Measurements of the total, elastic and inelastic pp cross sections with ATLAS

Christian Heinz
Justus-Liebig-University Giessen

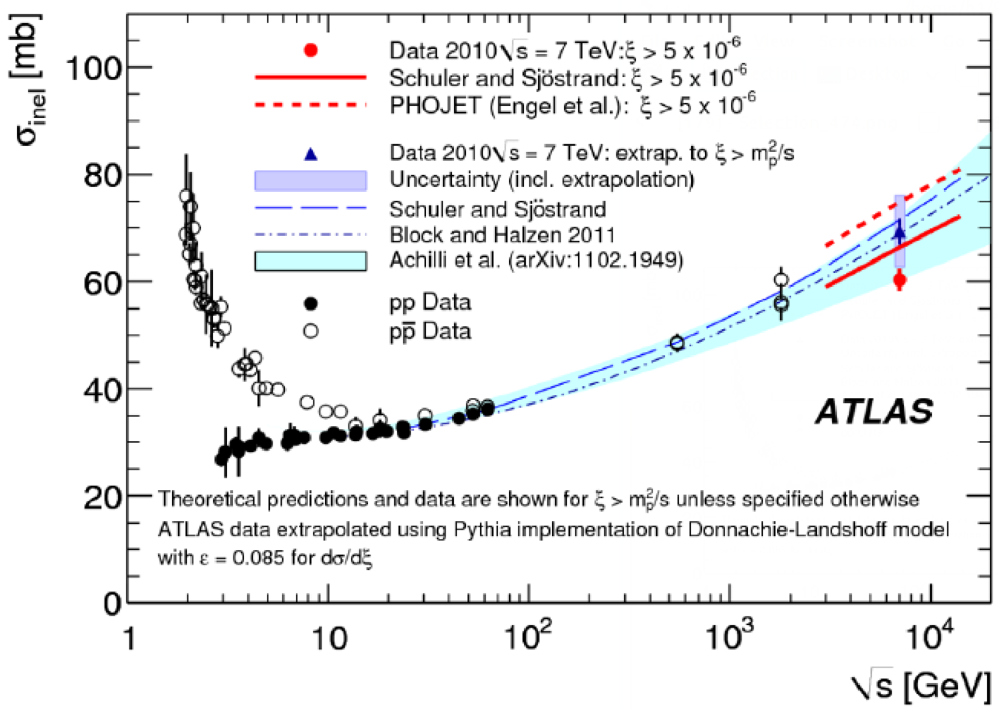
8th International Workshop on Multiple Partonic Interactions at the LHC
November 28 – December 2, 2016

SPONSORED BY THE
Federal Ministry of Education and Research

FSP 103 ATLAS

Motivation

- Probing the non-perturbative QCD regime
- Tuning of MC generators
- Predicting pile-up conditions at the HL-LHC
- Constraints on forward particle production in cosmic showers



Measurement of the inelastic cross section at $\sqrt{s} = 7\,\mathrm{TeV}$

[Nature Commun. 2 (2011) 463]

New measurements at 8 and 13 TeV

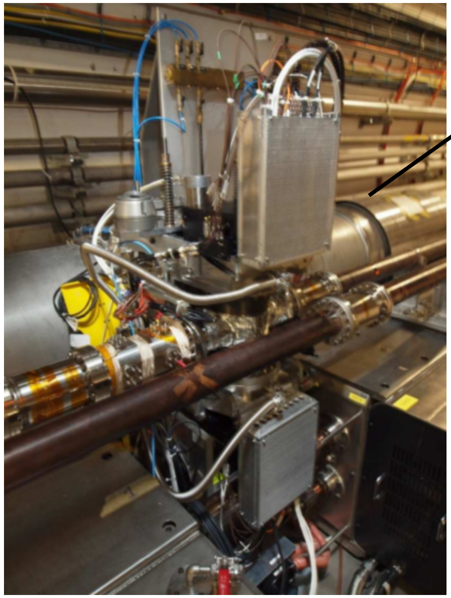
- First series of measurements at 7 TeV were performed by ATLAS where the basic methods were developed.
- New results recently published:

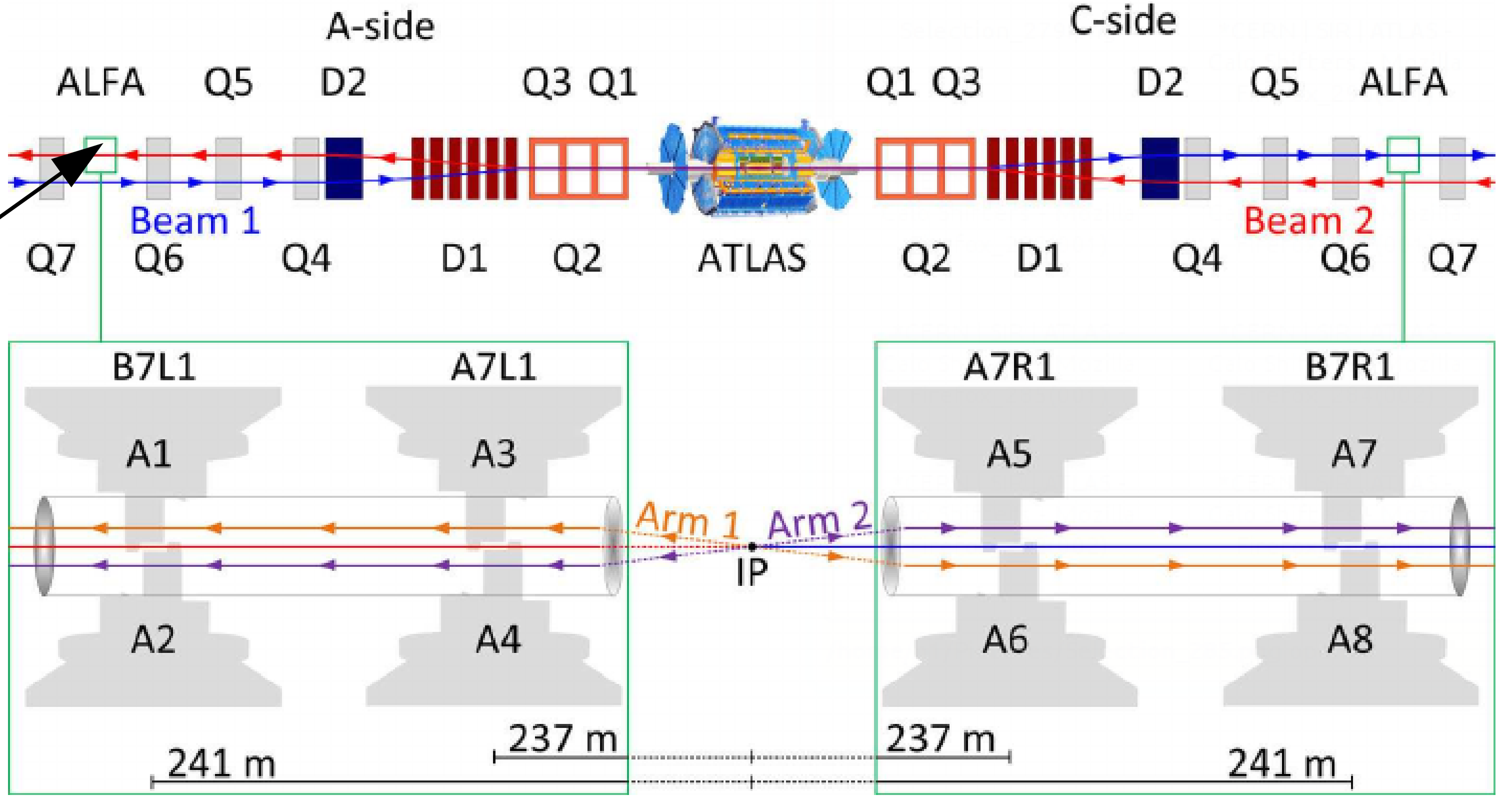
  - **Measurement of the total cross section at 8 TeV**
    [Phys. Lett B (2016) 158]
    - ALFA Roman Pot detector system used to measure the total cross section using the optical theorem and deriving the elastic and inelastic cross section
    - Dedicated LHC run at $\beta^* = 90\,\mathrm{m}$ optics with low average number of interaction per bunch crossing $\mu \approx 0.1$
    - Collected about $500\ \mu b^{-1}$ of data

  - **Measurement of the inelastic cross section at 13 TeV**
    [Phys. Rev. Lett. 117 (2016) 18200]
    - MBTS forward scintillator detector used to measure the inelastic rate in the according fiducial volume
    - Extrapolating to full phase space giving the inelastic cross section
    - Special run at $\mu \approx 2.3 \times 10^{-3}$
    - Collected about $60\ \mu b^{-1}$ of data

ALFA Detector

- Sub detector of ATLAS at the LHC
- Composed of eight roman pot housed detectors, installed about 240 meters away from the ATLAS IP in both forward directions
- Elastically scattered protons detected in two "spectrometer arms"
- Goal in elastic analysis is to measure the differential elastic cross section as a function of the 4-momentum transfer (t)





Reconstruction of scattering angle

- The **t-value** for each elastic event is given by its scattering angle at the IP and the beam momentum:

  $-\mathrm{t} = (\mathrm{p}\ \theta^*)^2$

- The **scattering angle** (at IP) can be expressed in relation to the measured position and local angle (at the detector) by means of the transport matrix:

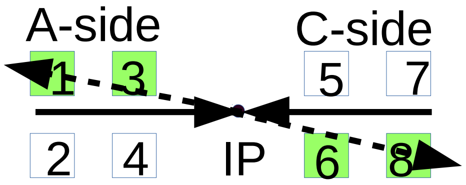
Position:
Angle:

$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} u^* \\ u^{*\prime} \end{pmatrix}$$

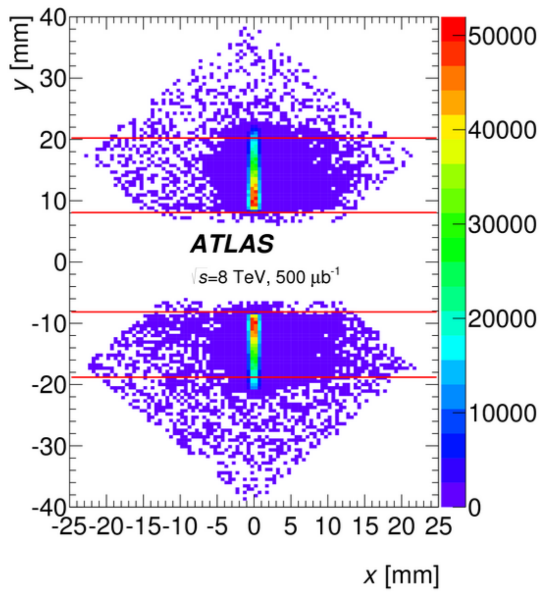
At Detector　　Transport matrix　　At ATLAS IP

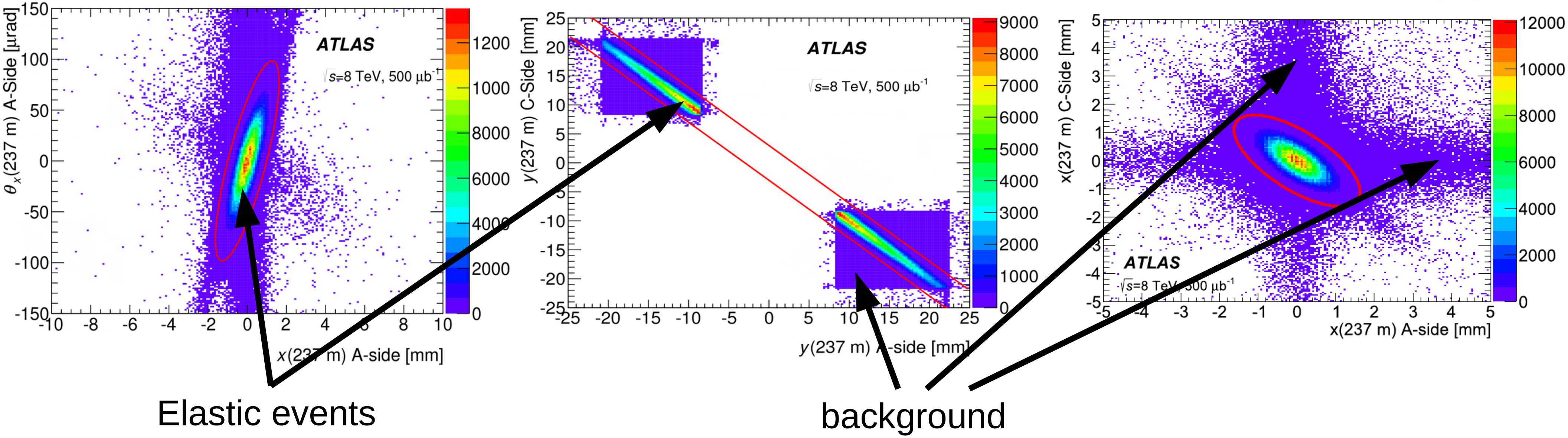
- Several techniques exist to translate measured proton positions at the detectors into the scattering angle.
  - Dedicated beam optic with parallel-to-point focusing in y (M_{11} small)

Event selection



- 3.8M elastic events selected
- Set several cuts on event selection to filter out background events:
  - Detector edge cuts
  - Elastic back-to-back topology cuts
- Event selection provides constraints for data driven beam optics model from which effective beam optic is derived





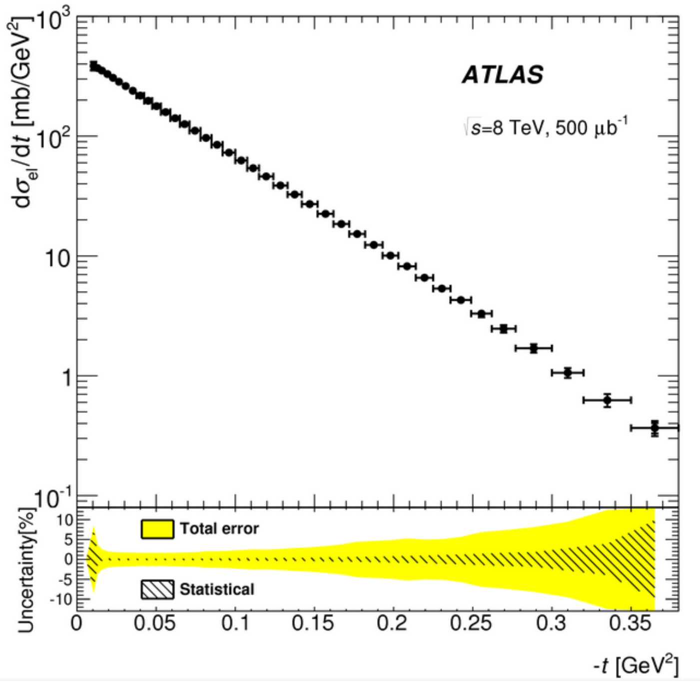
Differential elastic cross section

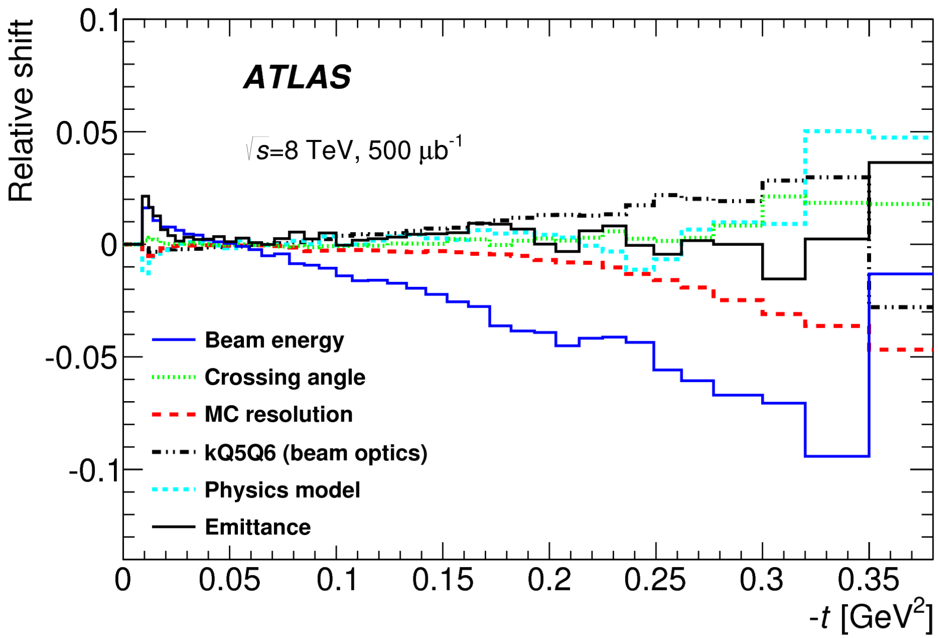
- Count rate transformed into differential elastic cross section

$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{t_i} \cdot \frac{M^{-1}\left[N_i - B_i\right]}{A_i \cdot \epsilon^{\text{reco}} \cdot \epsilon^{\text{trig}} \cdot \epsilon^{\text{DAQ}} \cdot L_{\text{int}}}$$

M^{-1}	Unfolding
A_i	Acceptance
ϵ^{reco}	Reconstruction efficiency
ϵ^{trig}	Trigger efficiency
ϵ^{DAQ}	DAQ efficiency
L_{int}	Luminosity

- Delivered luminosity determined by the ATLAS luminosity group in a dedicated analysis with an uncertainty of only 1.5%
  - makes up the main t-independent systematic contribution here
- Beam energy uncertainty of 0.65% makes up the main t-dependent systematic contribution





(a)

Theoretical prediction

- Model used to fit the differential elastic cross section consists of
  - The Coulomb term
  - The Coulomb-Nuclear-Interference term
  - The Nuclear term
- Total cross section and Nuclear B-Slope fitted

Proton dipole form factor

Coulomb term

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} \times G^4(t)$$

CNI term

$$- \sigma_{tot} \times \frac{\alpha G^2(t)}{|t|} \left[\sin(\alpha\phi(t)) + \rho\cos(\alpha\phi(t))\right] \times \exp\frac{-B|t|}{2}$$

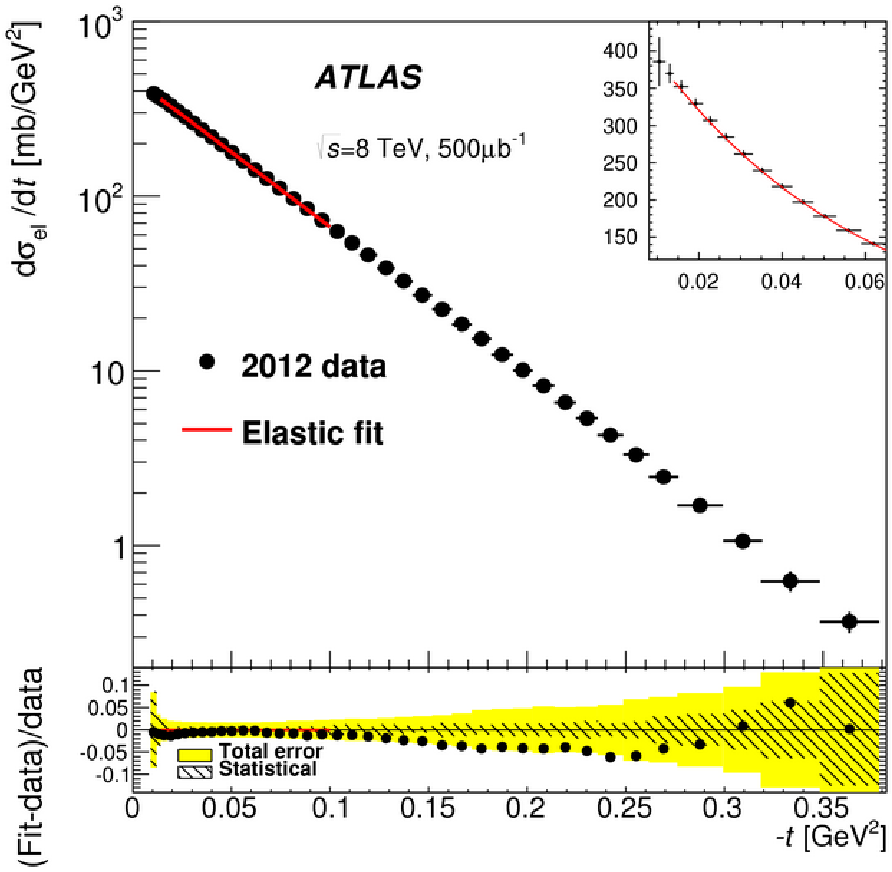
Nuclear term

$$+ \sigma_{tot}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \times \exp(-B|t|)$$

Coulomb phase

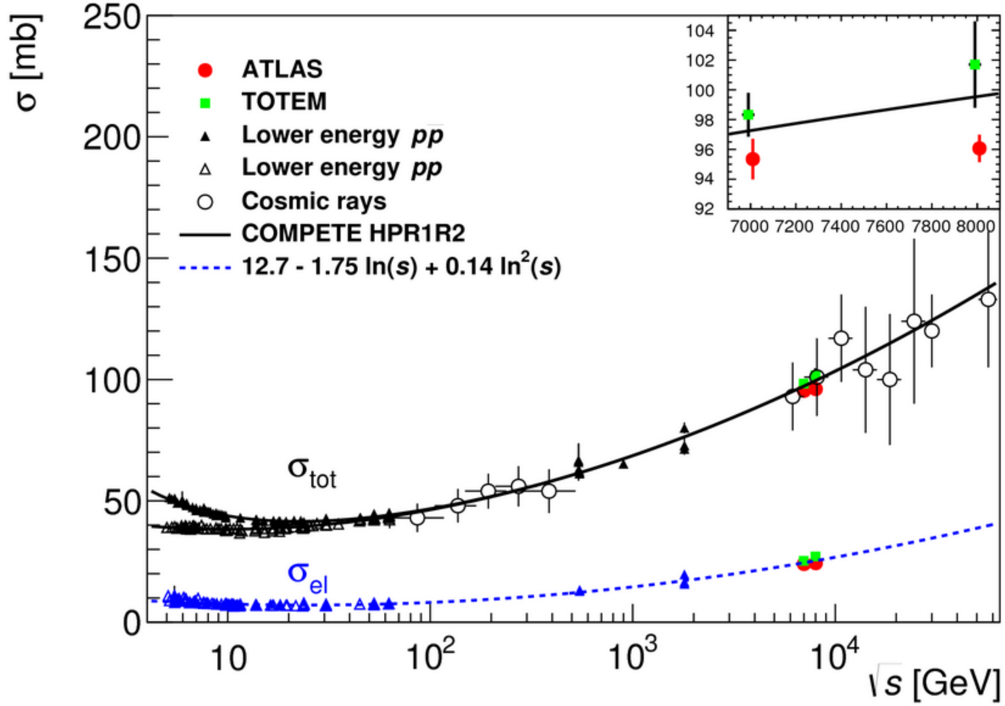
Fit results

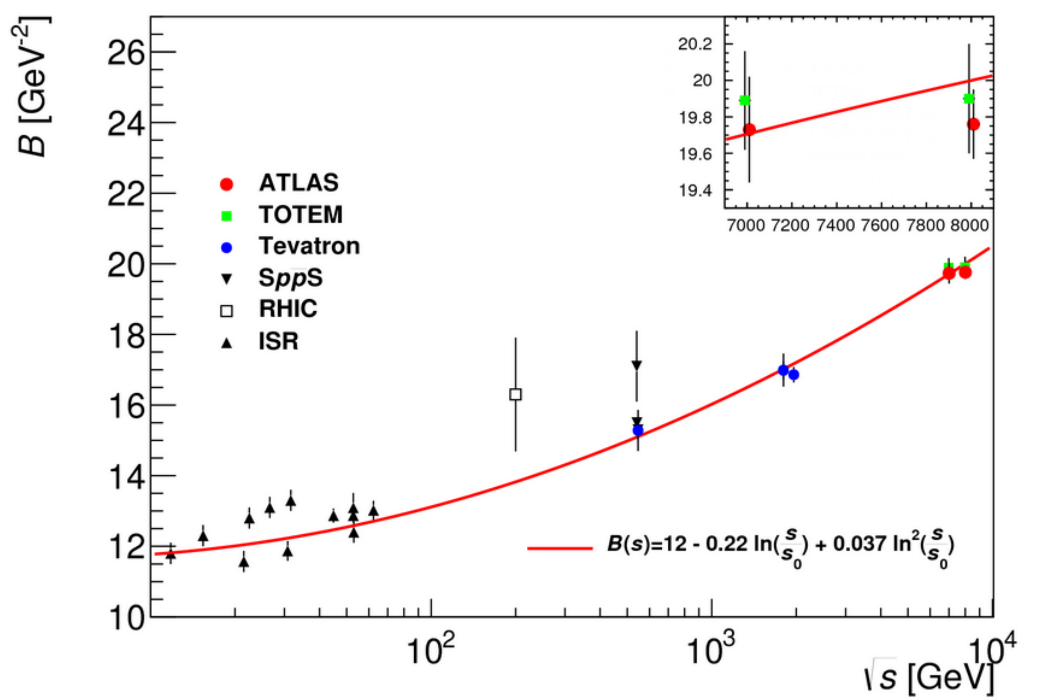
- Differential elastic cross section spectrum fitted with free parameters σ_{tot} and B in range: $0.014 \leq t \leq 0.1$



$$\sigma_{\text{tot}}(pp \to X) = 96.07 \pm 0.18(\text{stat.}) \pm 0.85(\text{exp.}) \pm 0.31(\text{extr.})\ \text{mb}$$
$$B = 19.74 \pm 0.05(\text{stat.}) \pm 0.23(\text{syst.})\ \text{GeV}^{-2}$$

Energy evolution of total cross section and nuclear B-slope





- Value for total cross section slightly smaller compared to COMPETE model as a function of center of mass energy
- Result on B slope in good agreement between ATLAS and TOTEM and also with model calculation including a linear and quadratic term in ln(s)

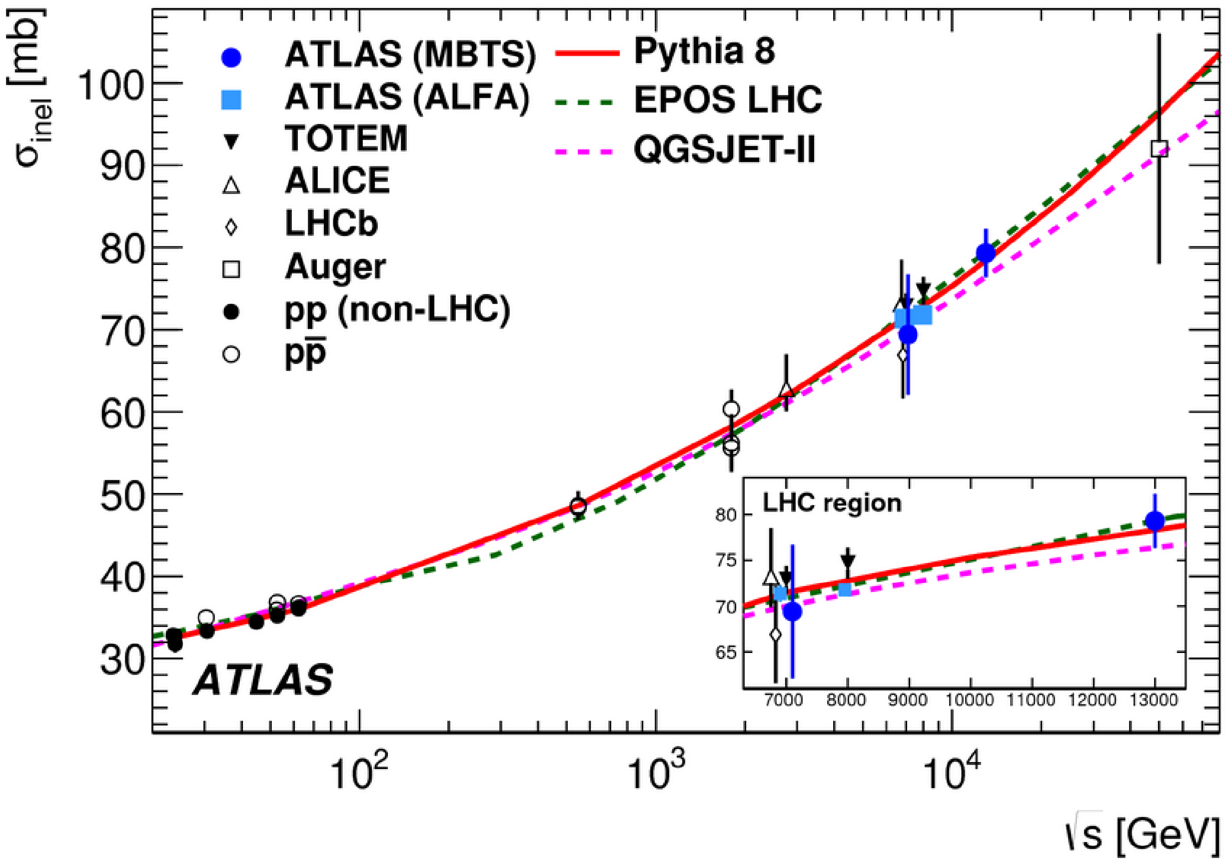
Derived quantities

- Integration over the differential elastic cross section yields elastic cross section as derived quantity:

$$\sigma_{\text{el, 8TeV}} = 24.33 \pm 0.04(\text{stat.}) \pm 0.39(\text{syst.})\,\text{mb}$$

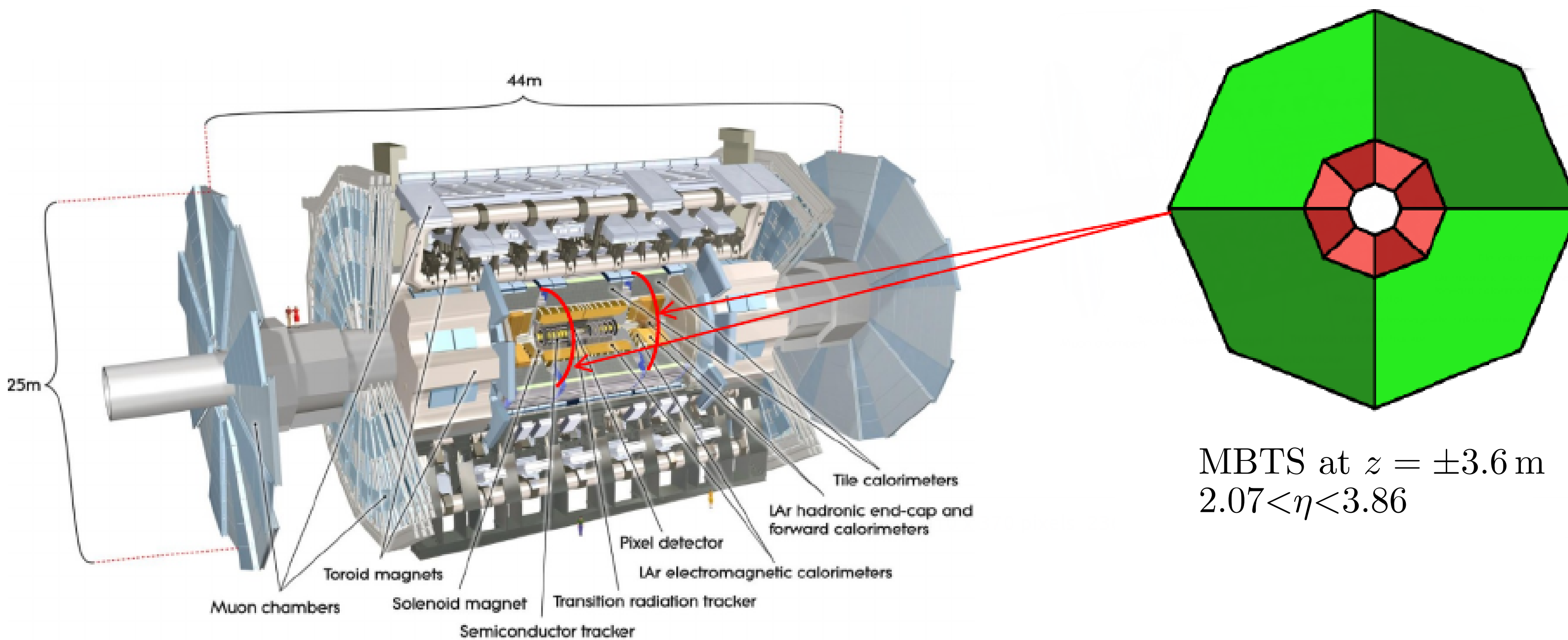
- Subtraction from total cross section yields inelastic cross section as derived quantity:

$$\sigma_{\text{inel, 8TeV}} = 71.73 \pm 0.15(\text{stat.}) \pm 0.69(\text{syst.})\,\text{mb}$$



Inelastic measurement with the MBTS at 13 TeV

- Measurement done using the Minimum Bias Trigger Scintillator located in front of the endcap calorimeters to detect inelastic interactions
- New detector was built for run 2 with slightly larger acceptance
- Two counters of the MBTS are requested with hits above threshold to select inelastic events



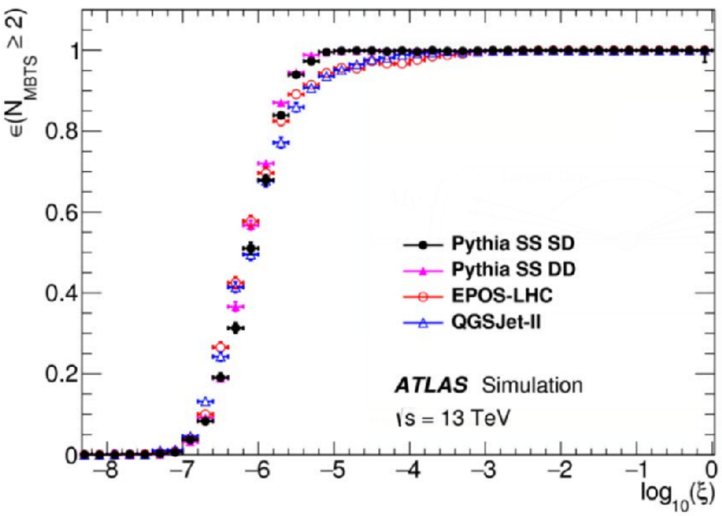
MBTS at $z = \pm 3.6\,\mathrm{m}$
$2.07 < \eta < 3.86$

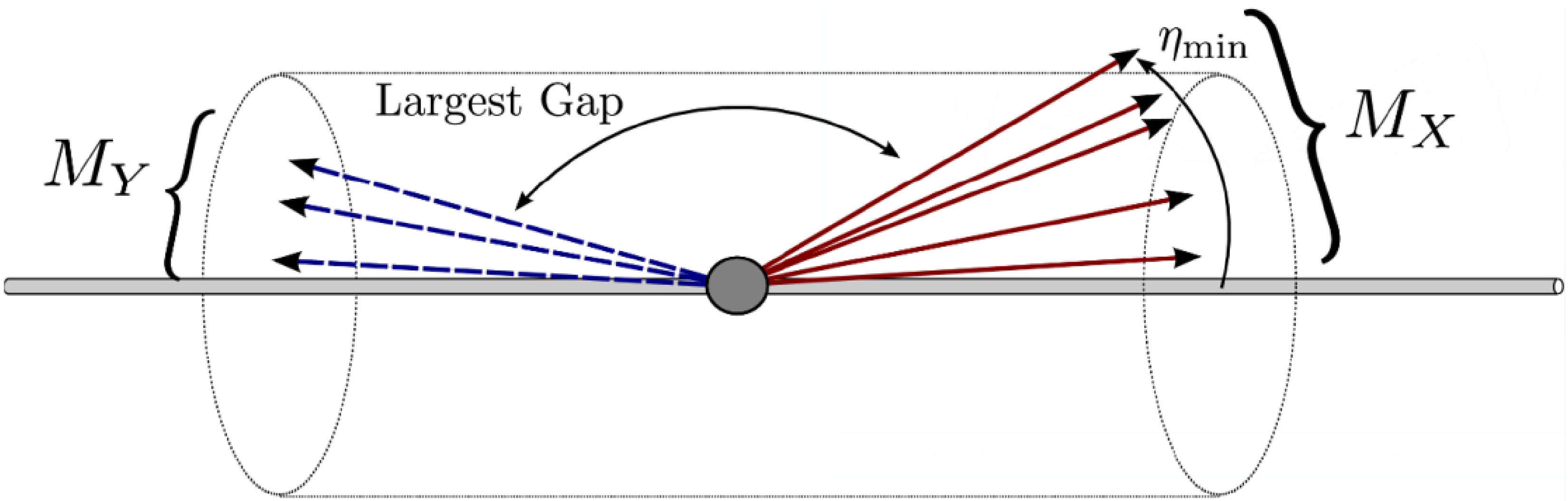
The diffractive component

- The fiducial volume is determined by MC and accounts for particles which escape the detector undetected
- Selection efficiency in the fiducial volume is above 50%
- Mass of dissociated system:

$$\mathrm{M}_X > 13\,\mathrm{GeV}$$

$$\xi = M_X^2/s > 10^{-6}$$





The fiducial cross section

$$\sigma_{\rm inel}^{\rm fid}(\xi > 10^{-6}) = \frac{N - N_{\rm BG}}{\epsilon_{\rm trig} \times \mathcal{L}} \times \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{\rm sel}}$$

N	Number of observed events
N_{BG}	Number of background events (beam-gas, beam halo, detector activation)
ϵ^{trig}	Trigger efficiency
ϵ^{sel}	Selection efficiency
f_{ξ}	Migration of small ξ events into the fiducial region
$\mathcal{L}$	Luminosity

- Simulation tuned by applying two selections:
  - Inclusive sample: at least 2 MBTS hits (4.2M events)
  - Single-sided sample: at least 2 MBTS hits on one side, veto on the other (440k events)

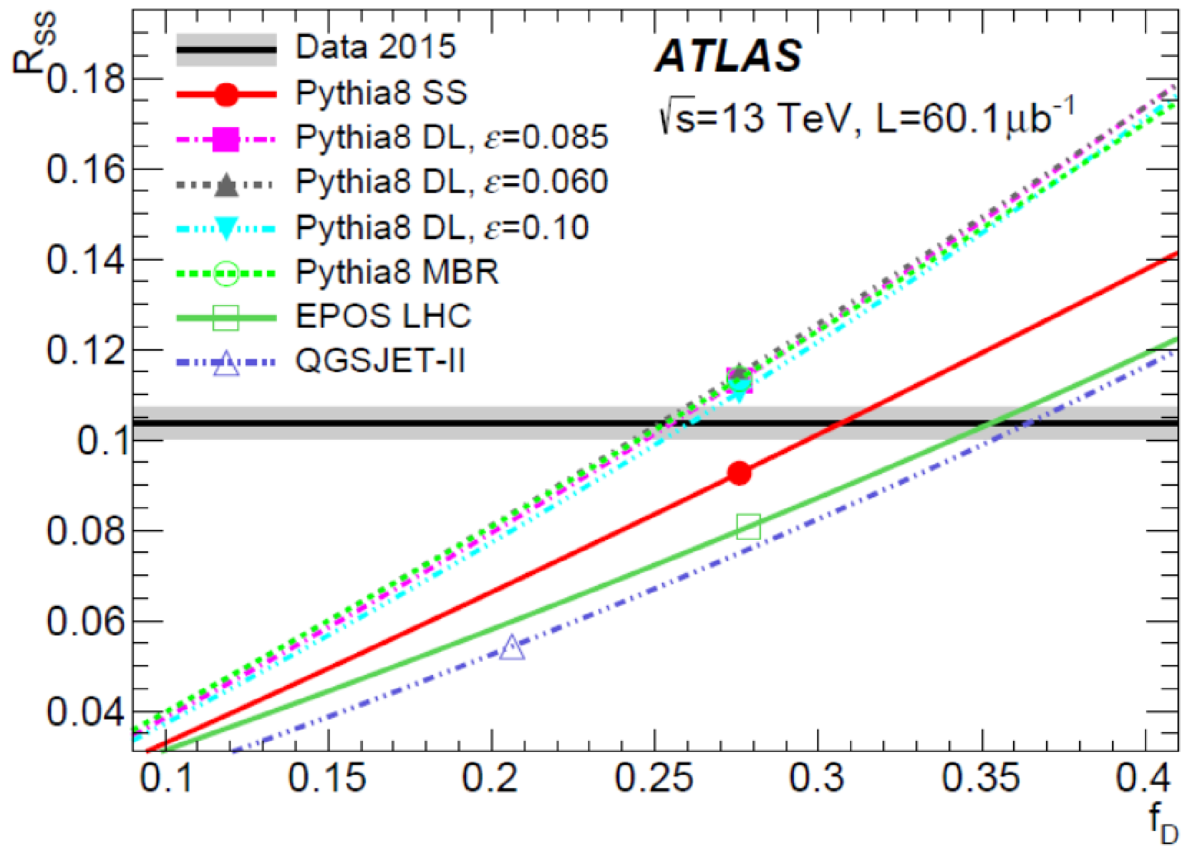
Model tuning

- MC is tuned by measuring the ratio of event count of diffractive and non-diffractive processes

$$\mathrm{R}_{SS} = \frac{N_{\text{single-sided}}}{N_{\text{inclusive}}} = (10.4 \pm 0.4)\%$$

$$\mathrm{f}_D = \frac{\sigma_{\text{SD}}+\sigma_{\text{DD}}}{\sigma_{\text{inel}}}$$

- The tuned models are used to calculate ϵ^{sel} and f_ξ

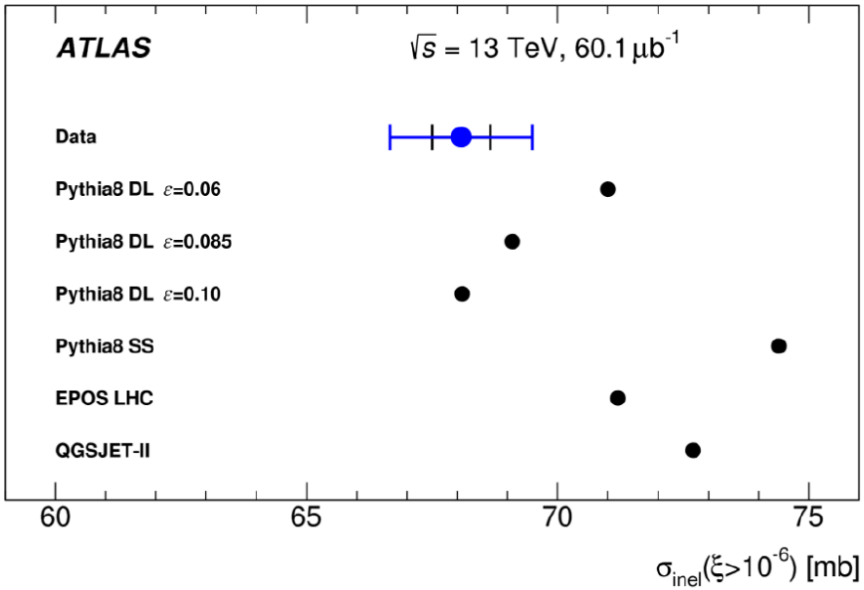


Results on fiducial inelastic cross section

$$\sigma^{\text{inel., fid.}}_{13\ \text{TeV}} = 68.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum})\,\text{mb}$$

Factor	Value	Rel. uncertainty
Number of events passing the inclusive selection (N)	4159074	–
Number of background events (N_{BG})	51187	$\pm 50\%$
Integrated luminosity [μb^{-1}] ($\mathcal{L}$)	60.1	$\pm 1.9\%$
Trigger efficiency (ϵ_{trig})	99.7%	$\pm 0.3\%$
MC correction factor (C_{MC})	99.3%	$\pm 0.5\%$

- Largest systematic contribution to fiducial cross section is the luminosity measurement
- Good agreement with PYTHIA DL models



Full inelastic cross section

$$\sigma^{\text{inel., full}}_{13\ \text{TeV}} = 78.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.6(\text{extr})\,\text{mb}$$

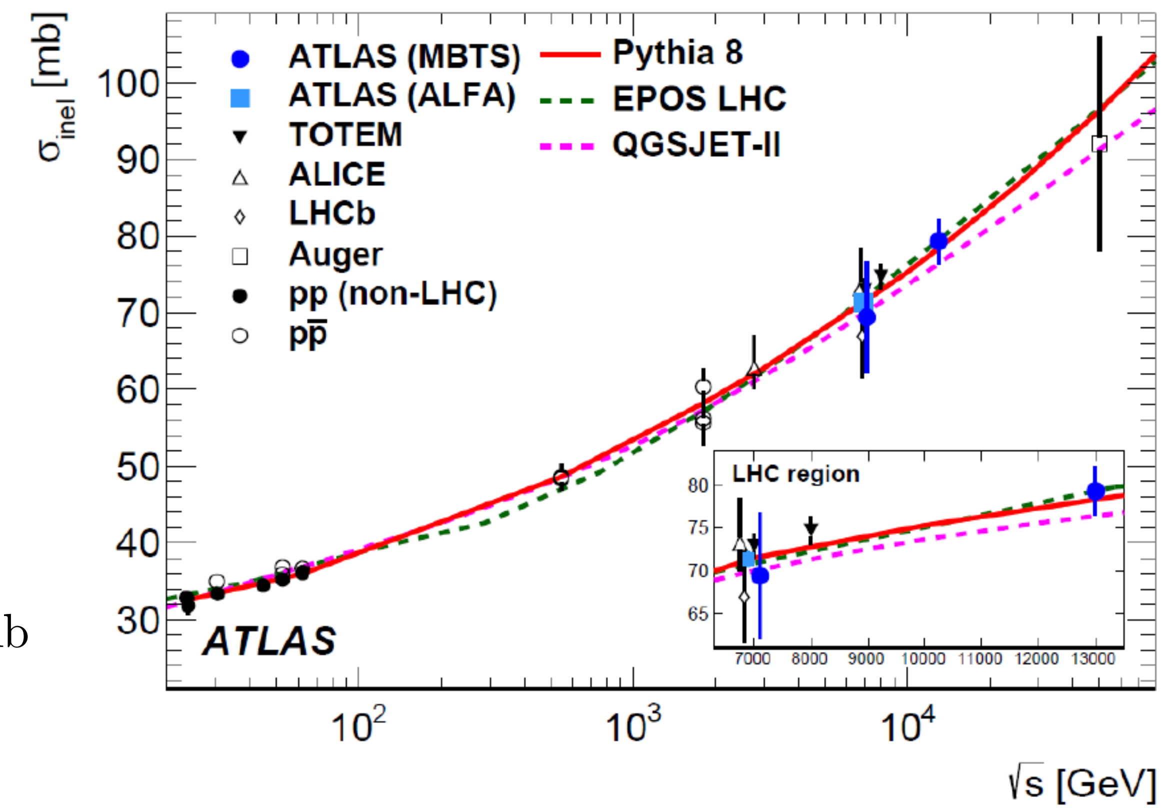
- Extrapolation from the fiducial cross section to the full inelastic cross section done using 7TeV measurements and MC correction:

$$\sigma_{\text{inel}} = \sigma^{\text{fid}}_{\text{inel}} + \sigma^{7\ \text{TeV}}(\xi < 5 \times 10^{-6})$$
$$\times \frac{\sigma^{\text{MC}}(\xi<10^{-6})}{\sigma^{7\ \text{TeV, MC}}(\xi<5\times10^{-6})}$$

- Where

$$\sigma^{7\ \text{TeV}}(\xi < 5 \times 10^{-6}) = (11.0 \pm 2.3)\,\text{mb}$$

is the difference between the full inelastic measurement from ALFA at 7 TeV and the fiducial measurement with the MBTS at 7 TeV



Summary

- Results on total cross section at 8 TeV with the ALFA detector now published in
  [Physics Letters B 761 (2016) 158–178]

$$\sigma_{\mathrm{tot}}(pp \to X) = 96.07 \pm 0.18(\mathrm{stat.}) \pm 0.85(\mathrm{exp.}) \pm 0.31(\mathrm{extr.})\,\mathrm{mb}$$

$$\sigma_{\mathrm{inel,\ 8TeV}} = 71.73 \pm 0.15(\mathrm{stat.}) \pm 0.69(\mathrm{syst.})\,\mathrm{mb}$$

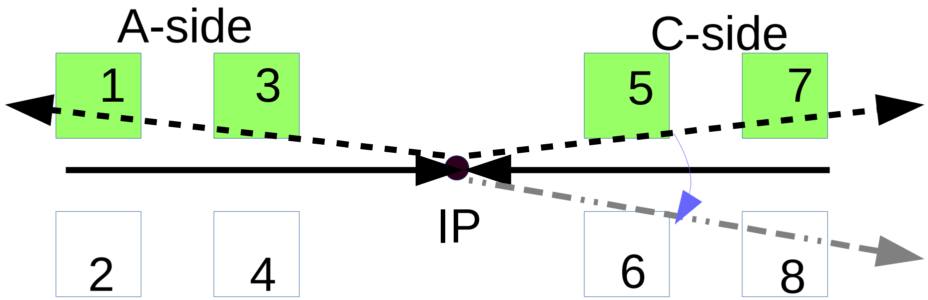
- Results on inelastic cross section measurement with MBTS now published
  [Phys. Rev. Lett. 117 (2016) 18200]

$$\sigma^{\mathrm{inel.,\ full}}_{\mathrm{13\ TeV}} = 78.1 \pm 0.6(\mathrm{exp}) \pm 1.3(\mathrm{lum}) \pm 2.6(\mathrm{extr})\,\mathrm{mb}$$

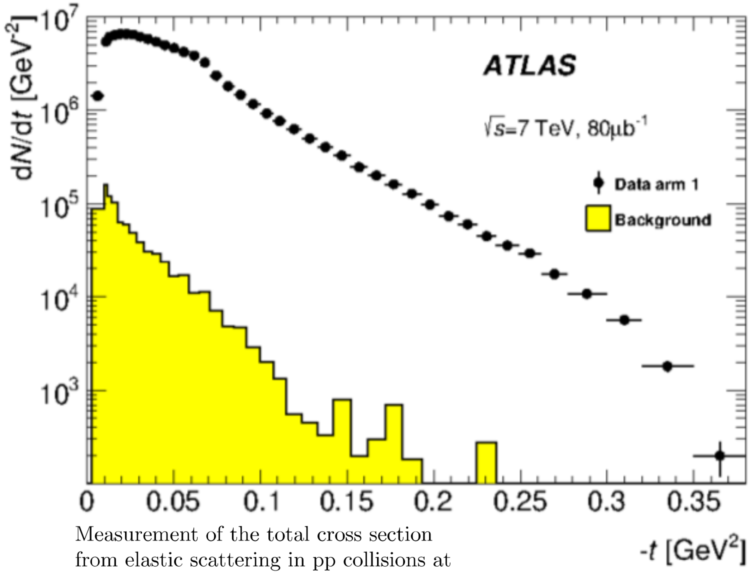

Thank you for your attention!

Backup

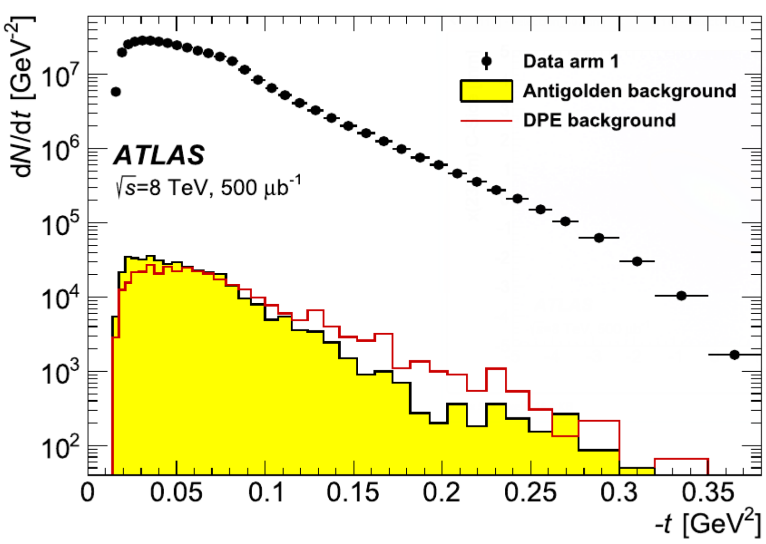
Background



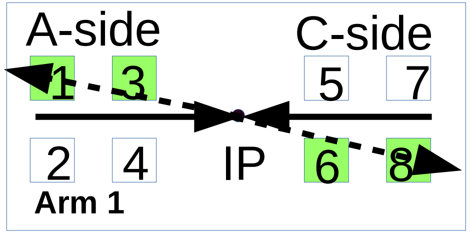
- Background pollution of event selection in this run very low (as in 7TeV, 90m)
- Irreducible background estimated by counting events in the so called "anti-golden" event topology
- Background fraction of 0.5% at 7TeV and 0.12% at 8TeV
- Smaller Background fraction at 8 TeV due to larger distance of detectors from the beam
- PYTHIA8 simulation yields the possibility of a large contribution of background (~70%) events from DPE events (MBR model)



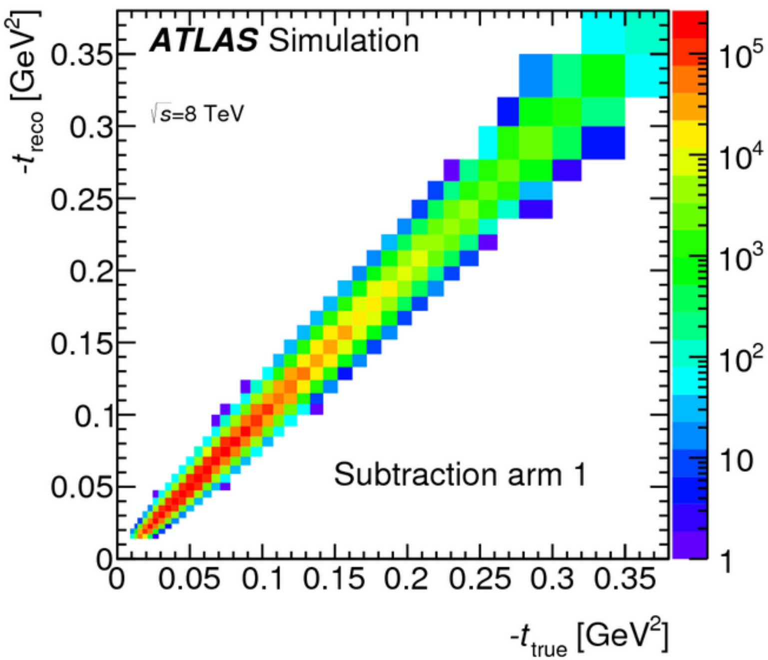
Measurement of the total cross section from elastic scattering in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ with the ATLAS detector ,ATLAS Collaboration, Nucl.Phys. B889:486-548

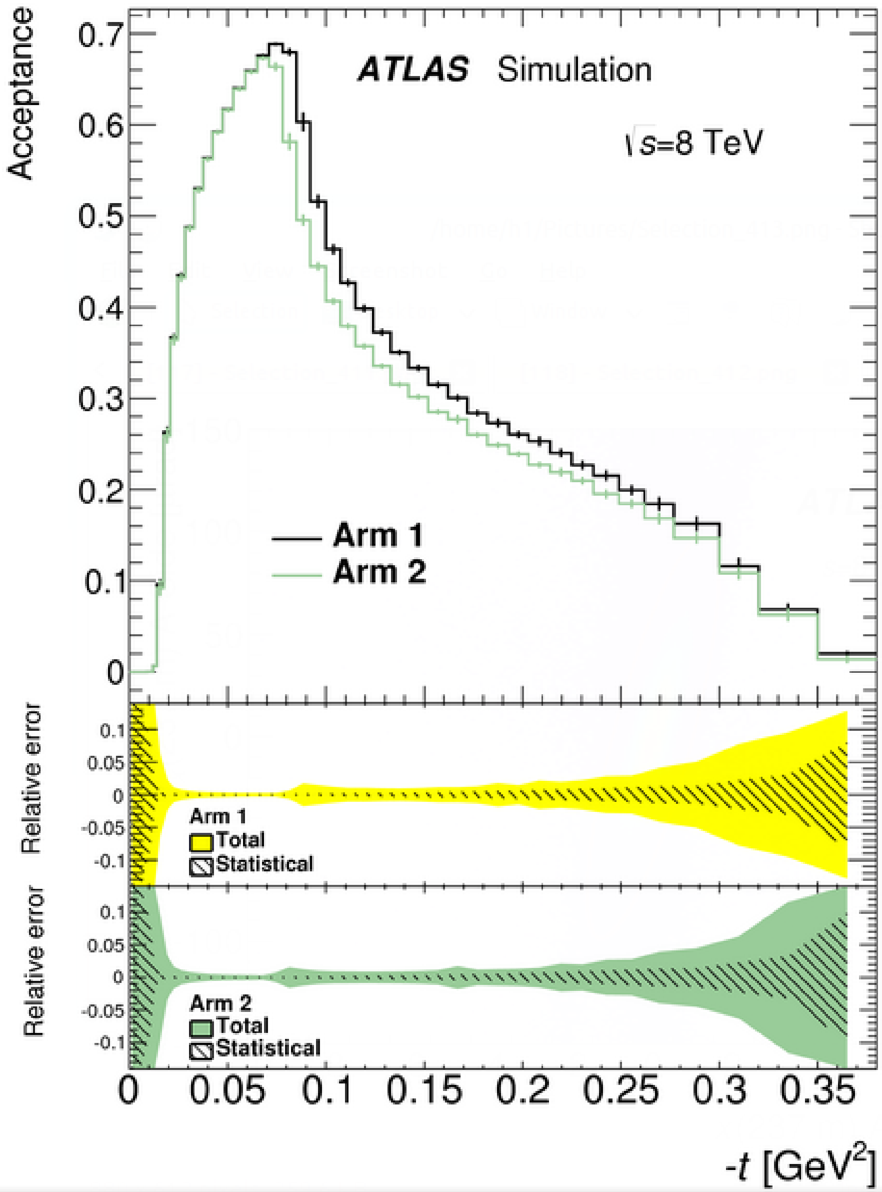


Acceptance and unfolding

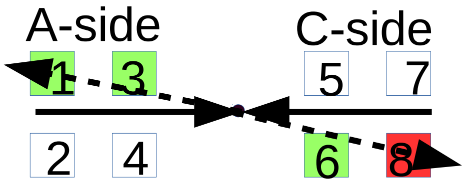


- Fast detector response simulated using PYTHIA8 and MadX to obtain transition matrix for t values and acceptance curve
- The acceptance is a combination of geometrical acceptance and background rejection cut efficiency
- Acceptance peaks around -t = 0.07 GeV^2
- For comparison:
  CNI region starts around $10^{-3}\mathrm{GeV}^2$





Reconstruction efficiency



- Data driven method to determine the fraction of elastic events, for which all four detectors have reconstructed tracks

$$\epsilon(t) = \frac{N_{4/4}}{N_{4/4}+N_{3/4}+N_{2/4}+N_{1/4}+N_{0/4}}$$

- Requires determination of the number of elastic events for all of the 30 cases where no track was reconstructed in any given detector(s)
- Easy when only one out of four detectors has not provided any tracks (template fit to compensate for any edge effects)
- Harder when two detectors have no tracks on a given side (background template fit required to suppress irreducible background)
- Number of elastic events with no tracks in any detector determined statistically
- Check was performed on 3/4 subsample to verify t-independence of reconstruction efficiency
- Final results per arm:

$$\epsilon_{\text{arm1}} = 90.50\% \pm 0.03\%(stat.) \pm 0.34\%(syst.)$$
$$\epsilon_{\text{arm2}} = 88.83\% \pm 0.03\%(stat.) \pm 0.45\%(syst.)$$