Performance of TOTEM in Run II

KENNETH ÖSTERBERG

Department of Physics and Helsinki Institute of Physics, P. O. Box 64, FI-0014 University of Helsinki, Finland.

kenneth.osterberg@helsinki.fi

On behalf of the TOTEM Collaboration

Abstract. The TOTEM experiment at the Large Hadron Collider is dedicated to diffractive and forward physics. Its consolidation and upgrade programme focuses on central diffractive processes. This article briefly describes the performance of the detectors in the 2015 run as well as the consolidation and upgrade work. Also a few highlights of the physics potential are discussed in detail.

Introduction

The TOTEM experiment [1] is dedicated to forward hadronic phenomena at the Large Hadron Collider (LHC). The three pillars of its physics programme are: an accurate determination of the total cross-section, a measurement of differential elastic scattering cross-section in a wide range of momentum transfer squared, \( t \), and studies of diffractive and forward processes, mainly in cooperation with the CMS experiment [2]. The combination of the CMS and TOTEM experiments gives an exceptionally large pseudorapidity coverage for tracking and calorimetry that is especially well suited for studies of forward and diffractive processes. TOTEM comprises three subdetectors: the inelastic telescopes T1 and T2 and Roman Pots (RP) for leading proton detection, see Figure 1.

T1 and T2 are embedded in the forward regions of CMS on each side of the LHC interaction point IP5. T1 consists of Cathode Strip Chambers (CSC) and T2 of Gas Electron Multipliers (GEM). The pseudorapidity coverages of T1 and T2 are \( 3.1 \leq |\eta| \leq 4.7 \) and \( 5.3 \leq |\eta| \leq 6.5 \), respectively. T1 and T2 measure the charged particles produced in inelastic events and are, in addition to inelastic event counters and primary charged multiplicity measurers, excellent for defining “rapidity gaps”, i.e. \( \eta \)-ranges without primary particle production, due to their low transverse momentum \( p_T \) thresholds, \( \sim 100 \text{ MeV/c} \) and \( \sim 40 \text{ MeV/c} \) for T1 and T2, respectively.

The RP system, that measures elastically and diffractively scattered protons very close to the outgoing beam, consists of two stations placed between \( z = 203 \) and \( 220 \text{ m} \) on each side of IP5, named “RP210” and “RP220”. Both of them are composed of two units (near and far with respect to IP5) separated by \( \sim 5-10 \text{ m} \) for reconstruction of the proton kinematics and background discrimination. Each unit includes two vertical (top and bottom) and one horizontal RP. The RPs are movable beam-pipe insertions that can bring sensitive detectors to sub-millimeter distance from the beam once it is stable. Each RP hosts 5 back-to-back mounted pairs of silicon-strip sensors with reduced (\( \sim 50 \mu \text{m} \)) insensitive edge facing the beam, to accept protons scattered at very low angles.

The main purpose of the improvement of the experimental apparatus in view of Run II was to enhance the experiment’s capability to measure Central Diffractive (CD) processes, \( p + p \rightarrow p \oplus X \oplus p \). In CD reactions, the protons stay intact and rapidity gaps (indicated by \( \oplus \)) are formed between the protons and the state \( X \). In CD reactions, the mass of \( X \), \( M_X \), can be reconstructed from the fractional momentum loss, \( \xi \), of the scattered protons by \( M_X = \sqrt{\xi_1 \xi_2 s} \). If the state \( X \) is a well-defined state, such as a particle or a fixed number of particles or jets, then the process is called Central Exclusive Production (CEP). In CEP reactions, to a very good approximation, the final state \( X \) obeys a \( J_z = 0 \), C-even, P-even, selection rule, where \( J_z \) is the projection of the total angular momentum along the beam axis.

The consolidation program of TOTEM [3] focuses on measurements of CD processes in special high-\( \beta^* \) optics runs with common data taking with CMS. The consolidation included the relocation of existing RPs to new RP210 near and far positions, see Figure 1, to improve the lever arm, to rotate the RP210 far by 8 degrees to improve the multitrack capability and upgrade the data acquisition system (DAQ) to sustain a significantly higher rate. By adding
proton timing detectors with ∼ 50 ps timing resolution in the vertical RPs [4], can CD processes with O(pb) cross-
sections be accessed in a β∗ = 90 m run of about a week. With the β∗ = 90 m optics, protons with any ξ can be detected
in the vertical RPs and hence, in CEP reactions, any MX, as long as the |t| of both scattered protons is ≥ 0.01 GeV².

The reach with β∗ = 90 m optics is complementary to the one of the other upgrade, CMS-TOTEM precision
proton spectrometer (CT-PPS) [5] that aims to measure CEP processes with O(fb) cross-sections in normal high-
luminosity running having access to MX ≥ 300 GeV/c². The CT-PPS upgrade included adding RF-shields to all
horizontal RPs to reduce the impedance seen by the LHC beams and adding a new additional cylindrical horizontal
RP at 216 m for timing detector purposes, see Figure 1. With normal high-luminosity optics, the diffractive
protons are measured in the horizontal RPs, whereas with high-β∗ optics the diffractive protons are entering mainly the vertical
RPs. The pile-up, multiple pp interactions per bunch crossing, is considerably smaller in high β∗ runs with an average
number of inelastic pp events per bunch crossing, μ ≲ 1, compared to μ = 20-50 in normal high-luminosity LHC runs.

Performance in 2015 run

During long shutdown 1 (LS1), the inelastic telescopes T1 and T2 were extracted and reinstalled. Few months after re-
installation, the DAQ loop of one of the T2 half arms started to be unreliable. It was decided to disconnect this half arm
from the DAQ loop to ensure proper functionality of the other half arm connected to the same DAQ loop. The effect
of the missing half arm on the trigger and veto efficiency as well as for the most important measurements involving
T2 (inelastic cross-section, charged multiplicity measurement and the exclusive low mass resonances) was estimated
to be acceptable, at most 1 %, and significantly smaller than the dominant uncertainty in any of the measurements.

With this exception, the indications from the 2015 data are that the performance of the inelastic telescopes T1 and T2 is similar to their performance in Run I in terms of efficiency, resolution and tracking. Their performance in Run I is described in detail in Reference [6]. Figure 2 shows examples of T1 and T2 distributions from the LHCf
run with a very low pileup, μ ∼ 0.003, and the CMS solenoid off. This makes the LHCf run data attractive for the
forward charged particle pseudorapidity density, dNch/dη, measurement, especially for the T1 were the magnetic
field effects are sizable. E.g. the transverse vertex resolution with the T1 is approximately a factor 2 better in the
LHCf run data compared to data taken during run I with the CMS solenoid on, mainly due to magnetic field effects.
Figure 2 (left) shows the reconstructed $\eta$ of T1 tracks with a good balance between left and right arm, indicating similar reconstruction efficiencies. Figure 2 (right) shows the distribution of the Z impact parameter [6] that is used for separating primary and secondary tracks for a pseudorapidity region in one half arm of T2.

FIGURE 2. Performance plots from the LHCf run. Left: the pseudorapidity distribution of tracks in T1, right: the Z impact parameter distribution of tracks in a specific pseudorapidity region in one of the half arms of T2. The result of a global fit to the Z impact distribution is shown with the exponential (double-Gaussian) component due to secondary (mainly primary) particles.

During Run I, the data throughput on the VME bus was the bottleneck of the DAQ system translating into a maximum trigger rate of 1 kHz. A new DAQ architecture [7] was introduced to get rid of the bottleneck replacing the VME interface with Scalable Readout System components [8], which provided a faster and cost effective transmission. Also a zero suppression firmware was developed. As a result a trigger rate of about 20 (50) kHz could be sustained during raw data (zero suppressed) readout i.e. a factor 20 (50) improvement compared to the performance in Run I, allowing to increase the number of bunches in special runs to about 700 bunches without significant efficiency loss.

The existing RPs units at 147 m were successfully relocated to their new positions, RP210 near and far, with the latter one rotated by 8 degrees. Also all the RP silicon-strip sensors were removed and reinstalled during LS1. Furthermore, RF-shields for the horizontal RPs were added and a new ferrite material was introduced for all RPs followed by a bake-out at 1000 °C. These actions reduce the impedance and the outgassing, respectively. Finally, a new cylindrical horizontal RP was manufactured and installed at 216 m for the CT-PPS timing detector. This makes the TOTEM RP system, containing 26 RP units, the largest ever at any collider. Not all of them are to be used at the same time, the RP210 far, RP220 near and far are to be used for high $\beta^*$ optics runs, whereas the RP210 near and far plus the cylindrical RP are to be used for normal high-luminosity running. It should also be noted that a new collimator, TCL6, was installed behind the RPs during LS1 to intercept showers from the RPs. This will allow the collimators between IP5 and RPs to be opened up even at highest luminosities and hence improve the high $\xi$ acceptance.

At the time of the LHCP 2015 conference, the RP system had been commissioned and taken data during a $\beta^* = 19$ m run as an exercise for the main run, a one week $\beta^* = 90$ m run in October 2015. The indications from the first data taking were that everything was working as expected. From the successful data taking in October, it is known that the RP are working with the same efficiency, resolution and tracking performance as in Run I, for details see Reference [6], with the added redundancy of measuring each proton with three units instead of two as in Run I.

During normal high-luminosity running, insertions of the horizontal RPs were exercised. The experience from run I (2012) was that when the RPs were inserted, showers created by collision debris caused beam dumps due to large signals in the Beam Loss Monitors (BLMs), and that the beams caused impedance heating combined with outgassing in the RPs. The actions taken during LS1 (new ferrites, addition of RF-shields and TCL6) were done to solve these issues. During 2015, the RPs were inserted after 1-2 h of stable beam conditions in the second fill of each step of luminosity increase. The horizontal RPs were at $25\sigma_{\text{beam,trans}}$ and no beam instabilities due to RP insertions were observed up to a luminosity of about $5 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$. Temperature and vacuum measurements in the RPs and BLM measurements were all OK. Extrapolation to a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ and closer distances (even to $15\sigma_{\text{beam,trans}}$) is well within the current BLM thresholds allowing regular insertions for physics in fills in 2016.

Physics Potential

As stated above, the motivation for the experimental apparatus improvements in Run II is to enhance the experiment’s physics potential, especially in measuring CD processes that are $t$-channel exchange processes with either a system of
gluons $g$ (with neutral color) or a photon $\gamma$. The leading order description of this color-singlet gluon system is called the Pomeron $P$. For CEP processes in proton-proton collisions the dominant contribution comes from $PP$ scattering, with a small contribution from “photoproduction” i.e. $P\gamma$ collisions and even smaller one from $\gamma\gamma$ fusion. The excellent CMS-TOTEM pseudorapidity coverage, allows, in addition to the comparison between the mass, $M_{pp}$, computed from the particle flow (PF) objects and $M_x$, to compare the summed transverse ($p_T$) and longitudinal ($p_z$) momentum of the PF objects with the two protons, as well as verify the rapidity gaps predicted by the proton $\xi$ measurements.

Physics topics covered in $\beta^* = 90$ m runs include spectroscopy of exclusively produced low-mass resonances and glueball states, measurement of exclusive production of charmonia, studies of the rapidity gap survival probability as well as searches for new physics in CD reactions via missing mass or momentum signature. The physics topics covered by CT-PPS include searches for exclusively produced new particle states, measurement of exclusive dijet and vector boson production as well as searches for anomalous quartic gauge couplings. Below follows a description of two selected topics, more details and description of topics not covered here is found in References [4, 5].

**Exclusive production of low mass resonances and glueballs**

The CD process effectively turns LHC to a gluon-gluon collider and provides an excellent opportunity to study gluon systems with a longitudinal momentum fraction $x \sim 10^{-4}$ and, in particular, to search for glueball candidates. In the case of CMS-TOTEM, this is complemented with an excellent mass resolution ($\sim 20$–$30$ MeV/$c^2$) with the tracker for charged-particle-only final states, in combination with a capability to measure and tag both outgoing protons as well as effectively select the exclusive events with high purity in the required very low $\xi$ range, thus allowing clearly to identify the produced resonances without further steps like model- and parameter-dependent partial-wave analysis.

Glueballs are predicted by QCD as gluon bound states with no valence quark content. The absence of valence quarks, in combination with the $J^{PC} = 0^{++}$ selection rule, makes CD reactions an ideal place to search for them. QCD lattice calculation foresee a $J^{PC} = 0^{++}$ ground state and a $2^{++}$ state followed by a spectrum of excited states [9, 10]. The $f_0(1500)$ or the $f_0(1710)$ are generally regarded as potential glueball $0^{++}$ states since one of them is in excess to the meson SU(3) multiplet and both are compatible with a glueball in terms of mass, spin, parity, and decay channels (e.g. suppressed $\gamma\gamma$ mode). Recent unified lattice calculations [10, 11] predict the $0^{++}$ glueball at $\sim 1700$ MeV/$c^2$ within $\sim 100$ MeV/$c^2$ of overall uncertainty (statistical and systematic), thus favoring the $f_0(1710)$ as a glueball candidate. Whether a resonance is a glueball or not, can be studied by measuring its CD production cross-section, e.g. in comparison with its production in $\gamma\gamma$-collisions, as well as its decay branching ratios [9]. The WA102 experiment [12] disfavored the $f_0(1710)$ to be the glueball by reporting that its branching ratio into $K^+K^−$ exceeded its branching ratio to $\pi^+\pi^−$, contrary to the case of the $f_0(1500)$. This lead to the conclusion of a higher coupling to the $s$-quark compared the $u,d$-quarks unexpected for a glueball. Moreover the predicted decay mode into $\rho\rho$ has not been observed so far. An observation of the decay $f_0(1710) → \rho\rho$ at the LHC would, in addition to be a first observation of this decay mode, change the branching ratio of its decay modes into $K^+K^−$ vs “pionic” channels and therefore renormalize the expected couplings to $u,d$-quarks vs $s$-quark in the one expected for glueballs.

![FIGURE 3](image.png)

**FIGURE 3.** Left: Estimated signal and background mass distributions for exclusive $f_0(1710) → \rho\rho → 2(\pi^+\pi^-)$ production in CMS-TOTEM. The background estimate from non-resonant exclusive $\rho\rho$ production is based on DIME [13]. Right: Schematical drawing of the the event topology used in the search for high missing momentum candidates.

Events with two RP protons and only two or four charged particles in the tracker with zero total charge are selected. Then, $p_T$ compatibility (within $\sim 50$ MeV/$c$) between the central and the $pp$ systems as well as horizontal vertex compatibility for the two RP protons, under a $\xi \sim 0$ assumption, is required to remove incompletely reconstructed events and pileup. Preliminary analysis of a CMS-TOTEM Run I $1 \text{ nb}^{-1}$ data sample reveals sensitivity to a...
possible decay of \( f_0(1710) \to \rho^0 \rho^0 \to 2(\pi^+ \pi^-) \). Figure 3 (left) shows \( f_0(1710) \) simulated signal distributions together with background due to non-resonant exclusive \( \rho^0 \rho^0 \) production for 0.06 pb\(^{-1}\) luminosity, which is estimated to be needed to observe the decay. As stated above, the precise measurement of \( f_0 \) branching ratios are essential in view of identifying the resonances as glueball candidates. As the branching ratios for low mass resonances may easily differ by an order of magnitude, a factor of ten of integrated luminosity, on top of the one estimated for observing \( f_0(1710) \to \rho^0 \rho^0 \to 2(\pi^+ \pi^-) \), will be required to precisely measure the \( \pi^+ \pi^- \). \( K^+ K^- \) and \( \rho^0 \rho^0 \) decays modes. In reality slightly more, i.e. an integrated \( \beta^* = 90 \) m luminosity of \( \sim 1 \) pb\(^{-1}\), will be required for a detailed \( f_0 \) branching ratios measurement when backgrounds from exclusive \( 2(\pi^+ \pi^-) \) production and adjacent \( f_2 \) states are taken into account.

A detailed angular momentum analysis is important to give full confidence that the measured branching ratios of the low mass glueball candidates are correct. Such a study has to be made as a function of the invariant mass in a wider interval than the resonance width itself to be able to deconvolute the overlapping contributions from adjacent resonances and background. The spin-parity analysis therefore has to be performed in mass steps \( \Delta M \) with the minimal step size limited by the mass resolution \( \sigma(M) \approx 20-30 \) MeV/c\(^2\). Taking all into account, a full spin-parity analysis of the exclusive \( f_0 \) production should be made in mass bins with a size \( \Delta M = 30-40 \) MeV/c\(^2\) and if requiring sufficient statistics in each \( \Delta M \) bin, it is strictly only fully feasible with an integrated \( \beta^* \) = 90 m luminosity of \( \sim 50 \) pb\(^{-1}\).

**Search for missing mass and momentum candidates**

CD provides simultaneous and precise measurement of the initial and final state kinematics, which can be used to search for events with missing mass or missing momentum signatures. This opens up ways for new physics searches that might have escaped the searches of the general purpose detectors, CMS and ATLAS. Only CD events with a \( M_{PF+P_{miss}} \leq M_X \) are examined to avoid contamination from pileup events. The rapidity gaps, \( \Delta y = -\ln \xi \), predicted by the proton \( \xi \) measurements are verified using the T2 detector with a rapidity coverage of \( 5.3 < |y| < 6.5 \). To probe \( O(pb) \) cross-sections, a statistics corresponding to an integrated \( \beta^* = 90 \) m luminosity of \( \sim 50 \) pb\(^{-1}\) is needed.

The search signature is high missing momentum pointing towards a region with good CMS-TOTEM instrumentation \( (|y| < 6.5) \) and not observing charged particles or energy deposits in \( \eta \) regions close to where the missing momentum points, see Figure 3 (right). This happens if a particle is created in the CD reaction and escapes the detectors undetected. Events are rejected if more forward rapidity gaps than T2 would be allowed by the proton \( \xi \) measurements. For \( \sqrt{s} = 13 \) TeV, the search is confined to the 200-700 GeV/c\(^2\) mass range, where the upper limit is due to the maximal central mass allowed by the T2 acceptance. Events with missing momentum up to 400 GeV/c were found in the Run I data set with background events expected from particles escaping detection in the forward region, due to “acceptance gaps” between detectors as well as from \( p + p \to N^+ X \oplus p \) or \( p \oplus X \oplus N^+ \) reactions. In the latter case, one of the observed protons comes from a decay of a nucleon resonance, \( N^+ \), and the other \( N^+ \) decays products escape detection. With increased statistics, it is expected that these backgrounds will be modeled sufficiently well.

An example process is squark \( q \bar{q} \) pair production with \( q \to g + \chi^0_1 \) decay for \( q \) masses of just a few hundred GeV, where a central diffraction cross-section of 1-10 pb can be expected [4]. Since \( \sim 50 \% \) are visible in the CMS-TOTEM acceptance, an integrated luminosity of \( \sim 50 \) pb\(^{-1}\) could yield \( \sim 25-250 \) events with the missing energy due to the two neutralinos \( (\chi^0_1) \). Such a search could allow to check the current exclusion limits on the \( m_{\tilde{q}} - m_{\chi^0_1} \) range without tight cuts on the centrally visible system, and especially explore the \( m_{\tilde{q}} - m_{\chi^0_1} \leq 30-40 \) GeV/c\(^2\) range in detail. The hypothesis of close \( \tilde{q} \) and \( \chi^0_1 \) masses is particularly relevant for the supersymmetric top quark \( t \) given the cosmological implications [14]. For \( t \) masses above \( \sim 250 \) GeV, the decay \( t \to c + \chi^0_1 \) is currently not fully excluded [15, 16].

**Status of upgrades**

For 90 m optics and \( \xi \approx 0.1 \% \), the reconstructed proton transverse vertex has sufficient resolution to reduce pileup background in CD events [4]. For all other cases, pileup rejection can only be obtained by matching the proton vertex with the central detector vertex using the reconstructed longitudinal position of the proton vertex as depicted in Figure 4 (left). This requires precise timing measurement of the outgoing protons combined with an accurate timing reference system. For \( \beta^* = 90 \) m optics with \( \mu < 1, 50 \) ps precision is sufficient according to estimates from simulations and Run I data, whereas for the normal high-luminosity running with \( \mu = 20-50 \), a precision of 10-30 ps is needed.

For the high \( \beta^* \) optics, 500 \( \mu m \) thick diamond sensors with variable pitch (0.7 - 4.2 mm) have been chosen due to the limited space in the vertical RPs [4]. The pitch has been adjusted to the expected track occupancy resulting in a double hit probability of \( \leq 1 \% \). Single sensors gave in test beams a time resolution better than 100 ps, see
FIGURE 4. Left: The measurement principle of the longitudinal (z) position of the proton production point using timing detectors. The picture shows the arrival time of the protons inside the RPs, on each side of the IP. \( z_{\text{vertex}} = c(\Delta t_{\text{collision, left}} - \Delta t_{\text{collision, right}})/2 \).

Right: The time resolution of a single diamond sensor as measured in test beams with the electrode numbering scheme as insert.

Figure 4 (right), indicating that a four-sensor package is able to provide the required resolution of 50 ps. The first sensor package will be installed in a RP in the LHC tunnel for the heavy ion run in November 2015 and the remaining three detector packages during the first half of 2016, being ready for a possible special run in the second half of 2016. The timing reference system is adopted from the “Universal Picosecond Timing System”, developed for FAIR [17]. It is currently being built and tested in the laboratory and is planned to be installed during the end of year stop 2015-16.

For the high-luminosity runs, the baseline option is 3 × 3 mm² quartz bars with silicon photo multipliers for light detection in a 4 × 5 geometry. Single bars have shown resolutions of ~30 ps in early test beams and with two modules ~20 ps could be achievable. First modules are currently being tested inside RPs with minimum ionization particles. Four modules are planned to be ready for installation during the end of year stop 2015-16. In parallel solid state timing detector alternatives, diamond and ultra fast silicon sensors [18], are being developed to be able to vary the pitch and thus reduce the double hit probability that is expected to significant (up to 50 % at \( \mu = 50 \)) for the pixels closest to the beam. These options are expected to be ready for a possible installation in the end of the year stop 2016-17. At high-luminosity, the number of tracks in the RPs are estimated to be several per event and thus the strip sensors are not capable to do the reconstruction. They are also not radiation hard enough. During 2016, strip modules in horizontal RPs will be replaced by 3D silicon modules with six sensor planes per RP. This should result in a ~ 10 \( \mu \)m position and a 1-2 \( \mu \)rad angular resolution. The 3D sensors will use the same readout as the Phase I CMS pixel upgrade.

REFERENCES

[16] The CMS collaboration, CMS Supersymmetry Physics Results/Summary plots for 8 TeV dataset, 11 September 2015, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS.