Results from Pb+Pb collisions at the LHC

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Physics at the LHC 2012
"Rewind dynamical evolution" to access QGP by studying many observables with different sensitivity to the stages of the collision
Radial flow and kinetic freeze-out

- Shape for particles with different masses indicate radial flow
- Hydrodynamical calculations describe the data
- Fits assuming a boosted thermal source with a common temperature and radial velocity

\[ p_T^{\text{flow}} = p_T + m \beta_T^{\text{flow}} \gamma_T^{\text{flow}} \]
Radial flow and kinetic freeze-out

- Shape for particles with different masses indicate radial flow
- Hydrodynamical calculations describe the data
- Fits assuming a boosted thermal source with a common temperature and radial velocity
  - Strong radial flow up to \( \beta_{\text{LHC,central}} = 0.66c \)
  - \( \beta_{\text{LHC,central}} = 1.1 \beta_{\text{RHIC,central}} \)
  - Kinetic freeze-out \( T_{fo} = 80\text{–}100\text{ MeV} \)
  - Up to \( \sim 25\% \) higher mean \( p_T \) at the same \( dN/d\eta \)

\( p_T^{\text{flow}} = p_T + m\beta_T^{\text{flow}} \gamma_T^{\text{flow}} \)

arXiv:1202.3233
Particle ratios and chemical freeze-out

- Statistical (thermal) model
  \[ N_i \propto V \int \frac{d^3p}{2\pi^3} \frac{1}{e^{(E_i-\mu_B B_i)/T_{ch}}} \pm 1 \]

- Chemical potential depends on baryon number, strangeness and isospin
- Two parameters: \( T_{ch}, \mu_B \)
- Obtain: \( T_{ch} \approx 164 \text{ MeV} \approx T_c \)
- In agreement with expectation from lattice
  - Holds for \( \sqrt{s_{NN}} > 10–20 \text{ GeV} \)
- Strangeness enhancement in AA well described
- Proton/pion ratio at the LHC to be understood
Initial and final state anisotropy

Initial spatial anisotropy: eccentricity $\varepsilon$

Interactions present early

Momentum space anisotropy: elliptic flow $v_2 = \langle \cos (2\phi - 2\Psi_R) \rangle$
Observe $v_2(p_T)_{LHC} \approx v_2(p_T)_{RHIC}$, despite factor 14 increase in cms energy! (Integrated $v_2$ 30% larger due to radial flow)
Identified particle elliptic flow

Observed mass ordering due to radial flow as predicted by hydrodynamical calculations

ALICE preliminary
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
Centrality 20-40%

$\eta/s=0.2$

arXiv:1202.3233

Flow coefficient $v_2$

$p_T$ [GeV/c]
D meson elliptic flow

- Invariant mass analysis of fully reconstructed decay topologies (inc. PID) displaced from primary vertex
- Feed-down from B (10-15% after cuts) subtracted using FONLL
  - Conservative hypothesis on $R_{AA}$ of D from B

ALICE PID (see C.Zampolli Mon)
Even the charm mesons exhibit elliptic flow

\[ V_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}} \]
Even the charm mesons exhibit elliptic flow

$$v_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$
Even the charm mesons exhibit elliptic flow (similar to the charged particle $v_2$)
Higher harmonics and viscosity

Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

\[ \frac{dN}{d\phi} \sim 1 + 2v_2 \cos[2(\phi - \psi_2)] + 2v_3 \cos[3(\phi - \psi_3)] + 2v_4 \cos[4(\phi - \psi_4)] + 2v_5 \cos[5(\phi - \psi_5)] + \ldots \]

Alver, Roland
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\[
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\]

Ideal hydrodynamical models preserves these “clumpy” initial conditions.
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\[
\frac{dN}{d\phi} \sim 1 + 2v_2 \cos[2(\phi - \psi_2)] + 2v_3 \cos[3(\phi - \psi_3)] \\
+ 2v_4 \cos[4(\phi - \psi_4)] + 2v_5 \cos[5(\phi - \psi_5)] + \ldots
\]

Viscosity suppresses higher harmonics, \( v_n \) provide additional sensitivity to \( \eta/s \)
Limits on $\eta/s$ from charged particle $v_2$ and $v_3$

- Significant $v_3$ component
- Viscosity dissipates initial pressure gradients and reduces the collective flow
- $v_3$ provides additional constraints on $\eta/s$
- Current bound at LHC
  - $\eta/s < \frac{2}{(4\pi)} = 2(\eta/s)^{_{ADS/CFT}}_{_{\min}}$

Qui, Shen, Heinz, PLB 707 (2012) 151

The quark-gluon plasma at the LHC is still a nearly perfect liquid
Soft, intermediate and hard $p_T$ region

$PbPb$, 30-40%

$v^2(\text{ALICE, CMS, ATLAS})$

Path-length dependent energy loss

Flow coefficient $v_n$

Soft $p_T$

High $p_T$

Parton energy loss

arXiv:1202.3233
Tomography of QCD matter

- Hard (large $Q^2$) probes of QCD matter: jets, heavy-quark, $Q\bar{Q}$, $\gamma$, $W$, $Z$
  - “Self-generated” in the collision at $\tau<1/Q$ (or $\tau<1/m$) $< 0.1$ fm/c
  - “Tomographic” probes of hottest and densest phase of medium

- “pQCD” probe in
- “pQCD” probe out
- Modification?

- Induced gluon radiation
- Radiative energy loss
- Dissociation
- Control
Tomography of QCD matter

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  - “Self-generated” in the collision at $\tau < 1/Q$ (or $\tau < 1/m$) $< 0.1$ fm/c
  - “Tomographic” probes of hottest and densest phase of medium

- Nuclear modification factor
  - $R_{AA}(p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{T_{AA} d\sigma_{pp}}$
  - $R_{AA} = 1 \rightarrow$ no deviation from scaling
  - $R_{AA} < 1 \rightarrow$ suppression

- Quantify change of production rates from expected binary scaling
Isolated $\gamma$, $W$ and $Z$ bosons in Pb+Pb
Control probes (isolated $\gamma$, $Z$, $W$) follow expected scaling ie. $R_{AA} \sim 1$

Isolated $\gamma$:
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

$Z$ boson:
ATLAS, ATLAS-CONF-2012-052
ATLAS, PLB 697 (2011) 294
CMS, PRL 106 (2011) 212301

$W$ boson:
ATLAS, ATLAS-CONF-2011-78
CMS, arXiv:1205.6334
Jet quenching

Elastic energy loss: $\frac{dE}{dx} = -C^2_2 \hat{e}$

Radiative energy loss: $\frac{dE}{dx} = -C^2_2 \hat{q} L$

Energy/momentum diffusion tensor: encodes properties of the medium.

- **Induced radiation**
  - Increased splitting probability (broadens radiation)
  - Finite quark mass vetos small angle radiation (dead-cone effect)
  - Modified angular pattern due to enhanced incoherence between successive splittings
- **Color exchange with medium**
  - Modifies color flow in the jet (affects hadronization)
- **Modelling dependence**
  - Piecewise description
  - Approximations

Search for effects in data:

- **Out-of-cone radiation** (Jet $R_{AA} < 1$)
- **In-cone radiation** (FF modification)

$\Delta E_{\text{loss}}(g) > \Delta E_{\text{loss}}(q) > \Delta E_{\text{loss}}(Q)$  
(color factor)  (dead-cone effect)

Check $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
Charged particle suppression

- Leading hadron suppression up to a factor $\sim 7$ (at $p_T \sim 7$ GeV/c)
  - Slow rise, up to a plateau that may be reached at $p_T > 35$ GeV/c
- Strong discrimination power for jet quenching models
  - Test role of initial state with $p+$Pb run

CMS, EPJC 72 (2012) 1945
ALICE, PLB 696 (2011) 30
ATLAS, ATLAS-CONF-2011-079
D meson suppression factor imposes new constraints on energy loss models (mass & colour charge dependence)

\[ R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) ? \]

Suppression pattern (within uncertainties) could be compatible with expected energy loss hierarchy

ALICE, arXiv:1203.2160
CMS, JHEP 1205 (2012) 063
Jet quenching in dijet events
Dijet momentum imbalance:  \( A_J = (p_T,1 - p_T,2)/(p_T,1 + p_T,2) \)  
\((p_{T,1} > 100, p_{T,2} > 25 \text{ GeV/c})\)

Larger momentum imbalance wrt to MC reference.
Difference increases with increasing centrality.
But no (very little) increasing azimuthal decorrelation.

ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906
Dijet momentum imbalance: \[ A_J = \frac{(p_{T,1} - p_{T,2})}{(p_{T,1} + p_{T,2})} \] (\( p_{T,1} > 100 \), \( p_{T,2} > 25 \) GeV/c)

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ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906

Dijet momentum ratio: \( \frac{p_{T,2}}{p_{T,1}} \) vs leading jet \( p_{T,1} \)

Even ~350 GeV/c jets are quenched! Fraction of energy lost constant up to ~350 GeV/c.

CMS, PLB 712 (2012) 176
Dijet momentum asymmetry: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

Lost energy emitted at low $p_T$ (<4 GeV/c) outside jet cone (R>0.8)

ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906
Jet fragmentation function

Fragmentation functions constructed using tracks with $p_T > 4$ GeV/c in $R < 0.3$ and the reconstructed (quenched) jet energy.

Leading and sub-leading jet in Pb+Pb fragment like jets of corresponding energy in pp

$R = 0.3$
$P_{T1} > 100$ GeV/c
$P_{T2} > 40$ GeV/c
$\Delta \Phi_{12} > \frac{2}{3}\pi$
Track $p_T > 4$ GeV/c

arXiv:1205.5872
Inclusive jet $R_{cp}$

No strong modification of the fragmentation function between peripheral and central events. Jet $R_{cp}$ independent on energy.
Identified particle $R_{AA}$ at high $p_T$"Protons and kaons"

Little room for in-medium modification at high $p_T$
Jet quenching in $\gamma$-jet events

Photon $p_T > 60$ GeV/c

Jet $p_T > 30$ GeV/c
Azimuthal correlation consistent with pp and MC (PYTHIA+HYDJET)
Azimuthal correlation consistent with pp and MC (PYTHIA+HYDJET)

Angular width parametrized with
\[
\frac{1}{N_{J\gamma}} \frac{dN_{J\gamma}}{d\Delta\phi_{J\gamma}} = \frac{e^{(\Delta\phi - \pi)/\sigma}}{(1 - e^{-\pi/\sigma})\sigma}.
\]
column constant vs centrality

Quenched jet is back-to-back to $\gamma$: Energy transfer not via one single hard gluon radiation
γ-jet momentum imbalance

Momentum ratio distribution

Increasing centrality

pp Data

PbPb Data

PYTHIA + HYDJET

CMS

\( p_T^\gamma > 60 \text{ GeV/c} \) \( |\eta| < 1.44 \)

\( p_T^{\text{jet}} > 30 \text{ GeV/c} \) \( |\eta| < 1.6 \)

\( \Delta \phi_{\gamma,jet} > \frac{7\pi}{5} \)

\( L \cdot dt = 150 \mu \text{b}^{-1} \)
γ-jet momentum imbalance

Momentum ratio distribution

- Momentum ratio \( x_{Jγ} = p_T^{\text{jet}}/p_T^γ \)
- Fraction of γ-jet associations \( R_{Jγ} \)

- Decrease significantly with centrality compared to pp or MC

Momentum ratio \( x_{Jγ} \) and fraction of γ-jet associations \( R_{Jγ} \)
decrease significantly with centrality compared to pp or MC

\[
\begin{align*}
\text{CMS} & \quad \sqrt{s_{NN}} = 2.76 \text{ TeV} \\
& \quad \int L dt = 150 \mu\text{b}^{-1} \\
(p_T^γ > 60 \text{ GeV/c} \mid l_\eta < 1.44) & \quad 50\% - 100\% \\
(p_T^{\text{jet}}>30 \text{ GeV/c} \mid l_\eta < 1.6) & \quad 30\% - 50\% \\
\end{align*}
\]

(a) \( \Delta \phi_{Jγ} > \frac{7}{8} \pi \)
(b) \( \Delta \phi_{Jγ} > \frac{7}{8} \pi \)

- Stronger effect due to jet \( p_T \) falling below the 30 GeV/c threshold
The LHC is ideal for studying the QGP

- Hotter, larger, longer lifetime, hard probes
- QGP has similar “perfect liquid” properties as at RHIC
  - Proton/pion ratio to be understood

The LHC is a “hard probes” machine

- There has been a burst of new data and observables.
- And there is still quite a lot of data to analyze.
- Should attempt to describe all aspects (incl. details) in common model.
- Upcoming p+Pb run in fall 2012 will reduce some of the uncertainties due to initial state effects

Special thanks to ALICE, ATLAS and CMS collaborations for their material, and to the LHC for an excellent performance.
Energy dependence of $dN/d\eta$

Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies

$(dN_{ch}/d\eta_{LHC}) \approx 1600 \sim 2 \times dN_{ch}/d\eta_{RHIC}$

Avg. Pb+Pb (ALICE, ATLAS, CMS)

~$s^{0.15}$ fit

Previous fit: ~ln $s$

pp (LHC energies)

~$s^{0.11}$ fit

ALICE, PRL 106 (2011) 032301
CMS, JHEP 1108 (2011) 141
ATLAS, PLB 710 (2012) 363
Energy dependence of $dN/d\eta$ and $dE_T/d\eta$  

Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies ($dN_{ch}/d\eta_{LHC} \approx 1600 \sim 2 \times dN_{ch}/d\eta_{RHIC}$)

Initial energy density at LHC (as at RHIC) is well above $\varepsilon_c \approx 0.5 \text{ GeV/fm}^3$
Centrality dependence of $dN/d\eta$

Centrality dependence is strikingly similar to RHIC. This actually holds all the way down to 19.6 GeV (not shown).

- RHIC Au+Au
  - Avg x 2.14

- LHC Pb+Pb
  - Average

**References:**

- ALICE, PRL 106 (2011) 032301
- CMS, JHEP 1108 (2011) 141
- ATLAS, PLB 710 (2012) 363

**Graph:**

- LHC PbPb 2.76 TeV
- RHIC AuAu 200 GeV x 2.14
- pp Inel 2.76 TeV
- pp Inel 200 GeV x 2.14

**Equation:**

$$\frac{\langle dN_{ch}/d\eta \rangle}{(0.5\langle N_{part} \rangle)}$$
Two-component models need to incorporate strong nuclear modification. Models based on Glauber and CGC initial conditions can describe the data.
Space-time evolution of the system

Freeze-out volume

- Use interferometry of identical particles (HBT)
  - Obtain HBT radii of spherical source in 3 orthogonal directions ($R_{\text{long}}$, $R_{\text{side}}$, and $R_{\text{out}}$)
- Compared to RHIC
  - Freeze-out volume: $V_{\text{LHC}} \approx 5000 \text{ fm}^3 \sim 2 \times V_{\text{RHIC}} > 6 \times V_{\text{Pb}}$
  - Decoupling time: $\tau_{\text{f}}(\text{LHC}) \approx 10-11 \text{ fm/c} \sim 1.4 \times \tau_{\text{f}}(\text{RHIC})$

Decoupling time

[Graphs showing freeze-out volume and decoupling time with data points from various experiments at different energies]
Intermediate region dominated by soft-hard interactions. Recombination (coalescence) could be at work with consequences on spectra (but also on v2).
Control probe: Isolated photons

- Good agreement between data and NLO
- Small nuclear modification in probed $x, Q^2$ region (Nuclear PDF uncertainties ±30%)

Isolated photons follow expected scaling ie. isolated photon $R_{AA} \sim 1$
Control probe: Z bosons

Scaled Z yields flat and consistent with NLO for all centralities:

\[ R_{AA} = 1 \pm 0.16 \text{ (stat)} \pm 0.14 \text{ (sys)} \]

(prep reference from Powheg)
Control probe: W bosons

Yields on $W^+$ and $W^-$ separately reflect the different $u$ and $d$ quark content in Pb and p.

Within uncertainties, no dependence of the binary scaled W yields on centrality:

$$R_{AA} = 1.04 \pm 0.07 \text{ (stat)} \pm 0.12 \text{ (sys)}$$
**Heavy-quark probes: D and B mesons**

**D mesons** reconstructord from displaced vertices in 3 invariant mass channels. Contribution from B subtracted with FONLL.

**ALICE, arXiv:1203.2160**

**B mesons via secondary J/ψ:**

CMS, JHEP 1205 (2012) 063

Clean separation of 2nd vertex for J/ψ with $p_T > 6.5$ GeV/c

Also recently presented (not discussed here):

ATLAS HF muon, mid-rapidity (ATLAS-CONF-2012-050)

ALICE HF muon, forward (arxiv:1205.6443)
Summary of single particle probes

D.d'Enterria, QNP 2012

![Graph showing suppression factors for different particles in central Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV.](image)
Near-side di-hadron correlations: $p/\pi$ ratio

- $p/\pi$ ratio in the bulk is consistent with inclusive $p/\pi$ ratio
  - NB. Inclusive ratio in 0-5% and feeddown corrected
- $p/\pi$ ratio in peak - bulk is consistent with ratio from Pythia (6.4 default tune)
- No evidence for medium-induced modification of jet fragmentation ($R \sim 0.4-0.5$) in this $p_T$ regime

$\Delta \phi$ (rad.)

$\Delta \eta$

$5.0 < p_{T,\text{trig}} < 10.0$ GeV/c

$\text{Pb-Pb, } \sqrt{s_{NN}} = 2.76$ TeV, 0-10% central

Bulk I

Peak region

Bulk II

$\Delta \phi$ (rad.)

$\Delta \eta$

*Bulk* I

*Peak region*

*Bulk* II

\[ \frac{(p+p_{\text{bar}})/(\pi^+ + \pi^-)}{\text{ratio}} \]

Bulk

Peak-Bulk

Pythia

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