CMS TOTEM Precision Proton Spectrometer

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On behalf of CMS and TOTEM collaborations
Outline

- Introduction
- Physics Motivation
- Detectors
- Project planning and summary
CMS-TOTEM Precision Proton Spectrometer:

A new tool increasing the CMS potential in the search for New Physics

CMS-TOTEM Memorandum of Understanding: CMS and TOTEM jointly undertake the PPS project

CT-PPS project approval: CERN Research Board, December 2014
Physics motivations

**LHC as a photon-photon collider**

- Measure $\gamma \gamma \rightarrow W^+W^-, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
- Search for AQGC with high sensitivity
- Search for SM forbidden $ZZ\gamma\gamma, \gamma\gamma\gamma\gamma$ couplings

**LHC as a gluon-gluon collider**

- Test of pQCD mechanisms of exclusive production.
- Gluon jet samples with small component of quark jets

**Search for new physics**

- Clean events (no underlying pp event)
- Independent energy-momentum measurement by pp system
- Search for new resonances and invisible states
Physics motivations ...

CEP : \[ p \ p \rightarrow p \ p \ X \] (central exclusive production)

where \( X \) is a state measured in the central detector

\[ X = \text{high } E_T \text{ jets, } Z, \ WW, \ ZZ, \ldots \]

\( i, j = \text{photon or gluon exchanges} \)

Four-momentum of \( X \) is fully constrained by the two protons kinematics:

- \( \xi \) – proton fractional momentum loss
- \( t \) – 4-momentum transferred squared
Beam line region

Collimators TCL 4 & TCL 6 in 4-5 and 5-6
Electrical patch panel
Service lines for LV/HV/DAQ
CT-PPS specific:
- 2 * RP box with RF shield in 4/5
- 2 * RP box with RF shield in 5/6
- 1 * RP cylinder in 4/5
- 1 * RP cylinder in 5/6
Beam line region ...

26 Roman Pots: the largest Roman Pot system ever operated at a collider
CT-PPS concept:

1) Proton spectrometer making use of machine magnets
2) Two tracking stations with 3D pixel detectors
3) One station with 10 ps timing detectors

Use timing to reject pileup background
- time difference of two protons is correlated to collision vertex
Main experimental issues

• Physics performance at high luminosity ($2.10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
  – pileup background, beam background

• Detector operation close to the LHC beam
  – RF impedance, showers originated in the detectors

• Radiation levels
  – in detectors and front-end electronics

• Timing detectors
  – challenge is 10 ps resolution and high rates

• Tracking detectors
  – challenge is fluence $5.10^{15} \text{ protons.cm}^{-2}$ (100 fb$^{-1}$)
Acceptance $\xi$-t ellipses in x-y detector plane

- Particle gun ($t, \xi, \phi$) based on HECTOR at $\sqrt{s} = 13$ TeV

Horizontal distance to beam center in the z-range of the PPS detectors
Mass acceptance and resolution

- Mass acceptance and resolution vs $M_x$
- PPS selects exclusive systems in 300-1700 GeV range ($\varepsilon > 5\%$)
- At 15\(\sigma\) acceptance larger by a factor of two (wrt 20\(\sigma\)) for lower masses
- Mass resolution $\sim 1.5\%$ at 500 GeV
Physics prospects

- Study of quartic gauge couplings
- CEP: WW pair production
- Triple (WWγ) and quartic (WWγγ) gauge couplings

Measurements of the quartic WWγγ coupling can show deviations from the SM
**Study of** $pp \rightarrow pWWp$:  
- W in the central detector and “nothing” else (protons are intact)  
- Exclusive production of W pairs via photon exchange: QED process

**Background sources:**  
- Inclusive WW, ttbar, W+jets processes  
- $\tau\tau$ pairs produced via the Drell-Yan process  
- Exclusive two photon processes: $\gamma\gamma \rightarrow \tau\tau$  
- WW production from single diffractive interactions  
- WW$\rightarrow$WW scattering (vector boson fusion)

**Events:**  
WW pair in the central region, leading protons in the PPS

**SM observation of WW events**

**Anomalous coupling study**  
- AQGCs predicted in BSM theories (Parameters: $a^W_0/\Lambda^2$ and $a^W_c/\Lambda^2$, with $\Lambda$ a new physics scale)
Different flavor dilepton decay channel:
\[ \gamma \gamma \rightarrow W^+ W^- \rightarrow \mu^\pm e^\mp \nu \bar{\nu} \]

**Selection:**
- Opposite sign leptons, with \( p_T > 20 \) GeV and \(|\eta| < 2.4\), matched to common primary vertex
- No extra tracks associated to the dilepton vertex
- Dilepton invariant mass greater than 20 GeV

**SM signal region:**
\[ p_T(\mu e) > 30 \) GeV

**AQGCs search:**
- 2 bins: \( p_T(\mu e) = 30-130 \) GeV
\[ p_T(\mu e) > 130 \) GeV
WW production: results

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>All backgrounds</th>
<th>Inclusive WW</th>
<th>$\gamma\gamma\rightarrow\tau\tau$</th>
<th>DY$\rightarrow\tau\tau$</th>
<th>Diff. WW</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3±0.1</td>
<td>3.5±0.5</td>
<td>2.0±0.4</td>
<td>0.9±0.2</td>
<td>0</td>
<td>0.1±0.1</td>
<td>0.5±0.2</td>
</tr>
</tbody>
</table>

Number of expected signal and background events

13 events are observed in data

SM prediction: 6.9 ± 0.6 fb

Observed significance above the background-only hypothesis: 3.6σ

$$\sigma(pp \rightarrow p^(*) W^+ W^- p^(*) \rightarrow p^(*) \mu^+ e^- p^(*) ) = 12.3^{+5.5}_{-4.4} \text{ fb}$$

Two orders of magnitude improvements over LEP/Tevatron
CEP production of W pairs with CT-PPS

- Exclusive WW
  - quartic gauge boson coupling \( WW\gamma\gamma \)
  - Sensitivity to anomalous couplings

- Exclusive dijets
  - High jet \( p_T \) events (\( M_{jj} \) up to \( \sim 400-500 \) GeV)
  - Test of pQCD mechanism of exclusive production
Study of WW production

• Study of process: $pp \rightarrow pWWp$
  – Exclusive production of W pairs via photon exchange at 13 TeV

• Events: W pair in central detector, intact protons detected in CT-PPS
  Study only $\mu\mu$ final state

• Two steps:
  1. SM observation of WW events
     • $\sigma_{WW}=95.6$ fb
  2. Study of anomalous coupling
     • Two points: $a_0^W/\Lambda^2=5\times10^{-6}$, $a_C^W/\Lambda^2=5\times10^{-6}$
Kinematical distributions

- SM vs AQGC
  Missing mass distributions provide a very clear separation of AQGC events

- \( \gamma\gamma \rightarrow W^+W^- \), SM
- Misreconstructed \( \gamma\gamma \rightarrow W^+W^- \), SM
- \( \gamma\gamma \rightarrow \tau^+\tau^- \times 10 \)
- Inclusive \( W^+W^- \)
- \( \gamma\gamma \rightarrow W^+W^- \), \( a_W^0/\Lambda^2 = 5 \times 10^{-6} \text{ GeV}^2 \), \( a_W^C/\Lambda^2 = 0 \)

- Central detector
- Dilepton \( p_T \)
- Leading lepton \( p_T \)
- Missing mass

30 Sept. 15

M. Khakzad, METU-IPM conference
Yields (in fb)

- Select WW events
- Apply central lepton and PPS acceptance cuts
- Additional timing and track multiplicity cuts
- Numbers in parenthesis are for time resolution of 30 ps

<table>
<thead>
<tr>
<th>Selection</th>
<th>exclusive WW</th>
<th>exclusive WW (incorrectly reconstructed)</th>
<th>inclusive WW</th>
<th>exclusive $\tau\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>generated $\sigma \times B(WW \rightarrow e\mu \nu\bar{\nu})$</td>
<td>0.86±0.01</td>
<td>N/A</td>
<td>2537</td>
<td>1.78±0.01</td>
</tr>
<tr>
<td>$\geq$ 2 leptons ($p_T &gt; 20$ GeV, $\eta &lt; 2.4$)</td>
<td>0.47±0.01</td>
<td>N/A</td>
<td>1140±3</td>
<td>0.087±0.003</td>
</tr>
<tr>
<td>opposite sign leptons, “tight” ID</td>
<td>0.33±0.01</td>
<td>N/A</td>
<td>776±2</td>
<td>0.060±0.002</td>
</tr>
<tr>
<td>dilepton pair $p_T &gt; 30$ GeV</td>
<td>0.25±0.01</td>
<td>N/A</td>
<td>534±2</td>
<td>0.018±0.001</td>
</tr>
<tr>
<td>protons in both PPS arms (ToF and TRK)</td>
<td>0.055 (0.054)±0.002</td>
<td>0.044 (0.085)±0.003</td>
<td>11 (22)±0.3</td>
<td>0.004±0.001</td>
</tr>
<tr>
<td>no overlapping hits in ToF + vertex matching</td>
<td>0.033 (0.030)±0.002</td>
<td>0.022 (0.043)±0.002</td>
<td>8 (16)±0.2</td>
<td>0.003 (0.002)±0.001</td>
</tr>
<tr>
<td>ToF difference, $\Delta t = (t_1 - t_2)$</td>
<td>0.033 (0.029)±0.002</td>
<td>0.011 (0.024)±0.001</td>
<td>0.9 (3.3)±0.1</td>
<td>0.003 (0.002)±0.001</td>
</tr>
<tr>
<td>$N_{\text{tracks}} &lt; 10$</td>
<td>0.028 (0.025)±0.002</td>
<td>0.009 (0.020)±0.001</td>
<td>0.03 (0.14)±0.01</td>
<td>0.002±0.001</td>
</tr>
</tbody>
</table>

$S/B \sim 1$
Potential enhancement of sensitivity with close approach:
- Signal yield increases by a factor of two going from 15σ to 10σ
- Background is almost flat
AQGC expected limits

Expected limits @95%CL:

with CT-PPS, 13 TeV, 100 fb$^{-1}$

\[
\frac{a_0^W}{\Lambda^2} = 2 \times 10^{-6} \quad (3 \times 10^{-6}) \quad \text{GeV}^{-2} \\
\frac{a_C^W}{\Lambda^2} = 7 \times 10^{-6} \quad (10 \times 10^{-6}) \quad \text{GeV}^{-2}
\]

Observed limits @95%CL:

CMS Run 1, 8 TeV, 20 fb$^{-1}$

\[
\frac{a_0^W}{\Lambda^2} < 1.0 \times 10^{-4} \quad \text{GeV}^{-2} \\
\frac{a_C^W}{\Lambda^2} < 3.4 \times 10^{-4} \quad \text{GeV}^{-2}
\]

Two orders of magnitude improvement is expected.
CT-PPS Detectors
Options considered:
- Roman Pots (RP) developed by TOTEM
- Movable Beam Pipe (MBP)

Main goals:
- Establish Roman Pot insertions for physics operation in regular fills from 2016
- Install detectors for run in 2016 and beyond

RP insertion commissioning:
- RP insertions at low $\beta^*$ and highest beam intensities are being tested in the exploratory phase in 2015.
Tests of TOTEM RPs at high luminosity revealed important issues (vacuum, beam dumps, heating).

Several improvements have been carried by TOTEM (and CMS):

- New RF shielding in standard box-shaped RPs
- New cylindrical RP for timing detectors
- 10 um thick copper coating
- New ferrites
Tracking detectors

- 3D silicon sensors
- PSI46dig ROC, with same readout scheme as for Phase I Upgrade of the CMS pixel system
  - existing CMS DAQ components and software can be reused
- 6 detector planes per station
  - detectors are tilted in one direction
  - number of planes provide adequate redundancy
3D sensors – wafer layout in production

Wafer thickness 230 $\mu$m

FZ HR <100> silicon
p-type $N=10^{12}$ atm/cm$^3$
p-stop isolation

- 6 detectors 2x3          4         2
- 4 detectors 2x2          2         2
- 8 detectors 2x1          5         3
- 4 single chip               3         1
- Diodes                        6         6

With the first 12 wafers:
- 48 sensors 2x3 & 2E
  and we need 24

In case of problems we could still mount 2x2 sensors (+ 2x1 sensors)
Quartic detector:

- Detector is a 4 x 5 array of quartz bars, 3 x 3mm², SiPM light detection.
- Two such modules in one Roman pot in each arm.
- Radiator bars separated by 100 μm for total internal reflection
- Beam tests achieved σ(t) = 30 ps/module (~ 20 ps for 2-in-pot)
GasTOF system  
- prototype for test beam was ready  

Diamond detectors  
- effort led by TOTEM  
- demonstrated 50 ps with 4 planes  

Silicon detectors  
- Fast Silicon Detectors (UFSD):  
  - 60 ps with new prototypes (laser)  
- Plan to exploit Avalanche PhotoDiodes as charged particle timing detectors (Hyperfast Silicon)
• The CT-PPS plan includes an **exploratory phase** in 2015-16 followed by a **production phase**.

• **Exploratory phase (2015-16):**
  Show that CT-PPS does not prevent the stable operation of the LHC beams and does not affect significantly the luminosity performance of the machine.
Test beam setup

H8C Beam

SPS beam:
- E=180 GeV protons
- Divergence: 40-250 μrad
- Rate 5-10KHz/cm²/spill

Tracker externally triggered by Scint-1 and Scint-2 (trigger area ~2 x 2 cm²)

- Quartic:
  - Integration of two Quartics in the RPs
  - 1st test of readout chain
    SiPM [ high radiation] + (Nino + HPTDC)

- GasTof: Cherenkov detector
  MCP-PMT + (Nino + HPTDC)

RP+2Quartics  Two Quartics  GasTOF  MCP

30 Sept. 15
– The addition of small high precision tracking and timing detectors to CMS together with the TOTEM Collaboration, CT-PPS opens up a new field of physics.
– Forward proton tagging allows physics in a LEP like environment:
  • photon-photon and gluon-gluon interactions at precisely known center-of-mass energy
  • no underlying pp event
– Rich physics program with emphasis in the search for New Physics:
  • sensitivity to anomalous gauge couplings is increased by two orders of magnitude
  • search for new resonances and invisible states
– Big experimental challenges are being addressed:
  • operation of Roman Pots at the highest LHC luminosity
  • pileup mitigation using timing detectors with 10 ps resolution
  • 3D pixels tracking at very large particle fluence
– Aim for physics in 2016, run to LS2 and possibly beyond.
Thank you