Recent ATLAS Results on Diffraction and QCD

Maciej Trzebiński

on behalf of
the ATLAS Collaboration

Institute of Nuclear Physics
Polish Academy of Sciences

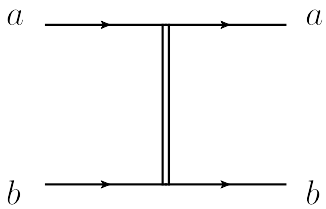
Workshop on QCD and Diffraction

Saturation 1000+

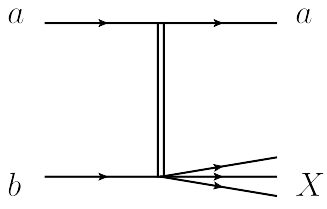
5th December 2016

Outline

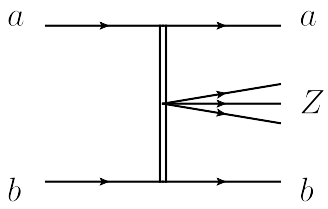
Diffractive signature: large rapidity gap due to colourless exchange
Exchange type: electromagnetic (photon) or strong (Pomeron)



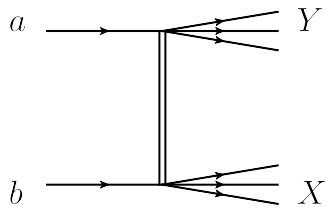
elastic scattering



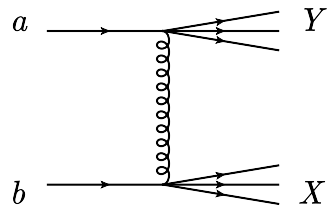
single diffraction (SD)



central diff. (CD)



double diff. (DD)

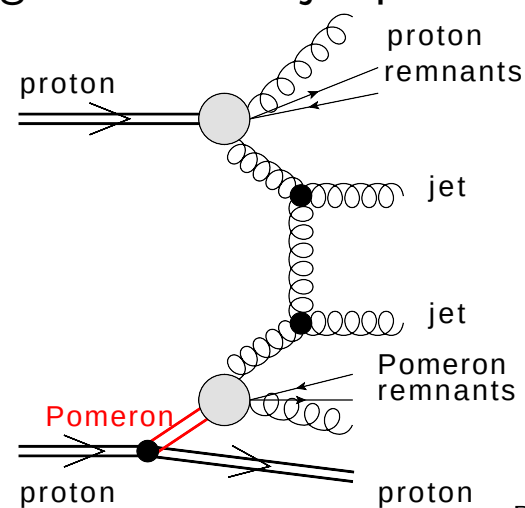


non-diff. scatt. (ND)

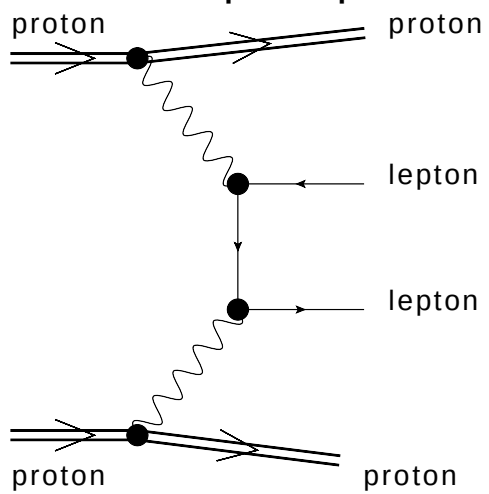
Elastic cross-section: elastic scattering measurement
Inelastic cross-section: single + double + central diff. + non-diff. scattering
Total cross-section: inferred from the elastic measurement via the optical theorem

Measurements of:

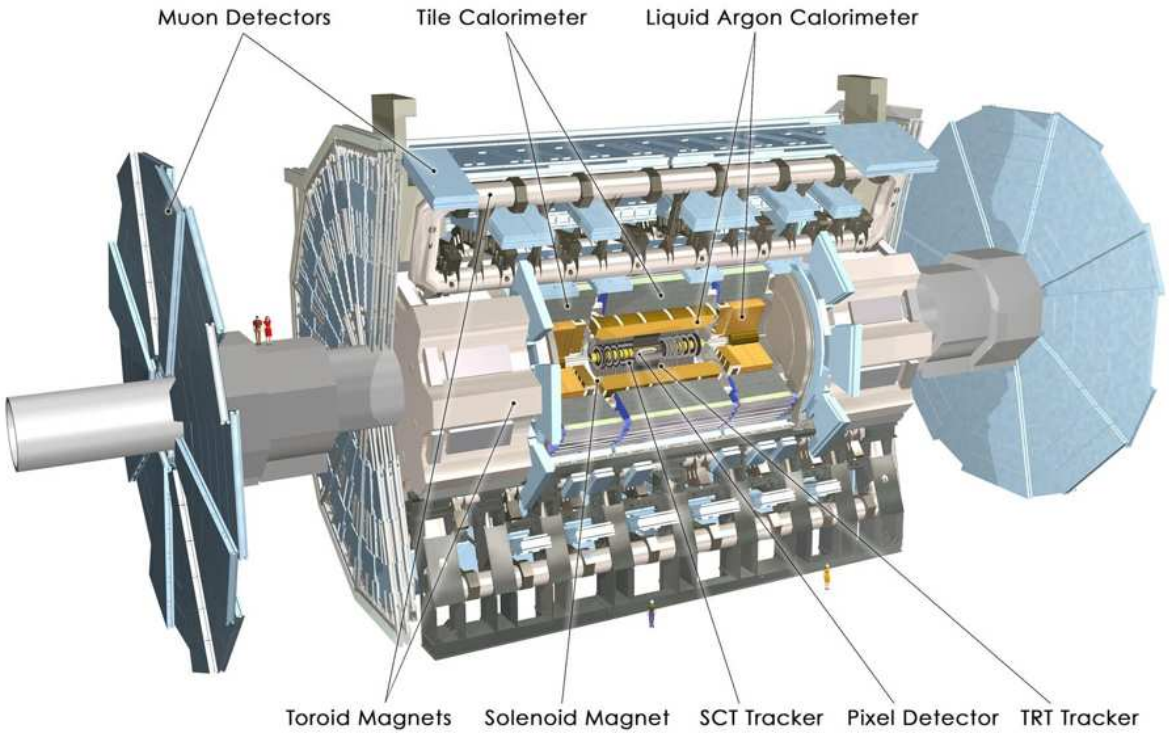
single diffractive jet production

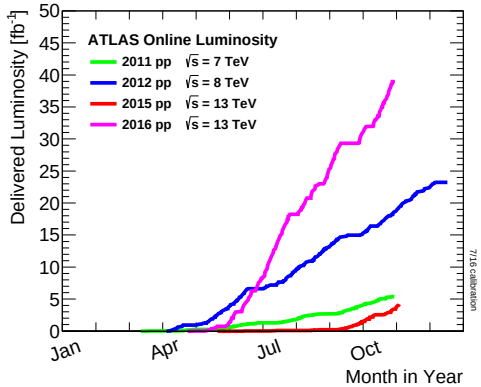


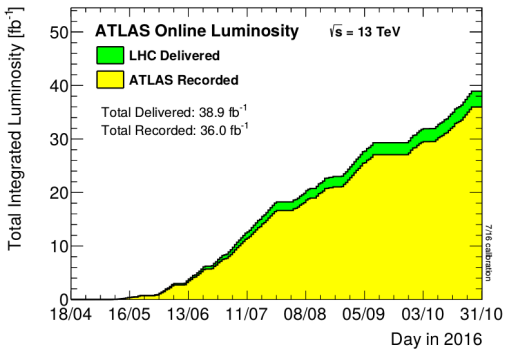
exclusive di-lepton production



ATLAS Detector

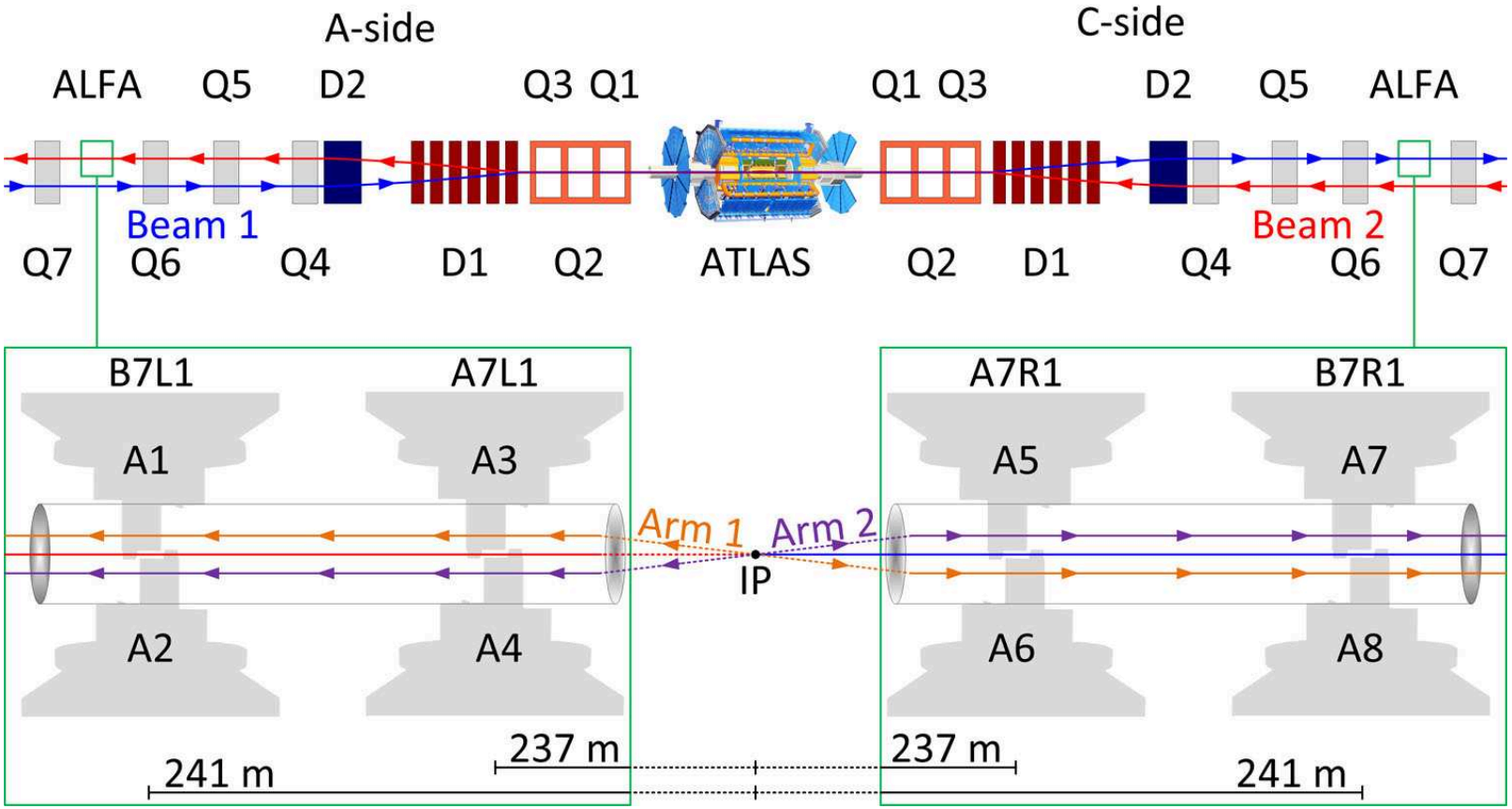






- General purpose experiment equipped with detectors for forward physics: MBTS, ZDC, ALFA, AFP.
- Excellent data taking performance.
- Recorded data:
  - 45 pb^{-1} in 2010 and 5.08 fb^{-1} in 2011 at $\sqrt{s} = 7$ TeV,
  - 21.3 fb^{-1} in 2012 at $\sqrt{s} = 8$ TeV,
  - 3.9 fb^{-1} in 2015 and 36 fb^{-1} in 2016 at $\sqrt{s} = 13$ TeV.
- Most of data were taken in high pile-up conditions, but we had several runs at low-μ dedicated for diffractive studies.

Total and Elastic Cross-Section: Measurement Idea

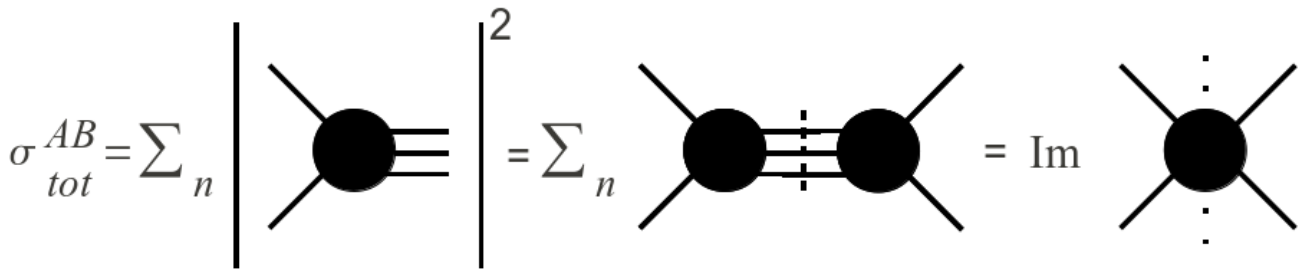


- elastic signature: two protons (scattered at small angle)
- dedicated detectors needed: Absolute Luminosity For ATLAS
- several LHC magnets (**D**ipoles and **Q**uadrupoles) coll. point and ALFA
- LHC run conditions: special magnet settings (so-called $\beta^* = 90$ m optics) needed to enhance detector acceptance
- data sample:
  - 80 μb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV,
  - 500 μb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV.

Optical theorem

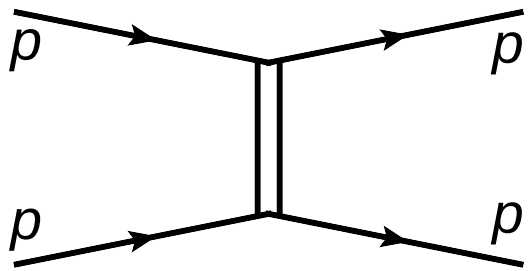
Total cross section is directly proportional to the imaginary part of the forward **elastic scattering** *amplitude extrapolated to* **zero momentum transfer**:

$$\sigma_{tot} = 4\pi \cdot Im[f_{el}(t=0)]$$



Elastic scattering:

- both protons stay intact,
- described by the four momentum transfer, t,
- protons are scattered at very small angles.



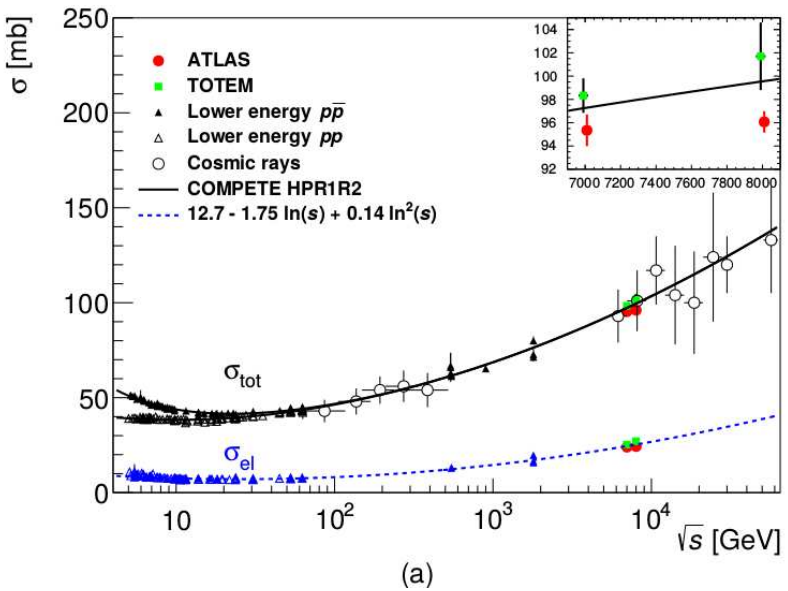
$$\left.\frac{dN}{dt}\right|_{t=0} = L\pi|f_C + f_N|^2 \approx L\pi\left|-\frac{2\alpha_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)\exp\left(\frac{-b|t|}{2}\right)\right|^2$$

red – Coulomb part, blue – nuclear part

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

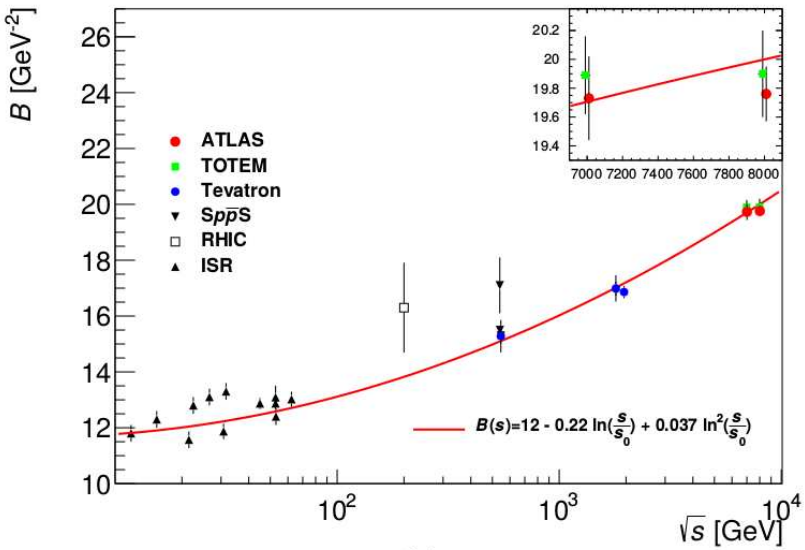
Total and Elastic Cross-Section: 7 and 8 TeV Results

total and elastic cross-section



(a)

nuclear slope



(b)

Total cross-section:

$$\sigma_{tot}^{ALFA}(7\,TeV) = 95.35 \pm 0.38\ (\text{stat.}) \pm 1.25\ (\text{exp.}) \pm 0.37\ (\text{extr.})\ \text{mb}$$
$$\sigma_{tot}^{ALFA}(8\,TeV) = 96.07 \pm 0.18\ (\text{stat.}) \pm 0.85\ (\text{exp.}) \pm 0.31\ (\text{extr.})\ \text{mb}$$

Nuclear slope:

$$B^{ALFA}(7\,TeV) = 19.73 \pm 0.14\ (\text{stat.}) \pm 0.26\ (\text{syst.})\ \text{GeV}^{-2}$$
$$B^{ALFA}(8\,TeV) = 19.74 \pm 0.05\ (\text{stat.}) \pm 0.23\ (\text{syst.})\ \text{GeV}^{-2}$$

Elastic cross-section:

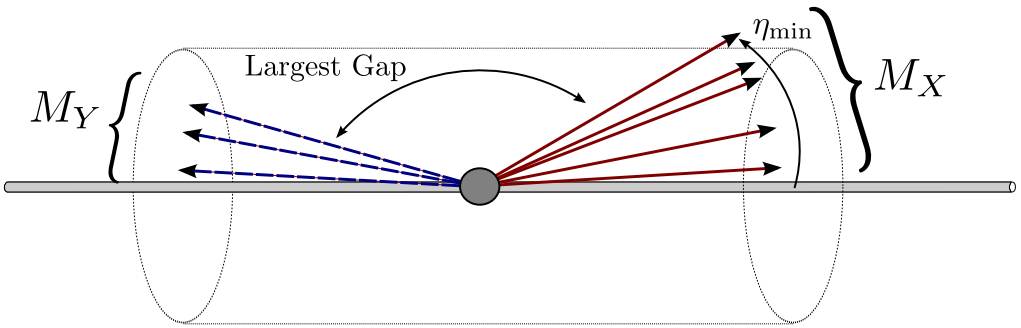
$$\sigma_{el}^{ALFA}(7\,TeV) = 24.00 \pm 0.19\ (\text{stat.}) \pm 0.57\ (\text{syst.})\ \text{mb}$$
$$\sigma_{el}^{ALFA}(8\,TeV) = 24.33 \pm 0.04\ (\text{stat.}) \pm 0.39\ (\text{syst.})\ \text{mb}$$

Inelastic cross-section:

$$\sigma_{inel}^{ALFA}(7\,TeV) = 71.34 \pm 0.36\ (\text{stat.}) \pm 0.83\ (\text{syst.})\ \text{mb}$$
$$\sigma_{inel}^{ALFA}(8\,TeV) = 71.73 \pm 0.15\ (\text{stat.}) \pm 0.69\ (\text{syst.})\ \text{mb}$$

Inelastic Cross-Section: Measurement Idea

Use events (single + double + central diffraction + non-diffractive scattering) triggered by ATLAS **M**inimum **B**ias **T**rigger **S**cintillators



M_x – larger of invariant masses of the two proton dissociated systems, $M_X^2 = \sqrt{s}\sum p_T e^{\pm\eta}$

$\xi = M_X^2/s$ – energy lost by proton

c.m. energy	**7 TeV**	**13 TeV**
integrated luminosity	$20.3 \pm 0.7\ \mu\text{b}^{-1}$	$63 \pm 6\ \mu\text{b}^{-1}$
mean number of int. per bunch crossing	0.01	0.0023
MBTS coverage	$2.09 < \lvert\eta\rvert < 3.84$	$2.07 < \lvert\eta\rvert < 3.86$
relative energy loss range	$\xi > 5 \cdot 10^{-6}$	$\xi > 10^{-6}$
minimal invariant mass	$M_X > 15.7$ GeV	$M_X > 13$ GeV
MC generators	Pythia6, Pythia8, Phojet	Pythia 8 (various tunes), EPOS, QGSJET-II

Backgrounds: collisions of the beam with gas particles in the beam-pipe or with material upstream from the detector, and slowly-decaying, collision-induced radiation (*afterglow*).

Inelastic Cross-Section: Results

Results for 7 TeV:

$\sigma(\xi > 5 \times 10^{-6})$ [mb]	
ATLAS Data 2010	60.33 ± 2.10(exp.)
Schuler and Sjöstrand	66.4
PHOJET	74.2
Ryskin *et al.*	$51.8 - 56.2$

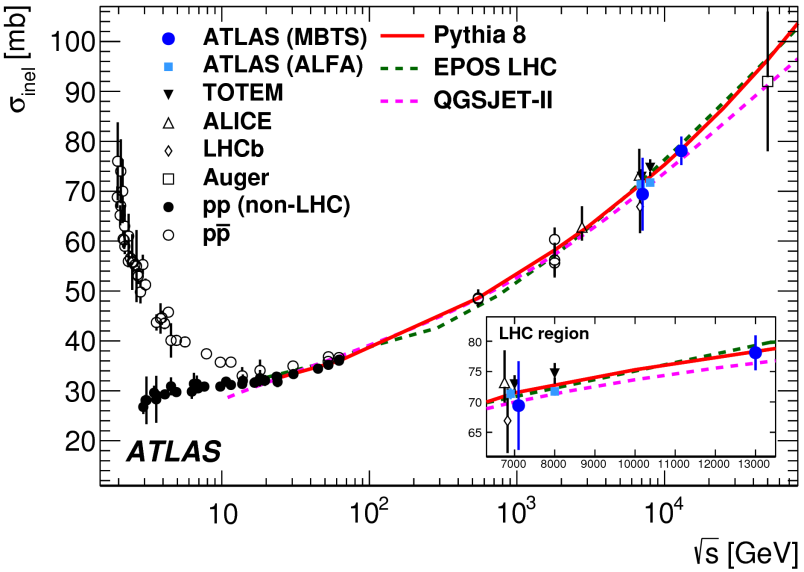
$\sigma(\xi > m_p^2/s)$ [mb]	
ATLAS Data 2010	69.4 ± 2.4(exp.) ± 6.9(extr.)
Schuler and Sjöstrand	71.5
PHOJET	77.3
Block and Halzen	69
Ryskin *et al.*	$65.2 - 67.1$
Gotsman *et al.*	68
Achilli *et al.*	$60 - 75$

Results for 13 TeV:

Source	Value
This measurement	65.2 ± 0.8 (exp.) ± 5.9 (lum.) mb
Pythia8 DL, $\epsilon = 0.06$	71.0 mb
Pythia8 DL, $\epsilon = 0.085$	69.1 mb
Pythia8 DL, $\epsilon = 0.1$	68.1 mb
Pythia8 A2	74.4 mb
EPOS LHC	71.2 mb
QGSJET-II	72.7 mb

Extrapolated cross-section:

73.1 $\pm$ 0.9 (exp.) $\pm$ 6.6 (lum.) $\pm$ 3.8 (extr.) mb



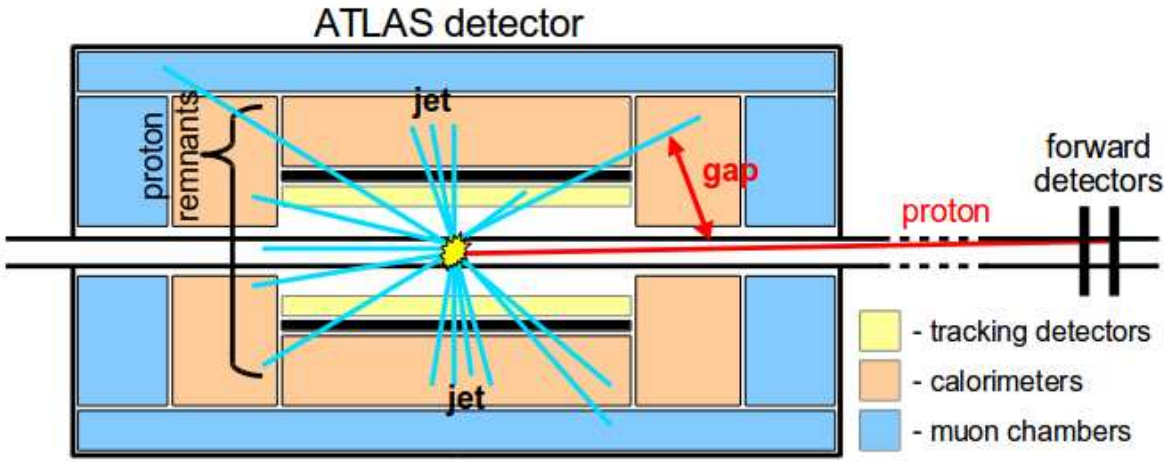
Results agree within the error with MC and general predicted trend.

More details in:

- 7 TeV analysis:
  Nature Commun. 2 (2011) 463
- 13 TeV analysis:
  Phys. Rev. Lett. 117 (2016) 182002

Single Diffractive Jets: Measurement Idea

Signature: at least two jets with $p_T > 20$ GeV + presence of gap in rapidity.



Data sample:

- c.m. energy: 7 TeV
- total integrated luminosity: 6.8 nb^{-1}
- average number of collisions per bunch crossing: 0.12

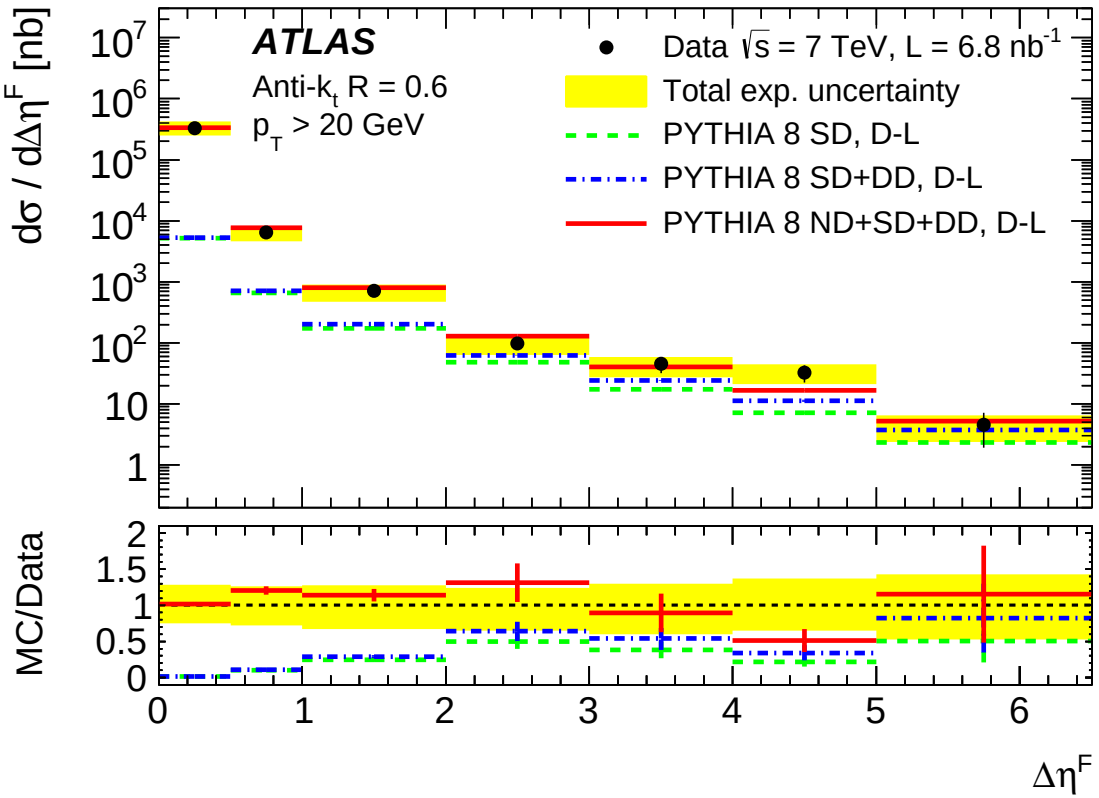
Jets:

- $p_T > 20$ GeV, $|\eta| < 4.4$
- anti-k_T algorithms (R=0.4 and R=0.6)

Rapidity gap $\Delta\eta^F$ – larger of the two empty pseudorapidity regions between detector edge and first reconstructed object:

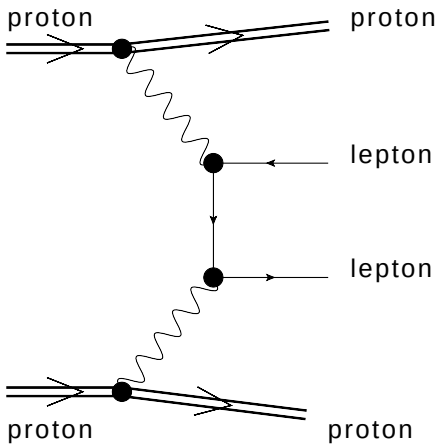
- $|\eta| < 2.5$: track with $p_T > 200$ MeV or
- $|\eta| < 4.8$: calorimeter cell with signal greater than 5σ above noise

Single Diffractive Jets: Results



- diffractive component is required for more complete description of data
- PYTHIA8 (DL model) gives a good description of shape and normalisation
- rapidity gap survival factor – probability of non-emission by other soft processes (e.g. underlying event) into the gap:
  $S^2 = 0.16 \pm 0.04$ (stat.) $\pm$ 0.08 (exp. syst.)
- **more details in: Physics Letters B 754 (2016) 214-234**

Exclusive Lepton Pair Production: Measurement Idea



Signal signature: two scattered protons (not measured) + two leptons + nothing else!

Data sample:

- c.m. energy: 7 TeV
- total integrated luminosity: 4.6 fb^{-1}

Electron channel:

- electron and positron originating from the same vertex,
- each with $p_T^e > 12$ GeV and $|\eta^e| < 2.4$
- invariant mass: $m_{e^+e^-} > 24$ GeV

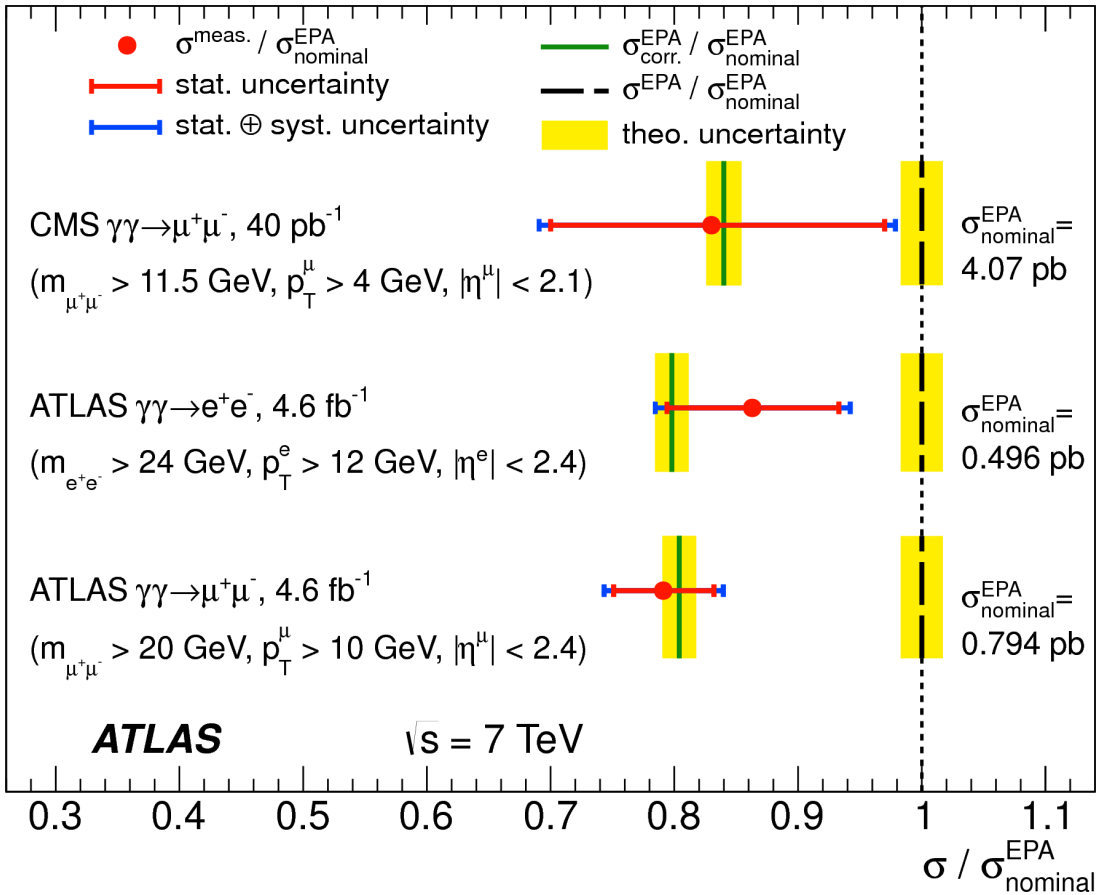
Muon channel:

- μ^+ and μ^- originating from the same vertex,
- each with $p_T^\mu > 10$ GeV and $|\eta^\mu| < 2.4$
- invariant mass: $m_{\mu^+\mu^-} > 20$ GeV

Exclusivity criteria:

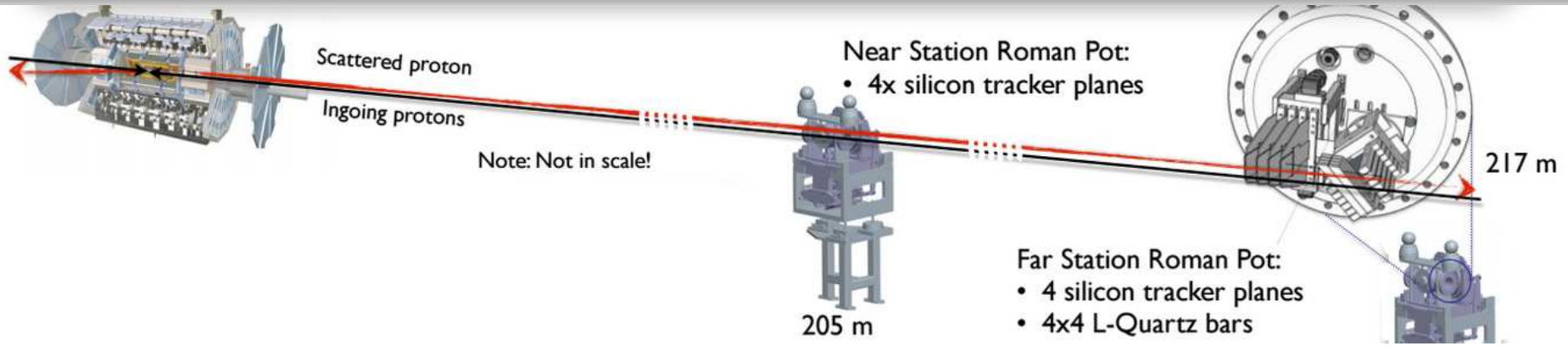
- no additional charged particle with $p_T > 400$ MeV from di-lepton vertex
- no additional track or vertex within 3 mm from di-lepton one
- remove Z-peak mass region: $70 < m_{l^+l^-} < 105$ GeV
- transverse momentum of lepton pair: $p_T^{l^+l^-} < 1.5$ GeV

Exclusive Lepton Pair Production: Results



- result consistent with the recent CMS measurement
- suppression (20%) with respect to the Equivalent Photon Approximation prediction
- suppression expected due to the contribution of re-scattering effects
- **more details in: Physics Letters B 749 (2015) 242-261**

ATLAS Forward Proton Project



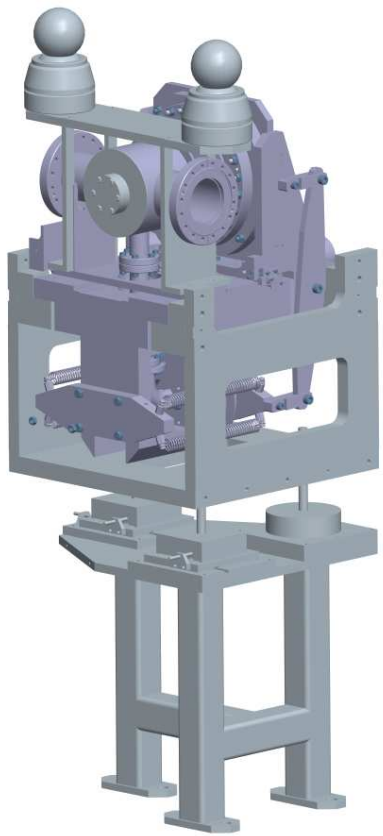
AFP TDR: CERN-LHCC-2015-009, ATLAS-TDR-024

Phase-1: AFP0+2 (2016)

- 2 horizontal Roman Pot stations at 205 (NEAR) and 217 m (FAR) in ATLAS C side – installed!
- study beam background in low and high intensity runs
- measure diffractive and exclusive events with one tag in a special low-μ runs (AFP trigger ATLAS)

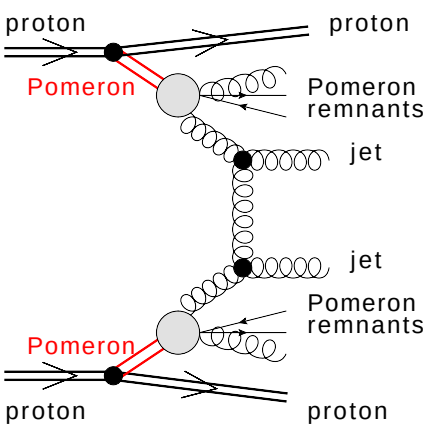
Phase-2: AFP2+2 (2017+)

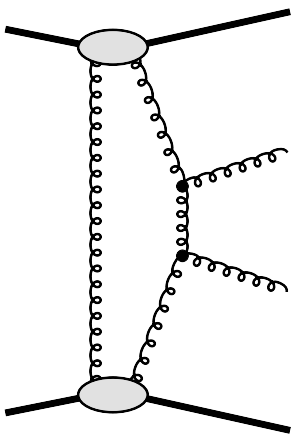
- add 2 horizontal RPs at 205 and 217 m on A side
- install time-of-flight detectors in far stations on both sides – new AFP trigger
- measure double tagged diffractive and exclusive events
- deliver diffractive triggers to ATLAS during standard runs



Special, low-μ runs

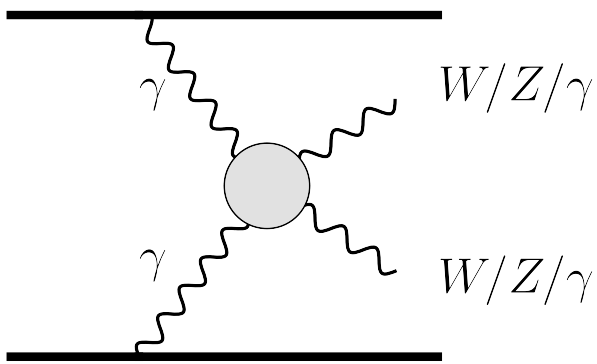
- diffractive physics:
  - soft diffraction (particle, gap, ξ spectra)
  - diffractive jets, jet-gap-jet, γ+jet, W, *etc.*
  - exclusive jets (low-p_T, single tagged)
- AFP can trigger ATLAS for presence of proton in:
  - one side (single difraction)
  - both sides (double Pomeron exchange)
- special trigger menu based on AFP
- expect to collect 1 – 10 pb^{-1} of data in special low-μ runs in 2017 and 2018





Standard, high-μ runs

- exclusive events (gluon/Pomeron and photon induced), *e.g.* exclusive di-jets ATL-PHYS-PUB-2015-003
- trigger based on coincidence (double tag) in AFP
- search for new, heavy resonances or anomalous couplings



Summary

- ATLAS precisely measured elastic, inelastic and total total cross sections as well as the nuclear slope.
- Obtained values are in agreement with each other, MC predictions and expected global trend.
- Measurement of jets with a gap indicates that diffractive component is needed to describe data.
- Rapidity gap survival was measured.
- Exclusive di-leptons were measured in electron and muon channels with a good precision.
- Results in agreement with theoretical predictions and the ones obtained by the CMS experiment.
- **Many new diffractive results based on AFP data are expected in the near future.**

The work of M.T. is supported by Polish Ministry of Science and Higher Education under the Mobility Plus programme (1285/MOB/IV/2015/0).