Results from ALICE
Christine Nattrass
University of Tennessee at Knoxville
Quark Gluon Plasma – a liquid of quarks and gluons created at temperatures above $\sim 170$ MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun.
How to make a Quark Gluon Plasma

- **Heat**
- **Compress**
- **nucleon boundary irrelevant**

nucleus

GGP
The phase transition in the laboratory

- Phase Transition/Cross-Over
- Chemical Freeze-Out (inel. collisions cease)
- Thermal Freeze-Out (el. collisions cease)

Collision pre-equilibrium

QGP

Hadron Gas

$T_c$, $T_{ch}$, $T_{fo}$

Christine Nattrass, SESAPS 2016
Large Hadron Collider
Geneva, Switzerland
8.6km diameter
p+p, p+Pb, Pb+Pb
$\sqrt{s_{NN}} = 2.76 \text{ GeV, } 5.5 \text{ TeV}$
**Trigger detectors:** When do we have a collision?

**Tracking detectors:** Where did the particle go?

**Identification detectors:** What kind of particle is it?

**Calorimeters:** How much energy does the particle have?
p+p collisions

3D image of each collision
Pb+Pb collisions
Charged particle multiplicity

- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - For 0–5% most central collisions, confirms trend from lower energies
- \( \langle dN_{ch}/d\eta \rangle \) vs. \( \langle N_{part} \rangle \): similar evolution with centrality between 5.02 and 2.76 TeV
  - Provides further constraints for models
  - \(~20\%\) increase going from 2.76 to 5.02 TeV
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$^3$
Energy dependence from $dE_T/dy$

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

Higher than extrapolations of RHIC data
Direct photons in Pb-Pb collisions

- Low-\(p_T\): 2.6\(\sigma\) excess w. r. t. models in 0–20% central — thermal contribution
- \(T_{\text{eff}} = 304 \pm 11\) (stat.) \(\pm 40\) (syst.) MeV in central Pb–Pb collisions at 2.76 TeV
- 30% higher than at RHIC (Au–Au at \(\sqrt{s_{NN}}=200\) GeV)
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
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We expect the medium to be dense → absorb/modify probe
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions

- If high-$p_T$ probes (jets) are suppressed, this is evidence of jet quenching

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

Enhancement

Suppression
\[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta} \]

- \( R_{AA} > 1 \): enhancement
- \( R_{AA} < 1 \): suppression
- Strong modification of the spectrum shape in most central collisions
- Strong centrality dependence
- \( R_{AA} \) at 5.02 TeV similar to 2.76 TeV
Jet $R_{AA}$

- Out-of-cone radiation: energy loss in jet cone
  - Jet yield suppression, di-jet energy imbalance, jet-jet/hadron-jet acoplanarity…
- In-cone radiation: medium modified fragmentation
  - Jet shape broadening, modification of transverse energy profile…
- Consistent with $R_{AA}$ of charged particles and charged-jet $R_{AA}$ at 2.76 TeV

$$R_{AA} = \frac{d^2 N_{AA} / dp_T d\eta}{T_{AA} d^2 \sigma_{pp} / dp_T d\eta}$$
Nuclear modification factor ($R_{AA}$)

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{NN}) d^2N_{AA}^{NN} / d\eta dp_T}{\langle N_{coll} \rangle (1/N_{PP}^{NN}) d^2N_{PP}^{NN} / d\eta dp_T}$$
Charm nuclear modification factor

\[ R_{AA} \]

ALICE
0-10% Pb-Pb, \( s_{NN} = 2.76 \) TeV

- Average \( D^0, D^+, D^{*+}, |y|<0.5 \)
- with pp \( p_T \)-extrapolated reference
- Charged particles, \( |\eta|<0.8 \)
- Charged pions, \( |\eta|<0.8 \)

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Relativistic fluids

- Initial overlap asymmetric → pressure gradients
- Momentum anisotropy → Fourier decomposition:

\[
\frac{d^2 N}{dp_T d\phi} \approx 1 + 2v_1 \cos (d\phi) + 2v_2 \cos (2d\phi) + 2v_3 \cos (3d\phi) + 2v_4 \cos (4d\phi) + 2v_5 \cos (5d\phi) + \ldots
\]
Fluid dynamics

- Same phenomena observed in gases of strongly interacting atoms
$v_n$ at different energies

Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is transparent to colored probes and translucent to electromagnetic probes...
- ...and an extremely hot and dense...
- ...perfect liquid.