Measurement of the elastic, inelastic and total pp cross section at 7 TeV and 13 TeV with the ATLAS detector

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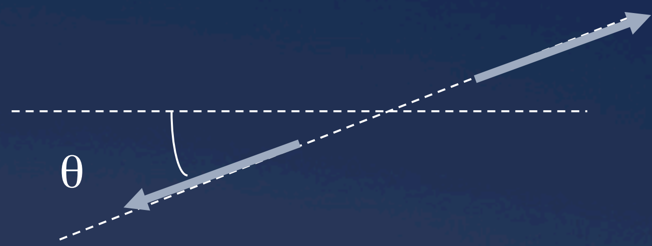
Outline

* Measurement using elastic scattering
  * Elastic scattering and σ_{tot} in LHC
  * Experimental setup: ALFA sub-detector
  * Data analysis
  * σ_{tot}, σ_{el}, and σ_{in} measurements (at $\sqrt{s}$ = 7 TeV)
* Measurement using scintillators at low pile-up
  * Experimental setup: MTBS sub-detector
  * Data analysis
  * Measurement of σ_{in} at $\sqrt{s}$ = 13 TeV
* Conclusion

Total cross section measurement using elastic scattering at $\sqrt{s}$ = 7 TeV

Elastic scattering and σ_{tot}



- Relevant parameter is:

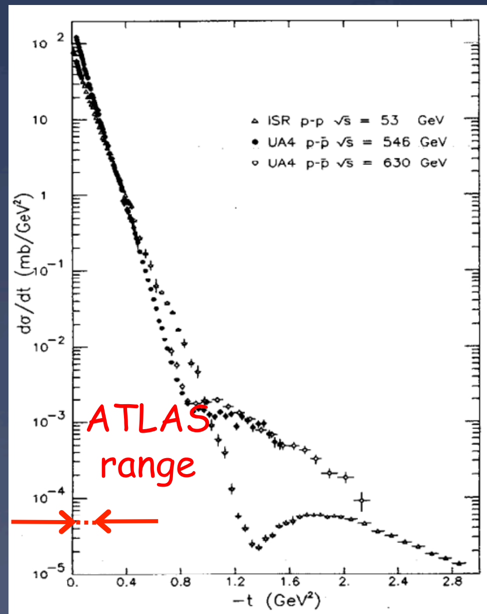
$$t = -2\,p^2\,(1-\cos(\theta)) \approx -\,p^2\,\theta^2$$

- σ_{tot} = can't be calculated in perturbative QCD, but can be measured using the Optical Theorem :

$$\sigma_{tot}^2 = \frac{16\,\pi\,(\hbar\,c)^2}{1+\rho^2}\,\frac{d\sigma_{el}}{dt}\bigg|_{t\to 0}$$

  - ρ is the ratio of the real to the imaginary elastic scattering amplitude at t = 0
  - Common technique for pp colliders (already used by UA4 in other *t*-range)

D. Bernard et al., UA4, Phys. Lett. B 171 (1986), 142



dσ/dt vs t

LHC case

* Theoretical prediction uses Coulomb, Nuclear and Coulomb-Nuclear interference terms:

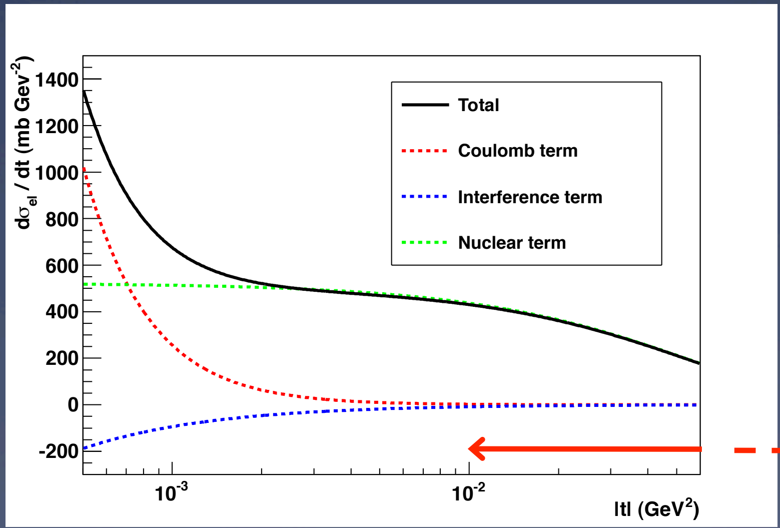
$$\frac{d\sigma_{el}}{dt} = \boxed{\frac{4\,\pi\,\alpha^2\,(\hbar\,c)^2\,G^4(t)}{|t|^2}} + \boxed{\frac{\sigma_{tot}^2\,(1+\rho^2)\exp(-B\,t)}{16\,\pi\,(\hbar\,c)^2}}$$

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

with values of G (electric form factor of the proton), $\rho = \mathrm{Re}(F_{el})/\mathrm{Im}(F_{el})$ and Φ (Coulomb phase) coming from measurements at lower energies

Coulomb scattering
a fit will give absolute luminosity

Coulomb nuclear interference region
a fit will give σ_{tot}, ρ and B

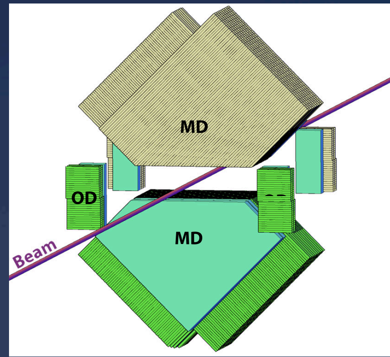


Nuclear scattering
a fit will give σ_{tot} and B

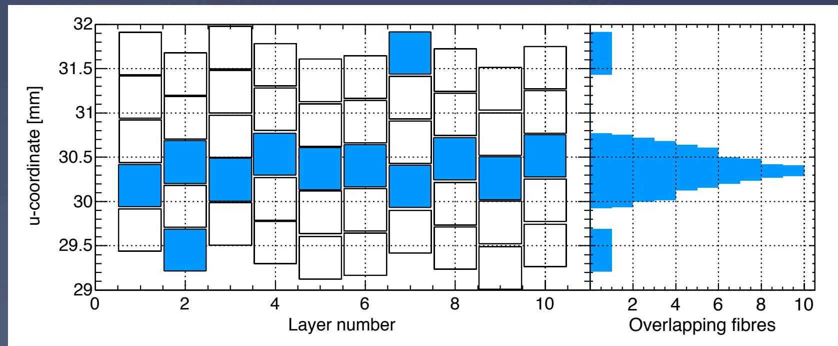
This talk

Experimental setup: ALFA (Absolute Luminosity for Atlas)

- During dedicated runs (“high β runs”), use 8 trackers (“roman pots”) at ~ 240 m from ATLAS IP
  - Scintillating fiber tracker, with U–V geometry, read by MAPMT
- Each main detector is made of 20 layers of 64 scintillating fibers (500x500 μm^2), shifted by 50 μm:
  - Resolution ≈ 35 μm
  - ≈ 4.3 photo electrons per hit
  - Position of the maximum gives the track position
- Each detector has 2 satellite detectors (Overlap Detectors) to measure distance between detectors



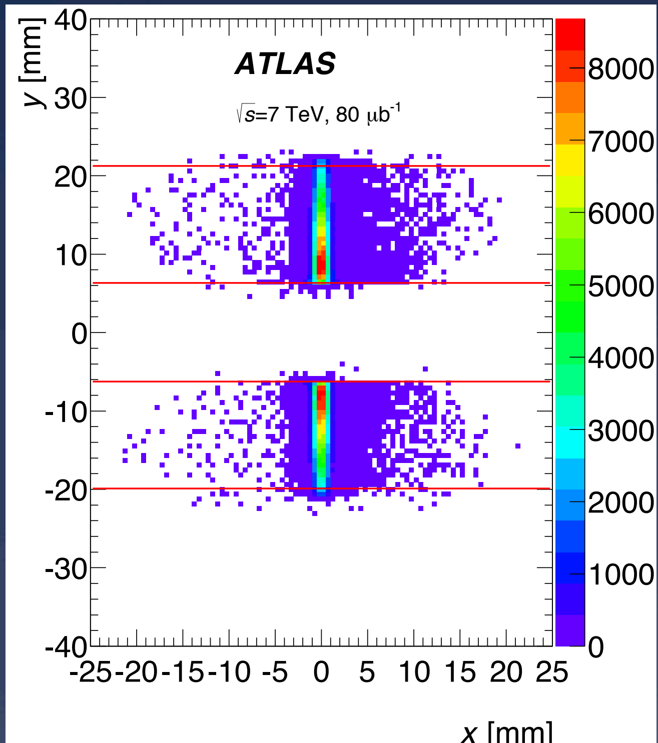
Roman Pots schematics



Hit pattern of a proton in the detector

From hits to *t*-reconstruction

Nucl. Phys. B (2014) 486–548



Experimental hit pattern in one detector, before any cut. Hit pattern is spread in the vertical plane. Due to "high β" optics, the optics lengths are different (270 m in y vs and 13 m in x)

- Scattering angle θ is deduced from the impact position on the detectors using the beam transport matrix:

$$\begin{pmatrix} u \\ \theta_u \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} u^* \\ \theta_u^* \end{pmatrix}$$

At the detector

At the IP

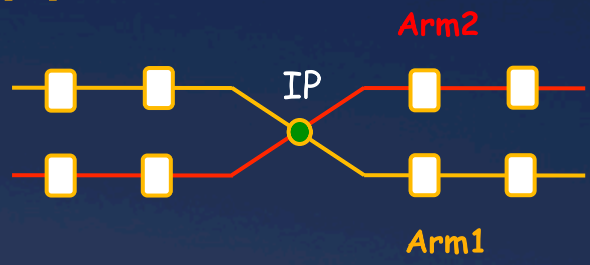
with $u = x$ or y

- By subtraction:

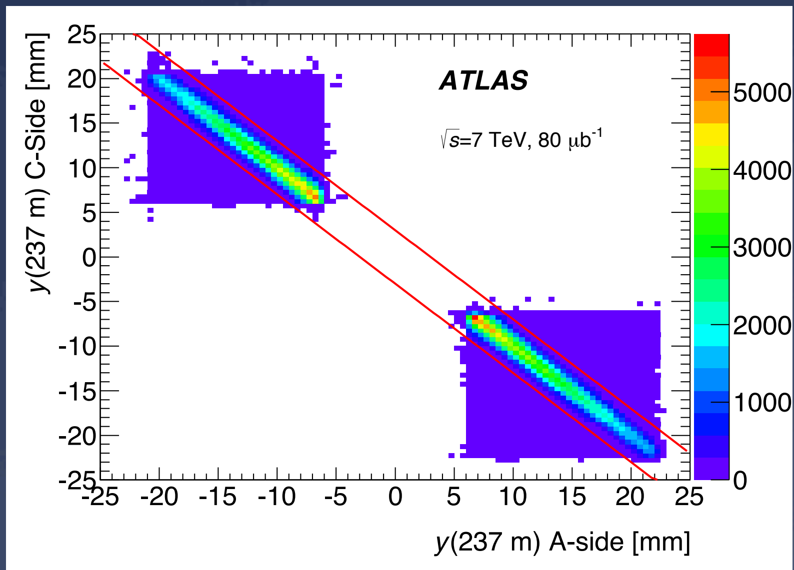
$$\theta_u^* = \frac{u_A - u_C}{M_{12\,A} + M_{12\,C}}$$

insensitive to vertex position

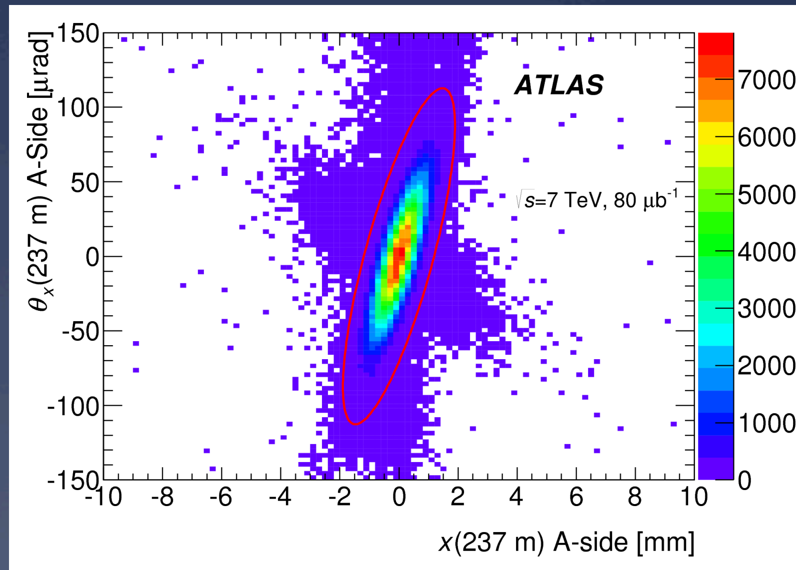
Elastic event selection



- Selection based upon:
  - First level elastic trigger (Arm1 or Arm2)
  - Back-to-back topology and background selection cut
  - Data quality cuts + geometrical acceptance cuts

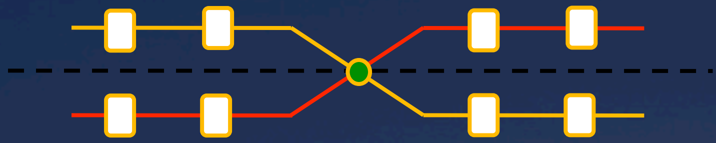


A–C correlation of y after data quality cuts but before acceptance and background cuts. Elastic events are required to lie between the red lines

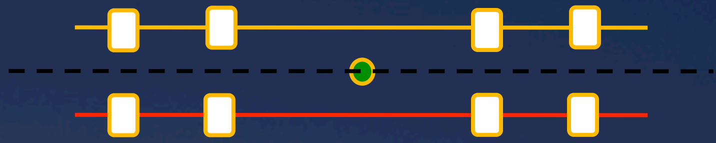


Correlation between x and θ_x on the A-side after data quality cuts but before acceptance and background cuts. Elastic events are required to lie inside the red ellipse

Background and efficiencies

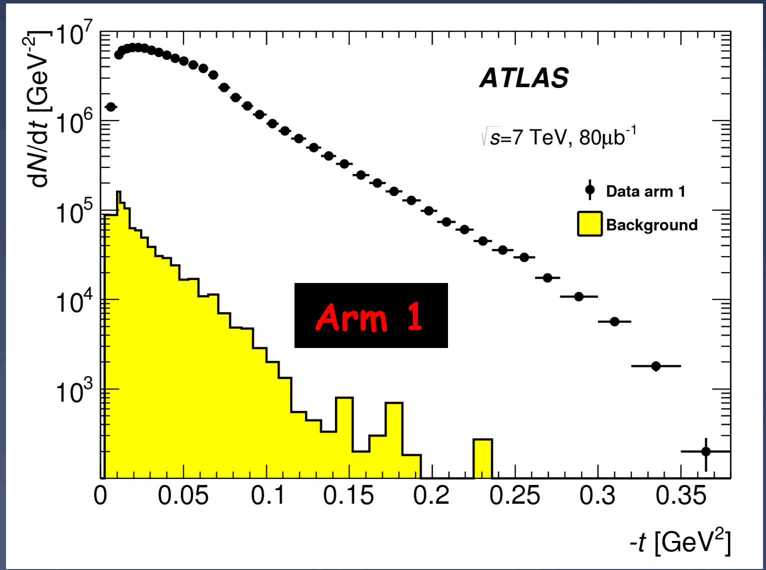


Signal (golden mode)



Background (anti-golden)

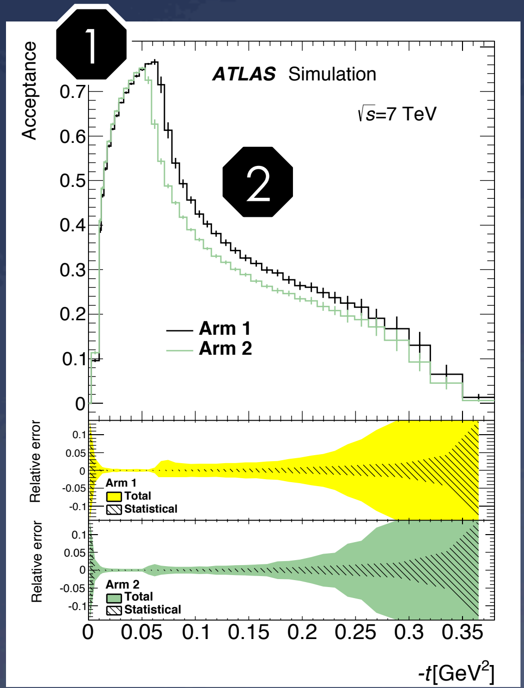
- Main way of looking for background events in the elastic peak:
  - Anti-golden rate is a background estimate (nominal method)
  - t-spectrum for background is estimated by flipping the coordinates of one of the tracks
  - Background 0.50 ± 0.25 % and comes from halo protons: other sources (including diffractive events) are negligible
  -
- Efficiency: 89.8 ± 0.6 % (Arm1) and 88.0 ± 0.9 % (Arm2)



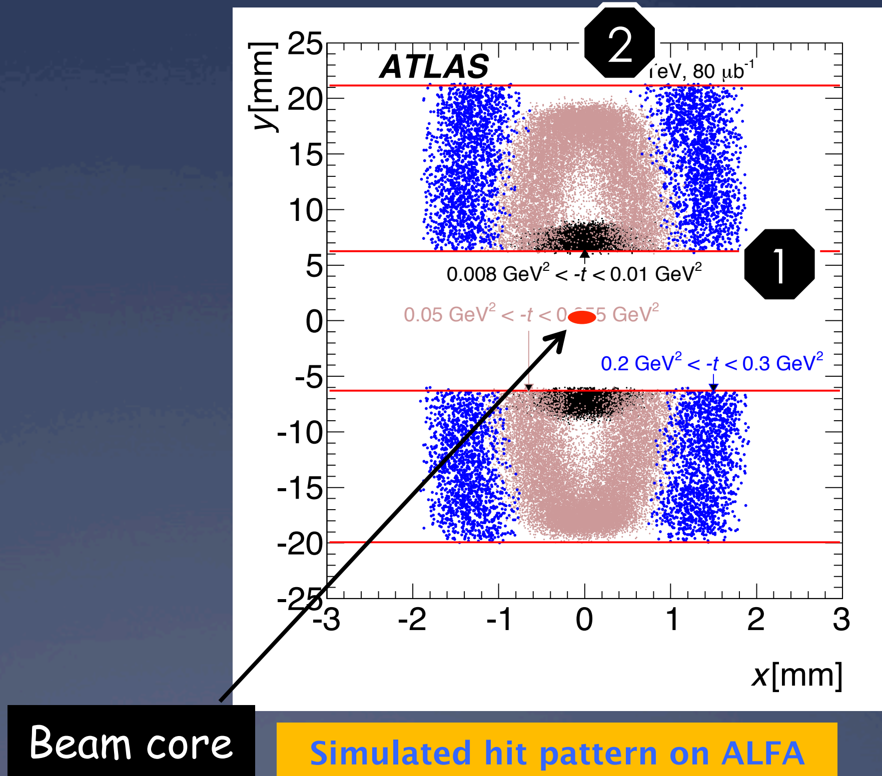
t-spectrum before corrections and background spectrum determined using anti-golden events

Acceptance

* Beam pipe geometry of crucial importance: vertical cuts
* Acceptance determined from simulation (Pythia8 + MadX) and used to correct the raw spectrum



Acceptance spectrum

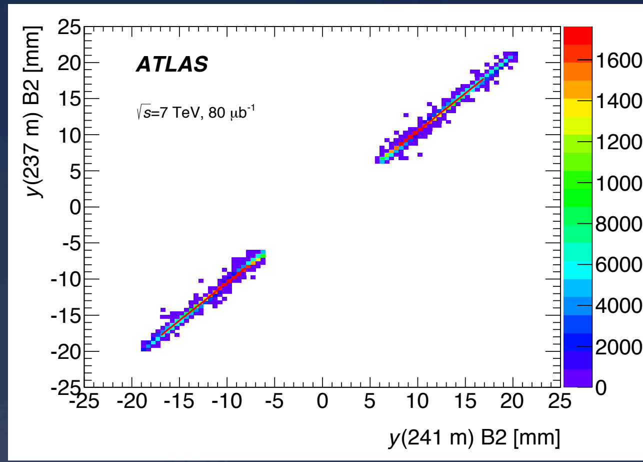


Simulated hit pattern on ALFA

Optics and luminosity

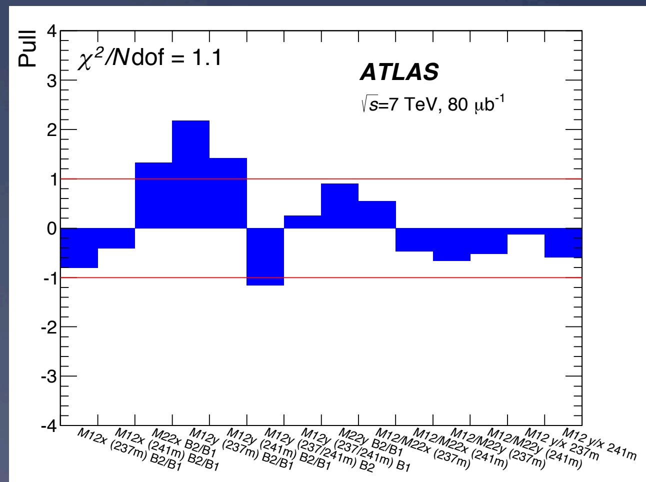
- Elastic events are used to rescale the transport matrix elements
  - For instance, we can use the lever arm ratio:

$$y = \theta_y^* \, M_{12} \quad \Rightarrow \quad \frac{y_{inner}}{y_{outer}} = \frac{M_{12}^{Inner}}{M_{12}^{Outer}}$$



y_{inner} vs y_{outer}

- 14 optics parameters are used for a global fit. Main effect is that strengths of the triplet were miscalibrated by 0.3%, with a difference of 10% between both beams
  - No concern for high lumi, but for ALFA



Constraints on the optics

- Luminosity estimated by ATLAS:

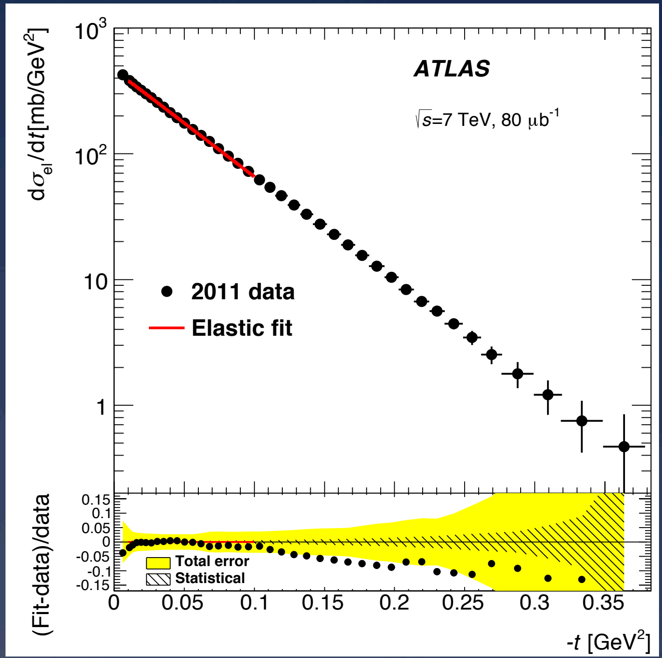
$$L = 78.7 \pm 1.9 \; \mu b^{-1}$$

Fit of σ_{tot} and B

* In a given bin t_i, one has:

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

  * A_i (acceptance), M (unfolding), N_i: (selected events, B_i (estimated background), ε^{reco} (reconstruction efficiency), ε^{trig} (trigger efficiency, ε^{DAQ} (DAQ efficiency), L_{int} (luminosity)



Fit of σ_{tot} and B

* Fit range [0.01 – 0.1] GeV^2 gives (χ^2/N_{dof}=7.4/16):

$$\begin{cases} \sigma_{tot} = 95.35 \pm 0.38_{stat} \pm 1.25_{syst(without\ extrap)} \pm 0.37_{extrap} \text{ mb} \\ B = 19.73 \pm 0.14_{stat} \pm 0.26_{syst} \text{ GeV}^{-2} \end{cases}$$

* Main systematic uncertainties: luminosity and beam energy
  * All other uncertainties are < than 50% of the luminosity error

Elastic and inelastic cross sections

- Elastic cross section from the integrated fit function:

$$\sigma_{el} = \frac{\sigma_{tot}}{B} \frac{1+\rho^2}{16\,\pi\,(\hbar\,c)^2} \quad \Rightarrow \quad \sigma_{el} = 24.00 \pm 0.19_{stat} \pm 0.57_{syst} \text{ mb}$$

- Inelastic cross section:

$$\sigma_{in} = \sigma_{tot} - \sigma_{el} \quad \Rightarrow \quad \sigma_{in} = 71.34 \pm 0.36_{stat} \pm 0.83_{syst} \text{ mb}$$

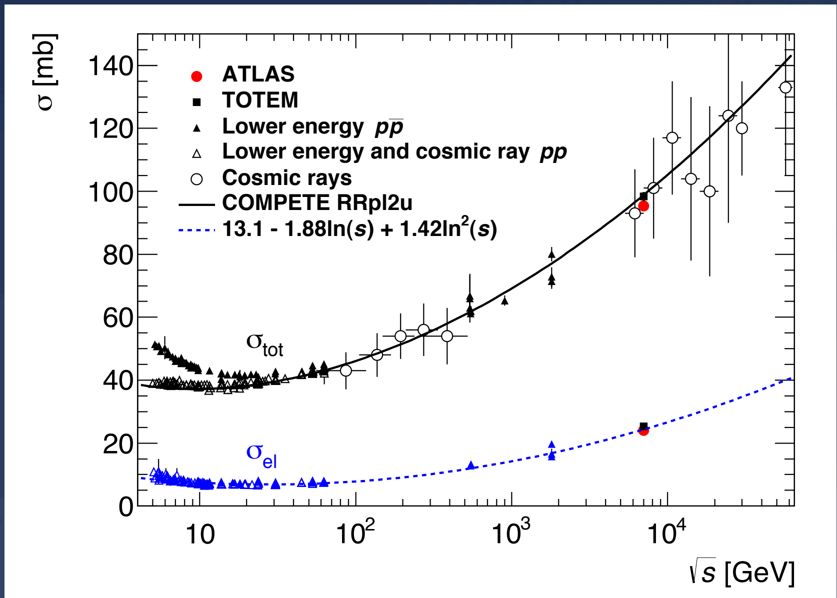
- Optical point:

$$\left.\frac{d\sigma}{dt}\right|_{t\to 0} = 474 \pm 13 \text{ mb.GeV}^{-2}$$

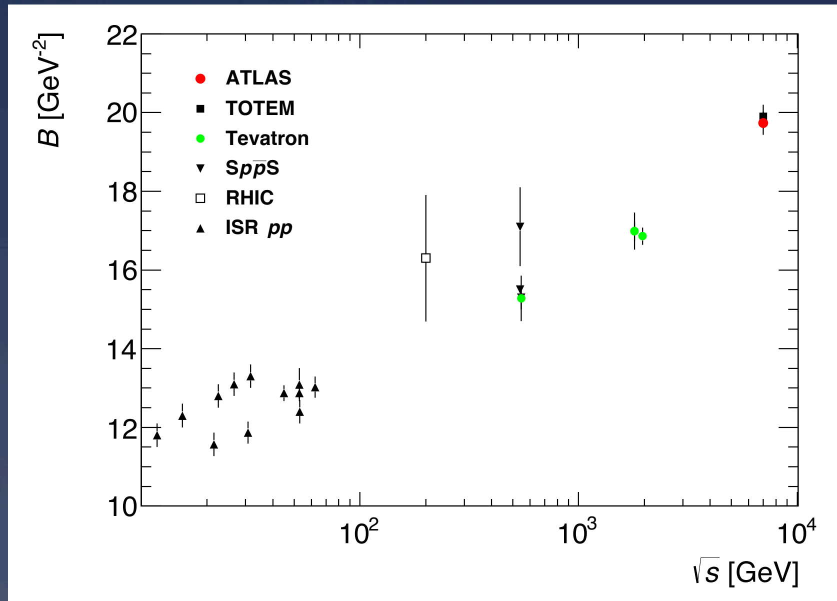
Comparison with TOTEM (1/2)

ATLAS: Nucl. Phys. B (2014) 486-548

TOTEM: EPL 101 (2013) 21004 with ATLAS data superimposed



σ_{tot} variation with $\sqrt{s}$



B variation with $\sqrt{s}$

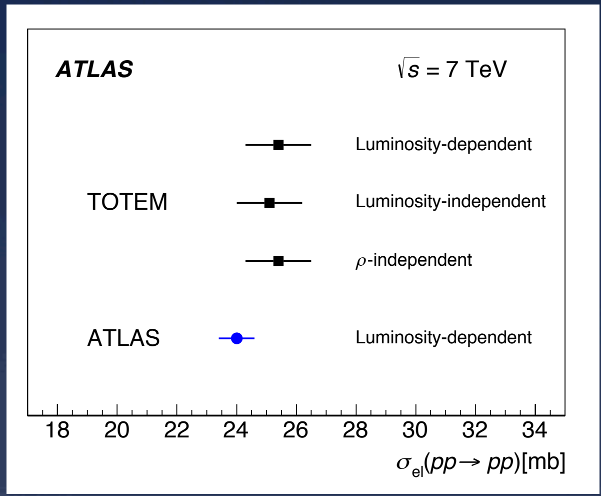
$$\begin{cases} \text{ATLAS} \quad \sigma_{tot} = 95.4 \pm 1.4 \text{ mb} \\ \text{TOTEM} \quad \sigma_{tot} = 98.6 \pm 2.2 \text{ mb} \end{cases}$$

$$\begin{cases} \text{ATLAS} \quad B = 19.7 \pm 0.3 \text{ GeV}^{-2} \\ \text{TOTEM} \quad B = 19.9 \pm 0.3 \text{ GeV}^{-2} \end{cases}$$

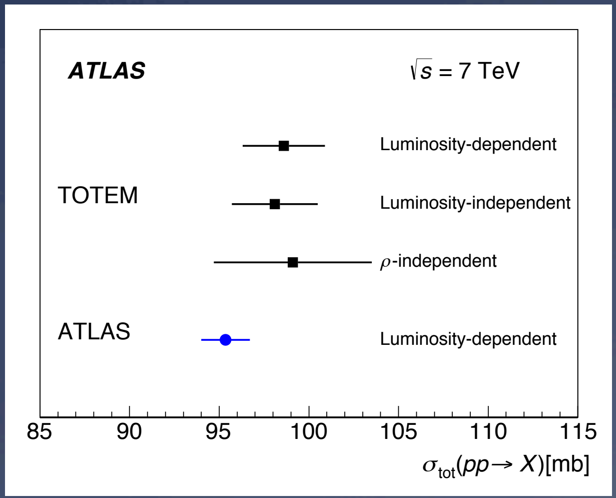
Comparison with TOTEM (2/2)

- Large part of the difference is coming from the luminosity
  - Uncertainty (2.3% for ATLAS and 4.5% for TOTEM)
  - It scales with a factor 0.5 in σ_{tot}

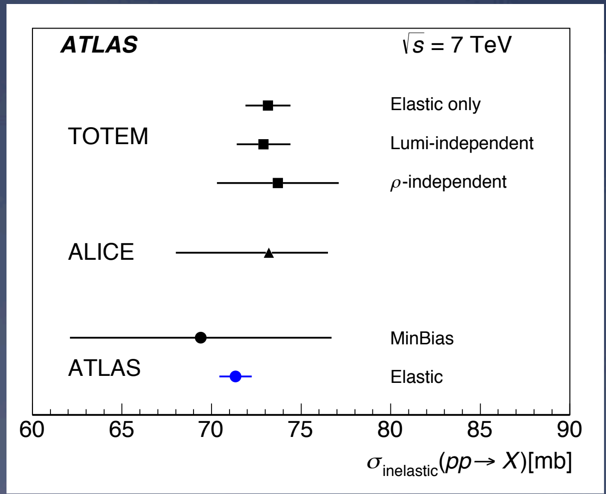
ALICE: EPJC 73 (2013) 2456



Elastic cross section σ_{el}



Total cross section σ_{tot}



Inelastic cross section σ_{in}

Inelastic cross section measurement using scintillators at low pile-up at $\sqrt{s}$ = 13 TeV

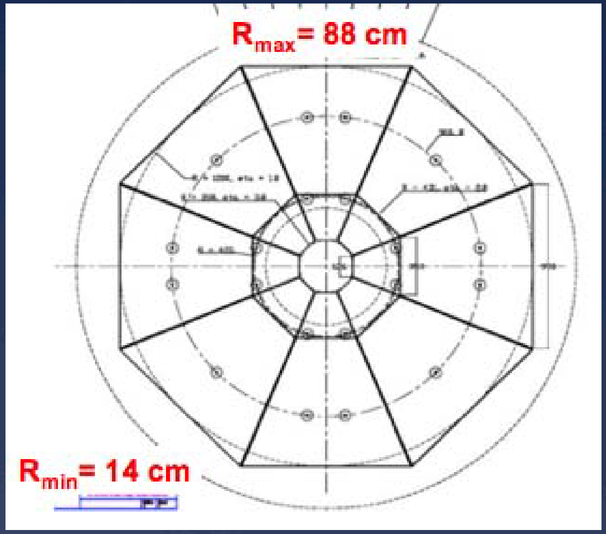
Experimental Setup

* June 2015 : 13 TeV but mean number of pp interactions per bunch crossing was $\mu=2.3\times10^{-3}$ (integrated lumi 63±6 μb^{-1})

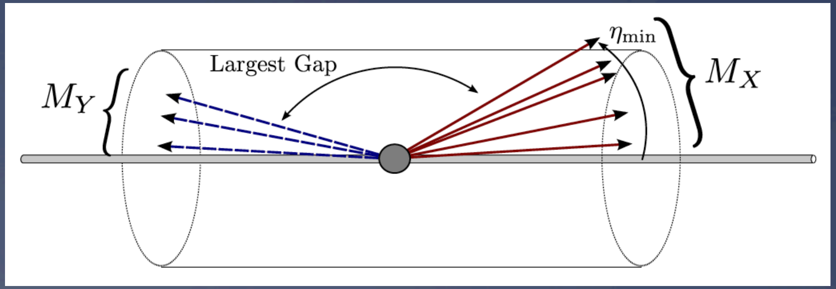
* Measurement done with two sets of scintillators (MBTS) at ±3.6 m from IP covering $2.07 < |\eta| < 3.86$

* Inelastic interaction : one of the two protons dissociate

* Fiducial measurement limited by the phase space where the larger of the invariant masses M_x is within the detector acceptance

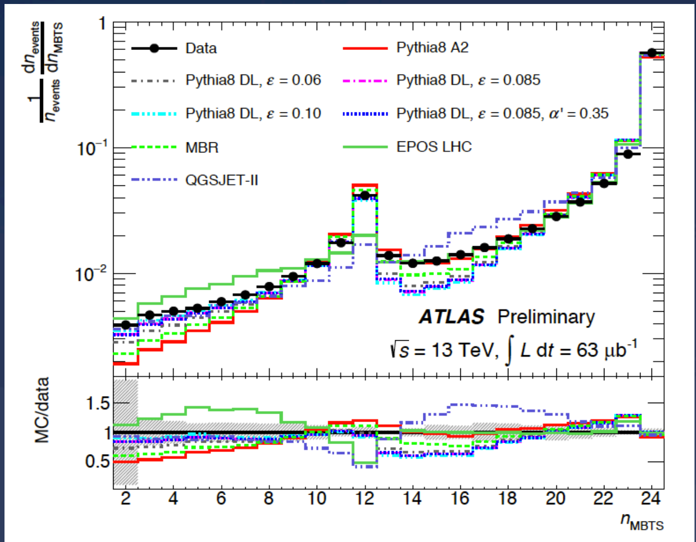


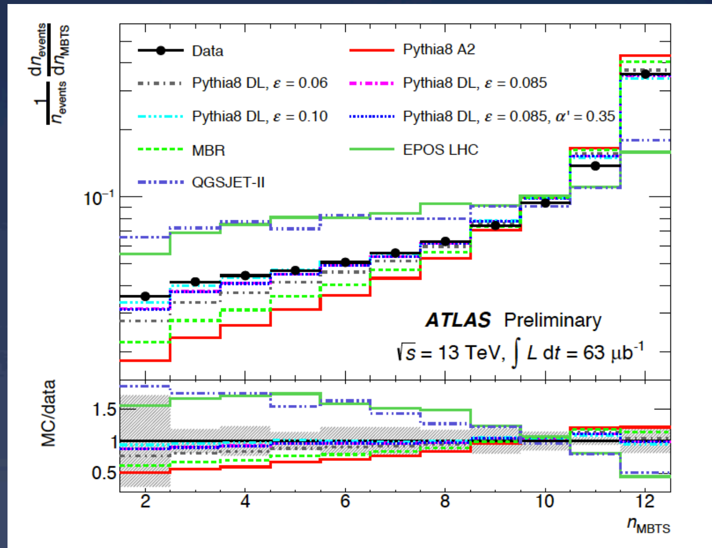
MBTS counters



M_x and M_y in a double-dissociation event

ATLAS-CONF-2015-038





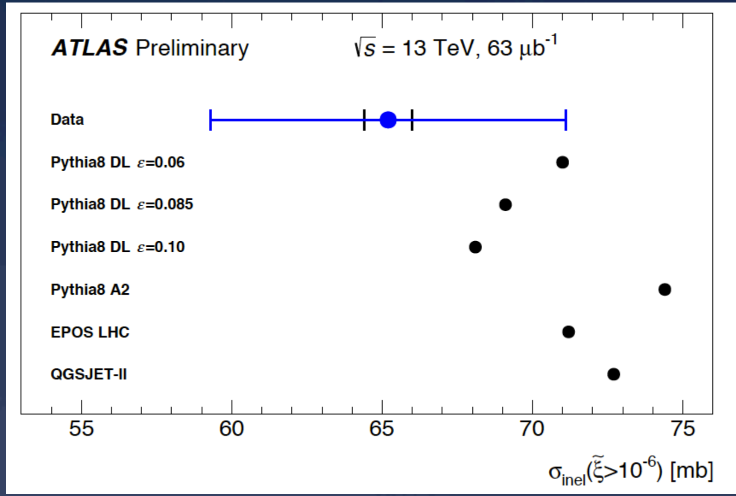
Number of scintillating counters above 0.15 pC after background subtraction for inclusive events (left) and single sided events (right)

- Trigger efficiency measured with the data is applied to the simulated samples
- Donnachie and Landshoff model of diffraction (with α'=0.25 and ε=0.085) is in good agreement in the low n_{MTBS} region and is used for MC based corrections

Fiducial measurement

	Value	Rel. unc.
Number of events (N)	4159074	
Number of bkgnd events (N_{BG})	43512	± 100%
Luminosity (μb^{-1})	62.9	± 9%
Trig efficiency (ε_{trig})	99.7%	± 0.1%
MC corr. factor	0.993	± 0.5%

Value used for the calculation of the fiducial cross section



Measured fiducial cross section compared with MC predictions

* Inelastic cross section:

$$\sigma_{in} = \frac{N - N_{BG}}{\varepsilon_{trig} \times L} \times \frac{1 - f_{\xi<10^{-6}}}{\varepsilon_{sel}}$$

* Measurement:

$$\sigma_{in} = 65.2 \pm 0.8_{exp} \pm 5.9_{lumi} \text{ mb}$$

  * exp includes all except luminosity

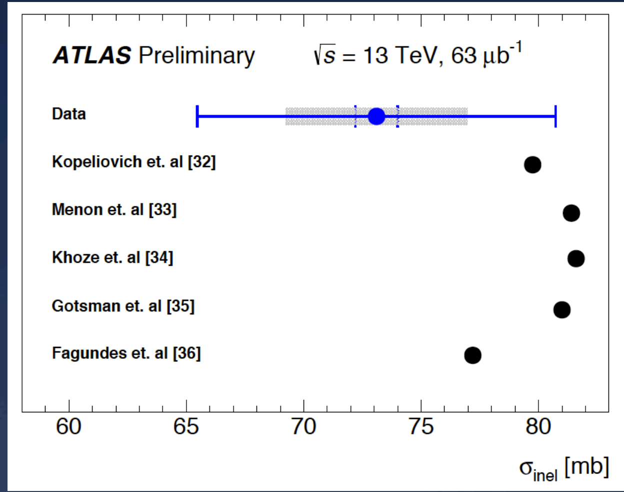
This measurement	65.2±0.8 (exp)±5.9(lum) mb
Pythia8 DL, ε = 0.060	71.0 mb
Pythia8 DL, ε = 0.085	69.1 mb
Pythia8 DL, ε = 0.100	68.1 mb
Pythia8 A2	74.4 mb
EPOS LHC	71.2 mb
QGSJET-II	72.7 mb

Inelastic cross section

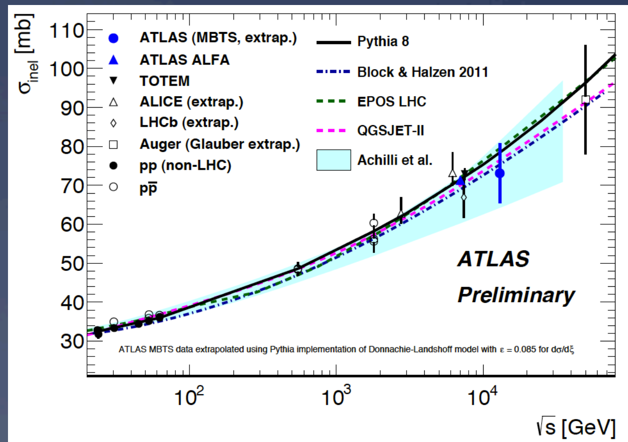
- Extrapolation to full inelastic cross section using models of inelastic interactions
- Depending on models, acceptance ranges from 87.6% to 93.7%. Final value is:

$$\sigma_{in} = 73.1 \pm 0.9_{\exp} \pm 6.6_{lumi} \pm 3.8_{extr}\ \text{mb}$$

  - About one standard deviation below theoretical predictions
- Improvement of the luminosity measurement will be made using Van der Meer scans



Measured σ_{in} compared with various predictions



σ_{in} vs $\sqrt{s}$

Conclusion

* Using elastic scattering, ATLAS has performed a measurement of σ_{tot}, σ_{el}, and σ_{in} at $\sqrt{s}$ = 7 TeV

$$\sigma_{tot} = 95.4 \pm 1.4 \text{ mb} \qquad \sigma_{el} = 24.00 \pm 0.60 \text{ mb} \qquad \sigma_{in} = 71.34 \pm 0.90 \text{ mb}$$

  * The analysis of data at $\sqrt{s}$ = 8 TeV is ongoing
  * Data at $\sqrt{s}$ = 13 TeV (same optics) where collected last month
  * Another run with $\beta^* \approx$ 2–3 km at $\sqrt{s}$ = 13 TeV is planned to measure σ_{tot}, σ_{el}, and σ_{in} in a luminosity independent method

* ATLAS performed a measurement of σ_{in} at $\sqrt{s}$ = 13 TeV using a set of scintillator counters

$$\sigma_{in} = 73.1 \pm 0.9_{\exp} \pm 6.6_{lumi} \pm 3.8_{extr} \text{ mb}$$

  * Measured value is one standard deviation below theoretical estimations