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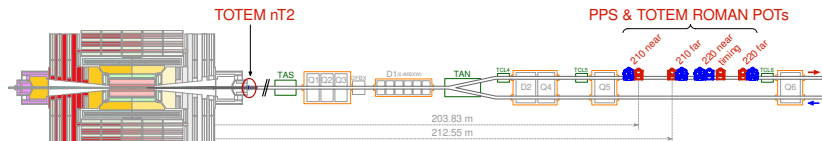
TOTEM overview

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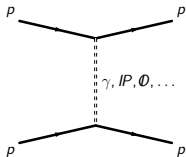
on behalf of the TOTEM Collaboration

Particle Physics Day 2020, Helsinki, Finland

November 5, 2020



- Combined TOTEM-DØ **evidence for odderon**
- Search for exclusive **light-by-light production** with forward proton tags with CMS-TOTEM PPS
- Development of nT2, a **diffractive interaction tagger** in TOTEM
- Other **TOTEM-PPS activities**



Multiple **elastic t-channel** scattering processes (i.e. where both protons arise unfragmented from their interaction) reachable at high- \sqrt{s} at LHC:

$$pp \rightarrow (p)(X)(p),$$

with a **colourless state** $X =$

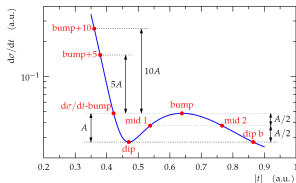
- low-mass mesons, γ (electromagnetic/Coulomb interaction),
- IP (C -even gluon doublet), or
- a C -odd three gluon compound: the **odderon**.

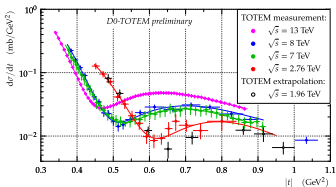
Different behaviour expected between pp and $p\bar{p}$ spectra for C -odd interaction:

$$d\sigma_{el}/dt, \quad \rho \text{ (real-to-imaginary ratio of nuclear elastic amplitude at } t = 0)$$

Combination of two **high- β^* /low bunch multiplicity** datasets with forward proton detectors:

- 2M elastic $p\bar{p}$ data collected at 1.96 TeV in DØ, $|t|$ resolution ranging from 0.02 – 0.04 GeV²
- elastic pp cross section measurement data collected at 2.76, 7, 8, and 13 TeV in TOTEM, **extrapolated to $\sqrt{s} = 1.96$ TeV** using 8 characteristic points of the $d\sigma_{el}/d|t|$ distribution





Data-driven **TOTEM/DØ relative normalisation** for total $pp/\rho\bar{p}$ cross section obtained from $(d\sigma/dt)$ at optical point ($t = 0$), and using optical theorem

$$(d\sigma/dt)|_{t=0} \propto (1 + \rho^2)\sigma_{\text{tot}}^2,$$

with $\rho = 0.145$ @ 1.96 TeV, predicted from COMPETE fits.

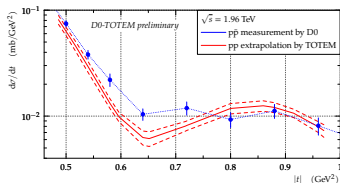
Total pp cross section extrapolated down to DØ CM energy from broad TOTEM \sqrt{s} range

Difference in elastic $pp/\rho\bar{p}$ cross sections can be explained by exchange of a **new C-odd gluonic compound**.

Two TOTEM/DØ compatibility tests performed:

- (shape-based) Kolmogorov-Smirnov for differential spectra: **2.33 σ discrepancy** observed,
- integrated elastic cross section difference in $0.48 < |t| < 1$ GeV² range: **2.11 σ significance**.

Combined **> 3 σ significance** through Stouffer method [Stouffer, S. *et al* (1949)].

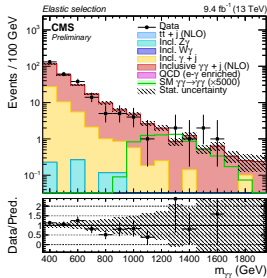
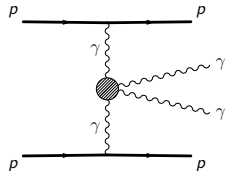


Evidence for two scattering amplitudes contributing to elastic differential cross section, one **C-even pomeron**, and one **C-odd odderon** exchange (with relative sign differing between pp and $\rho\bar{p}$).

Using the combined **CMS-TOTEM Precision Proton Spectrometer (PPS)** as forward proton tagger, **search for $\gamma\gamma \rightarrow \gamma\gamma$** performed with 9.4 fb^{-1} **high-luminosity data** collected in 2016.

Phase space probed:

- “standard” CMS run 2 high- p_T diphoton HLT paths, $p_T^\gamma > 75 \text{ GeV}$, $|\eta_\gamma| < 2.5$,
- high-mass $\gamma\gamma$ system ($m_{\gamma\gamma} > 350 \text{ GeV}$), ensuring **low QCD background** contamination at 13 TeV, at most one photon in ECAL endcap
- central (two-photon system) **elasticity condition** through *acoplanarity* $a \equiv 1 - |\Delta\phi_{\gamma\gamma}/\pi| < 0.005$



266 elastic diphoton candidates selected centrally, with a prediction of 263.1 ± 4.1 (stat) events

Main **background sources**: inclusive $\gamma\gamma$ production processes, mis-identification of W/Z associated production with γ

Negligible SM $\gamma\gamma$ component, **sensitive to anomalous quartic coupling** (e.g. dimension-8 EFT) extensions

$$\mathcal{L}_8 = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\mu\rho} F_{\rho\sigma} F^{\sigma\nu}$$

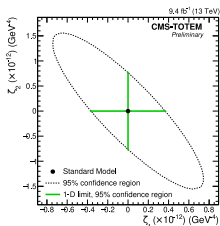
Further mitigation of inclusive background through selection of candidates with **two opposite-side proton tags**, and compatible central-forward systems kinematics:

$$m_{pp} = \sqrt{s\xi_1\xi_2} \text{ vs. } m_{\gamma\gamma}, \text{ and } y_{pp} = \frac{1}{2} \log \frac{\xi_1}{\xi_2} \text{ vs. } y_{\gamma\gamma},$$

with $\xi = \Delta p/p$ the **fractional proton momentum loss** ($\propto x$, proton track displacement in Roman pot).

Accounting for **asymmetric PPS ξ acceptance** in its two arms, **2 events remain** with prediction of $2.11^{+0.96}_{-0.66}$ (stat).

No event matches at 2σ both in mass and rapidity, with a data-driven prediction of $0.23^{+0.08}_{-0.04}$ (stat) background events

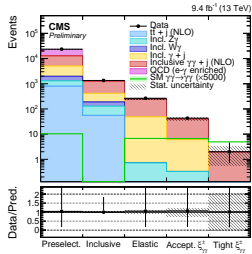


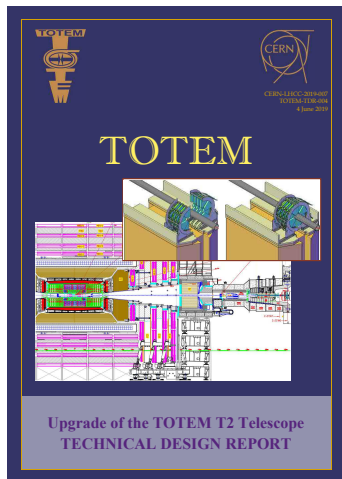
Upper limit set on $pp \rightarrow p(\gamma\gamma \rightarrow \gamma\gamma)p$ production cross section: at 95% C.L.,

$$\sigma_{\text{LbyL}} < 3.0 \text{ fb} \quad (0.070 < \xi_1 < 0.111, \text{ and } 0.070 < \xi_2 < 0.138),$$

which can be translated into 1D and 2D **limits on dimension-8 anomalous parameters:**

$$|\zeta_1| < 3.7 \times 10^{-13} \text{ GeV}^{-4} (\zeta_2 = 0), \quad |\zeta_2| < 7.7 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0).$$





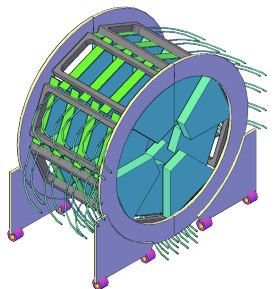
Used in **luminosity-independent measurement of total cross section** in LHC run 3 at $\sqrt{s} = 14$ TeV (low-luminosity special LHC fills)

- 80-85% detection efficiency of inelastic events with CMS tracker+HF only
- going up to > 90% with nT2

Reproduce the ρ and $(d\sigma_{el}/dt)|_{t=0}$ measurements at 14 TeV, and study of **energy evolution** for diffractive minimum/second maximum region in this regime

Expected operation mode:

- aiming at collecting 2.1×10^8 inelastic pp events (72h) at 14 TeV
- nominal $\mathcal{L}_{inst} = 10^{28} \text{ cm}^{-2}\text{s}^{-1}$, $\beta^* = 2.5$ km optics inducing a **very-low pileup** $\langle \mu \rangle \lesssim 0.1$



Mechanical integration and readout

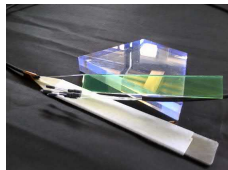
$5.3 < |\eta| < 6.5$ coverage on both sides of CMS
($z = \pm 15$ m), reaching $m_{X,\min} \sim 4.8$ GeV at 14 TeV

2×32 **plastic scintillator tiles** distributed 45 mm around both beamlines downstream from IP5, optical fibre light guides down to Hamamatsu S13361-6050 16-channel SiPMs.

Discrimination through **NINO chips**, readout through TOTEM-PPS digitiser board already **successfully operated in PPS timing detector**

Common effort between **HIP** (K. Österberg, F. Garcia, LF) , **INFN**, and **CERN** for the prototyping, characterisation, production, commissioning, and installation of scintillator tiles, to be ready for first special runs of LHC run 3.

Final prototype tested using **cosmic rays** at CERN during LS2, **detailed characterisation and optimisations** will be carried out with results obtained from forthcoming **test beam campaigns** at DESY-II, PSI π M1, and CERN SPS.



New timing station for PPS

High radiation hardness, fast response/low noise **scCVD (diamond) detectors** used since 2017 as **timing component of PPS** (~80 ps timing track resolution)

Second station to be installed in new PPS Roman pot for run 3, increased acceptance and time resolution expected

Helsinki Institute of Physics deeply involved in this process:

- procurement of all scCVDs (production at *Element Six*, metallisation at Dept. of Physics, Princeton University)
- quality assurance (optical and electrical characterisation) (K. Österberg, P. Koponen, M. Rantanen)
- installation and commissioning of final detectors (F. Garcia, LF)
- preparation of offline software (LF)

Offline software for PPS-TOTEM

HIP also involved in offline software maintenance and development for

- PPS **timing detectors** (reconstruction, online calibration loop, commissioning code)
- TOTEM **nT2** (integration into CMS environment of calibration, reconstruction, commissioning code)
- new CMS **trigger developments** with PPS proton tags

Finland & Helsinki Institute of Physics play a large role in TOTEM and PPS operations, analysis effort, and R&D programme

TOTEM once again proved its potential for **groundbreaking discoveries**, such as the effect of **odderon** on $pp/p\bar{p}$ differential elastic cross section discrepancy

With first two highlighted papers, PPS is also gaining a large interest exceeding the forward physics community, proven **potential for exotic searches**

Despite current sanitary situation, **heavy preparation work** ongoing along LS2 for nT2 installation/commissioning, and quest for increased sensitivity in TOTEM-PPS measurements at 14 TeV