Recent Results from CMS

Jing Wang (MIT)

For the CMS Collaboration

The 20th International Conference on Strangeness in Quark Matter (SQM 2022)
13 June 2022 Busan, Republic of Korea

MITHIG group’s work was supported by US DOE-NP
The Road: Past, Present and Future

• Great success of CMS heavy-ion project in Run 2
• Run 3 is around the corner
• Here we discuss part of our latest inputs contributing to the knowledge of HIC!
Section I

Initial stage
nPDF: Drell-Yan in pPb

- Drell-Yan: $Z/\gamma^* \rightarrow \mu\mu$
- Access small $x$ with $m_{\mu\mu}$ down to 15 GeV
  
  \[ x \propto m_{\mu\mu} e^{-y_{CM}} \]

- Smaller data uncertainty than nPDF
- Prefer nPDF (EPPS16, nCTEQ) to proton PDF around Z mass
Probe Initial State with Charm $v_3$

- First $J/\psi$ $v_3$ measurement of prompt component
• First $J/\psi$ $v_3$ measurement of prompt component
• Prompt $D^0$ $v_3 >$ Prompt $J/\psi$ $v_3 \Rightarrow$ charm is less sensitive to initial fluctuations than light quarks?
Probe Initial State with Beauty $v_3$

- $(b \rightarrow D^0) v_3 \approx (b \rightarrow J/\psi) v_3$ are consistent and reflect beauty $v_3$
- $(b \rightarrow D^0) v_3 < \text{Prompt } D^0 v_3 \rightarrow$ beauty less sensitive to initial state than charm?
Probe Initial State with D\(^0\) \(v_2\{4\}\)

**Prompt D\(^0\) \(v_2\{2\}\) vs. \(v_2\{4\}\)**

- Probe event-by-event fluctuation
  - \(v_2\{2\}\)^2 \(\approx\) \(\langle v_2\rangle^2 + \sigma^2\)
  - \(v_2\{4\}\)^2 \(\approx\) \(\langle v_2\rangle^2 - \sigma^2\)

- Indeed \(v_2\{4\}\) < \(v_2\{2\}\) for D\(^0\)
- Fluctuations of both initial geometry (soft) and energy loss (hard)
  - distinguished by \(v_2\{4\}/v_2\{2\}\) vs. \(p_T\)

- see Milan’s talk

*Calculation for prompt D\(^0\)*

\(v_2\{2\}\), Coll. E-loss (Langevin)

\(v_2\{4\}\), Coll. E-loss (Langevin)

\(v_2\{2\}\), Rad. E-loss

\(v_2\{4\}\), Rad. E-loss

- Syst.

PbPb 0.58 nb\(^{-1}\) (5.02 TeV)

\(0\) < \(p_T\) < 8 GeV

\(v_2\{2\}\)

\(v_2\{4\}\)

Centrality (%)
Section II

Hot medium effect
Charm $v_2$ in PbPb: Open vs. Hidden

- High precision measurement over wide $p_T$ range
- Low $p_T$: $v_2(h^\pm) > v_2$ (Prompt $D^0$) > $v_2$ (Prompt $J/\psi$)
  - Different constituent quarks
  - Recombination
- High $p_T$: $v_2(h^\pm) \approx v_2$ (Prompt $D^0$) \approx $v_2$ (Prompt $J/\psi$)
  - Mass effect disappears
  - Path-length dependence of energy loss
  - Non-zero $v_2$ up to high $p_T = 50$ GeV
Charm $v_2$ in PbPb: Open vs. Hidden

$v_2$ vs. centrality

- $v_2$ increase and then decrease from central to peripheral events for both $D^0$ and $J/\psi$
- as expected by hydrodynamics
- but different effects work differently for Prompt $D^0$ and $J/\psi$

CMS-PAS-HIN-21-008
PLB 816 (2021) 136253
Charm $v_2$ in PbPb: $v_2$ vs. $v_3$

- Centrality dependence: **strong for $v_2$ vs. weak for $v_3$** for both $D^0$ and $J/\psi \rightarrow$ hydrodynamics
Charm $v_2$ in PbPb: $J/\psi$ vs. $\psi(2S)$

- First measurement of $\psi(2S)$ $v_2$, $v_3$!
- Hint of $v_2(\psi(2S)) > v_2(J/\psi)$
  - Different relative contribution of recombination?
Beauty $v_2$ in PbPb: $b\to D$ and $b\to J/\psi$

- Probe collectivity of beauty quark using different channels
  - Unique measurements covering wide kinematic range
  - $(b\to D^0) v_2$ consistent with $(b\to J/\psi) v_2$
  - Low $p_T$: Smaller than prompt $D^0 v_2$
    - Weaker collective motion of beauty than charm
  - High $p_T$: All flavors tend to converge
Beauty $v_2$: $\Upsilon(1S)$ in pPb and PbPb

- No significant non-zero $v_2$ of $\Upsilon(1S)$ in both PbPb and high multiplicity pPb

CMS Preliminary

CMS-PAS-HIN-21-001
Summary: CMS Heavy Flavor $v_2$ Zoo

- Abundant physics behind these high precision and unique measurements from CMS!
- Strong constraint on theoretical calculations in different collision systems
Cumulant-mean $p_T$ Correlation in pPb

- Correlation of $v_2$ and average $p_T$ carries info on the origin of $v_2$ in small systems
  - Sign change predicted with initial momentum anisotropy in CGC

![Graph showing correlation between $p_T$ and $v_2$]
Correlation of $v_2$ and average $p_T$ carries info on the origin of $v_2$ in small systems
- **Sign change** predicted with initial momentum anisotropy in CGC\(^1\)

- No sign change with wider $\eta$ gap
- Sensitive to **nonflow** contribution

- Multi-particle correlation and $v_3$ results in multiple collision systems see S. Tuo’s poster

\(^1\)PRL 125 (2020) 192301
First Y(3S) Observation in HIC

- First observation of Y(3S) in PbPb!
- Signal significance > 5σ

- Smaller $R_{AA}$ of Y(3S) than Y(2S)
- Strong constraint to theoretical models
Section III

Hadronization

Click to see animation ➥
Hadronization: $B_s$ and $B_c$ in PbPb

- Statistically compatible b/w PbPb and pp
Hadronization: $B_S$ and $B_c$ in PbPb

- Statistically compatible b/w PbPb and pp
- Hint of larger $B_c R_{AA}$ than $B^+ R_{AA}$ at low $p_T$

F. Damas [06/14 11:30]

PLB 829 (2022) 137062

arXiv:2201.02659 Accepted by PRL
Freeze-out & Rescatterings

Section IV
Femtoscopy

• Femtoscopy: Use final state particle correlations to probe the particle emitting source on the femtometer scale

• Parameterization: Lévy-type source & core-halo model
  ➡ Source shape: $\alpha$
  ➡ Spacial scale: $R$
  ➡ Core-halo ratio: $\lambda$
Femtoscopy: Use final state particle correlations to probe the particle emitting source on the femtometer scale

Parameterization: Lévy-type source & core-halo model

- Source shape: $\alpha$
- Spacial scale: $R$
- Core-halo ratio: $\lambda$

Non-Gaussian behavior observed
- $\alpha < 2$

CMS Preliminary

PbPb $0.58 \text{ nb}^{-1} (5.02 \text{ TeV})$

CMS-PAS-HIN-21-011
Femtoscopy: h± - h± Correlation

1/R² for specific mₜ

- Centrality: 0%-5%, 5%-10%, 10%-20%, 20%-30%, 30%-40%, 40%-60%
- Fitted function: 1/R² = A mₜ + B
- Correlated syst. = h⁺h⁻

R vs. ⟨N_{part}⟩₁/³

- Fitted function: R = a N_{part}^{1/3} + b
- Correlated syst. = h⁺h⁻

• R extracted indeed reflects the spatial scale of system (homogeneity region for specific mₜ)

Jing Wang (MIT), CMS Highlights, SQM 2022 (Busan, Republic of Korea)
Femtoscopy: $h^\pm - h^\pm$ Correlation

- **Linear scaling** $1/R^2 = A m_T + B$
  - Predicted by hydrodynamics for Gaussian source
  - Also holds for Lévy source
  - Larger slope for peripheral events
    - Related with expansion velocity, freeze-out temperature, etc…

→ More parameters and differential results see R. Pradhan’s talk
Ultra-Peripheral Collisions
(g-2)_\tau: \gamma\gamma \rightarrow \tau\tau \text{ in PbPb UPC}

- Cross-section of $\tau\tau$ photoproduction in PbPb UPC sensitive to anomalous magnetic moment

\[ a_\tau = \frac{(g - 2)_{\tau}}{2} \]
(g-2)_τ: γγ→ττ in PbPb UPC

\[
a_\tau = (g - 2)_\tau / 2
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS Preliminary, PbPb→Pb^{(<em>)}(γγ→τµτ_{3prong})Pb^{(</em>)}</td>
<td>68% CL, 0.4 nb(^{-1})</td>
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<tr>
<td>CMS Phase 2 Projection Preliminary</td>
<td>PbPb→Pb^{(<em>)}(γγ→τµτ_{3prong})Pb^{(</em>)}, 68% CL, 13 nb(^{-1})</td>
</tr>
</tbody>
</table>

- Signal number \(N_{\text{sig}} = 77 \pm 12\)
- Significance above 5σ
- Constraint on \(a_\tau\) from the LHC
- Strong constraint with Run 3+4

Based on rate-only-analysis, assuming 4% uncertainty

G. Krintiras [06/14 16:10]

CMS-PAS-HIN-21-009
Dijet Angular Correlation in PbPb UPC

- Dijet photoproduction sensitive to multi-dimensional structure of the gluons
  - Gluon elliptical polarization
    - Dijet azimuthal angular correlations
  - $P_T > Q_T$: back-to-back limit

\[ \Phi \]
\[ Q_T = \vec{k}_1 + \vec{k}_2 \]
\[ P_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2) \]

$P_T,1 > 30$ GeV
$P_T,2 > 20$ GeV
$|y_{1,2}| < 2.4$
$Q_T < 25$ GeV
$P_T > Q_T$

arXiv:2205.00045
Dijet Angular Correlation in PbPb UPC

- Probe gluon elliptical polarization
- Data compared to simulation and calculation without effect of gluon polarization
  - RAPGAP overestimates correlation
  - Calculation\(^1\)
    - Final state soft gluon radiation
    - Reaches constant at \(Q_T > 2\) GeV ➔ different from data trend

\(^1\)PRL 126 (2021) 142001

arXiv:2205.00045
Two-particle Correlation in $\gamma p$ Interactions

- Search for azimuthal anisotropy in $\gamma p$ interactions with pPb UPC
- Non-flow subtraction not applied
- Consistent with simulations without collective effects for both $\gamma p$ and pPb in the $N_{\text{trk}}$ range

S. Behera [POS-BLK-04]
arXiv:2204.13486
### Summary: Recent Results in SQM’22

#### Parton distribution in Pb
- Drell-Yan process in pPb
- Dijet decorrelation in UPC

#### Initial state and hot medium effect
- Charmonium $v_n$ in PbPb
- Prompt and $(b \rightarrow D^0 v_n$ in PbPb
- $\Upsilon(3S)$ production in PbPb
- $B_s, B_c$ production in PbPb

#### Heavy quark hadronization
- $\Upsilon(1S) v_2$ in pPb
- Cumulant-[$p_T$] correlation
- $v_2$ in $\gamma p$ interactions with pPb UPC

#### Collective behavior in small systems
- Femtoscopic correlations
- $\gamma \gamma \rightarrow \tau \tau$ in PbPb UPC

#### Freeze-out and rescatterings

#### $\tau$ lepton (g-2)

> CMS HIN Publication
> CMS HIN Preliminary
### Summary: Talks & Posters in SQM’22

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Topic</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyunchul Kim</td>
<td>Drell-Yan process in pPb</td>
<td>06/14 15:20</td>
</tr>
<tr>
<td>Aleksandr Bylinkin</td>
<td>Dijet decorrelation in UPC</td>
<td>06/14 11:10</td>
</tr>
<tr>
<td>Subash Chandra Behera</td>
<td>Vector meson photoproduction</td>
<td>06/14 16:30</td>
</tr>
<tr>
<td>Gyeonghwan Bak</td>
<td>Charmonium $\Lambda_n$ in PbPb</td>
<td>06/14 09:40</td>
</tr>
<tr>
<td>Milan Stojanovic</td>
<td>Prompt and ($b \rightarrow D^0 \nu_n$ in PbPb</td>
<td>06/14 10:50</td>
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<tr>
<td>Soohwan Lee</td>
<td>Y(3S) production in PbPb</td>
<td>06/14 09:20</td>
</tr>
<tr>
<td>Florian Damas</td>
<td>$B_s, B_c$ production in PbPb</td>
<td>06/14 11:30</td>
</tr>
<tr>
<td>Soumik Chandra</td>
<td>$\Lambda_c$ production in PbPb</td>
<td>06/14 11:10</td>
</tr>
<tr>
<td>Kisoo Lee</td>
<td>Quarkonium $v_2$ in pPb</td>
<td>06/14 09:00</td>
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<tr>
<td>Shengquan Tuo</td>
<td>Cumulant-$p_T$ correlation</td>
<td>POS-BLK-03</td>
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<tr>
<td>Subash Chandra Behera</td>
<td>$v_2$ in $\gamma p$ interactions with pPb UPC</td>
<td>POS-BLK-04</td>
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<tr>
<td>Sunil Manohar Dogra</td>
<td>$B^+$ production in pPb</td>
<td>POS-HF-08</td>
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<tr>
<td>Raghunath Pradhan</td>
<td>Femtososcopic correlations</td>
<td>06/14 09:20</td>
</tr>
<tr>
<td>Georgios Krintiras</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$ in PbPb UPC</td>
<td>06/14 16:10</td>
</tr>
<tr>
<td>Riccardo Longo</td>
<td>ZDC upgrade for HL-LHC</td>
<td>06/14 16:30</td>
</tr>
</tbody>
</table>
Thanks for your attention!
Back up

Thanks for your attention!
## Heavy Flavor v2 Reference List

<table>
<thead>
<tr>
<th></th>
<th>PbPb</th>
<th>High-multiplicity pPb</th>
<th>High-multiplicity pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged hadrons</td>
<td><strong>PLB 776 (2017) 195</strong></td>
<td><em>(K_{S}^{0})</em>* PRL 121 (2018) 082301</td>
<td>-</td>
</tr>
<tr>
<td>Prompt D^0</td>
<td><strong>PLB 816 (2021) 136253</strong></td>
<td>PRL 121 (2018) 082301</td>
<td><strong>PLB 813 (2021) 136036</strong></td>
</tr>
<tr>
<td>Prompt J/ψ</td>
<td><strong>CMS-PAS-HIN-21-008</strong></td>
<td><strong>PLB 791 (2019) 172</strong></td>
<td>-</td>
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<tr>
<td><em>(b→D</em>) D^0</td>
<td><strong>CMS-PAS-HIN-21-003</strong></td>
<td><strong>PLB 813 (2021) 136036</strong></td>
<td>-</td>
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<tr>
<td>*(b→ψ) J/ψ</td>
<td><strong>CMS-PAS-HIN-21-008</strong></td>
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<td>-</td>
</tr>
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<td>Y(1S)</td>
<td><strong>PLB 819 (2021) 136385</strong></td>
<td><strong>CMS-PAS-HIN-21-001</strong></td>
<td>-</td>
</tr>
</tbody>
</table>
Femtoscopy: $V^0 - V^0$ Correlation

- Particle correlation also sensitive to
  - Quantum statistical effect
  - Coulomb interactions $\rightarrow$ Vanish for $V^0$
  - Strong interactions

$\Rightarrow$ So we can
- Probe strong interaction scatterings
- Search dibaryon bound states

CMS Preliminary PbPb, $\sqrt{s_{NN}} = 5.02$ TeV (0.61 nb$^{-1}$)

Scattering parameters

- Repulsive interaction
- Attractive interaction
- Possible bound state

CMS-PAS-HIN-21-006
CMS Phase-2 upgrades for HL-LHC

Table 1: Main features of CMS detector at present and Phase 2 upgrades.

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>CMS present</th>
<th>CMS Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tracker</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>Low-granularity</td>
<td>High-granularity end-cap with silicon sensors</td>
</tr>
<tr>
<td>Muon detector</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>L1 trigger bandwidth</td>
<td>30 kHz for PbPb, 100 kHz for pp and pPb</td>
<td>750 kHz (pass through all PbPb events)</td>
</tr>
<tr>
<td>DAQ throughput</td>
<td>6 GB/s</td>
<td>60 GB/s</td>
</tr>
<tr>
<td>Time-of-flight</td>
<td>N/A</td>
<td>MTD for charged hadron</td>
</tr>
<tr>
<td>for Particle ID</td>
<td></td>
<td>PID over $</td>
</tr>
</tbody>
</table>

- New MIP Timing Detector (MTD) for TOF-PID!
- Unique PID up to $|\eta| = 3$

Precision determination of the arrival time of the signal
CMS MIP Timing Detector (MTD)

- Large acceptance
- Barrel Timing Layer (BTL): |\(\eta| < 1.5\)
- End-cap Timing Layer (ETL): 1.6 < |\(\eta| < 3\)
- Serve as TOF detector for hadron particle identification
- Time resolution 30-40 ps

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(r) (m)</th>
<th>(\sigma_T) (ps)</th>
<th>(r/\sigma_T \times 100) (m (\times) ps(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR-TOF</td>
<td>2.2</td>
<td>80</td>
<td>2.75</td>
</tr>
<tr>
<td>ALICE-TOF</td>
<td>3.7</td>
<td>56</td>
<td>6.6</td>
</tr>
<tr>
<td>CMS-MTD</td>
<td>1.16</td>
<td>30</td>
<td>3.87</td>
</tr>
</tbody>
</table>
CMS MIP Timing Detector (MTD)

Separation Power vs. kinematic phase space

- CMS MTD brings complementarity and uniqueness in PID

CMS MTD ($|\eta| < 3$) vs. ALICE: mid-rapidity ($|\eta| < 0.9$)
LHCb: forward ($2 < \eta < 5$)

CERN-LHCC-2019-003
MTD Impact on HF hadron reconstruction

- Significant improvement of signal to background ratio with PID information from MTD

**Without MTD**

**With MTD**

CERN-LHCC-2019-003
b→D $v_n$ vs. Theory
Cumulant-mean $p_T$ Correlation in pPb

CMS Preliminary

$0.5 < p_T < 5$ GeV

$N_{ch} (0.5 < p_T < 5.0$ GeV, $|\eta| < 2.4)$

CMS-PAS-HIN-21-012
First Y(3S) Observation in HIC

CMS Preliminary

PbPb 1.6 nb$^{-1}$, pp 300 pb$^{-1}$ (5.02 TeV)

$R_{AA}$ as a function of $\langle N_{\text{part}} \rangle$

- $p_T < 30$ GeV/c
- $|y| < 2.4$
- Cent. 0-90 %

- $\Upsilon(1S)$ (2015 PbPb/pp)
- $\Upsilon(2S)$
- $\Upsilon(3S)$

CMS Preliminary

$R_{AA}$ as a function of $p_T$ (GeV/c)

- $|y| < 2.4$
- Cent. 0-90 %

- Data
- OQS + pNRQCD
- Coupled Boltzmann Eq.

CMS-PAS-HIN-21-007

S. Lee [06/14 9:20]
**B_c in PbPb**

B_c^+ less suppressed than quarkonia despite a binding energy between J/ψ and Y(1S)

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**arXiv:2201.02659**
Accepted by PRL
Femtoscopy: $h^\pm - h^\pm$ Correlation

Remove effect of pion ratio $\lambda^* = \frac{\lambda}{(N_{\text{pion}}/N_{\text{hadron}})^2}$

PbPb 0.58 nb$^{-1}$ (5.02 TeV)

Centrality
- 0%-5%
- 5%-10%
- 10%-20%
- 20%-30%
- 30%-40%
- 40%-60%

Correl. syst. = +5.7% -7.2%

$\lambda$

$0.6 \ 0.8 \ 1 \ 1.2 \ 1.4 \ 1.6 \ 1.8$

$m_T$ [GeV/c$^2$]

PbPb 0.58 nb$^{-1}$ (5.02 TeV)

Centrality
- 0%-5%
- 5%-10%
- 10%-20%
- 20%-30%
- 30%-40%
- 40%-60%

Correl. syst. = +5.7% -7.2%

$\lambda^*$

$0.6 \ 0.8 \ 1 \ 1.2 \ 1.4 \ 1.6 \ 1.8$

$m_T$ [GeV/c$^2$]

CMS-PAS-HIN-21-011

Jing Wang (MIT), CMS Highlights, SQM 2022 (Busan, Republic of Korea)
(g-2)_{\tau}: \gamma\gamma \rightarrow \tau\tau \text{ in PbPb UPC}

G. Krintiras [06/14 16:10]

CMS Preliminary

PbPb - 404\mu b^{-1} (\sqrt{s_{\mathrm{NN}}} = 5.02 \text{ TeV})

Data / Pred.

Events / (\pi / 80)

\Delta \phi(\tau_{\mu}, \tau_{3\text{prong}})

Data / Pred.

CMS Preliminary

PbPb - 404\mu b^{-1} (\sqrt{s_{\mathrm{NN}}} = 5.02 \text{ TeV})

Pb + Pb (\gamma\gamma) \rightarrow Pb^{(0)} + Pb^{(0)} \tau^{+}\tau^{-} at \sqrt{s_{\mathrm{NN}}} = 5.02 \text{ TeV}

- L. Beresford and J. Liu, Phys. Rev. D 102 (2020) 113008

4.8 \pm 0.6 \pm 0.5 \mu b

CMS-PAS-HIN-21-009
Section I
Section IV