

## The CMS-TOTEM Precision Proton Spectrometer: CT-PPS

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The CMS-TOTEM Precision Proton Spectrometer, CT-PPS, is an approved project to add 3D silicon tracking and quartz Cherenkov timing detectors in Roman pots at  $z = \pm 204\text{-}215$  m from the CMS collision point to study final states  $p + X + p$ . The central state  $X$  can be a  $W$ -pair from a photon-photon interaction, high  $E_T$  jets from gluon collisions, etc., with  $M(X)$  obtained directly as well as from the two outgoing protons. The project is designed to operate at high luminosity, with up to about 50 interactions per 25 ns bunch crossing, and to be fully operational for physics in 2016.

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## 1. Introduction

The addition of high precision tracking and timing detectors along the LHC beam lines at  $z = \pm 204 - 215$  m from the CMS central detectors will allow the study of central exclusive production reactions  $pp \rightarrow p + X + p$ . "Exclusive" here means that all the final state particles are detected. The outgoing protons lose a few percent ( $\xi = 1.0 - x_F \lesssim 0.1$ ) of their energy but generally have small transverse momenta  $p_T$ , and hence small enough scattering angles, so that they stay in the beam pipes. Bending (not superconducting) and quadrupole magnets deflect them such that at the  $z$ -position of the detectors they are  $\sim 3 - 20$  mm from the beam center, so the detectors must be placed in special movable vacuum chambers, Roman pots, allowing such a close approach when the beams are stable. Measurement of the proton tracks and knowledge of the collision point and beam optics gives the protons' momenta and hence the mass of the system  $X$ , for  $M(X) \gtrsim 300$  GeV, which is measured in the central detectors. The main physics channels are  $X = W^+W^-$  from 2-photon collisions (electroweak, EWK, physics), and 2, 3, 4, ... jets (QCD). Taking data during standard low- $\beta$ , high luminosity running, with pile-up of order 30-50 interactions per bunch crossing, will be possible thanks to kinematic constraints (4-momentum conservation) and a measurement of the time difference  $\Delta t$  between the protons, which gives the  $z$ -position of the collision for good signal events, allowing rejection of pile-up events. For exclusive  $W^+W^-$  decays to leptons, the requirement of no additional tracks on the dilepton vertex is an additional powerful constraint.

The project is a collaboration between CMS and TOTEM (CT) called CT-PPS for Precision Proton Spectrometers[1], and is approved by the LHCC and the CERN Research Board. During 2015 there is construction and beam tests; Roman pots of a new design to cope with high beam currents are already installed and will be tested at the end of stores to establish operating criteria. It is planned to install detectors in both directions in January 2016. This allows the LHC to be used as a "tagged" photon-photon collider with  $\sqrt{s(\gamma\gamma)}$  much higher than at LEP, as well as a "tagged" gluon-gluon collider (with a spectator gluon exchanged to allow the protons to stay intact). It extends the CMS and TOTEM physics programs into a new regime of both EWK and QCD physics.

As the outgoing protons are separated from  $X$  by  $\gtrsim 5$  units of rapidity, the only allowed  $t$ -channel exchanges are photons  $\gamma$  and pomerons  $\mathbb{P}$ , which to leading order are pairs of gluons in a color singlet. In common low- $Q^2$  interactions such as elastic scattering and diffractive dissociation, the strong coupling  $\alpha_s$  is too large for perturbative QCD calculations. In CT-PPS we will be able to study  $\mathbb{P} + \mathbb{P} \rightarrow$  jets at high  $Q^2$ , a new tool for QCD. Events with exactly two jets,  $X = JJ$ , are expected to be nearly all gluon jets with only a few percent of  $b\bar{b}$  dijets, according to the  $J_z = 0$  rule[2], which can be tested. In addition to the value of having a large sample of nearly pure gluon jets, this tests the prediction that exclusive Higgs boson production  $pp \rightarrow p + H(\rightarrow b\bar{b}) + p$  can be measured without a large QCD background. Because of the  $M(X) \gtrsim 300$  GeV limitation of CT-PPS the  $H(125)$  is not in reach; that would require additional detectors at  $z \sim 420$  m, a future possibility but not yet proposed. Three-jet events  $X = JJJ$  should be both  $ggg$  and  $q\bar{q}g$ , in the latter case with equal fractions of the five  $q\bar{q}$  flavors. Four-jet events can be from  $2 \rightarrow 4$  parton diagrams, or from double-parton scattering, DPS ( $2 \times (2 \rightarrow 2)$ ), as in non-diffractive  $pp$ -collisions. These can be distinguished using kinematics. It is possible (even likely) that the two leading gluons in a pomeron tend to be close (in configuration space) which will enhance the DPS events. This will probe the pomeron structure beyond the single parton distribution functions.

## 2. New Roman pots and Acceptance

The beam-line regions at  $z = \pm 204 - 215$  m are the locations of the TOTEM experiment, which measures elastic scattering and the derived  $pp$  total cross section  $\sigma_T$  in special high- $\beta^*$  runs with very low pile-up. Further special running in 2015 will measure these at  $\sqrt{s} = 13$  TeV, but those Roman pots and the detectors were not designed for high luminosity. An important issue is the effect of the impedance seen by the beam, which would prohibit running with high intensity beams. A new cylindrical design should operate with normal high intensity operation. These pots (in the horizontal plane) are installed and insertion tests will be done this year with beams to answer questions about their effect on the beam, generation of backgrounds, distance of closest approach ( $\lesssim 2$  mm?) etc. The closer the beam can be approached, the lower the values of  $M(X)$  that can be reached, but no significant increase in backgrounds can be allowed. With a distance of closest approach to the beam center of  $15\sigma$ , at  $\beta^* = 0.55$  m, the acceptance covers  $\xi = 0.03 - 0.1$  and  $|t| \lesssim 4.0$  GeV<sup>2</sup>. The track angles will be measured to about  $1 \mu\text{rad}$  ( $10 \mu\text{m} / 10$  m). The coverage of the timing detectors is  $12.3$  mm (in  $y$ )  $\times$   $15.4$  mm (in  $x$ ); the tracking detectors have larger coverage:  $16$  mm ( $y$ )  $\times$   $24$  mm ( $x$ ). With  $y(\text{beam}) = 0$ , protons from  $\gamma\gamma \rightarrow W^+W^-$  have  $|y| < 1.0$  mm, which would allow an enhanced selection of these events with a special trigger.

## 3. Physics: Electroweak ( $W^+W^-$ ) and QCD (Jets and not jets)

Measuring  $\gamma + \gamma \rightarrow W^+W^-$  with tagged photons will allow us to study anomalous  $WW$  final state interactions. Here the  $W$  are transverse, so the Higgs boson should not appear in this channel; in any case it is below our acceptance and  $M(H) < 2M(W)$  for real  $W$ . The main issue is to test triple and quartic gauge couplings, with sensitivities orders of magnitude better than LEP, thanks to the much higher  $\sqrt{s}$ . This is probably the only way to directly measure the  $\gamma\gamma W^+W^-$  coupling until we have a TeV-scale lepton-lepton collider.

To emphasize the power of "missing mass", basically 4-momentum conservation, in exclusive processes with both protons measured, a good example is provided by  $W^+W^-$  production. Missing transverse momentum  $p_T$ , commonly called missing  $E_T$  or  $MET$ , is familiar, but in these reactions we also measure missing longitudinal momentum and energy, four constraints altogether. This should allow, in addition to the purely leptonic  $W$ -decays, also the semileptonic case  $WW \rightarrow \ell\nu JJ$ , where  $\ell = e, \mu, \tau$  and  $J = \text{jet}$ . In the following  $MM$  means "missing mass" and  $p_i, p_f, J$  etc mean the 4-momenta of the initial- and final-state protons, jets, etc. Thus  $MM(p_i p_i - p_f p_f) = M(WW)$ , obtaining the central mass from the protons (after establishing that the central event was likely to be a  $W$ -pair). But we can go further, e.g.  $MM(p_i p_i - p_f p_f JJ) = M(\ell\nu)$  even without measuring (only detecting) the charged lepton. And  $MM(p_i p_i - p_f p_f JJ\ell) = M(\nu) = 0$ , within the resolution (of order 12-15 GeV) and the 3-momentum of the neutrino is determined. These several constraints can be applied, together with (a)  $M(JJ) = M(W)$ , and (b) in the  $JJ$ -frame the hadrons should all have limited momenta transverse to the  $JJ$ -axis ( $k_T$ ), following a distribution like that in  $e^+e^- \rightarrow Z \rightarrow JJ$  at LEP. The published CMS observation [3] of two exclusive  $W^+W^-$  candidates at  $\sqrt{s} = 7$  TeV used only the  $e^\pm\mu^\mp$  channel (2% of all), with no additional central tracks and no information on forward protons. While the fully hadronic ( $4J$ ) decays would have far too much QCD background, the leptonic and semileptonic channels are 54% of all  $WW$  decays and if they can be used, with the

higher  $\sqrt{s}$  and luminosity, hundreds of  $\gamma\gamma \rightarrow W^+W^-$  events can be measured. Similar remarks apply to a search for exclusive  $ZZ$  production, which is very rare in the Standard Model. If one  $Z$  is measured and the other decays to neutrinos (20%), missing mass tells us  $M(\nu\bar{\nu})$ , albeit with a resolution  $\sim 12$ -15 GeV.

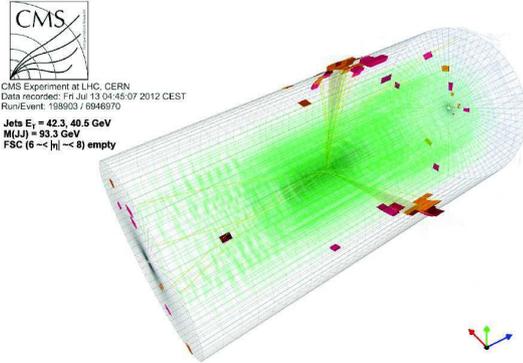


Figure 1: Dijet event recorded by TOTEM and CMS in low pile-up ( $90 \text{ m } \beta^*$ ) run at  $\sqrt{s} = 8 \text{ TeV}$ . Two leading protons and two jets with  $E_T > 20 \text{ GeV}$  were required.

with POMWIG and PYTHIA (which has no exclusive dijets) and EXHUME (which does). Exclusive dijets will be selected by 4-momentum balance ( $p_T, p_z, MM$ ) as well as a cut on  $k_T$  of tracks (w.r.t. the jet axes). Khoze et al. predict [2] that in the limit of small proton angles ( $|t| \rightarrow 0$ ) quark jets are suppressed relative to gluon jets by a term of order  $(m_q/M(JJ))^2$ , so this provides a unique sample of nearly pure  $gg$ -dijets, in contrast to the nearly pure  $q\bar{q}$  dijets in  $e^+e^-$  at LEP. It is important to test this prediction, not only as an interesting QCD test, but because the very good signal:background in exclusive  $H(125) \rightarrow b\bar{b}$  would be spoiled (if that future search is ever done) if it is not true. The exclusive 3-jet events at LEP were  $q\bar{q}g$  and here they will be a mix of  $ggg$  and  $q\bar{q}g$  with equal numbers of (u,d,s,c,b)-quark pairs. The latter events should tend to be more Mercedes-like than the  $ggg$  (gluon-splitting) events. During a short low-pile-up run in July 2012 (with  $\beta^* = 90 \text{ m}$ ) some events were recorded with two leading protons in the TOTEM Roman pots together with  $\gtrsim 2$  jets with  $E_T > 20 \text{ GeV}$  in CMS. Fig.1 shows one particularly clean  $X = JJ$  event, in which also the Forward Shower Counters (FSC) covering  $6 < |\eta| < 8$  were empty. A few clean  $X = JJJ$  events were also seen. These are the cleanest jet events ever seen at a hadron collider! In  $100 \text{ fb}^{-1}$  simulations predict  $\sim 250$  exclusive dijet events with leading jets with  $E_T > 150 \text{ GeV}$ . Of course the main CT-PPS running is with high pile-up and the events will look very different. And most of the QCD events with  $M(X) > 300 \text{ GeV}$  are not expected to be exclusive 2- or 3-jets; these final states are really unexplored territory and we do not have reliable predictions for event shapes. Perhaps some are roughly spherical with a very high multiplicity? Some should be 4-jet events from double parton scattering (distinct from double gluon bremsstrahlung), which can measure correlations between gluons in the pomeron. Is the typical transverse separation of the gluons in a pomeron  $\ll 1 \text{ fm}$ , which would enhance DPS? Non-perturbative, QCD-inspired and phenomenological event generators such as PYTHIA have been tuned to reproduce underlying event properties in hard  $pp$ -collisions. Developing similar generators for  $X$  in  $p + X + p$  events

Central exclusive production of jets will also open new windows on QCD. At the Tevatron both D-Zero and CDF found exclusive dijet candidates but without detecting the outgoing protons (CDF detected the  $\bar{p}$  in Roman pots). The signature was an excess of events with the dijet mass  $M(JJ)$  near the total central mass compared to simulations that ignored the exclusive process. The jet  $E_T$  range was limited to about 40 GeV at  $\sqrt{s} = 1.96 \text{ TeV}$ , while in CT-PPS it will extend above 250 GeV. Simulations have been done

challenges theory/phenomenology and should lead to a better understanding of QCD.

#### 4. Tracking

I will be brief on technical details, which can be found in Ref. [1]. In each direction there will be two Roman pots dedicated to tracking, with six detector planes in each station. The sensors will be  $16 \text{ mm} \times 24 \text{ mm}$  3D silicon pixel detectors with a pixel size  $150 \mu\text{m} (x) \times 100 \mu\text{m} (y)$ . The 3D sensors consist of an array of columnar electrodes from the front to the back surface, so the electrons drift sideways, which gives a fast collection time and a low depletion voltage,  $\sim 10 \text{ V}$ . They have a  $200 \mu\text{m}$  "slim edge" and are also more radiation-hard than usual planar detectors. These are the same as CMS pixel detectors, and the readout scheme will be the same as the Phase I upgrade of the CMS pixel tracker, so existing DAQ components and software can be used. The 3D sensors are in production, using the same technology as the ATLAS IBL detectors..

#### 5. Timing

Excellent timing is essential for pile-up rejection. Measuring the difference in proton times with  $\sigma(t) = 20 \text{ ps}$  gives the  $z$ -position of the collision with  $\sigma(z) = 4.2 \text{ mm}$  *iff* they came from the same interaction, so matching it to the vertex of the  $W^+W^-$ , jets etc. reduces pile-up by more than an order of magnitude. The baseline timing detectors are called QUARTIC for QUARtz TIMing Cherenkov [4]. Each  $3 \text{ mm} \times 3 \text{ mm}$  element of the  $4 \times 5$  array consists of an L-shaped bar. One leg is the "radiator bar", parallel to the proton path, and the perpendicular leg is the "light-guide bar" which transports the light to a silicon photomultiplier, SiPM, 7 cm from the beam and partially shielded from beam-induced backgrounds. There are no mirrors, only total internal reflection is used, utilizing the conditions that the protons are very nearly parallel to the radiator bar, and the refractive index of quartz is  $n > \sqrt{2}$ , so that the light that propagates up the light guide is also totally internally reflected. The radiator bars are separated by very small  $100 \mu\text{m}$  spacers. The detector is active within 0.4 mm of the *inside* of the vacuum chamber. Beam tests at Fermilab demonstrated  $\sigma(t) \sim 30 \text{ ps}$  in a prototype; there will be two in one Roman pot to give  $\sigma(t) \sim 20 \text{ ps}$ , with possible improvements. Further beam tests will be made at CERN from August 2015 with the DAQ intended for the final installation. This will use a NINO amplifier-discriminator board followed by the HPTDC trigger/DAQ interface.

Another Roman pot is planned for additional timing systems, which may supplement (or could eventually replace) the QUARTICs. Better than  $3 \text{ mm} \times 3 \text{ mm}$  granularity is desirable, especially close to the beam pipe. The quartz bars represent  $\sim 15\%$  of an interaction length, which gives some inefficiency and causes backgrounds. Radiation hardness of the SiPMs is also an issue, although they can easily be replaced in technical stops. One detector being developed is called "GASTOF", which has a gaseous Cherenkov radiator at atmospheric pressure. The very small Cherenkov angle  $\theta_{Ch}$  means there is little light (proportional to  $\sin^2 \theta_{Ch}$ ) but simplifies the optics (a  $45^\circ$  mirror), there is almost no optical dispersion, and very little material. The photodetector is a Microchannel plate (MCP-)PMT with an  $8 \times 8$  array of anode pads. Measuring individual photoelectrons, two protons from the same bunch crossing may be separately timed.

Other types of timing detectors, especially with high  $x,y$  segmentation using diamond or silicon, are being developed. Although at present diamond detector time resolutions are  $\sim 90$  ps, the detectors are thin and one might have 20 in line to give  $\sigma(t) = 20$  ps. As the CT-PPS detectors are relatively small and accessible, the system can evolve, e.g. into a hybrid with many layers of high-segmentation solid state detectors in front of a QUARTIC or GASTOF.

It is crucial to have a good reference time signal to synchronise the measurements at the + and - stations. We plan to use two independent systems, one based on an optical clock distribution, using a Dense Wavelength Division Multiplex technique, which makes it possible to send several reference signals on a single optical fiber. The other uses an RF cable with oscillators synchronised with a phase-locked loop. Both systems can provide signals at the two far detector stations with jitter at the ps-level, much better than the resolution of the detectors. For details see Ref.[1].

## 6. Plan and Schedule

The plan is for an exploratory phase in 2015-2016, followed by a production phase aiming to collect  $100 \text{ fb}^{-1}$  before Long Shutdown LS2. In 2015 we will test insertion of the pots close to the beams at high luminosity, to show that stable LHC operation is not affected and establish operating conditions. In test beams at Fermilab and CERN the performance of the tracking and timing detectors will be demonstrated, and they will be integrated into the CMS trigger/DAQ system. In January 2016 the timing and tracking detectors will be installed in the Roman pots, for commissioning with beams in Spring 2016. We expect physics data-taking in 2016.

## 7. Summary

The addition of small high precision tracking and timing detectors to CMS, in Roman pots together with the TOTEM Collaboration, will open up a new field of EWK and QCD physics:  $pp \rightarrow p + X + p$  with  $M(X) > 300 \text{ GeV}$ . It can uniquely measure the  $\gamma\gamma W^+W^-$  coupling to test anomalies, and study QCD in a novel region of interplay between perturbative and non-perturbative QCD. Suitable detectors are planned for installation in the LHC in January 2016, aiming for physics in 2016 and possibly beyond LS2.

## 8. Acknowledgements

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