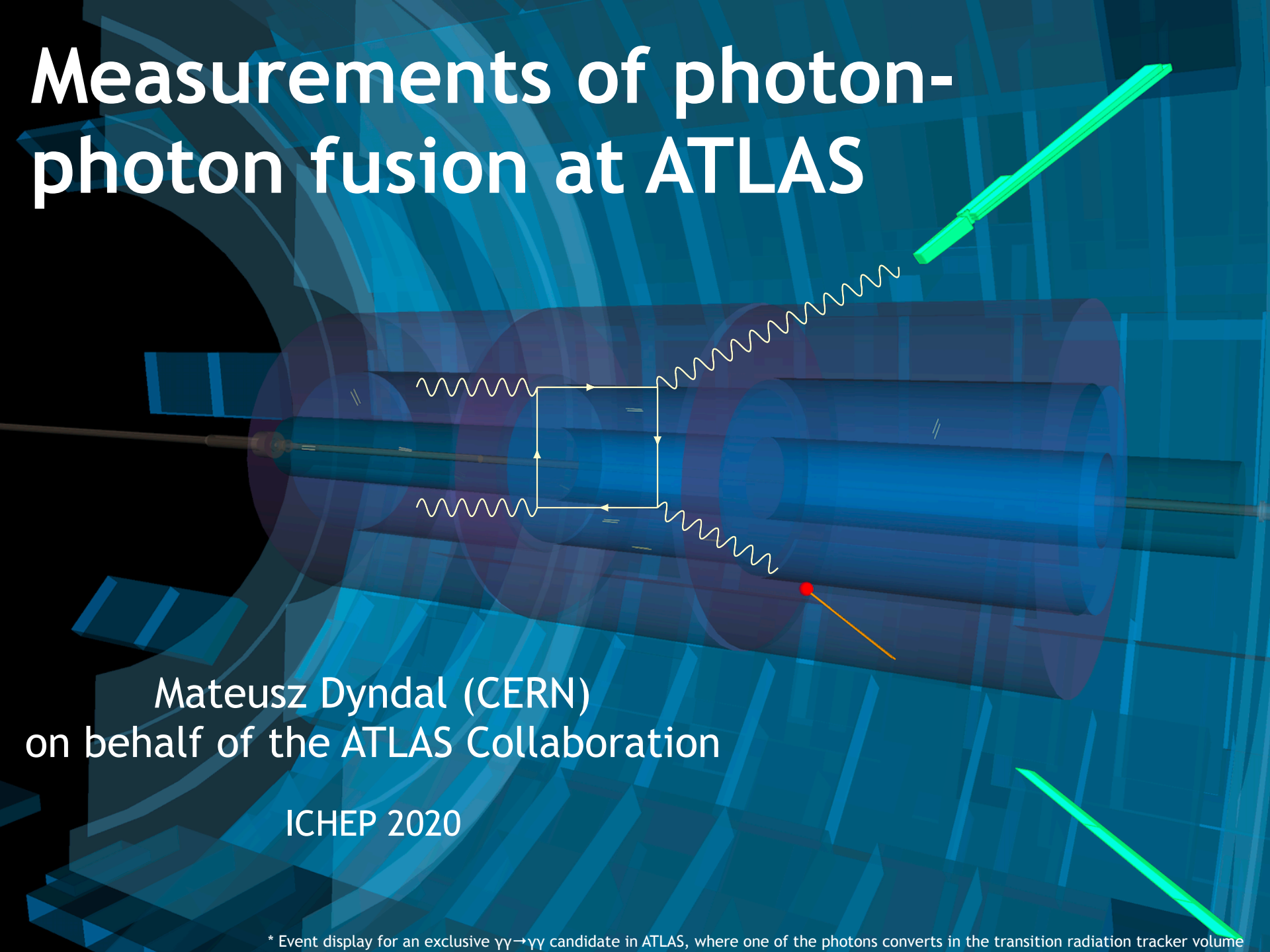
Measurements of photon-photon fusion at ATLAS



Mateusz Dyndal (CERN)
on behalf of the ATLAS Collaboration

ICHEP 2020

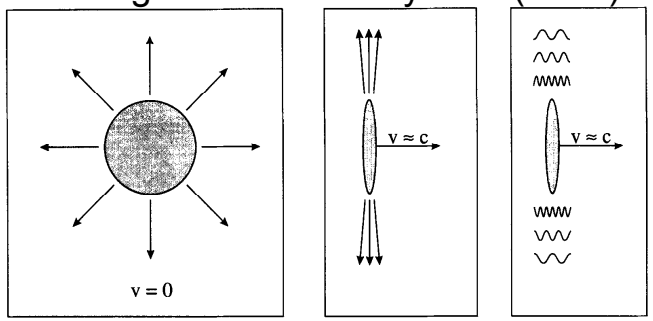
* Event display for an exclusive $\gamma\gamma \rightarrow \gamma\gamma$ candidate in ATLAS, where one of the photons converts in the transition radiation tracker volume

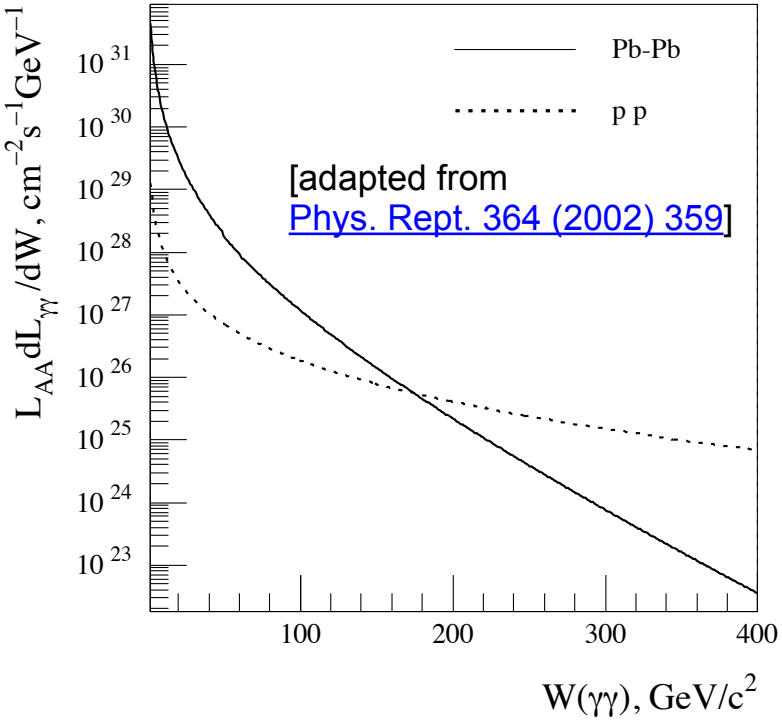
Introduction

- **Boosted charged-particles** are intense source of photons

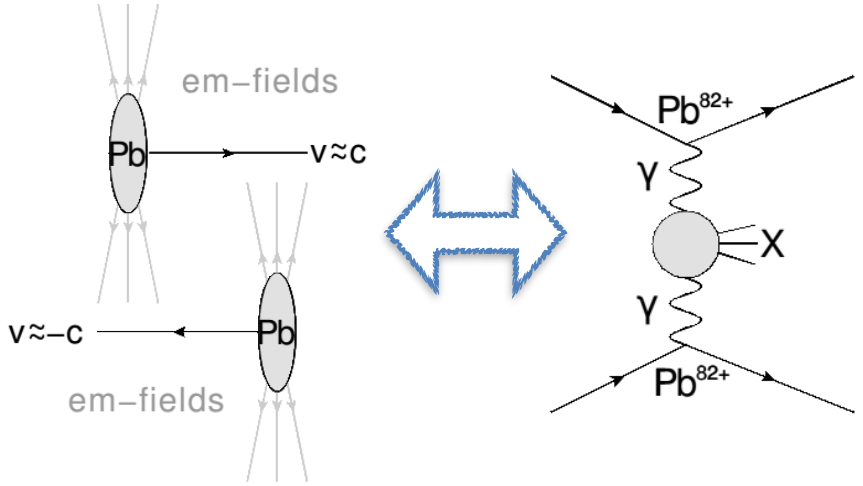
- **Quasi-real photon flux**
  - E_{max} ~γ/R ~**2 TeV** (protons @LHC)
    ~80 GeV (Pb ions @LHC)

[from Prog. Part. Nucl. Phys. 39 (1997) 503]



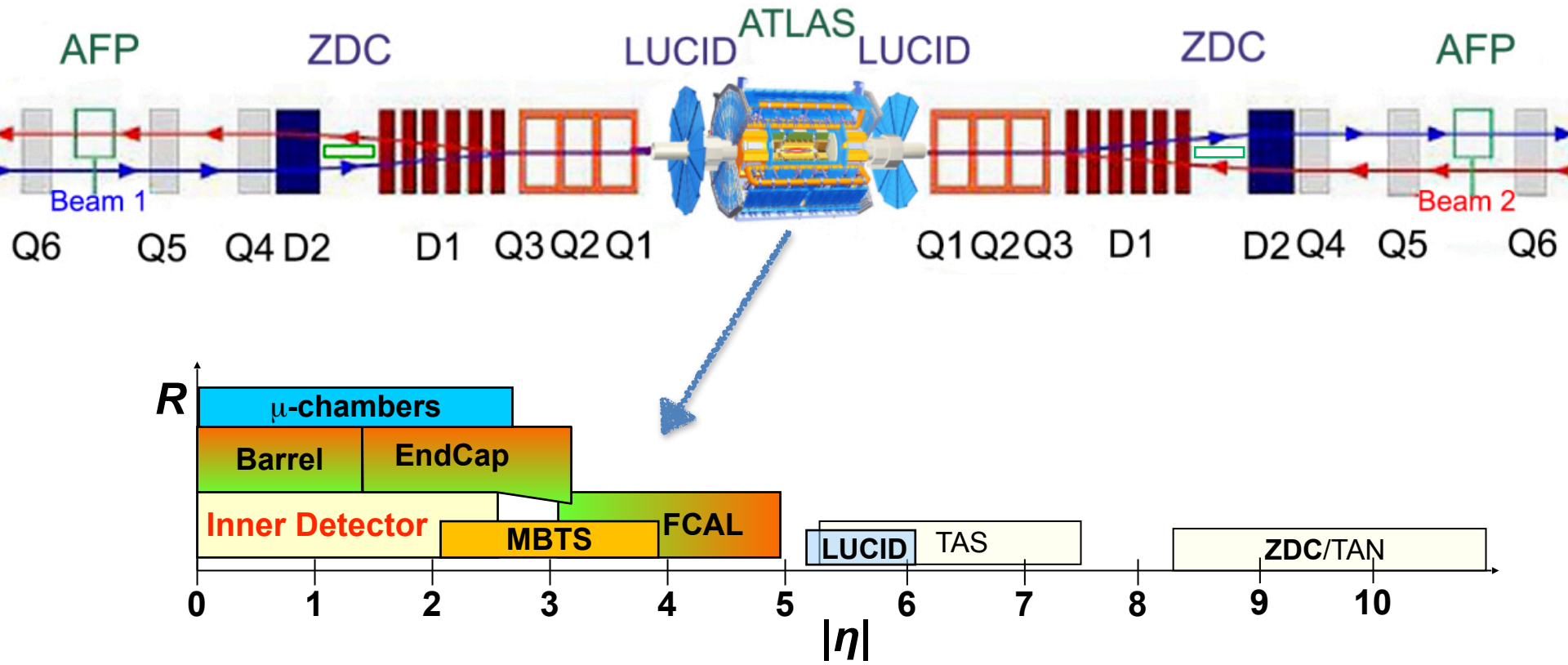


- Clean access to **high-energy electroweak interactions**



Experimental approach

- **Exclusive final states → Exclusivity requirements are essential**
  - Many sub-detectors available in ATLAS
  - Outgoing ions escape into beampipe, protons can be tagged by AFP
  - Accounting for proton/ion dissociation is also important



Outline

- A set of **new** ATLAS measurements will be covered in this talk:
  - *Exclusive **dimuon** production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ATLAS* [CERN-EP-2020-138]
  - *Measurement of **light-by-light** scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector* [ATLAS-CONF-2020-010]
  - *Observation and measurement of **forward proton** scattering in association with **lepton pairs** produced via the photon fusion mechanism at ATLAS* [ATLAS-CONF-2020-041]
  - *Observation of **photon-induced WW** production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector* [ATLAS-CONF-2020-038]

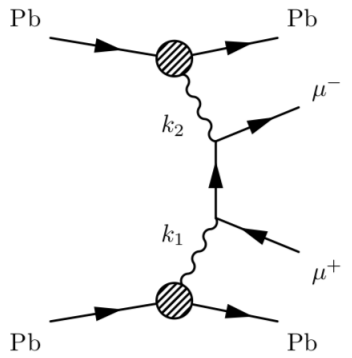
Pb+Pb data $\sqrt{s_{NN}}$ = 5.02 TeV

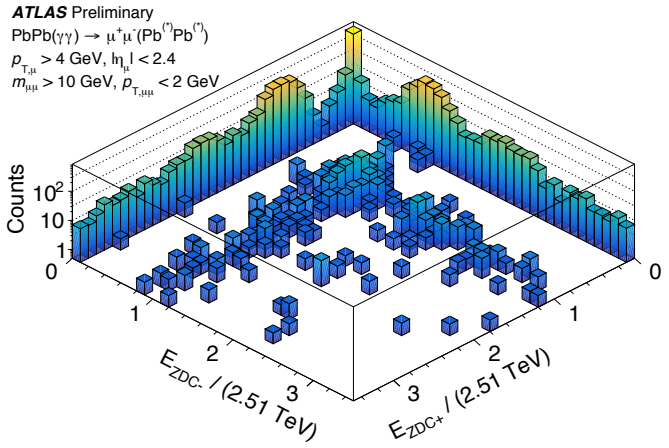
pp data $\sqrt{s}$ = 13 TeV

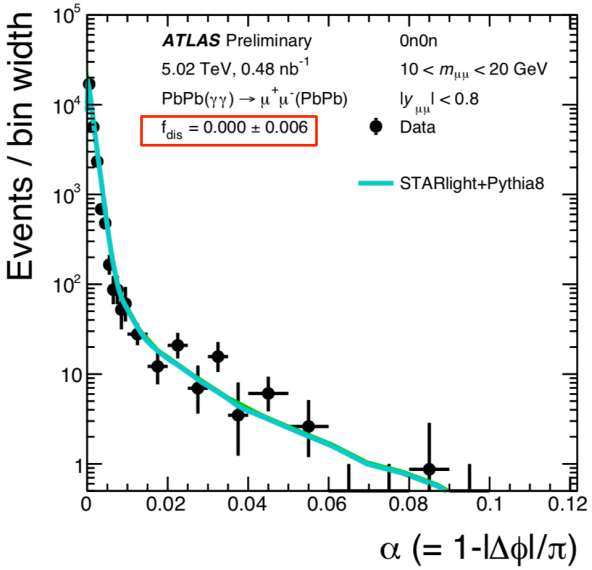
Exclusive dimuons in PbPb

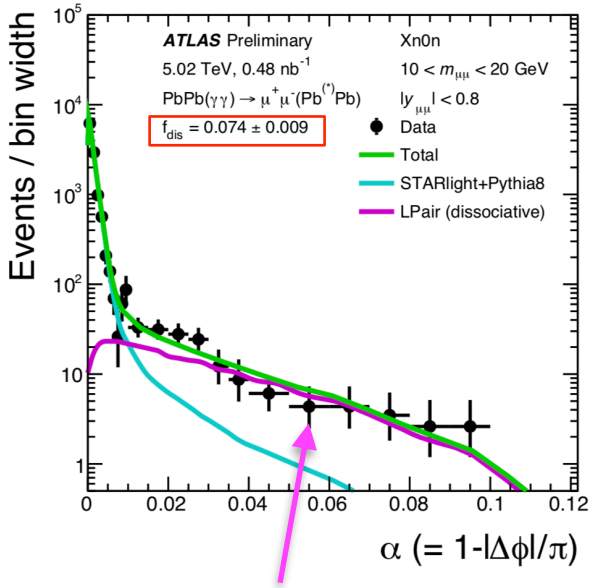
CERN-EP-2020-138

- ‘Standard candle’ process
  - Good sensitivity for Pb EM formfactors → **photon fluxes**
  - Sensitivity to probe **higher-order corrections** (FSR, Coulomb)
- Events categorised wrt **ZDC** activity (0n0n, 0nXn, XnXn)
- Signal and background modelling
  - Signal: STARlight+Pythia8 (LO+FSR)
  - Semi-coherent background (γ*γ→μμ): LPair 4.0 (pp)



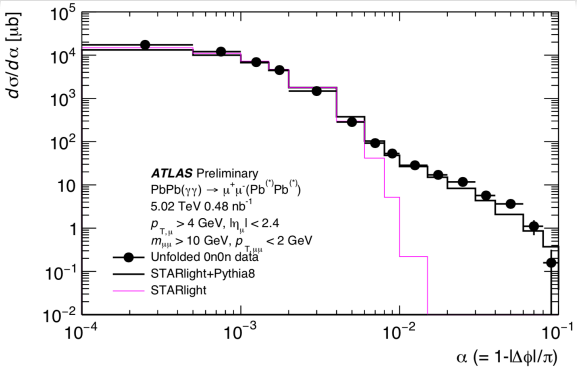


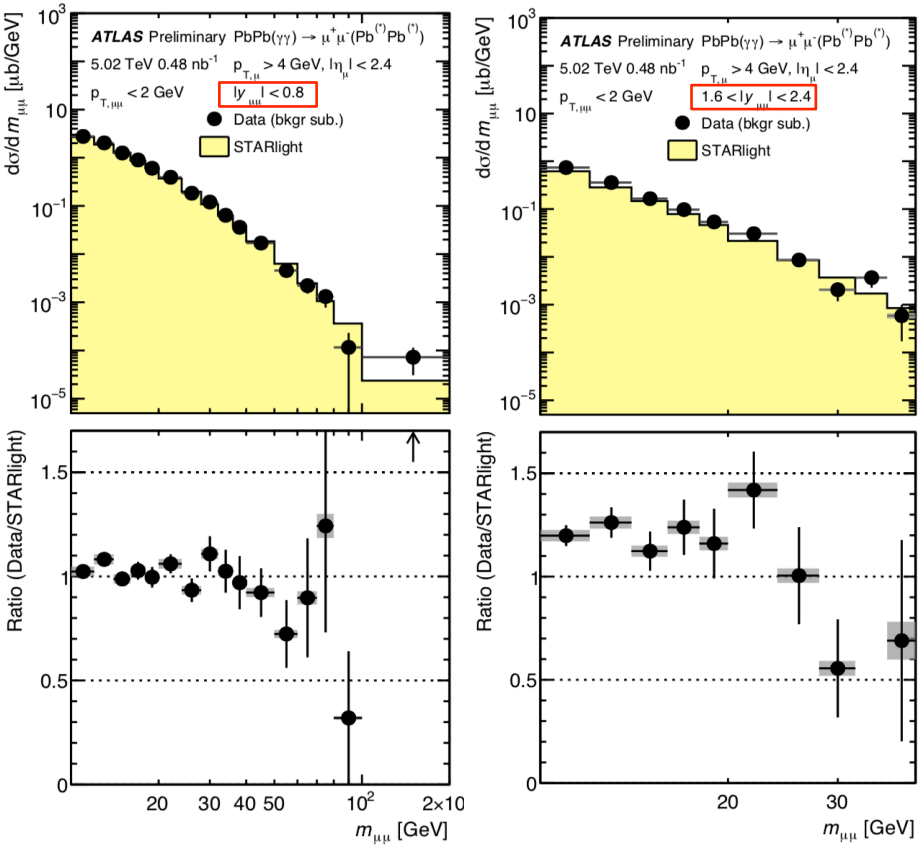




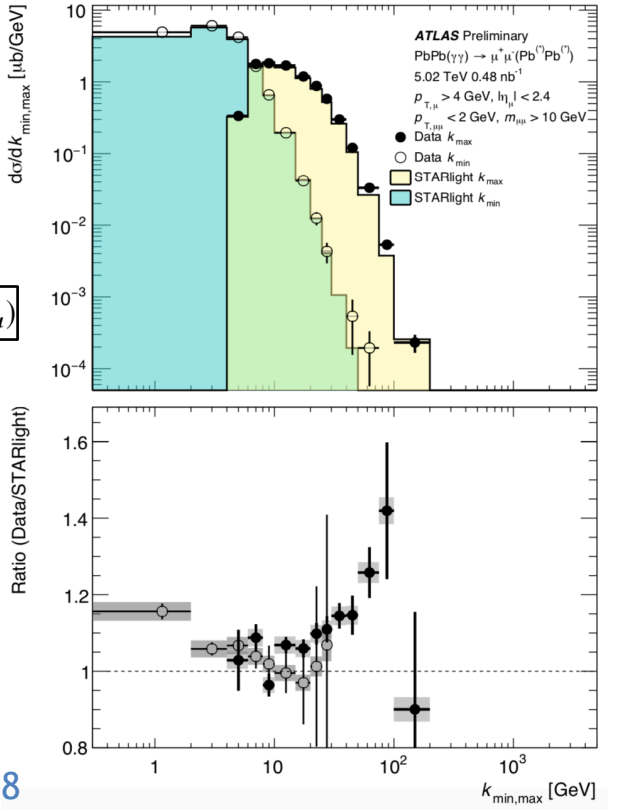
Exclusive dimuons in PbPb

- Measuring **differential** cross sections
  - As function of $m_{\mu\mu}$, $|y_{\mu\mu}|$, cos(θ*), Acoplanarity →
  - In reasonable agreement with STARlight+Pythia8
  - Some disagreement seen mainly at large $|y_{\mu\mu}|$
    →Translated into disagreement at low and high photon energies





$$k_1, k_2 = (1/2) m_{\mu\mu} \exp(\pm y_{\mu\mu})$$

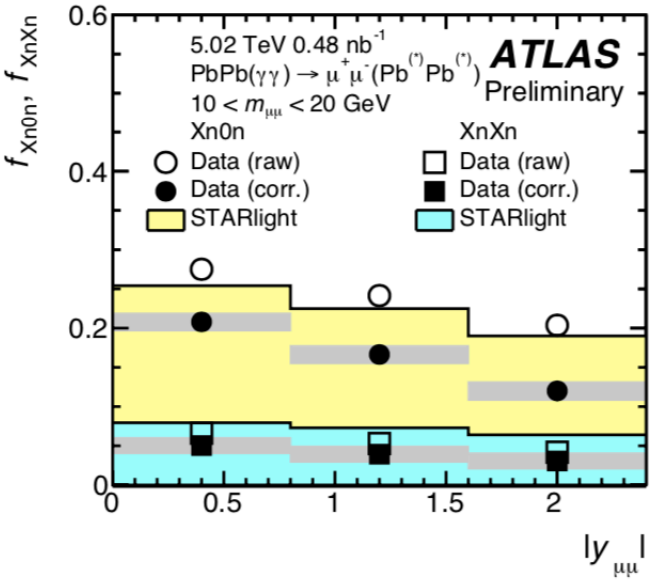


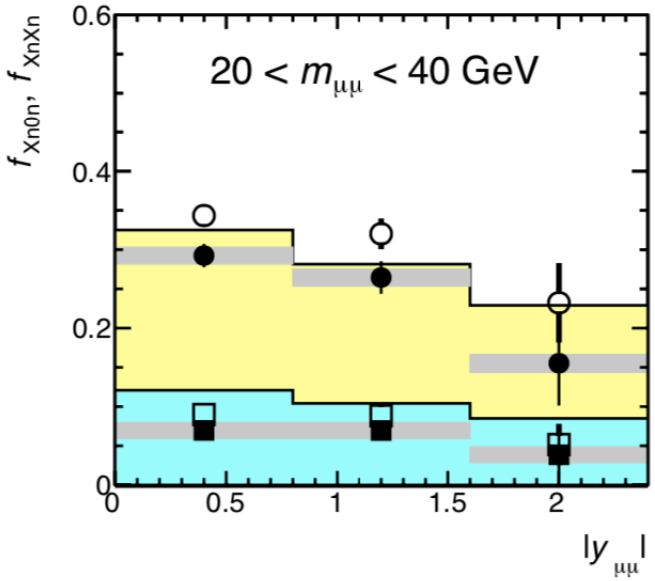
CERN-EP-2020-138

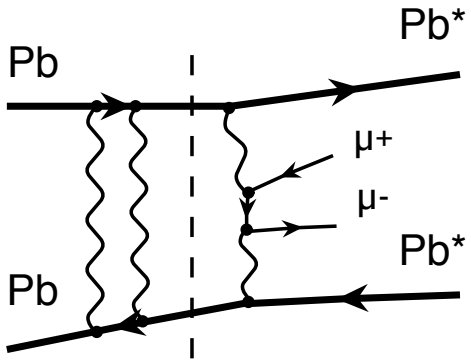
Exclusive dimuons in PbPb

CERN-EP-2020-138

- Event **fractions** with activity in **ZDC** are also measured
  - Sensitive to extra Coulomb interactions between Pb ions
    → indirect probe of impact parameter in UPC
  - Measurement needs correction for “EM pileup” contribution
  - Observing less fragmentation in data vs STARlight



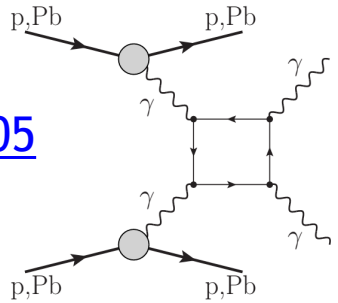




LbyL scattering in PbPb

- Rare $O(\alpha_{EM}^4)$ process
  - Sensitive to BSM physics

Original idea:
PRL 111 (2013) 080405

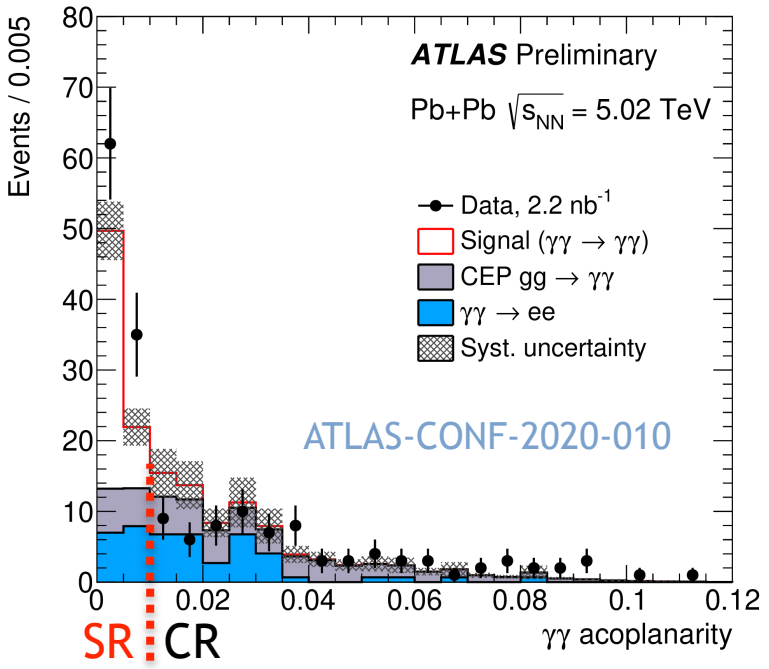


- Previous LHC measurements:
  - 2015 data: ATLAS & CMS (~4σ evidence)
  - 2018 data: ATLAS (8.2σ observation)

ATLAS, Nat. Phys. 13 (2017) 852
CMS, PLB 797 (2019) 134826
ATLAS, PRL 123 (2019) 052001

- **The new analysis covers:**
  - Exploration of full Run-2 Pb+Pb dataset
  - Differential cross-section measurement
  - Search for axion-like particles

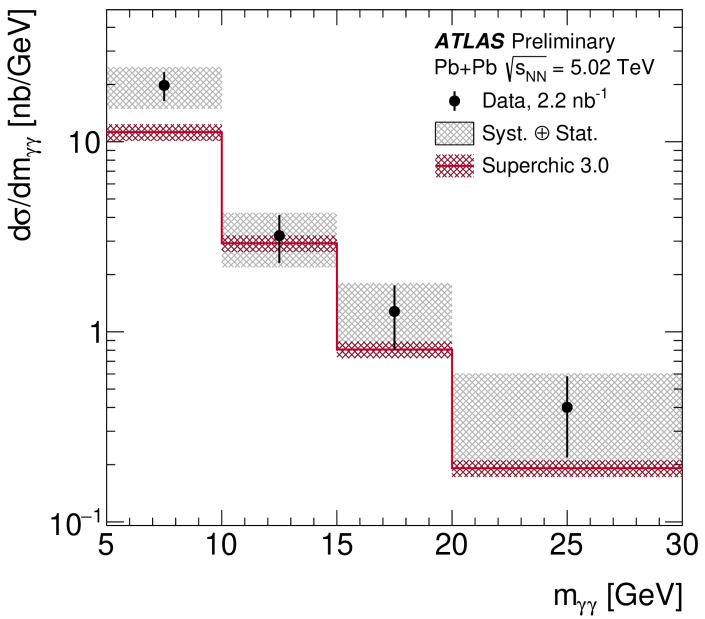
- Detectors are pushed to the limits
  - Very low E_T photons (E_T >2.5 GeV)
  - Track veto (p_T >100 MeV)
    + pixel track veto (p_T >50 MeV)

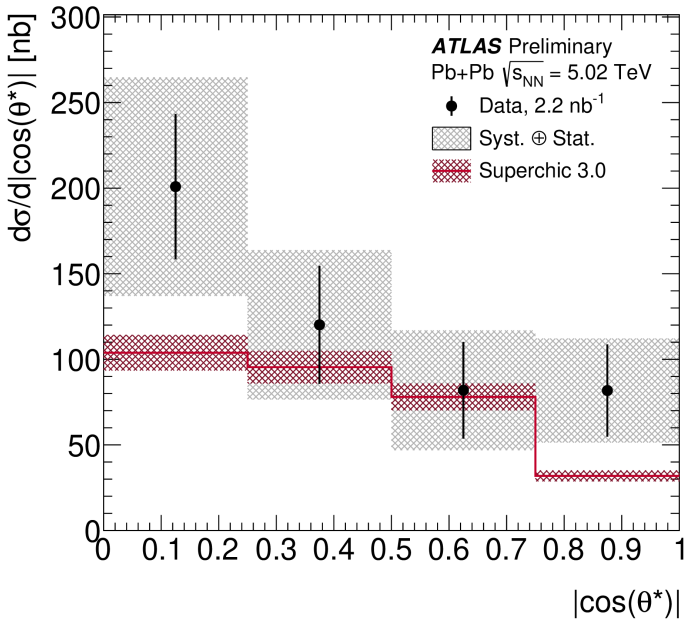


LbyL scattering in PbPb

ATLAS-CONF-2020-010

- Backgrounds
  - Dominated by misid γγ→ee and CEP γγ production
  - Estimated using data-driven methods
- Cross section measurement
  - Fiducial and differential ($m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $|\cos(\theta^*)|$, **average** p_T^{γ}) cross sections
  - Fiducial cross section about 1.7σ higher than the predictions [PRC 93 (2016) 044907, EPJC 79 (2019) 39]

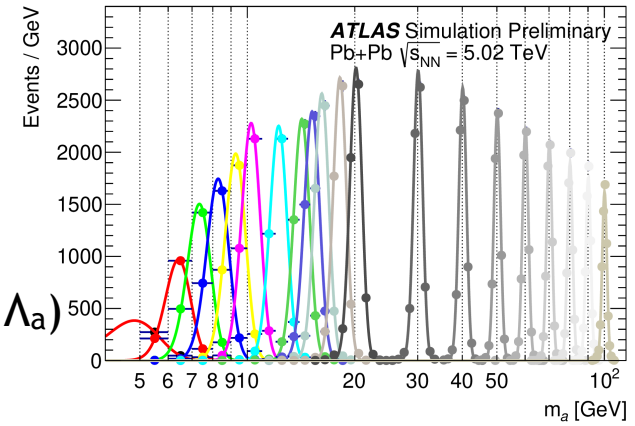


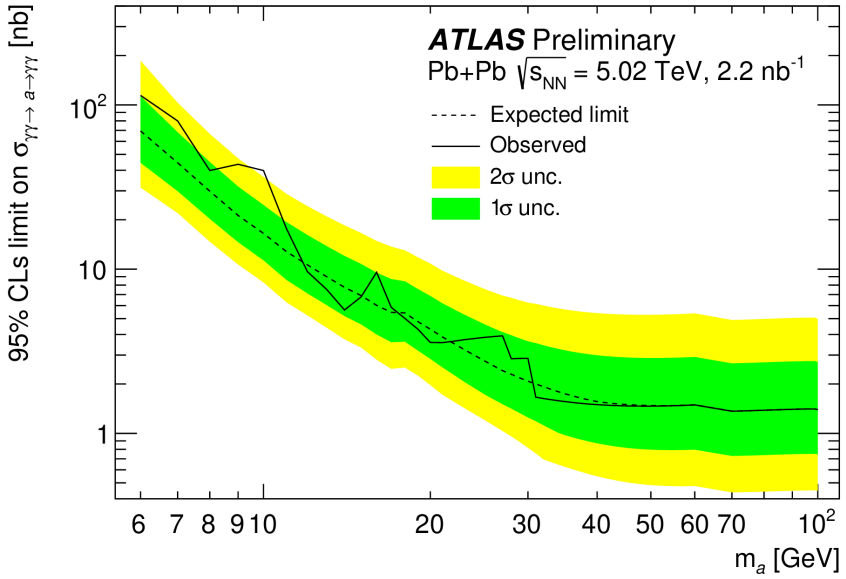


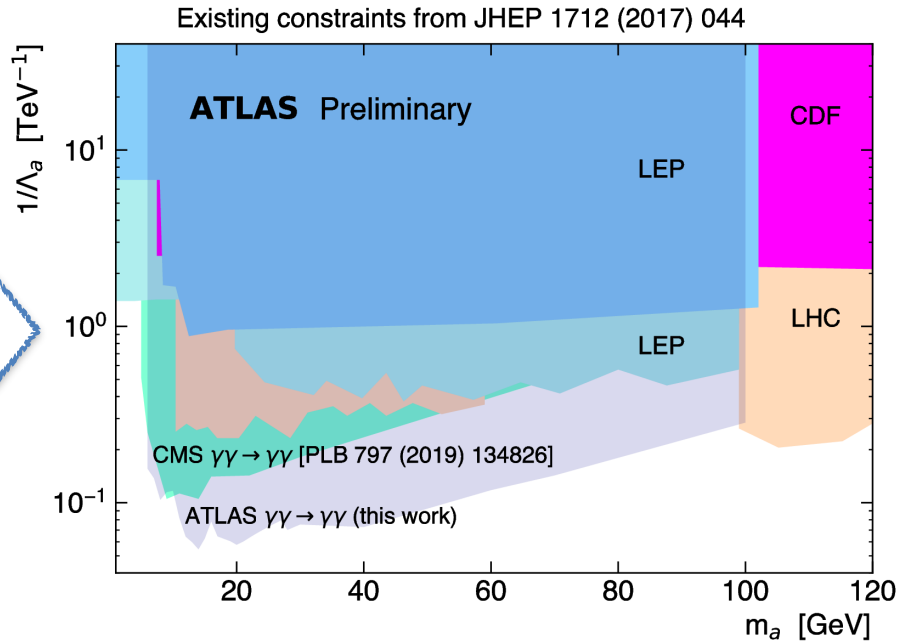
LbyL interpretation: ALP limits

ATLAS-CONF-2020-010

- Idea: search for new **γγ→a→γγ** resonances
  - Background includes SM LbyL, CEP γγ and ee
  - ALP signal generated with STARlight for various m_a
- Limits on $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ are extracted
  - Limits on σ are cast into limits on *a*γγ coupling ($1/\Lambda_a$)
  - Assuming Br(a→γγ)=1 provide the **most stringent ALP constraints (6< m_a <100 GeV)**



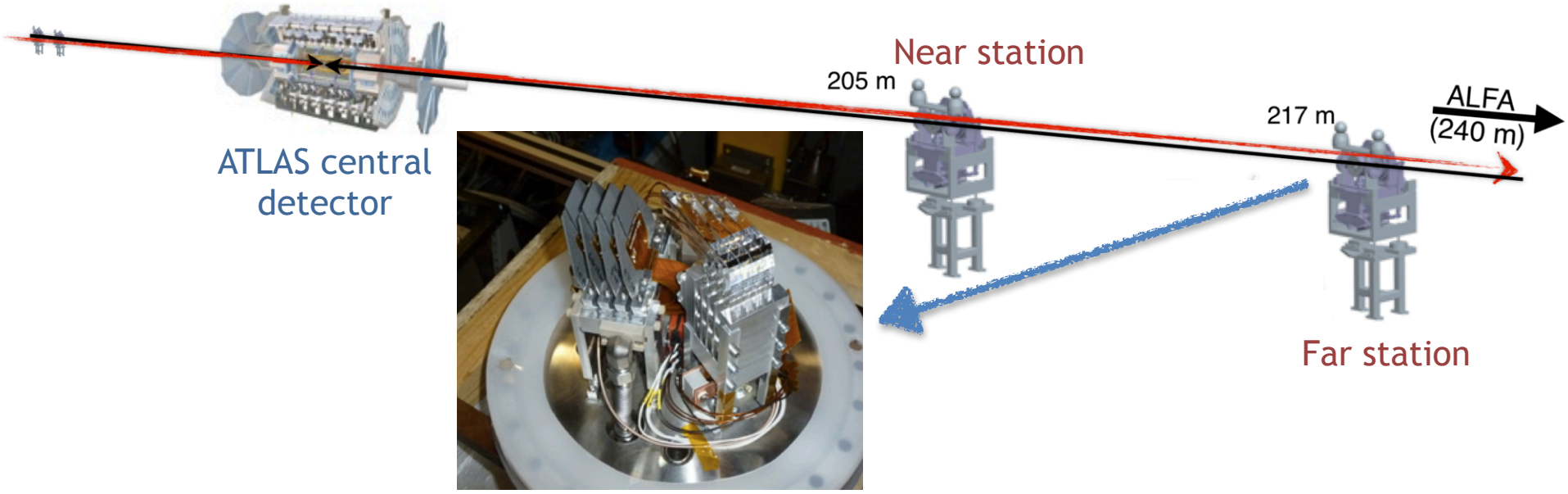




The ATLAS Forward Proton (AFP) detector

ATLAS-TDR-024

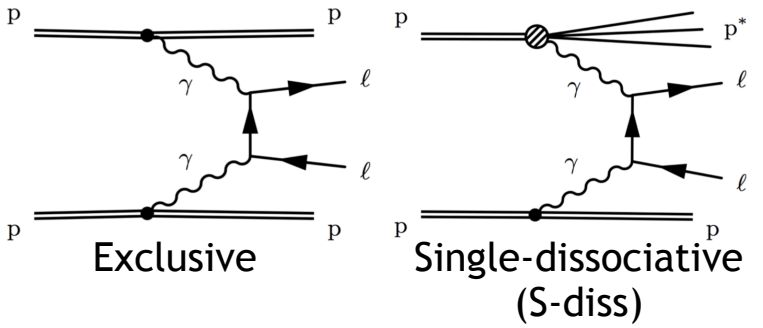
- Detectors are housed in **Roman Pots** (x4, two in each side: ±205 m and ±217 m from the ATLAS IP)
- **Near station**
  - **Silicon Tracker** with 4 planes (336 × 80 pixels per plane, 50 × 250 μm^2 pitch)
- **Far station**
  - **Silicon Tracker + Time-Of-Flight** detector (16 Cherenkov Quartz bars)
- **Full AFP** installation successful in **April 2017**
  - Participation in most LHC fills in 2017



Exclusive dileptons with AFP proton tag

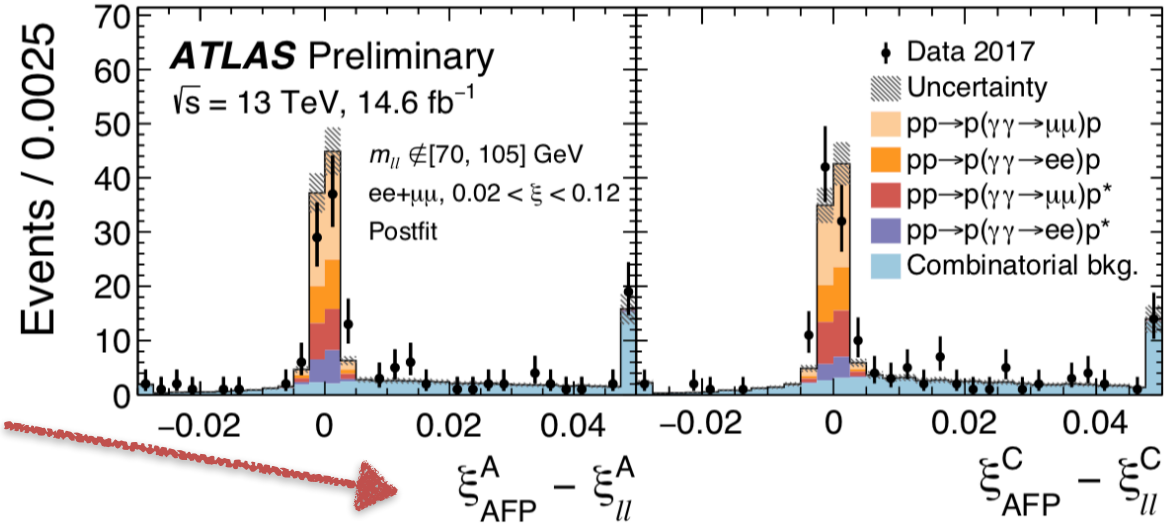
ATLAS-CONF-2020-041

- Goal: observe ($\gamma\gamma \to l^+l^-$) + p and measure cross-section
  - Exclusive and S-diss are treated as signal
- Dataset: 14.6 fb^{-1} of 13 TeV pp data
- Pioneering performance work is performed to understand new detector
  - Proton reconstruction: proton transport function based on MAD-X simulation
  - Reconstruction efficiencies: T&P method between Near and Far stations
  - Detector alignment: BLMs + in-situ corrections based on selected dimuon events
  - More details in J. Liu's talk on AFP performance (Jul 30, link)



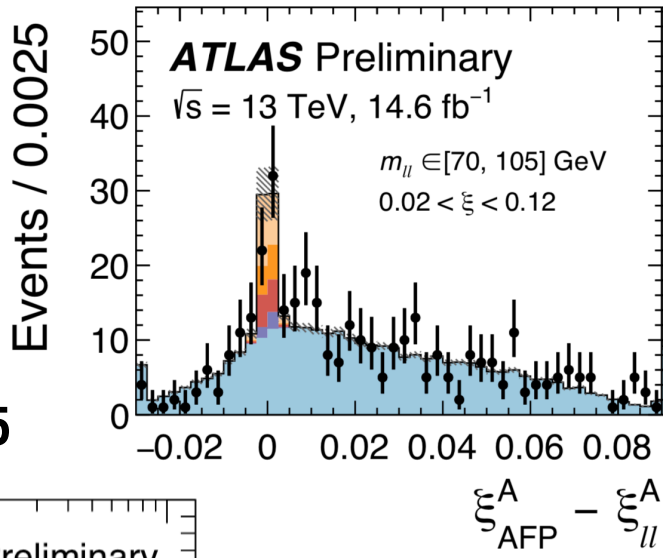
$$\xi^{\pm}_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$$
$$\xi_{AFP} = 1 - E_p/E_{beam}$$

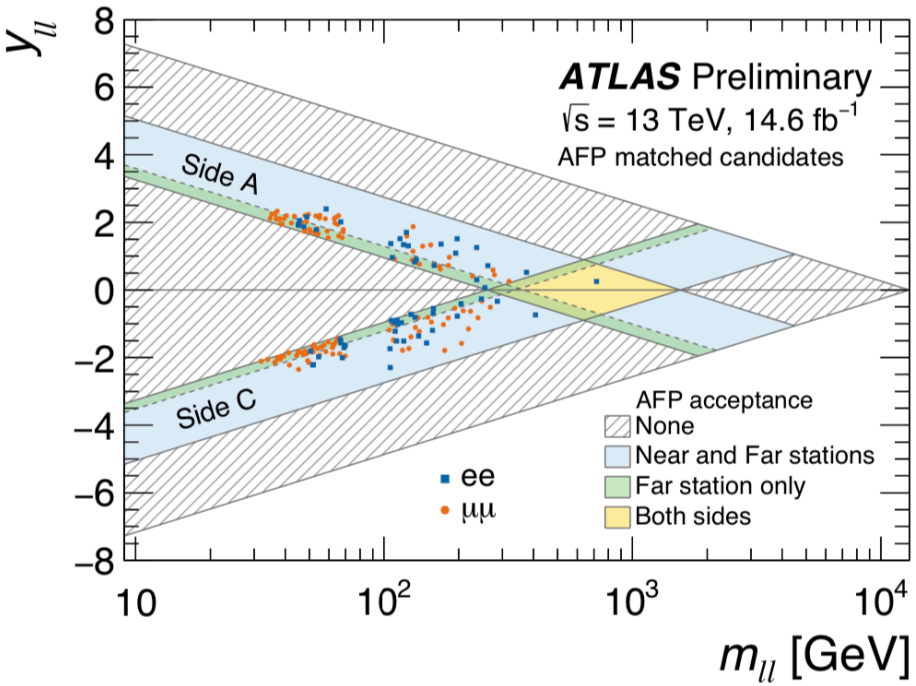
key observables!



Exclusive dileptons with AFP proton tag

- Background
  - Dominated by Drell-Yan (DY) +pileup proton **combinatorics**
  - Fully data-driven method is used (event mixing + sideband fit in $|\xi_{AFP}-\xi_{ll}|>0.005$)
  - Validated in $70< m_{ll} <105$ GeV region
- Signal events required to pass $|\xi_{AFP}-\xi_{ll}|<0.005$
  - Kinematic matching
  - Cleans events from inclusive background



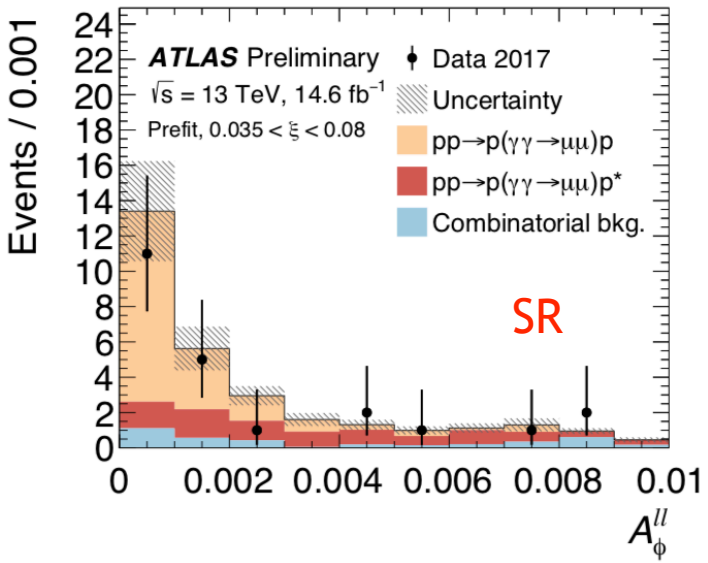


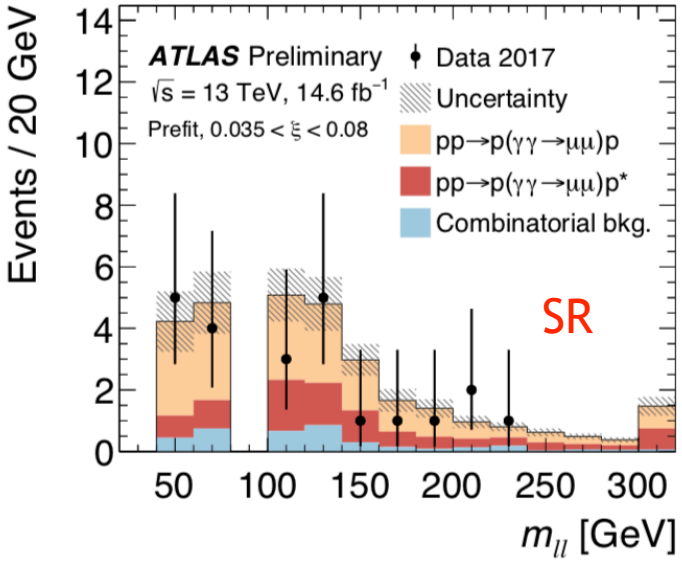
ATLAS-CONF-2020-041

Exclusive dileptons with AFP proton tag

- Fiducial cross-sections measured in the region $\xi \in [0.035, 0.08]$
  - Event kinematics in SR in agreement with expectations

ATLAS-CONF-2020-041





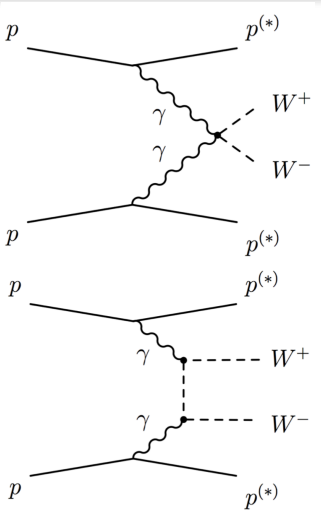
- Results are compared to proton soft survival models:

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.3 ± 1.1
S_{surv} from Ref. [30]	13.0 ± 1.0	11.1 ± 0.8
S_{surv} from Ref. [31]	10.9 ± 0.8	9.2 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

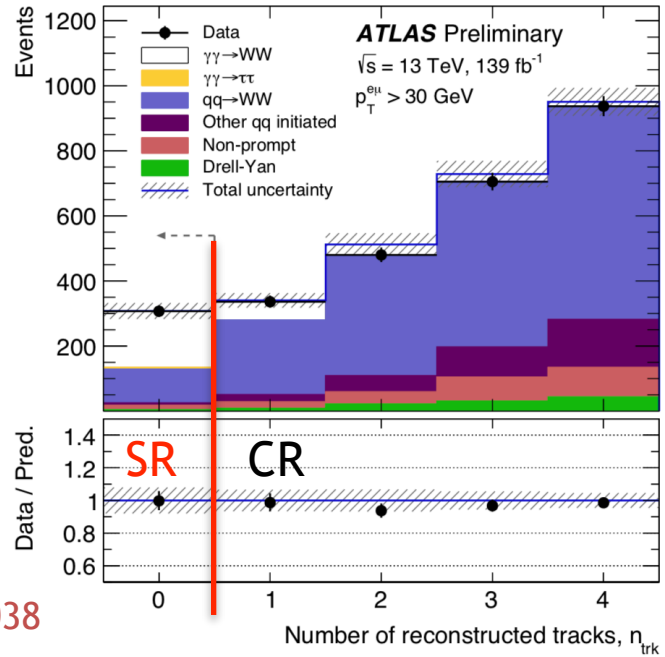
slightly different phase-space between ee and μμ

[30] Eur. Phys. J. C 76 (2016) 9
[31] Phys. Lett. B 741 (2015) 66

γγ→WW measurement in pp



- Rare electroweak process that probes SM γγWW vertex
- **New measurement** exploits full Run-2 pp dataset
  - Follow-up of Run-1 "evidence" measurements:
    ATLAS PRD 94 (2016) 032011,
    CMS JHEP 1608 (2016) 119
  - Tag **$e^{\pm}\mu^{\mp}$ pairs** with $p_T^{e\mu} > 30$ GeV ($p_T^{e\mu}$ as a MET proxy)
  - Key signature: No tracks near lepton vertex (note no AFP tag is used)
- Main background: QCD-induced WW
- Main challenge: Physics modelling of events with small particle activity (UE, pileup, …)

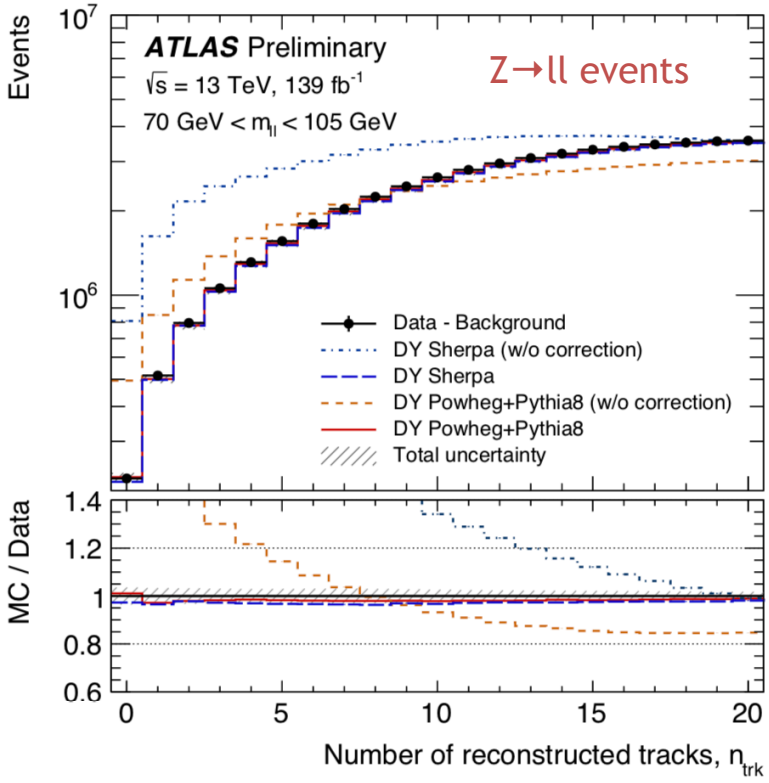


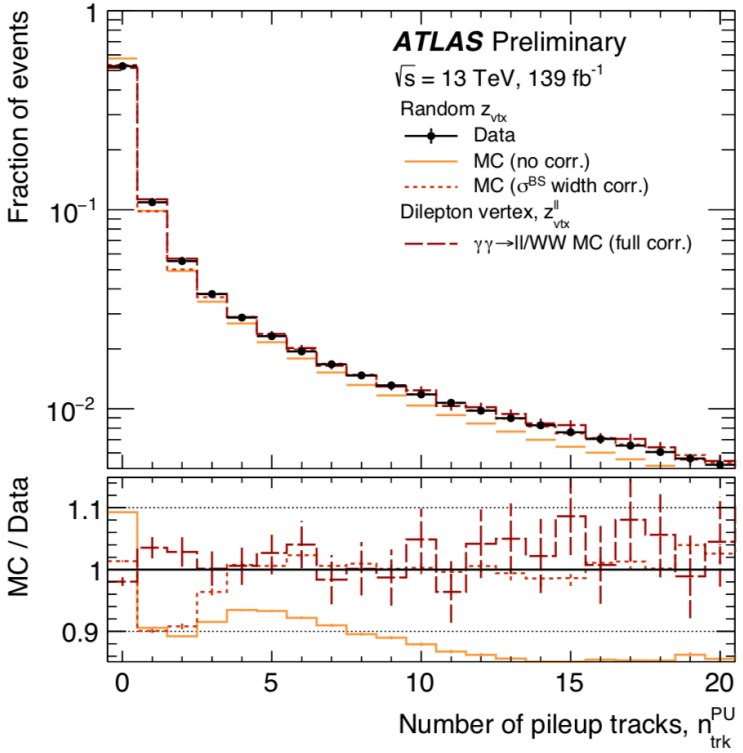
ATLAS-CONF-2020-038

γγ→WW measurement in pp

ATLAS-CONF-2020-038

- N_{ch} modelling corrections
  - Underlying event correction: reweight inclusive WW and DY ττ backgrounds such that N_{ch} spectrum matches data (weights derived in Z-peak region)
  - Pileup correction: correct for PU tracks randomly associated with the interaction vertex (data-driven z_0 sampling technique is employed)

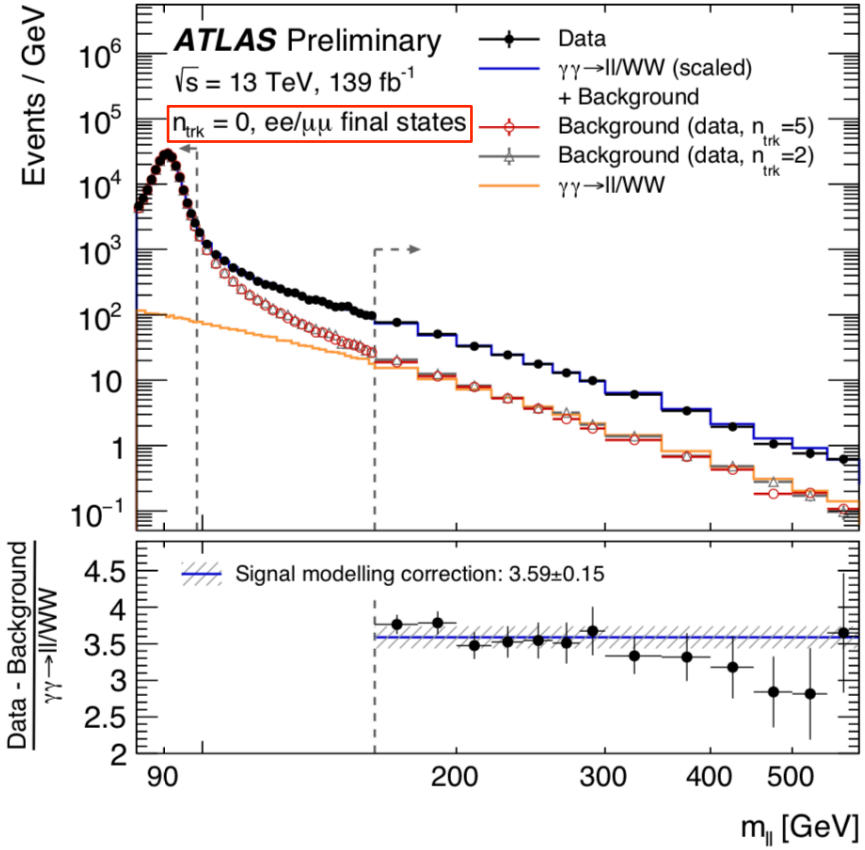




γγ→WW measurement in pp

ATLAS-CONF-2020-038

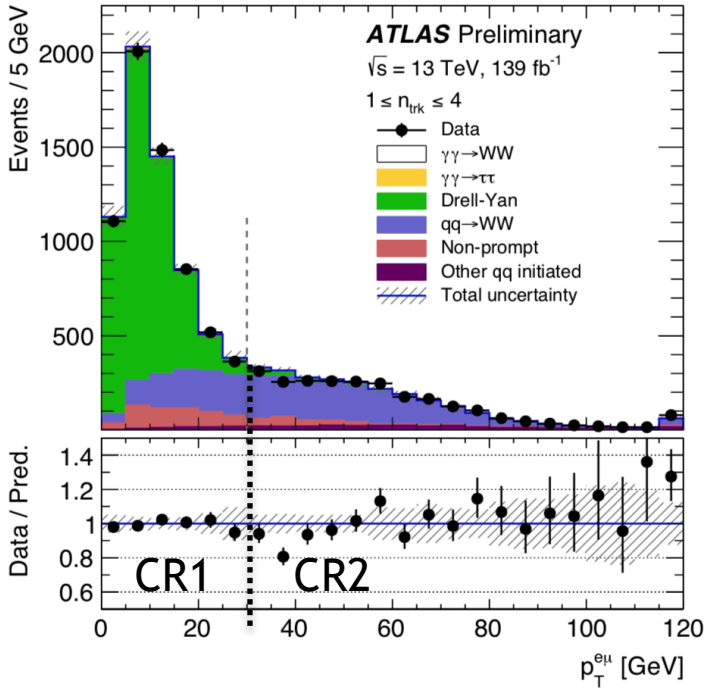
- Dedicated signal corrections
  - Exclusive efficiency (N_{trk} = 0) in MC signal corrected using z_0 sampling technique
  - Baseline signal MC includes only fully elastic contribution
    → N_{trk} = 0 events corrected with **dissociative SF (3.59±0.15)** using γγ→l+l- events for $m_{ll} > 2m_W$

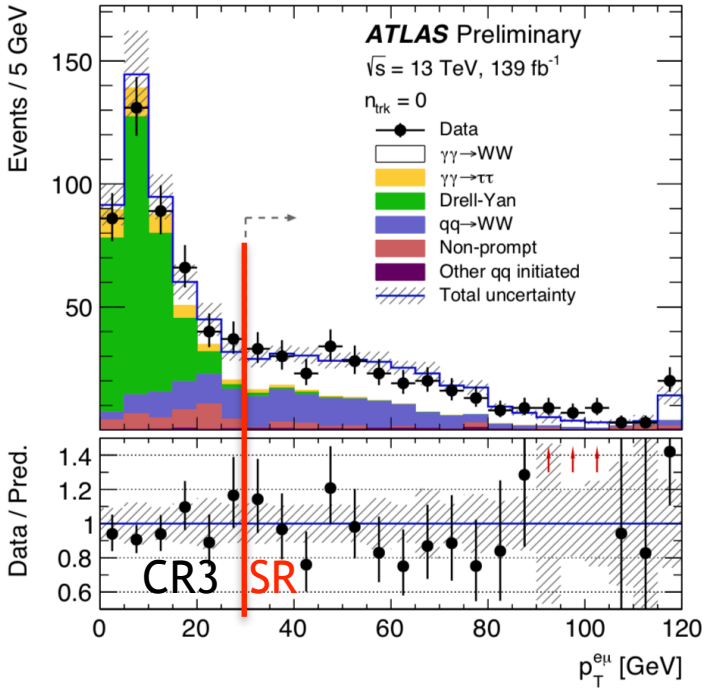


γγ→WW measurement in pp

ATLAS-CONF-2020-038

- Simultaneous fit performed to yields in **SR** and **3 CRs**
  - CRs used to constrain inclusive WW and DY ττ
- 307 events observed in SR (132 background events expected)
  - **γγ→WW observed with a significance of 8.4σ** (6.7σ expected)
  - Measured fiducial cross-section: **3.13 ±0.31(stat.) ±0.28(syst.) fb**
  - Theory predictions (MG5+Pythia8 based) lie in the range of **2.1** and **2.6 fb**
    - Depending on the choice of soft survival model





Summary

- Rich physics program of **two-photon interactions** at the LHC
  - At the 'boundary' of **electroweak**, **forward** and **heavy-ion** physics
  - Measurements utilise both **pp** and **Pb+Pb** dataset

- Diverse set of measurements performed with ATLAS, including:
  - **Observation** of new SM processes ($\gamma\gamma \rightarrow WW$ scattering)
  - **Precision** (differential) cross section measurements
  - Non-standard **BSM** searches
  - First proton-tagged photon collisions observed with new **AFP** detector

  - This is clearly way beyond "simple **QED** testing"
  - Excellent groundwork for future, more detailed studies → stay tuned!

Backup

γγ→WW measurement in pp

Source	Impact [%]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons	1.5
Background, statistical	6.7
Modelling	
Pileup modelling uncertainties	1.1
Underlying event modelling uncertainties	1.4
Signal modelling uncertainties	2.1
WW modelling uncertainties	4.0
Other background uncertainties	1.7
Luminosity	1.7
Total	8.9

Exclusive dileptons with AFP proton tag

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%

Summary of sources of systematic uncertainty and their impact on the cross-section measurement.