Review of Heavy-Ion Results from the CERN LHC

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Aims of Heavy-Ion Physics

- We collide lead ions (& p-p, p-Pb) to study QCD at extreme energy densities over large volumes and long time-scales.

- Study the **QCD phase transition** from nuclear matter to a deconfined state of quarks and gluons - **The Quark-Gluon Plasma**.

- Study the physics of the **Quark-Gluon Plasma** (QCD under extreme conditions).

- Study the role of **chiral symmetry** in the generation of mass in hadrons (accounts for ~ 99% of mass of nuclear matter).

- Study the nature of **quark confinement**.
Phases of Strongly Interacting Matter

Both statistical and lattice QCD predict that nuclear matter will undergo a phase transition, into a deconfined state of quarks and gluons – a quark-gluon plasma, at a temperature of, $T \sim 170$ MeV and energy density, $\varepsilon \sim 1 \text{ GeV/fm}^3$.

Lattice QCD, $\mu_B = 0$

Heavy-Ion collisions far exceed these temperatures & densities at the LHC.
Heavy Ion Collisions

Create QGP by colliding ultra-relativistic heavy ions

\[ \sqrt{S_{NN}} \text{ (GeV)} = 5.4 \quad 19 \quad 200 \quad 2760 \quad (5500) \]

pre-equilibration $\Rightarrow$ QGP $\Rightarrow$

hadronisation $\Rightarrow$ freeze out

Colliders: AGS, SPS, RHIC, LHC
Observables

Observables - Lattice Thermodynamics

Interferometry
\[ \pi\pi, \ldots \]

Temperature

120 MeV

Thermal masses
chiral symmetry restoration

170 MeV

Critical temperature
and energy density

190 MeV

Strange abundances

Heavy Quark Potential,
screening
no \( \chi_c \)

230 MeV

establish contact with
perturbative QCD

K, \( \Lambda \), \( \Omega \), ...

c/2

Last scattering

Smeared \( p \)

Equation of State

no \( \psi' \)

no J/\( \psi \)

Jets

Open charm, beauty
LHC Detectors

ALICE

ATLAS

CMS
Centrality Selection – Glauber Model

- Assume particle production is factorised into number of participants $N_{\text{part}}$ and number of collisions $N_{\text{coll}}$.
- Assume Negative Binomial Distribution for both $f N_{\text{part}} + (1-f) N_{\text{coll}}$.
- Relation of percentile classes to Glauber values (e.g., <$N_{\text{part}}$>, etc.) purely geometrical by slicing in impact parameter.
Charged Particle Multiplicity

\[ \frac{dN_{ch}}{d\eta}\ (\text{Pb-Pb})\ \text{Theory} \]

\[ \frac{dN_{ch}}{d\eta}\ =\ 1584 \pm 4\ (\text{stat.}) \pm 76\ (\text{syst.}) \]

Rises with \( \sqrt{s} \) faster than pp
Fits power law: Pb-Pb \( \sim s^{0.15} \)

Larger than most model predictions – good agreement between LHC experiments

Bjorken formula estimates energy density, \( \varepsilon > 15\ \text{GeV/fm}^3 \) (3 x RHIC)

Bose–Einstein correlations (HBT)

QM enhancement of identical Bosons at small momentum difference

enhancement of e.g. like-sign pions at low momentum difference $q_{inv}=|p_1-p_2|$, ...

- medium size: 2x larger than at RHIC
  - $R_{out} R_{side} R_{long} \sim 300 \text{ fm}^3$
  - Volume $\sim 5000 \text{ fm}^3$
- medium life time: 40% longer than at RHIC
  - $\tau \sim 10-11 \text{ fm}/c$

Particle Yields – Thermal Models

• ~ thermodynamic equilibrium .......... but with some tension!
• – $T \sim 156$ MeV especially $p$ and $k^*$

origin of deviations?
– feed down from resonance decays?
– sequential freeze-out?
– non-equilibrium freeze-out?
QPG Temperature

$p_T$ spectrum of (direct) photons emitted at LHC

“For Temperature” ≈ 300 MeV (→ highest man-made temperature)
Particle spectra

LHC results agree well between experiments

Very significant changes in slope compared to RHIC
Good agree between experiments e.g. ALICE/ATLAS in this case
Does QGP have elliptic Flow?

Study angular dependence of emitted particles

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)] \right)
\]

\( v_2 = \langle \cos 2\phi \rangle \)

\( V_1 = \text{directed flow.} \quad V_2 = \text{elliptic flow.} \)
Elliptic Flow

$\text{v}_2$ shape is identical to RHIC

$\text{v}_2 \sim 30\%$ larger than RHIC: larger $T_\pi, K$ reproduced by hydro calculation

$\text{p}$ ok for semi-peripheral but is a remaining challenge for central collisions


Flow vs Centrality

Flow strongest for semi-peripheral collisions (central collisions too symmetric).
Elliptic Flow

- $v_2$ decreases with centrality (as expected)
- ALICE and CMS data agree

$v_2$ and spectra show clear mass ordering, in AA, expected in collective expansion scenario: elliptic and radial flow
V₂ at High Pₜ

V₂ drops to zero at high Pₜ
Elliptic Flow – Higher Orders

Higher-order coefficients (n>2) do not show strong centrality dependence – consistent with fluctuations in initial state geometry being the driving force.

Superposition of flow harmonics, including higher orders, is sufficient to describe Ridge and Cone effects without implying medium response.

Full Harmonic Spectrum

Measure multi $V_n$ - Over-constrain Hydro Models to get $\eta/s$, initial conditions etc.

.closest Theory prediction $\eta/S > 1/4\pi \approx 0.08$

$\nabla$ AdS/CFT:

SUSY string theory in 5 dimensions!

Most perfect liquid ever produced
Elliptic Flow Charm

- Non zero D meson $v_2$ (3σ in $2 < p_T < 6 \text{ GeV/c}$)
- Comparable with charged hadrons elliptic flow
Jets in heavy ion collisions

• Studying deconfinement with jets

Free quarks not allowed when quark, anti-quark pairs are produced they fly apart producing back-to-back ‘jets’ of particles

Interaction at the quark (parton) level

The same interaction at the hadron level

key QCD prediction: jets are quenched


Quarks remain free in QGP and lose energy while travelling through
Jet Suppression

Significant imbalance between leading and sub-leading jets for central collisions
No Jet Suppression in p-Pb
**Nuclear Modification Factor**

- particle interaction with medium
- stronger suppression at LHC
- ~factor 7 at 7 GeV/c

\[
R_{AA}^D(p_T) = \frac{\frac{d\sigma_{AA}^D}{dp_T}}{\langle N_{coll} \rangle \times \frac{d\sigma_{pp}^D}{dp_T}}
\]

Divide \( p_T \) spectra in Pb-Pb by p-p (with suitable normalisation factor)

![Graph showing the modification factor with data points from ALICE, PHENIX, and STAR experiments.](image)

**ALICE Preliminary**

ALICE, charged particles, Pb-Pb
\( \sqrt{s_{NN}} = 2.76 \text{ TeV}, |\eta| < 0.8 \)
$R_{AA}$ vs centrality

- Suppression increases with centrality.
- Minimum remains around 6-7 GeV/c
\( R_{AA} \) In and Out of Plane

- Significant effect, even at 20 GeV and beyond

\[ v_2 = \langle \cos 2(\phi - \Psi_2) \rangle \]

Sensitive to path length dependence of energy loss
$R_{pA}$ & $R_{AA}$ for $\gamma$s, $W$s & $Z$s
Centrality Dependence of $Z$ Production

$Z \rightarrow e^+e^-, \mu^+\mu^-$


$Z^0$ yields consistent with $N_{\text{coll}}$ scaling
$R_{AA}$ for different particles

- For hadrons containing heavy quarks, smaller suppression expected
- At high $p_T$ (>8-10 GeV/c) $R_{AA}$ universality for light hadrons
Energy Loss of Heavier Quarks

Probe QGP with different quark flavours: $u, d, s, c$
(For ALICE: $b$ only after detector upgrade – 2018-2020)

Theoretical expectation: $\Delta E_{\text{light quark}} > \Delta E_{\text{massive quark}}$

High $p_T$ Suppression of charm

Indication of mass effects?
$R_{AA}$ Charm vs Bottom

- Comparing charm from ALICE and bottom (beauty) from CMS.
- First hint of flavour hierarchy
\[ \frac{N_{Y(2S)}}{N_{Y(1S)}}_{pp} = 0.56 \pm 0.13 \pm 0.01 \]
\[ \frac{N_{Y(3S)}}{N_{Y(1S)}}_{pp} = 0.21 \pm 0.11 \pm 0.02 \]
\[ \frac{N_{Y(2S)}}{N_{Y(1S)}}_{PbPb} = 0.12 \pm 0.03 \pm 0.01 \]
\[ \frac{N_{Y(3S)}}{N_{Y(1S)}}_{PbPb} < 0.07 \]

Ratios not corrected for acceptance and efficiency
• Strong suppression for less tightly bound Υ states
• Very efficient melting of Υ(3S) - not measurable (upper limit only)
P-Pb Data
High $p_T$ Puzzle

High $p_T$ $R_{pA}$ from CMS: enhancement?
(similar picture from ATLAS but Not ALICE)

Not seen in jets

Results rely on interpolated pp reference data → need pp data at 5 TeV
P-Pb – The Ridge

2 < $p_{T,\text{trig}}$ < 4 GeV/c
1 < $p_{T,\text{assoc}}$ < 2 GeV/c
20% highest multiplicity

Near-side jet
($\Delta \phi \sim 0, \Delta \eta \sim 0$)

Away-side jet
($\Delta \phi \sim \pi$, elongated in $\Delta \eta$)

Near-side ridge
($\Delta \phi \sim 0$, elongated in $\Delta \eta$)

in addition to near side peak and away-side recoil...
... there’s an additional near side ridge in p-Pb

first observed by CMS [PLB718 (2013) 795]

PLB719 (2013) 29
P-Pb: The Double Ridge

- Separation of jet and ridge components
  - In 60-100% no ridge seen, similar to pp
- What remains if we subtract 60-100%?

0-20% - 60-100% =

Leaves double ridged structure =>

the origin of this structure is still unknown!
similar structure observed in Pb-Pb is attributed to hydrodynamic flow...
CGC-glasma graphs can also produce symmetric ridges?
Summary

• We have started to piece together the standard model of heavy-ion collisions
• We have measured many of the global features
  – Phase transition temperature - Agrees with theory $T_c \sim 160$ MeV
  – Energy density - Over 10x critical energy density, $\varepsilon > 15$ GeV/fm$^3$
  – size & lifetime of system $\sim 5000$ fm$^3$, $\tau \sim 10^{-11}$ fm/c
• Started to measure dynamical features
  – Strong elliptical flow – ideal liquid
  – Strong suppression of jets and high $p_T$ particles
  – Little evidence of quark mass dependence on energy loss for lighter quarks (unlike predictions – although dependence seen between charm and bottom)
  – $\Upsilon'$ and $\Upsilon''$ suppressed.
• p-Pb reference data turning out to be interesting in its own right.
• lots of work and exciting physics to look forward to.
• Thank you for listening