Heavy ion physics with CMS

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Introduction: detector, data taking and centrality

Pb+Pb (selected) results
- global observables: charged particle multiplicity, energy and transverse energy
- control probes: isolated photons, electroweak bosons
- modified probes: jet quenching, $\gamma$+jet, hadrons and jets $R_{AA}$, quarkonia

Summary
- **inner tracking** system (|\(\eta|\) < 2.5)
- **calorimeters** (electromagnetic: |\(\eta|\) < 3, hadronic: |\(\eta|\) < 5)
- **muon** system (|\(\eta|\) < 2.4)
- **forwards** detectors (CASTOR: -6.6 < \(\eta|\) < -5.2 and ZDC: |\(\eta|\) > 8.3)
- magnetic field of 3.8 T
PbPb: $\sim 8.7$ [150] $\mu b^{-1}$ in 2010 [2011]

pp (at 2.76 TeV): $\sim 230$ $nb^{-1}$ in 2011

comparing PbPb results to pp reference

$$R_{AA} = \frac{1}{N_{\text{coll}}} \cdot \frac{N_{AA}}{N_{PP}}$$

$N_{\text{coll}}$: number of elementary NN collisions or

$$T_{AA} = \frac{N_{\text{coll}}}{\sigma_{PP}}$$

centrality concept: Pb ions are extended objects, particle production depends on the impact parameter

reflects the geometrical overlap of the two colliding nuclei

energy deposit in forward calorimeters
Global observables
↔ basic information on the created system
• **hadron** rapidity **density** $\propto$ number of **initially** released **partons** at a given $\eta$: reduced multiplicity in saturation models

charged hadron density for 0-5% collisions: $1612\pm55$

$\frac{dN_{ch}}{d\eta}$ is $\sim$ flat over $|\eta|<2.5$ ($<10\%$ variation)

similar $N_{part}$ dependence for all $\sqrt{s_{NN}}$

good description of the data by a parton saturation approach

$\sqrt{s_{NN}}$ dependence follows power law behavior with exponent $s^{0.13}$
- CASTOR coverage up to $\eta=-6.6$ ($y_{beam} \sim 8$); peak of the $dE/d\eta$
- HYDJET 1.8 and EPOS-LHC: good agreement for central data
- QGSJetII.3: describe better peripheral data; AMPT: quantitative agreement to the data

\[ R_{PC} = \frac{\langle E \rangle(\eta,N_{part})}{\langle E \rangle(\eta,N_{\text{part}}^{\text{max}})} \cdot \frac{N_{\text{part}}^{\text{max}}}{N_{\text{part}}} \]

- shape change in the forward $\eta$; flattening region for central events at high $\eta$
- data is challenging for models

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Initial distribution of partons (via $N_{\text{part}}$) and hydrodynamic flow that builds up after thermalization (via $\eta$); energy density via Bjorken’s formula:

$$\epsilon_{\text{BJ}} = \frac{dE_T}{dy} \cdot \frac{1}{\tau_0 \pi R^2}$$

- $\sim 2.1 \text{ TeV}$ at $\eta = 0$; at least 3 times larger than at RHIC
- Shape consistent with a Gaussian with $\sigma_{\eta} = 3.4 \pm 0.1$: larger than predicted by Landau hydro but narrower than given by HYDJET; AMPT overestimates
- $(dE_T/d\eta)/(0.5 \langle N_{\text{part}} \rangle)$ increases with $N_{\text{part}}$ for all $\eta$
- For $\tau_0 = 1 \text{ fm/c}$ and $R = 7.1 \text{ fm}$: energy density of $\approx 14 \text{ GeV/fm}^3$
- For $\sqrt{s_{NN}} \geq 8.7 \text{ GeV}$, $E_T$ at $\eta = 0$ reproduced by a power-law dependence $s_{NN}^n$ with $n \approx 0.2$
Control probes

$\leftrightarrow$ not affected by the medium
sources of high-$p_T$ photons:
- isolated (direct): blind to the created medium
- not-isolated (fragmentation, meson decay,...): affected by the medium

first adaptation of p+p photon identification methods to heavy ion experiment
photons are measured for $|\eta| < 1.44$, $E_T$ of 20–80 GeV in 3 centrality bins
significant background: mainly from neutral mesons

consistent with the NLO calculation at all transverse energies (within uncertainties)
$R_{AA}$ vs $E_T$ is flat
no dependence of $R_{AA}$ on $N_{part}$
Control probes $| Z \rightarrow \mu^+ \mu^- |$ [CMS-PAS-HIN-12-008]

- for the mass range 60-120 GeV/c$^2$: 616 events with opposite-sign muons; no events with same-sign muons
- very low pp statistics for 2.76 TeV: comparison to POWHEG generator (well tested at Tevatron and LHC at 7TeV)

$R_{AA} = 0.95 \pm 0.03 \pm 0.13$
also $W \rightarrow \mu\nu$ studies [PLB 715 (2012) 66]

- electroweak bosons are not affected by the medium (within uncertainties)
- confirmation of the validity of the binary ($N_{coll}$) scaling
- more precision: access to the nuclear PDFs
Modified probes affected by the medium
jets are produced at the initial impact
- radiative energy loss when they travel through the QGP
  - sensitive to the energy density of the medium
  - depends on the path length
  - azimuthal correlations between produced jets: for p+p or p+A peak at $\Delta \phi = 180^\circ$
  - for A+A important modification of the azimuthal correlations: the away side jets are suppressed
- investigating modification of jets: very useful tool for probing the QGP properties
- dijet asymmetry: \( A_J = \frac{p_T,1-p_T,2}{p_T,1+p_T,2} \)  \( (p_T,1 \text{ for leading, } p_T,2 \text{ for sub-leading}) \)
- here only calorimeter dijets: leading \( p_T >120 \text{ GeV, sub-leading } p_T >50 \text{ GeV} \)
- \( p_T \) imbalance (i.e. \( A_J \)) increases with the centrality

- azimuthal decorrelation \( \Delta \phi_{1,2} \): back-to-back \( (\Delta \phi_{1,2} \sim \pi) \) for all centralities
- at LO photons produced back-to-back with an associated parton (jet): $p_T^\gamma \sim p_T^{Jet}$
- transverse momentum balance $x_{J\gamma} = \frac{p_T^{Jet}}{p_T^\gamma}$
- when increasing the centrality of the collision
  - shift of the $x_{J\gamma}$ distribution towards lower values
  - reduction of the fraction of photons with an associated jet
modifed probes | $\gamma + \text{jet}$ [arXiv:1205.0206, accepted by PLB]

- average $\gamma$-jet $p_T$ balance decreases by $\sim 14\%$ compared to $pp$
- fraction of $\gamma$ with an associated jet partner drops by $\sim 20\%$
- using jet trigger to enhance $p_T$ reach (up to 100 GeV/c) and decrease fake rate

- large suppression of charged particles above a few GeV/c
- online PbPb jet trigger threshold of 80 GeV/c; offline: $p_T > 100$ GeV/c and $|\eta| < 2$

- suppression factor of $\sim 0.5$ in central PbPb when comparing to pp
- no suppression (within uncertainties) in the most peripheral PbPb
- $R_{AA}$ is approximately independent of $p_T$ in the measured range
no change in level of suppression due to jet cone size
b from non-promt $J/\psi$: produced at large distance from the primary vertex; $p_T < 30 \text{ GeV/c}$
the identification of $J/\psi$ coming from B hadron decays relies on the measurement of a secondary $\mu^+\mu^-$ vertex displaced from the primary collision vertex. The distance between the $\mu^+\mu^-$ vertex and the primary vertex is measured in the plane transverse to the beam direction.

D’s from ALICE

- in theory: energy loss depends on the quark mass
- $R_{AA}^b > R_{AA}^c$: b-quarks are less suppressed than c-quarks
jets tagged by cutting on discriminating variables:
  - Simple Secondary Vertex High Efficiency (SSVHE): based on the flight distance significance of reconstructed SV
  - Jet Probability (JP)

- $p_T > 100$ GeV/c; first b-jet identification in heavy ion collisions

- pp and PbPb b-jet fraction are the same: consistent with MC
- $R_{AA} < 1$
Modified probes | $R_{AA}$: summary

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

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

- * Z (0-100%) $p_t^{\ell} > 20$ GeV/c
- * W (0-100%) $p_t^{\nu} > 25$ GeV/c
- Isolated photon (0-10%)
- b-quarks (0-100%)
- (via secondary J/ψ)

- Charged particles (0-5%)

$R_{AA}$ vs $p_T(m_T)$ (GeV)

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

$jet\ p_T$ (GeV)
- **color screening** of static potential between heavy quarks
- quarkonia **melting** depending on the binding energy: thermometer of the medium
- $6.5 < p_T < 30 \text{ GeV/c}$: no rapidity dependence
- central collisions: suppression by factor $\sim 5$
- high $y$: low $p_T$ suppressed less than high $p_T$
- first look at $\psi(2S)$; raw ratios: $R_{\psi(2S)} = N_{\psi(2S)}/N_{J/\psi}$
- red curves: PbPb fit
- $|y| < 1.6$ and $6.5 < p_T < 30$ GeV/c

relative less $\psi(2S)$ than $J/\psi$
- $R_{\psi(2S)}^{PbPb} \sim 0.5 R_{\psi(2S)}^{pp}$
- excellent mass resolution ($\sim 1\%$): clear separation; acceptance down to $p_T = 0 \text{ GeV/c}$
- centrality-integrated $R_{AA}(\Upsilon(nS))$

$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08 \pm 0.07$
$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04 \pm 0.02$
$R_{AA}(\Upsilon(3S)) < 0.1 \ (95\% \ CL)$
- ordered suppression
centrality-integrated $R_{AA}$ vs binding energy seems ordered: looser bound states are more suppressed

but has to be done with more data: centrality dependence, feed-down contributions, cold nuclear matter effects (pA)
Pb+Pb data taking periods were very successful!

CMS collected a significant amount of data

thanks to CERN for fantastic LHC performance!

detailed measurements of global properties of medium in Pb+Pb collisions

measurement of control probes (γ, Z and W): unmodified as expected

jet quenching ... including b !!!

quarkonium suppression

looking forward for pA data ...

much more results not discussed here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN