MPI@LHC MADRID Nov 14-18, 2022

Elastic and exclusive forward proton measurements with ATLAS

On behalf of the ATLAS Collaboration

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Results discussed

1) **Measurement of exclusive pion pair production in proton–proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector**
(CERN-EP-2022-140, to be submitted)

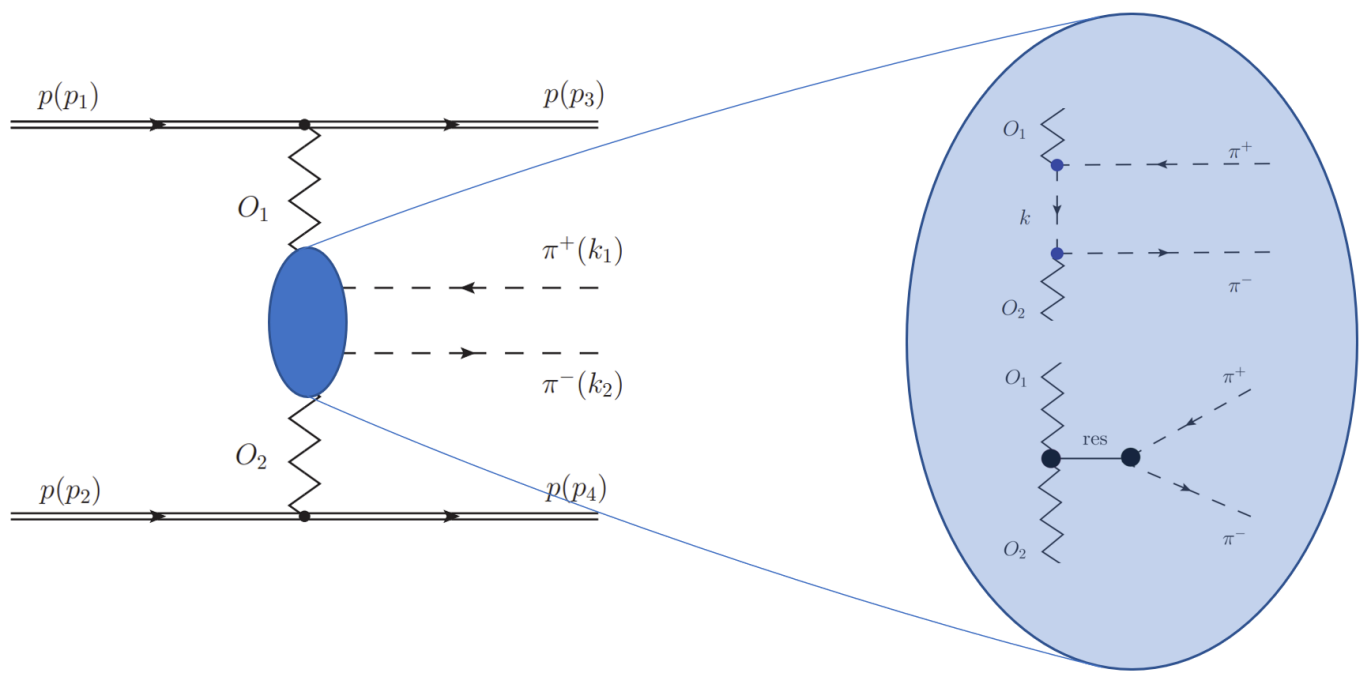
2) **Measurement of the total cross section and ρ-parameter from elastic scattering in *pp* collisions at $\sqrt{s}$=13 TeV with the ATLAS detector** (arXiv 2209.07874, to appear in EJP)

Both measurements have employed the ALFA forward detector system in ATLAS using special low-pile-up runs.

(1) One dedicated run at at β^* = 90 m, integrated luminosity =80 μb^{-1}

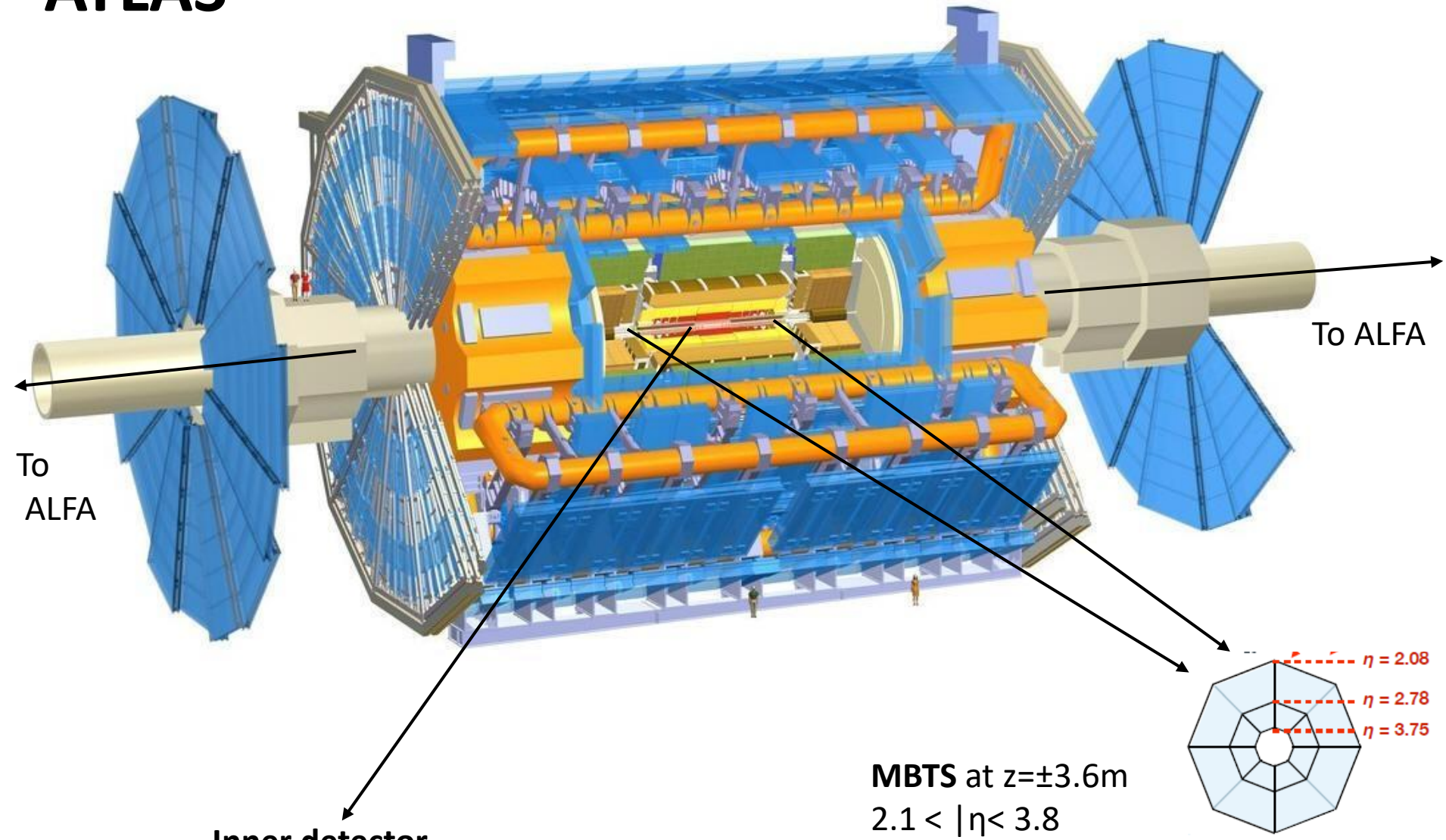
(2) 4 dedicated runs at β^* = 2500 m, integrated luminosity =340 μb^{-1}
b 1, 6.8 million elastic scattering

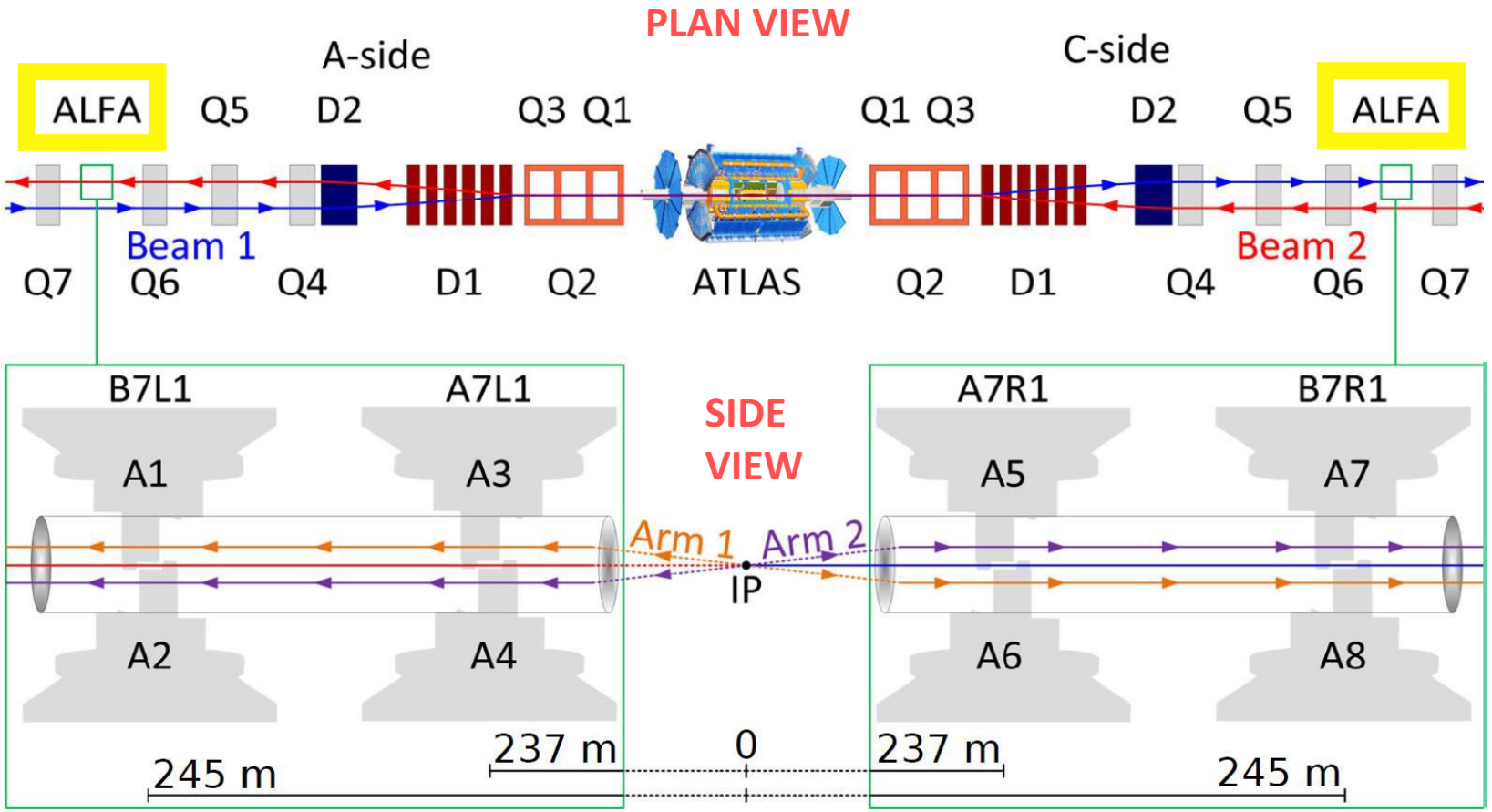
The exclusive diffractive dipion process at the LHC



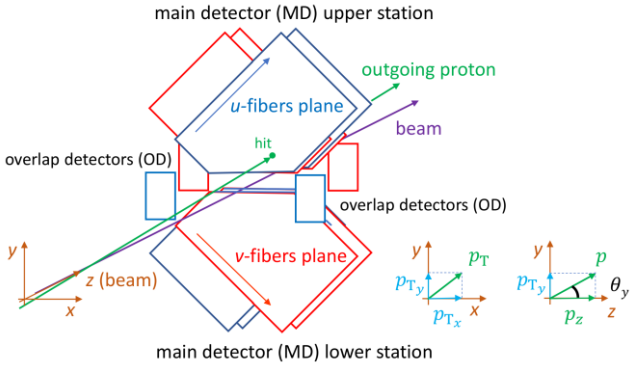
We measure this by measuring the two pions in the ATLAS inner detector and both forward protons in the ALFA detectors.
Proton excitation processes are excluded.

ATLAS


To ALFA
To ALFA
Inner detector
(tracker)
MBTS at z=±3.6m
2.1 < |η< 3.8
η = 2.08
η = 2.78
η = 3.75



(Vert scattered protons)



One proton in both ALFA stations on each side.

Elastic combinations: A1+3+6+8 and A2+4+5+7

Anti-elastic combs. A1+3+5+7 and A2+2+6+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 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.

In ALFA detectors:

One good quality track on each side (see later)

MBTS veto:

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

Overall momentum balance:

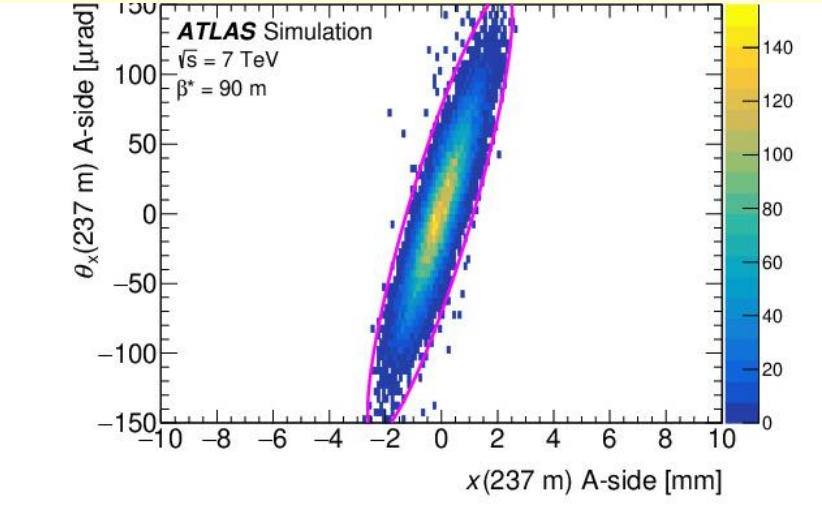
$pp\pi^+\pi^-$ momentum balance in x and in y consistent with zero (±3,5σ)

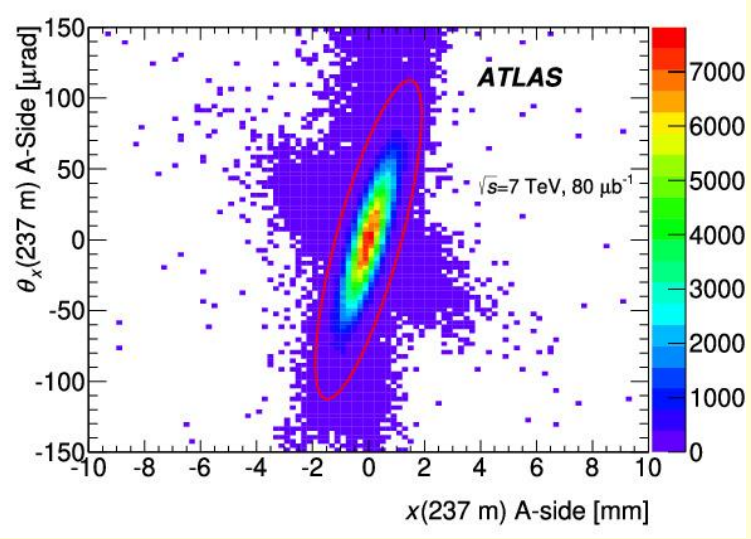
Conditions on ALFA tracks

uv condition:

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

Geometric condition (for all stations):





(left) calculated x vs θ_x (right) as seen in 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.

Monte Carlo simulations

GENEX:
(Model of Lebiedowicz et al)
Exclusive production of pion and kaon pairs, Reggeon exchange.
No absorption correction in MC, no rapidity-gap survival factor.

Used as the baseline generator for efficiency corrections

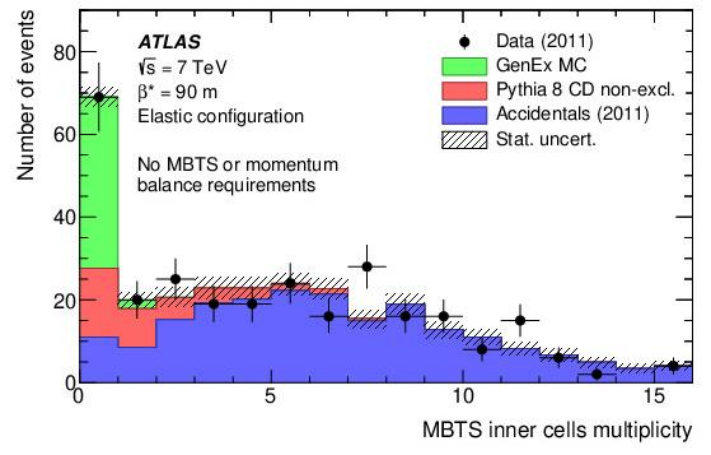
DIME (106):
Similar to GENEX but with more variant possibilities.
“Orear –like” meson form factor used here.

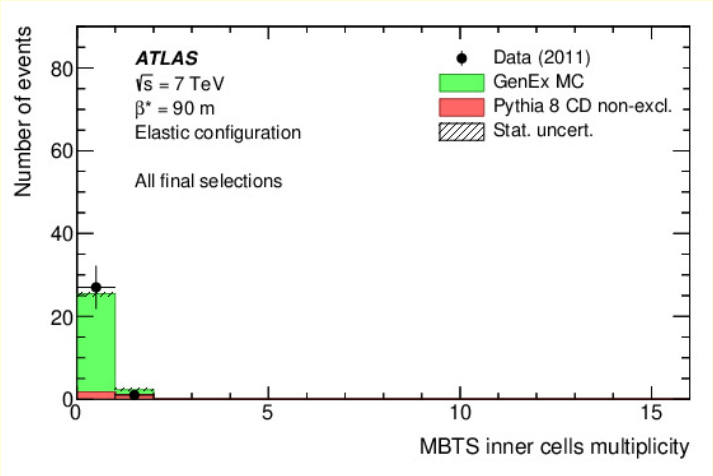
Used for systematics evaluation.
Absolute normalisation not required in either case.

PYTHIA 8
Used for central diffractive background calculations

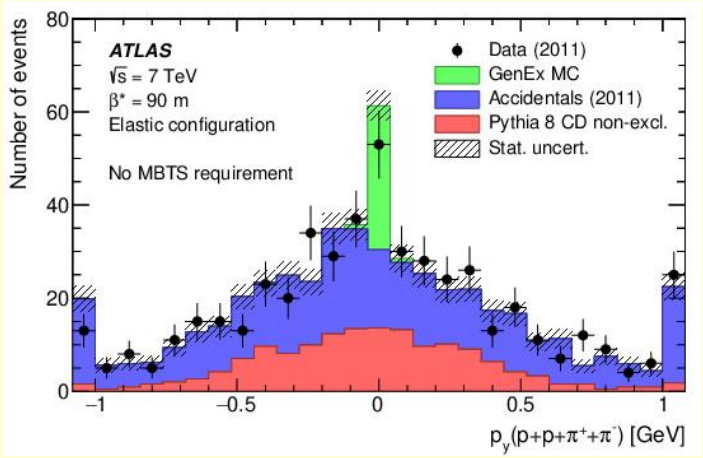
Background removal and evaluation of results. Elastic configuration

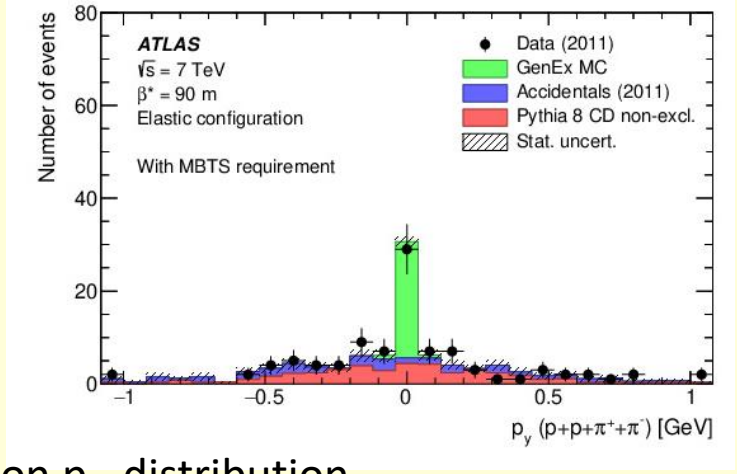
Background modelled in terms of PYTHIA 8 and “accidentals” formed from central pion pairs + ALFA proton pairs from random events.





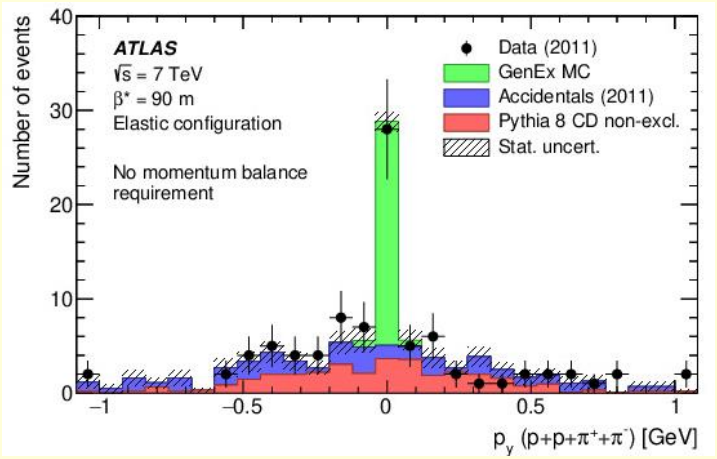
Effect of MBTS cut and other final requirements on MBTS count.

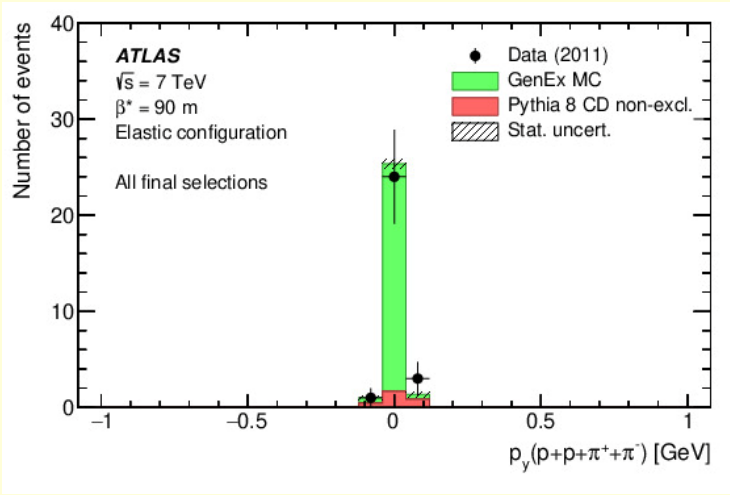




Effect of MBTS requirement on p_T distribution

Final results for elastic combination.





Before and after final momentum balance cut.

To note:

- The cuts are *very* effective at removing background.
- All backgrounds data-driven or fitted to data.
- Low statistics from this very short run in 2011 at 7 TeV (4 hours at high β^*, $\mu = 0.035$)
- Cross sections calculated using GENEX for acceptances.
- 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 and our result is purely indicative. (Prescaling factor)

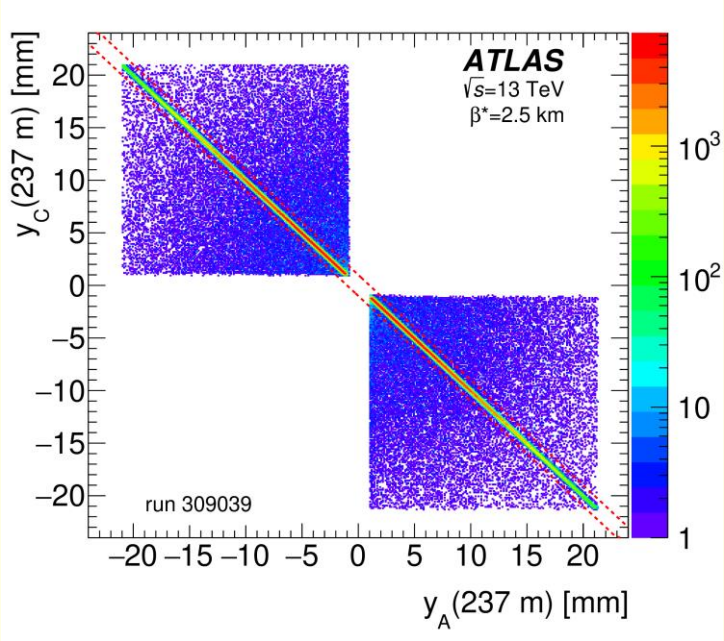
Results

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.

Elastic pp events in ALFA at 13 TeV

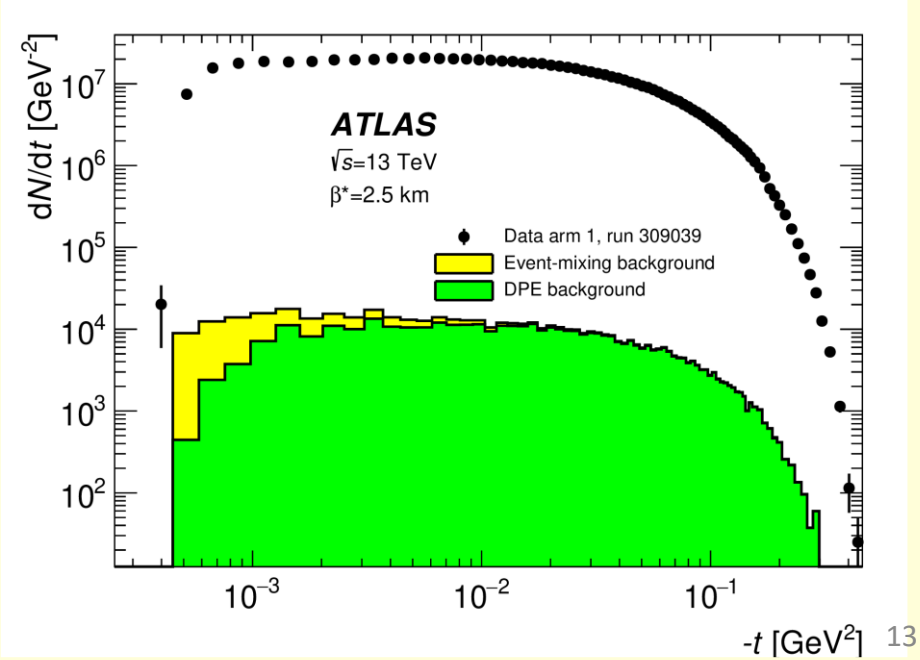


Quality cuts on the two protons in the two ALFA stations.

Geometric acceptance cuts.

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

Reconstruct *t* from beam optics and event kinematics.



Sources of **background**:

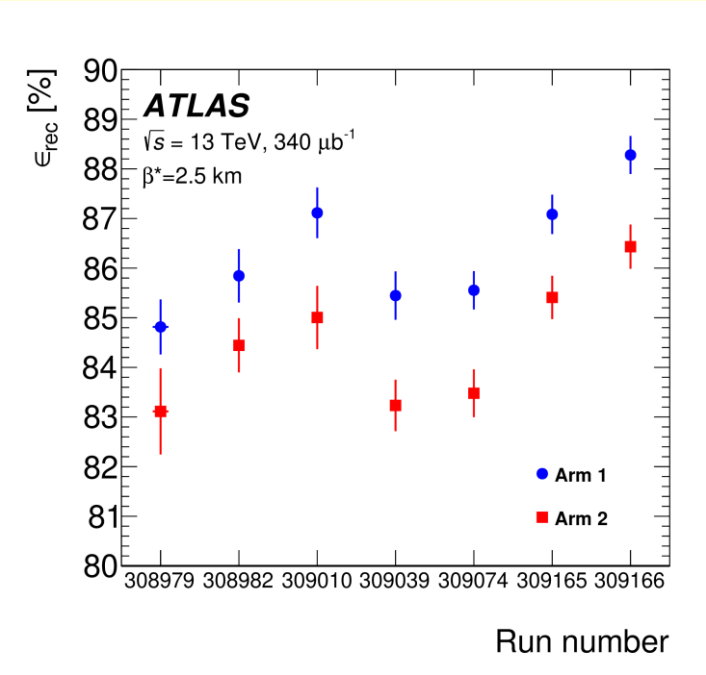
- accidental halo+halo and halo+SD coincidences (data-driven, determined with an event-mixing method)

- central diffraction (MC simulation)

The **ATLAS Luminosity** L is measured with LUCID, a forward counter system wrapped around the beampipe and calibrated using special van der Meer scans of the beams. L_{int} = 339.9 ± 0.1 (stat.) ± 7.3 (syst.) μb^{-1}

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 overlap counters on each horizontal side of the beam.



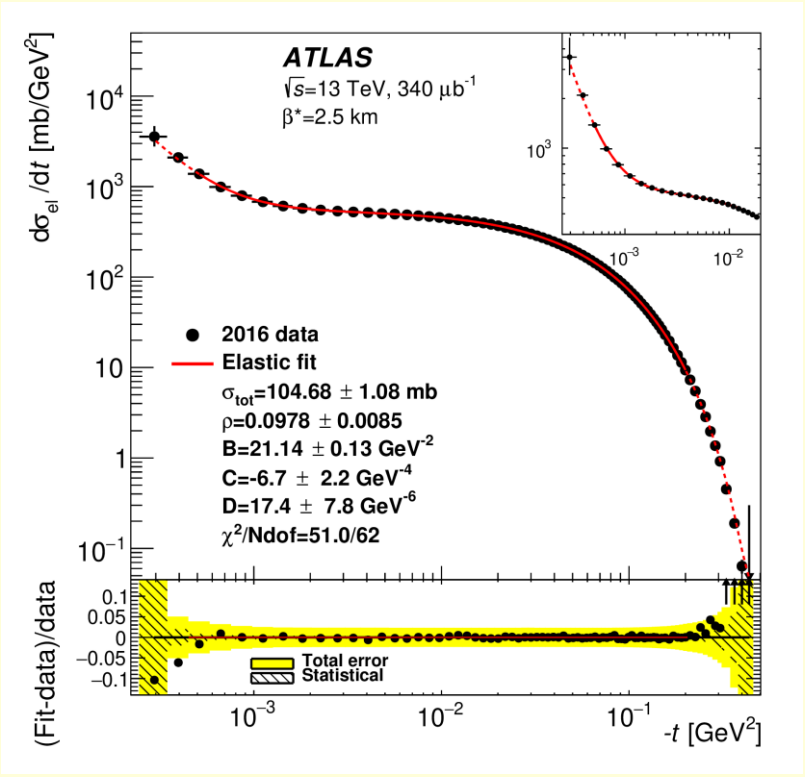
Systematics: between 0.4% and 0.9%, dominated by the evaluation of the templates for accidental coincidences and uncertainties in backgrounds.

Evaluation of results

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

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

(*M* corrects for transport back to IP.)



Now parametrise the data by fitting:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi}\left|f_{\mathrm{N}}(t) + f_{\mathrm{C}}(t)\mathrm{e}^{\mathrm{i}\alpha\phi(t)}\right|^2$$

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

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

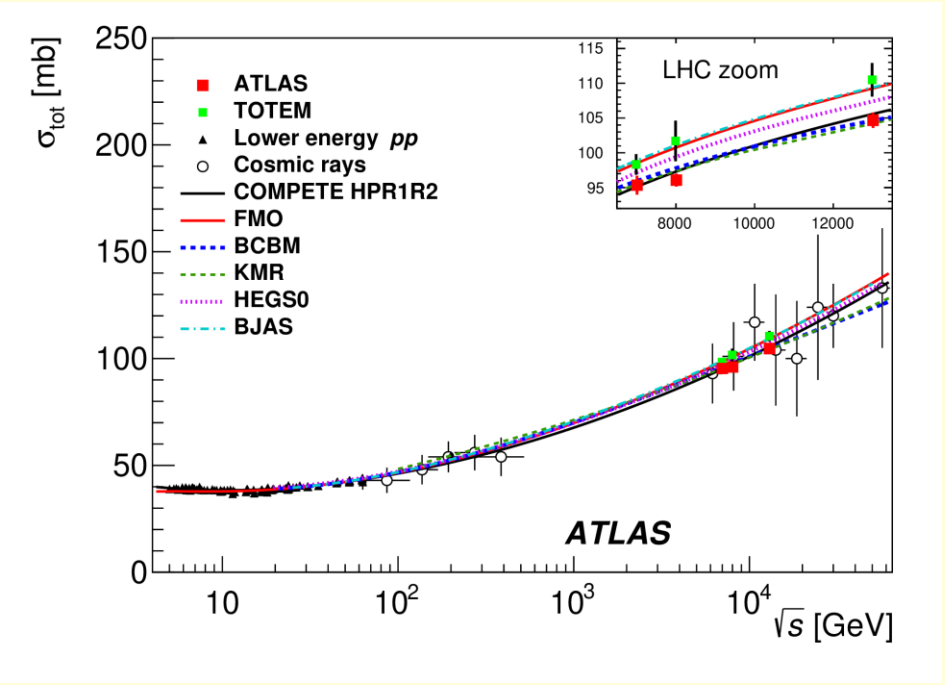
where the constants are known or fitted quantities but have uncertainties.

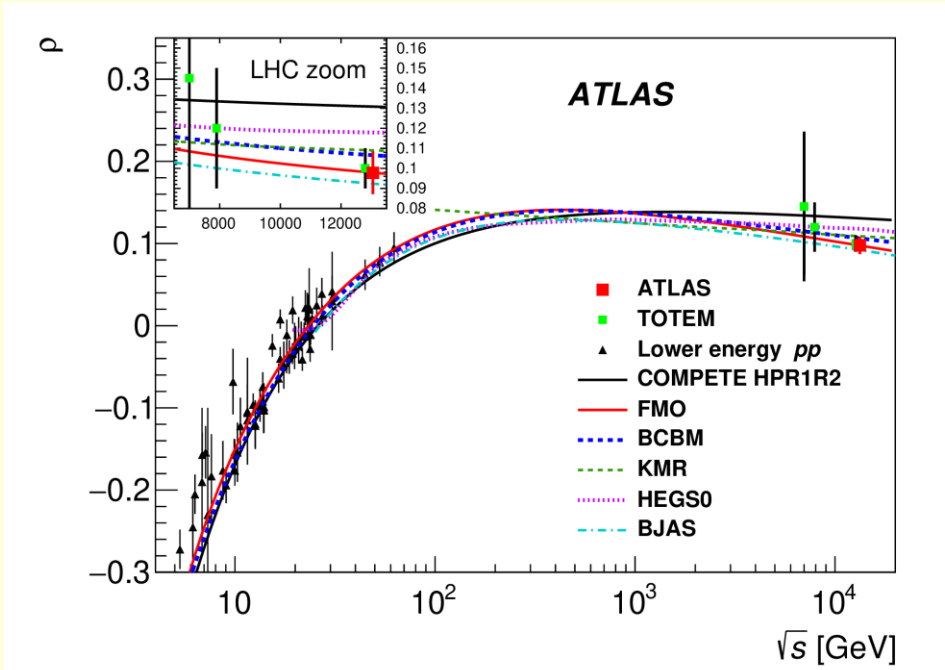
Finally we can get the **total cross section** using the Optical theorem:

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

where

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





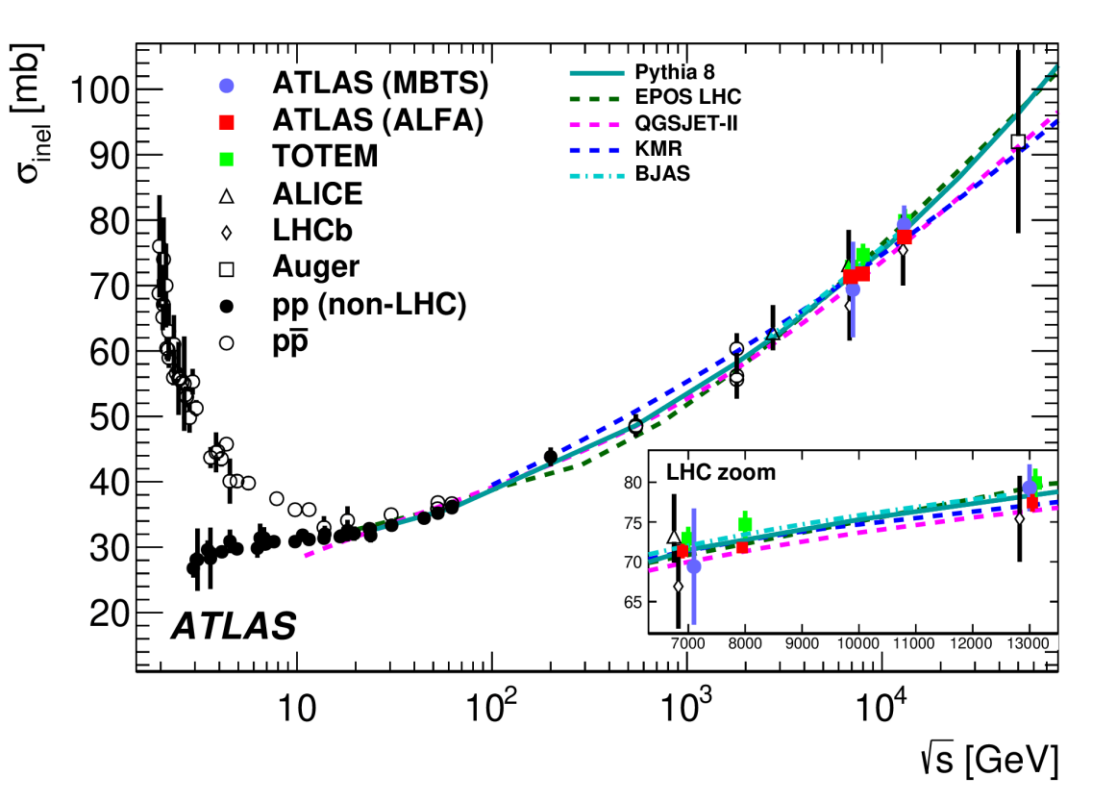
- The widely used model COMPETE is in poor agreement with above (predicts $\rho = 0.13$)
- It is a model with Odderon exchange tuned to TOTEM
- ALFA and TOTEM disagree at 2.2 σ level (similar trend at 7, 8 GeV)

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:

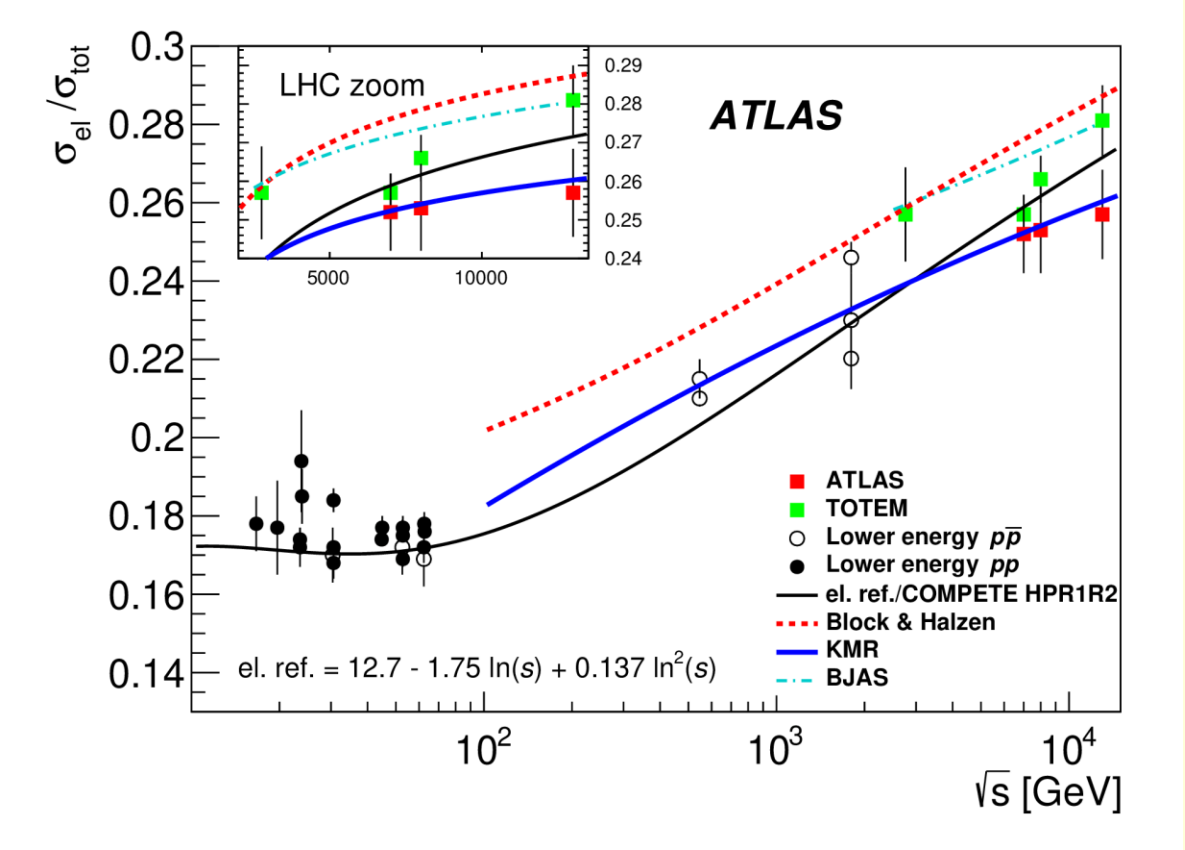
$$\sigma_{\rm el}^{\rm extr} = 27.27 \pm 1.10\ (\rm exp.) \pm 0.30\ (\rm th.)\ mb.$$

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 theory models also differ!

A few more comments:

- ATLAS measure using integrated luminosity, TOTEM use a lumi-independent formula that depends, however, on a low-mass extrapolation.
- This increases TOTEM's uncertainty relative to ATLAS.

Summary and conclusions

First completely **exclusive measurements of diffractive pion pair production** at LHC have been performed, 7 TeV LHC energy, using ALFA system at ATLAS

The method is shown to work well
Much more statistics to be analysed in Run 2. Resonances, glueballs?

Most precise LHC measurements of σ_{tot} **(pp)** , from ATLAS :

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

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

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