An introduction to high energy heavy ion physics

1 small bang in the ALICE experiment
The focus of this talks is quark and gluon physics

The strong interaction is very complex!

Quarks and gluons couples strong:

Complex vacuum:

CONFINEMENT

QUESTIONS
Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!
QCD & Confinement

The strong interaction potential

– Compare the potential of the strong & e.m. interaction

\[ V_{em} = -\frac{c}{r} \]
\[ V_s = -\frac{c'}{r} + kr \]

\( c, c', k \) constants

– Confining term arises due to the self-interaction property of the colour field. \( k \sim 1 \text{GeV/fm} \)

\[ q_1 \quad q_2 \]

a) QED or QCD \((r < 1 \text{ fm})\)

\[ q_1 \quad q_2 \]

b) QCD \((r > 1 \text{ fm})\)
Question

What is “the self-interaction property” of the strong force?
Exercise: How big is $k$?

- $k=1 \text{GeV/fm}$
- What force does that correspond to in kilograms?
  - $mg = 1 \text{ GeV/fm} \Rightarrow m = ?$
Consequences of 10 ton force!

- This is why QCD is also called the strong interaction
  - QCD can bind together quarks even though they are EM repulsed

- QCD is for low energies non-perturbative
  - We know the theory but we cannot solve it!
  - We don't know how to describe hadronic properties with QCD

- But at high energies (small distances $<< 1$ fm) we can use perturbative QCD

- Idea: Can we create high energy matter where the quarks and gluons are the fundamental degrees of freedom
  - This is also the phase of matter in the universe around 1 microsecond after the big bang!
  - It is first after this time that quarks and gluons “crystallize” into hadrons
**Lattice QCD results**
*(Numerical non-perturbative)*

**QCD energy denisty**

- RHIC
- LHC
- SPS

\[ \varepsilon / T^4 \]

- 3 flavour
- 2 flavour
- “2+1-flavour”

\[ \varepsilon_c \sim 0.7 \text{ GeV/fm}^3 \]

\[ T_c = (173 \pm 15) \text{ MeV} \]

**Heavy quark potential**

At \( T \sim T_c \) the strong potential is screened so e.g. \( c+c\bar{c} \) states can disassociate.

\[ 0.58 T_c \]
\[ 0.66 T_c \]
\[ 0.74 T_c \]
\[ 0.84 T_c \]
\[ 0.90 T_c \]
\[ 0.94 T_c \]
\[ 0.97 T_c \]
\[ 1.06 T_c \]
\[ 1.15 T_c \]

**Colōr Screening**
Exercise: What is the high energy limit of QCD?

\[ \epsilon_{QCD} = \frac{\pi^2}{30} \left( \sum \text{Bosonic} + \frac{7}{8} \sum \text{Fermionic} \right) T^4 \]

Bosonic degrees of freedom (gluons)  
Fermionic degrees of freedom (quarks)
Answer:

\[ \epsilon_{QCD} = \frac{\pi^2}{30} \left[ 2 \times 8 + \frac{7}{8} \times 2 \times 2 \times 3 \times 3 \right] T^4 \]

Gluon spin and color

(Anti+)quark spin, color and flavor

This suggests that the Quark Gluon Plasma should behave as a gas of quarks and gluons!
By colliding heavy ions we hope to create (and study the characteristics of) a new phase of matter called the Quark Gluon Plasma (where quarks and gluons are deconfined)
By colliding heavy ions it is possible to create a large (≫1fm³) zone of hot and dense QCD matter

Goal is to create and study the properties of the Quark Gluon Plasma

Experimentally only the final state particles are observed, so the conclusions have to be inferred via models
QGP – the phase of the universe 1 micro second after The Big Bang

Initial state

QGP and hydrodynamic expansion

Pre-equilibrium

Hadronization

Hadronic phase and freeze-out
Assumed knowledge

- Accelerators to produce the high energy beams
  - Relativistic Heavy Ion Collider at Brookhaven National Laboratory (outside new York)
  - Large Hadron Collider at CERN (near Geneva)

- Experiments to detect and reconstruct the final state particles
  - PHENIX and STAR at the Relativistic Heavy Ion Collider
  - ATLAS and ALICE at the Large Hadron Collider
Centrality (ex. for Au+Au):

The total energy is proportional to the participant

The number of parton-parton (quark-quark, quark-gluon, gluon-gluon) is proportional to the binary collisions

Example:

6 participant
8 binary collisions
(pp has 2 participant and 1 binary collision)
Peripheral Event
From real-time Level 3 display.

color code $\Rightarrow$ energy loss
Mid-Central Event

From real-time Level 3 display.
Central Event

From real-time Level 3 display.
ALICE first collisions: 8/11-2010
Factor 14 jump in energy!

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
What happens when we collide $pp$ and $Pb-Pb$

2 answers!

**SOFT**

- Non-perturbative physics (know the equations but not how to solve them)
- Bulk properties (=medium)

**HARD**

- Perturbative physics (theoretical predictions)
- Rare processes
- Jets (=probes)
Phenomenological model of soft physics e.g. Lund string model

- a) QED or QCD ($r < 1 \text{ fm}$)
- b) QCD ($r > 1 \text{ fm}$)
According to Bjorken:

\[ \epsilon \approx \frac{1}{A_t} \frac{dN}{d\eta} \frac{1}{\tau} < E_t > \]

Estimate the energy density, assume \(<E_t>\sim 0.5\text{GeV},\)
“Measured” initial energy density

Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy $E_T$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{c \tau_0} \left( \frac{dE_T}{dy} \right)$$

PHENIX: Central Au Au yields

$$\langle \frac{dE_T}{d\eta} \rangle_{\eta=0} = 503 \pm 2 \text{ GeV}$$

Formation (thermalization) time?
**LHC first results from ALICE**

- **Multiplicity at mid-rapidity** increases a factor ~2 from RHIC to LHC (energy density a factor ~2) but most likely also widens significantly.

- Centrality dependence is similar as at lower energy.
Break

- Please take 1 minute to write down on a piece of paper what the muddiest point so far has been
Short recap

- We want to prove that the matter formed in heavy ion collisions is the expected Quark Gluon Plasma predicted by theory
  - a high energy gas-phase of quarks and gluons

Problem: We have to derive this from the final state particles that are emitted after the system has cooled of

We have shown that the energy density derived from the charged particle density is larger than the energy density required from QCD numerical simulations
  - Necessary condition, but not sufficient condition

We want now to show that the matter formed is strongly interacting and that it shows quark and gluon degrees of freedom
Elliptic flow ($v_2$) unique in heavy ion collisions

Fourier decomposition:
\[ \frac{dN}{d\phi} = 1 + 2 v_2 \cos(2 \Delta \phi) \]

Initial spatial anisotropy → Strong pressure gradient → $v_2$ Azimuthal anisotropy → Sensitivity to early expansion
Example from atomic physics: Releasing Lithium atoms from a trap

http://www.physics.ncsu.edu/jet/index.html
Elliptic flow exercise(s)

Why is the elliptic flow sensitive to early interactions after the hot and dense matter has been formed?

– Hint: How would the phi distribution look if there were no interactions

Bonus question: Why is the flow generated in the event plane and not transverse to that

– Hint: How is the matter density distributed in the overlap region
Each nucleon-nucleon interaction produces on average a spherical symmetric distribution. Only by interacting elliptic flow is generated. Flow is strongest in the event plane because of the stronger matter gradient — hydrodynamic explanation.


Flow is strongest in the event plane because of the stronger matter gradient — hydrodynamic explanation.

Elliptic flow at RHIC is "Maximal"

Relativistic hydrodynamic predicts elliptic flow
- The high energy medium interacts very strongly immediately after being formed
- Medium does not behave as a gas, but an almost perfect fluid!
The QGP is less like a crowd and more like a synchro team

Big theoretical challenge:

- how to go from initial random collisions to organized state in a VERY short time (<1fm/c~10^{-23}s)
- Remains to be understood
**LHC first results from ALICE**

- **Differential flow at LHC** is very similar to RHIC!
  - Hydrodynamic limit?
- The total magnitude is larger because system is harder!
- **Question:** Where is QCD dynamics?
Hard probes (pQCD): parton-parton interactions
Centrality (ex. for Au+Au):

- Spectators

**Participants** = 2*197 - Spectators

- parton-parton collisions are proportional to binary collisions

- Exercise: Why is the number of binary collisions in central collisions proportional to $A^{4/3}$ while the number of participants is $A$?  
  - Hint: What is the average amount of nuclear matter covered in the “target” nuclei?
The nuclear modification factor for pions (1/2)

\[ R_{AA} = \frac{d^2 N^{AA}/d p_T dy}{\langle N_{bin} \rangle d^2 N^{NN}/d p_T dy} \]

Nbin
In central collisions we observe only 20% of the remnants from parton-parton collisions that we expected to observe!

What happens to the rest?
- They lose energy as they go through the high energy matter!
- This is the QCD signature we looked for!

But first let us consider other alternatives!
**Could the binary scaling be wrong?**

Direct photons does not interact with final state hadronic matter!

Direct photons shows no nuclear modification and therefore confirm binary scaling of hard processes!
The Z does not interact strongly and so can also be used to check binary scaling at LHC
Could it be an initial state effects? Au+Au vs d+Au
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Could it be an initial state effects? Au+Au vs d+Au

So it must be a final state effect!
The suppression is due to energy loss in the medium.

Most jets are created back to back!

Adler et al., PRL90:082302 (2003), STAR

\[ \frac{1}{N_{\text{trigger}}} \frac{dN}{d\Delta \phi} \]

- p+p min. bias
- Au+Au Peripheral

\[ 4 < p_T(\text{trig}) < 6 \text{ GeV}/c \quad p_T(\text{assoc}) > 2 \text{ GeV}/c \]
The suppression is due to energy loss in the medium.

Most jets are created back to back!

A large energy loss requires a QCD interacting medium, i.e., a colored medium!

4 < p_T(trig) < 6 GeV/c  p_T(assoc) > 2 GeV/c
Au+Au vs d+Au
Hot vs cold nuclear matter

No suppression seen in d+Au
→ Quarks and gluons loose/radiate energy as they interact with the colored quarks and gluons of the created matter.
This suggests that the quark gluon plasma has been discovered!
LHC first results from ALICE

The nuclear modification factor is lower than at RHIC suggesting that the energy loss is larger.

The rise with pT was not observed at RHIC and could give new insight into the energy loss mechanism.
Jet asymmetry confirms picture from RHIC – away side jet is absorbed/modified by the medium

- Advantage of jets is that they “map” onto the QCD degrees of freedoms: quarks and gluons
Summary:

- Hard experimental work at RHIC has lead to the conclusion that a Quark Gluon Plasma is most likely produced in central collisions of gold on gold! **BUT**
- Theoretical models are not very constrained by the data as they use many phenomenological inputs
  - New excitement: Can string theory describe non-perturbative QCD?
- Many observations suggests that the picture is more complicated (Quark Gluon Plasma is not like we expected)
  - Particularly heavy quark data challenges many models
- A lot of new results from LHC has to be digested by the community. This will hopefully help constrain the models.
RAA for identified charged hadrons (Lund)

Pushing the separation to the relativistic rise

Baryon anomaly in central PbPb. Quark recombination?

Baryon anomaly not observed at high pT as speculated pre-LHC.

pp

central PbPb

Baryon anomaly not observed at high pT as speculated pre-LHC.
**RAA identified hadrons**

- Extends ALICE unique PID capabilities to the hard regime.
Heavy quark thermometer

Observation of sequential suppression of $Y$ ($b\bar{b}$) family

Expected in terms of binding energy

Unfortunately heavy quark results are more complex when systematically studied!

Note: $6.5<p_T<30$ GeV for $J/\psi$ and $\psi(2s)$