L. Forthomme¹, on behalf of the TOTEM Collaboration

¹ Helsinki Institute of Physics, University of Helsinki
Outline

• Run 2 physics results
  - recent TOTEM papers and CMS-TOTEM paper in preparation

• Hardware upgrades
  - new T2 telescope
  - Roman pot related LS2 activities
  - timing detectors upgrades
Reminder: $\sigma_{\text{tot}}$ measurement at the LHC?

- Basic principle: detection of inelastic + elastic proton-proton scattering events in special, low-intensity (high-$\beta^*$) runs to quote a total p-p cross section measurement.

- Using luminosity-independent method:

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{[dN_{\text{el}}/dt]_{t=0}}{N_{\text{el}} + N_{\text{inel}}}$$
TOTEM (+ CMS PPS) layout

T2 telescope
- both LHC sectors, 15 m from IP5
- counting of inelastic events through detection of final state particles in high-|η| regions (5.3–6.5)
- at 14 TeV, > 90% detection efficiency of inelastic events (80–85% with CMS tracker+HF only)

Roman pots (RPs)
- direct measurement of outgoing scattered protons, LHC optics as spectrometer for kinematics reconstruction + time of flight
- located at ~220 m from IP5, multiple sensors technologies
- inserted in standard high-lumi fills (CMS PPS) and special high-β* runs (TOTEM)
Run II physics results
Status of physics papers

- "First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies"
Status of physics papers

- "First determination of the $\rho$ parameter at $\sqrt{s} = 13$ TeV – probing the existence of a colourless three-gluon bound state"

Abstract

The TOTEM experiment at the LHC has performed the first measurement at $\sqrt{s} = 13$ TeV of the $\rho$ parameter, the real to imaginary ratio of the nuclear elastic scattering amplitude at $t = 0$, obtaining the following results: $\rho = 0.09 \pm 0.01$ and $\rho = 0.10 \pm 0.01$, depending on different physics assumptions and mathematical modelling. The unprecedented precision of the $\rho$ measurement, combined with the TOTEM total cross-section measurements in an energy range larger than 10 TeV (from 2.76 to 13 TeV), has implied the exclusion of all the models classified and published by COMPETE. The $\rho$ results obtained by TOTEM are compatible with the predictions, from alternative theoretical models both in the Regge-like framework and in the QCD framework, of a colourless 3-gluon bound state exchange in the $t$-channel of the proton-proton elastic scattering. On the contrary, if shown that the 3-gluon bound state $t$-channel exchange is not of importance for the description of elastic scattering, the $\rho$ value determined by TOTEM would represent a first evidence of a slowing down of the total cross-section growth at higher energies. The very low-|$t$| reach allowed also to determine the absolute normalisation using the Coulomb amplitude for the first time at the LHC and obtain a new total proton-proton cross-section measurement $\sigma_{\text{tot}} = (110.3 \pm 3.5)\ \text{mb}$, completely independent from the previous TOTEM determination. Combining the two TOTEM results yields $\sigma_{\text{tot}} = (110.5 \pm 2.4)\ \text{mb}$
Status of physics papers

- "Elastic differential cross-section measurement at $\sqrt{s} = 13$ TeV by TOTEM"
  - Observation of diffractive dip at 13 TeV with high precision, absence of structure beyond second maximum

Elastic differential cross-section measurement at $\sqrt{s} = 13$ TeV by TOTEM

The TOTEM Collaboration

The TOTEM collaboration has measured the elastic proton-proton differential cross section $d\sigma/dt$ at $\sqrt{s} = 13$ TeV LHC energy using dedicated $\beta^* = 90$ m beam optics. The Roman Pot detectors were inserted to 10$\sigma$ distance from the LHC beam, which allowed the measurement of the range [0.04 GeV$^2$; 4 GeV$^2$] in four-momentum transfer squared $|t|$. The efficient data acquisition allowed to collect about $10^9$ elastic events to precisely measure the differential cross-section including the diffractive minimum (dip), the subsequent maximum (bump) and the large-$|t|$ tail. The average nuclear slope has been found to be $B = (20.40 \pm 0.002^{\text{stat}} \pm 0.01^{\text{syst}})$ GeV$^{-2}$ in the $|t|$-range 0.04 GeV$^2$ to 0.2 GeV$^2$. The dip position is $|t_{\text{dip}}| = (0.47 \pm 0.004^{\text{stat}} \pm 0.01^{\text{syst}})$ GeV$^2$. The differential cross section ratio at the bump vs. at the dip $R = 1.77 \pm 0.01$ has been measured with high precision. The series of TOTEM elastic pp measurements show that the dip is a permanent feature of the pp differential cross-section at the TeV scale.

$R = \frac{\text{max}}{\text{dip}} \text{ ratio of } d\sigma_{el}/dt$
Status of physics papers

- "Elastic differential cross-section at $\sqrt{s} = 2.76$ TeV and implications on the existence of a colourless 3-gluon bound state"
  - Observation of diffractive dip at this energy, comparison with D0 measurement at Tevatron

**Elastic differential cross-section $d\sigma/dt$ at $\sqrt{s} = 2.76$ TeV and implications on the existence of a colourless 3-gluon bound state**

The TOTEM Collaboration

**Abstract**

The proton-proton elastic differential cross section $d\sigma/dt$ has been measured by the TOTEM experiment at $\sqrt{s} = 2.76$ TeV energy with $\beta^* = 11$ m beam optics. The Roman Pots were inserted to 13 times the transverse beam size from the beam, which allowed to measure the differential cross-section of elastic scattering in a range of the squared four-momentum transfer ($|t|$) from 0.36 GeV$^2$ to 0.74 GeV$^2$. The differential cross-section can be described with an exponential in the $|t|$-range between 0.36 GeV$^2$ and 0.54 GeV$^2$, followed by a diffractive minimum (dip) at $|t_{\text{dip}}| = (0.61 \pm 0.03)$ GeV$^2$ and a subsequent maximum (bump). The ratio of the $d\sigma/dt$ at the bump and at the dip is $1.7 \pm 0.2$. When compared to the $p\bar{p}$ measurement of the D0 experiment at $\sqrt{s} = 1.96$ TeV, a significant difference can be observed. Under the condition that the effects due to the energy difference between TOTEM and D0 can be neglected, the result provides evidence for a colourless 3-gluon bound state exchange in the $t$-channel of the proton-proton elastic scattering.
Status of physics papers

- “Measurement of dijet production with a leading proton in proton-proton collisions at $\sqrt{s} = 8$ TeV”
  - first single-diffractive dijet measurement at LHC with measured protons

- “Search for central exclusive diphoton with proton tag using CT-PPS 2016 data”
  - under joint CMS-TOTEM review. [PAS-EXO-18-014]
Hardware upgrades
nT2 – a new T2 forward telescope

- **Physics goal for nT2**: measurement of inelastic events production rate for the extraction of total p-p cross section at 14 TeV

  - TDR submitted to LHCC in June 2019

**EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

**TDR - Upgrade of the TOTEM T2 Telescope**

The TOTEM Collaboration

**Abstract**

A new T2 detector for the TOTEM experiment is designed to measure the rate of inelastic proton-proton events in low luminosity special runs dedicated to the measurement of the total cross section at the highest LHC energy. With a pseudorapidity coverage of $5.3 < |\eta| < 6.5$, the new T2 will detect more than 90% of the inelastic events at a center-of-mass energy of 14 TeV and thus allow a precise inelastic rate and total cross section measurement. The corresponding elastic cross section will be used to normalize elastic differential cross section measurements at the same energy. The present TDR describes the physics motivation, the running scenarios, the technical requirements, the electronics and readout system as well as the construction timeline of the new T2.

Keywords: pp Total Cross Section, Detector, Tracking.
nT2 – a new T2 forward telescope

- **Pseudorapidity coverage**: $5.3 < |\eta| < 6.5$, in both sectors, “handbag-size detector”, same location as previous telescope (CASTOR tables, ± 15 m from IP5)

- **FLUKA study** of radiation doses in this region, in collaboration with CMS-BRIL
  - for 72h of data taking, $O(5 \text{ mGy})$ at 10 mm from beamline

- **Dedicated, low-luminosity runs** → fast scintillators + light guides ($4 \times 1$ mm radius fibres / counter)
  - good radiation tolerance (3-8% light collection loss for 0.8 MGy observed in ATLAS tile calorimeter ([J.Phys.: Conf. Ser. 645 012021](#)))
  - use of 2 mm wavelength shifter bars → overall expected 5-10% light collection efficiency
  - full coverage of $90 < r < 300$ mm region through $2 \times 4$ trapezoidal components + 10 mm overlaps, no dead zones

- first prototype successfully tested with ~5 GeV e$^-$ at DESY (using older components available)
nT2 readout and triggering

- Readout electronics, power supply, cables, ... inherited from previous T2
  - to be tested and commissioned prior to detector installation
  - new mezzanine for SiPMs → NINO chip → discriminated signal output, with services (DC-DC converter for HV, ...)
  - DAQ integration: TOTEM OptoRX (TOTEM DAQ → already fully interfaced to CMS DAQ)
- Detectors installed during technical stop in preparation to high-β* run (~days timescale)
- As used in legacy T2 for special runs, 4 bits included in CMS L1 trigger menu
  - expected rates and yields for dedicated runs:

<table>
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<tr>
<th></th>
<th>$\mu = 0.04$</th>
<th>$\mu = 0.1$</th>
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<tbody>
<tr>
<td>inst. luminosity</td>
<td>$2.2 \times 10^{28}$ Hz/cm$^2$</td>
<td>$5.5 \times 10^{28}$ Hz/cm$^2$</td>
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<tr>
<td>integrated lumi. (6h)</td>
<td>0.5 nb$^{-1}$</td>
<td>1.2 nb$^{-1}$</td>
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<tr>
<td>inelastic rate (events)</td>
<td>1.8 kHz (41M)</td>
<td>4.5 kHz (98M)</td>
</tr>
<tr>
<td>elastic rate (events)</td>
<td>0.7 kHz (16M)</td>
<td>1.8 kHz (38M)</td>
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### nT2 production timeline

- Full timeline compatible with commissioning in 1st trimester of 2021, to be ready for mid-year high-beta* run (slot still to be determined with LMC)

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>2019</th>
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<td>4</td>
<td>Approved by LHCC</td>
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<td>10</td>
<td>Procurement &amp; Construction</td>
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<td>12</td>
<td>Mezzanine design</td>
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<td>11</td>
<td>SiPM procurement</td>
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<tr>
<td>13</td>
<td>Mezzanine production</td>
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<td>14</td>
<td>Digitizer boards production, tests</td>
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<td>5</td>
<td>Detectors</td>
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<td>6</td>
<td>First sensor test with geometry</td>
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<td>7</td>
<td>Prototype beam and cosmic rays</td>
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<tr>
<td>8</td>
<td>Production of 32 sectors</td>
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<td>9</td>
<td>Tests of all scintillators</td>
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<td>15</td>
<td>Mechanics construction</td>
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<tr>
<td>16</td>
<td>Construction and installation</td>
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<td>19</td>
<td>Electronics integration</td>
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<td>Mechanical tests-CMS integration</td>
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<tr>
<td>18</td>
<td>Commissioning</td>
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<tr>
<td>21</td>
<td>Installation and run (Tbd ??)</td>
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*Note: High-beta run timing to be determined with LMC.*
Other LS2 activities (1)

- **Effects of CMS beamline downshift**
  - CMS PPS/TOTEM RP stations impacted by 3 mm-beamline downshift requested by CMS
  - mechanical movement of all pots stations, breaking of vacuum required prior to RP unit 3 feet support movement, iterative procedure for the vertical relocation,
  - engineering procedure under preparation

- **RP movements system**
  - PXI upgrade, monitoring of motor currents into TOTEM DCS (individual RPs movements), RP stopper & switches remain, decision taken with EP-DT group
  - procurement done, software & hardware already integrated, tests and commissioning ongoing
Other LS2 activities (2)

- **210-near-horizontal pots relocation at 220 m** [LHC-XRP-EC-0017]
  - **Physics goal**: maximum flexibility in combination of pots insertions (up to 4 in parallel)
  - **RF shielded pots** to be filled with **second timing station** only; general lower impedance load (expected factor 5 in “garage” position), both sectors affected
  - full operation requires **opening/breaking of LHC vacuum**, extraction of bellows (LHC vacuum group) → levelling (not yet fully implemented in LHC schedule)
  - tight time window for metrology/laser calibration & bake out (section between Q5 & Q6), relocation in parallel with beamline downshift
Timing detectors readout upgrade (1)

- Improved signal calibration/commissioning/monitoring for CMS PPS/TOTEM diamond timing detectors through new digitiser with SAMPIC fast sampling (ASIC) chip
  - [NIM A787 (2015) 245]
  - fully integrated within CMS readout/monitoring environment, smooth data taking during full operation

LHC beam (1 sector)

- used in parallel to HPTDC readout
- signal split into NINO discriminator board
- still under development, tests planned in lab and forthcoming test beam operations
Timing detectors readout upgrade (2)

- SAMPIC previously developed and used in July 2018 beta* = 90 m special runs, along with UFSD timing detectors
  - designed for 2x2 stations (192 channels), operated at 7.8 Gs/s at a 8-bit voltage resolution, 24 samples/waveform
  - SAMPIC bandwidth limited to ~1 MHz/16-channels chip, ~1 MHz/channel for PPS scCVD
  - possible readout reduction through operation over limited (programmable) selection of bunches (all channels enabled)
  - standard GOH readout, and additional USB control/readout possible at lower speed

Example of waveform

Full maximum, rising edge, and noise pedestal recorded.
Other activities

- Diamonds radiation hardness, efficiency and timing performances
  - 8 hybrid boards (used in 2018 PPS operations) + scCVD diamond + re-metallised prototypes (TISNCM, Russia) tested in DESY 4-GeV e- beams (T24 line, May 2019)
  - tracker system (EUDET) used in coincidence to check potential efficiency/performance variation ~ absorbed radiation dose
  - tested along with several other DUTs: fast Cerenkov radiators, scintillator tiles for nT2 (prototypes for different producers/geometry)
Summary

- **Run 2 physics output**
  - First elastic, inelastic, and total cross section measurement at 13 TeV published in EPJC
  - First determination of the $p$ parameter at 13 TeV submitted to EPJC
  - Observation of the diffractive minimum in $d\sigma/dt$ at 2.76 and 13 TeV to be submitted to EPJC
  - Together with CMS, single-diffractive dijet measurement at 8 TeV with proton tag, and search for central exclusive diphoton production at 13 TeV with proton tags in preparation

- **Upgrade plans**
  - Proposal for a new TOTEM T2 for the measurement of total p-p cross section at 14 TeV. TDR submitted to the LHCC for approval
  - Levelling of RPs in parallel to vertical CMS beamline shift
  - Relocation of the 210-near horizontal RF shielded pot to the 220 m station.
  - Timing detectors readout electronics updated with parallel readout chain & waveform sampling (improved flexibility in signal optimisation for run III)
Thanks for your attention!
σ_{tot} at 2.76 TeV with β^* = 2.5 km

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ β^* = 2.5 \text{ km} \]

(2016)

Example fit of approach 3

\[ σ_{tot}^2 = \frac{16\pi(\hbar c)^2}{1 + ρ^2} a \]

Fits to determine hadronic B-slope & amplitude a, ρ, and absolute normalisation.

Very low-|t| reach allows to determine normalisation using Coulomb amplitude for the first time at the LHC!!

Combining 2 independent data sets and methods!
Dip structure in $d\sigma_{el}/dt$ at 13 TeV

- Influence of 3-gluon/Odderon t-channel exchange different for pp & pp
  - expect deep dip in pp and shallower or no dip in pp
  - 13 TeV observation of the dip seen in pp at 7 TeV (EPL 95 (2011) 41001), with significantly higher precision!
Diffractive dip in pp / pp at TeV-scale

D0 Collaboration, Phys. Rev. D 86 (2012) 012009: "A comparison of the shape of our measured dσ/dt. [...] but, as in the UA4 data, we do not see a distinct minimum as observed in pp elastic scattering (TOTEM 7 TeV publication)."

Persistence of dip for pp & absence of dip for pp!
Expected radiation doses at nT2 position