# Forward Physics in the ATLAS Experiment at the LHC

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Measurements w/o forward proton tagging

Proton tagging: ALFA detectors

Proton tagging: AFP detectors

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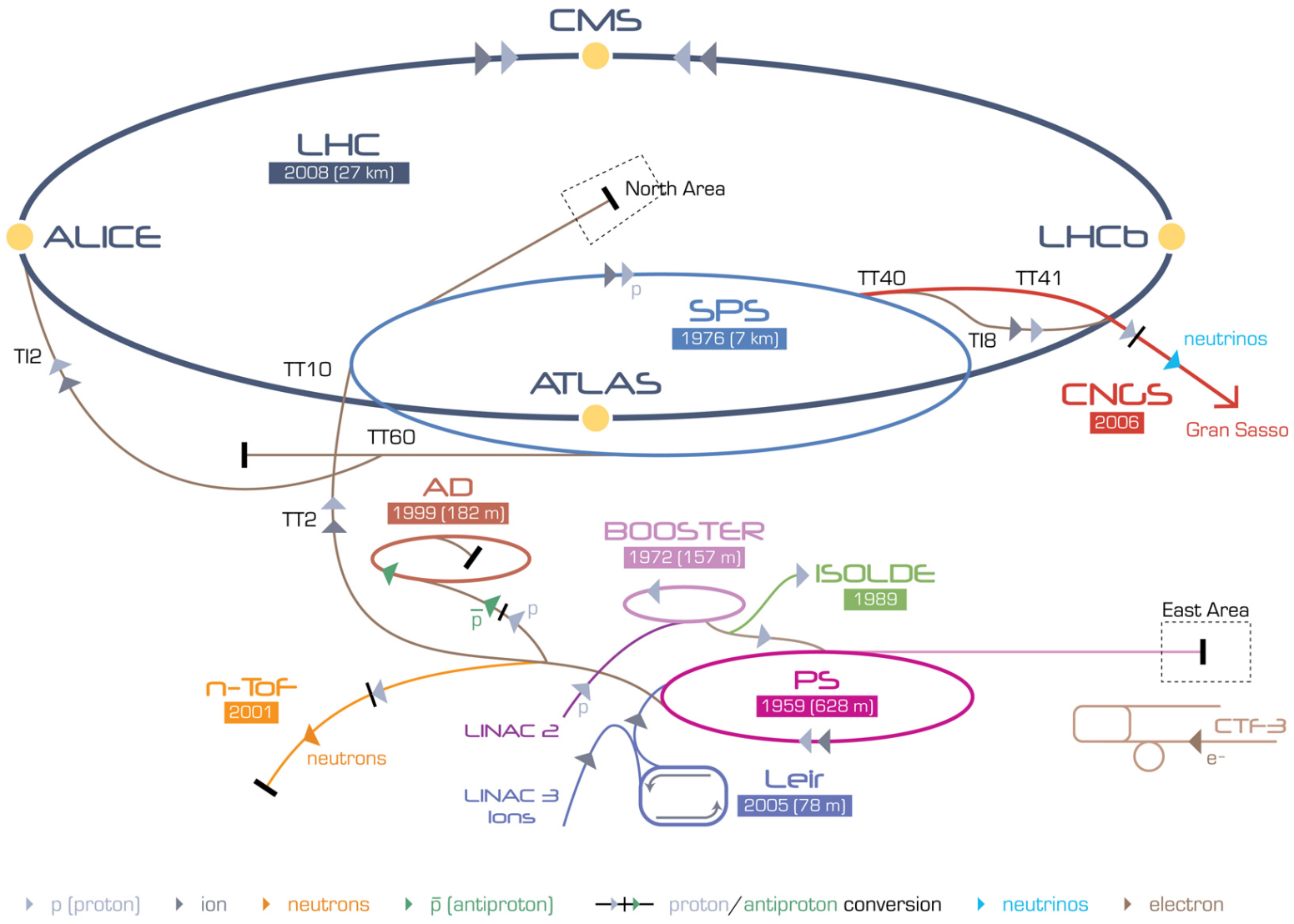
# Large Hadron Collider





# Proton–proton interaction at high energies



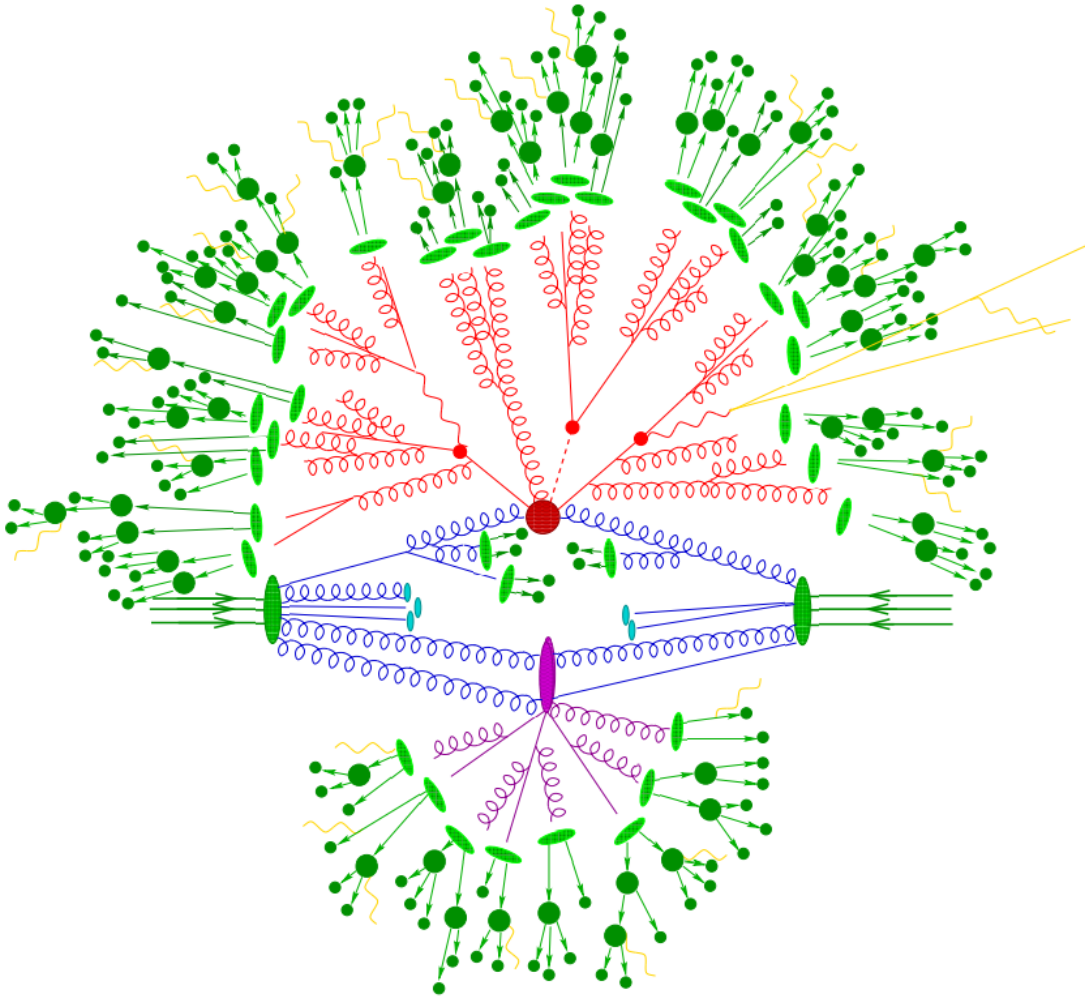
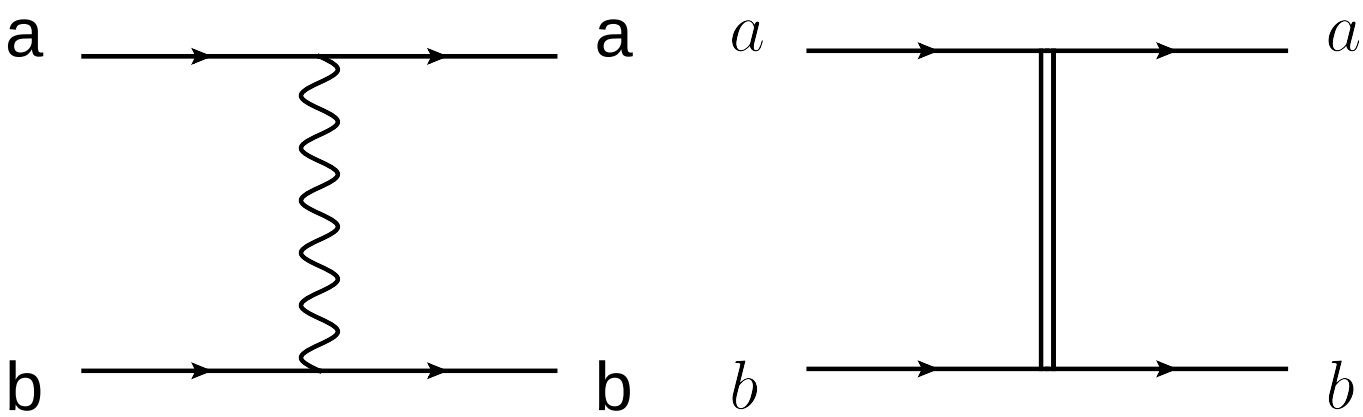


Figure from [arXiv:1411.4085]

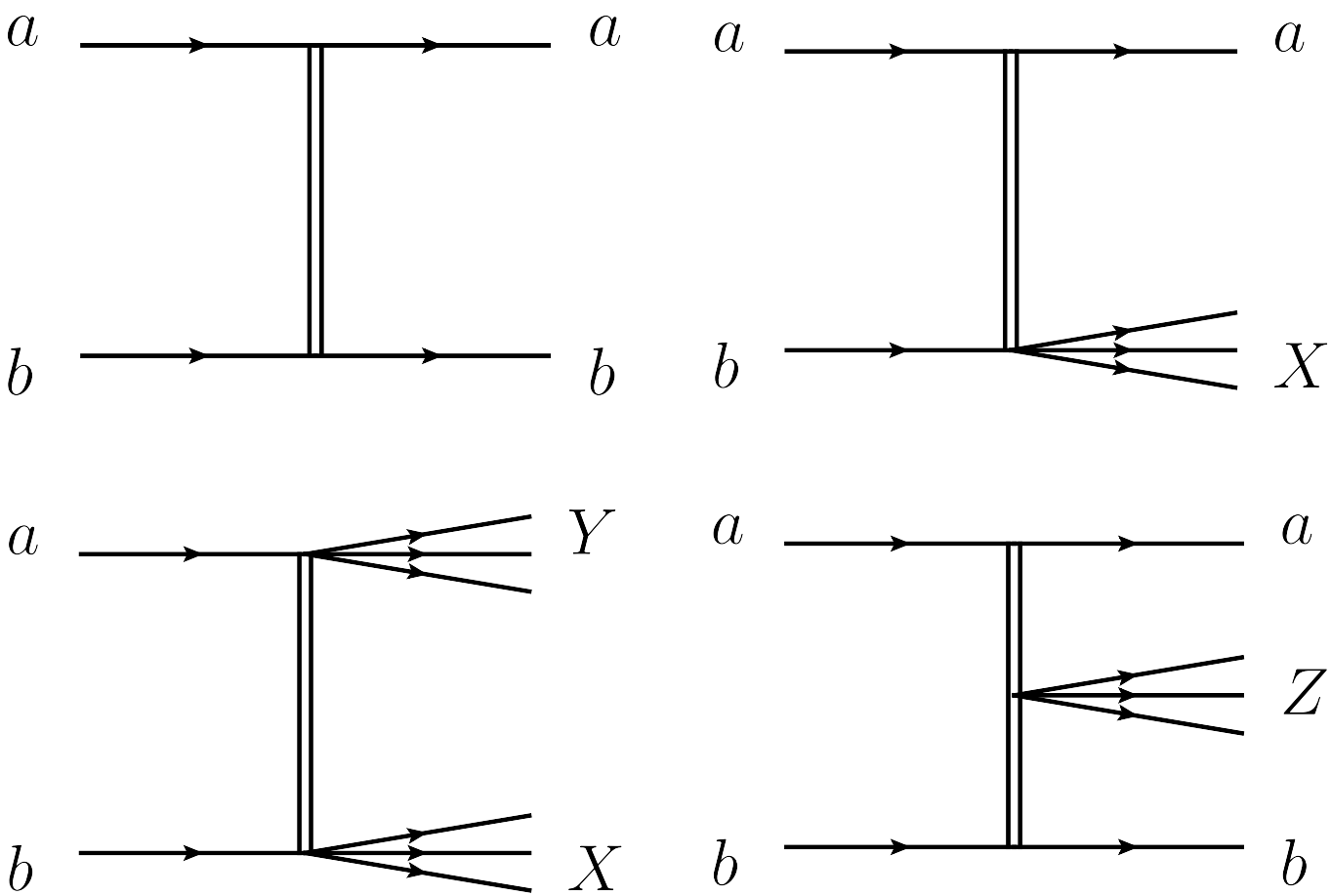
# Elastic scattering





# Diffractive processes



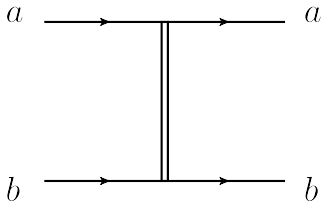


# Diffraction

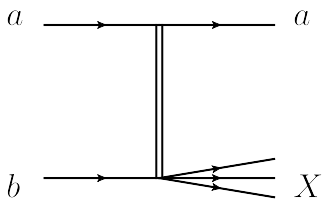


- Diffractive topologies

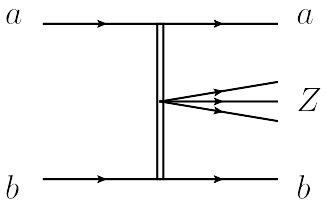
elastic scattering



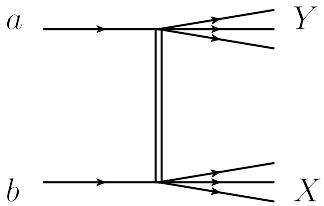

single diffraction




central diffraction




double diffraction



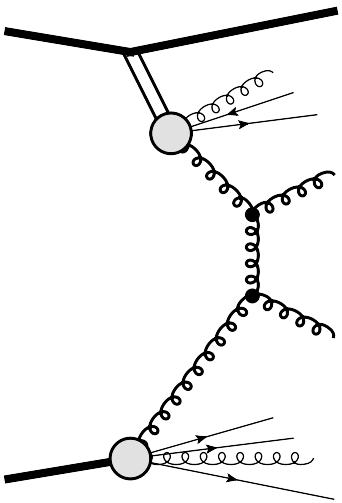

  - Diffractive signatures
    - large rapidity gap
    - forward (anti-)proton
  - Hard diffraction: diffraction + hard scale
  - Hard diffractive topologies
    - single diffraction
    - central diffraction (double pomeron exchange)
    - central exclusive production
    - jet–gap–jet

# Mechanism of hard diffraction



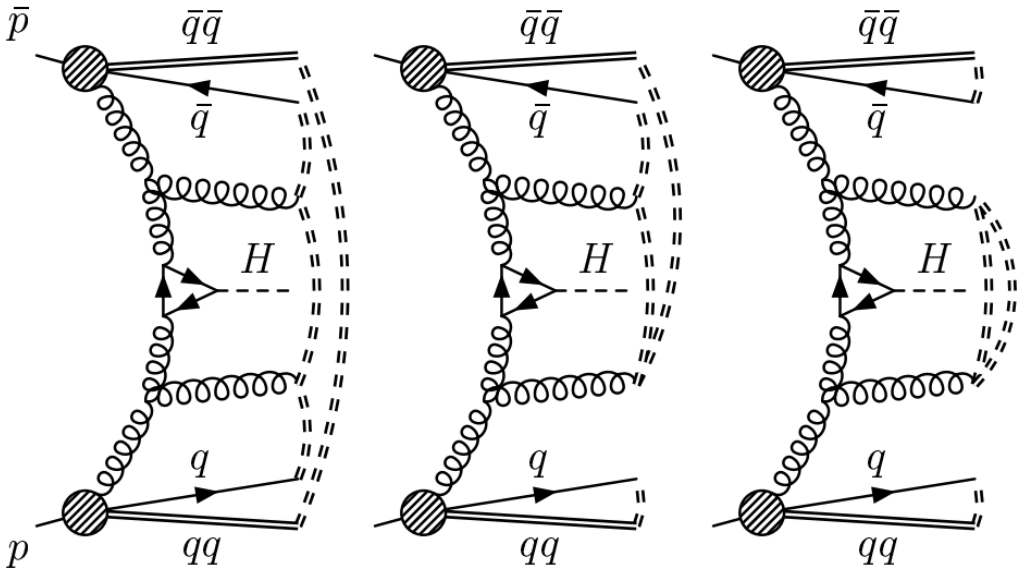
## Resolved pomeron

- Ingelman-Schlein model
- pomeron has partonic structure



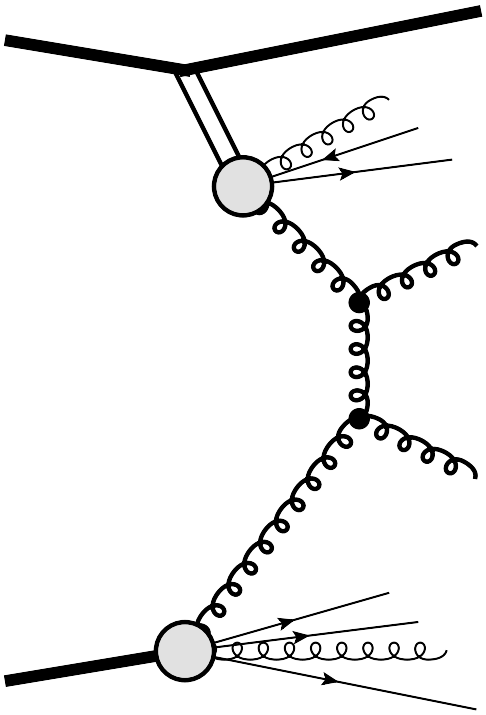
## Soft colour interactions

- QCD-inspired model
- additional gluon exchanges screen the color flow

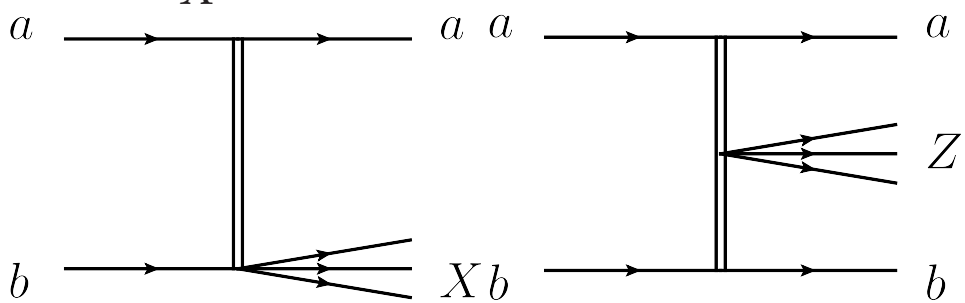


# Kinematics





- $\xi$ – momentum fraction of the proton carried by the pomeron
- $t$ – squared four-momentum transferred from the proton
- $\beta$ – momentum fraction of the pomeron carried by the interacting parton
- $M_X$ – diffractive mass



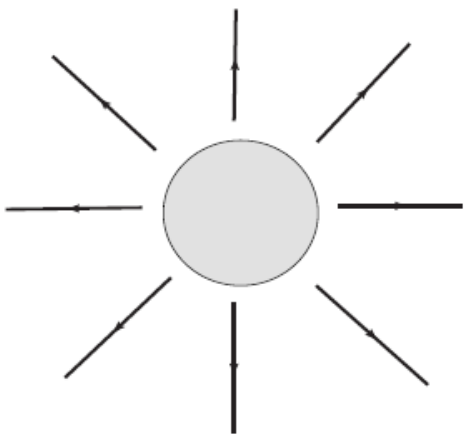

$M_X^2 = s\xi$ $\qquad$ $M_X^2 = s\xi_1\xi_2$

# Equivalent photons
(slides borrowed from Victor Gonçalves)



## Equivalent Photon Approximation

- Consider a charged nucleus at rest. The associated electromagnetic field can be represented by:



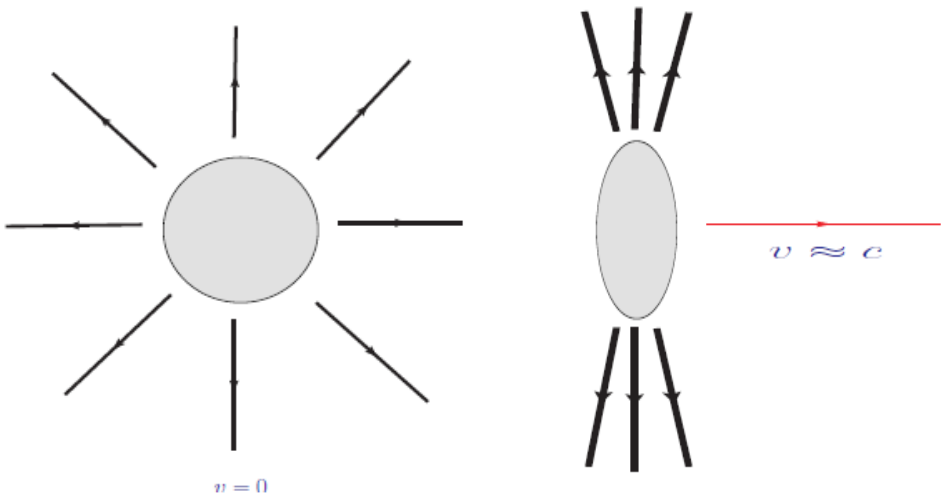
$v = 0$

# Equivalent photons
(slides borrowed from Victor Gonçalves)



## Equivalent Photon Approximation

- As a charged nucleus moves with nearly the speed of light, the electromagnetic field becomes transverse to its velocity.

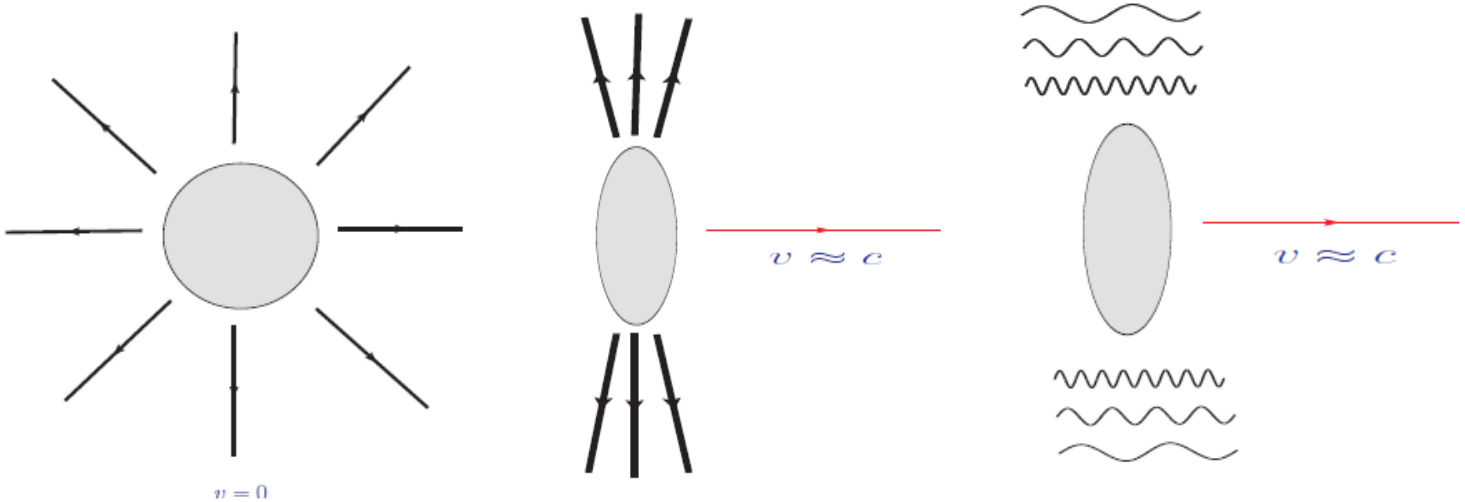


# Equivalent photons
(slides borrowed from Victor Gonçalves)



## Equivalent Photon Approximation

- Since the electric and magnetic field associated to the nucleus take on the same absolute value, this transverse electromagnetic field can be simulated by an equivalent swarm of photons [a].

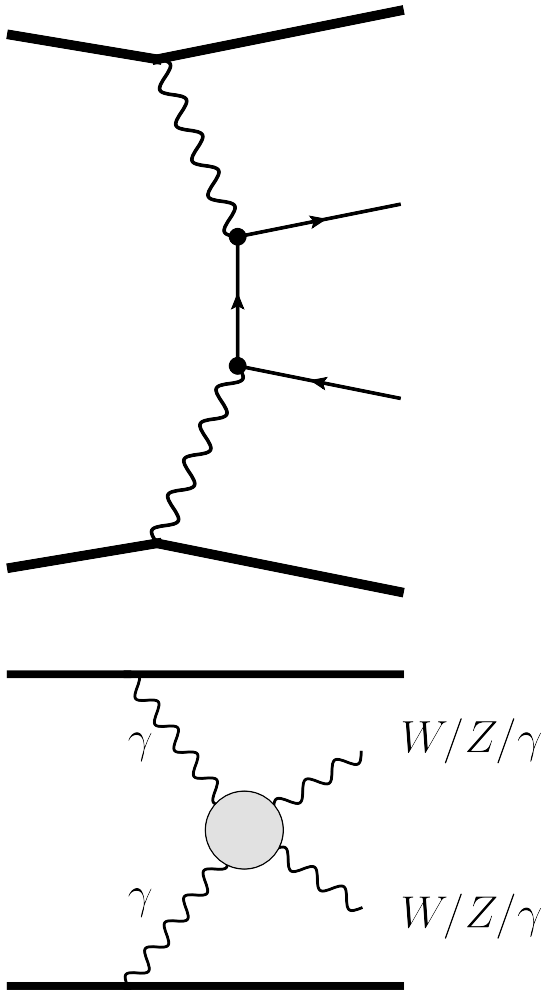



[a] E. Fermi (1924), E. J. Williams (1933), C. F. Von Weizacker (1934)

# Two-photon processes

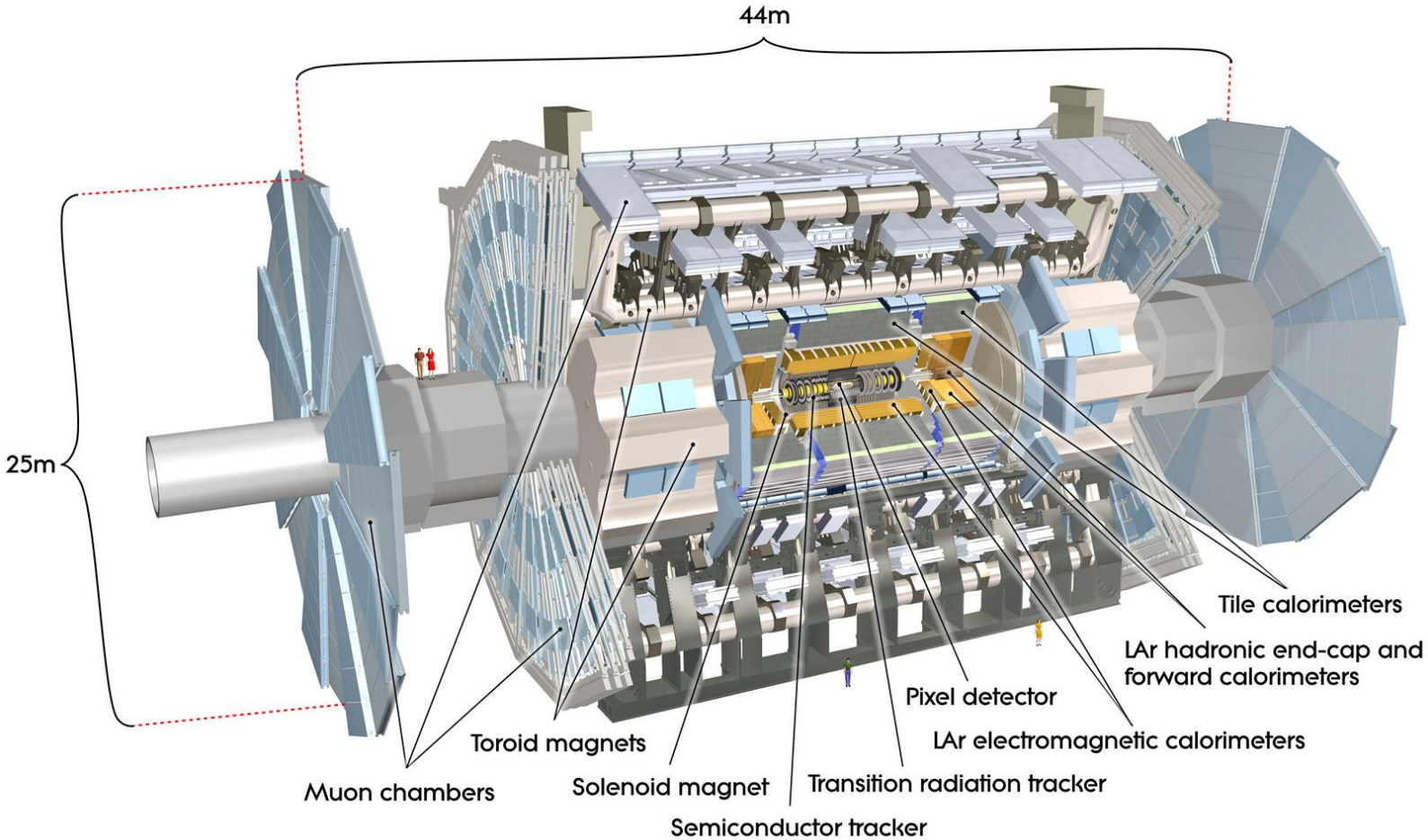


- Two-photon processes can be computed within QED
- Exclusive $\gamma\gamma \to ll$
  - Standard candle for photon-induced physics
  - Non-negligible background to Drell-Yan like reactions
- Test of SM $\gamma WW$ and $\gamma\gamma WW$ couplings
- Searches for new physics
- QCD:
  - absorptive corrections
  - dissociation



# ATLAS Detector






...but also forward detectors providing measurements of forward intact protons: **ALFA** and **AFP**

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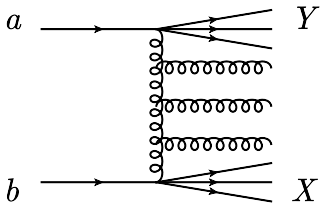
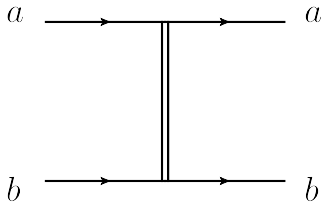
# Soft diffraction



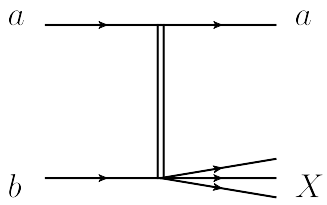
non-diffractive interaction



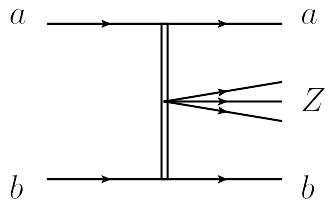

elastic scattering



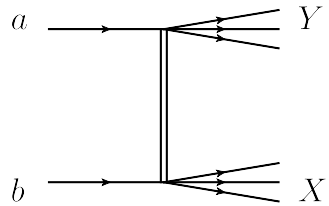

single diffraction

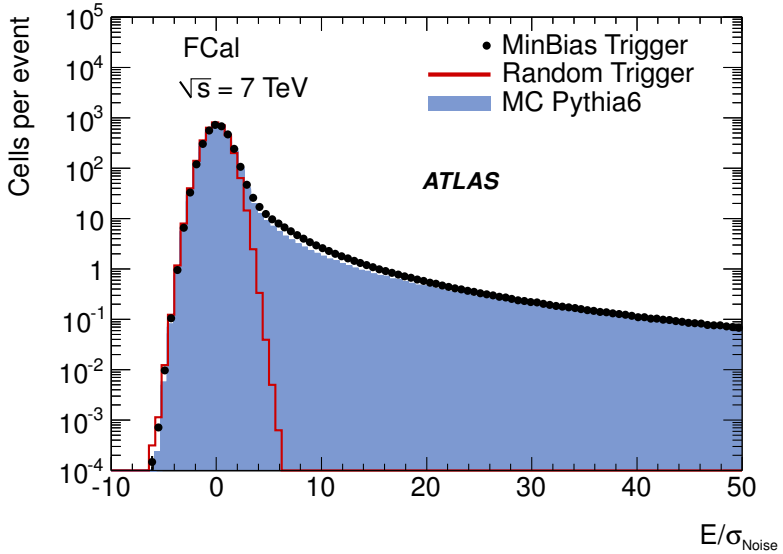


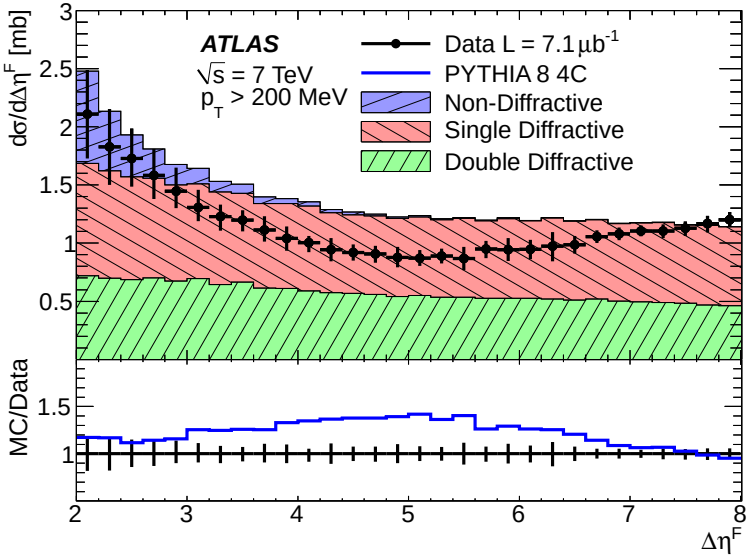

central diffraction




double diffraction



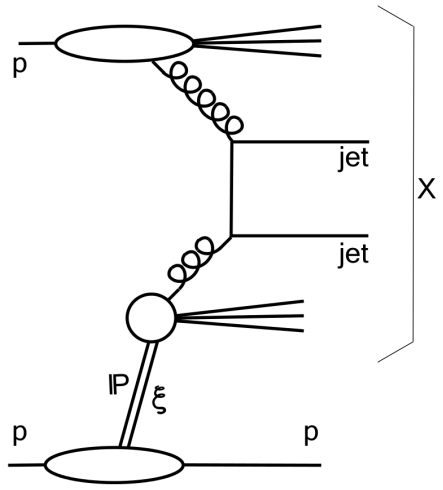




- Calorimeter used to measure rapidity gaps
- Separation of diffractive processes from non-diffractive processes
- Full separation of single and double diffraction not possible

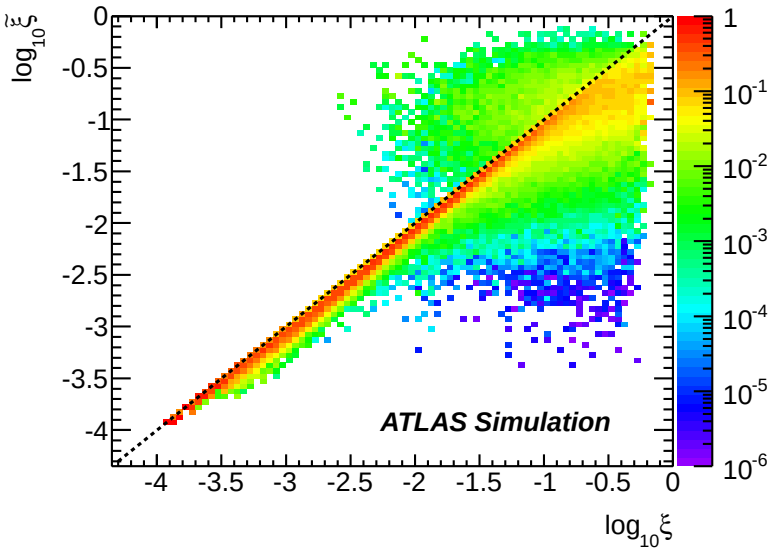
# Diffractive jets

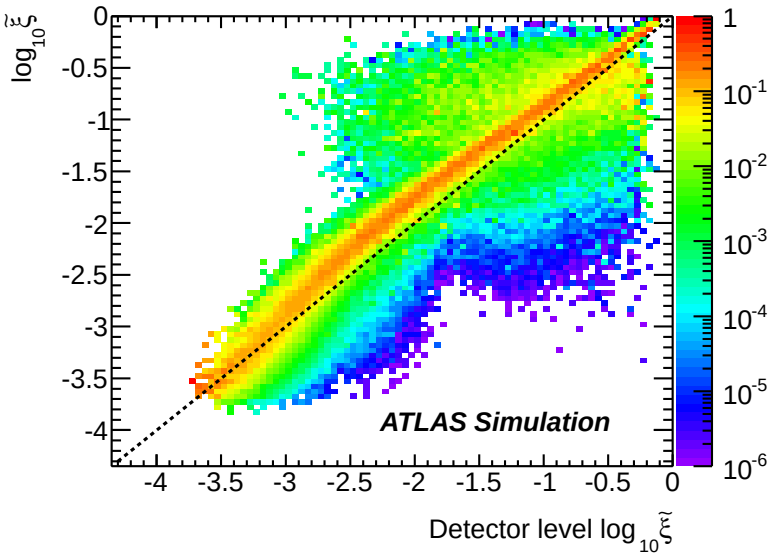


- Low pile-up data from 2010 ($\sqrt{s} = 7$ TeV)
- Rapidity gap based on
  - tracks ($|\eta| < 2.5$, pT $> 200$ MeV)
  - calorimeter cells ($|\eta| < 4.8$)
- Proton energy loss and diffractive mass



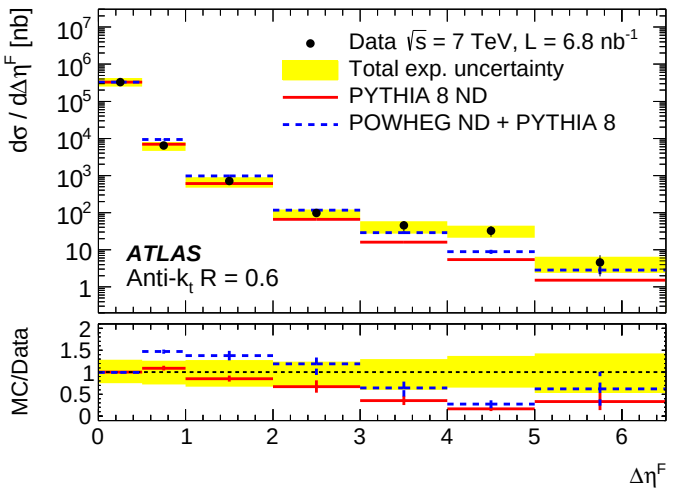

$$\xi = M_X^2/s \qquad \tilde{\xi} = \frac{\sum p_T e^{\pm\eta}}{\sqrt{s}}$$

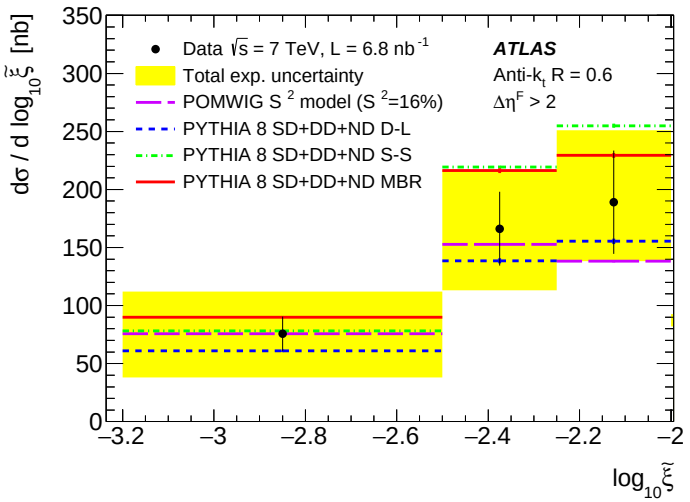


# Diffractive jets



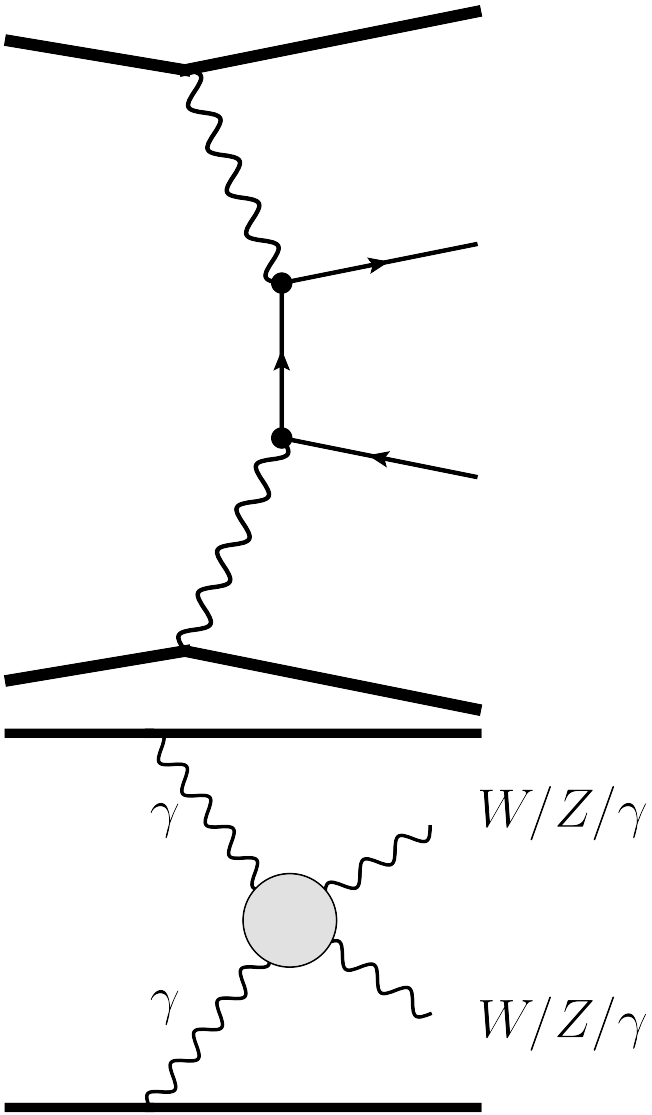



- Evidence of diffractive component
- Good description by Pythia8
- Gap survival probability: $0.16 \pm 0.04$ (stat) $\pm 0.08$ (exp. syst.)

# Two-photon processes






- Exclusive $\gamma\gamma \to ll$
  - Standard candle for photon-induced physics
  - QED calculations
  - QCD corrections
- Exclusive $\gamma\gamma \to VV$
  - Tests of Standard Model
  - Searches for new physics

# $\gamma\gamma \to \mu\mu$ in $pp$

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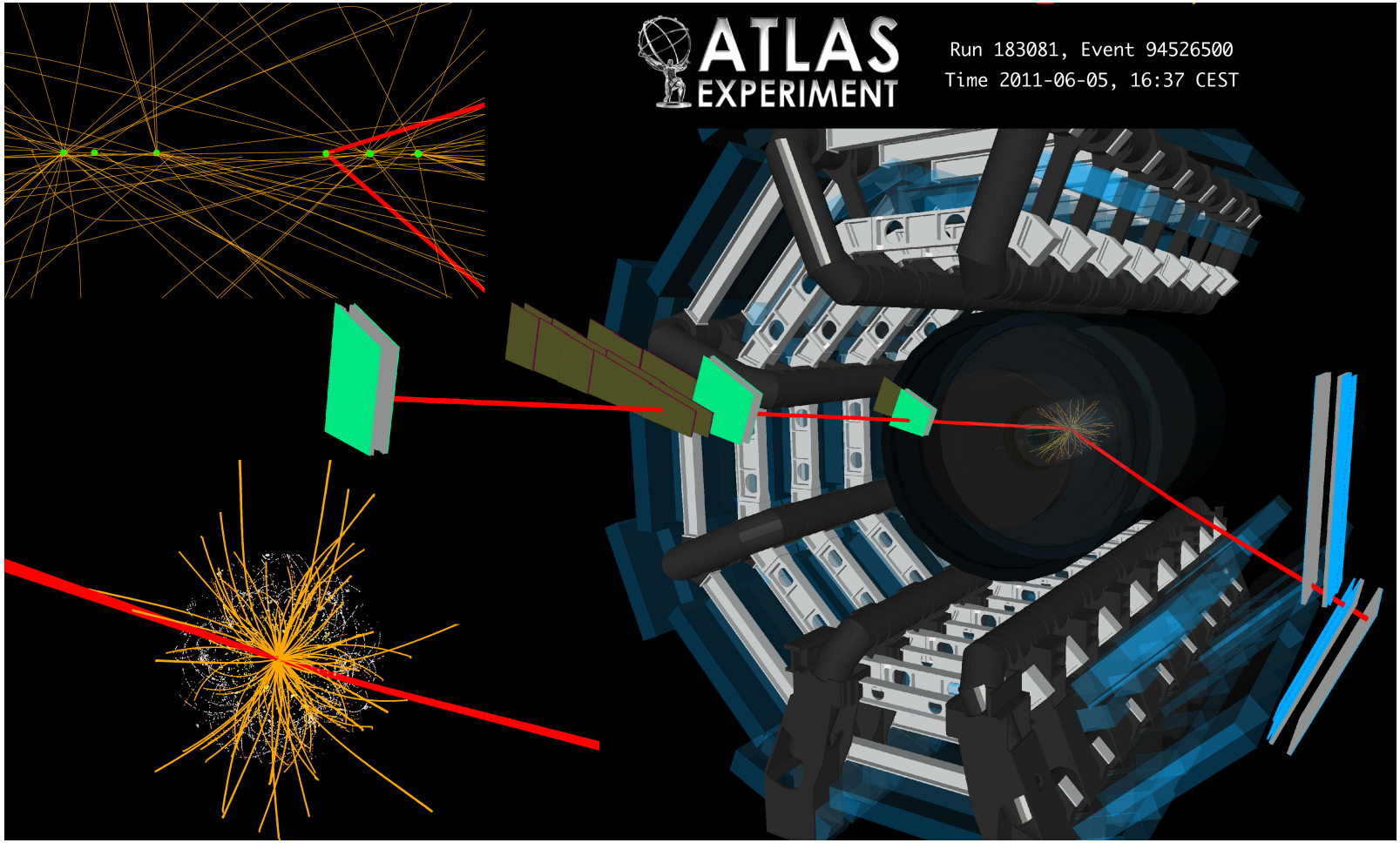
Proton tagging: ALFA detectors

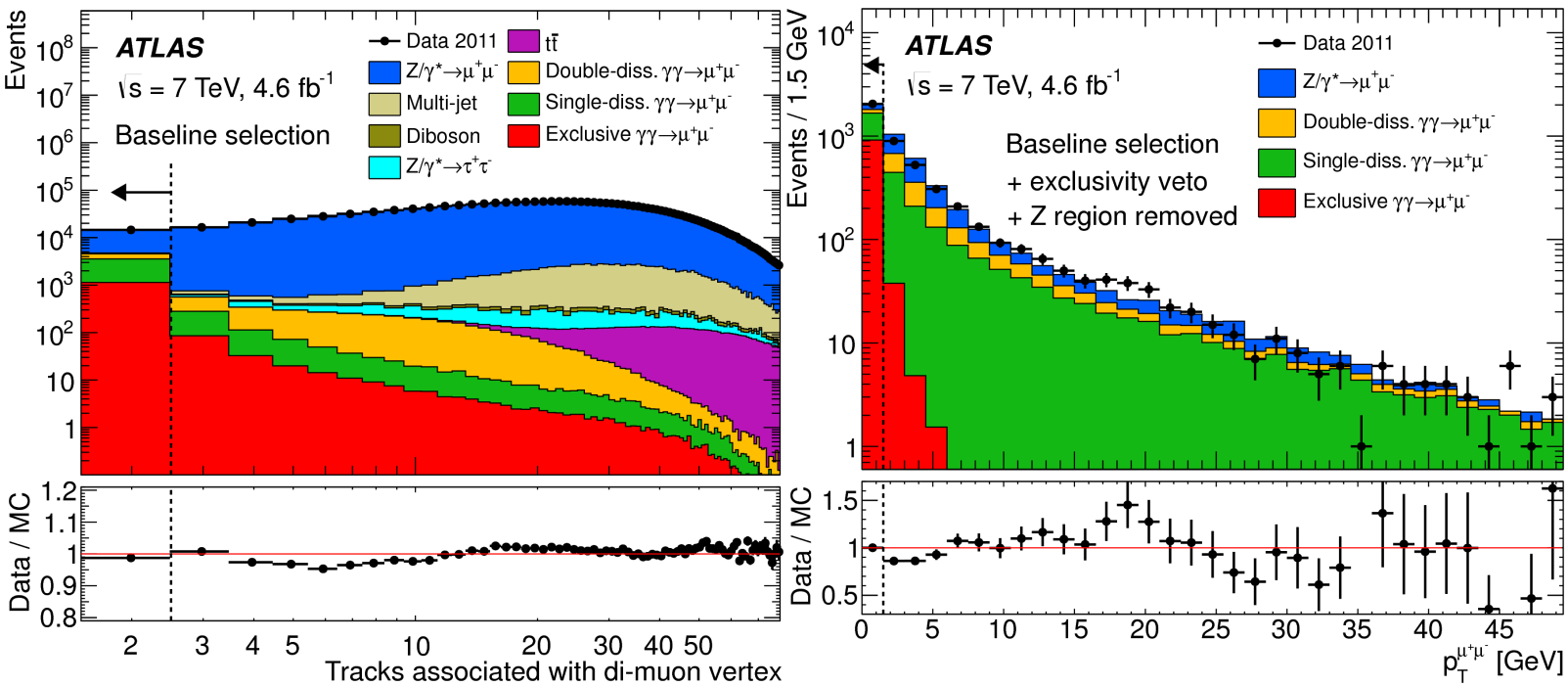
Proton tagging: AFP detectors



# $\gamma\gamma \to \mu\mu$ in $pp$: event selection

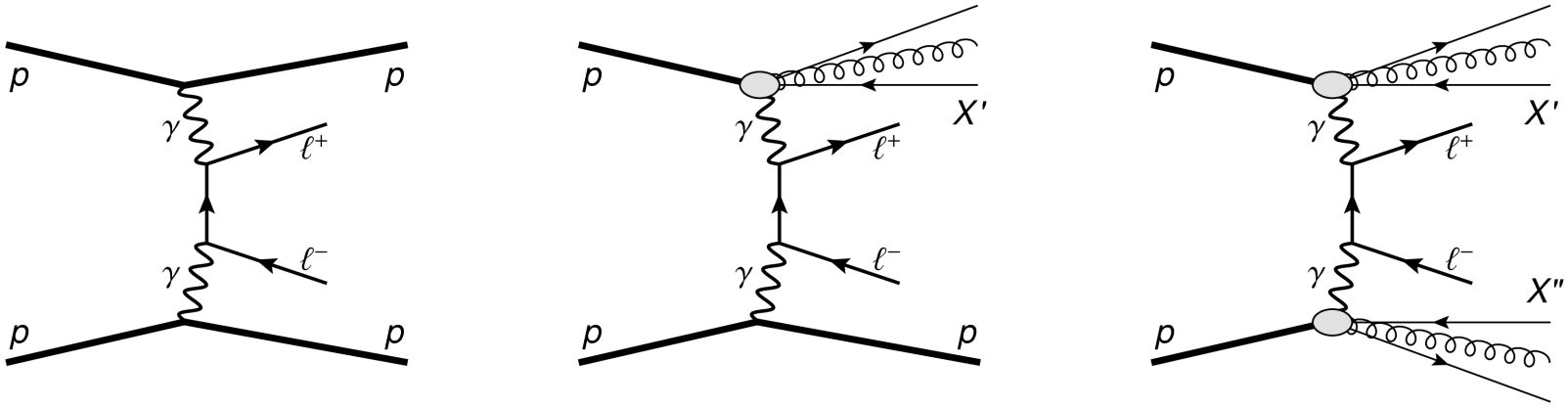


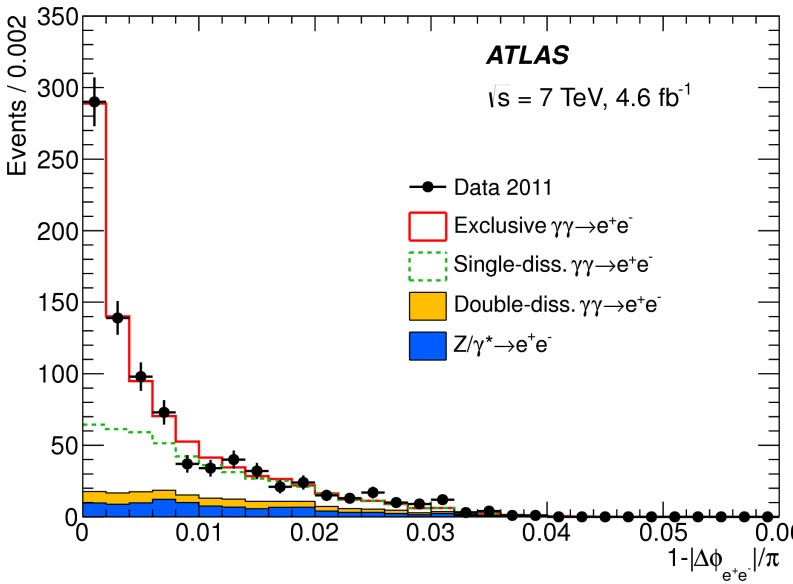
- Preselection:
  - muons: $p_T > 10$ GeV, $|\eta| < 2.4$, $M_{\mu\mu} > 20$ GeV
  - electrons: $p_T > 11$ GeV, $|\eta| < 2.4$, $M_{ee} > 24$ GeV
- Exclusive selection:
  - 3 mm vertex longitudinal isolation (efficiency = 74%)
  - $p_T$ of the pair below 1.5 GeV

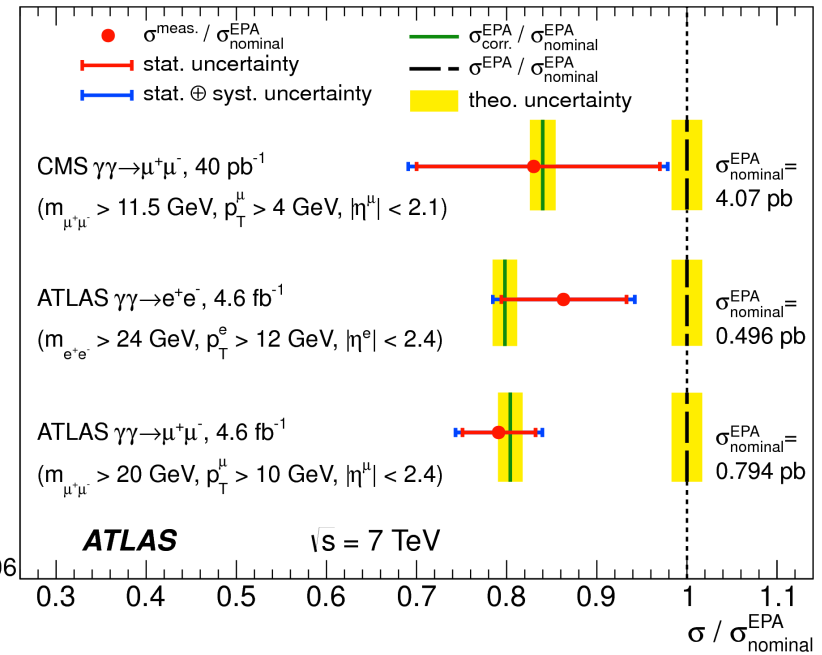


# $\gamma\gamma \to \mu\mu$ in $pp$: results





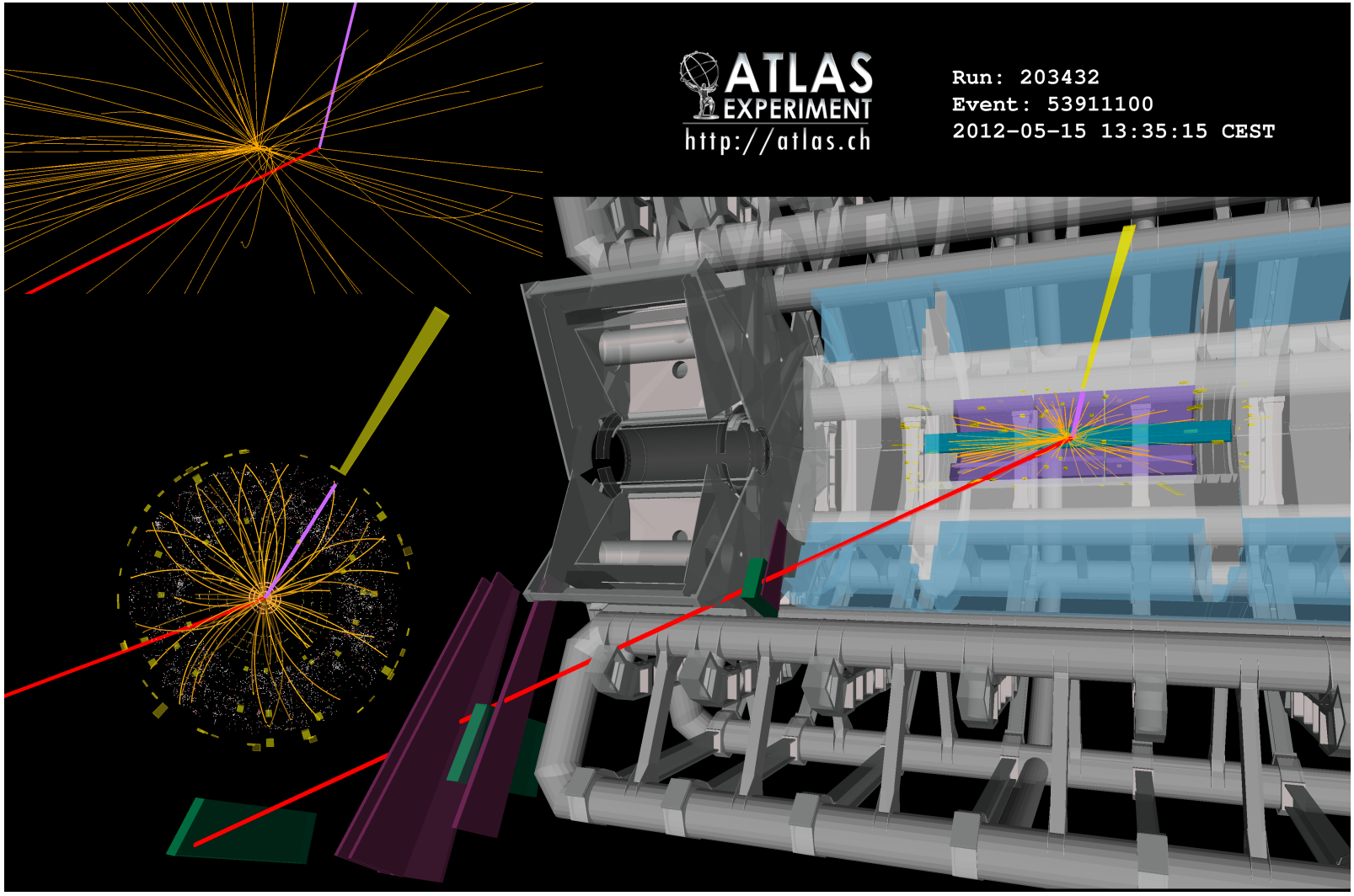




- Agreement with calculations (absorptive corrections are important)
- Measurement also at 13 TeV

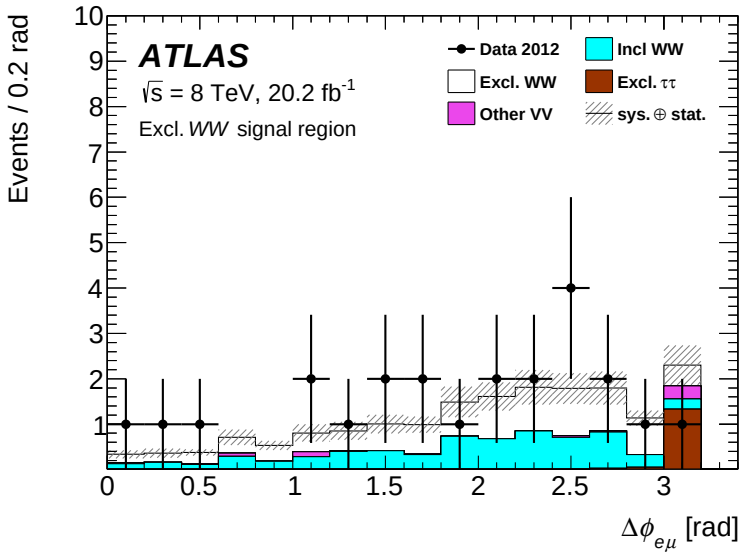
# $\gamma\gamma \to WW \to e\nu\mu\nu$

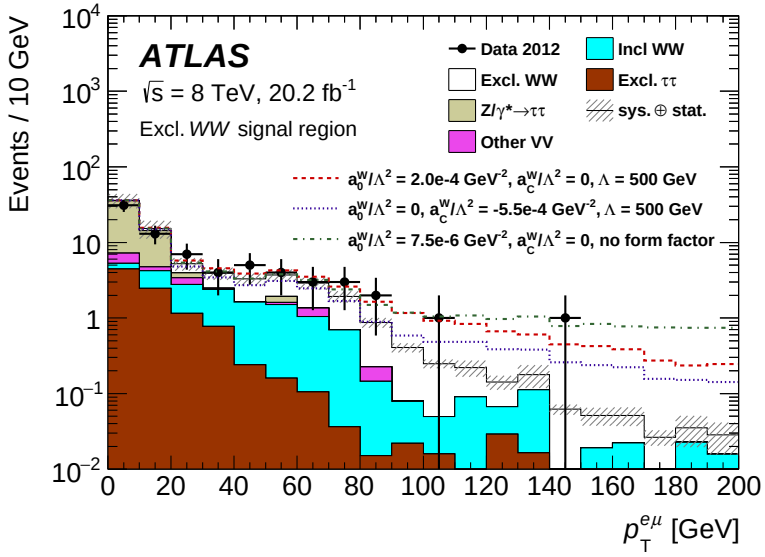


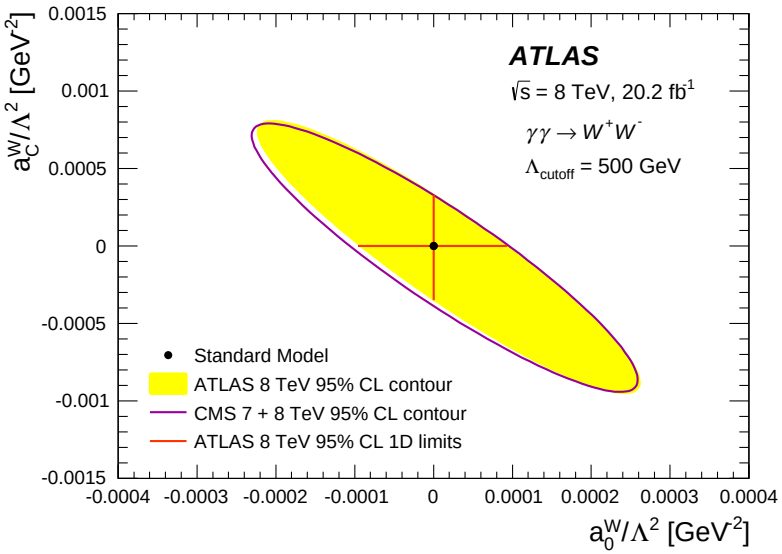


# Results for $\gamma\gamma \to WW \to e\nu\mu\nu$





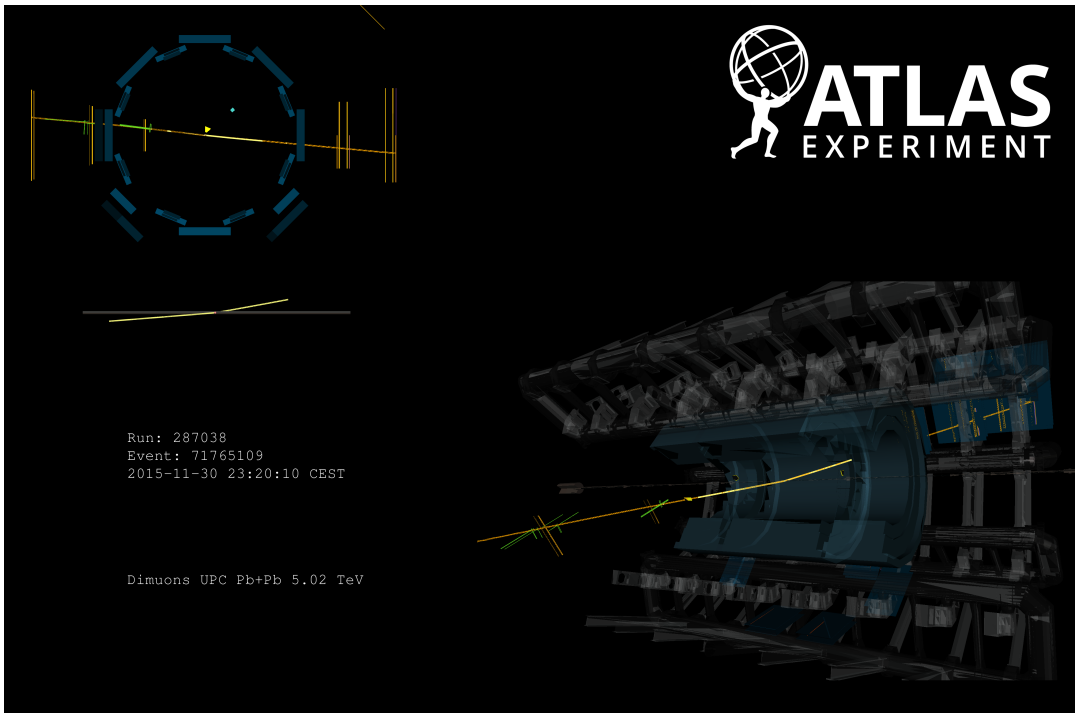



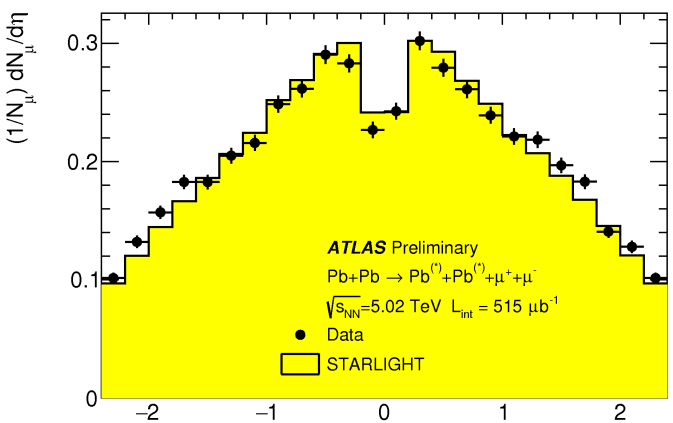

- Standard Model signal
  - $3\sigma$ significance
- New physics searches
  - $p_T^{e\mu} > 120$ GeV
  - Data: 1
  - Background: $0.37 \pm 0.13$
  - SM Signal: $0.37 \pm 0.04$
  - limits on anomalous $\gamma\gamma WW$ couplings

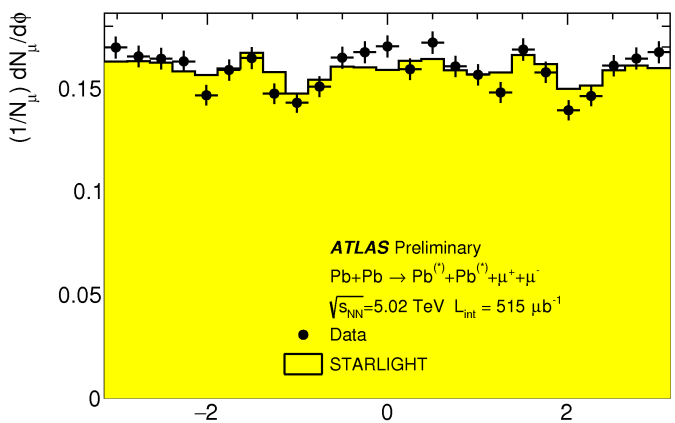
# $\gamma\gamma$ processes in heavy ion collisions



- $p_T > 5$ GeV $|\eta| < 2.4$ (both muons)
- $M_{\mu\mu} > 10$ GeV
- Muons form a vertex
- No other tracks
- 12069 events after selection

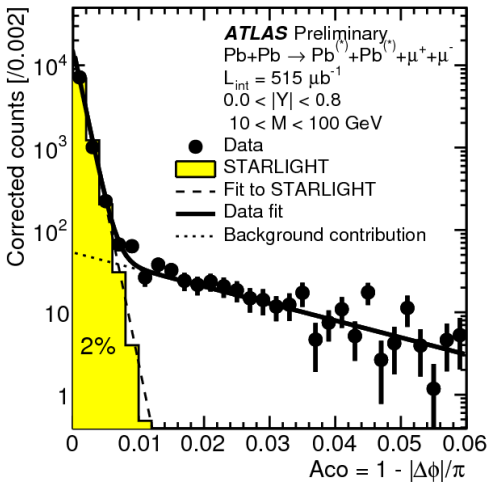


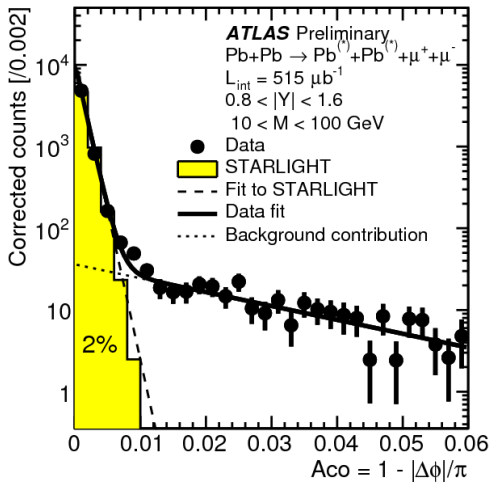



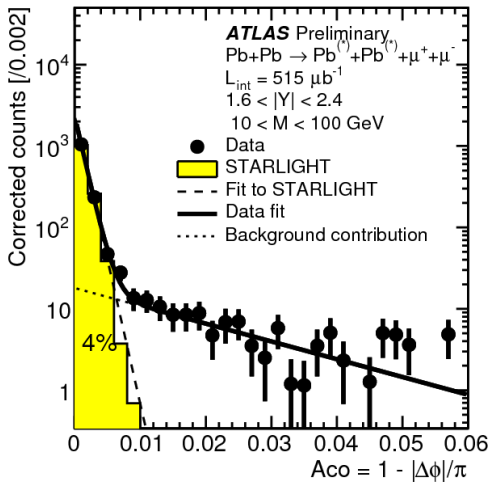



# Acoplanarity

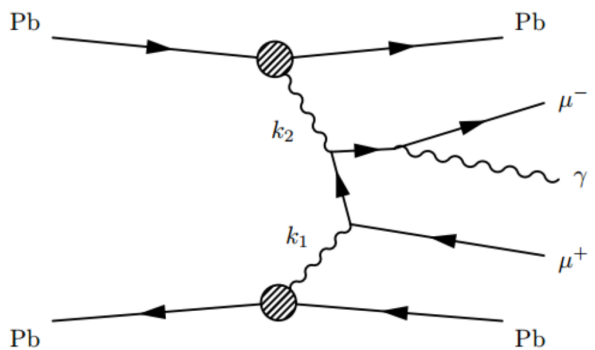





- No QED radiative corrections in MC (Starlight)
- Two variants assumed:
  - tail is background
  - tail is due to FSR




- The background fraction with acoplanarity$<0.08$ is 2 – 4%.
- The result is average of the two possibilities
- Difference is taken as systematic uncertainty

# Results

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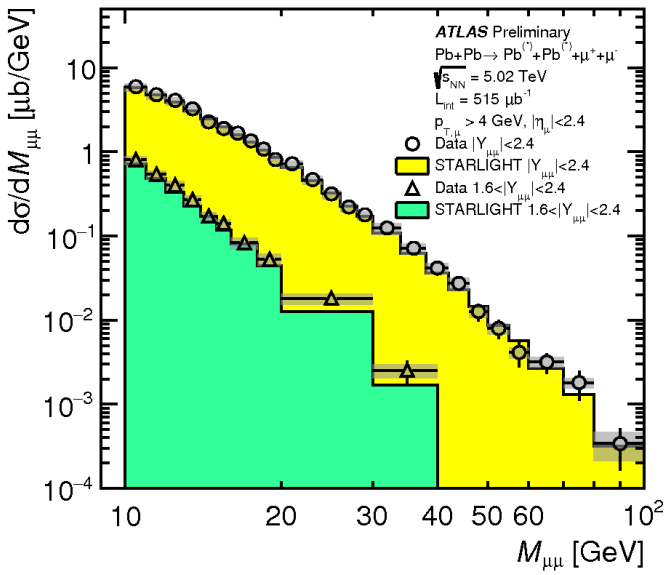
Rafał Staszewski

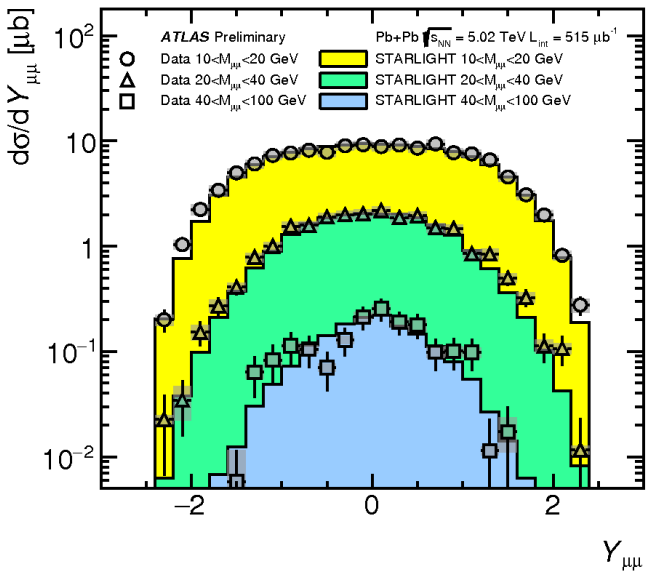
Introduction

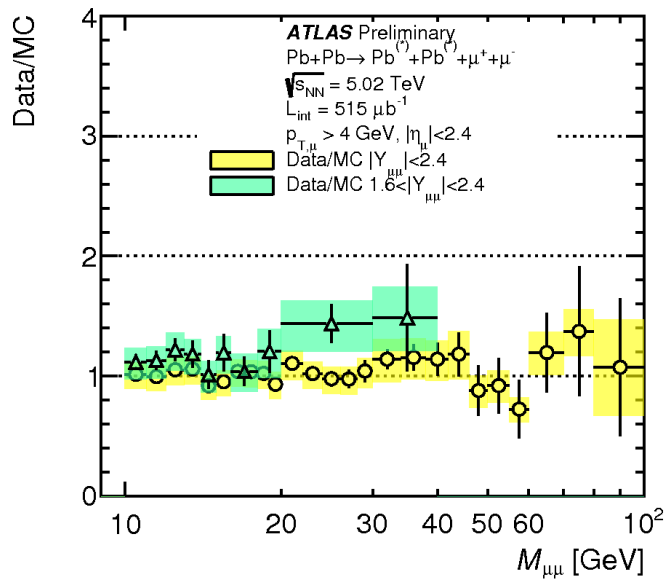
Measurements w/o forward proton tagging

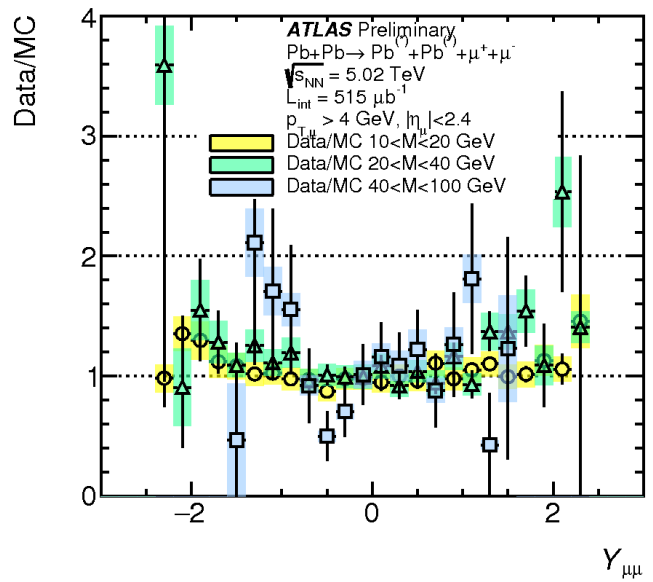
Proton tagging: ALFA detectors

Proton tagging: AFP detectors



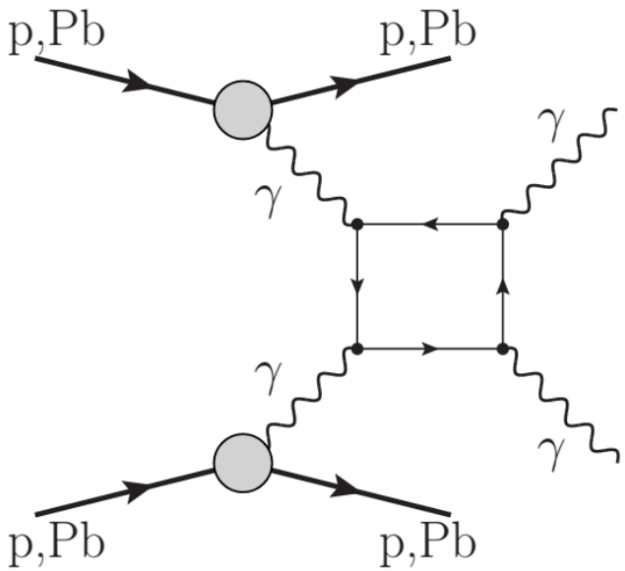



# Light-by-light scattering in $PbPb$



- Elastic scattering of two photons
- Quantum effect: not present in classical theory
- Very small cross section
- No direct observation so far
- Possible channel to study new physics



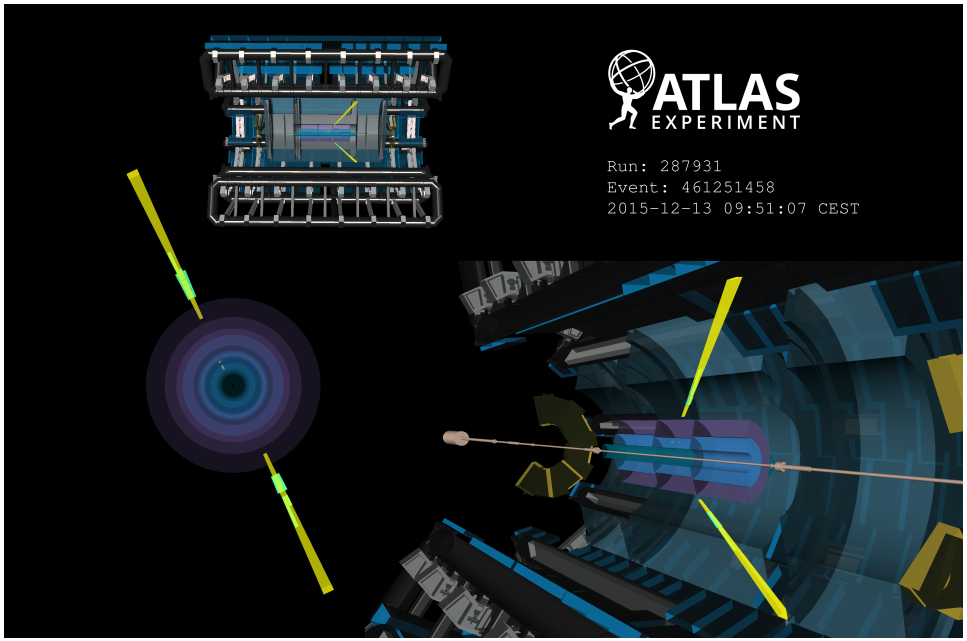
# Event selection

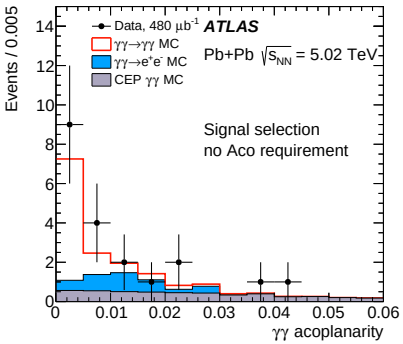


- Dedicated trigger: photons + clean event

Selection:

- Two photons, $E_T > 3$ GeV
- $M_{\gamma\gamma} > 6$ GeV
- Exclusivity: no tracks
- $p_T^{\gamma\gamma} < 6$ GeV
- Acoplanarity: $(1 - \Delta\Phi_{\gamma\gamma}/\pi) < 0.01$



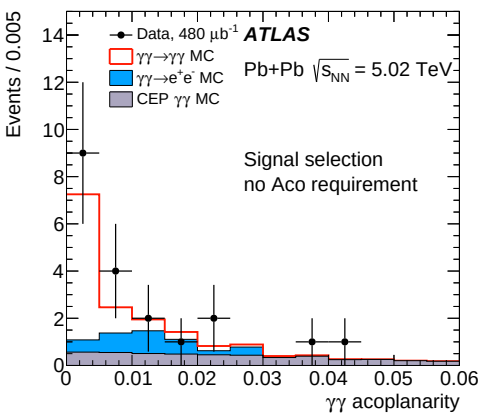

| Selection | $\gamma\gamma \to e^+e^-$ | CEP $gg \to \gamma\gamma$ | Hadronic fakes | Other fakes | Total background | Signal | Data |
|---|---|---|---|---|---|---|---|
| Preselection | 74 | 4.7 | 6 | 19 | 104 | 9.1 | 105 |
| $N_{\rm trk} = 0$ | 4.0 | 4.5 | 6 | 19 | 33 | 8.7 | 39 |
| $p_{\rm T}^{\gamma\gamma} < 2$ GeV | 3.5 | 4.4 | 3 | 1.3 | 12.2 | 8.5 | 21 |
| Aco $< 0.01$ | 1.3 | 0.9 | 0.3 | 0.1 | 2.6 | 7.3 | 13 |
| Uncertainty | 0.3 | 0.5 | 0.3 | 0.1 | 0.7 | 1.5 | |

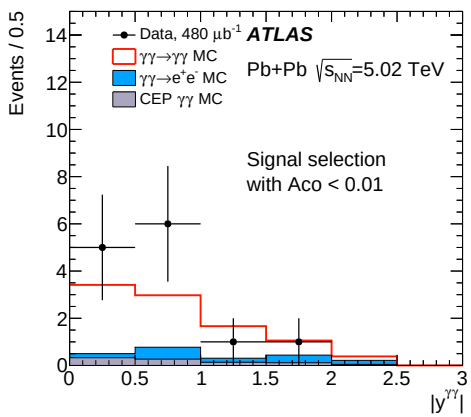
# Results

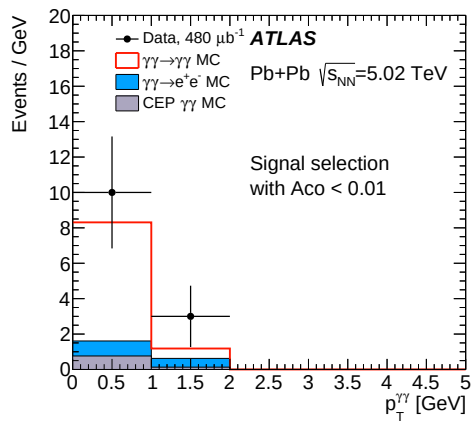


- First direct observation of the light-by-light signal
- Excess in the data consistent with predictions

$$\sigma_{\text{fid}}^{\text{meas}} = 70 \pm 24(\text{stat}) \pm 17(\text{syst}) \text{ nb} \qquad \sigma_{\text{fid}}^{\text{th}} = 49 \pm 10 \text{ nb}$$




- Observed significance: $4.4\sigma$ (expected: $3.8\sigma$)

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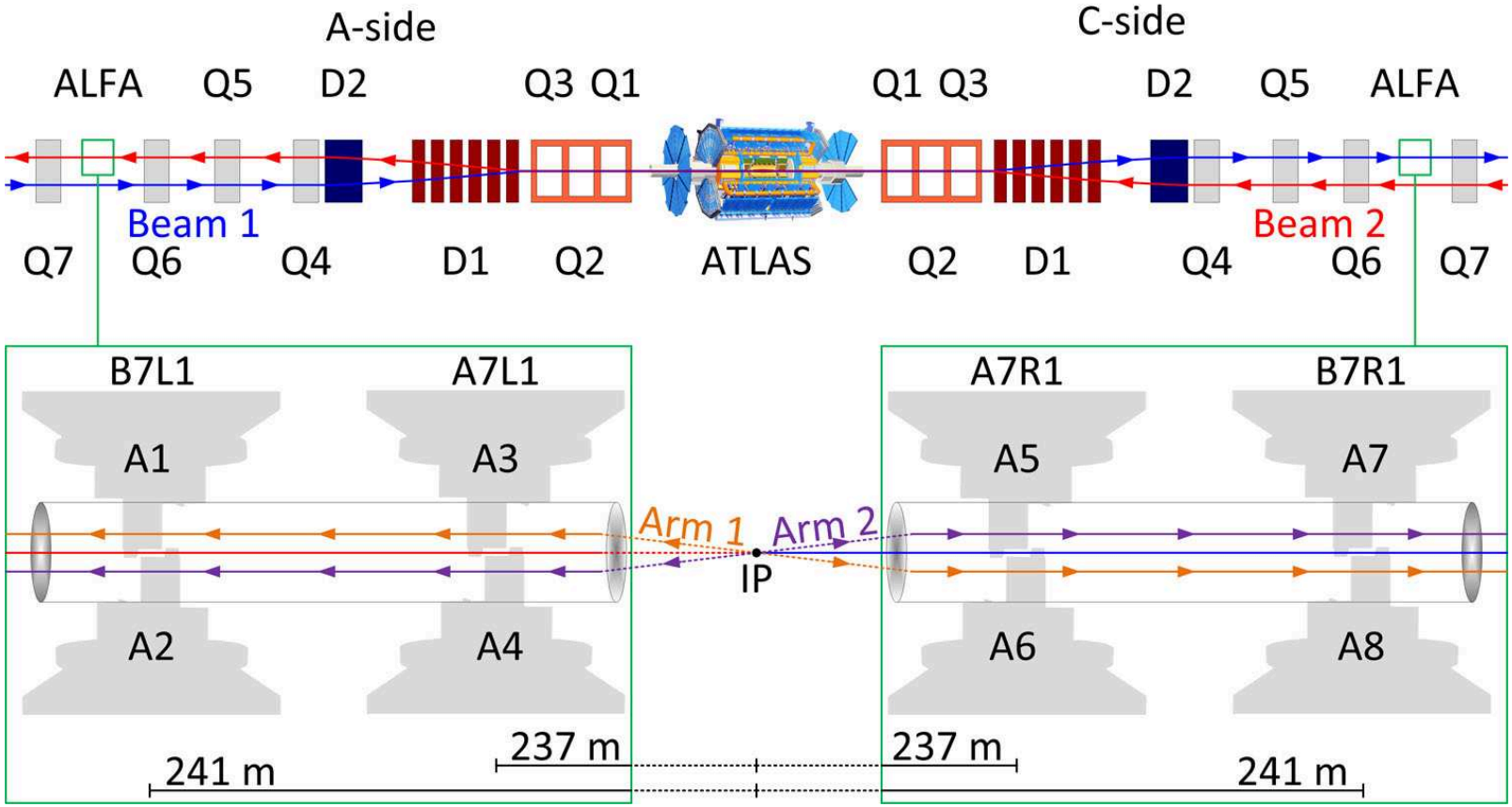
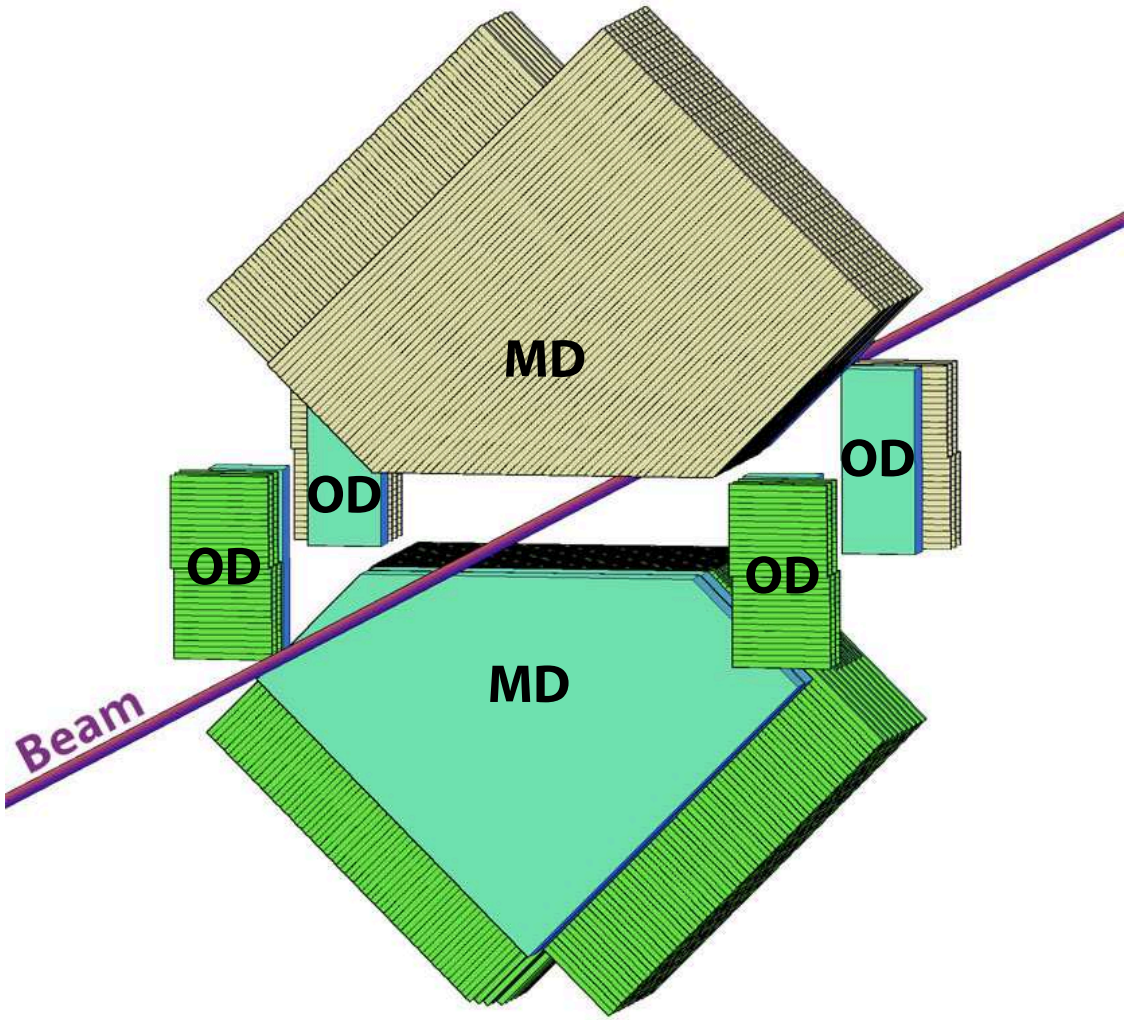
# ALFA Detectors





# ALFA station





# Optical theorem, total cross section and absolute luminosity



- Four momentum transfer squared

$$t = (p - p')^2 \approx -(p\theta)^2 = -p^2(\theta_x^2 + \theta_y^2)$$

- Optical theorem

$$\sigma_{\text{tot}} = 4\pi \text{Im} f_{\text{el}}\Big|_{t\to 0}$$

- Theoretical input

$$\rho = \frac{\text{Re} f_{\text{el}}}{\text{Im} f_{\text{el}}}\Big|_{t\to 0}$$

- Total cross section

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

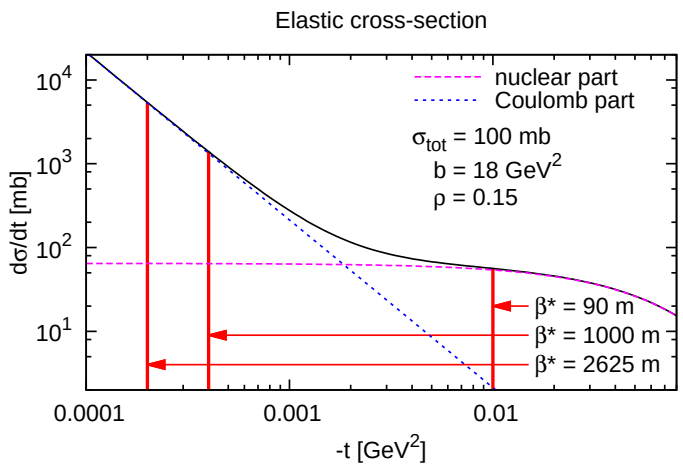
- Elastic scattering

$$\frac{\text{d}\sigma_{\text{el}}}{\text{d}t} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|$$

- Fit formula:

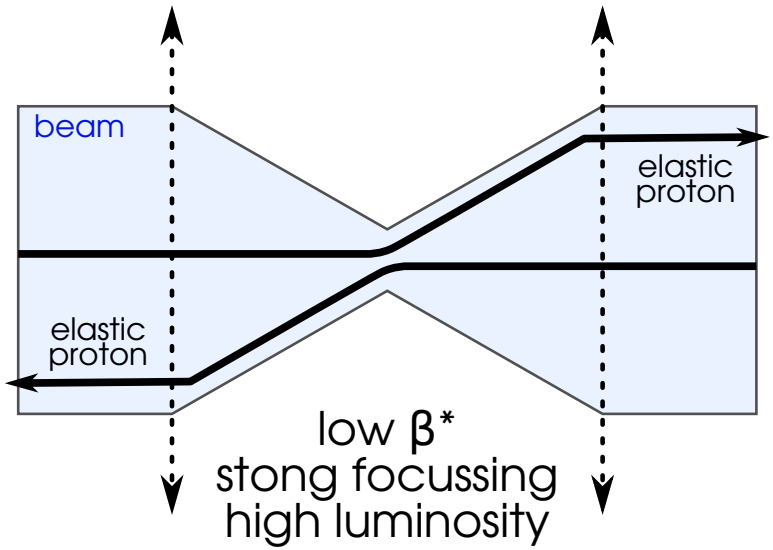
$$\frac{\text{d}\sigma}{\text{d}t} = \sigma_{\text{tot}}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \times \exp\left(-B|t|\right)$$

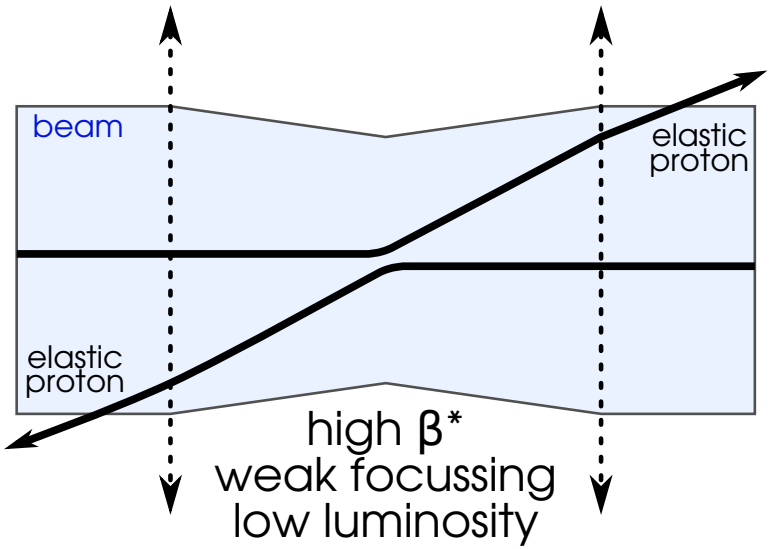
- Absolute luminosity



# High-$\beta$ optics





# Elastic events

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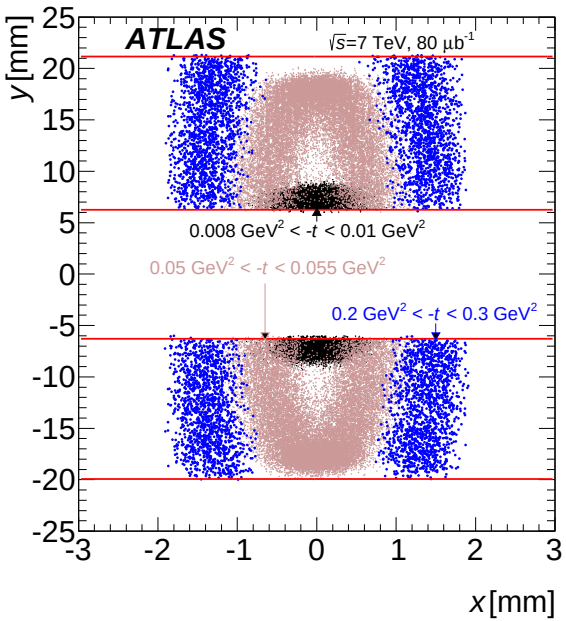
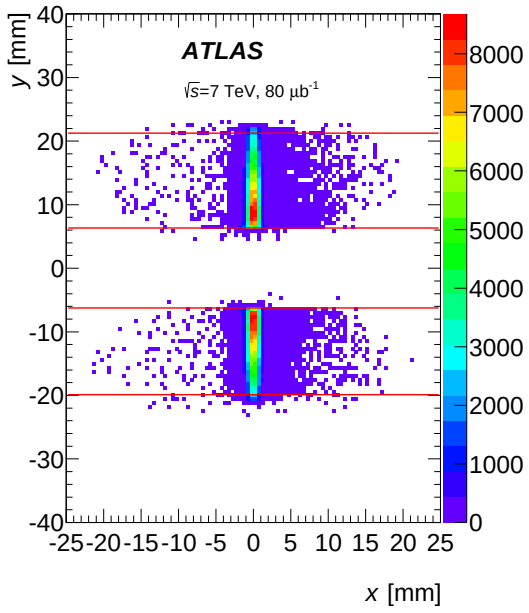
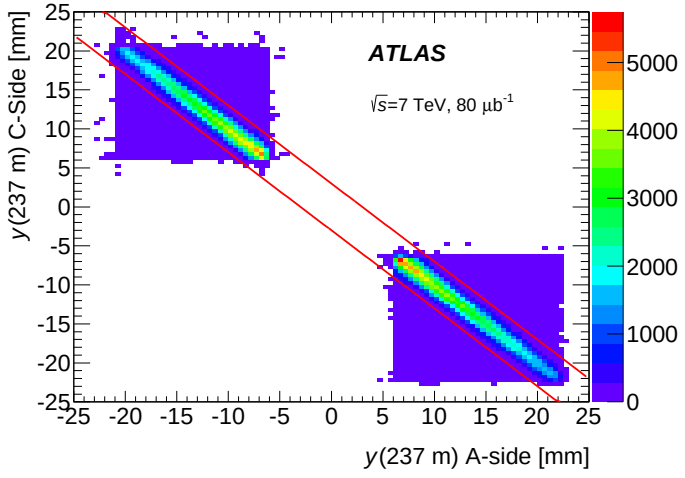
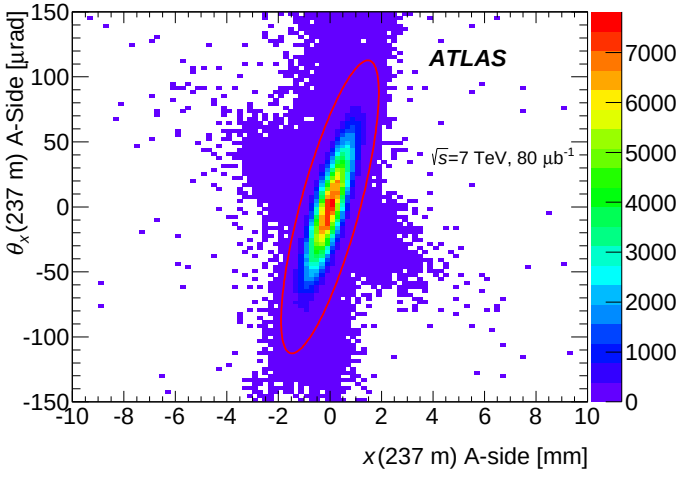


# Reconstruction



## Proton transport

$$\begin{bmatrix} x \\ \theta_x \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}_x \begin{bmatrix} x^* \\ \theta_x^* \end{bmatrix} \qquad \begin{bmatrix} y \\ \theta_y \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}_y \begin{bmatrix} y^* \\ \theta_y^* \end{bmatrix}$$

## $t$ reconstruction

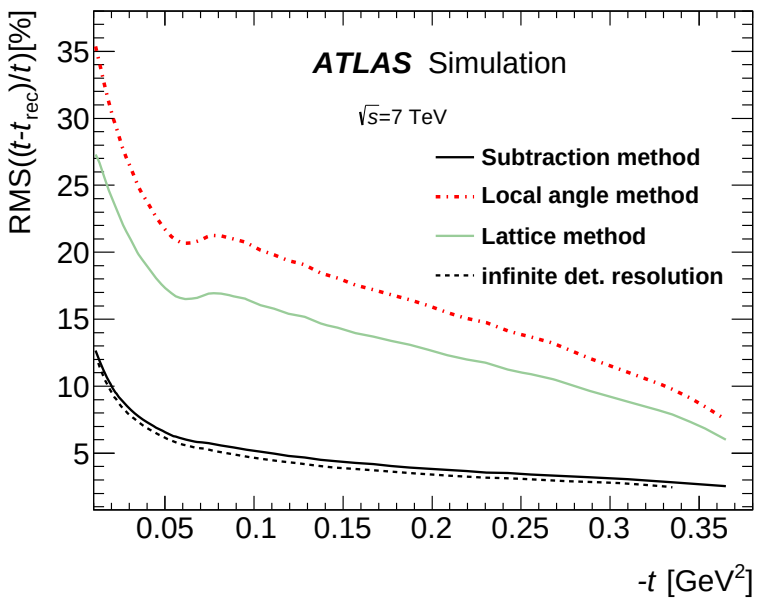
- $t$ subtraction method

$$\theta_x^* = \frac{x_A - x_C}{M_{12,A} + M_{12,C}}$$

- $t$ local angle method

$$\theta_x^* = \frac{\theta_{x,A} - \theta_{x,C}}{M_{22,A} + M_{22,C}}$$

- $t$ lattice method



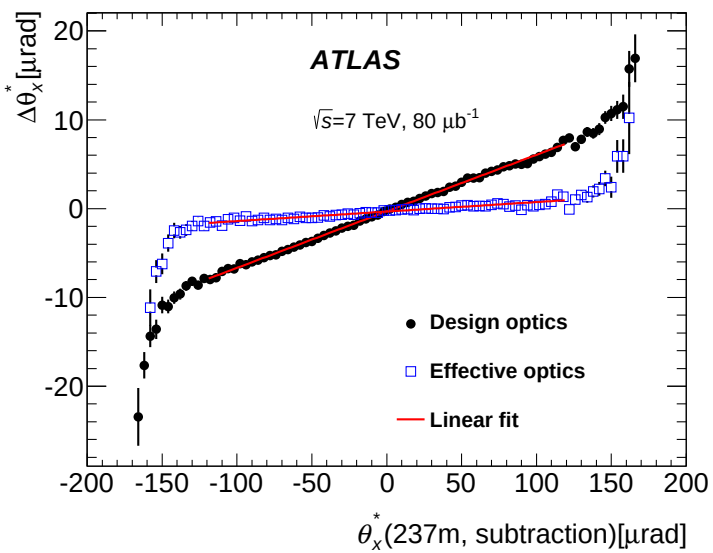
# Optics studies

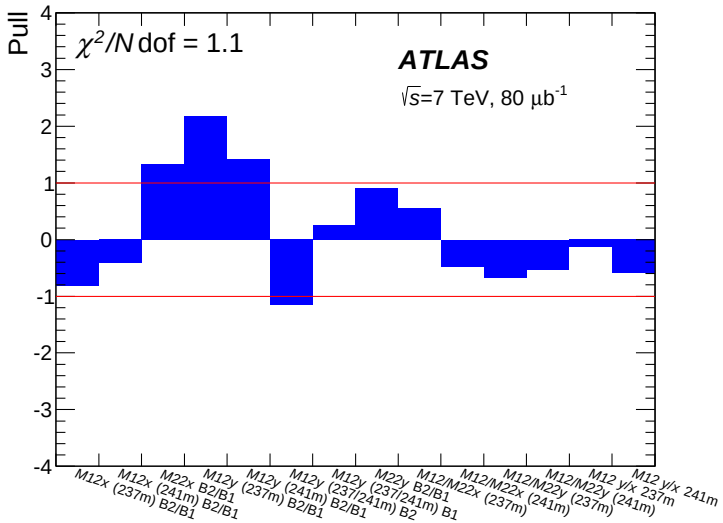


## Proton transport

$$\begin{bmatrix} x \\ \theta_x \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}_x \begin{bmatrix} x^* \\ \theta_x^* \end{bmatrix} \qquad \begin{bmatrix} y \\ \theta_y \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}_y \begin{bmatrix} y^* \\ \theta_y^* \end{bmatrix}$$

## Optics studies

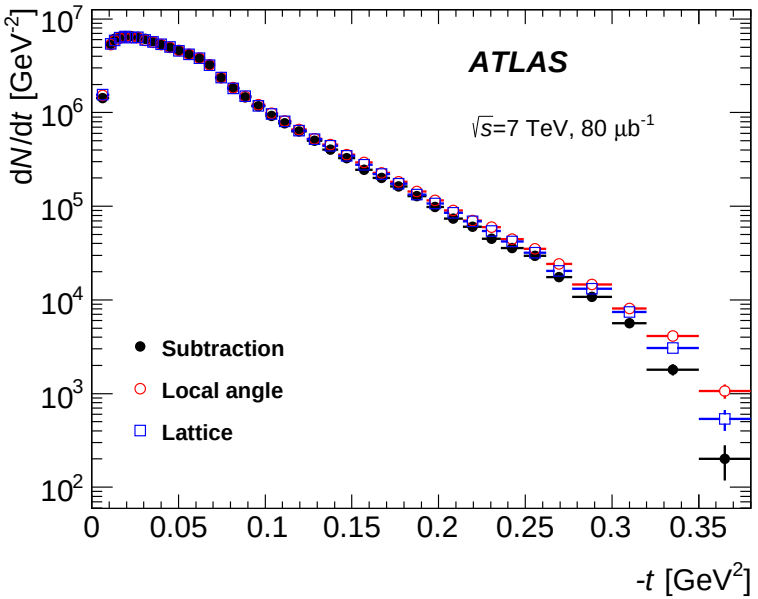


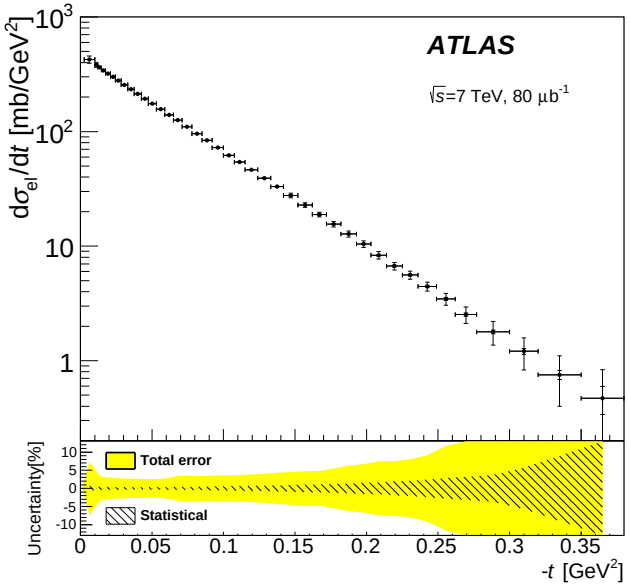
# Corrections



## Raw data




## Corrected data




- luminosity
- acceptance
- background
- unfolding
- reconstruction efficiency
- trigger efficiency
- dead-time correction

# Acceptance

Forward Physics in the ATLAS Experiment at the LHC

Rafał Staszewski

Introduction

Measurements w/o forward proton tagging

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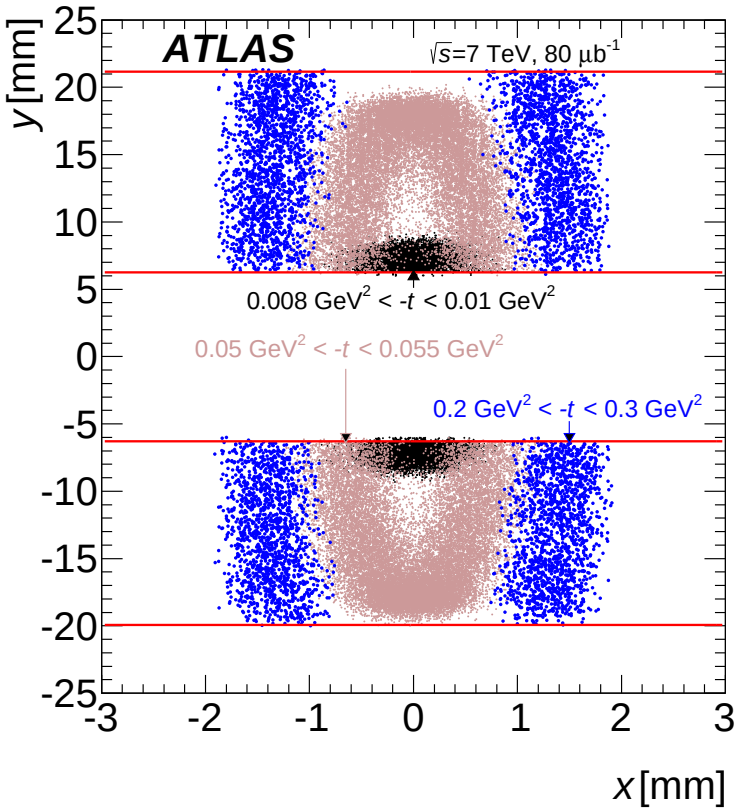


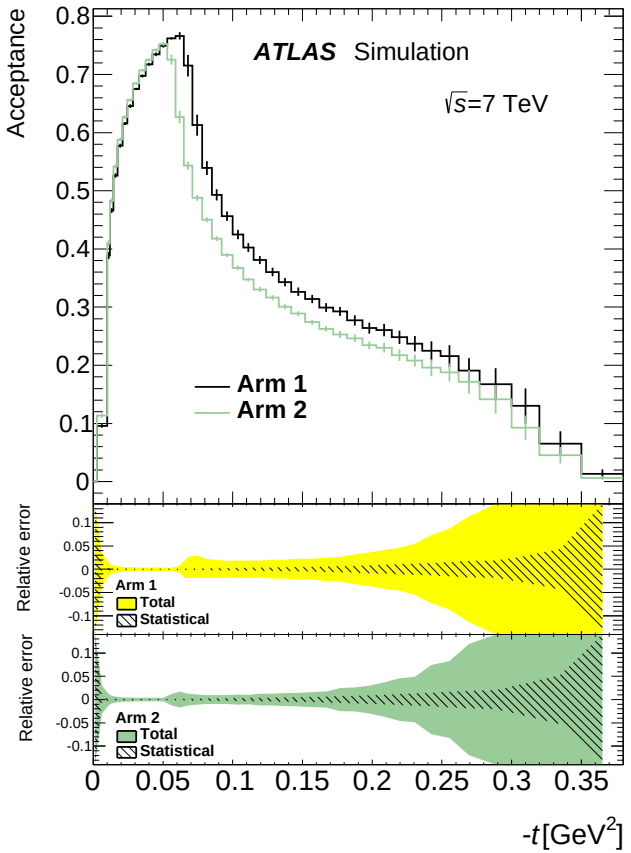

# Background

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Rafał Staszewski
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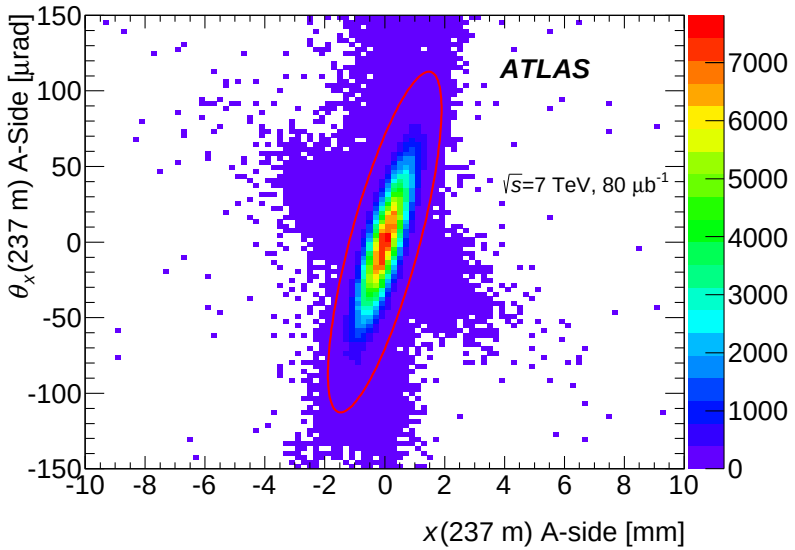
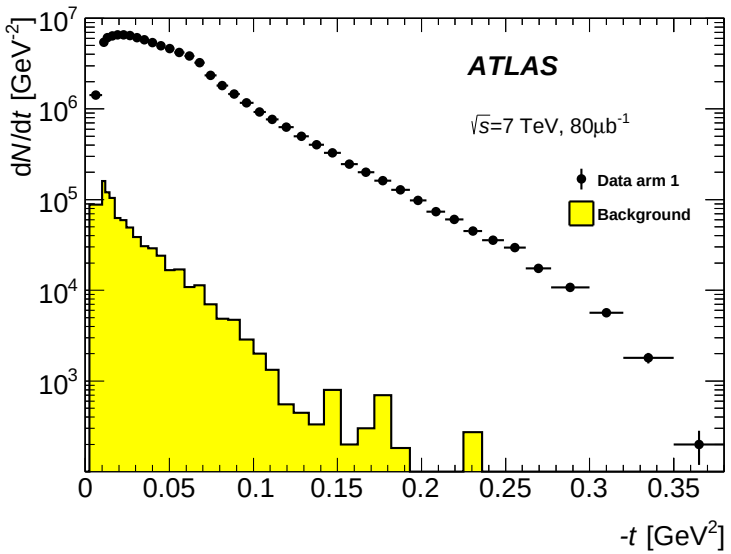
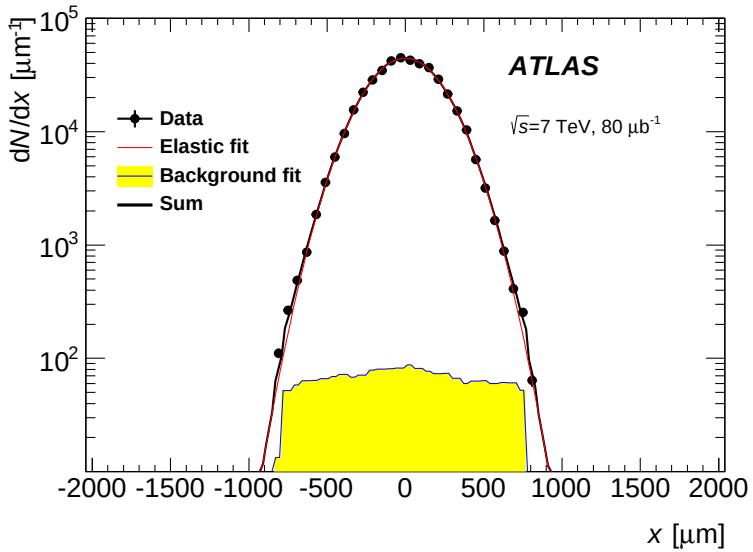



- Background contamination: $\sim 0.5$ %
- Systematic uncertainty: 50 – 80 %

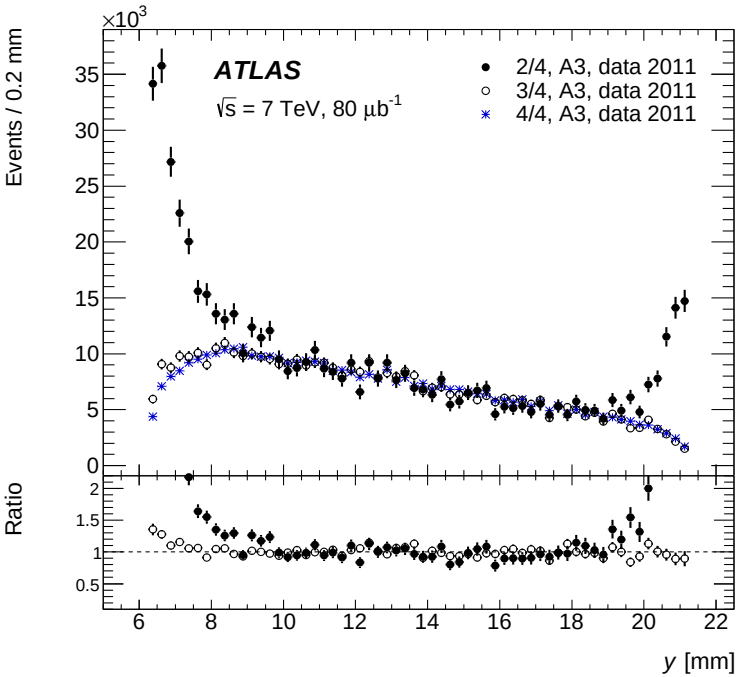


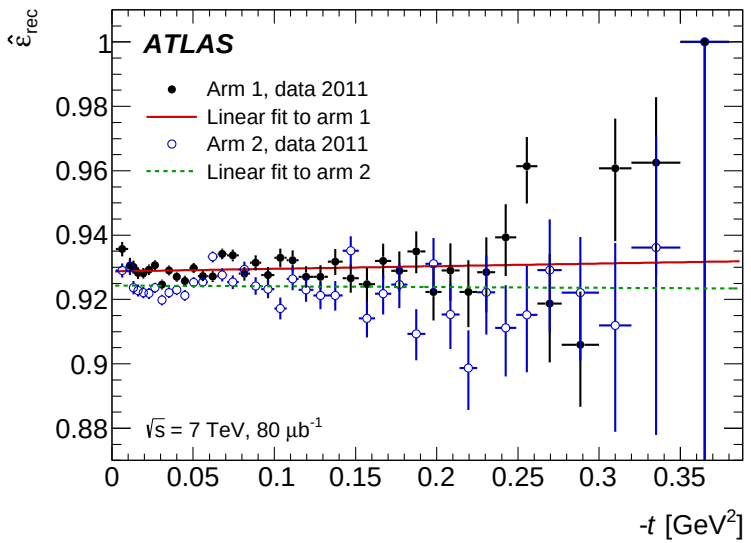



# Reconstruction efficiency



$$\varepsilon_{\text{rec}} = \frac{N_{\text{reco}}}{N_{\text{reco}} + N_{\text{fail}}} = \frac{N_{4/4}}{N_{4/4} + N_{3/4} + N_{2/4} + N_{(1+1)/4} + N_{1/4} + N_{0/4}}$$




$$\varepsilon_{\text{rec},1} = 0.8974 \pm 0.0004\ (\text{stat}) \pm 0.0061\ (\text{syst})$$
$$\varepsilon_{\text{rec},2} = 0.8800 \pm 0.0005\ (\text{stat}) \pm 0.0092\ (\text{syst})$$

# Fitting procedure

Forward Physics in the ATLAS Experiment at the LHC

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Introduction

Measurements w/o forward proton tagging

Proton tagging: ALFA detectors

Proton tagging: AFP detectors

- Ucorrelated statistical uncertainty

$$\chi^2 = \sum_i \Big( D(i) - T(i) \Big)^2$$

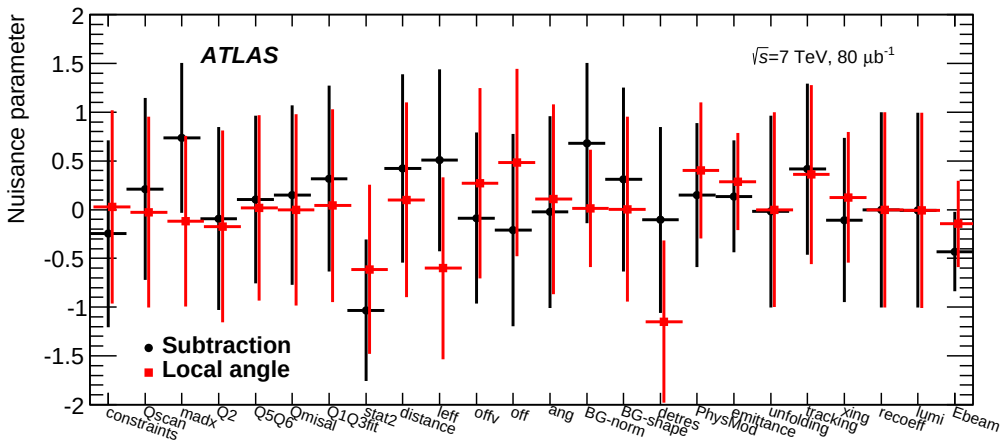
- Correlated statistical uncertainty

$$\chi^2 = \sum_{i,j} \Big( D(i) - T(i) \Big) \mathbf{V}^{-1}(i,j) \Big( D(j) - T(j) \Big)$$

- Nuisance parameter fit

$$\chi^2 = \sum_{i,j} \left[ \left( D(i) - \left( 1 + \sum_{l=1}^{2} \alpha_l \right) \cdot T(i) - \sum_{k=1}^{22} \beta_k \cdot \delta_k(i) \right) \cdot V^{-1}(i,j) \right.$$

$$\left. \cdot \left( D(j) - \left( 1 + \sum_{l=1}^{2} \alpha_l \right) \cdot T(j) - \sum_{k=1}^{22} \beta_k \cdot \delta_k(j) \right) \right] + \sum_{k=1}^{22} {\beta_k}^2 + \sum_{l=1}^{2} \frac{{\alpha_l}^2}{\epsilon_l^2}$$



# Results

Forward Physics in the ATLAS Experiment at the LHC

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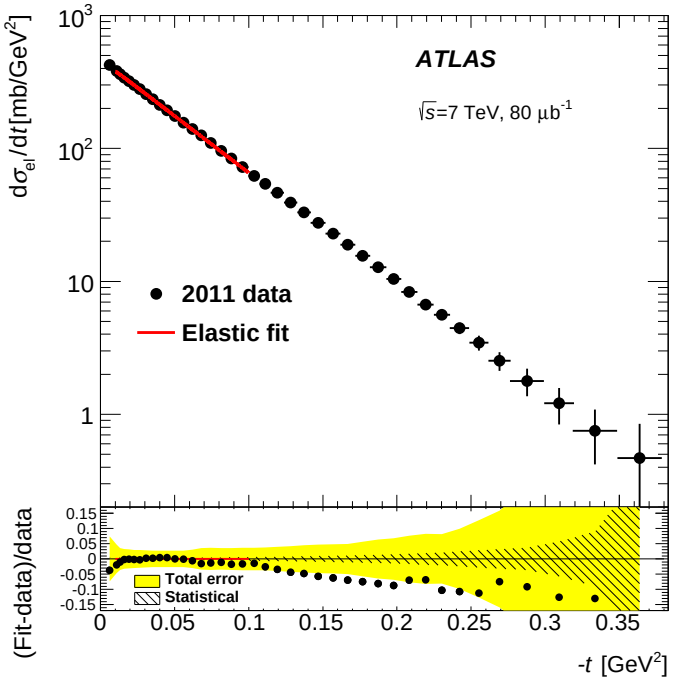
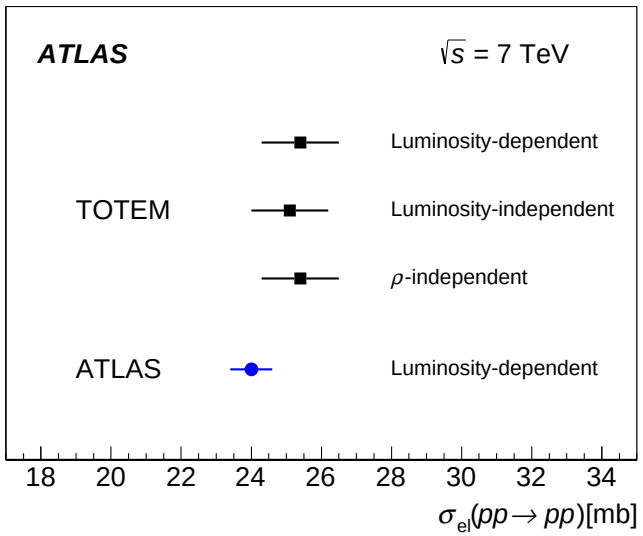
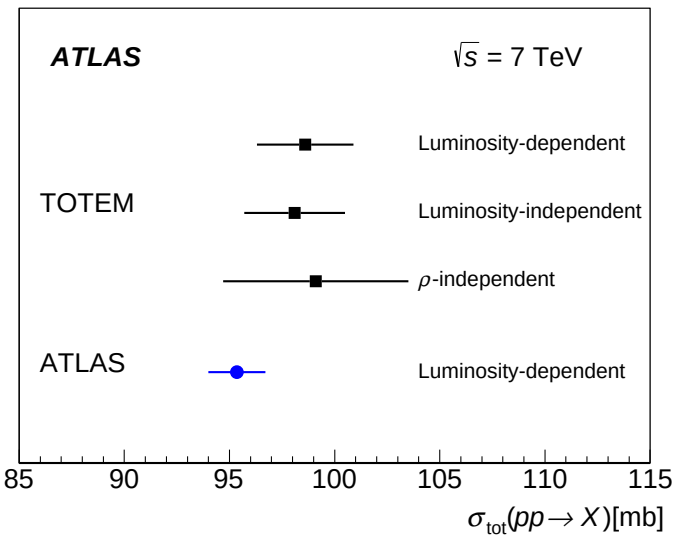
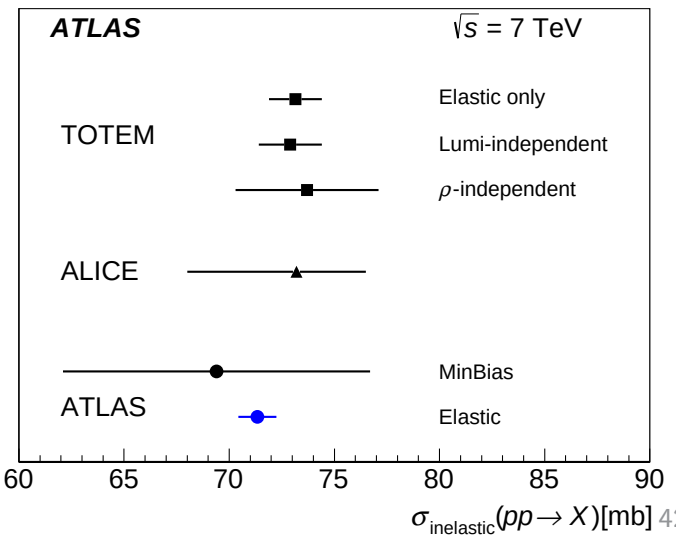


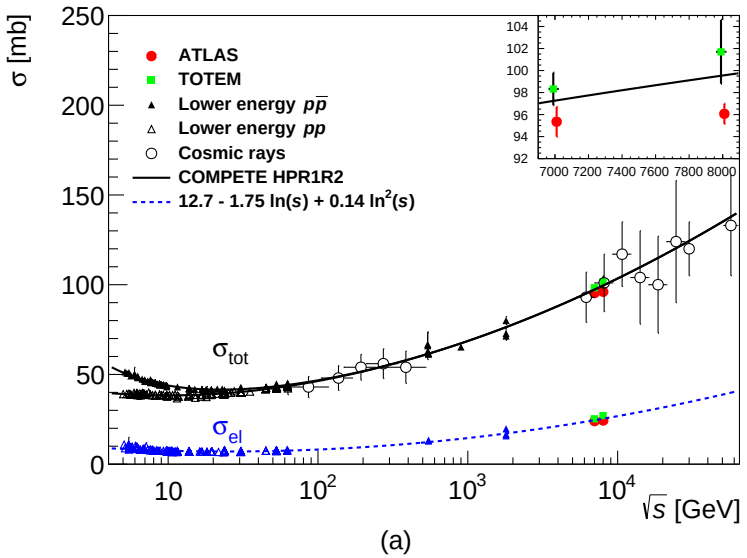



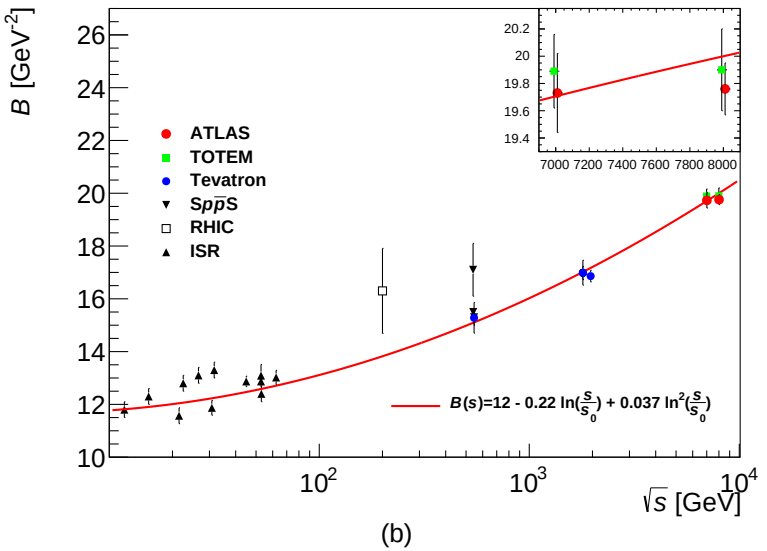



# Total cross section end elastic slope






- Published measurements at 7 and 8 TeV
- Ongoing measurement of $\rho$ at 8 TeV (1 km optics)
- Data at 13 TeV collected (90 m and 2.5 km)

# Diffraction with ALFA

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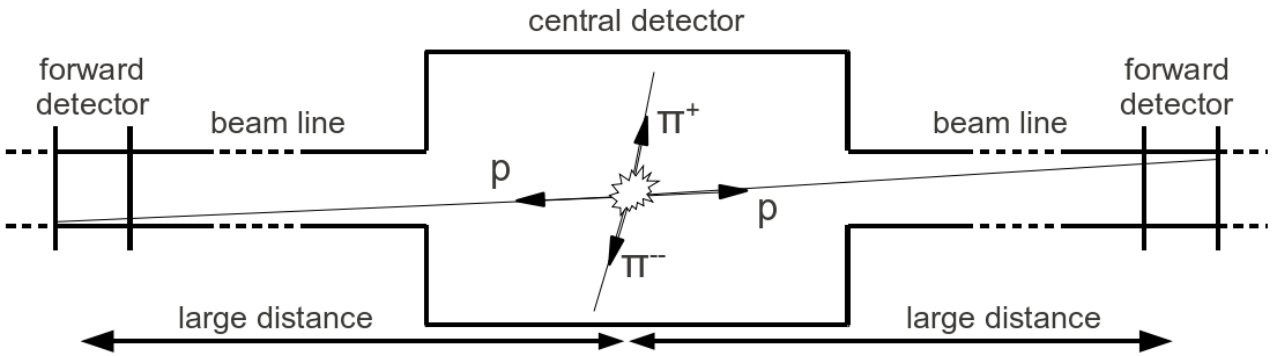
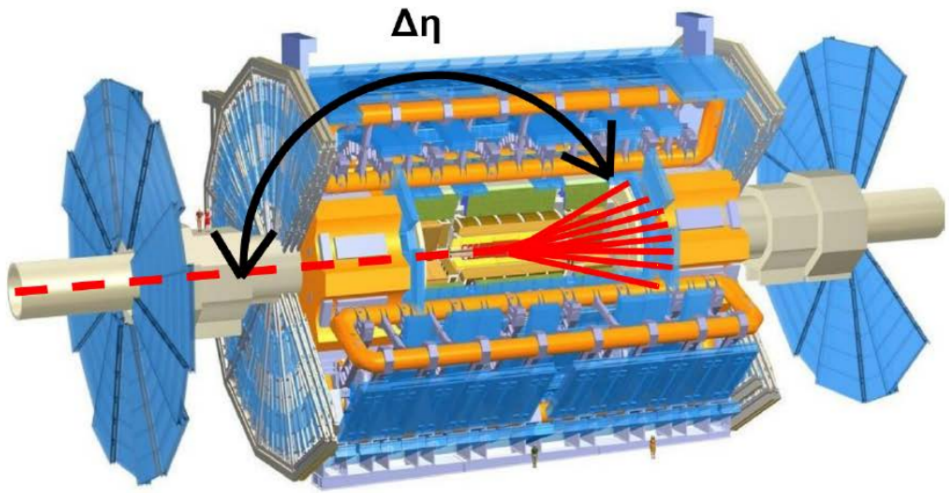
Ongoing measurements:

- Exclusive $pp \to p\pi^+\pi^- p$




- Single diffraction



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# AFP (ATLAS Forward Proton) detectors

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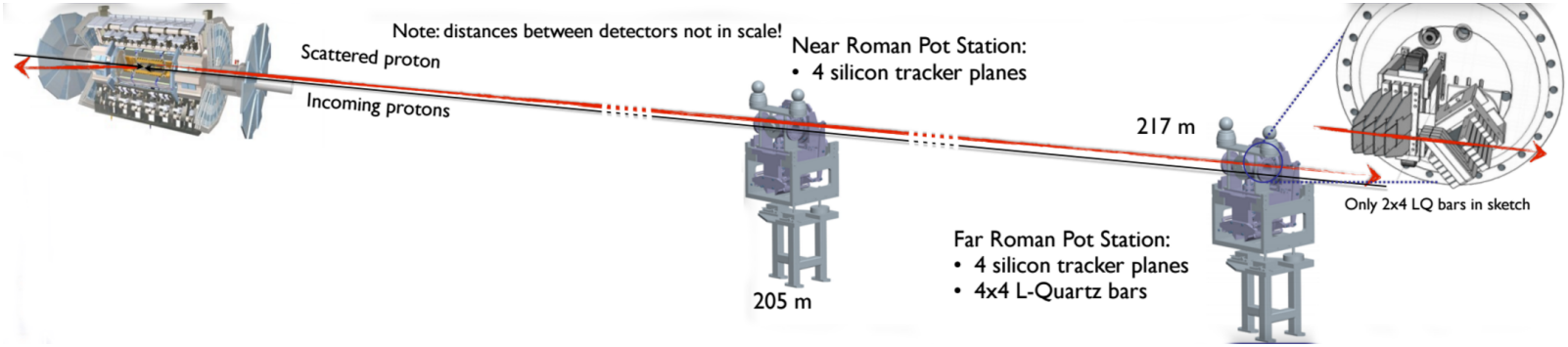
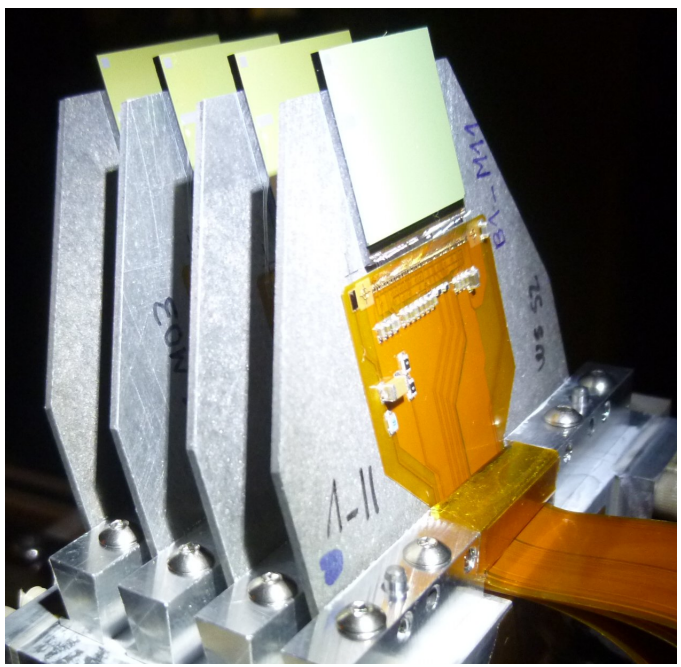
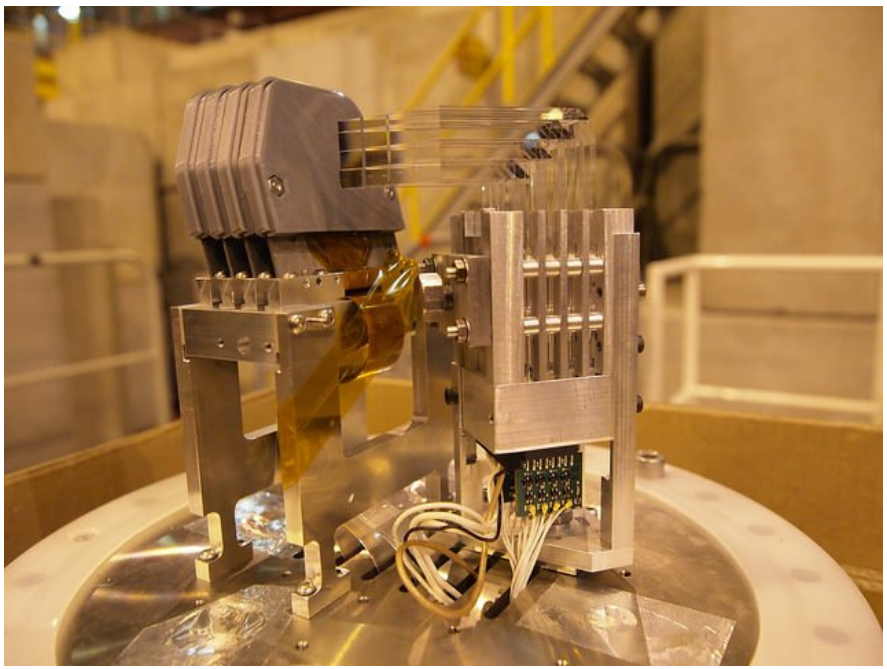
Proton tagging: AFP detectors

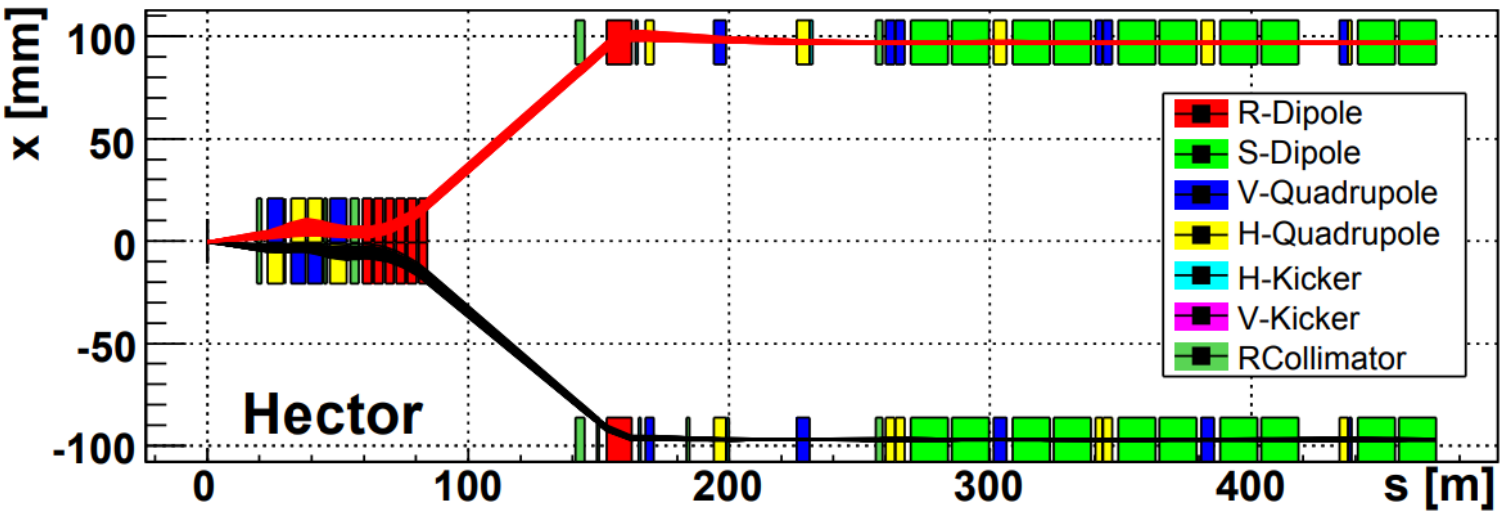


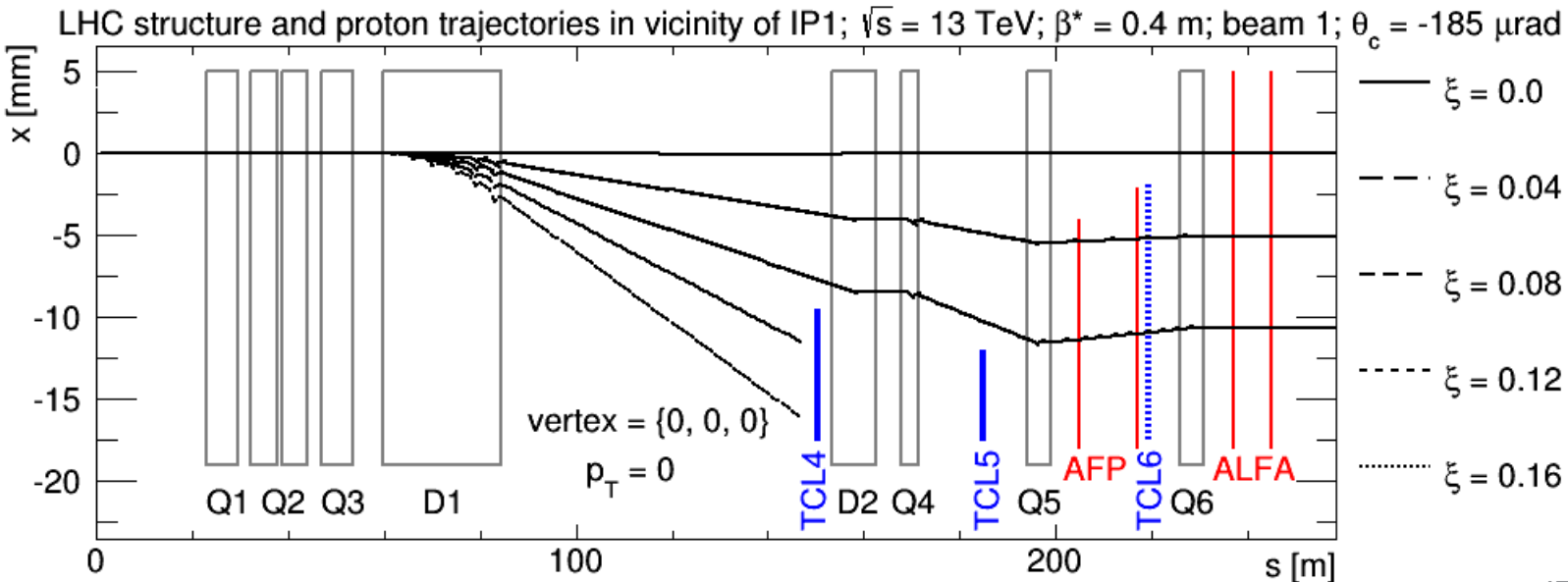





# Trajectories of forward protons





# Motivation for ToF detectors

Forward Physics in the ATLAS Experiment at the LHC

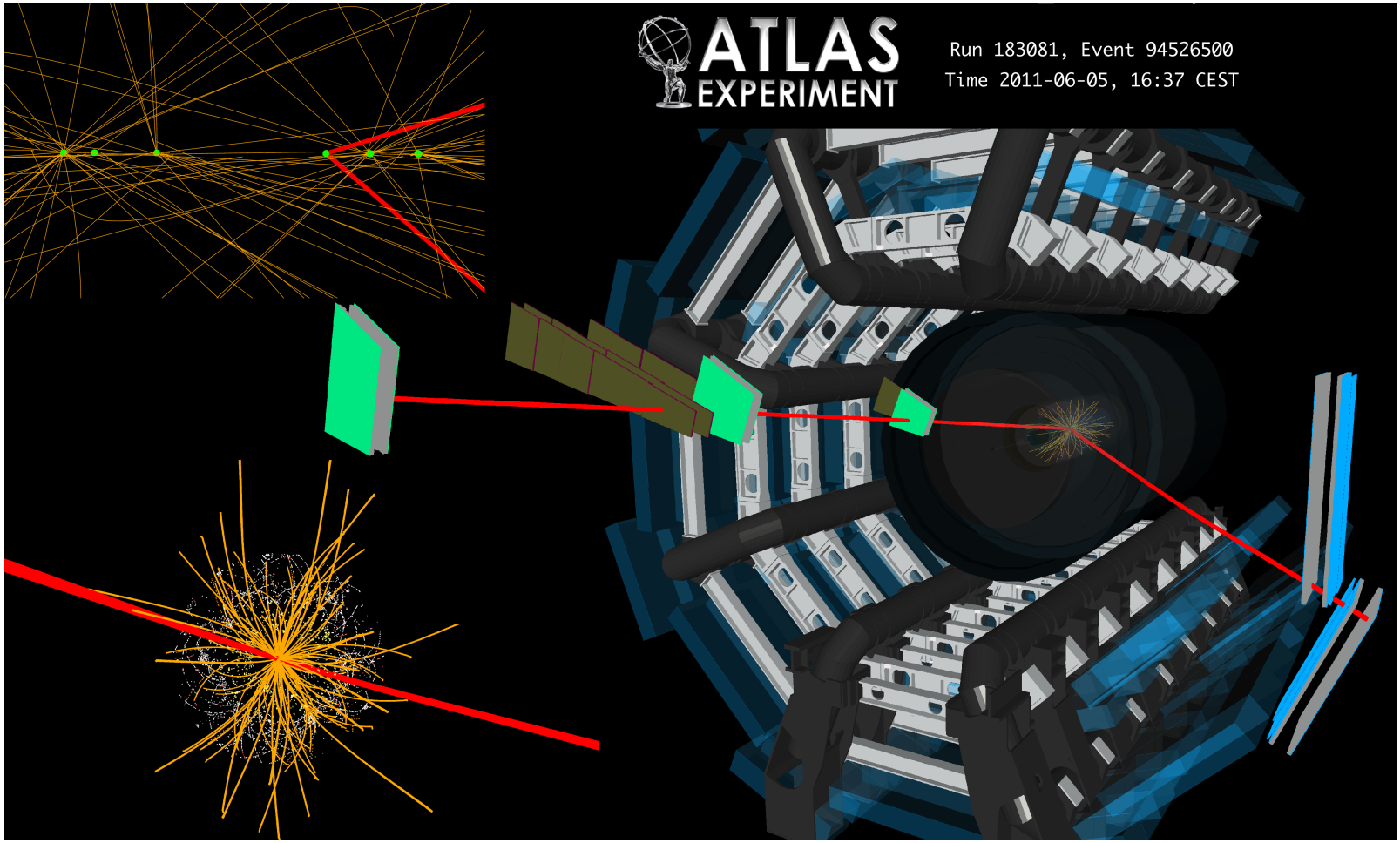
Rafał Staszewski

Introduction

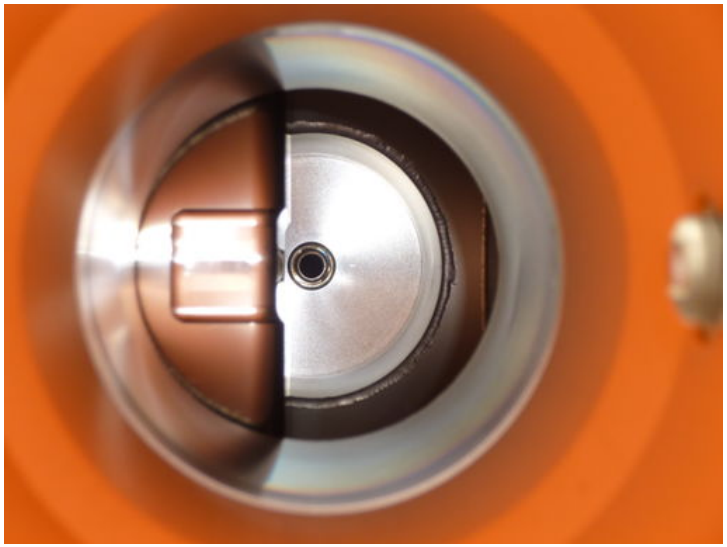
Measurements w/o forward proton tagging

Proton tagging: ALFA detectors

Proton tagging: AFP detectors

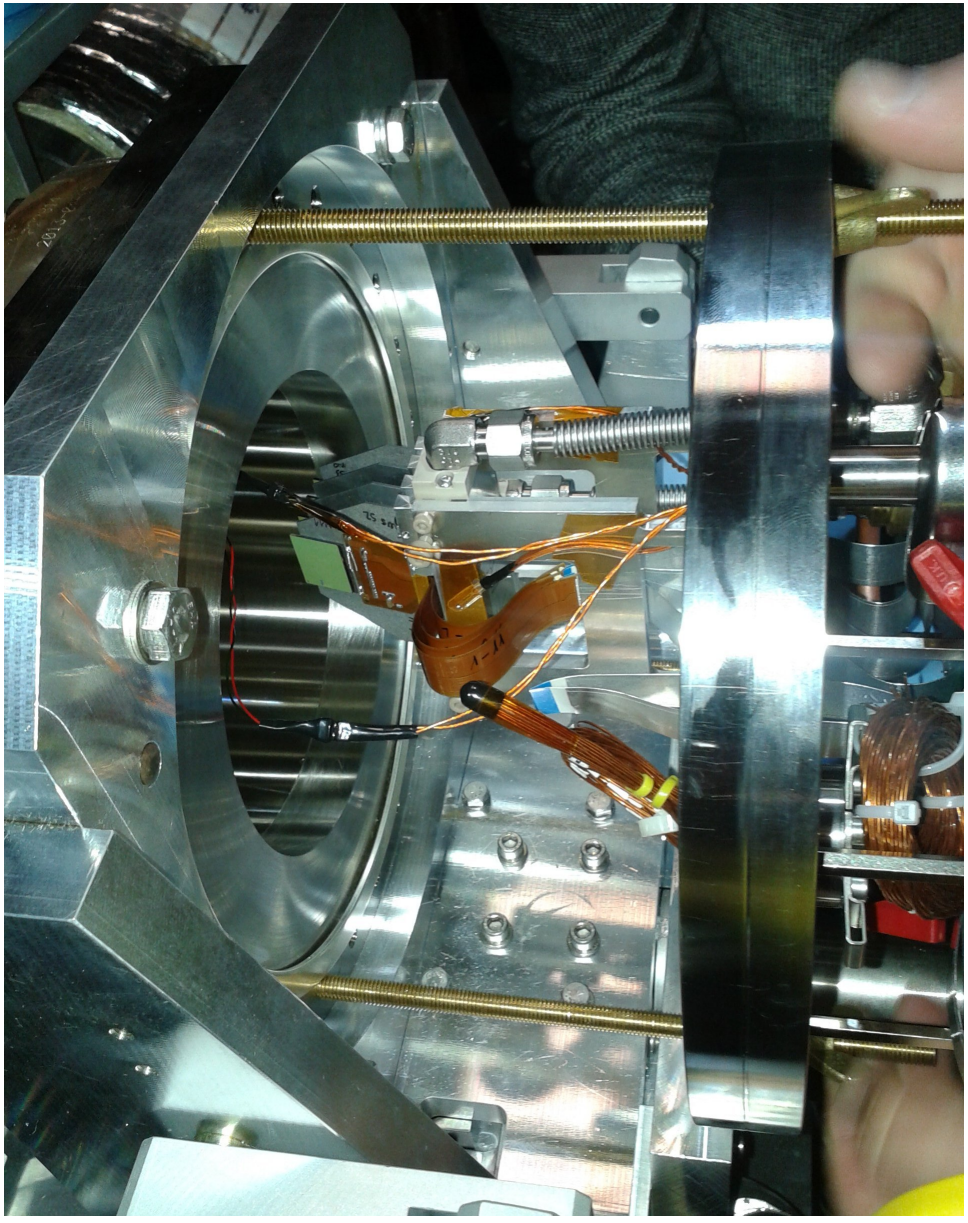


# Roman Pots



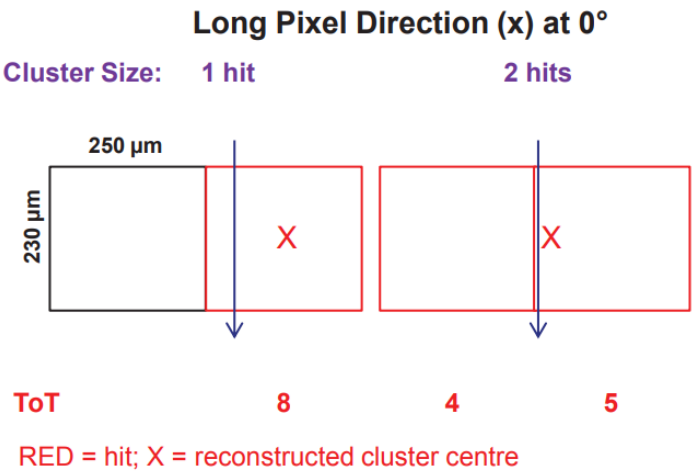
# Roman Pots

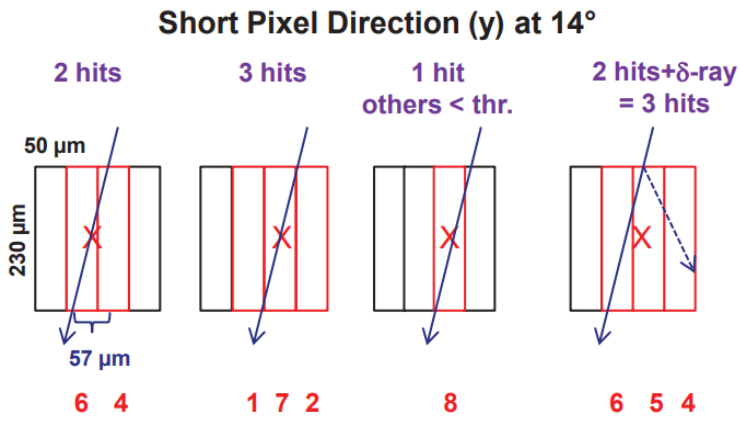


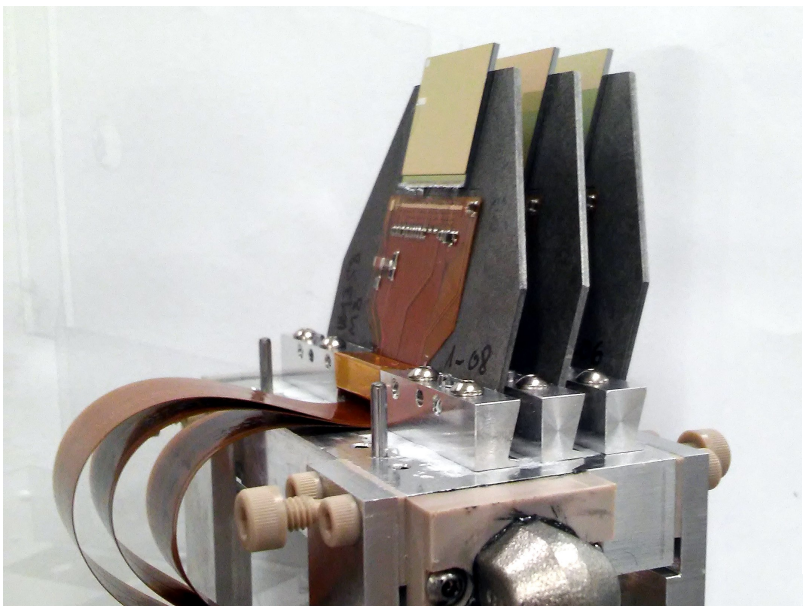


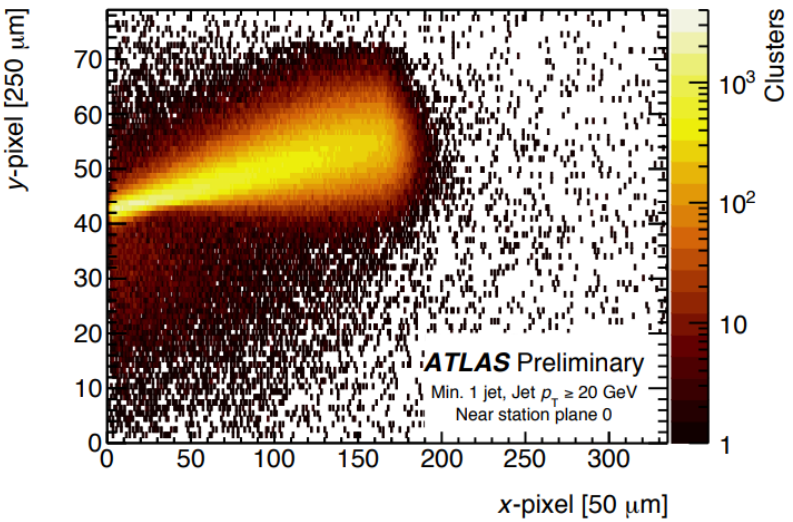
# Pixel clusters





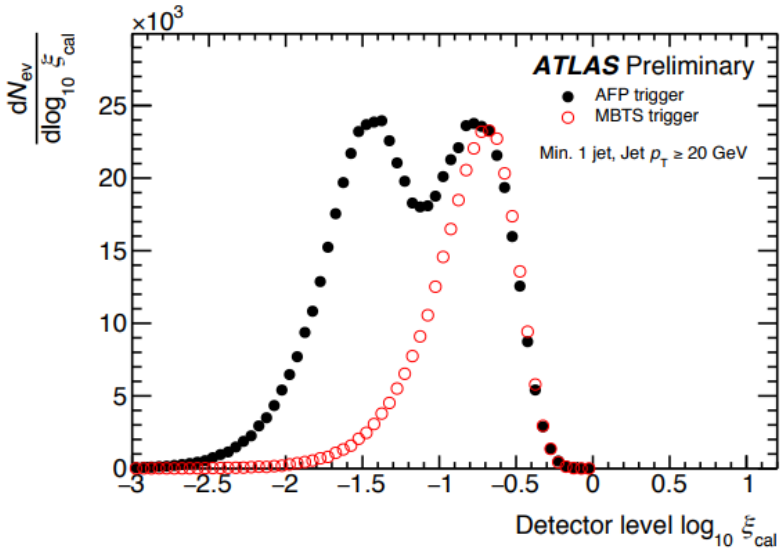



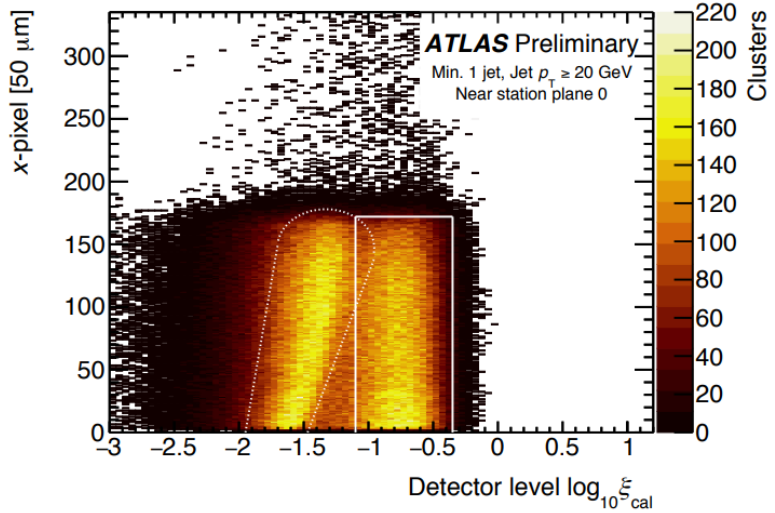


# Diffractive events seen in AFP



$$\xi_{\text{cal}} = \frac{\sum p_T e^{\pm\eta}}{\sqrt{s}}$$



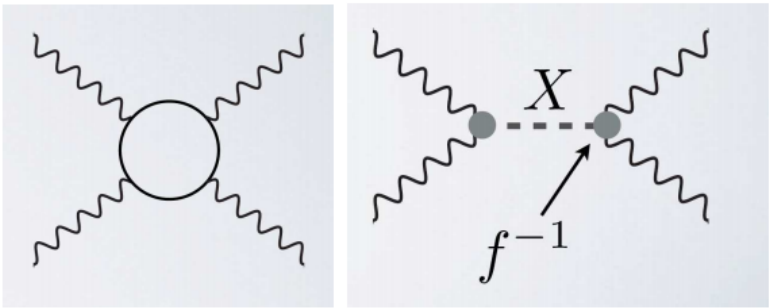



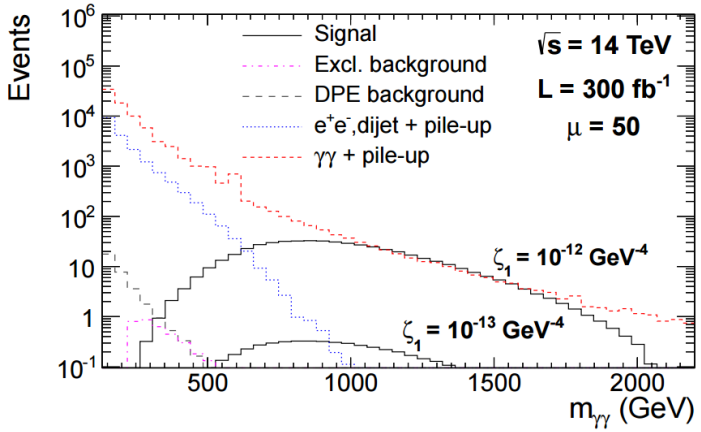

ATL-PHYS-PUB-2017-012

- Presence of diffractive events clearly seen
- Enhancement in the AFP acceptance region
- Overall sample is dominated by pile-up related background

# Example: $\gamma\gamma \to \gamma\gamma$



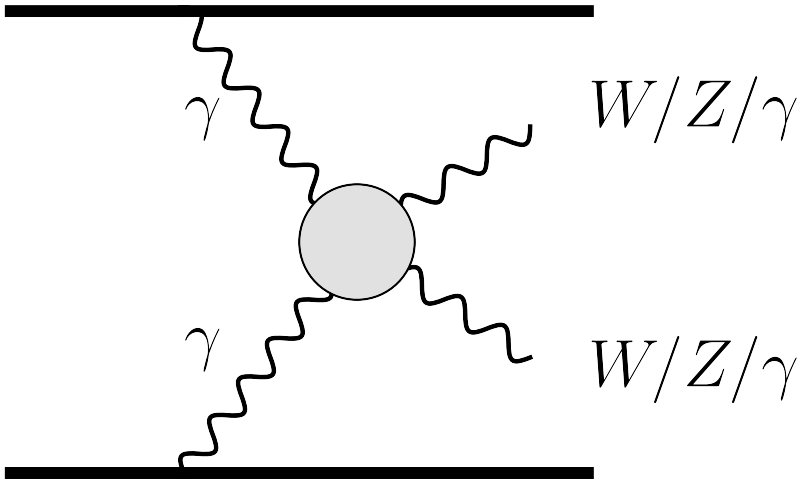


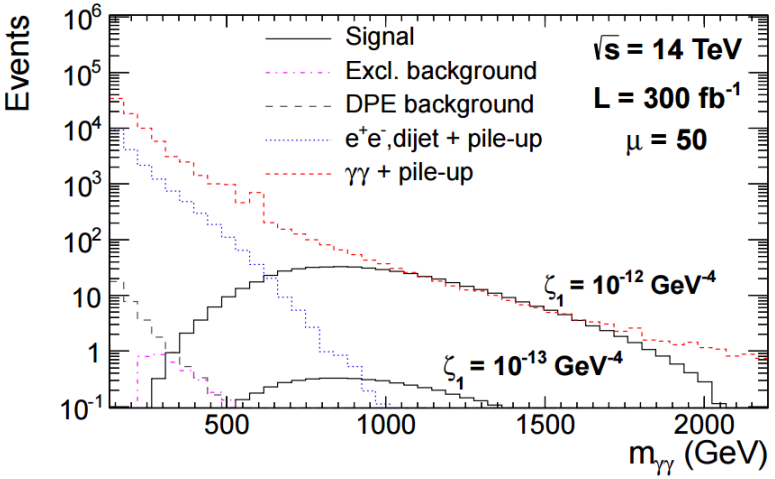



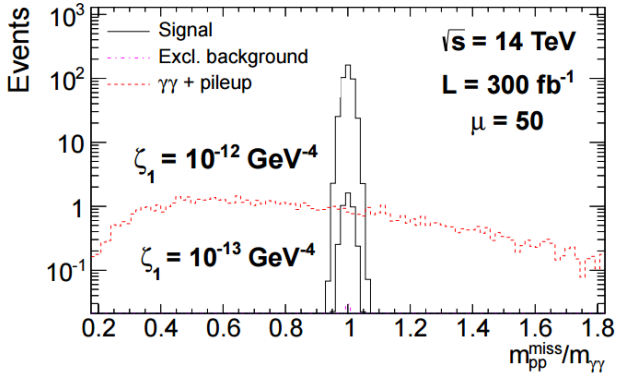

- couplings predicted by extra-dim, composite Higgs models: $10^{-14} - 10^{-13}$
- trigger: 2 high $p_T$ central photons, no AFP trigger needed
- high mass $\rightarrow$ not need to be very close to the beam

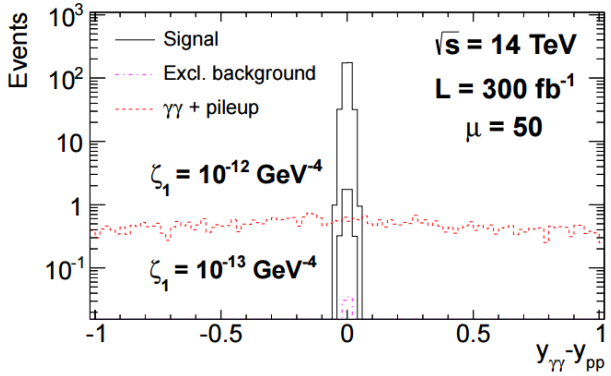
# Exclusivity selection





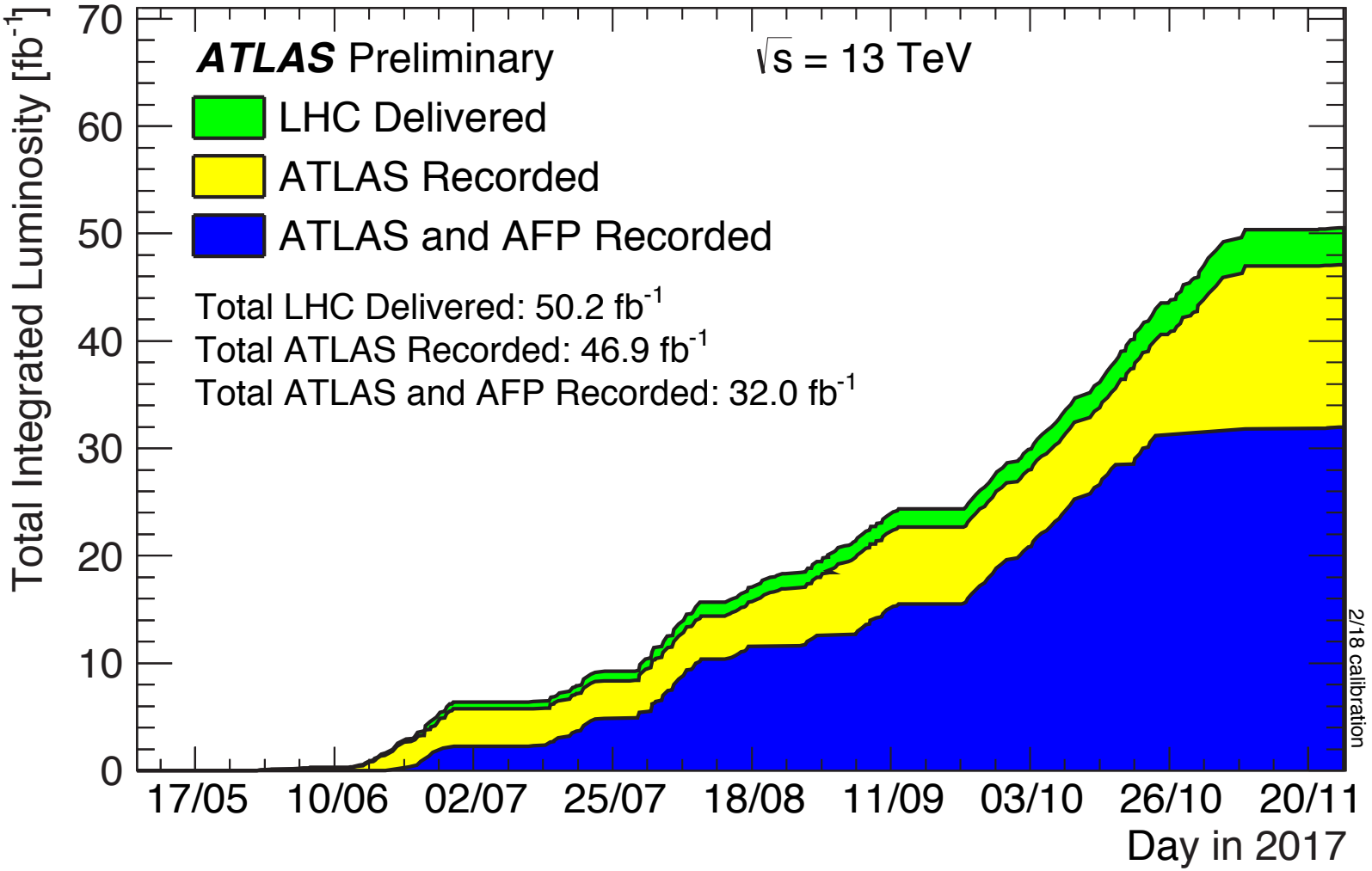




- main background: non-diff $\gamma\gamma$ + pile-up protons
- exclusivity selection kills all background (even without ToF)
- for 300 fb$^{-1}$ and $\mu = 50$: $<1$ background events for 15.1 (3.8) signal events for anomalous coupling of $2 \cdot 10^{-13} (10^{-13})$

# Lumi plot




ATLAS Preliminary
√s = 13 TeV
LHC Delivered
ATLAS Recorded
ATLAS and AFP Recorded
Total LHC Delivered: 50.2 fb-1
Total ATLAS Recorded: 46.9 fb-1
Total ATLAS and AFP Recorded: 32.0 fb-1
Total Integrated Luminosity [fb-1]
0
10
20
30
40
50
60
70
17/05
10/06
02/07
25/07
18/08
11/09
03/10
26/10
20/11
Day in 2017
2/18 calibration

# Summary



Rich forward physics programme of ATLAS:

- elastic scattering (total cross section, $\rho$, luminosity)
- soft diffraction
- hard diffraction
- two-photon processes
- new physics

Experimental methods

- rapidity gaps (calorimeter, tracks)
- measurement of forward protons (ALFA, AFP)