IMPRS
for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

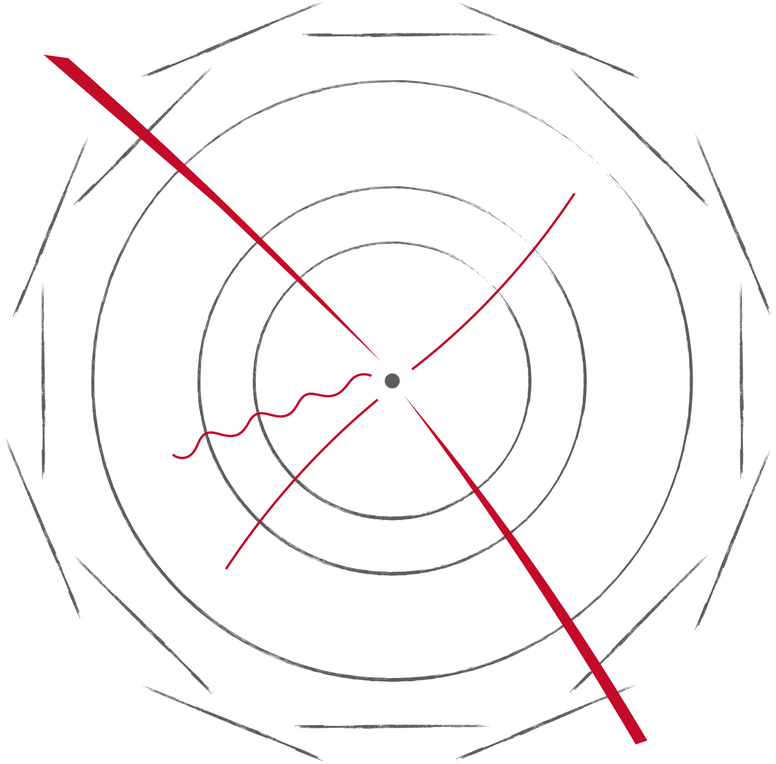
ATLAS EXPERIMENT

FSP ATLAS
Erforschung von Universum und Materie

KIRCHHOFF-INSTITUT FÜR PHYSIK

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Measurement of the ZZγ final state

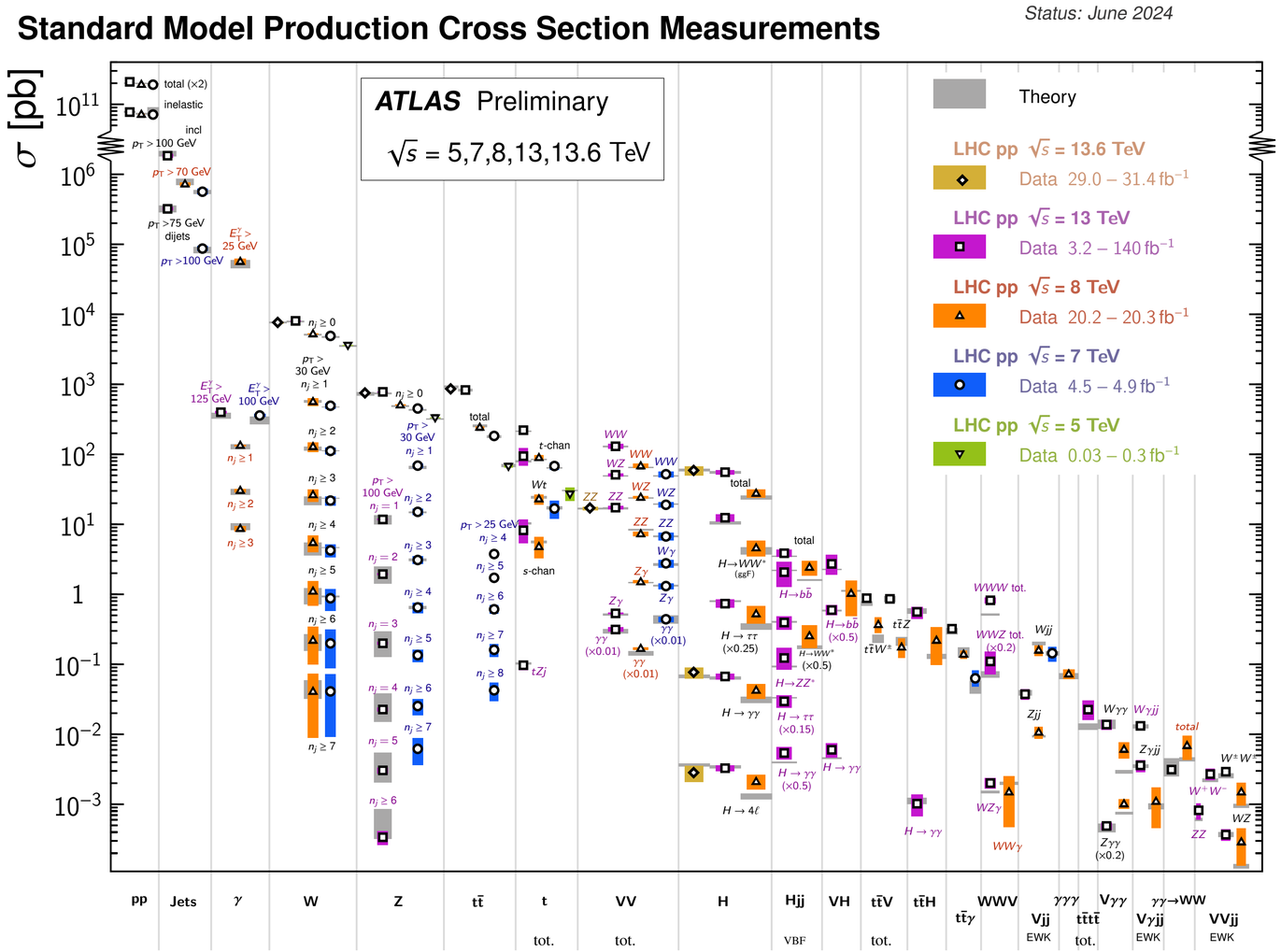


Anke Ackermann
on behalf of the ATLAS Collaboration

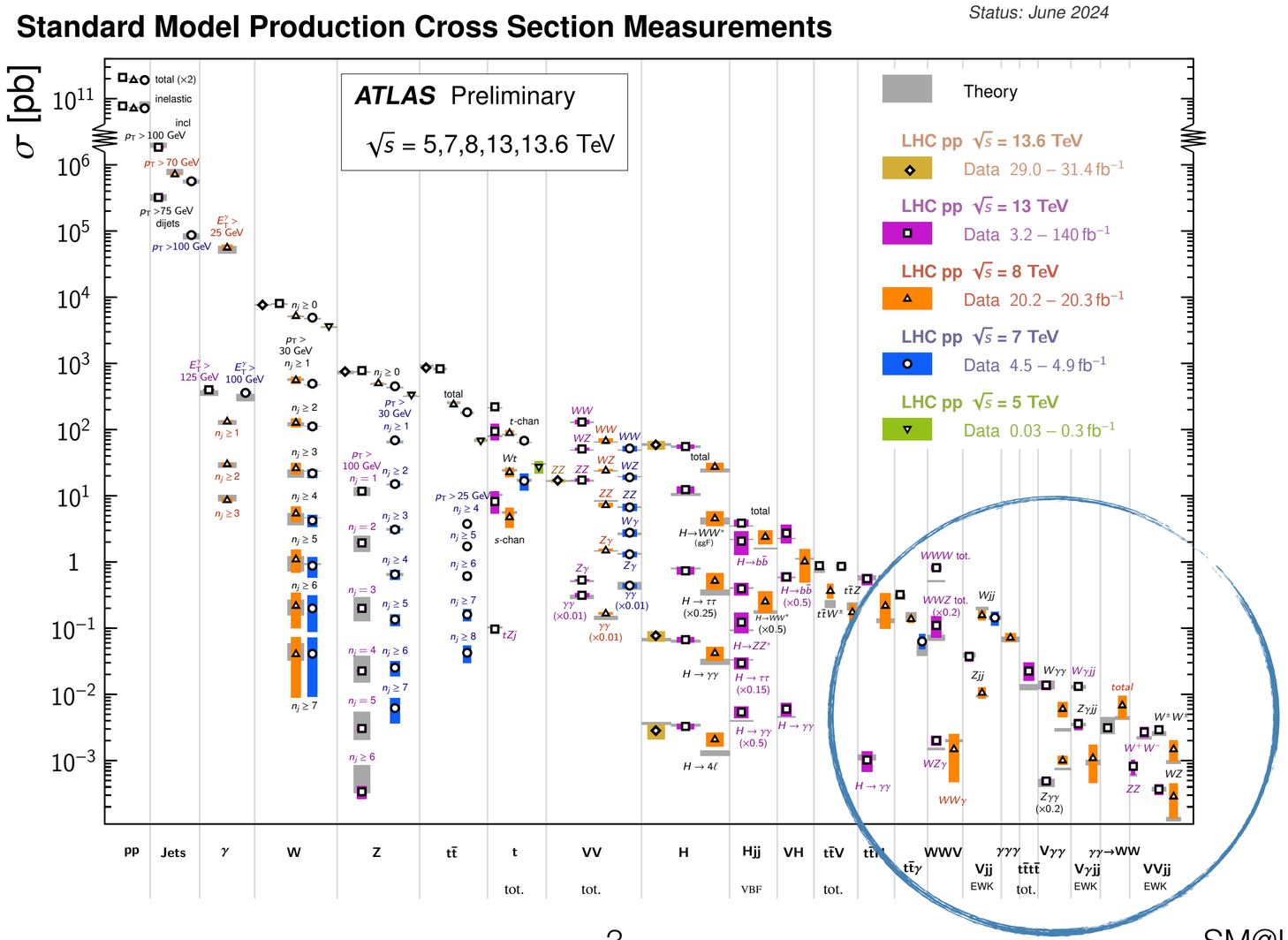
April 8, 2026

SM@LHC, Torino

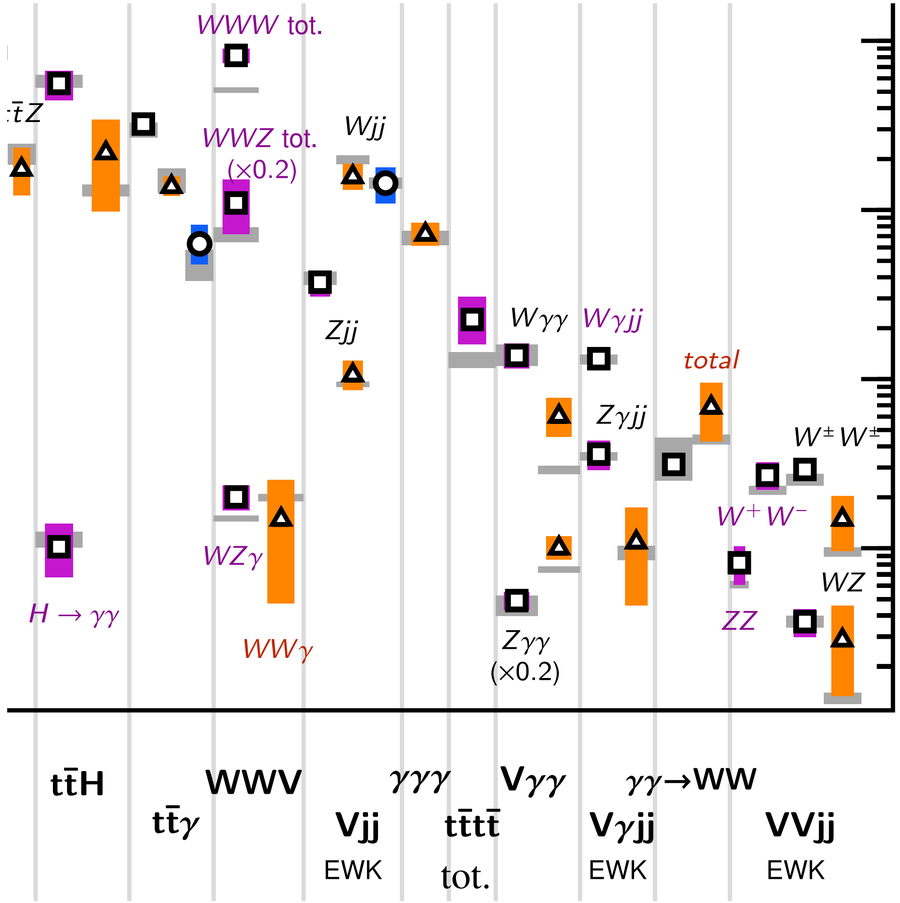
Triple-gauge-boson processes



Triple-gauge-boson processes



Triple-gauge-boson processes

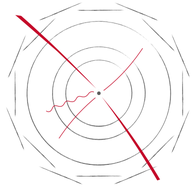


Run 1: first look at triboson processes (WWγ, Zγγ)

Run 2: several triboson-final-state discoveries (e.g., WWW, WZγ, Wγγ)

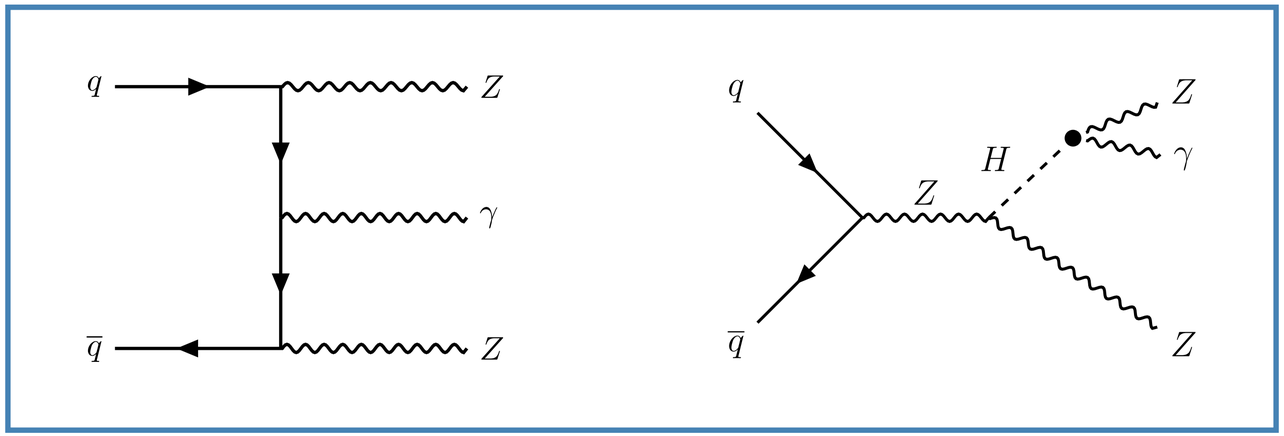
Run 3 & HL-LHC: differential triboson, enhance new physics searches

Today: first measurement of ZZγ



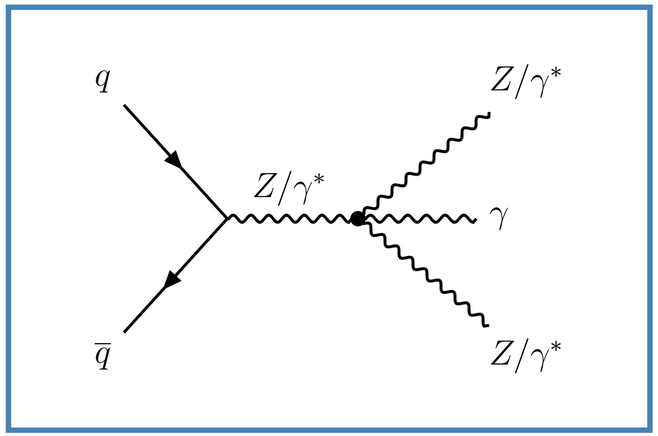
arXiv: 2602.17165

signal

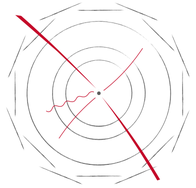


- analysis of full Run 2 data (140 fb^{-1})
- fully leptonic decay: Z → ee, μμ, signal: lllly
- rare final state, $\sigma^{\text{fid}}_{ZZ\gamma} \sim 10^{-4}$ pb

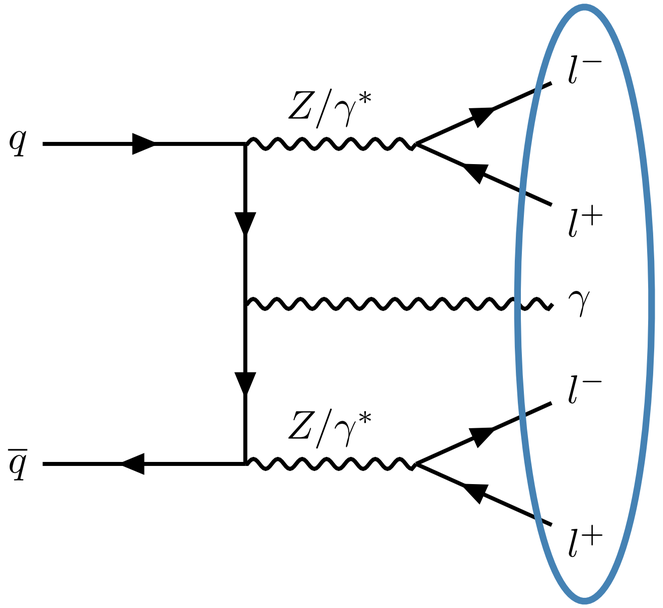
new physics?



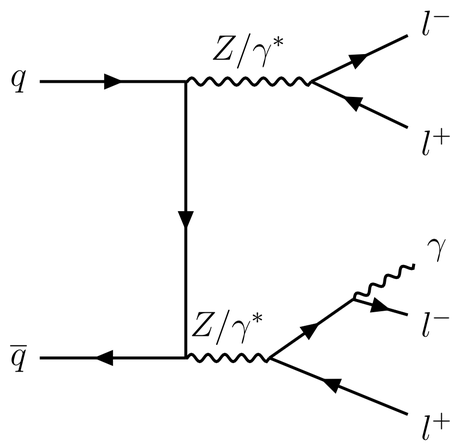
Event selection

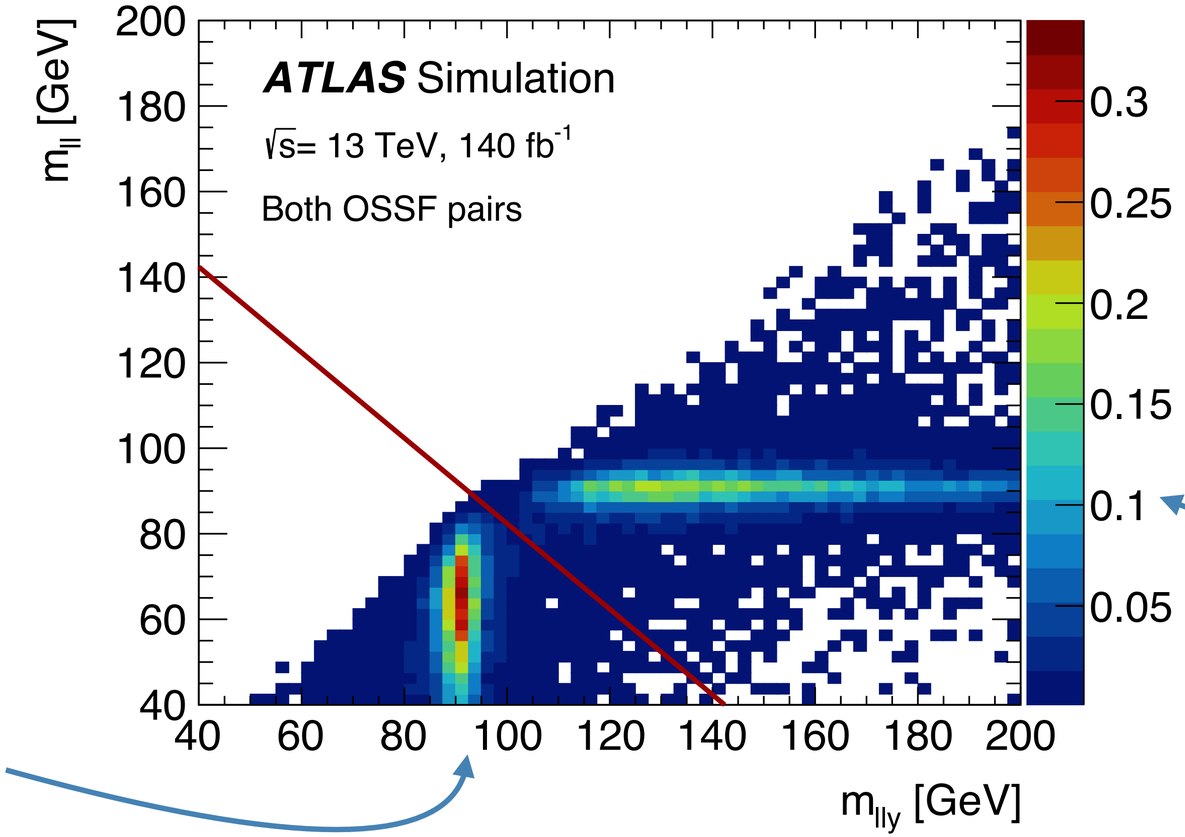


- 2 pairs of 2 opposite-sign same-flavour (OSSF) leptons → 4e, 4μ, 2e2μ
- invariant mass $m_{\ell\ell} > 40$ GeV
- $\min(| m_{\ell\ell,1} - m_Z | + | m_{\ell\ell,2} - m_Z |)$
- 1 photon, $p_T > 20$ GeV
- FSR rejection

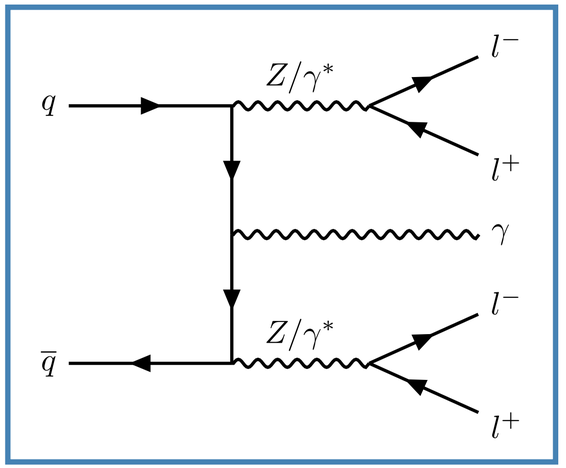


Final state radiation (FSR) rejection



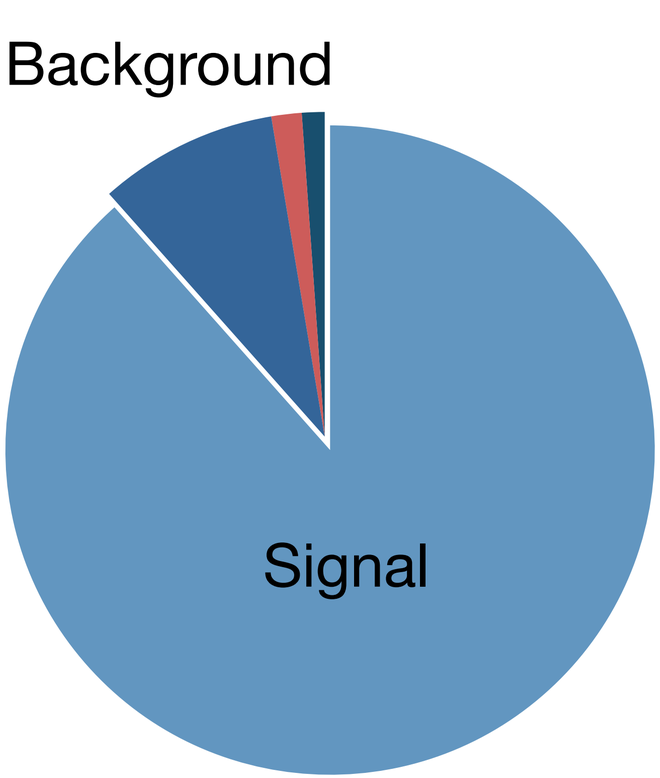


signal

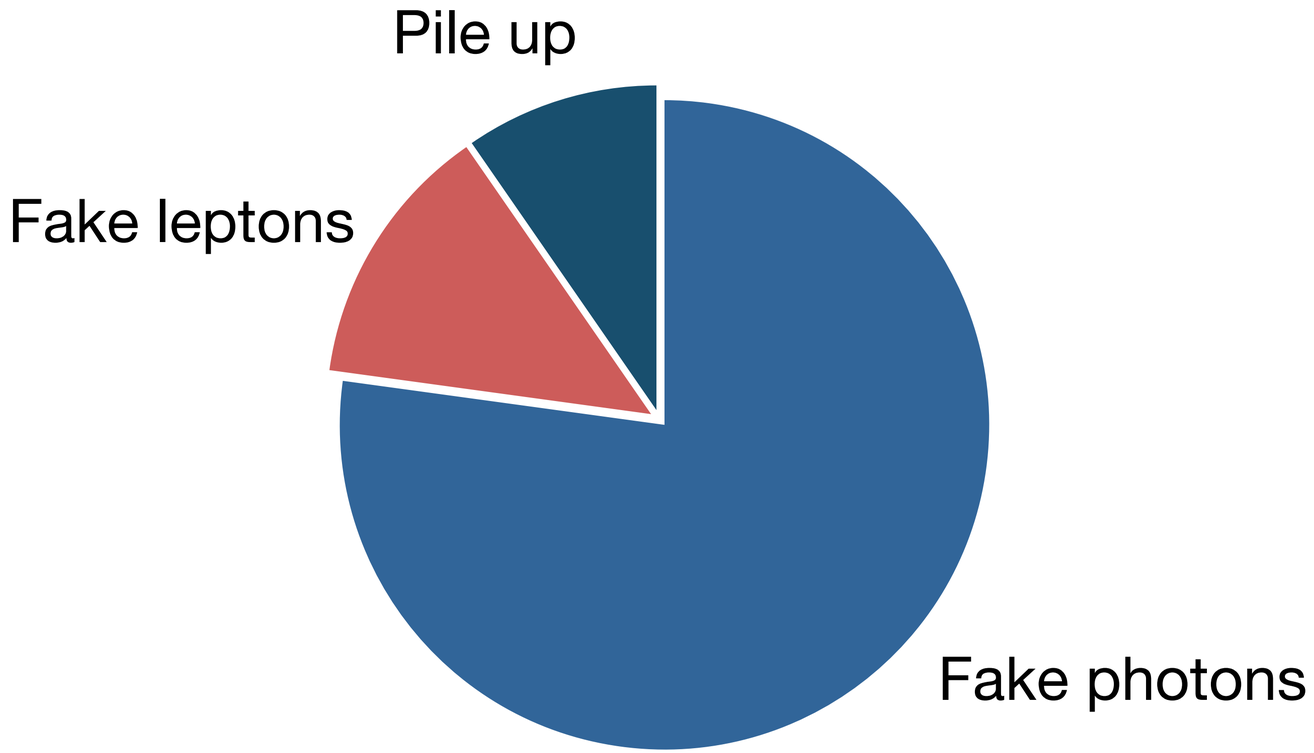


FSR rejection requirement: ($m_{\ell\ell\gamma} + m_{\ell\ell}$) > 2 m_Z

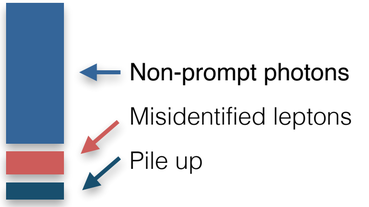
Signal and background composition



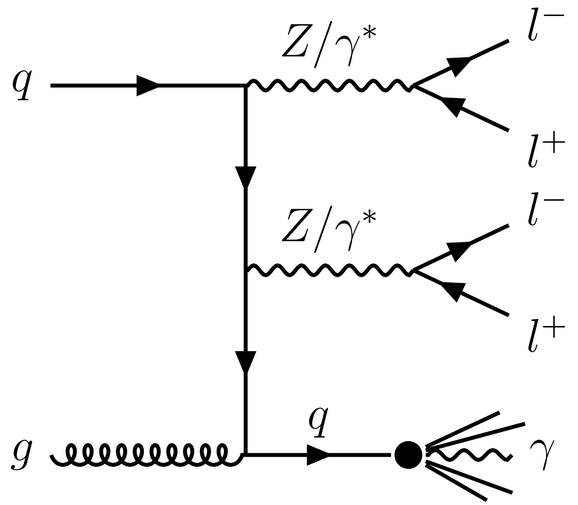
$N_{tot} \approx 8$



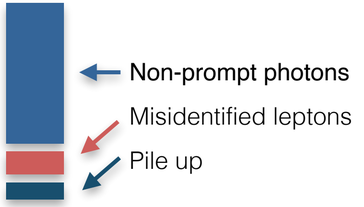
$N_{bkg} \approx 1$



Non-prompt photons

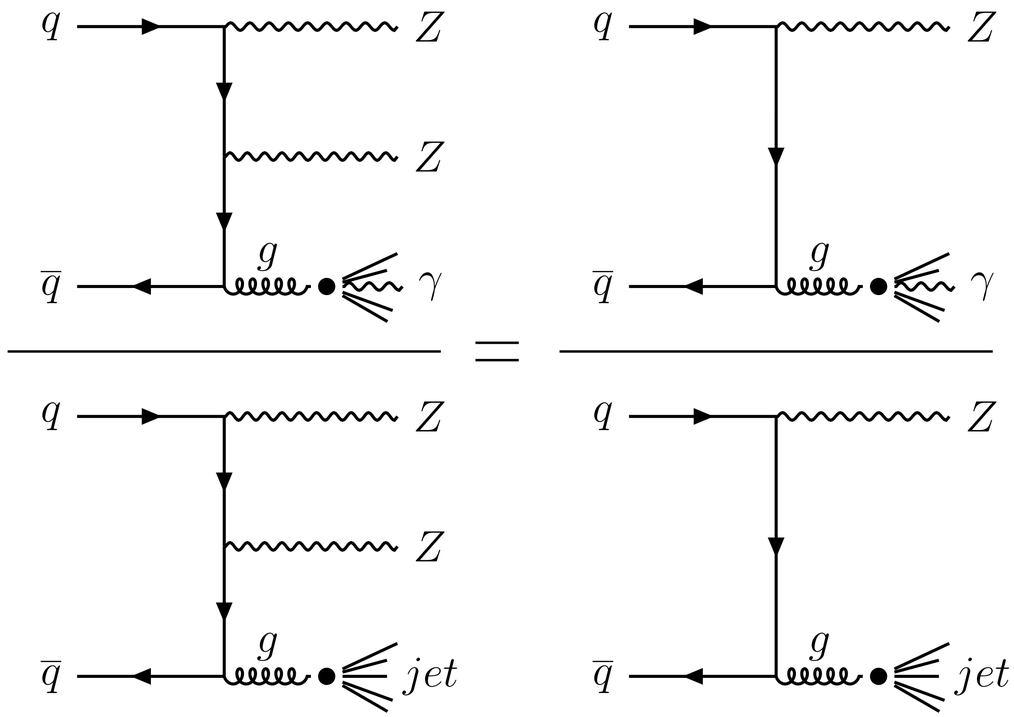


Non-prompt photons

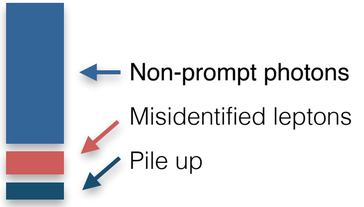


Ansatz: The ratio of non-prompt/fake photons produced in jets is independent of the simultaneous produced particles

$$\frac{N_{ZZ\gamma}^{\gamma\text{fake}}}{N_{ZZ}^{\text{jets}}} = \frac{N_{Z\gamma}^{\gamma\text{fake}}}{N_{Z}^{\text{jets}}}$$



Non-prompt photons



Ansatz: The ratio of non-prompt/fake photons produced in jets is independent of the simultaneous produced particles

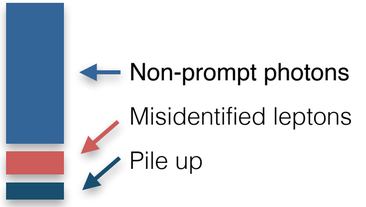
$$\frac{N^{\gamma\text{fake}}_{ZZ\gamma}}{N^{\text{jets}}_{ZZ}} = \frac{N^{\gamma\text{fake}}_{Z\gamma}}{N^{\text{jets}}_{Z}}$$

$$N^{\gamma\text{fake}}_{ZZ\gamma} = N^{\gamma\text{fake}}_{Z\gamma}\frac{N^{\text{jets}}_{ZZ}}{N^{\text{jets}}_{Z}}$$

Zγ analysis
JHEP03(2020)054

data & MC

Non-prompt photon estimation



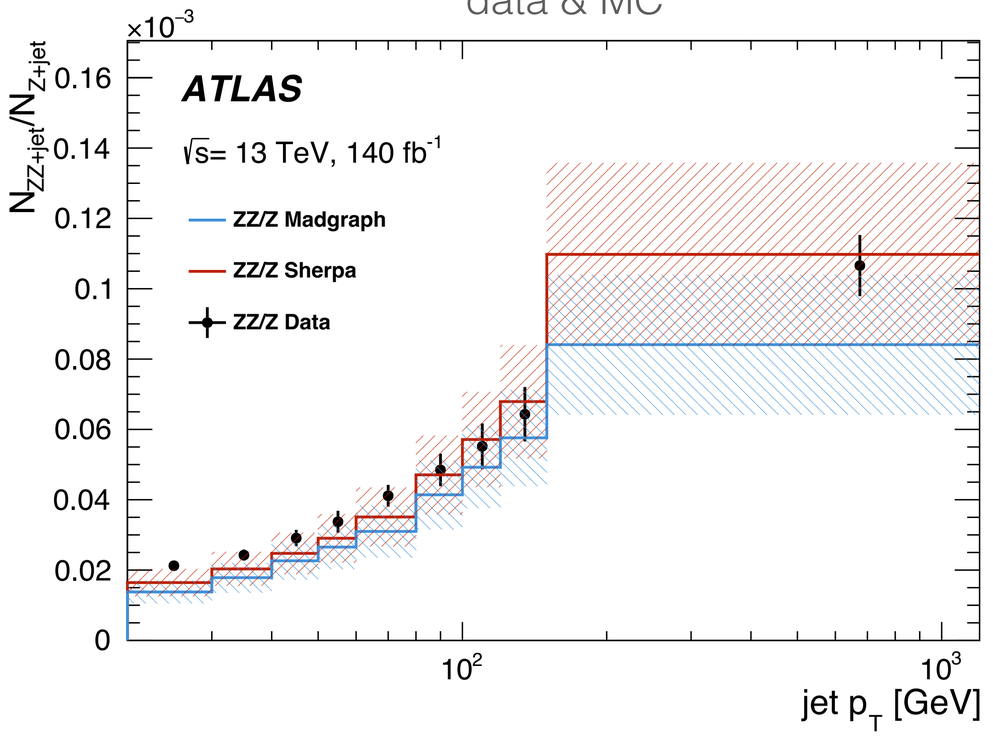
$$N^{\gamma\text{fake}}_{ZZ\gamma} = N^{\gamma\text{fake}}_{Z\gamma}\frac{N^{\text{jets}}_{ZZ}}{N^{\text{jets}}_{Z}}$$

Purity P:

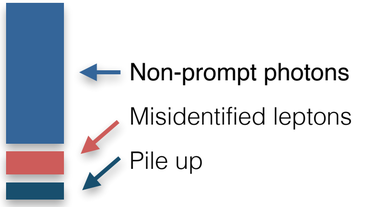
$$P = \frac{N^{\text{prompt}}_{Z\gamma}}{N^{\text{prompt}}_{Z\gamma} + N^{\text{fake}}_{Z\gamma}}$$

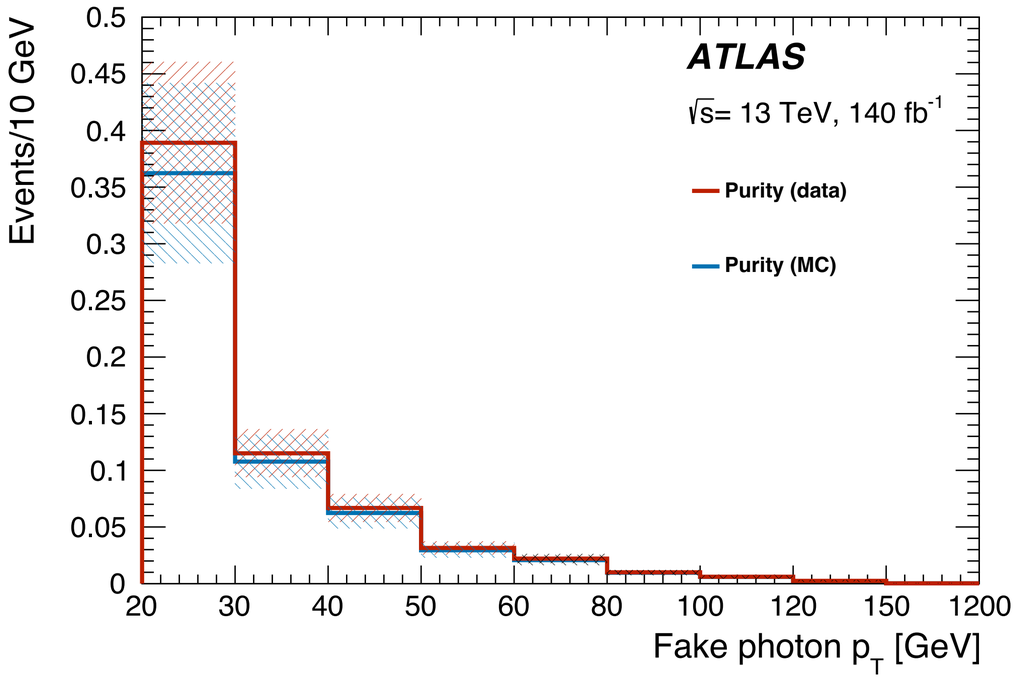
$$P = 1 - \frac{N^{\text{fake}}_{Z\gamma}}{N_{\text{obs}} - N_{\text{other bkg}}}$$

ZZ+jets/Z+jets data & MC



Non-prompt photon estimation

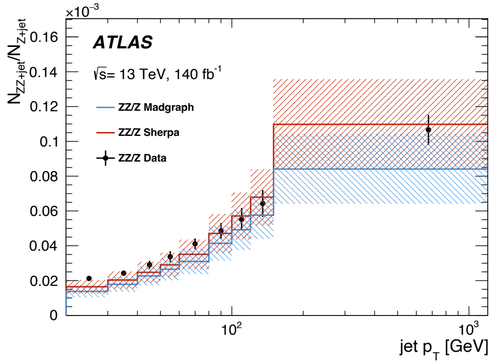




$$N_{ZZ\gamma}^{\gamma\text{fake}} = N_{Z\gamma}^{\gamma\text{fake}} \frac{N_{ZZ}^{\text{jets}}}{N_{Z}^{\text{jets}}}$$

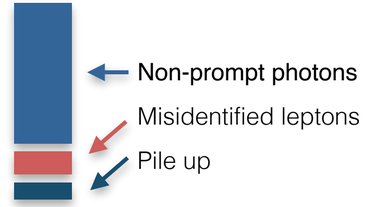
Zγ analysis

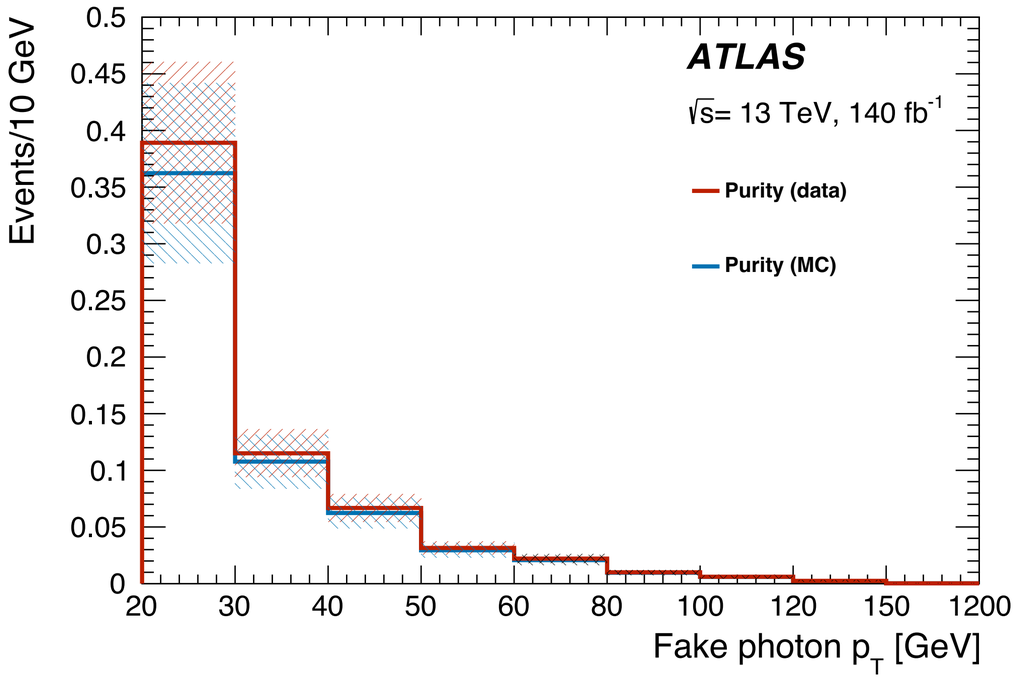
Z+jets/ZZ+jets data



$$N_{ZZ\gamma}^{\gamma\text{fake}} = 0.713 \pm 0.019\ (\text{stat.}) \pm 0.098\ (\text{syst.})$$

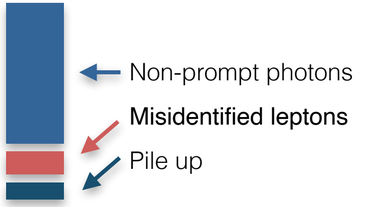
Non-prompt photon estimation



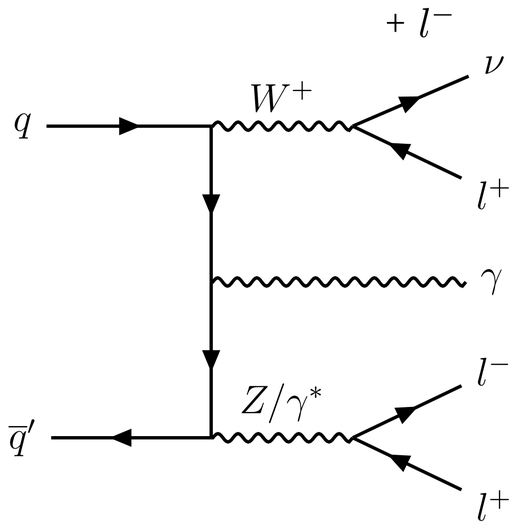


Source	Relative uncertainty	
	Purity (MC)	Purity (data)
Statistics (tot.)	2.6%	2.6%
Integrated luminosity	0.8%	0.8%
MC systematics	2.3%	-
Purity measurement (tot.)	18%	14%
Modelling uncertainty	7%	7%
Quark-gluon variations	10%	10%
Total uncertainty	22%	18%

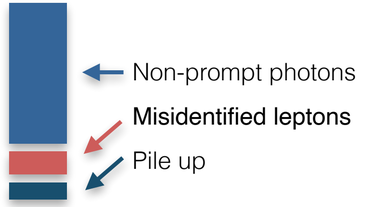
$$N_{ZZ\gamma}^{\gamma\text{fake}} = 0.713 \pm 0.019\ \text{(stat.)}\ \pm 0.098\ \text{(syst.)}$$



Misidentified leptons



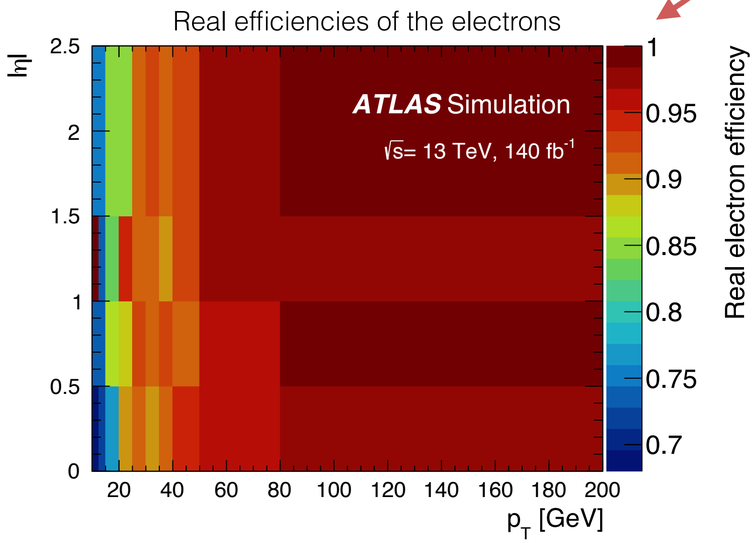
Matrix method

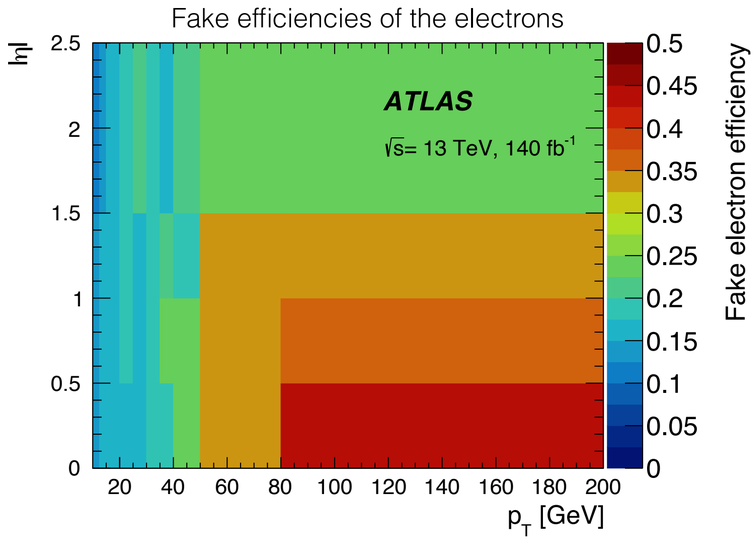


SR

$$\begin{pmatrix} N^t \\ N^l \end{pmatrix} = \begin{pmatrix} \epsilon_r & \epsilon_f \\ 1-\epsilon_r & 1-\epsilon_f \end{pmatrix} \begin{pmatrix} N^r \\ N^f \end{pmatrix}$$

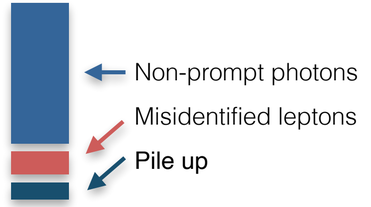
CR



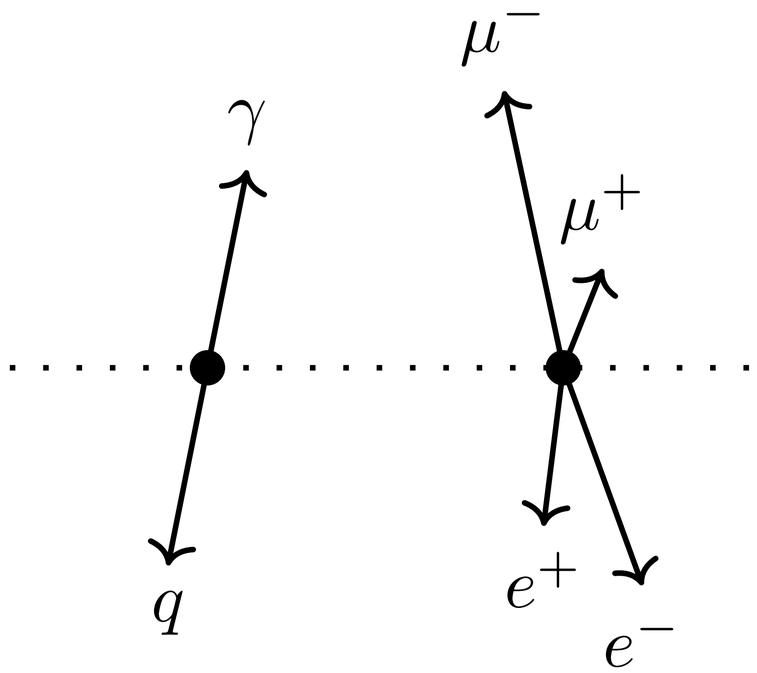


Source	Relative uncertainty
Statistics	18%
Efficiency ($N_{ZZ}^{\text{fake }\ell}$)	7%
MC variations ($N_{ZZ}^{\text{fake }\ell}$)	56%
Binning	14%
Modeling	31%
Systematic uncertainty	64%
Total uncertainty	66%

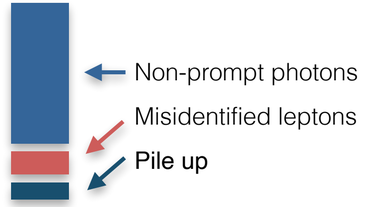
$$N_{ZZ\gamma}^{\ell\,\text{fake}} = 0.122 \pm 0.022\ (\text{stat.}) \pm 0.078\ (\text{syst.})$$


Non-prompt photons
Misidentified leptons
Pile up

Pile up


μ^-
γ
μ^+
e^+
q
e^-

Pile up



- two independent interactions in the same bunch crossing
- pile up contribution: ZZ + γ

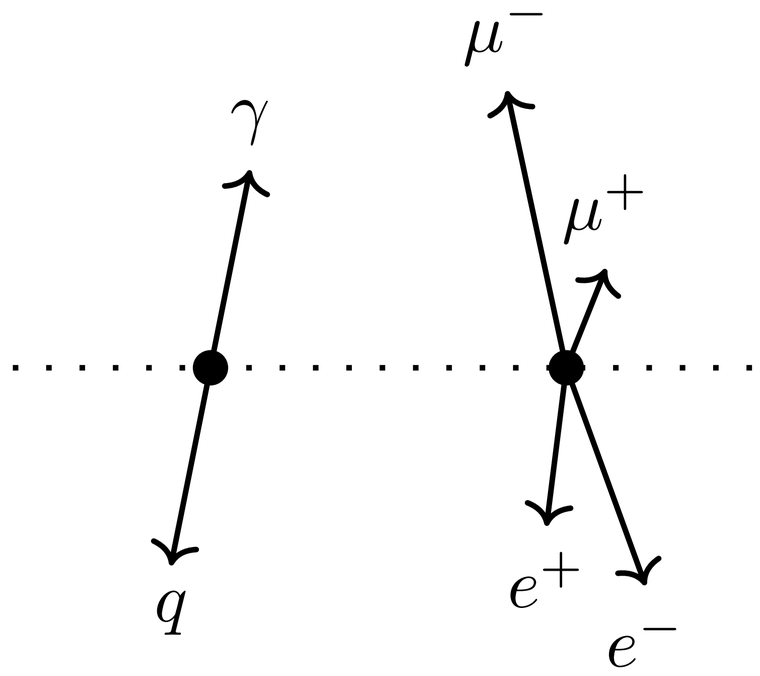
  ↪ photon cannot be associated to any vertex
- Ansatz: $N_{ZZ+\gamma} \sim P_{ZZ}\, P_{\gamma}$

MC cross-sections

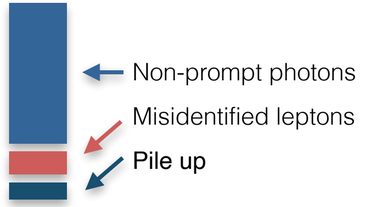
Selection efficiency at particle level

$$N_{PU} = \langle \mu \rangle \frac{\sigma_{ZZ}\sigma_{\gamma}}{\sigma_{inel}} \epsilon^{fid}_{ZZ+\gamma} \mathscr{L} \cdot C$$

Correction factor reconstruction/particle level



Pile up



- two independent interactions in the same bunch crossing
- pile up contribution: ZZ + γ

  ↪ photon cannot be associated to any vertex
- Ansatz: $N_{ZZ+\gamma} \sim P_{ZZ}\, P_{\gamma}$

$$N^{PU} = 0.09 \pm 0.02$$

MC cross-sections

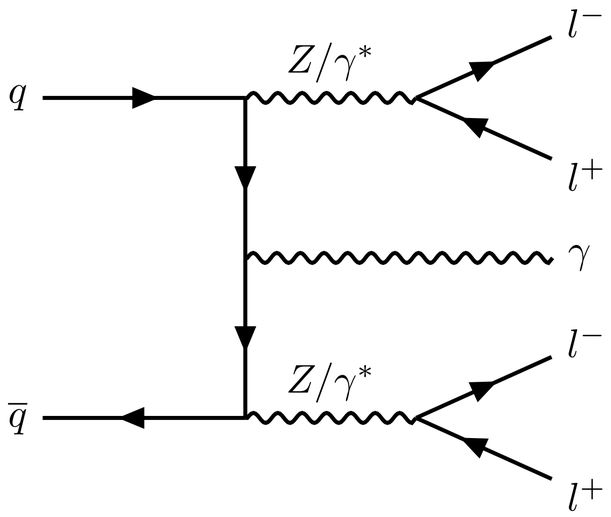
Selection efficiency at particle level

$$N_{PU} = \langle \mu \rangle \frac{\sigma_{ZZ}\sigma_{\gamma}}{\sigma_{inel}} \epsilon^{fid}_{ZZ+\gamma} \mathscr{L} \cdot C$$

Correction factor reconstruction/particle level

Source	Relative uncertainty
MC statistics	1.8%
σ_γ scale variations	28%
σ_γ PDF $\oplus \alpha_s$	2.4%
σ_{ZZ} (ATLAS measurement)	6%
Integrated luminosity	0.8%
$4\ell\gamma$ correction factor	2.5%
Total uncertainty	29%

Results

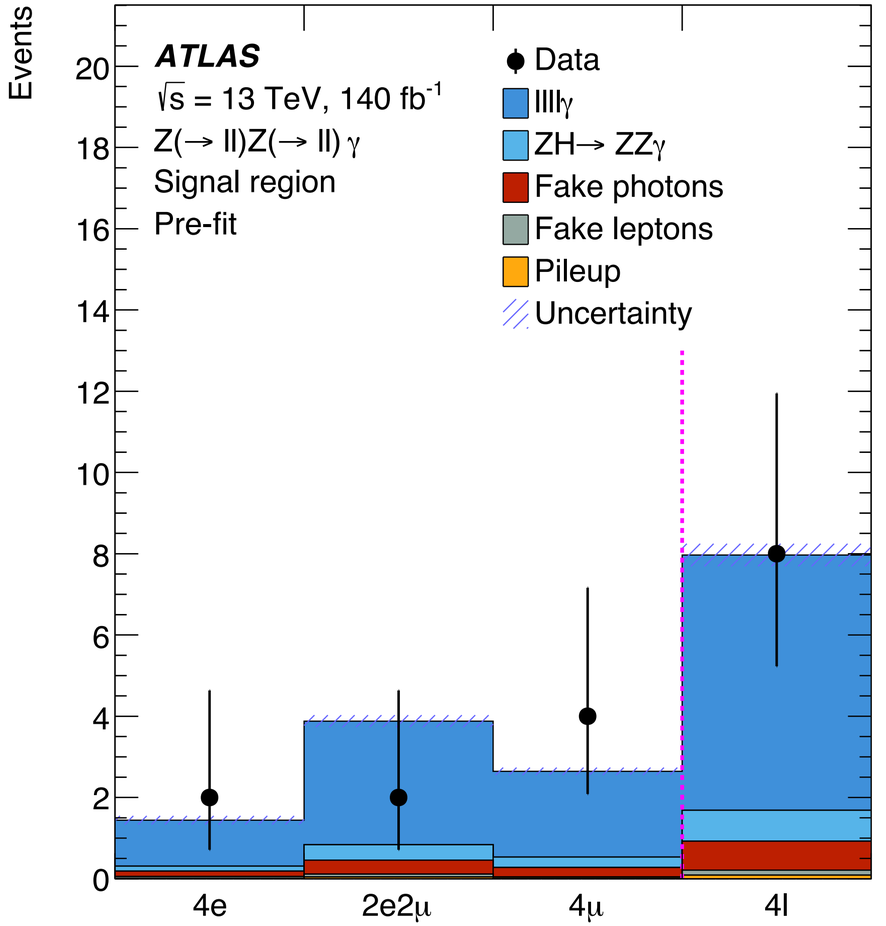


Results

	Number of events
SHERPA 2.2.11 $4\ell\gamma$	6.28 ± 0.09 (stat.) ± 0.18 (syst.)
POWHEG+PYTHIA8 $ZH \to ZZ\gamma$	0.76 ± 0.03 (stat.) ± 0.03 (syst.)
Signal	7.04 ± 0.09 (stat.) ± 0.18 (syst.)
Fake photons	0.71 ± 0.02 (stat.) ± 0.13 (syst.)
Fake leptons	0.12 ± 0.02 (stat.) ± 0.08 (syst.)
Pileup	0.09 ± 0.002 (stat.) ± 0.02 (syst.)
Total background	0.92 ± 0.03 (stat.) ± 0.15 (syst.)
N_{tot} prediction	7.96 ± 0.09 (stat.) ± 0.23 (syst.)
N_{tot} **data**	8

$$\sigma_{ZZ\gamma}^{\text{fid}} = 0.144^{+0.064}_{-0.051}\,(\text{stat.})^{+0.007}_{-0.005}\,(\text{syst.})\ \text{fb}^{-1}$$

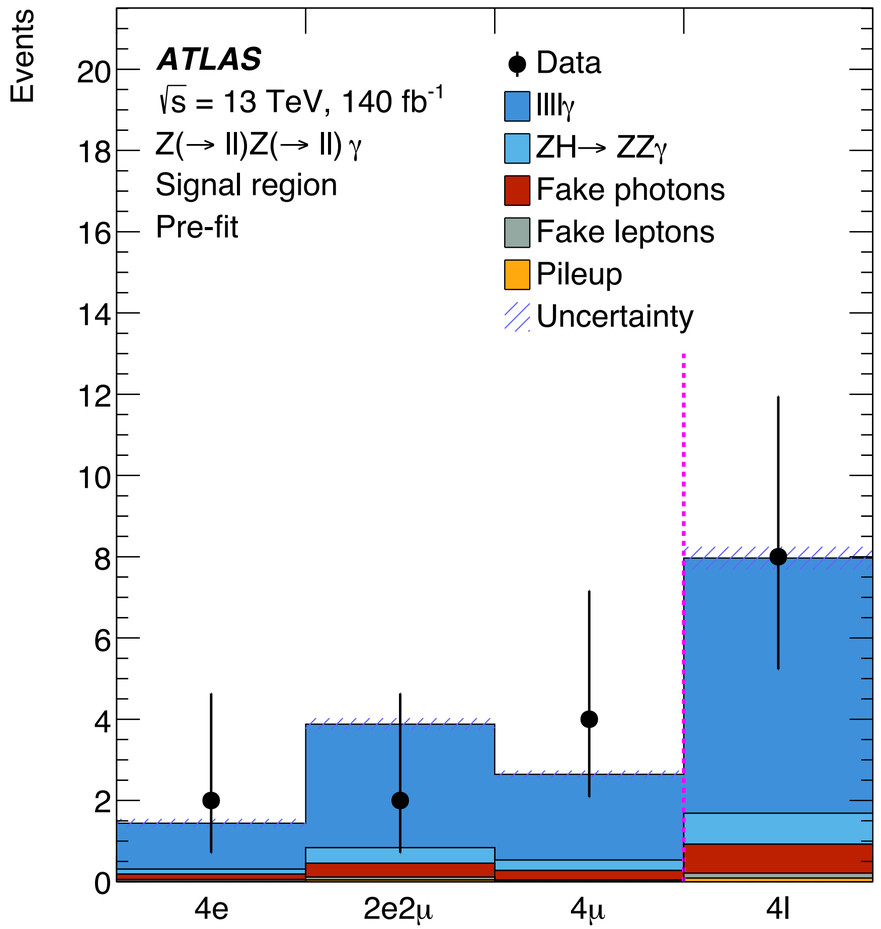
4.4σ



Results

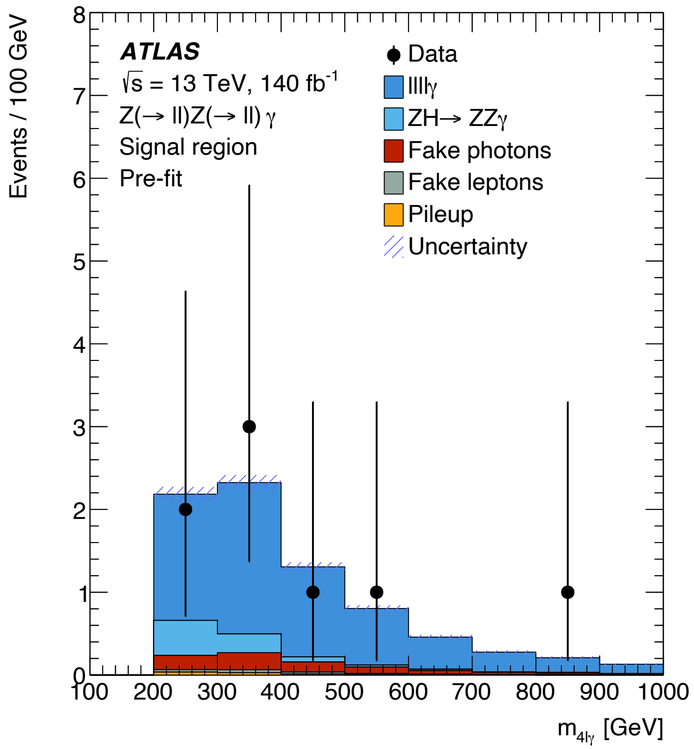
Source	Relative uncertainty [%]
Fake photon background	1.9
Fake lepton background	1.2
Pileup background	0.4
Photon identification and isolation efficiency	1.7
Pileup reweighting	1.6
Muon identification, isolation, reconstruction, momentum resolution and scale	0.9
Electron identification, isolation, reconstruction efficiency	0.6
Electron–photon resolution and energy scale	0.5
Signal PDF and α_s, QCD scales	1.4
Signal MC statistics	1.4
Integrated luminosity	0.9
Total systematic uncertainty	4.1
Data statistics	40
Total uncertainty	41

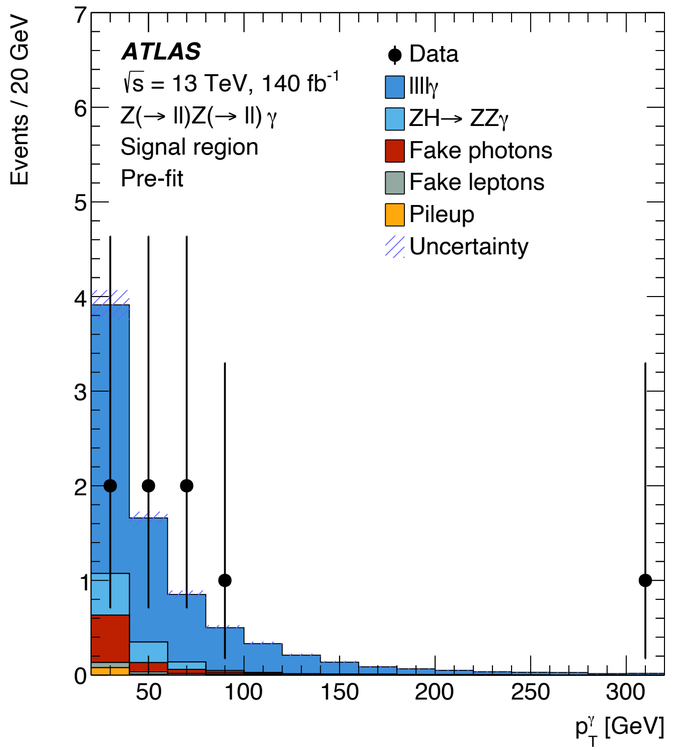
$$\sigma_{ZZ\gamma} = 0.144^{+0.064}_{-0.051}\,(\text{stat.})^{+0.007}_{-0.005}\,(\text{syst.})\ \text{fb}^{-1}$$

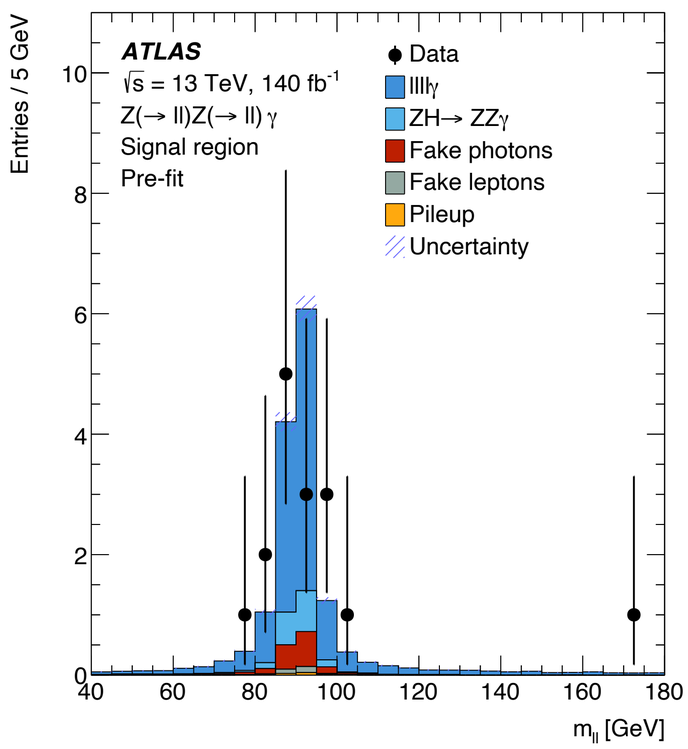


Results

$\sigma_{ZZ\gamma} = 0.144^{+0.064}_{-0.051}\,\text{fb}^{-1}$ in agreement with SM ($\sigma_{ZZ\gamma} = 0.143^{+0.007}_{-0.004}\,\text{fb}^{-1}$)







Summary

- first measurement of the ZZγ production
- test of SM and sensitive to new physics
- fully leptonic final state
- 8 observed events
- strong evidence

arXiv: 2602.17165