Photon-photon interactions at the LHC with proton tagging

Rafał Staszewski (IFJ PAN)

IFJ PAN Seminar
Cracow, 6 May 2021

Contents

Maxwell's equations

Gauss's law for electricity

$$\nabla \cdot \mathbf{E} = 4\pi\rho_{\mathrm{e}}$$

Gauss's law for magnetism

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's law of induction

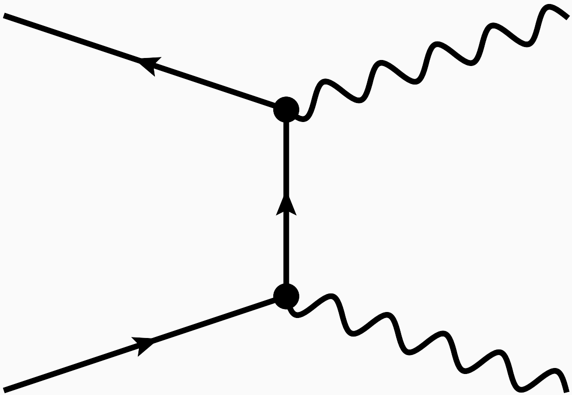
$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

Ampère's law

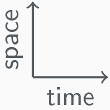
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_{\mathrm{e}}$$

Linear equations $\Rightarrow$ no interaction between two waves

Electron-positron annihilation $e^+e^- \to \gamma\gamma$

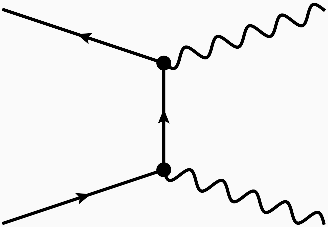


Feynman diagram:

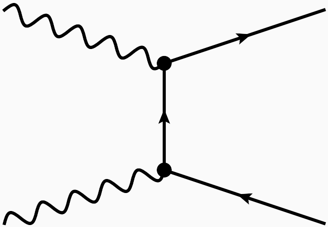


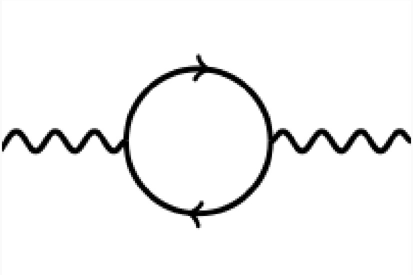
Quantum Electrodynamics

$$e^+e^- \to \gamma\gamma$$



$$\gamma\gamma \to e^+e^-$$





Motivation (1): $\gamma\gamma$ processes important in other areas

Propagation of γ rays through space

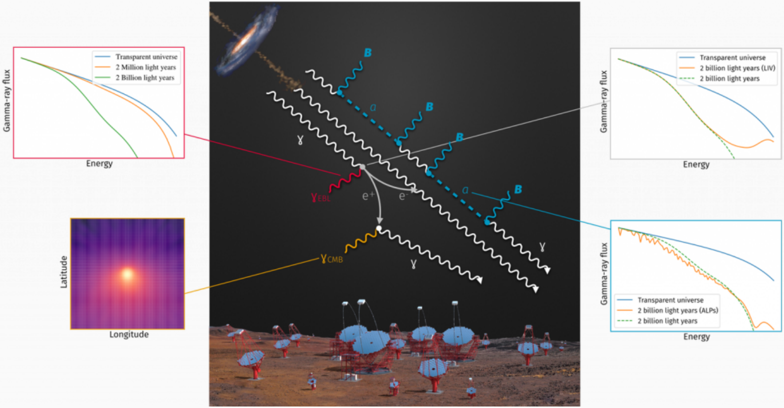
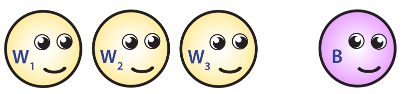
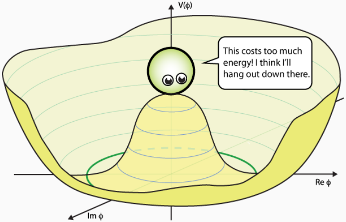
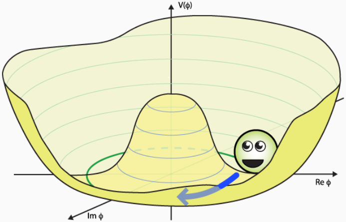
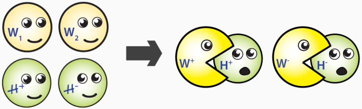


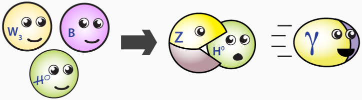
Figure from cta-observatory.org









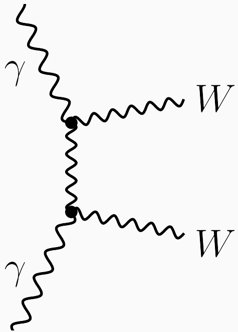


Drawings from `quantumdiaries.org`

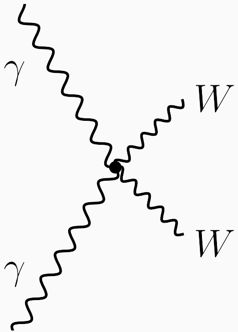
Motivation to study $\gamma\gamma$ interactions

Motivation (2): studies of electroweak unification

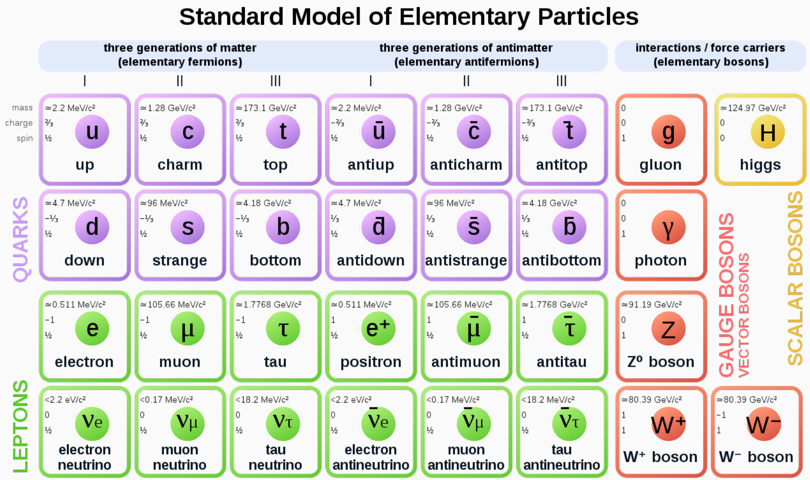
triple coupling



quartic coupling



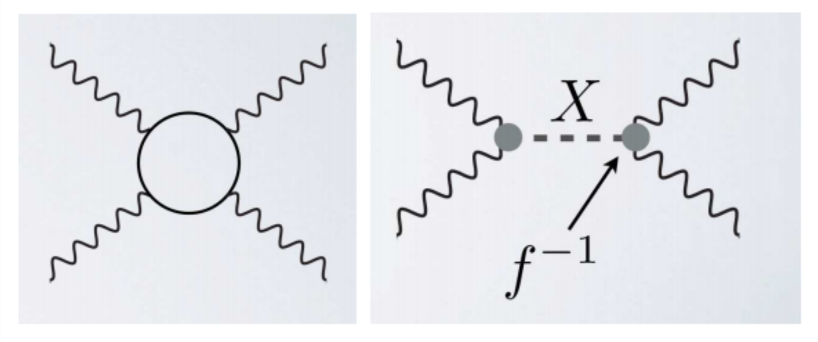
Standard Model of Particle Physics



Unsolved questions:

many free parameters, three generations, fine tuning, matter–antimatter asymmetry, dark matter, dark energy, . . .

Motivation (3): searches for new physics



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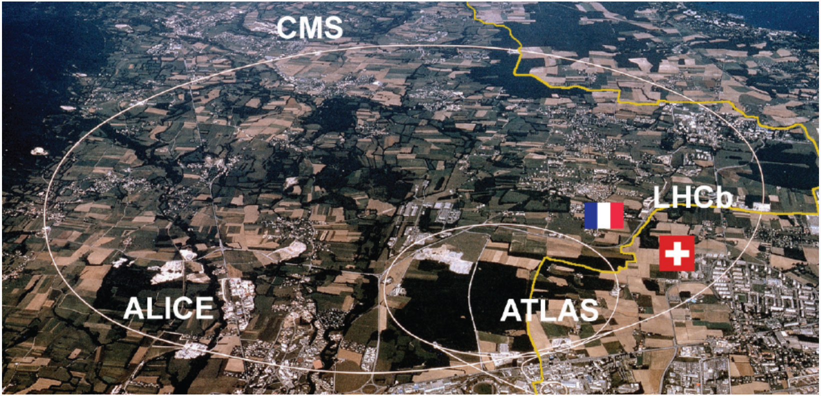
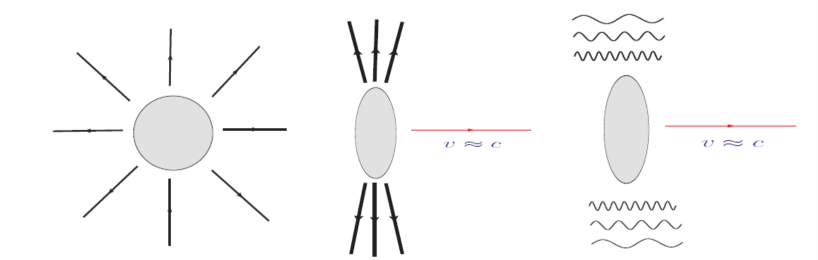
LHC accelerator



Equivalent photons



Drawings from Victor Gonçalves

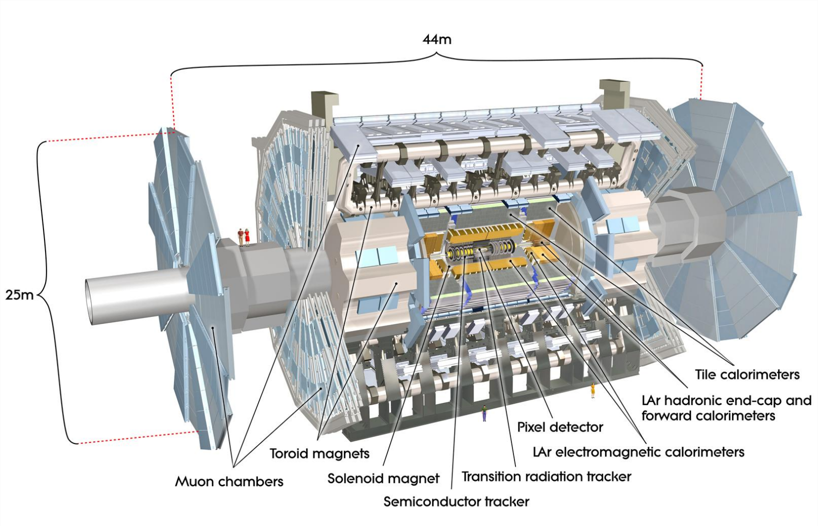
Pb beams

- high charge of ions
- clean events
- better at lower γ energies

Proton beams

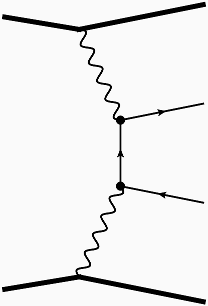
- high luminosity of collisions
- events contaminated by pile-up
- better at higher γ energies

ATLAS Detector

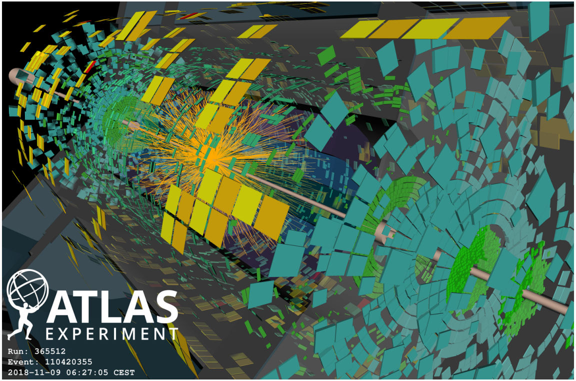


How to distinguish photon-induced events

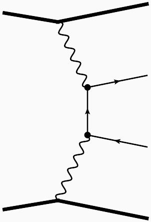
Signal

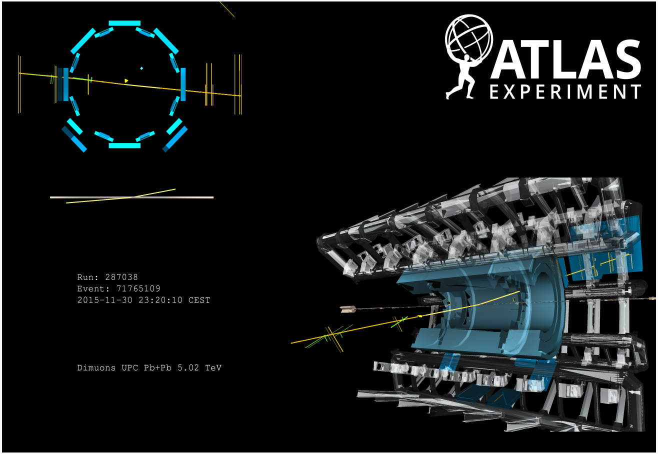


Background (PbPb interaction)

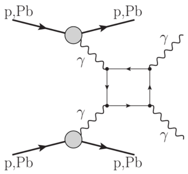


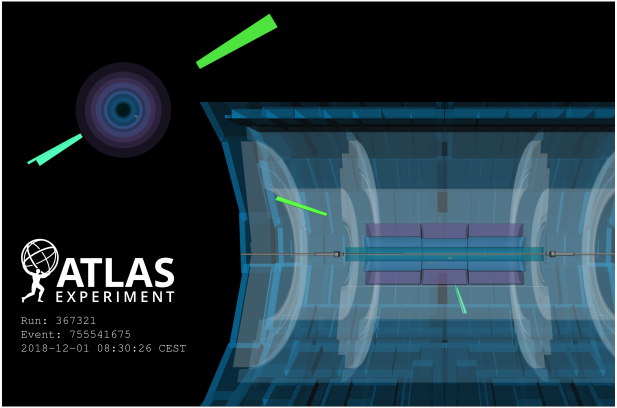
$\gamma\gamma \rightarrow \mu\mu$ in PbPb event candidate





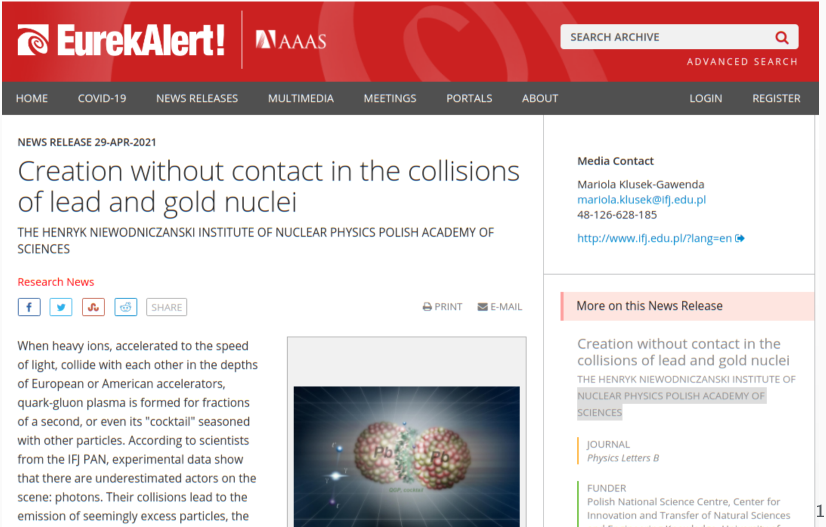
$\gamma\gamma \to \gamma\gamma$ in PbPb event candidate





Theoretical calculations

One of the world's leading groups at IFJ PAN:
Mariola Kłusek-Gawenda, Wolfgang Schäfer, Antoni Szczurek
(also Piotr Lebiedowicz for pp processes)



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NEWS RELEASE 29-APR-2021

Creation without contact in the collisions of lead and gold nuclei

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Research News

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When heavy ions, accelerated to the speed of light, collide with each other in the depths of European or American accelerators, quark-gluon plasma is formed for fractions of a second, or even its "cocktail" seasoned with other particles. According to scientists from the IFJ PAN, experimental data show that there are underestimated actors on the scene: photons. Their collisions lead to the emission of seemingly excess particles, the

Media Contact

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http://www.ifj.edu.pl/?lang=en

More on this News Release

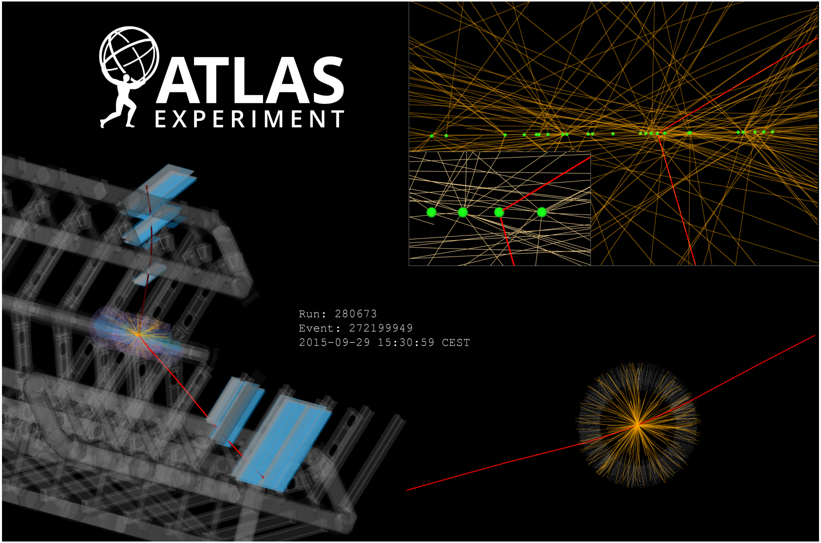
Creation without contact in the collisions of lead and gold nuclei

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

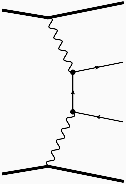
JOURNAL
Physics Letters B

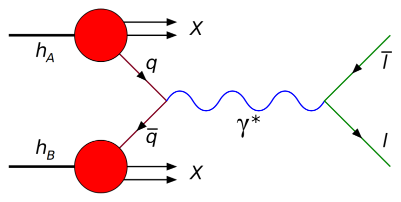
FUNDER
Polish National Science Centre, Center for Innovation and Transfer of Natural Sciences

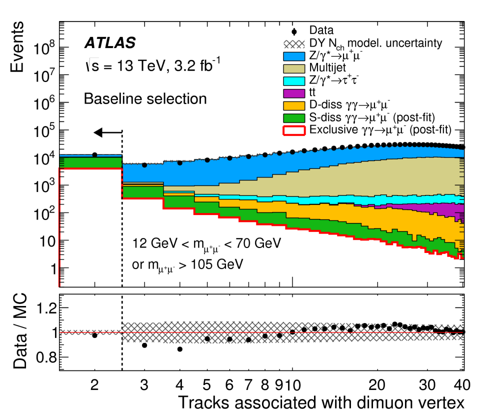
$\gamma\gamma \to \mu\mu$ in pp event candidate



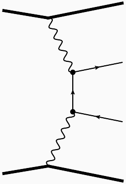
Background rejection – vertex isolation

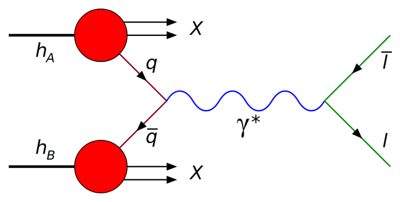


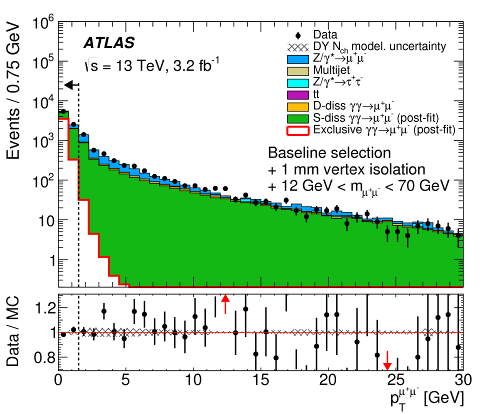




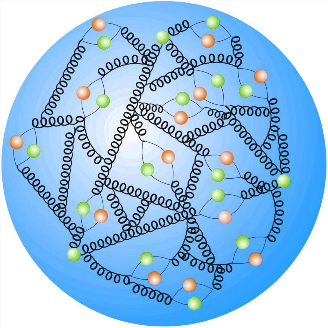
Background rejection – low transverse momentum of the pair

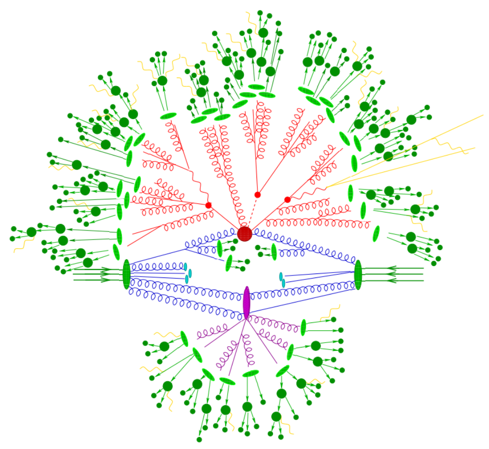




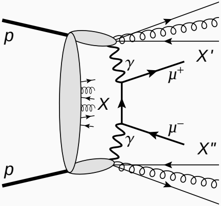


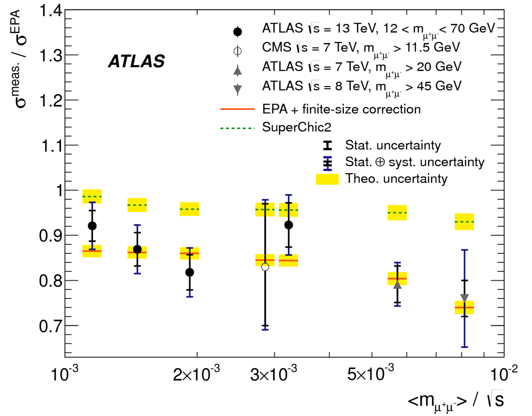
Multiple-parton interactions





Absorptive corrections

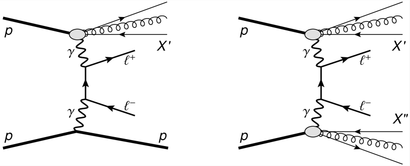


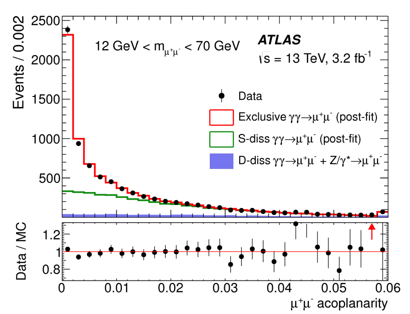


Motivation (4): understanding strong interactions of protons

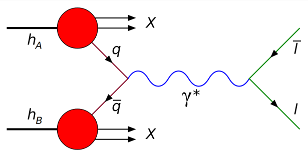
Limitations of the presented experimental approach

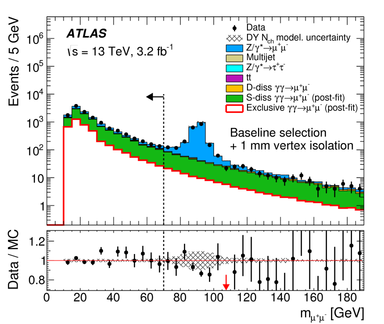
Processes with dissociation





DY background

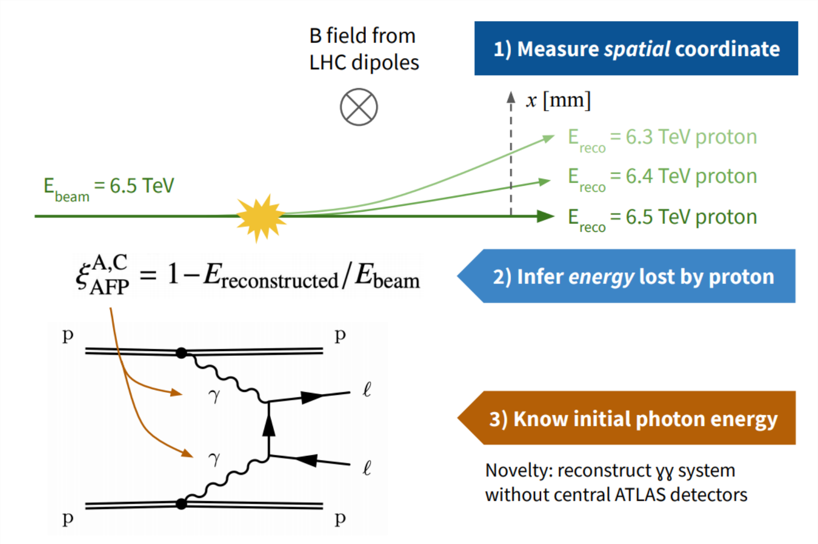




Also, signal efficiency worsens with increasing pile-up.

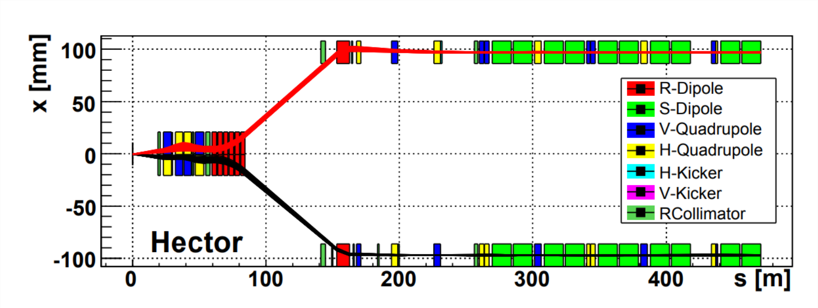
Contents

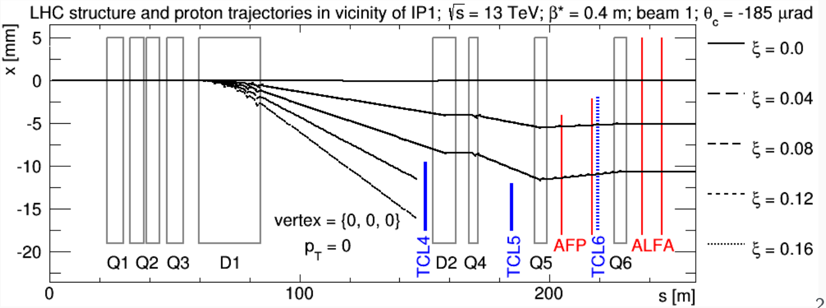
Forward proton spectrometer



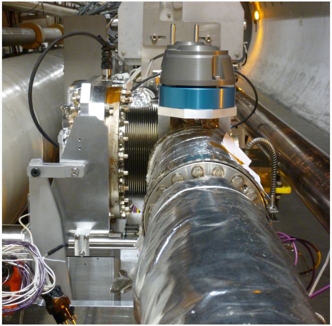
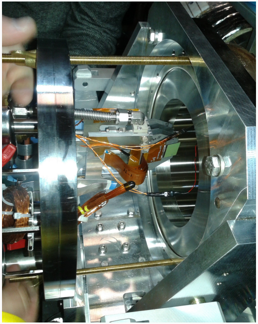
(drawing from Jesse Liu)

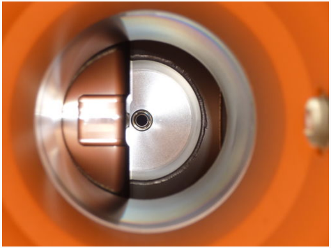
Trajectories of forward protons



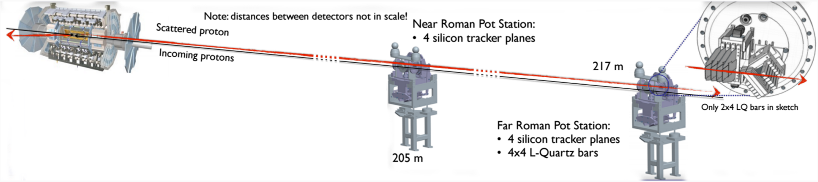


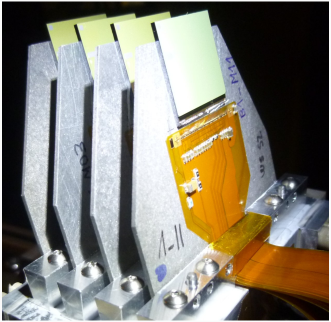
Roman pots

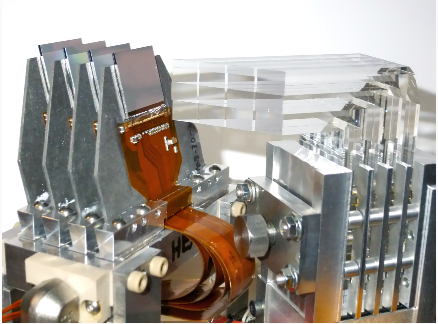





ATLAS Forward Proton detectors – one arm



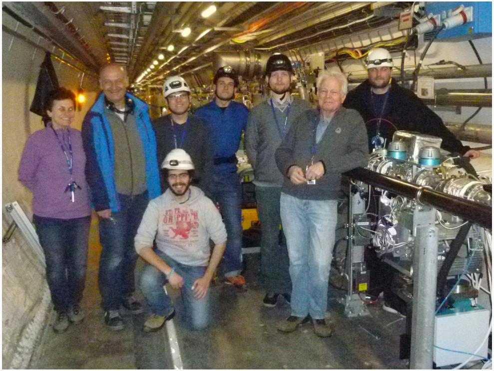




Involvement of IFJ PAN in AFP

Crucial involvement of IFJ PAN (and AGH-UST):

- 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

(*) leading role of physicists from IFJ PAN

Contents

First results

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)

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 5 standard deviations in each channel. Proton-tagging techniques are introduced for cross-section measurements in the fiducial detector acceptance, corresponding to $\sigma_{ee+p} = 11.0 \pm 2.6(\mathrm{stat}) \pm 1.2(\mathrm{syst}) \pm 0.3(\mathrm{lumi})$ and $\sigma_{\mu\mu+p} = 7.2 \pm 1.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 0.2(\mathrm{lumi})$ fb in the dielectron and dimuon channel, respectively.

DOI: 10.1103/PhysRevLett.125.261801

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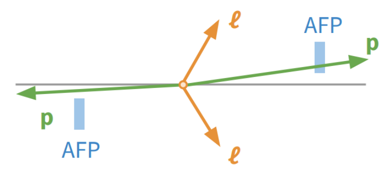
NEWS RELEASE 18-FEB-2021

LHC/ATLAS: A unique observation of particle pair creation in photon-photon collisions

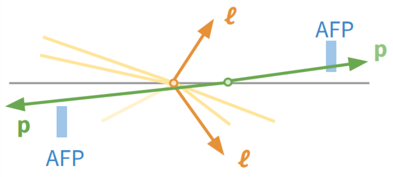
THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Analysis strategy

Signal:



Background:



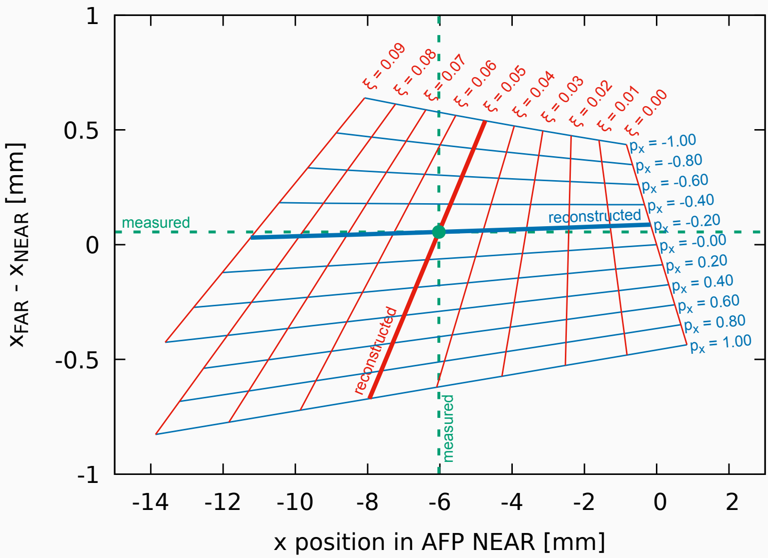
- ξ – fraction of proton energy carried by the photon
- ξ from proton measurement

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

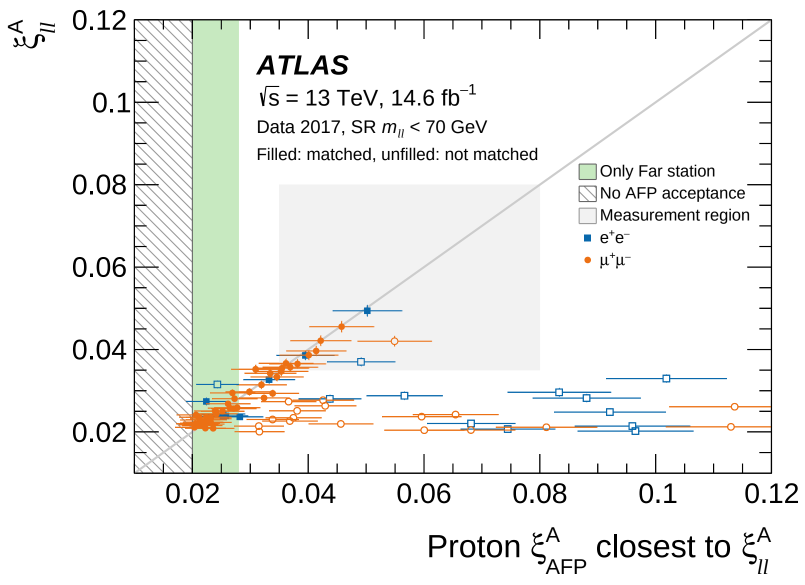
- ξ from $l\bar{l}$ system

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

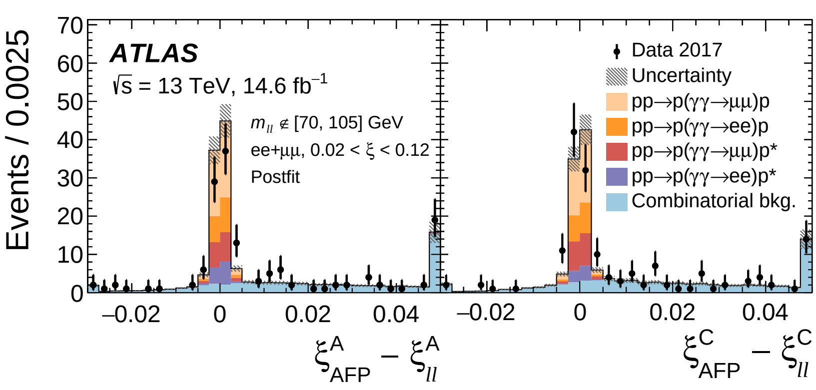
Reconstruction of proton kinematics



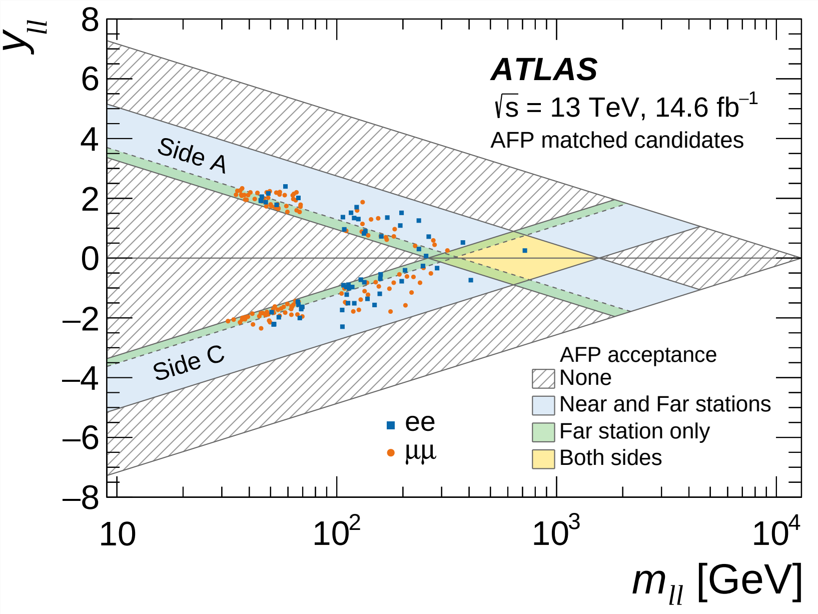
Kinematic matching



Signal evidence



Signal candidates



First measurement of the cross section

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

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

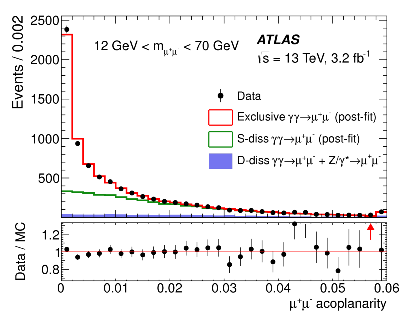
Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	< 1%
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon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

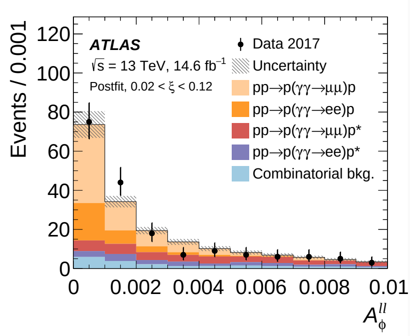
	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
Herwig+Lpair	15.5 ± 1.2	13.5 ± 1.1
Herwig	9.3 ± 0.7	8.0 ± 0.6
Lpair	6.2 ± 1.1	5.5 ± 0.9
S_{surv} using Refs. [31,30]		
Herwig+Lpair	10.9 ± 0.8	9.2 ± 0.7
Herwig	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

Without forward proton tagging



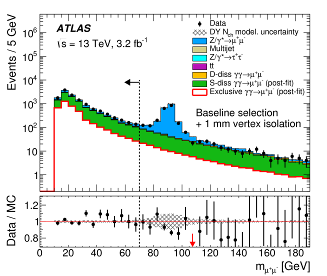
With forward proton tagging



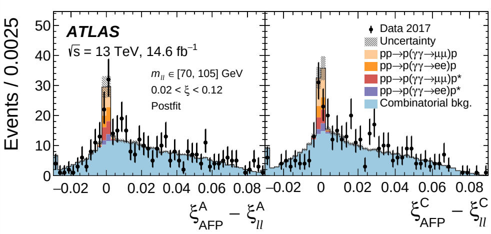
- Different sensitivity to processes with dissociation
- Double-tag measurement would provide more information

To tag or not to tag

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



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



Contents

Summary and outlook

Summary

- Photon–photon interactions present in hadron collisions
- A way to improve our understanding of the electroweak sector
- Forward proton tagging
  - a new class of observables made available
  - constraining the initial state

Outlook

- Several ongoing analyses using the existing data
- More data to come in LHC Run 3
- Additional constraints for double-tag events with timing detectors