Results from the LHC TOTEM Experiment

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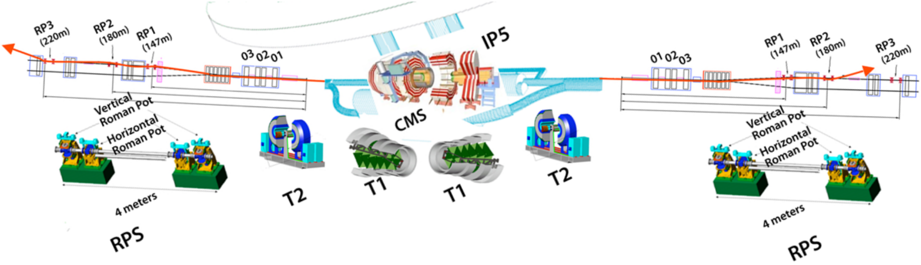
The TOTEM Collaboration

- TOTal cross-section, Elastic scattering and diffraction dissociation Measurement
- One of the small LHC experiments
- However, it has the largest longitudinal span
- Shares Interaction Point with CMS
- Rather small group: 59 participants from 9 institutions
- Czech Rep., Estonia, Finland, Hungary, Italy, USA + CERN

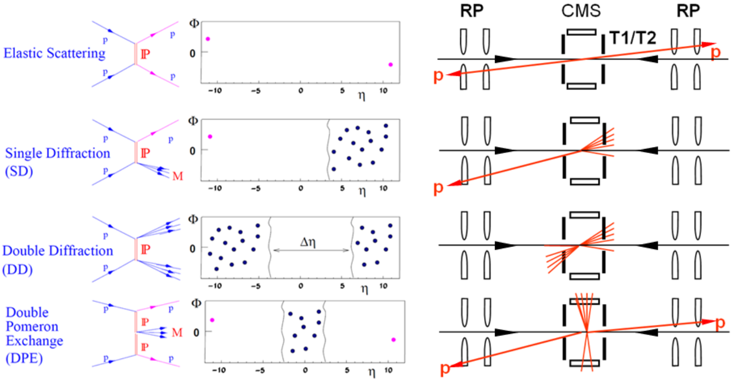


TOTEM goals

- Measure $\frac{d\sigma_{\text{el}}}{dt}$ in a broad t range
  - Strong constraint on models
  - $t \to 0$ needed for σ_{tot} (optical theorem, see later)
  - Measure extremely small t events!
- High precision σ_{tot} measurement, independent principles
  - Detect elastic and inelastic events
  - Events with almost zero momentum transfer
  - Three independent principles
  - High precision result on the "size" of a high energy proton
  - Measure luminosity as well (LHC: $\mathcal{L} = f \cdot n \cdot \frac{N^2}{A}$)
- Diffractive processes, small x physics
  - Proton structure functions interesting for small x
  - Interaction with a very small momentum fraction parton
  - Dissociated parts of proton barely deflected
  - Measure single diffraction, double diffraction cross-sections

Event classification

- Distinguish elastic, single & double diffractive events, etc.
- Detectors in well-placed pseudorapidity ranges:



- Event topologies with different detector signatures

How to measure cross-sections?

- Measure elastic and inelastic multiplicities (extrapolation):

$$N_{\text{el}},\, N_{\text{inel}},\, \left.\frac{dN_{\text{el}}}{dt}\right|_{t=0}$$

- Differential cross-section from multiplicity & (integrated) luminosity:

$$\mathcal{L}\sigma = N \text{ and } \mathcal{L}\frac{d\sigma}{dt} = \frac{dN}{dt}$$

- Cross-section is connected to $f(t)$ scattering amplitude as

$$\frac{d\sigma_{\text{el}}}{dt} = \frac{1}{t}|f(t)|^2$$

- The optical theorem says:

$$\sigma_{\text{tot}}^2 = \frac{16\pi^2(\hbar c)^2}{t}\left(\text{Im} f(0)\right)^2$$

- This connects σ_{tot} and $\left.\frac{d\sigma_{\text{el}}}{dt}\right|_{t=0}$
- Total cross-section measurable!

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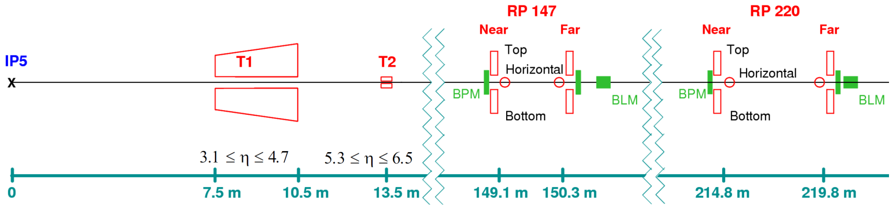
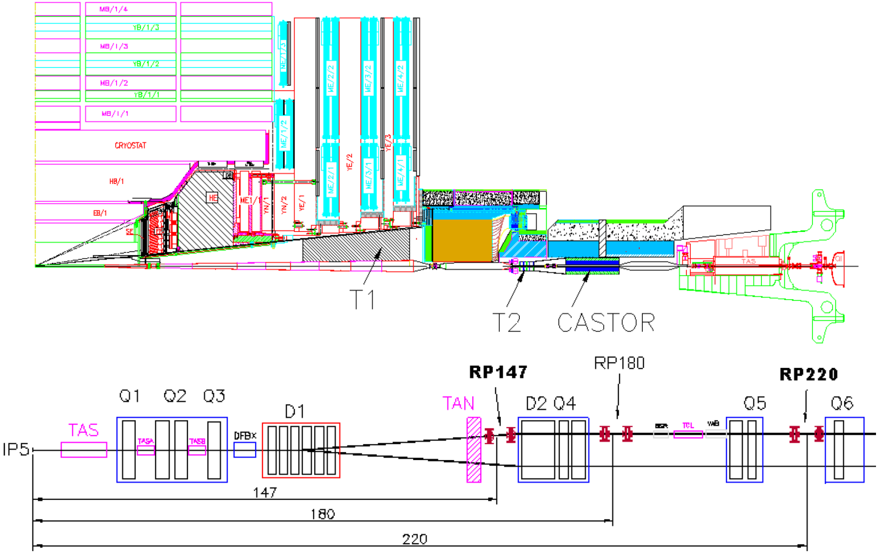
TOTEM setup

- Common interaction point with CMS, IP5
- Symmetric setup: same detectors on both sides
- T1 and T2 tracking detectors, integrated in CMS forward part
- "Roman Pot" (RP) stations ±147 m and ±220 m from IP5
- Longitudinal acceptance: $\Theta \approx$ few μrad scattering angle
- Pseudorapidity ($\eta = \ln \tan(\Theta/2)$): $|\eta|$ up to 12-13
- Full 2π acceptance ϕ azimuth angle
- Momentum transfer squared: $10^{-4}\,\mathrm{GeV}^2 < |t| < 10\,\mathrm{GeV}^2$

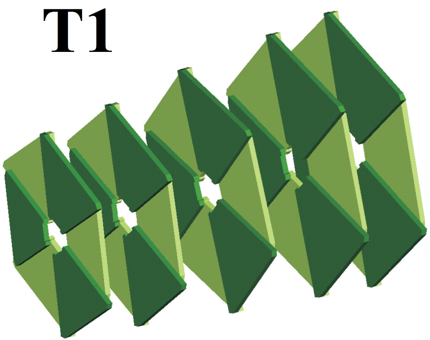


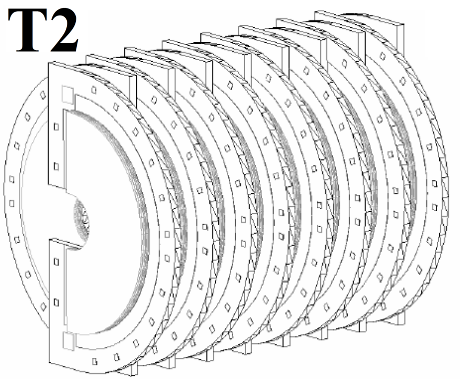
TOTEM and CMS



Tracking telescopes

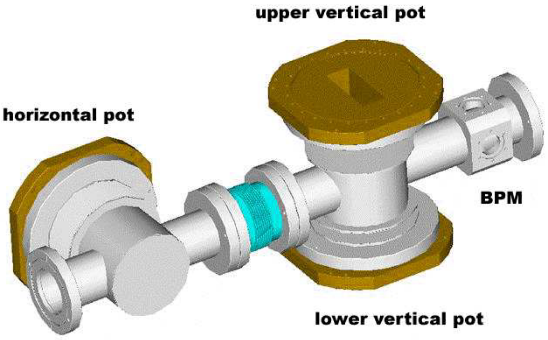
- T1: $3.1 < |\eta| < 4.7$, T2: $5.3 < |\eta| < 6.5$ (both sides of IP)
- T1: 5 uniform distance hexagonal "Cathode Strip Chambers" (CSC)
- T2: 10 circular "Gas Electron Multipliers" (GEM)

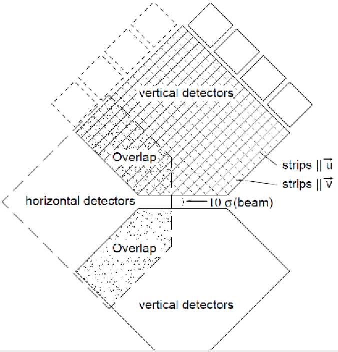




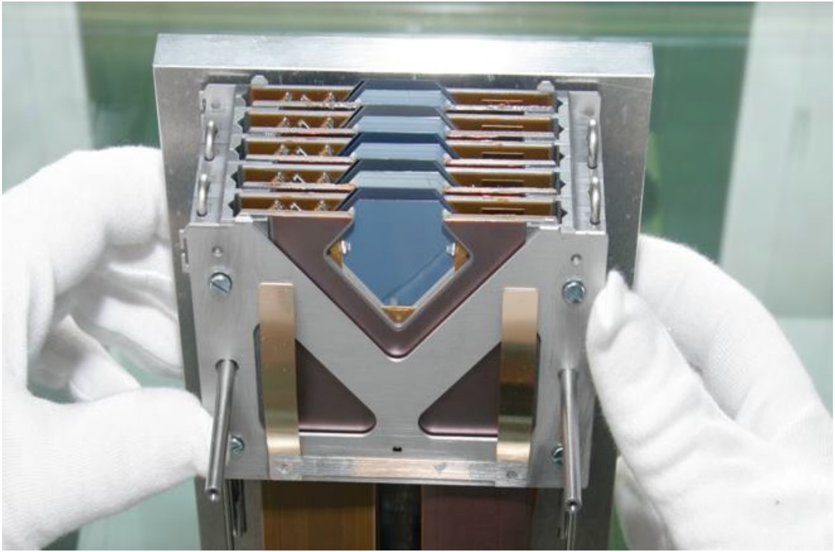
Roman Pot detectors

- Very small distance to the beam, in secondary vacuum
- 4 stations (at 147 and 220 meters, both sides), each has 2 units
- 3 pots per unit, one horizontal & two vertical (24 in total)
- 10 planes per pot, 512 “edgeless” Si strips in one plane
- Resolution: 16 μm, scattering angle: 5 μrad, alignment: 10 μm
- Beam Position Monitor included



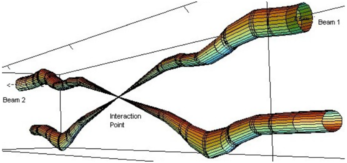


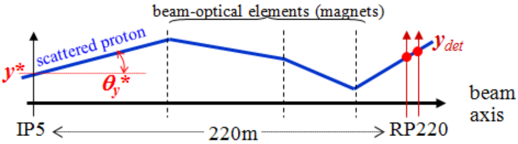
Planes in a Pot



TOTEM optics

- TOTEM records events with $t \to 0$, i.e. small angle, close to beam
- Understanding of LHC optics is crucial!





- Measured quantities (at RP) $\Leftrightarrow$ originals at IP: transport matrix
- Effective length $L(s)$, magnification $\nu(s)$, determined by $\beta(s)$
- Beta function around the IP: $\beta(s) = \beta^* + s^2/\beta^*$
- Beam size at IP $\propto \sqrt{\beta^*}$
- Beam divergence at IP $\propto 1/\sqrt{\beta^*}$
- Large β^*: poor focus, strong convergence
- Standard β^*: 3.5 m, TOTEM optics: 90 m, special 1000 m as well

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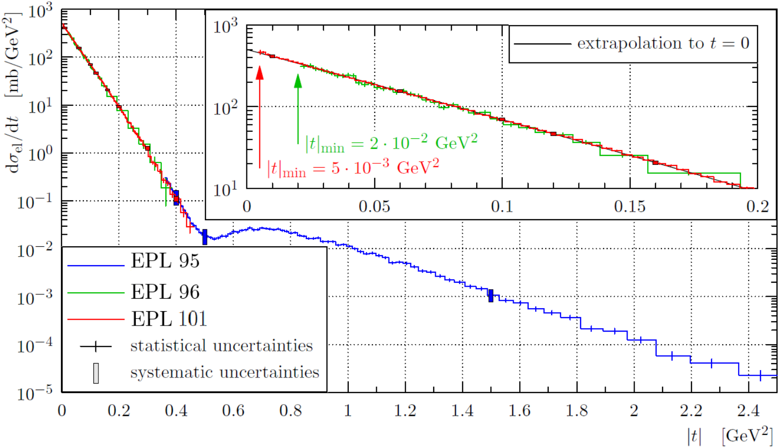
Differential elastic scattering results at 7 TeV

- Three measurements in three t-ranges $\beta^* = 3.5$ m and 90 m
- Small $|t|$: exponential, $\frac{d\sigma_{el}}{dt} = \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} e^{-B|t|}$
- Diffractive minimum, power law tail
- Via integration: $\sigma_{el} = (24.8 \pm 0.2_{stat} \pm 1.2_{syst})$ mb



Differential elastic scattering results

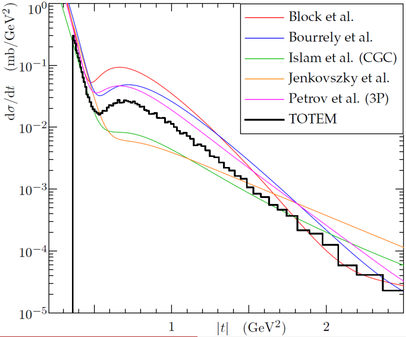
- Slope in different t-ranges:

$$0.36 < |t| < 0.47\ \text{GeV}^2: \quad B = (23.6 \pm 0.5_{\text{stat}} \pm 0.4_{\text{syst}})\ \text{GeV}^{-2}$$

$$0.02 < |t| < 0.33\ \text{GeV}^2: \quad B = (20.1 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}})\ \text{GeV}^{-2}$$

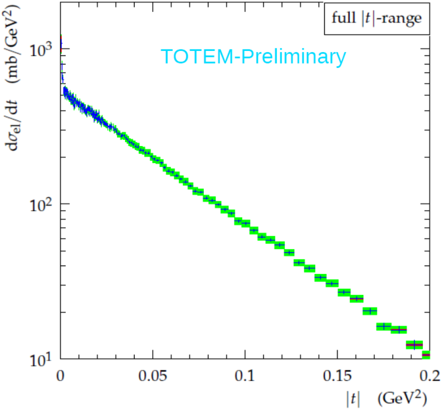
$$0.005 < |t| < 0.2\ \text{GeV}^2: \quad B = (19.89 \pm 0.03_{\text{stat}} \pm 0.3_{\text{syst}})\ \text{GeV}^{-2}$$

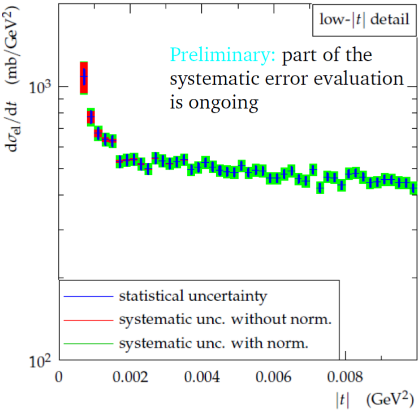
- Diffractive minimum: $|t| = (0.53 \pm 0.01_{\text{stat}} \pm 0.01_{\text{syst}})\ \text{GeV}^2$
- $|t| > 1.5\,\text{GeV}^2$: power law, exponent $-7.8 \pm 0.3_{\text{stat}} \pm 0.1_{\text{syst}}$
- Strong constraint on models (to say the least):



$d\sigma_{el}/dt$ at $\beta^* = 1000$ m

- Dedicated $\beta^* = 1000$ m run, measurement down to $|t| = 6 \cdot 10^{-4}$ GeV^2
- Sensitive to models describing Coulomb/nuclear interference
- Improvement on the total cross-section





Inelastic cross-section measurement

- Triggering with T2 gives luminosity dependent cross-section

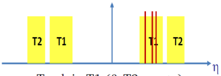
$$\sigma_{\text{inel,T2}} = (69.7 \pm 0.1_{\text{stat}} \pm 0.7_{\text{syst}} \pm 2.8_{\text{lumi}})\,\text{mb}$$

- Cross-section for events with at least one stable particle with $|\eta| < 6.5$:

$$\sigma_{\text{inel},|\eta|<6.5} = (70.5 \pm 0.1_{\text{stat}} \pm 0.8_{\text{syst}} \pm 2.8_{\text{lumi}})\,\text{mb}$$

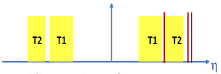
- Correction for events with particles only at $|\eta| > 6.5$ (QGSJET-II)

$$\sigma_{\text{inel}} = (73.7 \pm 0.1_{\text{stat}} \pm 1.7_{\text{syst}} \pm 2.9_{\text{lumi}})\,\text{mb}$$



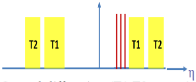
Track in T1 (& T2 empty)

~ 1.6%



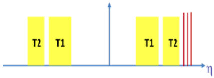
Rapidity gap in T2 for 1-arm events (hadronization fluctuation)

~ 0.35%



Central diffraction (T1,T2 empty)

~ 0.35%



Correction based on QGSJET-II-03 =4.2% ± 2.1% (syst)

- Low mass diffraction contribution under control: 2.62 ± 2.17 mb
- Ref: EPL **101** (2013) 21003

Total cross-section: independent measurement principles

- "Elastic only" method (optical theorem) (EPL 96,21002 & 101,21002):

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{d\sigma_{\text{el}}}{dt}\right|_{t=0}$$

  - $\rho = \text{Re}f(0)/\text{Im}f(0)$, COMPETE: $\rho = 0.14^{+0.01}_{-0.08}$, small effect
  - No assumption on low mass diffraction!
- Luminosity independent method (EPL 101,21004):

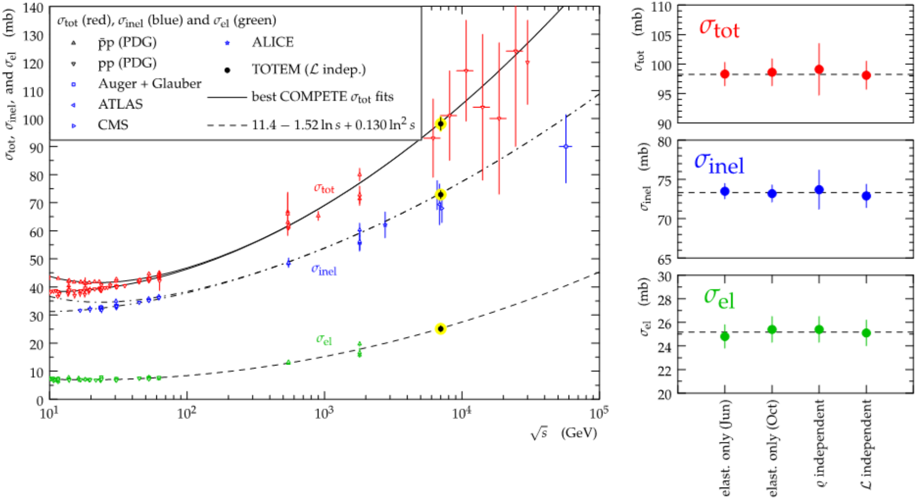
$$\sigma_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{dN_{\text{el}}/dt|_{t=0}}{N_{\text{el}} + N_{\text{inel}}}$$

- ρ independent method (EPL 101,21003 & 101,21004):

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

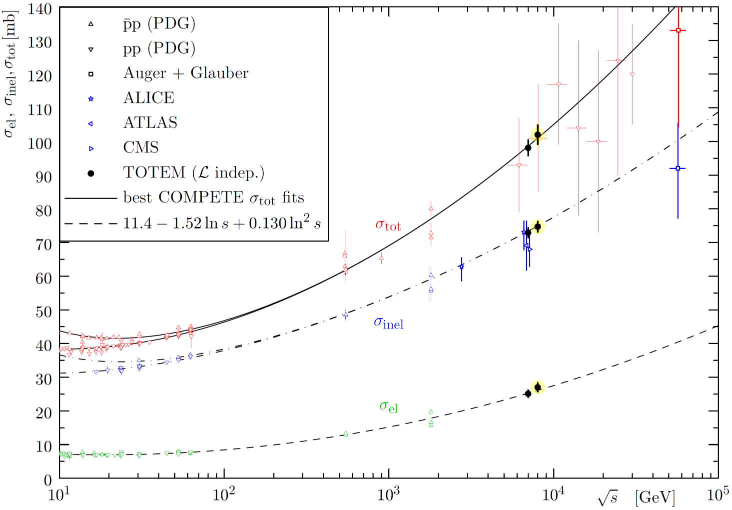
  - Total inelastic rate: obtained via T2 triggering
  - Corrections based on T1 tracks and minimal use of MCs
- Absolute calibration of CMS $\mathcal{L}$, and ρ measurable!
- ρ- & $\mathcal{L}$-independent quantitiy: e.g. $\sigma_{\text{el}}/\sigma_{\text{tot}}$
- Set upper limit on low mass diffraction

Comparison of different methods



Luminosity independent method: Europhys. Lett. **101**, 21004 (2013)

Results at 8 TeV



Source: CERN-PH-EP-2012-354 (Phys. Rev. Lett. accepted)

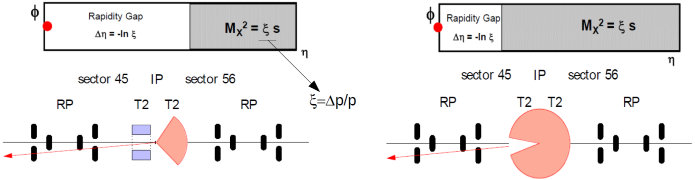
Quantitative σ_{tot} results

Measurement	σ_{el} [mb]	σ_{inel} [mb]	σ_{tot} [mb]
Elastic only, 7 TeV EPL**96**,21002	24.8±1.2	73.5±1.6	98.3±2.8
Elastic only, 7 TeV EPL**101**,21002	25.4±1.1	73.2±1.3	98.6±2.2
ρ-indep., 7 TeV EPL**101**,21003	25.4±1.1	73.7±3.4	99.1±4.3
Lumi.-indep., 7 TeV EPL**101**,21004	25.1±1.1	72.9±1.5	98.0±2.5
Lumi.-indep., 8 TeV CERN-PH-EP-2012-354	27.4±1.2	74.7±1.7	101.7±2.9

- Good agreement at 7 TeV
- $\rho^2 = 0.009 \pm 0.056$, i.e. $|\rho| = 0.145 \pm 0.091$ (uniform distr.)
- Low mass diffraction: 2.62 ± 2.17 mb
- Uncertainty dominated by luminosity (model uncertainty: 1%)

Soft diffraction results

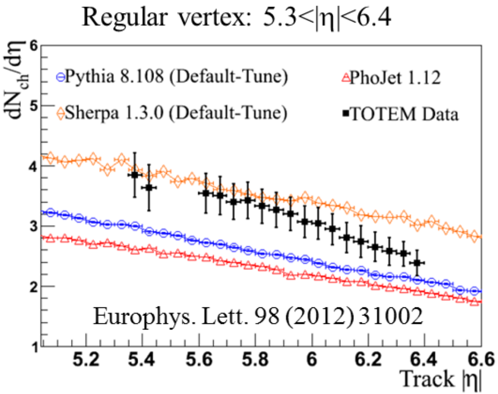
- Soft single diffraction: rapidity gap determines diffractive mass

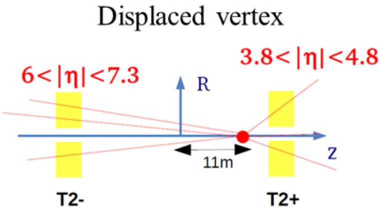


  - Event classification based on tracks in T2, T1 and proton in RP
  - M_X classes from 3.4 GeV to above 1.1 TeV (proton + both T2 arms)
  - Preliminary cross-section results for various M_x intervals: 3.4-7 GeV: 1.8 mb, 7-350 GeV: 3.3 mb, 350-1100 GeV: 1.4 mb
- Soft double diffraction: particle in both T2 arms, no T1 tracks
  - $0\times$T1 + $2\times$T2 topology
  - Range is $4.7 < \eta_{\text{min}} < 6.5$, i.e. $3.4 < M < 8$ GeV
  - Single diffractive background: $0\times$T1 + $1\times$T2 data with proton in RP
  - Non-diffractive background: MC prediction based on $2\times$T1 + $2\times$T2 data
  - Preliminary cross-sections for $4.7 < \eta_{\text{min}} < 6.5$: 120 ± 25 μb

Pseudorapidity distribution results

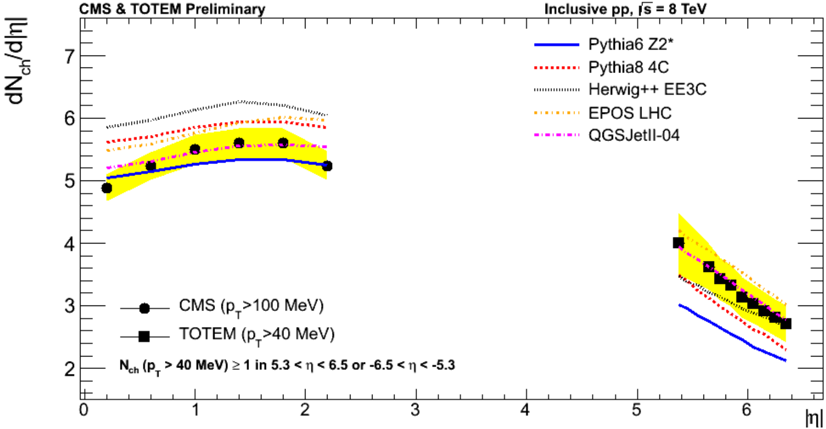
- Based on T2 trigger, at least one ch. particle with $p_t > 40$ MeV/c
- More than 99% of non-diffractive processes
- Diffractive as well, if $M_{\text{diff}} > 3.4$ GeV/c^2
- No MC generator describe the data fully within given uncertainty
- Gap to LHCb ⇒ T1 analysis, displaced vtx (500k events @ 11m)





Pseudorapidity distribution with CMS at 8 TeV

- CMS & TOTEM: common T2 trigger, same data sample!



- Non-single diffractive & single diffractive enhanced analysis ongoing
- Trigger: one or both T2 hemispheres on

p-Pb data taking, analyses

- Taken data together with CMS, trigger exchange and event sync, 150 Hz
- Approx. 100 TOTEM physics runs, only vertical RP, only on the p side
  - p-Pb, RPs (13σ, i.e. $|t| > 4.5$ GeV^2) + T2 + CMS: 60 M events
  - p-Pb, T2 + CMS: 70 M events
  - Pb-p, RPs (13σ) + T2 + CMS: 85 M events
  - Pb-p, RPs (4.5σ, i.e. $|t| > 0.5$ GeV^2) + T2 + CMS: 2.50 M events with (quasi-)ealastic events, but signature only in one arm
- Analyses: diffraction, $dN/d\eta$, correlations
- A further project: measure elastic differential cross-sections
  - Problem: ion stays in beam, only proton deflected
  - Only one side can be used, elastic tagging difficult
  - Inelastic veto possible with forward telescopes
  - Quasi-elastic veto via forward neutral particles
  - Status: several physics runs reconstructed, analysis on the way

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Summary, outlook

- TOTEM measures forward protons with extreme precision
- Works with regular and dedicated LHC optics
- Published: σ, $d\sigma/dt$, pseudorapidity distr.
- $\sigma_{\text{tot,el,inel}}$ via 3 independent principles
- $\beta^* = 1000$ m, $|t| > 0.0006$ GeV^2 preliminary
- Results on 7 & 8 TeV
- Preliminary soft diffractive results
- Common diffractive analyses with CMS
- p+A: common TOTEM & CMS data taking, analysis started
- Long Shutdown 1: upgrade of the experiment

Thank you for your attention

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A Letters Journal Exploring the Frontiers of Physics

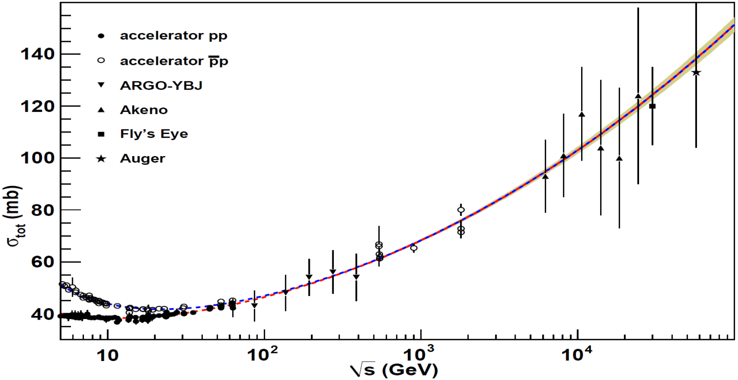
BEST OF 2011

First measurement of the total proton-proton cross-section at the LHC energy of $\sqrt{s} = 7$ TeV

The TOTEM Collaboration

2011 *EPL* **96** 21002

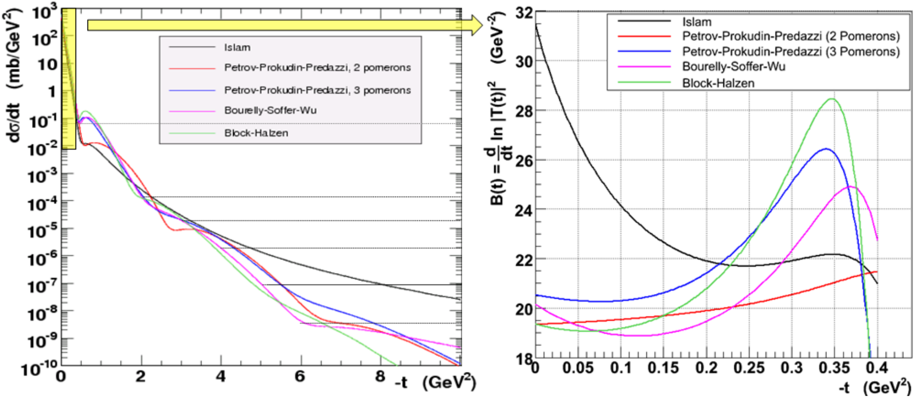
Energy dependence of total cross sections



- Total cross sections rise, impossible with normal Regge trajectories
- Solution: the "Pomeron trajectory", $\alpha(0) = 1.08$ and $\alpha' = 0.25$ GeV^{-2}
- What is the Pomeron?
- Even p+p scattering σ_{total} is not fully explained!

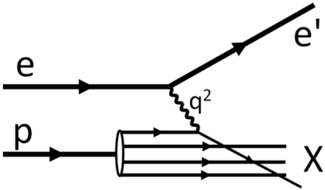
Differential elastic scattering

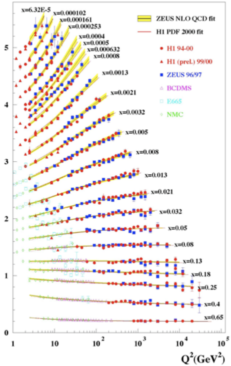
- Many different models for $d\sigma_{\mathrm{el}}/dt$
- Different number and location of diffractive minima
- Small t: exponential, slope ($B(t)$) very different



Small x physics

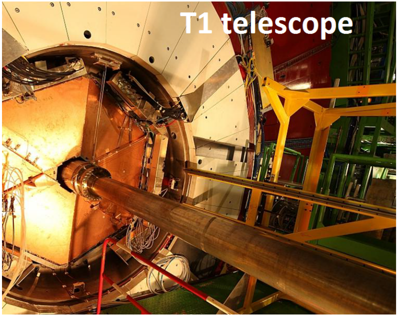
- Understanding the proton structure: high energy $e + p$ collisions
- Small E: nucleon resonances; large E: "deeply inelastic scattering"

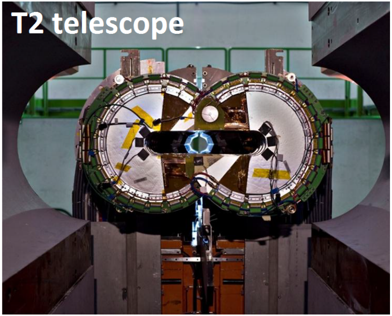


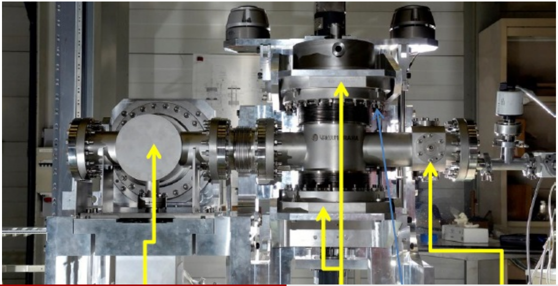


- SLAC, 60's: dimensionless x scaling variable
- Bjorken, 1969: "parton model", $p_{\text{parton}} = x \cdot p_{\text{proton}}$!
- $x > 0.1$: parton=valence-quark, Bjorken-scaling explainable
- Small x: sea-quarks and gluons appear, scaling violations, "small x physics"

Pictures of the detectors

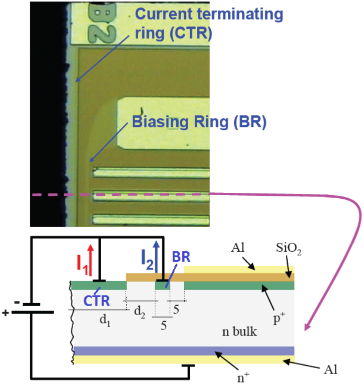


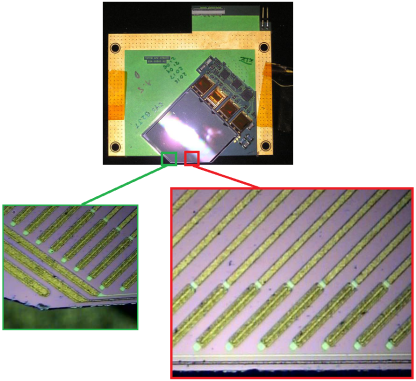




"Edgeless" technology

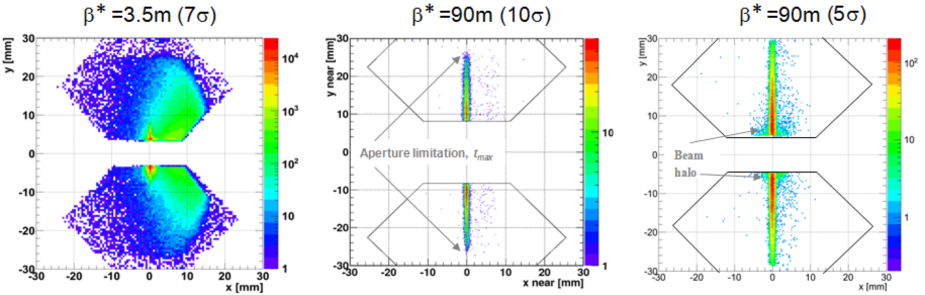
- Get as close to the beam as possible, 1 mm
- Planar Si detectors: generally 0.5-1 mm dead region
- Goal: reduce it to 50 μm
- Properties of cut edge undetermined: independence possible?
- So-called "Current Terminating Structure" ($\neq$ voltage termination)



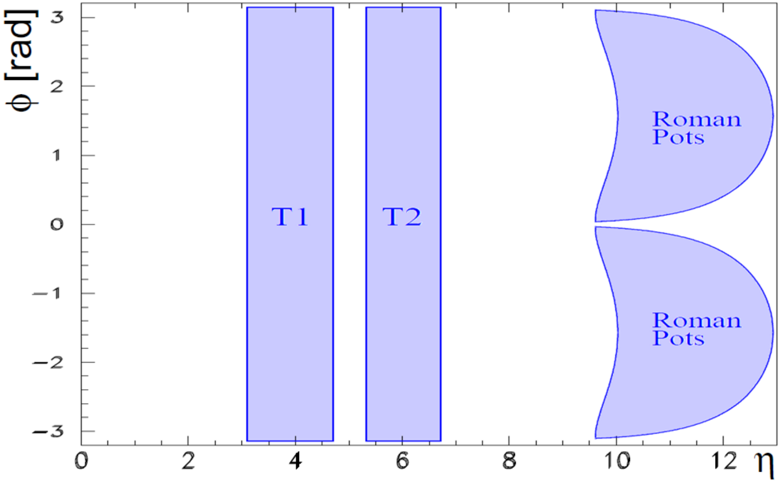


Hits at different β^* settings

- Beta function around the IP: $\beta(s) = \beta^* + s^2/\beta^*$
- Beam size at IP $\propto \sqrt{\beta^*}$
- Beam divergence at IP $\propto 1/\sqrt{\beta^*}$
- Large β^*: poor focus, strong convergence
- Beam distance in beam size (σ) units



TOTEM acceptance



- With CMS: largest acceptance experiment
- RP acceptance depends on optics

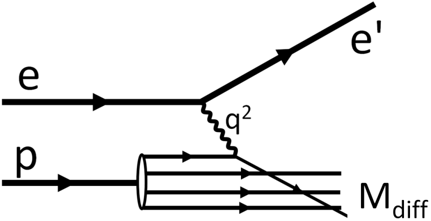
The transport matrix

- Effective length $L(s)$, magnification $\nu(s)$, determined by $\beta(s)$

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} \nu_x & L_x & 0 & 0 & D_x \\ \nu'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & \nu_y & L_y & 0 \\ 0 & 0 & \nu'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \Delta p/p \end{pmatrix}$$

Inelastic cross-section measurement

- Based on event numbers and luminosity, $\sigma = \frac{1}{\mathcal{L}} N$
- Inelastic events: diffractive excitation of the proton

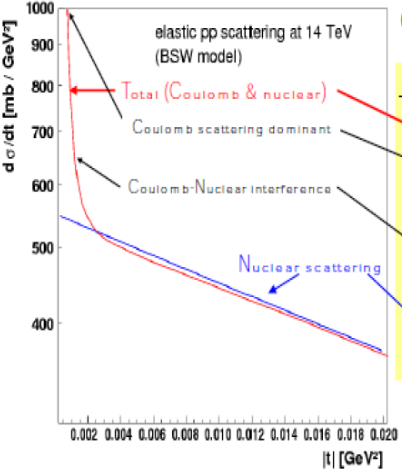


- Rapidity-range fixes minimal diffractive mass
- ALICE $M_{\rm diff} \geq 7$ GeV, CMS $M_{\rm diff} \geq 26$ GeV, $M_{\rm diff} \geq 16$ GeV
- TOTEM telescopes: $M_{\rm diff} \geq 3.4$ GeV

Inelastic results

- T2 trigger, from "all" inelastic events
- Ref.: Europhys. Lett. **101**, 21003 (2013)
- Corrections:
  - T2 trigger efficiency (2.6%)
  - Beam-gas collisions (0.6%)
  - Time-overlapping events (1.5%)
  - Reconstruction efficiency (1.0%)
  - Events only in T1 (1.6%)
  - Low diffractive mass events (4.6%)
- Model-independent result:
  $(73.74 \pm 0.09_{\mathrm{stat}} \pm 1.74_{\mathrm{N}} \pm 2.95_{\mathrm{lumi}} \pm)$ mb (total 3.43 mb)
- Maximal high rapidity contribution: 2.62 ± 2.17 mb
- Based on total & elastic:
  $(73.15 \pm 0.77_{t} \pm 0.29_{\mathrm{norm}} \pm 0.96_{\mathrm{lumi}} \pm 0.10_{\rho})$ mb (total 1.26 mb)

Coulomb-nuclear interference



Optical Theorem: $\sigma_{tot} = \frac{4\pi}{s}\Im\left(T_{elastic,nuclear}(t=0)\right)$

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho-\alpha\phi)\sigma_{tot}G^2(t)}{|t|}e^{-B|t|/2} + \frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar c)^2}e^{-B|t|}$$

α = *fine structure constant*

ϕ = *relative Coulomb-nuclear phase*

$G(t)$ = *nucleon el.-mag. form factor* = $(1+|t|/0.71)^{-2}$

$\rho = \Re/\Im\,[T_{elastic,nuclear}(t=0)]$

Measurement of ρ by studying the Coulomb – Nuclear interference region down to $|t| \sim 6\cdot10^{-4}$ GeV^2

Pseudorapidity distribution results

- Event selection: at least one charged particle with $p_t > 40$ MeV$/c$
- More than 99% of non-diffractive processes
- Diffractive as well, if $M_{\text{diff}} > 3.4$ GeV$/c^2$
- $dN_{\text{ch}}/d\eta$ decreases with $|\eta|$:
  $|\eta| = 5.375$: $3.84 \pm 0.01_{stat} \pm 0.37_{syst}$
  $|\eta| = 6.375$: $2.38 \pm 0.01_{stat} \pm 0.21_{syst}$
- Ref.: Europhys. Lett. **98**, 31002 (2012)
- Gap to LHCb $\Rightarrow$ ongoing T1 analysis,
- Runs with displaced vertex (500k events @ 11m)