Studies of QCD Matter From E178 at NAL to CMS at LHC

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“The Study of the Condensed Matter of QCD”, more commonly known as “Relativistic Heavy Ion Physics”

Aim of talk:

- What this field is all about
- The current status of our knowledge of relativistic heavy ion collisions
- How a particle physicist (me!) got involved in this physics

The talk will be subjective. It is not a review and no attempt is made to point out who obtained first a particular result
Why so much effort invested to study relativistic heavy ion collisions?
QED: few ingredients, yet

Gases
Liquids
Solids
...
PC
...
Rabbit running around Fermilab
...

QCD: ingredients richer & greater variety, yet

result is boring
Hadrons
Nucleons
Nuclei
We live in a world that is just right for a magnificent variety of QED phenomena and simply wrong for QCD phenomena.
Crucial difference between QED & QCD
- the role of vacuum fluctuations

It is only at extremely high densities, with quarks and gluons very close to each other that the vacuum is no longer important

asymptotic freedom – freedom from slavery
Enrico Fermi
Notes on thermodynamics and Statistics”, 1953
Based on this discussion a possible phase diagram of the QCD world

**Temperature** (Energy Density)

Quarks Confined

Hadrons

Chiral Condensate

Quarks deconfined and weakly interacting

Quark – Gluon Plasma

Chiral Symmetry Restored

In short, in this region the world is not dominated by the vacuum

~ 200 MeV

First order phase transition

Baryon Density

or

Baryon Chemical Potential

Nucleon/fm³
There was a time when “QGP” conditions did exist in our universe.
So where do we find or how do we create such matter now?

- look inside neutron stars – that’s difficult!

- Compress ordinary matter in the jaws of a press – no jaws are hard enough!

How about collisions of relativistic heavy ions?

- possible problem: it could be a bust! the outcome could be just the superposition of nucleon-nucleon collisions without much deposition of energy
Digress: Questions from the early 1970’s

- Mechanism of particle production in pp collisions?
- Space-Time evolution of the production process?

From E178 proposal
E178@NAL: study of multiparticle production in pA collisions (1972-1977)

Stage 1:

W. B and C. Young, Meeting on the HE collisions involving nuclei, Trieste 1974

Stage 2:

(J.E. Elias et al., PR D22 (1980) 13)
First observation of $N_{\text{part}}$-scaling or “wounded nucleon”-scaling

\[ \sqrt{s_{NN}} = 9.7 \text{ GeV} \]

Data for different $\bar{\nu}$ ($=N_{\text{part}}-1$)

W. Busza et al., PRL 34 (1975) 836
J. Elias et al., PR D22 (1980) 13
Participant ($N_{\text{part}}$) – Scaling

Example of collision with $N_{\text{part}} = 5$

E178: W.Busza et al. PRL34 (1975) 836
E178 led to E451: study of the rapidity loss by a baryon as it passes through various targets

\[ \Delta y \geq 2.0 \text{ for relativistic baryon passing through a large nucleus i.e. it deposits 85% of its energy! (independent of energy)} \]

Lessons from E178 and E451

- Higher and higher energy densities will be created as the energy of colliding nuclei increases and should exceed the critic value at RHIC
- Discovered participant scaling and with it a crucial observable quantity for characterizing the centrality, or impact parameter, of AA collisions
- Discovered extended longitudinal scaling (related to phenomenon of saturation)

For me:

- There are interesting not understood phenomena in many body QCD
- Much can be learnt from simple experiments (this led to PHOBOS, one of the small experiments at RHIC)
On earth, only realistic hope of finding and studying the QGP is through heavy ion collisions.

Heavy Ion Accelerators:

Bevalac, SIS → AGS → SPS

$\sqrt{s_{\text{NN}}} = 3\text{GeV} \quad 5\text{GeV} \quad 20\text{GeV}$

Heavy Ion Colliders:

First Au beams in 2000
Top energy $\sqrt{s_{\text{NN}}} = 0.2\text{TeV}$

First Pb beams in 2010
Top energy $\sqrt{s_{\text{NN}}} = 2.8\text{TeV}$
Heavy ion collisions constitute a splendid laboratory for studying the condensed matter of QCD

- You can adjust the initial energy density by changing the energy of the colliding nuclei

- You can adjust the shape of the initial system by selecting collisions with different impact parameter (through selection of events with different number of participants)

- System is self diagnosing (scattered hard partons “x-ray” the system)
Head-on PbPb collision at LHC produces > 40,000 particles and energy density > 5 GeV/fm³
Studies of heavy ion collisions, in particular those at RHIC and the LHC, in the last 12 years have led to

The standard “picture” of heavy ion collisions
MIT Heavy Ion Event Display: Pb+Pb 2.76 TeV

As seen in any frame in which both nuclei are still moving with relativistic velocity

Heavy Ion Group @ MIT
Yen-Jie Lee, Andre S. Yoon and Wit Busza

Time = -10.0 fm/c
The standard picture of heavy ion collisions

Temperature or Energy density

~ $1 \text{GeV/fm}^3$

$T \sim 180 \text{MeV}$

“slabs of energy” collide

Equilibrated strongly interacting system best described with quark & gluon degrees of freedom “QGP” redefined to be the state found in this region well described by relativistic hydrodynamics almost perfect relativistic fluid ($\eta/s \sim$minimum possible)

Forward

Color superconductor

Baryon Density or Baryon chemical potential

Mid-rapidity

Cross-over

LHC

RHIC

Terra incognita

Wit Busza

Fermilab Colloquium, May 2012

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Crucial facts that have led to the standard picture of heavy ion collisions:

- initial energy density $> 1$ GeV/fm$^3$

- The transition to the QGP is a rapid cross-over

- Azimuthal anisotropy consistent with extremely rapid ($< 1$ fm/c) production of a very strongly interacting state which flows as an almost perfect relativistic fluid.

- Strong suppression of jets and hadrons again consistent with the production of a very strongly interacting medium

- Comparison of the flow of different particles suggests that before hadronization the system which is flowing has quark degrees of freedom

- All of the above consistent with numerical ab-initio solution of QCD on a space-time lattice
Numerical ab-initio solution of QCD on a space-time lattice

Cross-over at $T_C \approx 170 \text{MeV}$

Above $T = 1000 \ T_C$ $\varepsilon / T^4 > 95\% \text{ SB}$
Azimuthal Angular Distributions

"head on" view of colliding nuclei

Phobos data for 130 and 200 GeV

This was the first direct evidence of collective effects and of the short times needed to produce a matter that flows

\[ \frac{dN}{p_T dp_T dy} = \frac{1}{2} \frac{dN}{p_T dp_T dy} (1 + 2v_2(p_T; b) \cos(2\phi) + \cdots) \]
At LHC you have to be blind not to see hydrodynamic behaviour

On-line displays of CMS events.
EM and hadronic energy in the transverse plane at mid-rapidity is shown
Jet quenching – the second indication that the QGP is very strongly interacting

balanced jets in pp

Jet 430GeV
Jet 420GeV

Unbalanced jets in PbPb

Jet 260GeV
Jet 100GeV
Indirect evidence that the fluid which is flowing has quark degrees of freedom

Note:  
\[(1 + 2v_2 \cos 2 + \ldots)^2 = 1 + 4v_2 \cos 2 + \ldots\]
\[(1 + 2v_2 \cos 2 + \ldots)^3 = 1 + 6v_2 \cos 2 + \ldots\]
We are now trying to get a more quantitative understanding of heavy ion collisions and of the properties of the QGP
Relative magnitude of $v_2$ and $v_3$ correctly predicted by hydrodynamic calculations with extremely low value of $\eta/s$
Shear Viscosity Olympiad

Shear viscosity/entropy density

Water (@100MPa)

Ultra-cold atoms at Feshbach resonance

Quark-Gluon Plasma in heavy-ion collisions

N=4SYM in strong coupling limit (using gauge gravity duality)

From Gunther Roland
PbPb→Z and PbPb→Photons show that quenching is not an initial state interaction.
Energy lost by the quenched jet is distributed over almost the complete solid angle. The energy goes into low momentum particles (<4 GeV).

Quenched jet fragments in the same way as a normal jet with a lower energy.

No broadening of quenched jet.

Observations suggest that the parton energy loss is through heating the medium rather than through radiation.
This new QCD medium seems to dissolve large states, e.g. the larger $\Upsilon$ states.

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

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

$$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)}{\text{PbPb}} / \frac{\Upsilon(2S + 3S)/\Upsilon(1S)}{\text{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$
Surprise in highest multiplicity pp collisions:
a “ridge” (long range correlation in rapidity) is seen, similar to that in heavy ion collisions

Lead-Lead 2.76TeV, 0-5% central

Proton-Proton 7TeV, N>110

CMS Preliminary

From Wei Li
The study of the condensed matter of QCD has begun and there is no shortage of surprises

QGP is a moving target

In my opinion, the following are still far from being understood:

- What happens during and immediately after an AA collision? (what is the origin of the rapid production of the fluid that flows? Does this follow from features seen in gauge gravity duality as suggested by Chesler?)
- The mechanism of jet quenching (radiation or heating of the medium?)
- Where is the critical point in the QCD phase diagram?
- The early stages of particle production in pp collisions (are we beginning to see AA behaviour?)