ATLAS Roman Pots
Status & Performance

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Diffraction and gluon saturation at the LHC and the EIC

Trento, Italy, 10^{th} **June 2024**

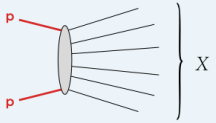
Usual proton-proton collisions at the LHC

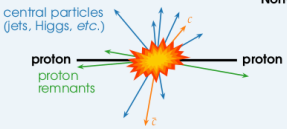
→ protons collide head-on

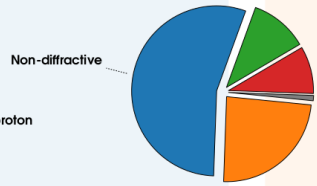
→ both protons break up

→ collision products are emitted in the central region

→ proton remnants may be found in the forward regions







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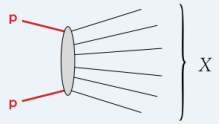
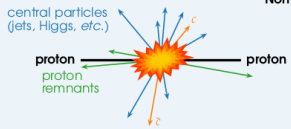
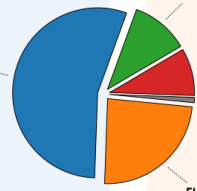
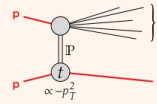
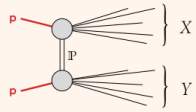






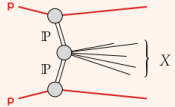


Single diffractive dissociation

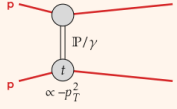


Double diffractive dissociation

Central diffraction



Elastic scattering



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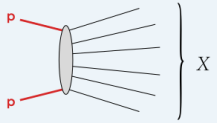

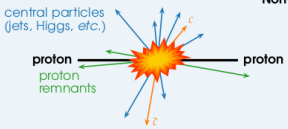

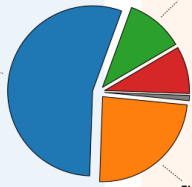

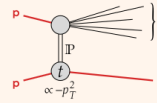

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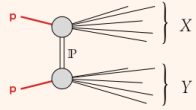
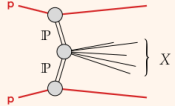


Double diffractive dissociation

Central diffraction



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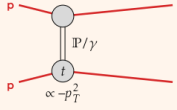
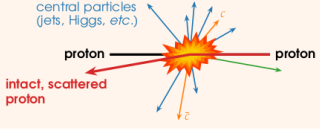


COLLISIONS AT LHC

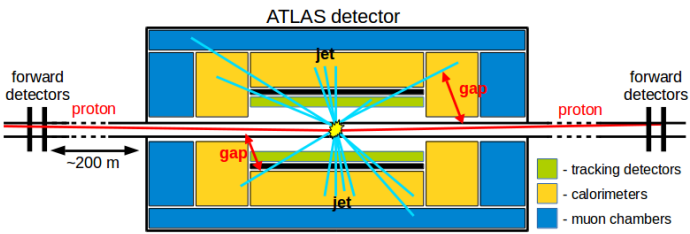
How can proton(s) remain intact?

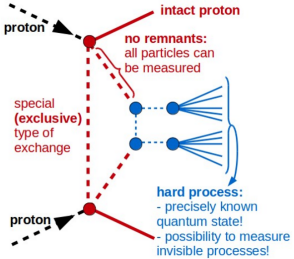


Proton can exchange objects that do not change its quantum numbers:

→ photon (γ) – via electromagnetic interactions

→ Pomeron ($\mathbb{P}$) – via strong nuclear force

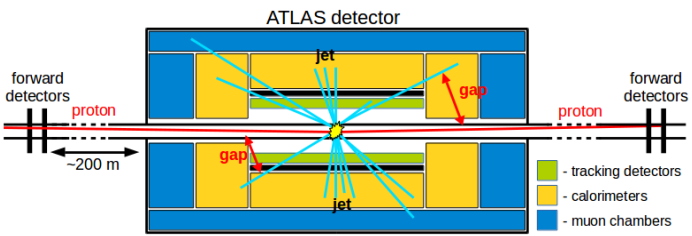


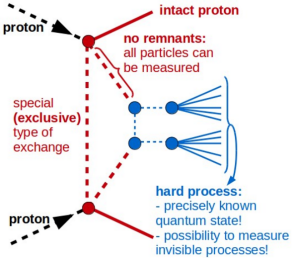


- Characteristic topology: presence of rapidity gap between the proton(s) and the "central" system;

Measuring rapidity gap:

+ "classically" used for diffractive pattern identification
+ no need for additional detectors
– gap is frequently destroyed due to pile-up background
– gap may be out of acceptance of "central" detector





- Characteristic topology: presence of rapidity gap between the proton(s) and the "central" system; one or both interacting proton(s) remain intact.
- Intact protons scattered at very small angles → very close to the beam after the interaction → detectors must be located far from the Interaction Point (IP) → LHC magnetic fields (**optics**) must be considered.

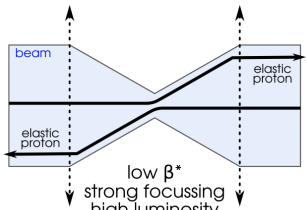
Measuring rapidity gap:

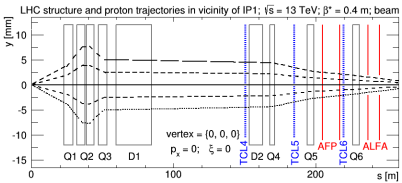
+ "classically" used for diffractive pattern identification
+ no need for additional detectors
– gap is frequently destroyed due to pile-up background
– gap may be out of acceptance of "central" detector

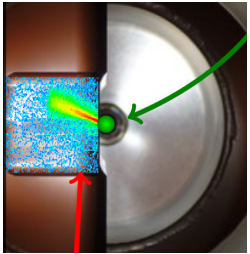
Measuring forward protons:

+ protons measured directly
+ suitable for pile-up environment
– protons are scattered at very small angles
– additional detectors required far downstream

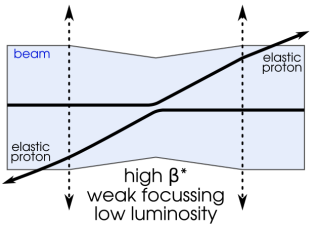
"Usual" conditions: β^* in range 0.3 – 1.2 m $\rightarrow$ strongly focused beam (high pile-up):

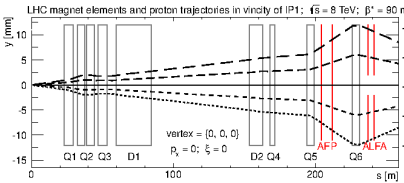


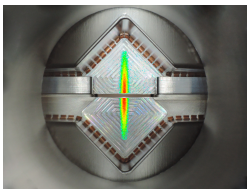




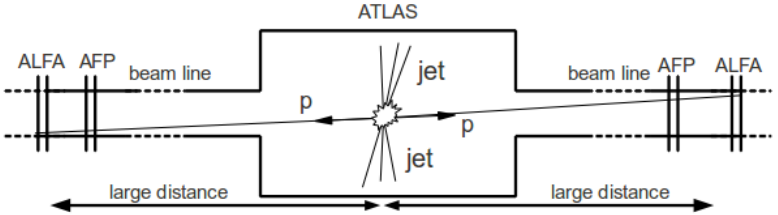
Special optics: β^* of 90 m, 120 m, 2.5 km, 3/6 km $\rightarrow$ weak, parallel-to-point focusing (low pile-up):







Intact protons → natural diffractive signature → usually scattered at very small angles (μrad) → detectors must be located far from the Interaction Point.

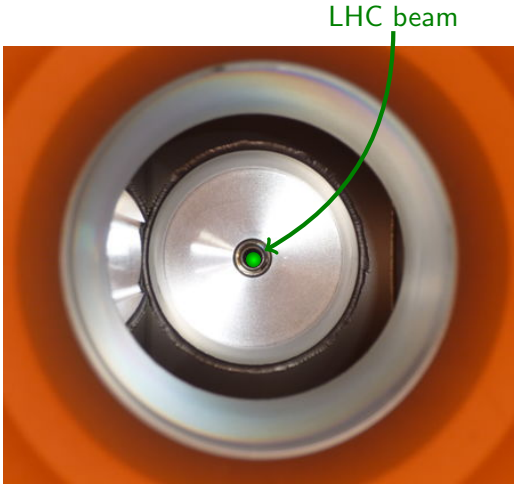


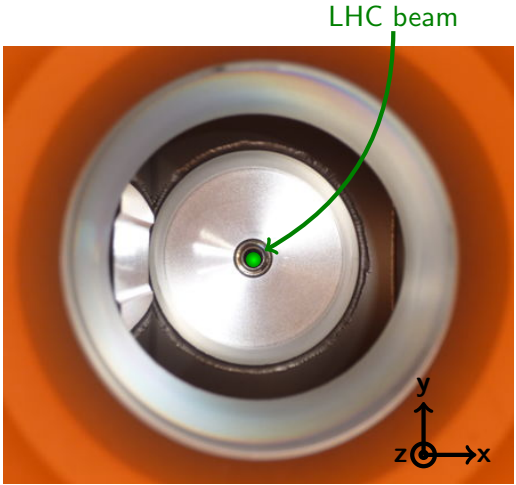
ALFA

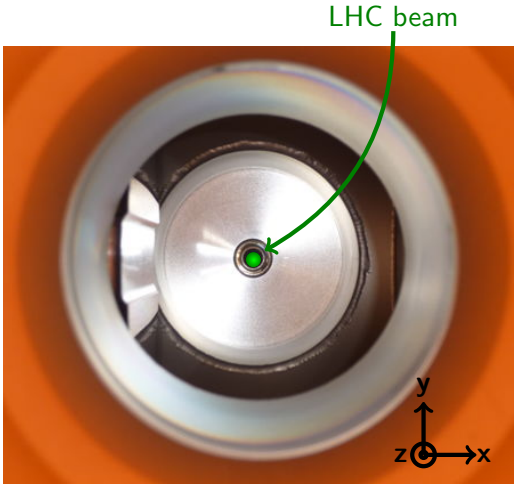
- **A**bsolute **L**uminosity **F**or **A**TLAS
- 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high β^* optics)
- vertically inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = \sigma_y = 30$ μm
- in operation between 2011 and 2023

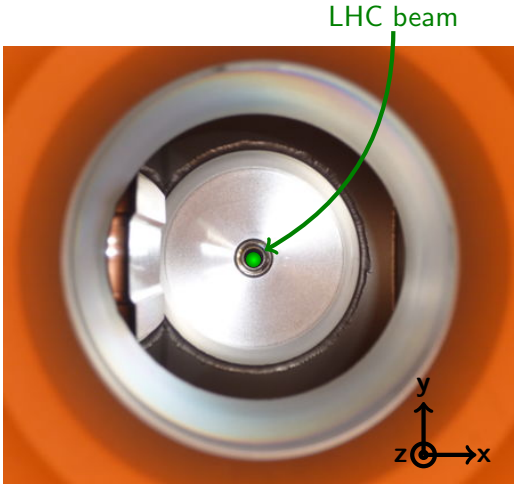
AFP

- **A**TLAS **F**orward **P**roton
- 210 m from ATLAS IP
- hard diffraction, BSM searches
- nominal runs (collision optics)
- horizontally inserted Roman Pots
- tracking detectors, resolution: $\sigma_{x/y} = 6/30$ μm
- timing detectors, resolution: $\sigma_t \sim 25$ ps
- in operation since 2016 (one side) / 2017 (full set)


LHC beam


LHC beam
y
z
x


LHC beam
y
z
x


LHC beam
y
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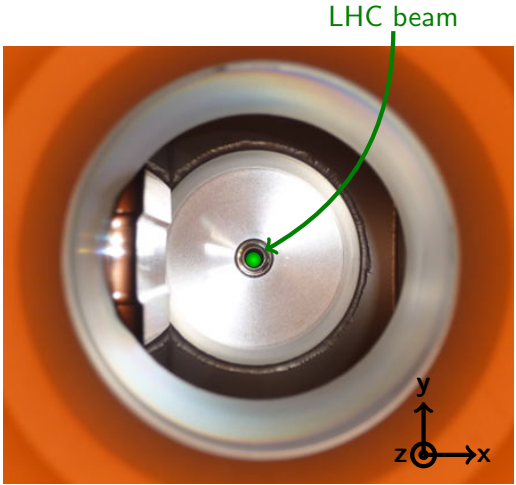
x


LHC beam
y
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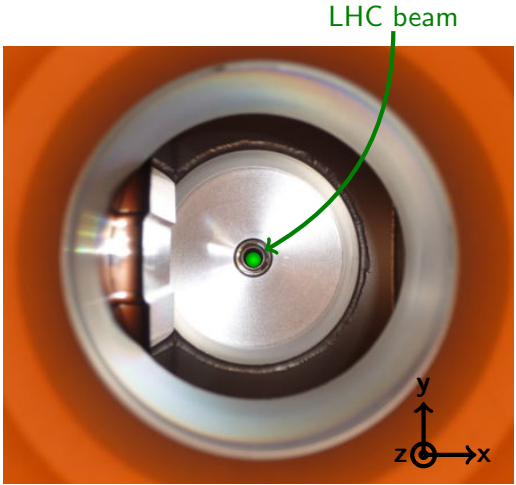
LHC beam
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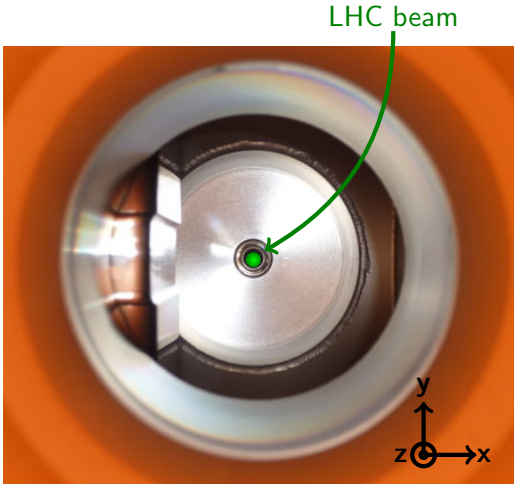
LHC beam
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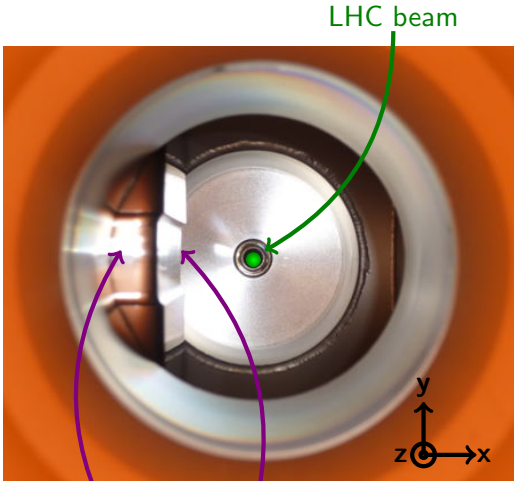
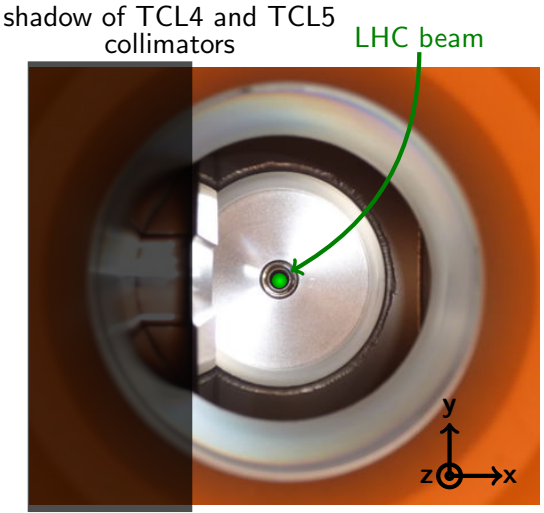
x


LHC beam
y
z
x
thin window and floor (300 μm)



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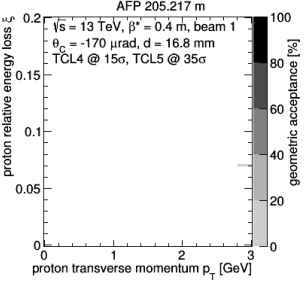
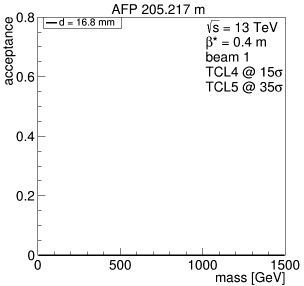


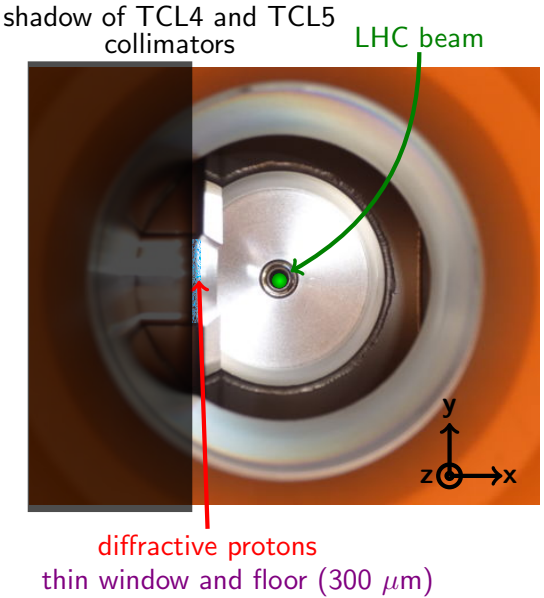
Geometric acceptance:

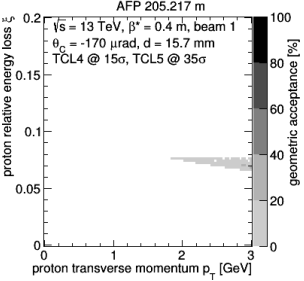
ratio of protons with a given $(\xi,\ p_T)$ that reached the detector to the total number of the scattered protons having given $(\xi,\ p_T)$



Mass acceptance:

mass of central system when both protons are tagged in Roman pot





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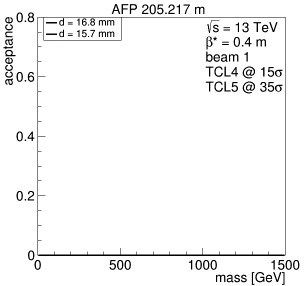
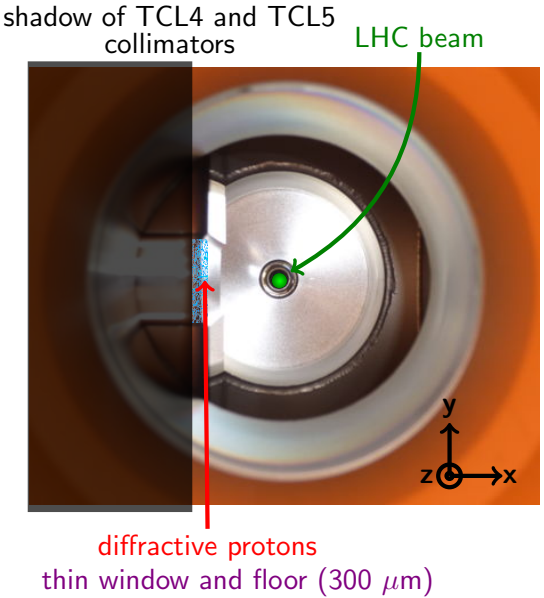
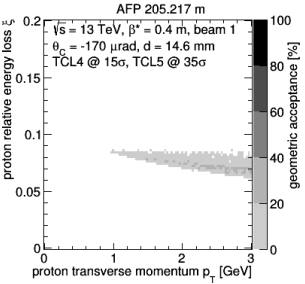


Mass acceptance:

mass of central system when both protons are tagged in Roman pot





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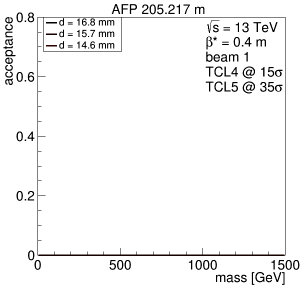
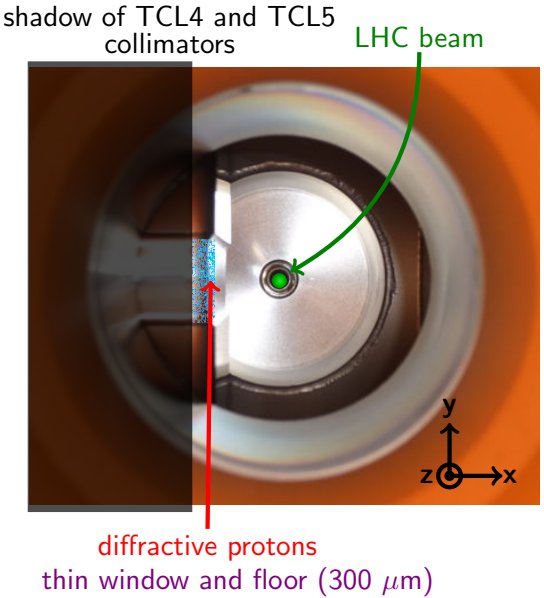
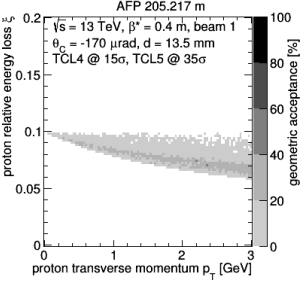


Mass acceptance:

mass of central system when both protons are tagged in Roman pot





Geometric acceptance:

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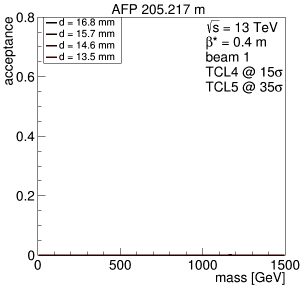
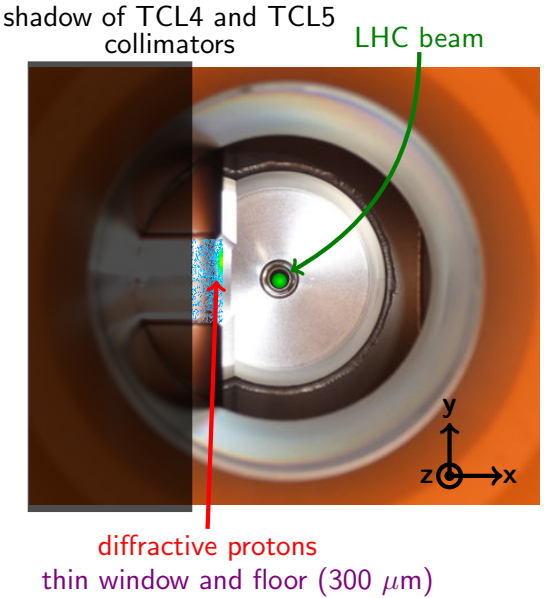
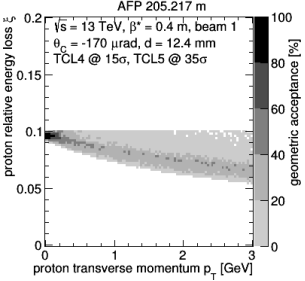


Mass acceptance:

mass of central system when both protons are tagged in Roman pot





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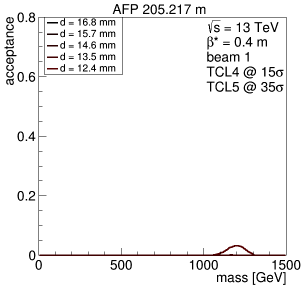
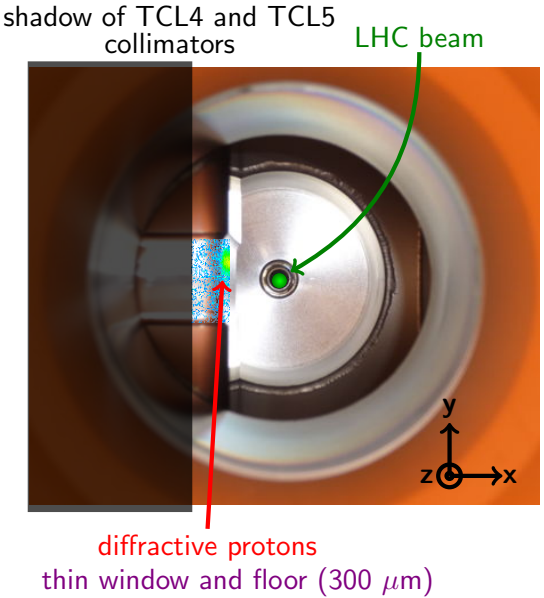
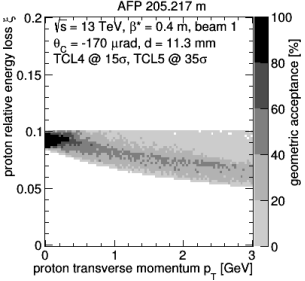


Mass acceptance:

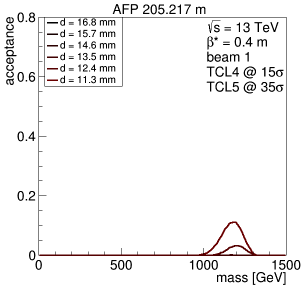
mass of central system when both protons are tagged in Roman pot





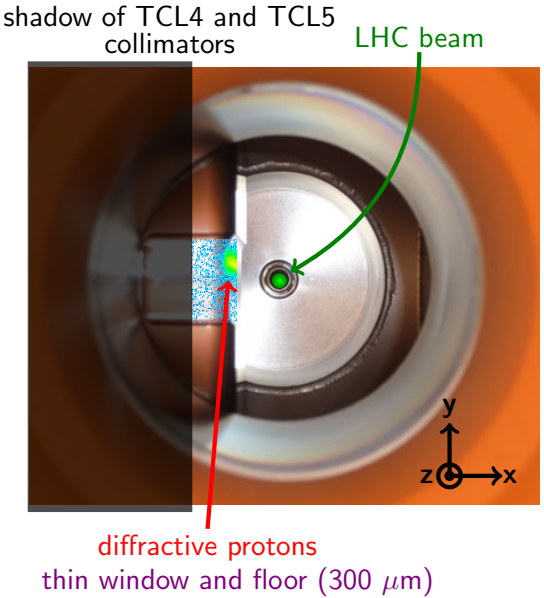
Geometric acceptance:

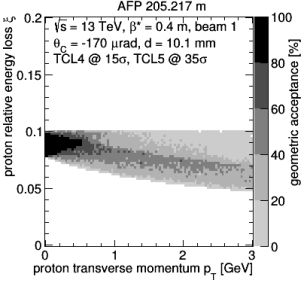
ratio of protons with a given $(\xi,\ p_T)$ that reached the detector to the total number of the scattered protons having given $(\xi,\ p_T)$



Mass acceptance:

mass of central system when both protons are tagged in Roman pot





Geometric acceptance:

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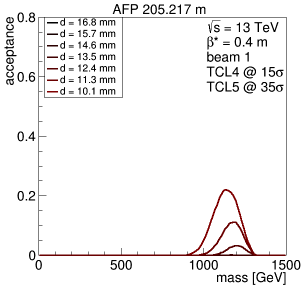
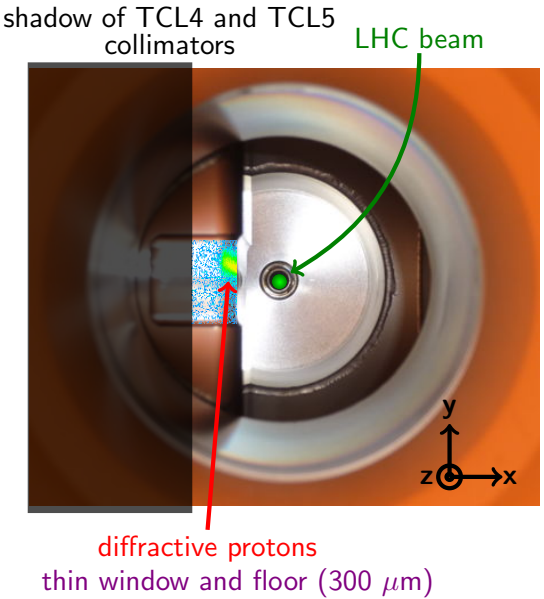
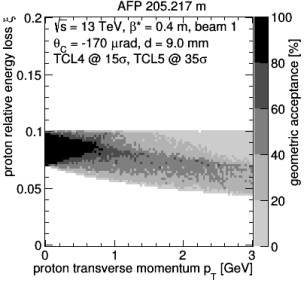


Mass acceptance:

mass of central system when both protons are tagged in Roman pot





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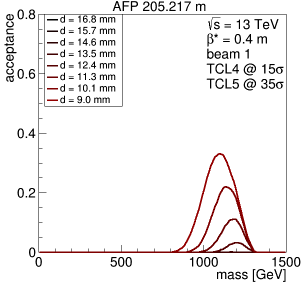
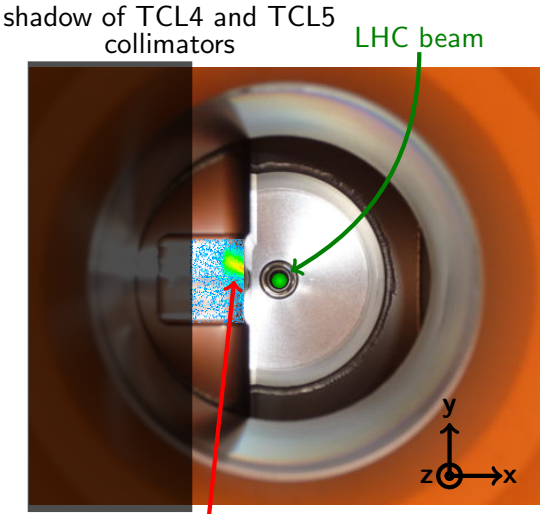
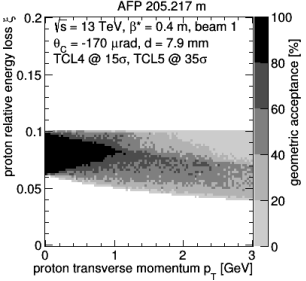


Mass acceptance:

mass of central system when both protons are tagged in Roman pot





Geometric acceptance:

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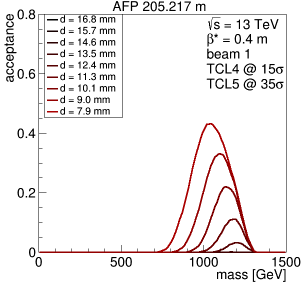

Mass acceptance:

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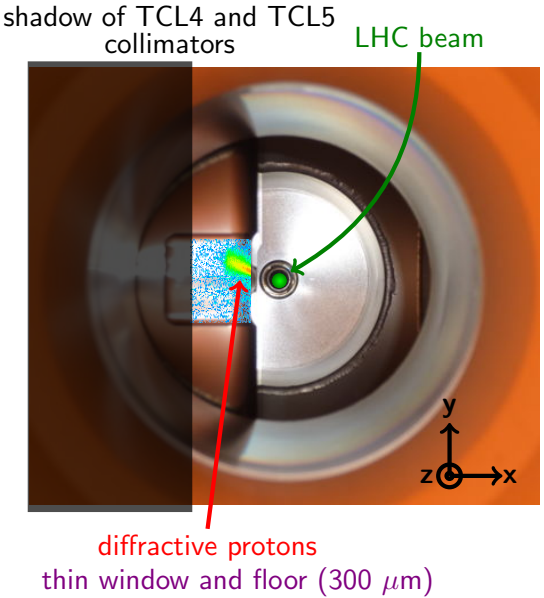

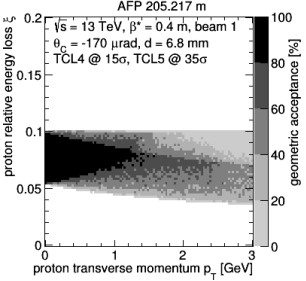

Geometric acceptance:

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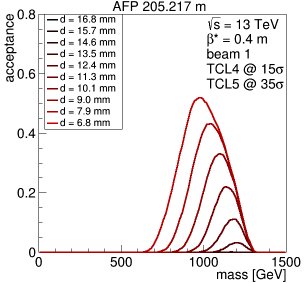

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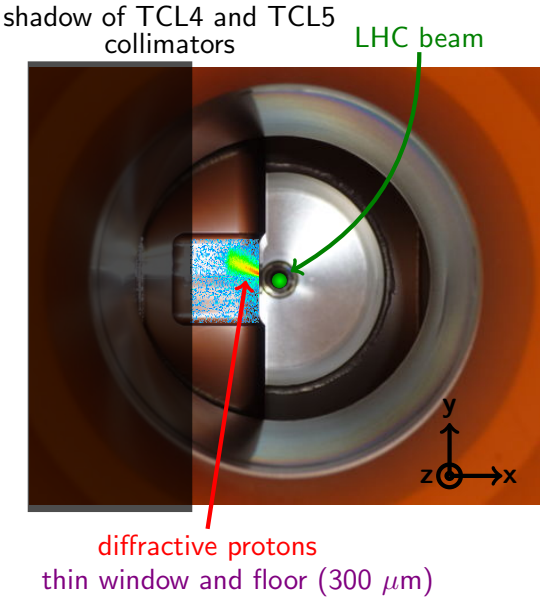

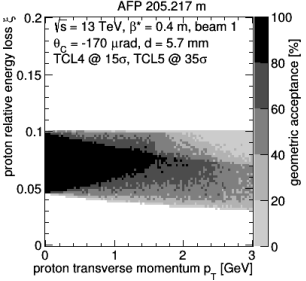

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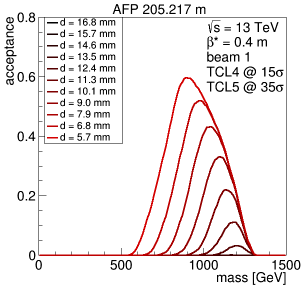

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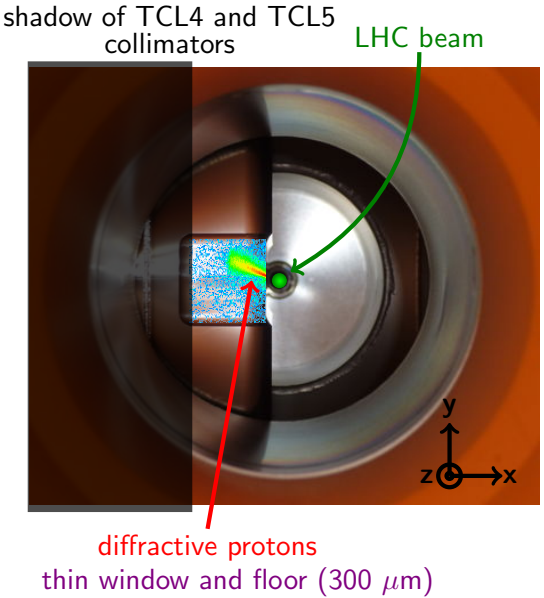

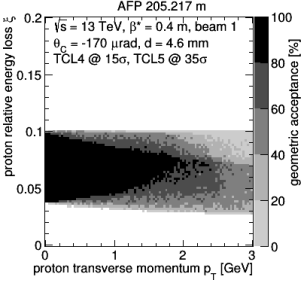

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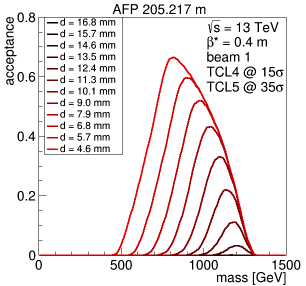

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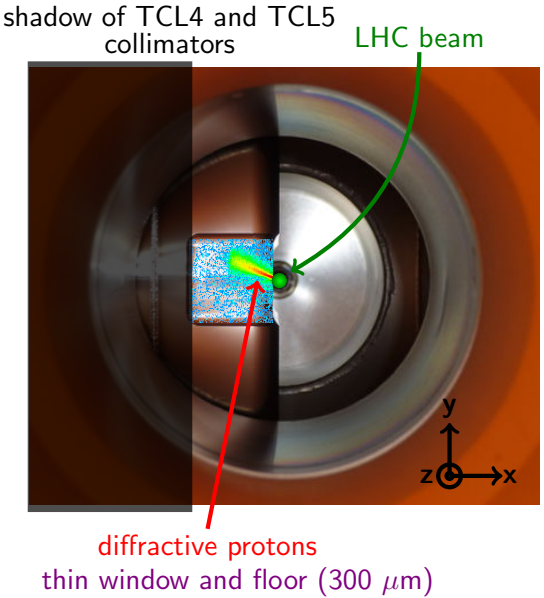

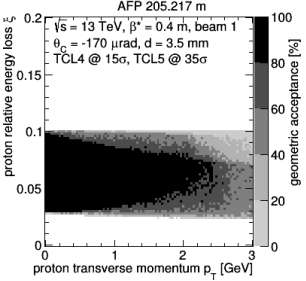

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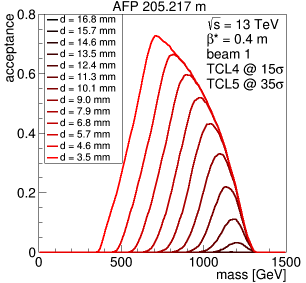
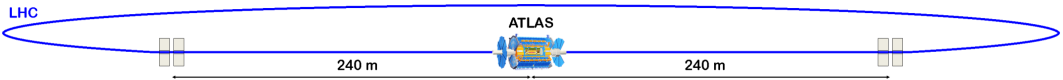


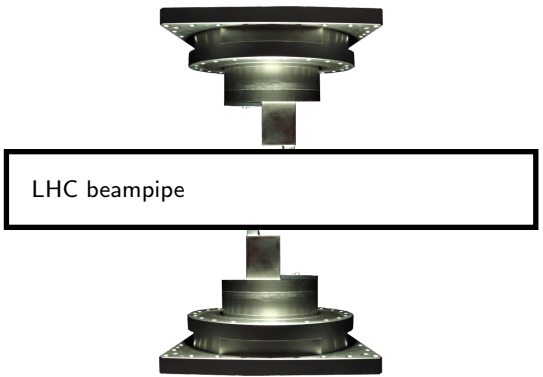
Mass acceptance:

mass of central system when both protons are tagged in Roman pot

ALFA

- Two stations at each ATLAS side, 240 m far from the IP1.
- Scintillating fibres – position measurement with precision of $\sim 30\mu$m,
- *Roman Pot* technology – detectors can move in vertical (y) direction.

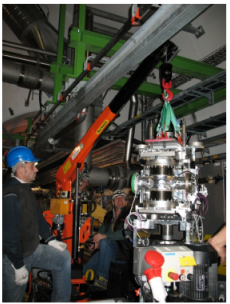




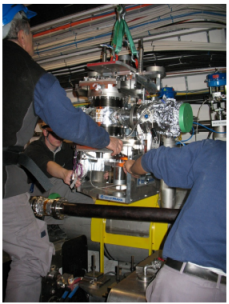
open

closed

Station installation sector 1-2

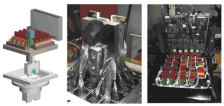


Installation of station B7R1



Installation of station A7R1

QRL-protection very close to station



Summary of ALFA's final run and discussion on its remains

Bartosz Dziedzic

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

ARP general meeting 13-15th December 2023

- After 12 years of operation life of ALFA detectors came to an end.
- However, the story is not finished:
  - stations donated to TWOCRYST experiment,
  - ongoing data analyses.

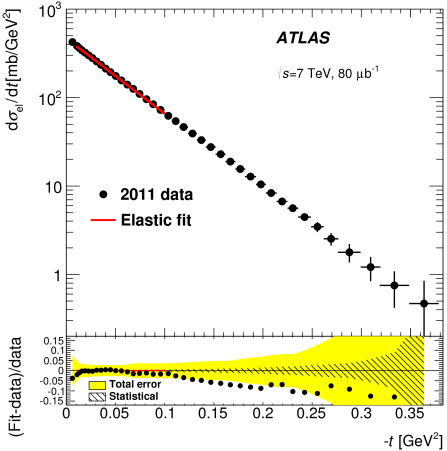
ALFA Data-taking (2011 – 2023)

Year	β*	√s [TeV]	Comments
2011	90 m	7	elastics: NPB 889 (2014) excl. $\pi^+\pi^-$: EPJC 83 (2023) 627
2012	90 m	8	elastics: PLB 761 (2016) single diff.: JHEP 02 (2020) 042
2012	1 km	8	elastics dataset
2013	0.8 m	2.76	proton-lead dataset
2013	0.8 m	2.76	proton-proton reference dataset
2015	90	13	diffractive dataset
2016	2.5 km	13	elastics: EPJC 83 (2023) 441
2018	90 m	13	elastic (large t) and diff. datasets
2018	11 m	0.9	elastics (large t) dataset
2018	50/100m	0.9	elastics dataset
2023	3/6 km	13.6	elastics dataset

- In 2023 ALFA successfully finished its programme!
- The initial focus to measure properties of elastic scattering was extended to measure diffractive events → a lot of interesting data-sets to be analysed!
- A few publications areleardy released; more in the pipeline.
- Many more interesting topics are waiting for analysers!

Short Title	Group	Journal Reference	Date	√s (TeV)	L	Links
alfa	search...	search...	search...	search...		search...
Measurement of exclusive pion pair production	STDM	Eur. Phys. J. C 83 (2023) 627	2022-12-01	7	78.7 μb^{-1}	Documents | 2212.00664 Inspire | HepData Internal
Measurement of the total cross section and rho-parameter from elastic scattering	STDM	Eur. Phys. J. C 83 (2023) 441	2022-07-25	13	340 μb^{-1}	Documents | 2207.12246 Inspire | HepData Briefing | Internal
Inclusive single diffractive dissociation cross-section of pp collisions at 8 TeV	STDM	JHEP 02 (2020) 042 (Erratum)	2019-11-01	8	24.11 nb^{-1}	Documents | 1911.00453 Inspire | HepData Internal
Total cross section with ALFA at 8 TeV	STDM	Phys. Lett. B (2016) 158	2016-07-22	8	500 μb^{-1}	Documents | 1607.06605 Inspire | HepData Internal
Total cross section with ALFA at 7 TeV	STDM	Nucl. Phys. B 889 (2014) 486	2014-08-25	7	80 μb^{-1}	Documents | 1408.5778 Inspire | HepData Briefing | Internal

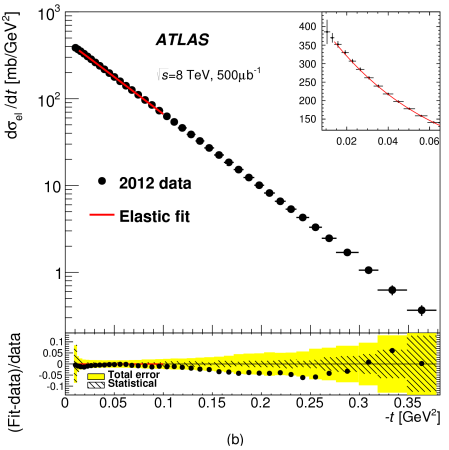
ALFA Analysis Example: Total Cross Section



$\sqrt{s} = 7$ TeV, $L = 80\mu\text{b}^{-1}$

$\sigma_{tot}(pp \to X) = 95.35 \pm 0.38\ (stat.) \pm 1.25\ (exp.) \pm 0.37\ (extr.)$ mb

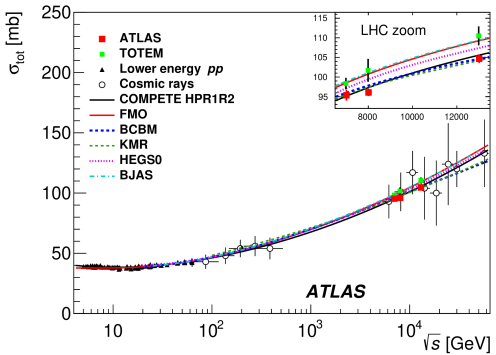
$B = 19.73 \pm 0.14\ (stat.) \pm 0.26\ (syst.)$ GeV^{-2}

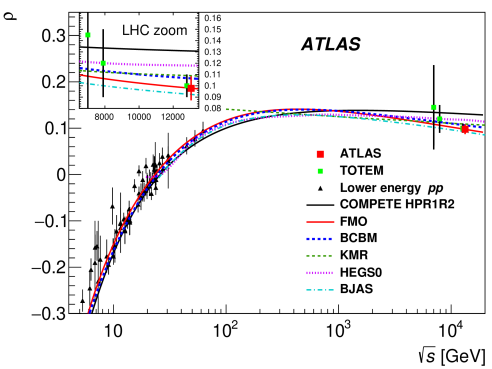


$\sqrt{s} = 8$ TeV, $L = 500\mu\text{b}^{-1}$

$\sigma_{tot}(pp \to X) = 96.07 \pm 0.18\ (stat.) \pm 0.85\ (exp.) \pm 0.31\ (extr.)$ mb

$B = 19.74 \pm 0.05\ (stat.) \pm 0.23\ (syst.)$ GeV^{-2}



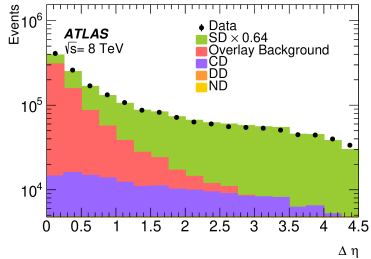


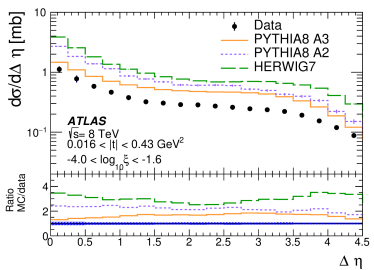
$\sqrt{s} = 13$ TeV, $L = 340\mu\text{b}^{-1}$

$\sigma_{tot}(pp \to X) = 104.7 \pm 1.1$ mb

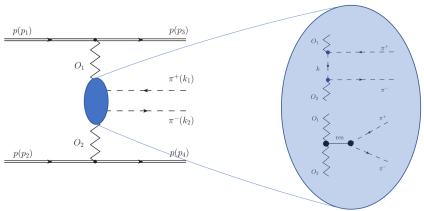
$\rho = 0.098 \pm 0.011$

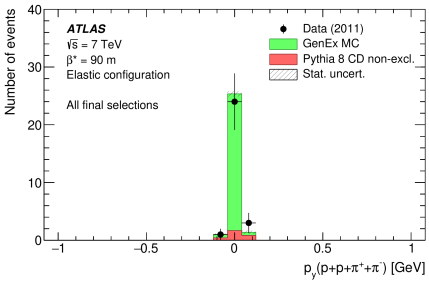
Differential cross sections for single diffraction



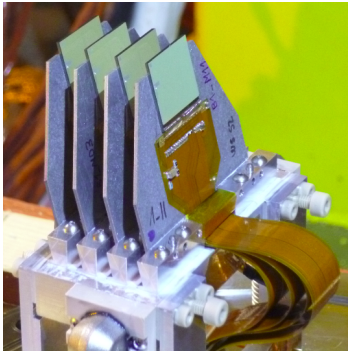


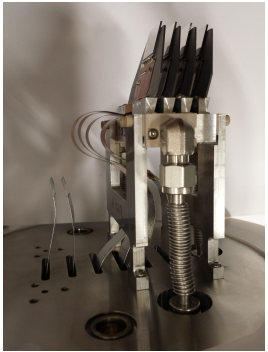
Exclusive pion pair production

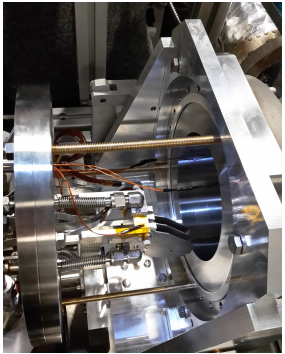




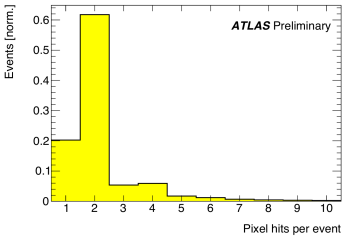
AFP

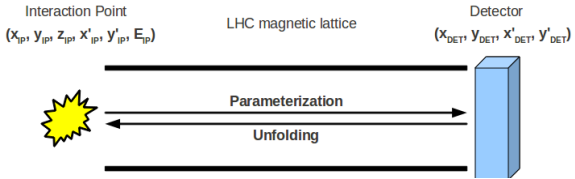




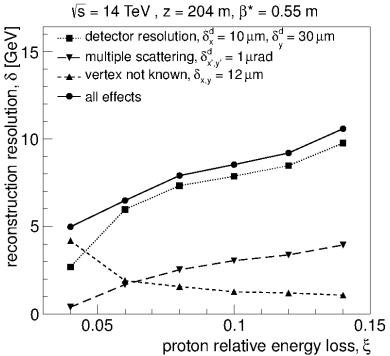


- Four detectors in each station.
- Technology: slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- Pixel size: $50x250\ \mu m^2$.
- Tilted by 14^0 to improve resolution in x.
- Resolution: $\sim 6\ \mu m$ in x and $\sim 30\ \mu m$ in y.
- Trigger: majority vote (2 out of 3; two chips in FAR station are paired and vote as one).





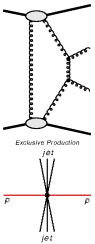
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics at the IP from their position in the AFP detector.
- Exclusivity: kinematics of scattered protons is strictly connected to kinematics of central system.
- Detector resolution play important role in precision of such method.



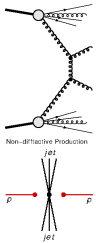
From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024

Pile-up – multiple collisions during one bunch crossing (mostly min-bias).

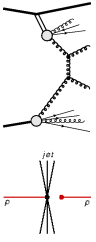
signal



background

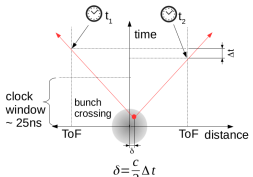


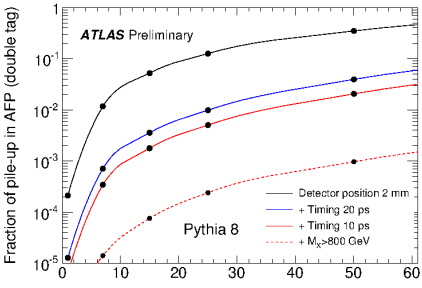
background

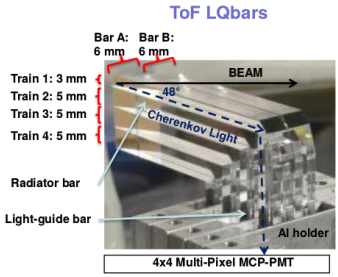


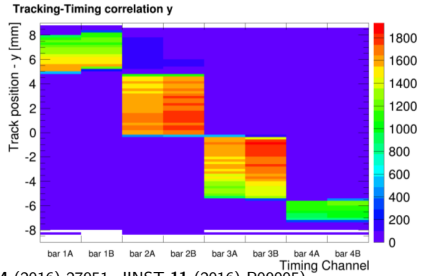
Idea:

- measure difference of time of flight of scattered protons, $(t_A - t_C)/2$
- compare to vertex reconstructed by ATLAS, $(t_A - t_C) \cdot c/2 - z_{ATLAS}$



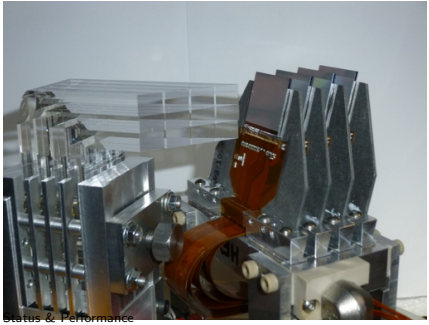


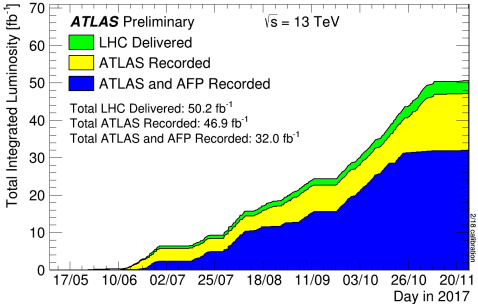


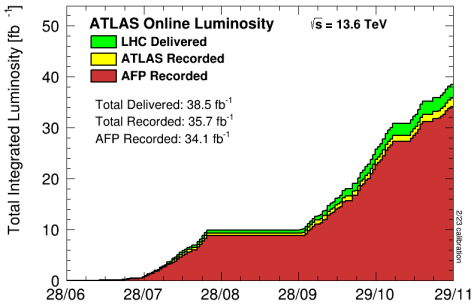


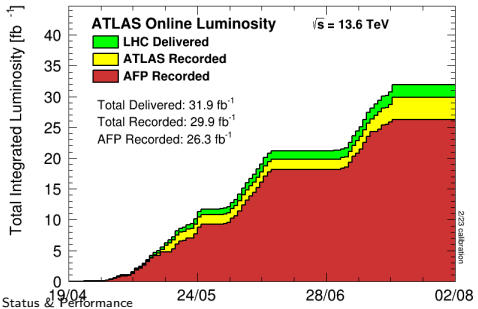
Setup and performance shown above are from test-beam (Opt. Express **24** (2016) 27951, JINST **11** (2016) P09005).

- 4x4 quartz bars oriented at the Cherenkov angle with respect to the beam trajectory.
- Light is directed to Photonis MCP-PMT.
- Expected resolution: $\sim$25 ps.
- Installed in both FAR stations.





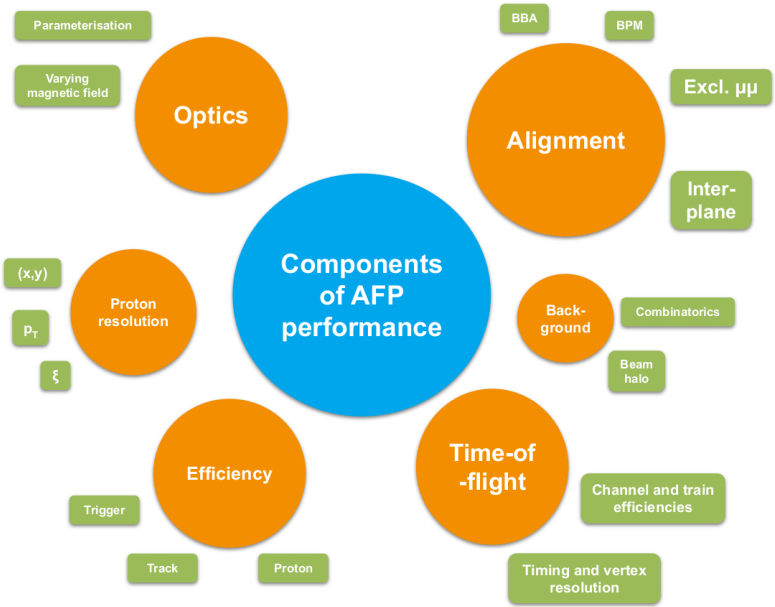


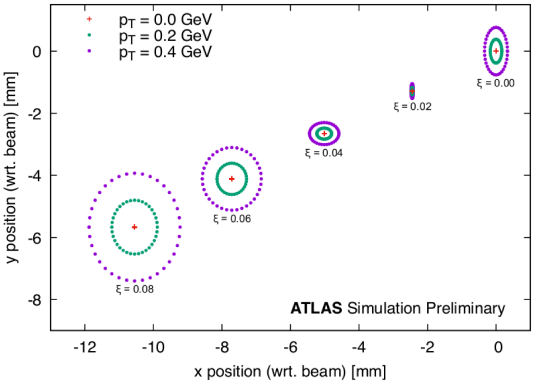


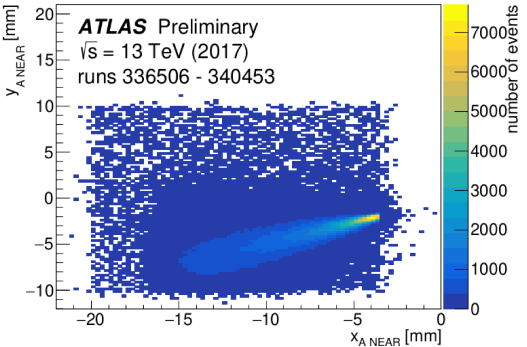
Data recorder so far:

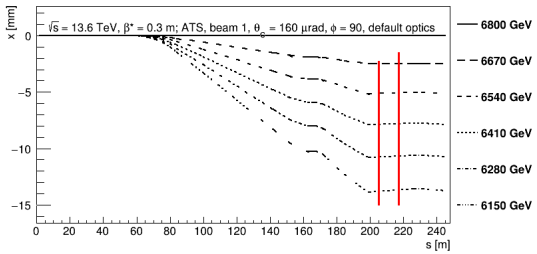
- 32.0 fb^{-1} in 2017 (left),
- 34.1 fb^{-1} in 2022 (top right),
- 26.3 fb^{-1} in 2023 (bottom right),
- **in total: 92.4 fb^{-1}.**

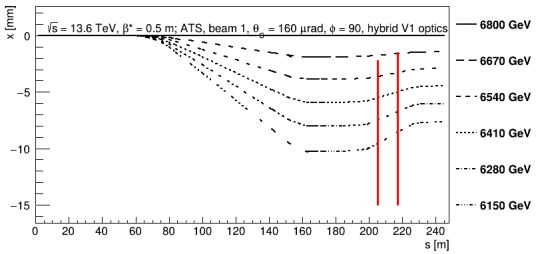
- Note: not all of recorded data is useful for physics analyses.


Components of AFP performance
Optics
Parameterisation
Varying magnetic field
Alignment
BBA
BPM
Excl. μμ
Inter-plane
Proton resolution
(x,y)
p_T
ξ
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution

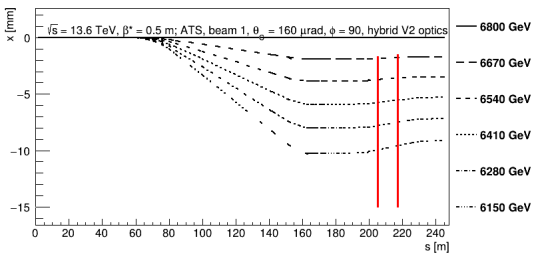

p_T = 0.0 GeV
p_T = 0.2 GeV
p_T = 0.4 GeV
ξ = 0.00
ξ = 0.02
ξ = 0.04
ξ = 0.06
ξ = 0.08
ATLAS Simulation Preliminary
y position (wrt. beam) [mm]
x position (wrt. beam) [mm]

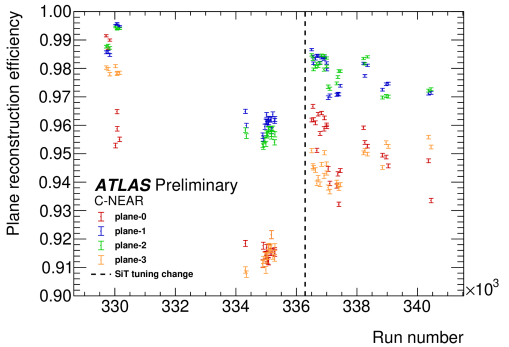

ATLAS Preliminary
√s = 13 TeV (2017)
runs 336506 - 340453
$y_{A\ NEAR}$ [mm]
$x_{A\ NEAR}$ [mm]
number of events

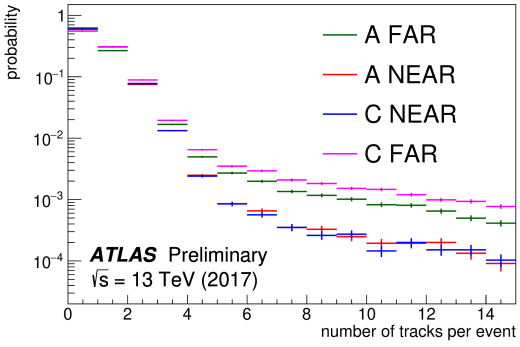


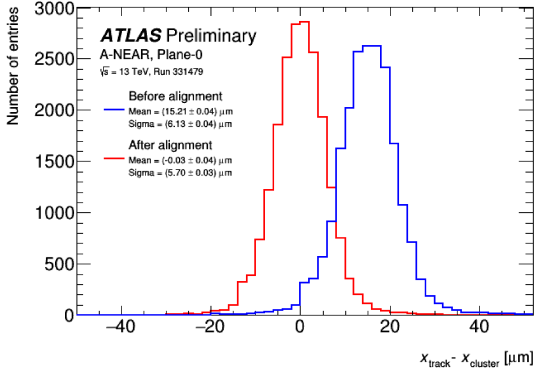


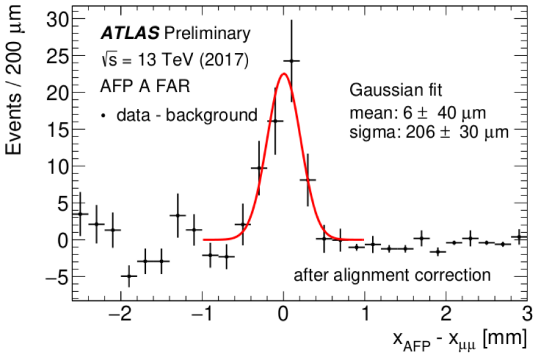
- New: V2 optics (bottom left) is better compared to V1 in terms of low-ξ acceptance (NEAR station).
- V2 is better than V1 in terms of resolution (especially for FAR stations), but worse than the default.
- High-ξ acceptance for V1 and V2 is due to TCL4 and TCL5 and may be an issue – see next slide.

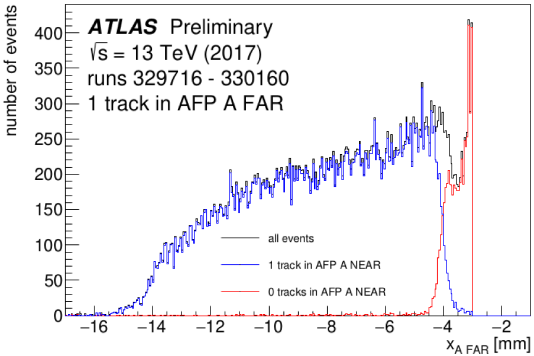


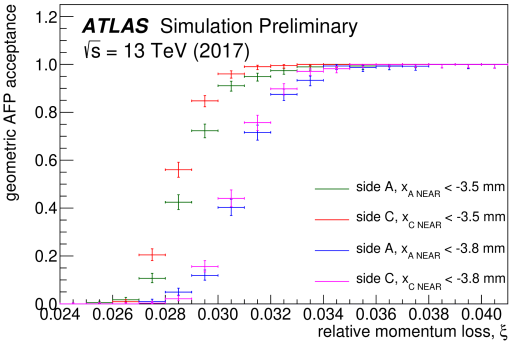

Plane reconstruction efficiency
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
330
332
334
336
338
340
×10^3
Run number
ATLAS Preliminary
C-NEAR
plane-0
plane-1
plane-2
plane-3
SiT tuning change


probability
1
10^-1
10^-2
10^-3
10^-4
0
2
4
6
8
10
12
14
number of tracks per event
A FAR
A NEAR
C NEAR
C FAR
ATLAS Preliminary
√s = 13 TeV (2017)

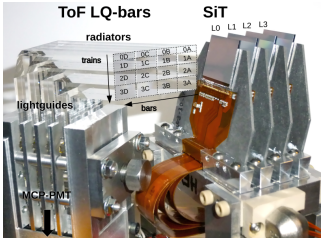

ATLAS Preliminary
A-NEAR, Plane-0
√s = 13 TeV, Run 331479
Before alignment
Mean = (15.21 ± 0.04) μm
Sigma = (6.13 ± 0.04) μm
After alignment
Mean = (-0.03 ± 0.04) μm
Sigma = (5.70 ± 0.03) μm
Number of entries
x_track - x_cluster [μm]

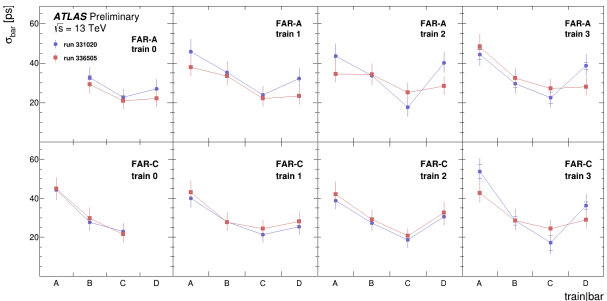

ATLAS Preliminary
√s = 13 TeV (2017)
AFP A FAR
• data - background
Gaussian fit
mean: 6 ± 40 μm
sigma: 206 ± 30 μm
after alignment correction
Events / 200 μm
x_AFP - x_μμ [mm]

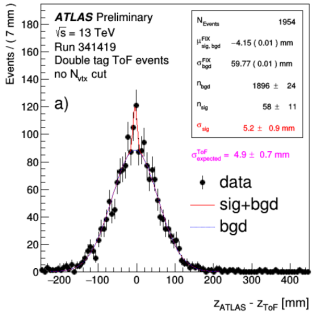

ATLAS Preliminary
√s = 13 TeV (2017)
runs 329716 - 330160
1 track in AFP A FAR
all events
1 track in AFP A NEAR
0 tracks in AFP A NEAR
number of events
x A FAR [mm]


ATLAS Simulation Preliminary
√s = 13 TeV (2017)
side A, x A NEAR < -3.5 mm
side C, x C NEAR < -3.5 mm
side A, x A NEAR < -3.8 mm
side C, x C NEAR < -3.8 mm
geometric AFP acceptance
relative momentum loss, ξ

- Performance analysis based on 2017 data (taken with $\mu \approx 2$): ATL-FWD-PUB-2021-002.
- Poor efficiency of few percent due to fast PMT degradation; effect not expected during Run 3 due to new PMTs.
- Very good timing resolution: 20 – 50 ps for single bar.
- Overall time resolution of each ToF detector:
  - 20 ± 4 ps for side A,
  - 26 ± 5 ps for side C,
  - note: systematic uncertainties dominate.







PHYSICAL REVIEW LETTERS **125,** 261801 (2020)

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

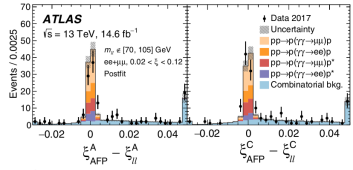
G. Aad *et al.*[*]
(ATLAS Collaboration)

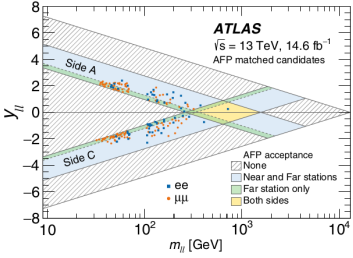
(Received 2 October 2020; revised 30 October 2020; accepted 23 November 2020; published 23 December 2020)

- Exclusive di-muons, $pp \to pl^-l^+p$:
  - proton(s) measured in AFP,
  - leptons ($\mu^+\mu^-$ or e^+e^-) measured in ATLAS.
- 2017 data; $\sqrt{s} = 13$; $L = 14.6$ fb^{-1}.
- Powerful background rejection due to AFP:
  - proton tagging,
  - kinematics match: proton vs lepton system.
- 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state.
- Background-only hypothesis rejected with a significance exceeding 5σ in each channel.
- Measured cross sections:

$\sigma_{ee+p} = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi})$,

$\sigma_{\mu\mu+p} = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi})$.





- ALFA and AFP "physics" publications:

Diphoton resonance search with AFP tag	EXOT	JHEP 07 (2023) 234	2023-04-21	13	30 fb^{-1}	Documents | 2304.10953 Inspire | HepData Internal
Measurement of exclusive pion pair production	STDM	Eur. Phys. J. C 83 (2023) 627	2022-12-01	7	78.7 μb^{-1}	Documents | 2212.00664 Inspire | HepData Internal
Measurement of the total cross section and rho-parameter from elastic scattering	STDM	Eur. Phys. J. C 83 (2023) 441	2022-07-25	13	340 μb^{-1}	Documents | 2207.12246 Inspire | HepData Briefing | Internal
Observation of forward proton scattering in association with lepton pairs produced in photon fusion	STDM	Phys. Rev. Lett. 125 (2020) 261801	2020-09-30	13	14.6 fb^{-1}	Documents | 2009.14537 Inspire | HepData Briefing | Internal
Inclusive single diffractive dissociation cross-section of pp collisions at 8 TeV	STDM	JHEP 02 (2020) 042 (Erratum)	2019-11-01	8	24.11 nb^{-1}	Documents | 1911.00453 Inspire | HepData Internal
Total cross section with ALFA at 8 TeV	STDM	Phys. Lett. B (2016) 158	2016-07-22	8	500 μb^{-1}	Documents | 1607.06605 Inspire | HepData Internal
Total cross section with ALFA at 7 TeV	STDM	Nucl. Phys. B 889 (2014) 486	2014-08-25	7	80 μb^{-1}	Documents | 1408.5778 Inspire | HepData Briefing | Internal

- ALFA concluded its programme in 2023:
  - few ongoing elastic and diffractive analyses,
  - many unique datasets → waiting to be analysed!
- AFP continues to take data in regular and special runs:
  - huge efforts of many to have system operational and in a good shape → BIG THANKS!
  - preliminary recommendations available and applicable via dedicated, user-friendly analysis tools,
  - a lot of ongoing efforts to deliver final recommendations for "proton object" (2022–2023),
  - eagerly waiting for 2024 (and 2025!) data-taking!

The work of MT was partially supported by Polish National Science Centre (project no. UMO-2019/34/E/ST2/00393).

Successful ATLAS Roman Pot Data-taking – Efforts of Many!