LHC Seminar

New physics results with the CMS Precision Proton Spectrometer

24 May 2022

Michael Pitt (CERN)
On behalf of the CMS and TOTEM Collaborations
Outline

- Physics with the PPS
- Experimental apparatus
- Results from Run 2
- Looking forward

*di-lepton (June 2018)*

*PPS Performance (March 2022)*

*WW/ZZ (March 2022)*

*ttbar (March 2022)*

*Di-photon (Sep 2020, Today)*

*ZX/γX (March 2022)*
Physics with the PPS
In typical $pp$ collisions at the LHC:

- Protons dissociate into multiparticle states
Introduction

- In typical $pp$ collisions at the LHC:
  - Protons dissociate into multiparticle states
  - A large number of energetic particles are produced
Introduction

- In rare cases:
  - Protons remain intact (tagged by PPS)
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- Low track activity due to exchange of color singlets via QCD (Pomeron) or QED ($\gamma$)
In rare cases:

- Protons remain intact (tagged by PPS)
- Low track activity due to exchange of color singlets via QCD (Pomeron) or QED (γ)
High mass range is dominated by photon-photon interactions
Photon-Photon fusion in $pp$ collisions:

- In Central Exclusive production (CEP) processes:
  
  **Central system** kinematics = **Proton** kinematics

- For given proton momentum loss $\xi = \Delta p/p$:

  Proton kinematics can be inferred from the central system:

  \[ \xi_{\pm} = \frac{\sum E_{\pm} p_z}{\sqrt{s}} \]

  Central system kinematics can be inferred from the protons:

  \[ m = \sqrt{s \xi_+ \xi_-} \]

  \[ Y = \frac{1}{2} \log \left( \frac{\xi_+}{\xi_-} \right) \]
Central exclusive production processes:

- Allows exploring the Electro-Weak sector in a new phase-space
  
  For example: $\gamma\gamma \rightarrow ll$ contributes to high $m(ll)$ spectra

- Opens a door to search new physics
  
  For example: $\gamma\gamma \rightarrow \gamma\gamma$ search for ALPs
Experimental apparatus
The Precision Proton Spectrometer (PPS)

- CMS+TOTEM expertise: PPS TDR (TOTEM-TDR-003)
- Operated in standard LHC runs since 2016
- Located ~ 200m from the CMS interaction point in both arms, equipped with tracking/timing detectors
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• A set of near-beam detectors, which approach the beam down to a few mm

*PPS is the farthest and, at the same time, the closest CMS subsystem*
Proton kinematics:

- Intact protons lose a fraction of momentum ($\xi = \Delta p/p$) and are scattered at small angles ($\theta_x^*, \theta_y^*$) → they deflected away from the beam and measured by PPS

$$
\begin{align*}
\delta x(z) &= x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta_x^* \\
\delta y(z) &= y_D(\xi) + v_y(\xi)y^* + L_y(\xi)\theta_y^*
\end{align*}
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Rapid detector evolution since commissioning in 2016!

2016: PPS inherits from TOTEM Silicon strip tracker (used in special runs, cannot resolve multiple tracks)
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2017: 3D Silicon pixels - a suitable detector technology was developed, and half of the stations were upgraded
Rapid detector evolution since commissioning in 2016!

2016: PPS inherits from TOTEM Silicon strip tracker (used in special runs, cannot resolve multiple tracks)

2017: 3D Silicon pixels - a suitable detector technology was developed, and half of the stations were upgraded

2018: Both stations per arm are equipped with 3D pixel detectors
Challenges in the standard LHC runs:

- Efficiency drop due to irradiation
- Higher $x$ -> Higher $\xi$ -> Higher minimal accepted mass

$$\int L dt = 0 \text{ fb}^{-1}$$
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- Detectors were shifted during LHC Technical Stops (TS) by 0.5mm

\[
\int \mathcal{L} dt = \begin{cases} 
0 \text{ fb}^{-1} & \text{TS} \\
\sim 21 \text{ fb}^{-1} & \text{TS}
\end{cases}
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$$\int L dt = \begin{array}{c} 0 \text{ fb}^{-1} \quad \text{TS} \quad \sim 21 \text{ fb}^{-1} \quad \text{TS} \quad \sim 50 \text{ fb}^{-1} \quad \sim 58 \text{ fb}^{-1} \end{array}$$
Challenges in the standard LHC runs:

- Efficiency drop due to irradiation
- Higher $x \rightarrow$ Higher $\xi \rightarrow$ Higher minimal

$350 \text{ GeV} < m_x < 2 \text{ TeV}$

$\int \mathcal{L} dt = 0 \text{ fb}^{-1} \quad \text{TS} \quad \sim 21 \text{ fb}^{-1}$
- Vertex z-coordinate is reconstruction using ToF:
  \[ V_{Z,PPS} = \frac{c}{2} (t_{PPS_1} - t_{PPS_2}) \]

- Diamond detectors technology was used with 2018 data with <50ps resolution per plane for DD.
Alignment (2 steps):
- Global alignment – performed in special runs (2-3 bunches / beam), vertical detectors are used, PPS position w.r.t. the beam
- Local alignment – match distribution of proton tracks from physics run to that of the alignment run (fill-by-fill)

Optics:
- Optical functions validated in data

\[ L_Y(\xi_0) = 0 \]
Tracking:
- Using (semi)-exclusive di-muon sample
- Compare $\xi$(CMS) vs $\xi$(PPS)
- A few% resolution(!!!)

Timing:
- Using central diffractive events in $\mu$~1 sample
- Compare $Z$(PV) vs $Z$(PPS)
- All track resolution: $\sigma_z = 2.77 \pm 0.17 cm$

Validation of the calibration sequence
Physics results from Run 2
Physics results from Run 2

- PPS analyses cover many physics groups (Top physics, Standard Model, Exotic searches)

PPS commissioning

2016

JHEP 07 (2018) 153

July 2018

CMS-PAS-EXO-18-014

Sep 2020

CMS-PAS-EXO-21-007

March 2022

Today

CMS-PAS-SMP-21-014
CMS-PAS-TOP-21-007
CMS-PAS-EXO-19-009
Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process

**Signal**

**Background**

- pileup proton

**CMS+TOTEM Simulation, $\sqrt{s} = 13$ TeV**

**No additional radiation**
Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process

**Signal**

**Background**

- pileup proton

**Drell-Yan**
Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process
- PPS selects a clean sub-sample of signal events:

\[ \xi_\pm = \frac{1}{\sqrt{s}} [p_T(l_1) e^{\pm \eta(l_1)} + p_T(l_2) e^{\pm \eta(l_2)}] \]

20 Total events observed (12\(\mu\mu\), 8ee)
Estimated 4 Background (1.5±0.6\(\mu\mu\), 2.4±0.6 ee)
Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process
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(Semi)-exclusive di-muons used to calibrate PPS performance
Exclusive production of weak bosons

- Exclusive WW production is the second most common CEP process
- Sensitive to TGC and QGC
- QGC enhance high mass spectra
- Run 1 results w/o proton tagging:
  - JHEP 08 (2016) 119
- QGC probed in WW same-sign (PLB 809 (2020) 135710) and VBS WW (2205.05711)
Exclusive production of weak bosons (WW/ZZ)

- Search with fully hadronic vector boson decays with 2 tagged protons with 100fb⁻¹
- Signal region defined based on the correlation between central system and tagged protons

Event Selection

At Least two V-tagged AK8 jets
- Jet pT > 200 GeV, |η|<2.5
- |Δηjj|<1.3, 1126<mjj/GeV<2500
- Jet1 pT / jet2 pT < 1.3, |1-φjj/π|<0.01
Exclusive production of weak bosons (WW/ZZ)

- Background dominated by inclusive QCD dijet production
- Estimated using the ABCD method – \( N_A = N_B \cdot N_C / N_D \)
Exclusive production of weak bosons (WW/ZZ)

- Background dominated by inclusive QCD dijet production
- At high mass, SM cross-sections are very small.
- The obtained limit on SM fiducial cross-section:
  \( \sigma_{WW} < 67 \text{fb} \) and \( \sigma_{ZZ} < 43 \text{fb} \) for \( 0.04 < \xi < 0.2 \) and \( m > 1 \text{TeV} \)
- Limits on EFT operators were extracted

- Limit on \( \gamma\gamma WW \) is 15-20 times more stringent than Run1
- Competitive with the inclusive VBS measurements
- First limit on \( \gamma\gamma ZZ \) coupling

\[
\begin{align*}
|a_0^W / \Lambda^2| &< 4.3 \times 10^{-6} \text{ GeV}^{-2} \\
|a_0^Z / \Lambda^2| &< 1.6 \times 10^{-5} \text{ GeV}^{-2} \\
|a_0^{\gamma / 2} / \Lambda^2| &< 0.9 \times 10^{-5} \text{ GeV}^{-2} \\
|a_0^{\gamma / 2} / \Lambda^2| &< 4.0 \times 10^{-5} \text{ GeV}^{-2}
\end{align*}
\]
Exclusive production of top quark pairs

- Searched in di-lepton and semi-leptonic \( \text{ttbar} \) decay mode.

[Image of a diagram showing protons, b-tagged jets, light jets, and a muon.]
- Exclusive production of top quark pairs
  - Searched in **di-lepton** and **semi-leptonic** ttbar decay mode.

<table>
<thead>
<tr>
<th><strong>dilep channel</strong> ($\bar{t}t \rightarrow l\nu b + l\nu \bar{b}$)</th>
<th><strong>Semilep channel</strong> ($\bar{t}t \rightarrow l\nu b + jj \bar{b}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object selection</strong></td>
<td><strong>Object selection</strong></td>
</tr>
<tr>
<td>Leptons: pT&gt;30(20)GeV,</td>
<td>$\eta</td>
</tr>
<tr>
<td>Jets: pT&gt;30GeV,</td>
<td>$\eta</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Event selection</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>≥2 leptons (OS pair),</td>
</tr>
<tr>
<td>≥2 b-jets</td>
</tr>
<tr>
<td>1 proton / side</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>
Exclusive production of top quark pairs

- Searched in di-lepton and semi-leptonic ttbar decay mode.
- Challenging due to huge background rate
- PU protons from data added to MC Simulation
• Semi-leptonic analysis relies on kinematic-fitter:
  
  • Use $t/W$ mass constraints to minimize
    \[ \chi^2 = \sum_{i=1}^{6} \frac{(p_{x,i} - p_{x,i,\text{initial}})}{\sigma_{x,i}} + \sum_{i=1}^{6} \frac{(p_{y,i} - p_{y,i,\text{initial}})}{\sigma_{y,i}} + \sum_{i=1}^{6} \frac{(p_{z,i} - p_{z,i,\text{initial}})}{\sigma_{z,i}} + \sum_{j=1}^{2} \frac{(\xi_j - \xi_{j,\text{initial}})}{\sigma_{\xi,j}} \]

  • The output of the kinematic-fitter used as a discriminating variable.
• Exclusive production of top quark pairs
  - Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events
Exclusive production of top quark pairs

- Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events
- Results were interpreted as an upper limit of the CEP of top quark pairs

Excluded Xsec of CEP ttbar above 0.6 pb
Light-by-light scattering

- Motivated by sensitivity to BSM:
  

- Almost background free after requiring matching between proton and photon kinematics

- First measurement with 2016 (~10fb\(^{-1}\)) publish the first limit on 4-photon coupling!

\[
|\zeta_1| < 2.9 \times 10^{-13} \text{ GeV}^{-4} (\zeta_2 = 0) \\
|\zeta_2| < 6.0 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0)
\]
• The full Run 2 data – low background

![Graph](image1)

• Limit on 4-photon coupling improved by x4(!)

\[
|\zeta_1| < 7.3 \times 10^{-14} \text{ GeV}^{-4} (\zeta_2 = 0)
\]

\[
|\zeta_2| < 1.5 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0)
\]

First search for ALPs in mass range between 500 GeV to 2000 GeV
- Searching for unknown particles using the "missing mass"
  - Implemented for the first time in hadron collider, based on $4\pi$ event reconstruction
Searching for unknown particles using the “missing mass”

- Implemented for the first time in hadron collider, based on $4\pi$ event reconstruction
- The 4-vector of unknown state $\chi$ is determined from protons and measured boson

$$m_{\text{miss}}^2 = \left[ (P_{1}^{\text{in}} + P_{2}^{\text{in}}) - (P_{V} + P_{1}^{\text{out}} + P_{2}^{\text{out}}) \right]^2$$

- Bump hunt of mass of $\chi$ state is performed in $Z+\chi$ and $\gamma+\chi$ channels
Searching for unknown particles using the “missing mass”

- Benefit from supreme mass resolution
• Searching for unknown particles using the “missing mass”
  • Benefit from supreme mass resolution
  • Data agree with the background-only model, a limit on the production cross-section of $Z/\gamma+\chi$ was derived
Looking forward
Several detector upgrades are taking place

- Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of $< 30$ ps ($<1$ cm vertex resolution) $\times 10$ less background
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- Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of $< 30 \text{ ps} (<1 \text{ cm vertex resolution}) \times 10$ less background
- New Silicon pixel tracker with internal motion Efficiency to lower $\xi$
Several detector upgrades are taking place

- Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of < 30 ps (<1 cm vertex resolution) \( \times 10 \) less background
- New Silicon pixel tracker with internal motion Efficiency to lower \( \xi \)
- Dedicated HLT line with proton tag for hadronic WW / multijet events

While \( \mathcal{L} \rightarrow x^2 \), sensitivity to searches will increase by \( \sim 4-5 \), due to improved acceptances (tracking) and background rejection (timing)
Several detector upgrades are taking place:

- PPS Will continue to operate in Run 3
- By the end of Run 3, PPS will be dismounted
- Since after LS3 the whole beamline will be rearranged, a new spectrometer design is proposed
- HL-LHC PPS research proposal: CMS-NOTE-2020-008

While $\ell \to \ell \ell$, sensitivity to searches will increase by ~4-5, due to improved acceptances (tracking) and background rejection (timing).
New proposal with extended mass range:

- 133 GeV – 2.7 TeV for the first 3 stations
- 43 GeV – 2.7 TeV for all stations

Run 2+3 acceptance between 350 and 2 TeV

Extends current LHC physics program (WW, di-τ, top, ALPs, SUSY, etc...)

Staged installation
Summary

- **Run 2:**
  - First set of results delivered by CMS using the PPS sub-detector
  - Many more analysis are in progress

- **Run 3:**
  - Expecting increase in sensitivity by factor 4-5(!!!)
  - High expectation from Run 3 results

- **HL-LHC:**
  - Feasibility studies are ongoing in context of a TDR

**Stay tuned for more new exiting results**
Backup
Exclusive production of top quark pairs

- Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events

15 variables used in MVA:

- The mass and the rapidity of the central system reconstructed both from the tt decay products and from proton kinematics
- Missing energy, the number of light-flavour jets
- The invariant mass and the angular distance ΔR of the two leptons
- |Δφ| of the two selected b-tagged jets
- the rapidity of the system formed by the two b-jets and the two leptons, and the sum of the absolute values of their individual rapidities
- the rapidity of the system formed by all other reconstructed jets, and the sum of the absolute values of their individual rapidities
- the squared energy sum for all objects used for the tt reconstruction
- the minimum absolute value of the rapidity difference for any two systems formed by a lepton and a b-tagged jet
Exclusive production of top quark pairs

- Multivariate Analysis (MVA) approach developed to tag exclusive tt\(\bar{t}\) events

10 variables used in MVA:
- Number of light-flavour jets and of b-tagged jets
- Sum of the invariant mass of all jets
- Total energy of all lightflavour jets
- Mean \(\Delta R\) for all pairs of light-flavour jets
- Total energy of all extra jets (not used for tt reconstruction)
- Lepton momentum and its isolation
- Difference in central system rapidity reconstructed from the tt and the pp systems
- \(\chi^2\) of the kinematic fit
(Elastic) Photon-Photon collisions at the LHC:

\[
\frac{dN_X}{dt} = \int \hat{\sigma}_{\gamma\gamma \rightarrow X} \frac{d\mathcal{L}_{\text{eff}}}{dm} \, dm
\]

Photon energy is related to charge size:

- Transverse momentum
  \[ k_\perp < \frac{1}{R} \] (0.06GeV for Pb, 0.3GeV for p)
- Longitudinal momentum
  \[ E < \frac{\gamma}{R} \] (80GeV for Pb, 2TeV for p)

Photon fluxes are harder in pp collisions
**PPS in HL-LHC**

- **Electro-weak physics:**
  - Exclusive WW gives stringent constraints on new physics
  - Exclusive di-tau to constrain electromagnetic moments

- **TOP physics:**
  - Near-threshold production of ttbar (although Xsec~0.1fb)

- **BSM physics:**
  - Best sensitivity to ALPs
  - SUSY program is complementary to LHC searches
Exclusive production of weak bosons (WW/ZZ)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Observed (expected) 95% CL upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>f_{M,0}/\Lambda^4</td>
</tr>
<tr>
<td>$</td>
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<tr>
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o Light-by-light scattering
  • Motivated by sensitivity to BSM:

  • Almost background free after requiring matching between protons and photons

First limit on 4-photon coupling!

\[ \mathcal{L}_{4\gamma} = \zeta_1 F_{\mu
u} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}. \]

\[ \frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2s} \left( s^2 + t^2 + st \right)^2 \left[ 48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2 \right] \]
The full Run 2 data – event selection

Table 3: A summary of the selection regions defined in the text.

<table>
<thead>
<tr>
<th>Region</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double photon HLT</td>
<td>$p_T^\gamma &gt; 75$ (100) GeV for 2016 (2017-2018) $H/E &lt; 0.10$</td>
</tr>
<tr>
<td>Preselection</td>
<td>MVA WP90 photon ID with electron veto</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Exclusive selection</td>
<td>$a &lt; 0.0025$</td>
</tr>
<tr>
<td>$\xi \in$ PPS</td>
<td>$0.02 &lt; \xi^\pm_{\gamma\gamma} &lt; 0.20$</td>
</tr>
<tr>
<td>Asymmetric $\xi$ acceptance</td>
<td>$0.035 &lt; \xi_{PPS} &lt; 0.15$ (0.18) for sector-45 (sector-56)</td>
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</table>
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