

# The CMS-TOTEM <br> Precision Proton Spectrometer and first physics results 

Enrico Robutti (INFN Genova) on behalf of the CMS and TOTEM Collaborations



CT-PPS is a joint CMS-TOTEM project
CERN-LHCC-2014-021
Detectors located in TOTEM horizontal roman pots (+ new dedicated ones) along the LHC beam line, at $\pm \sim 200 \mathrm{~m}$ from the CMS interaction point

- two tracking stations and one timing station per side

Detects intact protons emerging from the IP and driven by LHC magnets in proximity of the proton beam $\Rightarrow$ detectors approaching the beam at $\sim 1 \mathrm{~mm}$

Designed to operate continuously at standard LHC running conditions

## 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 (" $\gamma \gamma$ collider")

- dilepton/diboson production: $\gamma \gamma \rightarrow \mathrm{W}^{+} \mathrm{W}^{-}, \ell^{+} \ell^{-} \Rightarrow$ search for anomalous quartic gauge couplings (AQGC)
- search for SM-forbidden couplings: $\mathrm{YYYY}, \mathrm{ZZ} \mathrm{Z}$,

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




## Event signature

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



## Proton kinematics

Proton kinematics defined by:

- four-momentum transfer squared, $t \equiv\left(p_{f}-p_{i}\right)^{2}$;
- fractional momentum loss, $\xi \equiv\left(\left|p_{i}\right|-\left|p_{i}\right|\right) /\left|p_{i}\right|$

Proton acceptance in the detectors depends on the machine optics parameters:
measured at RP
$\left.\begin{array}{c}\quad \text { values at II } \\ D_{x} \\ D_{x}^{\prime} \\ D_{y}^{\prime} \\ D_{y}^{\prime}\end{array}\right)\left(\begin{array}{c}x^{*} \\ \theta_{x}^{*} \\ y^{*} \\ \theta_{y}^{*} \\ \xi\end{array}\right)$

Leading terms for "standard" LHC optics:

- $x \approx D_{x}(\xi) \xi$
- $y \approx L_{y}(\xi) \theta_{y}$
"waist" in proton impact point distribution




## Proton acceptance

Mass and rapidity of the central system related to the protons $\xi$ :

- $M^{2} x=s \xi_{1} \varepsilon_{2} ;$
- $y=1 / 2 \ln \left(\xi_{1} / \xi_{2}\right)$
$\Rightarrow$ 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 ( $\sim 30 \%$ ) for $M_{x} \approx 750 \mathrm{GeV}$


Procedure developed and used extensively by TOTEM
CERN-TOTEM-NOTE-2017-001

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)
3. alignment with respect to the beam from hit occupancy distributions

Physics fills

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

CMS+TOTEM 2016, $\sqrt{s}=13 \mathrm{TeV}$


## Data taking in 2016 and 2017



Start of CT-PPS data taking advanced to 2016:

- TOTEM silicon strip detectors used for tracking;
- diamond detectors (developed for TOTEM) in timing stations
$\sim 15 \mathrm{fb}^{-1}$ of data recorded with tracking roman pots inserted

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
$\sim 40 \mathrm{fb}^{-1}$ of data recorded with roman pots inserted



## Tracking detectors

## Silicon strips



- 10 planes per station of "edgeless" silicon strip detectors (5 ' $u$ ' +5 ' $v$ ')
- pitch: $66 \mu \mathrm{~m}$; track resolution: $\sim 12 \mu \mathrm{~m}$
- designed for low-luminosity running (TOTEM)


## Silicon pixels



- 6 planes per station of "slim-edge" silicon pixel detectors with 3D technology (tilted by $\sim 18^{\circ}$ )
- pixel size: $100 \mu \mathrm{~m} \times 150 \mu \mathrm{~m}$; track resolution ~20 $\mu \mathrm{m}$
- designed for high-luminosity running $\Rightarrow$ multi-track capability

TOF measurement to reduce background from pileup (uncorrelated proton tracks)

- Ideally, desired resolution $\sigma_{t} \approx 20 \mathrm{ps} \Rightarrow \sigma_{z} \approx 4 \mathrm{~mm}$

Diamond sensors

- 3 planes (4 in 2016) of CVD diamond sensors
- macro-pixels of varying size
- single-plane resolution: ~80 ps
- radiation hard


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

## Central dilepton production

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. $\mathrm{W}+\mathrm{W}-$ )


## Signal

- central exclusive production: small cross section for CT-PPS central mass range ( $m\left(\ell^{+} \ell^{-}\right) \geqslant 400 \mathrm{GeV}$ )
- single dissociation (SD): broader $\xi$ range



## Background

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

- double dissociation (DD)
- inclusive Drell-Yan processes:

$$
\mathrm{pp} \rightarrow \mathrm{Y}^{*} \mathrm{Z}^{*} \rightarrow \ell^{+} \ell^{-}+\mathrm{X}
$$

Analysis performed on $9.4 \mathrm{fb}^{-1}$ of data at 13 TeV collected in 2016 (only tracking)

## Event selection

## Dilepton selection:

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



## Matching of central and proton kinematics:

- at least one proton track
- $\xi$ from central system: $\xi\left(\ell^{+} \ell^{-}\right)=\frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}\left(\ell^{+}\right) e^{ \pm \eta\left(\ell^{+}\right)}+p_{\mathrm{T}}\left(\ell^{-}\right) e^{ \pm \eta\left(\ell^{-}\right)}\right]$ (exact for exclusive, mostly within resolution for single dissociation events)
- signal region defined by $\xi\left(\ell^{+} \ell^{-}\right)-\xi(\mathrm{p})$ match within $2 \sigma$


## Background estimate

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 <br> preselection | After kinematic <br> match |
| :---: | :---: | :---: | :---: |
| Muons | Drell-Yan | $11.36 \pm 0.18$ | $1.38 \pm 0.06$ |
|  | DD | $1.17 \pm 0.02$ | $0.108 \pm 0.005$ |
|  | Total | $12.52 \pm 0.18$ | $1.49 \pm 0.07$ |
|  | Observed | 17 | 12 |
|  | Drell-Yan | $12.33 \pm 0.19$ | $2.30 \pm 0.09$ |
|  | DD | $0.56 \pm 0.01$ | $0.067 \pm 0.003$ |
|  | Total | $12.89 \pm 0.18$ | $2.36 \pm 0.09$ |
|  | Observed | 23 | 8 |

## $\Rightarrow 5.1 \sigma$ excess over background

- no events with matching protons in both arms

First observation of proton-tagged $\gamma \vee$ collisions at the electroweak scale
arXiv:1803.04496 [hep-ex]

## Kinematics of signal events




## 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 $\beta^{*}$ and crossing angle tuning

## Summary and plans

CT-PPS has demonstrated the feasibility of studying forward proton-tagged events at high 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 $\gamma \gamma, W W, Z Z, \gamma Z, t \bar{t}$

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

Currently considering prospects to extend data taking in Run 3

- goal: ~300 fb-1

