

Measuring photon-photon interactions using ATLAS Forward Proton Detectors

Rafał Staszewski (IFJ PAN)

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Introduction

Experimental techniques

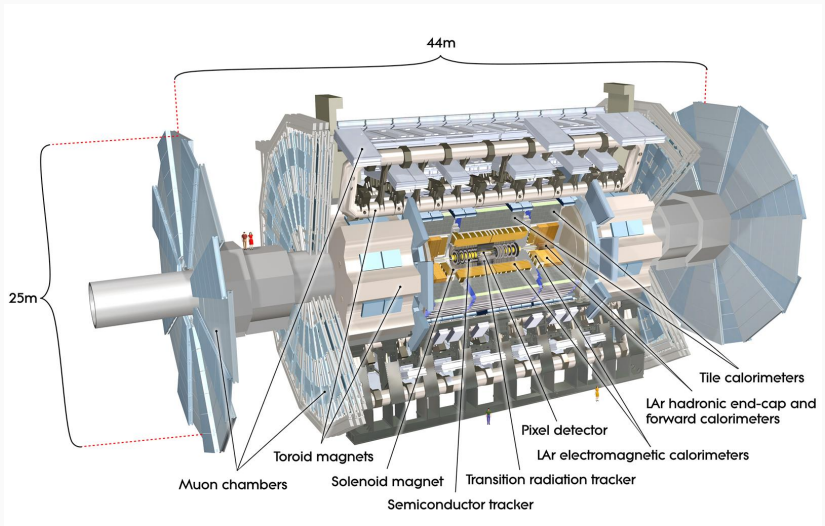
First results

Performance

Time-of-flight detector

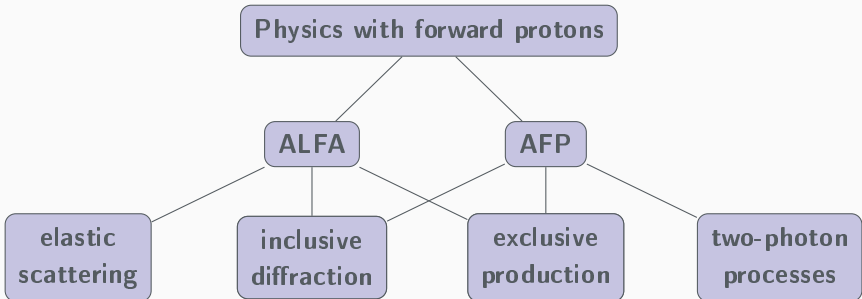
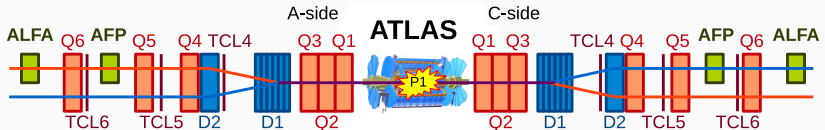
Conclusions

ATLAS Detector

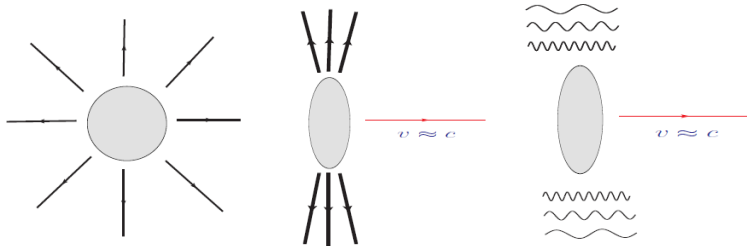


... but also **forward detectors**

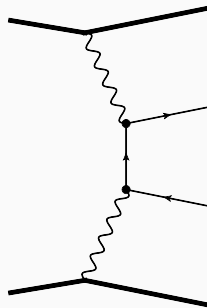
Forward detectors and physics



Two-photon processes

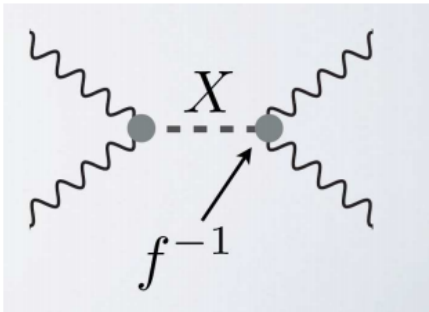
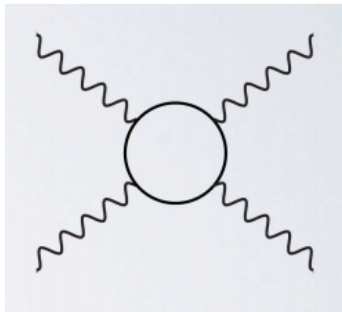


- Two-photon processes can be computed within QED
- Exclusive $\gamma\gamma \rightarrow ll$
 - Standard candle for photon-induced physics
 - Non-negligible background to Drell-Yan like reactions
- Test of SM γWW and $\gamma\gamma WW$ couplings

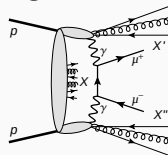
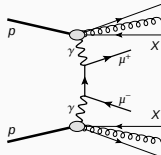
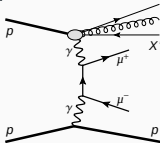
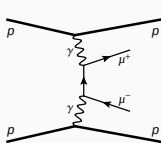


Complications (i.e. motivation)

BSM motivation – possible new particles:



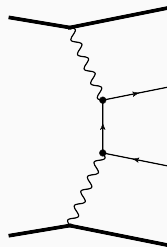
QCD motivation – proton dissociation and additional exchanges:



How to measure two-photon processes

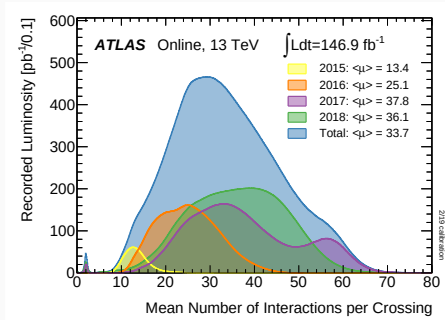
Signatures of $\gamma\gamma \rightarrow l\bar{l}$ events:

- clean final state
- low p_T of photons $\rightarrow$ low p_T of $l\bar{l}$ pair
 $\rightarrow$ low acoplanarity
- forward protons

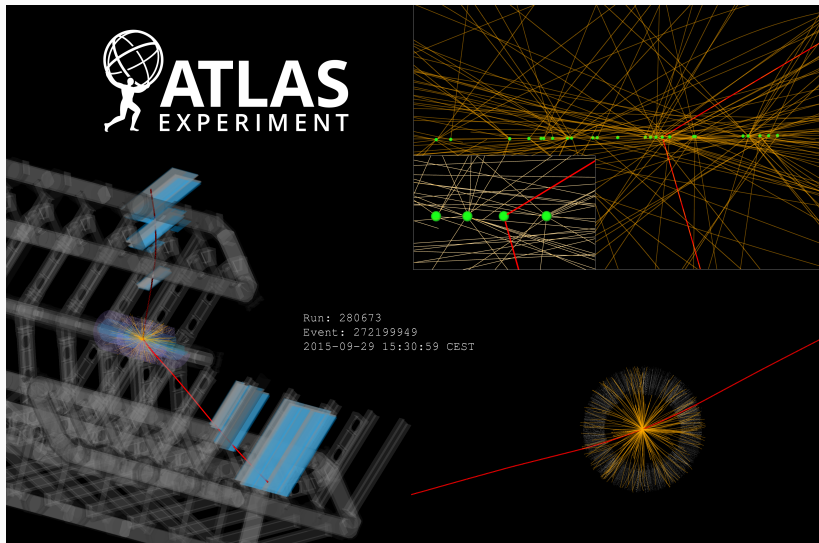


Challenges:

- small cross section
- triggering
- pile-up



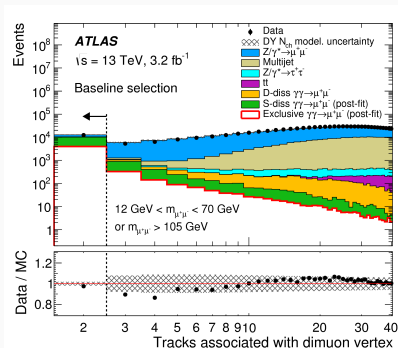
$\gamma\gamma \rightarrow \mu\mu$ in pp event candidate



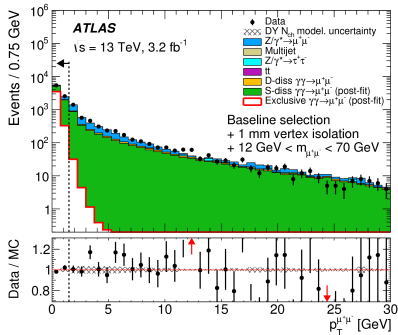
Analysis without forward protons

Exclusive selection:

- vertex isolation

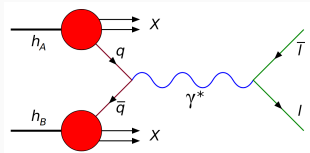


- low p_T of the $l\bar{l}$ pair

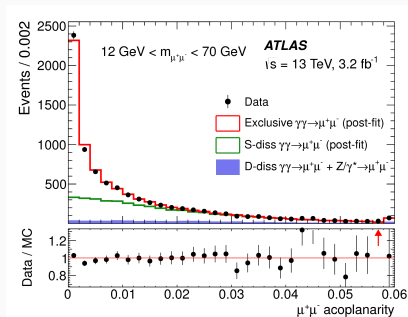
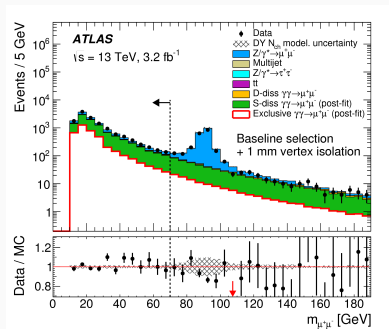
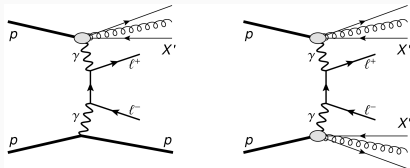


Limitations of analysis without forward protons

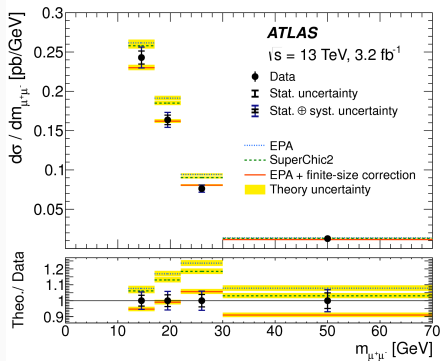
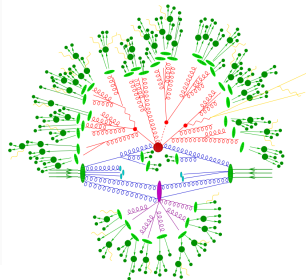
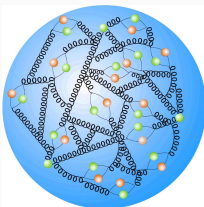
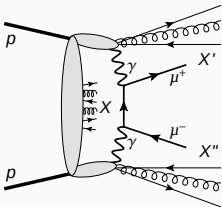
DY background



Processes with dissociation



Absorptive corrections



Contents

Introduction

Experimental techniques

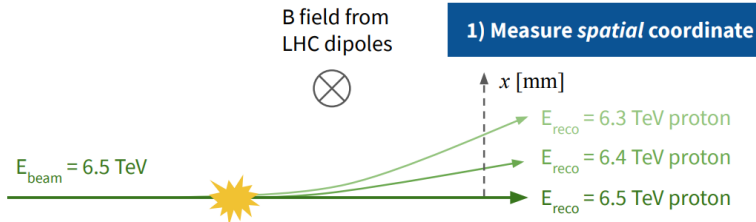
First results

Performance

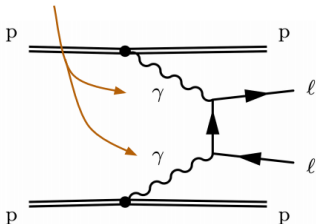
Time-of-flight detector

Conclusions

Forward proton spectrometer



$$\xi_{\text{AFP}}^{A,C} = 1 - E_{\text{reconstructed}} / E_{\text{beam}}$$



1) Measure *spatial coordinate*

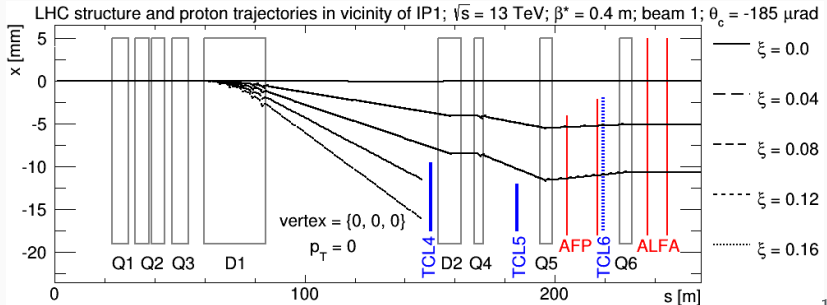
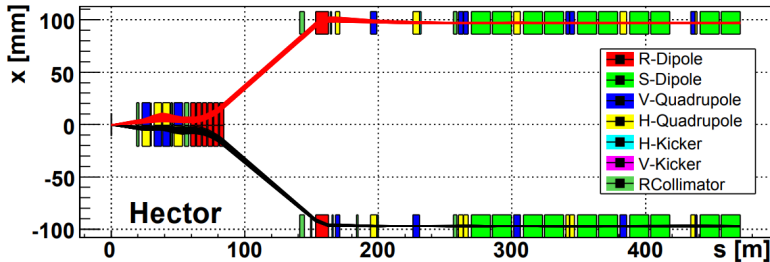
2) Infer *energy lost by proton*

3) Know *initial photon energy*

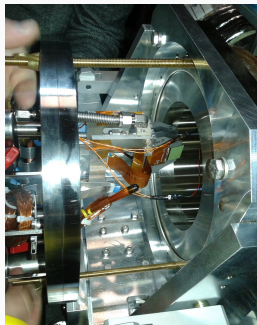
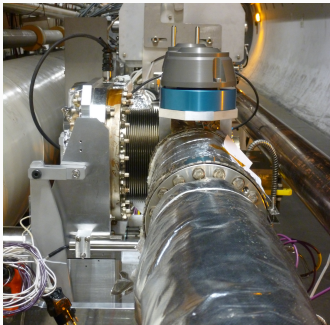
Novelty: reconstruct $\gamma\gamma$ system
without central ATLAS detectors

(drawing from Jesse Liu)

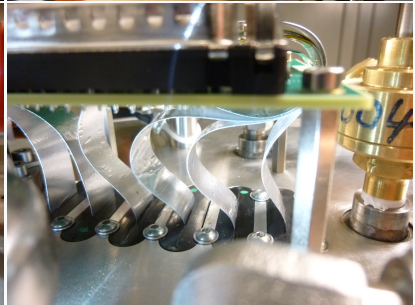
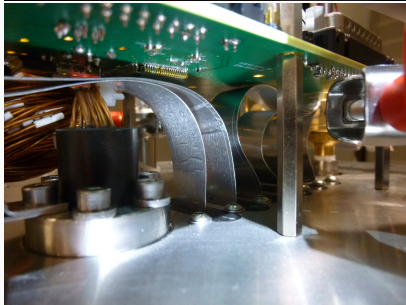
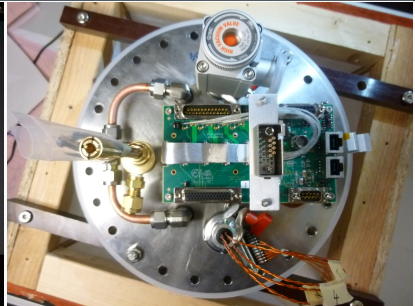
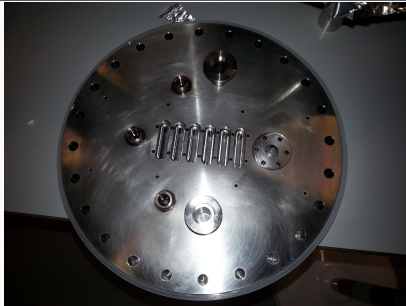
Trajectories of forward protons



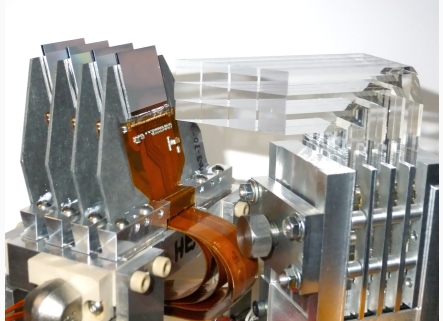
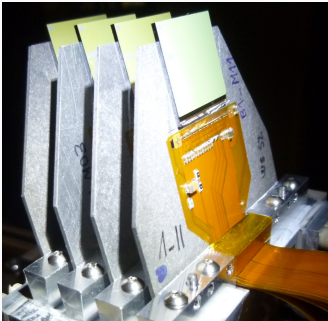
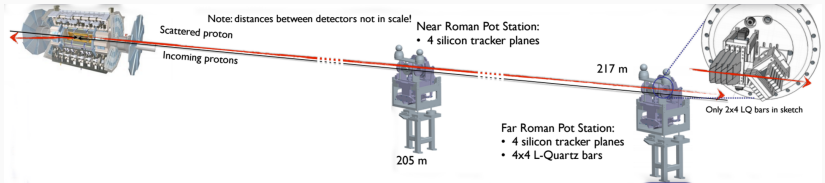
Roman pots



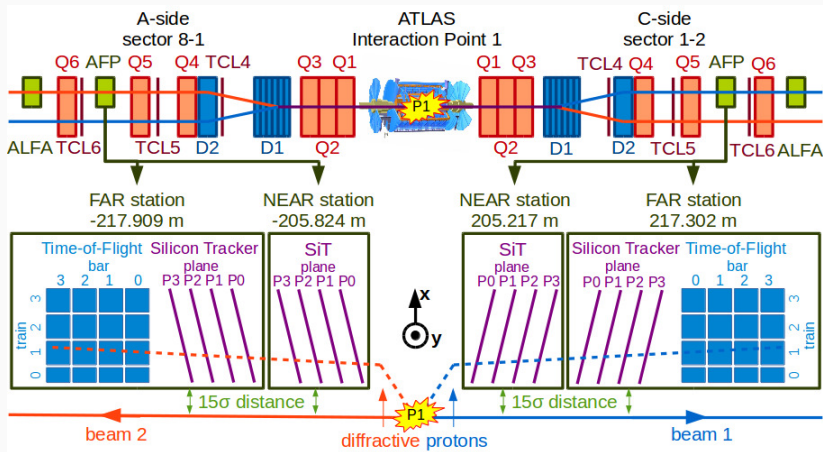
Feedthrough flange



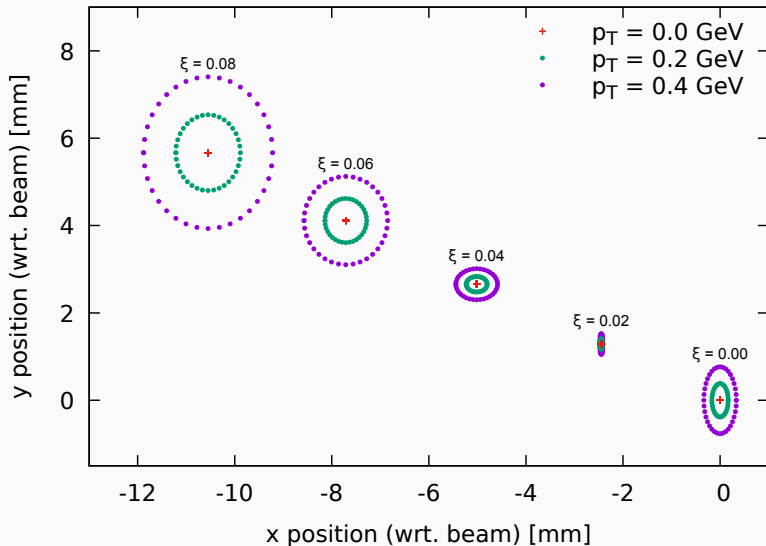
ATLAS Forward Proton detectors – one arm



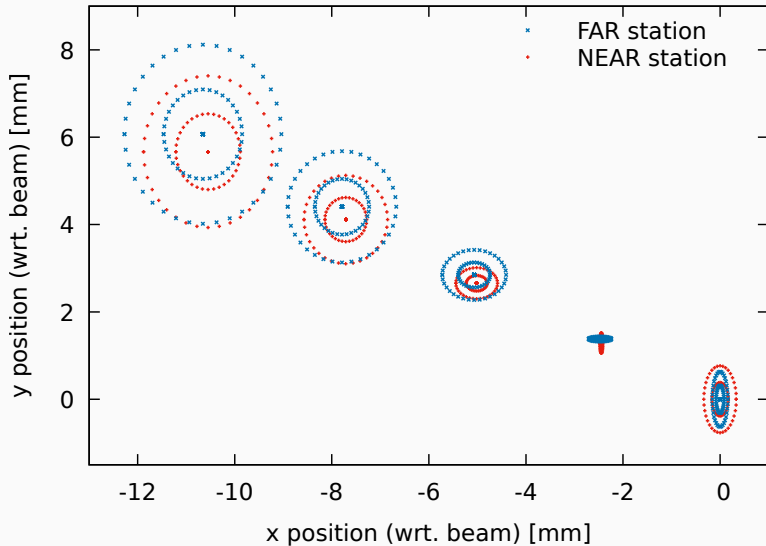
ATLAS Forward Proton detectors – full system



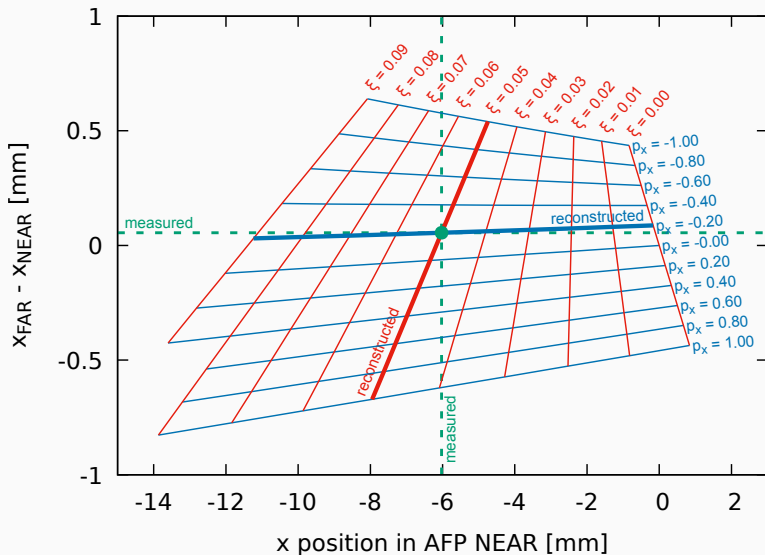
Reconstruction of proton kinematics



Reconstruction of proton kinematics



Reconstruction of proton kinematics



Contents

Introduction

Experimental techniques

First results

Performance

Time-of-flight detector

Conclusions

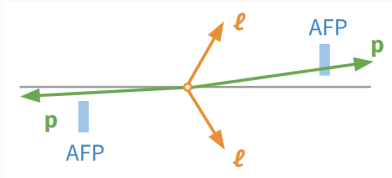
Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

The ATLAS Collaboration

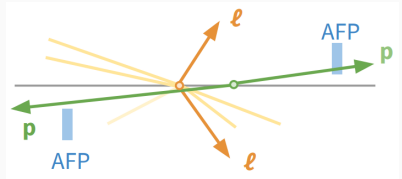
The observation of forward proton scattering in association with lepton pairs ($e^+e^- + p$ or $\mu^+\mu^- + p$) produced via photon fusion is presented. The scattered proton is detected by the ATLAS Forward Proton spectrometer while the leptons are reconstructed by the central ATLAS detector. Proton–proton collision data recorded in 2017 at a center-of-mass energy of $\sqrt{s} = 13$ TeV are analyzed, corresponding to an integrated luminosity of 14.6 fb^{-1} . A total of 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state are selected, allowing the background-only hypothesis to be rejected with a significance exceeding five standard deviations in each channel. Proton-tagging techniques are introduced for cross-section measurements in the fiducial detector acceptance, corresponding to $\sigma_{ee+p} = 11.0 \pm 2.6 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.3 \text{ (lumi.) fb}$ and $\sigma_{\mu\mu+p} = 7.2 \pm 1.6 \text{ (stat.)} \pm 0.9 \text{ (syst.)} \pm 0.2 \text{ (lumi.) fb}$ in the dielectron and dimuon channel, respectively.

Analysis strategy

Signal:



Background



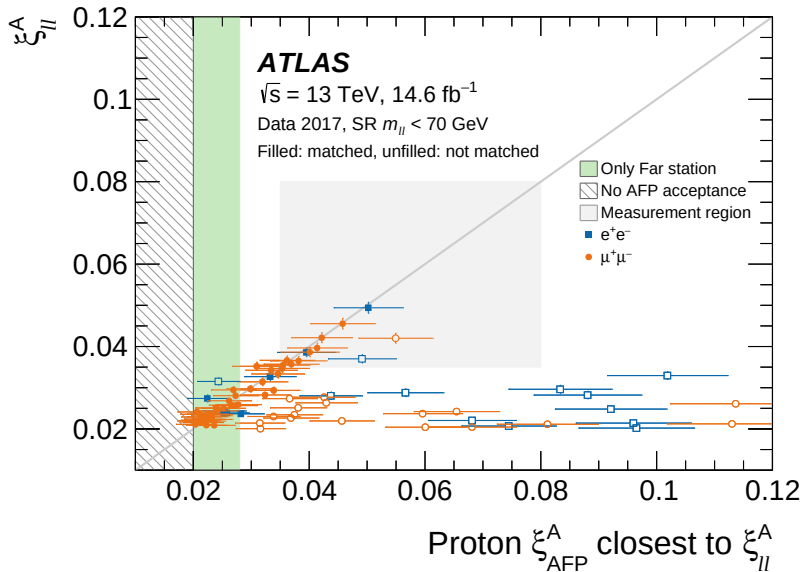
- ξ – fraction of proton energy carried by the photon
- approximations: neglecting proton mass and transverse momentum
- ξ from proton measurement

$$\xi = 1 - E_p/E_{\text{beam}}$$

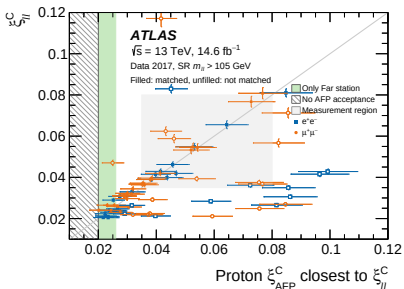
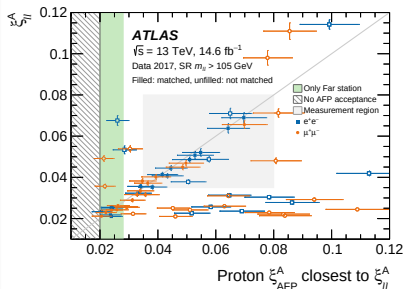
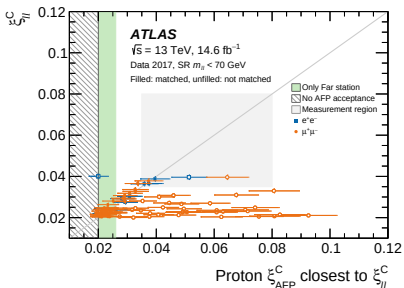
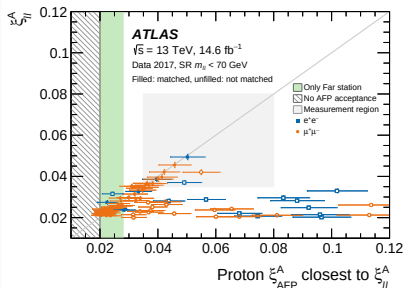
- ξ from $l\bar{l}$ system

$$\xi_{\pm} = \frac{M_{l\bar{l}}}{\sqrt{s}} \cdot e^{\pm y_{l\bar{l}}}$$

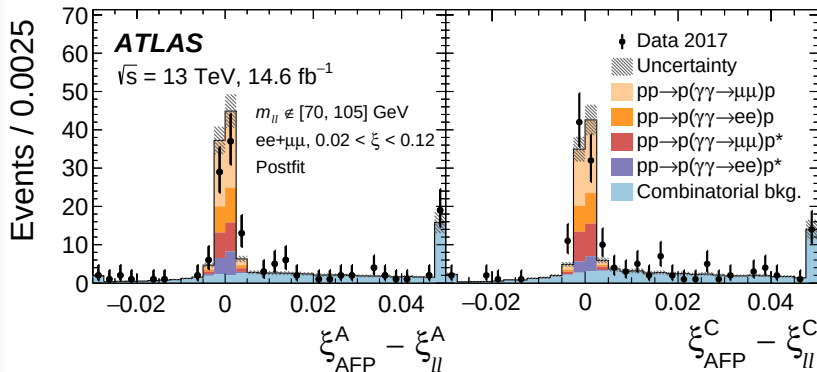
Kinematic matching



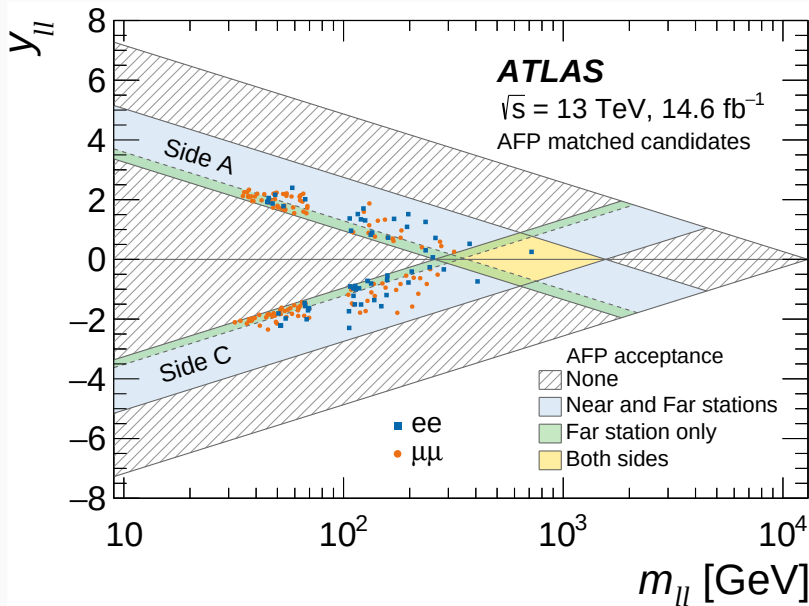
Kinematic matching – all channels



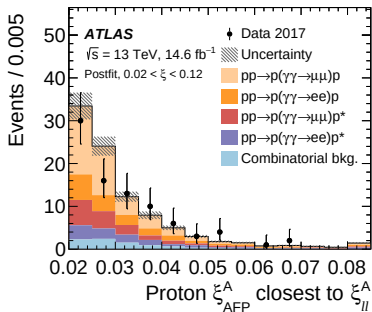
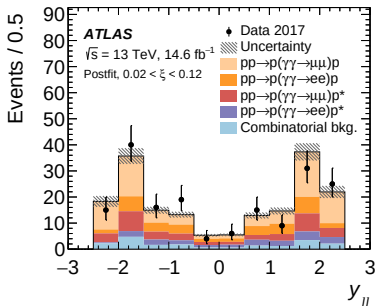
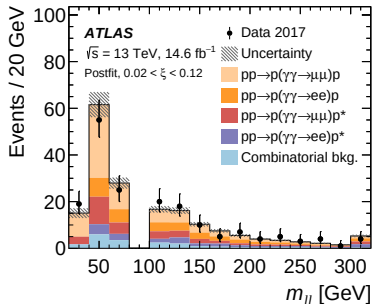
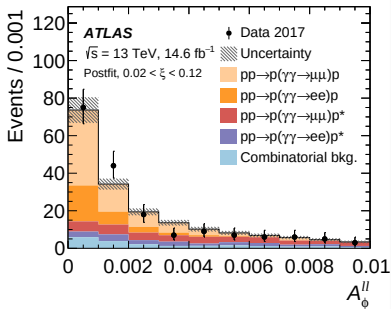
Signal evidence



Signal candidates



Distributions



Uncertainties

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

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

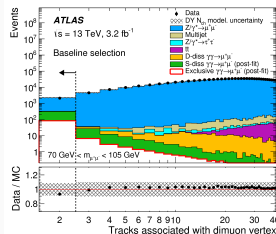
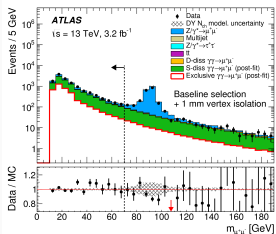
Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	< 1%
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon 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%

Experiment vs theory

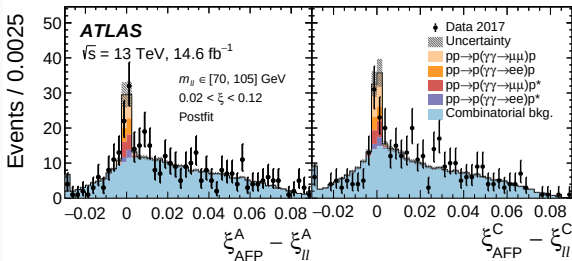
	$\sigma_{ee+p}^{\text{fid.}} \text{ [fb]}$	$\sigma_{\mu\mu+p}^{\text{fid.}} \text{ [fb]}$
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
HERWIG+LPAIR	15.5 ± 1.2	13.5 ± 1.1
HERWIG	9.3 ± 0.7	8.0 ± 0.6
LPAIR	6.2 ± 1.1	5.5 ± 0.9
S_{surv} using Refs. [31,30]		
HERWIG+LPAIR	10.9 ± 0.8	9.2 ± 0.7
HERWIG	7.0 ± 0.5	5.9 ± 0.4
LPAIR	3.9 ± 0.7	3.4 ± 0.6
SUPERCHIC 4 [94]		
Exclusive + single-dissociative	12.2 ± 0.9	10.4 ± 0.7
Exclusive	8.6 ± 0.6	7.3 ± 0.5
Single-dissociative	3.6 ± 0.6	3.1 ± 0.5

To tag or not to tag

$\gamma\gamma \rightarrow l\bar{l}$ in Z mass window **without** forward proton tagging:

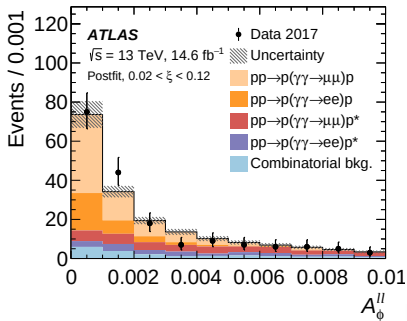


$\gamma\gamma \rightarrow l\bar{l}$ in Z mass window **with** forward proton tagging:

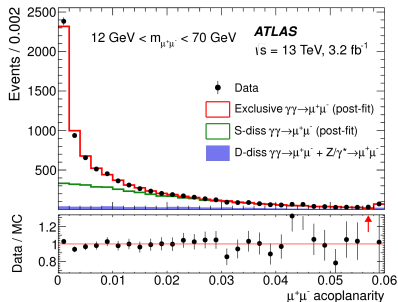


To tag or not to tag

With forward proton tagging



Without forward proton tagging



- Different sensitivity to processes with dissociation
- Double-tag measurement would provide more information

Contents

Introduction

Experimental techniques

First results

Performance

Time-of-flight detector

Conclusions

Beam-based alignment

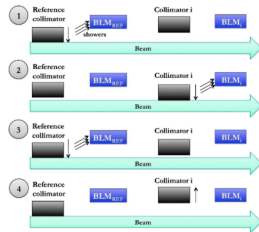
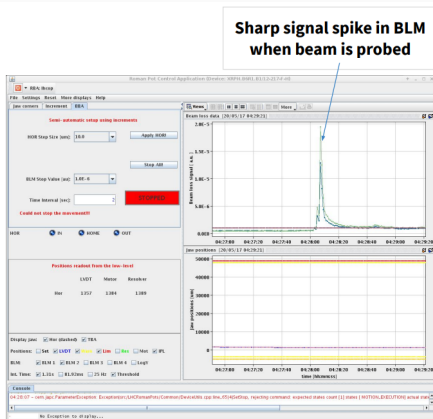
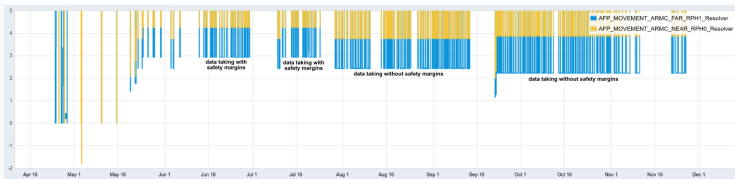


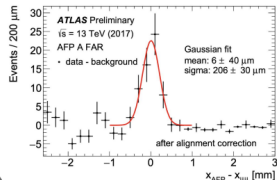
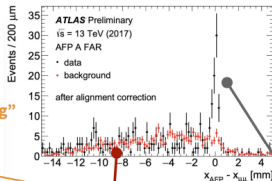
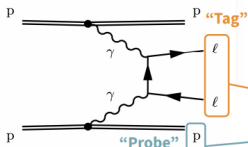
FIG. 4. The four-stage beam-based alignment procedure for collimator i . The reference collimator is aligned to form a reference cut in the beam halo (1). Collimator i is aligned (2), followed by a realignment of the reference collimator (3). Finally, collimator i is opened to its position in the hierarchy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

LHC operations: 20 May 2017



Data-driven alignment

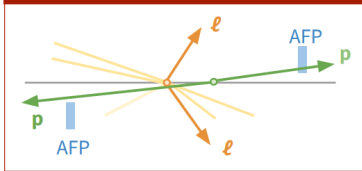
Use $(\gamma\gamma \rightarrow \mu\mu)+p$ signal
as standard candle:
“The J/ψ of AFP”



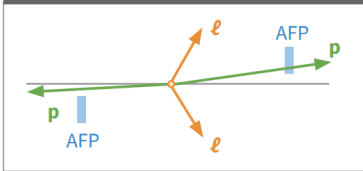
$$\xi_{\ell\ell}^{\pm} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$$

Expected proton energy loss
constrained by dimuon system

Background: no correlation (pileup)

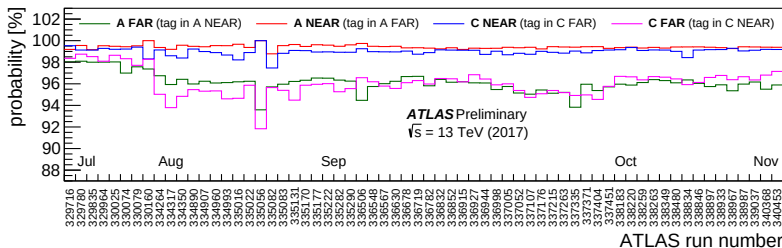
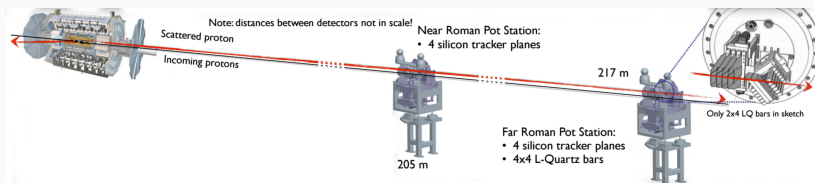


Signal: if $x_{\text{AFP}} = x_{\ell\ell} \Rightarrow$ aligned & calibrated



(drawing from Jesse Liu)

Reconstruction efficiency



Contents

Introduction

Experimental techniques

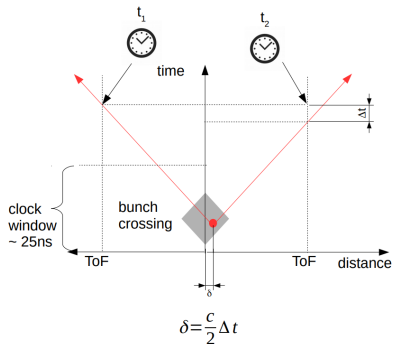
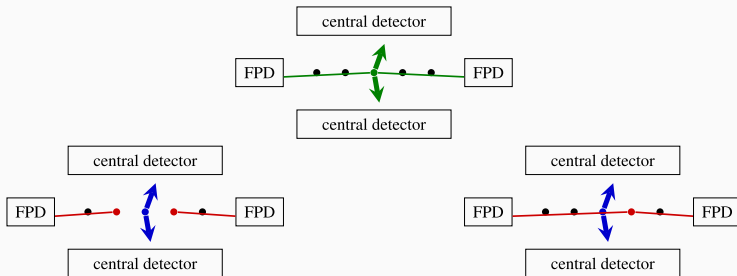
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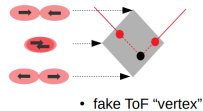
Time-of-flight detector

Conclusions

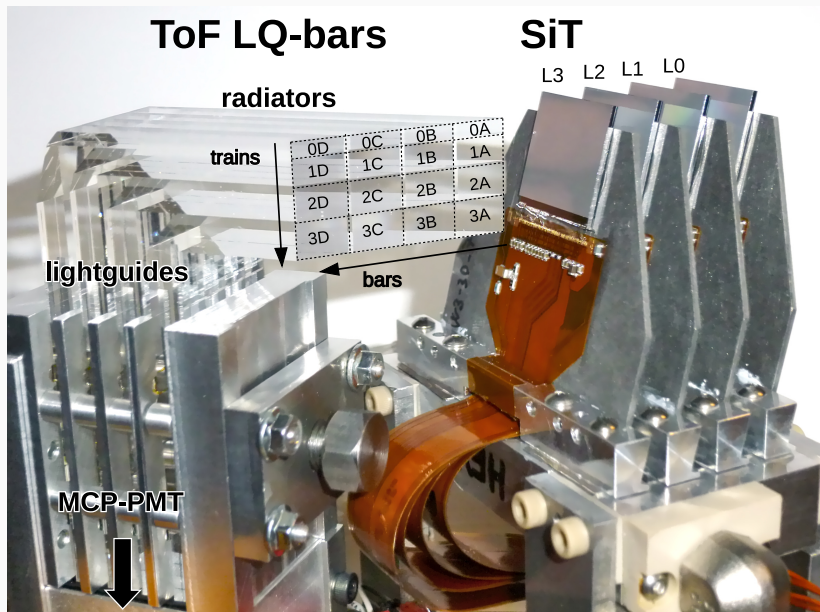
Combinatorial backgrounds



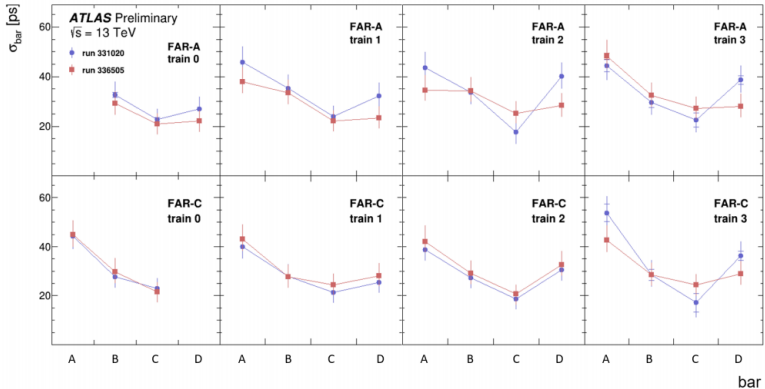
pile-up background



Time-of-Flight detector

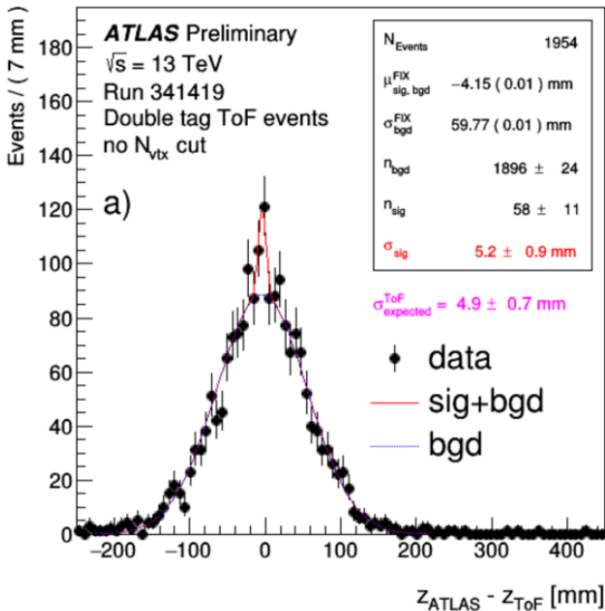


ToF resolutions



- 30 ps $\leftrightarrow$ 9 mm (at speed of light)
- More bars – better combined resolution

ToF-vertex matching



Contents

Introduction

Experimental techniques

First results

Performance

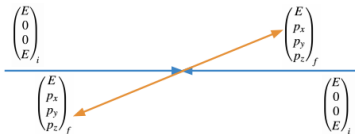
Time-of-flight detector

Conclusions

AFP → new physics object

Lepton collider

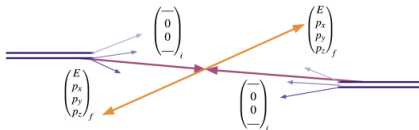
All initial & visible final state
4-vectors measurable



Hadron collider: no AFP

Initial state 4-vectors of
partons immeasurable in event

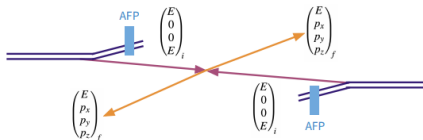
We cannot use what we cannot measure!



Hadron collider: with AFP

Measure energy lost by protons
⇒ measure initial state 4-vectors

New event kinematic information!

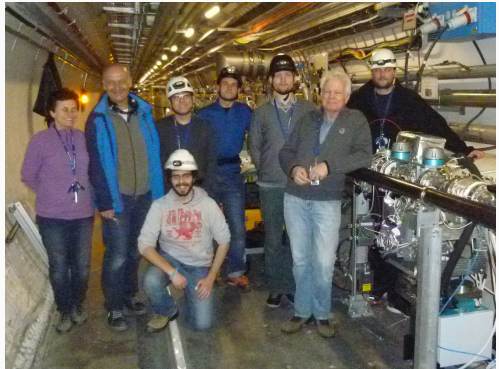


(drawing from Jesse Liu)

Involvement of Cracow groups in AFP

Crucial involvement (leading role in several activities) of IFJ PAN and AGH-UST teams:

- physics programme
- beam tests
- construction
- commissioning
- slow control
- trigger
- data acquisition
- operation
- detector simulation
- data preparation
- reconstruction software
- performance studies
- physics analyses



Installation of first arm in 2016