LHC Heavy Ion Results

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The main goal of Heavy Ion Collisions is to study the behavior of **matter under extreme condition**, to explore and test QCD phase diagram and to address the fundamental question of hadron confinement and chiral symmetry breaking, which are related to the existence and properties of the **Quark-Gluon Plasma (QGP)**.
QCD phase diagram

Normal conditions $\rightarrow$ quarks and gluons confined in Hadrons.

$\varepsilon \approx 0.15 \text{ GeV/fm}^3$
QCD phase diagram

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High T and low density, QCD predicts a phase transition to a deconfined state of Quarks and Gluons.
$T_C \approx 170$ GeV
$\epsilon_C \approx 1.0$ GeV/fm$^3$
At high density and low temperature, system can be considered a degenerate interacting quark gas. Approximate model calculations suggest that transition would be of the 1st order.
QCD phase diagram

A state of deconfined and thermalized quarks and gluons over a large volume predicted by QCD at high energy and density, also known as:

- Quark Gluon Plasma

HADRONS
In high T and low density, transition might be a rapid cross over, instead of a 1\textsuperscript{st} order transition.
At high density and low T, it is predicted that remnant attractive interaction between quarks causes q-q pairing and the formation of a color superconductor phase.
Heavy Ion Collisions

Temperature

Density

Quark Gluon Plasma

Hadrons

Color Super-Conductor
Heavy Ion Collisions

温度

密度

夸克胶子等离子体

色超导体

强子
Heavy Ion Collisions
Heavy Ion Collisions

Initial Conditions:
- Lorentz Contracted colliding nuclei
- Color Glass Condensate
- Pre-equilibrium
- Hard Scattering
- Fluctuations
Hot Nuclear Matter

Soft Thermal QCD matter.

- Extremely Dense
- Strongly interacting
- Shows collective behavior
- Expansion dynamics well described by hydrodynamic models with viscosity very close to theoretical limit.
- Partonic degrees of freedom.
Hard Scatterings produce **hard probes**.
- High $p_T$ particles
- Particle Jets
- Heavy flavored particles.
- Can be used to probe the medium through interactions: Jet modification and suppression, nuclear modification factors of light and heavy flavored particles.
The ALICE experiment
The ALICE experiment
Central Barrel:
2\pi Tracking and PID
| \eta | < 1
p_{T} > 100 \text{ MeV/c}
Excellent vertexing
Figure 2

The analysis, for the centrality classes 0–20% and 40–80%.

The centroids of the Gaussians were found to be compatible with the signal shape. The background was described with a threshold function multiplied by an exponential term that describes the long-tail behavior. The uncertainties on the signal yields reported in the figures are estimated statistically only.
The ALICE Collaboration

More than 1000 members
More than 100 institutions
More than 30 countries
The ALICE Collaboration
2010 – Pb-Pb at 2.76 TeV, integrated lum. \( \sim 10 \, \mu b^{-1} \)
Approx. 20 Million events,

2011 – Pb-Pb at 2.76 TeV, integrated lum. \( \sim 0.1 \, nb^{-1} \)
Approx. 140 Million events,
enriched with rare trigger events.

2012 – p-Pb at 5.02 short test run,
Approx. 2 Million events.

2013 – (Jan.-Fev.) p-Pb expected to run.
Charged particle multiplicity

Particle production

- Increase of x2.2 with respect to RHIC.
- Energy dependence is steeper for heavy-ion collisions than p-p.
- New p-Pb data, important for initial state effects.
Comparison to models

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**Pb-Pb**

- Empirical extrapolation from RHIC data under predicts data.
- HIJING tuned to 7 TeV p-p data yields prediction consistent with data.
- Saturation models vary level of agreement.
- Hydro models with multiplicity scaled from p-p also under predicts or over predicts the data.
Comparison to models

p-Pb

- Important to discriminate initial and final state effects.
- Probe small $x$ and the initial state.
- Set constrains to models.
- Models that include shadowing or saturation are consistent with data within 20%.
LHC spectra shows harder distribution than RHIC.
Consistent with stronger radial flow component.
Hydro models with late stage implementation describe well the data.

- **VISH2+1**: Viscous hydro model
- **HKM**: Hydro+UrQMD
- **Kraków**: Viscous hydro, with effective $T_{ch}$. 
Hadron Chemistry

Hadron Chemistry is used for statistical thermal models fits.

Very successful in describing RHIC data.
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Very successful in describing RHIC data.

At LHC, $p/\pi$ is considerably lower than RHIC, and it is over predicted by thermal models. Perhaps final state hadronic interactions play more important role at LHC than at RHIC.

Strange particles are needed to further constrain thermal models.
Strangeness enhancement $\rightarrow$ Proposed signature of QGP. Relative enhancement of Strange and Multi-strange baryons is also observed at LHC.
Direct photon spectrum

Inverse slope of an exp. fit to the low $p_T$ spectrum: $T = 304 \pm 51$ MeV

PHENIX/RHIC $T = 221 \pm 19 \pm 19$ MeV
Elliptic Flow

Out-of-plane

In-plane
Elliptic Flow
Elliptic Flow
Elliptic Flow
Elliptic Flow

In-plane

Out-of-plane

In-plane
Elliptic Flow
Elliptic Flow

Spatial anisotropy $\rightarrow$ Momentum anisotropy $\rightarrow \frac{d^2N}{dp_Td\phi}$

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_Tdp_Tdy} \left( 1 + \sum_{n=1}^{\infty} 2\nu_n \cos[n(\phi - \Psi_n)] \right)$$

$$\nu_n (p_T, \eta) = \left\langle \cos \left[ n(\phi - \Psi_n) \right] \right\rangle$$

Probe the system evolution.
Elliptic Flow

\[ v_2 \text{ measured at LHC is about 30\% higher than at RHIC.} \]
Elliptic Flow

Elliptic Flow

Hydrodynamical evolution

Elliptic Flow


Fragmentation processes, Quenching
Elliptic Flow

Difference due to flow fluctuations

Higher order anisotropic flow: $v_3$
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$$v_n(p_T, \eta) = \langle \cos[n(\phi - \Psi_n)] \rangle$$
Higher order anisotropic flow

- Large elliptic and triangular flow observed at LHC.
- $v_2$ at low-$p_T$ consistent with low viscous hydro evolution.
- $v_2$ at high-$p_T$ increase with centrality and well described by model.
Hydrodynamic flow

Low viscous hydro models describe well the data in the low $p_T$ region.

Centrality 30%-40%

- $v_2(2)$
- $v_3(2)$
- $v_4(2)$
- $v_5(2)$

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Centrality 0%-2%

- $v_2(\eta/s = 0.0)$
- $v_2(\eta/s = 0.08)$
- $v_3(\eta/s = 0.0)$
- $v_3(\eta/s = 0.08)$

$\langle p_T \rangle$ (GeV/c)

$\langle v_n \rangle$
Elliptic flow fluctuations

- Flow fluctuations are associated with fluctuations of the initial collisions geometry.
- Flow fluctuations measured extends up to $p_T=8$ GeV/c, and does not change significantly, suggesting a common origin.


$\frac{v_2(EP)^2 v_2(4)^2}{v_2(EP)^2 + v_2(4)^2}$

$\sqrt{s_{NN}} = 2.76$ TeV

ALICE Pb-Pb

Flow fluctuations originate entirely from fluctuations of the initial geometry.

Flow fluctuations are within errors independent of momentum up to those observed at RHIC energies [1]. It is remarkable that in minimal for mid-central collisions and become larger for peripheral collisions. The observed difference between results from all three LHC methods for 30-40% centrality to the analysis at top RHIC energy has a peak value about 10% lower than at LHC.

The ALICE Collaboration

The ALICE Collaboration

Flow fluctuations are associated with fluctuations of the initial geometry.

Flow fluctuations measured extends up to $p_T=8$ GeV/c, and does not change significantly, suggesting a common origin.
Identified particle $v_2$ is an important probe for NCQ scaling, used as argument for partonic degree of freedom.
Particle identified elliptic flow

Heavy-flavor quarks should feel less the collective expansion, but data shows non-zero $v_2$ for D and J/Ψ.
Comparing the spectra

Pb-Pb spectra are compared to p-p data, normalized by the number of binary collisions \( <N_{\text{Bin}} > \).

Spectra from Peripheral and Central collisions are compared and have different agreement to reference data.
Detailed comparison between Pb-Pb spectra and p-p spectra is done by ratio known as the Nuclear Modification Factor:

\[
R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_t}{dN_{pp} / dp_t}
\]

Photon \( R_{AA} \), presented by the CMS Collaboration (arXiv: 1210.3093) shows no suppression, as expected since photons should not be affected by QCD matter.
Detailed comparison between Pb-Pb spectra and p-p spectra is done by ratio known as the Nuclear Modification Factor:

\[ R_{AA}(p_T) = \frac{\frac{dN_{AA}}{dp_T}}{\langle N_{coll} \rangle \frac{dN_{pp}}{dp_T}} \]

LHC data extends the \( R_{AA} \) measurement to higher \( p_T \) and shows a slightly larger suppression than observed at RHIC, suggesting higher energy loss due to denser medium.
Nuclear Modification Factor

p-Pb data tests the effects due to initial state, no suppression is observed.

Suppression observed in central Pb-Pb collisions is not due to initial state effects, hence, related to the Jet interactions with the hot dense matter created in these heavy-ion collisions.
Constrains to models

Result consistent with CMS.

Many models can reproduce suppression at high-$p_T$, but uncertainties are still large.
p-Pb results can help with the understanding of cold nuclear matter.

Results are compared to different theoretical models:

- HIJING
- Color Glass Condensate.
- pQCD + cold nuclear matter effects and Shadowing calculations.
Heavy-flavor suppression at high $p_T$

Strong in-medium energy loss for charm quarks with suppression almost as large as observed for charged particles.
Heavy-flavor suppression at high $p_T$

- At high $p_T$ there is little shadowing effects (initial state) and suppression can be explained by parton energy loss models.
- New studies on $R_{AA}$ relative to event plane test variation due to energy loss path length.
Jet Modification by the medium

Jet interaction with the medium can result in:

- Quenching.
- Modification of shape due to interplay of flow with Jets.

arXiv:1210.6162
Jet Modification by the medium

Increase of near-side correlation width in eta direction with centrality, while in the azimuthal direction, width is independent of centrality.

$$\sigma_{\Delta \eta} > \sigma_{\Delta \phi}$$
Conclusions

Higher energy collisions at the LHC take us into regions not accessible before at lower energy experiments.

- High statistics and higher density allows for detailed and precision measurements of bulk properties and improve constrain to theoretical models.
- High $p_T$ probes and heavy-flavor observables can now be used to test the medium.

ALICE complete set of detectors and analysis methods allows for detailed studies of the hot and dense nuclear matter formed at LHC heavy-ion collisions. Ongoing analysis and upgrade program will bring much more new results.

Thank you !!!!!