Introduction to heavy-ion physics
Seen through ALICE’s eye
ALICE

It’s scientific program
It’s detectors layout
Back to Basics

From the Standard Model of particle physics to Big Bang cosmology
Modern-day physics describes the Universe at all scale
Modern-day physics describes the Universe at all scales from $10^{28}$ cm...
Modern-day physics describes the Universe at all scale

... down to $10^{-18}$ cm
Modern-day physics describes the Universe at all scale

Using 4 fundamental forces
Gravity
General relativity

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$
Strong, Electromagnetic, Weak

Relativistic Quantum field theory: the Standard Model of Particle Physics
The SM
A cartoon
Quarks

\[
\begin{array}{ccc}
3 & 100 & 10^5 \\
\text{u} & \text{c} & \text{t} \\
6 & 10^3 & 10^3 \\
\text{d} & \text{s} & \text{b} \\
0.5 & 100 & 10^3 \\
\text{e} & \text{\mu} & \text{T} \\
10^{-6} & 10^{-6} & 10^{-6} \\
\text{V}_e & \text{V}_\mu & \text{V}_T
\end{array}
\]

Leptons

Forces

\[
\begin{array}{cc}
0 & 10^4 \\
g & Z \\
0 & 10^4 \\
y & W
\end{array}
\]

\[
H \rightleftharpoons p + e^- + \bar{\nu} \]

\[
\text{H} \rightleftharpoons n + e^+ + \nu
\]
The ALICE scientific program is about the Strong Interaction

- Quantum Chromodynamics (QCD) is the relevant theory
- Quarks and gluons are the characters in our story
The outstanding puzzles

- How is the mass of hadrons generated
The outstanding puzzles

- How is the mass of hadrons generated?
- What confines quarks permanently inside hadrons?
Quark Mass

- Mass is generated through symmetry breaking phase transition
  - Bare mass: electroweak phase transition, existence of Higgs field?
  - Composite mass: chiral symmetry spontaneously broken, existence of chiral condensate?
Quark color

- Color \((R, G, B)\) is the relevant charge for the strong interaction
  - Only color singlet (color neutral) states appear in nature
  - This is called confinement: there exists no ab initio rigorous mathematical proof

- Quarks (fermions) degrees of freedom
  - 6 flavors
  - 3 colors
  - 2 charge states
  - 2 spin states
Gluon

- The mediator of the strong interaction
  - Gluon interact among themselves: asymptotic freedom, color confinement, chiral symmetry breaking

- Gluon (boson) degrees of freedom
  - 8 choice of colors
  - 2 helicity states
Vacuum polarization

Remember QED

Test charge

High energy probe

Low energy probe

1/137
QCD is different

vacuum polarization

Test charge

High energy probe: asymptotic freedom
Asymptotic freedom

- Interaction strength between quarks becomes smaller as the distance (transferred momentum) between them gets shorter (larger)
Asymptotic freedom

At short distance

- Vacuum polarization makes the interaction stronger ($q\bar{q}$ screening)

- Non linear gluon interaction makes the interaction weaker ($g\bar{g}$ anti screening)
Asymptotic freedom

- Momentum scale
  - $\mu \gg \Lambda_{\text{QCD}}$ hard, perturbative
  - $\mu \ll \Lambda_{\text{QCD}}$ soft, non-perturbative

\[
\alpha_s(\mu) = \frac{2\pi}{\beta_0 \ln(\mu/\Lambda_{\text{QCD}})}
\]
**Chiral Symmetry**

- **QCD vacuum**
  - An intrinsic symmetry of QCD for massless quarks: the strong interaction does not couple the left- and right-handed quarks

- **True QCD vacuum**
  - Quarks acquire a (small) mass through the spontaneous breaking of the symmetry
QCD conjecture

Any strongly interacting system at zero temperature and density must be a color singlet at distance scale larger than $1/\Lambda_{\text{QCD}} \approx 1 \text{ fm}$.
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What about a system at high temperature or density, i.e. high energy density?
Intuitively

If color charge density is sufficiently high, Debye screening (electric charge in a plasma) weakens the interaction also at large distances

\[ V(r) = e^{r/r_{Debye}} \frac{r_{Debye}}{r}, \quad r_{Debye} = \frac{1}{gT} \]
Intuitively

If color charge density is sufficiently high, Debye screening (electric charge in a plasma) weakens the interaction also at large distances

\[ V(r) = \frac{e^{r/r_{Debye}}}{r}, r_{Debye} = \frac{1}{gT} \]

The system becomes a color conductor with free color charges

We call it a Quark Gluon Plasma
Does such a system exist?

At very early times in the history of the Universe, temperature was high enough $T \approx 100$ GeV (electroweak phase transition):

- All particles of the SM are relativistic
- $N_{\text{particle}} = N_{\text{particle}}$ (chemical potential $\mu = 0$)
- Quarks interaction is weak
Does such a system exist?

- At very early times in the history of the Universe, temperature was high enough $T \approx 100$ GeV (electroweak phase transition):
  - All particles of the SM are relativistic
  - $N_{\text{particle}} = N_{\text{particle}}$ (chemical potential $\mu = 0$)
  - Quarks interaction is weak

- QGP is a free relativistic gas of partons (= quarks and gluons)
  - Statistical mechanics applies
Equation of state

Energy density for a free gas

\[ \epsilon_i = \int \frac{d^3p_i}{(2\pi)^3} \frac{E_i}{e^{\beta E_i} \pm 1} \]

\[ \epsilon = \sum_i g_i \epsilon_i = \left( g_b + \frac{7}{8} g_f \right) \frac{\pi^2}{30} (k_B T)^4 \]
Equation of state

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- At temperatures below \( k_B T \sim 1 \) GeV (u,d,s)

\[ \epsilon_{\text{QGP}} \sim 47.5 \frac{\pi^2}{30} (k_B T)^4 \]
Equation of state

- At temperatures below $k_B T \sim 1$ GeV (u,d,s)

\[ \epsilon_{\text{QGP}} \simeq 47.5 \frac{\pi^2}{30} (k_B T)^4 \]

- Equation of state

\[ p = \frac{1}{3} \epsilon \]
Phase transition

- From a pion gas

\[ P_\pi = B + \frac{3\pi^2}{90} T^4 \]

- To the QGP (u,d)

\[ P_{QGP} = \frac{37\pi^2}{90} T^4 \]

- Transition temperature

\[ T_c = \left(\frac{45B}{17\pi^2}\right)^{1/4} \sim 180\text{MeV} \]
Lattice QCD: to solve QCD in the strong coupling regime by simulating the theory on a finite space-time lattice
Phase transitions in nature
ALICE studies the QCD phase transition, the only SM phase transition that can be studied in the laboratory

\[ T_c \sim 170 \text{ GeV} \]
How?

Colliding heavy-ion ions at close to the speed of light
How?

Colliding heavy-ion ions at close to the speed of light
Colliding heavy-ion ions at close to the speed of light
How?

- Detecting the residues of the collisions
The todo program

- About 10,000 particles cross the detectors in each collision; the particle density reaches 90 particles per cm$^2$, near the interaction point!
- Measure every particle individually: count them, localize their trajectory, identify their nature, establish their 4-momentum;
- Localize the origin within a few $\mu$m;
- Identify the interesting rare events in less than 100 $\mu$s;
- Store data 1,2 Go/s (2 CD/s) and 1 Po/year (a 4 Km high CD pile);
- Give access of data to 1,000 physicists spread in 80 institutes in 28 countries.
Observing the phenomenon

Imagine...
- You lived in a frozen world where water existed only as ice
- and ice comes in only quantized sizes ~ ice cubes
- and theoretical friends tell you there should be a liquid phase
- and your only way to heat the ice is by colliding two ice cubes
- So you form a “bunch” containing a billion ice cubes
- which you collide with another such bunch
- 10 million times per second
- which produces about 1000 IceCube-IceCube collisions per second
- which you observe from the vicinity of Mars

Change the length scale by a factor of ~ $10^{13}$

You’re doing physics at LHC!
How to decipher
Big Bang

Present $t_0 + 13.7 \times 10^9$ years

Little Bang

Present $t_0 + 3 \times 10^{-23}$ seconds

CMB

QGP

Hadron gas

QGP

$2/20/11$
Big Bang

- Global characteristics
  - mass density $\Omega$, age

Little Bang

- Global characteristics
  - Energy density, size, lifetime
Big Bang

• Global characteristics
  • mass density $\Omega$, age
• Expansion (galaxies)
  • Hubble flow

Little Bang

• Global characteristics
  • Energy density, size, lifetime
• Expansion (hadrons)
  • Particles flow, $\pi$ interferometry
Big Bang

- Expansion (galaxies)
  - Huble flow
- Primordial nucleosynthesis (H, He, Li)
  - Thermodynamics at $\tau \sim 100$ s

Little Bang

- Expansion (hadrons)
  - Particles flow, $\pi$ interferometry
- Hadrochemistry ($\pi$, K, p ratios)
  - Thermodynamics at $\tau \sim 10^{-21}$ s

http://astro.berkeley.edu/~mwhite/darkmatter/bbn.html

http://arxiv.org/format/nucl-th/0511071v3
Big Bang

- Primordial nucleosynthesis (H, He, Li)
  - Thermodynamics at $\tau \sim 100$ s
- Large scale structures
  - Density fluctuations

Little Bang

- Hadrochemistry ($\pi$, K, p ratios)
  - Thermodynamics at $\tau \sim 10^{-21}$ s
- Event structures
  - Fluctuations at phase transition
Big Bang

- Large scale structures
- Density fluctuations
- Cosmic microwave background
- Temperature at decoupling

Little Bang

- Event structures
- Fluctuations at phase transition
- Thermal radiation ($\gamma, l^+l^-$)
- Time evolution of temperature

COBE (Cosmic Background Explorer)

Black body radiation
Big Bang

- Cosmic microwave background
  - Temperature at decoupling
- Temperatures fluctuations
  - Origin of big structures

Little Bang

- Thermal radiation
  - Time evolution of temperature
- Tomography of QGP
  - Density fluctuations,…

WMAP (Wilkinson Microwave Anisotropy Probe)
Let me tell you what I have learned so far.
Isn’t it fun to work with me!
Soft sector
Thermalized partonic phase

\[ \frac{dN_{\text{ch}}}{d\eta} |_{\eta=0} = 1600 \pm 76 \]

\[ \varepsilon > 15 \text{ GeV/fm}^3 \]

\[ T > 3 T_c \]
Hydrodynamics

Collective flow $v_2$
- partons $\rightarrow$ hadrons
Hydrodynamics

Collective flow $v_2$
- partons $\rightarrow$ hadrons

- Fluctuations
- $\eta/S$ (?)
Hadronization

- Radial flow
- Parton fragmentation
- Coalescence (?)

baryon/meson anomaly
Hadronic phase

Chemical freezeout:
- $T = 160$ MeV $\approx T_c$
- $\mu_b = 1$ MeV
- proton?
Hadronic phase

Chemical freezeout:
- $T = 160 \text{ MeV} \approx T_c$
- $\mu_b = 1 \text{ MeV}$
- proton ?

Strangeness excess PbPb/pp
- $\sqrt{s}$ (trivial ?)
- Strangeness (QGP ?)
- Centrality (QGP ?)
Hard sector
Dynamics of partons inside QGP

10-20% peripheral

168 GeV

192 GeV

Δφ

Δη

66
Dynamics of partons inside QGP
Dynamics of partons inside QGP

Partons energy loss
- mécanism (radiatif, collision)?
- thermalization?

ALICE, charged particles, Pb-Pb
$\sqrt{s_{NN}} = 2.76$ TeV, 0-5%, $|\eta| < 0.8$

ALICE Preliminary
Dynamics of partons inside QGP

Partons energy loss
- mécanism (radiatif, collision)?
- thermalization?

\( R_{AA}^{g} < R_{AA}^{q} < R_{AA}^{Q} \)?
Color screening

\[ V(r) = e^{\left( \frac{r}{r_{\text{debye}}} \right)} \]

Multiplicité

\begin{align*}
0.2 T_C & \quad 0.74 T_C \quad 1.2 T_C \quad 2 T_C \\
\psi' & \quad \chi_c & \quad J/\psi & \quad Y(1S) \\
Y(3S) & \quad Y(2S)
\end{align*}

<table>
<thead>
<tr>
<th>State</th>
<th>( J/\psi ) (1S)</th>
<th>( \chi_c ) (1P)</th>
<th>( \psi' ) (2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m ) (GeV/c²)</td>
<td>3.10</td>
<td>3.53</td>
<td>3.68</td>
</tr>
<tr>
<td>( r_0 ) (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
</tr>
<tr>
<td>( \Upsilon ) (1S)</td>
<td>9.45</td>
<td>9.99</td>
<td>10.02</td>
</tr>
<tr>
<td>( \chi_b ) (1P)</td>
<td>10.26</td>
<td>10.26</td>
<td>10.36</td>
</tr>
<tr>
<td>( \chi_b' ) (2P)</td>
<td>0.28</td>
<td>0.44</td>
<td>0.56</td>
</tr>
<tr>
<td>( \chi_b'' ) (3S)</td>
<td>0.68</td>
<td>0.44</td>
<td>0.56</td>
</tr>
</tbody>
</table>
J/ψ dynamics inside QGP

- Dissociation at high $p_T$
- Regeneration at high $c$ density
  - $y = 0$
  - $b = 0$
J/ψ dynamics inside QGP

- Dissociation at high $p_T$
- Regeneration at high c density
  - $y = 0$
  - $b = 0$
  - $p_T < 4$ GeV/c
J/ψ dynamics inside QGP

- Charms en équilibre avec QGP?
But there remains a lot to learn …
A magnetic field

Identify the charge

Larger momentum

Smaller momentum

Measure the momentum
Particles cross sensitive materials

\[ t=0 \quad t=t_1 \quad t=t_2 \quad t=t_3 \quad t=t_4 \]
ALICE: Many cells everywhere ...

- To localise, segmenting the system in hundreds of millions of sensitive cells;
- Surround the interaction point with detector envelopes.
... and a few specialized detectors

- Muons spectrometre:
  - Passif absorber
  - B dipole
  - Trajectographe
  - Filter
  - Trigger

Photons
How does it work

- Internal trajectographe: 6 layers of Si diodes with 2D localisation

![Diagram showing Si-p and Si-n layers with 300 mm scale]
3 Si technologies

256 anodes, 294 µm pitch
How does it work

- The main trajectographe: 1 time projection chamber

![Diagram showing the main trajectographe diagram with E and -HV labels and a graph of arrival time vs. q,f.]
TPC ALICE

- **Readout plane segmentation**: 18 trapezoidal sectors each covering 20 degrees in azimuth

- **GAS VOLUME**: 88 m$^3$
- **DRIFT GAS**: 90% Ne - 10% CO$_2$

- **Drift volume**: 400 V/cm
- **End plate**: NE / CO$_2$
- **Central electrode**: 88 ms
- **End plate**: 5 m
Particles identification

Measure energy loss

Measure time of flight

Trajectography: charge and momentum
**Distinguish relativistic electrons and pions**

- When a relativistic particle crosses an inhomogeneous medium an X ray is emitted.
- Select the medium such as only electrons create the transition radiation.
- Detect both the charged particle and the X ray.
- Multi-wire chamber filled with a heavy gas (Xe).
And to be complete

- Dense like lead and transparent like crystal to stop photons

- Photons materialise as a cascade of electrons and positons
- Electrons excite atomes of the crystal
- Atomes deexcitent by emitting an UV radiation
- UV radiations are detected at one end of the crystal by a photodiode
From volts to bytes

- The signal of each cell (~16 millions) is processed by highly miniaturised electronic systems;
- The electric signal is digitalised to be processed by computers;
- The information is transported by optical fibers.
Design the detector

Simulations:
- Generate physics events at the best of our theoretical knowledge
- Construct a virtual detector and simulate its response based of our knowledge on the interactions of particles with matter

Tools:
- Programming techniques: object oriented
- Huge computing and storage capacities: distributed computing
Process the data

- **Reconstruction**
  - Hits to clusters to tracklets to tracks
  - Compute for each track: 4-momentum and PID

- **Analyze data**
  - Generate physics information

- **Tools:**
  - Distributed computing: T1, T2, AF,...