Exclusive, elastic and total cross-section measurements in ATLAS

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on behalf of the ATLAS Collaboration

CERN, 20 September 2022

$$pp \to pp$$

arXiv:2207.12246

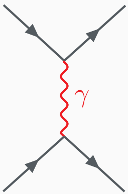
https://atlas.cern/Updates/Physics-Briefing/ALFA-scattering

Elastic *pp* scattering

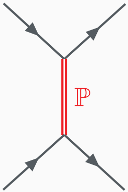
- Energy and momentum conservation
- 2 kinematic degrees of freedom: φ, θ
- φ – trivial (uniform)
- $t \approx -p^2\theta^2 = -p_T^2$
- small $|t|$ – large distance, large high $|t|$ – small distance

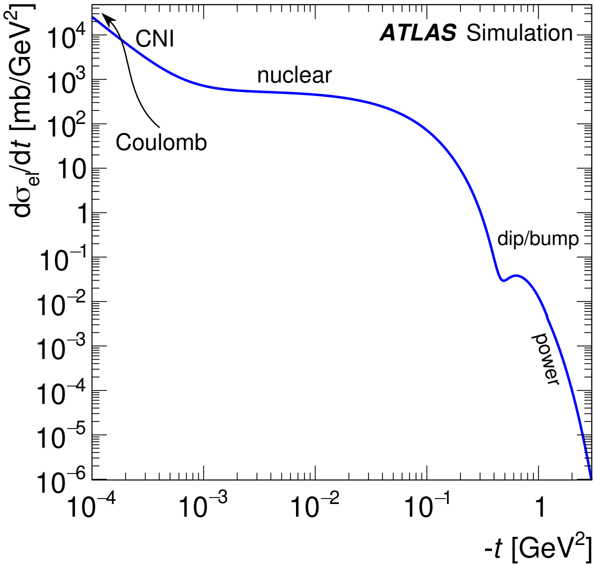
Mechanisms

Coulomb (electromagnetic)



Nuclear (strong)





Optical theorem

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

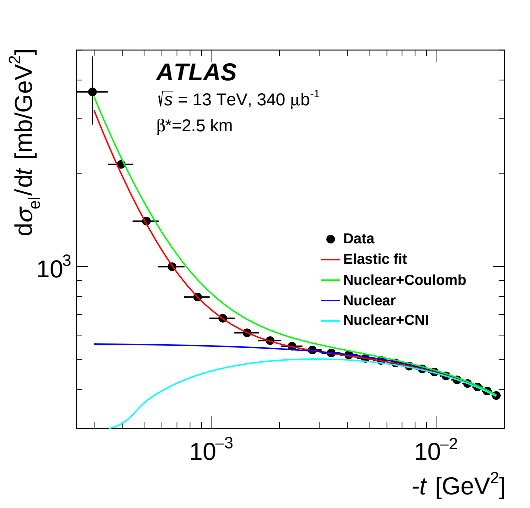
Differential elastic cross section

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

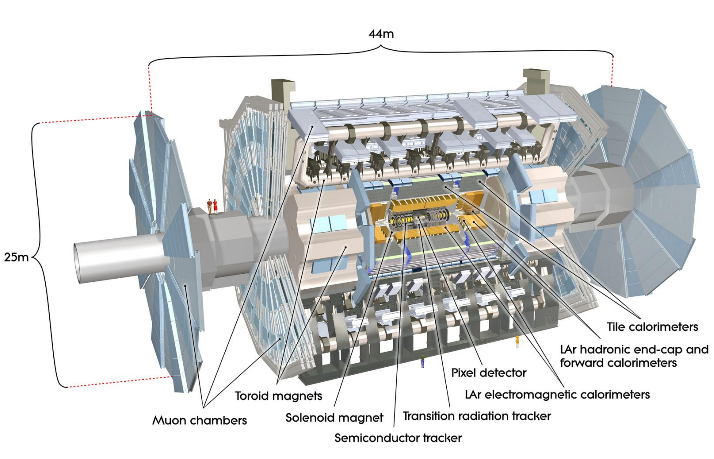
$$\frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t} = \sigma_{\text{tot}}^2 \frac{1+\rho^2}{16\pi} \exp\left(-B|t|\right)$$

Phase of the nuclear amplitude

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

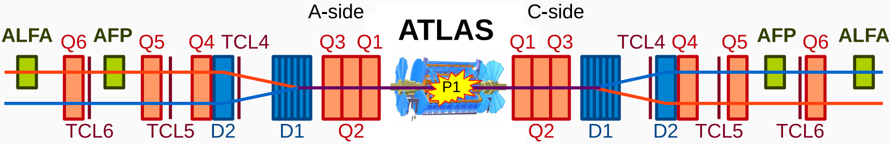


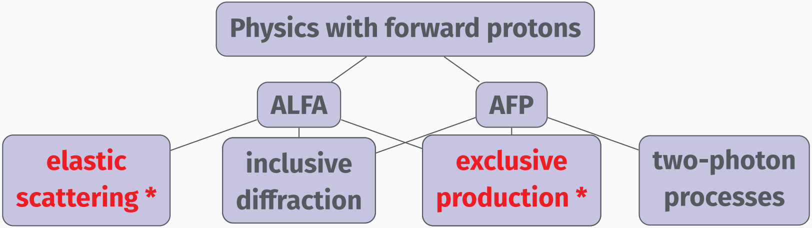
ATLAS Detector



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

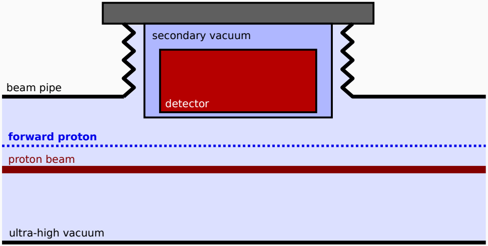
Physics with forward detectors in ATLAS

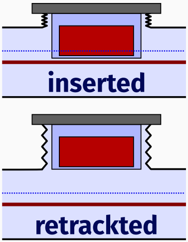


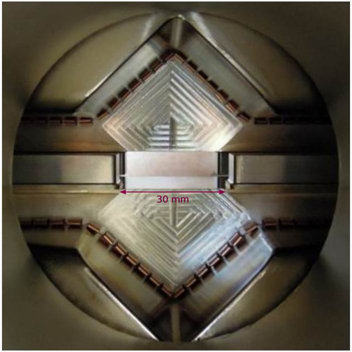


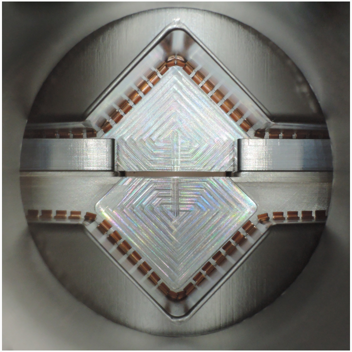
* covered in this talk

Roman pot mechanism

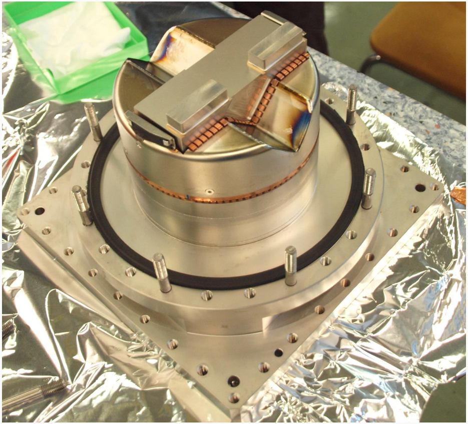


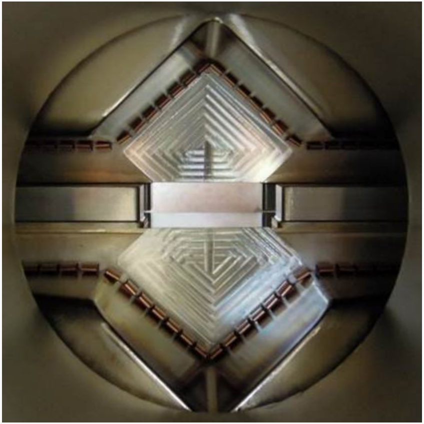




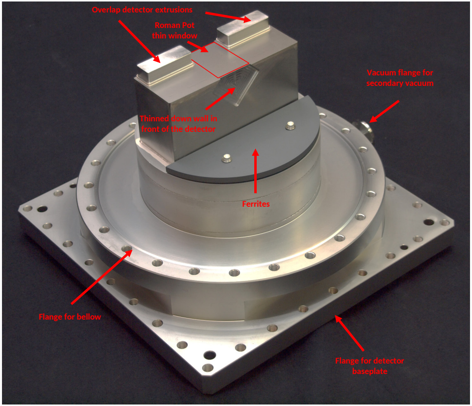


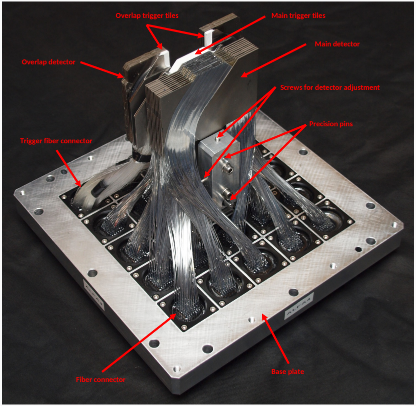
ALFA Roman pot



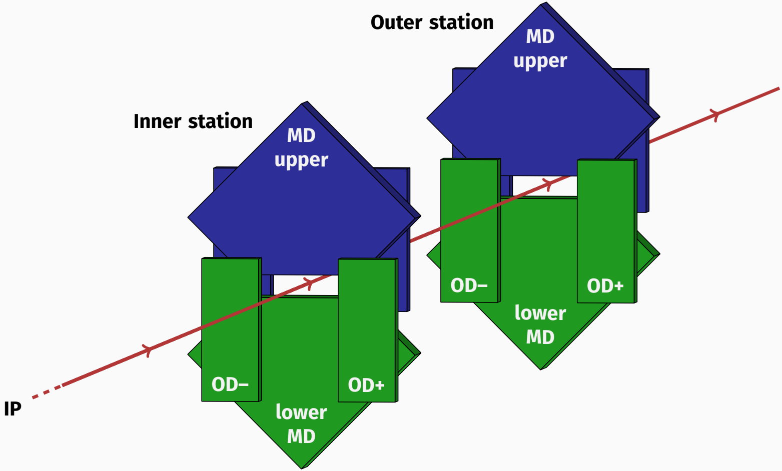


ALFA Roman pot



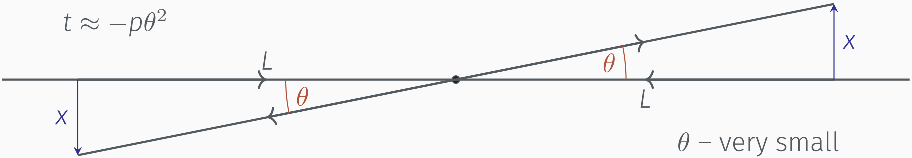


ALFA detectors



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:

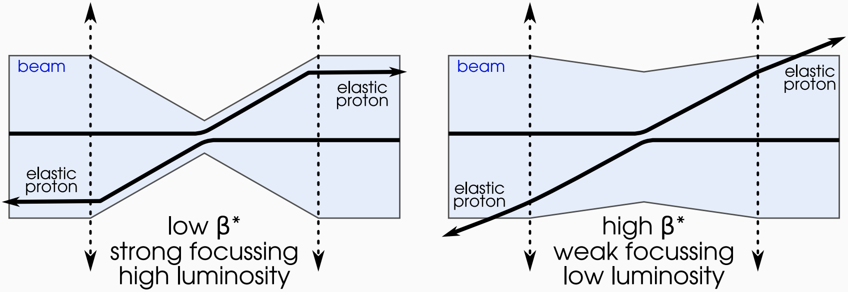
$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x^* \end{pmatrix}$$

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

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

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

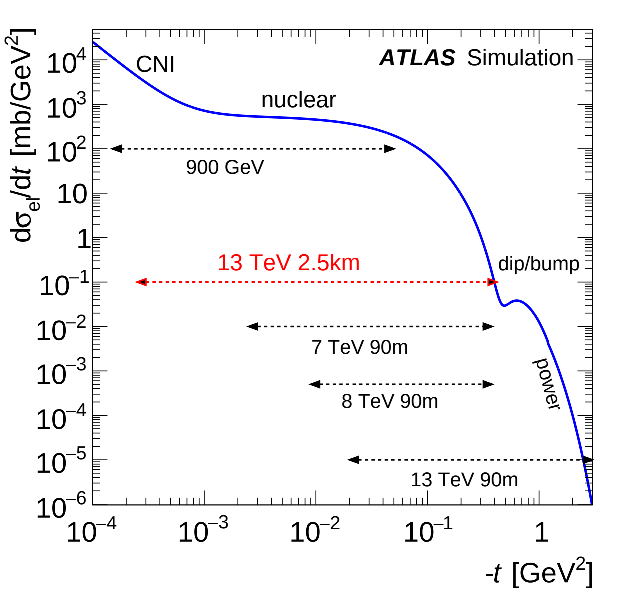
High-β optics



Typical values:

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

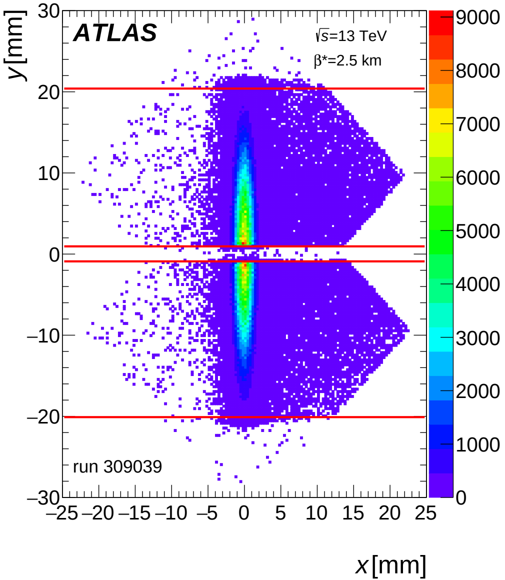
Experimental reach



13 TeV 2.5 km
2016

7 TeV 90 m
2011

Data

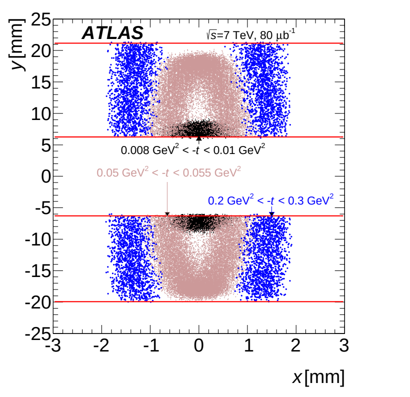


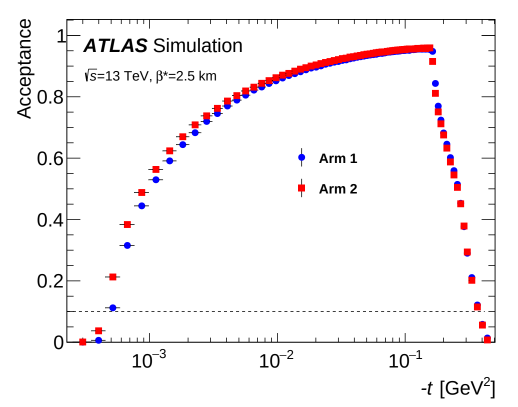
$$x = M_{11}^{x} x^{*} + M_{12}^{x} \theta_{x}^{*}$$

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

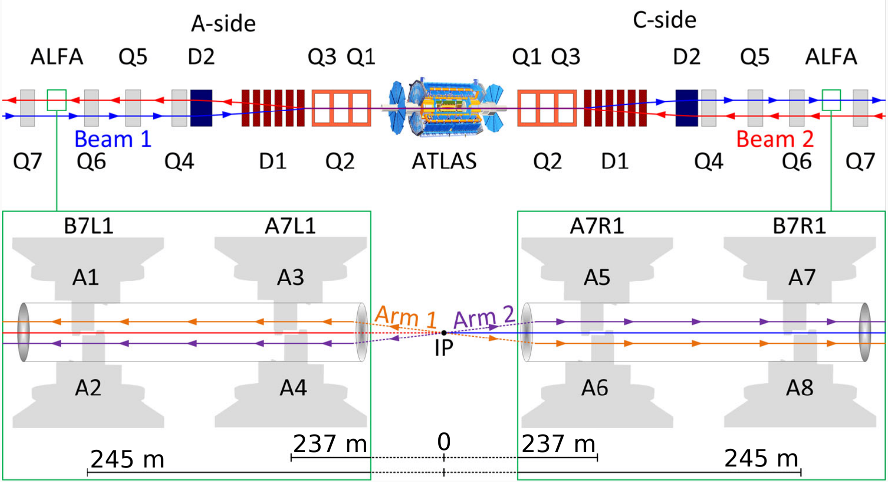
$$M_{12}^{x} \ll M_{12}^{y}$$

Geometric acceptance





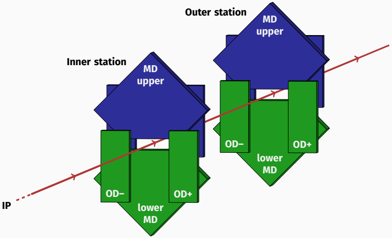
ALFA detectors



t reconstruction

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

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



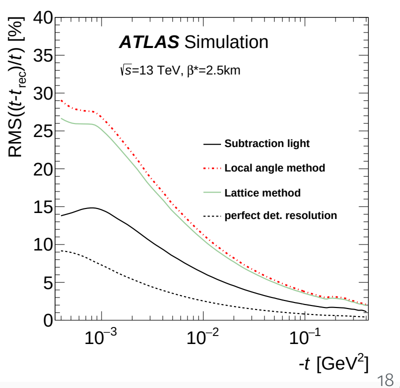
Subtraction

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

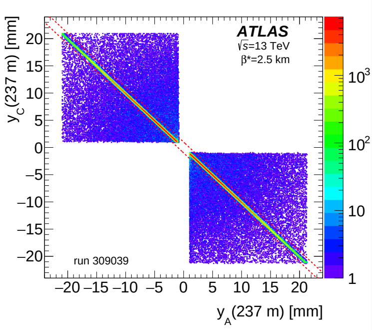
$$\rightarrow \quad \theta_x^* = \frac{x_A - x_C}{M_{12}}$$

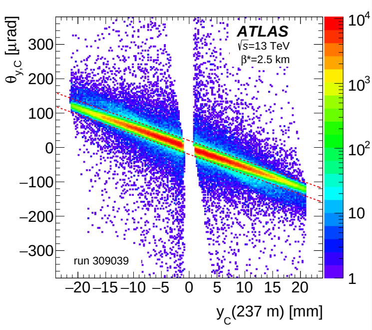
Local angle

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



Event selection and background estimation



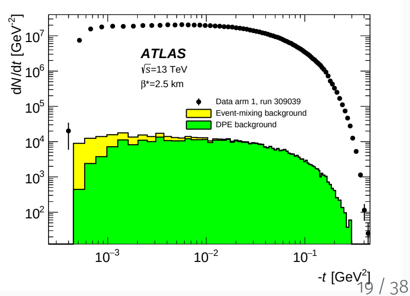


Event selection based on strong correlations present in elastic events

Background (normalized in control regions):

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

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

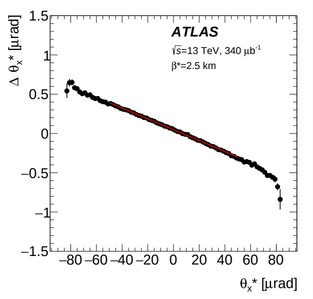


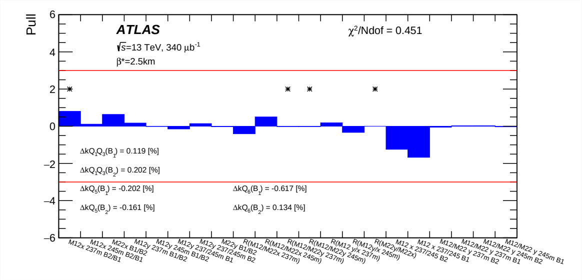
Data-driven methods

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

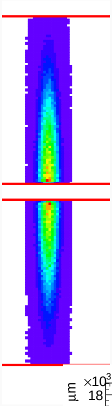
Optics tuning:

$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M^x_{11} & M^x_{12} \\ M^x_{21} & M^x_{22} \end{pmatrix} \begin{pmatrix} x^* \\ \theta^*_x \end{pmatrix} \qquad \begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M^y_{11} & M^y_{12} \\ M^y_{21} & M^y_{22} \end{pmatrix} \begin{pmatrix} y^* \\ \theta^*_y \end{pmatrix}$$

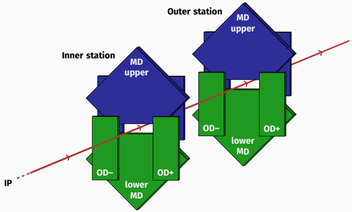


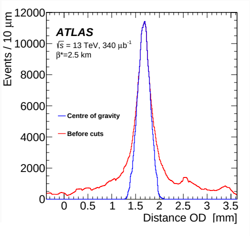


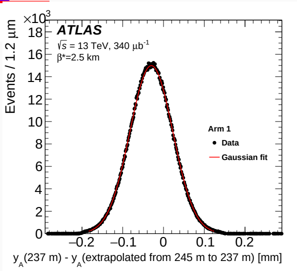
Alignment

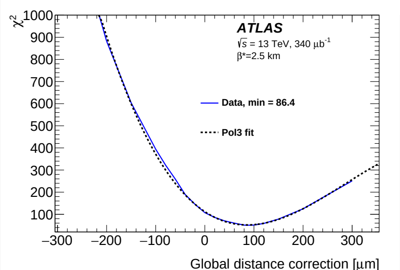


– Rotation, horizontal and vertical offsets obtained from the left–right and up–down symmetry of the elastic pattern
– Multi-step procedure of distance evaluation



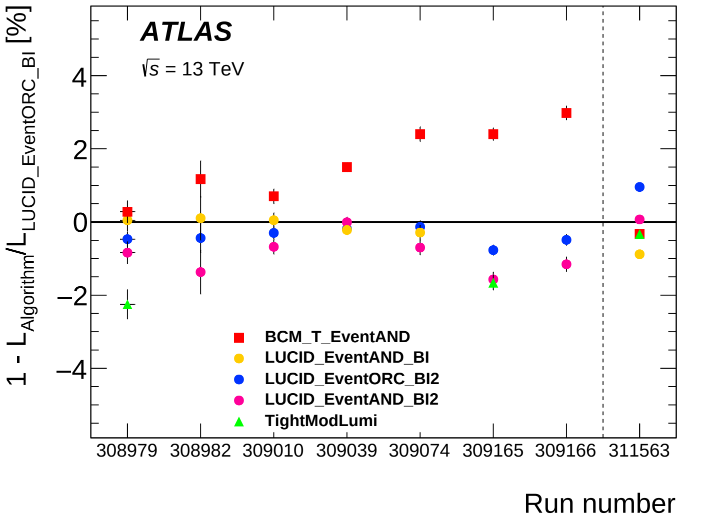




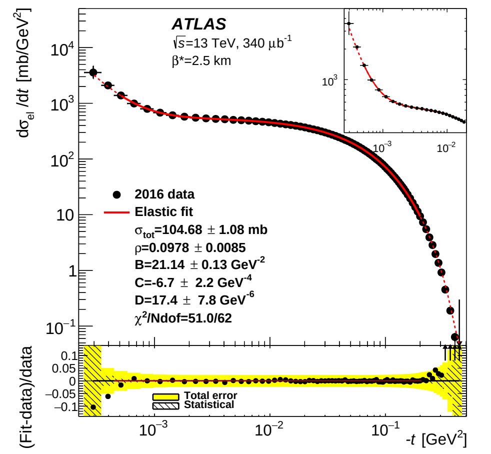


Luminosity measurement

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



Differential cross section



Fitted function:

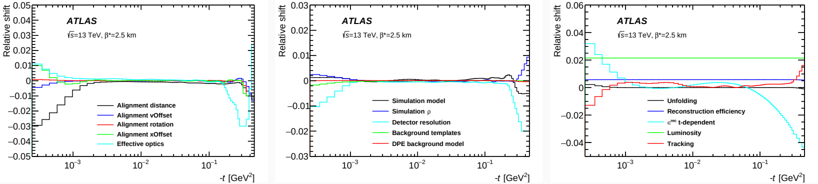
$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

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

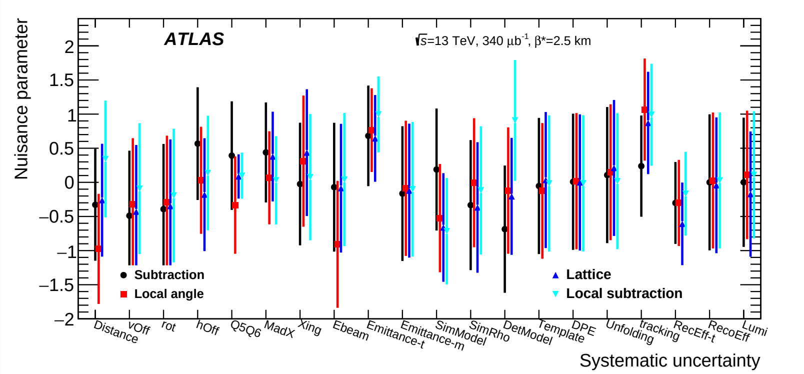
$$f_N(t) = (\rho + i)\,\frac{\sigma_{tot}}{\hbar c}\,e^{(-B|t|-C|t|^2-D|t|^3)/2}$$

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

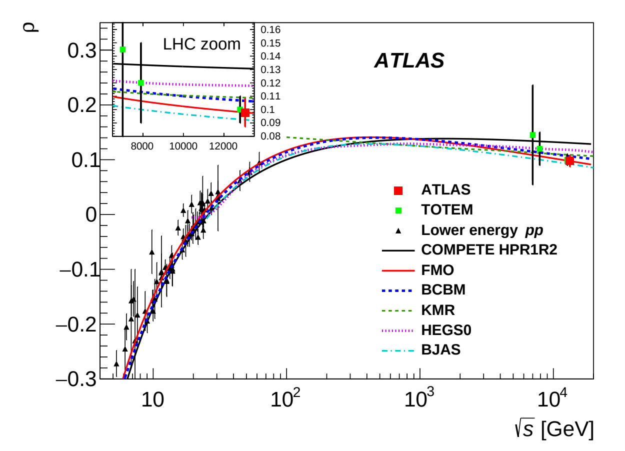
Systematic uncertainties



Main sources: luminosity, vertical alignment, reconstruction efficiency



Results in interference region



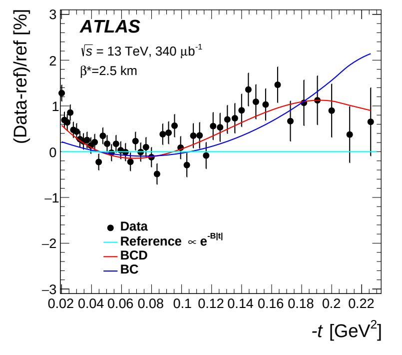
$$\rho = 0.0978 \pm 0.0043(\text{stat.}) \pm 0.0073(\text{exp.}) \pm 0.0064(\text{th.})$$

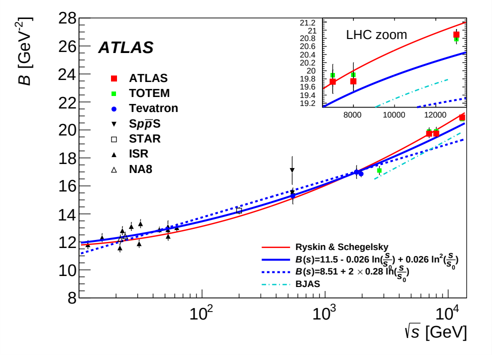
Result incompatible with COMPETE (community-standard semi-empirical fits) indicating Odderon exchange or a slowdown of σ_{tot} rise at high $\sqrt{s}$.

Results in nuclear region

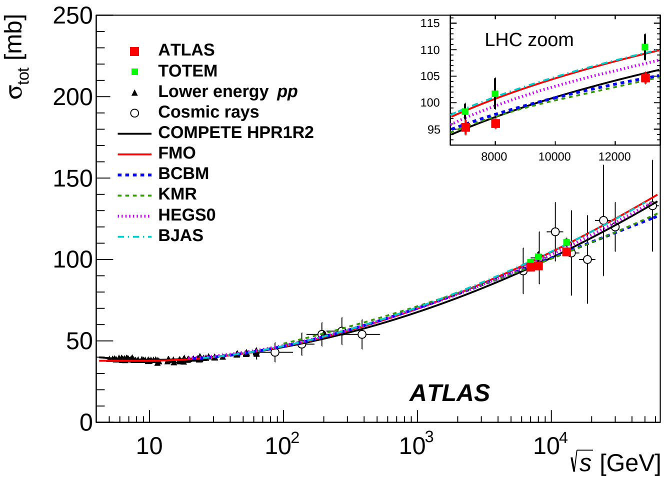
- Non-exponential shape of $d\sigma/dt$
- B–slope measurement (from a fit in a restricted t range)

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





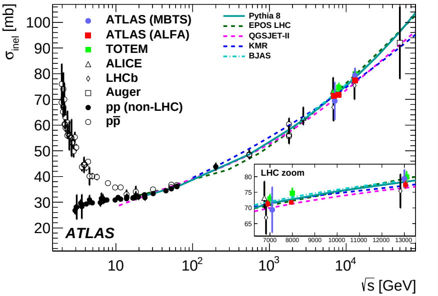
Results in nuclear region



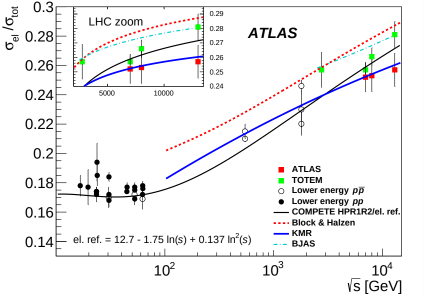
$$\sigma_{\text{tot}} = 104.68 \pm 0.22(\text{stat.}) \pm 1.06(\text{exp.}) \pm 0.12(\text{th.})\ \text{mb}$$

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

Derived quantities



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

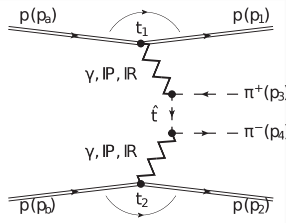


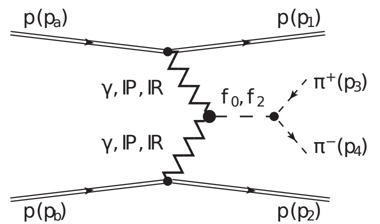
Ratio of elastic to total cross section in tension with TOTEM's results

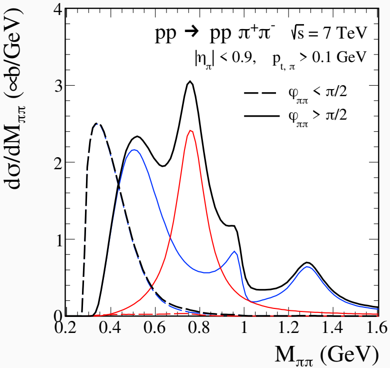
$$pp \to p\pi^+\pi^-p$$

CERN-EP-2022-140

Exclusive pion pair production







Interesting and complex mechanism

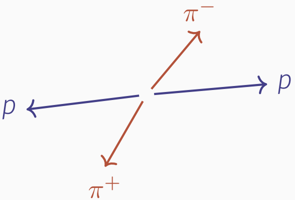
Non-trivial interplay of continuous and resonant production

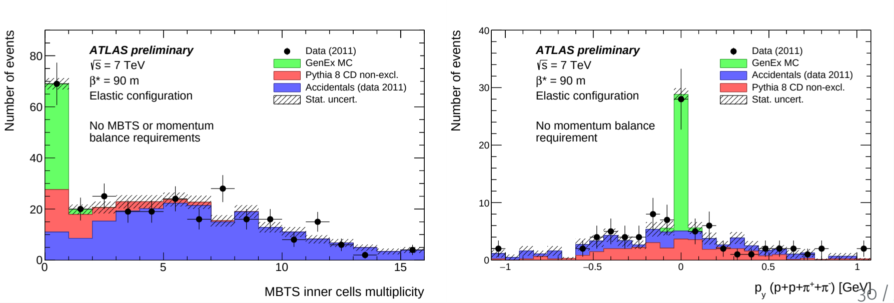
Plot and diagrams from
P. Lebiedowicz et al., Phys.Rev.D 93 (2016) 5, 054015.

Event selection

Selection of exclusive events:

- forward protons detected in ALFA
- opposite-charged pions detected in the central ATLAS detector
- vetoing activity in Minimum Bias Trigger Scintillator (MBTS)
- Exclusivity enforced by looking at p_T balance in the event





Cross section measurement

First exclusive $\pi^+\pi^-$ measurement with proton tagging at LHC!

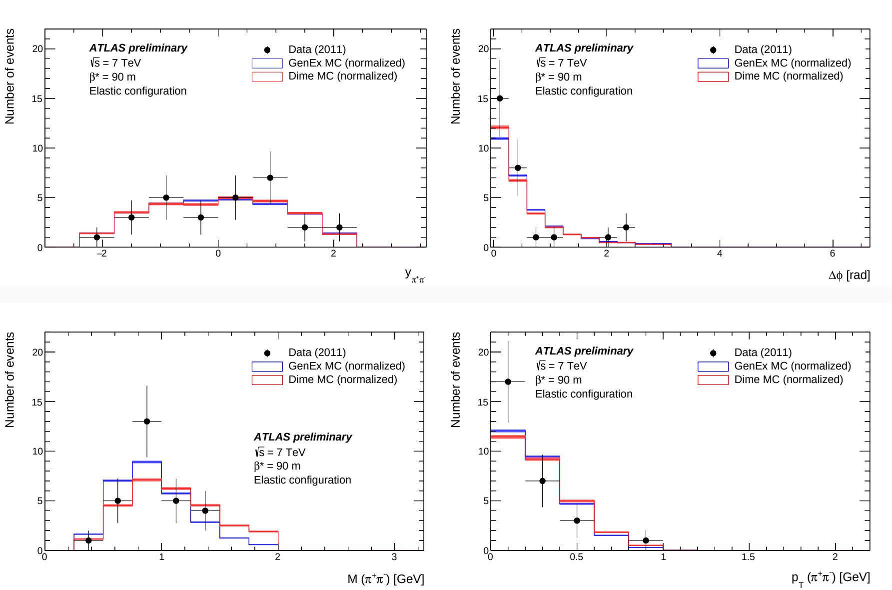
– elastic *pp* configuration

$$\sigma = 4.8 \pm 1.0(\text{stat})^{+0.3}_{-0.2}(\text{syst}) \pm 0.1(\text{lumi}) \pm 0.1(\text{model})\ \mu\text{b}$$

– anti-elastic *pp* configuration

$$\sigma = 9 \pm 6(\text{stat}) \pm 1(\text{syst}) \pm 1(\text{lumi}) \pm 1(\text{model})\ \mu\text{b}$$

Comparison of distributions



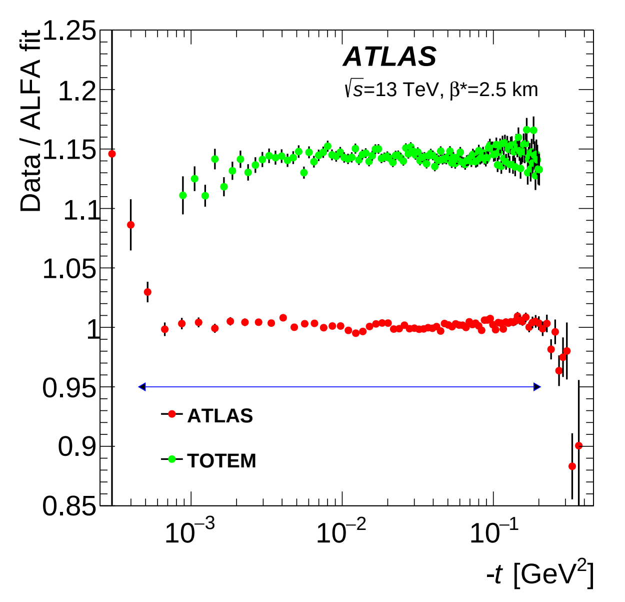
Summary

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
- First fully exclusive measurement of $pp \rightarrow p\pi^+\pi^-p$ at LHC

BACKUP

ATLAS vs TOTEM



Methods of σ_{tot} measurement

Luminosity-dependent (ATLAS)

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \frac{1}{L} \frac{dN_{el}}{dt}\bigg|_{t\to 0}$$

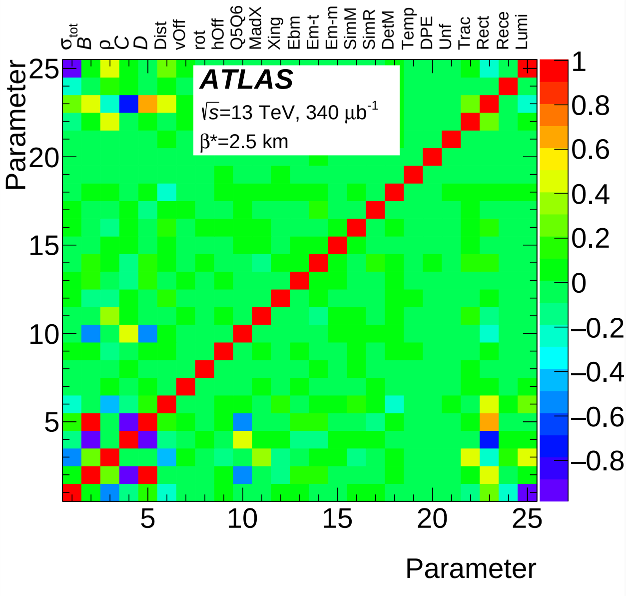
Requires a dedicated luminosity measurement

Luminosity-independent (TOTEM)

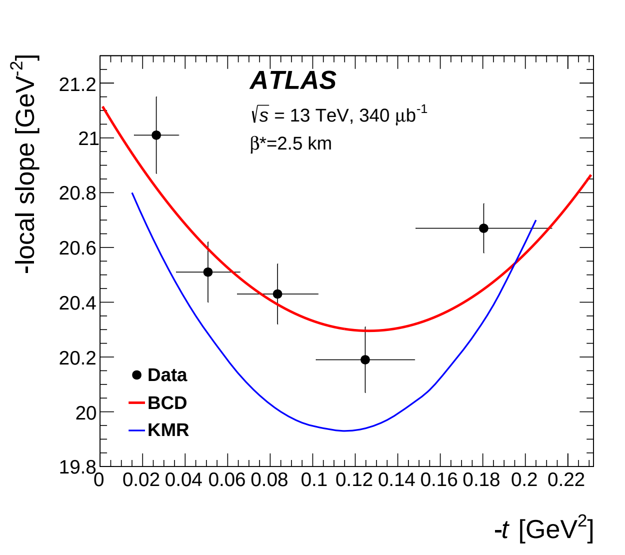
$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{1}{N_{el}+N_{inel}} \frac{dN_{el}}{dt}\bigg|_{t\to 0}$$

Requires correction for not measured small-mass diffraction

Correlations



Local exponential slope



Reconstruction efficiency