Observation of the $\gamma \gamma \rightarrow \tau^+ \tau^-$ production in PbPb collisions with the CMS experiment

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Anomalous Magnetic Moment

- Anomalous magnetic moment: \( a_l = \frac{g_l - 2}{2} \)

- Precise measurement of Standard Model
  - Measurements of \( a_\mu \) have discrepancy with SM predictions
    - Ongoing work in theory community to improve Lattice QCD calculations
  - Deviations of \( a_l \) from SM could indicate lepton compositeness or other BSM physics
  - BSM effects are 280 times more sensitive to \( a_\tau \) compared to \( a_\mu \) due to \( \tau \) mass

https://arxiv.org/abs/2104.03281
\( \gamma \gamma \rightarrow \tau \tau \) process

- \( \gamma \gamma \rightarrow \tau \tau \) cross-section can help determine \( a_\tau \)
- Using UPC heavy Ion events means:
  - Have clean sample with few backgrounds
  - Have \( Z^4 \) photon flux enhancement
- With luminosity already achieved by LHC, measurements of \( a_\tau \) should exceed precision of DELPHI

\[
a_\tau \text{ Harvard06 (error bar } \times 10^9)\]
\[
a_\mu \text{ BNL06 (error bar } \times 10^6)\]
\[
a_\tau \text{ DELPHI04}\]
\[
a_\tau \text{ 2 nb}^{-1}, 10\% \text{ syst}\]
\[
a_\tau \text{ 2 nb}^{-1}, 5\% \text{ syst}\]
\[
a_\tau \text{ 20 nb}^{-1}, 5\% \text{ syst}\]

SM \( a_\tau^{\text{pred}} \) (error bar \( \times 10^4 \))

SMEFT \( a_\tau^{\text{pred}}, C_{\tau B} = -1 \)

\[
a_\tau = (g_\tau - 2)/2\]

https://arxiv.org/abs/1908.05180
### Tau decays

- $\tau$ has mean lifetime of $2.9 \times 10^{-13}$ s
- Will decay within millimeters of IP
- CMS detector will only see decay products of 2 tau leptons

#### Decay Channel

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>17.4%</td>
</tr>
<tr>
<td>$e^- \bar{\nu}<em>e \nu</em>\tau$</td>
<td>17.8%</td>
</tr>
<tr>
<td>$\pi^- \nu_\tau + n * \pi^0$</td>
<td>47.9%</td>
</tr>
<tr>
<td>$\pi^- \pi^+ \pi^- \nu_\tau + n * \pi^0$</td>
<td>14.6%</td>
</tr>
<tr>
<td>Other</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

\( \gamma\gamma \rightarrow \tau\tau \) candidate events at CMS

- Analysis considers events with decay \( \tau + \tau \rightarrow \mu^\pm \nu_\mu \nu_\tau + \pi^\pm \pi^\mp \pi^\pm \nu_\tau \)
- Accounts for 5% of \( \tau \) decays.
- Expect \( \sim 100 \) events after cuts with available luminosity
- Provides cleanest sample
- Lepton + 1 track events have contamination from dilepton photoproduction
- Future analysis plan to add more channels to increase precision
Identifying signal and background

- Trigger requires 1 muon with 1 hit in pixel detector and no HF activity on at least 1 side
- Offline selections are shown in table
- After Cuts only signal MC events remain
- Signal region (D) consists of 1 muon and 3 charged hadrons
- Background estimates used ABCD method
  - ABCD regions shown in figure

| Muon selection | $p_T > 3.5 \text{ GeV for } |\eta| < 1.2$ |
|----------------|----------------------------------|
|                | $p_T > 2.5 \text{ GeV for } 1.2 < |\eta| < 2.4$ |

<table>
<thead>
<tr>
<th>Pion selection</th>
<th>$p_T &gt; 0.5 \text{ GeV for the leading}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T &gt; 0.3 \text{ GeV for the (sub-)subleading}$</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
</tbody>
</table>

| $\tau_{3\text{prong}}$ selection | $p_T^{\text{vis}} > 2 \text{ GeV and } 0.2 < m_T^{\text{vis}} < 1.5 \text{ GeV}$ |
Data and MC have consistent kinematics

- Have agreement in full $\tau\tau$ system (muon and 3 prong decay + combined system)
- Monte Carlo is scaled to luminosity
Signal yield estimations

- Signal yield calculated with binned likelihood
- Discriminating variables is $\Delta \phi$
  - $\Delta \phi = |\phi_\mu - \phi_{3\text{prong}}|$
  - $\Delta \phi < \pi$ due to neutrinos
- 77 ± 12 events after fit
  - Over 5.0 $\sigma$ observed significance
Uncertainties are dominated by statistics

- Largest source of uncertainty is statistical (13%)
- Main systematic uncertainties: trigger, tracking and luminosity
- Total uncertainty 16%

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon scale factor</td>
<td>6.7</td>
</tr>
<tr>
<td>Luminosity measurement</td>
<td>5.0</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 $N_{ch}$ on background shape</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>9.7</td>
</tr>
</tbody>
</table>
Cross section measurement is consistent with SM

\[ \sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = \frac{N_{\text{sig}}}{2\epsilon L_{\text{int}}B_{\tau\mu}B_{\tau3\text{prong}}} \]

- \( L = 404\mu b \), \( B_{\tau\mu} = 17.39\% \), \( B_{\tau3\text{prong}} = 14.55\% \), \( \epsilon = 78.5\% \)
- \( \sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{sys}) \mu b \)

![Graph showing cross section vs. mass](image)

**Data**

- 4.8 ± 0.6(stat) ± 0.5(sys)μb

**References**

- L. Beresford and J. Liu, Phys.Rev.D **102** (2020) 113008
Limits on $\alpha_T$ 

- Determine $\alpha_T$ via theoretical calculation of $\sigma_{\gamma\gamma \rightarrow \tau\tau}(\delta\alpha_T)$
- With phase 2 luminosity, can match DELPHI precision

https://arxiv.org/abs/1908.05180
• Searches for BSM phenomena via UPC data in multiple collaborations at LHC
  • Cross-experiment collaboration should lead to higher precision and statistical significance
• CMS has dedicated program studying $a_\tau$
  • 2018 Results with additional channels expected early 2024
  • 2023 data have 20% more luminosity than 2018
  • 2023 Data have hadronic only triggers
Conclusion

• First observation of $\gamma\gamma \to \tau\tau$ in heavy ion collisions
• $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6\text{(stat)}\pm 0.5\text{(sys)} \, \mu b$
• 68% CL limit of $(-8.8 < a_\tau < 5.6) \times 10^{-2}$
• Projected Run 3 + 4 68% CL limit of $(-1.8 < a_\tau < 1.5) \times 10^{-2}$
• Results published in PRL: Phys. Rev. Lett. 131, 151803
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Important Sources

• CMS $\gamma \gamma \rightarrow \tau\tau$: https://arxiv.org/abs/2206.05192
• ATLAS $\gamma \gamma \rightarrow \tau\tau$: https://arxiv.org/abs/2204.13478
• Theory $\gamma \gamma \rightarrow \tau\tau$: https://arxiv.org/abs/1908.05180
• Muon G-2: https://arxiv.org/abs/2308.06230