Forward proton measurements with ATLAS

New results for ICHEP2022

- Exclusive pion pair production at $\sqrt{s}$ = 7 TeV
- Measurement of the total cross section and ρ-parameter from elastic scattering at $\sqrt{s}$=13 TeV

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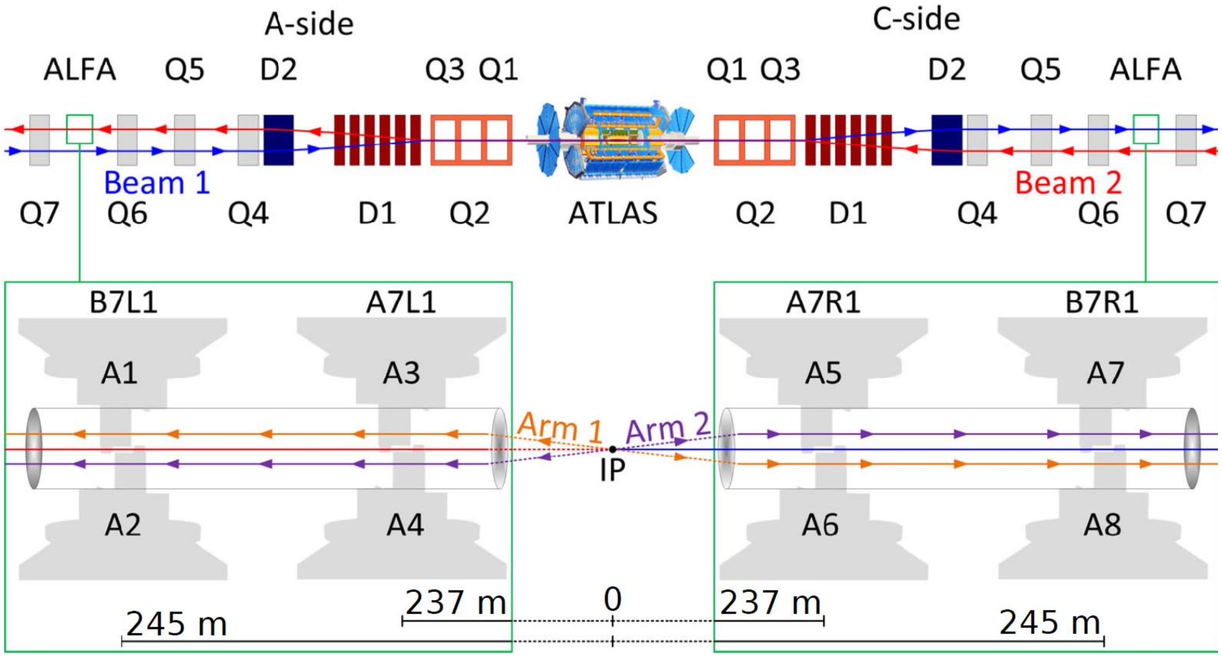
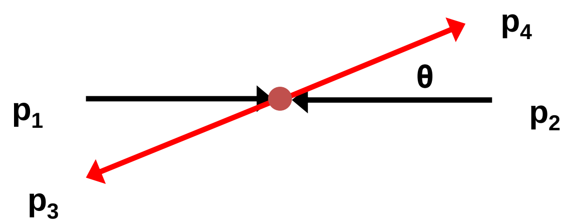
Bundesministerium für Bildung und Forschung

FSP ATLAS Erforschung von Universum und Materie

Forward proton measurements with ALFA



Elastic scattering

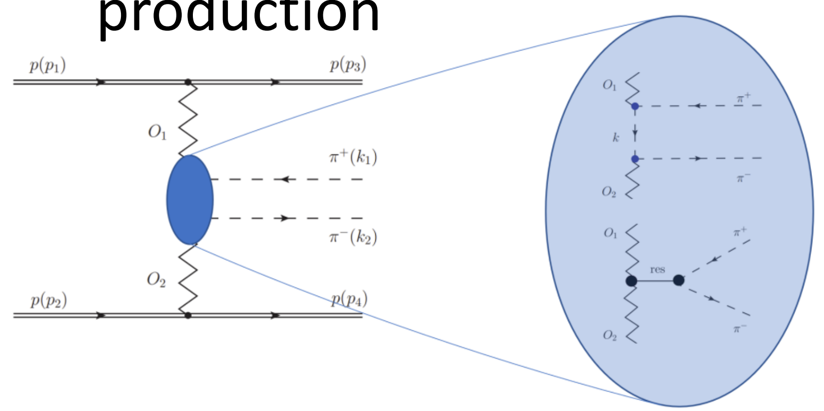


$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$t \approx -(p\theta)^2$$

ALFA the Roman Pot detector in ATLAS used for measurements of elastic scattering and diffraction in special runs of the LHC

- β*=90m at √s=7 TeV, excl. pions
- β*=2.5 km at √s 13 TeV, elastics

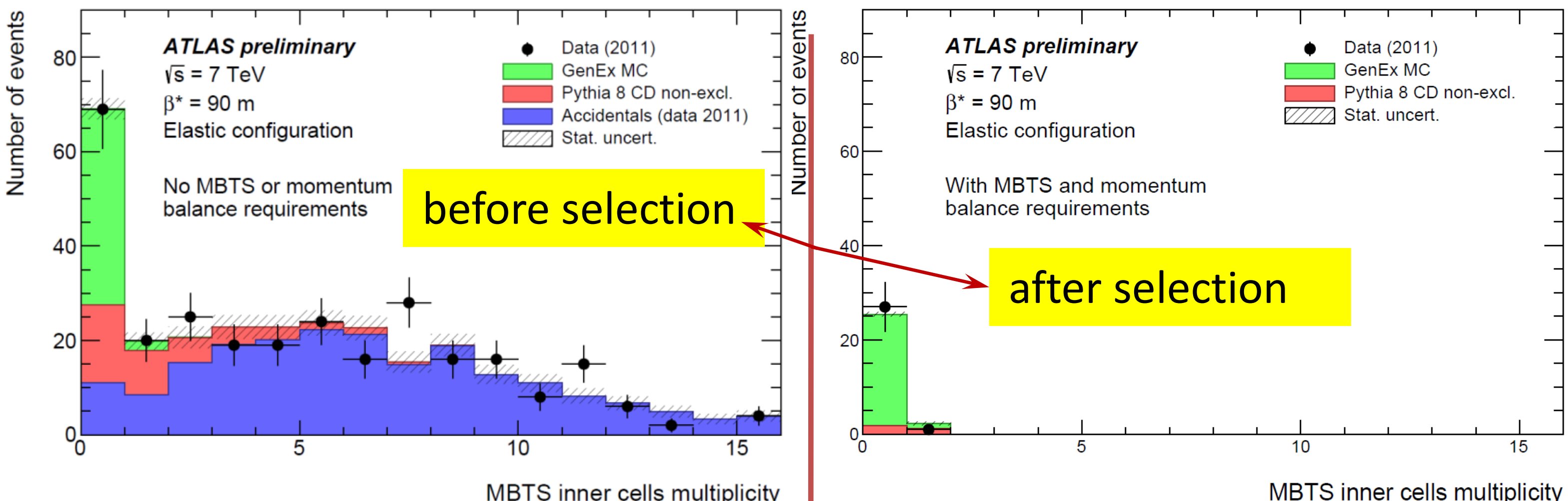
Exclusive pion pair production

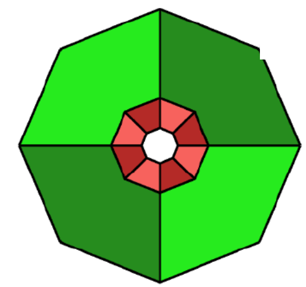


Exclusive pp→pp$\pi^+\pi^-$

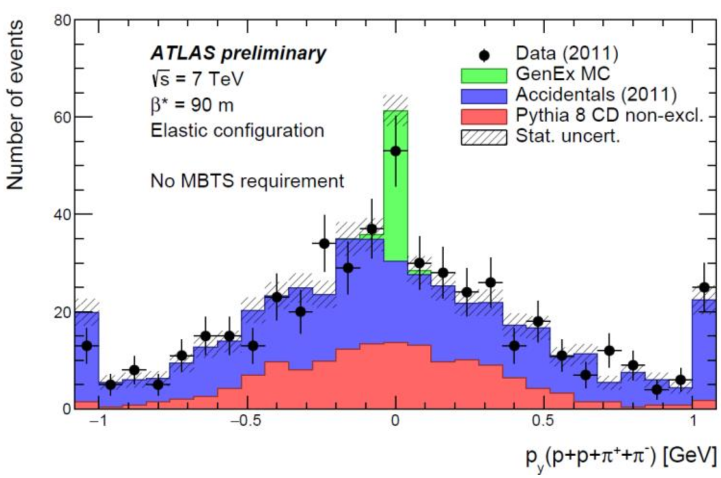
Selection of exclusive events:

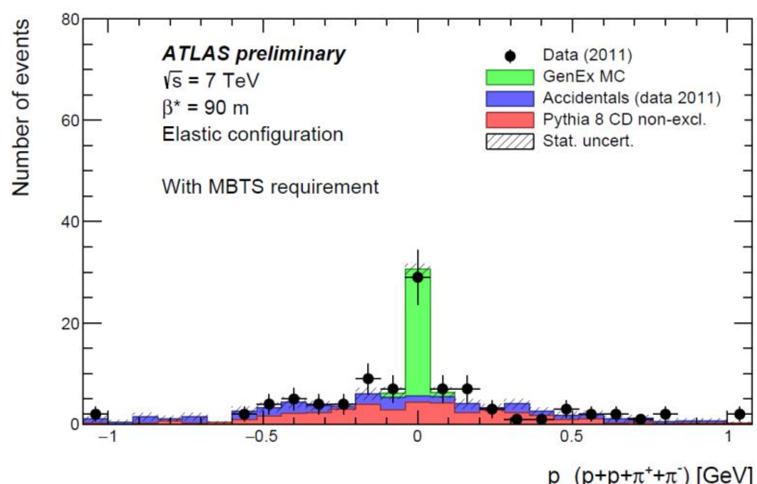
- Forward protons detected in ALFA
- Opposite-charged pions detected in the central ATLAS detector
- Exclusivity enhanced by vetoing activity in cells of the Minimum Bias Trigger Scintillator (MBTS)





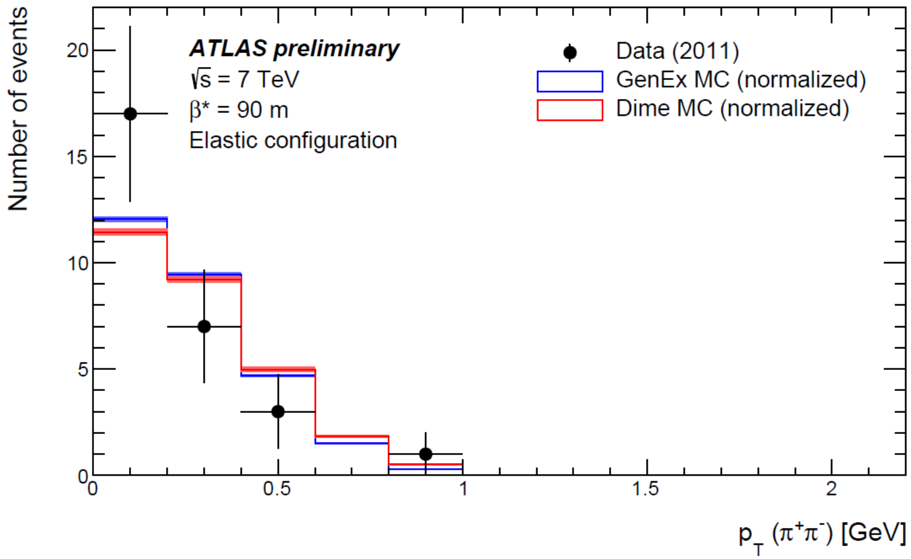
MBTS at z=±3.6m
2.1 < |η< 3.8

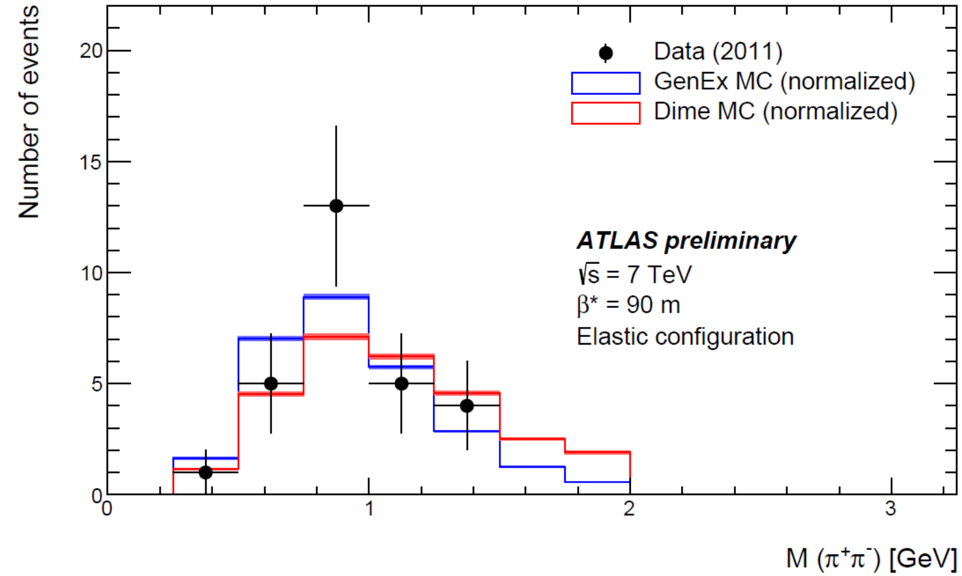




Momentum balance in ppππ system

Exclusive pp→ppπ⁺π results





The cross section is determined in two different fiducial volumes

elastic configuration: σ = $4.8 \pm 1.0\ (\mathrm{stat})\ ^{+0.3}_{-0.2}\ (\mathrm{syst}) \pm 0.1\ (\mathrm{lumi}) \pm 0.1\ (\mathrm{model})$ μb

anti-elastic configuration: σ = $9 \pm 6\ (\mathrm{stat})\ ^{+1}_{-1}\ (\mathrm{syst}) \pm 1\ (\mathrm{lumi}) \pm 1\ (\mathrm{model})$ μb

Model predictions: elastic 1.5-1.6 μb, anti-elastic 2-3 μb

→ First observation of exclusive diffraction with forward proton tag at LHC

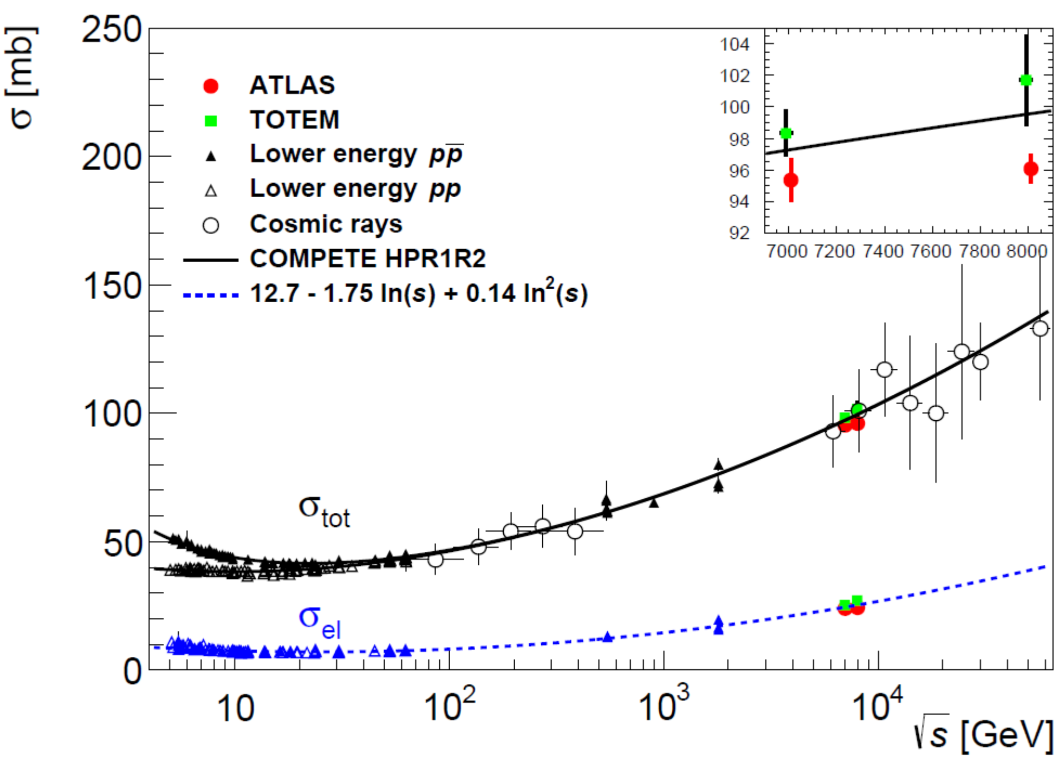
Elastic scattering at 13 TeV

The total $pp \to X$ cross section is a fundamental quantity.
Can't be calculated in perturbative QCD.
Can be measured using the Optical Theorem:

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

It is related through dispersion relations to the ρ-parameter, derived from unitarity and analycity of scattering amplitudes.

$$\rho = \left.\frac{\mathrm{Re}\big(f_{el}(t)\big)}{\mathrm{Im}\big(f_{el}(t)\big)}\right|_{t\to 0}$$



From a measurement of the elastic cross section differential in the Mandelstam *t*-variable σ_{tot} and ρ can be extracted together with parameters describing the shape of the *t*-spectrum.
Special optics with β*=2.5 km required to measure ρ at small t.

Measurement up to √s= 8 TeV
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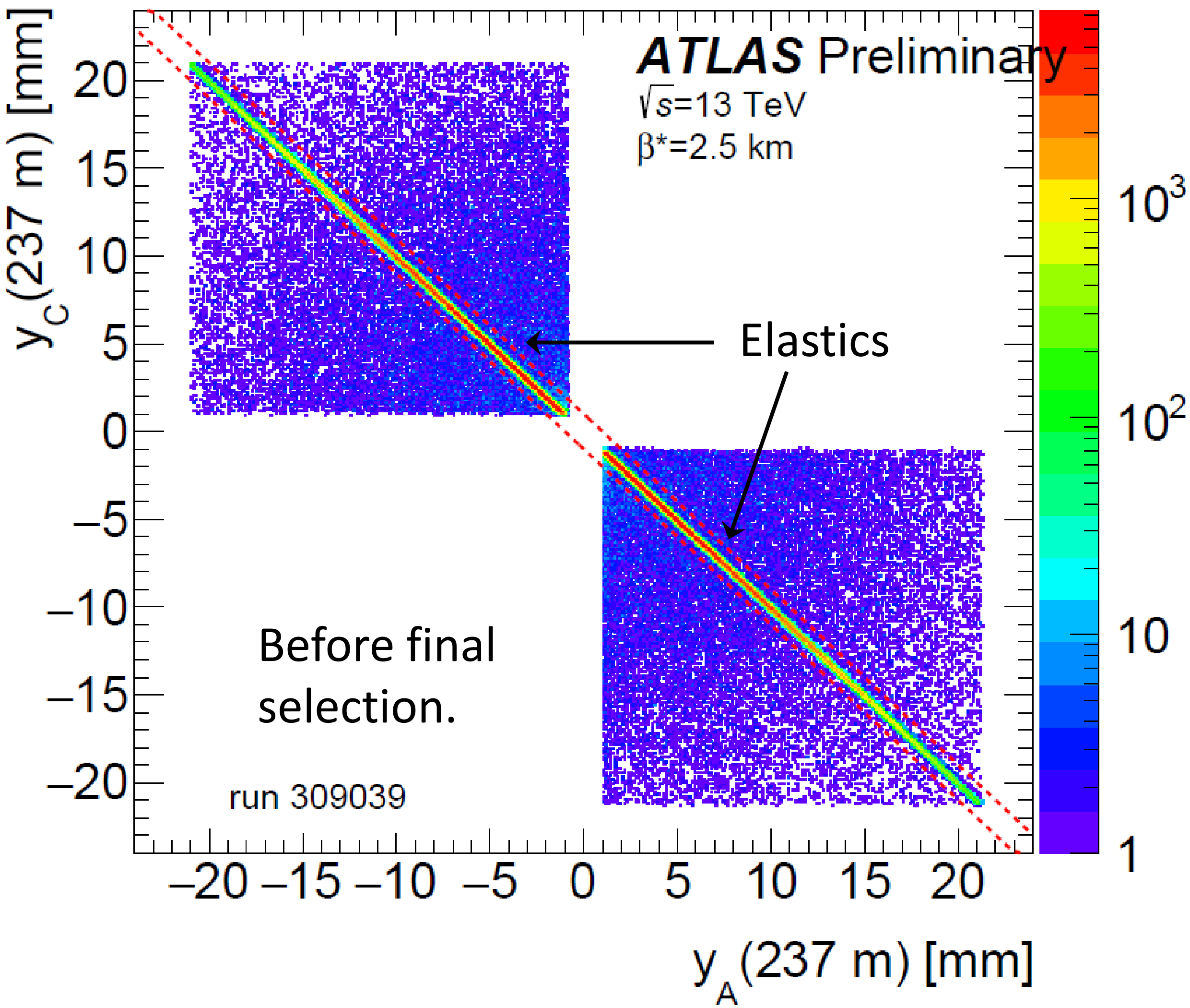
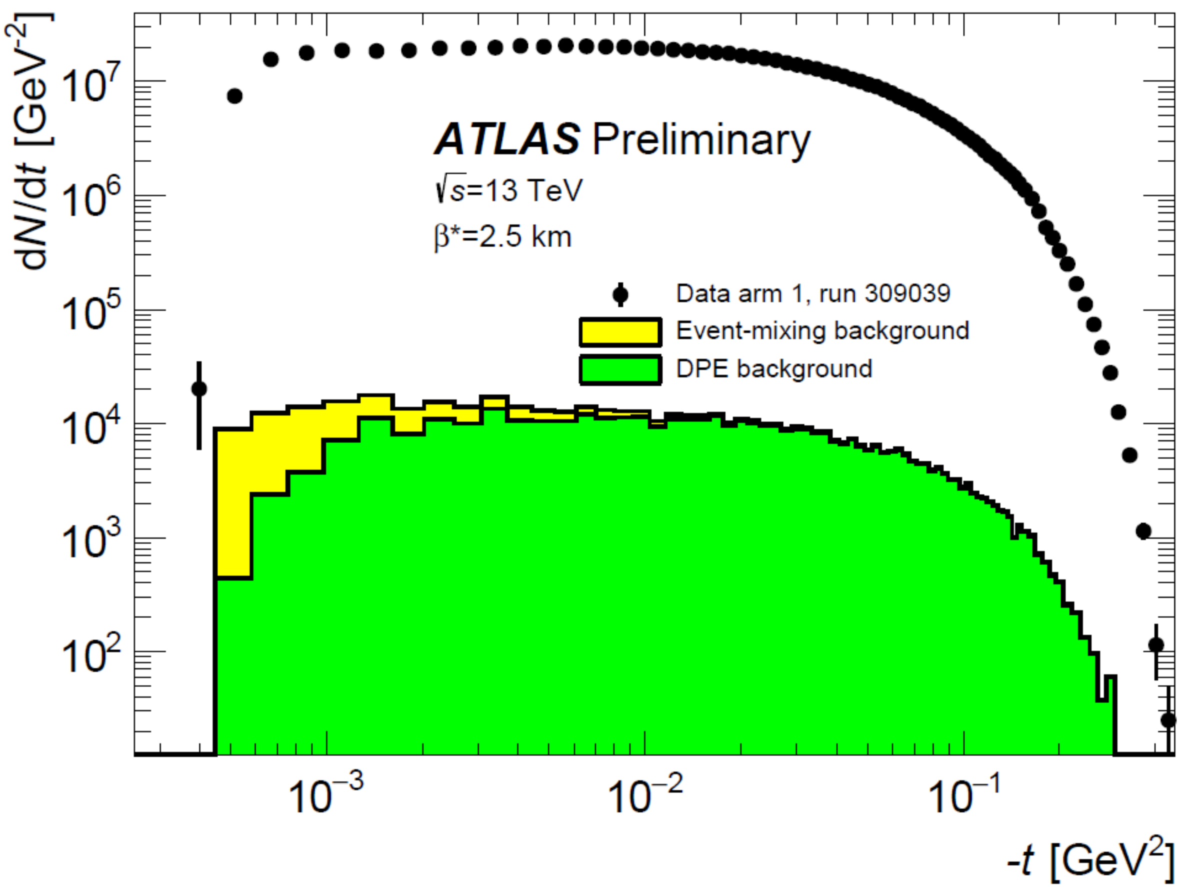
Selection of elastic events



The selection of elastic events is based on a pre-selection of data-quality and geometrical acceptance cuts.

The final selection exploits the back-to-back topology of elastic events

Background



Two sources of background are considered:

- Accidental halo+halo and halo+single diffraction coincidences
- Double-Pomeron exchange (DPE)

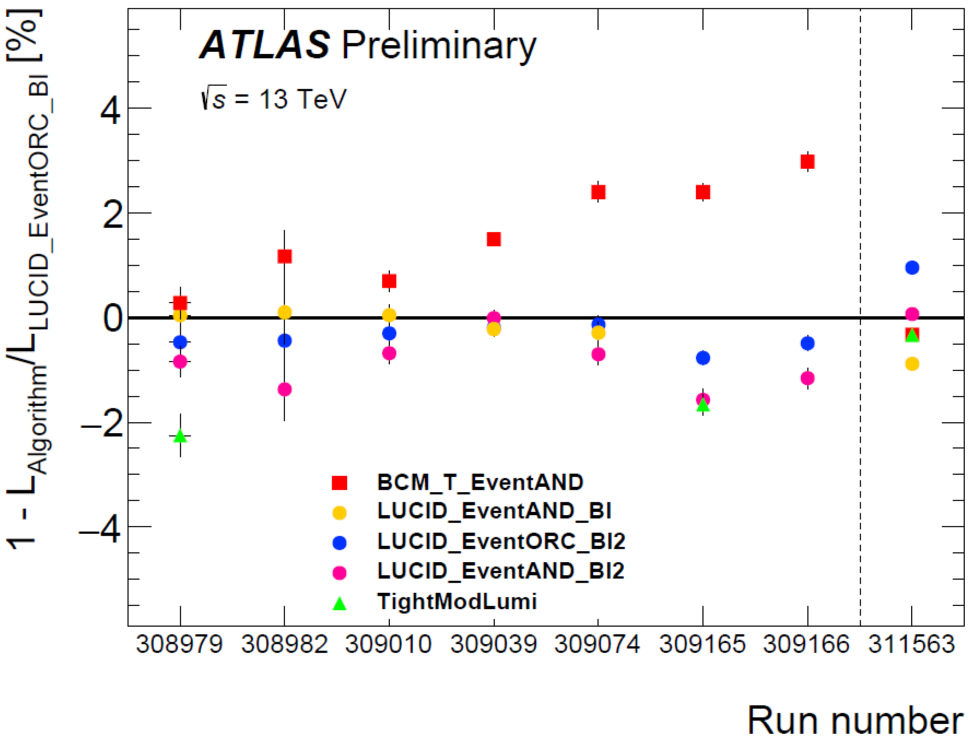
Accidental coincidence are determined from single-side templates, DPE from simulation.

Both backgrounds are normalized to control regions in the data.

The irreducible background fraction is very small: 0.75‰, with a relative uncertainty of 10-15%.

Luminosity

A dedicated analysis of the luminosity for this special low-μ run was performed. The main uncertainty is derived from the stability of different algorithms with respect to the nominal algorithm from LUCID.



Calibration transfer, long-term stability and background uncertainty : 1.85%
vdM calibration uncertainty: 1.1%
Total: 2.15%

$$L_{\text{int}} = 339.9 \pm 0.1\ (\text{stat.}) \pm 7.3\ (\text{syst.})\ \mu\text{b}^{-1}$$

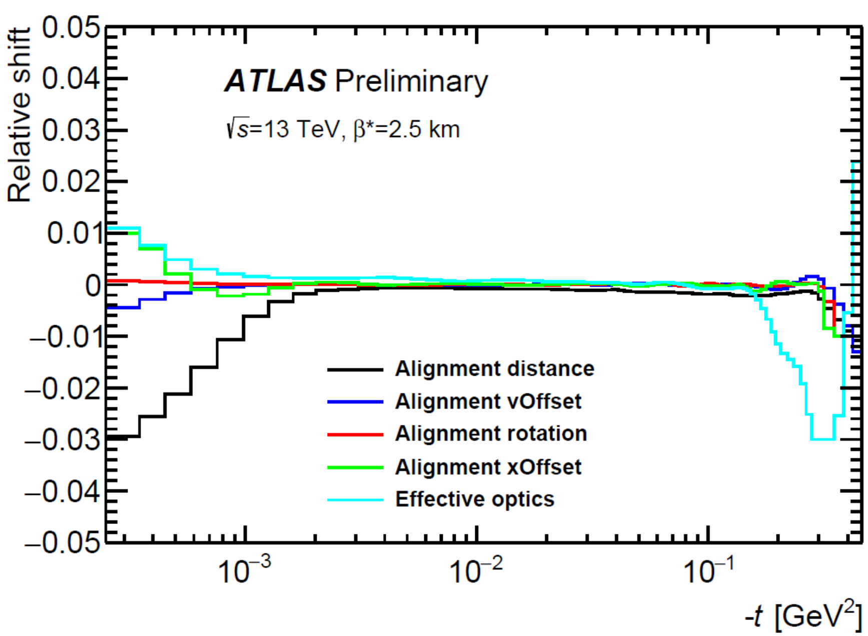
Systematic uncertainties for dσ/dt

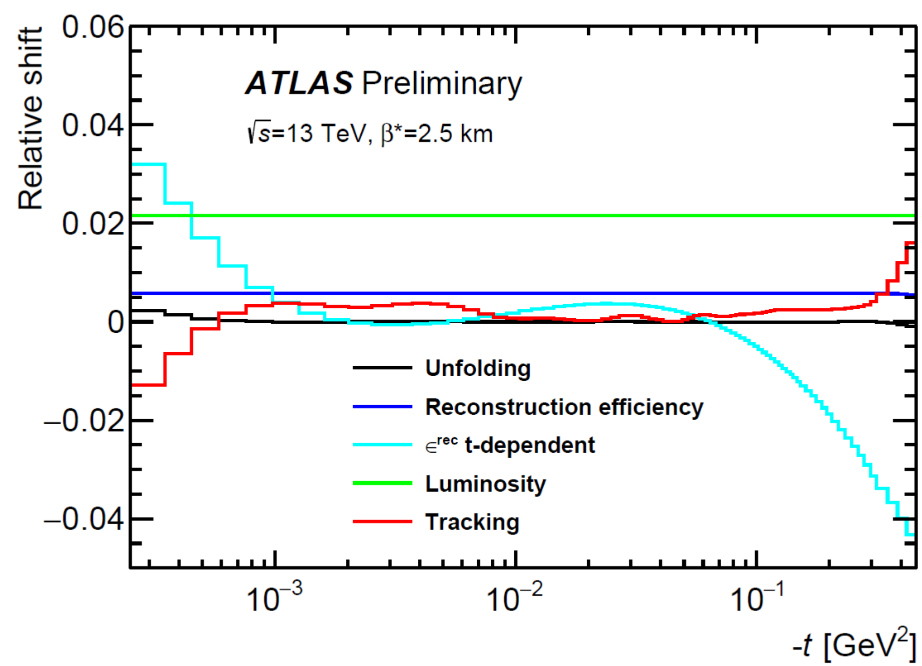
Calculation of the differential elastic cross section:

$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{\mathrm{reco}} \times \epsilon^{\mathrm{trig}} \times \epsilon^{\mathrm{DAQ}} \times L_{\mathrm{int}}}$$

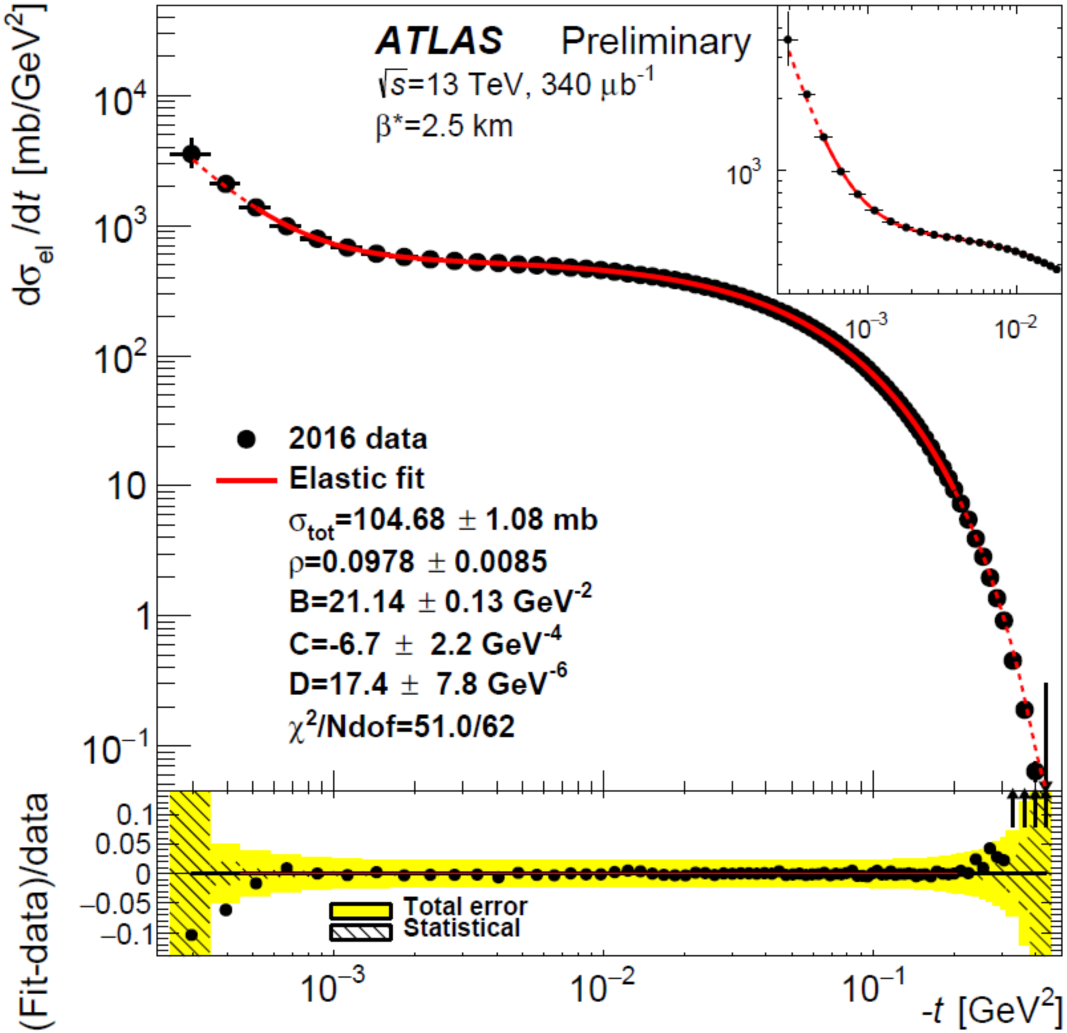
Experimental systematic uncertainties calculated as function of t.

Main uncertainties: Alignment, luminosity, reconstruction efficiency





Results



Physics parameters are extracted from a profile fit to the cross section including experimental systematic uncertainties.
Fit function:

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

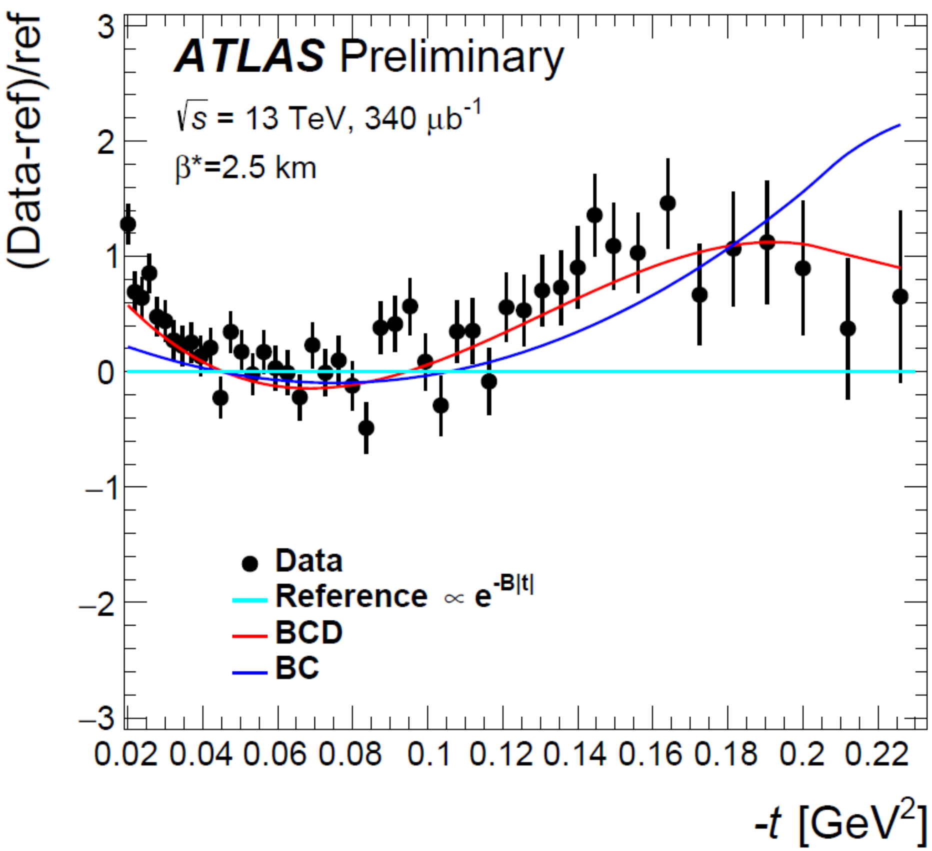
$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

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

The main uncertainties are related to the luminosity and the alignment, for ρ also theoretical uncertainties are important.

Results: Theory uncertainties

	σ_{tot}[mb]	ρ	B[GeV^{-2}]	C[GeV^{-4}]	D[GeV^{-6}]
Central value	104.68	0.0978	21.14	−6.7	17.4
Statistical error	0.22	0.0043	0.07	1.1	3.8
Experimental error	1.06	0.0073	0.11	1.9	6.8
Theoretical error	0.12	0.0064	0.01	0.04	0.15
Total error	1.09	0.0106	0.13	2.3	7.8



Theoretical uncertainties:

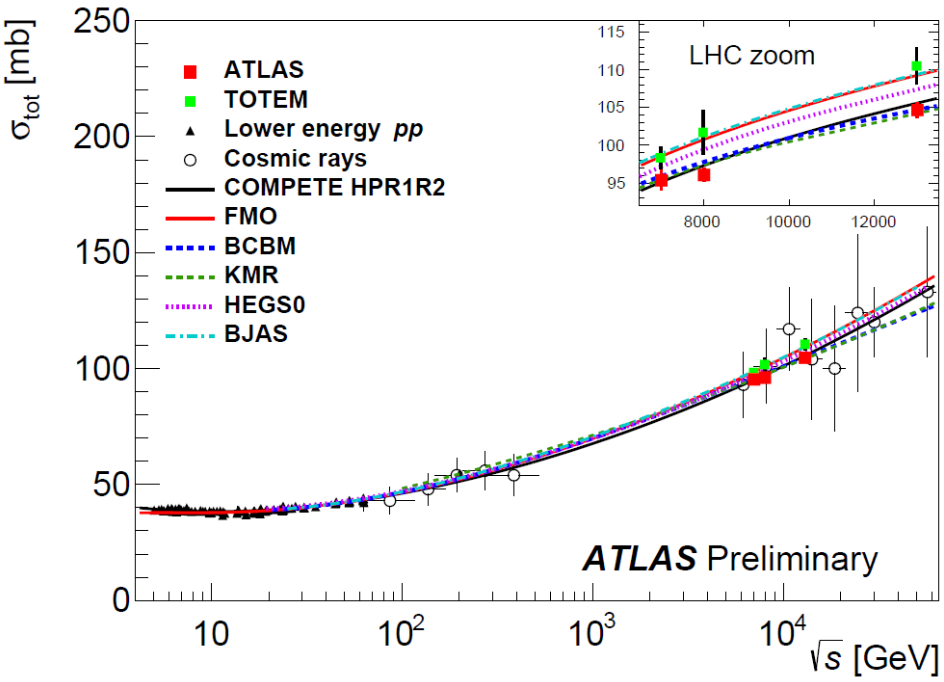
- Parametrization of the strong amplitude
- Coulomb phase
- Proton form factor
- Nuclear phase

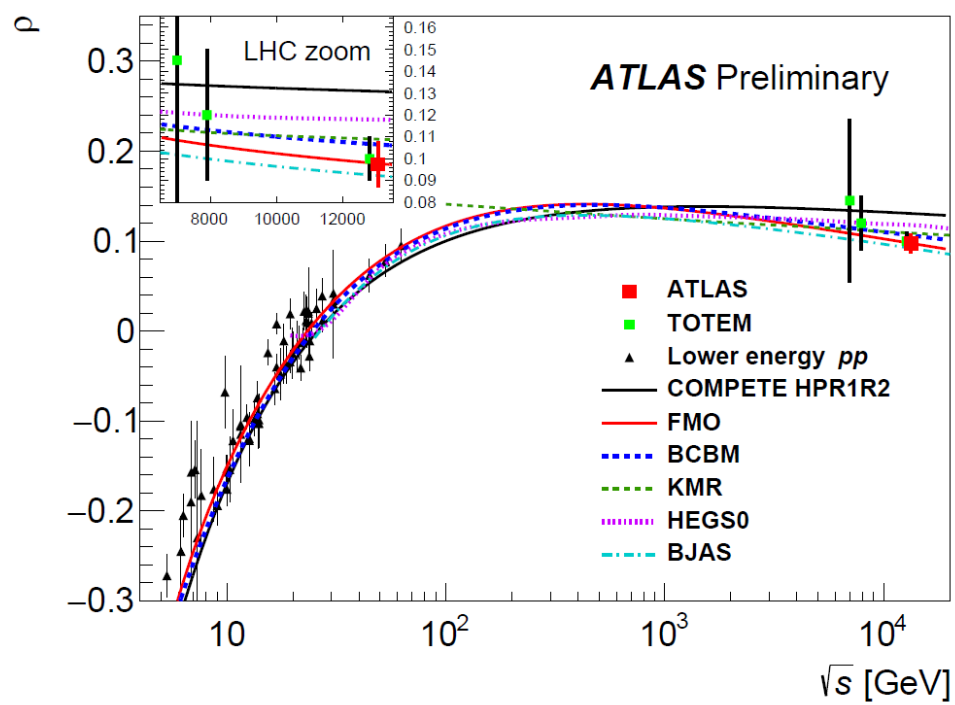
→ Important for ρ!

Stability:

- Time dependence
- Fit range
- Different t-reconstruction methods
- Difference between arms

Interpretation: energy evolution of σ_{tot} and ρ





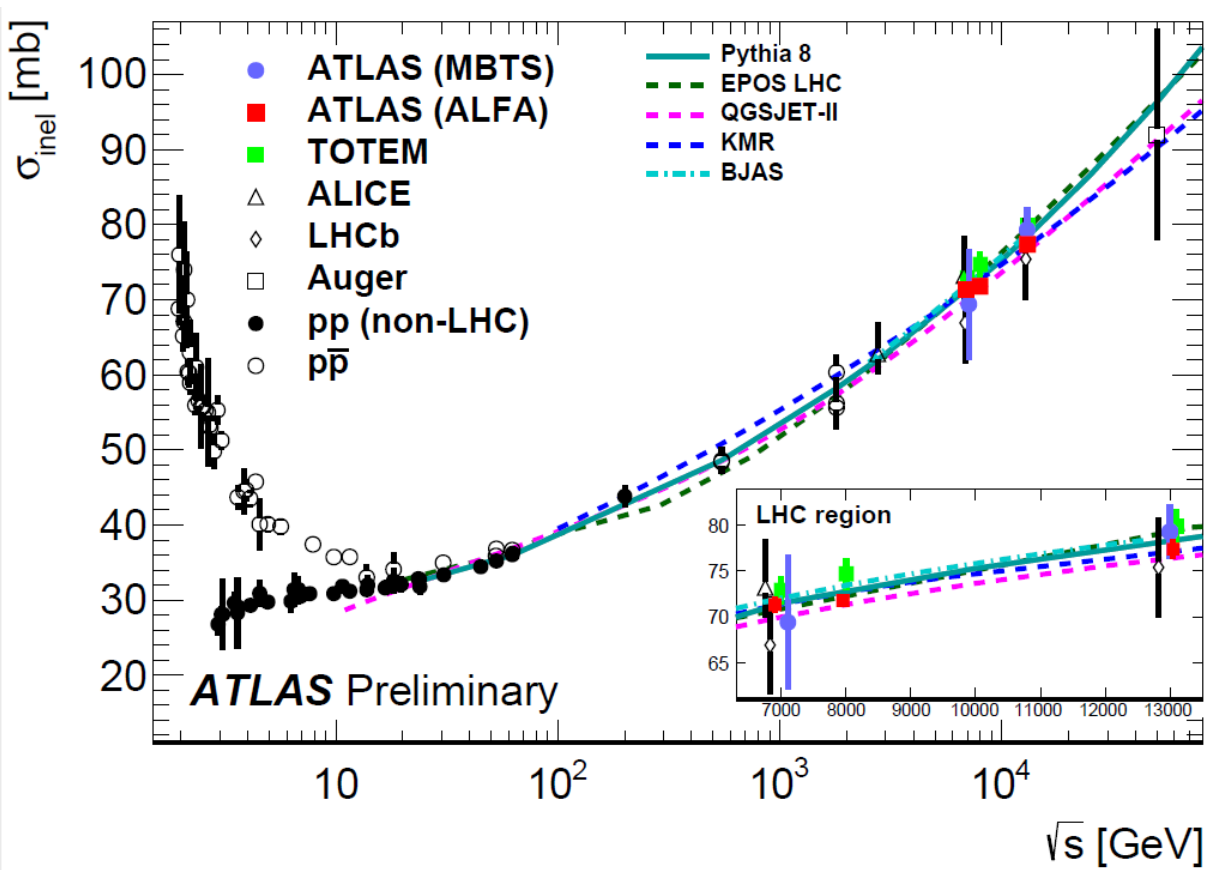
- Many models were investigated for the energy evolution of σ_{tot} and ρ (connected via dispersion relations)
- The canonical evolution model COMPETE is disfavoured (predicted $\rho \approx 0.13$)
- Model with an Odderon tuned to TOTEM, not in good agreement with our σ_{tot}
- Damped amplitude model in best agreement with our data
- ALFA and TOTEM difference in σ_{tot} about 2.2 σ (similar trend seen at 7 and 8 TeV)

Total elastic and inelastic cross sections

By integrating the nuclear part of the theoretical prediction of the differential elastic cross section over the full phase space:

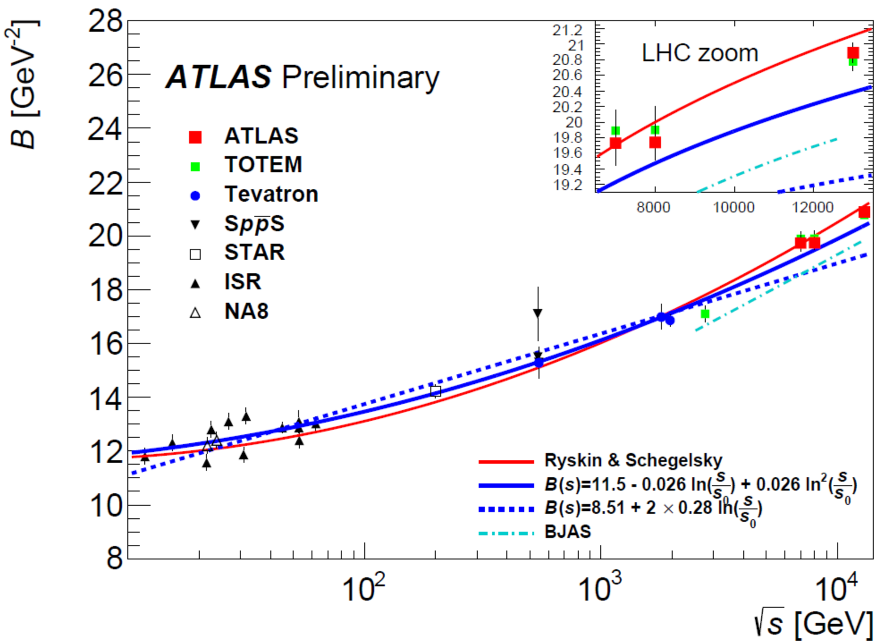
$$\sigma_{\mathrm{el}}^{\mathrm{extr}} = 27.27 \pm 1.10\,(\mathrm{exp.}) \pm 0.30\,(\mathrm{th.})\ \mathrm{mb}$$

The total inelastic cross section is obtained by subtraction off the total cross section.

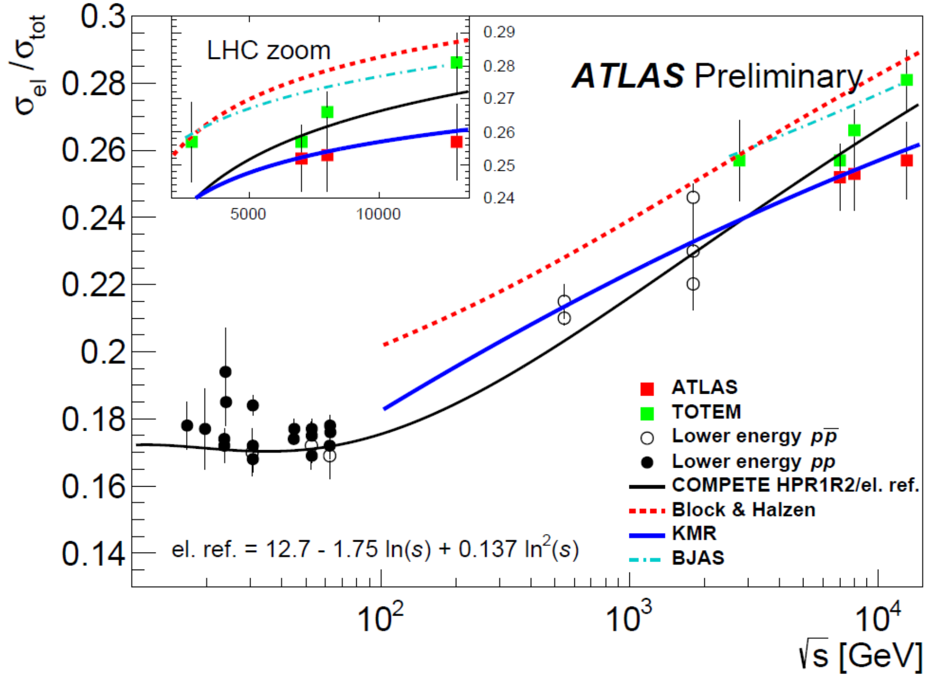


Evolution of B and $\sigma_{el} / \sigma_{tot}$

The B-slope determined at small t compared to lower energy and the evolution predicted by models:
→ shrinkage of the forward cone



Ratio of elastic to total cross section should reach asymptotically ½
→ Black disk limit



Conclusion

Elastic results:

$$\begin{aligned}
\sigma_{\text{tot}}(pp \to X) &= 104.68 \pm 1.08\,(\text{exp.}) \pm 0.12\,(\text{th.})\ \text{mb}, \\
\rho &= 0.0978 \pm 0.0085\,(\text{exp.}) \pm 0.0064\,(\text{th.}), \\
B &= 21.14 \pm 0.13\ \text{GeV}^{-2}, \\
C &= -6.7 \pm 2.2\ \text{GeV}^{-4}, \\
D &= 17.4 \pm 7.8\ \text{GeV}^{-6}.
\end{aligned}$$

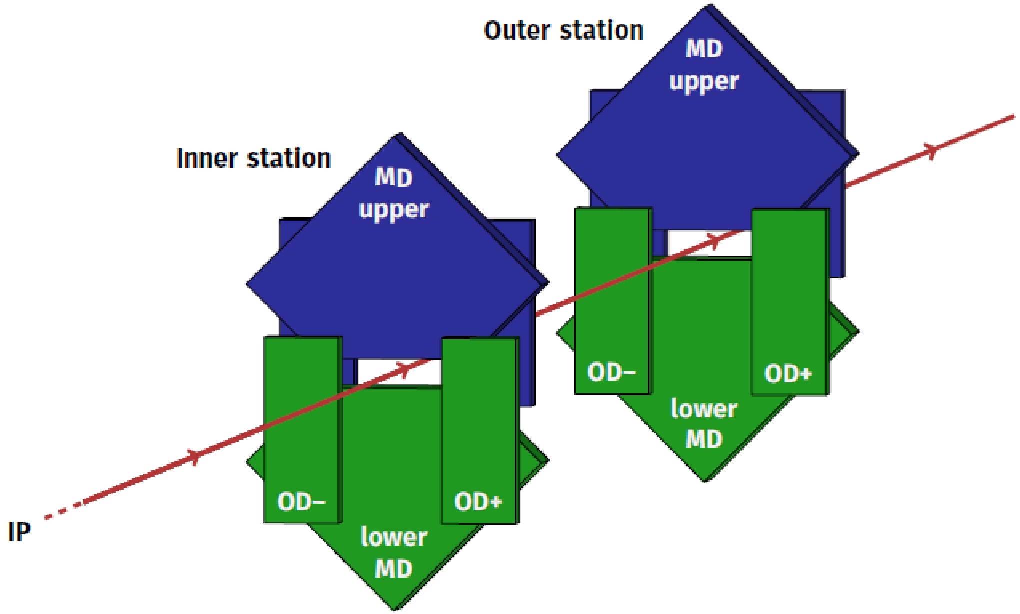
- The low value of ρ and our measurement of σ_{tot} are in tension with standard evolution models like COMPETE

- Our measurements of σ_{tot} are systematically lower than the results from TOTEM (5.9 mb, 2.2 σ at 13 TeV). The difference is mostly in the normalization.

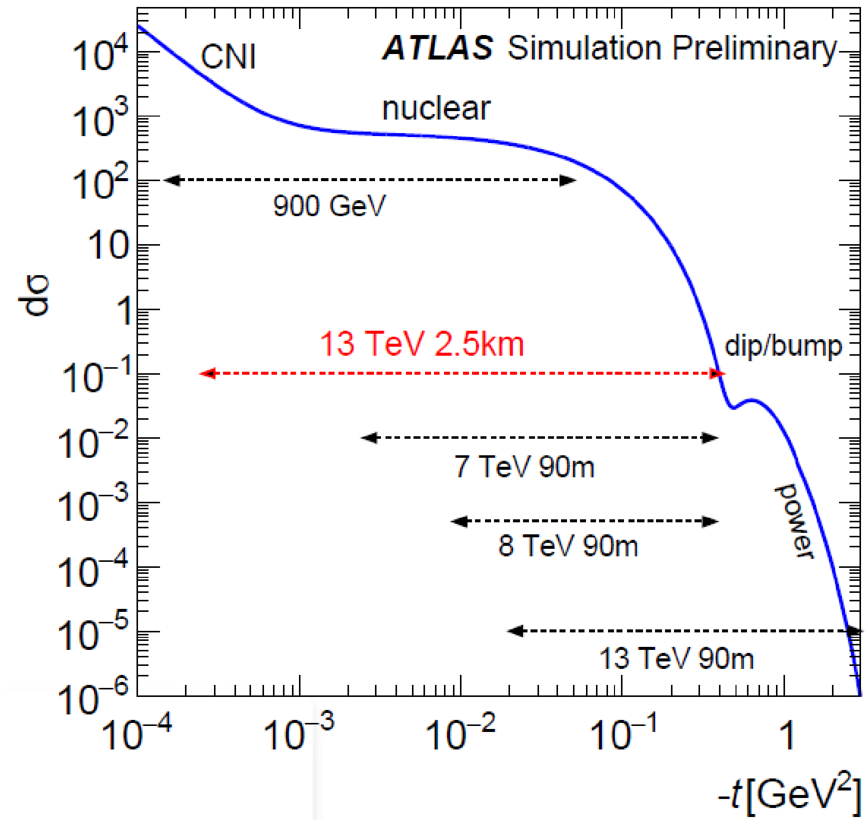
Exclusive pions: first observation of $pp \to pp\pi^+\pi^-$@7 TeV at LHC with forward proton tag.

Back-up

Forward proton measurements with ALFA

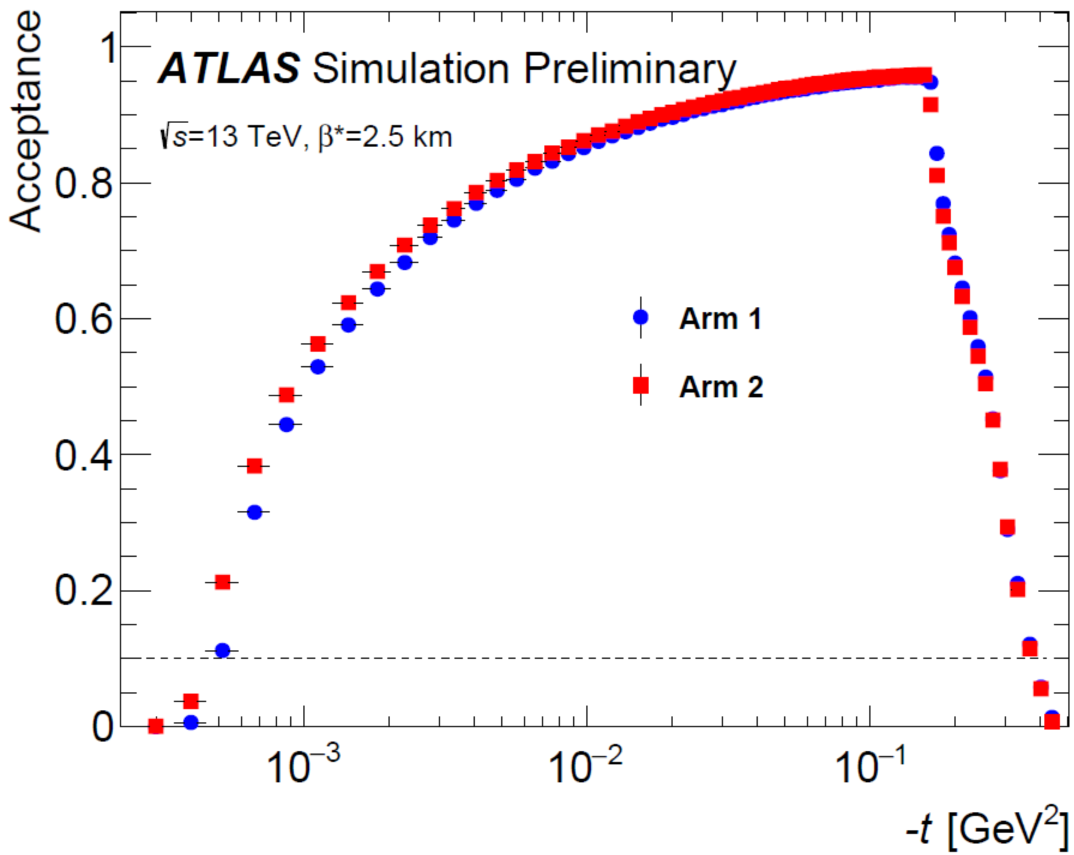


Coverage in t during special runs.



Elastic scattering data were taken in 2016 at √s 13 TeV with β*=2.5 km and Roman Pot insertion to 3.5 σ recording 6.8 M events in $\int L\mathrm{dt} = 340\ \mathrm{nb}^{-1}$ of integrated luminosity.

Acceptance

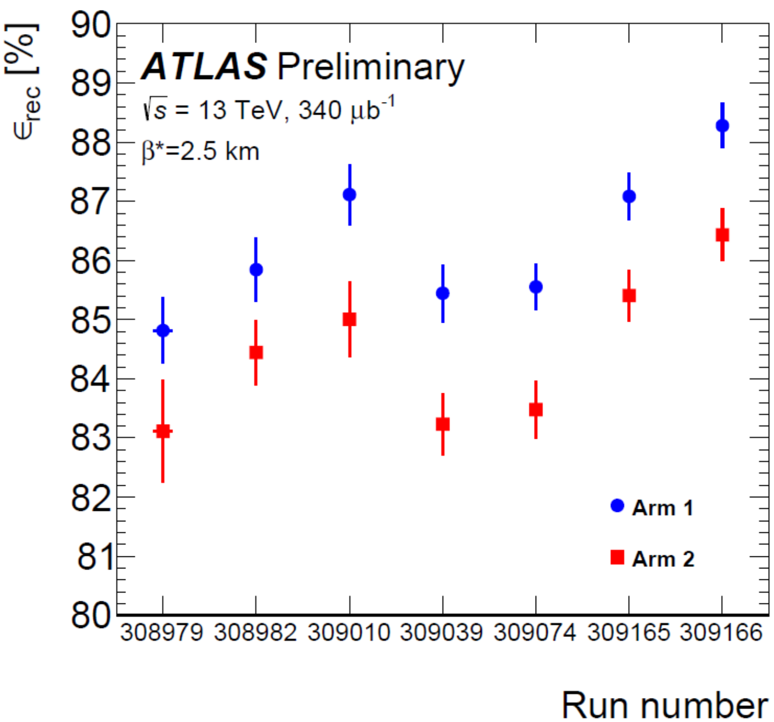


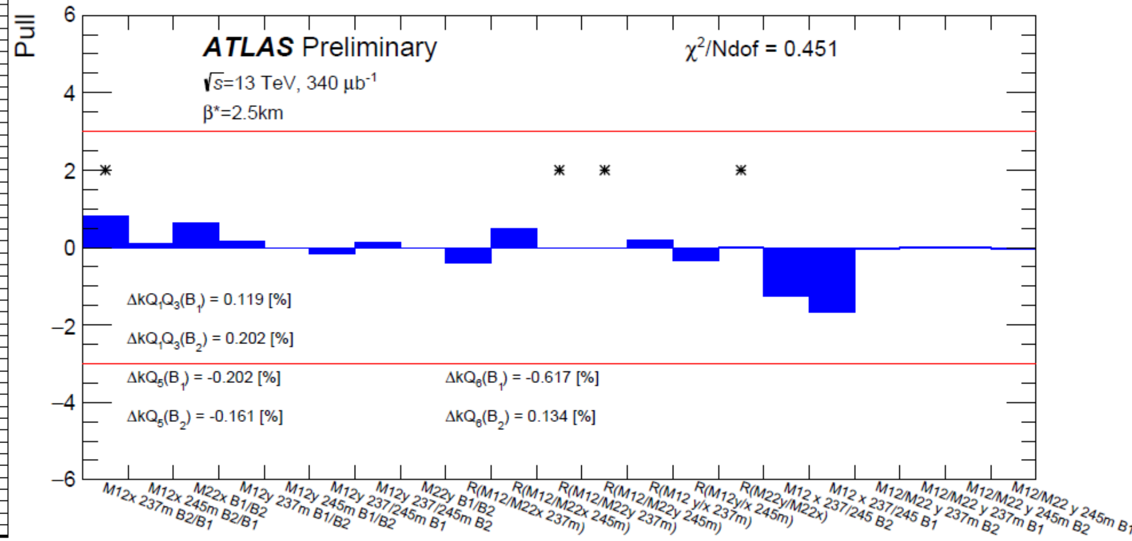
The acceptance is calculated from simulation and is mainly determined by the geometry of the ALFA detector and the distance to the beam.

The t-spectrum is unfolded for detector resolution and beam divergence.

The t-range for the fit to extract the physics parameters is set by requiring the acceptance to be above 10%.

Reconstruction efficiency and beam optics





Reconstruction efficiency by a tag-and-probe method (data-driven)

- Reconstruction can fail because of shower development
- Efficiency in arm1 slightly higher because of material distribution

Beam optics (transport matrix elements) needed for *t*-reconstruction

- An effective optics model is tuned using correlations in ALFA variables
- small corrections are derived to the strength of the quadrupoles

Luminosity values

Fill	Run	Luminosity [μb^{-1}]	Selected elastic candidates	Reconstruction efficiency Arm 1 [%]	Reconstruction efficiency Arm 2 [%]
5313	308979	21.38	423 862	84.82 ± 0.56	83.11 ± 0.87
5313	308982	6.81	136 499	85.84 ± 0.54	84.44 ± 0.55
5314	309010	41.27	846 581	87.11 ± 0.51	85.00 ± 0.64
5317	309039	120.08	2 409 968	85.45 ± 0.49	83.23 ± 0.52
5317	309074	44.31	887 373	85.55 ± 0.39	83.48 ± 0.48
5321	309165	55.87	1 149 499	87.08 ± 0.40	85.41 ± 0.44
5321	309166	50.17	1 043 576	88.28 ± 0.38	86.43 ± 0.45

Theoretical prediction

Cross section from squared amplitudes.

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

Coulomb amplitude

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

Proton form factor

$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2$$

Nuclear amplitude with curvature terms *C* and *D*.

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

Coulomb phase

$$\phi(t) = -\left(\gamma_E + \ln\frac{B|t|}{2} + \ln\left(1 + \frac{8}{B\Lambda}\right)\right) + \frac{4t}{\Lambda}\cdot\ln\frac{\Lambda}{4t} - \frac{2t}{\Lambda}$$

Full prediction

$$\begin{aligned}\frac{d\sigma}{dt} &= \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2}\times G^4(t)\\ &- \sigma_{tot}\times\frac{\alpha G^2(t)}{|t|}\left[\sin(\alpha\phi(t)) + \rho\cos(\alpha\phi(t))\right]\times\exp\frac{-B|t| - Ct^2 - D|t|^3}{2}\\ &+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\times\exp\left(-B|t| - Ct^2 - D|t|^3\right)\ ,\end{aligned}$$

N.b.: Also several models of strong phase tested.

Test of models

Model	global χ^2/Ndof	ALFA partial χ^2/Ndof	TOTEM partial χ^2/Ndof	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

→ Best agreement with ALFA data is observed for the BCBM model (damped amplitude) and the KMR model.

→ Main message:

- “Standard“ evolution model like COMPETE are not able to describe simultaneously σ_{tot} and ρ
- New effects in the evolution are observed, if these are induced by the Odderon or a flatter energy evolution of σ_{tot} will need to be studied further
- The situation complicated by the σ_{tot} discrepancy between ALFA and TOTEM

Model references

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