Quarks and Gluons in Heavy-Ion Collisions: A Quick Tour of Recent Results

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The Mission of Ultra-Relativistic Heavy-Ion Physics: Explore QCD in the High Temperature & High Density Sector

- **Well-tested sectors of QCD**
  - Weak coupling, low parton densities (pQCD):
    - Hard scattering, e.g., jet spectra, ...
  - Strong coupling at $T \approx 0$:
    - Hadron masses from lattice QCD

- **Heavy-Ion Physics**: Strong coupling at $T >> 0$:

- **Prediction from first QCD principles (lattice QCD)**:
  - Transition to deconfined quarks and gluons at $T_c = 150 - 160$ MeV, corresponding to $\varepsilon_c \approx 0.5$ GeV/fm$^3$

Heavy-Ion Physics = QCD thermodynamics

Borsanyi et al., JHEP 1011 (2010) 077

K. Reygers, Quarks and gluons in heavy-ion collisions: A quick tour of recent results
Early universe ($t \approx 10^{-5}$ s), $T_c = 150 - 160$ MeV from lattice QCD

- **RHIC/LHC:** zero net baryon density
- **RHIC energy scan / FAIR-CBM:**
  - Lower energies
  - Study dense, baryon rich nuclear matter
- **FAIR-CBM:**
  - High beam intensities → rare probes

[Diagram showing the phase diagram of QCD matter with regions for quark-gluon plasma, hadron gas, critical endpoint, and ground-state nuclear matter. Baryo-chemical potential $\mu_B$ reflects the net baryon density.]
The Role of the LHC

- **SPS**
  - First hints for deconfined matter

- **RHIC**
  - Strong evidence for deconfined matter
  - Start of characterization of this medium
  - QGP = strongly coupled fluid with small viscosity-to-entropy density ratio ($\eta/s$)
  - Medium opaque to jets

- **LHC**
  - Very high initial energy densities ($\varepsilon > 12 \text{ GeV/fm}^3$) and temperatures
  - Large volume, long QGP lifetime
  - Abundant production of hard probes (jets, heavy-quarks, ...) as tools to probe the medium
  - Test models at 14 times larger cms energies

[B. Muller, J. Schukraft and B. Wyslouch, First Results from Pb+Pb collisions at the LHC, arXiv:1202.3233]
What Do We Want to Learn?

1. Understand the complex phenomenology of A+A collisions
2. Based on that, learn something about QCD thermodynamics

- Proof of deconfinement
- Equation of State
- Number of degrees of freedom
- Viscosity
- Velocity of sound
- Mechanism of parton energy loss
- ...

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Example for Characterization of the Medium: Shear Viscosity to Entropy Ratio ($\eta/s$)

- $\eta/s$ of the QGP smaller than for most of known fluids („perfect liquid“)
- Contact to string theory via gauge gravity duality (AdS/CFT)
- Lower bound from AdS/CFT
  \[
  \frac{\eta}{s} \geq \frac{1}{4\pi} \quad (\hbar = k_B = 1)
  \]
- RHIC data + viscous hydro:
  \[
  \frac{\eta}{s} < (4 - 5) \times \frac{1}{4\pi}
  \]
Gluons liberated from the nuclear wave function during collision

Rapid thermalization: QGP created at \( \sim 1 \text{ fm/c} \)

Longitudinal and transverse expansion describable by almost ideal hydro

Transition QGP \( \rightarrow \) hadrons

Chemical freeze-out at \( T_{ch} \approx T_c, \ (T_c = 150 - 160 \text{ MeV}) \)

Kinetic freeze-out at \( T_{fo} \sim 100 \text{ MeV} \)
Heavy-Ion Experiments at the LHC: ALICE, ATLAS, CMS

**ALICE**
- Robust tracking over large $p_T$ range ($\sim 0.1 \, \text{GeV} < p_T < 100 \, \text{GeV}$)
- Excellent Momentum Reconstruction + Particle ID at low $p_T$ (TPC, TRD, TOF, ...)

**ATLAS/CMS**
- Ideal for high rates / jets
- Important contribution to heavy-ion program

Application of ALICE’s PID capabilities: Identification of anti nuclei up to anti-$^4\text{He}$

[ALICE upgrades, Talk by Thomas Peitzmann, Tuesday]
Global Event Properties
Initial energy density at LHC and RHIC well above $\varepsilon_c \approx 0.5$ GeV/fm$^3$
Centrality Dependence of $dN_{ch}/d\eta$: The Unreasonable Effectiveness of Geometry in A+A Collisions


- Relative Increase from p+p to central A+A identical at RHIC and LHC
- This actually holds for $20 < \sqrt{s_{NN}} < 2760$ GeV
- A bit surprising in two-component models (soft+hard)

Lesson: Geometry Rules
 Identified Particle Spectra: Compelling Evidence for Radial Flow

- Shapes of $p_T$ spectra for particles with different masses indicate radial flow
- Hydro models describe data
- Hydro inspired blast wave fits for central Pb+Pb at LHC:
  - $\langle \beta_{T,\text{flow}} \rangle \approx 0.65 \, c$
  - $\langle \beta_{T,\text{flow}} \rangle_{\text{LHC}} \approx 1.1 \times \langle \beta_{T,\text{flow}} \rangle_{\text{RHIC}}$
  - kinetic freeze-out: $T_{fo} \approx 80 - 100 \, \text{MeV}$

\[ p_T^{\text{w/ flow}} = p_T^{\text{w/o flow}} + \beta_{T,\text{flow}} \gamma T,\text{flow} \, m \]
Particle Ratios in Pb+Pb at the LHC: Chemical Freeze-Out at $T_{ch} \approx T_c$

- Statistical/thermal model
  - Yield $\propto m^{3/2} \exp(-m/T)$
  - chemical potential depending on baryon number, strangeness, and isospin of the particle
  - two free parameters: $T_{ch}$, $\mu_B$

- $T_{ch} \approx 164$ MeV $\approx T_c$, actually holds for $\sqrt{s_{NN}} > 10-20$ GeV

- Strangeness enhancement in A+A nicely described

- $p/\pi$ ratio at the LHC to be understood
Space-time Evolution of the System from Two-Pion Bose-Einstein Correlations (HBT)

Freeze-out volume:

\[ V_{fo} \sim (2\pi)^{3/2} R_{out} R_{side} R_{long} \]

Emission time:

\[ \tau_f \sim R_{long} \sqrt{m_T/T} \]

- \( V_{PbPb,central} \) at LHC: \( \approx 5000 \text{ fm}^3 \)
- \( V_{Pb} \approx 800 \text{ fm}^3 \)

\( \rightarrow V_{PbPb,central} \approx 6.25 \times V_{Pb} \)
Collective Flow
Anisotropic Flow

Fluctuations of the initial geometry & energy density distribution are important

\(\psi_2 \approx \psi_{RP}\)

\(\psi_3\) not correlated with \(\psi_2\)

Fourier decomposition:

\[
E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\varphi - \Psi_n)] \right)
\]

\(v_2\) : elliptic flow, \(v_3\) : triangular flow
Charged Particle $v_2(p_T)$ at Low $p_T$: RHIC vs. LHC

- $v_2(p_T)[\text{LHC}] = v_2(p_T)[\text{RHIC}]$, despite factor 14 increase in $\sqrt{s_{NN}}$
- $p_T$-integrated $v_2$ at LHC 30% larger due to larger $<p_T>$
Charged Particle $v_2(p_T)$ at High $p_T$

- $v_2$ at low $p_T$ ($< 1.5$ GeV/c) due to hydro expansion
- $v_2$ at high $p_T$ due to path length dependence of parton energy loss

CMS Preliminary

$v_2$ vs $p_T$ (GeV/c)

- $L_{int} = 150 \mu$b$^{-1}$
- PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- $|\eta|<1$

CMS 2011
CMS 2010, $|\eta|<0.8$
ATLAS

in plane
out-of-plane

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Limits on $\eta/s$ from Charged Particle $v_2$ and $v_3$

- Significant $v_3$ component
- Viscosity dissipates initial pressure gradients and reduces collective flow
- $v_3$ helps constrain $\eta/s$
- Current bound from LHC: $\eta/s < 2/(4\pi) = 2\cdot(\eta/s)_{\text{min}}$

Elliptic Flow of Identified Particles: Mass Ordering as Expected from Hydro Expansion

- **Hydro predicts mass ordering (due to radial flow):**
  \[ v_2 \sim \frac{1}{T} \left( p_T - v \cdot m_T \right) \]  
  \[ v = \text{mean transv. flow velocity} \]

- **Indeed observed → Further evidence for hydro picture**
Jet Quenching
Hard Probes in Heavy-Ion Collisions

- Hard probes are a useful tool because
  - they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
  - their initial production rate can be calculated with perturbative QCD ("calibrated probe")

- Observables related to jet quenching may help to
  - understand the mechanism of parton energy loss
  - characterize the new state of matter above $T_c$
Charged-Particle Nuclear Modification Factor

\[ R_{AA} = \frac{dN/dp_T(A + A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p + p)} \]

\[ \langle T_{AA} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}} \]

- \( R_{AA} = 1 \) in the hard scattering regime without nuclear effects
- Suppression by a factor of more than 5 observed
- \( R_{AA} \) affected by
  - nuclear shadowing \((p_T < 10 \text{ GeV/c})\)
  - parton energy loss
  - steepness of initial parton spectrum

ALICE, charged particles, Pb-Pb
\( \sqrt{s_{NN}} = 2.76 \text{ TeV}, |\eta| < 0.8 \)
Charged Particle $R_{AA}$ at the LHC:
Large $p_T$ Reach Helps Constrain Models

- Rise of $R_{AA}$ with $p_T$ for the first time established at the LHC
- Large $p_T$ reach helps unveil how energy loss depends on initial parton energy
- Data consistent with decrease of fractional energy loss $\Delta E/E$ with increasing parton energy $E$ (as in expected in pQCD energy loss models)
Test of $T_{AA}$ Scaling With Prompt Photons (and Z Bosons)

$$R_{AA} = \frac{dN/dp_T(A + A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p + p)}$$

Prompt Photons (and $Z^0$'s) are not suppressed: Strong Evidence for Parton Energy Loss Picture
Parton Energy for Heavy Quarks: D Meson $R_{AA}$

Surprisingly similar $R_{AA}$ for D mesons and pions

- pions mainly from gluons
- dead cone effect

Maybe some indication for expected hierarchy

[Talk by Rosa Romita, Tuesday, Heavy Flavour Session]
D Meson $R_{AA}$:
Expectation from Initial State Effects (Nuclear Shadowing)

- NLO pQCD calculation with EPS09 nuclear PDF
- Shadowing only relevant for $p_T < \sim 5 - 10$ GeV/c
Studying Jet Quenching with Jets

- ATLAS and CMS find large asymmetry in energy of dijets in Pb+Pb

- Observations
  - Jets in Pb+Pb still back-to-back (no angular decorrelation)
  - Particle distribution transverse to jet axis ($j_T$ distr.) like in p+p

- Question: Where is the missing energy?

CMS, Phys Rev C84 (2011) 024906
Nuclear Modifications Factor for Jets

\[ R_{CP} = \frac{1/\langle N_{\text{coll}}^{\text{central}} \rangle \times dN/dp_T(\text{central})}{1/\langle N_{\text{peri}}^{\text{central}} \rangle \times dN/dp_T(\text{peri})} \]

- Anti-\( k_T \) algorithm (\( R = 0.4 \))
- \( R_{CP} \approx 0.5 \) in central Pb+Pb

With a radius parameter of \( R = 0.4 \) the full jet energy is not recovered
Where is the Missing Energy?

Detailed study shows (correlate tracks with axis of leading jet [CMS]):
Momentum difference in dijets is balanced by low $p_T$ particles
($0.5 < p_T < 2$ GeV/c) at large angles relative to the away-side jet axis.
Quarkonia
Quarkonia as QGP Signature: Suppression at Low $\sqrt{s_{NN}}$ and $J/\psi$ Enhancement at High $\sqrt{s_{NN}}$?

- Color screening expected to prevent $c$ anti-$c$ (and $b$ anti-$b$) binding in deconfined matter
- Dissociation temperature depends on binding energy → „QGP thermometer“
- Recombination picture for $J/\psi$’s
  - $J/\psi$’s from quark recombination at phase transition (?)
  - Expect $J/\psi$ suppression at low beam energies (SPS, RHIC) and $J/\psi$ enhancement at high energies (LHC)

<table>
<thead>
<tr>
<th></th>
<th>$r$ (fm)</th>
<th>$T_D/T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ (1s)</td>
<td>0.42</td>
<td>1.2</td>
</tr>
<tr>
<td>$\psi'$ (2s)</td>
<td>0.86</td>
<td>1.0</td>
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<tr>
<td>$\chi_c$ (1p)</td>
<td>0.67</td>
<td>1.0</td>
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<tr>
<td>$Y$ (1s)</td>
<td>0.21</td>
<td>2.0</td>
</tr>
<tr>
<td>$Y'$ (2s)</td>
<td>0.50</td>
<td>1.2</td>
</tr>
<tr>
<td>$Y''$ (3s)</td>
<td>0.76</td>
<td>1.0</td>
</tr>
</tbody>
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$\sim 100 \; c\bar{c}$ pairs in central Pb+Pb at the LHC

$\rightarrow J/\psi$ through recombination?
**J/ψ $R_{AA}$ at RHIC and LHC:**

**Smaller Suppression at LHC for Low $p_T$ ($>\sim 0$ GeV/c)**

- **Pb+Pb at LHC:**
  - $J/ψ R_{AA} \approx 0.6$ (for $p_T > 0$)
  - independent of centrality
  - Indication for moderate final state suppression (expect $R_{AA} \approx 0.8$ from initial state effects, i.e. nuclear shadowing)

- **Suppression in central A+A weaker than at RHIC**

Note: Contribution from B feed-down small: 
~ 10% (from pp-measurement)

[Talk by Ionut Arsene, Wednesday, Heavy Flavour Session]
J/ψ $R_{AA}$ at RHIC and LHC:
Smaller Suppression at LHC for Low $p_T (> \sim 0 \text{ GeV/c})$

- Pb+Pb at LHC:
  - J/ψ $R_{AA} \approx 0.6$ (for $p_T > 0$)
  - independent of centrality
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[Talk by Ionut Arsene, Wednesday, Heavy Flavour Session]
J/ψ $R_{AA}$ at LHC vs. Statistical Hadronization Model

- Qualitatively consistent with recombination picture
- Need precise charm production cross section for firm conclusions

Recombination model requires thermalized charm quarks $\rightarrow$ QGP signature
J/ψ Suppression at Higher $p_T (> 6.5$ GeV/c): Stronger Suppression than at Low $p_T$

Stronger suppression at higher $p_T$ in qualitative agreement with recombination picture

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

Prompt J/ψ

CMS, arXiv:1201.5069
Upsilon States in Pb+Pb at the LHC: Suppression of $\Upsilon(2S)$, $\Upsilon(3S)$ Relative to $\Upsilon(1S)$

Consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed

CMS, PbPb, $\sqrt{s} = 2.76$ TeV

$p_T^\mu > 4$ GeV/$c$, $|\eta|^\mu < 2.4$

$p_T^\Upsilon < 20$ GeV/$c$

CMS, PRL 107 (2011) 052302

$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)}{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)}{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)}{pp} = 0.31^{+0.19}_{-0.15} \pm 0.03$
Thermal Photons
Low $p_T$ Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP

- Low $p_T$ direct photons measured via internal conversion ($e^+e^-$ pairs from virtual photons)
- Exponential excess in Pb+Pb above shape measured in p+p
- Slope: $T = 221 \pm 23 \pm 18$ MeV
- Hydro modeling leads to
  - $T_{\text{initial}} = 300 - 600$ MeV
  - $\tau_{\text{initial}} = 0.15 - 0.6$ fm/c
- Puzzle (arXiv:1105.4126):
  - Expect lower $v_2$ for thermal photons
  - Observed: similar $v_2$ as for pions

\[ \gamma_{\text{direct}} = \gamma_{\text{all}} - \gamma_{\text{decay}} \]

$\nu^3/d\nu^3$ (mb GeV$^{-2}$c$^{-2}$) or $d^3N/d\nu^3$ (mb GeV$^{-2}$c$^{-2}$)

\[ \nu_{\text{direct}} := \nu_{\text{all}} - \nu_{\text{decay}} \]

\[ \bullet \quad \text{AuAu 0-20\% x10}^2 \]

\[ \nabla \quad \text{p+p} \]

\[ \text{PHENIX} \]


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Low $p_T$ Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP

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Conclusions

- LHC ideal for studying the QGP:
  \( \varepsilon_{\text{initial}} >> \varepsilon_c \), large volume and QGP lifetime, hard probes

- Anisotropic flow
  - Standard reaction scenario confirmed
  - Medium at the LHC has same „perfect liquid“ properties as found at RHIC

- Medium opaque to jets
  - Large \( p_T \) reach of charged particle \( R_{AA} \) constrains models
  - Dijet energy asymmetry: energy recovered at very low \( p_T \) (0.5 < \( p_T < 2 \) GeV/c)

- Quarkonium saga:
  - Recombination picture for creation of low \( p_T \) \( J/\psi \)‘s consistent with data
  - Loosely bound \( \Upsilon(2s) \) and \( \Upsilon(3s) \) stronger suppressed than \( \Upsilon(1s) \)

- Outlook
  - \( p+Pb \) run in 2012 will reduce uncertainties due to initial state effects
Extra Slides
Direct Photon $v_2$ at RHIC

Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1
$R_{AA}$ for $\Upsilon(1S)$ in Min. Bias Pb+Pb

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

Cent. 0-100%

$|y| < 2.4$

$K.~Reygers$, Quarks and gluons in heavy-ion collisions: A quick tour of recent results
$R_{AA}$: LHC vs. RHIC
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