Heavy Ion Physics at the LHC

Scottish Universities' Summer School 57

St. Andrews  August 18 – 29, 2003

- QCD at high temperature: the quark-gluon plasma
- Probes of ultradense matter
- Structure of nuclei at small $x$
- Matter formation and breakup
- Insights from the first 3 years of RHIC
- The LHC heavy ion programme
Part I

QCD at high temperature:
The quark-gluon plasma (QGP)
Matter under extreme conditions

1. Squeeze slowly → Cold, dense matter
2. Squeeze fast → Hot, “dense” matter

(1) is much more difficult to do than (2): Beyond nuclear matter density ($\rho_B > \rho_0 = 0.15 \text{ fm}^{-3}$) only in the core of collapsed (neutron) stars.

(2) Happened once: $t < 20 \mu s$ after it all began.
Can also be achieved by colliding nuclei at high energy.
20 years of history: Bevalac, AGS, SPS, RHIC → LHC.
Goal: energy density $e \gg M_N ?_0 = 0.14 \text{ GeV/fm}^3$. 
The Big Bang “experiment”
Thermal history of the universe
The “Little Bang” experiment
Au+Au Collision at RHIC
The “Little Bang”
Quantum chromodynamics

\[
L_{\text{QCD}} = -\frac{1}{4} \sum_a G_{\mu\nu}^a G^{a\mu\nu} \\
+ \sum_f \overline{\Psi} \gamma^\mu \left( \partial_\mu + g \sum_a A_{\mu}^a \right) \Psi \\
+ \sum_f m_f \overline{\Psi} \Psi
\]
Degrees of freedom

- At extreme (energy) density, particle masses can be neglected relative to the kinetic energy:

\[ \varepsilon = \nu \int \frac{d^3 p}{(2\pi)^3} \frac{E}{e^{-E/T} \pm 1} \quad \text{with} \quad E = \sqrt{p^2 + m^2} \]

\[ \varepsilon = \nu \frac{\pi^2}{30} aT^4 \quad \text{with} \quad a = \begin{cases} \frac{7}{8} \text{ (fermions)} \\ 1 \text{ (bosons)} \end{cases} \]

Quarks: \( \nu = 2 \times 2 \times N_C \times N_F = 12N_F \)

Gluons: \( \nu = 2 \times (N_C^2 - 1) = 16 \)
If QCD had $N_F$ light quark flavors, there would be $(N_F^2 - 1)$ nearly massless Goldstone bosons ("pions"): 

$$\nu_\pi = N_F^2 - 1$$

For large $N_F$ the pions win out over quarks, but for $N_F = 2-3$ the quarks and gluons win out:

→ at high $T$ matter is composed of a colored plasma of quarks and gluons, not of hadrons!
$\varepsilon = \frac{\pi^2}{30} \nu T^4$

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 there a phase transition?

Most likely: NOT
Crossover of phases

Susceptibilities peak at $T_c$, but do not diverge. Vacuum properties change smoothly, but rapidly $\rightarrow$ “crossover”
A phase transition at high baryon density

\[ T_c(\mu_B) \]

First order phase transition line

Controls baryon density
Color screening

\[-\nabla^2 \phi^a = g \rho_G^a (\phi^b) + g \rho_Q^a (\phi^b)\]

Induced color density

\[\rho^a = \nu \text{Tr} \left[ t^a \int \frac{d^3 p}{(2\pi)^3} \left( e^{-(E+g\phi^b)/T} \pm 1 \right)^{-1} \right] = -\mu^2 \phi^a\]

with \(\mu_G^2 = (gT)^2\), \(\mu_Q^2 = \frac{N_F}{6} (gT)^2\)

Static color charge (heavy quark) generates potential

\[\phi^a = t^a \frac{\alpha_s}{r} e^{-\mu r}\]
Color screening (lattice)

Screened potential

Perturbative screening

$r$ in units of 0.45 fm

Linear confining potential disappears above $T_c \approx 160$ MeV
The perturbative QGP

At $T > 2T_c$ the QGP looks perturbative (neglect $m_q$):

\[
\varepsilon = \left(1 - \frac{15\alpha_s}{4\pi}\right)\frac{16\pi^2}{30} T^4 + \left(1 - \frac{50\alpha_s}{21\pi}\right)\frac{21\pi^2}{30} N_f T^4
\]

\[
+ \sum_q \left(1 - \frac{2\alpha_s}{\pi}\right) \frac{3}{\pi^2} \mu_q^2 (\pi^2 T^2 + \frac{1}{2} \mu_q^2) + \cdots
\]

Expansion in $\alpha_s$ does not converge, rather one must include interactions into the particle modes (“quasiparticles”) as basis for the expansion.
Quasiparticles in the QGP

Physical excitation modes at high $T$ are not elementary quarks and gluons, but “dressed” quarks and gluons:

Propagator of transversely polarized gluons

$$D(k, \omega)^{-1} = \omega^2 - k^2 - \frac{1}{2} (gT)^2 \left[ 1 - \frac{1}{2} \left( \frac{\omega}{k} - \frac{k}{\omega} \right) \ln \frac{\omega + k}{\omega - k} \right]$$

$\rightarrow$ Effective mass of gluon:

$$m_G^{*} \xrightarrow{k \to 0} \frac{1}{\sqrt{3}} gT$$

$$m_G^{*} \xrightarrow{k \to 0} \frac{1}{\sqrt{2}} gT$$
QCD phase diagram

LHC

initial state

RHIC

LHC

quark-gluon plasma

Color superconducting quark matter
Part II

Probes of ultra-dense matter
Signatures of a QCD phase change

- Effects of “latent heat” in $(E,T)$ relation
- Effects of large $C_V$ on thermal fluctuations
- Net charge and baryon number fluctuations
- Enhancement of $s$-quark production
- Thermal $l^+l^-$ and $\gamma$ radiation
- Disappearance of light hadrons ($^0$)
- Dissolution of $\Upsilon$, $\Upsilon$ bound states
- Large energy loss of fast partons (jet quenching)
- Bulk hadronization
- Collective vacuum excitations (DCC)
Thermodynamics near $T_c$

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

Additional energy is used up to liberate new degrees of freedom (color!) in transition region.
Plateau is an indicator of latent heat of phase transformation.
Anisotropic or “elliptic” flow is defined for $b > 0$ collisions.

Elliptic flow “measures” the transverse pressure at very early times ($\tau < 3 \text{ fm/c}$).

**Force** = $-\nabla P$

More flow in collision plane than perpendicular to it.

- Reaction plane analysis
  $$\frac{dN}{d\phi} \sim 1 + 2v_2\cos 2(\phi_{\text{lab}} - \Psi_{\text{plane}})$$

- Two-particle correlations
  $$\frac{dN}{d(\phi_1 - \phi_2)} \sim 1 + 2v_2\cos(2[\phi_1 - \phi_2])$$

- Four-particle correlations
  $$\langle\exp[i2(\phi_1 + \phi_2 - \phi_3 - \phi_4)]\rangle = -v_2^4$$
Strangeness enhancement…

…probes chiral symmetry restoration and deconfinement

Mass (MeV)

NA57 data

(sss)
(qss)
(qqs)
Charmonium suppression…

$V_{QQ}(r)$ is screened at distance scales $r > (gT)^{-1}$

→ heavy quark bound states dissolve above some $T_d$:

$J/\Psi$ suppression.

But: $J/\Psi$ may survive above $T_d$ as a narrow resonance, as recent lattice calculations of the spectral function suggest.

Karsch et al.
Or charmonium enhancement?

If more than one c-quark pair is formed within $\Delta y \approx 1$, and if the c-quarks are thermalized, $J/\Psi$ may be formed by recombination:

This could easily result in a large enhancement of $J/\Psi$ production under LHC conditions. Depends critically on the stopping power for c-quarks (less than for light quarks)
Data are consistent with:
Hadronic comover breakup w/o QGP
Limiting suppression via surface emission
Dissociation + thermal regeneration
High-energy parton loses energy by rescattering in dense, hot medium.

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

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

Gluon radiation is suppressed due to multiple scattering by LPM effect. LPM suppression differs from QED due to rescattering of the radiated gluon. Critical frequency:

\[ \omega_c = \frac{1}{2} \hat{q} L^2 \quad \text{with} \quad \hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \]

Energy loss spectrum for a fast parton is \((\tilde{\alpha} = 2\alpha_s C_2 / \pi)\):

\[ \varepsilon D(\varepsilon) = \sqrt{\tilde{\alpha}^2 \omega_c \over 2\varepsilon} \exp \left( -\frac{\pi \tilde{\alpha}^2 \omega_c}{2\varepsilon} \right) \]

→ Radiative energy loss is suppressed like \((\omega_c/E)^{1/2}\) overall, and more strongly at small \(\varepsilon\) (Landau-Pomeranchuk-Migdal effect).
Energy loss in QCD - II

Scattering “power” of QCD medium:

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

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

\[ \Delta p_T \approx -\alpha_s \sqrt{\pi \hat{q} L^2} \frac{p_T}{\nu} \]

Including expansion:

\[ \hat{q} L^2 \Rightarrow \hat{q}_0 L_{\text{eff}}^2 = \frac{2\hat{q}_0}{\rho(r)} \int \tau d\tau \rho(r, \tau) \]
Analytical model: Surface emission

Quenching factor: \[ \frac{d\tilde{N}}{d^2p_T} = Q(p_T) \frac{dN}{d^2p_T} \]

\[ Q(p_T) \approx \frac{2(p_0 + p_T)}{\pi R\eta\rho(\nu - 1)p_T^\mu} \]

Volume / \( R \) = surface

\( \eta = \text{QCD energy loss parameter:} \)

\[ \eta = \pi\alpha_s^2 \int q^2 dq^2 \left( \frac{d\sigma}{dq^2} \right) = \frac{3}{2} C_2 (\pi\alpha_s^2)^2 \ln \left( \frac{q_{\text{max}}^2}{\mu_D^2} \right) \]

\( \eta \approx 0.5 \ln(...) \) for gluons; \( \eta \approx 0.25 \ln(...) \) for quarks
Jet correlations

Jet correlations provide a mechanism for generating an anisotropy with respect to the collision plane for hadron production in non-central collisions. The predicted anisotropy is less than 10%.

\[ Q \sim \Delta R / R \]

\[ Q' \sim (\Delta R / R)^2 = Q \times Q_{asj} \]

Away-side jet

Back-to-back jets (leading hadrons) are quadratically suppressed!

Quenching provides a mechanism for generating an anisotropy with respect to the collision plane for hadron production in non-central collisions. The predicted anisotropy is less than 10%.
Part III

The initial state:

Structure of nuclei at small $x$
Au+Au Collision at RHIC
Space-time picture of a HI collision
Initial state: The naïve picture

For partons of flavour $a$ in a nucleus the distribution is given by:

$$ F_a (\vec{r}, \vec{k}) = \sum_{i=1}^{N_h} P^N_{a i} (\vec{k}, \vec{P}, Q_0^2) \times R^N_{a i} (\vec{r}, \vec{R}) $$

- with the initial momentum distribution:
  $$ P^N_{a i} (\vec{k}, \vec{P}, Q_0^2) \propto F^N_a (x, Q_0^2) \times ?^A_a \times g(\vec{k}_\perp) \times d(P_z - P) \times d^2(\vec{P}_\perp) $$
  ($Q_0$: initial resolution scale, $?^A_a$ optional shadowing, $g$: opt. primordial $k_T$)

- and the initial spatial distribution:
  $$ R^N_{a i} (\vec{r}, \vec{R}) = d(\vec{R}_{AB}^\perp - \vec{b}) \times \left[ h^N_{a i} (\vec{r}) \times H^N_{N i} (\vec{R}) \right]_{\text{boosted}} $$
  - $H_{N i}$: distribution of nucleons in nucleus (e.g. Fermi-Distribution)
  - $h_a$: distribution of partons in hadron (based on elastic form factor)
Initial state II: Parton momenta

- flavour and $x$ are sampled from PDFs at an initial scale $Q_0$ and low $x$ cut-off $x_{\text{min}}$
- initial $k_t$ is sampled from a Gaussian of width $Q_0$ (case of no initial state radiation)
Initial State III: Spatial Distribution

- partons are spatially distributed according to elastic form factor of nucleon:
  \[ h_a^N(r) = \frac{1}{8\pi\omega^3} e^{-r/\omega} \text{ with } \omega = 0.24 \text{ fm} \]

- Lorentz contraction utilizing \( y^* \); on-shell rapidity of partons, or \( r_z \sim 1/p_z \)
Parton saturation at small $x$ 

\[ \sim \frac{1}{Q^2} \]

\[
\text{DGLAP splitting:} \\
GLRMQ \text{ parton fusion:}
\]

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

\[
\Rightarrow Q_{\text{sat}}^2 \sim A^{1/3} x^{-\lambda}
\]

$\lambda \approx 0.5$ from HERA data
Saturation suggests a picture of quasiclassical glue fields at small $x$, where $gA \sim k$, and the perturbation expansion is in powers of $\alpha_s$, but not in powers of $gA$. In the extreme limit ($x \rightarrow 0$) the probability distribution of classical color fields is random and completely determined by the saturation scale:

$$P[A] \sim \exp\left(- \int d^2 x_\perp g^2 A^2(x_\perp)/Q_s^2 \right)$$

This ensemble of fields is called \emph{color glass condensate}. $Q_s$ evolves with $x$ and satisfies a nonlinear RG equation, generalizing the BFKL equation, which is universal in the limit $x \rightarrow 0$, i.e. independent of the hadron species (meson, baryon, or even nucleus).
Parton saturation III

How many of these partons are “liberated” due to interactions when two nuclei collide?

In the limiting case \((x \to 0\) and \(s \to \infty\)) all partons are liberated, but PCM calculations suggest that the liberation probability drops for partons at small \(x\) at fixed collision energy \(s\).
Net baryon number content of a hadron or nucleus:

\[ B(x) = \frac{1}{3} \sum_q [f_q(x) - f_{\bar{q}}(x)] \]

- net baryon contribution in the initial state (valence quark distribution) extends to small x, and accounts for a net baryon density at mid-rapidity \( dN/dy \approx 5 \)
- parton rescattering in the PCM then fills up the mid-rapidity region to explain the net baryon density observed in Au+Au collisions at RHIC.
- At the LHC, the midrapidity region is almost completely net baryon free.
Part IV

Matter formation and breakup
Space-time picture of a HI collision

Hadronization

Equilibration

Expansion

Hard scattering

Freeze-Out

time

Hadron Gas

QGP

$T_c$
* **Hard scattering:** Occurs on short time scale $\Delta t \sim 1/Q < 1/Q_s$ and is described by pQCD.

* **Equilibration:** Can be described by multiple parton scattering in the PCM or by chaotic dynamics of classical color fields. Characteristic time scale: $\Delta t \sim 1/g^2 T$.

* **Expansion of the QGP:** Described by relativistic fluid dynamics. Simplest case = boost invariant longitudinal flow (Bjorken model) gives cooling like $T(t) \sim 1/t^{1/3}$.

* **Hadronization:** Slow or fast – that is the question!
Hadron formation

Fragmentation

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

Recombination

\[
\frac{\text{Baryon}}{\text{Meson}} \approx 1
\]
Assumptions:

- Quarks and antiquarks recombine into hadrons locally “at an instant”:
  \[ q\bar{q} \rightarrow M \quad qqq \rightarrow B \]
- Gluons get absorbed into valence quarks \textit{before} hadronization
- Competition between fragmentation and recombination;

Hadron momentum \( P \) much larger than internal momentum \( \langle \Delta p^2 \rangle \) of the quark wave function of the hadron;

Parton spectrum has thermal part (valence quarks) and a power law tail (quarks and gluons) from pQCD.
Recombination of thermal quarks

Relativistic formulation using hadron light-cone frame:

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

\[
E \frac{dN_M}{d^3 P} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha, \beta} \int dx w_\alpha (R, xP^+) \bar{w}_\beta (R, (1-x)P^+) \left| \tilde{\varphi}_M (x) \right|^2
\]

\[
E \frac{dN_B}{d^3 p} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_{\alpha, \beta, \gamma} \int dx dx' w_\alpha (R, xP^+) w_\beta (R, x' P^+) w_\gamma (R, (1-x-x')P^+) \left| \tilde{\varphi}_B (x, x') \right|^2
\]

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

\[
w_\alpha (R, xP^+) \bar{w}_\beta (R, (1-x)P^+) = \exp(-P \cdot u / T) \quad \text{Meson}
\]

\[
w_\alpha (R, xP^+) w_\beta (R, x' P^+) w_\gamma (R, (1-x-x')P^+) = \exp(-P \cdot u / T) \quad \text{Baryon}
\]
Recombination vs. Fragmentation

Fragmentation:

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

Recombination…

\[ w_\alpha (r, xP^+) \bar{w}_\beta (r, (1-x)P^+) = \exp (-P \cdot u / T) \] \text{ Meson}

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

… always wins over fragmentation for an exponential spectrum:

\[ \exp (-P \cdot u / T) > \exp (-P \cdot u / zT) = w (P / z) \]

… but loses at large \( p_T \), where the spectrum is a power law \( \sim (p_T)^{-b} \)

Apparent paradox: At given value of \( p_T \)…

- The average hadron is produced by recombination
- The average parton fragments
Model fit to hadron spectrum

R.J. Fries, BM, C. Nonaka, S.A. Bass (PRL in print)

\( T_{\text{eff}} = 350 \text{ MeV} \) fitted to spectrum

\( 2.2 \text{ GeV} \)

Charged Hadrons at 200 GeV

Recomb+Fragm

Fragm

Recomb

shifted pQCD spectrum
Part V

Insights:

The first 3 years of RHIC
RHIC & its detectors

CM energy
500 GeV for p-p
200 GeV (per N-N) for Au-Au

Luminosity
Au-Au: $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
p-p : $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
The Solenoidal Tracker At RHIC

- Magnet
- Coils
- TPC Endcap & MWPC
- ZCal
- Endcap Calorimeter
- Barrel EM Calorimeter
- RICH
- Time Projection Chamber
- Silicon Vertex Tracker *
- FTPCs
- Vertex Position Detectors
- Central Trigger Barrel
- * yr.1 SVT ladder
- + TOF patch

2000  2001  2003
PHENIX (central part)

Not showing the North and South muon arms
Flavour equilibration

The statistical (thermal) model for hadron abundances works well with \( T \approx T_c \).
Blast wave parametrization fit for STAR data works well for $\pi,K,P,\Lambda$. Multiply strange baryons $\Xi,\Omega$ show less, but still substantial flow: These particles with smaller interaction cross section decouple earlier; much flow is generated before the hadronization.

$$\beta = \tanh \rho$$
\( \pi^0 \) spectra in peripheral \( \text{AuAu} \) and \( pp \)
Suppression of high-$p_T$ hadrons in Au+Au collisions

PHENIX Data: Identified $\pi^0$

$R_{AA}^{\pi^0}$ 200 GeV:
- $\Delta o < 0.75$, $|\varphi_{ij}| < 6$ GeV/c
- $\Delta o > 2.25$, $|\varphi_{ij}| < 6$ GeV/c

STAR

Same side jet

Away side jet
Charged hadron suppression

suppression increases with centrality

Au+Au 200GeV

PHENIX preliminary

$R_{AA}$ vs $p_T$ [GeV/c]
Suppression patterns: baryons vs. mesons

What makes baryons different from mesons?
HIGH-ENERGY PHYSICS: Wayward Particles Collide With Physicists’ Expectations

Charles Seife

EAST LANSING -- At a meeting here last week, researchers announced results that, so far, nobody can explain. By slamming gold atoms together at nearly the speed of light, the physicists hoped to make gold nuclei melt into a novel phase of matter called a quark-gluon plasma. But although the experiment produced encouraging evidence that they had succeeded, it also left them struggling to account for the behavior of the particles that shoot away from the tremendously energetic smashups.

![Graph showing p/π ratio with data points for different percentage ranges and two regions marked as central and peripheral.](image-url)
Hadron spectra I

Graphs showing the distribution of particle yields as a function of transverse momentum ($P_T$), with different curves representing various processes such as recombination, fragmentation, and combinations thereof. The graphs compare data from PHENIX experiments with STAR data, highlighting differences and overlaps in the observed particle spectra.
Hadron spectra II

The image shows four subplots comparing the transverse momentum ($P_T$) distributions of different hadrons. The $y$-axis represents the normalized distribution as $1/(2\pi P_T) dN/dP_T$ in (GeV$^2$). The $x$-axis represents $P_T$ in GeV. Different hadrons and their distributions are compared, with lines and markers indicating various experimental data points and theoretical predictions.
• R+F model describes different $R_{AA}$ behavior of protons and pions
• Jet quenching becomes universal in the fragmentation region
Azimuthal anisotropy \(v_2\)

**Semiperipheral collision**

Coordinate space: initial asymmetry

Momentum space: final asymmetry

\[ v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right) \]

Collective flow behavior extends to higher \(p_T\) for baryons (p,\(\Lambda\)) than mesons (\(\pi, K\))

Mesons and baryons behave differently
Does $v_2$ reflect parton flow?

Recombination model suggests that hadronic flow reflects partonic flow ($n = \text{number of valence quarks}$):

\[ v_{2\text{had}} \approx nv_{2\text{part}} \]

\[ p_{T\text{had}} \approx np_{T\text{part}} \]

Provides measurement of partonic $v_2$!
d+Au compared with Au+Au

Proton/deuteron nucleus collision

Nucleus-nucleus collision

Graph showing the ratio R as a function of p_T (GeV/c) with different data points and error bars.
• Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
Azimuthal distributions

No back-side jet in central Au+Au
CONCLUSION

The strong suppression of the inclusive yield and back-to-back correlations at high $p_T$ previously observed in central Au+Au collisions are due to final-state interactions with the dense medium generated in such collisions.
Part VI

The LHC heavy ion programme
What’s different (better) at the LHC?

Much larger “dynamic range” compared to RHIC

• Higher energy density $\varepsilon_0$ at earlier time $\tau_0$.
• 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 more dominant over final-state hadron interactions.
$E_{CM}$ dependence of $dN/dy$, $dE/dy$

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

Overestimate of growth of $dN/dy$, $dE/dy$ with $E_{CM}$??
Jet quenching at the LHC
Hadron production at the LHC

R.J. Fries et al.

\( r = 0.75 \)

\( r = 0.85 \)

\( r = 0.65 \)

Includes estimated parton energy loss
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

One dedicated HI experiment: ALICE
One pp experiment with a HI program: CMS
One pp experiment considering HI: ATLAS
LHC running conditions for Pb+Pb

- CM energy: 5.5 TeV/NN

- Luminosity: \( L_{\text{max}} = 1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \)

- Charged multiplicity
  - Estimates \( dN/dy = 2 - 3000 \)
  - Design for \( dN_{\text{ch}}/dy|_{\text{max}} = 8000 \)

- Event rate:
  - 8000 minimum bias coll./s
  - \( 10^9 \) events/year
  - 1% recorded
The ALICE Experiment

- **HMPID**: PID (RICH) @ high $p_t$
- **TOF**: PID
- **TRD**: Electron ID
- **PMD**: $\gamma$ multiplicity
- **TPC**: Tracking, $dE/dx$
- **ITS**: Low $p_t$ tracking, Vertexing
- **PHOS**: $\gamma, \pi^0$
- **MUONS**
- **PID (RICH)** @ high $p_t$
ALICE central detector acceptance

- ITS tracking
- TRD TOF
- PHOS
- HMPID
- TPC

**ITS multiplicity**

**Muon arm**: $2.4 < \eta < 4$, **PMD**: $2.3 < \eta < 3.5$, **FMD**: $-5.4 < \eta < -1.6$, $1.6 < \eta < 3$
ALICE event display for Pb+Pb

HMPID
TOF
TRD
TPC
PHOS

2° slice of TPC
full TPC volume

Alice event: 0, Run: 0
Nparticles = 3550  Nhits = 1171925

Alice event: 0, Run: 0
Nparticles = 36276  Nhits = 1943104
Unstable particles: $K^*$, $D^0$

Detection of unstable neutral hadrons via “$V$” decays in TPC.

$K^{*0} \rightarrow K^+ \pi^-$

$D^0 \rightarrow K^- \pi^+$

![Graph](https://example.com/graph.png)

M($K^+\pi^-$) (GeV/c$^2$)
Quarkonia in ALICE

- $\sigma_M = 94.5$ MeV/ c$^2$
at the $\gamma$

- Separation of $\gamma, \gamma', \gamma''$

- Total efficiency
$\sim 75\%$

- Expected statistics (kevents – 1 month): (central, min. bias)

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<tbody>
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<td>$J/\psi$</td>
<td>310</td>
<td>574</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>39</td>
<td>69</td>
</tr>
<tr>
<td>$\gamma'$</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>$\gamma''$</td>
<td>12</td>
<td>22</td>
</tr>
</tbody>
</table>
**Quarkonia in CMS**

**J/ψ**

**Y** family

Yield/month (kevents, 50% eff)
(including barrel and endcaps)

<table>
<thead>
<tr>
<th></th>
<th>Pb+Pb</th>
<th>Sn+Sn</th>
<th>Kr+Kr</th>
<th>Ar+Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>$10^{27}$</td>
<td>$1.7 \times 10^{28}$</td>
<td>$6.6 \times 10^{28}$</td>
<td>$10^{30}$</td>
</tr>
<tr>
<td>J/ψ</td>
<td>28.7</td>
<td>210</td>
<td>470</td>
<td>2200</td>
</tr>
<tr>
<td>ψ'</td>
<td>0.8</td>
<td>5.5</td>
<td>12</td>
<td>57</td>
</tr>
<tr>
<td>Y</td>
<td>22.6</td>
<td>150</td>
<td>320</td>
<td>1400</td>
</tr>
<tr>
<td>Y'</td>
<td>12.4</td>
<td>80</td>
<td>180</td>
<td>770</td>
</tr>
<tr>
<td>Y''</td>
<td>7</td>
<td>45</td>
<td>100</td>
<td>440</td>
</tr>
</tbody>
</table>

Pb+Pb, 1 month at $L=10^{27}$
Jet Reconstruction in CMS

- Subtract average pileup
- Find jets with sliding window
- Build a cone around $E_T^{\text{max}}$
- Recalculate pileup outside the cone
- Recalculate jet energy

Window Algorithm

Full jet reconstruction in Pb+Pb central collisions ($dN/dy \sim 8000$)

**Efficiency**

**Measured jet energy**

**Jet energy resolution**
Balancing γ or Z⁰ vs Jets: Quark Energy Loss

\[ E_{T\text{jet}}, \gamma > 120 \text{ GeV} \text{ in the barrel} \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Barrel+Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>jet+jet, ( E_{T\text{jet}} &gt; 100 \text{ GeV} )</td>
<td>8.7 \times 10^6</td>
</tr>
<tr>
<td>γ+jet, ( E_{T\gamma} &gt; 100 \text{ GeV} )</td>
<td>6 \times 10^3</td>
</tr>
<tr>
<td>( Z(\rightarrow \mu^+\mu^-)+\text{jet}, \ E_{T\gamma}^{\text{jet}}, P_T^{\gamma} &gt; 100 \text{ GeV} )</td>
<td>90</td>
</tr>
<tr>
<td>( Z(\rightarrow \mu^+\mu^-)+\text{jet}, \ E_{T\gamma}^{\text{jet}}, P_T^{\gamma} &gt; 50 \text{ GeV} )</td>
<td>600</td>
</tr>
</tbody>
</table>

Z+jet event in the Heavy Ion collision

\[ dN_{\text{ch}}/dY = 5000 \]

Jet + Z⁰

\[ P_T(Z) = E_T(\text{Jet}) = 100 \text{ GeV} \]

\[ \langle E \rangle = 0 \text{ GeV} \]
\[ \langle E \rangle = 4 \text{ GeV} \]
\[ \langle E \rangle = 8 \text{ GeV} \]

Background

\[ E_T^{\gamma//\pi^0} - E_T^{\text{Jet}} \text{ (GeV)} \]
Conclusions

- ALICE, CMS, (and ATLAS ?) are nicely complementary in their physics capabilities to study hot, ultradense matter created in nuclear collisions.

- Hard probes (jets, heavy quarkonia) extend the range of matter probes into regimes that allow for more reliable calculations.

- Hadrons containing b- and c-quarks will become abundant components in the final state.

- Soft probes are governed by quantitatively so different parameters that conclusions drawn from RHIC data can be put to a serious test.