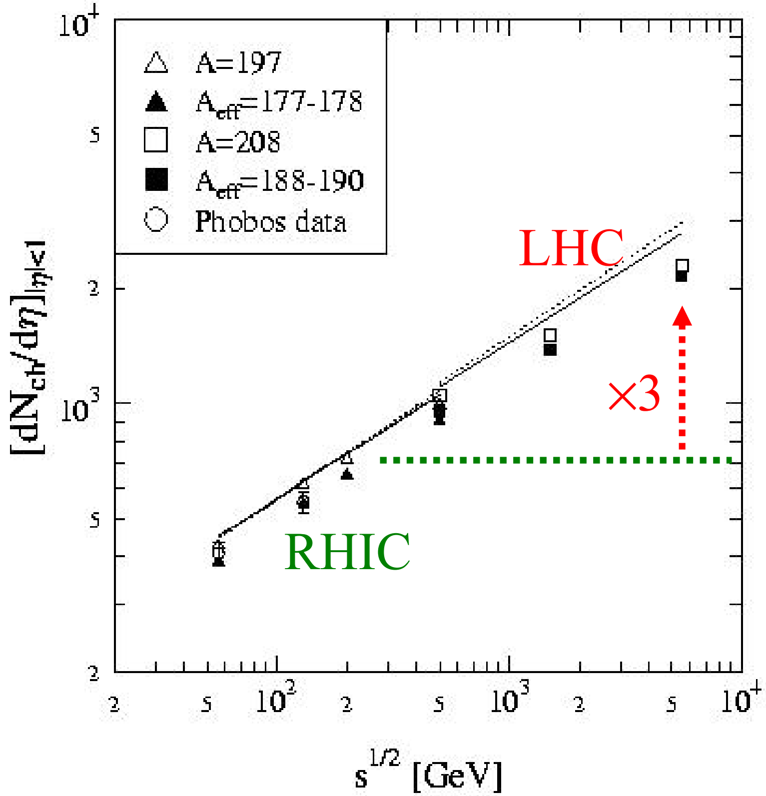


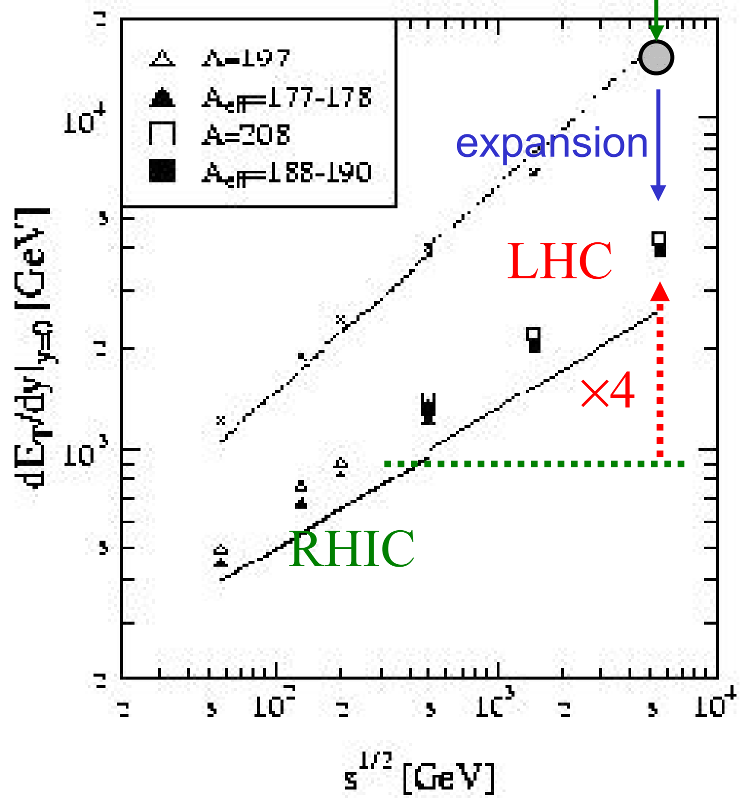
$$\Rightarrow \quad T_{\rm in}^{\rm LHC} \approx \sqrt{3}\, T_{\rm in}^{\rm RHIC} \approx 600\ {\rm MeV}$$

E_{CM} dependence of dN/dy, dE/dy

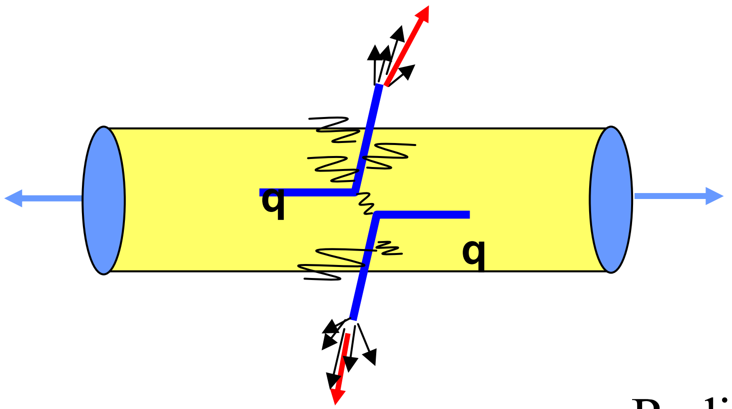
NLO pQCD with geometric parton saturation (Eskola et al. - EKRT)

$\varepsilon_{in} \approx 200\ \text{GeV/fm}^3$ at $\tau_{in} = 0.2\ \text{fm/c}$



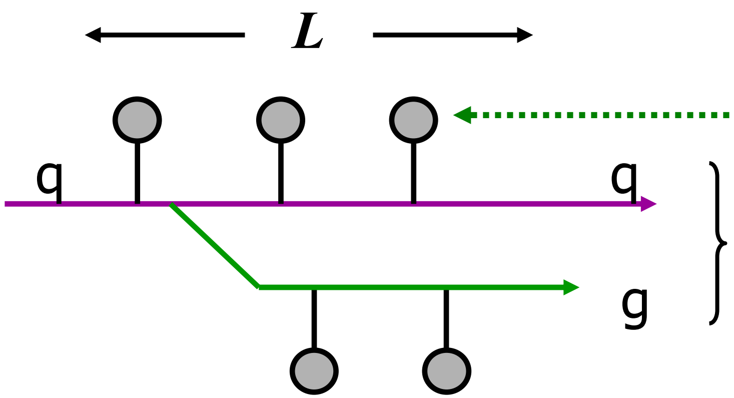


Jet Quenching



High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: $dE/dx \propto \rho L \langle k_T{}^2 \rangle$



Scattering centers = color charges

medium modifed jet

Can be described as medium effect on parton fragmentation:

$$D_{p\to h}(z,Q^2) \to \tilde{D}_{p\to h}(z,Q^2) \approx D_{p\to h}\left(\frac{z}{1-\Delta E/E}, Q^2\right)$$

Energy loss in QCD

Density of scattering centers

Scattering "power" of QCD medium:

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma \left\langle k_T^2 \right\rangle = \lambda_F^{-1} \left\langle k_T^2 \right\rangle$$

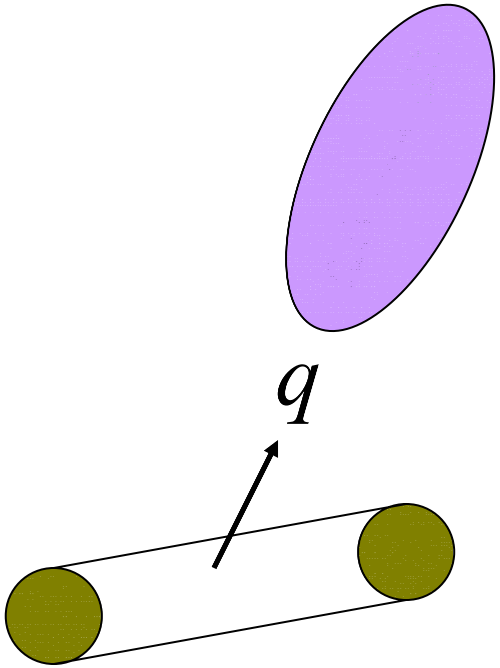
Property of medium (range of color force)

For power law parton spectrum ($\sim p_T^{-\nu}$) energy loss leads to an effective momentum shift for fast partons (BDMS):

$$\Delta p_T \approx -\alpha_s \sqrt{\pi \hat{q} L^2 p_T / \nu}$$

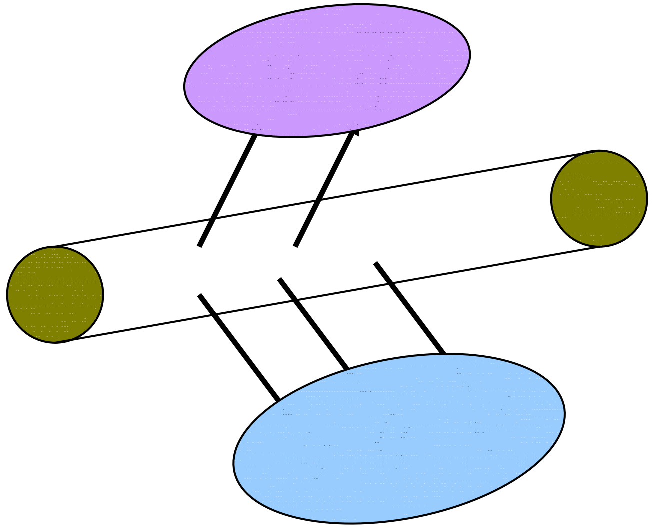
With expansion: $\hat{q} \quad \Rightarrow \quad \hat{q}_{\mathrm{eff}} = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau (\tau - \tau_0) \hat{q}(r_\tau, \tau)$

Quark recombination



Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$



Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

Recombination vs. Fragmentation

$w_\alpha(r,p) =$ Quark distribution function at "freeze-out"

For a thermal distribution: $w(r,p) \propto \exp(-p \cdot u / T)$

Recombination:

$$w_\alpha(R, xP^+)\bar{w}_\beta(R,(1-x)P^+) = \exp\left(-P \cdot u / T\right)$$

$$w_\alpha(R, xP^+)w_\beta(R, x'P^+)w_\gamma(R,(1-x-x')P^+) = \exp\left(-P \cdot u / T\right)$$

Fragmentation…

$$E\frac{dN_{\mathrm{h}}}{d^3p} = \int d\sigma \frac{p \cdot u}{(2\pi)^3} \int_0^1 \frac{dz}{z^3} \sum_\alpha w_\alpha(r, \tfrac{1}{z}p) D_{\alpha \to \mathrm{h}}(z)$$

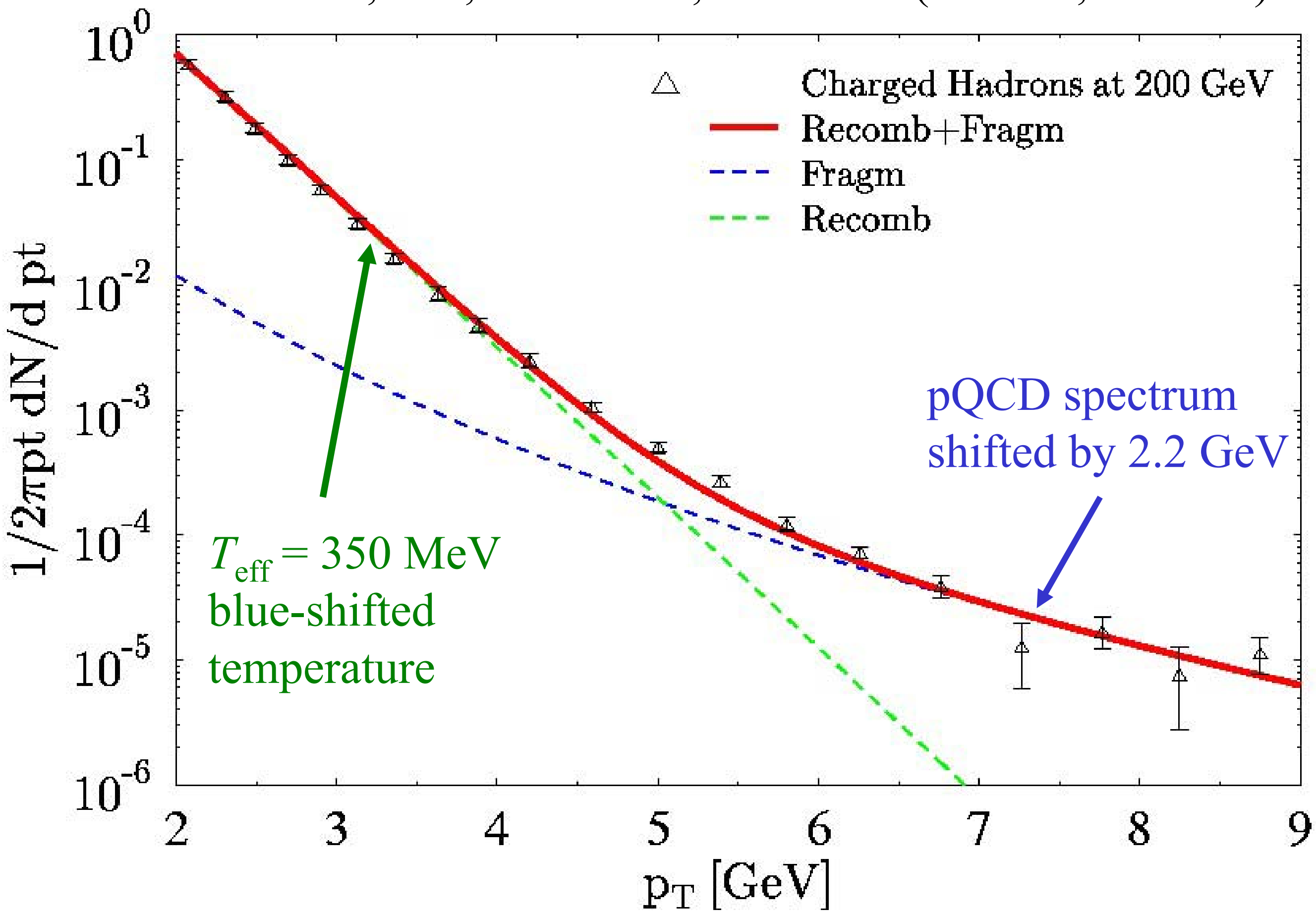
… never competes with recombination for an exponential spectrum:

$$\left[w\left(p/n\right)\right]^n = \exp(-p \cdot u / T) > \exp(-p \cdot u / zT) = w\left(p/z\right)$$

… but wins out at large p_T, where the spectrum is a power law ~ $(p_T)^{-b}$

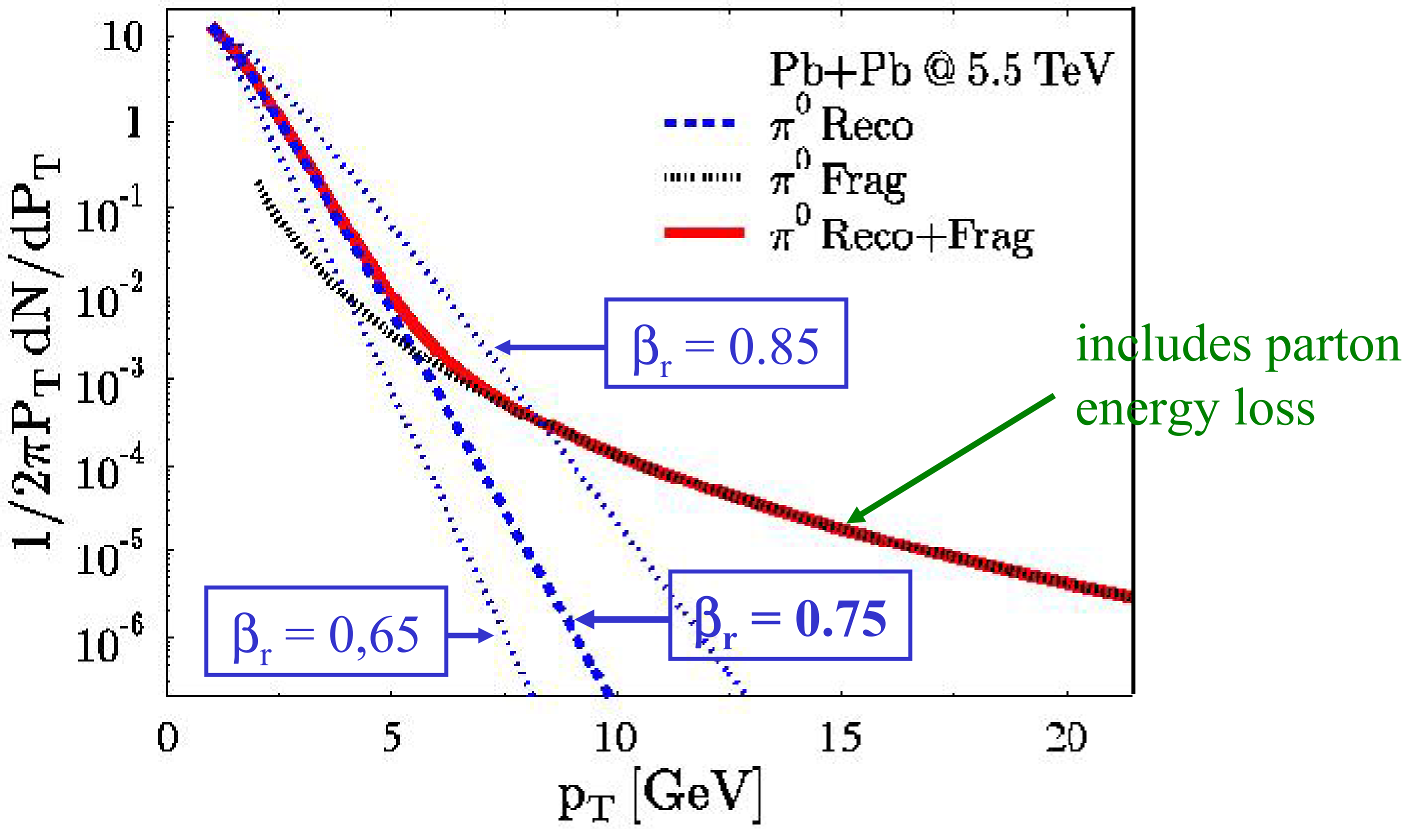
Fit to RHIC hadron spectrum

R.J. Fries, BM, C. Nonaka, S.A. Bass (PRL 90, 202303)



Hadron production at the LHC

R.J. Fries, BM, nucl-th/0307043

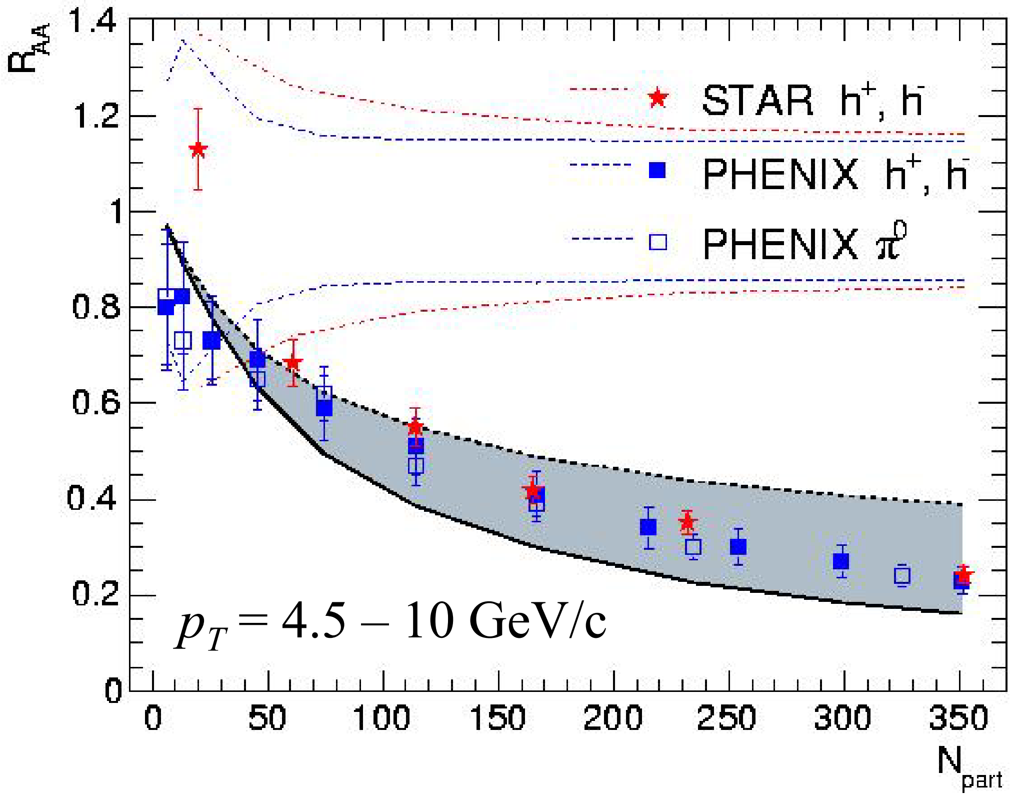


Energy loss at RHIC

- Data can be fitted with a large loss parameter for central collisions:

$$\langle \hat{q} \rangle \approx 10\ \mathrm{GeV}^2/\mathrm{fm}$$

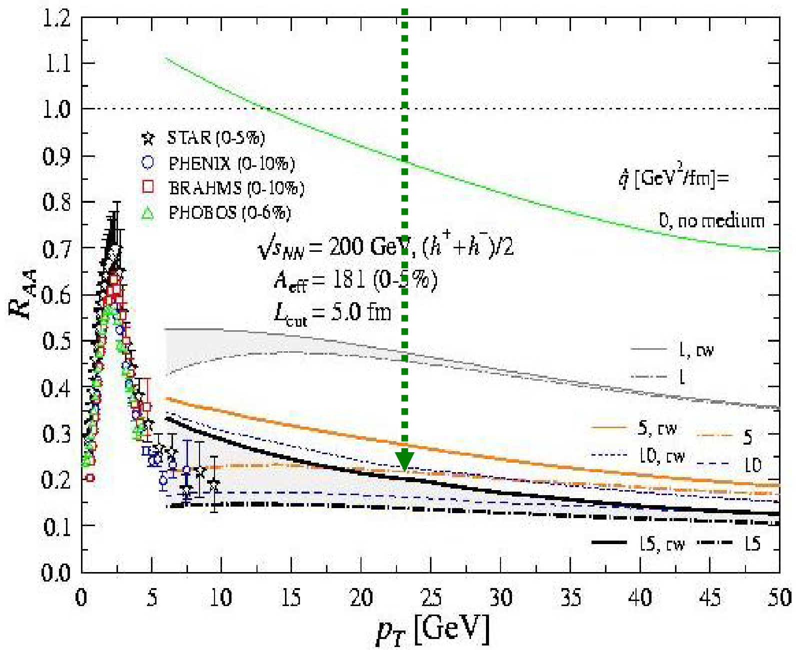
(Dainese, Loizides, Paic, hep-ph/0406201)



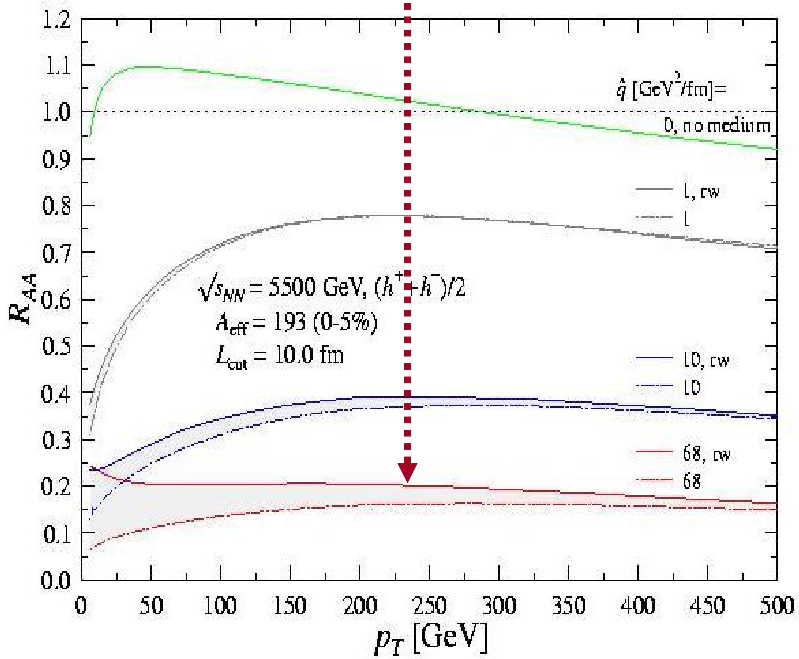
From RHIC to LHC (I)

Eskola, Honkanen, Salgado & Wiedemann, hep-ph/0406319

RHIC

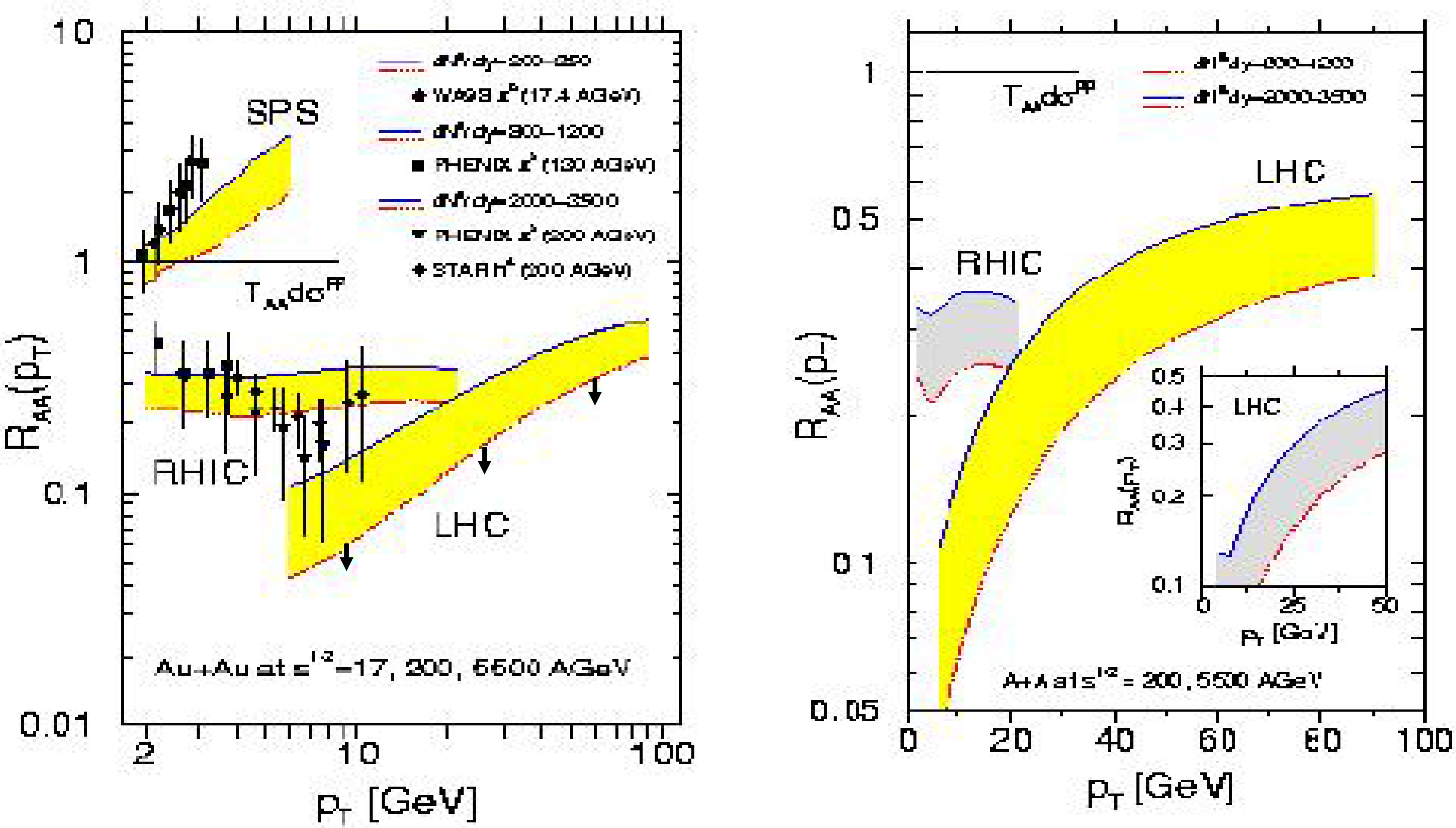


LHC



From RHIC to LHC (II)

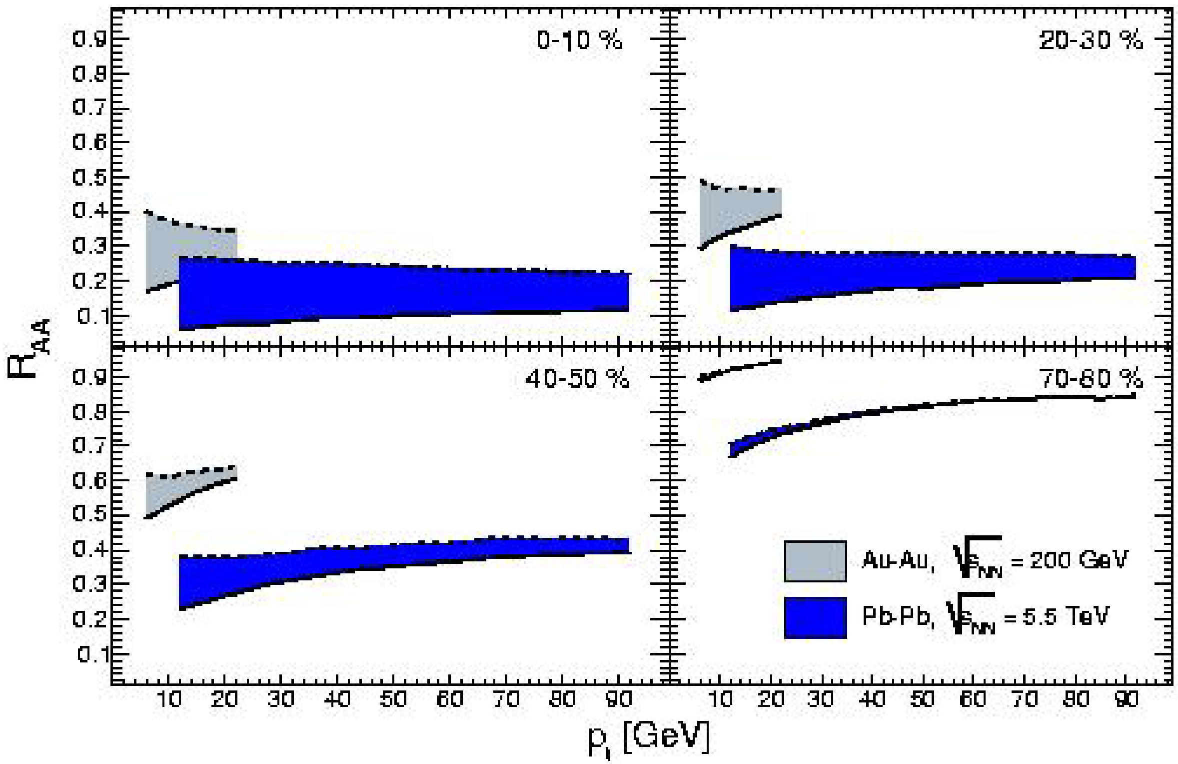
I. Vitev, M. Gyulassy, PRL 89 (2002) 252301



From RHIC to LHC (III)

Centrality dependence of nuclear suppression

Dainese, Loizides, Paic, hep-ph/0406201



The "corona" effect

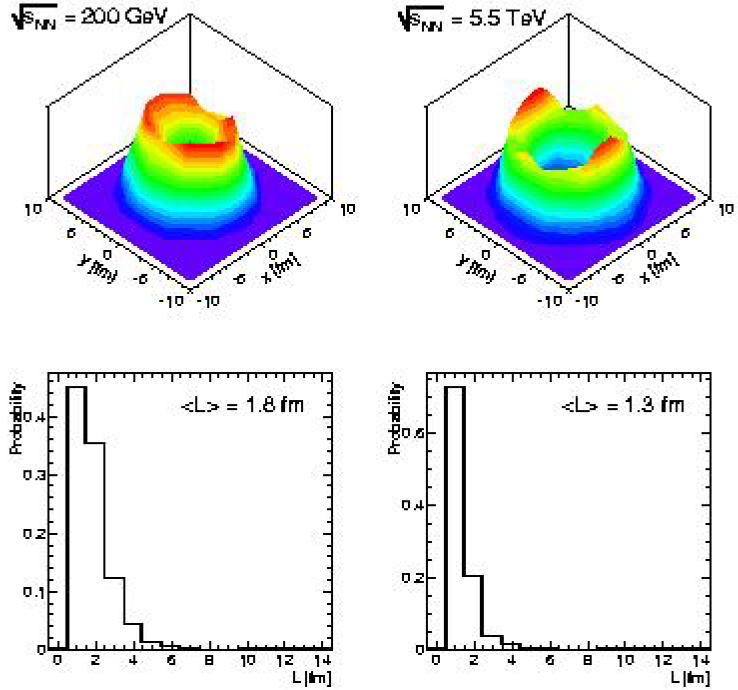
For power law spectrum ($p_T^{-\nu}$):

$$R_{AA}(p_T) \square \frac{(p_0 + p_T)}{R\,\hat{q}\,p_T^{\nu}}$$

Volume / ***R*** = surface

Emission of hard hadrons is predominantly from a thin surface layer. But "jets" still originate from throughout the volume:

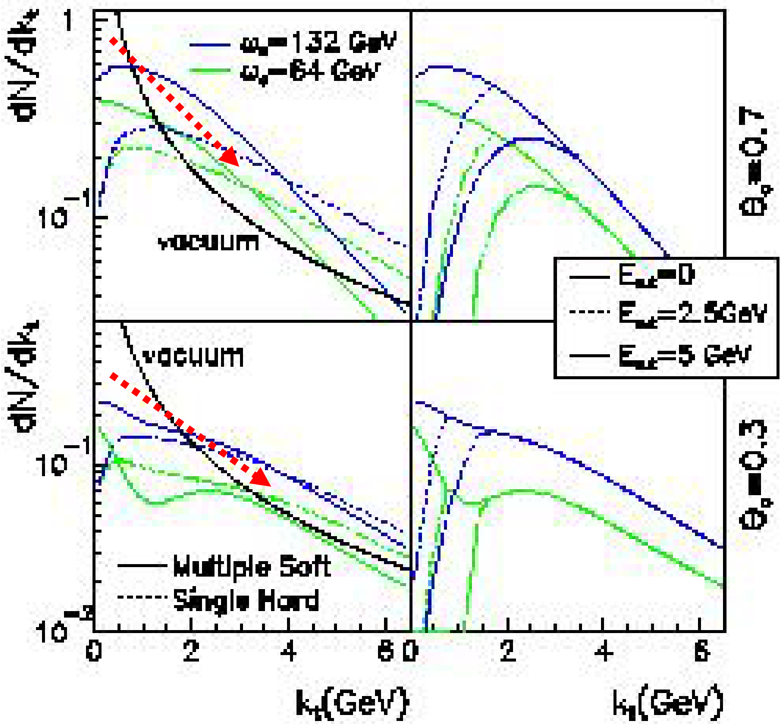
$$R_{AA}^{\text{had}} \square \; R_{AA}^{\text{jet}}$$

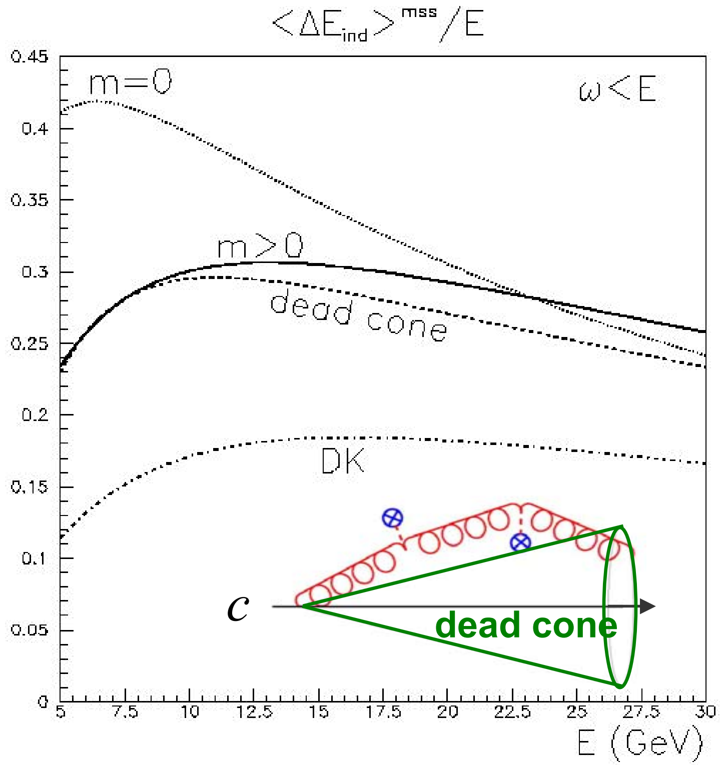


"Jet quenching" is a misnomer

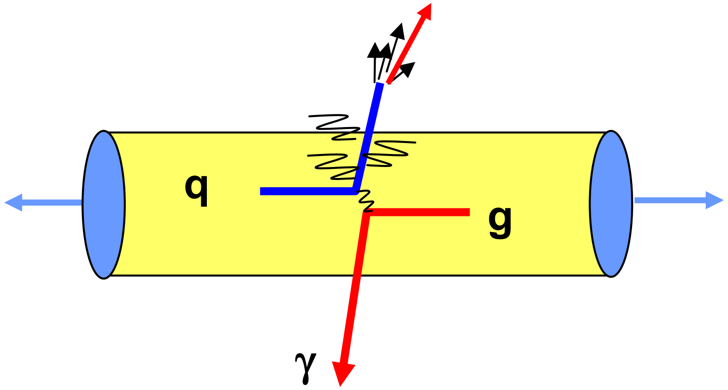
Jet energy is not lost, just redistributed inside the jet cone to larger k_t (LPM effect).

Heavy quarks lose less energy than light quarks (in vacuum as well as in dense matter).

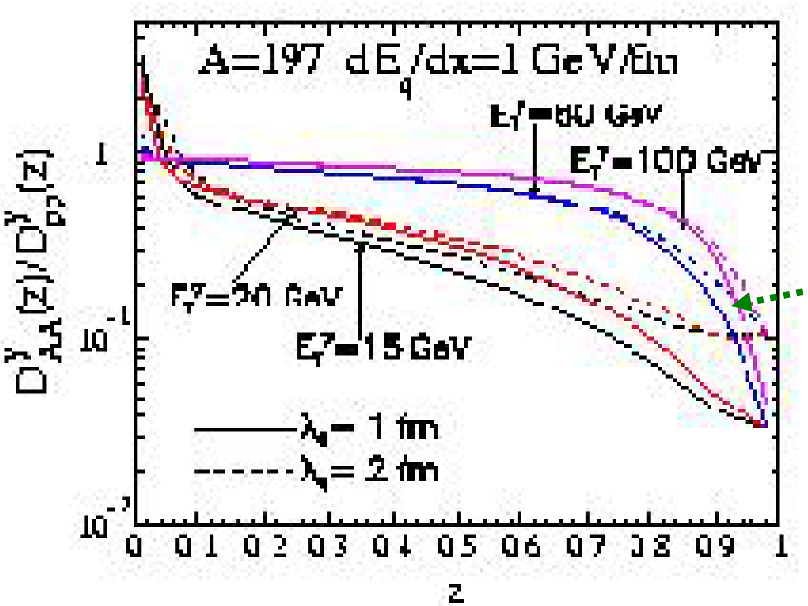




Photon tagged jets



High-energy photon defines energy of the jet, but remains unaffected by the hot medium.



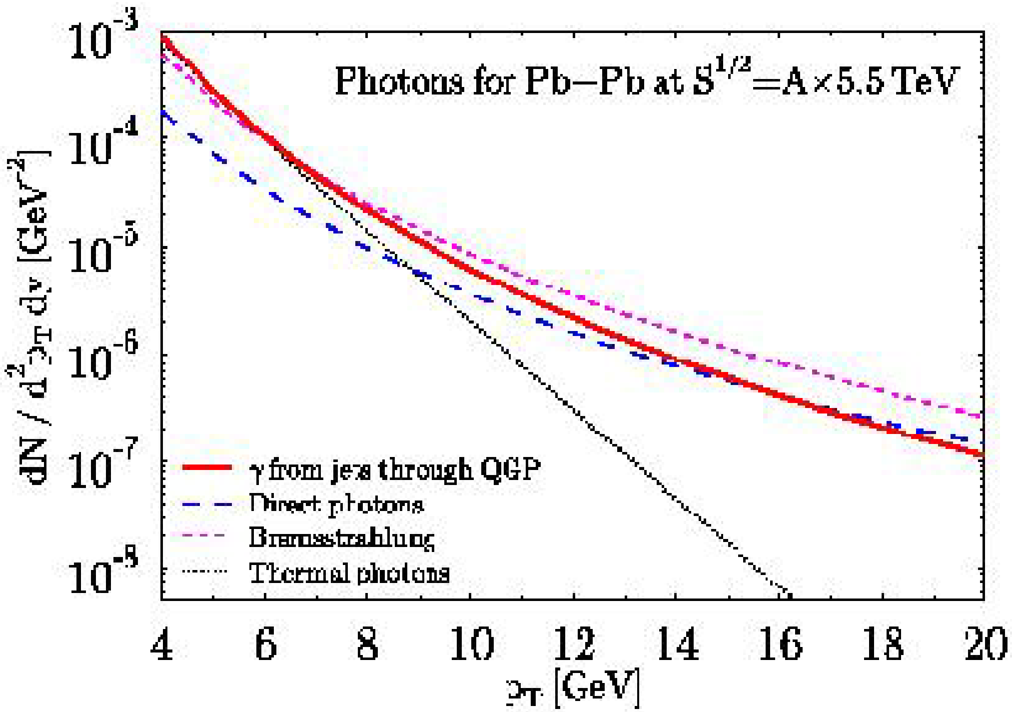
Parton energy loss is measured by the suppression of the fragmentation function *D*(z) near z→1 .

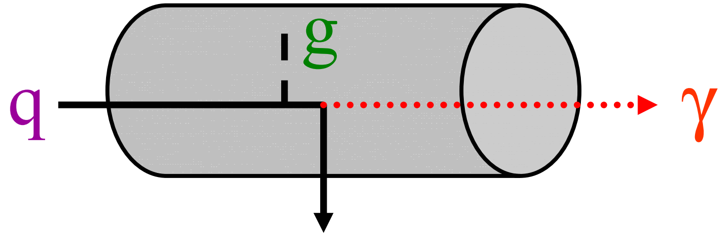
Measuring the density

$$q + g \rightarrow q + \gamma$$

$$q + \bar{q} \rightarrow g + \gamma$$

Backscattering probes the plasma density and initial parton spectrum





$$\frac{d\sigma}{dt} = \frac{\pi \alpha \alpha_s e_q^2}{s^2}\left(\frac{u}{s} + \frac{s}{u}\right)$$

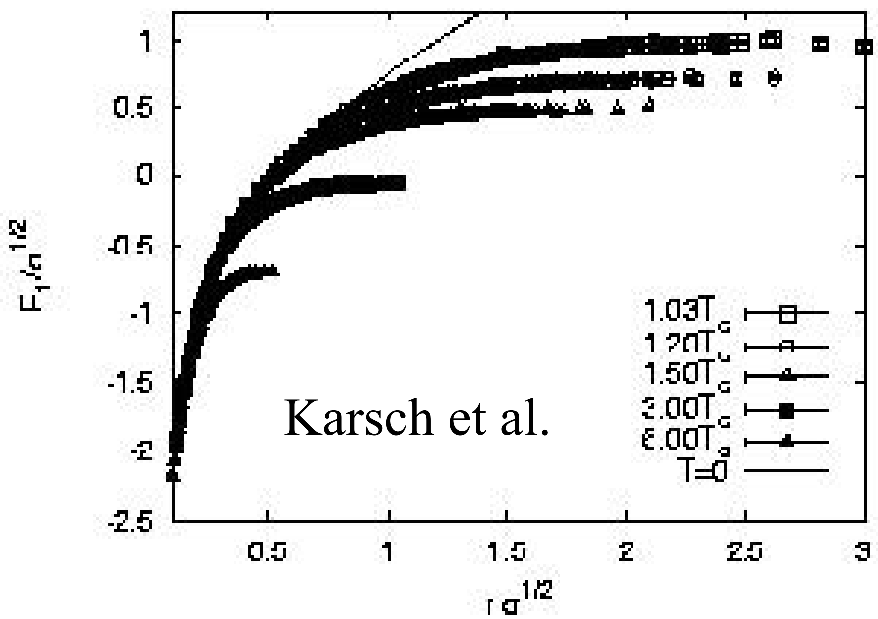
R.J. Fries, BM, D.K. Srivastava, PRL 90 (2003) 132301

J/Ψ suppression ?

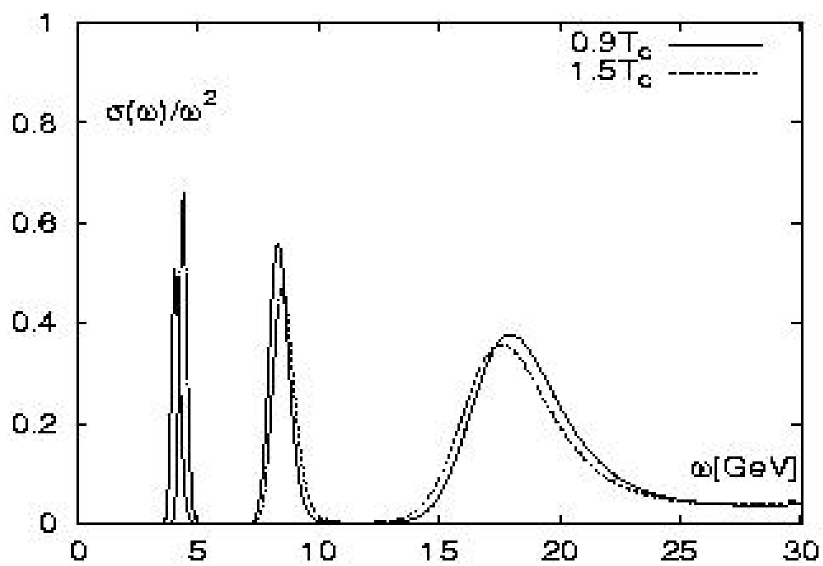
V_{qq} is screened at scale $(gT)^{-1}$ → heavy quark bound states dissolve above *some* T_d.

Quenched LQCD simulations, with analytic continuation to real time, suggest $T_d \geq 2T_c$!

Color singlet free energy



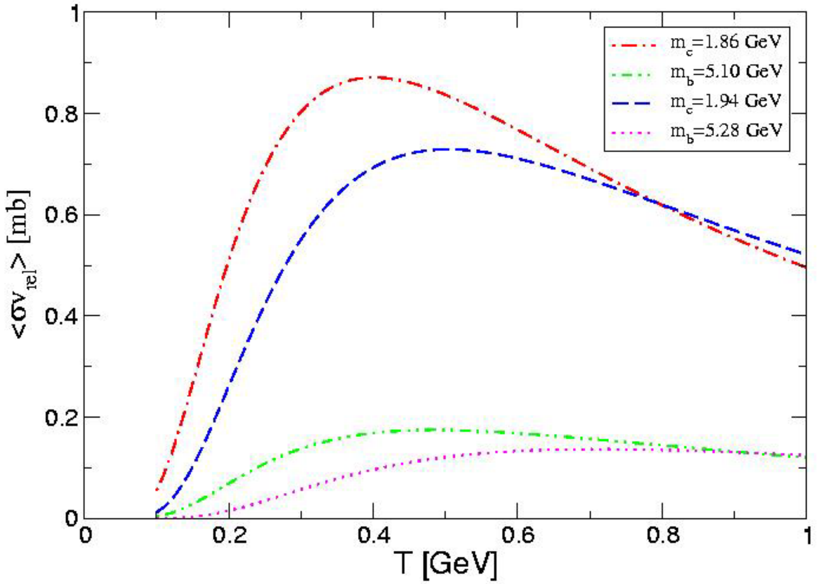
S. Datta et al. (PRD 69, 094507)

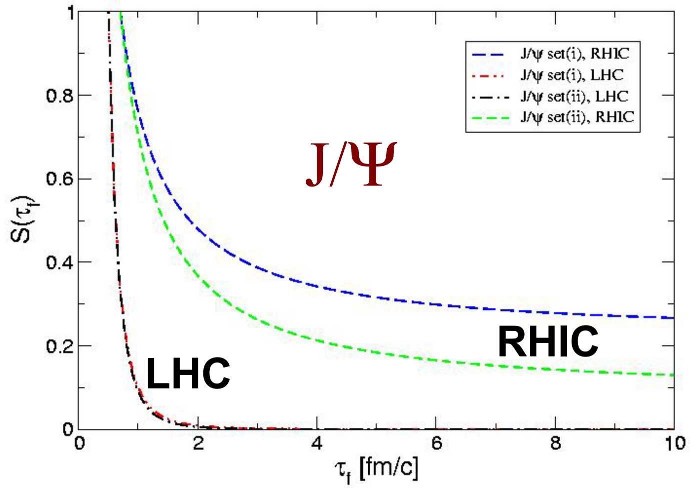


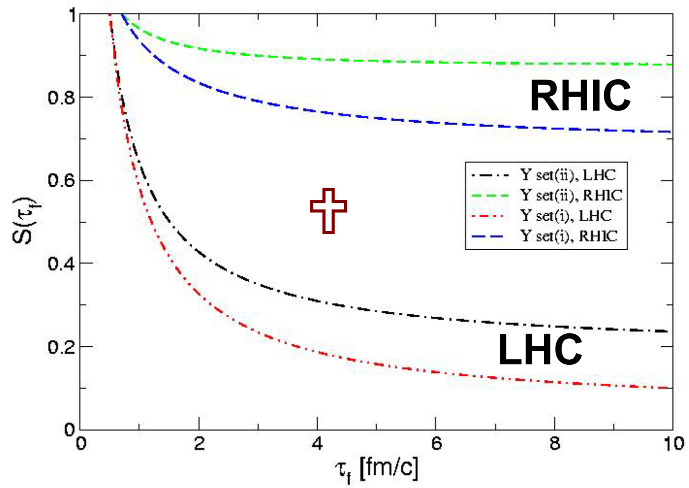
Quarkonium suppression !!

- Ionization of bound J/Ψ and ϒ in plasma by thermal gluons:

HPC collab. hep-ph/0311048

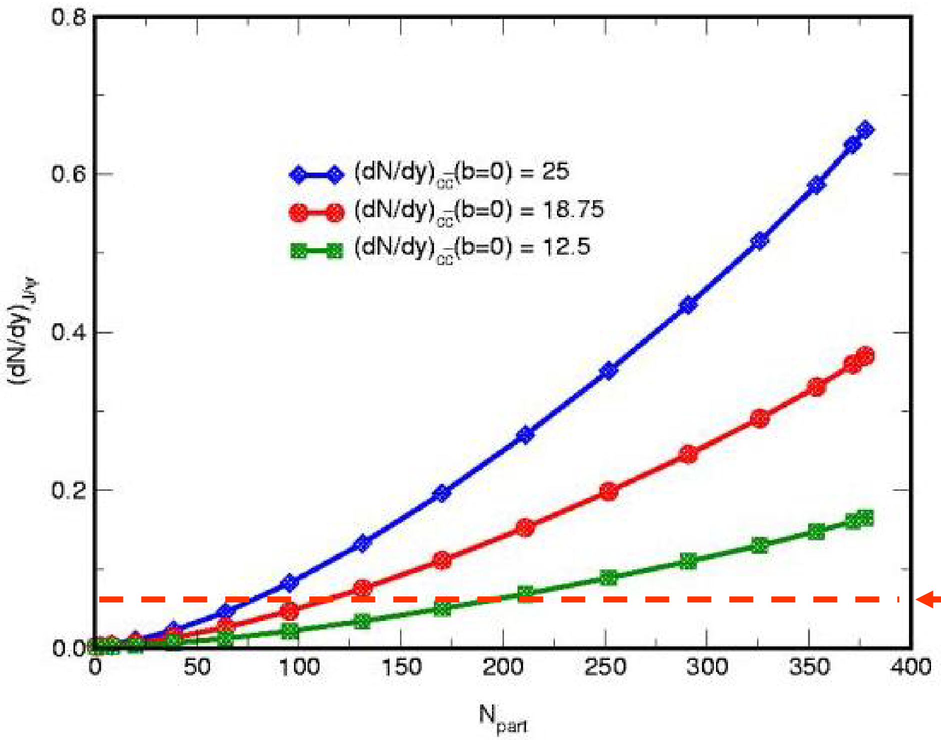




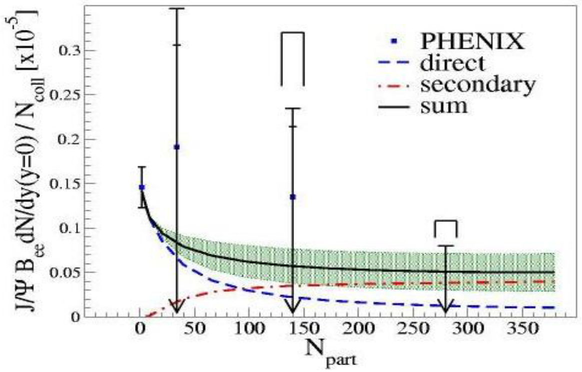


Charmonium recombination

But deconfined *c*-quarks and *c*-antiquarks can recombine and form new J/Ψ at hadronization. Statistical model yields predict J/Ψ enhancement.



Braun-Munzinger et al.;
R.Thews, hep-ph/0302050



Direct production without nuclear suppression

Summary

- SPS: First glimpse ("evidence") of the QGP
- RHIC: Discovery of the (s)QGP ?!
- LHC: Exploration and quantitative confirmation of the QGP facilitated by plentiful hard probes, which are accessible to theoretical treatment !

- Specific questions:
  - How does dE/dx depend on energy density?
  - How is the fragmentation function modified?
  - Are *c* (and *b*) quarks thermalized?
  - Gluon saturation in nuclei at small *x*