Recent results with the CMS Precision Proton Spectrometer

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ISMD 2023, Győngyös, Hungary

August 21-26 2023

Contents

- Proton tagging at the LHC in CMS/TOTEM
- $\gamma\gamma\gamma$, $\gamma\gamma Z$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma t\bar{t}$ anomalous coupling studies
- Search for Axion-like particles
- Search for $Z+X$ and $\gamma+X$ events
Consider exclusive production of $ee, \mu\mu, WW, \gamma\gamma$, etc

Dilepton production is a QED ($\gamma$-exchange) process

In $pp$ interactions, QCD production of $\gamma\gamma$ dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$ (similar for $WW, ZZ, Z\gamma, t\bar{t}$ production)

At high masses, in $pp$ interactions, possibility to select photon-induced events by tagging protons and by measuring high mass objects in CMS/ATLAS

Pb Pb interactions: $\gamma\gamma$ exchanges enhanced by $Z^4$, measure low mass exclusive $\gamma$-induced processes ($\gamma\gamma$)
Roman pot detectors from PPS installed in the tunnel

- Good acceptance at high mass in standard runs (PPS in CMS, TOTEM-TDR-003; CMS-TDR-13)
- >100 fb$^{-1}$ collected in Run II
Quasi-exclusive $\mu\mu$ and $ee$ production in CMS-TOTEM

- Turn the LHC into a $\gamma\gamma$ collider at high luminosity: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
- The dilepton mass acceptance of PPS/AFP starts at about $\sim 400$ GeV $\rightarrow$ expect very small number of double tagged events
- The two first diagrams are signal, the last one background
Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (resp. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (resp. $ee$) channel
- Significance $> 5\sigma$ for observing 20 events for a background of 3.85 (1.49 $\pm$ 0.07(stat) $\pm$ 0.53(syst) for $\mu\mu$ and 2.36 $\pm$ 0.09(stat) $\pm$ 0.47(syst) for $ee$)
Search for quartic $\gamma\gamma\gamma\gamma$ anomalous coupling

Additional channels: $WW, ZZ, \gamma Z, t\bar{t}$

Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, axion-like particles

Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons


Search for production of two photons and two intact protons in the final state:

$pp \rightarrow p\gamma\gamma p$
Removing pile up at the LHC

- Possibility to use fast timing detectors to measure proton time of flights

**Recent results with the CMS Precision Proton Spectrometer**
First search for high mass exclusive $\gamma\gamma$ production

- Search for exclusive diphoton production: back-to-back, high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- First limits on quartic photon anomalous couplings: $|\zeta_1| < 2.9 \times 10^{-13}$ GeV$^{-4}$, $|\zeta_2| < 6.1 \times 10^{-13}$ GeV$^{-4}$ with about 10 fb$^{-1}$, accepted by PRL (2110.05916)
- Limit updates with 102.7 fb$^{-1}$: $|\zeta_1| < 7.3 \times 10^{-14}$ GeV$^{-4}$, $|\zeta_2| < 1.5 \times 10^{-13}$ GeV$^{-4}$
First search for high mass production of axion-like particles

- First limits on ALPs at high mass (CMS-PAS-EXO-21-007)
Exclusive production of $W$ boson pairs

- 2 “fat” jets (radius 0.8), jet $p_T > 200$ GeV, $1126 < m_{jj} < 2500$ GeV, jets back-to-back ($|1 - \phi_{jj}/\pi| < 0.01$)
- Signal region defined by the correlation between central $WW$ system and proton information

Search with fully hadronic decays of $W$ bosons: anomalous production of $WW$ events dominates at high mass with a rather low cross section
**WW and ZZ exclusive productions**

- **Searches performed in full hadronic decays of** $W$ **bosons (high cross section) with AK8 jets**
- SM cross section is low
- Limits on SM cross section
  $\sigma_{WW} < 67\text{fb}$, $\sigma_{ZZ} < 43\text{fb}$ for $0.04 < \xi < 0.2$ (CMS-PAS-EXO-21-014)
- New limits on quartic anomalous couplings (events violating unitarity removed) : $a_0^W/\Lambda^2 < 4.3 \times 10^{-6}$ GeV$^{-2}$, $a_C^W/\Lambda^2 < 1.6 \times 10^{-5}$ GeV$^{-2}$, $a_0^Z/\Lambda^2 < 0.9 \times 10^{-5}$ GeV$^{-2}$, $a_C^Z/\Lambda^2 < 4.0 \times 10^{-5}$ GeV$^{-2}$ with $52.9$ fb$^{-1}$
The future: Observation of exclusive $WW$ production

- SM contribution appears at lower $WW$ masses compared to anomalous couplings
- Use purely leptonic channels for $W$ decays (the dijet background is too high at low masses for hadronic channels)
- SM prediction on exclusive $WW$ (leptonic decays) after selection: about 50 events for 300 fb$^{-1}$ (2 background)
- JHEP 2012 (2020) 165, C. Baldenegro, G. Biagi, G. Legras, C.R.
**Exclusive $t\bar{t}$ production**

**dilep channel ($\tilde{t}\tilde{t} \rightarrow l\nu b + l\nu\bar{b}$)**

<table>
<thead>
<tr>
<th>Object selection</th>
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<tbody>
<tr>
<td>Leptons: $p_T&gt;30, (20)$ GeV, $</td>
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<tr>
<td>Jets: $p_T&gt;30$ GeV, $</td>
</tr>
</tbody>
</table>

**Semilep channel ($\tilde{t}\tilde{t} \rightarrow l\nu b + jj\bar{b}$)**

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<tbody>
<tr>
<td>Leptons: $p_T&gt;30$ GeV, $</td>
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<tr>
<td>Jets: $p_T&gt;25$ GeV, $</td>
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**Event selection**

<table>
<thead>
<tr>
<th>dilep channel</th>
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</thead>
<tbody>
<tr>
<td>$\geq 2$ leptons (OS pair), $</td>
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<tr>
<td>$\geq 2$ b-jets</td>
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<tr>
<td>1 proton / side</td>
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<table>
<thead>
<tr>
<th>Semilep channel</th>
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</thead>
<tbody>
<tr>
<td>$=1$ lepton</td>
</tr>
<tr>
<td>$\geq 2$ b-jets, $\geq 2$ non b-jets</td>
</tr>
<tr>
<td>1 proton / side</td>
</tr>
</tbody>
</table>
Exclusive $t\bar{t}$ production

- Kinematic fitter based on $W$ and $t$ mass constraints to reduce background

- Search for exclusive $t\bar{t}$ production in leptonic and semi-leptonic modes
  \[ \sigma_{t\bar{t}}^{\text{excl.}} < 0.59 \text{ pb} \] (CMS-PAS-TOP-21-007)
Search for $Z + X$ events: use total mass reconstructed using intact protons, allows obtaining the mass of $Z + X$, $X$ might be not reconstructed, or decaying resonance

No signal found but should be redone with higher lumi (CMS-PAS-EXO-21-009)
Conclusion

- LHC can be seen as a $\gamma\gamma$ collider! Lead to extremely clean events where all particles in the final state are measured, like at LEP
- First sensitivities to quartic $\gamma\gamma\gamma\gamma$ anomalous couplings at high diphoton mass and to ALP production
- First sensitivities to $\gamma\gamma ZZ$, $\gamma\gamma WW$, $\gamma\gamma t\bar{t}$ anomalous coupling and sensitivities expected to increase by more than one order of magnitude at Run III also using new detectors (timing detectors as an example) - SM observation possible in Run III
- $\gamma\gamma Z$ anomalous coupling studies to be performed in CMS: very clean events, easy triggers
Summary of 20 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that are double tagged: The two dielectron events in the acceptance region are compatible with pile up contamination (2.36 events expected)
- Highest mass event: 917 GeV
- JHEP 1807 (2018) 153
Search for axion like particles: complementarity with heavy ion runs

- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to $pp$ running
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$ couplings in $pp$ collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142
$\gamma \gamma \gamma Z$ quartic anomalous coupling: leptonic and hadronic decays of $Z$ boson

- Best expected reach at the LHC by about three orders of magnitude
- Sensitivity to wide/narrow resonances, loops of new particles

<table>
<thead>
<tr>
<th>Coupling (GeV$^{-1}$)</th>
<th>$\zeta$ ($\zeta = 0$)</th>
<th>$\zeta = \zeta$</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>300 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>Pile-up ($\mu$)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Channels</td>
<td>$\ell\ell\gamma$</td>
<td>$jj\gamma$</td>
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<tr>
<td></td>
<td>$2.8 \cdot 10^{-13}$</td>
<td>$2.3 \cdot 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>95% CL</td>
<td>1.8 $\cdot 10^{-13}$</td>
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<tr>
<td></td>
<td>$5 \sigma$</td>
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</tr>
<tr>
<td></td>
<td>95% CL</td>
<td>$1.5 \cdot 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>$j\gamma \oplus \ell\ell\gamma$</td>
<td>$1.93 \cdot 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>1.2 $\cdot 10^{-13}$</td>
<td>1.7 $\cdot 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>$1 \cdot 10^{-13}$</td>
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</table>
Search for $\gamma\gamma t\bar{t}$ anomalous coupling in semi-leptonic decays with 300 fb$^{-1}$

Use similar selection: high $t\bar{t}$ mass, matching between $pp$ and $t\bar{t}$ information

Use fast timing detectors to suppress further the pile up background


<table>
<thead>
<tr>
<th>Coupling $[10^{-11}$ GeV$^{-4}]$</th>
<th>95% CL</th>
<th>5$\sigma$</th>
<th>95% CL (60 ps)</th>
<th>5$\sigma$ (60 ps)</th>
<th>95% CL (20 ps)</th>
<th>5$\sigma$ (20 ps)</th>
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<tbody>
<tr>
<td>$\zeta_1$</td>
<td>1.5</td>
<td>2.5</td>
<td>1.1</td>
<td>1.9</td>
<td>0.74</td>
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<td>$\zeta_2$</td>
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<td>0.70</td>
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<td>$\zeta_3$</td>
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<td>0.70</td>
<td>1.4</td>
</tr>
<tr>
<td>$\zeta_4$</td>
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<td>2.5</td>
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<td>1.4</td>
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<tr>
<td>$\zeta_5$</td>
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<td>0.84</td>
<td>1.5</td>
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<td>$\zeta_6$</td>
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<td>0.92</td>
<td>1.6</td>
<td>0.66</td>
<td>1.3</td>
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