PHYSICS AND STATUS OF TOTEM

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on behalf of the
TOTEM Collaboration
http://totem.web.cern.ch/Totem/
TOTEM Physics Overview

Total cross-section

Elastic Scattering

Forward physics

Diffraction: soft and hard

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Current models predictions: 90-130 mb

Aim of TOTEM: ~1% accuracy

COMPETE Collaboration fits all available hadronic data and predicts:

\[ \sigma_{tot} = 111.5 \pm 1.2 \pm 4.1 \text{ mb} \]

[PR 89 201801 (2002)]
Facts about the proton

Regge:
\[ \sigma_{\text{tot}} \sim \sum A_i s^{\alpha_i(0)-1} \]
\[ \alpha_p = 1.08 \quad \alpha_R = 0.54 \]
\[ \sim 21.7 \quad s^{0.0808} + 56.08 \quad s^{-0.4525} \]

Geom. Scaling:
\[ \sigma_{\text{el}} \sim \sigma_{\text{tot}} \sim B(s,0) \sim R^2(s) \sim \ln^2 s \]
pp Interactions

Non-diffractive
Color exchange

\[ \frac{dN}{d\Delta\eta} = \exp(-\Delta\eta) \]

Diffractive
Colorless exchange with vacuum quantum numbers

\[ \frac{dN}{d\Delta\eta} = \text{const} \]

Incident hadrons acquire colour and break apart

Incident hadrons retain their quantum numbers remaining colourless

GOAL: understand the QCD nature of the diffractive exchange
Inelastic and Diffractive Processes \( (\eta = -\ln \tan \theta/2) \)

- **Non-diffractive inelastic (ND)**: \( \sim 30 \text{ mb} \)

- **Elastic Scattering**: \( \sim 30 \text{ mb} \)

- **Single Diffraction**: \( \sim 10 \text{ mb} \)

- **Double Diffraction**: \( \sim 7 \text{ mb} \)

- **Double Pomeron Exchange**: \( \sim 1 \text{ mb} \)

- **Multi Pomeron Exchange**: \( \ll 1 \text{ mb} \)

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Experimental layout

Leading Protons detectors at 147,220m from the IP

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The TOTEM Detectors

Inelastic Telescopes:
T1: $3.1 < |\eta| < 4.7$
T2: $5.3 < |\eta| < 6.5$

Roman Pots:

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T1 support structure

Two trusses with rails will be fixed to the internal walls of CMS return yoke

Insertion and fixation test successfully done at IP5

CSC mounted on frames will slide into final position

Mounting and sliding test of “half basket” performed at Genova
T1 Telescope

Production at Gatchina (PNPI)
Final Mounting at CERN

Ageing studies at the GIF: 12-month test, with ~0.07 C/cm accumulated charge on wires corresponding to ~ 5 years at $L=10^{30} \text{cm}^{-2} \text{s}^{-1}$
The T2 Telescope

Installation design together with CMS

Collar

Castor

Beam

10 triple-GEM planes on each side of the IP to cope with high particle fluxes.

5.3 < |\eta| < 6.6

Final GEM chamber
T2 Telescope (GEM)

65(ϕ) x 24(η) = 1560 pads

Pads: \( \Delta \eta \times \Delta \phi = 0.06 \times 0.015\pi \)

2\times2\text{ mm}^2 \quad 7\times7\text{ mm}^2

Strips: 256 (width: 80 \( \mu \)m, pitch: 400 \( \mu \)m)

Technology used in COMPASS
First arm of the T2 telescope is installed!
T2 GEM Assembly

Production at Helsinki
Final assembly at CERN
Installation of the T2 detector
GEM chambers
Silicon Detectors inside the RP

Ferrite
Roman Pot

Horizontal Pot  Vertical Pot  BPM
All Roman Pots Installed at the LHC
Total cross-section and elastics scattering $d\sigma/dt$ at $t=0$
related via the optical theorem

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

$\alpha$ = fine structure constant
$\phi$ = relative Coulomb-nuclear phase
$G(t)$ = nucleon em form factor = $(1 + |t|/0.71)^2$
$\rho$ = $\text{Re/Im } f(p\rightarrow p)$

Measure: the exponential slope $B$ in the t-range $0.002 - 0.2$ GeV$^2$

total inelastic and elastic rates
Level-1 Trigger Schemes

\[ (L = 1.6 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}) \]

- **Elastic Trigger:**
- **Single Diffractive Trigger:**
- **Double Diffractive Trigger:**
- **Central Diffractive Trigger:**
- **Minimum Bias Trigger:**

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η–Acceptance

All detectors with trigger capability

Trigger acceptance > 95%
for all inelastic events
Measurement of the Inelastic Rate

- Inelastic double arm trigger: robust against background, inefficient at small $M$
- Inelastic single arm trigger: suffers from beam-gas + halo background, best efficiency
- Inelastic triggers and proton (SD, DPE): cleanest trigger, proton inefficiency to be extrapolated
- Trigger on non-colliding bunches to determine beam-gas + halo rates.
- Vertex reconstruction with T1, T2 to suppress background
- Extrapolation of diffractive cross-section to large $1/M^2$ assuming $d\sigma/dM^2 \sim 1/M^2$

![Graph showing acceptance and single diffraction](image)

### Table: Inelastic Rates

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$ [mb]</th>
<th>Trigger loss [mb]</th>
<th>Systematic error after extrapolations [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-diffractive inelastic</td>
<td>58</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Single diffractive</td>
<td>14</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Double diffractive</td>
<td>7</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Double Pomeron</td>
<td>1</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>3.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

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Measurement of Forward Protons: the principle

Diffractive protons: hit distribution @ RP220

low $\beta = 0.5 - 2$ m

high $\beta = 90$ m

$y \sim \Theta_{y}^{\text{scatt}} \sim |t_y|^{1/2}$

$x \sim \xi = \Delta p/p$

Detect the proton via:

its momentum loss (low $\beta$)

its transverse momentum (high $\beta$)
Beam focus ($\beta^*$)

Phase space area occupied by the beam is given by the emittance $\varepsilon$

Small $\beta^*$

$\varepsilon = \sigma_x \cdot \sigma_\theta$

$= \frac{\varepsilon_\mu}{\gamma} = 0.5 \text{ nm} \cdot \text{rad}$

$\sigma_x = \sqrt{\varepsilon \cdot \beta^*}$

$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^*}}$

$\beta^* = 0.5 \text{ m}$

$\sigma_x = 16 \mu\text{m}$

$\sigma_\theta = 31 \mu\text{m}$

Large $\beta^*$

$\beta^* = 1540 \text{ m}$

$\sigma_x = 0.9 \text{ mm}$

$\sigma_\theta = 0.6 \mu\text{m}$

Large $\beta^*$ $\Longrightarrow$ small beam divergence
Elastic Scattering Acceptances

$\beta^* = 1540 \ 90 \ 2 \ \text{m}$

$\beta^* = 1540 \text{ m}$

Detector distance to the beam: $10\sigma + 0.5\text{mm}$

$-t = 0.01 \ \text{GeV}^2$

$-t = 0.002 \ \text{GeV}^2$

Beam

Detector distance: 1.3 mm, 6 mm

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Combined Uncertainty in $\sigma_{\text{tot}}$

\[
\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{dN_{\text{el}}}{dt} \bigg|_{t=0} / \frac{N_{\text{el}} + N_{\text{inel}}}{16\pi} \frac{dN_{\text{el}}}{dt} \bigg|_{t=0} \quad L = \frac{1 + \rho^2}{16\pi} \left( \frac{N_{\text{el}} + N_{\text{inel}}}{dN_{\text{el}}/dt} \bigg|_{t=0} \right)^2
\]

$\beta^* = 90 \, \text{m} \quad 1540 \, \text{m}

- Extrapolation of elastic cross-section to $t = 0$: $\pm 4 \% \quad \pm 0.2 \%$
- Total elastic rate (strongly correlated with extrapolation): $\pm 2 \% \quad \pm 0.1 \%$
- Total inelastic rate:
  (error dominated by Single Diffractive trigger losses) $\pm 1 \% \quad \pm 0.8 \%$
- Error contribution from $(1 + \rho^2)$
  using full COMPETE error band $\delta \rho / \rho = 33 \% \quad \pm 1.2 \%$

$\Rightarrow$ Total uncertainty in $\sigma_{\text{tot}}$ including correlations in the error propagation:

$\beta^* = 90 \, \text{m} : \pm 5 \%, \quad \beta^* = 1540 \, \text{m} : \pm (1 \div 2) \%$.

Slightly worse in $L$ (~ total rate squared!): \( \pm 7 \% \ (\pm 2 \%).

Precise Measurement with $\beta^* = 1540 \, \text{m}$ requires:
- improved knowledge of optical functions
- alignment precision < 50 $\mu$m
Elastic Scattering Cross-Section at large $t$

Photon - Pomeron interference $\propto \rho$

Multigluon (“Pomeron”) exchange $\propto e^{-B|\mathbf{t}|}$

diffractive structure

$pQCD$

wide range of predictions

$\beta^* = 1540$ m

$\beta^* = 11$ m

$\beta^* = 1$ m
Elastic pp Scattering: Predictions for 14 TeV

Big uncertainties at large $t$

TOTEM will measure the complete range with good statistics

$$\frac{d\sigma}{dt} \sim C t^{-s} \quad \text{independent of } s$$

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Rapidity Gaps in Fireworks

Dino Goulianos
Diffractive scattering is a unique laboratory of confinement & QCD:
A hard scale + protons which remain intact in the scattering process
Forward protons observed, independent of their momentum losses

'wee' parton cloud - grows logarithmically

Baryonic charge \( r \sim 0.5 \text{fm} \)

Valence quarks in a bag with \( r \sim 0.2 \text{fm} \)

Lorentz contracted longitudinal view

Soft Diffractive Scattering

Hard DPE

Elastic soft SD

hard SD

soft DPE

hard DPE

Rapidity gap survival & "underlying" event structures are intimately connected with a geometrical view of the scattering - eikonal approach!

Cross sections are large

Measure \( \sigma (M, \xi, t) \)

Soft processes:
Coherent interactions
Impact parameter picture.

Hard processes:
Jet momenta correlated with the initial parton momenta.

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Soft Diffraction

- Measure $\xi$
- Compare with rap gap $\Delta \eta = -\ln \xi$
  - gap suppression
- Cross-section $\sigma (\xi, t)$

\[
\left( \frac{d\sigma}{d\Delta \eta} \right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}
\]
Measurement of Forward Protons: the Acceptance

\[ \log(\xi) = \Delta p/p \]

\[ \log(-t) \text{ (GeV}^2) \]

\[ \beta = 1540 \]

\[ \beta = 90 \text{ m} \]

\[ \xi \sim 2\% \]

\[ \beta = 2, 0.5 \]

\[ \log(M) \text{ (GeV)} \]

DPE

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90% (65%) of all diffractive protons are detected for $\beta^* = 1540 \text{ (90) m}$

$\eta = -\ln \tan \theta/2$
Running scenarios

- **Soft diffraction**
  - $pp \rightarrow pX$
  - $pp \rightarrow pXp$

- **(Semi)-hard diffraction**
  - $pp \rightarrow pjX$
  - $pp \rightarrow pjXp$

- **Hard diffraction**
  - $pp \rightarrow pj$ (bosons, heavy quarks, Higgs...)
  - $pp \rightarrow pj p$

<table>
<thead>
<tr>
<th>$\beta$ (m)</th>
<th>1540</th>
<th>90</th>
<th>2</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm$^{-2}$ s$^{-1}$)</td>
<td>$10^{29}$</td>
<td>$10^{30}$</td>
<td>$10^{32}$</td>
<td>$10^{34}$</td>
</tr>
</tbody>
</table>

TOTEM runs

Standard runs

Accessible physics depends on luminosity & $\beta^*$

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Particle production in Double Pomeron Exchange

Advantage: Selection rules: \( J^P = 0^+, 2^+, 4^+; C = +1 \) for exclusive particle production

\[ \Rightarrow \] Determination of quantum numbers

Production of gluonic states, \( \chi_c, \chi_b, \) Higgs, supersymmetric Higgs,…..

- Low mass states need high \( \beta^* \) (e.g. 90 m)
- Higgs and high mass states need high luminosity
- Enlarge the mass acceptance down to \( \sim 100 \text{ GeV} \)

Additional Si-detectors at IP3

Use the LHC as a gluon-gluon collider
Outlook: Proton Detection at Lower $\xi$-Values

Good acceptance and momentum resolution for diffractive protons needs:
  - large dispersion $D$ (few m) ($x = \xi \cdot D$)
  - small beam width (< 1 mm)

Where in the LHC are these requirements best fulfilled?
Proton Acceptance of a “Combined IP3 + RP220 TOTEM” Experiment

\[ M_{PP}^2 = \xi_1 \xi_2 s \]

DPE Mass Spectrum with Detector Acceptance

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14 TeV => $10^{17}$ eV

10$^4$ CR events / km$^2$ year =>

10$^4$ events /s @ LHC (L=$10^{29}$ cm$^{-2}$ s$^{-1}$)

Extensive Air Shower characteristics (~ $E_0$, mass)

$X_{max}$ & $N_e$: sensitive to cross-sections

$N_\mu$: depends on $N_{ch}$

=> Disentangle Energy, Mass, hadronic models

Measurement of the forward energy flux @LHC – including diffraction and of the total cross section are essential for the understanding of the CR events (shower development, composition)
Model Predictions at the LHC

Total multiplicity in T2 (5<\eta<7)

![Graph showing probability distribution of multiplicity n against multiplicity n.]

![Graph showing multiplicity (Diffractive events) against pseudorapidity (Eta).]

Measurement of multiplicities and correlations

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Cosmic Rays surprises

Extraordinary high-multiplicity muon bundle (p>70 GeV) observed in ALEPH

Multi-muon bundles with small angular spreads
Forward coherent pion production with large multiplicities
Disoriented Chiral Condensate (DCC)
Centauro and Anticentauro events
Long flying components
Anomalous heavy flavor production
Chirons, Halo events, Mini Clusters
TOTEM measurements for CR

Cross-section measurements:
- total cross-section
- elastic scattering
- minimum bias (non diffractive)
- single diffraction with proton detection
- Double Pomeron exchange with detection of two protons

Multiplicity distributions and correlations:
- for each of the above processes separately

Forward particle production (including protons)
- in combination with forward calorimeters of CMS
  (HF, Castor and ZDC)
- will be ready with a partial detector for calibrations in 2008
- will run under all beam conditions with a complete detector in 2009
- will need special high $\beta^*$ runs (hopefully in 2009) for:
  - total cross-section
  - diffraction
- will pursue a common physics program with CMS

LHC programme starts now
The TOTEM Collaboration

Penn State University, University Park

Case Western Reserve Univ., Cleveland, Ohio

USA

Estonian Academy of Sciences, Tallinn, Estonia

Academy of Sciences, Praha, Czech Republic

MTA KFKI RMKI, Budapest, Hungary

CERN, Geneva, Switzerland

INFN Sezione di Bari and Politecnico di Bari, Bari, Italy

University of Helsinki and HIP Helsinki, Finland

INFN Sezione di Bari and Politecnico di Bari, Bari, Italy

University of Siena and Sezione INFN-Pisa, Italy

Università di Genova and Sezione INFN, Genova, Italy
Try to reach the Coulomb region and measure interference:

- move the detectors closer to the beam than $10 \sigma + 0.5 \text{ mm}$
- run at lower energy $\sqrt{s} < 14 \text{ TeV}$