ATLAS Forward Proton

A TERASCALE PROTON SPECTROMETER

Forward Physics and QCD with LHC, EIC and Cosmic Rays
Online Workshop at Jefferson Lab
23 January 2021

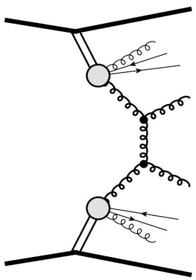
Jesse Liu (University of Chicago)
On behalf of *ATLAS Forward Detectors*

ATLAS EXPERIMENT

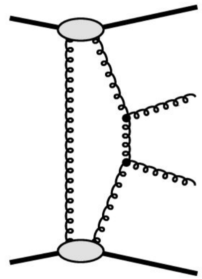
THE UNIVERSITY OF CHICAGO

How can we see incident protons stay intact during LHC particle creation?

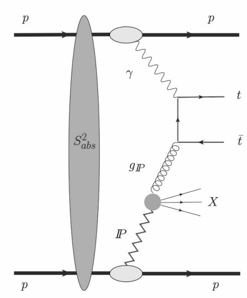
Diverse physics predicts forward proton scattering



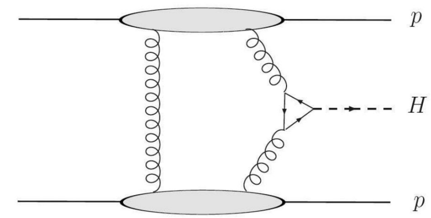
Diffractive jets
ATL-PHYS-PUB-2017-012



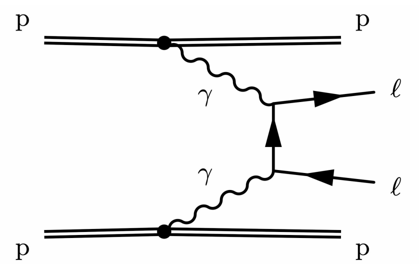
Exclusive jets
Trzebinski et al 1503.00699



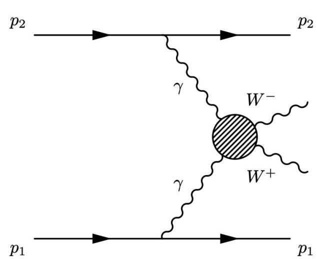
Top quarks
Goncalves et al 2007.04565
Howarth 2008.04249



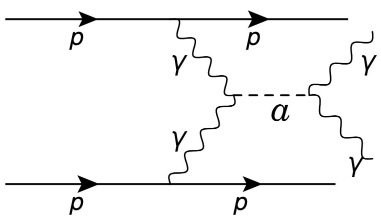
Higgs boson
Cox et al 0709.3035
Heinemeyer et al 0708.3052



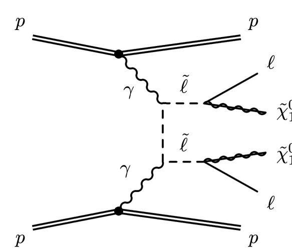
Leptons
CMS 1803.04496
ATLAS 2009.14537



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 & JL 1811.06465
Harland-Lang et al 1812.04886

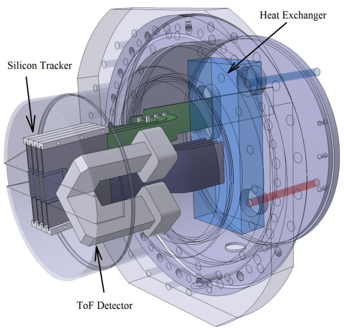
Important probes of nonperturbative QCD & electroweak scale

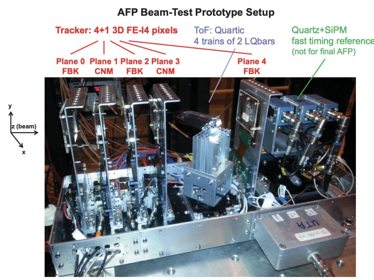
Interesting searches for physics beyond the Standard Model

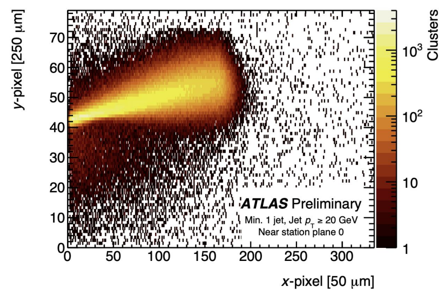
See also physics overviews by Cristian Baldenegro, Deniz Sunar Cerci

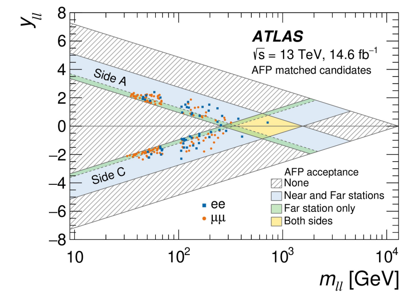
AFP from design to data

TDR	Prototype	Single arm low-μ	Double arm high-μ









ATLAS Forward Proton Phase-I Upgrade

Technical Design Report

ATL-TDR-024 (2015)

Technical simulation
For LHC Run 2 installation

Published by IOP Publishing for Sissa Medialab
Received: July 4, 2016
Accepted: September 5, 2016
Published: September 19, 2016

Beam tests of an integrated prototype of the ATLAS Forward Proton detector

JINST 11 (2016) P09005

Beam tests
Integrated prototype

ATLAS NOTE

ATL-PHYS-PUB-2017-012

29th June 2017

Proton tagging with the one arm AFP detector

The ATLAS Collaboration

ATL-PHYS-PUB-2017-012

Data 2016
Diffractive jets performance

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)

NEW!

PRL 125 (2020) 261801

Data 2017
(γγ → ℓℓ)+p measurement

Today: highlight in situ AFP detector performance & innovations with recent LHC data

Just published: first physics paper with AFP

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)

Physics Briefing

[ATLAS Physics Briefing]

Tags: Physics Results, ICHEP2020, ICHEP, forward detectors

Looking forward: ATLAS measures proton scattering when light turns into matter

By ATLAS Collaboration, 30th July 2020

Today, at the International Conference for High Energy Physics (ICHEP 2020), the ATLAS Collaboration announced first results using the ATLAS Forward Proton (AFP) spectrometer (Figure 1). With this instrument, physicists directly observed and measured the long sought-after prediction of proton scattering when particles of light turn into matter.

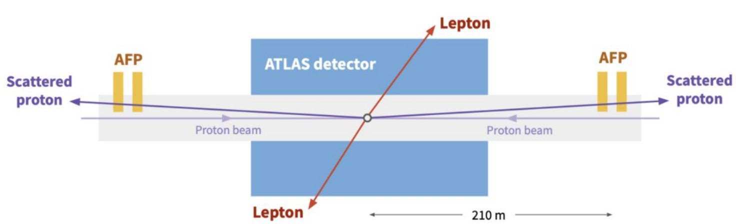


Figure 1: Schematic diagram of ATLAS Forward Proton (AFP) spectrometer relative to the main ATLAS detector (not to scale). After the incident proton beams intersect, the leptons are detected by the main ATLAS detector and the scattered proton is detected by AFP. (Image: ATLAS Collaboration/CERN)

[CERN Courier]

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

The LHC as a photon collider

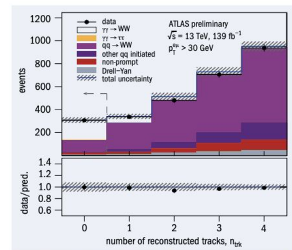


Fig. 1. *To isolate a sample of $\gamma\gamma \to WW$ interactions, events with no additional reconstructed charged-particle tracks in the vicinity of the electron–muon pair ($n_{trk}=0$) are selected.*

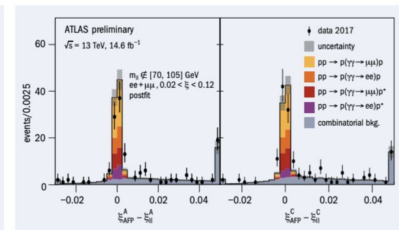


Fig. 2. *A sample of $\gamma\gamma \to \ell\ell$ events can be isolated by observing a scattered proton in the AFP spectrometer. Here, the proton energy loss measured in the AFP installed either side (A and C) of the collision point (ξ_{AFP}, dimensionless) is shown to agree with that predicted from measurements of the lepton pair in the main detector ($\xi_{\ell\ell}$).*

Protons accelerated by the LHC generate a large flux of quasi-real high-energy photons that can interact to produce particles at the electroweak scale. Using the LHC as a photon collider, the ATLAS collaboration recently announced a set of landmark results, among which is the first observation the photo-production of W-boson pairs.

As it proceeds via trilinear and quartic gauge-boson vertices involving two W bosons and either one or two photons, the production of a pair of W bosons from two photons ($\gamma\gamma \to WW$) tests a long-standing prediction of the Standard Model (SM). This process is extremely rare but predicted precisely by electroweak theory, such that any observed deviation would suggest that new physics is at play. The measurement relies on the large 139 fb^{-1} dataset of proton–proton collisions recorded by ATLAS in LHC Run 2.

Protons usually remain intact or are excited into a higher energy state in photon collisions, with the products of any subsequent decay not reaching the innermost components of the ATLAS detector. In these cases, the electron and muon decaying from the W bosons – an event topology chosen to avoid the high background for same-flavour lepton pairs – are the only particles detected in the vicinity. However, if charged particles arise from nearby proton–proton collisions, the clean $\gamma\gamma \to WW$ signal can be missed. The main background is W boson pairs produced in head-on proton–proton collisions where particles from the breakup of the protons are not detected due to imperfect detector coverage or reconstruction (figure 1). A total of 127 background events are predicted compared to 307 events observed in data. This signal excess corresponds to a statistical significance of 8.4 standard deviations. This establishes the existence of light transforming into particles with weak-scale masses – a remarkable and previously unobserved phenomenon.

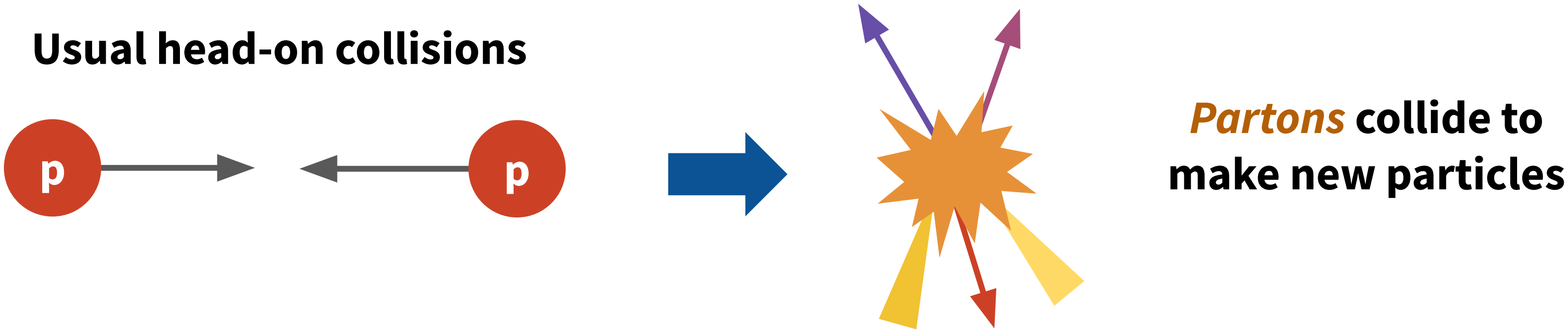
Precisely testing SM predictions of photon collisions requires accurate knowledge of the rate protons remain intact relative to those that break apart. This is challenging to predict theoretically and probing these rates unambiguously requires directly detecting the intact protons. The ATLAS Forward Proton (AFP) spectrometer is becoming increasingly indispensable for this task. Among the newest additions to the ATLAS experiment, and located a few millimetres from the beam 210 metres either side of the collision point, the AFP can detect protons that have been scattered in photon–photon collisions but which have nevertheless been focused by the LHC's magnets. Its pioneering results so far analyse a standard-candle process where a proton is scattered in photon collisions that produce electron or muon pairs ($\gamma\gamma \to \ell\ell$). For these signals, the measured proton energy loss is equal to that predicted from the lepton pairs measured in the main ATLAS detector (figure 2). ATLAS reported 180 events with a proton having matched kinematics to the lepton pair with an expected background of about 20 events. This corresponds to a significance exceeding nine standard deviations for both lepton flavours, establishing the presence of the signal and the successful operation of the AFP spectrometer in high-luminosity data. The detectors were sufficiently well understood to measure the cross sections of these processes.

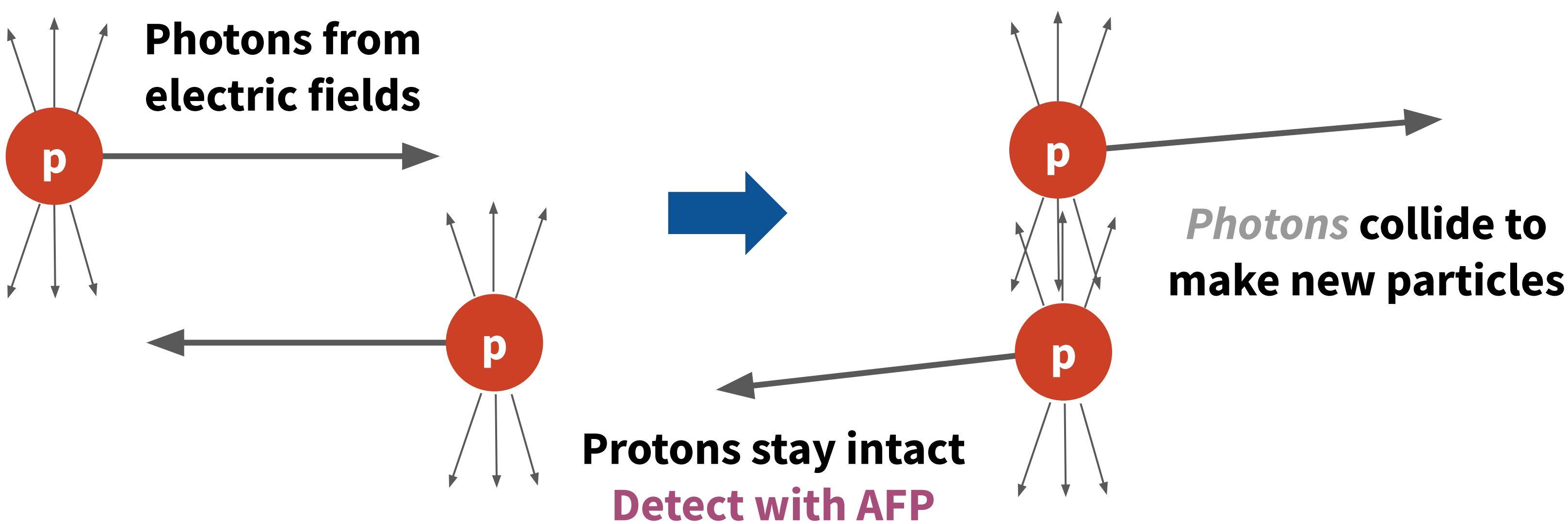
Observing $\gamma\gamma \to$ WW and scattered protons in $\gamma\gamma \to \ell\ell$ interactions are long-awaited milestones

Observing $\gamma\gamma \to$ WW and scattered protons in $\gamma\gamma \to \ell\ell$ interactions are long-awaited milestones in an emerging experimental programme studying photon collisions. These complement recent heavy-ion results where ATLAS measured muon pairs from photon ▷

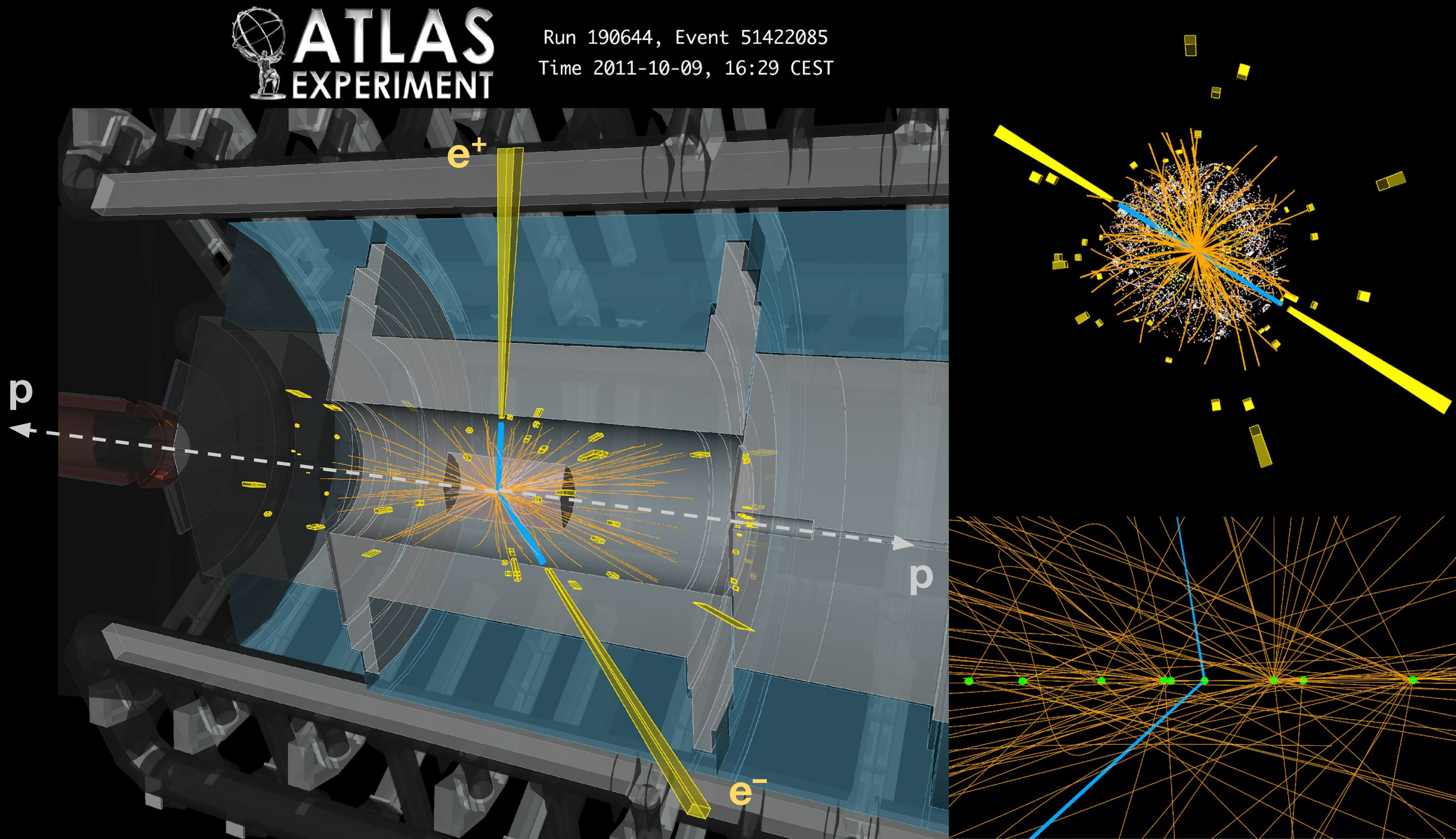
Major milestone: showcase for AFP detector performance & innovations at high-pileup

Photons collide while protons scatter





Fermi (1925) [hep-th/0205086], Breit & Wheeler (1934), Weizsäcker (1934), Williams (1934), Heisenberg & Euler (1936), Schwinger (1952)
Brodsky, Kinoshita, Terazaw (1971), Budnev, Ginzburg, Meledin, Serbo (1975), Bruce et al [1812.07688], Klein & Steinberg [2005.01872]



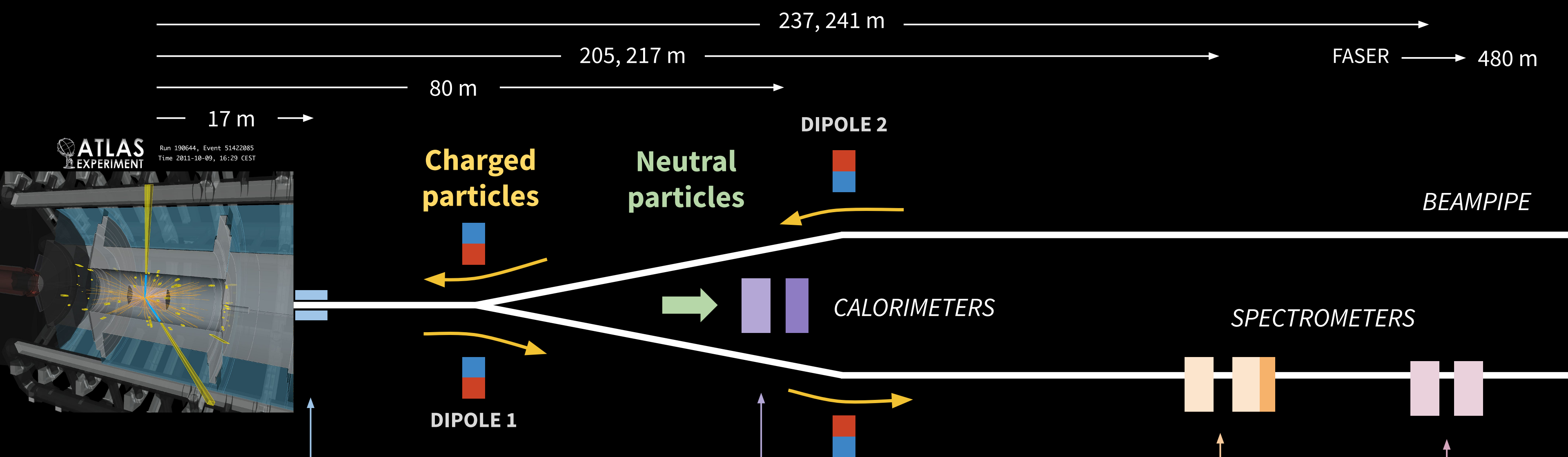
γγ → ee @ 7 TeV event display [1506.07098]

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

Without AFP can only see this

With AFP: directly observe intact protons

LOOKING FORWARD



LUCID
Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

For luminosity measurement

LHCf
LHC Forward

ZDC
Zero Degree Calorimeter

Low-μ, $|\eta| > 8.0$

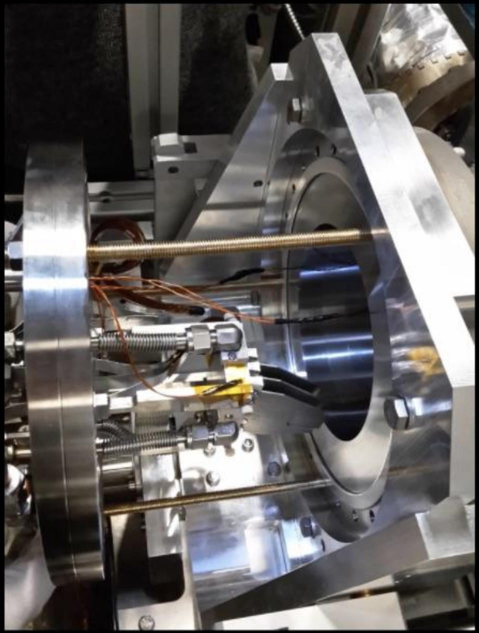
For cosmic-ray & heavy-ion physics

AFP
ATLAS Forward Proton
Low & high μ
$0.02 < \xi < 0.12$

ALFA
Absolute Luminosity For ATLAS
Low-μ, $0 < \xi < 0.2$
$10.6 < |\eta| < 13.5$

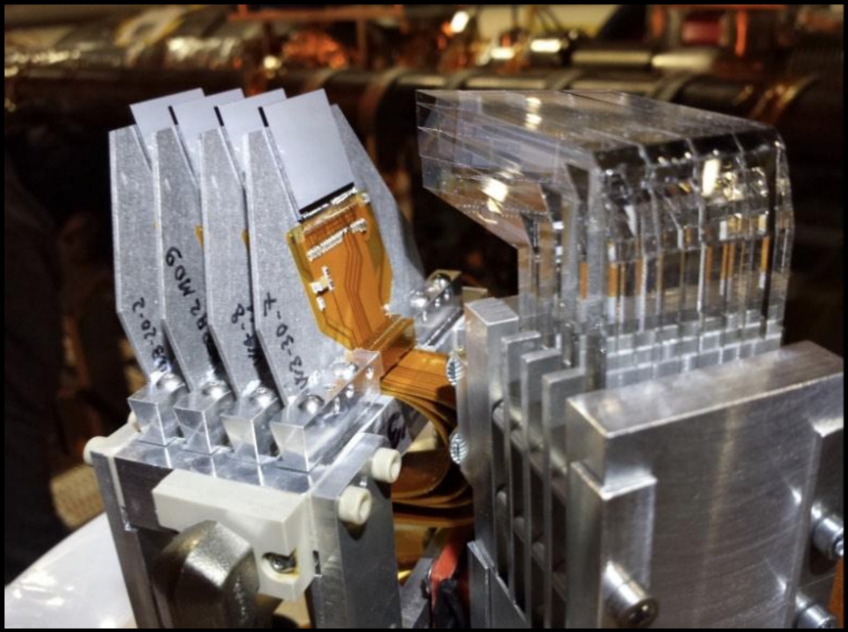
ARP (ATLAS Roman Pot)

AFP DETECTOR



ROMAN POT

Insertion into beam pipe
40mm → 2mm when stable



TRACKER & TIME-OF-FLIGHT

3D silicon pixels σ_x ~ 10 µm
Quartz Cerenkov bars σ_t ~ 30 ps

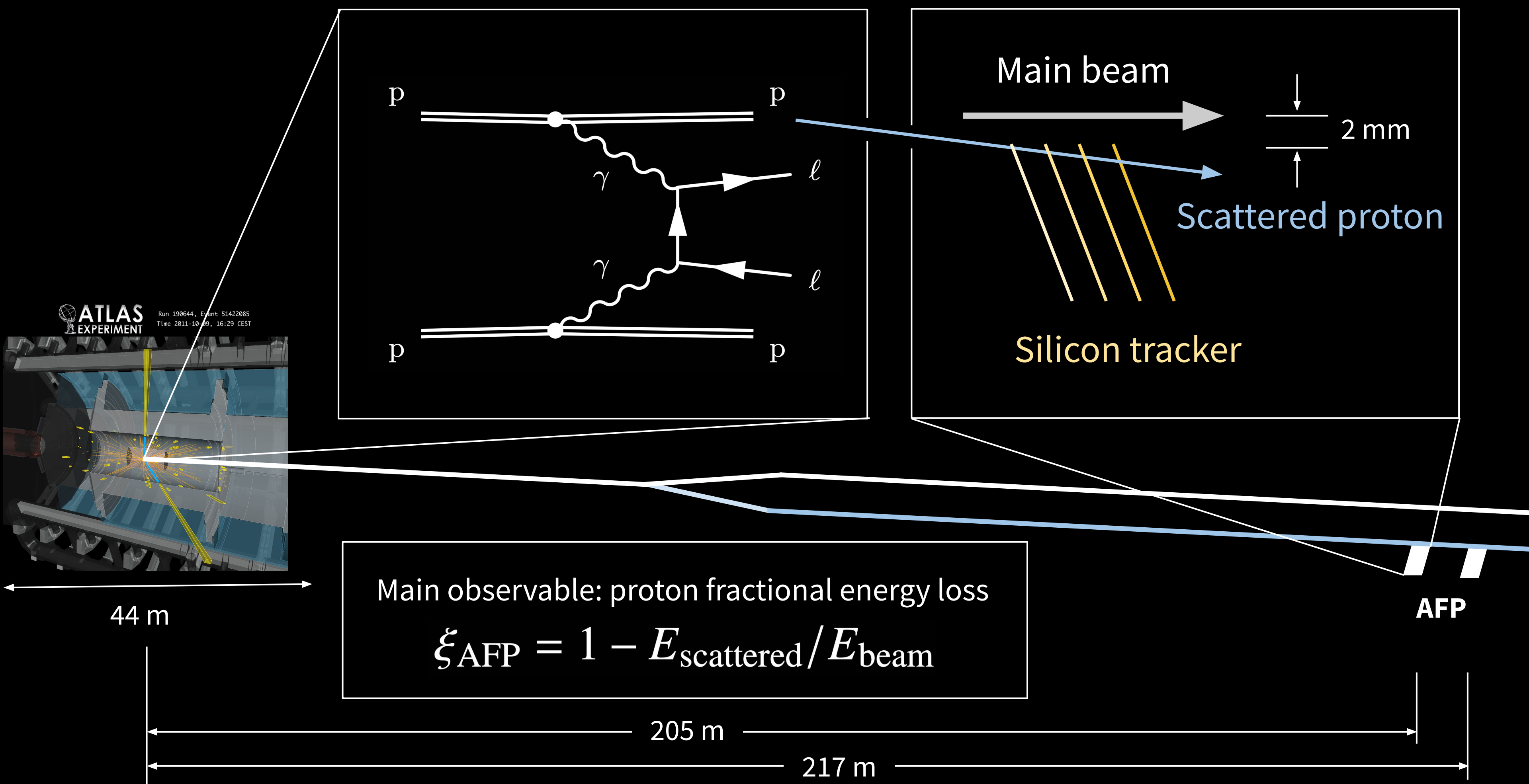
INSTALLATION

One side 2016
Both sides 2017

Adamczyk et al [AFP TDR]

ATLAS Forward Proton

Both arms installed in 2017 for standard high-luminosity LHC data-taking
New analysis object opening exciting program of diffractive & photon collision physics

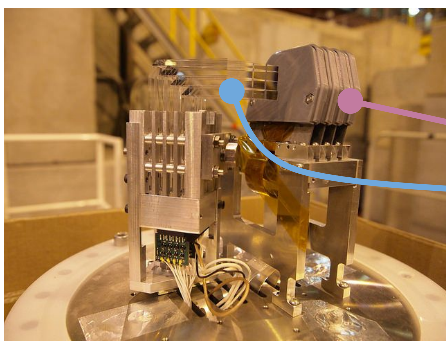


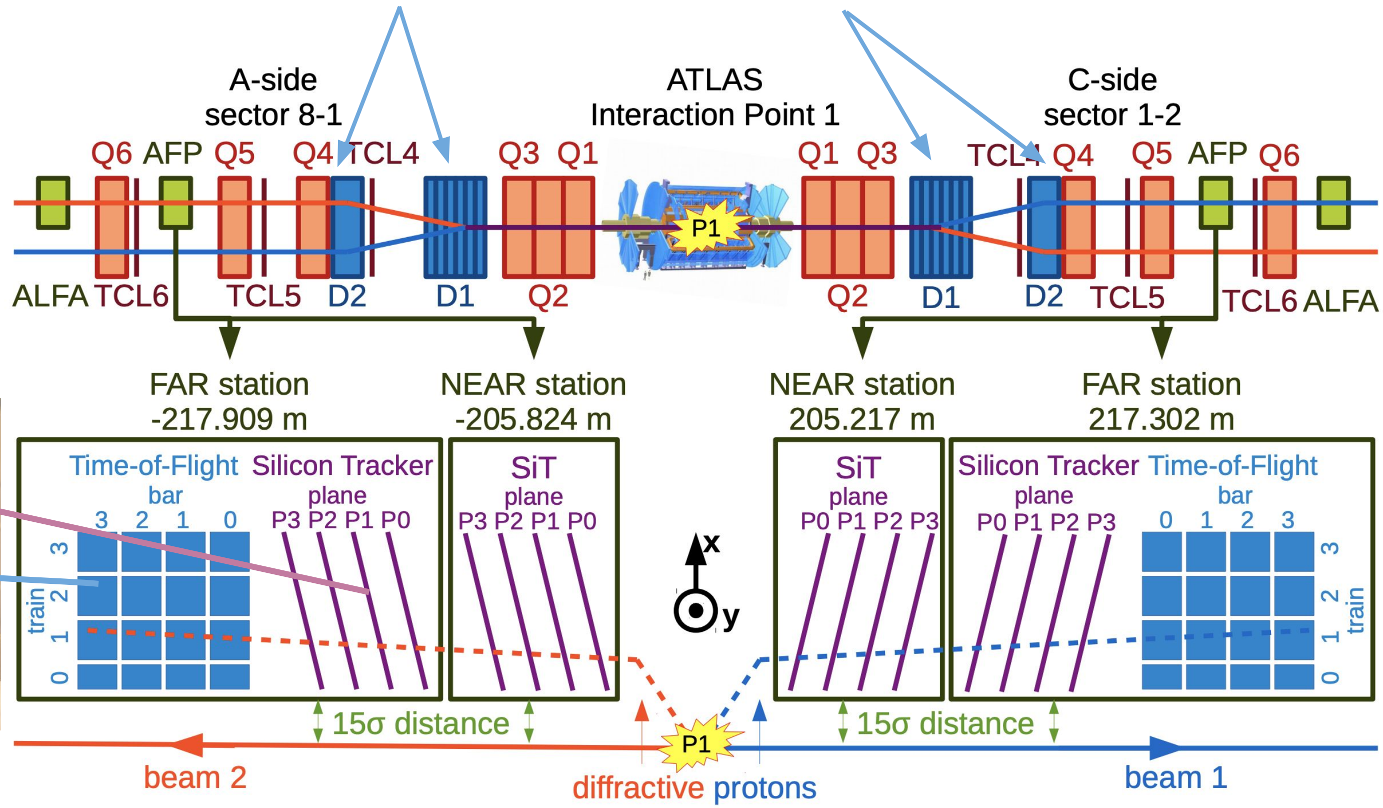
Main observable: proton fractional energy loss

$$\xi_{\mathrm{AFP}} = 1 - E_{\mathrm{scattered}}/E_{\mathrm{beam}}$$

Detailed schematic

LHC dipoles D1/2 act as spectrometer magnets

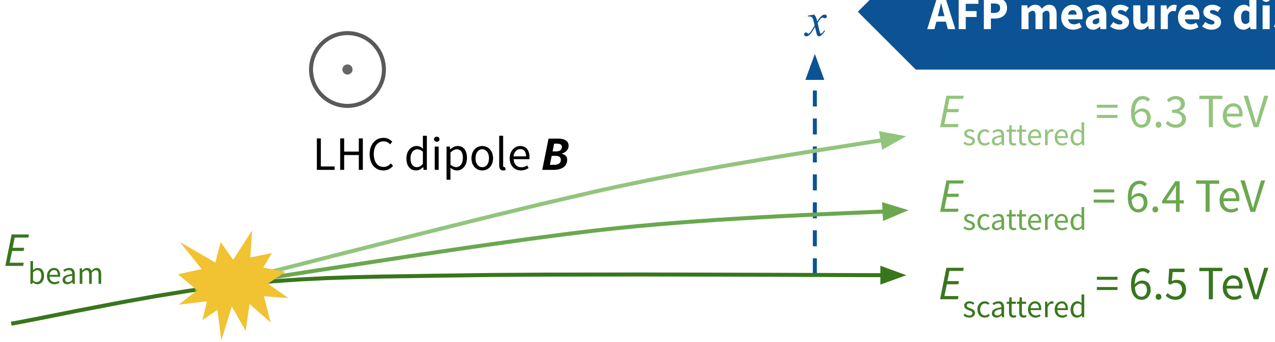




Towards Point 8 (LHCb)

Towards Point 2 (ALICE)

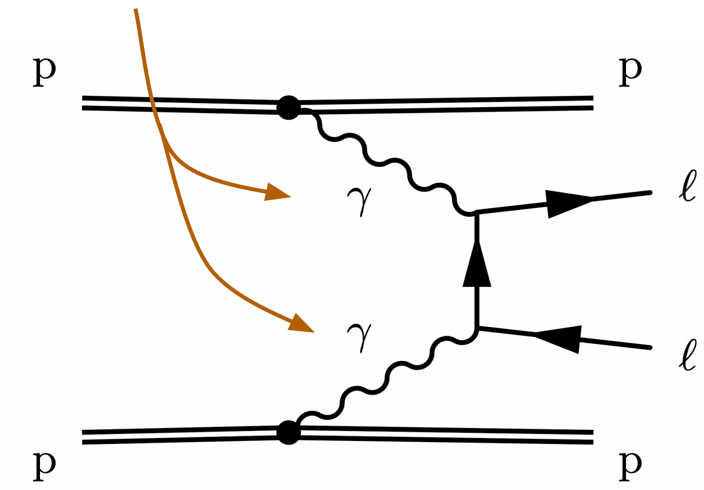
The idea of a TeV proton spectrometer



AFP measures displacement 1

$$\xi_{\text{AFP}} = 1 - E_{\text{scattered}} / E_{\text{beam}}$$

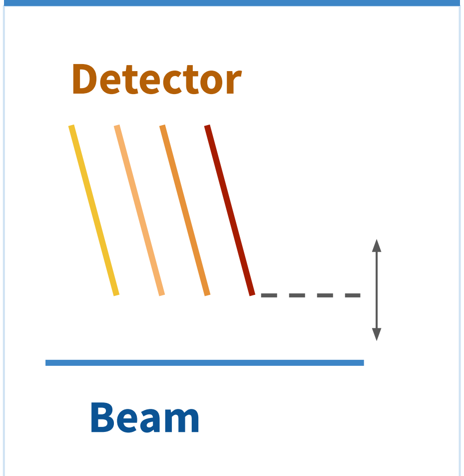
Infer proton energy loss 2



Know initial photon energy 3

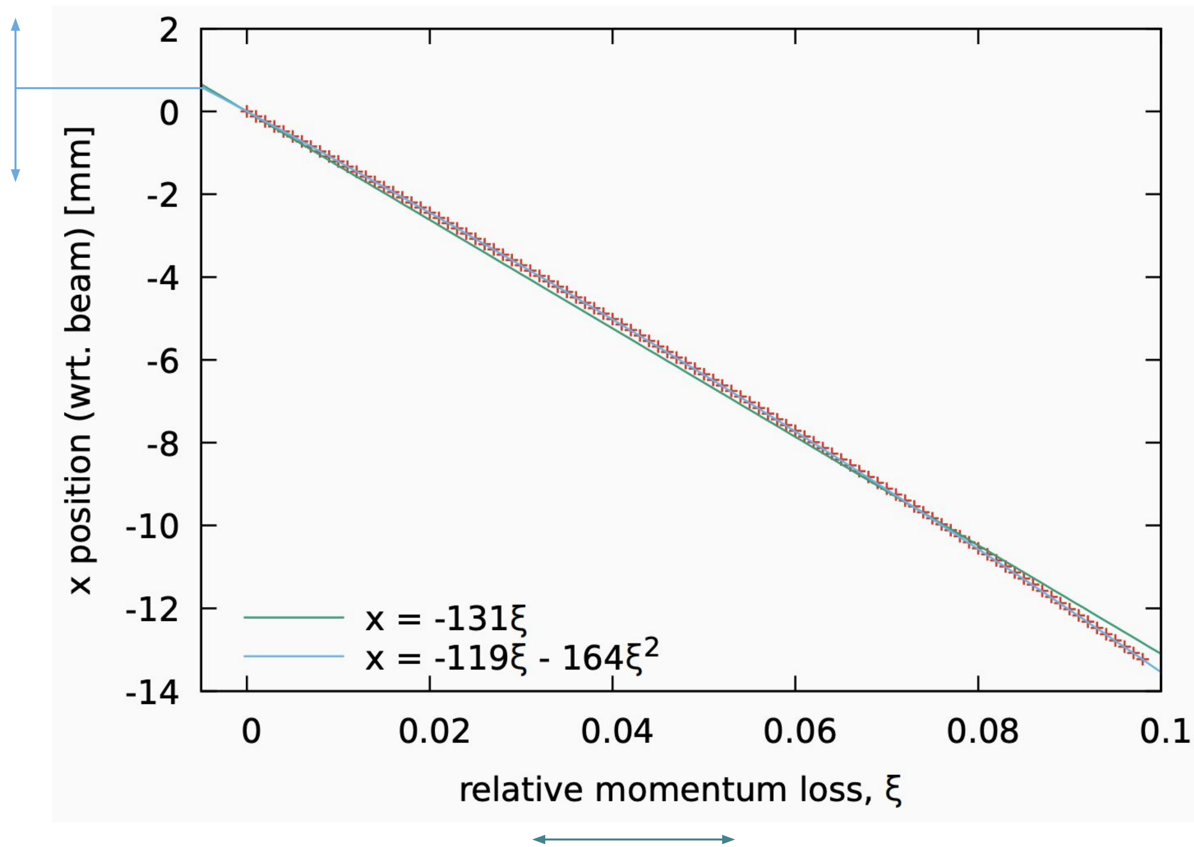
Global alignment scale calibration: importance & idea

Global absolute offset



Spectrometer:
Instrument turning ***spatial measurements*** into ***energy measurements***

MAD-X beam propagation simulation



Directly impacts reconstructed fractional proton energy loss ξ

Beam based alignment: in principle

https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.15.051002

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 051002 (2012)

Semiautomatic beam-based LHC collimator alignment

Gianluca Valentino,[1,2,*] Ralph Aßmann,[1] Roderik Bruce,[1] Stefano Redaelli,[1]
Adriana Rossi,[1] Nicholas Sammut,[1,2] and Daniel Wollmann[1]
[1]*CERN, Geneva, Switzerland*
[2]*University of Malta, Msida, Malta*
(Received 27 January 2012; published 8 May 2012)

"What is the absolute position (& transverse size) of the beam?"

The idea:
Collimators probe beam & Beam Loss Monitors (BLM) monitor impact

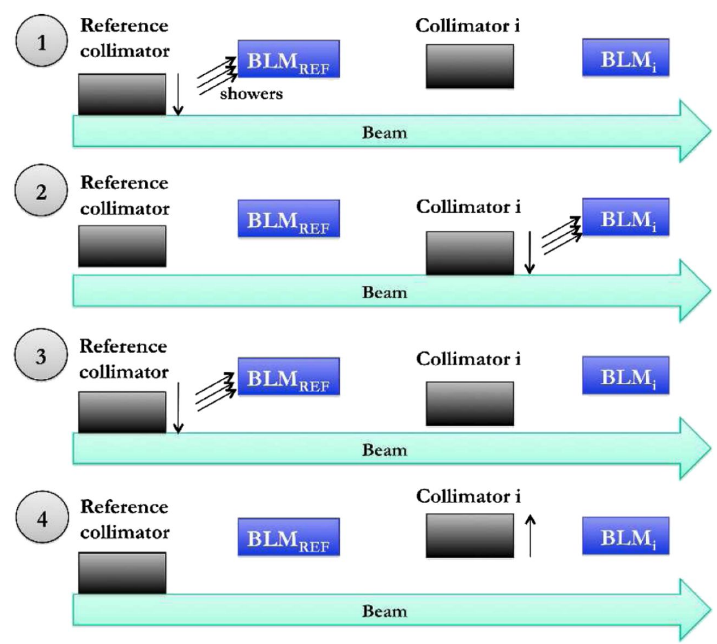
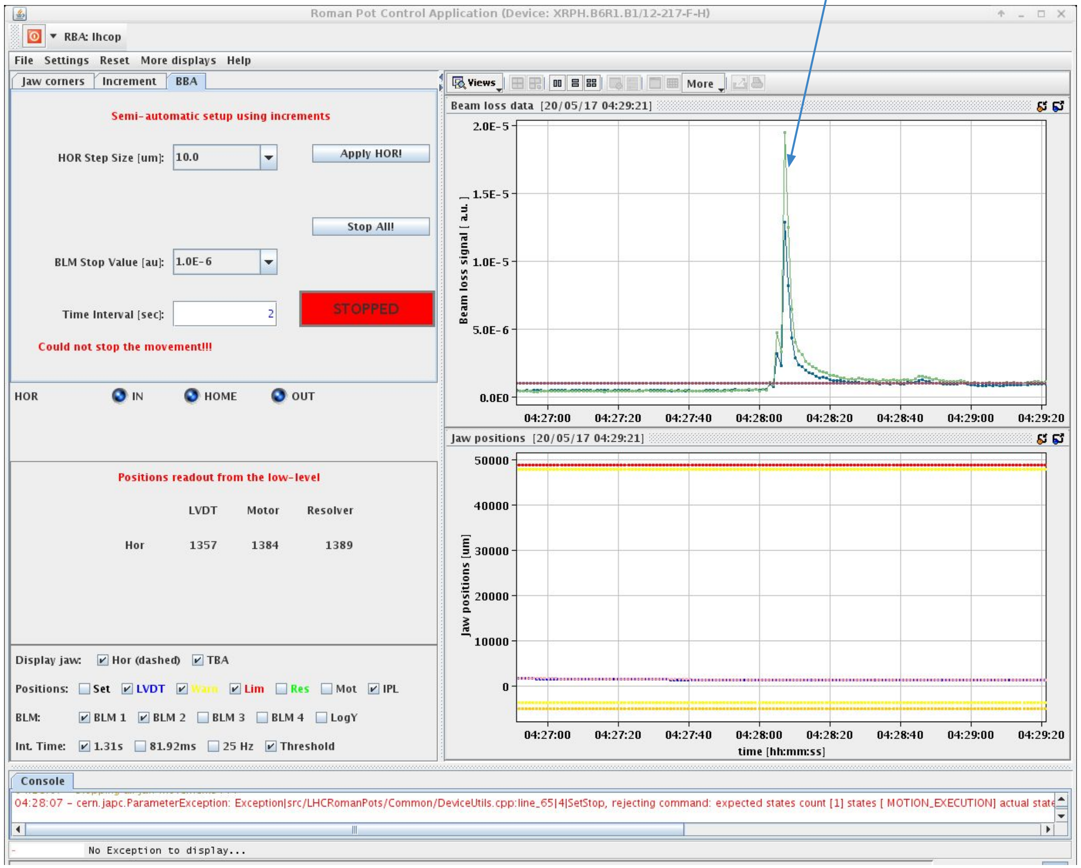


FIG. 4. The four-stage beam-based alignment procedure for collimator *i*. The reference collimator is aligned to form a reference cut in the beam halo (1). Collimator *i* is aligned (2), followed by a realignment of the reference collimator (3). Finally, collimator *i* is opened to its position in the hierarchy (4).

Beam based alignment: in practice

Sharp signal spike in BLM when beam is probed



LHC operations: 20 May 2017

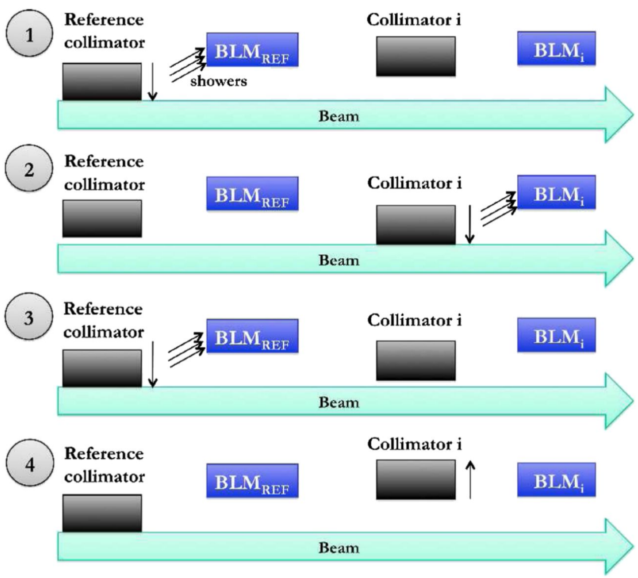
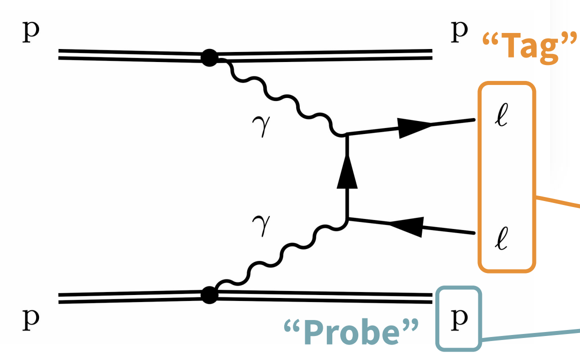
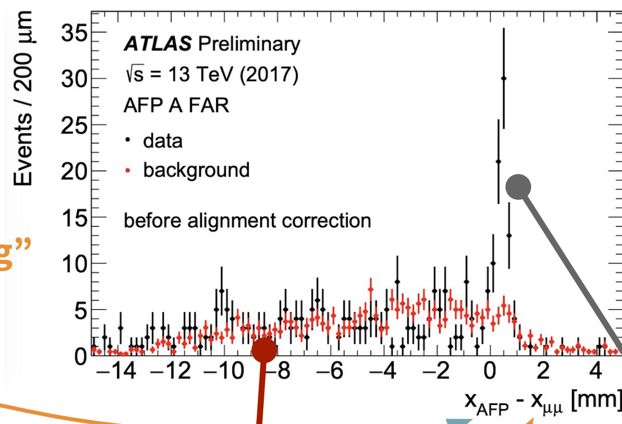


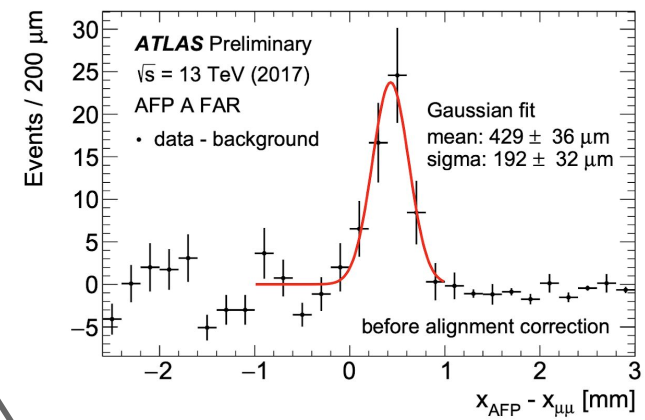
FIG. 4. The four-stage beam-based alignment procedure for collimator i. The reference collimator is aligned to form a reference cut in the beam halo (1). Collimator i is aligned (2), followed by a realignment of the reference collimator (3). Finally, collimator i is opened to its position in the hierarchy (4).

Innovative technique: in situ dimuon calibration

Use ($\gamma\gamma \to \mu\mu$)+p signal as standard candle: "The J/ψ of AFP"



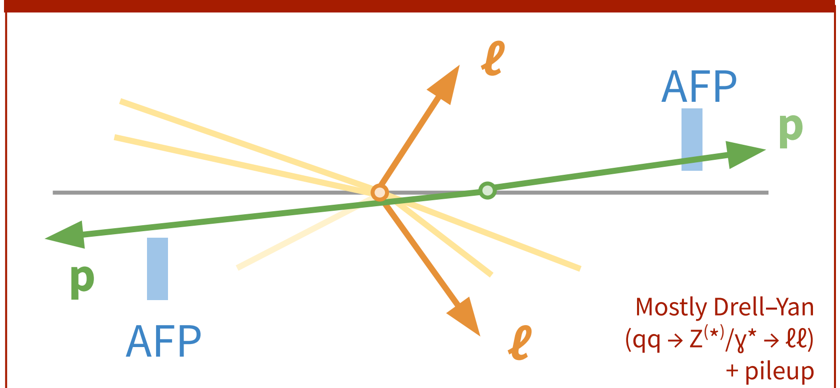




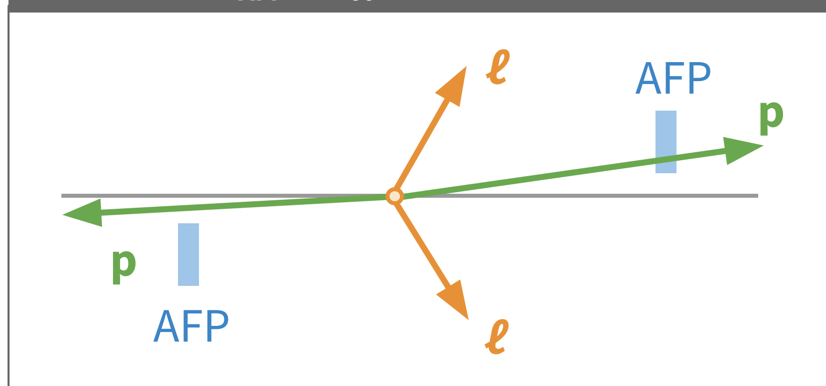
$$\xi^{\pm}_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$$

Expected proton energy loss constrained by dimuon system

Background: no correlation (pileup)

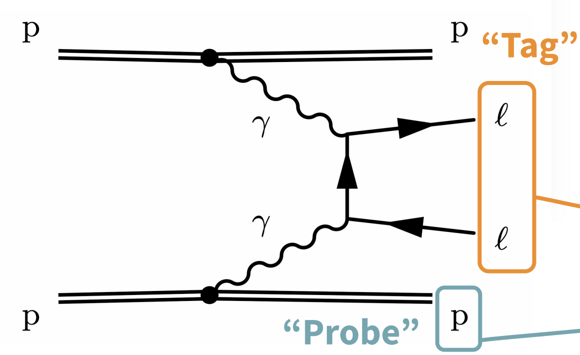


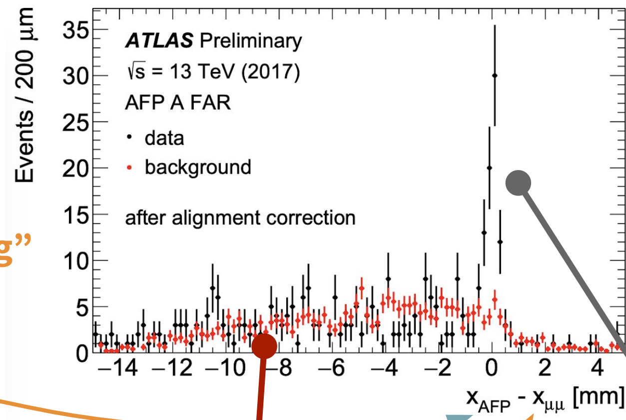
Signal: if $x_{AFP} = x_{\ell\ell} \Rightarrow$ aligned & calibrated

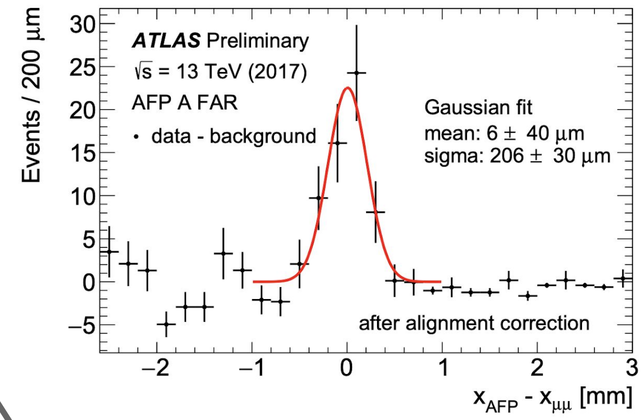


In situ dimuon calibration: fit & shift residuals

Use ($\gamma\gamma \rightarrow \mu\mu$)+p signal as standard candle: "The J/ψ of AFP"



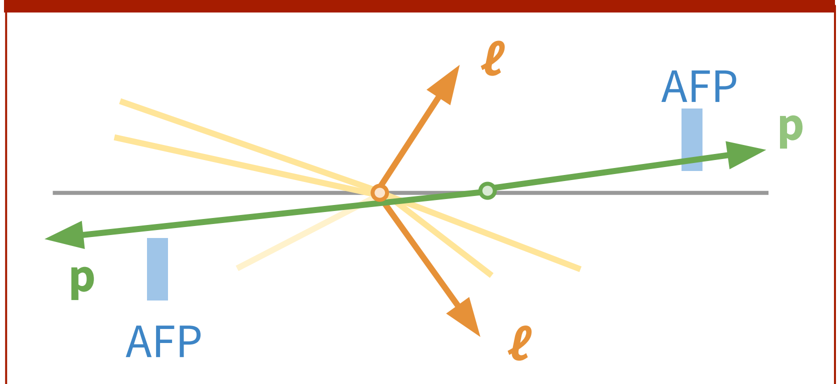




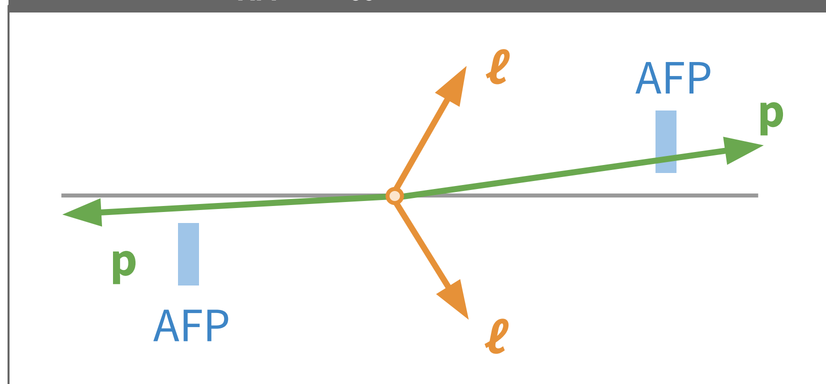
$$\xi^{\pm}_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$$

Expected proton energy loss constrained by dimuon system

Background: no correlation (pileup)



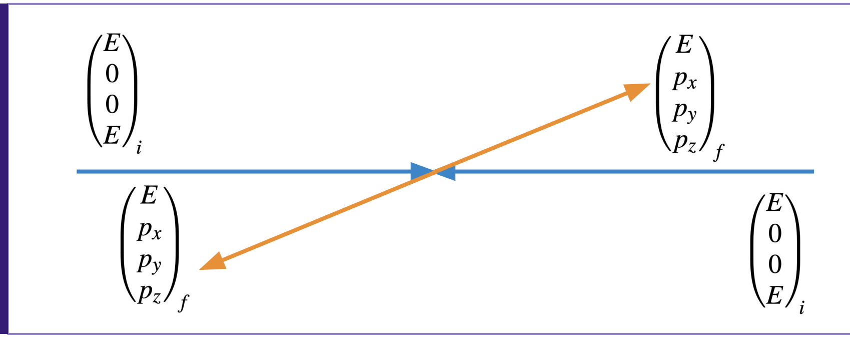
Signal: if $x_{AFP} = x_{\ell\ell} \Rightarrow$ aligned & calibrated



How AFP qualitatively changes the game

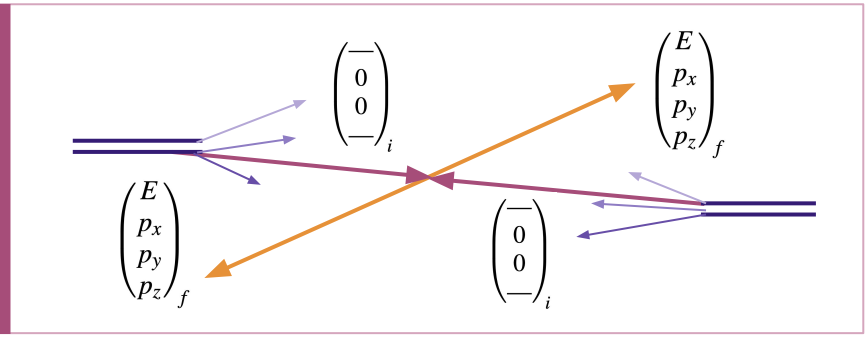
LEPTON COLLIDER

All initial & visible final state 4-vectors measurable



HADRON COLLIDER (NO AFP)

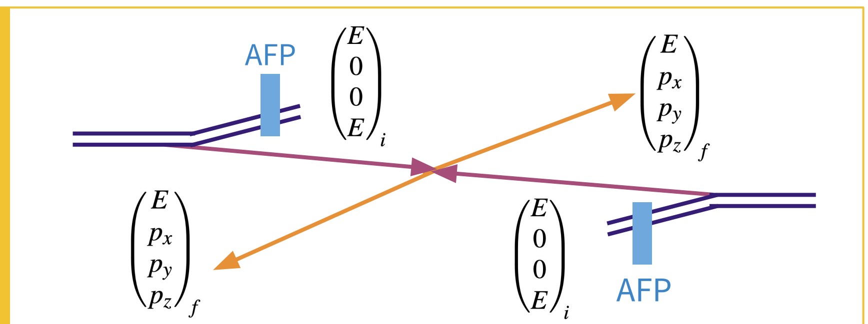
p^{z}_{initial} immeasurable



HADRON COLLIDER (+ AFP)

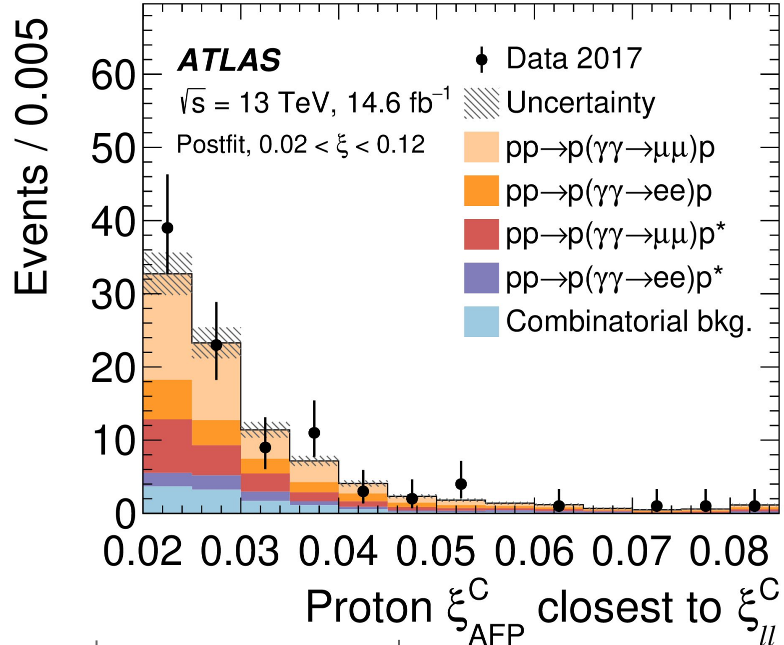
⇒ Full p_{initial} measurable

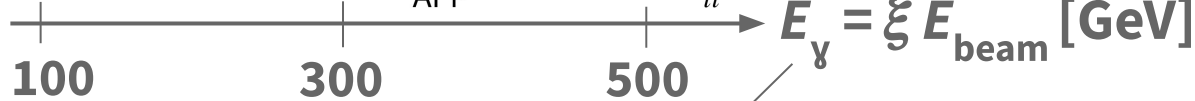
New event kinematic information!



Post-calibration colliding photon energy in data

ATLAS [2009.14537]





Details for interested experts

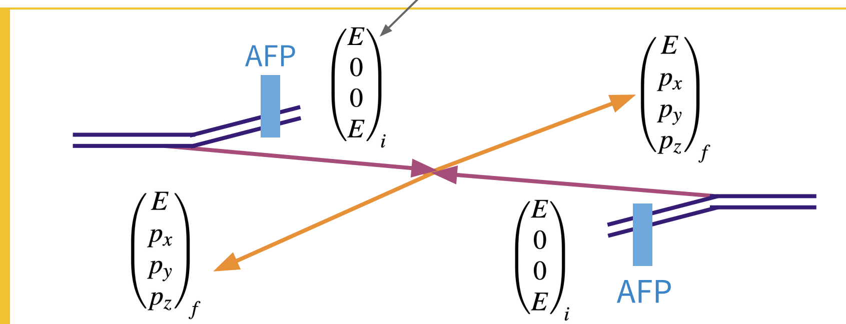
2ℓ triggers, $p_T(e/\mu) > 18/15$ GeV,
$|z_{\ell\ell} - z_{trk}| > 0.5$ mm, $m_{\ell\ell} \notin [70, 105]$ GeV,
$|\Delta\phi_{\ell\ell}|/\pi > 0.99$, $p_T(\ell\ell) < 5$ GeV

p* = proton dissociates after EM excitation and undetected

HADRON COLLIDER (+ AFP)

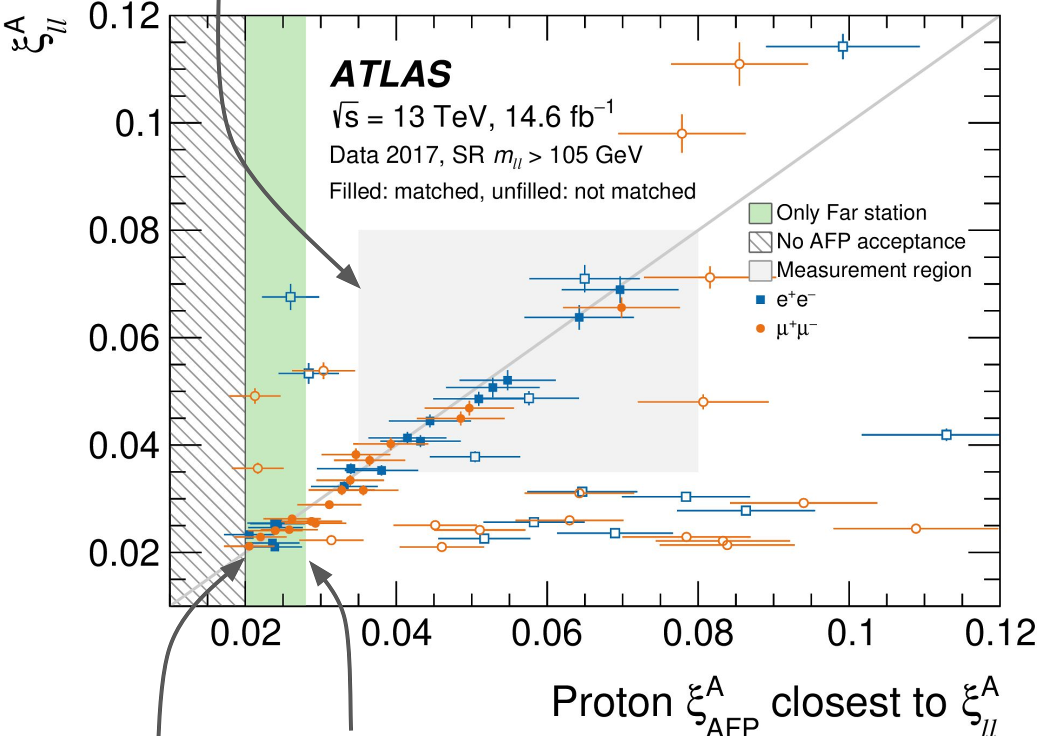
⇒ Full $p_{initial}$ measurable

New event kinematic information!

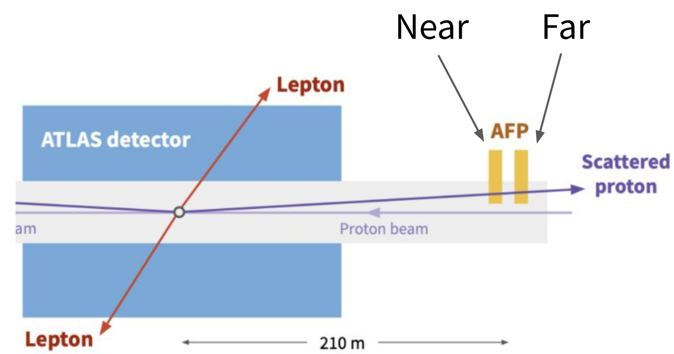


AFP acceptance

Near station acceptance "turn-on" due to e.g. edge effects plateaus at $\xi \gtrsim 0.035$



ATLAS [2009.14537]



Near station acceptance switches on at $\xi \gtrsim 0.026$

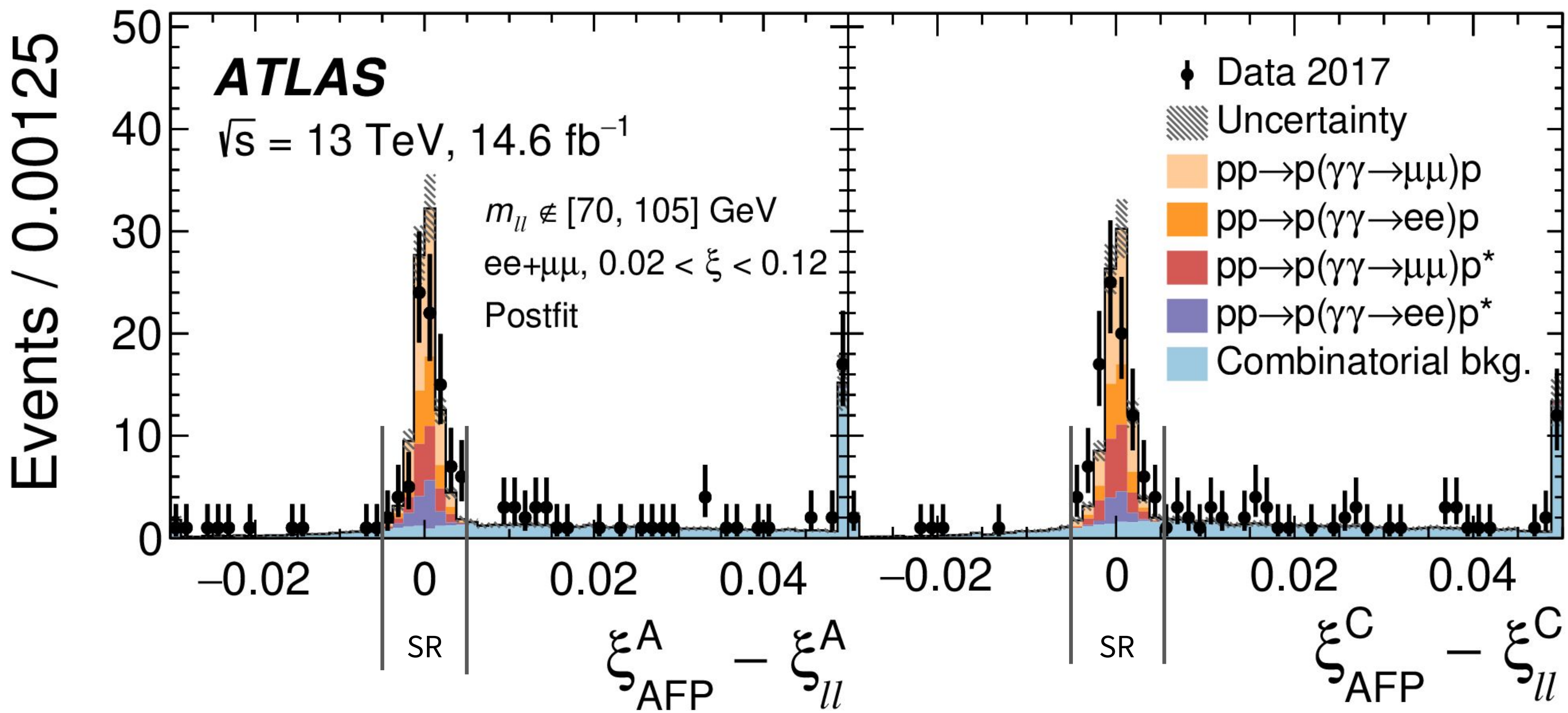
Far station acceptance plateaus at $\xi \gtrsim 0.02$ bounded by beam–detector distance

Upper $\xi \lesssim 0.12$ bounded by beam collimators

[Side C is very similar]

Proton energy resolution

ATLAS [2009.14537]

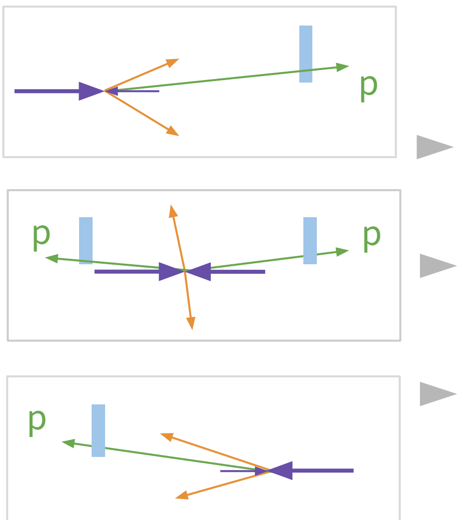


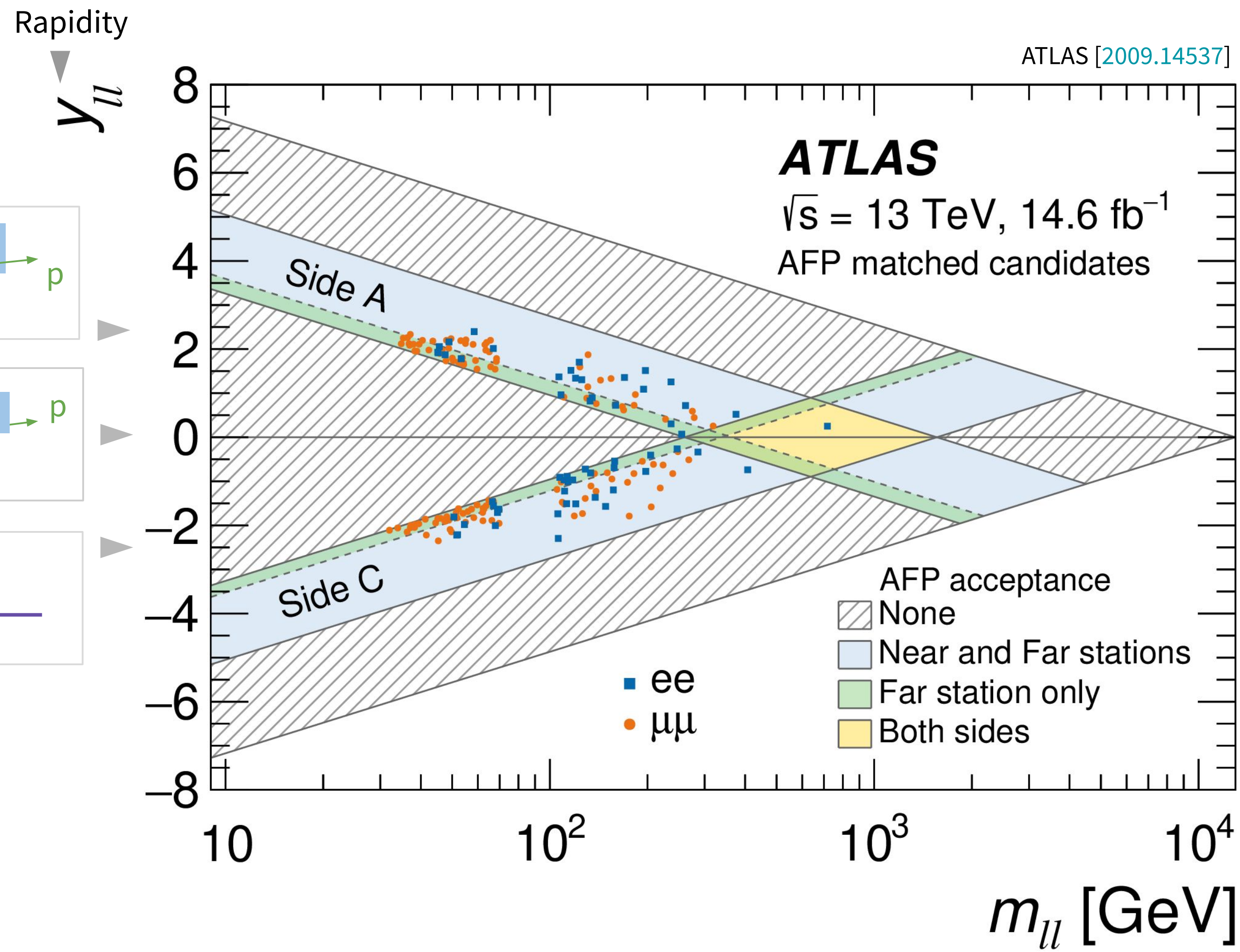
Full width at half maximum ~ 0.005 ⇒ proton energy resolution better than ~ 10%

Good resolution enables **95% signal acceptance** for **85% background rejection**

Detailed studies/more statistics to precisely quantify but first look in situ & early days

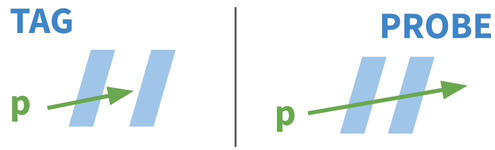
Kinematics of 180 (γγ → ℓℓ) + p SR candidates



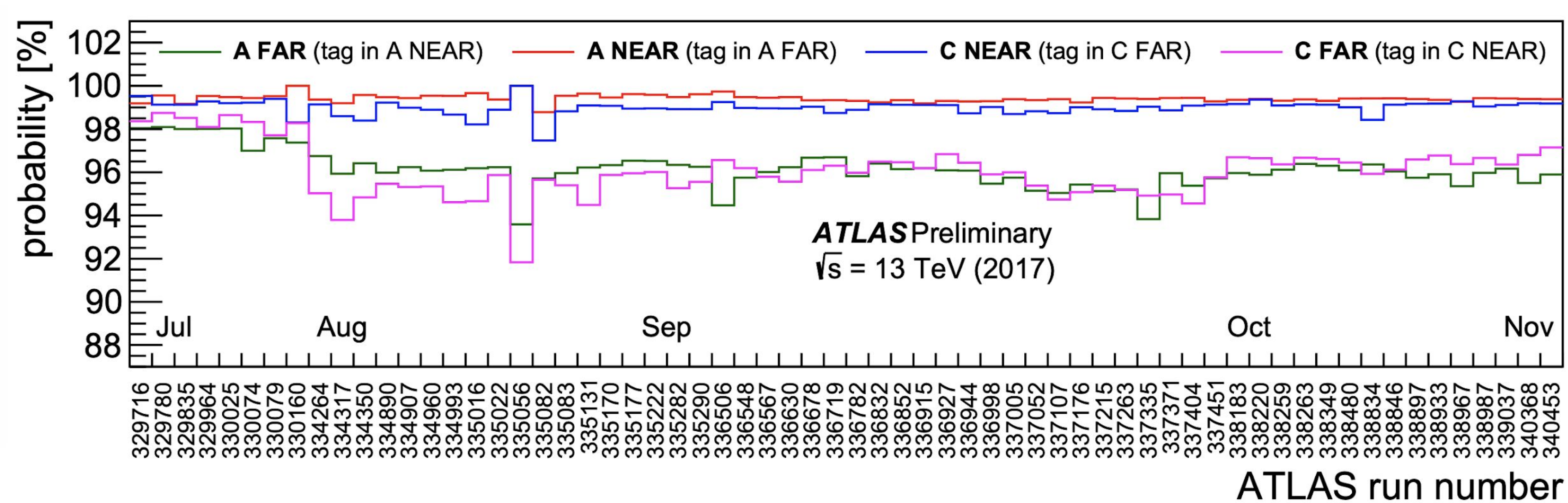


m_{ee} = 717 GeV event in both-side acceptance but side A fails $|\xi_{AFP} - \xi_{\ell\ell}| < 0.005$
So side A proton likely dissociated + pileup faked proton

Track reconstruction efficiency & data stability



$\Rightarrow$ Require $|x_{Near} - x_{Far}| < 2$ mm



Efficiencies: data-driven tag-and-probe determination of station
Evidence of showers: Far stations lower efficiency than Near
Data quality: used this to scrutinise problematic runs – vetoed in Good Runs List

Snapshot of results enabled by AFP performance

Data counts

	Observation	Measurement
ξ range	[0.02, 0.12]	[0.035, 0.08]
ee+p	57 (9.7σ)	19
μμ+p	123 (13σ)	23

CMS–TOTEM: saw ee+p (μμ+p) 2.6 (4.3σ)
No cross-sections measured [1803.04496]

1st unfolded measurements of ($\gamma\gamma \rightarrow \ell\ell$) + p

$\sigma_{\text{Herwig+Lpair}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [30, 31]	10.9 ± 0.8	9.4 ± 0.7
SuperChic 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

$$\sigma_{\text{fid.}} = (N_{\text{obs}} - N_{\text{bkg}})/(\mathcal{L} \cdot C_{\text{cent}} \cdot C_{\text{AFP}})$$

Khoze, Martin, Ryskin [1601.03772], Harland-Lang, Khoze, Martin, Ryskin [1410.2983]
Harland-Lang, Tasevsky, Khoze, Ryskin [2007.12704], ATLAS [2009.14537]

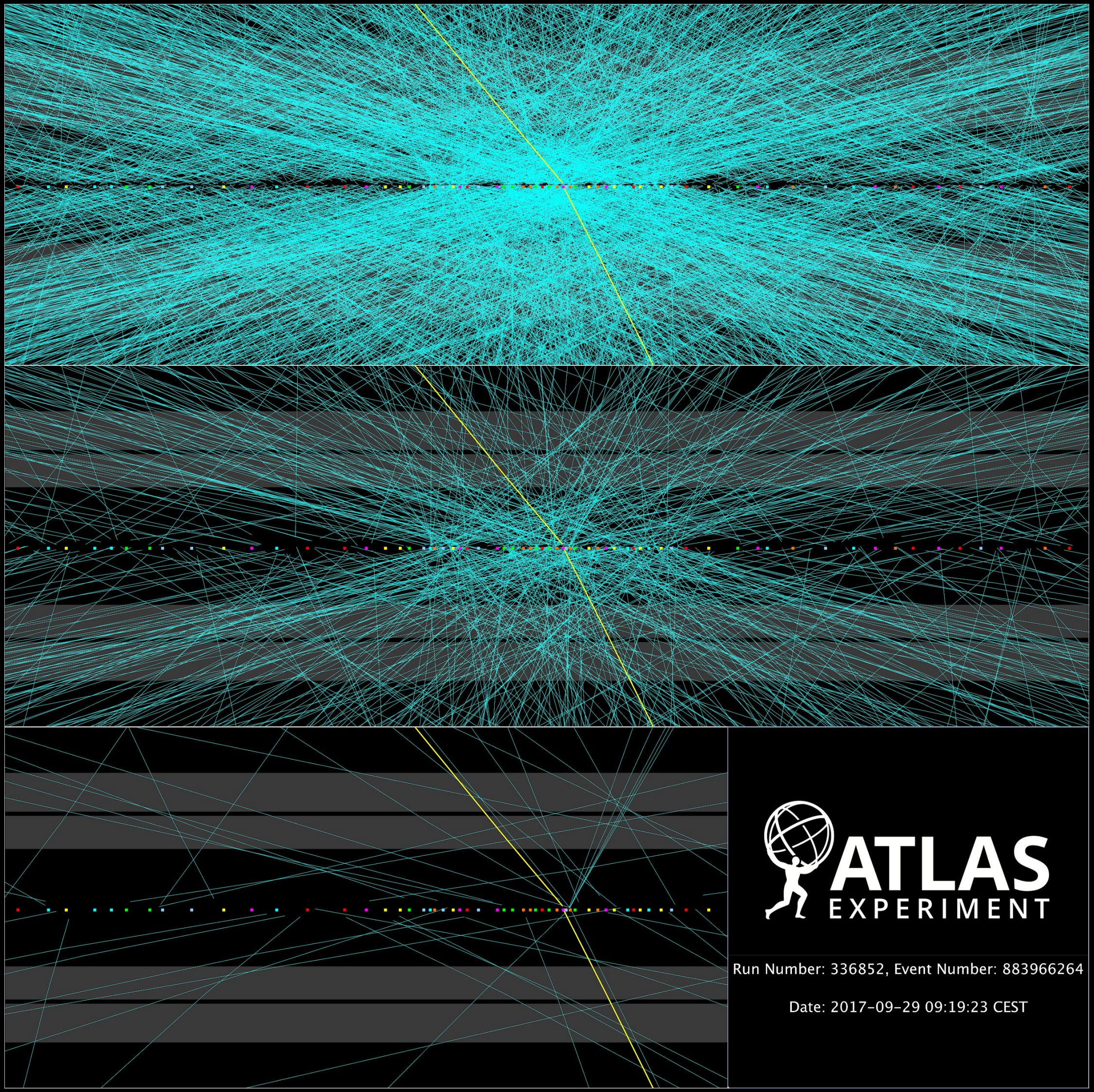
Observation bkg: ee = 6.2 ± 1.2, μμ = 13.4 ± 2.5; measurement bkg: ee = 1.7 ± 0.3, μμ = 2.3 ± 0.5
Measurement uncertainties: 22-24% stat, 11-13% syst dominated by AFP alignment, optics
S_{surv} = proton soft survival probability from non-perturbative QCD dynamics

[ATLAS Run 2 Event Displays]

p_T > 100 MeV tracks

p_T > 1 GeV tracks

p_T > 5 GeV tracks

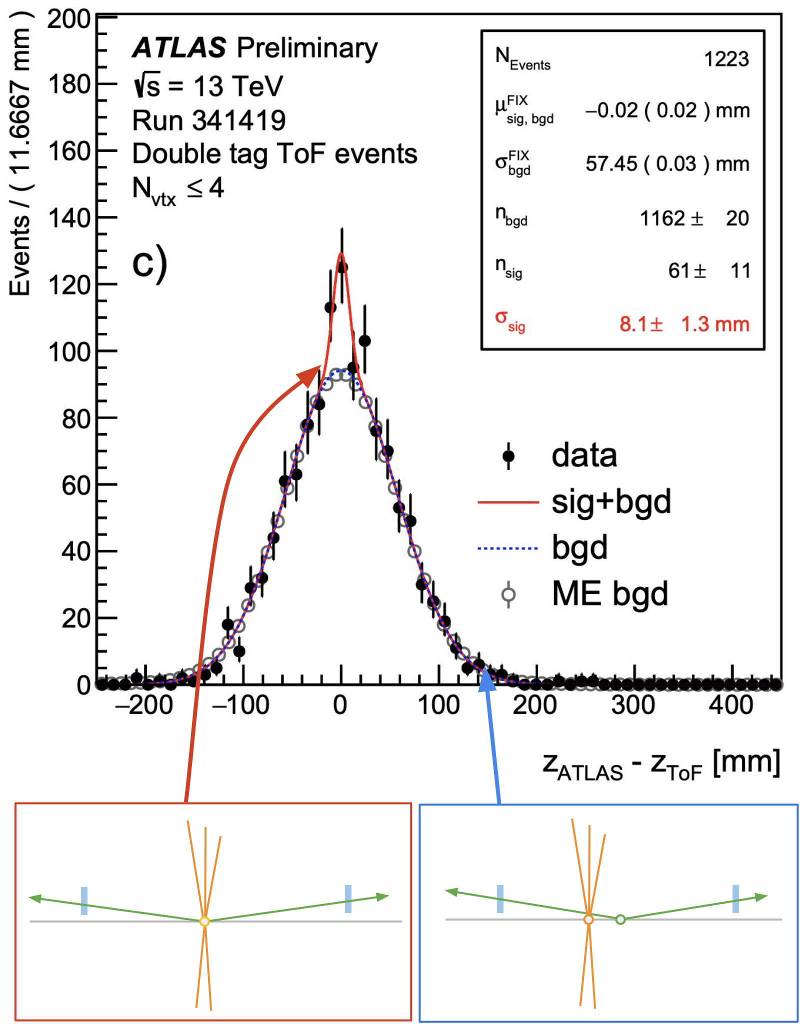


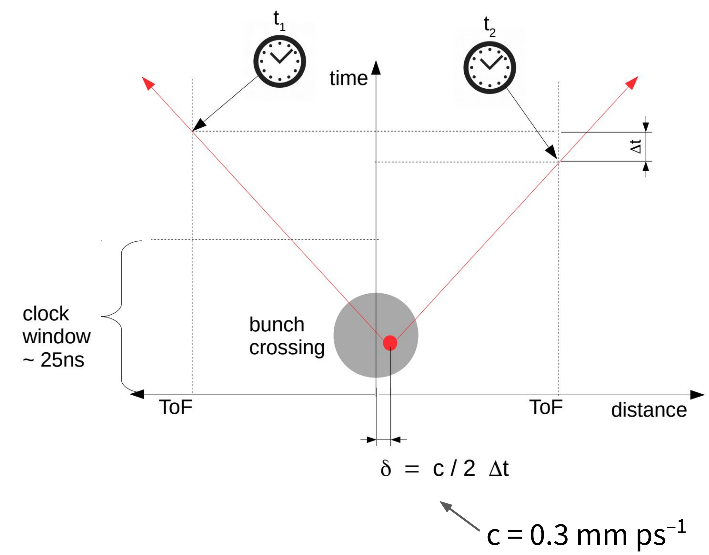
TIME-OF-FLIGHT MOTIVATION

So much pileup: can AFP identify primary pp vertex?

"The Z boson candidate is reconstructed in a beam crossing with 65 additionally reconstructed vertices from minimum bias interactions…The invariant mass of the two muons is 87 GeV."

Time-of-flight enables AFP pp vertex reconstruction





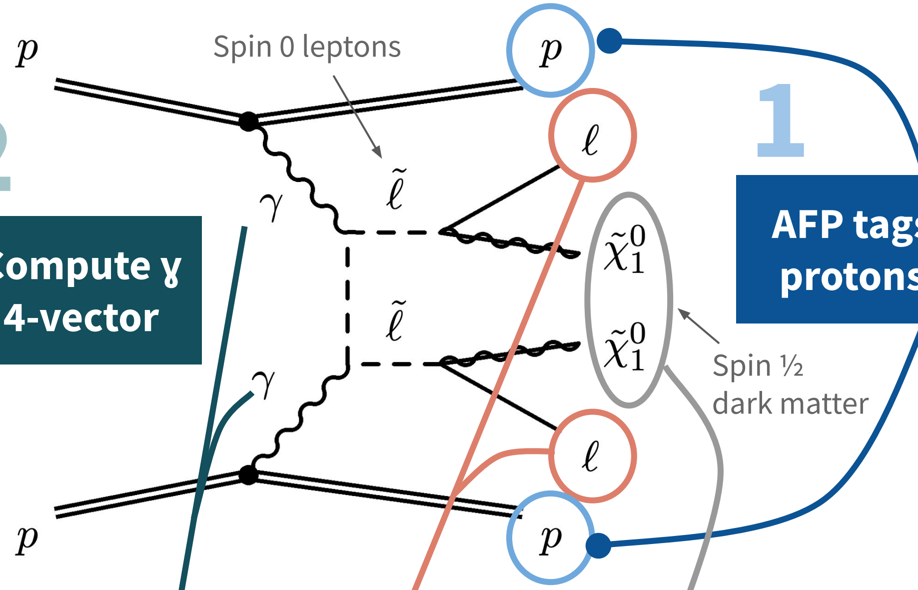
AFP deployed state-of-the-art time-of-flight
Demonstrated in situ using μ ~ 2 LHC collisions

Measured time resolution: 20 ± 4 ps (A) 26 ± 5 ps (C)
Measured pp vertex resolution: 5 ± 1 mm

Improvements ongoing for Run 3 data taking
Long-lifetime PMTs to ensure higher efficiencies

K Cerny PoS 373 Vertex2019 (2020) 055
ATL-FWD-PUB-2021-002 **[NEW!]**
More about timing in talk by Tommaso Isidori

Near future: p_{miss} 4-vector for dark matter searches?



2 **Compute γ 4-vector**

1 **AFP tags protons**

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

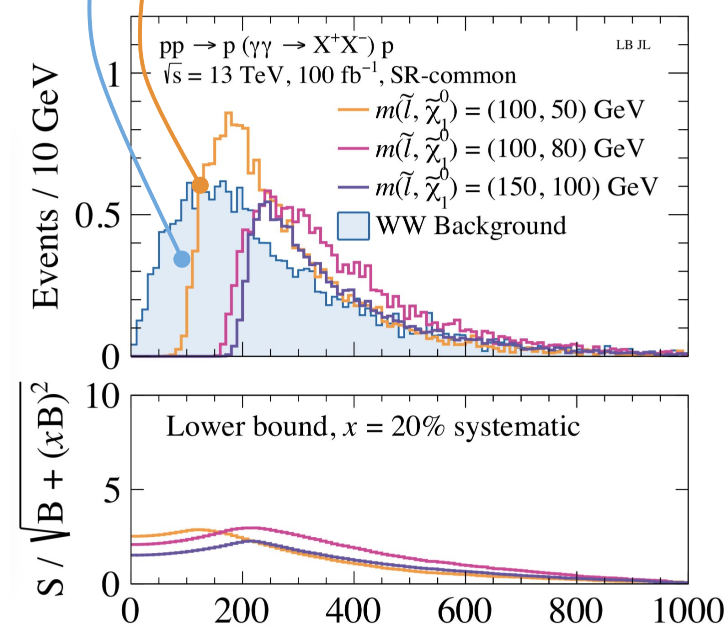
3 **Square 4-vector to measure DM mass**

Impossible @ pp colliders *no more*

ATLAS [2010.04019]

γγ → WW just observed

Sharp threshold at $2 \times m_{\text{DM}}$

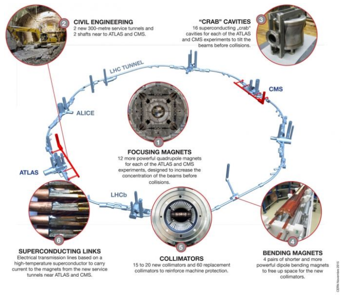


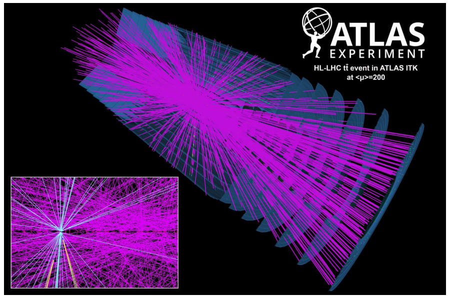
$$W_{\text{miss}} = \sqrt{(p_1^\gamma + p_2^\gamma - p_1^l - p_2^l)^2}\ [\text{GeV}]$$

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

Beresford & JL [1811.06465], Harland-Lang, Khoze, Ryskin & Tasevsky [1812.04886]

Long term: discovery science @ HL-LHC + AFP? [Discussion]





RICH PHYSICS OPPORTUNITIES

Today's 14.6 fb^{-1}/3 ab^{-1} = 0.5%: HL-LHC = discovery machine for rare & precision science

Precision SM: differential $\gamma\gamma \to WW/\gamma\gamma/\tau\tau$, $\gamma\gamma \to tt$ threshold(?), Exclusive Higgs(?)/jets

Rare BSM: anomalous couplings, SUSY dark matter, axion-like particles, dark sectors

CHALLENGES & OPEN QUESTIONS

Novel beamline: crab cavities, collimators, magnets vs AFP 220/320/420m locations?

Crossing angle complementarity: Point 1 & 5 sees different optics & RP acceptance?

Instrumentation: synergise Phase II Upgrades of 3D silicon pixels & data acquisition?

Pileup 200 rejection: demands sub-10 ps ToF with Silicon/LGAD/Cherenkov technology?

Reproducibility principle: HL-LHC+RP discovery science needs 2 independent experiments?

Future ee/ep/eA machines: tag scattered electrons/hadrons with Roman Pot technology?

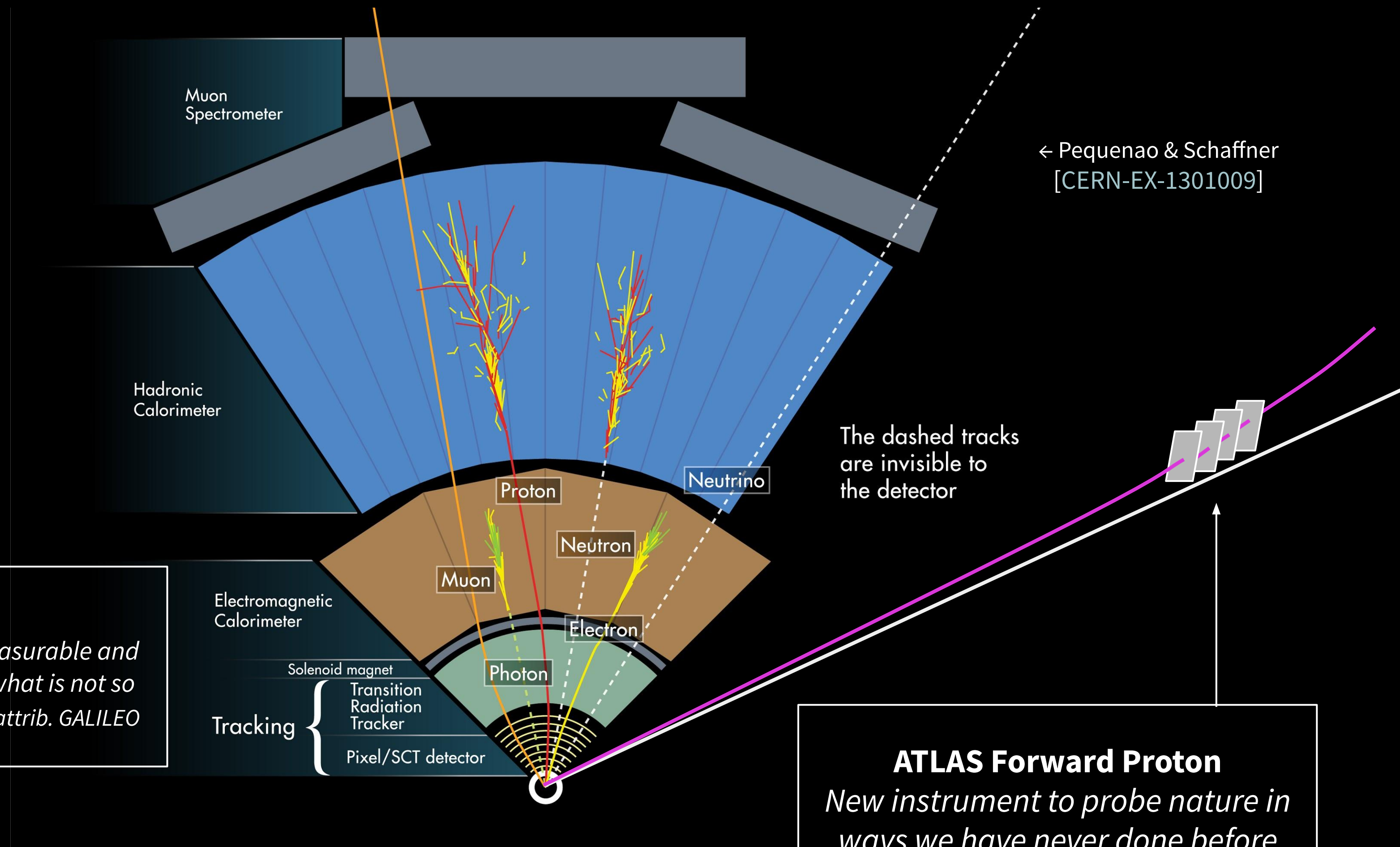
Community: how to attract & sustain talent, resources & careers for 20+ years?

[HL-LHC, ATLAS Phase II]

SUMMARY

AFP expands our repertoire to probe the microcosm

Deployed TeV proton spectrometer | Developed innovative techniques
Demonstrated in situ performance | Delivered physics measurements

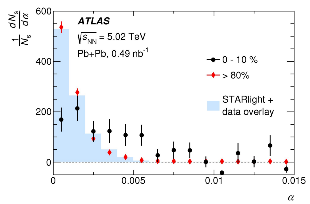


“
Measure what is measurable and make measurable what is not so
– attrib. GALILEO

ATLAS Forward Proton
New instrument to probe nature in ways we have never done before

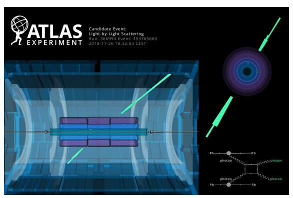
EXTRAS

Exciting & unique LHC γγ collider program emerging



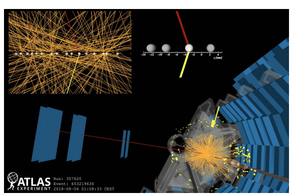
Observation of centrality-dependent acoplanarity for muon pairs produced via two-photon scattering in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector

[ATLAS Briefing, 1806.08708]



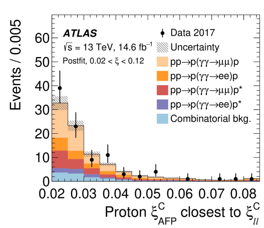
Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

[CERN Press Statement, ATLAS Briefing, 1904.03536]



Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector

[CERN Press Statement, ATLAS Briefing, 2010.04019]



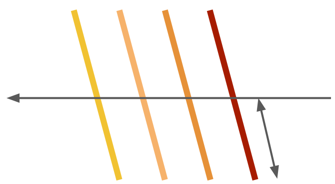
Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

[CERN Courier feature, ATLAS Briefing, 2009.14537]

Local interplane alignment

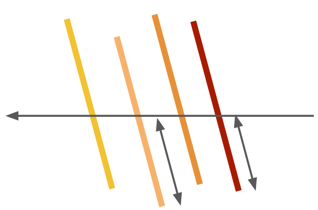
Proton leaves clusters measured at *x* position relative to plane edge

Ideal alignment

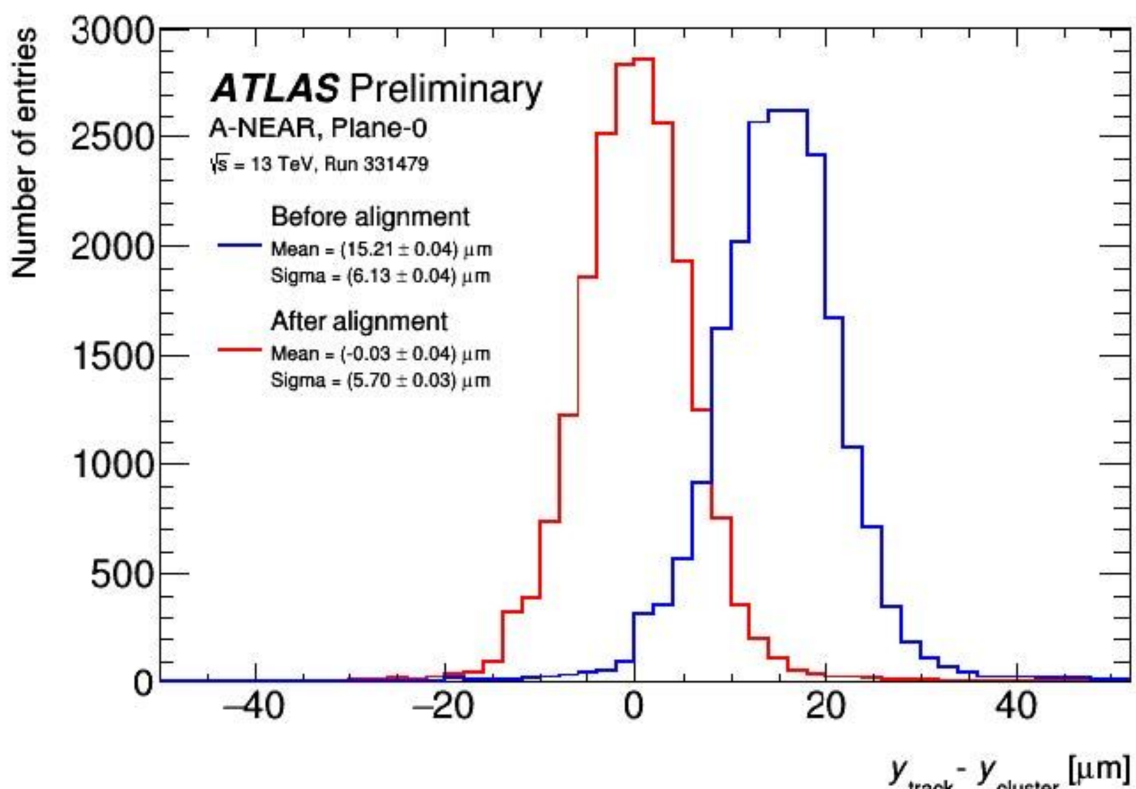


Cluster to edge distance is the same for all planes

In reality



Cluster positions relative to plane edge can be different before interplane alignment



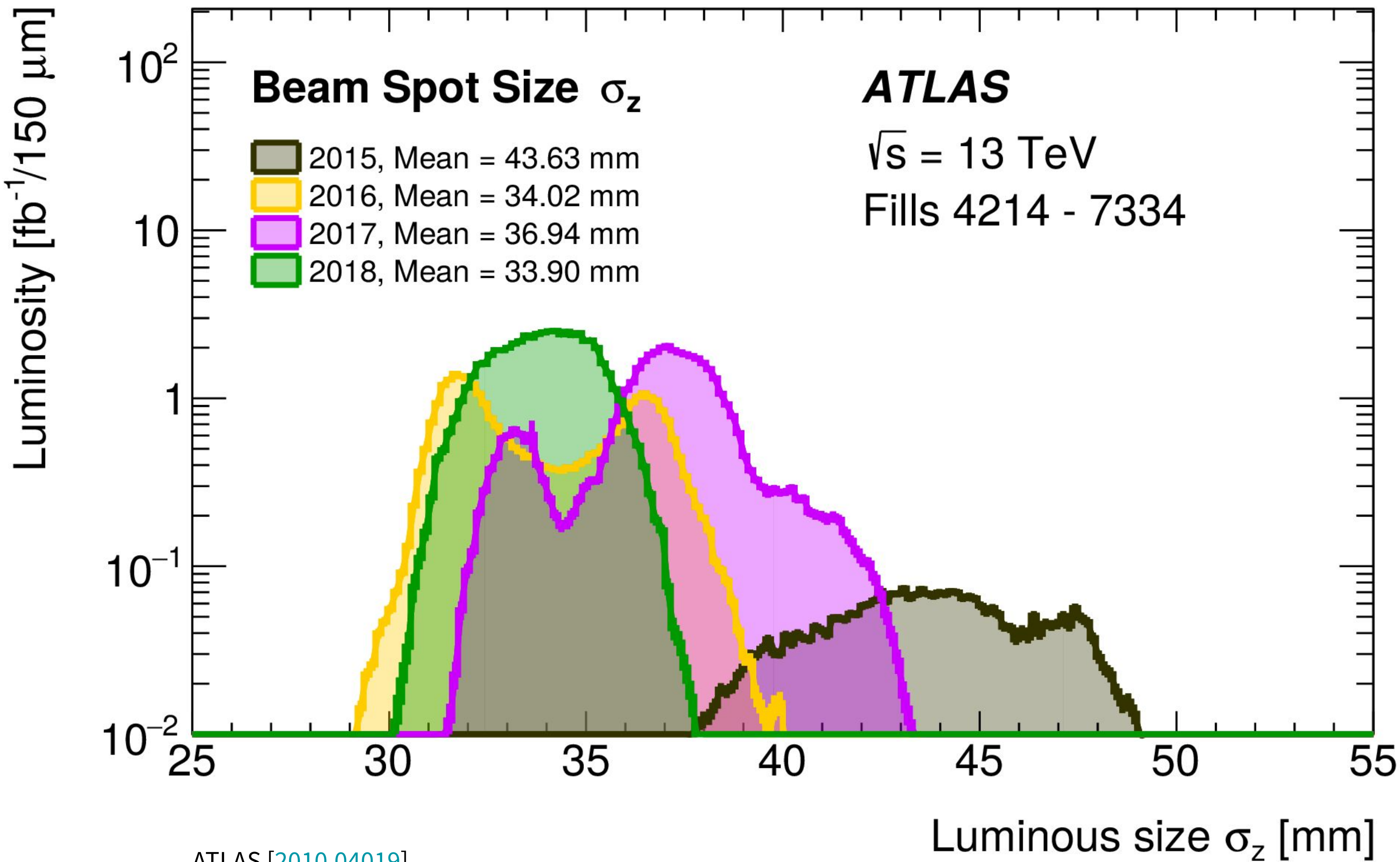
[Forward Detector Figures]

Systematic uncertainties: impact on cross-section

Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	$< 1\%$
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon scale and resolution	3%
Muon trigger, isolation, reconstruction efficiencies	1%
Electron trigger, isolation, reconstruction efficiencies	1%
Electron scale and resolution	1%
Background modeling	2%
Luminosity	2%

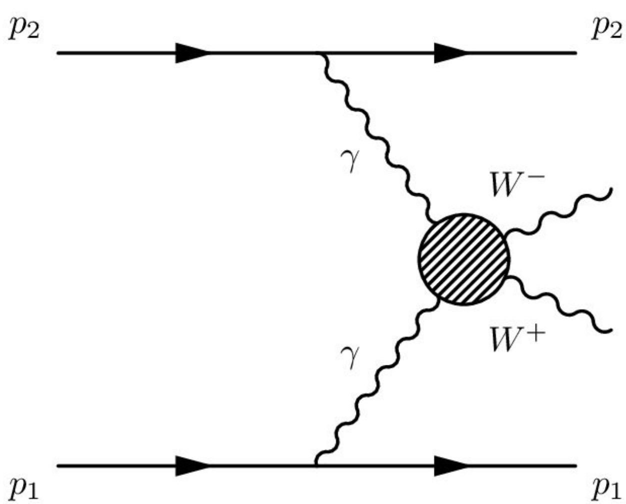
AFP systematics evaluated for first time in an analysis

pp vertices distributed as Gaussian with width σ_z

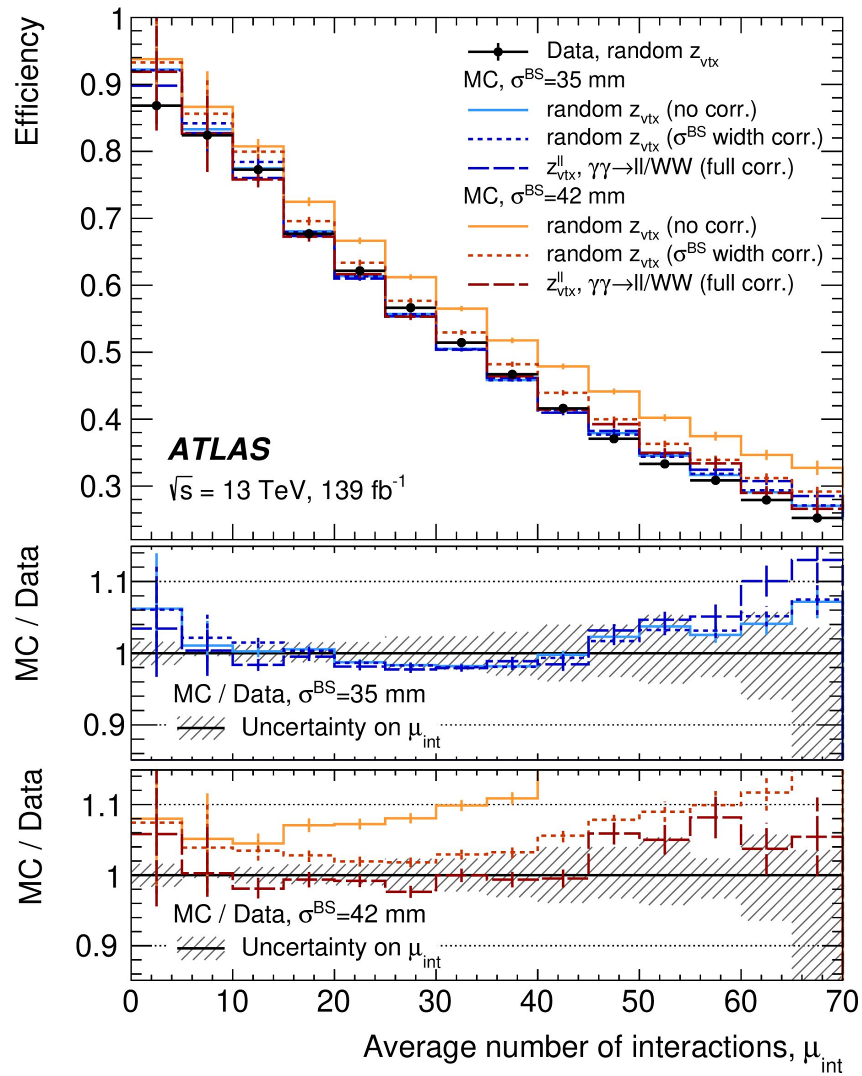


ATLAS [2010.04019]

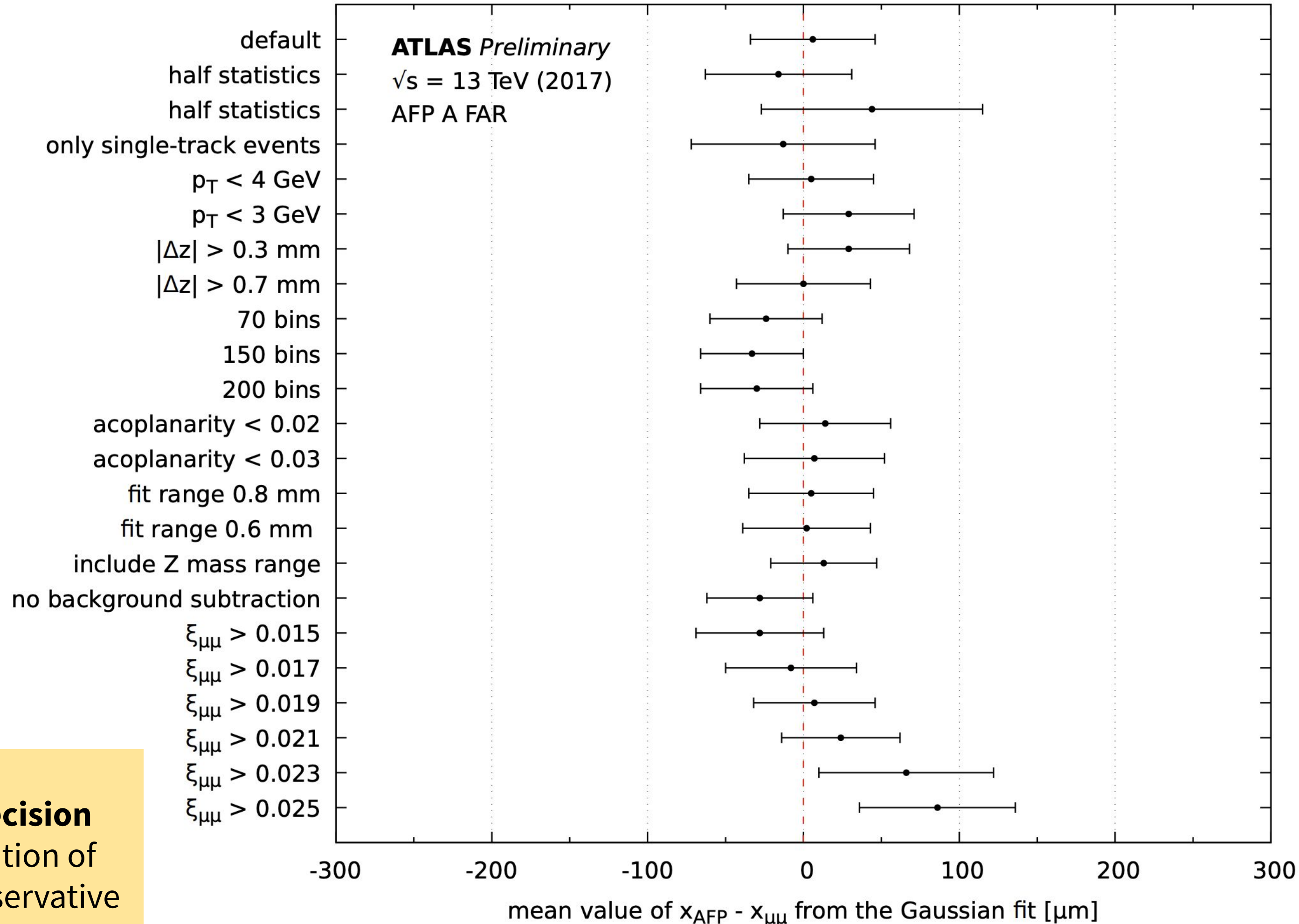
N(track) veto efficiency vs pileup



ATLAS [2010.04019]



In situ dimuon calibration: systematic uncertainties



The road towards precision
Comprehensive evaluation of variations for initial conservative 300 micron systematic

Time of flight resolutions for each channel

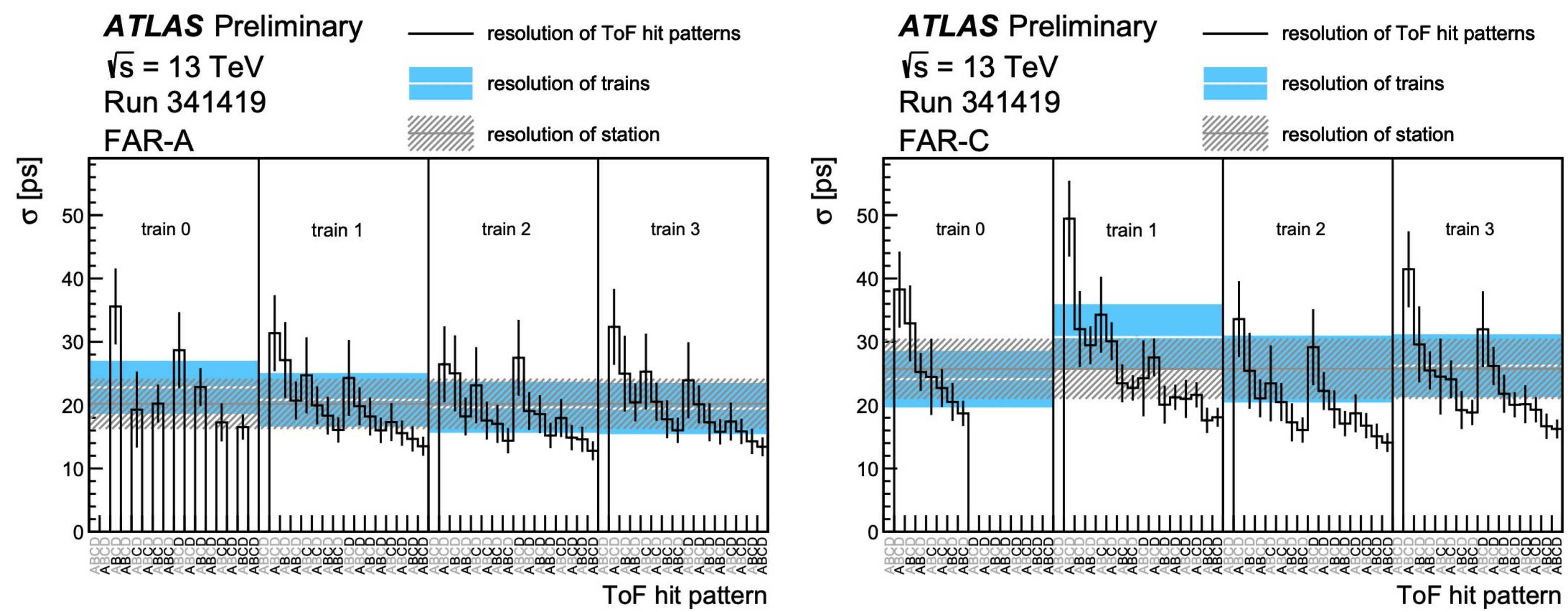
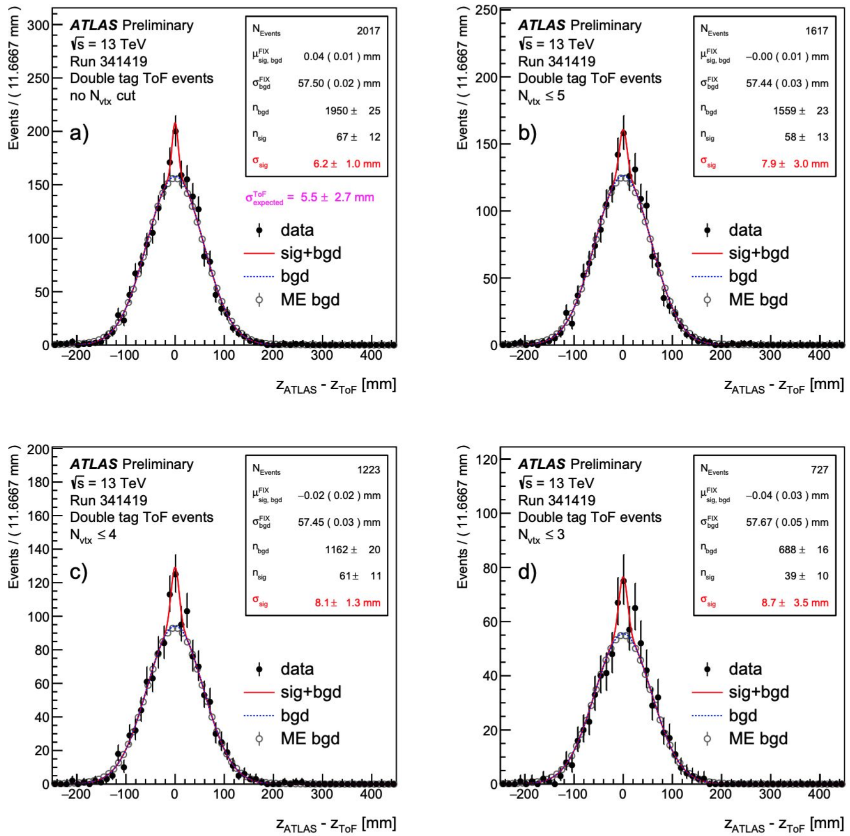


Figure 12: The resolutions of the ToF, in run 341419, for all observed signal patterns shown as a simple histogram where the hit channels are highlighted in the ABCD sequence of channels. The resolutions of trains are indicated by the white line histogram with blue error band. The station resolutions are visualised by a hatched histogram.

ATL-FWD-PUB-2021-002

Double-tagged ToF-ATLAS matching for different vertex cuts



ATL-FWD-PUB-2021-002

Figure 14: The distributions of $z_{ATLAS} - z_{ToF}$ measured in events with ToF signals on both sides of the interaction region in run 341419, where z_{ATLAS} stands for vertex z-positions reconstructed as primary ones by ATLAS. The distributions shown in figures a)-d) correspond to ATLAS data containing a reconstructed primary vertex together with coincidence of signals in both ToF detectors in four cut scenarios with respect to number of vertices reconstructed by ATLAS, no N_{vtx} cut, $N_{vtx} \leq 5$, $N_{vtx} \leq 4$ and $N_{vtx} \leq 3$, respectively. A double Gaussian function representing the signal and background components is fitted to unbinned data samples using the extended negative log-likelihood fit as implemented in RooFit in all N_{vtx} cut scenarios. The mean of the signal component as well as the mean and width of the background component are always estimated from a Gaussian fit to the mixed event data in each N_{vtx} cut scenario separately, denoted as μ^{FIX}_{sig}, μ^{FIX}_{bgd} and σ^{FIX}_{bgd}. The mixed event data $z_{ATLAS} - z_{ToF}$ distributions are obtained by random mixing of times measured by ToF in either station and the z_{ATLAS} values which do not originate in the same collision event. The expected resolution of the ToF detector, quoted as $\sigma^{ToF}_{expected}$ is obtained from the known single-channel resolutions convoluted with the actual channel-hit-patterns observed in the data in the no N_{vtx} cut scenario.