Recent ATLAS measurement of elastic pp scattering

and what it tells us about strong interactions at high energies

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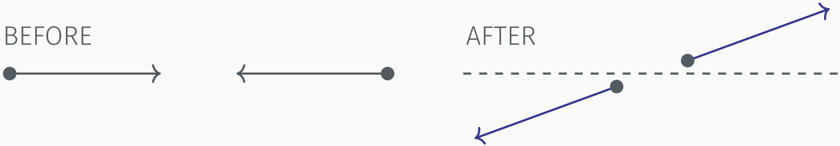
Białasówka, 28 October 2022

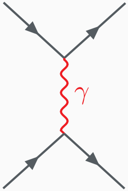
Elastic pp scattering



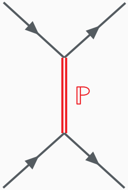
- Energy and momentum conservation
- 2 kinematic degrees of freedom: φ, θ
- φ – trivial (uniform)
- $t \approx -p^2\theta^2 = -p_T^2$
- small $|t|$ – large distance, large high $|t|$ – small distance

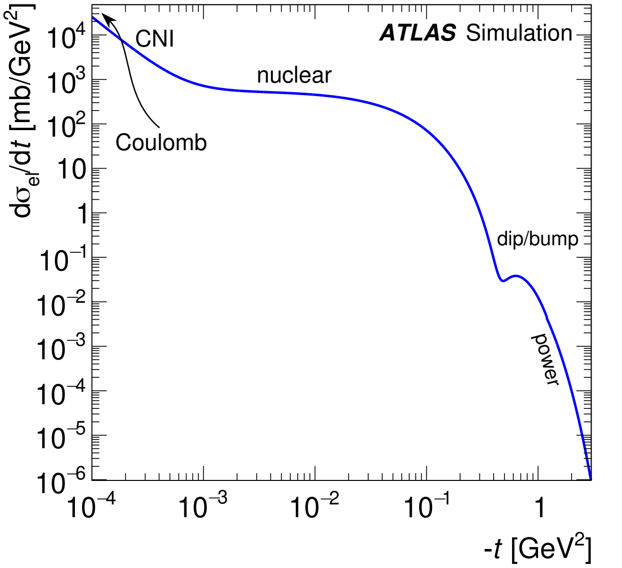
Mechanisms

Coulomb (electromagnetic)



Nuclear (strong)





Optical theorem

$$\sigma_{\textbf{tot}} = 4\pi \textbf{Im}\, f_{\textbf{el}}(t = 0)$$

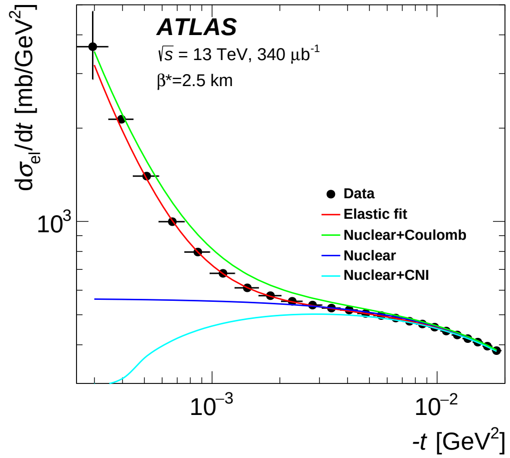
Differential elastic cross section

- Assuming a simplistic t dependence: $f_{\text{el}}(t) \propto \exp(-B|t|/2)$
- Introducing $\rho = \text{Re}\, f_{\text{el}} / \text{Im}\, f_{\text{el}}|_{t=0}$

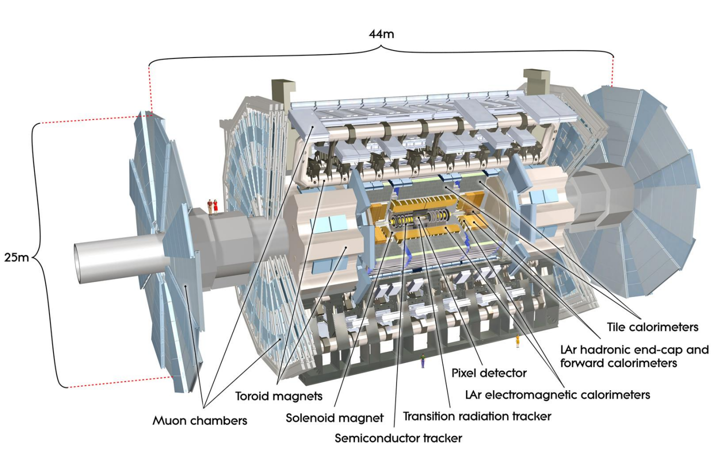
$$\frac{\mathrm{d}\sigma_{\textbf{el}}}{\mathrm{d}t} = \sigma_{\textbf{tot}}^2 \frac{1+\rho^2}{16\pi} \exp\left(-B|t|\right)$$

Phase of the nuclear amplitude

$$\frac{d\sigma_{\mathbf{el}}}{dt} \propto \left| f_{\mathbf{N}}(t) + f_{\mathbf{C}}(t) \right|^2$$

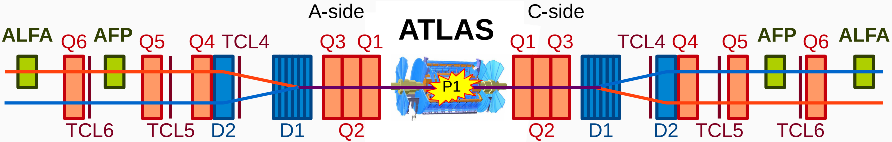


ATLAS Detector



...but also **forward detectors** providing measurements of forward intact protons: **ALFA** and AFP

Physics with forward detectors in ATLAS

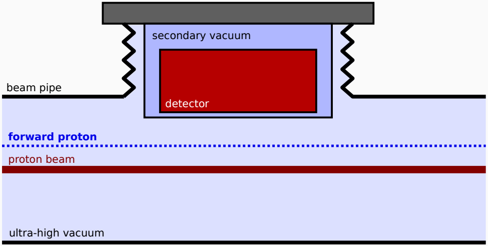


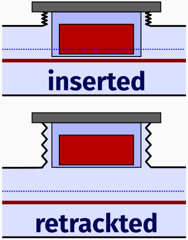
Physics with forward protons

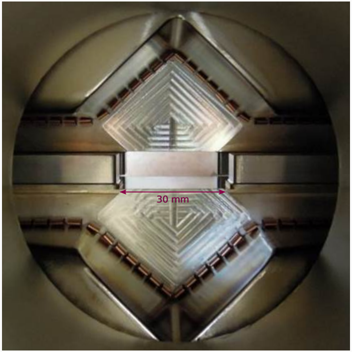
- **ALFA**
  - **elastic scattering ***
  - **inclusive diffraction**
  - **exclusive production**
- **AFP**
  - **inclusive diffraction**
  - **exclusive production**
  - **two-photon processes**

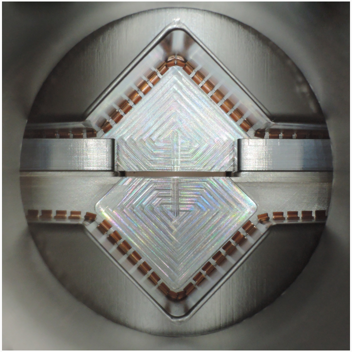
*** covered in this talk**

Roman pot mechanism

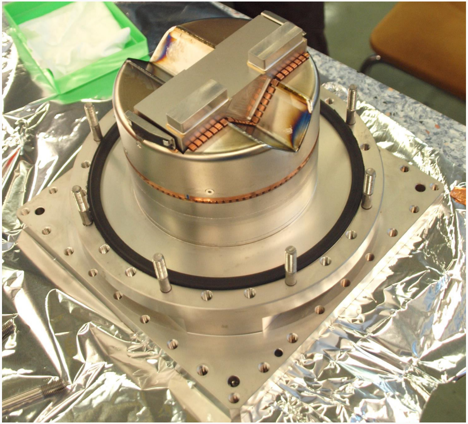


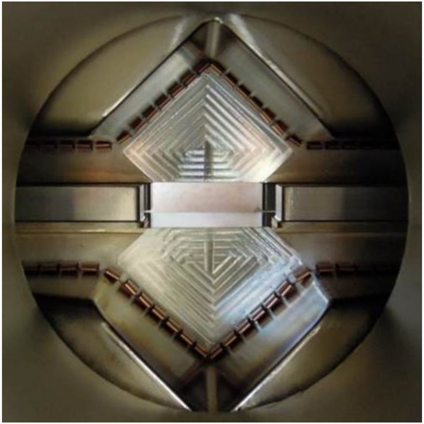




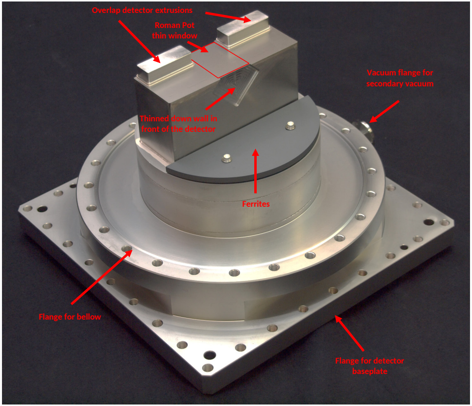


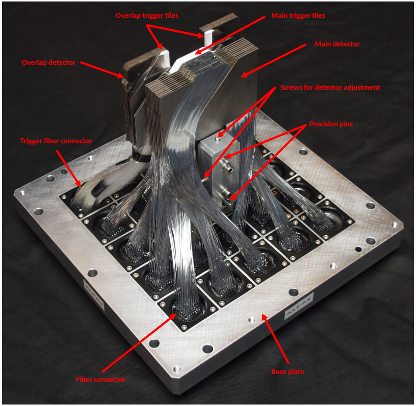
ALFA Roman pot



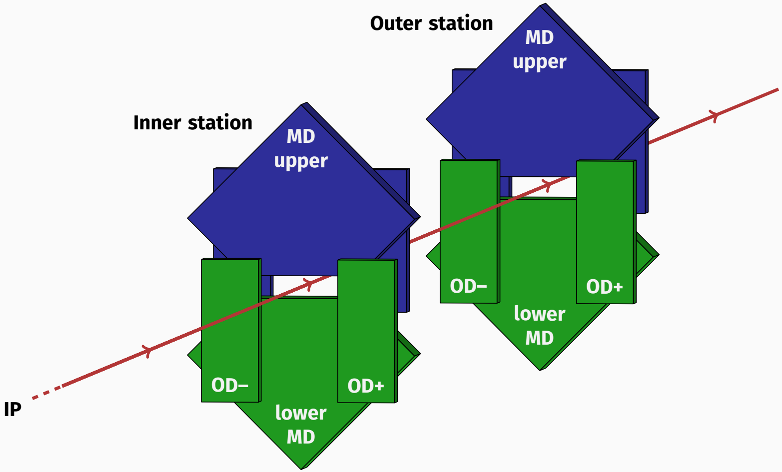


ALFA Roman pot





ALFA detectors



Main detectors (MDs) – for physics
Overlap detectors (ODs) – for alignment

Measurement principle

No magnetic fields:

$$x = L\theta \qquad \theta_{\text{local}} = \theta^*$$

With magnetic fields

$$x = L_{\text{eff}}\theta \qquad \theta_{\text{local}} \propto \theta^*$$

Finite beam size:

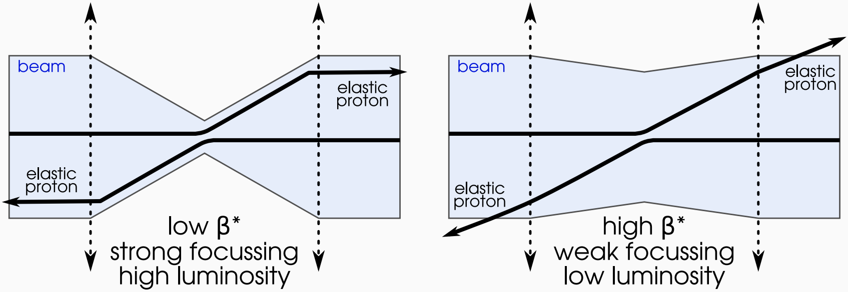
$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x^* \end{pmatrix}$$

$$(\theta, \varphi) \leftrightarrow (\theta_x, \theta_y)$$

$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11}^x & M_{12}^x \\ M_{21}^x & M_{22}^x \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x^* \end{pmatrix}$$

$$\begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11}^y & M_{12}^y \\ M_{21}^y & M_{22}^y \end{pmatrix} \begin{pmatrix} y_0 \\ \theta_y^* \end{pmatrix}$$

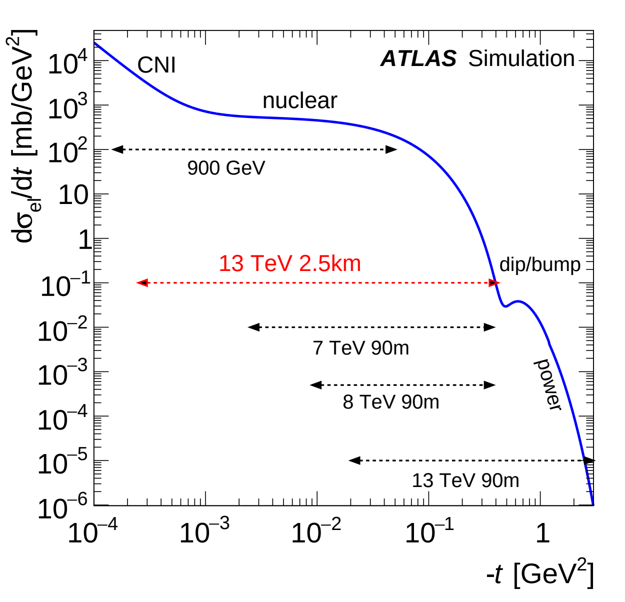
High-β optics



Typical values:

$\beta^* < 1$ m　　　　$\beta^* \geq 90$ m

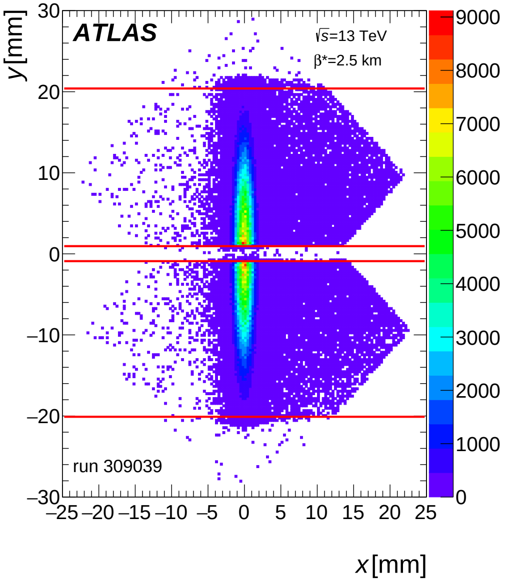
Experimental reach



13 TeV 2.5 km
2016

7 TeV 90 m
2011

Data

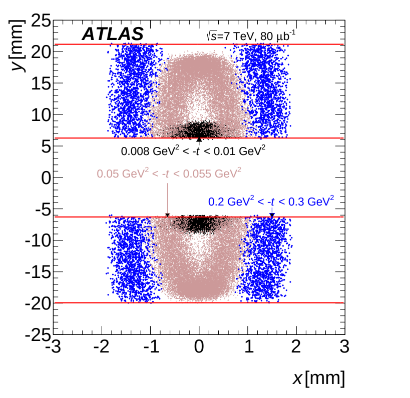


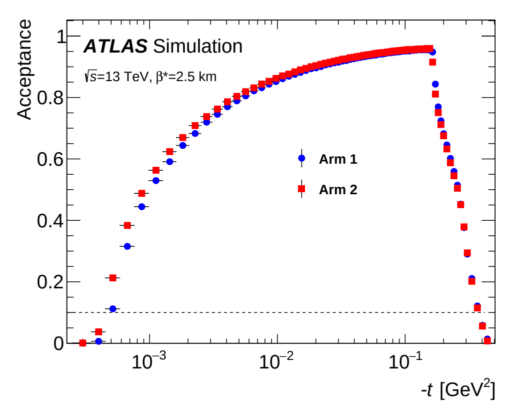
$$x = M_{11}^{x} x^{*} + M_{12}^{x} \theta_{x}^{*}$$

$$y = M_{11}^{y} y^{*} + M_{12}^{y} \theta_{y}^{*}$$

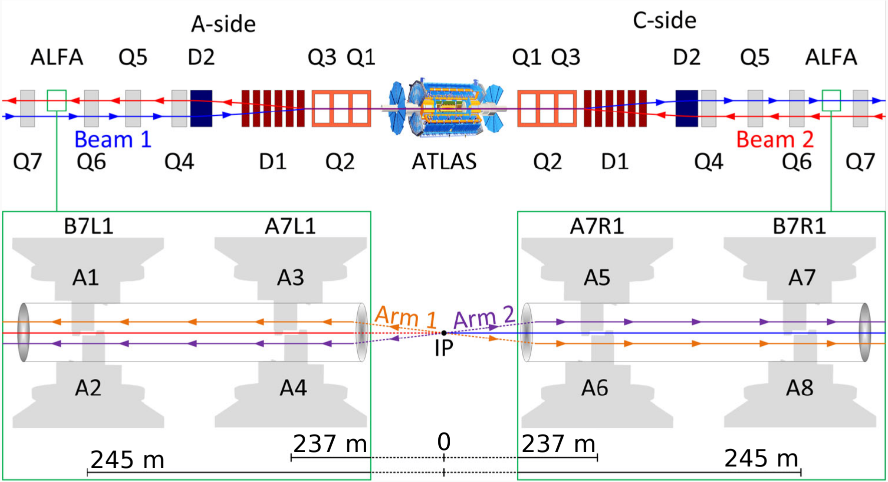
$$M_{12}^{x} \ll M_{12}^{y}$$

Geometric acceptance





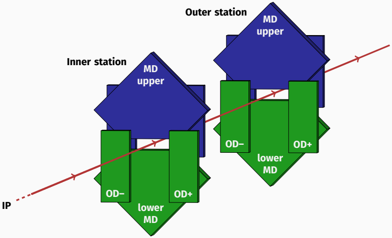
ALFA detectors



t reconstruction

$$t = -p^2\theta^2 = -p^2(\theta_x^2 + \theta_y^2)$$

$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x^* \end{pmatrix}$$



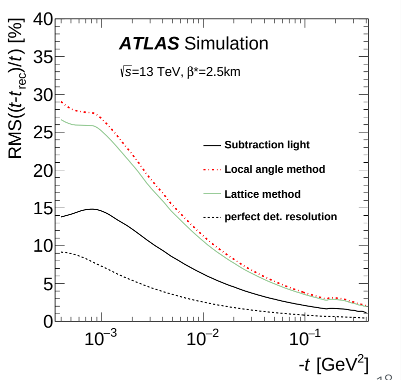
Subtraction

$$\theta^*_{x,A} = -\theta_{x,C} \rightarrow \begin{array}{l} x_A = M_{11}x_0 + M_{12}\theta_x^* \\ x_C = M_{11}x_0 - M_{12}\theta_x \end{array}$$

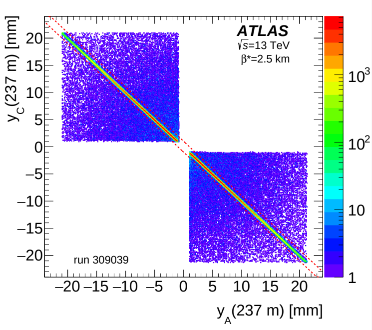
$$\rightarrow \quad \theta_x^* = \frac{x_A - x_C}{M_{12}}$$

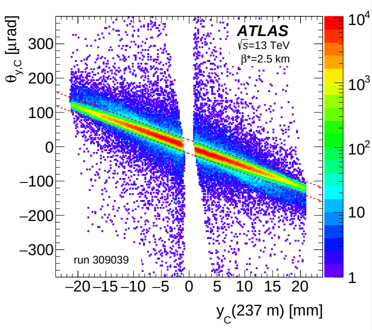
Local angle

$$\theta_x^* = \frac{\theta_{x,A} - \theta_{x,C}}{M_{22}}$$



Event selection

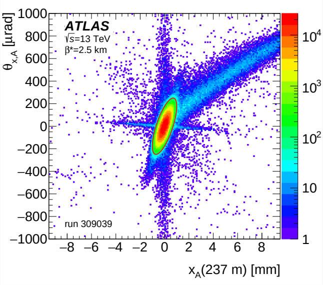




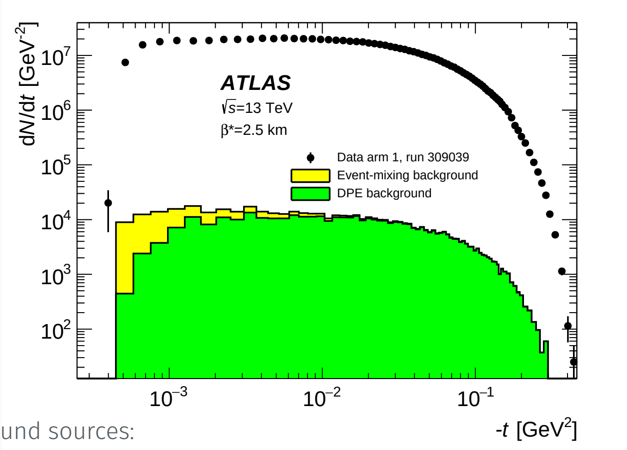
Event selection based on strong correlations present in elastic events

$$x_A \propto x_C \qquad y_A \propto y_C$$

$$\theta_x \propto x \qquad \theta_y \propto y$$



Background estimation



Two background sources:

- accidental halo+halo and halo+SD coincidences (data-driven templates)
- central diffraction (MC simulation)

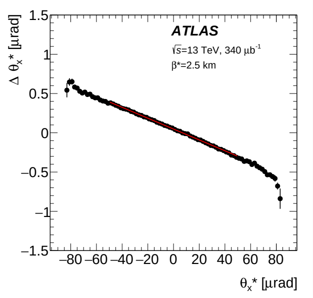
Less then 1‰ of background (relative uncertainty of 10 – 15%)

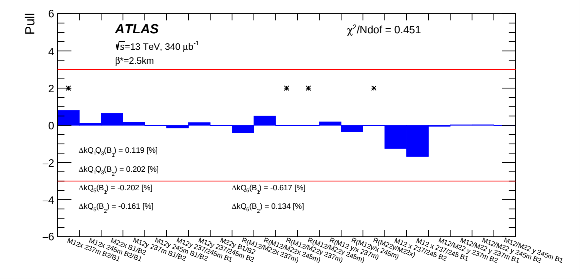
Data-driven methods

Many ingredients based on data, exploiting strongly constrained elastic events: alignment, reconstruction efficiency (tag&probe), optics

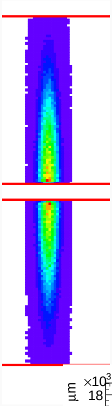
Optics tuning:

$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11}^x & M_{12}^x \\ M_{21}^x & M_{22}^x \end{pmatrix} \begin{pmatrix} x^* \\ \theta_x^* \end{pmatrix} \qquad \begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11}^y & M_{12}^y \\ M_{21}^y & M_{22}^y \end{pmatrix} \begin{pmatrix} y^* \\ \theta_y^* \end{pmatrix}$$



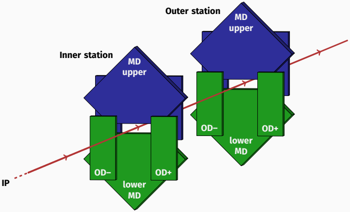


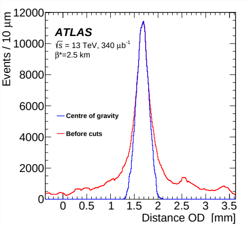
Alignment

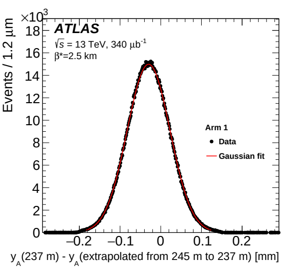


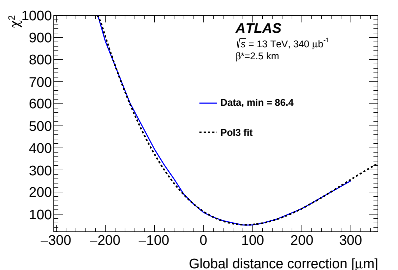
– Rotation, horizontal and vertical offsets obtained from the left–right and up–down symmetry of the elastic pattern

– Multi-step procedure of distance evaluation



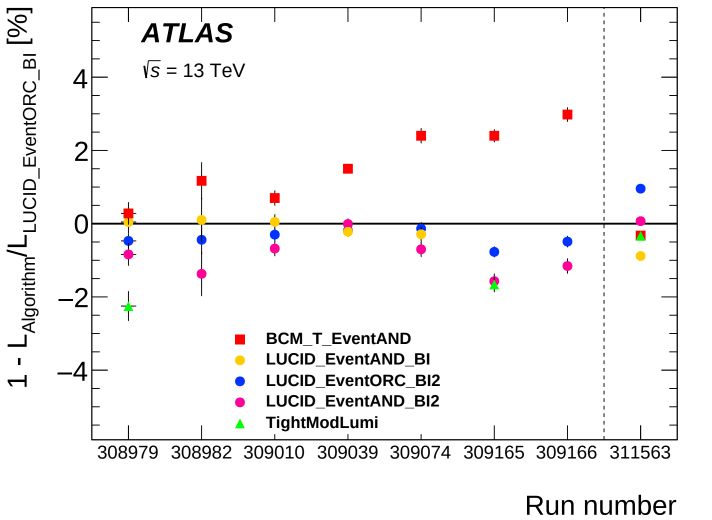




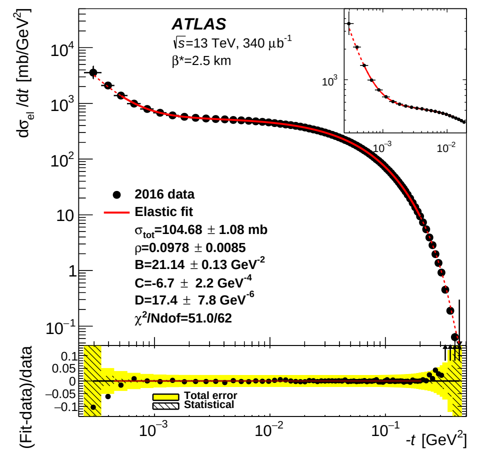


Luminosity measurement

Total systematic uncertainty: 2.15%. Main sources: vdM calibration, calibration transfer, long-term stability and background.



Differential cross section



Fitted function:

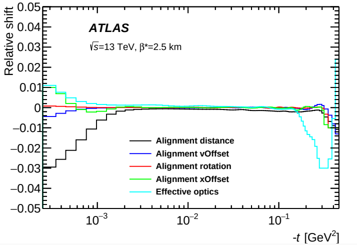
$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_{N}(t) + f_{C}(t)e^{i\alpha\phi(t)}\right|^2$$

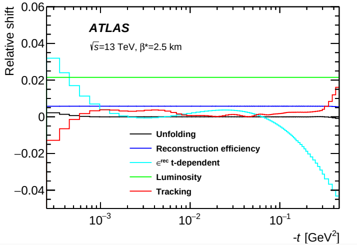
$$f_{C}(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

$$f_{N}(t) = (\rho + i)\,\frac{\sigma_{tot}}{\hbar c}\,e^{(-B|t|-C|t|^2-D|t|^3)/2}$$

$$\rho = \frac{\mathrm{Re}\, f_{N}(0)}{\mathrm{Im}\, f_{N}(0)}$$

Systematic uncertainties





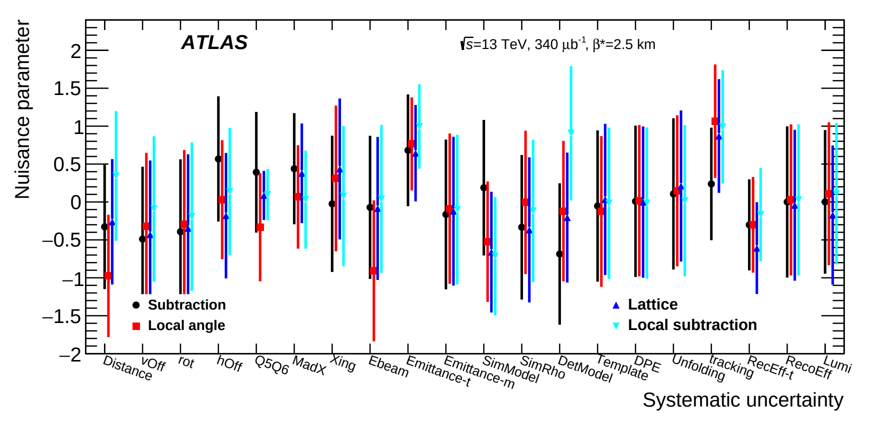
Main sources: luminosity, vertical alignment, reconstruction efficiency

Fitting procesure

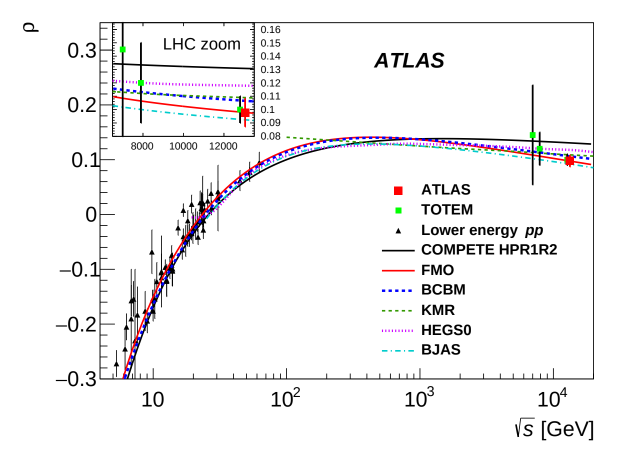
$$\chi^2 = \sum_{i,j} \Bigg[\left(\mathbf{D}(i) - \left(1 + \sum_{l=1}^{2} \alpha_l \right) \cdot \mathbf{T}(i, \ldots) - \sum_{k=1}^{18} \beta_k \cdot \delta_k(i) \right) \cdot V^{-1}(i,j)$$

$$\cdot \left(\mathbf{D}(j) - \left(1 + \sum_{l=1}^{2} \alpha_l \right) \cdot \mathbf{T}(j, \ldots) - \sum_{k=1}^{18} \beta_k \cdot \delta_k(j) \right) \Bigg] + \sum_{k=1}^{18} \beta_k^2 + \sum_{l=1}^{2} \frac{\alpha_l^2}{\epsilon_l^2},$$

Systematic uncertainties



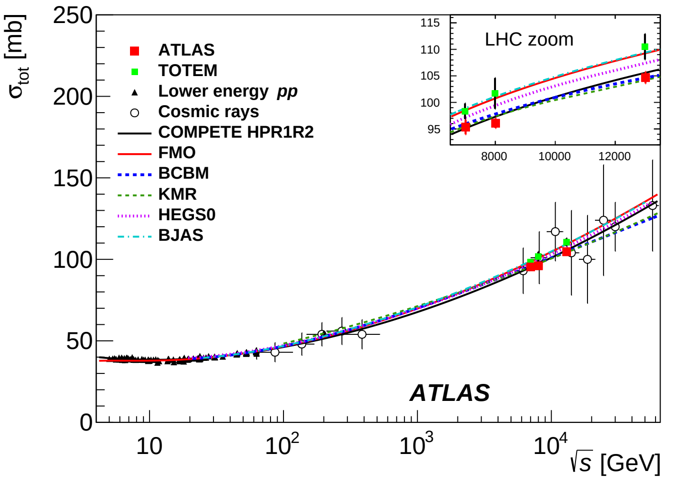
Results in interference region



$$\rho = 0.0978 \pm 0.0043(\text{stat.}) \pm 0.0073(\text{exp.}) \pm 0.0064(\text{th.})$$

Result incompatible with COMPETE (community-standard semi-empirical fits) indicating Odderon exchange or a slowdown of σ_{tot} rise at high $\sqrt{s}$.

Results in nuclear region



$$\sigma_{\text{tot}} = 104.68 \pm 0.22(\text{stat.}) \pm 1.06(\text{exp.}) \pm 0.12(\text{th.})\ \text{mb}$$

Most precise σ_{tot} measurement. 2.2σ tension with TOTEM σ_{tot} result.

Description of data

Model	Global $\chi^2/N_{\rm dof}$	ALFA partial $\chi^2/N_{\rm dof}$	TOTEM partial $\chi^2/N_{\rm dof}$	LHC data included in model tuning
COMPETE HPR1R2	1.42	3.00	3.50	A 7; T 7, 8
FMO	1.61	9.50	0.13	T 7, 8, 13
BCBM	1.03	0.81	2.04	all
KMR		0.85	2.29	A 7, 8; T 7, 8, 13
HEGS		8.10	0.83	A 7; T 7, 8
BJAS		11.90	0.29	A 7; T 7, 8, 13

COMPETE: J. R. Cudell, et al., Phys. Rev. Lett. 89 (2002) 201801

FMO (Froissaron Maximal Odderon): E. Martynov and B. Nicolescu, Phys. Lett. B 778 (2018) 414

BCBM: M. M. Block and R. N. Cahn, Phys. Lett. B 120 (1983) 224; C. Bourrely and A. Martin, https://cds.cern.ch/record/153114

KMR: V. A. Khoze, A. D. Martin and M. G. Ryskin, Phys. Lett. B 784 (2018) 192

HEGS (High Energy General Structure): O. V. Selyugin, Phys. Rev. D 91 (2015) 113003

BJAS: W. Broniowski, L. Jenkovszky, E. Ruiz Arriola and I. Szanyi, Phys. Rev. D 98 (2018) 074012

Description of data

Model	Global χ^2/N_{dof}	ALFA partial χ^2/N_{dof}	TOTEM partial χ^2/N_{dof}	LHC data included in model tuning
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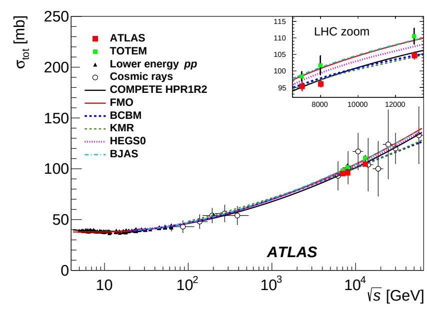
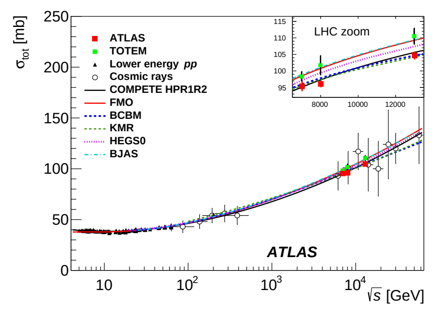
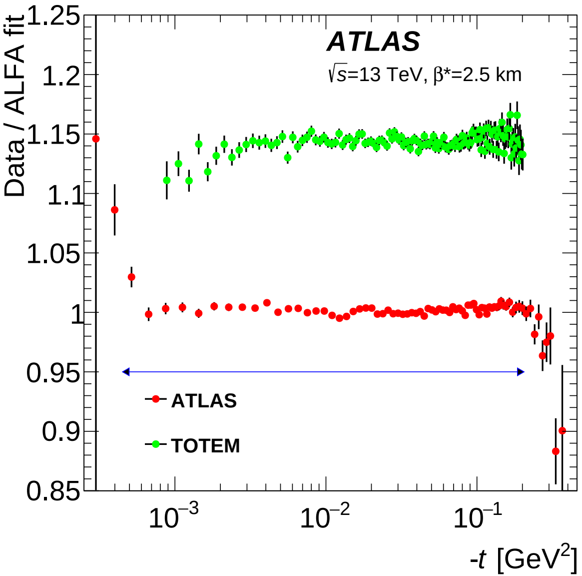




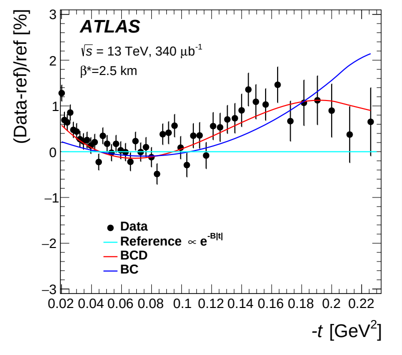
ATLAS vs TOTEM

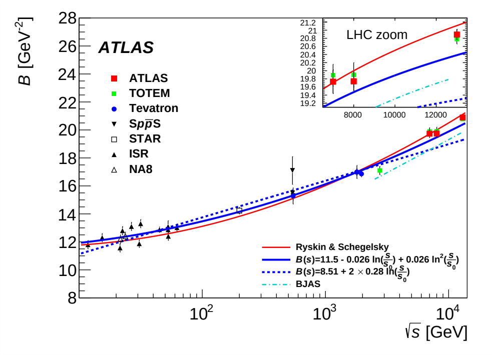


t slope and shape

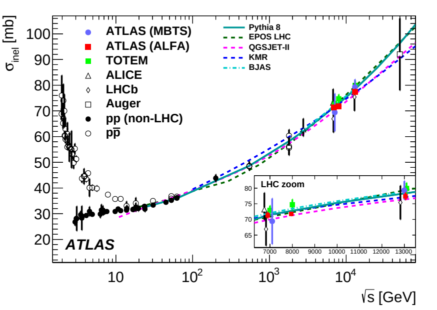
- Non-exponential shape of $d\sigma/dt$
- B–slope measurement (from a fit in a restricted t range)

$$B = 21.14 \pm 0.07(\text{stat.}) \pm 0.11(\text{exp.}) \pm 0.01(\text{th.})\ \text{GeV}^{-2}$$

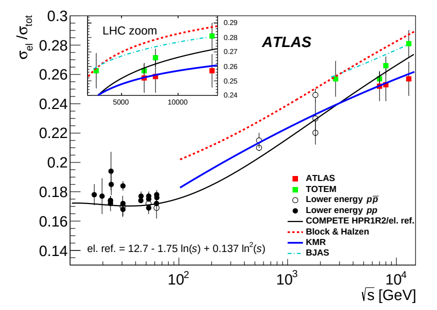




Derived quantities



Total inelastic cross section in agreement with previous ATLAS measurements using MBTS detectors



Ratio of elastic to total cross section in tension with TOTEM's results

Summary

Summary

- Interesting physics performed using ATLAS-ALFA
- $\beta^* = 2500$ m $\rightarrow$ access to CNI region
- Measurement of $\rho \rightarrow$ slow-down of σ_{tot} evolution with $\sqrt{s}$ or existence of the odderon exchange
- Most precise σ_{tot} measurement at 13 TeV

arXiv:2207.12246

https://atlas.cern/Updates/Physics-Briefing/ALFA-scattering

BACKUP

Methods of σ_{tot} measurement

Luminosity-dependent (ATLAS)

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\rho^2} \frac{1}{L} \frac{\mathrm{d}N_{\text{el}}}{\mathrm{d}t}\bigg|_{t\to 0}$$

Requires a dedicated luminosity measurement

Luminosity-independent (TOTEM)

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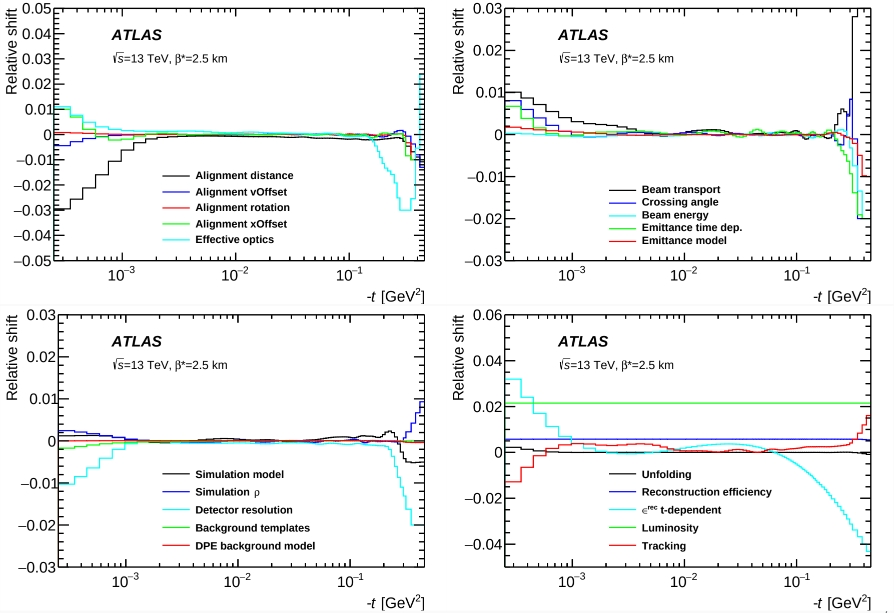
Requires correction for not measured low-mass diffraction

Systematic uncertainties



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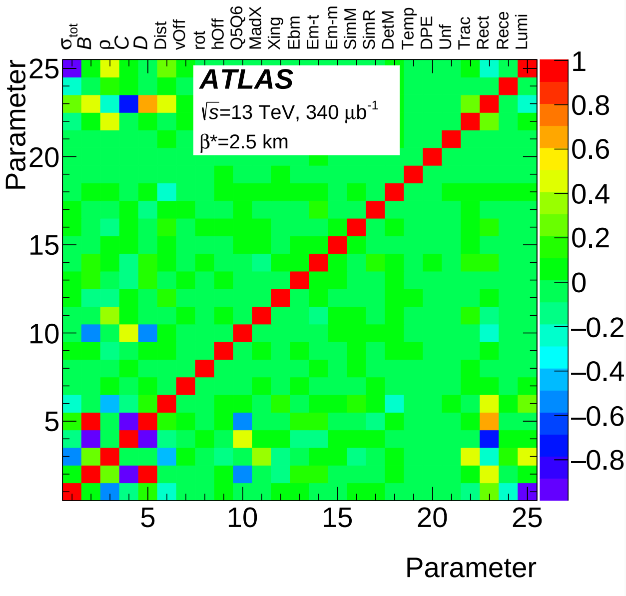
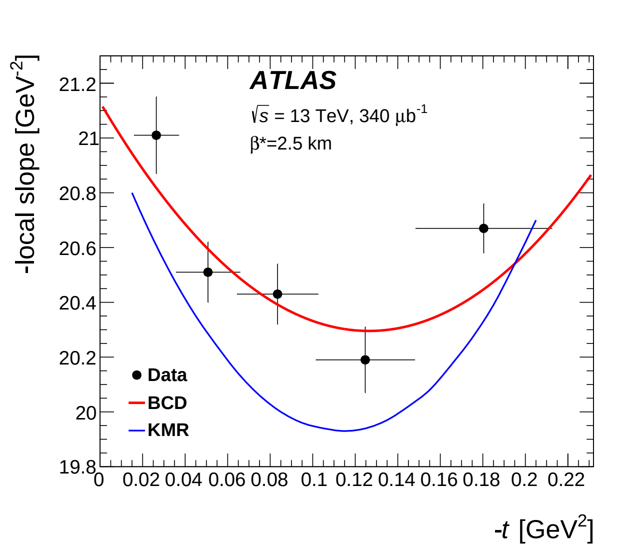
Correlations



Local exponential slope



Reconstruction efficiency