The TOTEM Experiment at the LHC

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(University of Siena & Pisa INFN)
(on behalf of the TOTEM Collaboration)

Rencontres de Moriond – QCD & HEI
La Thuile – March 20, 2009

- Physics program
- Detector overview
TOTEM @ CERN Large Hadron Collider (LHC)

- p-p collisions at $\sqrt{s} = 14$ TeV
- $L_{\text{inst}}$ up to $\sim 10^{33}$ cm$^{-2}$s$^{-1}$
- start up $\sim$ Fall 2009
- 6 experiments

TOTEM
- Total Cross Section
- Elastic Scattering
- Diffractive Dissociation

TOTEM Collaboration: Bari, Budapest, Case Western Reserve, CERN, Genova, Helsinki, Penn State, Pisa/Siena, Prague, Tallin ($\sim$ 80 physicists)
Leading Protons measured at -147m & -220m from IP

Leading Protons measured at +147m & +220m from IP

Leading protons: RPs at ±147m and ±220m
Rap gaps & Fwd particle flows: T1 & T2 telescopes
Fwd energy flows: Castor & ZDC (CMS)
TOTEM Physics Program Overview

Stand-Alone

- $\sigma^{pp}_{TOT}$ with a precision $\sim 1-2\%$, simultaneously measuring:
  - $N_{el}$ down to $-t \sim 10^{-3}$ GeV$^2$ and $N_{inel}$ with losses $< 3\%$
  - Elastic pp scattering in the range $10^{-3} < |t| \sim (p\theta)^2 < 10$ GeV$^2$
  - Soft diffraction (SD and DPE)
  - Particle flow in the forward region (cosmic ray MC validation/tuning)
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CMS-TOTEM (CMS/TOTEM Physics TDR, CERN/LHCC 2006-039/G-124)

- Soft and hard diffraction in SD and DPE (production of jets, bosons, h.f.)
- Central exclusive particle production
- Low-x physics
- Particle and energy flow in the forward region
Current models predict at $\sqrt{s} = 14$ TeV: $\sigma_{pp} = 90 - 130$ mb

- TOTEM goal: absolute error $\sim 1$ mb ($L_{\text{inst}} \sim 10^{28}$ cm$^{-2}$s$^{-1}$)

  ⇒ possibility to distinguish among different models

- Luminosity independent method:
  - elastic scattering (down to $|t| \sim 10^{-3}$ GeV$^2$)
  - inelastic scattering

  ⇒ proper tracking acceptance in forward region required

\[ \sigma_{tot} = 111.5 \pm 1.2^{+4.1}_{-2.1} \text{ mb} \]

Optical Theorem:
\[ \sigma_T = \frac{8\pi}{p\sqrt{s}} \text{Im} F(s,t)_{|t=0} \]
\[ L\sigma_T^2 = \frac{16\pi}{1 + \rho^2} \frac{dN_{el}}{dt} \bigg|_{t=0} \left( \rho = \frac{\text{Re} F}{\text{Im} F}_{|t=0} \approx 0.136 \right) \]
\[ L\sigma_T = N_{el} + N_{inel} \]
Elastic Scattering Cross Section $d\sigma^{\text{el}}_{pp}/dt$

Predicted at LHC:

$\sigma^{\text{el}}_{pp} \approx 18 - 35 \text{ mb}$

Wide range of predictions;
big uncertainties at large $|t|$;
whole $|t|$ range measured
with good statistics.

Allowed $|t|$ range depends on
beam optics

(1) $\beta^* = 1540 \text{ m}$ (typical $L_{\text{inst}} = 1.0 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$): $|t|_{\text{min}} = 0.002 \text{ GeV}^2$

(2) $\beta^* = 90 \text{ m}$ (typical $L_{\text{inst}} = 1.0 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$): $|t|_{\text{min}} = 0.04 \text{ GeV}^2$
Elastic Scattering Cross Section $d\sigma_{pp}^{el}/dt$

Predicted at LHC:

$\sigma_{el}^{pp} \sim 18 - 35$ mb

Wide range of predictions; big uncertainties at large $|t|$; whole $|t|$ range measured with good statistics.

Allowed $|t|$ range

Dedicated short runs at high-$\beta^*$ (and reduced $\varepsilon$) are required for precise measurement of the scattering angles of a few $\mu$rad

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## Running Scenarios

<table>
<thead>
<tr>
<th>Scenario Physics:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics:</strong></td>
</tr>
</tbody>
</table>
| low | large/semi-hard elastic, 
| $\sigma_{\text{tot}}$ (@ ~1%), MB, soft diff. |
| low/large | large | $|t|$ elastic, 
| $\sigma_{\text{tot}}$ (@ ~5%), MB, soft/hard diff. |

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^*$ [m]</td>
<td>1540</td>
<td>90</td>
</tr>
<tr>
<td>N of bunches</td>
<td>43 ÷ 156</td>
<td>156</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>2025 ÷ 525</td>
<td>525</td>
</tr>
<tr>
<td>N of part. per bunch</td>
<td>(0.6 ÷ 1.15) $\times 10^{11}$</td>
<td>1.15 $\times 10^{11}$</td>
</tr>
<tr>
<td>Half crossing angle [\micro rad]</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Transv. norm. emitt. $\varepsilon_n$ [\mu m rad]</td>
<td>1</td>
<td>3.75</td>
</tr>
<tr>
<td>RMS beam size at IP [\mu m]</td>
<td>450</td>
<td>213</td>
</tr>
<tr>
<td>RMS beam diverg. at IP [\mu rad]</td>
<td>0.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Peak Luminosity [cm$^{-2}$ s$^{-1}$]</td>
<td>$10^{28} + 2 \times 10^{29}$</td>
<td>$3 \times 10^{30}$</td>
</tr>
</tbody>
</table>

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### Cross section

- **Luminosity**
- **Beam ang. spread at IP:** $\sigma_{\theta^*} = \sqrt{\varepsilon / \beta^*}$
- **Beam size at IP:** $\sigma^* = \sqrt{\varepsilon \beta^*}$

- **Optimal $\beta^*$ = 1540m optics requires special injection optics: probably NOT available at the beginning of LHC**
- **‘Early’ $\beta^*$ = 90m optics achievable using the standard LHC injection optics**

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

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Combined Uncertainty in $\sigma_{tot}$

$\sigma_{tot} = \frac{16 \pi}{1 + \rho^2} \left. \frac{dN_{el} / dt}{N_{el} + N_{inel}} \right|_{t=0}$

$L = \frac{1 + \rho^2}{16 \pi} \left( \frac{N_{el} + N_{inel}}{dN_{el} / dt} \right)^2$

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

- 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: $\pm 1 \% \quad \pm 0.8 \%$
  (error dominated by Single Diffractive trigger losses)
- Error contribution from $(1+\rho^2)$: $\pm 1.2 \%$
  (using full COMPETE error band $d\rho/\rho = 33 \%$)

$\Rightarrow$ Total uncertainty in $\sigma_{tot}$ 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
\[ \sigma_{tot} = \frac{16 \pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0} \]

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

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

\( \beta^* = 90 \text{ m} \) required for early \( \sigma_{tot} \) measurement during the first year of LHC running at \( \sqrt{s} = 10 \text{ TeV} \)
CMS + TOTEM ⇒ largest acceptance detector ever built at a hadron collider:
the large $\eta$ coverage and $p$ detection on both sides allow the study of a wide range of physics processes in diffractive interactions.
Early TOTEM Measurements ($p = 5$ TeV, $\beta^* = 3m$)

**Roman Pots**

- **Sing. Diff. (horizontal RPs):**
  \[ \frac{d\sigma^{SD}}{dM} \text{ at high masses, } 1.4 < M < 4.2 \text{ TeV, } \frac{\sigma(M)}{M} < 10 \% \]

- **DPE (horizontal RPs):**
  \[ \frac{d\sigma^{DPE}}{dM} \text{ at high masses, } 0.2 < M < 1.8 \text{ TeV, } \frac{\sigma(M)}{M} < 10 \% \]

- **El. Scatt. (vertical RPs):**
  \[ \frac{d\sigma^{ES}}{dt} \text{ for } 2 < |t| < 10 \text{ GeV}^2, \frac{\sigma(t)}{t} \sim 0.2/\sqrt{|t|} \]

**Acceptance:** $0.02 < \xi = \Delta p/p < 0.18$

**Resolution:**
\[ \sigma(\xi) \sim 1/6 \cdot 10^{-3}, \sigma(\theta) \sim 15 \mu\text{rad} \]

**T1/T2**

- **Charged multiplicity studies** (min. bias and cosmic ray MC generators tuning/val.)

- **Rapidity gap studies** (topologies of diffr. events)
TOTEM Detectors: Setup in CMS

**Detectors on both sides of IP5**

**Inelastic Telescopes:**
reconstruction of tracks and interaction vertex; trigger capability with acceptance > 95%

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

\[ \eta = -\log(tg(\theta/2)) \]

⇒

- T1: 18 - 90 mrad
- T2: 3 - 10 mrad

**Elastic Detectors (Roman Pots):**
position of p scattered elastically at small angles
Active area up 1-1.5 mm from beam: 5-10 μrad
**TOTEM Detectors: Setup in CMS**

*Inelastic Telescopes:*
- Reconstruction track and interaction vertex;
- Trigger capability with acceptance > 95%.
- **T1:** $3.1 < |\eta| < 4.7$
- **T2:** $5.3 < |\eta| < 6.5$

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Each RP station has 2 units, 4m apart.
Each unit has 2 vertical insertions (‘pots’) and 1 horizontal

Horizontal Pot:
extend acceptance; overlap for relative alignment using common track.

Absolute (w.r.t. beam) alignment from beam position monitor (BPM)

Protons at few $\mu$rad angles detected at $10\sigma + d$ from beam ($\sigma_{\text{beam}} \sim 80\mu$m at RP)

⇒ ‘Edgeless’ detectors to minimize $d$
Roman Pots

Each Pot:

- **10 planes** of Si detectors
- **512 strips at 45° orthogonal**
- **Pitch**: 66 µm
- **Total ~ 5.1K channels**
- **Digital readout (VFAT):**
  - trigger/tracking
- **Resolution**: $\sigma \approx 20$ µm

Edgeless Si detector:

- **50 µm of dead area**
Roman Pots

Each Pot:
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- **Resolution**: $\sigma \sim 20 \mu m$

Integration of traditional Voltage Terminating Structure with the Current Terminating Structure

Detectors expected to work up to $\mathcal{L}_{int} \sim 1 \text{ fb}^{-1}$

Installation ongoing: RP220 (147) m fully (partially) equipped by June

Edgeless Si detector: 50 μm of dead area
Each arm:

- **5 planes** with 3 coordinates/plane, each formed by 6 trapezoidal CSC detectors
- 3 degrees rotation and overlap between adjacent planes
- Trigger with anode wires
- Digital readout (VFAT) for ~ 13.5K ch.
- Resolution: $\sigma \sim 1 \text{ mm}$
Each arm:

- **5 planes** with 3 coordinates/plane, each formed by 6 trapezoidal CSC detectors
- 3 degrees rotation and overlap between adjacent planes
- Trigger with anode wires
- Digital readout (VFAT) for ~ 13.5K ch.
- Resolution: $\sigma \sim 1$ mm

Ageing studies at CERN GIF: no loss of performance during 12-month test, with ~ 0.07 C/cm accumulated charge on wires, a dose equivalent to ~ 5 years at $\mathcal{L}_{\text{inst}}=10^{30}$ cm$^{-2}$s$^{-1}$

**Installation foreseen for May/June (if necessary also in September)**
Each arm:

- 10 planes formed by 20 triple-GEM semi-circular modules, with “back-to-back assembly and overlap between modules.
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- **10 planes** formed by 20 triple-GEM semi-circular modules, with “back-to-back assembly and overlap between modules
- Double readout layer: Strips for radial position (R); Pads for R, \( \phi \)
- Trigger from Pads (1560/chamber)
- Digital readout (VFAT) for \( \sim 41.4K \) ch.
- Resolution: \( \sigma_R \sim 100 \, \mu m, \sigma_\phi \sim 1^o \)

**GEM Technology:**
- Gas Detector
- Rad-hard
- High rate
- Good spatial and timing resolution

**T2 Triple GEM technology adequate to work at least 1 yr at \( \mathcal{L}=10^{33} \, cm^{-2}s^{-1} \)**

**Installation ongoing:** fully done by May
- **TOTEM** will be **ready** for data taking at the LHC restart and will run under all beam conditions.
- Measurement of **total pp cross-section** (and $\mathcal{L}$) with a precision of **1-2% (2%)** with $\beta^* = 1540$ m (dedicated runs).
- Measurement of **elastic scattering** in the range $10^{-3} < |t| < 10$ GeV$^2$
- Early measurements
  - low $\beta^*$:
    - study of SD and DPE at high masses
    - elastic scattering at high $|t|$
    - measurement of forward charged multiplicity
  - $\beta^* = 90$ m:
    - first measurement of $\sigma_{\text{tot}}$ (and $\mathcal{L}$) with a precision of ~ **5% (~7%)**
    - elastic scattering in a wide $|t|$ range
    - inclusive studies of diffractive processes
    - measurement of forward charged multiplicity
- Later: common CMS/TOTEM Physics Programme
Determination of $d\sigma/dt$ at $t=0$

Model dependent uncertainty due to Coulomb interferences

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

- Very approximate formula: West and Yennie model for Coulomb-Nuclear interference ($\rho(t) = \text{const}$)

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

Measurement of the exponential slope $B$ in the $t$-range 0.002 - 0.2 GeV$^2$ needs beams with tiny angular spread $\Rightarrow$ large $\beta^*$

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Possibilities of $\rho$ measurement

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

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Details on Optics

Proton transport equation:

\[ x = L_x \theta_x^* + v_x x^* + D\xi \]
\[ y = L_y \theta_y^* + v_y y^* \]

Optical functions:
- \( L \) (effective length); - \( v \) (magnification);
- \( D \) (machine dispersion)

Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP.
⇒ Define \( t \) and \( \xi \) range (acceptance)

Example
same sample of diffractive protons at different \( \beta^* \)
- low \( \beta^* \): p detected by momentum loss (\( \xi \))
- high \( \beta^* \): p detected by trans. momentum (\( t_y \))
**Optical Functions (β* = 90 m)**

\[ L = (\frac{\beta^*}{\beta^*})^{1/2} \sin(\mu(s)) \]

Idea:

- \( L_y \) large, \( L_x = 0 \)
- \( v_y = 0 \)
- \( \mu_y(220) = \pi/2 \), \( \mu_x(220) = \pi \)
  (parallel-to-point focussing on \( y \))

hit distribution (elastic)

Optical functions:
- \( L \) (effective length)
- \( v \) (magnification)
  defined by \( \beta \) (betatron function)
  and \( \mu \) (phase advance);
- \( D \) (machine dispersion)

\[ \xi = \frac{\Delta p}{p} \]

\((x^*, y^*)\): vertex position at IP

\((\theta_x^*, \theta_y^*)\): emission angle at IP

\[ t = t_x + t_y \]

\[ t_i \sim -(p\theta_i^*)^2 \]
Roman Pots Acceptances

- $\beta^* = 1540 \text{ m}$
  - $L = 10^{28} - 2 \times 10^{29}$
  - 95% of all $p$ seen; all $\xi$

- $\beta^* = 90 \text{ m}$
  - $L = 10^{29} - 3 \times 10^{30}$
  - 65% of all $p$ seen; all $\xi$

- $\beta^* = 0.5 - 2 \text{ m}$
  - $L = 10^{30} - 10^{34}$
  - $p$ with $\xi > 0.02$ seen; all $t$

Elastic Scattering (RP220)

- $\beta^* = 1540 \text{ m}$
  - $L = 10^{28} - 2 \times 10^{29}$
  - 95% of all $p$ seen; all $\xi$

- $\beta^* = 90 \text{ m}$
  - $L = 10^{29} - 3 \times 10^{30}$
  - 65% of all $p$ seen; all $\xi$

- $\beta^* = 0.5 - 2 \text{ m}$
  - $L = 10^{30} - 10^{34}$
  - $p$ with $\xi > 0.02$ seen; all $t$

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

- $\beta^* = 1540 \text{ m}$
  - $-t = 0.01 \text{ GeV}^2$
  - $-t = 0.002 \text{ GeV}^2$

- $\beta^* = 90 \text{ m}$
  - $-t = 0.01 \text{ GeV}^2$
  - $-t = 0.002 \text{ GeV}^2$

- $\beta^* = 2 \text{ m}$
  - $-t = 0.01 \text{ GeV}^2$
  - $-t = 0.002 \text{ GeV}^2$

Det. dist. 1.3 mm 6 mm
Measurement of $\sigma_{\text{TOT}}$ at 1%

**Trigger Losses (mb):**

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$(mb)</th>
<th>Double arm T1/T2</th>
<th>Single arm T1/T2</th>
<th>Uncertainty after Extrapolation (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>58</td>
<td>0.3</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Single diffractive</td>
<td>14</td>
<td>-</td>
<td>2.5</td>
<td>0.6</td>
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<tr>
<td>Double diffractive</td>
<td>7</td>
<td>2.8</td>
<td>0.3</td>
<td>0.1</td>
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<tr>
<td>Double Pomeron</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>Elastic Scattering</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$$\Delta \sigma_T/\sigma_T \sim \sqrt{[(0.006)^2 + (0.002)^2 + (0.012)^2]} \sim 0.014$$

Total 0.8%
Interpreting cosmic ray data depends on hadronic simulation programs. Forward region poorly known/constr. Models differ by factor 2 or more. Need forward particle/energy measurements e.g. $dN/d\eta$, $dE/d\eta$…
In 1 year @
\[ \mathcal{L}_{\text{inst}} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

At RPs locations =>

(b) Radiation Dose (rad)
Si CTS Edgeless Detectors for Roman Pots

Planar technology with CTS (Current Terminating Structure)

AC coupled microstrips made in planar technology with novel guard-ring design and biasing scheme

50 μm of dead area

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Si CTS Edgeless Detectors for Roman Pots

Planar technology with CTS (Current Terminating Structure)

AC coupled microstrips made in planar technology with novel guard and biasing scheme

50 µm of dead area
T1 Cathode Strip Chamber (CSC)

- Detector design similar to CMS
  CSC muon chamber
- Gas Mixture Ar/CO$_2$/CF$_4$
- Max size: ~ 1m x 0.68 m
- Gas gap: 10 mm
- Anode wires: Ø30µm, 3mm pitch
- Cathode strips: 4.5 mm width, 5mm pitch
- Digital readout (VFAT)

Ageing studies at CERN
Gamma Irradiation Facility:
no loss of performance during 12-month test, with ~0.07 C/cm
accumulated charge on wires corresponding to a dose equivalent
to ~ 5 years at L=10$^{30}$cm$^{-2}$s$^{-1}$
Gas Electron Multiplier (GEM)

GEM Technology
- Developed at CERN (F. Sauli ~ 1997)
- Used in COMPASS, LHCb, …
- Gas Detector
- “Rad-hard”, high rate, good spatial and timing resolution
- Electrodes: 50 μm kapton + 2x5 μm Cu
- Density: 50-100 holes/mm²
- Electric field (channel) ~ 100 KV/cm
  \( (V_{\text{gem}} = 500 \text{ V}) \Rightarrow \text{electron cascade} \)
- Gain: 10 - 100

T2 GEM:
- 70 µm
- 140 µm

Electrons

Ions

Gain: 10 - 100

5 µm Cu
50 µm Kapton
55 µm
70 µm
- Ar/CO$_2$ 70/30 gas mixture
- Operating gas gain $M = 8000$
- Digital readout (VFAT)
- T2 Triple GEM technology adequate to work at least 1 yr at $L=10^{33}$ cm$^{-2}$s$^{-1}$

$pads: 65(\phi) \times 24(\eta) = 1560$ pads

Pads: $\Delta \eta \times \Delta \phi = 0.06 \times 0.018\pi$
$\sim 2\times2$ mm$^2 - \sim 7\times7$ mm$^2$

Strips: 256x2 (width 80 $\mu$m, pitch 400 $\mu$m)
Totem Electronics

VFAT Chip

- Developed at CERN by the Micro-Electronics group
- 128 channels of tracking front-end with digital storage and data transmission
- 8 programmable trigger outputs
- Designed for radiation tolerance

<table>
<thead>
<tr>
<th></th>
<th>Roman Pots</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. and type of detectors</td>
<td>240</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Si strip detectors</td>
<td></td>
<td>Cathode Strip Chambers</td>
<td>Gas Electron Multipliers</td>
</tr>
<tr>
<td>No. of channels</td>
<td>122880</td>
<td>12540 anodes</td>
<td>62400 pads</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20900 cathodes</td>
<td>20480 strips</td>
</tr>
<tr>
<td>No. of VFATs</td>
<td>960</td>
<td>480</td>
<td>680</td>
</tr>
<tr>
<td>Typical input charge</td>
<td>~4 fC</td>
<td>~50 fC</td>
<td>~50 fC</td>
</tr>
<tr>
<td>Occupancy</td>
<td>&lt;1%</td>
<td>anodes: &lt;10%</td>
<td>pads: &lt;5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cathodes: &lt;20%</td>
<td>strips: &lt;30%</td>
</tr>
<tr>
<td>Radiation Dose</td>
<td>&lt;10 Mrad</td>
<td>&lt;50 krad</td>
<td>&lt;50 Mrad</td>
</tr>
</tbody>
</table>

Table 5: Overview of electronics requirements from the different detectors.

Standardization for all detectors: identical front-end electronics (VFAT chips); identical DAQ and trigger cards

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