ALPS

ALpine **P**article physics **S**ymposium

Axion-**L**ike **P**article**S**

ALPS 2023
ALpine Particle physics Symposium

Obergurgl, 29.03.2023

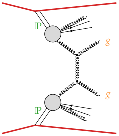
Overview of ATLAS forward proton detectors: status, performance and new physics results

Maciej Lewicki

on behalf of ATLAS Forward Detectors

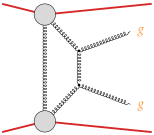
Institute of Nuclear Physics
Polish Academy of Sciences

Forward proton scattering in a diverse physics program



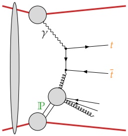
Diffractive jets

ATL-PHYS-PUB-2017-012



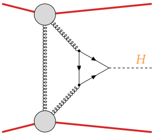
Exclusive jets

Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



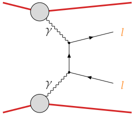
Top quarks

Goncalves et al 2007.04565
Howarth 2008.04249



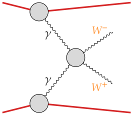
Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052



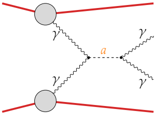
Leptons

CMS 1803.04496
ATLAS 2009.14537



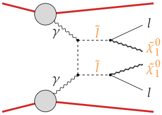
W bosons

Tizchang, Etesami 2004.12203
Baldenegro et al 2009.08331



Axion-like particles

Fichet et al 1312.5153
Baldenegro et al 1803.10835



SUSY dark matter

Beresford & Liu 1811.06465
Harland-Lang et al 1812.04886

Diffraction
≡ colour singlet exchange:

- Pomeron
  (two gluons + …)
- photon

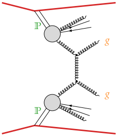
Measurements of diffractive processes –
– **discrimination tool** for models:

- **QCD – hard and non-perturbative,**
- **probing electroweak scale,**
- **physics beyond SM.**

Natural ways to seek for diffraction

- rapidity gaps,
- **forward protons**

Forward proton scattering in a diverse physics program



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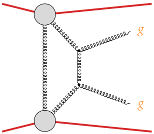
ATL-PHYS-PUB-2017-012



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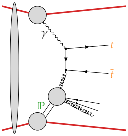

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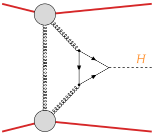

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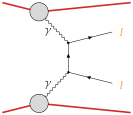

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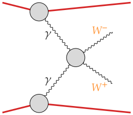

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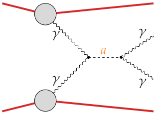

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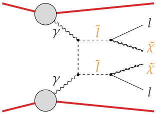
ATLAS-CONF-2023-002



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Natural ways to seek for diffraction

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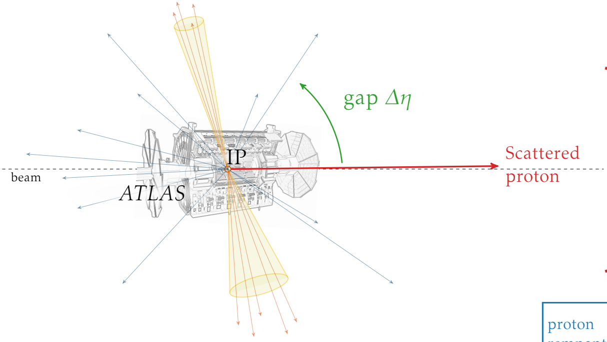
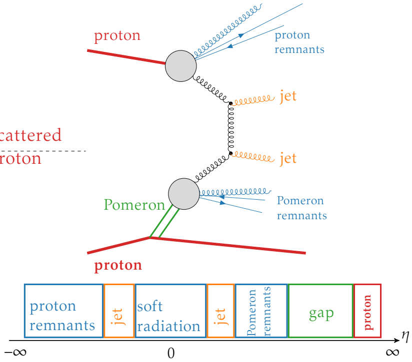
- **forward protons**

Measurements methods





Measuring rapidity gap:

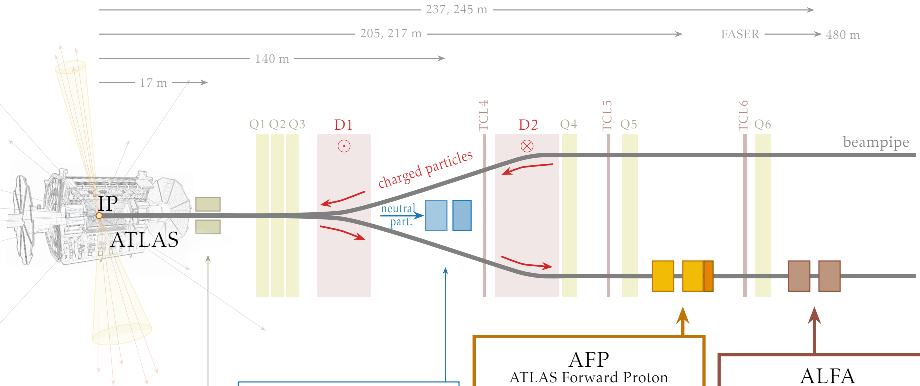
- + widely used for diffractive pattern recognition
- + no need for additional detectors
- – **gap is frequently destroyed** (pile-up, rescattering)
- – **gap may be out of acceptance**
- – **gap may be a statistical fluke**

Measuring forward protons:

- + **Protons measured directly** (deflection→$\vec{p}, E$)
- + **Suitable for pile-up environment**
- – Protons are scattered at very small angles
- – Additional detectors required far downstream.

ATLAS, Eur.Phys.J.C 72 (2012) 1926
ATLAS, Phys.Lett.B 754 (2016) 214-234

Forward Detectors in ATLAS



LUCID
Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

For luminosity measurement

ZDC + LHCf
Zero Degree Calorimeter
LHC Forward

Low-μ, $|\eta| > 8.0$

For cosmic-ray & heavy-ion physics

AFP
ATLAS Forward Proton

Low & high μ

$0.02 < \xi < 0.12$

soft & hard diffraction, $\gamma + \gamma$

- 4 Roman Pots, 2-4 mm from beam
- tracker: 3D sillicon pixel sensor
- spatial res. $\sigma_x = 6\mu m$
- ToF: 16 Quartz Cherenkov bars
- **timing res.** $\sigma_t \approx 25$ **ps**

ALFA
Absolute Luminosity
For ATLAS

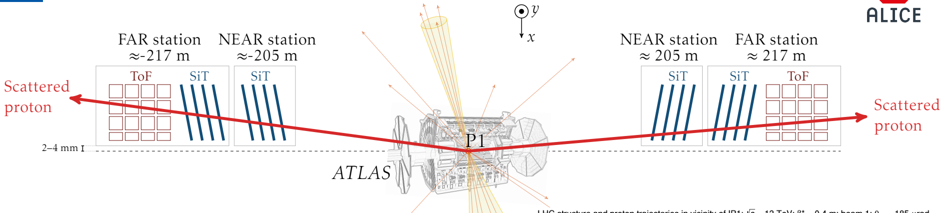
Low-μ, $0 < \xi < 0.2$

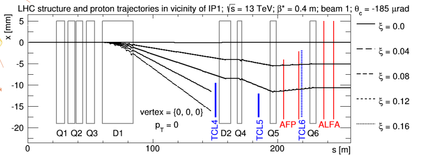
special high-$\beta^\star$ optics

Elastic scattering, soft diffraction

- 4 Roman Pots, <2 mm from beam
- layered SciFi, spatial res. $30\mu m$
- Multi-Anode-Photo-Multipliers

ATLAS Forward Proton detector



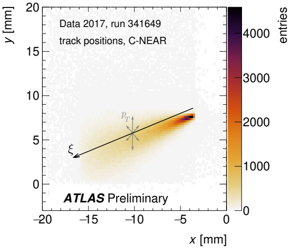


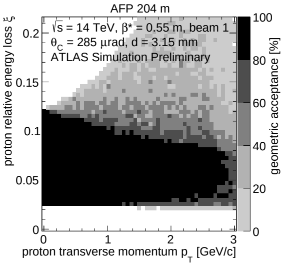
Main observable:

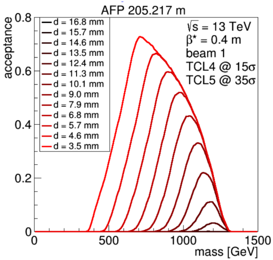
$$\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}$$

Typical **acceptance**:

$0.02 < \xi < 0.12, \quad p_T \lesssim 3\ \text{GeV}/c$

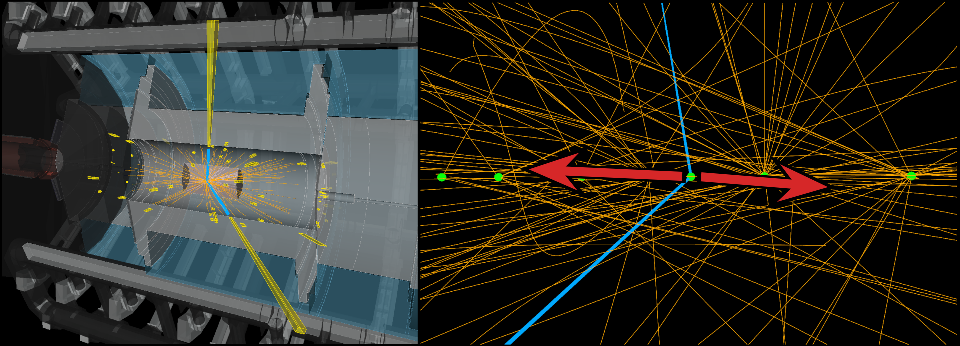






ATLAS EXPERIMENT

Run 190644, Event 51422085
Time 2011-10-09, 16:29 CEST



Signal: $pp \to p + (\gamma\gamma \to ee) + p$

Scattered protons originate from the signal vertex

ATLAS EXPERIMENT

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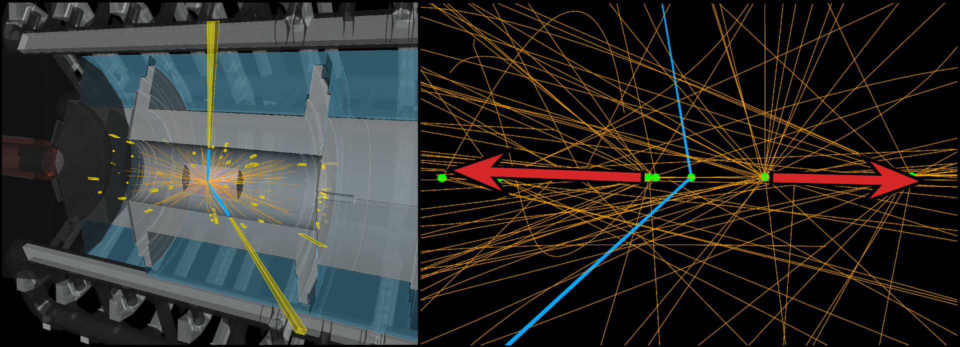


Background: Non-diffractive di-lepton production
+ forward protons from pile-up

Scattered protons originate from pile-up vertices

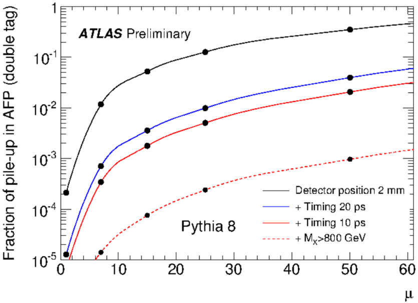
Reducing physics background with ToF

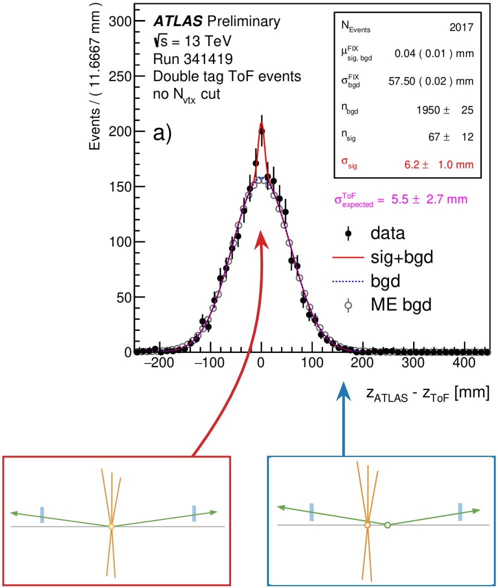
For events with **double proton tag**:

- Measure ToF difference: $\Delta t = t_A - t_C$
- Calculate vertex position: $z_{\text{ToF}} = \frac{c}{2}\Delta t$
- Compare z positions reconstructed by ATLAS and AFP ToF

Performance analysis (2017 data, $\mu \approx 2$) ATL-FWD-PUB-2021-002:

- **Measured time resolution:** 20 ± 4 ps (A), 26 ± 5 ps (C)
- **Measured pp vertex resolution:** 5.5 ± 2.7 mm





AFP status

Run 2

- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ m, 0.4 m
- **Standard runs:** ≈ 32 fb^{-1}
  after AFP quality selection: 14.6 fb^{-1}
- **Low pile-up runs**:
  - $0.03 \lesssim \mu \lesssim 0.05$, 100 nb^{-1}
  - $0.3 \lesssim \mu \lesssim 1$, 1.15 pb^{-1}
  - $\mu \approx 2$, 150 pb^{-1}

Run 3 (2022)

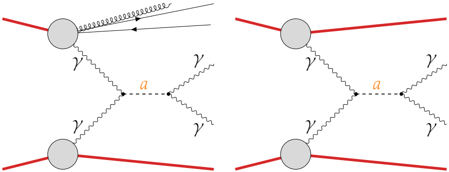
- $\sqrt{s} = 13.6$ TeV, $\beta^* = 0.2$–1.1 m, 19.2 m
- **Standard runs:** ≈ 34.1 fb^{-1}
- **Low pile-up runs**:
  - $\mu \approx 0.005$, 0.4 nb^{-1}
  - $\mu \approx 0.05$, 34.6 nb^{-1}
  - $\mu \approx 0.02$–1.0, 170 nb^{-1}
- More to come in **2023**!

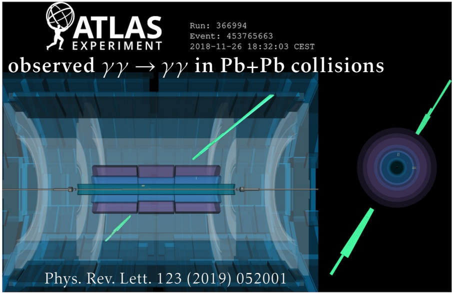
AFP hardware updates during LS2:

- **ToF:** new flange design Out-of-Vacuum, new photo-multipliers
- **tracker:** new modules produced.
- New trigger module,
- Improvement in tracker **cooling**.

Search for axion-like particles in

$$p + p \to p^{(*)}(\gamma\gamma \to \gamma\gamma)p$$





- **Strong electromagnetic fields** arise around **the proton** due to relativistic effects.
- EM fields interact: $\gamma\gamma$ collisions
- $\sigma(\gamma\gamma \to \gamma\gamma)$
  - very low in SM, pp collisions.
  - **can be enhanced with BSM processes!**
- **Axion-like particles?** (assumed for signal modeling):
  - Mass: m_X
  - Coupling constant: f^{-1}
- **Kinematic match**:
  - Di-photon (back-to-back: $\Delta\phi \approx \pi$):

$$\xi^{\pm}_{\gamma\gamma} = m_{\gamma\gamma}\frac{e^{\pm y_{\gamma\gamma}}}{\sqrt{s}}$$

  - Forward proton ($0.035 < \xi < 0.08$):

$$\xi^{\pm}_{\rm AFP}$$

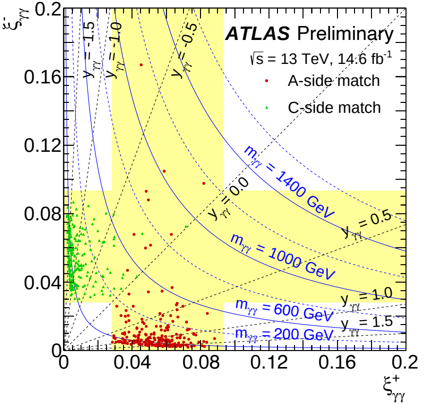
  - $|\xi_{\rm AFP} - \xi_{\gamma\gamma}| < 0.004 + 0.1\,\xi_{\gamma\gamma}$

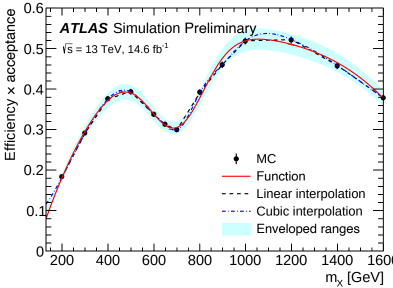
Measurement phase-space

ATLAS: pp at $\sqrt{s} = 13$ TeV, 14.6 fb^{-1}

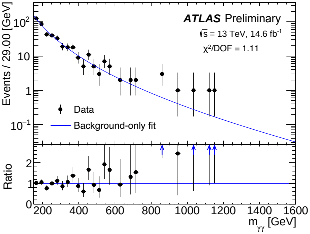
$M_{\gamma\gamma} \in [150, 1600]$ GeV
Central-Exclusive Production and Single Dissociation
ATLAS-CONF-2023-002

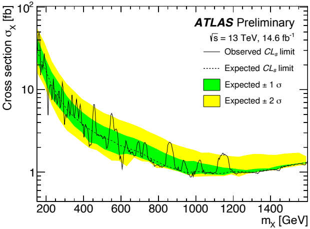
- **at least one proton matched with $\gamma\gamma$ system** (double-match not observed)
- pile-up $\mu = 36$
- triggering on $E_T = E\sin(\theta) > 35$ GeV, 25 GeV
- isolated photons ($E_T^{\text{iso}} < 0.022 E_T + 2.45$ GeV)
- subtraction of underlying event & pile-up (on detector level)
- **combinatorial background**: non-diffr. $\gamma\gamma$, proton from pile-up
- **background modelled with mixed events**
- Efficiency × acceptance shape due to single- and double-tag

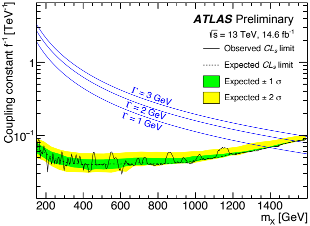


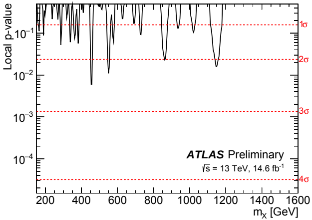


Measurement results









- Dominant systematic uncertainty: AFP global alignment $d \sim 3$ mm, $\sigma_d = 300$ μm (10% of signal yield)
- **No excess from the BG-only hypothesis**
- Statistical uncertainty is dominant
- **Exclusion limits** are set on
  - cross section
  - ALP coupling constant to $\gamma\gamma$: 0.04–0.09 TeV^{-1}

(Assumption of 100% ALP $\to \gamma\gamma$ branching ratio)

Similar measurements and similar conclusions from CMS-TOTEM:

- Central-Exclusive Production, pp at $\sqrt{s} = 13$ TeV, 9.4 fb^{-1}, $M_{\gamma\gamma} \in [900, 1800]$ GeV

Summary

New results with proton tag in ATLAS

- ALFA: $\sigma_{\text{tot}}, \rho$ in $p + p \to p + p$ @ 13 TeV, [2207.12246]
- ALFA: $p + p \to p + \pi^+\pi^- + p$ @ 7 TeV, [2212.00664]
- AFP: $p + p \to p^{(*)}(\gamma\gamma \to \gamma\gamma)p$ @ 13 TeV, [ATLAS-CONF-2023-002]

presented today

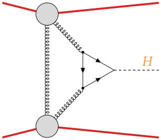
Analysis and data

- Data available from 2017 and 2022, more to come in 2023.
- Continuation of performance studies with Run 2&3 data.
- Ongoing elastic, diffractive and (semi-)exclusive analyses based on Run 2&3 data
  $\to$ stay tuned!

Backup Slides

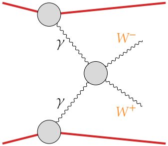
Run ~~4~~ 5 potentially rich physics programme!

Exclusive Higgs
($b\bar{b}$ decay, spin, QCD mechanism)



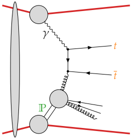
JINST 4 (2009) T10001: *"Higgs and New Physics with forward protons at the LHC"*
JHEP 090(2007) 0710: *Detecting Higgs bosons in the bb decay channel using forward proton tagging at the LHC*
EPJ C 53 (2008) 231–256: *Studying the MSSM Higgs sector by forward proton tagging at the LHC*

SM E-W: $\gamma\gamma \rightarrow WW$



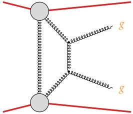
JHEP 07 (2020) 191: *"Pinning down the gauge boson couplings in $WW\gamma$ production using forward proton tagging"*
JHEP 12 (2020) 165: *"Central exclusive production of W boson pairs in pp collisions at the LHC in hadronic and semi-leptonic final states"*

Top quarks production



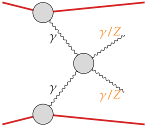
arXiv:2008.04249: *"Elastic Potential: A proposal to discover elastic production of top quarks at the Large Hadron Collider"*
Phys. Rev. D 102 (2020) 074014: *"Top quark pair production in the exclusive processes at LHC"*

Exclusive jets (SM & BSM)



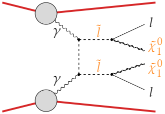
Eur. Phys. J. C (2015) 75: 320: *"On the Possibility of Measuring the Single-tagged Exclusive Jets at the LHC"*

New physics in two-photon processes at high mass
($\gamma\gamma \rightarrow \gamma\gamma, \gamma\gamma \rightarrow ZZ/Z\gamma$)



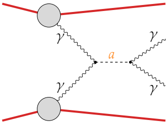
JHEP 02 (2015) 165: *"Light-by-light scattering with intact protons at the LHC: from Standard Model to New Physics"*
0808.0322: *"Anomalous $WW\gamma$ coupling in photon-induced processes using forward detectors at the LHC"*

Searches for SUSY



PRL 123 141801: *"Search Strategy for Sleptons and Dark Matter Using the LHC as a Photon Collider"*
JHEP 04 (2019) 010: *"LHC searches for Dark Matter in compressed mass scenarios: challenges in the forward proton mode"*

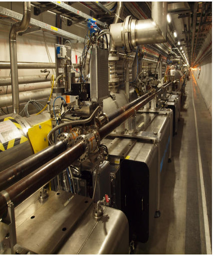
Searches for ALPS
($\gamma\gamma \rightarrow$ invisible, $\gamma\gamma \rightarrow \gamma\gamma$)



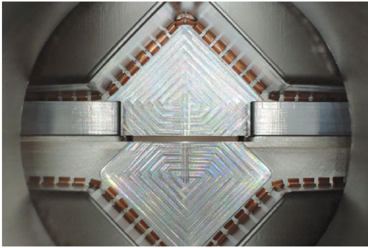
JHEP 06 (2018) 131: *"Searching for axion-like particles with proton tagging at the LHC"*

Absolute Luminosity For ATLAS

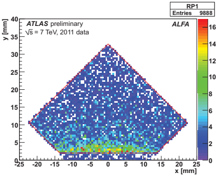
JINST **11** (2016) P11013



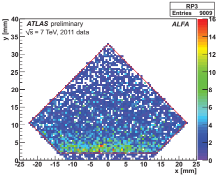
- Elastic scattering, soft diffraction
- Input for MC generators:
  cosmic ray showers,
  pile-up simulation



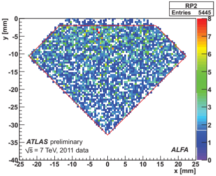
- 4 vacuum-sealed spectrometers housed in **Roman Pots** (RP), inserted vertically; NEAR and FAR on both sides of IP (at 237 and 241/245 m, < 2mm from beam).
- Trigger capability
- Multi-layer scintillating fibre (SciFi)
- Tracking detectors, resolution: $\sigma_x = \sigma_y = 30\mu$m
- Read-out by Multi-Anode-Photo-Multipliers
- Special runs: low pile-up, high β^* optics



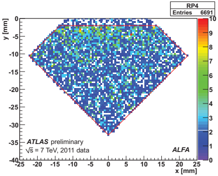
(a) RP 1



(b) RP 3

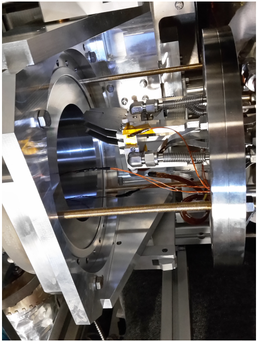


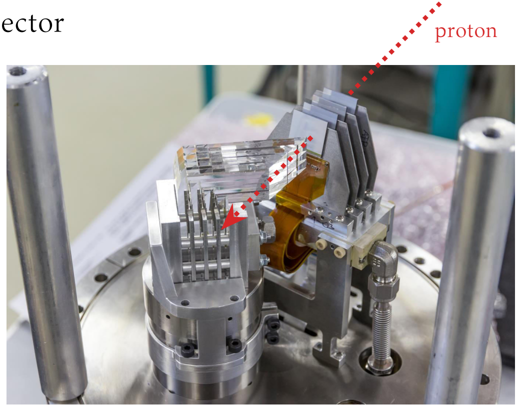
(c) RP 2



(d) RP 4

ATLAS Forward Proton detector

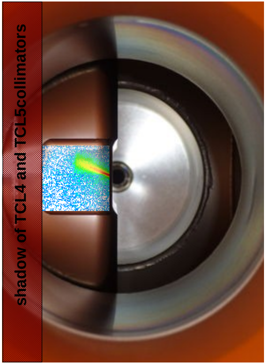


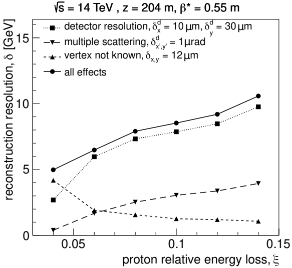


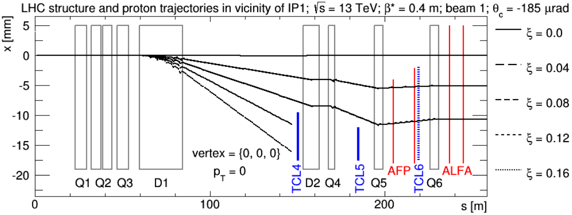
- 4 **Roman Pots** devices:
  NEAR and FAR, both sides of IP (205, 217 m), inserted horizontally onto beam.
- 4 **Silicon Tracker** (SiT) planes in each RP:
  - 336×80 pixels, 50×250 μm^2, 230 μm thick,
  - SiT **resolution**: σ_x=6 μm at 14° tilt.
- FE-I4 readout chips; as in ATLAS IBL
- Trigger capability

- Time of Flight (ToF) detectors in FAR stations:
  - 16 Quartz Cherenkov bars,
  - ToF resolution $\sigma_t \approx 25$ ps.
  - Light gathered by: Micro-Channel Plate Multi-Anode PMT

Unfolding proton kinematics

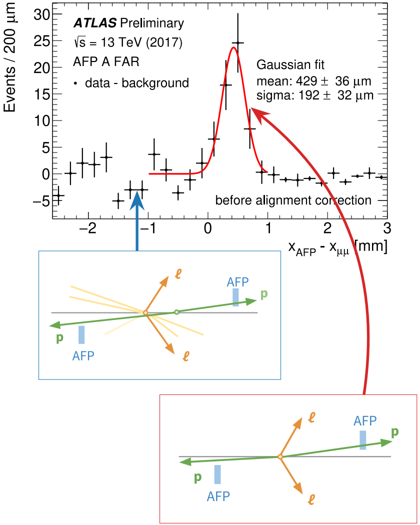






- Proton deflection angle is determined by its ξ and p_T.
- Further trajectory along the beam line is shaped by the beam optics.
- AFP acceptance is affected by the **distance to the beam** and the **upstream collimators**.
- **Challenges:**
  non-uniform high radiation environment,
  background from showers, **high pile-up**
- Detector resolution directly affects precision of measuring proton kinematics:

In situ AFP global alignment with exclusive di-muon events

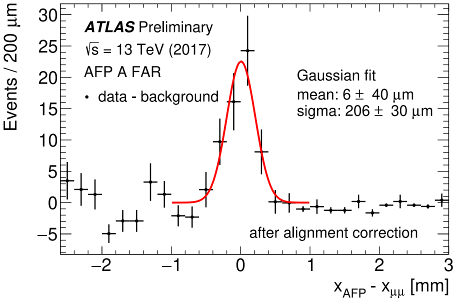


$(\gamma\gamma \to \mu\mu) + p$ as a "standard candle":

1. Compare:

$$\xi_{AFP} = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}} \quad \text{with} \quad \xi_{ll}^{A/C} = \frac{m_{ll} e^{(+/-)y_{ll}}}{\sqrt{s}}$$

2. Adjust global RP shift to match ξ_{AFP} to ξ_{ll}

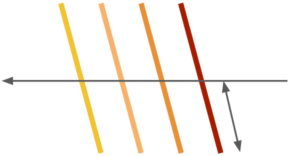


- Background – small and well modelled by event mixing,
- Alignment precision uncertainty currently quoted as 300 μm
  → Ongoing work to improve – 100 μm seems realistic.

AFP Inter-plane local alignment

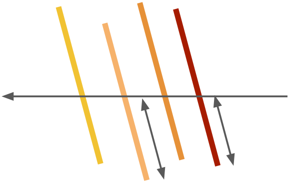
- Proton traversing AFP SiT creates charge deposits in each plane, measured at x position relative to the edge.

Ideal alignment:

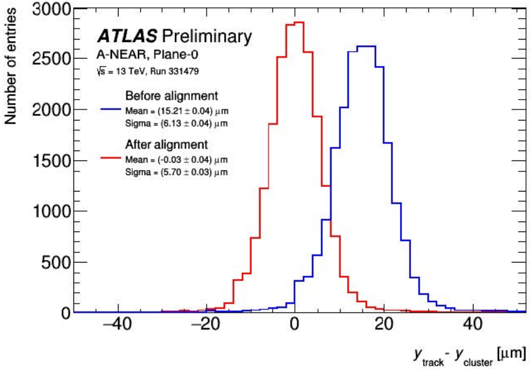


Hit to edge distance:
→ same for all planes

In reality:



Hit to edge distance:
→ may differ for each plane

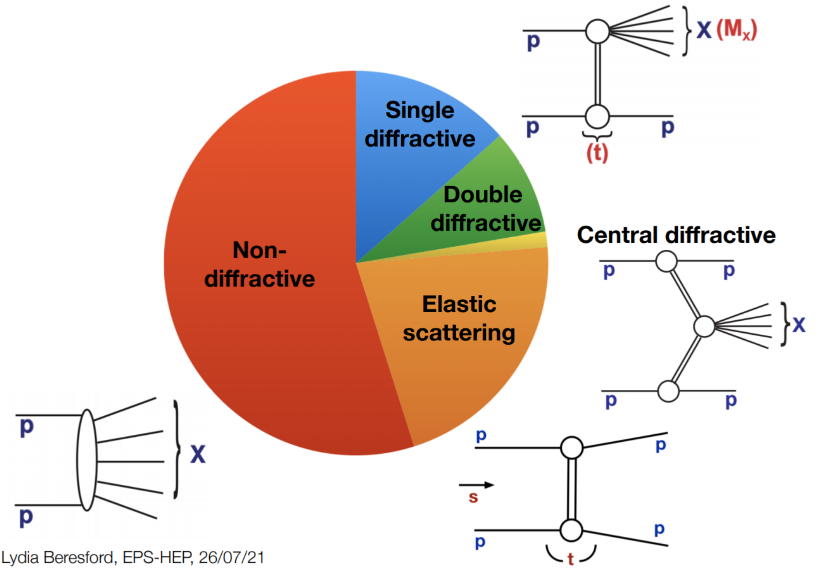


Employed procedures account for:

- offsets in x and y,
- (rotation about z axis.)

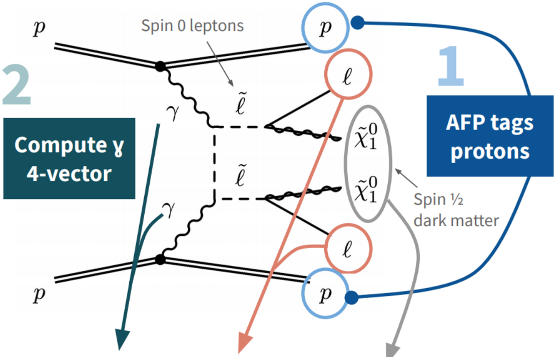
LHC interactions

Double line = Pomeron
Pair of gluons (colourless)



Lydia Beresford, EPS-HEP, 26/07/21

p_{missing} 4-vector for dark matter searches



$$p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_f^{\text{visible}} \Rightarrow m^2_{\text{miss}} = p^2_{\text{miss}}$$

3

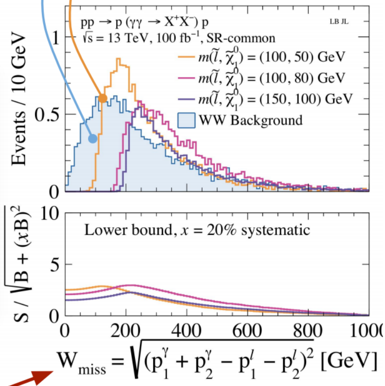
Impossible @ pp colliders *no more*

Square 4-vector to measure DM mass

ATLAS [2010.04019]

γγ → WW just observed

Sharp threshold at 2 × m_{DM}



Run 3: rich physics enabled by ~10x good quality data with efficient time-of-flight

Data

Run 2

- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ m, 0.4 m
- Two setups (2016, 2017):
  - one-arm
  - two-arms (+ TOF *(poor efficiency)*)
- Data taken during in **low pile-up runs**:
  - $0.03 \lesssim \mu \lesssim 0.05$
    int. lumi.: ≈ 100 nb^{-1},
    main goal: soft diffraction
  - $0.3 \lesssim \mu \lesssim 1$
    int. lumi.: ≈ 1.15 pb^{-1},
    main goal: low-p_t jets
  - $\mu \approx 2$:
    int. lumi.: ≈ 150 pb^{-1},
    main goals: electro-weak physics,
    hard diffraction, SD $t\bar{t}$
- Data taken during **standard runs**:
  - int. lumi.: ≈ 46.9 fb^{-1}
    goal: hard diffraction

Run 3 plans

- $\sqrt{s} = 13.6$ TeV, $0.2 < \beta^* < 1.1$ m
- Setup: two-arms setup + TOF
- Data to be taken mainly at **high-μ**
- Requested special **low pile-up runs**:
  - $\mu \approx 0$
    main goal: soft diffraction
  - $\mu \approx 1$
    main goal: low-p_t jets
  - $\mu \approx 2$:
    main goals: electro-weak physics,
    hard diffraction, SD $t\bar{t}$

ATLAS + AFP $\rightarrow$ 32 fb^{-1}
+ GRL $\rightarrow \approx$15 fb^{-1}
Unprecedented amount of data for diffractive physics!

AFP detector updates during LS2

No major changes between Run 2 and Run 3 detector design.

AFP:

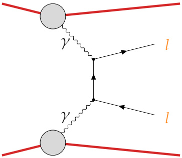
- New design of detector flange: **Out-of-Vacuum** solution for **ToF** detectors.
- **New photo-multipliers**: addressing inefficiency issues from Run 2 data-taking.
- Production of **new tracking modules**.
- **New trigger module**: possibility to trigger on single train.
- Above items were successfully **tested at DESY and SPS**.
- Improvement in silicon detector **cooling** (new heat exchangers).
- **ToF resolution of 20 ps** expected for Run 3.
  [Opt. Express 26 (2018) 8028-8039, JINST 11 (2016) P09005].

ALFA hardware updates:

- improvement and maintenance of **cooling system**,
- **exchange of readout** system due to radiation damage,
- installation of **radiation shielding**: concrete blocks around LHC beampipe upstream ALFA.

Already registering Run 3 data!

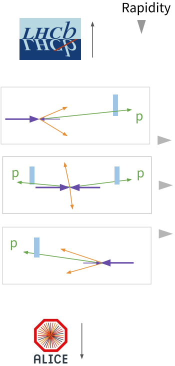
First High Lumi AFP Publication

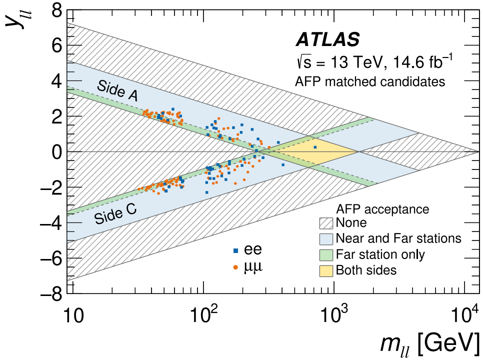


Phys. Rev. Lett. 125, 261801 (2020):

*Observation and Measurement of **Forward Proton Scattering** in Association with **Lepton Pairs Produced via the Photon Fusion** Mechanism at ATLAS*

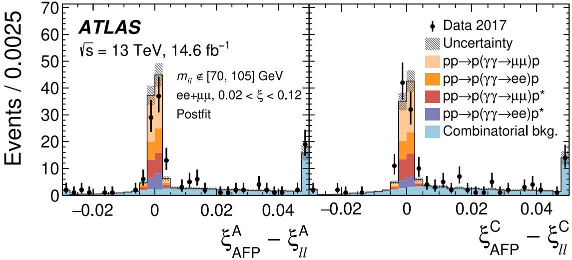
- $\approx$15 fb^{-1}, single proton tag
- (double tag possible in future!)





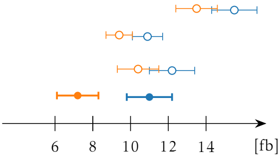
- Exclusive di-leptons, $pp \to pl^-l^+p$:
  – proton(s) measured in AFP,
  – leptons ($\mu^+\mu^-$, e^+e^-) measured in ATLAS
- 2017 data; $\sqrt{s} = 13$ GeV$/c$; $L = 14.6$ fb^{-1}
- 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state.

Physics Analysis: Exclusive Di-lepton Measurement with AFP Tag



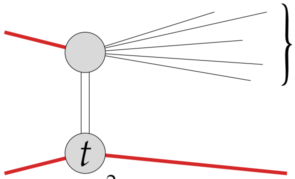
- Proton energy resolution at $\lesssim$10% (FWHM≈0.005)
- Powerful **background rejection** with AFP:
  – proton tagging,
  – kinematics match: proton vs lepton system
- Great performance: 95% signal acceptance with 85% background rejection
- Background-only hypothesis rejected with a significance exceeding **5σ** in each channel.

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using EPJC 76 (2016) 9 PLB 741 (2015) 66	10.9 ± 0.8	9.4 ± 0.7
SuperChic	12.2 ± 0.9	10.4 ± 0.7
Measurement	**11.0 ± 2.9**	**7.2 ± 1.8**



Physics analysis: Single Diffraction with ALFA tag

First single diffraction ALFA publication!
JHEP 02 (2020) 042

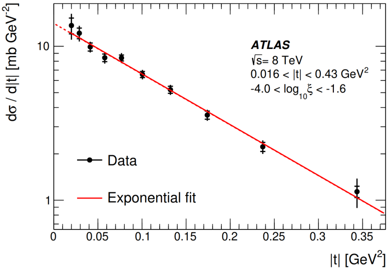


$$X \left(M_X = \sqrt{\xi s}\right)$$

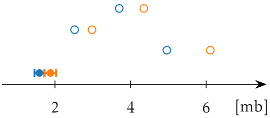
$\propto -p_T^2$

Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s}$ = 8 TeV pp collisions using the ATLAS ALFA spectrometer

- $\sqrt{s}$ = 8 TeV, very low μ,
- intact proton reconstructed in ALFA ($10^{-4} < \xi < 0.025$),
- remnants X measured in ATLAS,
- measured also: $\mathrm{d}\sigma/\mathrm{d}\xi$, $\mathrm{d}\sigma/\mathrm{d}t$, $\mathrm{d}\sigma/\mathrm{d}\Delta\eta$
- Regge interpretation:
  Pomeron intercept $\alpha(0) = 1.07 \pm 0.09$



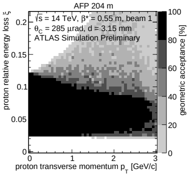
Distribution	$\sigma_{SD}^{\mathrm{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t-\mathrm{extrap}}$ [mb]
Pythia8 A2 (Schuler-Sjöstrand)	3.69	4.35
Pythia8 A3 (Donnachie-Landshoff)	2.52	2.98
Herwig7	4.96	6.11
Measurement	**1.59 ± 0.13**	**1.88 ± 0.15**

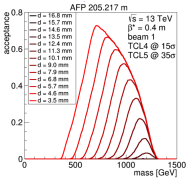


AFP acceptance at Run 2, Run 3 and Run 4

Run 2:

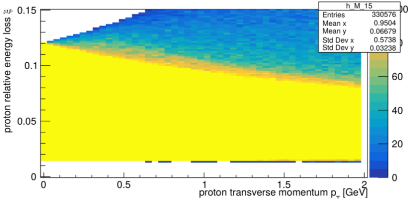
- Acceptance:
  $0.03 < \xi < 0.1, \;\; 390 < M_{\text{central}} < 1300$ GeV

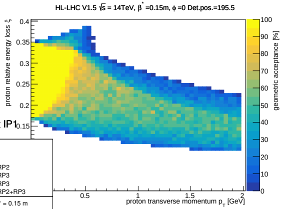


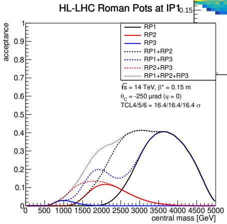


Run 3:

- Acceptance:
  $0.015 < \xi < 0.12, \;\; 195 \lesssim M_{\text{central}} < 1560$ GeV







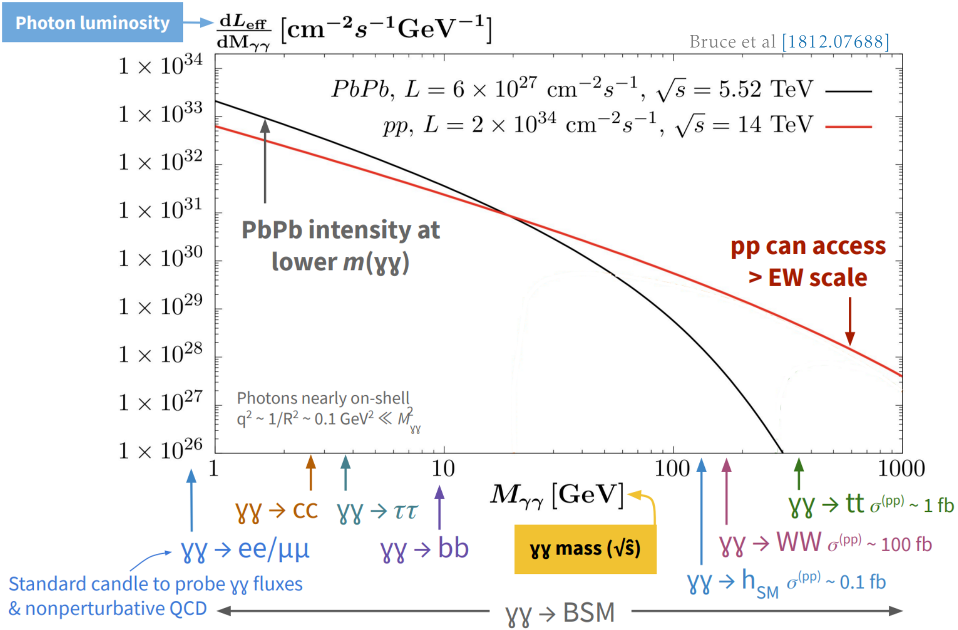
Run 4: preliminary studies with HL-LHC optics (v1.4):

- RP @ 195 m: $0.17 \lesssim \xi \lesssim 0.31$ (plotted←)
  RP @ 217 m: $0.10 \lesssim \xi \lesssim 0.19$
  RP @ 234 m: $0.06 \lesssim \xi \lesssim 0.09$
- RP at 15σ from the beam, $\beta^* = 0.4$ m
- Crossing angle $\phi = 180°$ disadvantageous for AFP:
  → diffractive protons closer to the beam
  → affecting energy resolution: large $\frac{dE}{dx_{\text{AFP}}}$
- Also studied configuration with 3 RP stations
  → gain in acceptance towards lower masses.

ALPs – summary of the systematic uncertainties

Source	**Uncertainty**
Signal yield uncertainty	
Pileup reweighting	$^{+2.7}_{-2.6}\%$
Luminosity	$\pm 2.4\%$
Photon identification efficiency	$^{+1.6}_{-1.5}\%$
Photon isolation efficiency	$\pm 1.9\%$
Beam optics between ATLAS central and AFP detectors	$^{+0.8}_{-3.4}\%$
AFP global alignment	$^{+10.0}_{-8.6}\%$
Proton reconstruction efficiency	$^{+3.0}_{-2.2}\%$
Showering in the AFP	-6.6%
Background modelling (mass-dependent)	$\pm(0.02\text{–}0.7)$
Signal modelling	
Photon energy resolution	$^{+14.1}_{-4.8}\%$
Photon energy scale	$\pm(0.5\text{–}1.0)\%$
Signal cross section uncertainty	
Soft survival factor (exclusive process)	$\pm 2\%$
Soft survival factor (single-dissociative process)	$\pm 10\%$
Soft survival factor (double-dissociative process)	$\pm 50\%$

$\gamma\gamma$ factory at LHC



$\gamma\gamma \to \gamma\gamma$ ATLAS Pb+Pb 2.2 nb^{-1} @ 5 TeV (JHEP 03 (2021) 243)