

The CMS-TOTEM Precision Proton Spectrometer and first physics results

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CT-PPS is a joint CMS-TOTEM project

beam line, at \pm ~200 m from the CMS interaction point

• two tracking stations and one timing station per side

proton beam \Rightarrow detectors approaching the beam at ~1 mm

Designed to operate continuously at standard LHC running conditions

The CT-PPS project



- Detectors located in TOTEM horizontal roman pots (+ new dedicated ones) along the LHC
- Detects intact protons emerging from the IP and driven by LHC magnets in proximity of the











The CT-PPS physics program

Main target of the CT-PPS physics program is the study of Central Exclusive Production (CEP) processes, where both protons remain intact and get detected in the roman pots. Electroweak physics ("vy collider") =

- dilepton/diboson production: $\gamma\gamma \rightarrow W+W-$, $\ell+\ell \rightarrow search$ for anomalous quartic gauge couplings (AQGC)
- search for SM-forbidden couplings: γγγγ, ZZγγ QCD ("gg collider")
- pQCD tests of exclusive production
- characterisation of gluon jets (small quark component)
- Search for New Physics
- CEP of new resonances
- search for invisible decays















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Events of interest characterised by distinct signature:

- two leading protons reconstructed on opposite sides of the IP;
- large rapidity gap between central system and leading protons (colour-singlet exchange);
- possibility to "close" the event by matching central system and leading protons kinematics



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Event signature



from CMS + TOTEM low luminosity run, for illustration purposes only









Proton kinematics defined by:

- four-momentum transfer squared, $t = (p_f p_i)^2$;
- fractional momentum loss, $\xi = (|p_f| |p_i|)/|p_i|$

Proton acceptance in the detectors depends on the machine optics parameters: measured at RP

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \end{pmatrix} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \end{pmatrix}$$

Leading terms for "standard" LHC optics:

- $X \approx D_X(\xi) \xi$
- $y \approx L_y(\xi) \theta_y^*$

18/04/2018









Mass and rapidity of the central system related to the protons ξ :

- $M^2_X = s\xi_1\xi_2;$
- $y = 1/2 \ln(\xi_1/\xi_2)$

 \Rightarrow powerful matching requirement

Proton acceptance depends on the machine optics (mainly D_x) and on minimum attainable distance of detectors from beam

In 2016, maximum acceptance (~30%) for $M_X \approx 750 \text{ GeV}$

Proton acceptance









Procedure developed and used extensively by TOTEM Dedicated alignment fills (low luminosity)

- once per beam optics setting
 - 1. detector approach to the edge of the scraped beam;
 - 2. local alignment with overlapping verticalhorizontal detectors (minimise residuals)





Detector alignment





Physics fills

- each fill
- match x distribution with distribution from alignment fill







Data taking in 2016 and 2017



- TOTEM silicon strip detectors used for tracking;
- diamond detectors (developed for TOTEM) in timing stations

2017: towards design detector configuration

- tracking: per each side, one station with silicon strips, one station with 3D silicon pixels;
- timing: per each side, one mixed diamond silicon (UFSD) station

~40 fb⁻¹ of data recorded with roman pots inserted



Start of CT-PPS data taking advanced to 2016:

~15 fb⁻¹ of data recorded with tracking roman pots inserted









Silicon strips





- 10 planes per station of "edgeless" silicon 6 planes per station of "slim-edge" silicon strip detectors (5 u' + 5 v')pixel detectors with 3D technology (tilted by ~18°)
- pitch: 66 μ m; track resolution: ~12 μ m
- designed for low-luminosity running (TOTEM)

Tracking detectors



Silicon pixels



- pixel size: 100 μ m × 150 μ m; track resolution ~20 µm
- designed for high-luminosity running \Rightarrow multi-track capability











TOF measurement to reduce background from pileup (uncorrelated proton tracks) • Ideally, desired resolution $\sigma_t \approx 20 \text{ ps} \implies \sigma_z \approx 4 \text{ mm}$

Diamond sensors

• 3 planes (4 in 2016) of CVD diamond sensors



- macro-pixels of varying size
- single-plane resolution: ~80 ps
- radiation hard



Timing detectors



Ultra-Fast Silicon Detectors

• 1 plane (in 2016) of UFSD, based on LGAD technology



- macro-pixels of varying size
- single-plane resolution in test beam: ~30 ps
- R&D to improve radiation hardness

Common readout electronics







Search for a centrally produced pair of oppositely charged leptons with forward proton tag

- photon-photon fusion process, never observed before
- test of theoretically clean exclusive cross section
- benchmark for similar searches of centrally produced high mass objects (e.g. W+W-)

Signal

- central exclusive production: small cross section for CT-PPS central mass range $(m(\ell^+\ell^-) \gtrsim 400 \text{ GeV})$
- single dissociation (SD): broader ξ range

Analysis performed on 9.4 fb⁻¹ of data at 13 TeV collected in 2016 (only tracking)

Central dilepton production





Background

(in coincidence with unrelated proton from pileup or beam background)

- double dissociation (DD)
- inclusive Drell-Yan processes: $pp \rightarrow \gamma^* Z^* \rightarrow \ell^+ \ell^- + X$



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Dilepton selection:

- Trigger: two muons (electrons) with $p_T > 38$ (33) GeV
- Dilepton vertex consistent with primary interaction
- "Good" leptons with $p_T > 50$ GeV and opposite charge
- Combined selection on distance of closest track to vertex and acoplanarity $a = 1 - |\Delta \phi(\ell^+ \ell^-)|/\pi$
- m(ℓ+ℓ-) > 110 GeV



- at least one proton track
- ξ from central s

(exact for exclusive, mostly within resolution for single dissociation events)

signal region defined by $\xi(\ell^+\ell^-) - \xi(p)$ match within 2σ

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Event selection





Matching of central and proton kinematics:

system:
$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}} \left[p_T(\ell^+) e^{\pm \eta(\ell^+)} + p_T(\ell^-) e^{\pm \eta} \right]$$









Background mostly due to Drell-Yan or double dissociation events with unrelated proton track from pileup or beam background

mostly data-driven estimate

| | Contribution | After preselection | After kin mat |
|-----------|--------------|-----------------------|------------------|
| Muons | Drell-Yan | 11.36 ± 0.18 | 1.38 ± |
| | DD | 1.17 ± 0.02 | 0.108 ± |
| | Total | 12.52 ± 0.18 | 1.49 ± |
| | Observed | 17 | 12 |
| Electrons | Drell-Yan | 12.33 ± 0.19 | 2.30 ± |
| | DD | 0.56 ± 0.01 | 0.067 ± |
| | Total | 12.89 ± 0.18 | 2.36 ± |
| | Observed | 23 | 8 |

Background estimate



- nematic
- atch
- ± 0.06
- ± 0.005
- ± 0.07
- 2
- ± 0.09 ± 0.003
- ± 0.09

- \Rightarrow 5.1 σ excess over background
- no events with matching protons in both arms
- First observation of proton-tagged yy collisions at the electroweak scale

arXiv:1803.04496 [hep-ex]



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Kinematics of signal events











CT-PPS data taking in 2018



Tracking

All stations equipped with 3D silicon pixel detectors (2 per side)

- Silicon strips still equipping TOTEM vertical pots, for TOTEM low luminosity physic program and for alignment
- Planned upgrade with internal movement system, to better distribute radiation damage

Timing

Stations equipped with diamond and double-diamond detector layers (1 station per side)

• larger signal expected \Rightarrow faster rise time

LHC "dynamic" beam settings

Will have to deal with luminosity levelling through multi-step β^* and crossing angle tuning



















luminosity

First observation of central (semi)exclusive production of high mass lepton pairs

Several analyses currently ongoing or starting on 2016+2017 data

• central production of $\gamma\gamma$, WW, ZZ, γ Z, tt

Total data sample of $\sim 100 \text{ fb}^{-1}$ expected for Run 2 (2016-2018)

Currently considering prospects to extend data taking in Run 3

• goal: ~300 fb⁻¹

Summary and plans



- CT-PPS has demonstrated the feasibility of studying forward proton-tagged events at high



