Collisioni protone-Piombo ad LHC: risultati e sorprese.

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History of the Universe

Big Bang

LHC

Quark Gluon Plasma

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
Quarks and gluons are usually confined inside hadrons, but what happens if they collapse in a wide space region as during the Big-Bang?

**Require**
- Energy density $\gg 1 \text{ GeV/fm}^3$
- Lasting for $> 1 \text{ fm/c}$
- In a volume much larger than a hadron, $\approx 10 \text{ fm}^3$

Create QGP with Pb-Pb collisions
Temperature decreases
Where to look for QGP: The Phase Diagram

High temperature and low baryon density (RHIC + LHC)

Intermediate baryon density and temperatures (SpS, Fair) -> Critical point

Very high baryon density and low temperatures (neutron stars)

\[ n_{\text{baryon}} \approx n_{\text{anti-baryon}} \]
Hard Scattering + Thermalization
(< 1 fm/c)

Pb

Pb

QGP (≈ few fm/c)

Hadronization
particle composition
is fixed (no more
inel. Collisions) T_{ch}

Freeze-out
(≈ 10 fm/c)
(no more elastic
collisions) T_{kin}

http://urqmd.org/~weber/CERNmovies/alice.mpg
Present Ion Colliders

**LHC Collider**
- Protons $\rightarrow$ 7000 GeV
- Pb $\rightarrow$ 2500 GeV/N

**RHIC Collider**
- Protons $\rightarrow$ 250 GeV
- Au $\rightarrow$ 100 GeV/N

Brookhaven Nat. Labs - USA
How Lead beam is obtained at LHC

Lead $^{82+}$ accelerated up to 2.5 TeV/N

Lead $^{82+}$ stripped via carbon foil and accelerated up to 177 GeV/N

Lead $^{54+}$ accelerated up to 5.9 GeV/N

Lead $^{54+}$ stripped via carbon foil and accelerated up to 70 MeV/N

Lead vapour is ionized via electron beam
Lead and proton beam inside LHC

LHC magnets: two beam pipes within the same structure

Lead ions are 208 times heavier and have 82 times more positive charge than protons, but in the same magnets.

Use the two separate radiofrequency systems and their careful tuning of the two beam orbits to reliably collide the two beam in the four interaction regions.

Collisions with asymmetric and different beams:
PB = 1.58 TeV, p = 4.0 TeV → 5.02 TeV/N c.m.s.
LHC world premiere!
<table>
<thead>
<tr>
<th>Year</th>
<th>Collisions</th>
<th>Energy c.m.s</th>
<th>$\int \mathcal{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>0.01 nb$^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>0.1 nb$^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02 TeV</td>
<td>30 nb$^{-1}$</td>
</tr>
</tbody>
</table>

All 4 LHC experiments involved
**Centrality definition**

- **$N_{\text{part}}$**: Number of nucleons participating to the collision
- **$N_{\text{coll}}$**: Number of binary collisions between nucleons

Centrality = fraction of $\sigma_{\text{PbPb}}$

- 60-80%
- 0-5%

**Example LHC**: Centrality 0-1%
- $N_{\text{par}} = 403$
- $N_{\text{coll}} = 1681$

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**PhysRevC.88.044909 (2013)**
How to characterize the hot medium I: Hadrochemistry based on thermal model

Agreement over 7 orders of magnitude!
Temperature ≈ 150 MeV
How to characterize the hot medium II: Particle production

Relativistic hydrodynamical models describe reasonably well particle production validating the assumption of a matter which has reached thermal equilibrium after the collisions.
How to characterize the hot medium III: Nuclear Modification Factor

\[ R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{\text{coll}} \rangle_{AA} \text{Yield}_{pp}(p_T)} \]

- Indicates if in HI collisions the yield of particles, compared with pp yield, scales with the number of collisions or not.

- At low \( p_T \), \( R_{AA} < 1 \) dominated by soft interactions with the medium.

- Expected if nothing happens

- \( R_{AA} = 1 \) simple scaling
- Expected at high \( p_T \)
Nuclear modification factor $R_{AA}$: a compilation

Hadron traversing a hot and dense medium lose substantial energy via gluon radiation and elastic scattering
How to characterize the hot medium IV from inside via hard probes

C: Hot medium tomography using hard probes produced in the collision

Heavy Flavours, Jets, high $p_t$ particles: we can calculate how many are produced
Jet quenching in PbPb

Jets traversing the hot medium are quenched up to several hundred GeV
How to characterize the hot medium $V$: Elliptic flow $v_2$

Hot medium with thermal equilibrium reached in very short time, maintaining the shape.

$$\frac{d^2N}{dp_t d\phi} = \frac{dN}{dp_t} \left[ 1 + 2v_2 \cos(2\phi) + 2v_4 \cos(4\phi) + \ldots \right]$$

$\nu_1 = 10\%$, $\nu_2 = 10\%$, $\nu_3 = 10\%$

Magnitude depends on the viscosity/entropy ($\eta/s$) ratio of the medium and on the $p_t$ of the particles considered.
Hydrodynamical models points toward low viscosity/entropy (≈ perfect liquid) for the produced medium.

Elliptic flow $v_2$

$\frac{\eta}{s} = 0.08$

Pb+Pb 2.76-TeV centrality 30–40%
http://en.wikipedia.org/wiki/Pitch_drop_experiment

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Duration (months)</th>
<th>Duration (years)</th>
</tr>
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<tbody>
<tr>
<td>1927</td>
<td>Hot pitch poured</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>October 1930</td>
<td>Stem cut</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>December 1938</td>
<td>1st drop fell</td>
<td>98</td>
<td>8.1</td>
</tr>
<tr>
<td>February 1947</td>
<td>2nd drop fell</td>
<td>99</td>
<td>8.2</td>
</tr>
<tr>
<td>April 1954</td>
<td>3rd drop fell</td>
<td>86</td>
<td>7.2</td>
</tr>
<tr>
<td>May 1962</td>
<td>4th drop fell</td>
<td>97</td>
<td>8.1</td>
</tr>
<tr>
<td>August 1970</td>
<td>5th drop fell</td>
<td>99</td>
<td>8.3</td>
</tr>
<tr>
<td>April 1979</td>
<td>6th drop fell</td>
<td>104</td>
<td>8.7</td>
</tr>
<tr>
<td>July 1988</td>
<td>7th drop fell</td>
<td>111</td>
<td>9.2</td>
</tr>
<tr>
<td>November 2000</td>
<td>8th drop fell</td>
<td>148</td>
<td>12.3</td>
</tr>
<tr>
<td>17 April 2014</td>
<td>9th drop touched 8th drop</td>
<td>(156)</td>
<td>(13.4)</td>
</tr>
<tr>
<td>24 April 2014</td>
<td>9th drop separated from funnel during beaker change</td>
<td>156</td>
<td>13.4</td>
</tr>
</tbody>
</table>
Understanding universe structure

Understanding initial QGP conditions and transport theory
But are we observing effects related to the creation of a hot, dense new QGP state or these are reflections of the presence of a Heavy Ion projectile?

It is mandatory to check the magnitude of Cold Nuclear Matter Effects (CNM) using p-Pb collisions.
Uncertainties in the Parton Distribution Functions (PDF) for Nuclei: nPDF

Even first results from p-Pb gives important informations on nPDF and shadowing models
In Pb–Pb $R_{AA}$ jet suppression extends down to 30 GeV and up to 300 GeV.

In p–Pb no CNM effects from 25 up to 800 GeV.
$R_{pA}$ with $Z$ Boson

ATLAS: arXiv:1507.06232

$W$ production

$Z$ production proportional to $n_{\text{coll}}$ : no suppression
Rapidity asymmetry $\rightarrow$ sensitivity to $nPDF$
Cold Nuclear Matter effects cannot explain D meson suppression in Pb-Pb
Cold Nuclear Matter effects cannot explain Beauty hadron suppression in Pb-Pb
At high $p_t$ CNM effects in p-Pb collisions are not present in jets, hadrons, HF.

W/Z production are in agreement with pQCD scaled by the number of collisions.

↓

What measured in Pb-Pb collisions at high $p_t$ reveals the presence of a hot, dense QGP medium with low viscosity.

p-Pb data allow important informations on the nPDF
Production of quarkonia \((cc)\) \((bb)\) in \(\text{Pb-Pb}\)

- **Statistical regeneration**
  - Colour screening
  - Sequential suppression

- **Energy Density**

- **Low pt enhanced**
  - Expected mainly for charm

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Matsui T, Satz H (1986)
PHYSICS LETTERS B 178(4): 416-422.
Production of quarkonia in Pb-Pb

At LHC higher production than RHIC: statistical regeneration at work?

Sequential suppression observed in Pb-Pb


arXiv:1506.08804
Production of quarkonia in p-Pb

- CNM suppression for J/ψ only at low pt
- Lower effect for ϒ(1s)
- Effect in the nPDFs shadowing region
- Other possibilities: comover

\[ 10^{-2} \div 5 \cdot 10^{-2} \]
\[ 2 \cdot 10^{-5} + 8 \cdot 10^{-5} \]
\[ 4 \cdot 10^{-4} \div 2 \cdot 10^{-3} \]
At high $p_t$ CNM effects in p-Pb collisions are not present in quarkonia

However at lower $p_t$ effect not negligible.

Contribution of regeneration in Pb-Pb very important especially for $J/\psi$

Quarkonia suppression in medium is observed

Shadowing in nPDFs is a possible explanation for suppression at low $p_t$ in p-Pb
LHC as the highest energy $\gamma p$, $\gamma$Pb, $\gamma\gamma$ collider!

$J/\psi$ production in untraperipheral collisions

With nuclei very high flux of $\gamma$ ($\propto Z^2$)

$\gamma A \rightarrow J/\psi$

$\gamma\gamma \rightarrow J/\psi$

$\gamma p \rightarrow J/\psi$

Cross section sensitive to $g_{\text{Pb}}^2$ at low-$x$
Preference of LO-pQCD models with moderate gluons shadowing and nuclear modifications for gluon nPDFs

Strikman: “...provide the first direct experimental evidence for the strong nuclear gluon shadowing in lead”!

Data in line with and extend HERA measurements: no change in PDF with energy

ALICE: EPJ C73, 2617 (2013), PLB 718 (2013) 1273-1283
CMS: HIN-12-009

J/ψ production in UPC
LHC as $\gamma p$, $\gamma$Pb, $\gamma\gamma$ collider reach of important data for comparisons with different nPDF and gluon pPDF.
Flow and correlations: The ridge

(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c

Trigger Particle

Associated Particle

Δφ, Δη

trigger

associated

Near-side

Away-side

trigger

associated

Near-side

Away-side

36
The "ridge " as measured at RHIC

Interpreted as a collective behavior in the dense hot medium
Unexpected observation of a "ridge" in pp collisions.

(b) MinBias, 1.0 GeV/c < p_T < 3.0 GeV/c

(d) N > 110, 1.0 GeV/c < p_T < 3.0 GeV/c

Collective phenomena connected to multiplicity?
The near side ridge in Pb-Pb and p-Pb

Collective phenomena connected to multiplicity

CMS, JHEP 1009 (2010) 91
CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{min}}^{\text{coll}} \geq 110$

1 < $p_T$ < 3 GeV/c

CMS, PLB 718 (2012) 795

PbPb

ATLAS, PRL 110 (2013) 182302

LHCb-CONF-2015-004

CMS, PLB 718 (2012) 795

ATLAS, PRL 110 (2013) 182302

CMS, PLB 718 (2012) 795

LHCb-CONF-2015-004

2.0 < $\eta$ < 4.9

CMS, JHEP 1009 (2010) 91
The unexpected "double ridge" in p-Pb

Collective phenomena related to multiplicity

ALICE PLB 719:29 (2013)
Where is the ridge in p-Pb?

Ridge more pronounced in the Pb outgoing region

Compare ridges not looking at Pb or p side but with the same activity in the detector i.e. take the same multiplicity in Pb or p side

“The ridge appear to be independent of the beam (p) or the target (Pb) fragmentation, but only depends on the activity in the respective direction”.

$LHCb$ $\sqrt{s_{NN}} = 5$ TeV

$N_{hit}^{VELO} = 2200-2400$

$N_{hit}^{VELO} = 3000-3500$

Pb+p

p-Pb

0-3% $1< pt < 2$ Gev/c
Idea of using effective activity/energy to compare different collisions: an old idea

M. Basile et al:
Universality Features in (pp), (e+e-) and Deep-Inelastic.Scattering Processes.
Nuovo Cim. 79 A (1984) 1
Analogy with Pb-Pb suggests a formation of mini-QGP with later hydrodynamic expansion

**OK** for PID flow

**BUT** is there enough time to thermalize the system?

*PRL 111 - 172303 (2013)*

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The ridge in theory
Hydrodynamical models

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The ridge in theory
GLASMA + BFKL models

Colour reconnection and gluon saturation in the framework of a colour-glass condensate

Ok for double ridge

BUT not clear if it can explain mass hierarchy behavior observed in flow(s)

\[ \frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d \Delta \phi} \]

GLASMA + BFKL


Yield

\[ \text{Yield} \]

+ ATLAS PRL 110.182302

\[ \Delta \phi \]
But is "the ridge" the only measurement where collective phenomena appear in high multiplicity events?

Several other analysis show similar behaviour between high multiplicity p-Pb events and Pb-Pb collisions.
Baryon (proton and $\Lambda$) to meson ratio

- Baryon/meson ratio in p-Pb events at high/low multiplicity show a behavior similar to Pb-Pb collisions.
Multiplicity/activity is an important parameter in the comparison of different processes, allowing the appearance of similarities and common features among systems of different sizes.

It suggests a new approach in understanding QCD using different collisions as inputs and gives constraints on the dynamics of the collisions.
Charm production show and increase with multiplicity faster than linear: presence of MPI or other QCD processes related to the high multiplicity environment.
Particle ratio vs event multiplicity/activity

- Continuous evolution across different system size
- Multiplicity as a system temperature monitor?
- Need different variables (energy density ...)?

\[ \Xi/\pi \text{ ratio} \]

\[ \Omega/\pi \text{ ratio} \]

\[ \langle dN_{\text{ch}}/d\eta_{\text{lab}} \rangle_{\eta_{\text{lab}}<0.5} \]

\[ \langle dN_{\text{ch}}/d\eta_{\text{lab}} \rangle_{\eta_{\text{lab}}<0.5} \]

\[ \text{Multiplicty} \]

\[ \text{d/p ratio} \]

\[ \text{pp} \]

\[ \text{pPb} \]

\[ \text{PbPb} \]
Analysis as function of multiplicity/activity across several type of collisions and system sizes are fundamental to better understand QCD processes and particle formation.

A new challenge for RUN II.
Cold Nuclear Matter effects cannot explain results from lead-lead collisions → LHC has produced a hot dense medium (QGP) with low viscosity

Importance of shadowing effects in the nuclear Parton Distribution Functions

Strong similarities among lead-lead collisions and high multiplicity events in pp and proton-Lead collisions → Evidence for similar collective effects and QCD dynamics

Proton-Lead collisions has opened a window on new interesting QCD studies crossing different collisions systems using the multiplicity/activity variables.