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TOTEM collaboration

- Introduction
- Soft diffraction @ $\sqrt{s} = 7$ TeV
- Soft & semi-hard diffraction @ $\sqrt{s} = 8$ TeV with CMS
- Further plans on diffraction
Inelastic telescopes: rapidity gaps

\[ \begin{align*}
T1 &: \ 3.1 \ < \ \eta \ < \ 4.7 \\
T2 &: \ 5.3 \ < \ \eta \ < \ 6.5 \quad \text{(inelastic trigger)}
\end{align*} \]

\( P_T \) threshold: 40 MeV (T2) & 100 MeV (T1)

Roman Pots: diffractive protons (di-proton trigger)
Experimental setup @ IP5

Inelastic telescopes: rapidity gaps

Roman Pots: diffractive protons (di-proton trigger)

Si-det stack

HF (CMS)  T1  T2  CASTOR (CMS)

IP5

~ 10 m  ~ 14 m
Soft pp processes

- Elastic Scattering
- "colourless" exchange
- Single Diffraction (SD)
- Double Diffraction (DD)
- Central Diffraction (CD)
- Non-diffusive minimum bias (MB)

Diffraction a large fraction of total pp cross-section !!

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

- $\sigma$ @ LHC
  - $\sim 25$ mb
  - $\sim 10$ mb
  - $\sim 5$ mb
  - $\sim 1$ mb
  - $\sim 60$ mb
Diffractive protons @ RP220

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

\( \xi = \Delta p/p \)

dispersion shifts diffractive protons in horizontal direction

Generally \( v_{x,y}, L_{x,y} & D_x \) functions of \( \xi \rightarrow \) reconstruction non-linear problem

Low \( \beta^* \): 0.5 – 3 m, \( \xi > 2\% \)

\( \beta^* = 90 \text{ m}, \text{ full } \xi\text{-coverage, } |t_y| > 0.01 \text{ GeV}^2 \)

\[ L_x & L_y \text{ low, protons shifted due to } \xi \]
\[ \text{vertex not critical: small transverse } \sigma_{\text{beam}} \]

\[ L_x = 0, L_y \text{ large} \]
\[ \text{large transverse } \sigma_{\text{beam}} (~200 \mu\text{m}) \rightarrow \]
\[ v_x, v_y \text{ important (worse } \xi\text{-resolution)} \]
\[ \text{CMS vertex improves } \xi\text{-resolution} \]
Soft diffraction @ $\sqrt{s} = 7$ TeV

Based on $\beta^* = 90$ m Oct 2011, $\mathcal{L} = 0.1$ nb, inelastic pileup $\sim 0.03$
T2 or RP45+RP56 trigger, RP approach: 4.8, 5.5 and 6.5$\sigma_{\text{beam}}$

$M_{\text{diff}}$ acceptance (50 % @ 3.4 GeV)

Already estimated low mass ($M_{\text{diff}} < 3.4$ GeV)
diffraction (mainly SD):

$\sigma_{\text{inel}}$ (from elas.) –
$\sigma_{\text{inel}}, |\eta| < 6.5$ (from inelas.)
$= 2.62 \pm 2.17$ mb

$\sigma_{\text{inel}}, |\eta| > 6.5 <$
6.3 mb @ 95 % CL

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NB! Single proton trigger swamped by beam halo !!
SD candidate: small $\xi$

Tracks in T2 only opposite to proton $\Rightarrow$

$2 \times 10^{-7} < \xi < 2.5\%$

Run: 37280003, event: 3000
SD candidate: large $\xi$

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

$M_\chi^2 = \xi \cdot s$

Tracks in T2 on proton side
$\Rightarrow \xi > 2.5\%$

Correlation between proton in RP & tracks in T2 (& T1)!!

run: 37280006, event: 9522
Soft SD cross-section @ $\sqrt{s} = 7$ TeV

- tracks in T2 (T2 trigger) $\Rightarrow \xi > 2 \times 10^{-7}$
- exactly 1 proton (only 1 RP track + veto RP45+RP56 trigger)

- $\xi$–classification based on rapidity gap
  - low $M_{\text{diff}}$: $p + T2$ opposite only + no T1 ($1 \times 10^{-6} > \xi > 2 \times 10^{-7}$)
  - medium $M_{\text{diff}}$: $p + T2$ opposite + T1 opposite ($0.25 \% > \xi > 1 \times 10^{-6}$)
  - high $M_{\text{diff}}$: $p + T2$ opposite + T1 same ($2.5 \% > \xi < 0.25 \%$)
  - very high $M_{\text{diff}}$: $p + T2$ both ($\xi > 2.5 \%$)

Inelastic + beam halo background estimated from data:
- $p X$ gap events i.e. $p + T2$ same only for low $M_{\text{diff}}$ class etc..
- beam halo ($\xi \sim 0$) from single RP trigger data for very high $M$ ($\xi > 2.5 \%$)

- Separate analysis top RP45, bot RP45, top RP56, bot RP56...

- Correct for T2 trigger efficiency, $\phi$ acceptance, $p$ reco inefficiency ...
Soft SD cross-section @ $\sqrt{s} = 7$ TeV

rapidity gap based $\xi$-classification (T1, T2)

TOTEM Preliminary

$2 \times 10^{-7} < \xi < 1 \times 10^{-6}$

$\sigma(\xi) \sim 0.8\%$

TOTEM Preliminary

$1 \times 10^{-6} < \xi < 0.25\%$

TOTEM Preliminary

$0.25\% < \xi < 2.5\%$

rapidity gap reconstruction using T1 & T2: $\sigma(\xi)/\xi \sim 1$

proton $\xi$ (& MC) for class migration

background & acceptance in highest $M_{\text{diff}}$ class ($\xi > 2.5\%$) under study!
Soft SD cross-section @ $\sqrt{s} = 7$ TeV

t-distributions (acceptance/inefficiency corrected, background subtracted)

**TOTEM Preliminary**

1. $d\sigma/dt \sim C e^{-Bt}$
   - $B = 9.6 \pm 1.5 \text{ GeV}^{-2}$
   - $2 \times 10^{-7} < \xi < 1 \times 10^{-6}$

2. $d\sigma/dt \sim C e^{-Bt}$
   - $B = 8.0 \pm 1.5 \text{ GeV}^{-2}$
   - $1 \times 10^{-6} < \xi < 0.25\%$

3. $d\sigma/dt \sim C e^{-Bt}$
   - $B = 6.6 \pm 1.5 \text{ GeV}^{-2}$
   - $0.25\% < \xi < 2.5\%$

**t-distributions still to be corrected for beam divergence & effect of $\xi$ on proton $\phi$-acceptance correction**

$$\frac{d\sigma_{SD}^{\text{class } i}}{dt} = e^{-B,t} - \text{backgr.}$$

$$\sigma_{SD} (\xi > 2 \times 10^{-7}) = \sum_{i} \int_{0}^{\infty} dt \frac{d\sigma_{SD}^{\text{class } i}}{dt}$$
Soft DD cross-section \( @ \sqrt{s} = 7 \text{ TeV} \)

\( \sigma_{\text{DD}} \) require large \( \eta \) coverage \( \Rightarrow \)

CMS + TOTEM \( @ \sqrt{s} = 8 \text{ TeV} \)

Select clean DD sample (\( S/B >> 1 \)):

Require \( 3.4 < M_{\text{diff}} < 8 \text{ GeV} \) on both sides:
require tracks in both T2s & no tracks on both T1s

\( \Rightarrow \sigma_{\text{DD}} (|\eta_{\min}|) \) for \( 3.4 < M_{\text{diff}} < 8 \text{ GeV} \) region
CD candidate: large $\xi$ & small $\xi$

Rapidity Gap
$\Delta \eta = -\ln \xi_1$

$M_X^2 = \xi_1 \xi_2 s$

Rapidity Gap $\Delta \eta = -\ln \xi_2$

sector 45 IP sector 56

$5 \times 10^{-7} < \xi_1 < 3\%$, T2 forbidden

$\xi_2 > 10\%$, T2 full

Correlation between proton in RP & tracks in T2 (& T1) !!

run: 37220007, event: 9904

$\xi_1 > 3\%$, T2 forbidden
Soft CD cross-section @ $\sqrt{s} = 7$ TeV

- 2 protons with top RP45 + top RP56 or bot RP45 + bot RP56 topology (removing elastic background)
- $y_{RP} < 11\sigma_{beam}$ removed: protection against pile-up
  - beam halo $\times$ beam halo
  - beam halo $\times$ elastic proton

1 arm CD rate (integrated $\xi$, acceptance corrected)

\[ \sigma_{DPE} \text{ estimation:} \]
\[
\frac{d^2\sigma_{CD}}{dt_1dt_2} = C(\Delta\phi_{1,2})e^{-Bt_1}e^{-Bt_2} - \text{backgr.}
\]
\[
\sigma_{CD} = \int_{0}^{\infty} dt_1 \int_{0}^{\infty} dt_2 \frac{d^2\sigma_{CD}}{dt_1dt_2}
\]
\[
\approx 1 \text{ mb}
\]

\[ dN/dt \sim Ce^{-Bt} \]

$B = 7.8 \pm 1.4$ GeV$^2$
CMS-TOTEM common runs 2012

Separate data taking with bidirectional exchange of trigger information (RP & T2 trigger to CMS, combined dijet & lepton/γ trigger to TOTEM)

Orbit number difference

Bunch number difference

Offline matching with orbit & bunch number

Unique setup!
Large η-coverage:
- CMS: -5.5<η<5.5,
- T1: 3.1 < |η| < 4.7
- T2: 5.3 < |η| < 6.5
- FSC: 6 < |η| < 8
- RP: diffractive protons

On-going analysis:
- dN/dη with CMS tracker (|η| < 2.4) & T2 (5.3 < |η| < 6.5) with same T2 trigger
- SD dijet with proton
- Soft & semi-hard CD
- ...
CMS + TOTEM @ $\sqrt{s} = 8$ TeV

Soft CD

![Diagram of Soft CD]

Semi-hard CD

![Diagram of Semi-hard CD]

**2-arm proton reconstruction**, $\xi_{1,2} = \Delta p_{1,2}/p_{1,2}$ (never before)

Mass to be seen in CMS from reconstructed protons: $M^2 = s \cdot \xi_1 \xi_2$

**Initial vs. final state comparison**: $M_{\text{TOTEM}}(pp) =? M_{\text{CMS}}$ (never before)

Prediction of central particle flow topology from proton $\xi$’s (rapidity gaps):

$\Delta \eta_{1,2} = -\ln \xi_{1,2}$
CMS-TOTEM CD samples

Jul 2012, $\beta^*=90$ m, $\sim 7\times10^{10}$ p/bunch, inelastic pileup 0.03-0.05, RP@$9\sigma_{\text{beam}}$

- **Soft CD sample** (RP45×RP56 trigger): 0.8 nb$^{-1}$ (2-3 bx)
  - inelastic proton pair (+ CMS vertex): 330 k (80 k of which 48 k good)
  - $\text{RP}_{\text{inelastic trigger}}/T2_{\text{trigger}} = 0.5\% \approx \sigma_{\text{DPE}}/\sigma_{\text{Min.Bias}}$ (as expected)

- **Semi-hard CD sample** (CMS dijet $p_T > 20$ trigger): 43 nb$^{-1}$ (112 bx)
  - Inelastic proton pair (+ 1 valid CMS vertex) / dijet: 1248 (860) / 2.5 M

# of vertices, soft CD, 2 inelastic p in RPs  # of vertices, dijet, 2 inelastic p in RPs
Soft CD pileup

\[ N = 7 \times 10^{10}, \beta^* = 90m, \varepsilon_N = 3.5 \mu m, \frac{L}{bx} \approx 6.0 \times 10^{27} cm^{-2} s^{-1} \]

Soft CD pile-up estimation

<table>
<thead>
<tr>
<th>Events &amp; Pile-up</th>
<th>Acc. t</th>
<th>Rate/bx</th>
<th>Expected events #</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD (~1mb)</td>
<td>35%</td>
<td>0.022 %</td>
<td>263k</td>
<td>80 %</td>
</tr>
<tr>
<td>Soft SD × Soft SD</td>
<td></td>
<td>6.9 \times 10^{-6}</td>
<td>9 k</td>
<td>3 %</td>
</tr>
<tr>
<td>SD × beam halo</td>
<td></td>
<td>1.9 \times 10^{-5}</td>
<td>5k – 25k</td>
<td>1.5% - 8%</td>
</tr>
<tr>
<td>beam halo × beam halo</td>
<td></td>
<td>2.5 \times 10^{-5}</td>
<td>7k – 34k</td>
<td>2% - 10%</td>
</tr>
<tr>
<td>CD + QCD</td>
<td></td>
<td></td>
<td>10k</td>
<td>3%</td>
</tr>
</tbody>
</table>

Pile-up removal:

- 0 or 1 vertex in CMS
- RP near edge area removed (1 elastic p. + beam halo or SD)
- top RP45 + top RP56 or bot RP45 + bot RP56 topology
- \( \xi > 1.5\% \) (far enough from resolution effects)
- FSC empty : QCD background protection
- \( M_{CMS}(\text{Particle Flow + missing momentum}) \leq M_{TOTEM}(pp) \)
### Semi-hard CD pile-up

\[ N = 0.7 \times 10^{11}, \quad \beta^* = 90 \text{m}, \quad \varepsilon_N = 3.5 \ \mu\text{m}, \quad L/\text{bx} \approx 6.0 \times 10^{27} \ \text{cm}^{-2} \ \text{s}^{-1} \]

#### Semi-hard CD pile-up estimation

<table>
<thead>
<tr>
<th>Pile-up case</th>
<th>Accept.</th>
<th>Rate/bx</th>
<th>Events in 2.5M</th>
<th>Fraction of accepted semi-hard CD candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\times Soft SD (+QCD JJ)</td>
<td>25%</td>
<td>1.7\times10^{-5}</td>
<td>42.5</td>
<td>3.4 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\cdot 4.9\times10^{-5})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft CD (+QCD JJ)</td>
<td>35%</td>
<td>2.9 \times 10^{-4}</td>
<td>721</td>
<td>58 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\cdot 4.9\times10^{-5})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-hard SD + Soft SD</td>
<td></td>
<td>7.2\times10^{-10}</td>
<td>37-370</td>
<td>3 % – 30 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 7.2\times10^{-9}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-hard CD + SD</td>
<td></td>
<td>3.5\times10^{-11}</td>
<td>2 – 20</td>
<td>0.1 % – 1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5\times10^{-10}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam halo (+QCD JJ)</td>
<td></td>
<td>3.5\times10^{-10}</td>
<td></td>
<td>\sim 1%</td>
</tr>
</tbody>
</table>
Soft & semi-hard CD - logic 0

- CMS and TOTEM consistent (within resolution)
  \[ M_{CMS}(\text{Particle Flow}) = M_{TOTEM}(pp) \]
  \[ p_{CMS}(\text{Particle Flow}) = p_{TOTEM}(pp) \]
- Few semi-hard (pp → p + Xjj + p) candidates observed of which none exclusive (pp → p + jj + p)
- Soft (pp → p + X + p) sample many candidates

Constraints & checks applied:
- Pile-up rejection
- Selection criteria (kinematics, rapidity gaps...)
- Single, well defined CMS vertex
- Jets resolutions & detector thresholds (checked with elastic scattering)

Selected semi-hard CD events:

<table>
<thead>
<tr>
<th>(M_{TOTEM})</th>
<th>(M_{CMS})</th>
<th>(M_{dijet})</th>
<th>(p_{Z_{TOTEM}})</th>
<th>(p_{Z_{CMS}})</th>
<th>(\xi_{left})</th>
<th>(\xi_{right})</th>
<th>(p_{T_{CMS}})</th>
<th>(p_{T_{TOTEM}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>204.673</td>
<td>179.616</td>
<td>81.0462</td>
<td>-364.838</td>
<td>-295.344</td>
<td>-0.0979</td>
<td>-0.00669</td>
<td>3.50267</td>
<td>4.94E-01</td>
</tr>
<tr>
<td>243.97</td>
<td>219.344</td>
<td>138.422</td>
<td>-343.07</td>
<td>-254.548</td>
<td>-0.0955</td>
<td>-0.00973</td>
<td>3.3627</td>
<td>5.64E-01</td>
</tr>
</tbody>
</table>

only 1 additional track in T2
Semi-hard CD - logic 1

$M_{CMS}(\text{Particle Flow + missing momentum}) \leq M_{TOTEM}(pp)$

- Additional momentum undetected by CMS
- Tracks in forward detectors, when allowed by $\xi$-predicted gaps
- No tracks in forward detectors when forbidden by $\xi$-predicted gaps

~ 50 candidates

no exclusive

(largest $M_{jj}/M_{TOTEM} \sim 0.57$)

Best events in terms: $M_{CMS}(\text{Particle Flow + missing p}) \approx M_{TOTEM}(pp)$

<table>
<thead>
<tr>
<th>$M_{jj}$</th>
<th>$M_{CMS}$</th>
<th>$M_{CMS+missing\ p}$</th>
<th>$M_{TOTEM}$</th>
<th>$P_{zCMS}$</th>
<th>$P_{zTOTEM}$</th>
<th>$X_{i\ left}$</th>
<th>$X_{i\ right}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>107.171</td>
<td>266.948</td>
<td>297.845</td>
<td>301.281</td>
<td>254.787</td>
<td>331.096</td>
<td>-0.0146</td>
<td>-0.0973</td>
</tr>
<tr>
<td>138.422</td>
<td>219.344</td>
<td>250.076</td>
<td>243.97</td>
<td>-254.548</td>
<td>-343.07</td>
<td>-0.0955</td>
<td>-0.00973</td>
</tr>
<tr>
<td>93.3026</td>
<td>254.456</td>
<td>341.96</td>
<td>335.624</td>
<td>319.223</td>
<td>612.358</td>
<td>-0.0107</td>
<td>-0.164</td>
</tr>
<tr>
<td>81.0462</td>
<td>179.616</td>
<td>198.14</td>
<td>204.673</td>
<td>-295.344</td>
<td>-364.838</td>
<td>-0.0979</td>
<td>-0.00668</td>
</tr>
<tr>
<td>123.347</td>
<td>188.163</td>
<td>251.145</td>
<td>234.579</td>
<td>-140.216</td>
<td>-286.387</td>
<td>-0.081</td>
<td>-0.0105</td>
</tr>
<tr>
<td>61.3357</td>
<td>162.727</td>
<td>215.088</td>
<td>198.103</td>
<td>-359.435</td>
<td>-639.511</td>
<td>-0.164</td>
<td>-0.00375</td>
</tr>
</tbody>
</table>

NB! Almost all soft CD events satisfy logic 1
Soft & semi-hard CD - logic 2

- Look for *secondaries* (decay products) violating $\xi$-predicted gaps
- Standard pile-up protection
- $M_{\text{CMS}}(\text{Particle Flow + missing } p) \leq M_{\text{TOTEM}}(p p)$
- Normally discarded due to presence of tracks in forbidden gaps

Semi-hard CD sample: no candidates

Soft CD sample: some candidates
expect background from $2 \times$ soft SD & soft SD + beam halo
Soft & semi-hard CD - logic 3

- Check *escaping-mass candidates*
- Standard pile-up protection
- \( p_{CMS}(\text{Particle Flow}) \neq p_{TOTEM}(pp) \)
- \( M_{CMS}(\text{Particle Flow} + \text{missing } p) \leq M_{TOTEM}(pp) \)
  \[ \rightarrow \text{existence of tracks undetected by CMS} \]

- No tracks observed in forward detectors ‘allowed’ by gaps
- More forward regions excluded by gaps \( \rightarrow \) ‘allowed’ = ‘required’?

- Energetic gammas in T2, \( N^* \rightarrow p \)
- Detector ‘inefficiencies’?
- Acceptance gaps between detectors?
- High energy neutrinos?
- Neutral particle flow in T2 (under simulation)?
- Real escaping energy?
  - This depends on amount of missing energy

\[ \sim 10 \text{ candidates with } \Delta M = M_{TOTEM} - M_{CMS} \sim 400 \text{ GeV or more} \]
Semi-hard CD - logic 4

- Same selection as Logic-3 (escaping-mass candidate search)
  \[ p_{\text{CMS}}(\text{Particle Flow}) \neq p_{\text{TOTEM}}(pp) \]
  \[ M_{\text{CMS}}(\text{Particle Flow} + \text{missing momentum}) < M_{\text{TOTEM}}(pp) \]
  → existence of energy undetected by CMS

- **additional tracks** would be required to appear in forbidden rapidity regions
- those tracks not observed in the detectors.

Semi-hard CD sample: no candidates observed

NB! In soft CD events overwhelmed by pileup
**Soft & semi-hard CD – highest mass**

Soft CD $M_{TOTEM}$ distribution

Highest soft CD $M_{TOTEM}$ candidates:

<table>
<thead>
<tr>
<th>$M_{TOTEM}$</th>
<th>$Pz_{TOTEM}$</th>
<th>$X_{i_{left}}$</th>
<th>$X_{i_{right}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1830.91</td>
<td>-91.5223</td>
<td>-0.240589</td>
<td>-0.217709</td>
</tr>
<tr>
<td>1792.09</td>
<td>-147.443</td>
<td>-0.243199</td>
<td>-0.206338</td>
</tr>
<tr>
<td>1719.7</td>
<td>220.329</td>
<td>-0.189179</td>
<td>-0.244261</td>
</tr>
<tr>
<td>1718.48</td>
<td>-17.6895</td>
<td>-0.217033</td>
<td>-0.212611</td>
</tr>
<tr>
<td>1716.62</td>
<td>-103.546</td>
<td>-0.227911</td>
<td>-0.202024</td>
</tr>
</tbody>
</table>

$M_X = 1.8$ TeV with pp survival (never before)

In semi-hard CD candidates up to $M_{TOTEM}$ of 1.45 TeV:

<table>
<thead>
<tr>
<th>$M_{TOTEM}$</th>
<th>$x_{i_{left}}$</th>
<th>$x_{i_{right}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1402.31</td>
<td>0.191</td>
<td>0.161</td>
</tr>
<tr>
<td>1432.62</td>
<td>0.241</td>
<td>0.133</td>
</tr>
<tr>
<td>1436.38</td>
<td>0.189</td>
<td>0.171</td>
</tr>
<tr>
<td>1453.09</td>
<td>0.180</td>
<td>0.183</td>
</tr>
</tbody>
</table>
Future plans – diffraction

- Lots of potential studies & measurements ahead
- TOTEM alone: soft SD, CD, DD
- CMS + TOTEM data analysis:
  - Homework: beam halo pile-up, optics, resolutions, acceptance, reconstruction …
  - SD & CD cross-sections
  - Further studies of particular events (event displays)
  - pA data with p measured in RP (+ Castor & ZDC)
- Upgrade of TOTEM Roman Pot detectors to profit from low-$\beta^*$ optics after LHC shut-down
- Data taking: 1000 bunches + x-angle @ $\beta^* = 90$ m
The End
Optics

\[ (x^*, y^*): \text{vertex position} \]
\[ (\theta_x^*, \theta_y^*): \text{emission angle: } t = -p^2 (\theta_x^{*2} + \theta_y^{*2}) \]
\[ \xi = \Delta p/p: \text{momentum loss (diffraction)} \]

\[ y_{\text{det}} = L_y \theta_y^* + v_y y^* \]

\[ \beta^* = 3.5 \text{ m: } L_y \approx 25 \text{ m, } v_y \text{ small} \]
\[ \beta^* = 90 \text{ m: } L_y \approx 260 \text{ m, } v_y \approx 0 \]
\[ \Rightarrow \theta_y^* \text{ reconstructed from track position} \]

\[ x_{\text{det}} = L_x \theta_x^* + v_x x^* + D \xi \]

\[ \beta^* = 3.5 \text{ m & 90 m: } L_x \approx 0 \text{ m, } v_x \text{ sizable} \]
\[ \Rightarrow \theta_x^* \text{ reconstructed from track angle} \]

\[
\frac{dx_{\text{det}}}{ds} = \frac{dL_x}{ds} \theta_x^* + \frac{dv_x}{ds} x^*
\]

| Beam width @ vertex | Angular beam divergence | Min. reachable $|t|$ |
|---------------------|-------------------------|---------------------|
| $\sigma_{x,y}^* = \sqrt{\varepsilon \beta^*}$ | $\sigma_\theta^* = \frac{\varepsilon}{\sqrt{\beta^*}}$ | $|t_{\text{min}}| = n_\sigma \frac{p^2 \varepsilon}{\beta^*}$ |
| Standard optics $\beta^* \approx 1-3 \text{ m}$ | $\sigma_{x,y}^* \text{ small}$ | $\sigma(\theta_{x,y}^*) \text{ large}$ | $|t_{\text{min}}| \approx 0.3-1 \text{ GeV}^2$ |
| Special optics $\beta^* = 90 \text{ m}$ | $\sigma_{x,y}^* \text{ large}$ | $\sigma(\theta_{x,y}^*) \text{ small}$ | $|t_{\text{min}}| \approx 10^{-2} \text{ GeV}^2$ |
Optics verification

\[
\begin{align*}
L_y(s) &= \int_0^s \frac{dL_y(\tau)}{d\tau} d\tau + C_1 \\
\frac{dL_y(s)}{ds} &= \int_0^s L_y(\tau) k(\tau) d\tau + C_2
\end{align*}
\]

with \( L_y(0) = 0 \) and \( \frac{dL_y}{ds}(0) = 1 \)

\[ dL_x/ds \]
\[ dL_y/ds \]

\[ \left. dL_y/ds \right|_{s=220m} \text{ measured by TOTEM} \]

\[ L_x \]
\[ L_y \]

\[ s: L_x=0 \text{ measured by TOTEM} \]
s: $L_x(s) = 0$ determination

- Four fits per diagonal, 8 in total, diagonals averaged

$\text{Top 45 bottom 56, 45 near } s = 214.463 \text{ m}$

$a = -3.142$

$\text{Top 45 bottom 56, 45 far } s = 220 \text{ m}$

$a = 2.229$

Interpolation: $L_x(s) = 0$ for $s = 217.8 \text{ m}$ (nominally $222.1 \text{ m}$)
Matched parameters

- Perturbation of (nominal) actual LHC settings
  - $\sim 30$ parameters per beam
  - Magnet positions, rotations, $k$
  - Beam energy, displacement, crossing angle, harmonics...

- Selected fitted parameters
  - 6 strengths per beam (MQXA, MQXB, MQXB, MQXA, MQY, MQML)
  - 6 corresponding rotations per beam
  - Mean $\xi$ per beam
  - Total of 26 fitted parameters
Constraints

- **TOTAL of 36**
- **LHC design constraints (a total of 26):**
  - \( \sigma(k)/k = 0.1\% \)
  - \( \sigma_{\text{rot}} = 1\text{mrad} \)
  - \( \Sigma(\xi)/\xi = 10^{-3} \)
- **Measured constraints of individual arms (a total of 8):**
  - \( (dL_y/ds)/L_y; \text{ near unit rotation (coupling); far unit rotation (coupling)} \)
  - \( s: L_x=0 \) (1 m precision)
- **Measured elastic scattering kinematics constraints between arms (a total of 2):**
  - Ratio of \( L_y56 / L_y45 \) (0.2 % precision)
  - Ratio of \( (dL_x/ds 56) / (dL_x/ds 45) \) (0.5 % precision)
Matching solution

Strong correlations between fitted parameters

Principle Component Analysis (PCA) ideally should be applied

\[ \frac{\chi^2}{\text{NDF}} = \frac{25.8}{(36-26)} = 2.6 \]

(would be lower in correlations are eliminated)

Matching results within the LHC tolerance

<table>
<thead>
<tr>
<th></th>
<th>( \frac{dL_x}{ds} )</th>
<th>( L_y ) [m]</th>
<th>ROT [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP215</td>
<td>-0.311962</td>
<td>22.1464676</td>
<td>0.0432331</td>
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<tr>
<td>RP220</td>
<td>-0.311962</td>
<td>22.6191755</td>
<td>0.0396463</td>
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<td>( \Delta ) RP215</td>
<td>-2.84%</td>
<td>+0.78%</td>
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<tr>
<td>( \Delta ) RP220</td>
<td>-2.84%</td>
<td>+0.81%</td>
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</table>

<table>
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<tr>
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<th>( \frac{dL_x}{ds} )</th>
<th>( L_y ) [m]</th>
<th>ROT [mrad]</th>
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</thead>
<tbody>
<tr>
<td>RP215</td>
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<td>0.0400268</td>
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<tr>
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<td>( \Delta ) RP215</td>
<td>-4.51%</td>
<td>+10.19%</td>
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</tr>
<tr>
<td>( \Delta ) RP220</td>
<td>-4.51%</td>
<td>+10.79%</td>
<td></td>
</tr>
</tbody>
</table>
Beam-based RP alignment (scraping)

- Sharp edges to beam scraped by collimators

- Each RP approaches beam in 10 μm steps until touches beam edge (spike in beam loss monitors downstream of RP) \( \Rightarrow \) RPs at same distance (in \( \sigma_{beam} \)) as collimators & beam centre in middle

Alignment of RPs w.r.t. beam