Overview of heavy ion CMS results

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Rencontres de Moriond
QCD and High Energy Interactions
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We aim at creating a **hot and dense deconfined** medium by means of ultra-relativistic heavy ion collisions.

**Did we create a strongly interacting “medium”?**

**Have we observed quarkonia dissociation in the medium?**

**How partons interact with the medium?**
“Did we create a medium?”

In presence of a strongly interacting medium:

- **Initial azimuthal asymmetry of the fireball**
- **Azimuthal particle anisotropy**

\[ \frac{dN}{d(\phi - \Psi_2)} \sim 1 + 2v^2 \cos[2(\phi - \Psi_2)] \]

- \( v_2 \): elliptic flow

Determination by an ultracold atom gas system

**Pressure-driven expansion**

**Data**

- \( \frac{dN}{d(\phi - \Psi_2)} \) vs. \( \phi - \Psi_2 \) [rad]
- \( v_2 \): elliptic flow
- \( v_2 > 0 \)

**Anisotropic azimuthal distribution:**

- Smaller particle density here
- Higher particle density here
Indications of a “medium” in PbPb

Precise measurement of other harmonics $v_n \rightarrow$ constraint on the initial energy fluctuations

$v_n$ measurements well described by hydrodynamic models with very low shared viscosity ($\eta/s \sim 0.2$) $\rightarrow$ We created an almost perfect fluid!
The “ridge”

**PbPb**

**pPb**

Back-to-back jet contribution

single jet contribution

"collective effect" two particles with very different $\eta$ are “connected”

Same structure observed in high multiplicity PbPb, pPb and pp collisions!

Do we observe “flow” phenomena in pPb and even in pp?
Alternative explanation that does not involve QGP?

Long range correlation in pp at 13 TeV

Predictions from gluon saturation model: long-range correlation arising from initial collimated gluon emissions, NOT from “collective” phenomenal

CMS PAS FSQ-15-002
Probing the medium with high $p_T$ particles

High $p_T$ quarks and gluons interact with the medium and lose energy

High $p_T$ hadrons and jets get “quenched” by the medium

Di-jet event in PbPb collisions:
- **leading jet** $p_T = 205$ GeV
- **subleading jet** $p_T = 70$ GeV
Quantifying the jet quenching

\[ A_J \approx 0 \quad \text{for} \quad p_{T,1} \sim p_{T,2} \]
\[ A_J \approx 1 \quad \text{for} \quad p_{T,1} \gg p_{T,2} \]

\[ \frac{dN^J}{dX_J} \bigg|_{X_J \approx 1} \]

\[ X_{J\gamma} = \frac{p_{T,\text{Jet}}}{p_{T,\gamma}} \]

\[ \sim 10\% \quad \text{of the jet energy is lost. Where does the energy go?} \]

PRC 84 (2011) 024906, CMS-HIN-13-006
How transverse energy is distributed in the jet cone

Enhancement of low $p_T$ particles inside the jet cone.

Depletion of intermediate $p_T$ particles.

No modification in pPb
(Observed modification in PbPb is not from initial state effect)

PRC 90 (2014) 024908, CMS-HIN-15-004
Where the energy goes?

What is the **angular distribution** of these particles with respect to the dijet system?

\[
\rho_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Dijet}})
\]

Projection on the dijet axis

Charged particle azimuthal angle

Dijet axis

\[
\Delta = \sqrt{\Delta \phi_{\text{Trk,jet}}^2 + \Delta \eta_{\text{Trk,jet}}^2}
\]
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Projection on the dijet axis

Charged particle azimuthal angle

Dijet axis

\[ \Delta = \sqrt{\Delta \phi_{\text{Trk,jet}}^2 + \Delta \eta_{\text{Trk,jet}}^2} \]
Subleading jet direction

High $p_T$ imbalance at small $\Delta$

Balanced by more low $p_T$ particles in subleading jet direction
Extends up to large $\Delta$

Missing $p_T$ versus $\Delta$ in PbPb

$p_{T,1} > 120$; $p_{T,2} > 50$ GeV
$|\eta_1|, |\eta_2| < 0.6$; $\Delta\phi_{1,2} > 5\pi/6$

anti-$k_t$ $R = 0.3$

166 $\mu$b$^{-1}$ (2.76 TeV)

JHEP 01 (2016) 006
Does the energy loss depend on parton flavour?

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

Hints of different suppression for D and non-prompt J/ψ at low \( p_T \)!

\[ R_{\text{light particle}}^{\text{AA}} < R_{\text{D}}^{\text{AA}} < R_{\text{B}}^{\text{AA}} ? \]

Same suppression observed for inclusive jets and b-tagged jets

CMS-HIN-15-005, PRL 113 (2014) 132301
Heavy-Flavour production in pPb

B^+ production in pPb
→ compatible with predictions from FONLL scaled by A=208

HF pPb production not significantly modified by cold nuclear matter effects (e.g. PDF modification in nuclei)

Have we observed quarkonia dissociation?

in presence of a coloured medium, the qqbar potential is screened

Quarkonia melt in the QGP!

Less bounded states melts at lower temperature

\[ T_{\text{diss}}^{(1S)} > T_{\text{diss}}^{(2S)} > \ldots \]

We should observe a hierarchy in the dissociation of different quarkonia states depending on their binding energies
We observe what we call “sequential” suppression of Υ states in PbPb collisions!

CMS-HIN-15-001
Conclusions

Did we create a strongly interacting “medium”?  
• evidences that we created in PbPb collisions a medium that behaves like a perfect fluid  
• pp and pPb? did we create QGP there?

How partons interact with the medium?  
• high $p_T$ partons lose energy in the deconfined medium as observed by studying jet suppression  
  • the energy lost by the quenched partons goes to soft particles far from the initial parton direction

Did we observe quarkonia dissociation in the medium?  
• evidence of sequential suppression of bottomonia states
BACKUP
CMS detector

- **EM and hadronic calorimeters**
  - Photons, Jet

- **Forward Calorimeter**
  - MB triggers, centrality

**Inner tracker:**
- charged particles

**Muon detectors**

**CMS detector layers:**
- **Tracker**
  - $|\eta| < 2.5$
- **ECAL**
  - $|\eta| < 3.0$
- **HCAL**
  - $|\eta| < 5.2$
- **Muon**
  - $|\eta| < 2.4$
Charged particle $R_{AA}$

In absence of in-medium effect

$\rightarrow R_{AA} = 1$

In presence of in-medium energy loss:

$\rightarrow p_T$ spectra in Pb-Pb shifted at low $p_T$  $\rightarrow R_{AA} < 1$

\[
R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}
\]
How to quantify the energy loss?

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

- **Nuclear modification factor**
- **Number of binary nucleon-nucleon collisions in a PbPb collision**

In absence of in-medium energy loss:
\[ R_{AA}=1 \]

In presence of in-medium energy loss:
\[ p_T \text{ spectra in Pb-Pb shifted at low } p_T \]
\[ R_{AA}<1 \]
Flow in PbPb collisions = geometry + fluctuations

Collective behaviour in heavy-ion collisions as crucial probes to test:
• hydrodynamics and transport coefficient in the bulk
• Initial state conditions
• degree of freedom and particle production mechanisms

\[
f(p_T, \phi, \eta) \sim 1 + 2v_2(p_T, \eta)\cos[2(\phi - \Psi_2)] + 2v_3(p_T, \eta)\cos[3(\phi - \Psi_3)] + 2v_4(p_T, \eta)\cos[4(\phi - \Psi_4)] + 2v_5(p_T, \eta)\cos[5(\phi - \Psi_5)] + \ldots
\]
We did create a medium in PbPb!

\[ \frac{dN}{d(\Phi - \Psi_2)} \sim 1 + 2v_2 \cos[2(\Phi - \Psi_2)] \]

As expected due to initial geometry asymmetry!

non zero elliptic flow \((v_2 > 0)\) suggests we created a strongly interacting medium that also exhibits properties of a almost perfect fluid!
$v_2$ in peripheral PbPb collisions

$v_2 > 0$ in peripheral collisions is the first important evidence that the fireball exhibits a collective behaviour:

- different pressure gradient due to the geometric anisotropy of the fireball
- well predicted by hydrodynamics!

Is this really collectivity?

- $v_2\{2\}$ can be affected by non-flow phenomena
- $v_2\{4\} = v_2\{6\} = v_2\{8\}$ telling that similar results are extracted by considering 2, 4, 8 particles.
Understanding the ridge in pPb collisions

Many evidences suggests hydro behaviour in pPb collisions:

- $v_n$ present similar behaviour vs $p_T$ as observed in PbPb collisions
  E.g. $v_2{2} > v_2{4} \approx v_2{6} \approx v_2{8}$

- stronger radial flow ($v_1$) that in PbPb as a consequence of the more explosive system created in pPb collisions

- Clear mass ordering in the $v_2$ as function of $p_T$ as expected in the HP of collective motions

Are there alternative explanations to hydro? Other explanations describes this collective phenomena as a consequence of pure initial state interactions:

- Color Glass Condensate (CGC)
- pQCD-based models
Testing hydrodynamics models

- In ultra-central PbPb collisions not sensitive to the geometry anisotropy
- we can test the transport coefficients of the fireball
- Hydro-models can reproduce the various harmonics $v_n$ assuming values of the shared viscosity close to KKS bound

The medium shows collective behaviours well described by hydrodynamics calculation and presents the properties of an almost perfect fluid
“ridge” in pp collisions

- similar “ridge” observed in high multiplicity pp collisions at 7 and 13 TeV
- CGC models fails at describing the ridge yield at high multiplicity

A full understanding of the pp flow-like phenomena is still far…

- in high multiplicity pp collisions, hints of non zero $v_2$ from 4-particle correlations
- limited by low statistics
Missing $p_T$ versus $\Delta$ in pp

Subleading jet direction

Asymmetry inside the jet cone

Integrated curve from 0 to $\Delta$

JHEP 01 (2016) 006
$p_T$-dependence of the di-jet imbalance

CMS

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

- PbPb $\sqrt{s_{_{\text{NN}}}} = 2.76$ TeV
- PYTHIA+HYDJET

120 < $p_{T,1}$ < 150 GeV/c

150 < $p_{T,1}$ < 180 GeV/c

180 < $p_{T,1}$ < 220 GeV/c

Anti-$k_T$ (PFlow), $R = 0.3$

$\Delta_{\phi_{12}} > \frac{2\pi}{3}$

Centrality 0-20%

$p_{T,2} > 30$ GeV/c

$\langle p_{T,1}/p_{T,2} \rangle$ PbPb

$\langle p_{T,1}/p_{T,2} \rangle$ PYTHIA+HYDJET

$220 < p_{T,1} < 260$ GeV/c

$260 < p_{T,1} < 300$ GeV/c

$300 < p_{T,1} < 500$ GeV/c
di-jet angular correlation

Correlation peak is the same in data and Pythia across all values of $p_T$. 

\[ \int Ldt = 150 \mu b^{-1} \]

Centrality 0-20%

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220 < $p_{T,1}$ < 260 GeV/c

260 < $p_{T,1}$ < 300 GeV/c

300 < $p_{T,1}$ < 500 GeV/c
In MC, large components of tracks with $p_T$ 4-8 GeV/c

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Dijet}})$$

Overall momentum balance of the events is always recovered

$$<p_T^\parallel>=0$$

Dijet momentum imbalance is not related to undetected activity

In both MC and Data, the large negative contribution (leading jet) with $p_T>$8 GeV balanced by tracks with $p_T$ 0.5–8 GeV/c

In data the missing $p_T$ is compensated mostly by low $p_T$ particles < 4 GeV
Jet shapes

\[ \rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{tracks} \in [r_a, r_b]} \frac{p_T^{\text{track}}}{p_T^{\text{jet}}} \]

radial distribution of transverse momentum of tracks inside the jet cone

- \( r \) track axial distance from the jet axis

Deviations from unity indicate modification of jet structure in the nuclear medium

No sizeable modification of the jet shape with respect to pp in peripheral PbPb

excess of transverse momentum fraction emitted at large radii

\[ \rightarrow \text{moderate broadening of jets!} \]
Photon-jet correlations

CMS Preliminary $\sqrt{s_{NN}}$=2.76TeV, PbPb 150 $\mu$b$^{-1}$, pp 5.3 pb$^{-1}$

$R_{J\gamma}$ = fraction of dijet events with a jet partner

$x_{J\gamma}$ = $p_{T,\text{jet}}/p_{T,\gamma}$
Sequential suppression

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- Inclusive $\psi(2S)$ ($6.5 < p_T < 30$ GeV/c, $|y| < 1.6$)
- $\Upsilon(3S)$ ($|y| < 2.4$), 95% upper limit
- $\Upsilon(2S)$ ($|y| < 2.4$)
- Prompt $J/\psi$ ($6.5 < p_T < 30$ GeV/c, $|y| < 2.4$)
- $\Upsilon(1S)$ ($|y| < 2.4$)

$R_{AA}$ vs. Binding energy [GeV]

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2

$T/T_c$  

$\frac{1}{\langle r \rangle}$ [fm$^{-1}$]

$Y(1S)$
$\chi_b(1P)$
$J/\psi(1S)$
$\Upsilon(2S)$
$\chi_c(1P)$
$\psi(2S)$

$\phi$
$\Upsilon(3S)$
$\psi(2S)$

$\Upsilon(2S)$

$\Upsilon(1S)$

$\psi(2S)$

$\psi(2S)$

$\psi(2S)$

$\psi(2S)$

$\psi(2S)$

$\psi(2S)$

$\psi(2S)$
$J/\psi$-$\psi(2S)$ suppression: a proof of recombination?

- Low $p_T$ $J/\psi$ measurements from ALICE compared to CMS results suggest a possible contribution of charm recombination in the medium.

- $\psi(2S)$ more suppressed than $J/\psi$ in central PbPb collisions.
- Is recombination more relevant for excited $J/\psi$ states? (sequential recombination)
- Simple kinematic effect? radial flow?
Also puzzles in pp…

Other phenomena, other that color screening, could lead to a suppression sequence that depends on the binding energy!

• Evolution (w.r.t. minbias) of the individual x-sections with the increase of track multiplicity around the state **even in pp collisions**:

\[
\frac{\gamma(3S)}{\langle \gamma(3S) \rangle} < \frac{\gamma(2S)}{\langle \gamma(2S) \rangle} < \frac{\gamma(1S)}{\langle \gamma(1S) \rangle}
\]

Additional final-state effects affecting more the excited states than the ground state?
what happens to charmonia?

J/ψ $R_{AA}$ at lower $p_T$ (<6.5 GeV)

J/ψ $R_{AA}$ at higher $p_T$ (>6.5 GeV)

What does it mean?
At low $p_T$ there could be an antagonistic mechanism to “dissociation” or melting

Much more J/ψ seems to “survive” at low $p_T$

J/ψ created by combining c-cbar quarks that are abundant in the deconfined QCD medium
Long range correlation in pp at 13 TeV

We can extract the double ridge associated “yield” projecting the correlation plot along $\Delta \Phi$.

Very similar behaviour in pp, pPb and PbPb collisions but with different magnitude.

Almost no dependence on the collision energy.

What kind of phenomenal are we observing?