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Diffractive and Parton Processes with CMS and TOTEM Forward Detectors

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Abstract

The Compact Muon Solenoid (CMS) experiment, in the Large Hadron Collider (LHC) at CERN, has several forward sub-detectors, consisting of calorimeters close to the beam pipe, that complement the central part of CMS, which covers a pseudorapidity range from -3 to +3. The TOTEM experiment, installed around the same interaction point as CMS, is tailored for diffractive measurements. CMS and TOTEM have strengthened their collaboration on a common project to achieve maximum forward acceptance and to perform measurements at full LHC luminosity.

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Diffractive and Parton Processes with CMS and TOTEM Forward Detectors ☆,☆☆

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Abstract

The Compact Muon Solenoid (CMS) experiment, in the Large Hadron Collider (LHC) at CERN, has several forward subdetectors, consisting of calorimeters close to the beam pipe, that complement the central part of CMS, which covers a pseudorapidity range $|\eta| < 3$. The TOTEM experiment, installed around the same interaction point as CMS, is tailored for diffractive measurements. CMS and TOTEM have strengthened their collaboration on a common project to achieve maximum forward acceptance and to perform measurements at full LHC luminosity.

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1. Introduction

The Compact Muon Solenoid (CMS) detector of the LHC at CERN, is described in [1]. The central part of CMS covers a pseudorapidity range $|\eta| < 3$. In the forward region CMS is complemented by several subdetectors, designed for events with activity at small angles.

1.1. CMS Forward Detectors

Detectors based on Cherenkov light produced in quartz elements meet the requirements of superior radiation resistance and time resolution to survive and operate near the intense LHC beams and are ideal components for forward calorimeters [2]. In CMS three such calorimeter systems extend its forward $|\eta|$-acceptance:

- *Two Hadron Forward (HF) calorimeters* [3] , located 11 m from the CMS interaction point (IP5), cover the $3.0 < |\eta| < 5.2$ region.
- *The CMS CASTOR calorimeter* [4], located 14 m from IP5, only at one side of CMS, covers the range of $-5.2 > \eta > -6.6$.
- *Two CMS Zero Degree Calorimeters (ZDC)* [5] , are installed at 140 m from IP5, at the end of the straight sections, to detect very forward neutral particles, with $|\eta| > 8$.

Forward Shower Counters (FSC) [6], made of scintillator paddles, cover the non-instrumented region ($6 < |\eta| < 8$) between CASTOR and ZDC, with the role of detecting hadron production at large rapidity and selecting events with diffractive rapidity gaps, i.e. η-intervals devoid of particles [7].

1.2. The TOTEM experiment

The TOTEM experiment [8], located at IP5, aims at detecting forward hadronic phenomena, in particular diffractive processes, and comprises three subdetectors:

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- *The Forward Trackers T1, T2* are embedded in the forward parts of CMS on each side of the interaction point IP5.The η-coverage is $3.1 \le |\eta| \le 4.7$ for T1 and $5.3 \le |\eta| \le 6.5$ for T2; they can be used also for defining rapidity gaps.
- *The Roman Pots (RP) system* consists of four stations placed between 203 m and 220 m on both sides of IP5. The RPs are movable beam-pipe insertions that can bring detectors to millimetric distance from the beams once they are stable.

The combination of CMS and TOTEM setups (Fig. 1) gives an exceptionally large η-coverage for tracking and calorimetry that is well suited for studies of a wide range of proton and nuclear interaction phenomena.

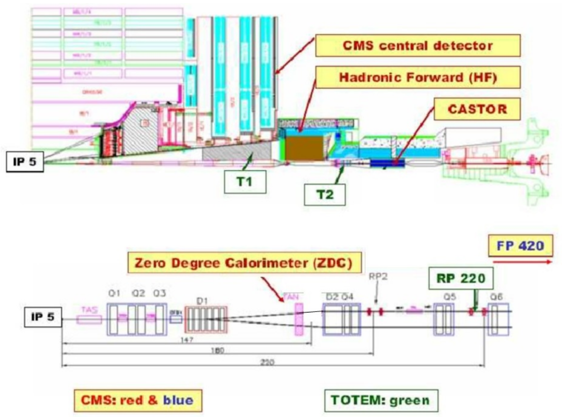

Figure 1: The CMS and TOTEM forward setups at IP5. A first stage of the FP420 project is concretizing in the CMS+TOTEM PPS [9].

2. Physics Goals

With such a large acceptance CMS and TOTEM represent powerful tools to access a broad physics program within and beyond the Standard Model [10]. Events populating the forward regions can be mapped in detail and give access to soft hadronic processes (in a non-perturbative regime of QCD) or to hard parton interactions (probing perturbative QCD and EW phenomena).

The forward detectors may have different roles, besides measuring the forward particles, for instance providing special tags to identify interesting classes of events. Typically the presence of diffractively or elastically scattered protons in RPs (neutrons in ZDCs) may be the signature of Pomeron ($\mathbb{P}$) exchange [11]. Another characteristic tag provided by forward detectors is the detection in HF of associated jets from vector boson fusion (VBF) processes. Extending detection capability, in particular calorimetric, to very large rapidity, is important to correctly evaluate the missing energy E_T, for instance in SUSY searches. Physics topics accessible with CMS + TOTEM forward instrumentation are:

- *soft processes* (non-perturbative QCD): Pomeron-mediated processes such as elastic pp cross section [12], soft diffractive processes, rapidity-gaps and underlying events (UE);
- *hard processes* (perturbative QCD) : hard diffraction, low-x physics [13], gluon saturation, QCD evolution, parton distribution functions (PDFs), double-parton scattering (DPS);
- *very high energy cosmic rays*: hadronic models of interactions in the atmosphere can be compared with forward energy ($dE/d\eta$) and particle ($dN/d\eta$) flows measured at the LHC in pp, pA, and AA collisions, and may be tuned accordingly [14].

The Pomeron (colourless exchange without parton emission) leads to rapidity gaps, where forward detectors may be used as veto. When a hard scale is present in the process (the final state includes high-p_T jets, W or Z bosons, etc.) perturbative QCD is applicable and the dynamics can be formulated in terms of partons. Data are usually described in terms of the DGLAP or BFKL evolution equations [15] which govern parton radiation in Q^2 and in x respectively.

In the EW sector, vector boson fusion (VBF) processes (tagged with forward jets) and central exclusive production (CEP) from gluon/photon scattering (tagged with forward protons in the TOTEM RPs) allow to investigate production of hadronic or EW states and Higgs bosons, or (anomalous) gauge boson couplings [16].

3. Some significant/recent results

With the LHC operating since 2009 at $\sqrt{s}$ =0.9 TeV, 2.76 TeV, 7 TeV, 8 TeV, and recently 13 TeV, the experiments had unique opportunities to probe new domains for measurements and discovery. The physics items studied with the help of the forward equipment of CMS (and TOTEM) in LHC Run I, have been reviewed for instance in [17]; here few selected results are presented, including some from Run II at $\sqrt{s}$ = 13 TeV.

3.1. Forward particle and energy flow

A CMS + TOTEM joint paper [18] concerns measurements of charged-particles over a large pseudorapidity range for pp collisions at $\sqrt{s}$ = 8 TeV. Events of three categories: inclusive, single diffractive (SD) and non-single diffractive (NSD) are compared (Fig. 2) to five different Monte-Carlo (MC) event generators that do not provide a completely satisfactory description of the measured distributions; however it seems that central events are more compatible with PYTHIA, while in the forward region, cosmic ray MC generators, based on Gribov-Regge formalism, better approach the data.

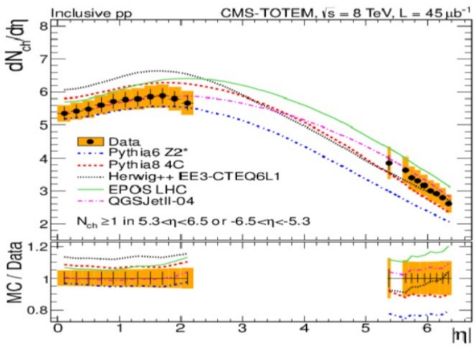

Figure 2: $dN/d\eta$ distributions for charged particles in pp collisions at $\sqrt{s}$ = 8 TeV. Inclusive events from a common CMS-TOTEM data sample (orange), are compared with 5 MC generators [18].

In fact, forward production data from the LHC may help to understand the air shower development of ultra-high energy cosmic rays; comparison of cosmic ray to accelerator data is not trivial, but important progress has been recently achieved [19].

Furthermore, measurements at the LHC may suggest ways to extrapolate from accelerator to cosmic ray energies; for instance, at $\eta = 0$, $dN/d\eta$ in different pp and $p\bar{p}$ experiments (Fig. 3), is found to depend on primary energy with a power-law: $dN/d\eta \sim s^{\epsilon}$. On the other hand, for a rapidity close to that of the beam (y_b), the hypothesis of limiting fragmentation, recently revisited and compared to data from $pp(p\bar{p})$, pA and AA collisions [20], implies a longitudinal scaling behavior in terms of a shifted pseudorapidity $\eta' = \eta - y_b$: particle production in the beam fragmentation region, $\eta' \approx 0$, becomes independent of $\sqrt{s}$ as seen also in Fig. 4.

The data at different $\sqrt{s}$ values tend to line up in the range $3 < |\eta| < 7$; full and dotted lines represent several PYTHIA-8 tunes and other generators, commonly used for cosmic rays. They provide reasonably accurate descriptions of the measured (transverse) energy flows.

3.2. Forward jets and dijets

High energy jets are very frequent in the LHC regime, and their presence witnesses the partonic structure of the interaction. CMS has valuable results, in particular from Run I at $\sqrt{s}$ = 7 or 8 TeV [22].

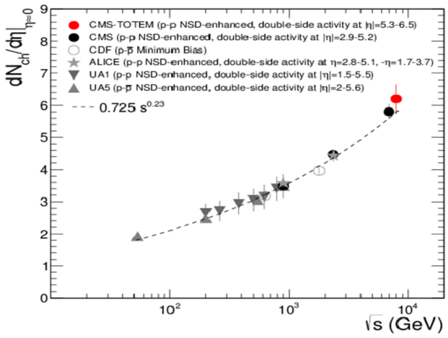

Figure 3: $dN/d\eta$ at $\eta = 0$ as a function of $\sqrt{s}$ in pp and $p\bar{p}$ collisions. Data with different NSD event selections from UA1, UA5, CDF, ALICE and CMS [18]. The dashed line is a power-law fit, giving $\epsilon = 0.23 \pm 0.01$.

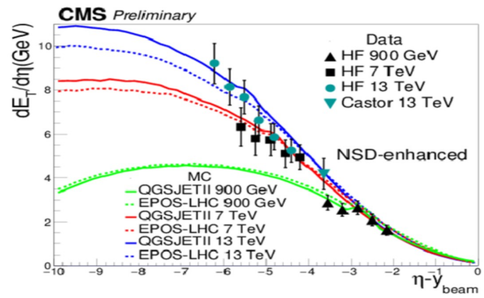

Figure 4: 13 TeV measurements of $dE_T/d\eta$ for NSD-enhanced events [21], as a function of η' compared to MC models and earlier pp data at several energies.

In multi-TeV collisions at the LHC, the parton fractional momenta $x = (2p_T/\sqrt{s})e^y$ can be as low as 10^{-5} at large y. Low-x gluon distributions affect the cross sections of forward inclusive jets. More insight in the regime of parton evolution (DGLAP *vs.* BFKL) could be obtained from dijets (Mueller-Navelet jets) with wide rapidity separation. For BFKL, extra parton radiation between the two jets could alter the DGLAP back-to-back topology, producing an azimuthal decorrelation $\Delta\phi$ with increasing $\Delta\eta$.

In inclusive single jet production only modest sensitivity to PDF is observed; instead the data are sensitive to multi-parton (MPI) effects [23]. For Mueller-Navelet jets, distributions of $\Delta\phi$ and functions thereof, enhancing sensitivity to azimuthal asymmetries, were measured in CMS at 7 TeV [24] in order to distinguish between DGLAP and BFKL regimes; recent NLL BFKL calculations [25], seem to give a better agreement with the data (to be possibly further improved [26]).

3.3. Central Production with Leading Protons

When CMS is supplemented with forward information from TOTEM, new classes of events become accessible. For instance the production of a central state X through a diffractive process, $pp \to p\ (+)\ X\ (+)\ p$, where the interacting protons remain intact and rapidity gaps (+) are formed between the protons and the state X. If the state X has definite quantum numbers the process is called Central Exclusive Production (CEP) [27]. The dominant contribution comes from $\mathbb{PP}$ scattering, and the state X should obey the following selection rules: $J_z = 0$, C-even, P-even.

In these events, the 4-momentum of X is measured in the CMS central detector, but can be also calculated from the fractional momentum loss ξ of the proton(s) (ξ=$\Delta p/p$). The invariant mass M_X of the system X, obtained in CMS should agree with $M_{pp} \approx \sqrt{\xi_1 \xi_2 s}$. Transverse ($p_T$) and longitudinal ($p_z$) momenta of X and of the pp system should match. The rapidity gap $\Delta\eta$ may be expressed as $\Delta\eta \approx -ln\ \xi$.

The physics topics covered by measurements of CEP processes include spectroscopy of low-mass resonances and glueball states [28], studies of the rapidity gap survival probability as well as searches for new physics via missing mass or E_T. Some results have been obtained already, in particular at the Tevatron [29]. A more general review of CEP phenomenology, techniques and results, of interest also for the LHC, is given in [30].

The first CMS+TOTEM common data taking was performed in July 2012, during special pp runs at $\sqrt{s}$ = 8 TeV with β^* = 90 m and low luminosity giving small pileup. Each experiment took data separately as usual, but with a bidirectional exchange of trigger information; the events were synchronized offline and data buffers were merged. The results presented in [18] on $dN_{ch}/d\eta$ were obtained in this way. Data corresponding to high-p_T triggers in CMS central detector and one proton in TOTEM RPs on each side of IP5 come from an integrated luminosity $\approx 50\ nb^{-1}$. In addition, the CMS FSC ($6 < |\eta| < 8$) were required to have no hits (rapidity gap tag). The low pileup condition is essential when studying these events, which would be spoiled by multiple interactions in the same bunch crossing.

A preliminary analysis using the CMS+TOTEM data identified few candidates [31] for central high-p_T jets production with two leading protons $pp \to p + jets + p$. One such candidate event is shown in Fig. 5. The runs in 2012 did not reach useful statistics for significant CEP studies, but gave a base for determining the best operating conditions for Run II.

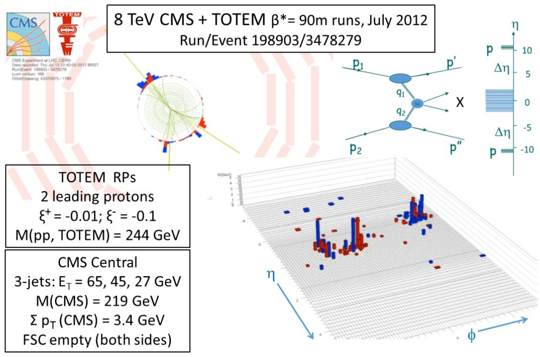

Figure 5: Triple jet event with leading protons from 8 TeV, CMS+TOTEM β^* = 90 m, pp run, July 2012 [31]. Proton tracks ($\xi^+ \approx -0.01$) and ($\xi^- \approx -0.1$) in TOTEM RPs. Three jets E_T = 65, 45, 27 GeV; $M_X(pp, \text{TOTEM})$ = 244 GeV, $M_X(\text{CMS})$ = 219 GeV. FSC empty in both sides (rapidity gaps).

4. Plans for CMS+TOTEM PPS

The standard LHC program leaves little time for CMS-TOTEM special runs with β^* = 90 m at low luminosity, as needed to unequivocally identify diffractive events in low pile-up conditions. On the other side, some CEP processes have small cross sections, and would need extended running with high luminosity. Therefore CMS and TOTEM studied methods to allow forward measurements in normal LHC high luminosity runs. This project, called CMS+TOTEM Precision Proton Spectrometer (CT-PPS) [9] aims at measuring with high precision processes with O(fb) cross-sections in normal LHC high luminosity runs.

The experimental challenges are essentially related to large pileup, giving multiple pp interactions per bunch crossing, and detectors operating very close to the LHC beams under critical radiation levels: proton flux up to 5×10^{15} cm^{-2} on the detectors and 100 Gy on the readout electronics, for 100 fb^{-1} luminosity. The detectors should be radiation resistant, and precise time-of-flight (ToF) measurement of leading protons should reduce pileup effects by precisely selecting the associated interaction vertex (σ_t = 10 ps corresponds to σ_z = 2 mm). Two ToF options have been considered:

- Cherenkov detectors associated with high resolution photodectors: the radiators could be gaseous (GasToF)[32] or quartz bars (Quartic) [33]; these materials suffer very little radiation damage and produce very fast signals with extremely precise time resolutions: $\sigma_t \approx$ 10 ps was achieved in test beam for an individual GasToF detector and $\sigma_t \approx 30$ ps for a Quartic.

- Solid state detectors: for diamond detectors [34] time resolution σ_t in the range $80-110$ ps has been measured for a single element; for a group of 4 diamond detectors, $\sigma_t = 50$ ps was demonstrated, corresponding to $\approx$ 1cm vertex resolution. Ultrafast silicon detectors [35] achieve $\sigma_t = 26-35$ ps individually and $\sigma_t = 15-20$ ps for a triplet.

In 2016, diamond detectors, already baseline for the TOTEM upgrade, have been adopted also for CT-PPS and installed in the RPs dedicated to the ToF system; tracking was provided by TOTEM silicon strip detectors. After a preliminary phase to prove the compatibility of the CT-PPS setup with standard operation of the LHC beams, the CT-PPS RPs were inserted at 15σ from the beams. A fully integrated CMS-TOTEM DAQ collected 15 fb^{-1} of pp data at $\sqrt{s}$ = 13 TeV, at instantaneous luminosities up to 1.3×10^{34} cm^{-2}s^{-1}.

5. Conclusions

The field traditionally known as "Forward Physics" has undergone an important evolution at the LHC; originally using modest amounts of beam and requiring special running conditions, incompatible with the standard LHC operation, it has developed a successful strategy to take full advantage of the rapid progress in the LHC luminosity. CT-PPS was able to rise to the challenge of operating at standard LHC conditions (low-β^* and high luminosity) as normally done by CMS, paving the way to new diffractive studies of unprecedented precision. The situation is here described from a CMS viewpoint; thanks to close collaboration with TOTEM, the necessary upgrades are well advanced. ATLAS has similar plans in development.

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