# Measurements of the elastic, inelastic and total *pp* cross sections with the ATLAS, CMS and TOTEM detectors

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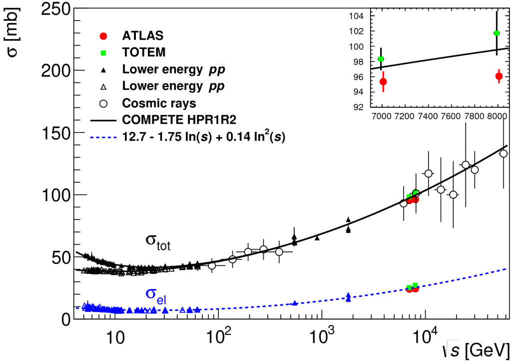
Outline:

- Physics motivation.
- Inelastic cross section at $\sqrt{s} = 13$ TeV with the ATLAS and CMS detectors.
- Elastic, inelastic and total cross sections at $\sqrt{s} = 8$ TeV with the ATLAS and TOTEM detectors.

- The elastic ($\sigma_{el}$), inelastic ($\sigma_{inel}$) and total ($\sigma_{tot}$) *pp* cross sections are fundamental quantities which cannot be calculated with perturbative QCD.
- Regge theory provides a description but data is needed to constrain models.
- $\sigma_{tot}$ gives the upper bound on any *pp* process and is seen to rise with collision energy.
- A substantial fraction of $\sigma_{inel}$ is diffractive processes. Measurement of $\sigma_{inel}$ will constrain models also for cosmic-ray shower in the atmosphere.




(a)

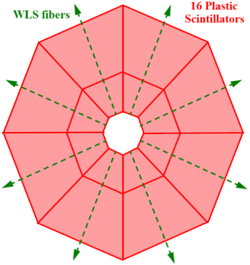
Inelastic cross section measurement at $\sqrt{s} = 13$ TeV with ATLAS and CMS

arXiv:1606.02625
CMS-PAS-FSQ-15-005

- Strategy: Measure the inelastic cross section in a fiducial region and extrapolate to full phase-space with input from theoretical models.
  - The better detector coverage, the smaller extrapolation uncertainty.
- The fiducial $\sigma_{\text{inel}}$ is the number of observed events corrected for background, pile-up, efficiencies and luminosity.

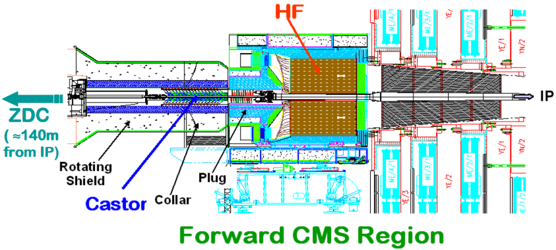
ATLAS:

- MBTS plastic scintillators at $z = \pm 3.6$ m covering $2.07 < |\eta| < 3.86$.

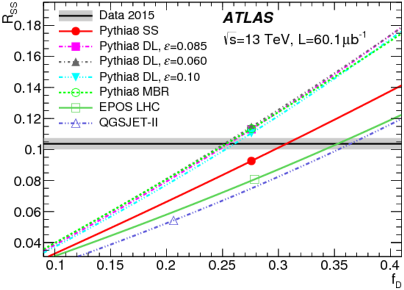



CMS:

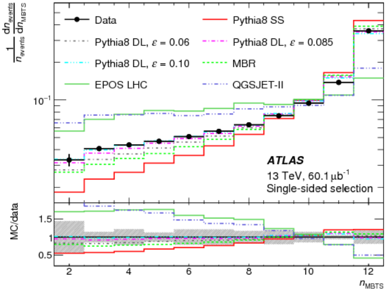
- HF calorimeter of iron absorbers and quartz fibers covering $3.0 < |\eta| < 5.2$.
- CASTOR calorimeter of tungsten and quartz covering $-6.6 < \eta < -5.2$.



- The inelastic cross section is the sum of the non-diffractive and the diffractive cross section.
- The ratio $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$ is poorly known and differs between models.
- The fraction of single-sided events, $R_{SS}$, is related to $f_D$ and used to tune $f_D$ in the models.




- Using the $f_D$-tuned models, the hit multiplicity in the MBTS for the models are compared to data:
  - The DL (Donnachie-Landshoff) pomeron flux model is best.
  - The EPOS LHC and QGSJET-II models (developed for cosmic-ray showering) are worst.
- CMS checks that models predict correct ratio of cross sections between the HF-only and the HF+CASTOR phase-space regions.



# Inelastic cross section - Extrapolation

CMS:

- The average of the model extrapolation factors is used to go from fiducial to full phase-space cross section.
- Maximum difference between models is used as systematic uncertainty.

ATLAS:

- A precise (and independent) measurement of $\sigma_{\text{inel}}$ at $\sqrt{s} = 7$ TeV is used:

$$\sigma_{\text{inel}} = \sigma^{\text{fid}}_{\text{inel}} + (\sigma^{\text{ALFA}}_{\text{inel, 7 TeV}} - \sigma^{\text{fid}}_{\text{inel, 7 TeV}}) \times \frac{\sigma^{\text{MC}}_{\text{inel}}(\xi < 10^{-6})}{\sigma^{\text{MC}}_{\text{inel, 7 TeV}}(\xi < 5 \times 10^{-6})}$$

- The difference between Pythia8 DL and Pythia8 MBR is used as systematic uncertainty.

# Inelastic cross section - Results

CMS:

$$\sigma_{\text{inel}}^{\text{fid,HF}} = 65.8 \pm 0.8(\text{exp.}) \pm 1.8(\text{lum.})\ \text{mb}$$

$$\sigma_{\text{inel}}^{\text{fid,HF+CASTOR}} = 66.9 \pm 0.4(\text{exp.}) \pm 2.0(\text{lum.})\ \text{mb}$$

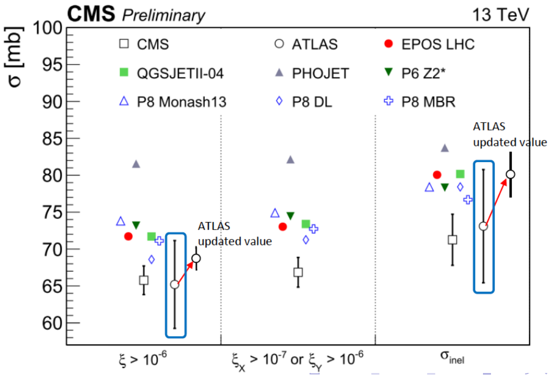
$$\sigma_{\text{inel}} = 71.3 \pm 0.5(\text{exp.}) \pm 2.1(\text{lum.}) \pm 2.7(\text{ext.})\ \text{mb}$$

ATLAS:

$$\sigma_{\text{inel}}^{\text{fid}} = 68.1 \pm 0.6(\text{exp.}) \pm 1.3(\text{lum.})\ \text{mb}$$

$$\sigma_{\text{inel}} = 79.3 \pm 0.6(\text{exp.}) \pm 1.3(\text{lum.}) \pm 2.5(\text{ext.})\ \text{mb}$$

ATLAS $\sigma_{\text{inel}}^{\text{fid}}$ and CMS $\sigma_{\text{inel}}^{\text{fid,HF}}$ have same fiducial region and are directly comparable.



Elastic, inelastic and total cross sections measurement at $\sqrt{s} = 8$ TeV with ATLAS and TOTEM


Phys. Lett. B (2016) 158

Phys. Rev. Lett. 111, 012001 (2013)

Nucl. Phys. B 899 (2015) 527-546

CERN-PH-EP-2015-325

# Elastic analysis - Strategy

- From the optical theorem we get:

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{1}{L}\frac{dN_{\text{el}}}{dt}\Big|_{t=0} \quad \text{with} \quad \rho = \frac{\text{Re}\left[F_{\text{el}}(t)\right]}{\text{Im}\left[F_{\text{el}}(t)\right]} \quad \text{(ATLAS)}$$

$$\text{equiv.} \qquad \sigma_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{1}{N_{\text{el}}+N_{\text{inel}}}\frac{dN_{\text{el}}}{dt}\Big|_{t=0} \quad \text{(TOTEM).}$$

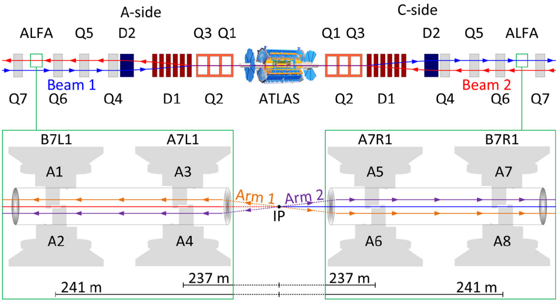
- The four-momemtum transfer $t$ is calculated as

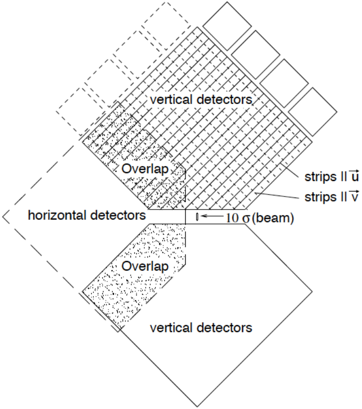
$$t = -(p \times \theta^*)^2.$$

where the scattering angle $\theta^*$ is calculated from the proton trajectories and $p$ is the beam momentum.

- Data are taken in runs with low pile-up ($\mu \lesssim 0.1$) and high $\beta^*$ collision optics since $t_{\text{min}} \propto \frac{p^2}{\beta^*}$:
  - $\beta^* = 90$ m results from ATLAS (one dataset) and TOTEM (two datasets).
  - $\beta^* = 1$ km results from TOTEM (one dataset).

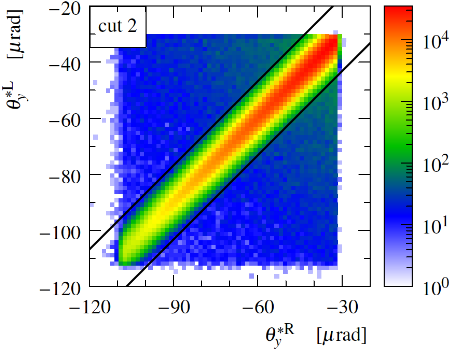
- ATLAS and TOTEM use tracking detectors in Roman Pots at $z \sim 230$ m to approach outgoing beams in vertical direction.
  - ATLAS uses $10 \times 2$ orthogonal layers of scintillating fibers giving $\approx 30$ $\mu$m tracking resolution.
  - TOTEM uses a stack of 10 silicon strip detectors giving $\approx 11$ $\mu$m tracking resolution.
- In addition, TOTEM has two tracking telescopes:
  - T1 is a cathode strip chamber at $z = \pm 9$ m covering $3.1 \leq |\eta| \leq 4.7$.
  - T2 is based on gas electron multiplier chambers at $z = \pm 13.5$ m covering $5.3 \leq |\eta| \leq 6.5$.

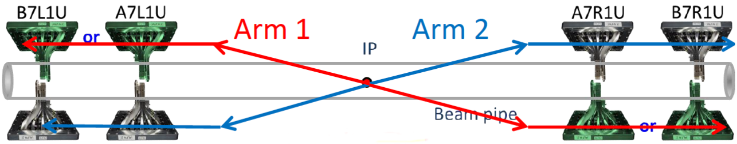


# Elastic analysis - event selection

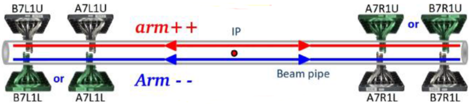
- Elastic events are selected when all four detectors in an arm have a track.
- The tracks are required to fulfill certain correlations between inner-outer stations and between left and right side.
- ATLAS $\beta^* = 90$ m: 3.8 M elastic events.
- TOTEM $\beta^* = 90$ m: 0.65 M elastic events.
- TOTEM $\beta^* = 1$ km: 0.35 M elastic events.



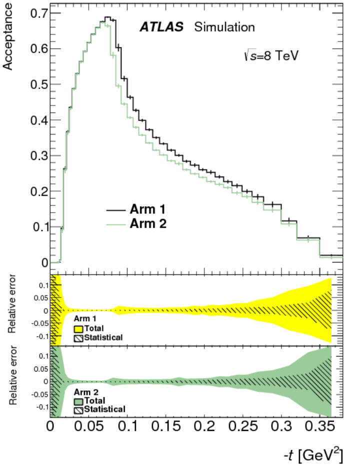



# Elastic analysis - Experimental effects

- **Background** comes from beam halo, single diffractive and central diffractive protons.
- Fraction is $\leq 0.12$ % estimated from antigolden topology.




- **Detector acceptance** is highly dependent on detector distance to the beam and beam divergence.
- Found from simulation tuned to data.
- ***t*-resolution** is influenced by detector resolution and beam divergence.
- Relative *t*-resolution is better than 10 % and corrected for by unfolding.
- **Track reconstruction inefficiency** is data driven.



# Elastic analysis - Theoretical prediction

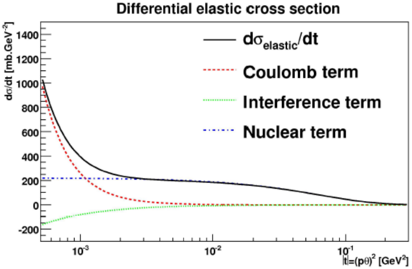
- The differential elastic cross section is a superposition of the strong interaction amplitude $F_N$ and the Coulomb amplitude $F_C$ added in quadrature giving

$$\frac{d\sigma_{el}}{dt} \propto \frac{G^4(t)}{|t|^2} + \sigma_{tot}^2(1+\rho^2)\cdot\exp(-\mathbf{B}|t|) - \frac{\sigma_{tot}G^2(t)}{|t|}[\sin(\phi(t))+\rho\cos(\phi(t))]\cdot\exp\left(\frac{-\mathbf{B}|t|}{2}\right)$$

- The corrected differential cross section is fitted with $\sigma_{tot}$ and $B$ as free parameters.

- ATLAS fit-range: $0.014 \leq |t| \leq 0.1$ GeV$^2$.
  - $G(t), \phi(t), \rho$ fixed.
- TOTEM $\beta^* = 90$ m fit-range:
  $0.01 \leq |t| \leq 0.2$ GeV$^2$ (1. dataset)
  $0.02 \leq |t| \leq 0.2$ GeV$^2$ (2. dataset)
  - TOTEM neglects the Coulomb and interference terms.
- TOTEM $\beta^* = 1$ km:
  $6\cdot 10^{-4} \leq |t| \leq 0.2$ GeV$^2$.

Simulation




$\sigma_{tot} = 100$ mb, $B = 18$ GeV$^{-2}$, $\rho = 0.13$

# Elastic analysis - Measurement of $N_{\text{inel}}$ (TOTEM)

- TOTEM measures simultaneously the elastic and inelastic rate and is hence independent of luminosity.
- The inelastic rate is determined with the T1 ($3.1 \leq |\eta| \leq 4.7$) and T2 ($5.3 \leq |\eta| \leq 6.5$) telescopes, detecting about 95% of the inelastic rate.
- The strategy is similar to the CMS and ATLAS inelastic cross section measurement.
- Events are triggered by the T2 telescope and corrected for experimental effects.
- Uncertainty from extrapolation of fiducial region is dominating (”Low mass diffraction”).

| Source | Correction | Uncertainty | Effect on |
|---|---|---|---|
| Beam gas | 0.45% | 0.45% | all rates |
| Trigger efficiency | 1.2% | 0.6% | all rates |
| Pileup | 2.8% | 0.6% | all rates |
| T2 reconstruction | 0.35% | 0.2% | $N_{\text{inel}}$, $N_{\vert\eta\vert<6.5}$ |
| “T1 only” | 1.2% | 0.4% | $N_{\text{inel}}$, $N_{\vert\eta\vert<6.5}$ |
| Internal gap covering T2 | 0.4% | 0.2% | $N_{\text{inel}}$, $N_{\vert\eta\vert<6.5}$ |
| Central diffraction | 0% | 0.35% | $N_{\text{inel}}$, $N_{\vert\eta\vert<6.5}$ |
| Low mass diffraction | 4.8% | 2.4% | $N_{\text{inel}}$ |

# Elastic analysis - Results

- $\sigma_{el}$ is the integral of the nuclear part: $\sigma_{el} = \frac{\sigma_{tot}^2}{B}\frac{1+\rho^2}{16\pi(\hbar c)^2}$.
- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$.

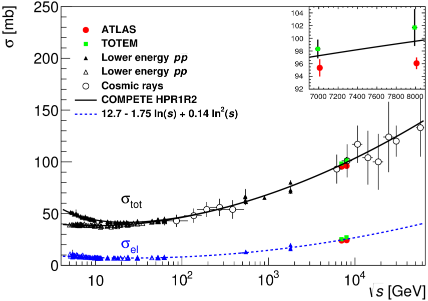
| | ATLAS ($\beta^* = 90$ m) | TOTEM ($\beta^* = 90$ m) | TOTEM ($\beta^* = 1$ km) |
|---|---|---|---|
| $\sigma_{tot}$ | $96.07 \pm 0.92$ | $101.7 \pm 2.9$ | $102.9 \pm 2.3$ |
| $\sigma_{el}$ | $24.33 \pm 0.39$ | $27.1 \pm 1.4$ | - |
| $\sigma_{inel}$ | $71.73 \pm 0.71$ | $74.7 \pm 1.7$ | - |

- The total cross section is still rising with energy.
- The difference between ATLAS and TOTEM $\beta^* = 90$ m corresponds to $1.9\sigma$.
- Using $\beta^* = 1$ km data, TOTEM also measured

$$\rho = 0.12 \pm 0.03$$

Model extrapolation from lower energies:

$$\rho = 0.140 \pm 0.007$$




(a)

(fit not updated with latest ATLAS result)

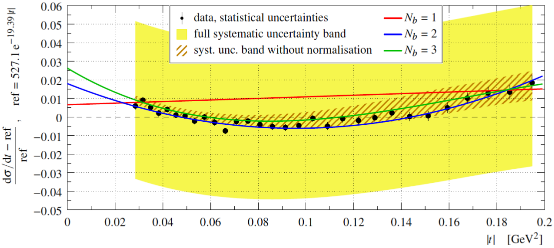
# Elastic analysis - Non-exponential slope

- Hints of a slight deviation from an exponential fall-off of the elastic nuclear amplitude was reported at ISR and SppS, but not at the Tevatron.

- TOTEM used $\frac{d\sigma}{dt}(t) = \frac{d\sigma}{dt}\Big|_{t=0} \exp\left(\sum_{i=0}^{N_b} b_i t^i\right)$ to exclude a purely exponential form with more than 7σ!

| $N_b$ | $\chi^2/\text{ndf}$ | $\sigma_{\text{tot}}$ |
|---|---|---|
| 1 | $117.5/28$ | $(101.7 \pm 2.9)$mb |
| 2 | $29.3/27$ | $(101.5 \pm 2.1)$mb |
| 3 | $25.5/26$ | $(101.9 \pm 2.1)$mb |

- This approach was impossible for ATLAS as the $t$-dependent systematic uncertainties are too large.
  - Average beam energy uncertainty dominates.
  - ATLAS uses a larger uncertainty than TOTEM.
  - An official value will be available later this year.




- ATLAS has tested different $B$-parametrizations giving an RMS of 0.28 mb on $\sigma_{\text{tot}}$.

# Summary

- The inelastic cross section at $\sqrt{s} = 13$ TeV was measured by a MC extrapolation from the fiducial region:

$$\sigma_{\text{inel}} = 79.3 \pm 2.9 \text{ mb (ATLAS)}$$
$$\sigma_{\text{inel}} = 71.3 \pm 3.5 \text{ mb (CMS)}$$

  The largest uncertainty contribution comes from the extrapolation and the luminosity determination.

- The elastic, inelastic and total cross sections at $\sqrt{s} = 8$ TeV have been measured by ATLAS and TOTEM exploiting the optical theorem:

  ATLAS (luminosity-dependent):

$$\sigma_{\text{tot}} = (96.07 \pm 0.92) \text{ mb}$$
$$\sigma_{\text{el}} = (24.33 \pm 0.39) \text{ mb}$$
$$\sigma_{\text{inel}} = (71.73 \pm 0.71) \text{ mb}$$

  TOTEM (luminosity-independent):

$$\sigma_{\text{tot}} = (101.7 \pm 2.9) \text{ mb}$$
$$\sigma_{\text{el}} = (27.1 \pm 1.4) \text{ mb}$$
$$\sigma_{\text{inel}} = (74.7 \pm 1.7) \text{ mb}$$

- TOTEM has excluded a single-exponential shape of $d\sigma_{\text{el}}/dt$ with more than $7\sigma$.
- TOTEM also measured $\sigma_{\text{tot}} = (102.9 \pm 2.3)$ mb and $\rho = 0.12 \pm 0.03$ with the $\beta^* = 1$ km dataset.

Backup slides

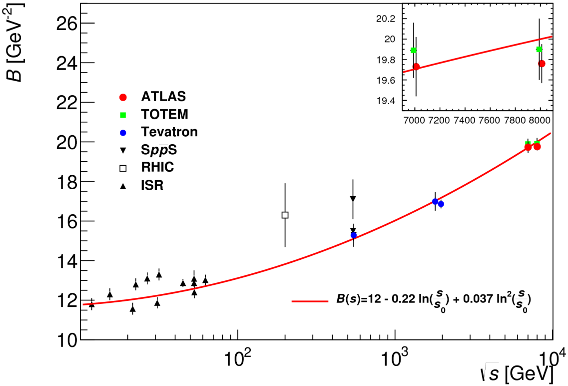
# Backup - ATLAS test of nuclear slope parametrization

- ATLAS has tried different parametrizations for the nuclear slope.
- The upper limit of the fit range was increased to $|t| = 0.3$ GeV$^2$ in order to increase the sensitivity of additional parameters.
- The quality of the fit is increased due to the higher number of free parameters.

| | $\sigma_{\mathrm{tot}}$[mb] | Model |
|---|---|---|
| Nominal | $96.07 \pm 0.86$ | $f_{\mathrm{N}}(t) = (\rho + i)\,\frac{\sigma_{\mathrm{tot}}}{\hbar c} e^{-Bt/2}$ |
| $Ct^2$ | $96.16 \pm 0.80$ | $f_{\mathrm{N}}(t) = (\rho + i)\,\frac{\sigma_{\mathrm{tot}}}{\hbar c} e^{-Bt/2 - Ct^2/2}$ |
| $c\sqrt{-t}$ | $96.40 \pm 0.80$ | $f_{\mathrm{N}}(t) = (\rho + i)\,\frac{\sigma_{\mathrm{tot}}}{\hbar c} e^{-Bt/2 - c/2(\sqrt{4\mu^2 - t} - 2\mu)}$ , $\mu = m_\pi$ |
| SVM | $96.16 \pm 0.80$ | $f_{\mathrm{N}}(t) = \rho \frac{\sigma_{\mathrm{tot}}}{\hbar c} e^{-B_R t/2} + i \frac{\sigma_{\mathrm{tot}}}{\hbar c} e^{-B_I t/2}$ |
| BP | $96.81 \pm 0.95$ | $f_{\mathrm{el}}(t) = i\left[G^2(t)\sqrt{A}e^{-Bt/2} + e^{i\phi}\sqrt{C}e^{-Dt/2}\right]$ |
| BSW | $96.67 \pm 0.99$ | $\mathrm{Re} f_{\mathrm{el}}(t) = c_1(t_1 + t)e^{-b_1 t/2}$ , $\mathrm{Im} f_{\mathrm{el}}(t) = c_2(t_2 + t)e^{-b_1 t/2}$ |

# Backup - Results for the nuclear B-slope

- ATLAS measurement: $B = 19.73 \pm 0.24\ \text{GeV}^{-2}$
- TOTEM measurement: $B = 19.9 \pm 0.3\ \text{GeV}^{-2}$
- Pre-LHC expectations was a linear evolution of the $B$-slope with $\ln(s)$
- LHC measurements of the $B$-slope favours a second $\ln^2(s)$ term.




(b)

(fit not updated with latest ATLAS result)

# Backup - $t$-reconstruction methods

- The scattering angle is calculated from the proton transverse positions far from IP:

$$\begin{pmatrix} u \\ \theta_u \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} u^* \\ \theta_u^* \end{pmatrix} , \quad u = (x, y) .$$

- Subtraction method:

$$\theta_u^* = \frac{u_A - u_C}{M_{12,A} + M_{12,C}} , \quad u = x, y$$

- Local angle method method:

$$\theta_x^* = \frac{\theta_{x,A} - \theta_{x,C}}{M_{22,A} + M_{22,C}} , \quad \theta_y^* \text{ as for subtraction}$$

- Local subtraction method:

$$\theta_{x,S}^* = \frac{M_{11,S}^{241} \cdot x_{237,S} - M_{11,S}^{237} \cdot x_{241,S}}{M_{11,S}^{241} \cdot M_{12,S}^{237} - M_{11,S}^{237} \cdot M_{12,S}^{241}} , \quad S = A, C , \quad \theta_y^* \text{ as for subtraction}$$

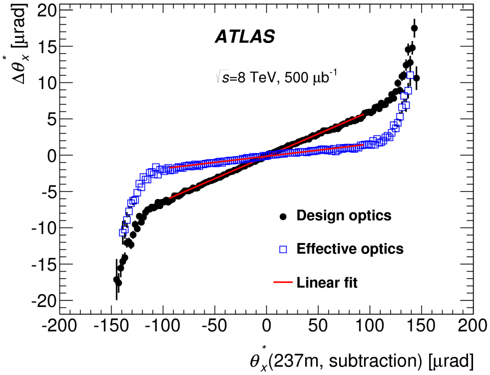
- Lattice method:

$$\theta_x^* = M_{12}^{-1} \cdot x + M_{22}^{-1} \cdot \theta_x , \quad \theta_y^* \text{ as for subtraction}$$

- The beam optics has direct influence on the *t*-reconstruction through the transport matrix.
- Different *t*-reconstructions gives different results
  $\Rightarrow$ the initial **design** optics needs modifications.
- Both TOTEM and ATLAS use elastic data to constrain an optics fit including magnet strengths whereby an **effective** optics in obtained.

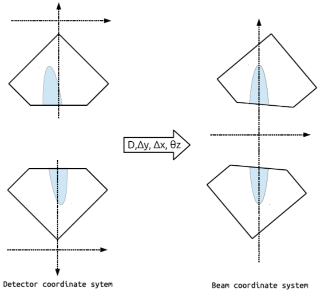
Example of a constraint:

$$\frac{y_L}{y_R} = \frac{M_{12}^L}{M_{12}^R} .$$

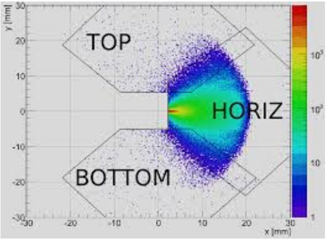


# Backup - RP alignment

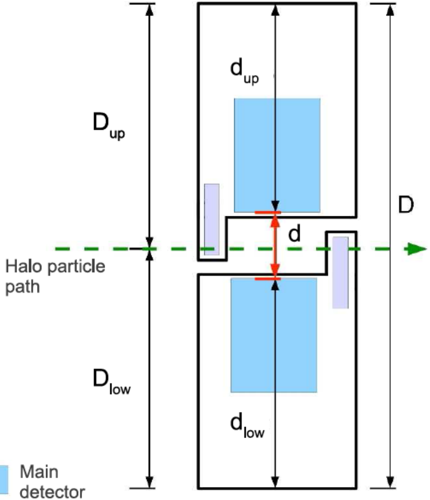
## ATLAS alignment




## TOTEM alignment




## ATLAS distance





$D = D_{up} + D_{low}$

$d = D - d_{up} - d_{low}$