Measuring the energy density of the QGP

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Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/
Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun.
The phase transition in the laboratory
Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, U+U
$\sqrt{s_{NN}} = 9 - 200$ GeV

Large Hadron Collider

Geneva, Switzerland
8.6km diameter
p+p, p+Pb, Pb+Pb
$\sqrt{s_{NN}} = 2.76$ GeV, 5.5 TeV

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Pb+Pb collisions
How can we estimate the energy density?

- Transverse energy ($E_T$)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- $\tau =$ formation time
- Energy density $\varepsilon$

$$\varepsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d\eta}$$

- QGP formation for $\varepsilon > 0.5$ GeV/fm$^3$
Where is the energy?

The distribution of energy is surprisingly centrality independent.
Where is the energy?

Scale: diameter in inches = \( \sqrt{\text{fraction}} \times 5 \)
Methods for measuring $E_T$

- CMS: Tracking + electromagnetic calorimeter + hadronic calorimeter
- PHENIX: Electromagnetic calorimeter
- STAR: Tracking + Electromagnetic calorimeter
- ALICE: Tracking

*Other methods tried – focusing on this one here*
How does it hit your detector?

\[ \pi^0 \rightarrow \gamma \gamma \]

\[ K_S^0 \rightarrow \pi^+ \pi^- \]
\[ \sim 69\% \]
\[ K_{L}^0 \rightarrow \pi^0 \pi^0 \]
\[ \sim 31\% \]

\[ \Lambda \rightarrow p \pi \]
\[ \sim 64\% \]
\[ \sim 36\% \]

\[ \bar{\Lambda} \rightarrow p \pi^+ \]
\[ \sim 64\% \]
\[ \sim 36\% \]

Scale: diameter in inches = \( \sqrt{\text{fraction}} \times 5 \)

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How does it hit your detector?

Tracking detectors

Scale: diameter in inches = \sqrt{\text{fraction} \times 5}

35% No signal

7% Secondaries

58% Primaries
\[ E_T = \frac{1}{f_{p_T \text{cut}}} \frac{1}{f_{\text{total}}} \sum_{i=0}^{n} f_i^b (p_T) \frac{1}{f_{\text{notID}}} \frac{1}{\text{eff} (p_T^i)} E_i \sin(\theta^i) \]

But known well!

What we measure directly

Corrections

3%  2%  3%  40%

15%  20%  25%  30%
ALICE: $f_{\text{total}} = 0.567 \pm 0.009$

Scale: diameter in inches = $\sqrt{\text{fraction}} \times 5$

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Measuring energy with tracking detectors

- $f_{\text{total}}$ is robust
- Other corrections are either small or known well
What can we learn from measuring $E_T$?

- Reach energy densities around $10 \text{ GeV/fm}^3$, several times the energy density necessary to form QGP
- $E_T$ higher than expected at LHC
- $E_T$ seems to scale with $N_{\text{quark}}$
- At LHC increasing energy $\rightarrow$ increasing energy/particle, not more particles
Energy density

\[ \varepsilon \tau_0 \approx 1 \text{ fm/c} \]

\[ \varepsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy} \]

ALICE Pb–Pb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

Standard estimate $\tau_0 \approx 1 \text{ fm/c}$

RHIC

QGP formation

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Energy dependence

Higher than extrapolations of RHIC data
Comparison of different methods

ALICE Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\langle dE_T/d\eta \rangle / \langle N_{\text{part}} / 2 \rangle$ (GeV)

$E_T$ from spectra
$E_T$ from tracking
$E_T$ from PHOS+tracking
$E_T$ from EMCal+tracking

$\langle N_{\text{part}} \rangle$
Scaling

- Same centrality dependence as at RHIC
- $E_T$ appears to scale better with $N_{\text{quark}}$ than $N_{\text{part}}$
Average energy/particle

→ Same centrality dependence as at RHIC
→ At RHIC: more energy → more particles
   At LHC: more energy → higher energy/particle
Conclusions:
What can we learn from measuring $E_T$?

- Reach energy densities around $10 \text{ GeV/fm}^3$, several times the energy density necessary to form QGP
- $E_T$ higher than expected at LHC
- $E_T$ seems to scale with $N_{\text{quark}}$
- At LHC increasing energy $\rightarrow$ increasing energy/particle, not more particles
Conclusions

- Energy distribution in an event:
  - NOT 1/3 neutral!
    ...but hits your detector as ~1/3 neutral

- Measurements of $E_T$: tracking only measurements highly accurate!

- $E_T$ higher than expected at LHC
The End
Comparison of colliders

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (GeV)</td>
<td>9-200</td>
<td>2760, 5500</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta$</td>
<td>$\sim$1200</td>
<td>$\sim$1600</td>
</tr>
<tr>
<td>$T/T_c$</td>
<td>1.9</td>
<td>3.0-4.2</td>
</tr>
<tr>
<td>$\varepsilon$ (GeV/fm$^3$)</td>
<td>5</td>
<td>$\sim$15</td>
</tr>
<tr>
<td>$\tau_{QGP}$ (fm/c)</td>
<td>2-4</td>
<td>$&gt;10$</td>
</tr>
</tbody>
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**RHIC and LHC:**
Cover 2 –3 decades of energy ($\sqrt{s_{NN}} = 9$ GeV –5.5 TeV)
To discover the properties of hot nuclear matter at $T \sim 150 –600$ MeV
Hybrid method

\[ E_{t}^{\text{had}} \]

A. Well-measured by TPC
\[ \pi^{\pm}, k^{\pm}, p, \bar{p} \]

B. Not well measured but included in def.
\[ n, K_{L}^{0}, \bar{n} \]

C. Not included in def. but occurs as a background
\[ e^{\pm} \]

D. Included in def, but will exclude with DCA and correct for missing energy
\[ K_{S}^{0}, \Lambda, \bar{\Lambda} \]

\[ E_{t}^{\text{em}} \]

E. Well-measured by EMCal
\[ \pi^{0}, e^{\pm}, \gamma, \eta \]

F. Not included in def. but occurs as a background
\[ \pi^{\pm}, k^{\pm}, p, \bar{p} \]
\[ n, K_{L}^{0}, \bar{n} \]

Stuff the tracking detectors measure well

Stuff the EMCal measures well
Calculation from spectra

- Use spectra data and use Blast wave fits to extrapolate to higher and lower $p_T$

- Three assumptions

\[ E_T^n = E_T^p \]
\[ E_T^n = E_T^\bar{p} \]
\[ K^0_L = K^0_S \]

- Then, neglecting pseudorapidity dependence and assuming that the correction is the same for 900 GeV, 2.76 TeV, and 7 TeV:

\[ E_T = E_T^p + E_T^n + E_T^K + E_T^\pi + E_T^\Lambda + E_T^{\bar{\Lambda}} + E_T^\eta \]

Everything else is negligible
What does the EMCal measure?

Note that this gets the fraction from kaons wrong. The fraction from kaons is actually about 10% of what we measure. Signal is actually ~30%.
Kaon deposits

- There are several kaon decays into π0's and π0's decay mostly into photons
  \[ K_S^0 \rightarrow \pi^0\pi^0 \ (30.7\% \ B.R.) \]
  \[ K^\pm \rightarrow \pi^\pm\pi^0 \ (20.7\% \ B.R.) \]
  \[ K^\pm \rightarrow \pi^0e^\pm\nu_e \ (5.1\% \ B.R.) \]
  \[ K^\pm \rightarrow \pi^0\mu^\pm\nu_\mu \ (3.4\% \ B.R.) \]
  \[ K^\pm \rightarrow \pi^\pm\pi^0\pi^0 \ (1.8\% \ B.R.) \]
  \[ K_L^0 \rightarrow \pi^0\pi^0\pi^0 \ (19.5\% \ B.R.) \]
  \[ K_L^0 \rightarrow \pi^+\pi^-\pi^0 \ (12.5\% \ B.R.). \]
- These will (mostly) not be matched to tracks
- Simulations are unreliable because of how far off simulations are for strange particles
Kaons – measured vs simulation
\[ E_{T}^{\text{em}} = \frac{1}{f_{\text{acc}}} \frac{1}{f_{E_{T}\text{min}}} \left( \sum_{i} \delta_{\text{matched}} \frac{1}{\varepsilon_{\gamma}} \frac{1}{f_{\text{nonlin}}} E_{i} \sin(\theta_{i}) - E_{T}^{\text{kaons}} - E_{T}^{\text{ch}} - E_{T}^{(\text{anti})\text{neutrons}} - E_{T}^{\text{secondary}} \right) \]

- **Sum over clusters**
- **Geometric acceptance, not including dead channels**
- **Correction for minimum energy threshold** \( \sim 6\% \)
- **Correction for nonlinearity of detector response** \( \sim 0.5\% \)
- **All energy deposited by \( K^{0}_{S}, K^{0}_{L}, K^{\pm} \), including decays like \( K^{0}_{S} \rightarrow \pi^{0}\pi^{0} \rightarrow \gamma\gamma\gamma\gamma \) <3\%**
- **Correction for other charged hadron deposits in calorimeter** \( \sim 10-20\% \)
- **Correction for (anti)neutron deposits in calorimeter** \( \sim 1.5-5\% \)
- **Correction for deposits by particles from secondary interactions** <4 \( <5\% \)
- **Efficiency x acceptance within geometric acceptance of detector** \( \sim 1\% \)
\[ E_{T}^{\text{had}} = \frac{1}{f_{\text{acc}}} \frac{1}{f_{p_T \text{cut}}} \frac{1}{f_{\text{neutral}}} \sum_{i=0}^{n} f_{bg}^{i}(p_T) \frac{1}{f_{\text{notID}}} \text{eff}(p_T^{i}) E_{i}^{\text{had}} \sin(\theta^{i}) \]

\[
\frac{1}{f_{\text{acc}}} \quad \text{Correction for the geometric acceptance – 1, with acceptance due to sector boundaries, etc. rolled into the track efficiency}
\]

\[
\frac{1}{f_{p_T \text{cut}}} \quad \text{Correction for the low p}_T \text{ cut off in the acceptance}
\]

\[
\frac{1}{f_{\text{neutral}}} \quad \text{Correction for neutral hadrons included in the definition but not measured well:} \ K_{s}^{0}, \ \Lambda, \ \bar{\Lambda}, \ K_{L}^{0}, \ n, \ \bar{n}
\]

\[
\text{Not trying to measure} \ K_{s}^{0}, \ \Lambda, \ \bar{\Lambda} \text{ in TPC – apply DCA cut to eliminate, correct for missing energy}
\]

\[
f_{bg}^{i}(p_T) \quad \text{Correction for background not included in definition (e^{\mp}) or not measured easily event-by-event (} K_{s}^{0}, \ \Lambda, \ \bar{\Lambda})
\]

\[
\frac{1}{f_{\text{notID}}} \quad \text{Correction for } \pi, \ K, \ p \text{ not identified}
\]

\[
\text{eff}(p_T^{i}) \quad \text{Correction for tracking efficiency}
\]

\[
E_{\text{had}} = \sqrt{p^2 + m^2} - m(\text{nucleons})
\]

\[
E_{\text{had}} = \sqrt{p^2 + m^2} + m(\text{anti–nucleons})
\]

\[
\sqrt{p^2 + m^2}(\text{all others})
\]

Definition of energy to mimic the behavior of a calorimeter

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