The ALICE experiment
at the Large Hadron Collider
Christine Nattrass
University of Tennessee at Knoxville
Exploring QCD at high temperatures

\[ T_c \sim 175 \pm 8 \text{ MeV} \rightarrow \epsilon_c \sim 0.3 -1 \text{ GeV/fm}^3 \]

Confined - fewer degrees of freedom

Deconfined - more degrees of freedom

Quark-gluon plasma

\[ \frac{\epsilon}{T^4} \rightarrow 0.3 - 1 \text{ GeV/fm}^3 \]

F. Karsch, et al.
Phase diagram of nuclear matter
Simple Expectations for Heavy Ion Physics at LHC

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (GeV)</td>
<td>17</td>
<td>200</td>
<td>5500</td>
<td>28x</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta$ (~)</td>
<td>~700</td>
<td>~1200</td>
<td>~2000-8000</td>
<td>2-7x</td>
</tr>
<tr>
<td>$T/T_c$</td>
<td>1.1</td>
<td>1.9</td>
<td>3.0-4.2</td>
<td>Hotter</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm$^3$)</td>
<td>3</td>
<td>5</td>
<td>15-60</td>
<td>Denser</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>≤2</td>
<td>2-4</td>
<td>&gt;10</td>
<td>Longer lived</td>
</tr>
</tbody>
</table>

**RHIC and LHC:**
Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$ ~ 20 GeV –5.5 TeV)
To discover the properties of hot QCD at $T$ ~ 150 –600 MeV
The phase transition in the laboratory

Collision

- Phase Transition/Cross-Over: $T_c$
- Chemical Freeze-Out (inel. collisions cease): $T_{ch}$
- Thermal Freeze-Out (el. collisions cease): $T_{fo}$

QGP

Hadron Gas

Time

$\tau_0$
Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
p+p collisions
Pb+Pb collisions

Pb+Pb @ sqrt(s) = 2.76 AToV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x0000000271EC693
ALICE
~1000 members
~30 countries
~100 institutes
The ALICE Collaboration

≈1000 Members
63% from CERN member states
≈30 Countries
≈100 Institutes
≈150 MCHF capital cost (+magnet)

US ALICE
11 Institutions 53 members (inc. 12 grad. Students)
Cal. St. U. – San Luis Obispo, Creighton University, University of Houston, Lawrence Berkeley Nat. Lab, Lawrence Livermore Nat. Lab, Oak Ridge Nat. Lab, Ohio State University, Purdue University, University of Tennessee, Wayne State University, Yale University
UT and ORNL people on ALICE

- EMCal hardware support
- EMCal Simulations and calibrations
- Measurements using EMCal
  - $\pi^0$ mesons
  - heavy flavor
  - jets
  - transverse energy
- Upgrades
  - Di-jet calorimeter
  - Forward Calorimeter
The Electromagnetic Calorimeter
EMCal

- Lead-scintillator sampling calorimeter
- 13 k towers
- Each tower $\Delta \eta \times \Delta \varphi = 0.014 \times 0.014$
- Shashlik geometry
- Avalanche phototodiodes
- $\Delta \eta=1.4, \Delta \varphi=107^\circ$
- $\sigma(E)/E=0.12/\sqrt{E} + 0.02$

- EMCal: $-0.7 < \eta < 0.7, 80^\circ < \varphi < 120^\circ$ in 2010
  $\rightarrow 80^\circ < \varphi < 180^\circ$ in January 2011
  - Ahead of schedule!

- DCAL: $-0.7 < \eta < 0.7, 260^\circ < \varphi < 320^\circ$ in 2013
EMCal Assembly

- 3072 identical modules, 2x2 towers
- 1.5° taper in $\eta$
- Tower granularity $\delta \eta = \delta \phi = 0.014$
- $20.1 \times X_0$
- 77 layers Pb:Sc = 1.44 : 1.76 mm
Front end electronics card:
34/supermodule
~$1k/each
Soren Sorensen
EMCal
Physics goals
Capabilities

• Measurements of $\gamma$ and $\pi^0$

• Heavy flavor measurements
  • Charm and beauty quarks

• Measurements of jets
  • Access to quark and gluon momenta

$\pi^0$: Single particle energy loss
$\gamma$: Thermal photons $\rightarrow$ temperature

Main differences between ATLAS and CMS
• Low momentum tracking ($p_T > 100$ MeV/c vs $p_T > 900$ MeV/c)
• Particle identification
Hard probe rates in ALICE

**ALICE hard physics capabilities:**
- Electron/hadron discrimination (TRD, EMCal)
- \(\mu\) measurements (forward muon arm)
- Good \(\gamma/\pi^0\) discrimination (EMCal, PHOS)
- Fast trigger on jets (EMCal)

**Hard Probes statistics in ALICE:**

10\(^4\)/year minbias Pb+Pb at nominal luminosity\(^*\)

- Inclusive jets: \(E_T \sim 200\) GeV
- Dijets: \(E_T \sim 170\) GeV
- \(\pi^0\): \(p_T \sim 75\) GeV/c
- Inclusive \(\gamma\): \(p_T \sim 45\) GeV/c
- Inclusive e: \(p_T \sim 30\) GeV/c

\(^*\)One year of running = one month of Pb+Pb collisions
Single particle measurements
π^0 measurements

ALICE performance
pp → π^0(γ_{EMCAL} γ_{conv}) \times
\sqrt{s}=7 \text{ TeV}
17 May 2011

ALICE performance
pp @ \sqrt{s}=7 \text{ TeV}
EMCAL
08/10/2010

4 < p_{T,γγ} < 6 \text{ GeV/c}
A = 4057.37 \pm 34.92
μ = 135.565 \pm 0.076
σ = 9.864 \pm 0.094
p_0 = -1402.8 \pm 170.3
p_1 = 29.8 \pm 2.6
p_2 = -0.1 \pm 0.0
Single particles

- Measure spectra of hadrons and compare to those in p+p collisions or peripheral A+A collisions
- If high-\(p_T\) hadrons are suppressed, this is evidence of jet quenching
- Assumption: sufficiently high-\(p_T\) hadrons mostly come from jets
- Unmodified spectra:

\[
R_{AA} = \frac{d^2N_{AA}/d\rho_T d\eta}{T_{AA}d^2\sigma_{pp}/d\rho_T d\eta}
\]
Experimental results

No suppression


Observed

Renk – 8 GeV hadron
Heavy flavor
Why study heavy flavor?

- Produced in early stages of the collision
  - Must be from energetic collisions because of mass
- Energy loss and flow are related to the transport properties of the medium in heavy ion collisions
  - Light quark data indicate
    - Medium evolves as if a fluid of quarks at equilibrium
    - Energy loss in medium is large
  - Heavy quarks may propagate through the medium differently
### Heavy flavor decay

<table>
<thead>
<tr>
<th>Decay</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\pm$ $e^+ \nu_e$ anything</td>
<td>16.07 ± 0.30 %</td>
</tr>
<tr>
<td>$D^0$ $e^+$ anything</td>
<td>6.49 ± 0.11 %</td>
</tr>
<tr>
<td>$B^\pm$ $l^+ \nu_l$ anything</td>
<td>10.99 ± 0.28 %</td>
</tr>
<tr>
<td>$B^0$ $l^+ \nu_l$ anything</td>
<td>10.33 ± 0.28 %</td>
</tr>
</tbody>
</table>
Measuring electrons from heavy flavor

- Identify electrons
- Background subtraction
- Efficiency and acceptance
- Heavy flavor \(p_T\) spectrum
- Heavy flavor \(R_{AA}\)
- Separate charm and beauty
- Measure angular dependence of electron distribution

\[\rightarrow\text{Complicated analysis}\]

\[\rightarrow\text{Requires identification of electrons at high momentum}\]

Stolen from Rebecca Scott's thesis proposal
Particle identification

TPC $dE/dx$

$\sigma \approx 5-6\%$

Vertex detector $p_T (min) < 100 \text{MeV/c}$

TOF 150k channels!

$\sigma \approx 90 \text{ ps}$

Particle identification

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Electron identification

- Electron $m \ll p$
- $E/p \approx 1$ for electrons
- $E/p < 1$ for hadrons
- EMCal can be used to identify electrons even at very high momenta

Graph showing the distribution of $E/p$ for different $p_T$ ranges.
Non-photonic electrons

Without EMCal

With EMCal

Efficiency corrected non-photonic electrons

MC Electrons
Eff. corrected EMCAL N-P electrons
Systematic uncertainty

Annual yield in EMCAL dN/dp_T (GeV/c)

MC/Data

Christine Nattrass (UTK), ORNL Brown Bag Seminar, March 9, 2012
Jets
Probes of the Quark Gluon Plasma

Want a probe which traveled through the collision
QGP is short lived $\rightarrow$ need a probe created in the collision
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived $\rightarrow$ need a probe created in the collision
We expect the medium to be dense $\rightarrow$ absorb/modify probe
**Jets**

**Jets** – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles.

\[ p + p \rightarrow \text{dijet} \]
Inclusive spectra

\[ \frac{1}{2\pi} \frac{d^2 \sigma_{\text{jet}}}{dp_T^2} \text{[mb GeV}^{-1}\text{c}^{-1}] \]

- Corrected spectrum
- Systematic uncertainty (uncorrelated)
- Systematic uncertainty (100% correlated)

\( p+p \ \sqrt{s}=5.5 \text{ TeV} \)
\( \text{Anti-}k_T \ R=0.4 \)
\( 3 \text{ pb}^{-1} \)

\( \text{p-p cross section uncertainty} \)

\( \frac{\text{Corrected}}{\text{Input}} \)

\[ \frac{1}{2\pi} \frac{d^2 \sigma_{\text{jet}}}{dp_T^2} \text{[mb GeV}^{-1}\text{c}^{-1}] \]

- qPYTHIA spectrum
- Systematic uncertainty (uncorrelated)
- Systematic uncertainty (100% correlated errors from p+p, uncorrelated bkg fluctuations)

\( \text{Pb+Pb} \ \sqrt{s_{NN}}=5.5 \text{ TeV} \)
\( 10\% \text{ Central} \)
\( 0.5 \text{ nb}^{-1} \)

\( \text{Anti-}k_T \ R=0.4 \)
\( \hat{q}=17 \text{ GeV}^2/\text{fm} \)

\[ \frac{1}{2\pi} \frac{d^2 \sigma_{\text{jet}}}{dp_T^2} \text{[mb GeV}^{-1}\text{c}^{-1}] \]

- Pb+Pb cross section uncertainty

\[ \frac{\% \text{ stat and syst. uncertainty}}{\ } \]

\[ \frac{\text{Corrected}}{\text{Input}} \]

\( 40 \text{ GeV/c} \)
\( 60 \text{ GeV/c} \)
\( 80 \text{ GeV/c} \)
\( 100 \text{ GeV/c} \)
\( 120 \text{ GeV/c} \)
\( 140 \text{ GeV/c} \)
\( 160 \text{ GeV/c} \)
\( 180 \text{ GeV/c} \)
\( 200 \text{ GeV/c} \)
\( 220 \text{ GeV/c} \)
R_{AA} : From RHIC to the LHC

- Much greater kinematic reach at the LHC
- Smaller systematic errors
- Comparison between RHIC and LHC: studies of partonic energy loss at different regions on the phase diagram
Conclusions
Conclusions

- EMCal useful for measurements of
  - Measurements of $\gamma$ and $\pi^0$
  - Heavy flavor measurements
    - Charm and beauty quarks
  - Measurements of jets
    - Access to quark and gluon momenta

*Plus other things I haven't talked about*
Backup
Jets – azimuthal correlations

$p+p \rightarrow \text{dijet}$

Select high momentum particles $\rightarrow$ biased towards jets
Jets – azimuthal correlations

Jet quenching – absorption of jets by the medium

Big background subtraction $\Delta \phi$ (radians)

$\frac{1}{N_{\text{Trigger}}} dN/d(\Delta\phi)$
Jets at the LHC
Jet broadening

- QPYTHIA not optimized (yet) – do not draw conclusions from shape differences
- Jet energy profile (Au+Au data) BROADENED indicating JET QUENCHING
- Small experimental systematic uncertainties in measurements (ratios from same data set) → a precision measurement in ALICE
Jet reconstruction algorithms

\[ R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]

**Sequential recombination:**
Cluster pairs of objects close in relative \( p_T \)

1. Mid Point Cone: Merging & Splitting
2. SIS CONE
   - Insensitive to “soft” radiation
   - Splitting doesn’t change jets
3. Leading Order High Seed Cone (LOHSC)
4. \( K_T \) (starting point: low \( p_T \) particles)
5. Anti-\( K_T \) (starting point: high \( p_T \) particles)
Background subtraction: Cocktail Method

Steps for the cocktail method:

a) determine all other processes producing electrons
b) determine the relative weight
c) determine the momentum and rapidity distribution

Photonic electrons: $\gamma \rightarrow e^+ e^-$, $\pi^0 \rightarrow \gamma e^+ e^-$, $\eta \rightarrow \gamma e^+ e^-$...
Centrality dependence of $\frac{dN_{\text{ch}}}{d\eta}$

$dN_{\text{ch}}/d\eta = \text{Number of charged tracks per unit pseudorapidity}$

$\eta = \text{pseudorapidity} = -\ln[\tan(\theta/2)]$

- $|\eta| < 0.5$
- $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$
- $\text{Pb+Pb}$
- $\text{pp NSD 2.76 TeV}$
- $\text{pp Inel 2.76 TeV}$

Interpolation between 2.36 and 7 TeV pp

RHIC data scaled by 2.1

PRL 106, 032301 (2011)

PHENIX
PRC 71, 034908 (2005)
Centrality dependence of $dN_{ch}/d\eta$

$|\eta| < 0.5$

PRL 106, 032301 (2011)

$\sqrt{s_{NN}} = 2.76 \text{ TeV}$

2.5% bins

$\frac{dN_{ch}}{d\eta} = \text{Number of charged tracks per unit pseudorapidity}$

$\eta = \text{pseudorapidity} = -\ln[\tan(\theta/2)]$

$N_{part} = \text{number of participating nucleons}$

RHIC data scaled by 2.1

PHENIX
PRC 71, 034908 (2005)
Transverse Energy

- $E_T^{\text{had}}$ from charged hadrons directly measured by the tracking detectors
- $f_{\text{total}}$ from MC to convert into total $E_T$
- From RHIC to LHC
  - $\sim 2.5$ increase
  - $dE_T/d\eta/ (0.5*N_{\text{part}})$
- Energy density (Bjorken)
  - $\varepsilon \approx 16 \text{ GeV}/(\text{fm}^2c)$
  - RHIC: $\varepsilon \tau = 5.4 \pm 0.6 \text{ GeV}/(\text{fm}^2c)$

PRC71:034908 (2005)

Centrality dependence similar to RHIC (PHENIX)
\( \sqrt{s_{NN}} \) dependence

- \( \frac{dN}{d\eta}(0.5*N_{\text{part}}) \sim 8 \)
- \( 2.1 \times \text{RHIC} \)
  1.9 \times \text{pp (NSD)} \text{ at } 2.36 \text{ TeV}
- growth with \( \sqrt{s} \) faster in AA than pp

\( \frac{dE}{d\eta}(0.5*N_{\text{part}}) \sim 9 \) in 0-5%

- \sim 5\% increase of \( N_{\text{part}} \) (353 \rightarrow 383)
  \rightarrow 2.7 \times \text{RHIC}
  (consistent with 20\% increase of \( \langle p_T \rangle \))

Grows faster than simple logarithmic scaling extrapolated from lower energy

\( \sqrt{s_{NN}} = \text{Center of mass energy per nucleon} \)
Probes of the Quark Gluon Plasma
Probes of the Quark Gluon Plasma

Want a probe which traveled through the collision
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb probe
Single particles

Measure spectra of hadrons and compare to those in p+p collisions or peripheral A+A collisions

If high-\(p_T\) hadrons are suppressed, this is evidence of jet quenching

Assumption: sufficiently high-\(p_T\) hadrons mostly come from jets

Unmodified spectra:

\[ R_{AA} = \frac{1}{N_{\text{evt}}^{AA}} \frac{d^2 N_{\text{ch}}^{AA}}{d\eta dp_T} \frac{N_{\text{coll}}}{\langle N_{\text{coll}}^{pp} \rangle} \frac{d^2 N_{\text{ch}}^{pp}}{d\eta dp_T} \]

\(R_{AA} < 1\) “soft”

\(R_{AA} = 1\) “hard”
Nuclear modification factor ($R_{AA}$)

\[ R_{AA} = \frac{1/N_{\text{evt}} \frac{d^2 N_{ch}^{AA}}{d \eta dp_T}}{\langle N_{\text{coll}}^{\text{pp}} \rangle \frac{1/N_{\text{evt}}^{\text{pp}}}{d^2 N_{ch}^{\text{pp}}/d \eta dp_T}} \]

ALICE, charged particles, Pb-Pb
\( \sqrt{s_{NN}} = 2.76 \text{ TeV}, |\eta| < 0.8 \)

Unidentified hadrons- \( \pi, K, p \)

ALICE Preliminary

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Nuclear modification factor ($R_{AA}$)

\[
R_{AA} = \frac{1 / N_{\text{evt}}^{AA} d^2 N_{\text{ch}}^{AA} / d \eta d p_T}{\langle N_{\text{coll}} \rangle (1 / N_{\text{evt}}^{pp}) d^2 N_{\text{ch}}^{pp} / d \eta d p_T}
\]

ALICE, charged particles, Pb-Pb
$\sqrt{s_{NN}} = 2.76$ TeV, $| \eta | < 0.8$

ALICE Preliminary

- ALICE Pb-Pb $\sqrt{s} = 2.76$ TeV (0-5%)
- PHENIX Au-Au $\sqrt{s} = 200$ GeV (0-10%)
- STAR Au-Au $\sqrt{s} = 200$ GeV (0-5%)
Nuclear modification factor ($R_{AA}$)

\[
R_{AA} = \frac{1/N_{evt} \ d^2 N_{ch}^{AA} / d \eta dp_T}{\langle N_{coll}^{pp} \rangle (1/N_{evt}^{pp}) d^2 N_{ch}^{pp} / d \eta dp_T}
\]

ALICE $\sqrt{s_{NN}} = 2.76$ TeV, $|y|<0.75$

- $K^0_s$
- $K^+ + K^-$
- charged
- $\Lambda$

$\Lambda$~494 MeV/$c^2$
$K^0_s$~1116 MeV/$c^2$
$K^\pm$~140 MeV/$c^2$

$\sim 8.6$ cm
Baryon anomaly: $\Lambda/K^0_S$

$\Lambda^0/K^0_S$ vs $p_T$ (GeV/c)

Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV, $|y|<0.75$

- 0-5% centrality
- 20-40% centrality
- 40-60% centrality
- 60-80% centrality
- 80-90% centrality
- (pp at $\sqrt{s} = 7$ TeV)
- (pp at $\sqrt{s} = 0.9$ TeV)

Only stat. errors shown.
Baryon anomaly: $\Lambda/K^0_S$

$\Lambda^0/K^0_S$ vs $p_T$ (GeV/c) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, $|y| < 0.75$.
Charm nuclear modification factor

\[
R_{AA} = \frac{1}{N_{\text{evt}}^{AA}} \frac{d^2 N_{\text{ch}}^{AA}}{d \eta dp_T} \frac{d^2 N_{\text{ch}}^{pp}}{d \eta dp_T}
\]

\[
\langle N_{\text{coll}} \rangle \left( \frac{1}{N_{\text{evt}}^{pp}} \right) d^2 N_{\text{ch}}^{pp} / d \eta dp_T
\]

\[
D^0_{\text{meson}} \simeq 1865 \text{ MeV/c}^2
\]

\[
\sim 123 \mu m
\]

\[
312 \mu m
\]

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Conclusions

- Charged particle production and transverse energy follow same trends as seen at RHIC
- Energy higher than experimental extrapolation, lower than many models
- High $p_T$ particle production suppressed to $\sim 0.15$ of what we would expect from scaling $p+p$ collisions $\rightarrow$ hot, dense medium produced
- Significant suppression observed even for heavy quarks
Charm cross section

![Graph showing charm cross section vs. \( \sqrt{s} \) (GeV)]