Heavy Ion Highlights from the experiment

CMS Experiment at LHC, CERN
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Manuel Calderón de la Barca Sánchez
for the CMS Collaboration

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Physics Highlights from CMS Heavy Ions

- Onset of collective effects: from small systems to PbPb
  - Are QGP effects present even in pPb?
- System size dependence of QGP effects: XeXe vs. PbPb.
- Flavor dependence of parton shower modification: gluon vs quark vs Heavy Quark
- Quark distribution functions in Pb: W boson measurements
- Quarkonia in hot medium
- New physics observables:
  - Limits on chiral-magnetic effect
  - Observation of light-by-light scattering
COLLECTIVE EFFECTS: AZIMUTHAL CORRELATIONS

Kolb et al., PRC 62 (2000) 054909
Strange and charm $v_2$ in pPb

- Charm ($D^0$, $J/\psi$) and strange quark flow in pPb

  - Charm $v_2$ observed in pPb collisions.
    - Weaker than flow for light quarks for $K_{ET}/n_q > 1$ GeV.
    - Less collectivity for charm quarks in pPb?

arXiv:1804.09767, CMS PAS HIN-18-010
Collectivity in small systems

- Suppressing contamination (jets, resonances) in low multiplicity events using $\eta$ subevents
- Goal: understand onset of collective behavior

CMS PAS HIN-18-015

$N_{\text{trk}} > 80$: All methods consistent.  
$\Rightarrow$ negligible contamination

$N_{\text{trk}} < 80$: Contamination suppressed via subevents.

$\Rightarrow$ Observe $v_2, v_3$ anti-correlation in pPb collisions for $N_{\text{trk}} \sim 50$.

$\Rightarrow$ Similar to PbPb: attributed to hydrodynamic flow.

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Higher harmonics: PbPb and pPb

\( v_2 \), pPb vs PbPb:
- Multiparticle \( v_2 > 0 \) in both pPb and PbPb:
  - Collective behavior.
- Different trend with multiplicity
  - Fluctuation-driven eccentricity decreases in pPb?

\( v_3 \), pPb vs PbPb
- Comparable
  - Dominated by initial state geometry fluctuation
  - pPb: consistent with magnitude from hydro
SYSTEM SIZE DEPENDENCE

XeXe measurements

\[ 5.4 \text{ fm} \]

\[ \text{Xe} \]

\[ 6.6 \text{ fm} \]

\[ \text{Pb} \]
XeXe: Particle production

- XeXe ~1.4 less multiplicity than PbPb.
- For $N_{\text{part}} \sim 200$, Xe produces more particles per participant than Pb.
- No system size scaling
Flow in XeXe

- Xe $v_2$ higher than Pb in central, lower in peripheral
  - Most-central events: Xe quadrupole deformation matters.
- $v_3$ behavior as expected, but not $v_4$?

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XeXe: high-\(p_T\) hadron suppression

\[ R_{AA}^* : \]
- Similar scaling with \(N_{\text{part}}\) in Xe and Pb.
- At same \(N_{\text{part}}\), \(R_{AA}(p_T)\) consistent within uncertainties between Xe and Pb.
Studying the QGP density and Temperature via

**HARD PROBES**

Jet Energy Loss/Tomography

Quarkonium Melting

Production

\[ \mu^{-1} \]

In-medium Energy Loss

Fragmen-tation

\[ p \]

\[ k \]

\[ \lambda \]

\[ q \]

\[ L \]

\[ T=0 \]

\[ T_{C}>T>0 \]

\[ T>T_{C} \]

J/ψ
Photon-tagged jet fragmentation

- Final state: $\gamma$-quark
  - photon $p_T$ constrains parton energy.
- Quark enriched sample:
  - flavor dependence of jet quenching.
- Most central collisions:
  - Depletion of high momentum particles
    - Sensitive to hard parton shower
  - Enhancement of particles carrying small fraction of jet momentum
    - Recoil

\begin{align*}
\sqrt{s_{NN}} &= 5.02 \text{ TeV} \\
PbPb &= 404 \mu b^{-1} \\
p p &= 27.4 \text{ pb}^{-1}
\end{align*}

\begin{align*}
p_T^{\text{trk}} &> 1 \text{ GeV/c, anti-}k_T \text{ jet } R = 0.3 \\
p_T^{\text{jet}} &> 30 \text{ GeV/c, } |\eta|^{\text{jet}} < 1.6 \\
p_T^{\gamma} &> 60 \text{ GeV/c, } |\eta|^{\gamma} < 1.44, \Delta \phi^{\gamma} > \frac{7\pi}{8}
\end{align*}
Jet Shapes: gluon vs quarks

Observe Jet-shape modification in PbPb compared to pp

r~0.1: Depletion for inclusive jets, no depletion for photon-tagged jets.

- Due to changing q/g fraction for inclusive sample?

r>0.15: Redistribution of energy to large angle for both light quark and gluon jets

Inclusive: Gluon/quark mixture

γ-jet: quark dominated

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

- anti-$k_T$ jets: $R = 0.3$

CMS PbPb, $\sqrt{s_{NN}} = 5.02$ TeV

- pp 27.4 pb$^{-1}$, PbPb 404 μb$^{-1}$

$\rho(r)$

$\rho(r)_{PbPb}/\rho(r)_{pp}$

Cent. 0 - 10%
How does the jet-shape modification depend on $p_T$?

Peripheral collisions: radial distribution similar to pp

Central collisions: enhancement of low $p_T$ tracks, depletion for $p_T > 4$ GeV

Inclusive: Quark/Gluon Mixture

$P(\Delta r)_{PbPb}/P(\Delta r)_{pp}$

- $p_{\text{trk}}^{T} > 0.7$ GeV
- $p_{\text{trk}}^{T} > 2$ GeV
- $p_{\text{trk}}^{T} > 4$ GeV

Central 0-10%
Jet shapes: charm quarks

- Radial distributions of D0’s in pp and PbPb

- Indication that D mesons are further away from jet axis in PbPb.
Jet substructure via groomed jet mass

Jet grooming: sequentially prune soft constituents of jet until pair of hard subjets is found ⇒ information about hard splitting in medium

Flat : insensitive to multiple emissions
Large angle: Focus on jet core

Jet core unaffected by medium

Possible high mass enhancement

Jet quenching models do not describe large mass data for both large angle and flat grooming

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Non-prompt D: Beauty suppression

- First measurement of non-prompt $D^0 R_{AA}$.

- Non-prompt $D^0$ and non-prompt $J/\psi$: $b$ hadrons less suppressed than prompt $D^0$ and light hadrons for $p_T<10$ GeV/c
  - Consistent with dead-cone effect for heavy quarks.

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Strange B mesons

- First probe of recombination between beauty and strange quarks.

- Hint of enhancement of $B_s$ with respect to $B^+$. 
  - Recombination with abundantly produced s quarks in QGP?

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Charmonia: $J/\psi$ and $\psi(2S)$

- $\psi(2S)$ $R_{AA} < J/\psi$ $R_{AA}$
  - Observed in both PbPb and pPb
- Effects beyond shadowing and energy loss in pPb
- Quantitative comparison in PbPb and pPb: towards disentangling cold vs. hot nuclear matter effects
Clear suppression of Upsilon family.
Sequential suppression observed in all centralities
\( \Upsilon(3S) \): smallest \( R_{AA} \) observed for any hadron.
Prompt $J/\psi$: PbPb and pp

- **PbPb**: Suppression of charm
  - Similar $R_{AA}$ for open and hidden charm for $p_T>6.5$ GeV/c.

- **pp**: production of $J/\psi$ in jets
  - $J/\psi$ carries only half of jet $p_T$.
  - Not well described by Pythia.
Nuclear modification of quark PDF needed to describe our data.

- Constrains $q+\text{antiquark PDF } 10^{-3} < x < 10^{-1}$. 
Nuclear PDFs with top quark

First experimental observation of the top quark in nuclear collisions (>5σ)

top cross section: Compatible with nPDF expectation.
Nuclear PDFs with dijets

Large $x (>0.3)$ in lead ions:
- Clearly suppressed wrt unbound nucleons
  - Inconsistent with DSSZ
  - Evidence of strong gluon EMC effect

Small $x$:
- Stronger shadowing effect than models
  - Data more precise than nPDF uncertainties
  - Improve description of gluon nPDF
NEW OBSERVABLES
Chiral magnetic effect: null result

CME signal: consistent with 0.

Possible CME signal in PbPb at LHC energies < 7% @ 95% CL
Significance of signal: 4.1σ observed (4.4σ expected)

Measured fiducial cross section:

- $\sigma_{\text{fid}} = 122 \pm 46$ (stat) ± 29 (syst) ± 4 (th) nb

Consistent with Standard Model:

- $\sigma_{\text{fid,SM}} = 138 \pm 14$ nb
Summary

- Redistribution of light and charm quarks within a jet
- Core of jet not modified
- Bottomonium melting. $\Upsilon(3S)$ smallest $R_{AA}$ observed
- Hint for beauty recombination with strange
- XeXe similar to PbPb
- Evidence of guon EMC effect and quark modification in Pb
- First observation of top quark in nuclear collisions
- Collectivity in $pPb$ down to $N_{trk}=50$
- CME effect not observable at LHC energies
- Observation of light-by-light scattering