HIGH ENERGY HEAVY ION COLLISIONS AT LHC

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Outline

1. Introduction
2. Paton energy loss in QGP
3. QGP properties probing via hadrons
4. ALICE-DCal project (Italy-Japan collaboration)
5. Summary
**QGP:** Quark Gluon Plasma

Time: after 10 µsec after the Big Bang

Temperature: \( T = 2 \times 10^{12} \) K

Energy density: \( \varepsilon = 1 \) GeV/fm³

**Lattice QCD calculations:**
\( T_c = 150-200 \) MeV, cross over phase transition from hadronic phase to partonic phase (QGP).
QGP: probing phase transitions

- QCD phase transition
- Chiral symmetry restoration
Heavy ion program @ CERN-LHC

**ALICE**
- Excellent PID
- low $p_T$ tracking
- photons, e, muons

**ATLAS**
- jet, hard probes

**CMS**
- jet, hard probes, di-muons
“Phase transition” in our research:
From discovery to the understanding of QGP

- Initial condition: $\eta/s$
- Temperature ($T$)
- Energy loss
- Thermalization

$\beta_T$, $T_{fo}$

Hadron Gas

QGP

Freeze-Out

See R. Nania’s talk
1. PARTON ENERGY LOSS

Jet quenching
One way to measure QGP property; paton energy loss

- In QGP, parton loses energy mainly due to the gluon radiation, and jet produced by the hard parton scattering is quenched (jet quenching).
- On the other hand, photon from hard scattering does not lose energy in QGP (EM int.)
- Using these jets and (direct) photons, one can perform:
  - QGP tomography
  - Study of medium response
    - low $p_T$ particle spectra, flow, HBT, etc. with jet axis.
Jet Suppression at RHIC

Quarks

Hot and Dense Nuclear Matter

Animation by Jeffrey Mitchell
Yield

Soft particle production

Hard parton scattering (jet)

soft-hard transition $\sim 4$ GeV/c

$p_T$ (GeV/c)

Data/Model

$\frac{1}{N_e} \frac{1}{2\pi p_T} dN/cd\Omega \left( \frac{d\phi}{d\phi} \right)$ (GeV/c)$^2$

$\pi^+ + \pi^-$ ($\times 100$)

$K^- + K^-$ ($\times 10$)

$p + \bar{p}$ ($\times 1$)

$\pi^+ + \pi^-$

$K^+ + K^-$

$p + \bar{p}$

$0.5\%$ Central collisions

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

STAR, Au-Au $\sqrt{s_{NN}} = 200$ GeV

PHENIX, Au-Au $\sqrt{s_{NN}} = 200$ GeV

VISH2+1

HKM

Kraków
Nuclear modification factor ($R_{AA}$) for light hadrons

- Hadrons with $p_T > 8$ GeV/c are equally suppressed.
- A large baryon enhancement at intermediate $p_T$ (2-5 GeV/c), recombination.
- Hadron: strong yield suppression, dip at ~7 GeV.
- EM probes: do not suppressed.
Instead of leading hadron, one can reconstruct “jet” directly.

- Strong jet suppression observed ($R_{AA} \sim 0.5$).
- A hit of stronger suppression at lower jet $p_T$ (ALICE).
Suppression of inclusive jets

Fully unfolded inclusive jet $R_{AA}$
pp 2.76 TeV reference

Like for charged particles, high-$p_T$ jet $R_{AA}$ flat at $\approx 0.5$
Parton ID: b-quarks

Parallel talk
Mihee Jo (Fri)

Parallel talk
Matt Nguyen (Tue)
Poster
Jorge Robles

CMS (* preliminary)
$\text{PbPb} \sqrt{s_{NN}} = 2.76 \text{ TeV}$

$\int L \ dt = 7\text{-}150 \ \mu\text{b}^{-1}$

- $Z (0\%-100\%) \ p_{T} > 20 \text{ GeV}/c$
- $W (0\%-100\%) \ p_{T} > 25 \text{ GeV}/c$
- Isolated photon (0-10%)$
- $b$-quarks (0-100%) via secondary $J_{1}$
- Charged particles (0-9%)

$R_{AA}$ vs $p_{T}(m_{T})$ (GeV)

- $q/g$-jet (0-5%) | $|\eta|<2$
- $b$-jet (0-100%) | $|\eta|<2$

First observation of $b$-jet suppression at high $p_{T}$

Distinct $b$-quark suppression pattern at low $p_{T}$

Gunther Roland
Quark Matter 2012, Washington DC
First p+Pb data at LHC

- Successful p+Pb pilot run (Sep. 13, 2012)
- p+Pb Physics run (Jan. – Feb., 2013)
  - Beam energy: $\sqrt{s_{NN}} = 5.02$ TeV
  - Expected statistics: $\sim 30$ nb$^{-1}$
    $\Rightarrow$ rare probe statistics equivalent to $0.15$ nb$^{-1}$ of Pb-Pb.
p-Pb results (ALICE)

- No suppression for p-Pb collisions.
- Indicated that suppression seen in central Pb-Pb is the final state effect, not the initial state effect.

arXiv:1210.4520 (ALICE)
Di-jets
A_{J}: di-jet asymmetry

\[ A_{J} = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

CMS R=0.5

- Quantify jet energy imbalance by the asymmetry ratio.
- Large asymmetry is seen in energy imbalance in central Pb-Pb
Large $A_J$ : low momentum particle (< 4 GeV/c) emitted at large angle on away side.
γ-jet:
jet quenching study with energy calibrated probes (photons)
γ-Jet momentum balance (CMS)

arXiv:1205.0206

- Momentum ratio \( \frac{p_T^{\text{Jet}}}{p_T^{\gamma}} \) shifts/decreases with collisions centrality.
2. PROPERTIES OF QGP

Probing via spectra, yield, flow
To characterize the global properties on expanding source; introduce common velocity field; “radial flow”
Identified hadron spectra at LHC

- ALICE data for pions, K, p
- Lines = blast-wave fits
  \( \Rightarrow \) Parameters of the system at the kinetic freeze-out \((T_{f0}, \beta_T)\).
- Very significant changes in slope compared to RHIC
- Most dramatically change for protons
- Very strong radial flow, $\beta \approx 0.66$ (10% higher than RHIC)
- Even larger than predicted by most recent hydro (e.g. protons)
Thermal Model Comparison

- All ratios other than $p/\pi$ are predicted accurately.
- Protons: different $T_{ch}$ than strange/multi-strange, indicating the importance of re-scattering at hadronic phase.

A. Andronic et al, PLB 673: 142-145 (2009)
Anisotropic flow; sensitive to the early time of collisions, pressure gradients, EOS.
Elliptic flow; $v_2$

\[
\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy} (1 + 2v_2(p_T; b) \cos(2\varphi) + \ldots)
\]
strongly coupled system at $10^{-6}$ K

\textbf{World at }$10^{-6}$ K

$^6\text{Li}$ (optical laser cooling)

Fermi gas system

= strongly coupled system

\textbf{Very similar at }$10^{12}$ K

= strongly coupled QGP (sQGP)
Identified particle $v_2$

- **Large mass splitting** at LHC compared to RHIC as predicted by hydrodynamics models.
- Pion $v_2$: described well by hydro. predictions with MC-KNL CGC initial conditions and $\eta/s = 0.2$.
- (K and ) Anti-protons: overestimated by the same calc. for central collisions.
Higher order harmonics; $v_n$

- $v_2$ sensitive to shear viscosity $\eta/s$ and to initial conditions (Glauber, CGC).
- No simultaneous description of $v_2$ and $v_3$ with the same $\eta/s$. 

PRL 107, 032301 (2011), ALICE
RHIC v2 data: $\eta/s \sim 0.1$.
Smallest $\eta/s$ in the world, approaching the quantum viscosity bound ($1/4\pi$).
\[ C(\Delta \varphi) = \frac{1}{\Delta \eta_{\text{max}} - \Delta \eta_{\text{min}}} \int_{\Delta \eta_{\text{min}}}^{\Delta \eta_{\text{max}}} C(\Delta \eta, \Delta \varphi) \propto 1 + 2 \sum_{n=1}^{5} v_{n\Delta} \cos(n \Delta \varphi) \]

- Extract 1D $\Delta \varphi$ correlations by integrating the $C(\Delta \eta, \Delta \varphi)$ in $0.8 < |\Delta \eta| < 1.8$ range and do a Fourier decomposition.
- 5 components describe completely the correlations at large $\Delta \eta$ and low $p_T$.

arXiv:1109.2501
WMAP vs. Heavy Ion Collisions

**WMAP**
Cosmological parameters

**Heavy ion collisions**
initial condition, QGP properties (e.g. $\eta/s$)
3. ALICE-DCAL

From view point of Italy-Japan collaboration
ALICE Dijet Calorimeter (DCal)

- Extension of the acceptance of EMCal.
  - Lead-scintillator sampling type EMC with APD readout.
    - EMCal: $\Delta \phi = 110^\circ$
    - DCal: $\Delta \phi = 60^\circ$ (on opposite side of EMCal leads to good uniformity, less sys. uncertainty)
    - $\Delta \eta = 0.7$ for both EMCal and DCal + PHOS
  - Energy resolution: $\sim 10\% / \sqrt{E}$

- Allow back-to-back hadron-jet, di-jet measurements in ALICE, with $R = 0.4$ jet cone radius, up to $p_T \sim 150$ GeV/c.
- Enhance jet, $\gamma$ trigger capability.
- Full energy scale for $\gamma$: 250 GeV.
ALICE-DCal Collaboration

China
Huazhong Normal University (CCNU), Wuhan

Finland
University of Jyvaskyla

France
LPSC Grenoble, Subatech Nantes, IPHC Strasbourg

Italy
INFN Catania (Armando Palmeri, Angela Badala), LNF Frascati (Alessandra Fantoni)

Japan
Hiroshima University, University of Tokyo, University of Tsukuba

Switzerland
CERN

USA
Lawrence Berkeley National Laboratory, Wayne State University, University of Houston, University of Tennessee, Lawrence Livermore National Laboratory, Yale University, Oak Ridge National Laboratory, Creighton University, Cal Poly San Luis Obispo, Purdue University
DCal components

- Lead
- Paper
- Scint.
- Module (77 layers)
- 4 APD/module
- Strip (12 modules)
- DCal (6 S.M.)
- S.M. (192 modules)
Tsukuba team at Catania in Oct.-Dec, 2010

- Module Assembly & APD assembly/calibration at Catania
  - Assembly of modules (96 modules, 1/2 S.M.)
  - APD assembly & calibration (2400)

Hiroki & Maya at Catania for APD & module assembly

Maya Shimura

Hiroki Yokoyama
Tsukuba team at Catania in Oct.-Dec. 2010

✓ Completed 96 modules production with Catania’s help.
✓ APD assembly/calibration for 2,400 APDs with Angela B.’s team

Hiroki & Maya at Catania

Strip assembly also done at Catania, then ship to France.
Francesco N. & Maurizio S. from Catania, visited Tsukuba (Nov. 11-18, 2010)

- Francesco & Maurizio visited Tsukuba in Nov. 9-17, 2010
- Second assemble station becomes operational
All modules are in Subatech / Grenoble, will install in LHC long shutdown (2013-2014), physics in 2015.
Perspective of physics with DCal: Medium response with jets

- Excellent hadron PID (0.15 – 20 GeV/c), suitable detector to measure the medium response with PID, jet ID and trigger by EMCal.
- Bulk properties (PID spectra, $v_2$, HBT, etc.) with a large jet energy imbalance.
- Key to access $c_s$, EOS?
SUMMARY

- Rich harvest of LHC new HI data by the complimentary measurements by ALICE, ATLAS, CMS.
- Hottest, small eta/s, strongly coupled QGP produced at LHC heavy ion collisions.
- A lot of progress towards the precession measurements of QGP properties for next decade.
BACK UP SLIDES
Jet suppression

First LHC result on jet suppression
Unfolded $p_T$ spectra
For jet sizes $R=0.2$, 0.3, 0.4 and 0.5

$R_{cp} = \frac{1}{N_{coll}} \frac{\int E d^3N_{cont}}{d^3p} \frac{1}{N_{perph}} \frac{\int E d^3N_{perph}}{d^3p}$

peripheral reference: 60-80%

- A factor of 2 suppression in 0-10% most central collisions
- Suppression independent of jet $p_T$

B. Wosick
Very similar $v_2$ at RHIC and LHC

- At LHC, $p_T$ integrated $v_2$ increases by 30% compared to RHIC data at $\sqrt{s_{NN}}=200$ GeV.
- $v_2$ vs. $p_T$ does not change within uncertainties between $\sqrt{s_{NN}}=200$ GeV and 2.76 TeV
Just simple $p_T/n_q$ scaling does not work at LHC.

Scaling works better as a function of transverse energy, but not perfect.