Results from the LHC Heavy-Ion Programme: an Overview

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Contents

a (personal!) choice of results…

• Pb-Pb collisions
  – correlations
  – direct photons
  – particle yields
  – jet quenching
    • high pT suppression
    • di-jet imbalance
    • modified fragmentation
  – quarkonia
  – heavy flavour

• p-Pb collisions
  – nuclear modification factor
  – quarkonia
  – signs of collectivity

• conclusions
Ultrarelativistic AA Collisions

basic idea:
compress large amount of energy in small volume
→ produce a “fireball” of hot matter:
temperature $O(10^{12} \text{ K})$
  – $\sim 10^5 \times T$ at centre of Sun
  – $\sim T$ of universe @ $\sim 10 \mu\text{s}$ after Big Bang

• extreme conditions: how does matter behave?
  → study the fireball properties
  – QCD predicts state of deconfined quarks and gluons
    (Quark-Gluon Plasma)
  – evidence for deconfinement already at lower energy
    (CERN-SPS, BNL-RHIC)
  – LHC: controlled probes → properties of QCD medium
Nuclear collisions at the LHC

- large cross-section for “hard probes”

→ novel tools to probe QCD medium
e.g. heavy flavour:
ALICE (dedicated to AA)

ATLAS (general purpose, AA capabilities)

CMS (general purpose, AA capabilities)

LHCb (dedicated to beauty, joined in pA run)
Heavy Ions in Run 1

- two successful Pb-Pb runs already
  - 2010 $\rightarrow$ $\sim 10/\mu$b
  - 2011 $\rightarrow$ $\sim 150/\mu$b
- $+ p$-Pb “control” run
  - 2013 $\rightarrow$ $\sim 30/nb$

some numbers (2011 Pb-Pb run):
- $\sim 1.2 \times 10^8$ ions/bunch
- 358 bunches
  - 200 ns basic spacing
- $\beta^* = 1$ m
- $L \sim 5 \times 10^{26}$ cm$^{-2}$s$^{-1}$
  $\rightarrow$ $\sim 4000$ Hz interaction rate
Geometry of a Pb-Pb collision

- Central collisions
  - small impact parameter $b$
  - high number of participants $\rightarrow$ high multiplicity
- Peripheral collisions
  - large impact parameter $b$
  - low number of participants $\rightarrow$ low multiplicity

For example: sum of the amplitudes in the ALICE V0 scintillators reproduced by Glauber model fit (red):
- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- simple model of particle production
- deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes
Azimuthal asymmetry

... in the transverse momentum distribution of produced particles

- why is it important?
- non-central collisions are asymmetric in azimuth
  azimuth = angle in the plane of the screen

→ transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)

- Small mean free path
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)
Azimuthal asymmetry

• to quantify the asymmetry:
  → Fourier expansion of the angular distribution:
    \[ \propto 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2[\varphi - \psi_2]) + \ldots \]
    – in the central detector region (\( \theta \sim 90^\circ \)) \( v_1 \sim 0 \) → asymmetry quantified with \( v_2 \)

• experimentally: \( v_2 \sim \) as large as expected by hydrodynamics
Higher harmonics

• a beautiful tool…

initial state geometrical asymmetries $\rightarrow$ final state momentum asymmetries

• connects final state distribution to initial state fluctuations, via medium transport
The QGP shines!

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

- “temperature” ~ 300 MeV (→ largest ever man-made, btw…)
Particle yields

- ~ thermodynamic equilibrium
  - $T \sim 156$ MeV
  - now including $^3\Lambda\!H$!

- ... but with some tension
  - especially p and $K^*$

- origin of deviations?
  - feed down from resonance decays?
  - sequential freeze-out?
  - non-equilibrium freeze-out?
High $p_T$ suppression

- production of particles at high $p_T$
  - above 2-3 GeV/c, say
- is expected to scale like the number of binary nucleon-nucleon collisions:
  \[
  \left. \frac{dN}{dp_T} \right|_{AA} = \langle N_{\text{coll}} \rangle \left. \frac{dN}{dp_T} \right|_{pp}
  \]
- can be modified by nuclear effects
  - e.g.: particles can lose energy when traversing the QCD plasma fireball ("jet quenching")
    \[ \rightarrow \text{suppression of particle production at high } p_T \]
- define a "nuclear modification factor" $R_{AA}$
  \[
  R_{AA} = \frac{\left. \frac{dN}{dp_T} \right|_{AA}}{\langle N_{\text{coll}} \rangle \left. \frac{dN}{dp_T} \right|_{pp}}
  \]
- in the absence of nuclear effects \[ R_{AA} = 1 \]
Strong quenching

- Pb-Pb significantly below scaled pp for central collisions (filled points)

\[ R_{AA} : \]
- minimum around 6-7 GeV \( (R_{AA} \sim 0.14) \)
- clear increase at higher \( p_T \)
Strong angular dependence

• significant effect, even at 20 GeV and beyond!

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

→ sensitivity to path length dependence of energy loss
Dependence on particle species

- particle mass / type (baryon/meson) dependence of quenching
  - e.g.: proton enhancement

→ sensitivity to hadronisation in medium
\( R_{AA} \) for vector bosons

- electroweak probes, on the other hand, are unmodified
→ (essential cross check!)
Di-jet imbalance

- Pb-Pb events with large di-jet imbalance observed at the LHC

\[ \rightarrow \text{recoiling jet strongly quenched!} \]

CMS: arXiv:1102.1957
Di-jet imbalance

- imbalance quantified by the di-jet asymmetry variable $A_J$:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \quad E_{T1} > 100\text{GeV} \quad E_{T2} > 25\text{GeV}$$

\[ R = 0.4 \quad |\eta| < 2.8 \]

- with increasing centrality:
  - enhancement of asymmetric di-jets with respect to pp
    - & HIJING + PYTHIA simulation

**ATLAS: PRL105 (2010) 252303**
Di-jet $\Delta \phi$

- no visible angular decorrelation in $\Delta \phi$ wrt pp collisions!

$\Rightarrow$ large imbalance effect on jet energy, but very little effect on jet direction!
Jet $R_{AA}$

CMS Preliminary

Bayesian

$70-90\%$

$50-70\%$

$30-50\%$

$10-30\%$

$5-10\%$

$0-5\%$

Jet $p_T$ (GeV/c)

Jet $p_T$ (GeV/c)

Jet $p_T$ (GeV/c)

Jet $p_T$ (GeV/c)

CMS PAS HIN-12-004

F Antinori - SEWM 14 - EPFL - 15 July 2014
Jet $v_2$

- substantial azimuthal asymmetry up to highest jet energies!
Jet fragmentation is modified

- ratio of Pb-Pb and pp Fragmentation Functions

\[ z = \frac{p_T(\text{track})}{p_T(\text{jet})} \]

ATLAS-CONF-2012-115
Where does the energy go?

- look at missing $p_T$ projected on leading jet axis

\[
p_{\parallel} = \sum_{\text{Tracks}} -p_{\text{T}}^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}})
\]

- the energy reappears, degraded, outside of the jet cone…

[CMS: PRC 84 (2011) 024906]
Particle composition

- peak excess particle composition similar to pp!
Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986
- $Q\bar{Q}$ potential screened in QGP for $r > \lambda_D$ (Debye length) → binding suppressed for states with $r > \lambda_D$
- substantial suppression at SPS & RHIC – effect similar at the two machines

$J/\psi$ nuclear modification factor $R_{AA}$

![Graph showing $R_{AA}$ vs $N_{part}$ with data points for different collision systems such as Au+Au, Cu+Cu, and p+p. The graph indicates a trend of suppression as $N_{part}$ increases.]
J/ψ suppression at the LHC

- LHC (ALICE, 2.5 < y < 4, p_T > 0)

\[ \rightarrow \text{less suppression than RHIC} \]
\[ \text{(PHENIX, 1.2 < y < 2.2, p_T > 0)} \]

\[ \rightarrow \text{weaker centrality dependence} \]

\[ \rightarrow \text{new regime wrt RHIC!} \]
\[ \rightarrow \text{c-cbar coalescence?} \]
J/ψ $R_{AA}$: $p_T$ dependence

- decreases with $p_T$

- consistent with coalescence models!

- at RHIC: opposite behaviour

![Graph showing $R_{AA}$ vs. $p_T$ for different centrality bins.](STAR, arXiv:1310.3563)
J/ψ flow?

• some hint for a modulation…?

• more statistics needed!
Bottomonium suppression

- stronger suppression for less bound Y states
  - very efficient melting: Y(3S) not measurable (upper limit only)
Charm and beauty: ideal probes

• study medium with probes of known colour charge and mass
  → e.g.: energy loss by gluon radiation expected to be:
    – parton-specific: stronger for gluons than quarks (colour charge)
    – flavour-specific: stronger for lighter than for heavier quarks (dead-cone effect)

• study effect of medium on fragmentation
  – (no extra production of c, b at hadronization)
  → independent string fragmentation vs recombination
    – e.g.: D^+_s vs D^0, D^+

• + measurement important for quarkonium physics
  – open Q\bar{Q} production natural normalization for quarkonium studies
  – B meson decays non negligible source of non-prompt J/ψ
$R_{AA}$: Flavour Dependence!

- $p_T < 8$ GeV/c:
  - hint of less suppression than for $\pi$ ?
- $p_T > 8$ GeV/c
  - same suppression as for $\pi$...

- indication of $R_{AA}(b) > R_{AA}(c)$!
D meson $v_2$

- indication of non-zero $v_2$
  - consistent with strong coupling of $c$ to medium

- theory must describe simultaneously $v_2$ and $R_{AA}$ …
Parton shadowing...

- complication in interpretation of Pb-Pb results:
  different parton distribution functions in protons and nuclei

\[ R_{V}^{Pb} \quad R_{S}^{Pb} \quad R_{G}^{Pb} \]

\[ Q^2 = 1.69 \text{ GeV}^2 \quad Q^2 = 100 \text{ GeV}^2 \]

\[ x = \text{fraction of nucleon momentum carried by parton} \]

→ uncertainty on “trivial” nuclear effects baseline
→ measure p-Pb collisions!!!
p-Pb collisions in the LHC!

• tricky, but can be done…
• 2-in-1 design…
  → identical bending field in two beams
  → locks the relation between the two beam momenta:
    \[ p (\text{Pb}) = Z p(\text{proton}) \]
  → different speeds for the two beams!
• adjust length of closed orbits!
  – to compensate different speeds
• different RF freq for two beams at injection and ramps
• short low lumi pilot run (a few hours) on 12/9/2012
• first run in Jan-Feb 2013!
→ ~ 30/nb
Control experiment: $R_{pPb}$

- measurement of nuclear modifications in initial state

$R_{pPb} \sim 1$ for $p_T > 3$ GeV/c \(\rightarrow\) confirms quenching is due to QCD medium
High-$p_T$ puzzle!

- high-$p_T$ $R_{pA}$ from CMS: enhancement??
  - similar picture from ATLAS (not from ALICE)

- but not for jets?

- results rely on interpolated pp reference…
  → need pp data at 5 TeV!

à suivre…
$R_{pPb}$ for Heavy Flavours

- D mesons

- HF muons

→ Pb-Pb suppression not due to initial state
J/ψ in p-Pb

- $R_{pPb}$ consistent with shadowing
  - $p_T$-integrated

- $R_{pPb}$ back to 1 at high $p_T$
  - opposite behaviour for Pb-Pb!

$L_{\text{int}} (-4.46 < y_{\text{CM},\text{LAB}} < -2.96) = 5.8 \text{ nb}^{-1}$, $L_{\text{int}} (2.03 < y_{\text{CM},\text{LAB}} < 3.53) = 5.0 \text{ nb}^{-1}$

← LHCb joins the Heavy-Ion club!
ψ(2S) in p-Pb

- surprise: more suppressed than J/ψ!
  - how can shadowing (initial state) do that?
  - at odds with shadowing in Pb hemisphere

- more “active” events → larger effect
  - i.e.: effect increases with multiplicity

→ indication of final state effects?
Bottomonia in p-Pb

- $Y(1S) \sim$ OK with shadowing
- excited states more suppressed

![Graph showing $R_{pPb}$ vs $y_{cms}$ for p-Pb and Pb-Pb collisions.](image)

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV
- $|y_{CM}| < 1.93, L = 31 \text{ nb}^{-1}$
- 95% upper limit
  PRL 109 (2012) 222301

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- $|y_{CM}| < 2.4, L = 150 \mu \text{b}^{-1}$

$\gamma(nS)/\gamma(1S)$ vs $y_{CM}$ for p-Pb and Pb-Pb collisions.
The Ridge

- 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]

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

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

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

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

PLB719 (2013) 29
The Double Ridge

- Can we separate the jet and ridge components?
  - in 60-100% no ridge seen, similar to pp
  → what remains if we subtract 60-100%?

- the ridge is doubled!

→ 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?

[ALICE, PLB719 (2013) 29]
Identified particles

- how does the correlation depend on the particle species?
  - p-Pb
  - Pb-Pb

- p-Pb remarkably similar to Pb-Pb.
  - where particle species dependence is attributed to collective flow!
Multiparticle correlations

• $v_2$ calculated with higher order cumulants

• again: $p$-$\text{Pb}$ very similar to $\text{Pb}$-$\text{Pb}$

• azimuthal asymmetry is a true multi-particle effect, in both systems!
Multi-strange baryons

- p-Pb smoothly bridges $\Xi$, $\Omega$ abundances from pp to Pb-Pb values!

$\rightarrow$ onset of collective effects in p-Pb?
Conclusions

• the LHC has ushered in a new era for ultrarelativistic AA collisions
  – abundance of hard probes
  – state-of-the-art collider detectors (ALICE, + AA capabilities in ATLAS, CMS)

• Run 1: two major discoveries…
  – new regime for J/ψ production \(\rightarrow\) evidence for recombination?
  – double ridge in p-Pb (and pp?) \(\rightarrow\) signal of collectivity? parton saturation?

• … one outstanding puzzle…
  – is \(R_{pPb}\) enhanced at high \(p_T\)?

• … + rich harvest of other results
  – system still very close to thermodynamic equilibrium and ideal hydro behaviour
  – strong jet quenching, up to highest jet energies
    • no evidence of angular decorrelation
    • angular dependence: sensitivity to path length dependence
  – indication of parton mass ordering in heavy flavour quenching
  – hints of final state effects in p-Pb? (ψ(2S) in p-Pb)

• the future looks bright \(\rightarrow\) stay tuned!
  – Run 2: O(10) increase in statistics, int lumi
  – Run 3: O(100) increase, ALICE 2.0 upgrade!
Thank you!
Particle yields

- At thermodynamic equilibrium...
  - Now including $^3\Lambda H$!

- At RHIC?
  - Some tension too?
  - Higher precision needed...
The $D_s$

- HF in-medium hadronisation!
- a hint of strangeness enhancement?
- more stats needed!