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

LHC

initial state

RHIC

LHC

quark-gluon plasma

Dense Hadronic Medium
\[ n_\pi = 0.5 \text{ fm}^3 \]
\[ n_b = 0.38 \text{ fm}^3 = 2.5 n_0 \]

Fodor, Katz, hep-lat/0106002

PBM, JS, Nucl. Phys.

A606 (1996) 220

Dilute Hadronic Medium
\[ n_\pi = 0.34 \text{ fm}^3 \]
\[ n_b = 0.038 \text{ fm}^3 = 1/4 n_0 \]

atomic nuclei

neutron stars

baryonic chemical potential \( \mu_B \) [GeV]
From hadrons to QGP

\[ \varepsilon = \frac{\pi^2}{30} g_{\text{DOF}} T^4 \]

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 $\alpha_s^{\text{eff}} \approx 0.5$.

- 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 (\(?^0\))
- Thermal \(l^+l^-\) and \(\gamma\) radiation
- Hadronization = quark recombination
- Critical fluctuations (momentum, baryon number)
- Collective vacuum excitations (DCC, etc.)
- Disappearance of \(?\), \(\Upsilon\) 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)

Photons

Chemistry

Charmonium

Suppression/Enhancement

$V_2$

Jet quenching

Spectra

Moderate stopping and dominant longitudinal expansion
What’s different (better) at the LHC ?

Much larger “dynamic range” compared to RHIC

• Higher energy density $\varepsilon_0$ at earlier time $\tau_0$: “sQGP” → 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) → Initial state effects less important.
• QGP even more dominant compared with final-state hadron interactions.
Parton saturation at small $x$

Gribov, Levin, Ryskin ’83:

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

“color glass condensate”

parton density $\times$ 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
**$E_{\text{CM}}$ dependence of $dN/dy$**

Geometric scaling à la Golec-Biernat & Wüsthoff

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

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

(Armesto et al. hep-ph/0407018)

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

$$dN / dy \sim Q_{\text{sat},A}^2 \pi R_A^2$$

$$\Rightarrow T_{\text{in}}^{\text{LHC}} \approx \sqrt{3} T_{\text{in}}^{\text{RHIC}} \approx 600 \text{ MeV}$$
$E_{CM}$ 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 $\tau_{in} = 0.2 \text{ fm/c}$
High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: \( \frac{dE}{dx} \sim \rho L \left\langle k_T^2 \right\rangle \)

Scattering centers = color charges

Can be described as medium effect on parton fragmentation:

\[
D_{p\rightarrow h}(z, Q^2) \rightarrow \tilde{D}_{p\rightarrow h}(z, Q^2) \approx D_{p\rightarrow h}\left( \frac{z}{1 - \frac{\Delta E}{E}}, Q^2 \right)
\]
Energy loss in QCD

Scattering “power” of QCD medium:

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

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:

\[ \hat{q} \Rightarrow \hat{q}_{\text{eff}} = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau (\tau - \tau_0) \hat{q}(r_\tau, \tau) \]

Density of scattering centers

Property of medium (range of color force)
Quark recombination

Fragmentation

\[
\frac{\text{Baryon}}{\text{Meson}} \ll 1
\]

Recombination

\[
\frac{\text{Baryon}}{\text{Meson}} \approx 1
\]
Recombination vs. Fragmentation

\[ w_\alpha(r, p) = \text{Quark distribution function at “freeze-out”} \]

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

Recombination:

\[ w_\alpha(R, xP^+)w_\beta(R, (1-x)P^+) = \exp(-P \cdot u / T) \]

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

Fragmentation…

\[
E \frac{dN_h}{d^3 p} = \int d\sigma \ \frac{p \cdot u}{(2\pi)^3} \int_0^1 dz \sum_{\alpha} w_\alpha(r, \frac{1}{z} p)D_{\alpha \rightarrow h}(z)
\]

… never competes with recombination for an exponential spectrum:

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

… but wins out at large \( p_T \), where the spectrum is a power law \( \sim (p_T)^{-b} \)
Fit to RHIC hadron spectrum

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

$T_{\text{eff}} = 350$ MeV

blue-shifted temperature

pQCD spectrum shifted by 2.2 GeV
Hadron production at the LHC

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

$\beta_r = 0.75$

$\beta_r = 0.85$

$\beta_r = 0.65$

includes parton energy loss
Energy loss at RHIC

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

\[ \langle \hat{q} \rangle \approx 10 \text{ GeV}^2/\text{fm} \]

(Dainese, Loizides, Paic, hep-ph/0406201)
From RHIC to LHC (I)

Eskola, Honkanen, Salgado & Wiedemann, hep-ph/0406319
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 ($p_T^{-\nu}$):

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

Volume / $R = \text{surface}$

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

$$ R_{AA}^{\text{had}} \ll R_{AA}^{\text{jet}} $$
“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).

![Graph showing energy loss distribution](image)
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 $z \rightarrow 1$. 
Measuring the density

\[ q + g \rightarrow q + \gamma \]

\[ q + \bar{q} \rightarrow g + \gamma \]

Backscattering probes the plasma density and initial parton spectrum

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

$V_{qq}$ 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**

Karsch et al.

S. Datta et al. (PRD 69, 094507)
Quarkonium suppression !!

- Ionization of bound $J/\Psi$ and $\Upsilon$ in plasma by thermal gluons:

  HPC collab. hep-ph/0311048
Charmonium recombination

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


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 $x$