Measurements of light-by-light scattering and lepton pair photoproduction in PbPb collisions with the CMS experiment

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QuarkMatter2022
4-10 Apr. 2022, Kraków, Poland
UPC PbPb @ LHC

• 3 periods of heavy ion collisions during Run2
• Ultraperipheral Collisions (UPC) of PbPb at $\sqrt{S_{NN}} = 5.02$ TeV
• Elastic and diffractive topologies tagged by Zero-Degree Calorimeter (ZDC) activity
• Small energy deposit at the Hadronic Forward (HF) calorimeters at $3 < |\eta| < 5$
• Photoproduction in UPC → Cross section scales with $Z^4$
Two-photon reactions are sensitive to many BSM processes

The subprocess $\gamma\gamma \rightarrow \gamma\gamma$ proceeds only via a charged-particle box diagram

- Cross section sensitive to all charged particles, including BSM particles such as axion-like particles (ALPs) and magnetic monopoles

UPC $\rightarrow$ quasireal photons with $p_T < 30$ MeV
LbyL scattering @ CMS

- Acoplanarity \( (A_\phi) = 1 - \frac{\Delta \phi_{\gamma\gamma}}{\pi} \)
- CEP normalized to data for \( A_\phi > 0.02 \)
- Evidence (4\( \sigma \)) of light-by-light scattering in UPC PbPb collisions

![Diagram showing signal and backgrounds with relevant processes]

### Graphical Representation

- **Signal**: Diagrams representing LbyL scattering processes.
- **Backgrounds**: Various processes contributing to background.

*Phys. Letter B 797, 134826 (2019)*
LbyL scattering @ CMS

- Kinematic distributions in agreement with sum of LbyL+QED($e^+e^-$)+CEP
LbyL scattering @ CMS

• Exclusion limits on the production of pseudoscalar axion-like particles (ALPs)
• Lower trigger thresholds beneficial for limits at low (< 5-6 GeV) ALP masses
Muon pair photoproduction

- low $p_T$ quasireal photons $\Rightarrow$ low dimuon $p_T$ $\Rightarrow$ $\alpha_{\mu\mu} = 1 - \frac{\Delta \phi_{\gamma\gamma}}{\pi} \ll 1$

- Higher $\alpha$ seen in hadronic collisions ($b<2R$) than UPC
  - Final-state interaction of muons with QGP?
  - QED Initial-State Interaction(ISI) increases the dimuon $p_T$?
Muon pair photoproduction

- Nuclei exchange soft $\gamma$ and emit 0, 1, $X(>1)$ neutrons
  - QED $\Rightarrow$ $b$ anticorrelates with ISI
  - QED $\Rightarrow$ #neutrons anticorrelates with $b$
  - #neutrons correlates with ISI
- ZDC can count #neutrons
- Correlation of $\alpha$ and #neutrons $\rightarrow$ indication of ISI
Muon pair photoproduction

- Strong neutron multiplicity dependence of $<\alpha^L_{\mu\mu}> (5.7\sigma)$ and $<M_{\mu\mu}> (\gg 5\sigma)$
- First & direct evidence for $b$ dependence of initial photon $p_T$ and energy
- Fundamental input for searching possible final-state EM interactions in QGP
- Strongest constraint on initial photon induced models
$(g - 2)_{\tau}$ measurement at LHC

- Anomalous magnetic moment: $a_\ell = \frac{(g-2)_{\ell}}{2}$
- di-$\tau$ photoproduction in PbPb UPC $\rightarrow$ Cross section scales with $Z^4$
- Cross section & tau kinematics sensitive to $a_\tau$

Phys. Rev. D 102, 113008 (2020)
Event selection

• Trigger: 1 muon + 1 track in the pixel detector + no Hadronic Forward (HF) calorimeter activity on one side
• Leading HF tower < 4 GeV
• Keeping events with exactly 3 charged pions ($N_{ch}$) and 1 muon

<table>
<thead>
<tr>
<th>Object</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>$p_T &gt; 3.5$ GeV for $</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 2.5$ GeV for $1.2 &lt;</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>$p_T &gt; 0.5$ GeV for leading $\pi^\pm$</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 0.3$ GeV for (sub-)sub-leading $\pi^\pm$</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>$\tau_{3prong}$</td>
<td>$p_T^{vis} &gt; 0.2$ GeV</td>
</tr>
<tr>
<td></td>
<td>$0.2$ GeV $&lt; m_{\pi\pi\pi} &lt; 1.5$ GeV</td>
</tr>
</tbody>
</table>
Kinematics consistent with signal
Signal yield

- Binned maximum likelihood fit on the distribution of $\Delta \phi(\tau_\mu, \tau_{3\text{prong}})$
- Postfit $N_{\text{signal}} = 77 \pm 12$
- Observation significance well above $5\sigma$

CMS-PAS-HIN-21-009
Fiducial cross section

- Efficiency ($\epsilon$) from MC = 78.5%
- $L = 404 \mu b^{-1}$
- $BR_{\mu-3\text{prong}} = 5.06\%$

$$\sigma_{\text{fiducial}} = \frac{N_{\text{signal}}}{L \times BR \times \epsilon}$$

- $\sigma_{\text{fiducial}} = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{sys}) \mu b$
Limits on $a_\tau$

- DELPHI's 68% CL limit on $a_\tau$ is $(-3.5 < a_\tau < 0.1) \times 10^{-2}$
- Using the theoretical calculation of $\sigma_{\gamma\gamma \rightarrow \tau\tau}$ as a function of $a_\tau$ this analysis puts a 68% CL limit of $(-8.8 < a_\tau < 5.6) \times 10^{-2}$
- Projected CMS limit for Runs 3+4 is $(-1.8 < a_\tau < 1.5) \times 10^{-2}$
Summary

• UPC $\gamma\gamma$ processes: test of QED & search for BSM
• Evidence ($4\sigma$) of LbyL scattering in UPC PbPb
• $<\alpha_{\mu\mu}^{LO}>$ & $<M_{\mu\mu}>$ depend on #neutron & b
• Observation of the $\tau$ pair production in HI collisions
  • Fiducial cross section of $\gamma\gamma \rightarrow \tau\tau$ & limits on $(g - 2)_{\tau}$
Backup
### Systematic uncertainties of $\tau\tau$ analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon scale factor</td>
<td>6.7</td>
</tr>
<tr>
<td>Luminosity measurement</td>
<td>5</td>
</tr>
<tr>
<td>Pion scale factor</td>
<td>3.6</td>
</tr>
<tr>
<td>MC sample size (bin by bin)</td>
<td>3.0</td>
</tr>
<tr>
<td>MC sample size (efficiency)</td>
<td>1.1</td>
</tr>
<tr>
<td>HF scale effect on background shape</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tau$ lepton branching fraction measurement</td>
<td>0.6</td>
</tr>
<tr>
<td>Effect of high $N_{ch}$ on background shape</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>9.7</td>
</tr>
</tbody>
</table>

**CMS-PAS-HIN-21-009**
Acoplanarity fits for the dimuon analysis

- Leading order: $c_0 \times e^{-\frac{\alpha}{c_1}} + c_2 \times \alpha^{0.25} \rightarrow <\alpha_{LO/Core}>

- High order: $t_0 \times \left(1 + \left(\frac{t_1}{t_2}\right) \times \alpha\right)^{-t_2}$

Neutron multiplicity with ZDC

CMS-HIN-19-014
energy resolution in barrel and endcap region

HINEGammaDPForQM22