Physics with forward protons at LHC - high-β^* case

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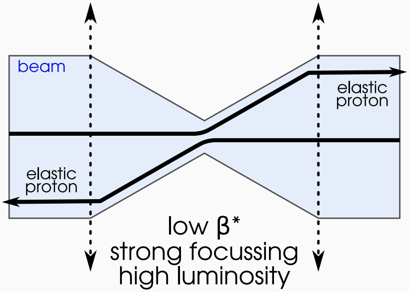
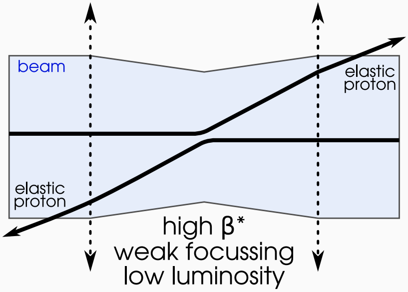
Forward Physics in ALICE 3
18–20 October 2023, Heidelberg

High-β optics



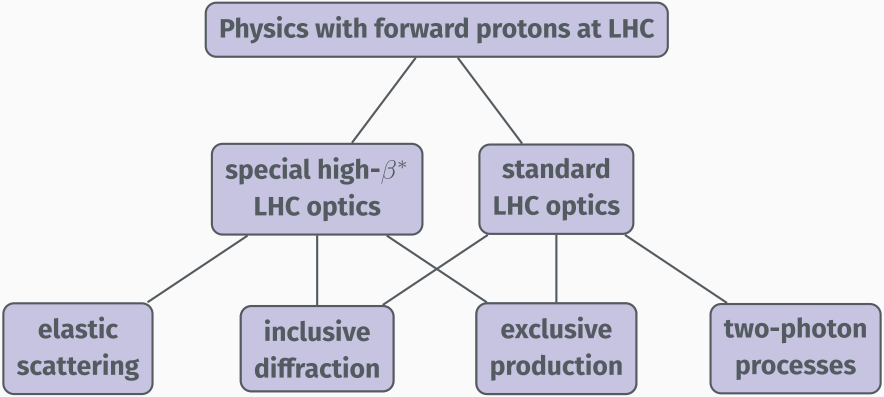


Typical values:

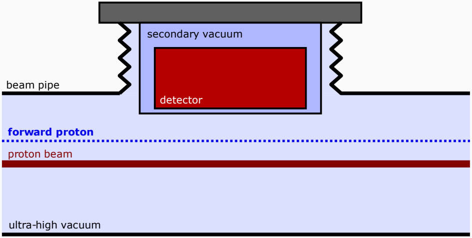
$\beta^* < 1$ m

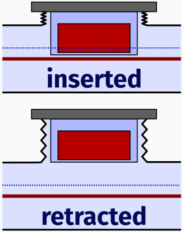
$\beta^* \geq 90$ m

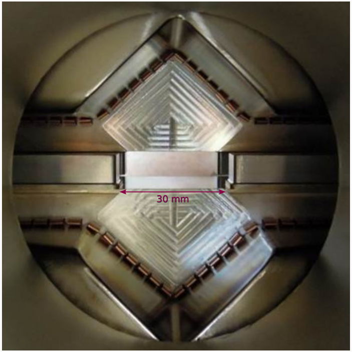
Physics overview

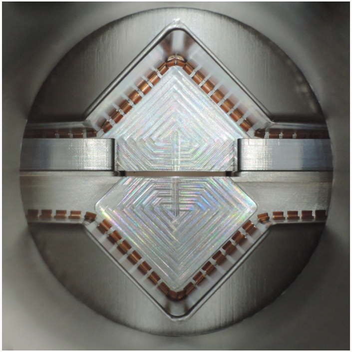


Roman pot mechanism

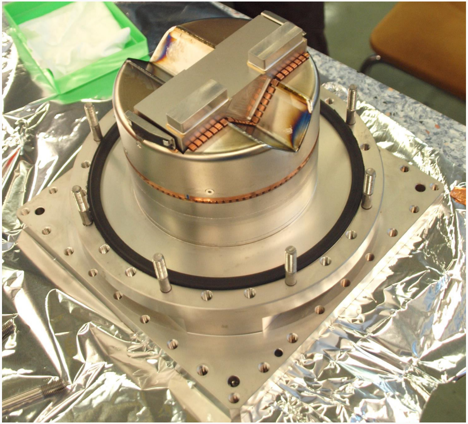


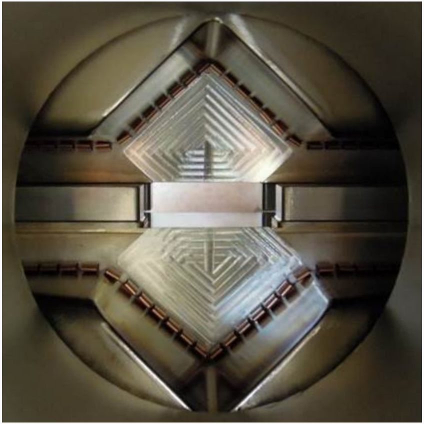




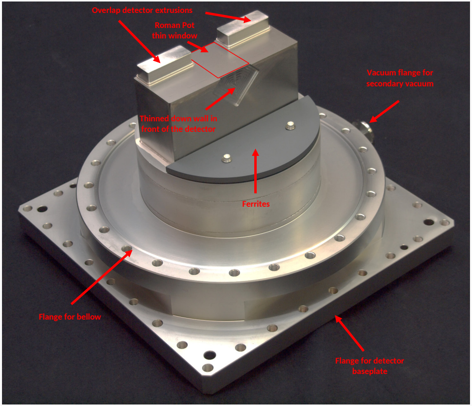


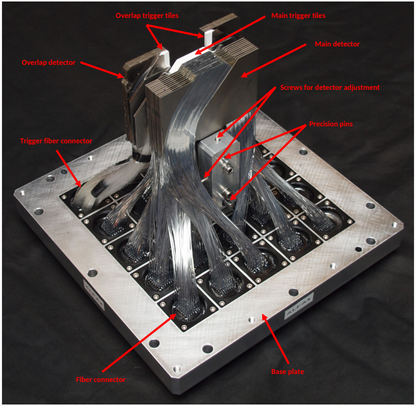
ALFA Roman pot



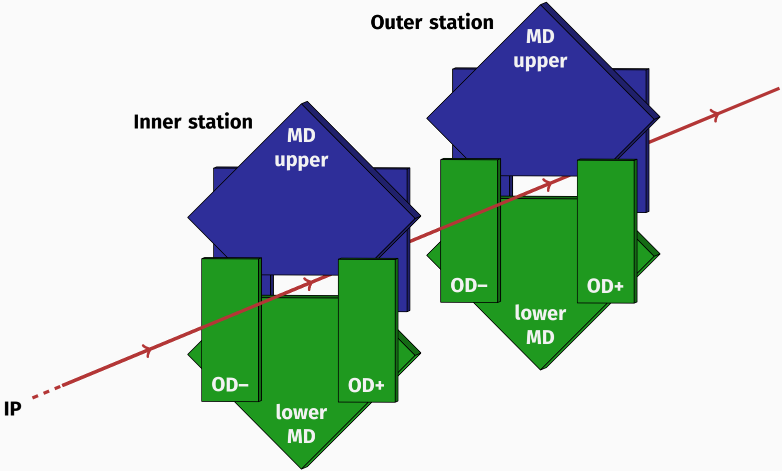


ALFA Roman pot





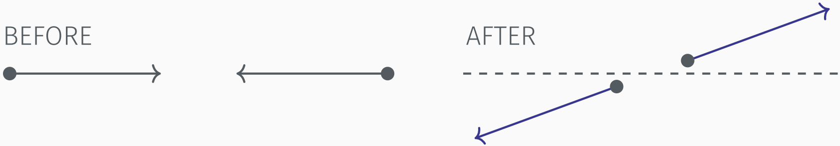
Full detector system



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

Elastic scattering

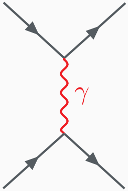
Elastic *pp* scattering



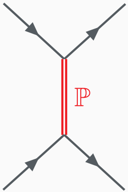
- Energy and momentum conservation
- 2 kinematic degrees of freedom: φ, θ
- φ – trivial (uniform)
- $t \approx -p^2\theta^2 = -p_T^2$
- small $|t|$ – large distance, large high $|t|$ – small distance

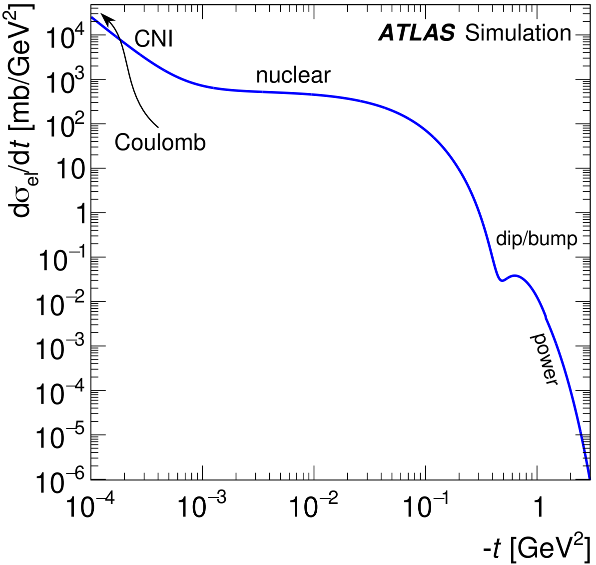
Mechanisms

Coulomb (electromagnetic)



Nuclear (strong)





Optical theorem

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

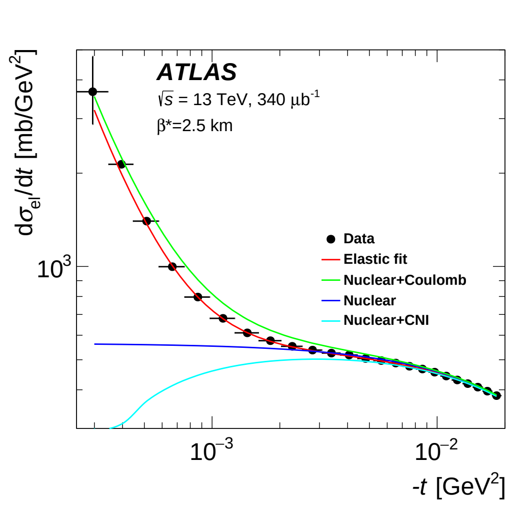
Differential elastic cross section

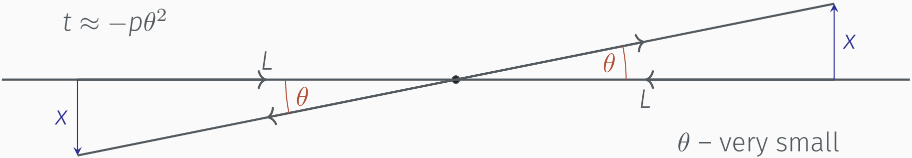
- Assuming a simplistic t dependence: $f_{\text{el}}(t) \propto \exp(-B|t|/2)$
- Introducing $\rho = \text{Re}\, f_{\text{el}} / \text{Im}\, f_{\text{el}}|_{t=0}$

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

Phase of the nuclear amplitude

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





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:

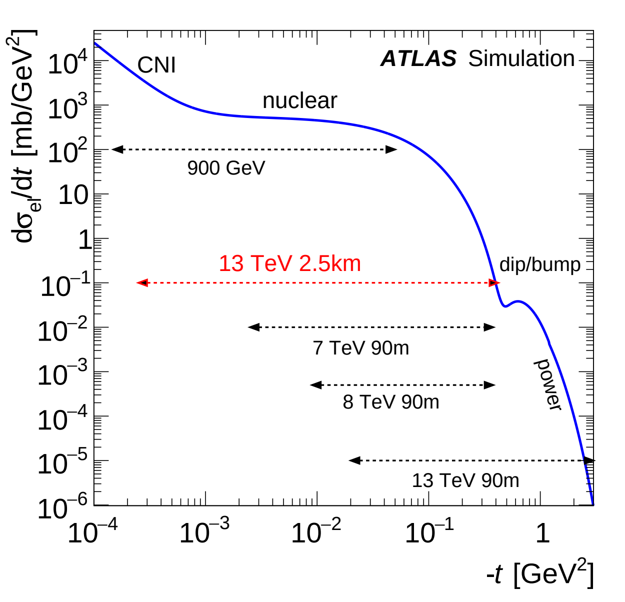
$$\begin{pmatrix} x \\ \theta_x \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x^* \end{pmatrix}$$

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

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

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

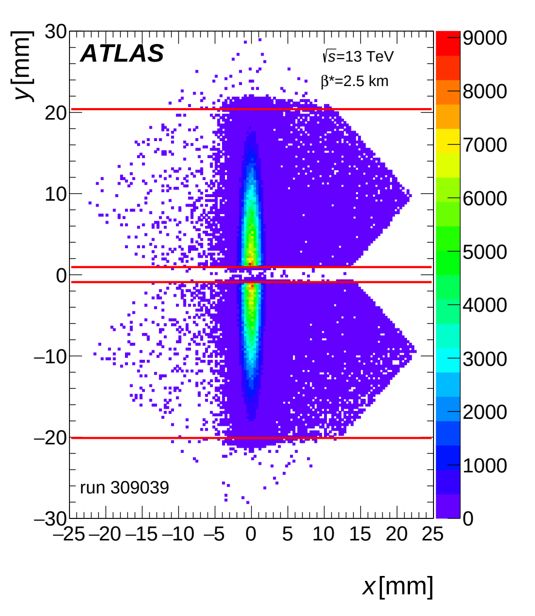
Experimental reach



13 TeV 2.5 km
2016

7 TeV 90 m
2011

Data

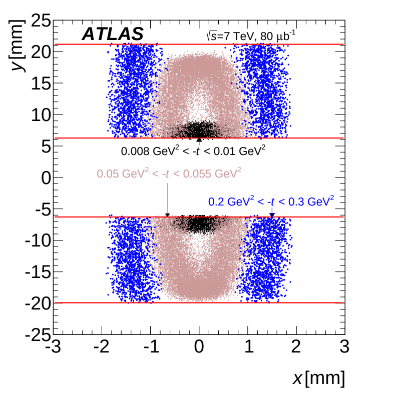


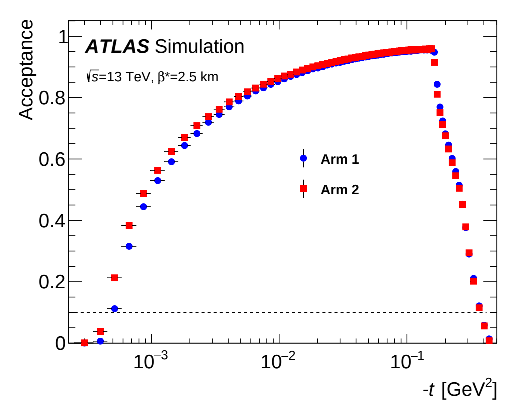
$$x = M_{11}^{x} x^{*} + M_{12}^{x} \theta_{x}^{*}$$

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

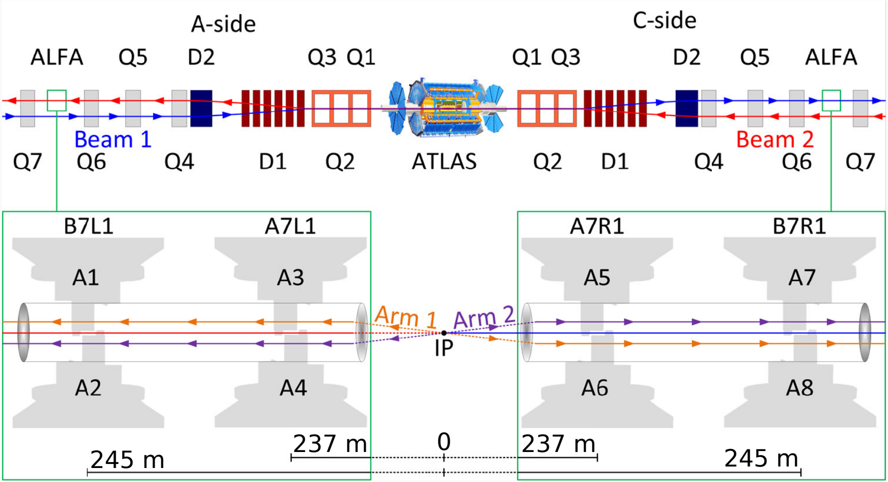
$$M_{12}^{x} \ll M_{12}^{y}$$

Geometric acceptance





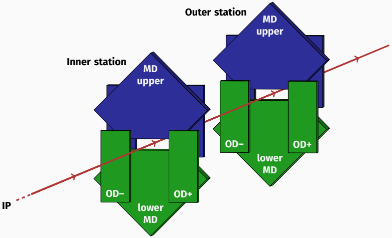
ALFA detectors



t reconstruction

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

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



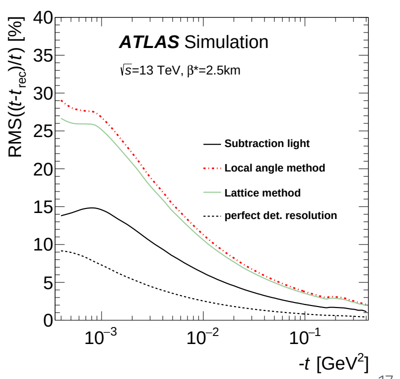
Subtraction

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

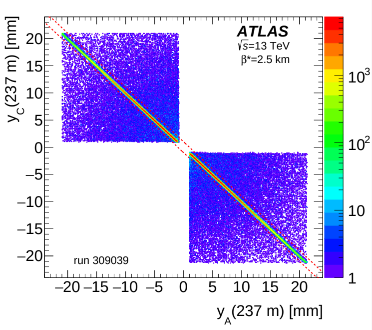
$$\rightarrow \quad \theta_x^* = \frac{x_A - x_C}{M_{12}}$$

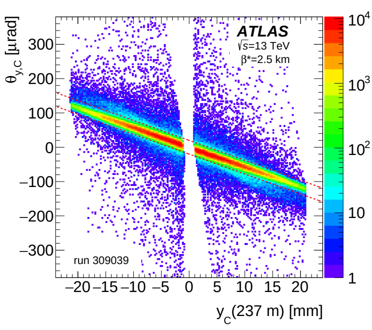
Local angle

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



Event selection and background estimation

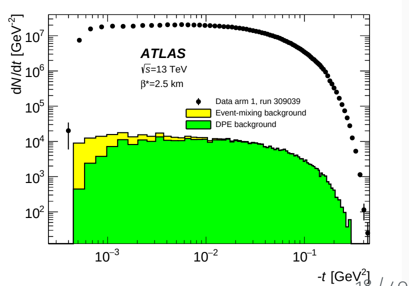




Event selection based on strong correlations present in elastic events

Background (normalized in control regions):

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

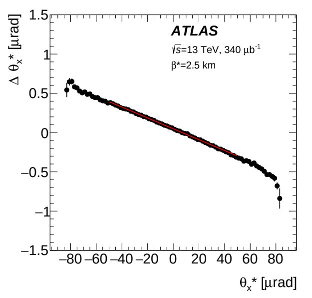


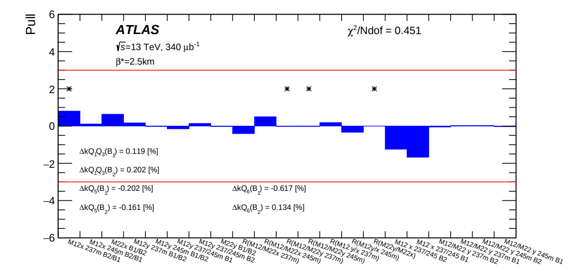
Less then 1‰ of background (relative uncertainty of 10 – 15%)

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

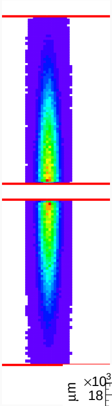
Optics tuning:

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

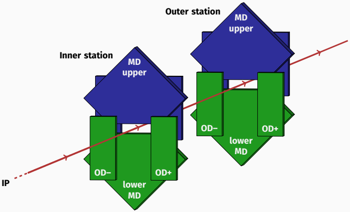


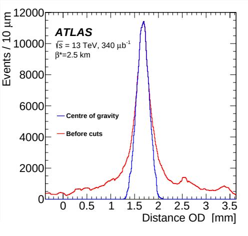


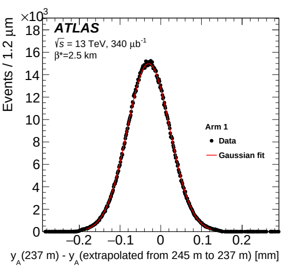
Alignment

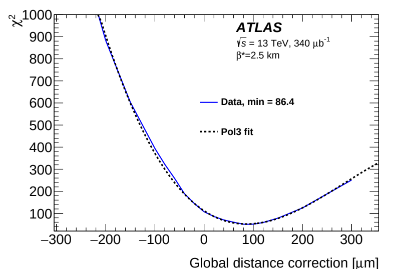


– Rotation, horizontal and vertical offsets obtained from the left–right and up–down symmetry of the elastic pattern
– Multi-step procedure of distance evaluation









Luminosity

Luminosity-dependent (ATLAS)

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

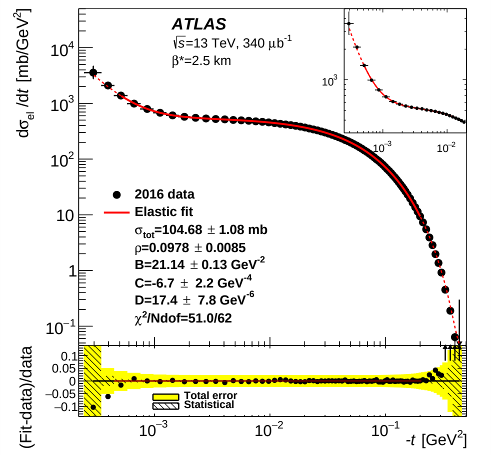
Requires a dedicated luminosity measurement

Luminosity-independent (TOTEM)

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

Requires correction for not measured small-mass diffraction

Differential cross section



Fitted function:

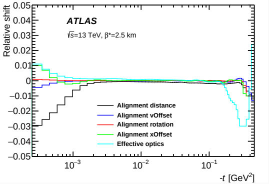
$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

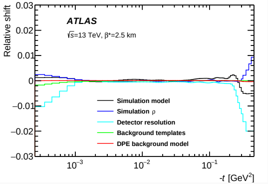
$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

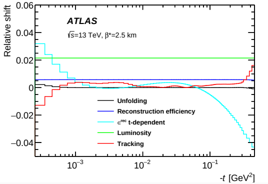
$$f_N(t) = (\rho + i)\,\frac{\sigma_{tot}}{\hbar c}e^{(-B|t|-C|t|^2-D|t|^3)/2}$$

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

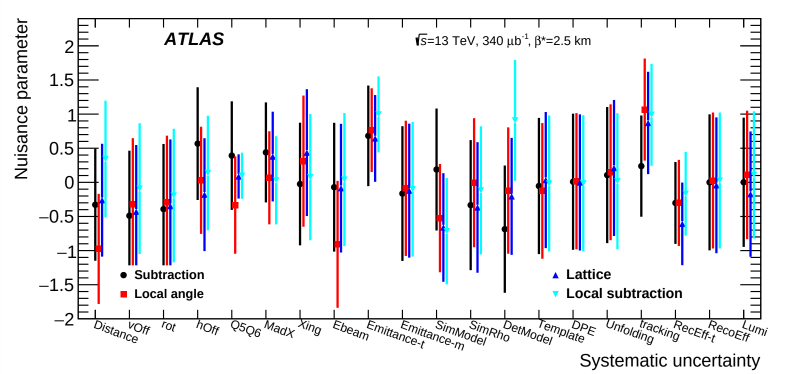
Systematic uncertainties



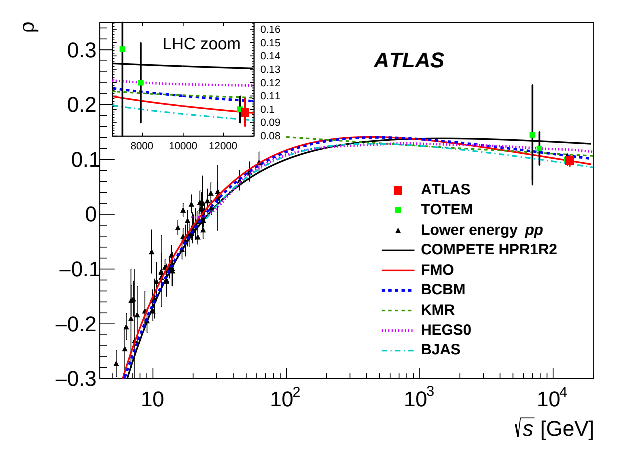




Main sources: luminosity, vertical alignment, reconstruction efficiency



Results in interference region



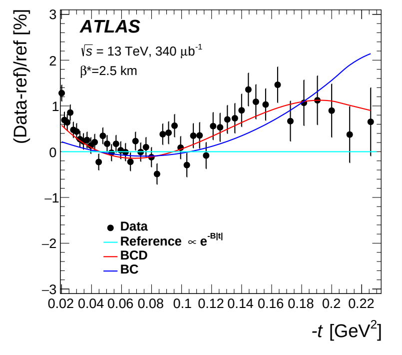
$$\rho = 0.0978 \pm 0.0043(\text{stat.}) \pm 0.0073(\text{exp.}) \pm 0.0064(\text{th.})$$

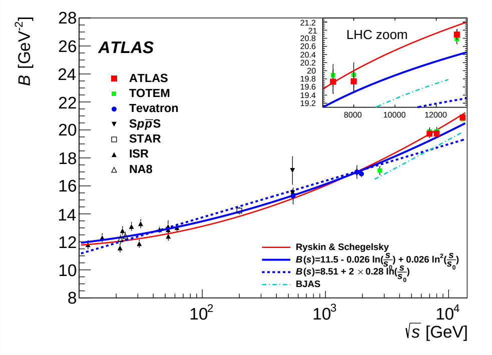
Result incompatible with COMPETE (community-standard semi-empirical fits) indicating Odderon exchange or a slowdown of σ_{tot} rise at high $\sqrt{s}$.

Results in nuclear region

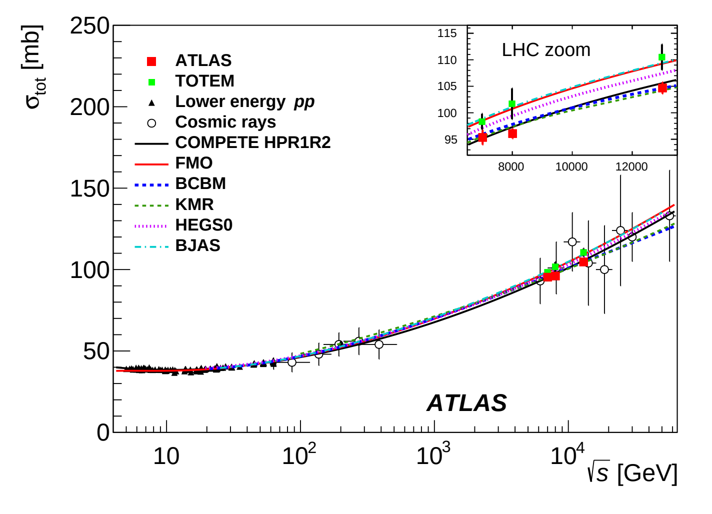
- Non-exponential shape of $d\sigma/dt$
- B–slope measurement (from a fit in a restricted t range)

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





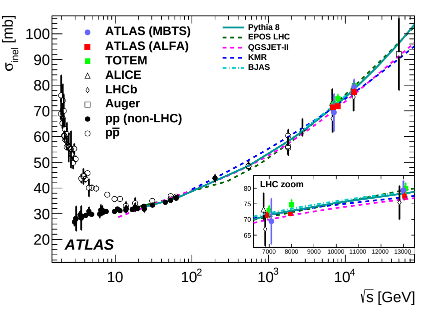
Results in nuclear region



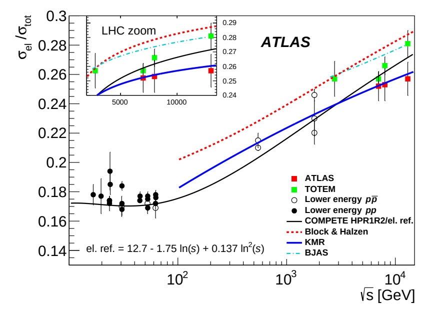
$$\sigma_{\text{tot}} = 104.68 \pm 0.22(\text{stat.}) \pm 1.06(\text{exp.}) \pm 0.12(\text{th.}) \text{ mb}$$

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

Derived quantities



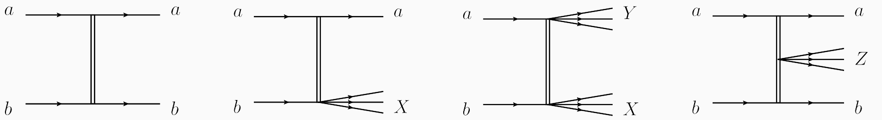
Total inelastic cross section in agreement with previous ATLAS measurements using MBTS detectors



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

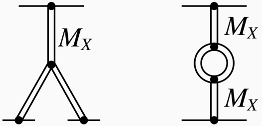
Inclusive diffraction

Inclusive diffraction



Regge theory

Triple pomeron vertex



Good-Walker

Ψ_k – mass eigenstates

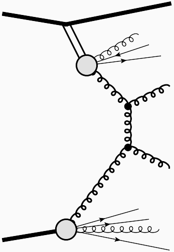
Φ_n – diffractive eigenstates

$$\Psi_k = \sum c_{kn}\Phi_n$$

$$d\sigma_{\text{diss}}/d^2b = \langle T^2 \rangle - \langle T \rangle^2$$

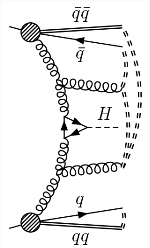
Resolved pomeron

- Ingelman-Schlein model
- pomeron has partonic structure
- absorptive corrections (survival probability)



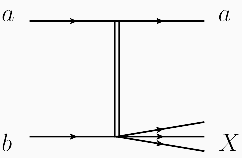
Soft colour interactions

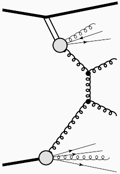
- QCD-inspired model
- additional gluon exchanges screen the color flow



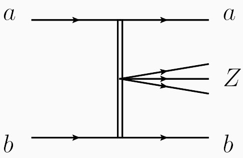
Inclusive diffraction

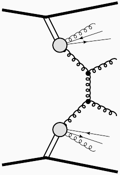
Single diffraction

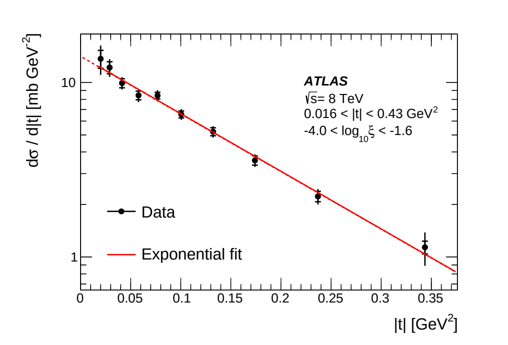




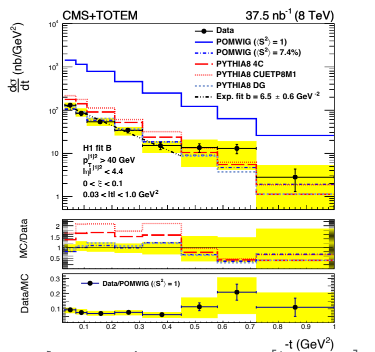
Central diffraction





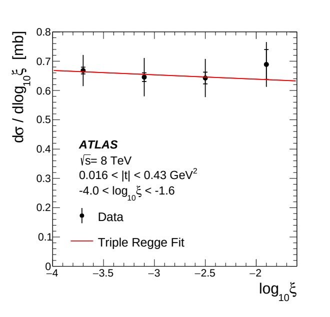


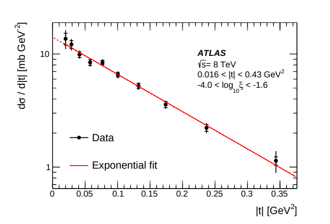
Soft SD, arXiv:1911.00453 [hep-ex]



Hard SD, arXiv:2002.12146 [hep-ex]

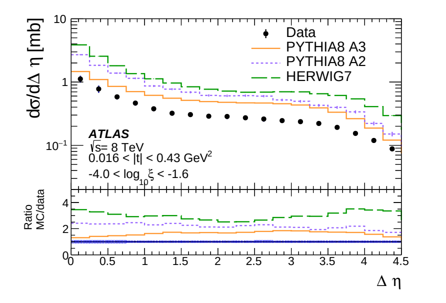
Proton kinematics distribution





- Distribution fitted with:
  $\frac{d\sigma}{d\log_{10}\xi} = \left(\frac{1}{\xi}\right)^{\alpha(0)-1} \frac{\exp(Bt_{\text{high}})-\exp(Bt_{\text{low}})}{B}$,
  where $B = B_0 - 2\alpha' \log\xi$
- Measured Pomeron intercept
  $\alpha(0) = 1.07 \pm 0.02\,(stat.) \pm 0.06\,(\text{syst.}) \pm 0.06\,(\alpha')$
- Main systematic uncertainty from
  $\alpha' = 0.25 \pm 0.25$ GeV^{-2}
- PYTHIA 8 A3 (Donnachie-Landshoff): α(0) = 1.14
  PYTHIA 8 A2 (Schuler-Sjostrand): α(0) = 1.00
- Measured exponential slope:
  $B = 7.60 \pm 0.23\,(\text{stat.}) \pm 0.22\,(\text{syst.})$ GeV^{-2}
- In agreement with Pythia 8 prediction:
  PYTHIA8 A2: 7.82 GeV^{-2}, PYTHIA8 A3: 7.10 GeV^{-2}
- Main systematic uncertainty from overlay background subtraction

Integrated cross sections and rapidity gap size



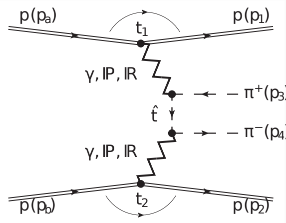
- Unfolded hadron level cross sections after background subtraction
- Diffractive plateau is visible
- Increase at small rapidity gaps: limited acceptance of ATLAS tracker
- Decrease at large rapidity gaps: loss of small-ξ events close to the ξ-edge (10^{-4})

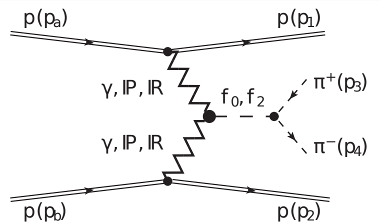
MCs describe the shape but not the overall cross section:

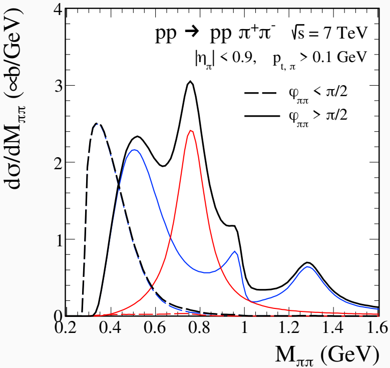
Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t\text{-extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
Pythia8 A2 (Schuler–Sjöstrand)	3.69	4.35
Pythia8 A3 (Donnachie–Landshoff)	2.52	2.98
Herwig7	4.96	6.11

Exclusive diffraction

Exclusive pion pair production







Interesting and complex mechanism

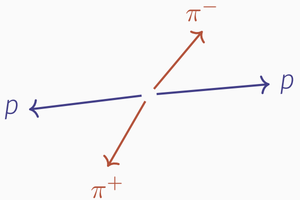
Non-trivial interplay of continuous and resonant production

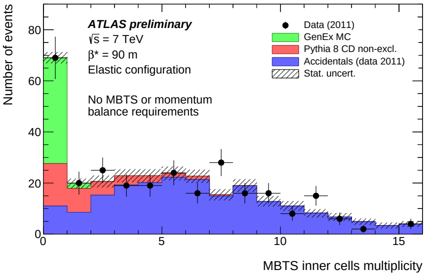
Plot and diagrams from
P. Lebiedowicz et al., Phys.Rev.D 93 (2016) 5, 054015.

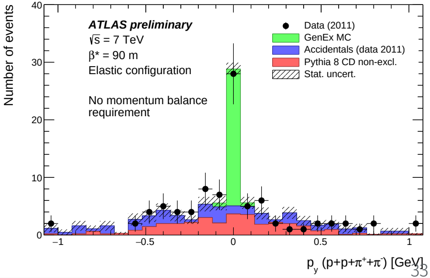
Event selection

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!

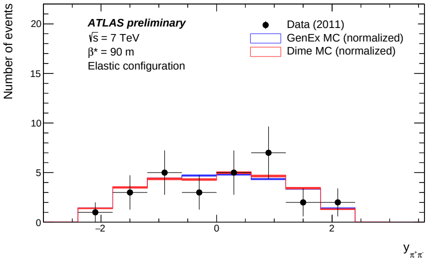
– elastic *pp* configuration

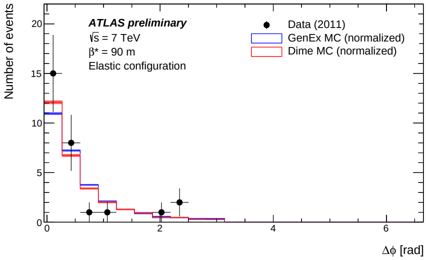
$$\sigma = 4.8 \pm 1.0(\text{stat})^{+0.3}_{-0.2}(\text{syst}) \pm 0.1(\text{lumi}) \pm 0.1(\text{model})\ \mu\text{b}$$

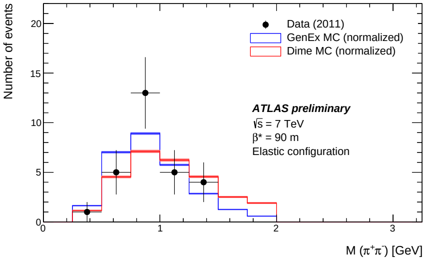
– anti-elastic *pp* configuration

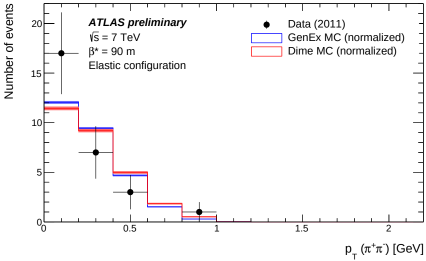
$$\sigma = 9 \pm 6(\text{stat}) \pm 1(\text{syst}) \pm 1(\text{lumi}) \pm 1(\text{model})\ \mu\text{b}$$

Comparison of distributions



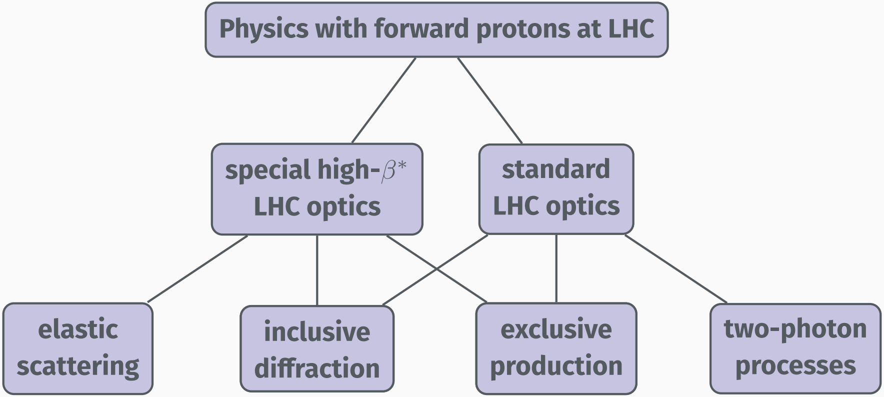






Summary

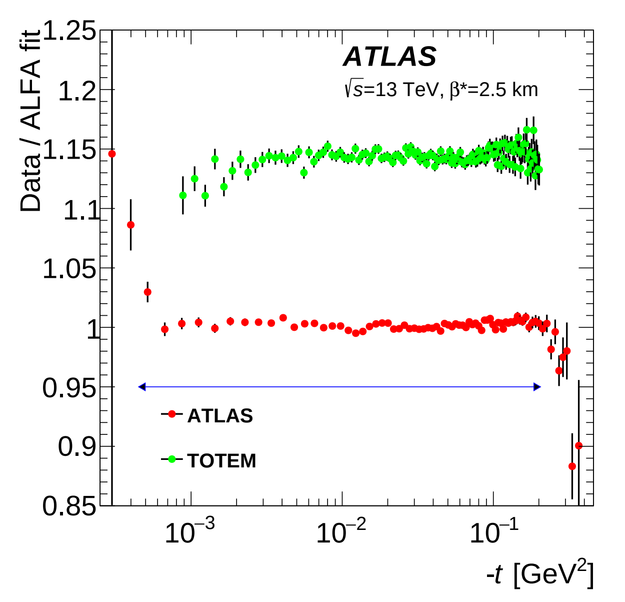
Summary



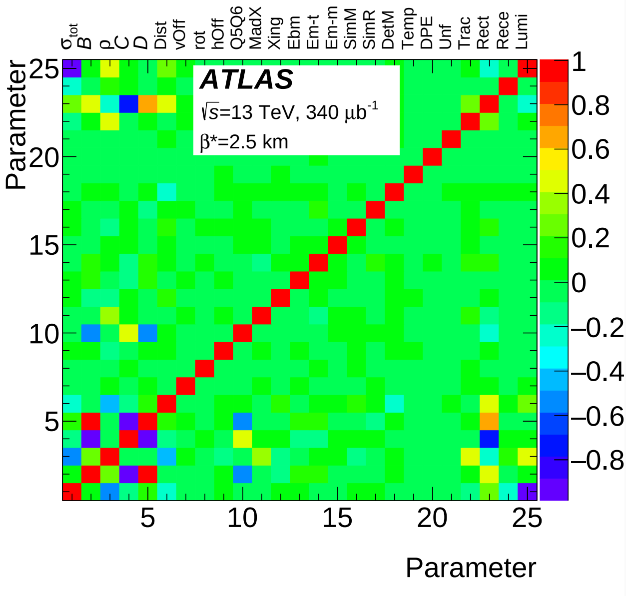
Physics with forward protons at LHC
special high-β^* LHC optics
standard LHC optics
elastic scattering
inclusive diffraction
exclusive production
two-photon processes

BACKUP

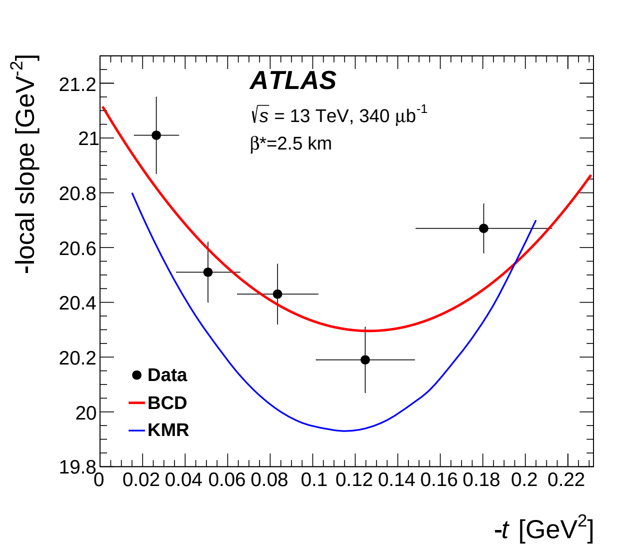
ATLAS vs TOTEM



Correlations



Local exponential slope



Reconstruction efficiency