Overview of the ATLAS ALFA detectors: performance and physics analysis

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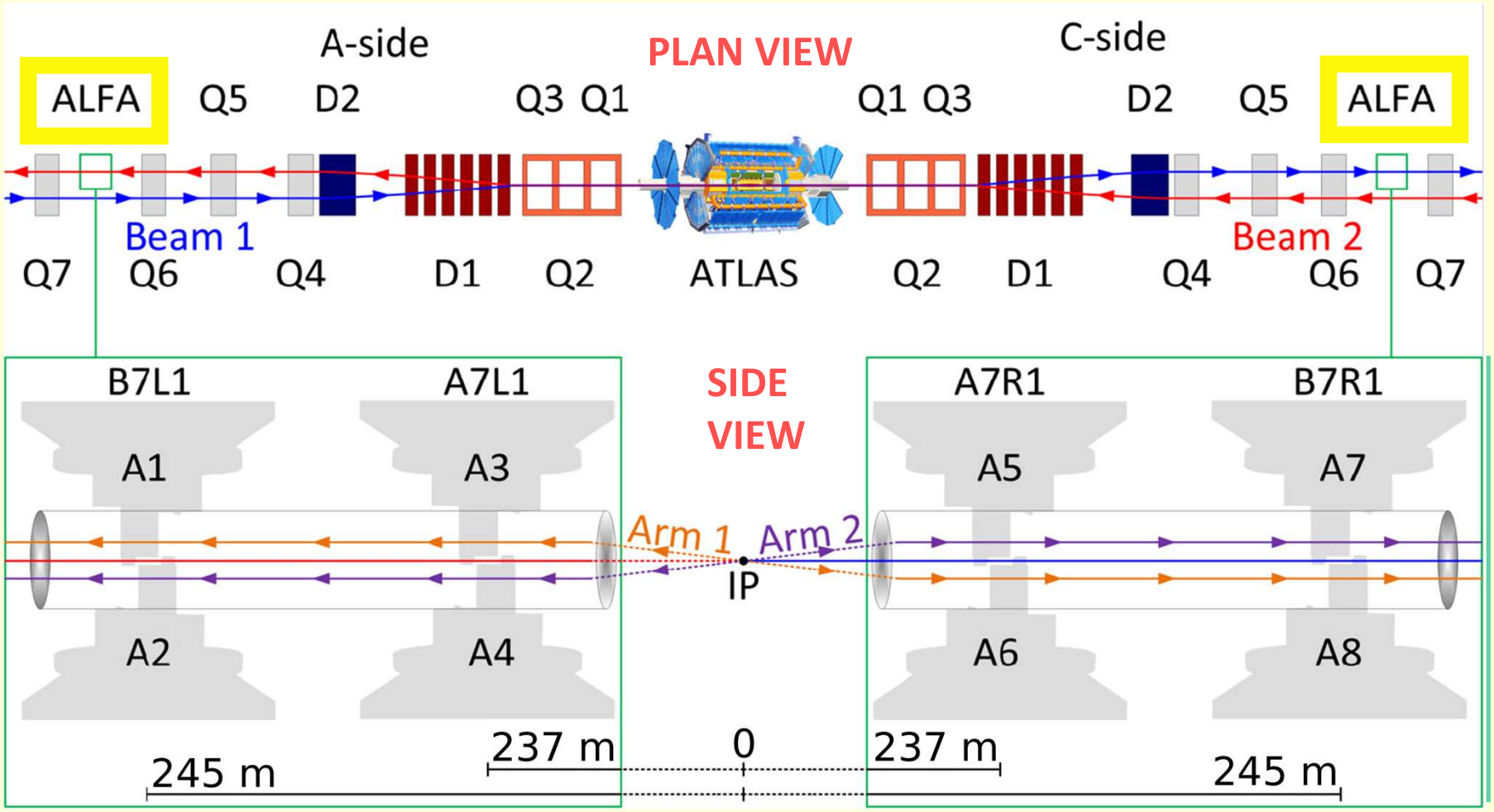
On behalf of the ATLAS Collaboration

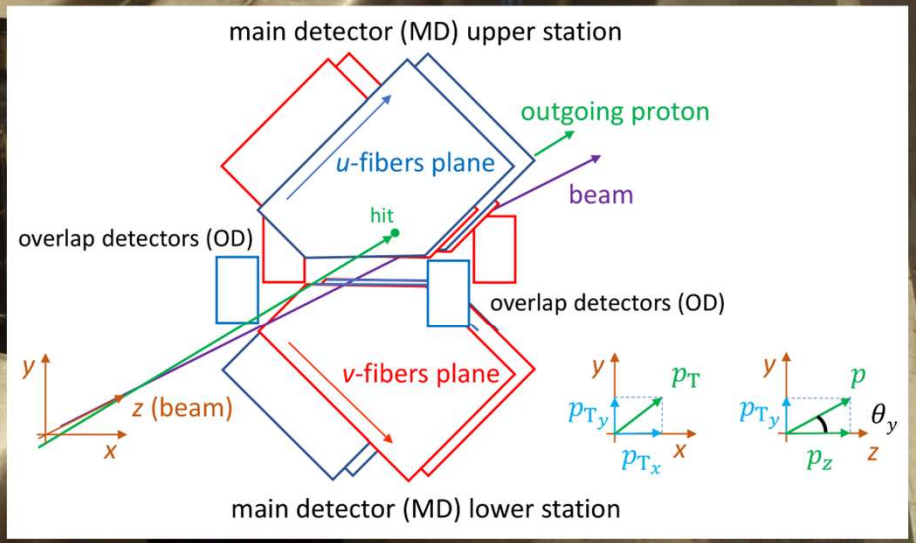


(Vert scattered protons)

Location of ALFA stations relative to ATLAS.

S. Abdel Khalek *et al* 2016 *JINST* **11** P11013

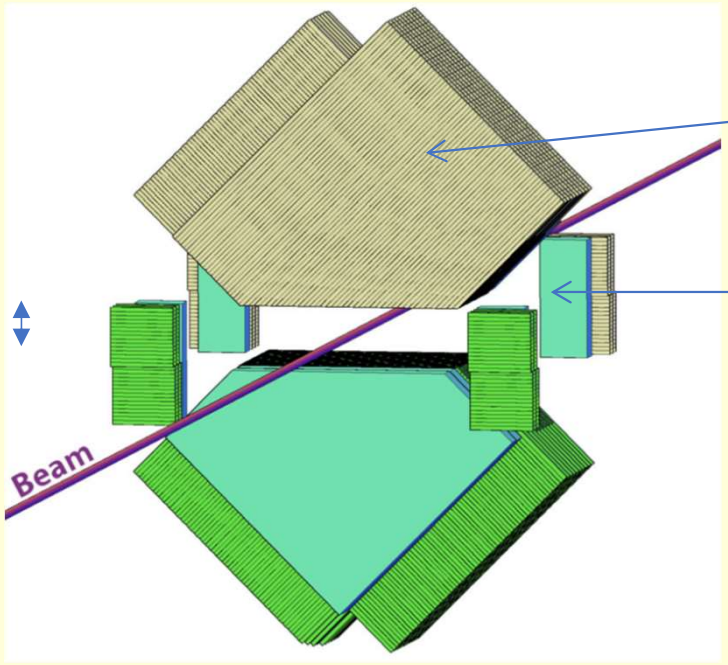
ALFA - Absolute Luminosity For ATLAS



In fact, ALFA is *not* primarily used for ATLAS **luminosity measurement.**
Now done chiefly using **LUCID**: LUminosity Cherenkov Integrating Detector.
(Other methods are also available and have been used.)

- A set of Cherenkov devices with PMTs surrounds each beampipe.
- Van der Meer scans are performed in special runs to measure the shape of the intersecting beams. The beams are steered across each other.
- LUCID counters measure interaction rate as a function of beam separation.
- For given beam intensity, the luminosity can be calculated.

More detail on the ALFA detectors.



e.g. 2 mm

Main detector (MD)

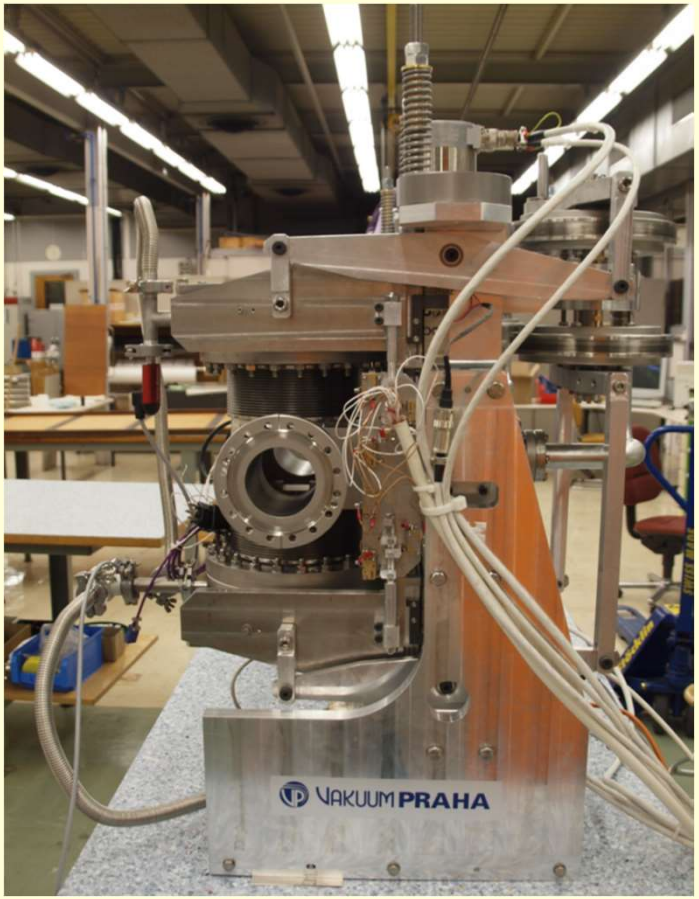
Overlap detector (OD)

Square-shaped scintillating fibres, oriented ±45°. (0.5mm x 0.5mm).
Read out by Multi-Anode Photo-Multiplier Tubes (MAPMTs). Edgeless.

MD: each module has 10 double-sided layers.
A perfect track measurement is to ±30-35 μm in *x* and in *y*

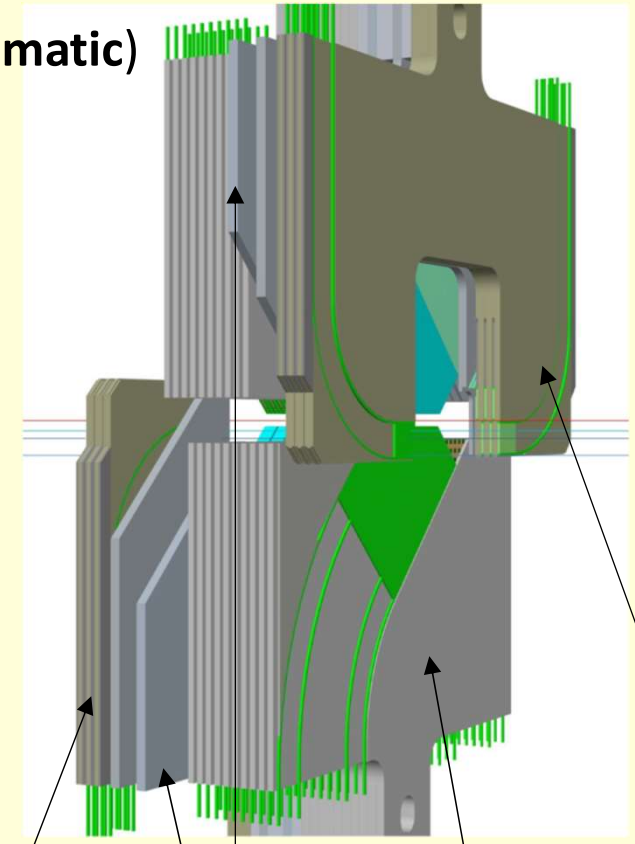
OD: measure the vertical track coordinate using horizontal fibres (3 layers) to determine the vertical distance between the upper and lower main detectors.

Roman Pot system.



Trigger counters are 3mm plastic scintillator tiles.
A coincidence between two diamond-shaped tiles is used.

(**Schematic**)



OD module

Trigger counters

MD modules

OD module

Contained within upper and lower Roman pots under reduced atmospheric pressure.

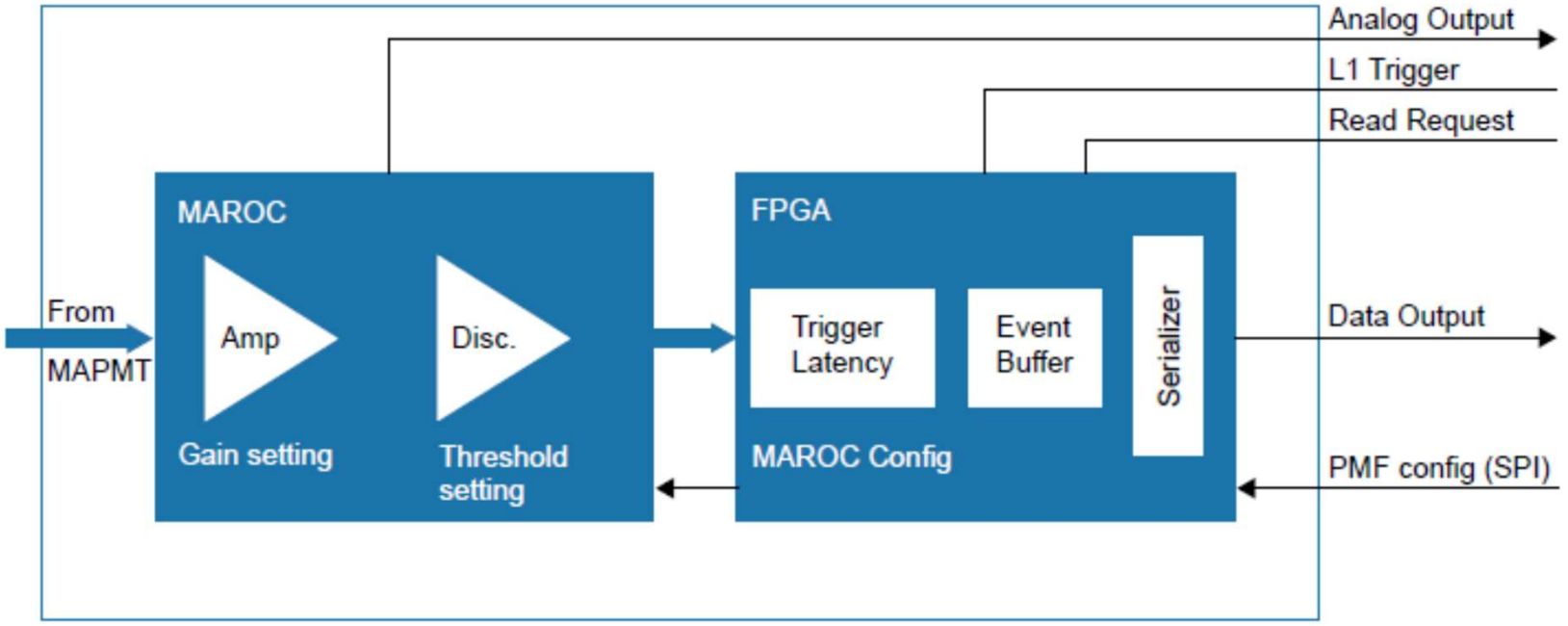
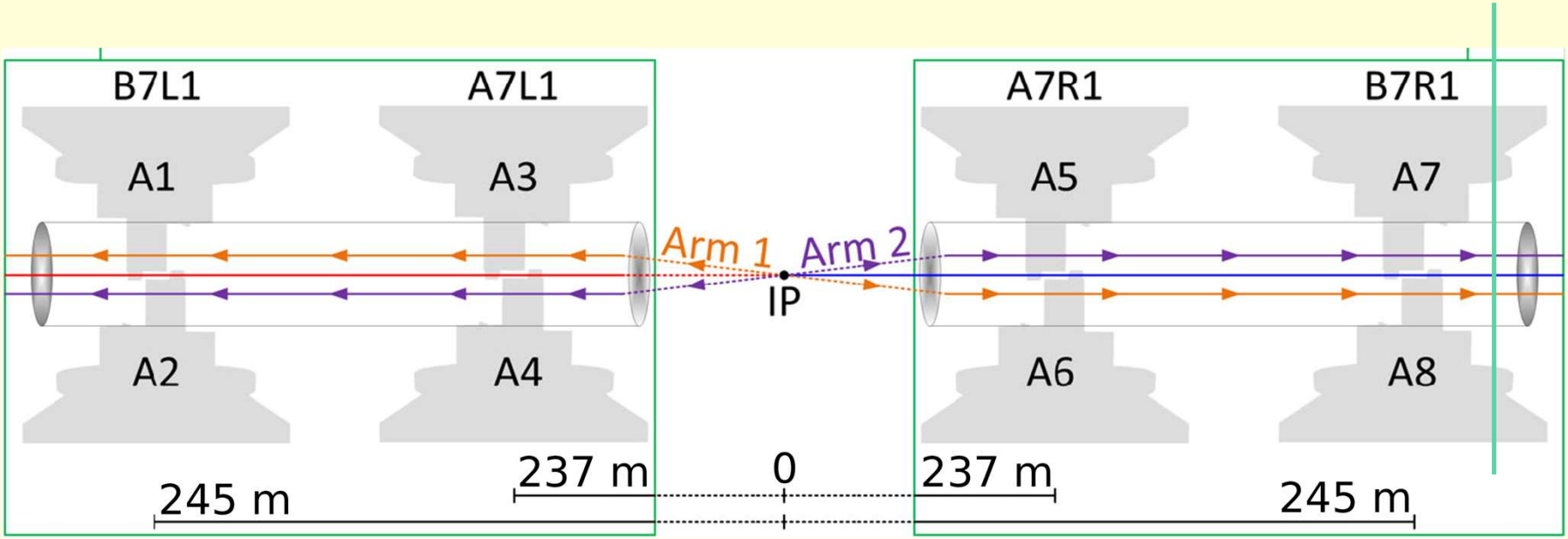


Figure 9. The architecture of the front-end electronics for the readout of the fibre signals from the MAPMTs,

Triggering.

There is a stand-alone mode that ignores the main ATLAS detector.

Otherwise, signals are taken from each module, integrated into the ATLAS trigger system (with latency) and used in appropriate combinations



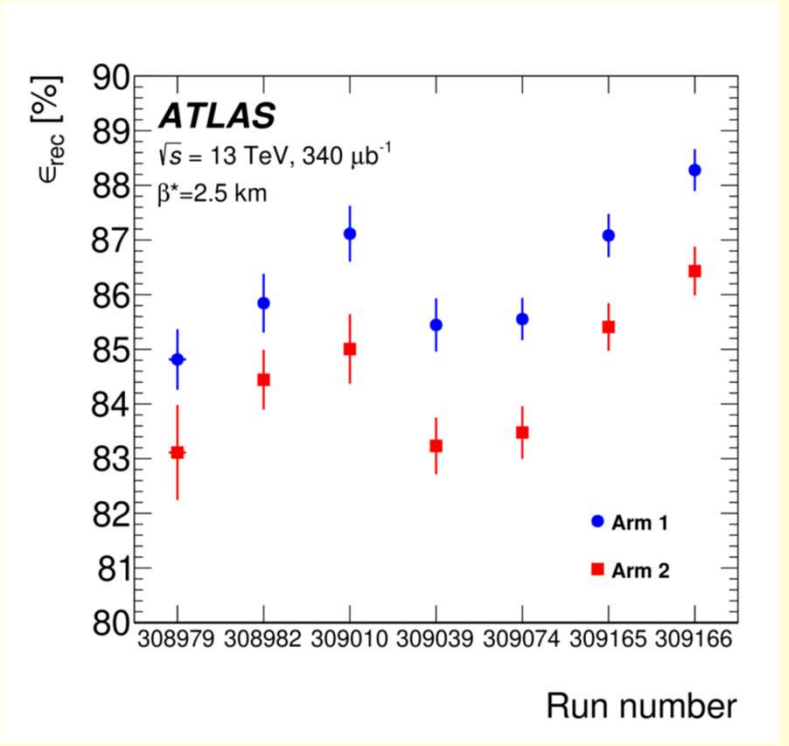
One proton in >=1 ALFA station on each side.

Elastic combinations: Arm1 OR Arm2. i.e.
A1or3 and 6or8 OR A2or4 and 5or7

Anti-elastic combs. A1or3 and 5or7 OR A2or4 and 6or8

Reconstruction efficiency is measured by a tag-and-probe method (well-measured protons on one side as tags for a proton on the other side.)

An elaborate **alignment method** makes use of the overlap counters OD.
"Global tracks" are used, which are back-to-back pairs of tracks, giving alignment accuracy of 5-10 microns.



Systematics: reconstruction efficiency uncertainty is 0.4% - 0.9%, dominated by the evaluation of accidental coincidences and uncertainties in backgrounds, and t-dependent effects.

The tracking accuracy is dominated by the global vertical distance uncertainty (after alignment) of +/- 22 microns.

Data taking

ALFA cannot normally run with high LHC luminosity because the detector is radiation-sensitive.

Also special beam conditions are normally required.

Standard high-lumi LHC running uses beam focussed to a small region at the ATLAS interaction point. Protons at different angles are focussed together and emerge in a broad beam.

ALFA running needs to measure pp → pp elastic cross sections down to low scattering angles θ. Outgoing protons at different θ must be detected at different positions *y* at ALFA !

→ "parallel to point" vertical focussing from the IP.
Requires large values of the beam parameter β^* at the IP.

Implies larger beam size at IP and therefore low pile-up, also needed for these measurements.

Results

1) Measurement of the total cross section from elastic scattering in pp collisions at √s = 7 TeV with the ATLAS detector.
Nucl. Phys. B (2014) 486. σ_{tot} = 95.35 ± 1.36 mb
One dedicated run at at β^* = 90 m, integrated luminosity =80 μb^{-1}.

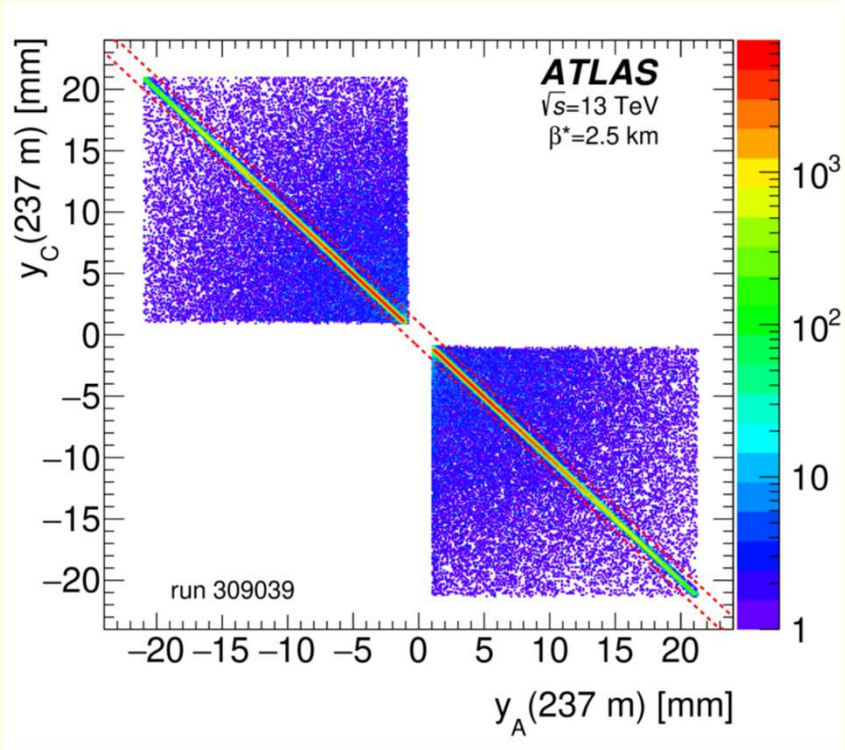
2) Measurement of the total cross section from elastic scattering in pp collisions at √s = 8 TeV with the ATLAS detector.
Phys. Lett. B 761 (2016) 158. σ_{tot} = 96.07 ± 0.92 mb
One dedicated run at at β^* = 90 m, integrated luminosity =500 μb^{-1}.

3) Measurement of the total cross section and ρ-parameter from elastic scattering in *pp* collisions at √s=13 TeV with the ATLAS detector.
arXiv 2207.12246, to appear in EJPC, σ_{tot} = 104.7 ± 1.1 mb, ρ = 0.098 ± 0.011.
7 dedicated runs at β^* = 2500 m, total integrated luminosity =340 μb^{-1}

4) Measurement of differential cross sections for single diffractive dissociation in √s= 8 TeV *pp* collisions using the ATLAS ALFA spectrometer.
JHEP 2020 (2020) 42
As 2)

5) Measurement of exclusive pion pair production in proton–proton collisions at √s = 7 TeV with the ATLAS detector.
arXiv 2212.00664, to appear in EJPC
As 1)

Selection of elastic pp events in ALFA

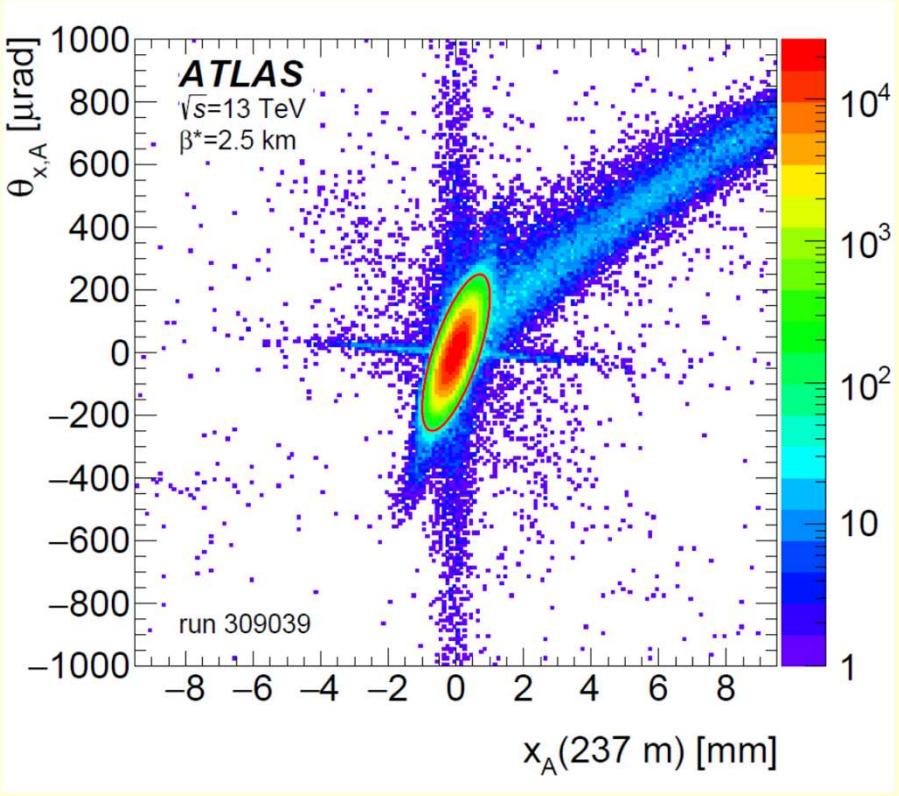


Quality cuts on the two proton tracks in the two ALFA stations.

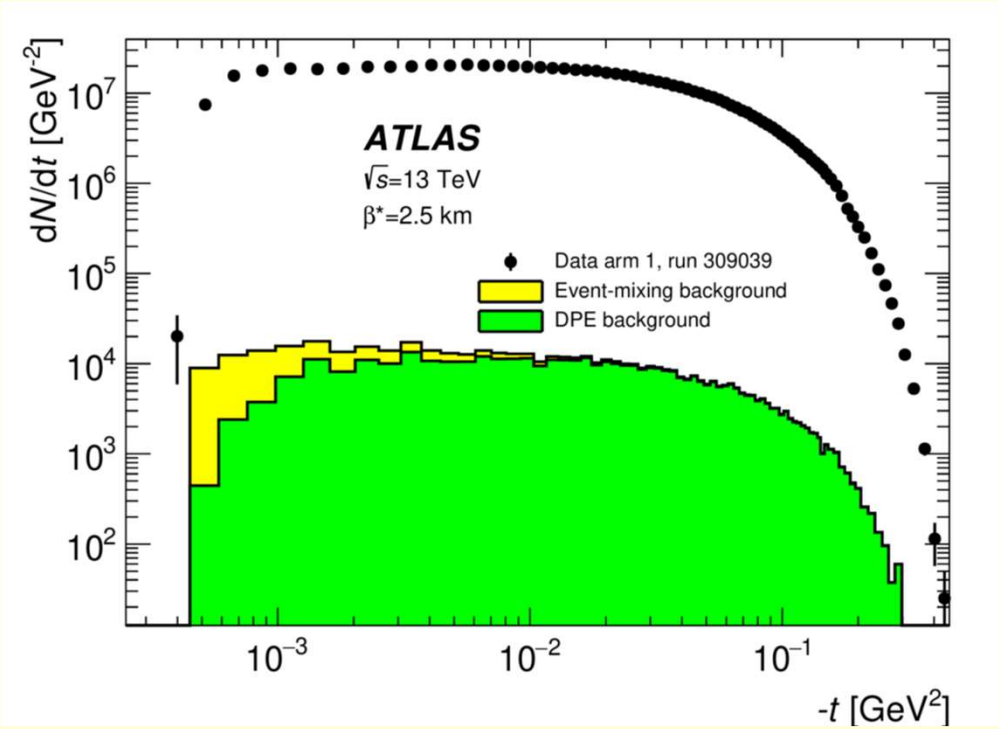
Geometric acceptance cuts.

Select back-to-back events, as indicated.
Also selection on x vs θ_x

Elastic events are within ellipse:



Background levels



Sources of **background**:

- accidental halo+halo and halo+SD coincidences (data-driven, determined with an event-mixing method)
- central diffraction (MC simulation)

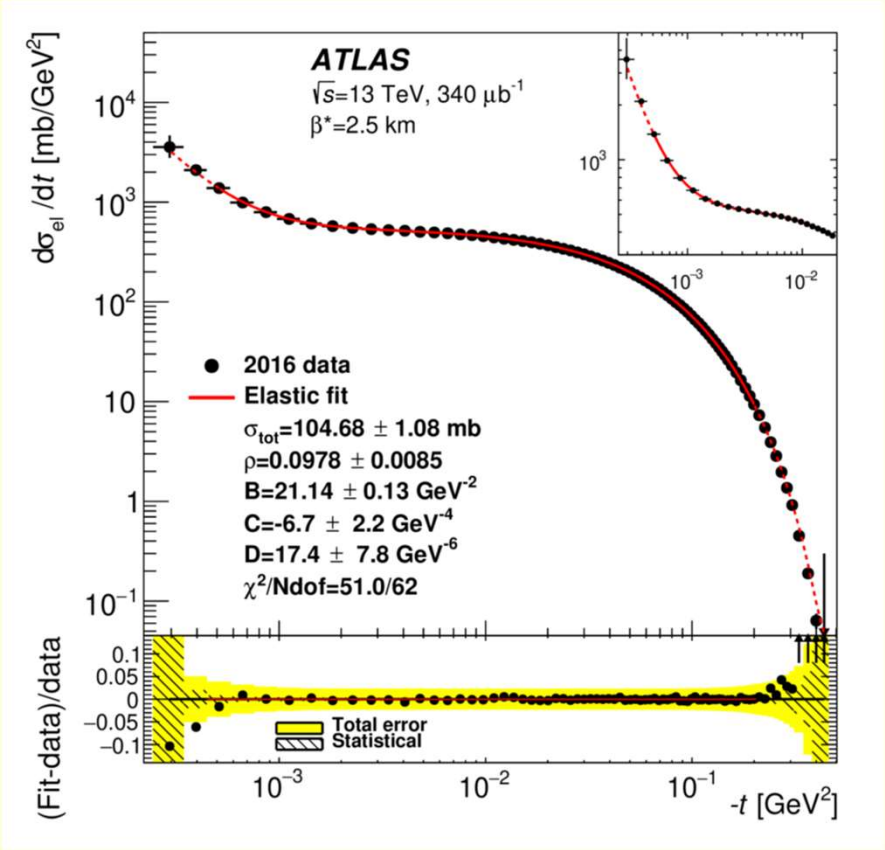
Reconstruct *t* from beam optics and event kinematics using standard tracking of effective beam optics.

Evaluation of results

$-t = (\theta_x^2 + \theta_y^2)p$ at IP.

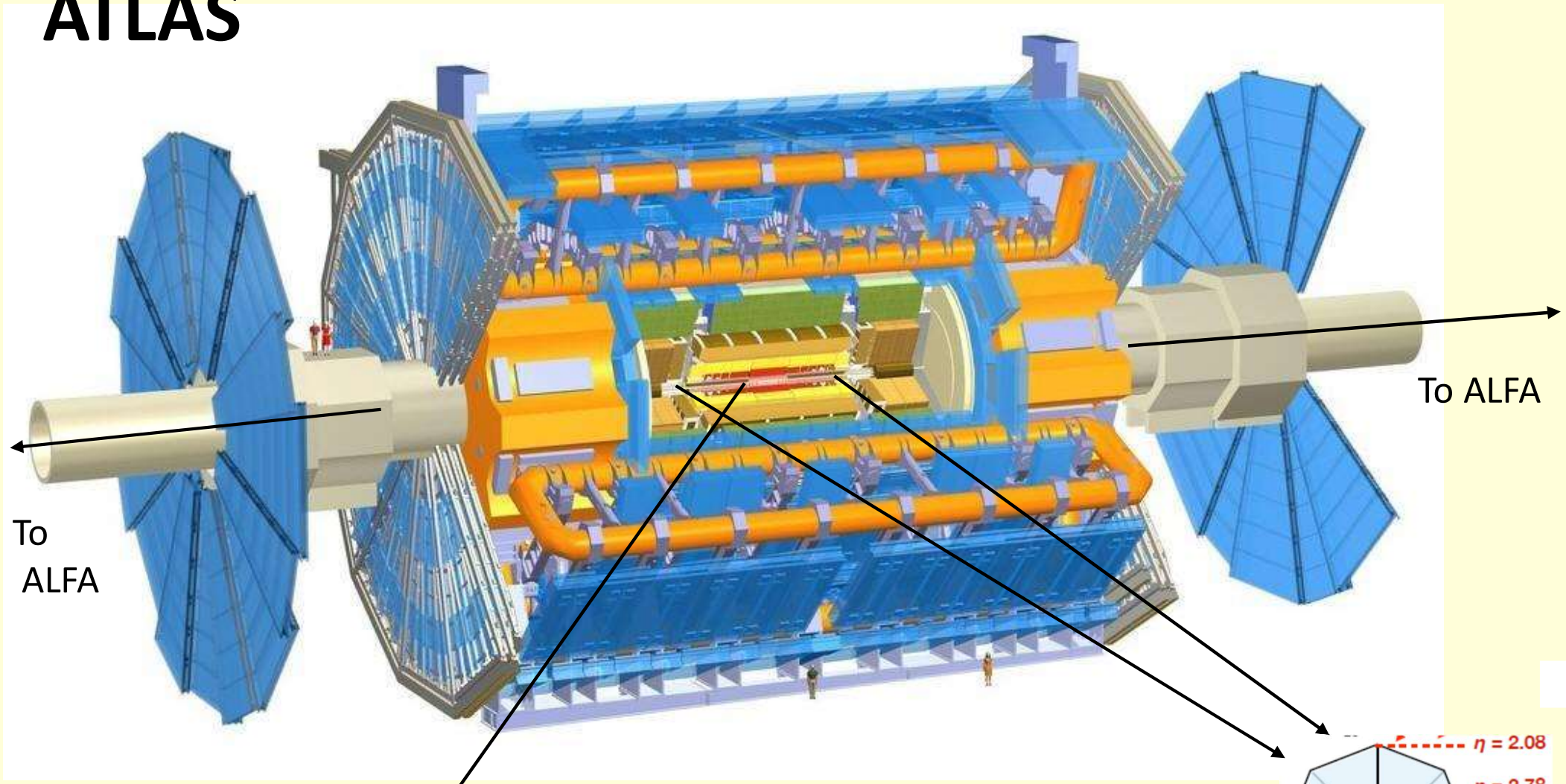
$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{M^{-1}[N_i - B_i]}{A_i \times \epsilon^{\text{reco}} \times \epsilon^{\text{trig}} \times \epsilon^{\text{DAQ}} \times L_{\text{int}}}$$

(*M* corrects for unfolding procedure in *t*)

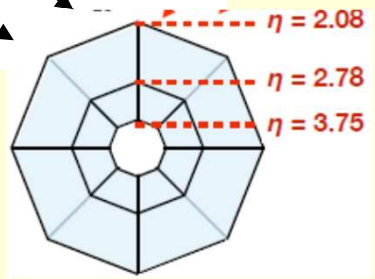


Further details of results – see talk by Tom Sykora.

ATLAS



Inner detector
(tracker)



MBTS at z=±3.6m
2.1 < |η< 3.8

Measurement of exclusive process $pp \rightarrow pp\pi^+\pi^-$

Trigger:

Elastic - ALFA coincidence of detectors in an elastic combination.
Anti-elastic – signal in any ALFA detector, prescaled by 15

In ALFA detectors:

One good quality track on each side

In ATLAS Inner Detector:

Two oppositely charged tracks, taken as pions,
satisfying $|\eta(\pi)| < 2.5$, $p_T(\pi) > 0.1$ GeV, $2m\pi < 2.0$ GeV. (fiducial)

Quality requirements on the pion tracks were imposed.

MBTS veto:

At most one hit in the combined inner MBTS scintillators, to remove diffractive-dissociative and non-diffractive events.

Overall momentum balance:

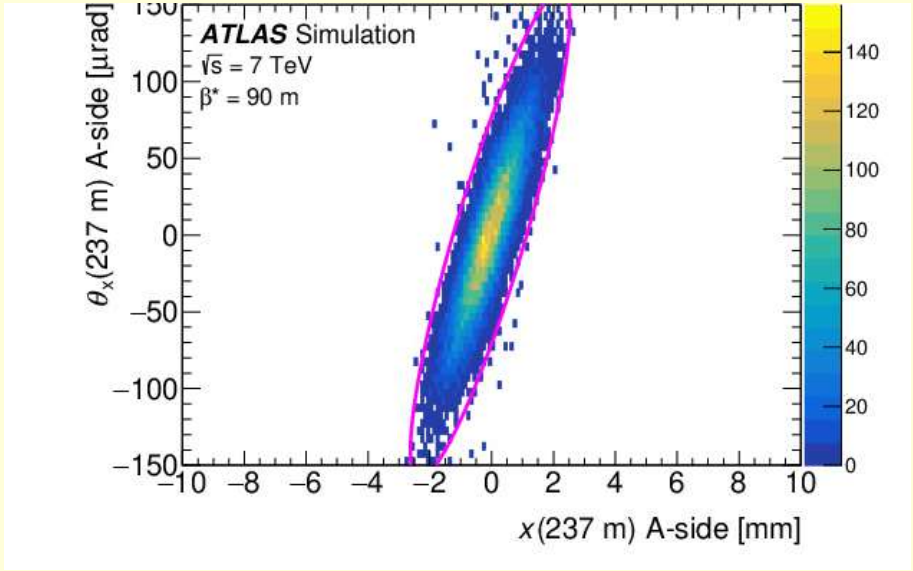
$pp\pi^+\pi^-$ momentum balance in x and in y consistent with zero (±3,5σ)

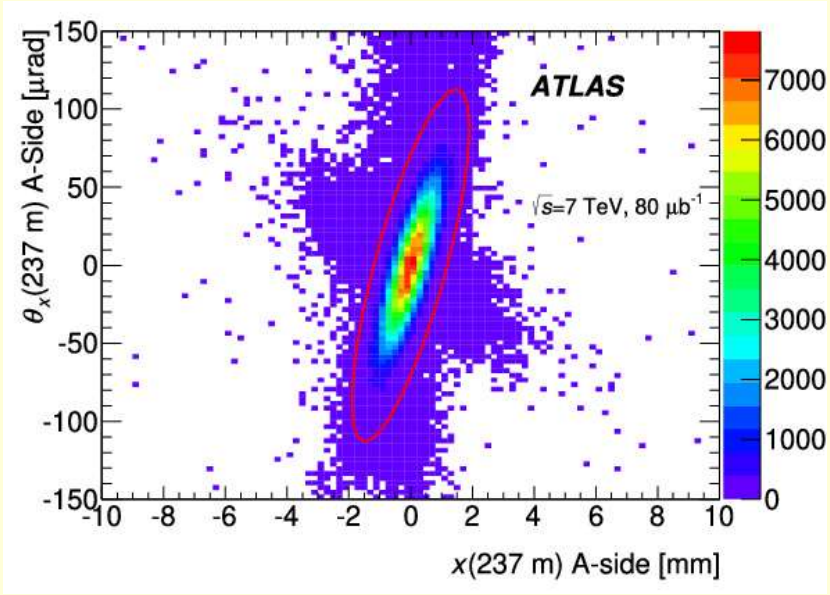
Conditions on ALFA tracks

Track condition:

Track must have sufficient hits in MD layers, with limit on number of multiple hits in a layer

Geometric condition:



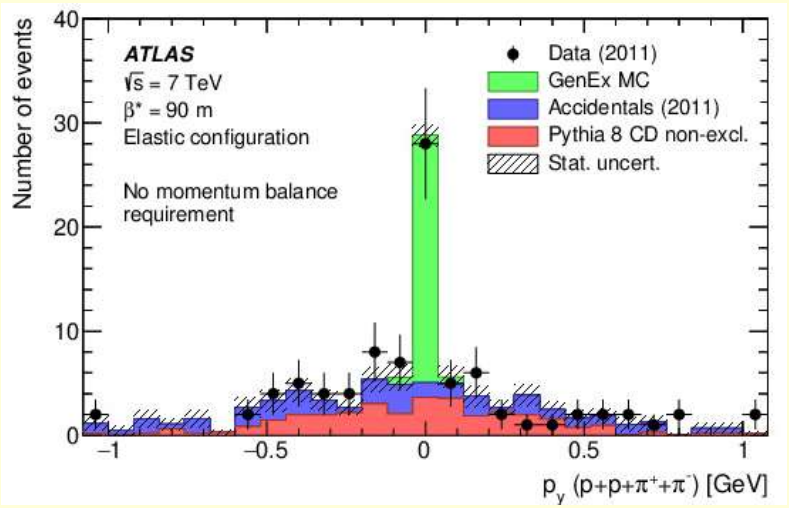


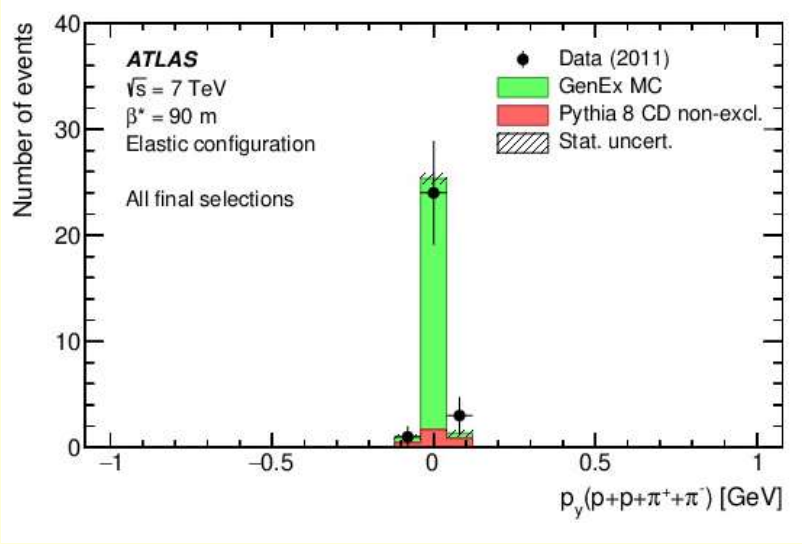
(left) calculated x vs θ_x (right) for all protons.

This red ellipse is imposed on the ALFA tracks to reduce background.

Fiducial condition: cuts of typically $0.08 < |p_y| < 0.26$ GeV are imposed.

Final results for elastic combination.





Before and after final momentum balance cut.

To note:

- The cuts are *very* effective at removing background.
- A cut on the MBTS counts was essential.
- Low statistics from this short run in 2011 at 7 TeV
  (4 hours at high β^*, $\mu = 0.035$)
- Feasibility of the measurement has been demonstrated.

Uncertainties

Source of uncertainty %	elastic	anti-elastic
Systematic:		
Trigger efficiency ϵtrig	±0.1	±0.3
Background determination	±3.5	±3.5
Signal and background corrections:		
Beam energy	±0.1	±0.1
Inner Detector material	+4.8	+4.1
Veto on MBTS signal	±1.3	±2.0
ALFA single-track selection	±0.9	±0.9
ALFA reconstruction effic.	±0.9	±0.8
ALFA geometry selection	±0.5	±0.5
Optics	±1.1	±1.0
Overall syst uncertainty	+6.4	+6.0
	−4.2	−4.4
Statistical uncertainty	±21.2	±61.6
Theoretical modelling	±2.8	±8.0
Luminosity	±1.2	±1.2

All systematics quite small but ID material is biggest.

Statistics on anti-elastic are poor, result is of right order.

For the future

- A final run with ALFA is planned early in LHC Run 3 using $\beta^* = 3/6$ km. Improved ρ measurement, with total cross section and parameters of elastic pp scattering.

- Exclusive pion pair analysis using Run 2 dataset.
  -- resonance analysis
  -- possible glueball search
  -- possible search for other exclusive final states.

- Data at 900 GeV (2018) $\beta^* = 50/100$m for total cross section and ρ.

- High-luminosity running at 13 GeV for study of dip/bump in t distribution.

Summary

ALFA has worked extremely successfully and has generated excellent results on pp elastic scattering. More to come!

First completely exclusive measurements of diffractive pion pair production at LHC have been performed.

The analysis methods are shown to work well.

Much more statistics to be analysed in Run 2 data.

Special run coming in Run 3.

Backup

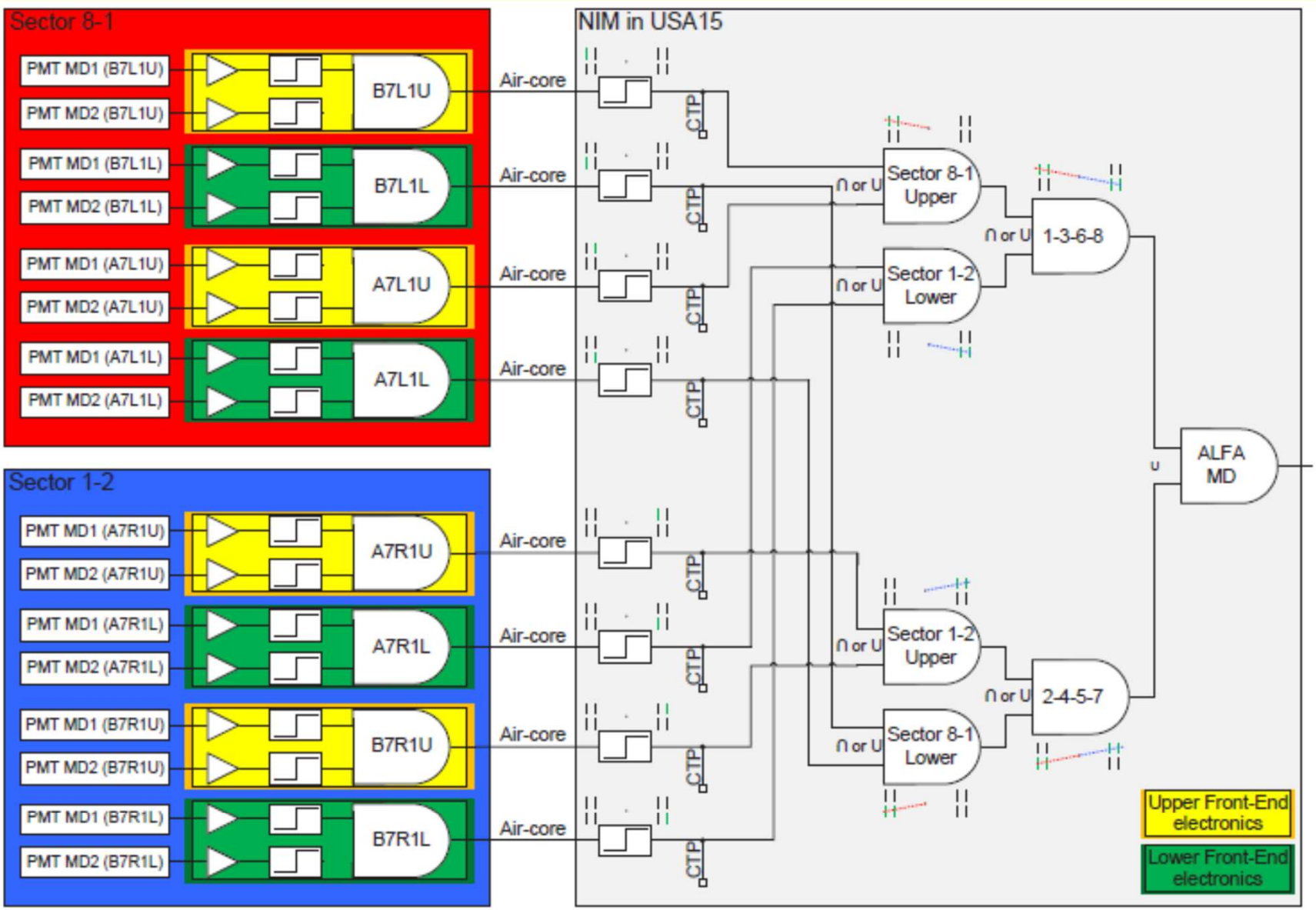


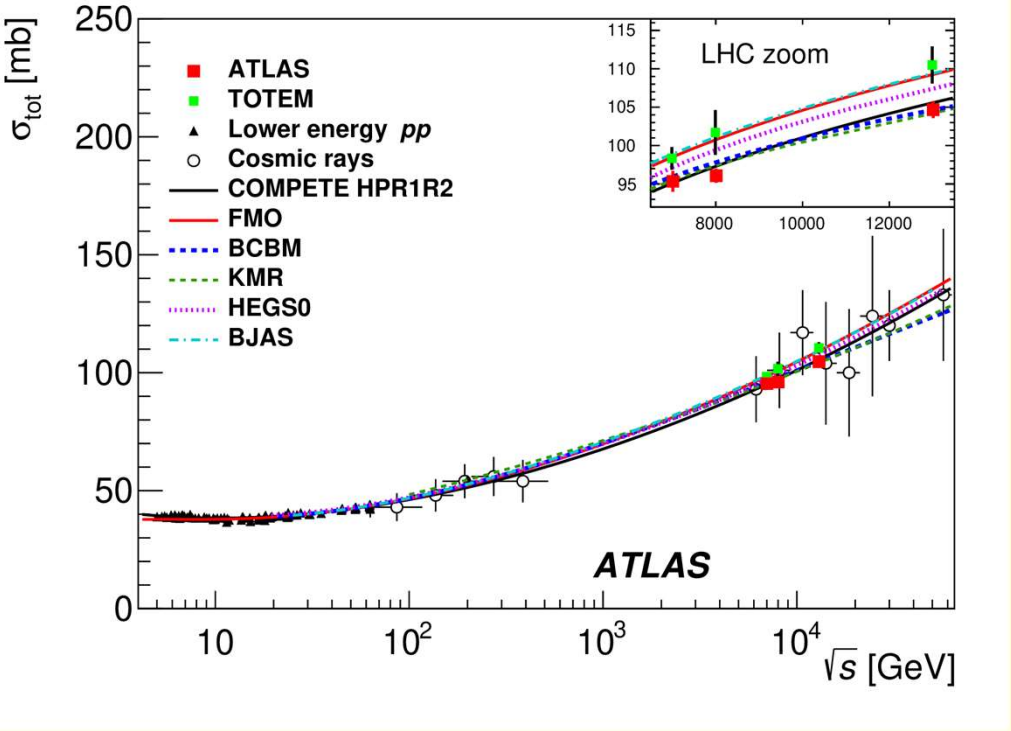
Figure 19. The logic scheme of the MD standalone trigger system. The two left boxes contain the local signal handling in the triggerboards at the stations. The right box contains the tree levels of coincidences for the formation of the final trigger signal.

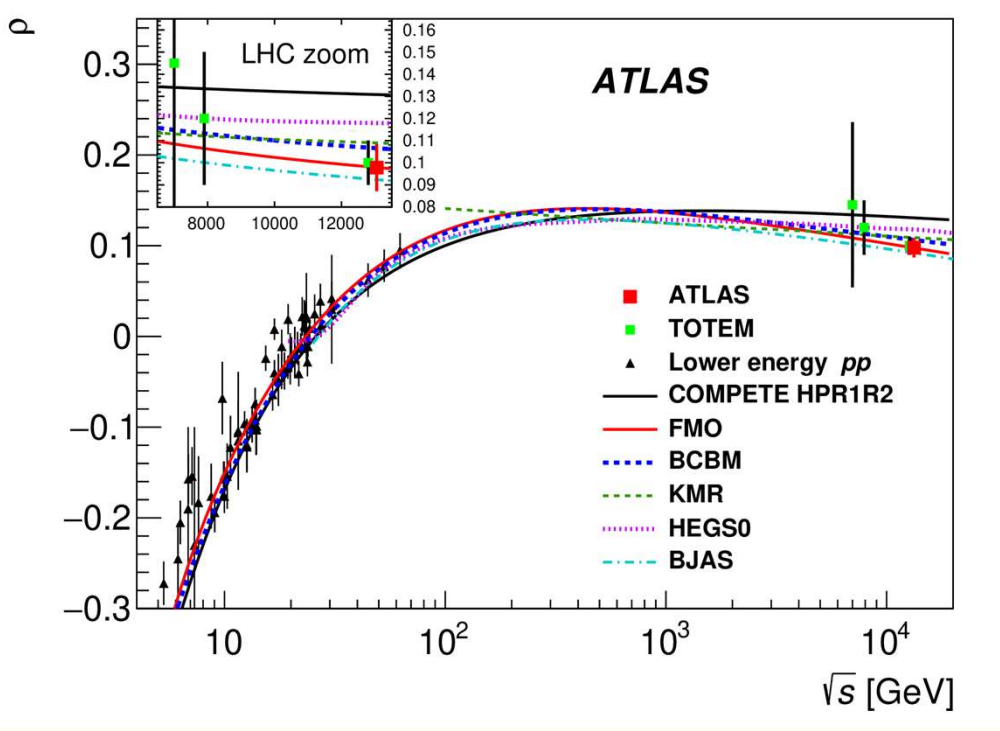
Finally we can get the **total cross section** using the Optical theorem:

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

where

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





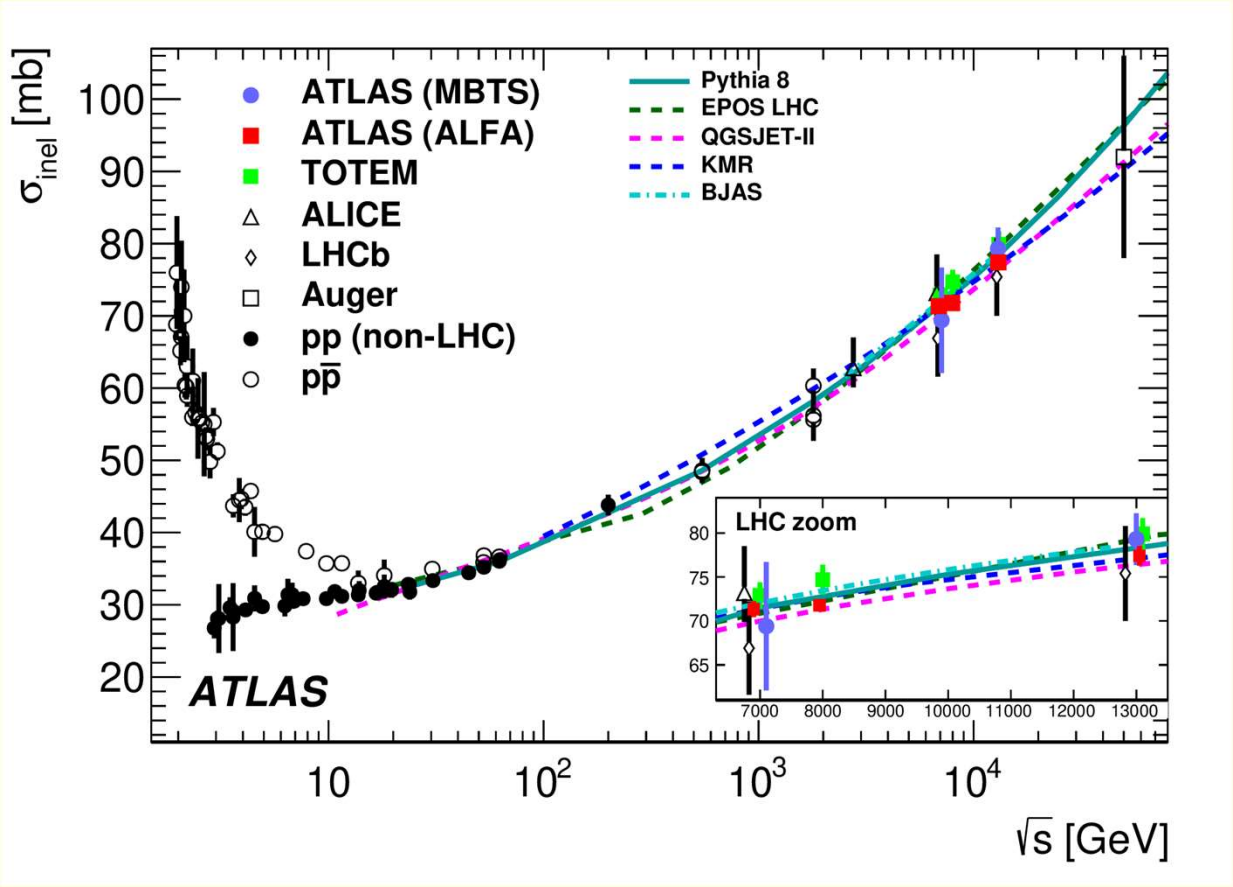
- The widely used model COMPETE is in poor agreement with above (predicts $\rho = 0.13$)
- Model with Odderon tuned to TOTEM is in poor agreement with ATLAS
- ALFA and TOTM disagree at 2.2 σ level.

Total elastic and inelastic cross sections

Can perform a (model-dependent) integration of the nuclear part of the elastic cross section over all phase space to get:

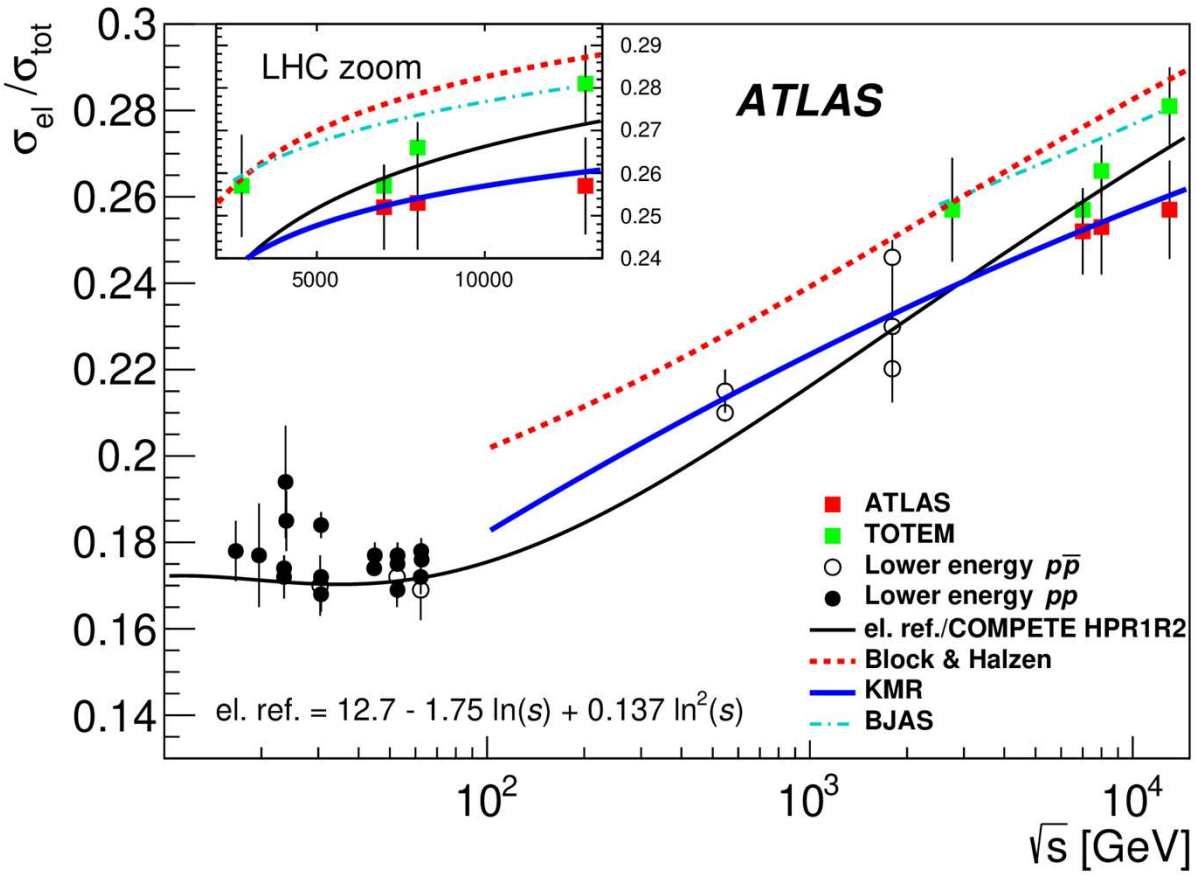
$$\sigma_{\mathrm{el}}^{\mathrm{extr}} = 27.27 \pm 1.10\ (\mathrm{exp.}) \pm 0.30\ (\mathrm{th.})\ \mathrm{mb}.$$

which can be subtracted off the total measured cross section to give the inelastic xsec.



Apparently better agreement

Ratio of elastic to total:



Data not in perfect agreement, and the models also differ!

Conclusions from total pp cross section measurements from ATLAS:

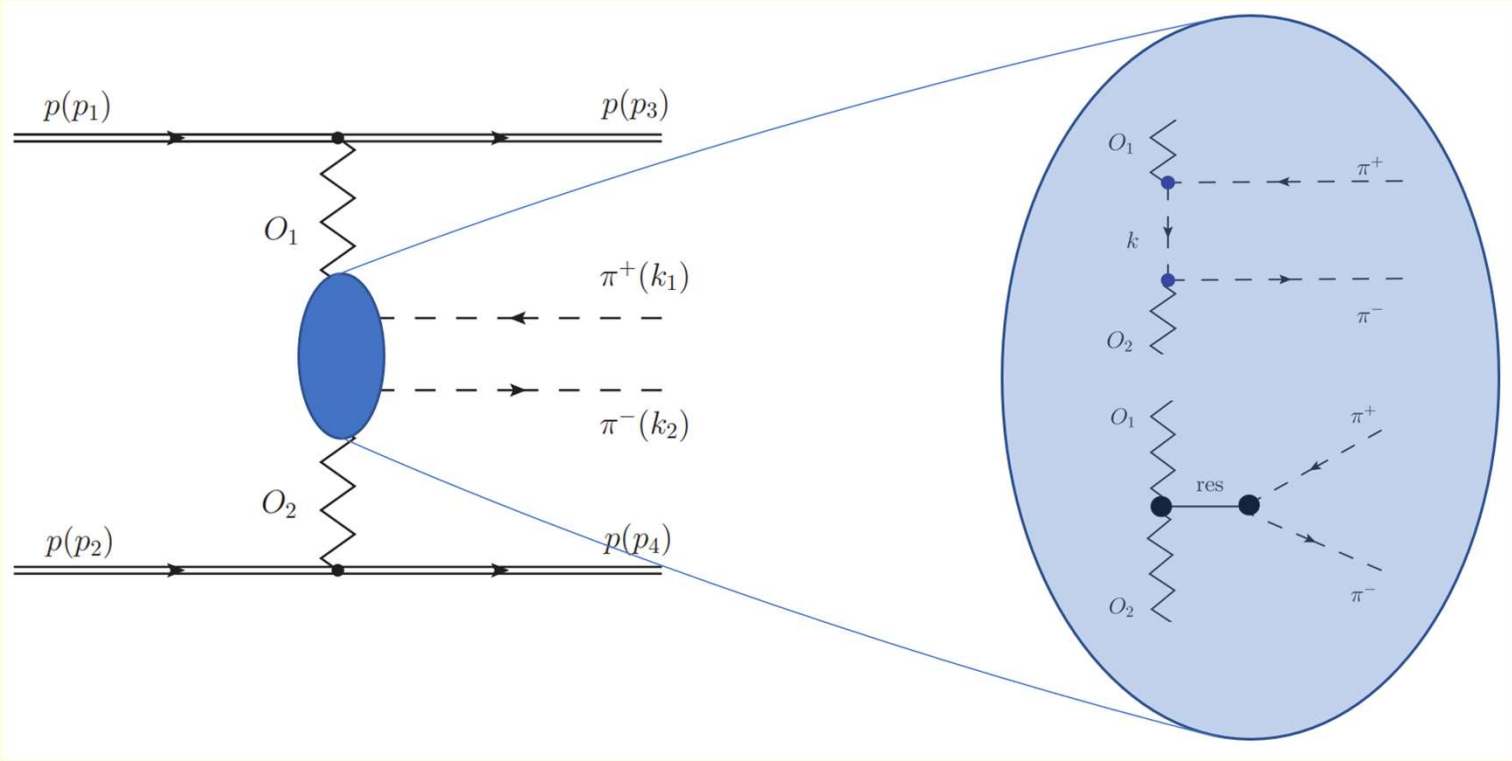
- Most precise LHC measurements of σ_{tot} , measured numbers from ATLAS are:

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

- ATLAS values of ρ and σ_{tot} are in tension with COMPETE

- σ_{tot} somewhat lower than TOTEM, largely due to normalisation

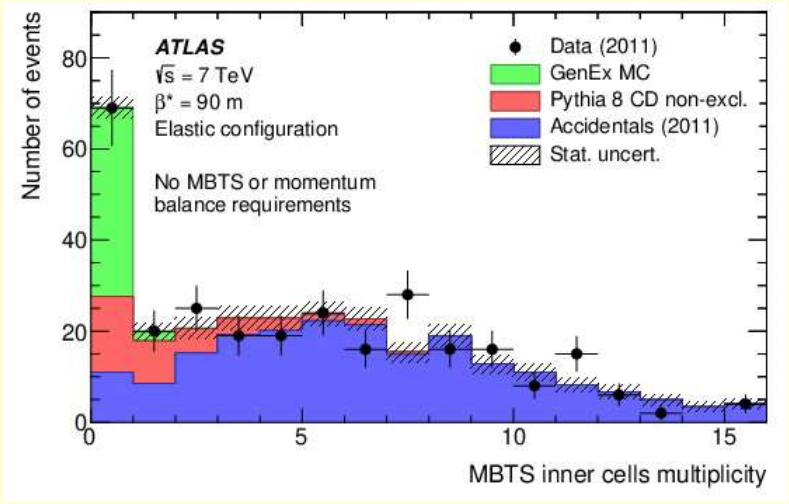
The exclusive diffractive dipion process at the LHC

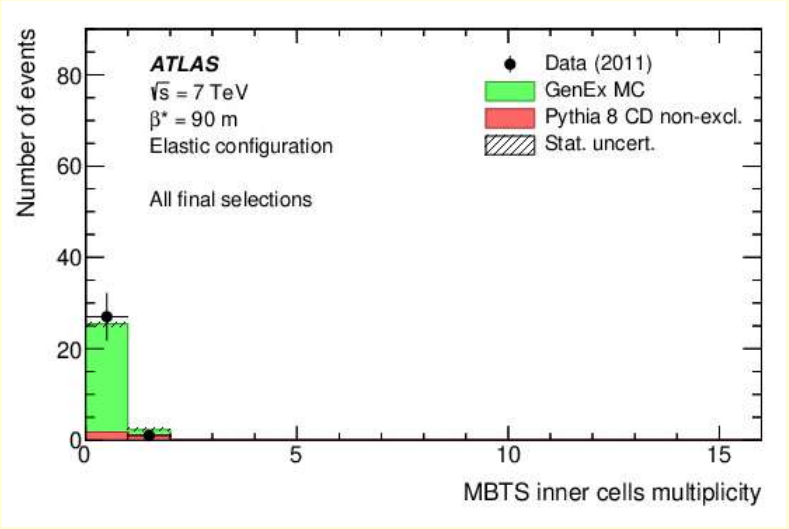


We measure this by measuring the two pions in the ATLAS inner detector and both forward protons in the ALFA detectors.
Proton excitation processes are excluded.

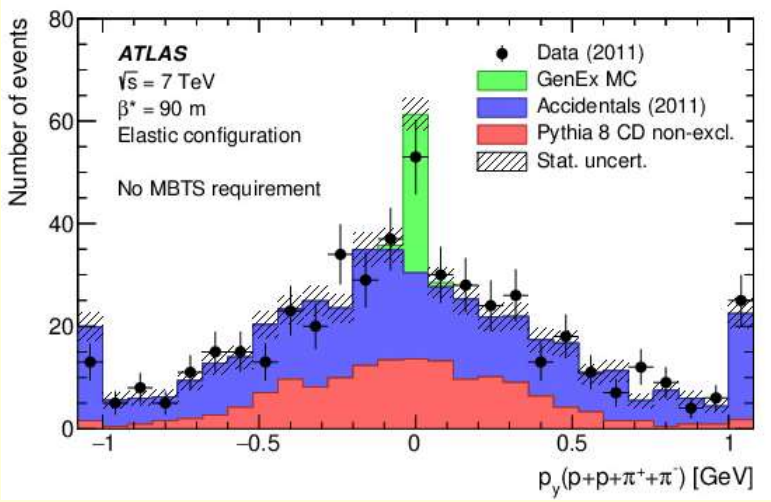
Background removal and evaluation of results. Elastic configuration

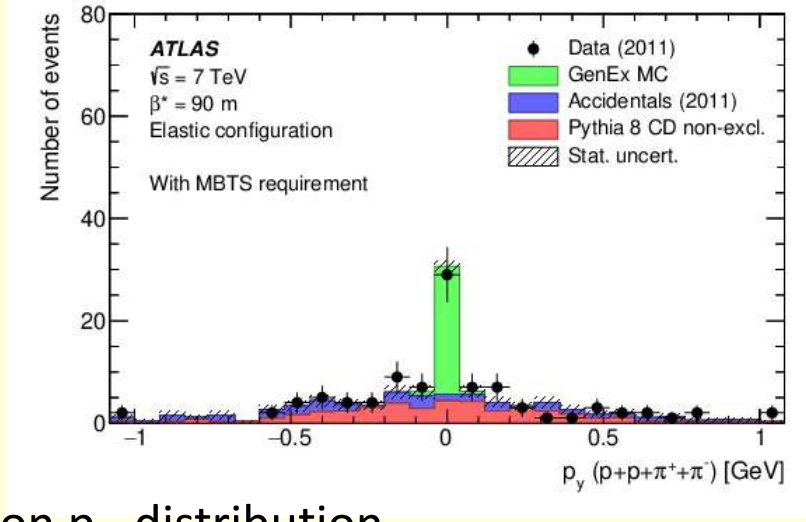
Background modelled in terms of PYTHIA 8 and “accidentals” formed from central pion pairs + ALFA proton pairs from random events.





Effect of MBTS cut and other final requirements on MBTS count.





Effect of MBTS requirement on p_T distribution

Results

Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) ± 0.1 (lumi) ± 0.1 (model)
GenEx $\times$ 0.22 (absorptive correction)	1.5
Dime	1.6
Anti-elastic configuration	
measurement	9 ± 6 (stat) $^{+1}_{-1}$ (syst) ± 1 (lumi) ± 1 (model)
GenEx $\times$ 0.22 (absorptive correction)	2
Dime	3

Comments:

- The absorptive correction included here was recommended by the author
- These are just first measurements,
- The MC appears a little low but there are parameters that could be varied.