Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC

Marco Bozzo - INFN Genova e Università di Genova (Italy)

[for the TOTEM collaboration]
Outlook

- The TOTEM experiment
- LHC special runs and TOTEM data
- $pp$ elastic scattering differential cross-section
  - Large $t$ (0.36-2.5 $\text{GeV}^2$)
  - Small $t$ (0.02-0.33 $\text{GeV}^2$)
- Total, elastic, and inelastic cross-sections
- Perspectives on diffractive physics & cross-sections
**TOTEM Physics Overview**

**Total cross-section**

- Best fit with stat. error band incl. both TEVATRON points
- Total error band of best fit
- Total error band from all models considered

**Elastic Scattering**

**Forward physics**

**Optical Theorem**

\[
L \sigma_{tot}^2 = \frac{16\pi}{1 + \rho^2} \times \frac{dN}{dt} \bigg|_{t=0}
\]

\[
L \sigma_{tot} = N_{elastic} + N_{inelastic}
\]

**Diffraction: soft and hard**
**Roman Pots:** measure elastic & diffractive protons close to outgoing beam

**Inelastic telescopes:** charged particle & vertex reconstruction in inelastic events

- **T1:** $3.1 < \eta < 4.7$
- **T2:** $5.3 < \eta < 6.5$
- T1 and T2 detectors are installed and fully operational
- 220 m Roman Pot Silicon detectors are fully operational
- 147 m Roman Pot detectors are installed and tested
TOTEM nella regione forward di CMS

**T1 Telescope**
- 5 CSC planes
- Anode wires and both cathode strips
  - $3.1 \leq \eta \leq 4.7$

**T2 Telescope**
- 10 GEM planes
- Strips and pads
  - $5.3 \leq \eta \leq 6.5$

**Roman Pots**
- 10 Si planes
- u and v strips
  - $9.5 \leq \eta \leq 11$

200 m away!
The Roman Pots

Beam Position Monitor (BPM) fixed to the RP structure gives precise beam position

**RP unit**

**Horizontal Pot**

**Vertical Pots**

**BPM**

**unit:** 2 vertical pots / 1 horizontal & 1 BPM

**station:** 2 unit, at 4 m distance

**Detectors in 1 Pot**

- 10 Si detector planes
- 512 strips at ± 45°
- Pitch: 66 μm
- Resolution: ~ 20 μm

Special development: Detectors are efficient already 50 μm from mechanical edge
**pp ELASTIC SCATTERING and TOTAL CROSS-SECTION**

_t-range:_ 0.36 – 2.5 GeV$^2$

0.02 – 0.33 GeV$^2$
\[
\frac{d\sigma}{dt} = 4\pi\alpha^2 (\hbar c)^2 G^4(t) + \frac{\alpha(\rho - \alpha\phi)\sigma_{tot}G^2(t)}{|t|} e^{-B|t|/2} + \frac{\sigma_{tot}^2 (1 + \rho^2)}{16\pi(\hbar c)^2} e^{-B'|t|}
\]

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

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

**Requires beams with tiny angular spread (or large \(\beta^*\)**)

**A special optics has to be implemented in the LHC**
**Special Optics with large $\beta^*$ and low $\varepsilon$**

*A precise measurement of scattering angles down to a few $\mu$rad requires a very large $\beta^*$*

- Beam angular spread:
  \[ \sigma(\theta^*) = \sqrt{\varepsilon / \beta^*} = 0.3 \, \mu\text{rad} \]

- Beam size at the IP:
  \[ \sigma^* = \sqrt{\varepsilon \beta^*} = 0.4 \, \text{mm} \ (\text{large}) \]

$\Rightarrow$ Large beam size requires parallel-to-point focussing

$\Rightarrow$ Independence of measurement from vertex position

Min detector distance from the beam determines minimum $t$. 

$\Rightarrow$ Si-detector as close as possible to the beam

(NEEDS edgeless detectors!)
Proton reconstruction

- Both scattering angle projections reconstructed: $\Theta_x^*$ and $\Theta_y^*$
  - $\Theta_x^*$ from $\Theta_x \oplus RP220$ (through $dL_x/ds$) \[ \Theta_x = dL_x/ds \Theta_x^* \]
  - $\Theta_y^*$ from $\gamma \oplus RP220$ (through $L_y$) \[ \gamma = L_y \Theta_y^* \]

→ Excellent beam optics understanding
  - Magnet currents measured
  - Measurements of actual beam optics parameters with elastic scattering
    - $\Theta_{\text{left}}^* = \Theta_{\text{right}}^*$ (proton pair colinearity)
    - Proton position ↔ angle correlations
    - $L_x=0$ determination, coupling corrections

→ Fine geometric alignment
  - Alignment between pots with overlapping tracks (~1μm)
  - Alignment with respect to the beam - scraping exercise (~20μm)
  - Mechanical constraints between top and bottom pots (~10μm)
Both scattering angle projections reconstructed: $\Theta_x^*$ and $\Theta_y^*$
- $\Theta_x^*$ from $\Theta_x$ at RP220 (through $dL_x/ds$)
  \[ \Theta_x = \frac{dL_x}{ds} \Theta_x^* \]
- $\Theta_y^*$ from $y$ at RP220 (through $L_y$)
  \[ y = L_y \Theta_y^* \]

→ Excellent beam optics understanding
- Magnet currents measured
- Measurements of actual beam optics parameters with elastic scattering

→ Fine geometry
- Alignment
- Magnet currents measured

\( L_x = 0 \) measured by TOTEM

Line of 10 detectors
Track based alignment
First p-p Elastic Scattering Event Candidate [LPCC July 2010]

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \beta^* = 3.5 \text{ m} \]
**Proton tracks in one diagonal**

*(left-right coincidences)*

\[ t = -p^2 \theta^2 \]

\[ \xi = \Delta p/p \]

\[ y = L_y \Theta_y \]

\[ x = L_x \Theta_x + \xi D \]

\[ L_x \sim 0 \]
Elastic colinearity cuts

Co-linearity in $\theta_y$, $\xi \sim 0$  Co-linearity in $\theta_x$.

Data outside the $3\sigma$ cuts used for background estimation.
Acceptance (1)

$y$-acceptance corrections

Near edge efficiency transition 60 $\mu$m (removed)

Missing acceptance in $\theta_y^*$
**Acceptance (2)**

**φ-acceptance corrections**

![Graph showing Accepted φ(t) and Diagonal 1, 2](image)

**Total φ-acceptance correction**

<table>
<thead>
<tr>
<th>No.</th>
<th>t [GeV^2]</th>
<th>Θ^* [rad]</th>
<th>Accepted φ (2 diag.) [°]</th>
<th>φ accept. correct. factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33</td>
<td>1.65E-04</td>
<td>38.6</td>
<td>9.3</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>1.71E-04</td>
<td>76.4</td>
<td>4.7</td>
</tr>
<tr>
<td>3</td>
<td>0.60</td>
<td>2.21E-04</td>
<td>162.5</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>2.86E-04</td>
<td>209.8</td>
<td>1.7</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>3.83E-04</td>
<td>246.3</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>4.95E-04</td>
<td>269.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Correction critical at low t
Background determination

\[ B/S = (8.2 \pm 1)\% \]
\[ \sigma^* = 17.8 \, \mu \text{rad} \] (beam divergence)

Signal to background normalisation
(also as a function of \( \Delta \theta_y \))

\[ \sigma^* \rightarrow t\text{-reconstruction resolution:} \]

\[ \frac{\sigma(t)}{t} = \frac{\sqrt{2} p \sigma^*}{\sqrt{t}} : \]
- 0.4 GeV\(^2\) : 14% 
- 1 GeV\(^2\) : 8.8% 
- 3 GeV\(^2\) : 5.1%

\( |t| = 0.4 \text{GeV}^2: B/S = (11 \pm 2)\% \)
\( |t| = 0.5 \text{GeV}^2: B/S = (19 \pm 3)\% \)
\( |t| = 1.5 \text{GeV}^2: B/S = (0.8 \pm 0.3)\% \)
Efficiency (1)

Method 3T/4:
full elastic analysis with 3 track segments instead of 4
3 pots out of 4 used to determine efficiency of missing pot
4 pot-diagonal efficiency computed via consequent combinations

Efficiency correction t-independent = 1.18 - 1.19
5.9% + 2.9% + 4.3% + 4.7% + (5.9% + 2.9%) · (4.3% + 4.7%) =
17.8% + 0.792% = 18.6%

Huge data reduction factor before analysis sample?
Checked:
Correlated inefficiencies pots for 2T/4
Goal: Understand the data reduction step-by-step
Criteria: select pp candidates (elastic, 2*SD, DPE)
    reject MB, background,.....
Determine inefficiency in detection of pp

Events’ scan
• MiniDST (pots empty, shower, hits)
• Multi-track algorithm
• Theoretical rates vs observed
• Trigger vs detector acceptance
• Mini-bunch data reduction
• Events topology and rates

>>> triggers: ~90% on background (showers) ; ~5% cut by RP acceptance ; ~5% pp pairs
Strong correlations of fitted parameters

Principle Component Analysis (PCA) should ideally be applied.
Results checked with MAD-X.

$$\chi^2/NDF = 25.8/(36-26)=2.6$$
(lower if correlations eliminated)

Mean pull = 0.043  Pull RMS = 0.86
Full nonlinear fitting with harmonics and displacements.
TOTEM elastic : 2 “Experiments”

top 45 bot 56 ; bot45 top 56

2 diagonals:
2 different experiments, and NOT
2 independent experiments
TOTEM: large-\(t\) Result

\[ B = 23.6 \pm 0.5 \text{ stat} \pm 0.4 \text{ syst} \text{ GeV}^{-2} \]

\[ t_{\text{dip}} = -0.53 \pm 0.01 \text{ stat} \pm 0.01 \text{ syst} \text{ GeV}^2 \]
Large $\beta$ run

small-t ELASTIC SCATTERING

TOTAL CROSS-SECTIONS
**June 2011  $\beta^* = 90 \text{ m optics}$**

Un-squeeze from injection optics $\beta^*$ from 11m to 90m

[Helmut Burkhardt, Andre Verdier]

Very robust optics with high precision (doesn’t depend strongly on machine elements parameters)

- Two bunches:
  - 1 and $2 \times 10^{10}$ protons / bunch
- Instantaneous luminosity:
  - $8 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated luminosity: $1.7 \mu\text{b}^{-1}$
- Estimated pile-up: $\sim 0.5 \%$
- Vertical Roman Pots at 10 $\sigma$ from beam center
- Trigger rate: $\sim 50 \text{ Hz}$
- Recorded events in vertical Roman Pots: 66950
**Proton tracks in one diagonal (left-right coincidences)**

\[
t = -p^2 \theta^2
\]

\[
\xi = \Delta p/p
\]

\[
\begin{align*}
\{ y &= L_y \Theta_y \\
\{ x &= L_x \Theta_x + \xi D
\end{align*}
\]

\[
L_y \sim 260 \text{ m} \\
L_x \sim 0\text{- }3 \text{ m}
\]

Inel. pile-up $\sim 0.005 \text{ ev/bx}$
Colinearity

Colinearity plots - events with tracks in both arms
Angular difference between the two outgoing protons

\[
\frac{\Theta_y^* \text{ (proton1)} - \Theta_y^* \text{ (proton2)}}{\sqrt{2}}
\]

beam divergence \( \sigma_{\Theta^*} \)

\[
* = \sqrt{\frac{n}{\sigma^*}} = 2.4 \text{ rad}
\]
Optics, $t$-scale and acceptance

- Perturbations: optics very robust ($L_y \sim s_{RP}$), better than:
  - $d\Theta_x^*/\Theta_x^*=1.3\%_{syst}$
  - $d\Theta_y^*/\Theta_y^*=0.4\%_{syst}$
- Non-linearities in $\Theta_x^*(y)$ reconstruction due to $dL_x/ds$ measured and corrected for: (checked via $L_x$)
- $t$ systematics: $\frac{dt}{t} = 0.8\%$ (at low $|t|$) up to $2.6\%$ (at large $|t|$)
- Acceptance cut correction at low $|t|$ is a factor $<3$ ($\phi$ symmetry)
Efficiency Detector + Tracking

- **Method**: 3 pots out of 4

  - **Near bottom 56**: 1.3%
  - **Far top 45**: 3.3%

- **Diag. “top56 bot45”**: $1.5+2.5+1.4+3.3+(1.5+2.5)(1.4+3.3)=8.9\%$
- **Diag. “bot56 top 45”**: $1.3+2.7+1.4+3.1+(1.3+2.7)(1.4+3.1)=8.7\%$

- **Uncorrelated 2 pots out of 4 taken into account**
- **No far-far or near-near correlations observed**

Detector and tracking efficiency $> 91\%$
Elastic $d\sigma/dt$ and $\sigma_{el}$

small $t$ and large $t$ data (published in EPL95(2011)41001) superimpose.

Extrapolation to $t=0$

$$d\sigma/dt\big|_{t=0} = 5.037 \times 10^2 \text{ mb/GeV}^2$$

Elastic cross section

$$\sigma_{EL} = \begin{cases} 8.3 \text{ mb}^{(\text{extrap})} + 16.5 \text{ mb}^{(\text{measured})} \\ = 24.8 \text{ mb} \end{cases}$$

Red zone delimits the uncertainty region from the large $t$ measurement
Cross-Section Formulae

Optical Theorem:
\[ \sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1 + \rho^2} \cdot \frac{d\sigma_{EL}}{dt} \bigg|_{t=0} \]

Need luminosity from CMS:
\[ \frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt} \]

\( \rho \) from COMPETE fit:
\[ \rho = 0.14^{+0.01}_{-0.08} \]

\[ \sigma_{TOT} = \sqrt{19.20 \text{ mb GeV}^2} \cdot \frac{d\sigma_{EL}}{dt} \bigg|_{t=0} \]

\[ \sigma_{TOT} = \sigma_{EL} + \sigma_{INE}\]
Elastic exponential slope:

\[ B|_{t=0} = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}) \text{ GeV}^{-2} \]

Elastic diff. cross-section at optical point:

\[ \frac{d}{dt} \bigg|_{t=0}^{\text{el}} = (503.7 \pm 1.5^{\text{stat}} \pm 26.7^{\text{syst}}) \text{mb/GeV}^2 \]

Optical Theorem, \( \rho = 0.14^{+0.01}_{-0.08} \)

Total Cross-Section

\[ T = \left( 98.3 \pm 0.2^{\text{stat}} \pm 2.7^{\text{syst}} +0.8 \begin{array}{c} 0.2 \end{array}^{\text{syst from}} \right) \text{mb} \]
TOTEM: pp Inelastic Cross-Section

\[ \sigma_{el} = \left( 24.8 \pm 0.2^{(\text{stat})} \pm 1.2^{(\text{syst})} \right) \text{mb} \]

\[ T = \left( 98.3 \pm 0.2^{(\text{stat})} \pm 2.7^{(\text{syst})} + 0.8^{(\text{syst from } \rho)} \right) \text{mb} \]

Inelastic Cross-Section

\[ \sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left( 73.5 \pm 0.6^{(\text{stat})} \left[ +1.8 \right]^{(\text{syst})} \right) \text{mb} \]

\[ \sigma_{inel} \text{ (CMS)} = \left( 68.0 \pm 2.0^{(\text{syst})} \pm 2.4^{(\text{lumi})} \pm 4.0^{(\text{extrap})} \right) \text{mb} \]

\[ \sigma_{inel} \text{ (ATLAS)} = \left( 69.4 \pm 2.4^{(\text{exp})} \pm 6.9^{(\text{extrap})} \right) \text{mb} \]

\[ \sigma_{inel} \text{ (ALICE)} = \left( 72.7 \pm 1.1^{(\text{mod})} \pm 5.1^{(\text{lumi})} \right) \text{mb} \]
Compilation of $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$

$\sigma_{\text{tot}}$ (red), $\sigma_{\text{inel}}$ (blue) and $\sigma_{\text{el}}$ (green)

- $\Delta$ pp (PDG)
- $\triangledown$ pp (PDG)
- Auger + Glauber
- $\triangle$ ATLAS
- $\blacklozenge$ CMS

$\sigma_{\text{tot}}$ (best COMPETE $\sigma_{\text{tot}}$ fits)

$\sigma_{\text{tot}}$ (black line)

$\sigma_{\text{inel}}$ (dashed black line)

$\sigma_{\text{el}}$ (dashed green line)

$\sqrt{s}$ (GeV)

$\sqrt{s}$ vs. $\sigma_{\text{tot}}$, $\sigma_{\text{inel}}$, and $\sigma_{\text{el}}$.
Energy dependence of the exponential slope $B$
The proton structure

increasing energy

blackened radius, edge area increases

proton profile

Total cross-section

Marco Bozzo
**Diffractive minimum: analogous to Fraunhofer diffraction:** $|t| \sim p^2 q^2$

- exponential slope $B$ at low $|t|$ increases
- minimum moves to lower $|t|$ with increasing $s$ 
  $\rightarrow$ interaction region grows (as also seen from $\sigma_{\text{tot}}$)
- depth of minimum changes 
  $\rightarrow$ shape of proton profile changes
- depth of minimum differs between $pp, p\bar{p}$ 
  $\rightarrow$ different mix of processes
Models and TOTEM, a Comparison

$\sqrt{s} = 7$ TeV
Comparison with models

<table>
<thead>
<tr>
<th>Model</th>
<th>B (t=-0.4 GeV^2)</th>
<th>t_{DIP}</th>
<th>t^{-X} [1.5–2 GeV^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>25.3</td>
<td>0.48</td>
<td>10.4</td>
</tr>
<tr>
<td>Bourrely</td>
<td>22.0</td>
<td>0.54</td>
<td>8.4</td>
</tr>
<tr>
<td>Islam</td>
<td>20.2</td>
<td>0.60</td>
<td>5.0</td>
</tr>
<tr>
<td>Jenkovsky</td>
<td>20.1</td>
<td>0.72</td>
<td>4.2</td>
</tr>
<tr>
<td>Petrov</td>
<td>23.3</td>
<td>0.51</td>
<td>7.0</td>
</tr>
<tr>
<td>TOTEM</td>
<td>23.6 ± 0.3</td>
<td>0.53 ± 0.01</td>
<td>7.8 ± 0.3</td>
</tr>
</tbody>
</table>
PERSPECTIVES ON DIFFRACTIVE PHYSICS & CROSS-SECTIONS
Non-diffractive

Colour exchange

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

Incident hadrons acquire colour and break apart

Diffractive

Colourless exchange with vacuum quantum numbers

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

Incident hadrons retain their quantum numbers remaining colourless

GOAL: understand the QCD nature of the diffractive exchange
Diffractive forward protons @ RPs

\[ y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \]
\[ x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \]

Dispersion shifts diffractive protons in the horizontal direction.

**Low \( \beta^* \): 0.5 – 2 m**

- For low-\( \beta^* \) optics \( L_x, L_y \) are low
- \( v_x, v_y \) are not critical because of small IP beam size

**\( \beta^* = 90 \) m**

- \( L_x = 0 \), \( L_y \) is large
- beam \( \sigma = 212 \mu m \) → \( v_x, v_y \) important (deterioration of rec. resolution)
All the drawings show soft interactions. In case of hard interactions there should be jets, which fall in the same rapidity intervals.

Inelastic and Diffractive Processes

\[ \eta = -\ln \tan \theta/2 \]

Inelastic + Diffractive Processes

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

Intact in the scattering process. A hard scale + hadrons which remain laboratory of confinement & QCD:

Diffractive scattering is a unique
Single diffraction low $\xi$

Correlation between leading proton and forward detector $T_2$

Rapidity Gap
$\Delta \eta = -\ln \xi$

$M_x^2 = \xi \, s$

Low $\xi$
$\xi < 0.15\%$

run: 37280003, event: 3000

Marco Bozzo
Single diffraction large $\xi$
correlation between leading proton and forward detector T2

\[ \Delta \eta = -\ln \xi \]

\[ M_x^2 = \xi s \]

Large $\xi$
$\xi > 6.5\%$

run: 37280006, event: 9522
Double Pomeron Exchange (DPE)

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

\[ \Delta \eta = -\ln \xi_1 \]

\[ -\ln \xi_2 \]

\[ \eta = -\ln \tan \theta/2 \]

USE the LHC as a Pomeron-Pomeron (Gluon - Gluon) Collider
Double Pomeron Exchange

correlation between leading proton and forward detector T2

sector 45  IP  sector 56

RP  T2  T2  RP

low $\xi$  $\xi < 1.5\%$

high $\xi$  $\xi > 1.5\%$

run: 37220007, event: 9904
Example of DPE Mass Reconstruction

\[ \xi_1 < 1.5\% \; ; \; \xi_2 > 5.0\% \]

Conditions:
- Low-\(\beta\)
- Vertical RP
- Horizontal RP
- T2

\[ M_{pp} \text{ at rap. } y_{pp} \]
$\beta^* = 90\text{m}$ Oct'11: Elastic + DPE

RP 45
AND
RP 56

$\beta^* = 90\text{m}$
RP @ 4.8 $\sigma$

~no pile-up
$\beta^* = 90\,\text{m} \quad \text{Oct'11: Elastic + DPE}$

Angular correlations

Preliminary
\( \beta^* = 90 \text{ m} \) Oct'11: Elastic + DPE

Resolution

Preliminary

\[ \sigma_{RP} = 13 \mu \text{m} \]
Data Oct'11: Elastic Differential Cross-Section

Extends low-t limit

Raw data distribution

(to be corrected for acceptance, ...)

Preliminary

$6 \times 10^{-3}$
DPE (logic complement to the elastic tag)

DPE RP candidates

Preliminary
DPE Cross-Section

DPE RP candidates t-distribution
B=10 GeV^{-2}

Raw distribution
(to be corrected for acceptance, ...)

Preliminary

\sim 8 \times 10^{-3} \text{ GeV}^2

\text{Distribution integrated on } \xi
90% (65%) of all diffractive protons are detected for $\beta^* = 1540 \text{ (90) m}$
TOTEM + CMS running scenarios

- pp→pX
- pp→pXp
  - Soft diffraction

- pp→pjjX
- pp→pjjXp
  - (semi)-hard diffraction

- pp→pjj (bosons, heavy quarks, Higgs...)
  - Hard diffraction

---

Cross section | Luminosity
---|---

| $\beta$ (m) | 1540 | 90 | 2 | 0.5 |
| L (cm$^{-2}$ s$^{-1}$) | $10^{29}$ | $10^{30}$ | $10^{32}$ | $10^{34}$ |

TOTEM LHC runs | Standard LHC runs
Acknowledgments

• Special acknowledgments to the LHC team for their support and for the development of the 90m optics.

• Special acknowledgments to CMS for their collaboration and for providing TOTEM with the luminosity measurements.
Thank you for your attention

Large-$t$ elastic published in EPL, 95 (2011) 41001

Small-$t$ elastic and total cross-section published in EPL, 96(2011) 21002.
BACKUP
Measurement of $\rho$ in the Coulomb-nuclear Interference Region?

Obtain the last ingredient for $\sigma_{\text{tot}}$ from measurement rather than from theory.

$might$ be possible at $\sqrt{s}=7$ TeV with RPs at 5 to 6 $\sigma$.

Incentive to develop very-high-$\beta^*$ optics before reaching 14 TeV!

E.g., try to use the same optics principle as for 90m and unsqueeze further.
Possibilities of $\rho$ measurement

$$\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d \ln s}$$

asymptotic behaviour: $\propto 1 / \ln s$ for $s \to \infty$

$\rho_{\text{pred.}} \sim 0.13$ at LHC

Try to reach the Coulomb region and measure interference:

- move the detectors closer to the beam than $10 \sigma + 0.5$ mm
- run at lower energy @ $\sqrt{s} < 14$ TeV
Proton-proton elastic scattering at the LHC energy of $\sqrt{s} = 7$ TeV

The TOTEM Collaboration

G. Antchev$^{(a)}$, P. Aspell$^8$, I. Atanassov$^8$ (a), V. Avati$^8$, J. Baechler$^8$, V. Bernardi$^{5b,5a}$, M. Berretti$^{7b}$, M. Bozzo$^{6b,6a}$, E. Brückner$^{3a,3b}$, A. Buzzo$^{6a}$, F. S. Cafagna$^{5a}$, M. Calicchio$^{5b,5a}$, M. G. Catanesi$^{5a}$, C. Covaulli$^{9}$, M. Csányi$^{8}$ (b), T. Csörgő$^{4}$, M. Deile$^{5a}$, E. Dimovasil$^{8}$, M. Doubek$^{1b}$, K. Eggert$^{9}$, V. Eremin$^{(c)}$, F. Ferro$^{6a}$, A. Fiergoski$^{(d)}$, F. Garcia$^{3a}$, S. Gian$^{8}$, V. Greco$^{7b,8}$, L. Grzanka$^{8}$ (e), J. Heino$^{3a}$, T. Hilden$^{3a,3b}$, M. Janda$^{1b}$, J. Kaspar$^{1a,8}$, J. Kopal$^{1a,8}$, V. Kundrát$^{1a}$, K. Kurvinen$^{3a}$, S. Lam$^{7a}$, G. Latino$^{7b}$, R. Lauhakangas$^{3a}$, T. Leszko$^{(d)}$, E. Lippmaa$^{2}$, M. Lokačíček$^{1a}$, M. Lo Vetrere$^{6b,6a}$, F. Lucas Rodríguez$^{8}$, M. Macrì$^{6a}$, L. Macalettì$^{5b,5a}$, G. Magazzù$^{7a}$, A. Mercadante$^{5b,5a}$, S. Minutoli$^{6a}$, F. Nemes$^{4}$ (b), H. Niewiadomski$^{8}$, E. Noschis$^{8}$, T. Novák$^{4}$ (f), E. Oliveri$^{7b}$, F. Oljemark$^{3a,3b}$, R. Orava$^{3a,3b}$, M. Oriunno$^{8}$ (g), K. Österberg$^{3a,3b}$, A.-L. Perrot$^{8}$, P. Palazzi$^{7b}$, E. Pedreschi$^{7a}$, J. Petäjäätärvi$^{3a}$, J. Procházka$^{1a}$, M. Quinto$^{5a}$, E. Radermacher$^{8}$, E. Radicioni$^{5a}$, F. Ravotti$^{8}$, E. Robutti$^{6a}$, L.ROKElewski$^{8}$, G. Ruggiero$^{8}$, H. Saarikko$^{3a,3b}$, A. Santroni$^{6b,6a}$, A. Scribano$^{7b}$, G. Sette$^{7b,7a}$, W. Snoeys$^{8}$, F. Spinella$^{7a}$, J. Sziklai$^{4}$, C. Taylor$^{9}$, N. Turini$^{7b}$, V. Vacek$^{1b}$, M. Vitek$^{1b}$, J. Welti$^{3a,3b}$ and J. Whitmore$^{10}$

\begin{flushleft}
1a Institute of Physics of the Academy of Sciences of the Czech Republic, Praha, Czech Republic.

1b Czech Technical University, Praha, Czech Republic.

2 National Institute of Chemical Physics and Biophysics NICPB, Tallinn, Estonia.

3a Helsinki Institute of Physics, Finland.

3b Department of Physics, University of Helsinki, Finland.

4 MTA KFKI RMKI, Budapest, Hungary.

5a INFN Sezione di Bari, Italy.

5b Dipartimento Interateneo di Fisica di Bari, Italy.

6a Sezione INFN, Genova, Italy.

6b Università degli Studi di Genova, Italy.

7a INFN Sezione di Pisa, Italy.

7b Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Italy.

8 CERN, Geneva, Switzerland.

9 Case Western Reserve University, Dept. of Physics, Cleveland, OH, USA.

10 Penn State University, Dept. of Physics, University Park, PA, USA.
\end{flushleft}
OFFPRINT

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

The TOTEM Collaboration (G. Antchev et al.)

EPL, 96 (2011) 21002
Background Subtraction

Extrapolation of the background of the EPL paper should be an upper limit (2SD + DPE + ...) for the real contamination of the low t-distribution: found to be <=1% @ |t|<0.1 GeV^2

\[
\frac{[\Theta_y^* (proton1) - \Theta_y^* (proton2)]}{\sqrt{2}}
\]

Data confirm that there is no measurable background.
**Statistical and Systematic uncertainties for the $t$ and $d\sigma/dt$ results**

Table 3: Statistical and systematic errors on $t$ and $d\sigma/dt$.

| $|t|$ | $\delta t$ | $\delta (d\sigma/dt)$ |
|-----|------------|----------------------|
| 0.4GeV$^2$ | $\frac{\delta t}{t} = \pm 0.5\%_{Stat} \pm 2.6\%_{Syst}$ | $\frac{\delta (d\sigma/dt)}{d\sigma/dt} = \pm 2.6\%_{Stat}^{+25}_{-37} \%_{Syst}$ |
| 0.5GeV$^2$ | $\frac{\delta t}{t} = \pm 0.7\%_{Stat} \pm 2.5\%_{Syst}$ | $\frac{\delta (d\sigma/dt)}{d\sigma/dt} = \pm 4.4\%_{Stat}^{+28}_{-39} \%_{Syst}$ |
| 1.5GeV$^2$ | $\frac{\delta t}{t} = \pm 0.8\%_{Stat} \pm 2.3\%_{Syst}$ | $\frac{\delta (d\sigma/dt)}{d\sigma/dt} = \pm 8.2\%_{Stat}^{+27}_{-30} \%_{Syst}$ |
Table 1: Results of the TOTEM measurements at the LHC energy of $\sqrt{s} = 7$ TeV.

<table>
<thead>
<tr>
<th></th>
<th>Statistical uncertainties</th>
<th>Systematic uncertainties</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>(\pm [3.4 \div 11.9]%) single measurement(*)</td>
<td>(\pm [0.6 \div 1.8]% \text{optics} \pm &lt; 1% \text{alignment})</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/,dt$</td>
<td>5% / bin</td>
<td>(\pm 4% \text{luminosity} \pm 1% \text{analysis} \pm 0.7% \text{unfolding})</td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>(\pm 1%)</td>
<td>(\pm 1% t\text{-scale} \pm 0.7% \text{unfolding})</td>
<td>((20.1 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}) \text{ GeV}^{-2})</td>
</tr>
<tr>
<td>$d\sigma/,dt</td>
<td>_{t=0}$</td>
<td>(\pm 0.3%)</td>
<td>(\pm 0.3% \text{optics} \pm 4% \text{luminosity} \pm 1% \text{analysis})</td>
</tr>
<tr>
<td>$\int d\sigma/,dt$</td>
<td>(\pm 0.8% \text{extrapolation})</td>
<td>(\pm 4% \text{luminosity} \pm 1% \text{analysis})</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}$</td>
<td>(\pm 0.2%)</td>
<td>((^{+0.8%}_{-0.2%})^{(\rho)} \pm 2.7%)</td>
<td>((98.3 \pm 0.2_{\text{stat}} \pm 2.8_{\text{syst}}) \text{ mb})</td>
</tr>
<tr>
<td>$\sigma_{\text{el}} = \int d\sigma/,dt$</td>
<td>(\pm 0.8%)</td>
<td>(\pm 5%)</td>
<td>((24.8 \pm 0.2_{\text{stat}} \pm 1.2_{\text{syst}}) \text{ mb})</td>
</tr>
<tr>
<td>$\sigma_{\text{inel}}$</td>
<td>(\pm 0.8%)</td>
<td>((^{+2.4%}_{-1.8%}))</td>
<td>((73.5 \pm 0.6_{\text{stat}} \pm 1.8_{\text{syst}}) \text{ mb})</td>
</tr>
<tr>
<td>$\sigma_{\text{inel (CMS)}}$</td>
<td>(\pm 0.8%)</td>
<td>((^{+2.4%}_{-1.8%}))</td>
<td>((68.0 \pm 2.6_{\text{syst}} \pm 2.4_{\text{lumi}} \pm 4_{\text{extrap}}) \text{ mb})</td>
</tr>
<tr>
<td>$\sigma_{\text{inel (ATLAS)}}$</td>
<td>(\pm 0.8%)</td>
<td>((^{+2.4%}_{-1.8%}))</td>
<td>((69.4 \pm 2.4_{\text{exp}} \pm 6.9_{\text{extrap}}) \text{ mb})</td>
</tr>
<tr>
<td>$\sigma_{\text{inel (ALICE)}}$</td>
<td>(\pm 0.8%)</td>
<td>((^{+2.4%}_{-1.8%}))</td>
<td>((72.7 \pm 1.1_{\text{model}} \pm 5.1_{\text{lumi}}) \text{ mb})</td>
</tr>
</tbody>
</table>

(*) corrected after unfolding, analysis (includes tagging, acceptance, efficiency, background)