CMS-TOTEM highlights

LHCP2021: 9th Edition of the Large Hadron Collider Physics Conference

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on behalf of the CMS and TOTEM Collaborations

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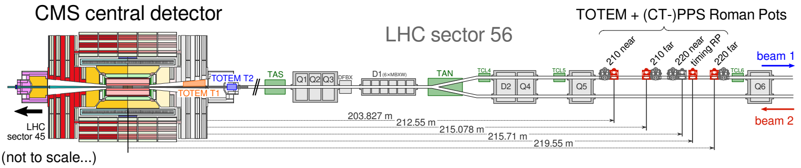
Joint CMS-TOTEM operations



TOTEM in a CMS environment [low-PU]:

- Tracking telescopes (T1 and T2) for the measurement of inelastic interactions in the $3.2 \leq |\eta| \leq 6.5$ range [not covered here]
- Horizontal + vertical Roman pots (RPs) for the **detection** of **forward scattered protons**, measurement of $\xi_p = 1 - |\mathbf{p}_f / \mathbf{p}_i|$, and $t = (p_f - p_i)^2$
- coordination of 2 data acquisition systems sharing one trigger scheme

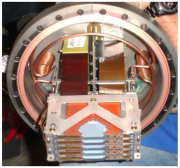
CMS(–TOTEM) Precision Proton Spectrometer [high-PU]:

- Horizontal Roman pots (RPs), located at $>$ 200 m from CMS interaction point
- **tracking** and **timing components** fully integrated in the CMS readout environment
- designed for **high-luminosity** operation mode

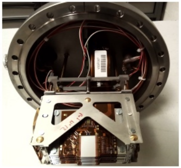
With **CERN-CMS-TOTEM MoU** [CERN-MoU-2018-003], the two Collaborations merged in 2018. TOTEM will nevertheless measure diffraction and total *pp* cross section at 14 TeV along run 3.

This talk will cover the **physics output of the common operations** during LHC runs 1–2.

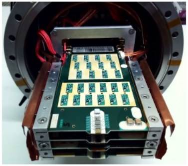
PPS-TOTEM Roman pots



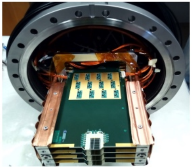
Silicon strips



3D pixels



scCVD (diamond)



ultra-fast Si-detector

TOTEM silicon strips [CERN-CMS-DP-2018-056, CERN-CMS-DP-2019-035]

- horizontal (**PPS cylindrical RP**) and vertical (**TOTEM only**) stations, 10 planes, $\sigma \sim 12\ \mu$m
- optimised for TOTEM with **high-**β^* conditions: no multi-tracking, radiation damage: $\Phi_{\mathrm{max}} \sim 5 \times 10^{14}$ p/cm^2
- used **all along TOTEM operations** ; in PPS, only used first two years of operations
- [this talk will cover this subdetector only for the PPS-TOTEM part]

PPS diamond timing detectors [CERN-CMS-DP-2019-034, CERN-CMS-DP-2020-046]

- hybrid single/double layer diamond, first time installed at LHC
- expected $\delta t \sim 80$ ps/plane + 1 plane of UFSD with $\delta t \sim 30$ ps/plane, $\Phi_{\mathrm{max}} \sim 10^{15}$ nev/cm^2

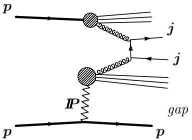
PPS 3D pixels [CERN-CMS-DP-2019-036]

- 6 planes stations, same readout technology as CMS phase 1 central pixel
- $\sigma_x \sim 15\ \mu$m, $\sigma_y \sim 30\ \mu$m, $\Phi_{\mathrm{max}} \sim 5 \times 10^{15}$ p/cm^2

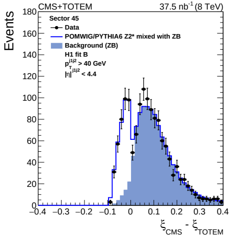
Physics output

Topology of single diffraction interesting experimentally: at least one proton observed with large rapidity gap (LRG)

- theoretically described through factorisation theorem: diffractive PDFs convolution with pQCD
- more complex in *pp* than e.g. in *ep* (soft rescattering between spectator partons)



Low-pileup, **special** β^* **= 90 m optics run** ($\langle\mu\rangle$ = 6 − 10%), 37.5 nb^{-1} at 8 TeV in 2012



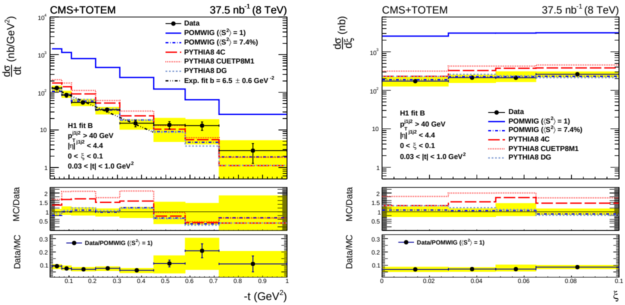
Kinematic selection:

- two **anti-k_T jets**, $p_{T,j} > 40$ GeV, within $|\eta_j| < 4.4$
- jets observed in **opposite sides of CMS**
- primary vertices multiplicity ≥ 1
- at least **one intact proton** observed in TOTEM RPs acceptance:
  - $0 < x_{RP} < 7$ mm and $8.4 < |y_{RP}| < 27$ mm,
  - $\xi_p < 0.1$, and $0.03 < |t| < 1$ GeV^2

Main background arising from **beam halo** and **pileup**

- yield estimated using proton kinematics from **zero bias events** mixed with SD POMWIG and Pythia MC events
- large rejection (84.3 and 83.2% for the two sectors) through $\xi_{central} - \xi_p \leq 0$, with $\xi_{central} = (1/\sqrt{s}) \sum_{j_1, j_2} (E \pm p_z)$

Single-diffractive dijet production in proton-proton [Eur. Phys. J. C 80, 1164 (2020)]



Iterative D'Agostini unfolding with early stopping ($<$ 5% relative χ^2 variation between iterations)

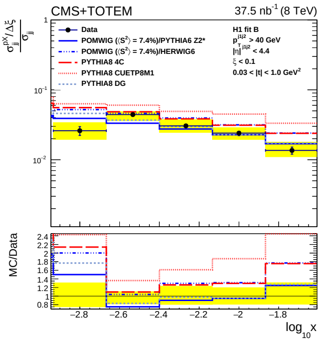
- Total cross section extracted for $p_\mathrm{T} > 40$ GeV, $|\eta| < 4.4$, $\xi < 0.1$, and $0.03 < |t| < 1$ GeV^2:

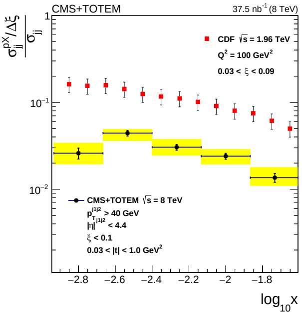
$$\sigma_{jj} = 21.7 \pm 0.9\ \text{(stat)}\ {}^{+3.0}_{-3.3}\ \text{(syst)} \pm 0.9\ \text{(lumi) nb}$$

Best described by diffractive dijet modellings:

- **Pythia 8 dynamic gap** (DG) and **POMWIG** with $7.4^{+1.0}_{-1.1}$% constant survival factor (incl. Reggeon exchanges)
- central Pythia 8 (4C and CUETP8M1) tunes predict uniformly larger yields

Single-diffractive dijet production in proton-proton [Eur. Phys. J. C 80, 1164 (2020)]





Ratio of **SD dijet** and **inclusive dijet cross sections** is extracted in bins of ξ

Large deviation observed at low-x, although POMWIG and Pythia 8 DG give better description

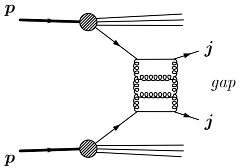
Cross section lower compared to CDF observation at 1.96 TeV [Phys. Rev.D86, 032009]

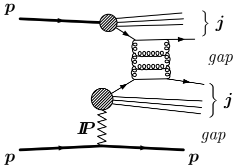
- **centre-of-mass energy dependence** already observed at CDF using $\sqrt{s}$ = 0.63 and 1.8 TeV runs comparison

Hard colour-singlet exchange in 2-jet events [arXiv:2102.06945 [hep-ex], submitted to PRD]

Scope: study of the non-perturbative/perturbative limits of QCD through the study of events with LRG observed without, and with association to intact protons

- exploiting signature of a **colour-singlet *t*-channel** (perturbative pomeron) exchange
- allows to probe the BFKL evolution
- main background: colour-exchange dijet production

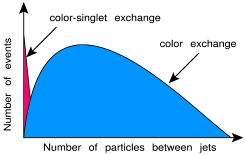




High-β^* run ($\langle\mu\rangle$ = 5 − 10%), 0.66 pb^{-1} at 13 TeV in 2015

Kinematic selection:

- two **anti-k_T jets**, $p_{\mathrm{T,j}} > 40$ GeV, within $1.4 < |\eta_j| < 4.7$
- jets observed in **opposite sides of CMS**
- primary vertices multiplicity ≥ 1

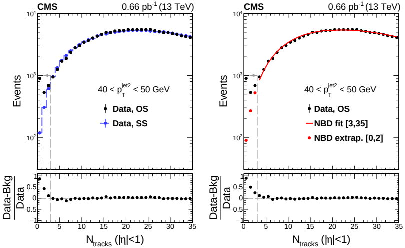


For subclass of events **with leading proton**:

- at least one intact proton observed in TOTEM RPs: $\xi_p < 0.2$, $0.025 < |t| < 4$ GeV^2
- central-forward association through matching in ξ_p and $\xi_{\mathrm{central}} = (1/\sqrt{s}) \sum_{j_1,j_2} (E \pm p_z)$

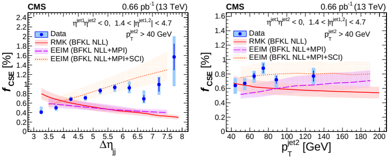
Data-driven approach to estimate colour-exchange background contribution fluctuations at low track multiplicities:

- Background-dominated dijet control sample built from two jets on the same-side (SS) of CMS, normalised to opposite-side (OS) dijet events, for $N_{\text{track}} > 3$
- Negative binomial distribution (NBD) function: fit data with $3 \leq N_{\text{track}} \leq 35$, and extrapolate to $N_{\text{track}} = 0$.

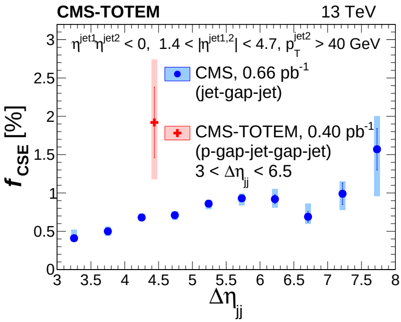


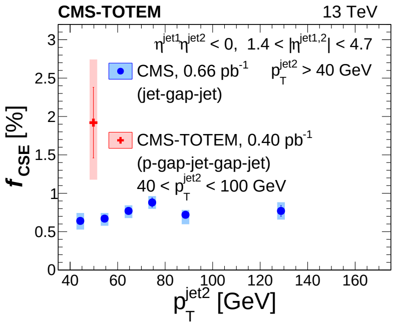
Fraction $\mathbf{f_{CSE}} = \frac{\mathbf{N^F - N^F_{non\text{-}CSE}}}{\mathbf{N}} = \frac{N(N_{\text{tracks}}<3) - N_{\text{bkg}}(N_{\text{tracks}}<3)}{N_{\text{all}}}$ of colour-singlet exchange events both studied in subsamples **without** and **with leading proton** selection.

- For the former, studied differentially and compared with **BFKL NLL resummation** with LO impact factors predictions.
- Well described with **EEIM model** [Phys.Lett.B 524:273] with **MPI** and **soft colour interaction** (SC)



Hard colour-singlet exchange in 2-jet events [arXiv:2102.06945 [hep-ex], submitted to PRD]





For events **with leading proton**, observed a f_{CSE} fraction 2.91 ± 0.70 (stat) $^{+1.02}_{-0.94}$ (syst) times larger than **without proton selection**, with similar dijet kinematics.

Consistent with previous findings by CDF in DPE dijet/SD dijet results.

Better likelihood of central gap surviving the collision due to lower spectator parton activity in events with intact protons.

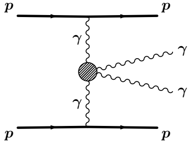
Perfect example of a CMS-TOTEM synergy for such precision measurements

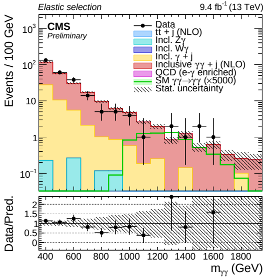
Using the combined **CMS-TOTEM Precision Proton Spectrometer (PPS)** as forward proton tagger, **search for $\gamma\gamma \to \gamma\gamma$** performed with 9.4 fb^{-1} **high-luminosity data** collected in 2016.

Same run conditions as used for **first CT-PPS paper**: observation of $\gamma\gamma \to l^+l^-$ with leading proton [JHEP 07 (2018) 153]

Phase space probed:

- "standard" CMS run 2 high-p_T $\gamma\gamma$ triggers, $p_T^\gamma > 75$ GeV, $|\eta_\gamma| < 2.5$,
- high-mass $\gamma\gamma$ system ($m_{\gamma\gamma} > 350$ GeV), ensuring **low QCD background** contamination at 13 TeV, ≤ 1 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 $\pm$ 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

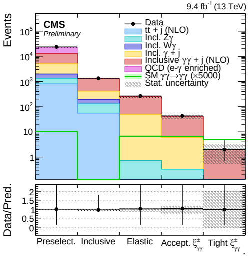
$$\mathcal{L}_8 = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

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

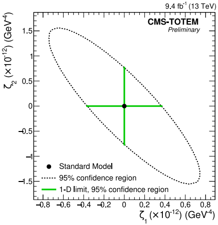
$$m_{pp} = \sqrt{s\xi_1\xi_2} \text{ vs. } m_{\gamma\gamma}, \quad \text{and} \quad y_{pp} = \frac{1}{2}\log\frac{\xi_1}{\xi_2} \text{ vs. } y_{\gamma\gamma},$$

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 $pp \to p(\gamma\gamma \to \gamma\gamma)p$ **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**:

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

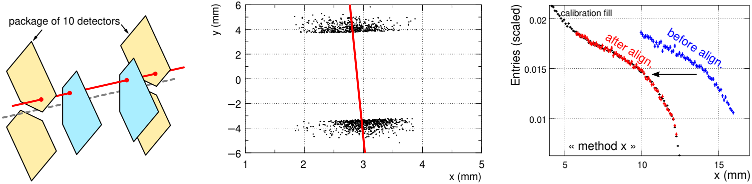
Summary

The close collaboration between the CMS and TOTEM experiments has made it possible to explore a rich forward QCD and exclusive physics programme:

- limits of **perturbative QCD** and **factorisation theorem** probed through measurement of single diffraction, and colour-singlet t-channel exchanges
- search for **anomalous light-by-light production** process in the exclusive mode, using scattered two-proton system
- combined complex, **central system objects** (dijet, diphoton) with **leading proton tag** as detected in forward Roman pots, combining expertise of the two “worlds”
- much more high quality run 2 data are available, and an upgraded PPS will operate in high luminosity run 3.

Backup

TOTEM-PPS detectors alignment [CERN-TOTEM-NOTE-2017-001]



General **alignment technique** developed and **extensively used** by the TOTEM Collaboration, adapted to high-luminosity operation mode

Absolute Roman Pots alignment using dedicated low-intensity bunches (alignment runs):

- **beam-based absolute alignment** between LHC collimators and RPs (rate monitoring with BLMs of beam edge scraping with pots)
- use ***pp*** $\longrightarrow$ ***pp*** **scattering events** with both horizontal and vertical pots inserted very close to the beam to extract **absolute** and **relative** (in overlapping regions) **per-pot alignments** (incl. rotations)

Per-LHC fill pots alignment:

- one-dimensional match of hit distributions in **inclusive proton sample** from high-luminosity fills and from **alignment run**

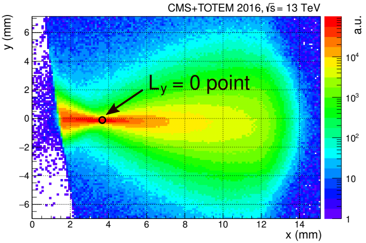
“x-to-ξ” calibration [New J. Phys. 16 (2014) 103041, CERN-TOTEM-NOTE-2017-002]

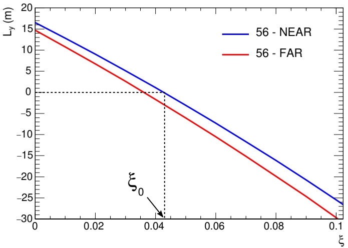
- Optics matching uses MAD-X modelling of full beamline optical components (quadrupole strengths, RPs/BPMs positions, ...)
- Dispersion calibration uses the **vertical pinch point $L_y(\xi_0) = 0$** at which vertical impact points spread is minimal.
- Final result is a (non-linear) calibration of ξ vs. the measured track x position:

$$x = D_x(\xi) \cdot \xi$$

Overall uncertainty of **5.5%** in the $D_x(\xi)$ determination procedure

- added in quadrature to kinematic (angular/transverse) tracks kinematic uncertainties to extract the ξ resolution

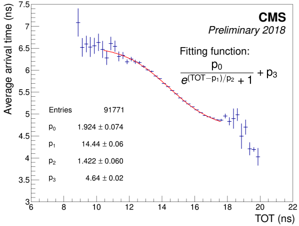


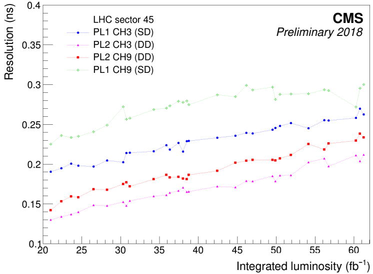


Timing detectors calibration [CERN-CMS-DP-2019-034]

Two-steps **per-channel calibration** for single- and double-diamond pads:

- correction and alignment of measured time of arrival as a function of signal pulse width (TOT) from NINO ($\propto Q$)
- iterative computation of time precision for each pad





Double diamond sensors 70% more efficient than single diamonds

Two components identified in timing precision degradation:

- 20-50% damage for sensor and readout electronics (preamplification stage)
- region closest to the beam: metallisation/bulk creation of trapping centres, thus reducing signal yield

With this calibration technique, and improved knowledge of operational parameters, ultimate run 3 resolution goal of < 30 ps per station within reach