Recent measurements of the Zγ production with the ATLAS detector

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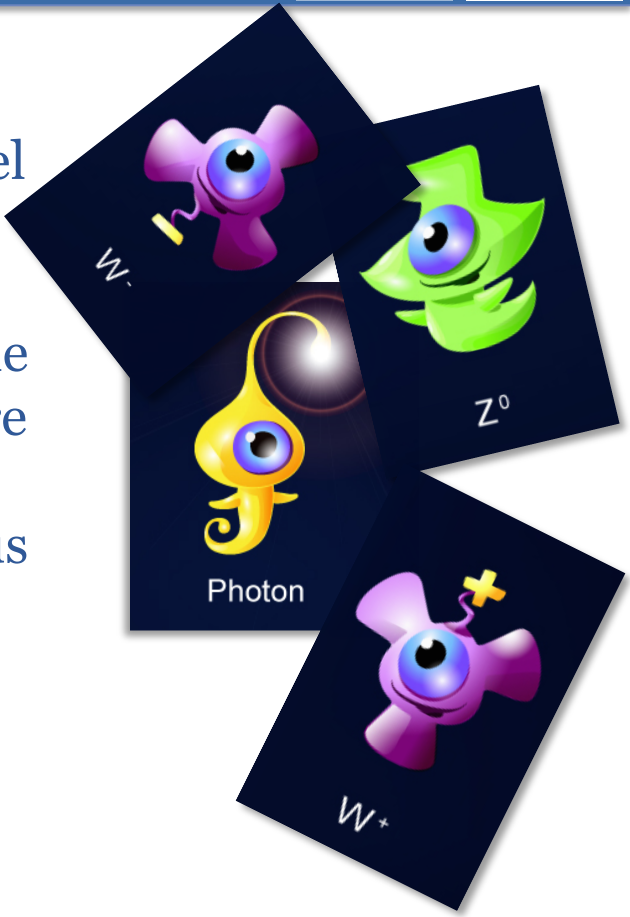
Outline

- ☐ Motivation
- ☐ Standard Model measurements
- ☐ Anomalous gauge boson couplings
- ☐ Prospects and summary

Importance of Vγ measurements

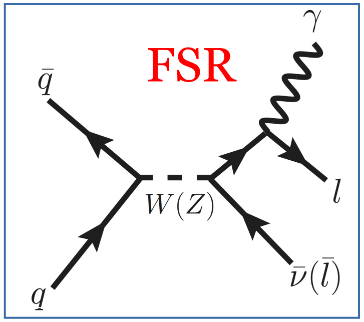


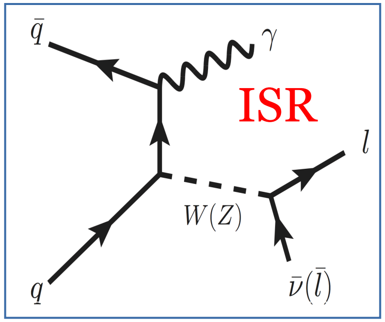
- To test the electroweak sector of the Standard Model with high accuracy using multi-boson production cross section measurements.
- To probe the $SU(2)_L \times U(1)_Y$ gauge symmetry of the electroweak theory that determines the structure and self-couplings of the vector bosons.
- To search for signs of new physics using anomalous triple gauge-boson couplings (aTGC) studies.

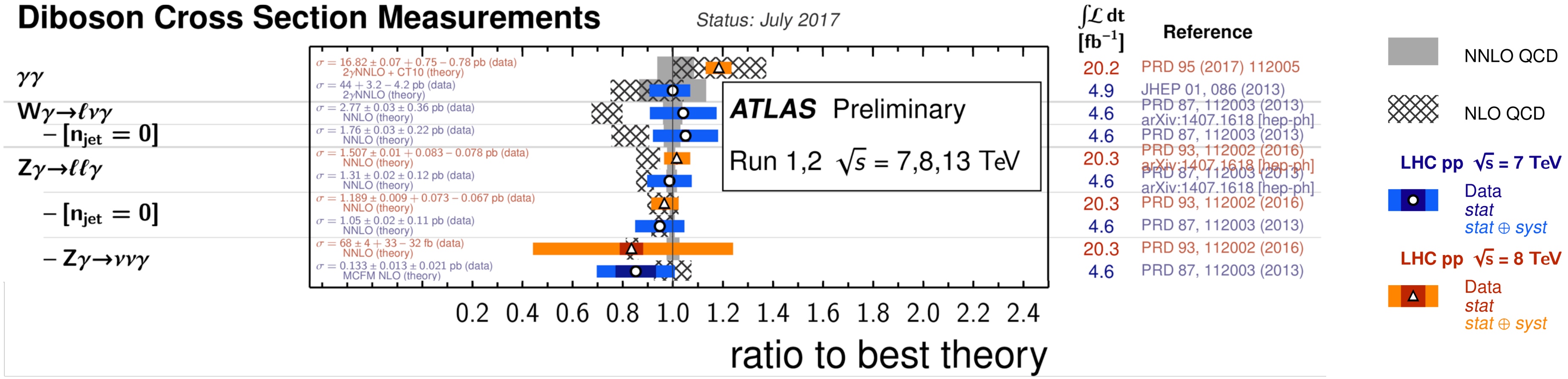
Last but not least:
SM multi-boson production is a background for Higgs and exotic searches. Precision Photon+V measurements help to tune Monte-Carlo, which describes some of these backgrounds.

Vγ analysis retrospective

Standard Model cross sections for Vγ production in ATLAS were measured with high accuracy already with 7 TeV data. Proton-proton collisions at 8 TeV **allowed to improve measurements.**







Agreement between data and NNLO theory predictions

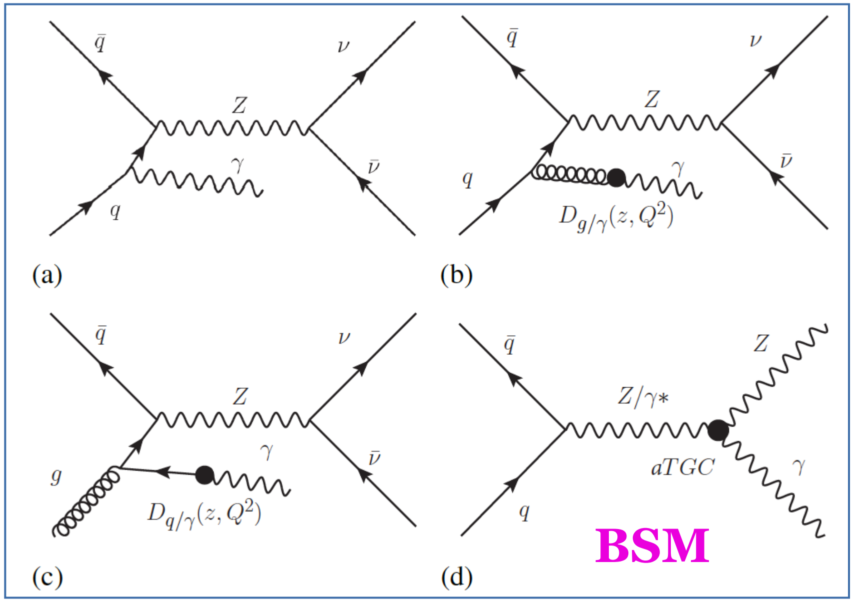
Measurements at 13 TeV

Proton collisions at 13 TeV is a new area of precision for SM studies.

Z(νν)γ production – the first LHC Zγ measurement with pp collisions with early Run 2 data.

Why Z(νν)γ ?

- not observed with significance > 5σ yet;
- experiment vs theory comparison at the level of NNLO QCD corrections;
- develop analysis techniques to probe NLO EWK corrections with a full Run 2 data.



Search for BSM physics:

- Limits on aTGC *(strongest limits for neutral couplings in ATLAS)*
- Anomalous neutrino magnetic moment measurements (not possible yet to improve LEP results ***arXiv:1712.02439v1***)

Paper was just accepted by JHEP
arXiv: 1810.04995

Z(νν)γ signature

Photons	Leptons	Jets
$E_{\mathrm{T}} > 150$ GeV $\lvert\eta\rvert < 2.37$, excluding $1.37 < \lvert\eta\rvert < 1.52$	$p_{\mathrm{T}} > 7$ GeV $\lvert\eta\rvert < 2.47(2.7)$ for $e(\mu)$, excluding $1.37 < \lvert\eta^{e}\rvert < 1.52$	$p_{\mathrm{T}} > 50$ GeV $\lvert\eta\rvert < 4.5$ $\Delta R(\mathrm{jet}, \gamma) > 0.3$

Motivated by trigger

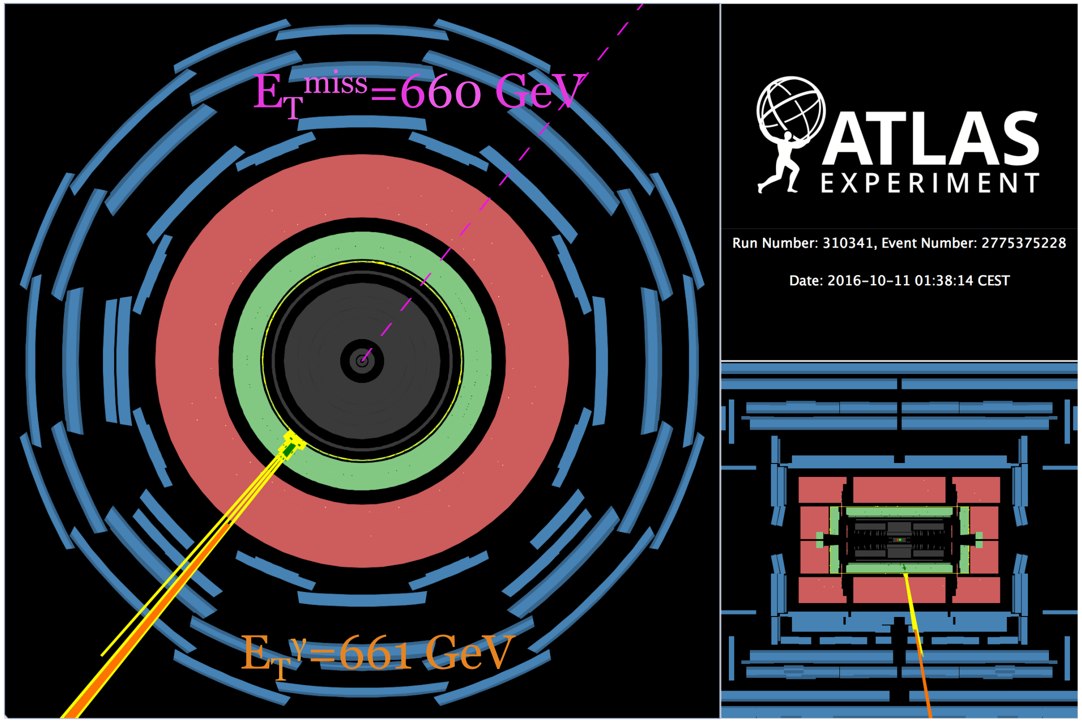
Suppress syst. uncertainties

Event selection

$N^{\gamma} = 1, \quad N^{e,\mu} = 0, \quad E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $\quad E_{\mathrm{T}}^{\mathrm{miss}}$ signif. $> 10.5\ \mathrm{GeV}^{1/2}, \quad \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \gamma) > \pi/2$

Inclusive : $N_{\mathrm{jet}} \geq 0$, $\quad$ Exclusive : $N_{\mathrm{jet}} = 0$

$$E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\Sigma p_{\mathrm{T}}^{\mathrm{jet}} + E_{\mathrm{T}}^{\gamma}}$$



- 25% total background reduction and less than 1% signal loss with lepton veto.
- Exclusive selection (Njets=0) is used for aTGC searches, providing higher sensitivity for the aTGC due to further background suppression.

Background sources

- ☐ **e→γ misID background from W(eν), single top, ttbar processes.**

Estimated with data-driven method using Z-peak distribution and e+E_T^{miss} CR.

- ☐ **jet→γ misID background from Z+jet, multijet processes.**

Estimated by 2D-sideband (ABCD) method.

- ☐ **τνγ and lνγ events from the Wγ production, when the τ decays into hadrons or when the electron or muon from τ or W decay is not reconstructed.**

Estimated from the simultaneous fit in the Wγ and γ+jet CRs.

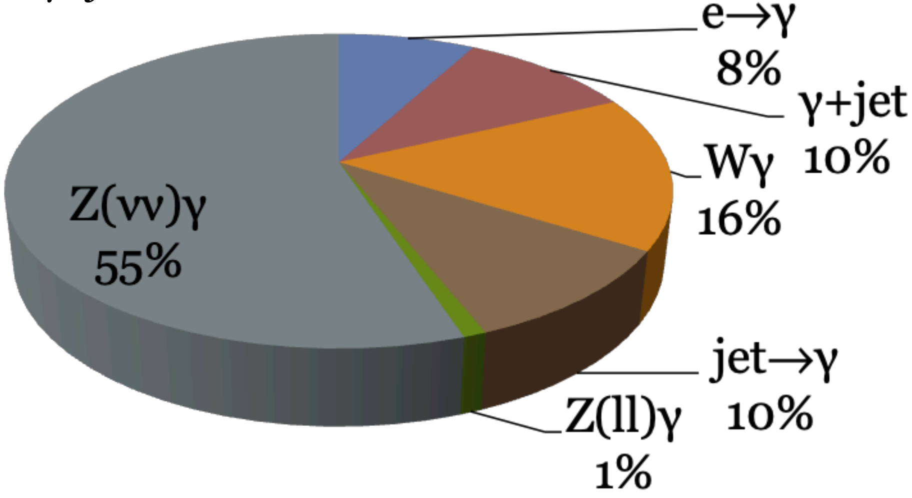
- ☐ **γ+jet events, when large apparent E_T^{miss} is created by a combination of real E_T^{miss} from neutrinos in heavy quark decays (top) and mis-measured jet energy.**

Estimated from the simultaneous fit in the Wγ and γ+jet CRs.

- ☐ **Z(ll)γ (mainly ττγ)**

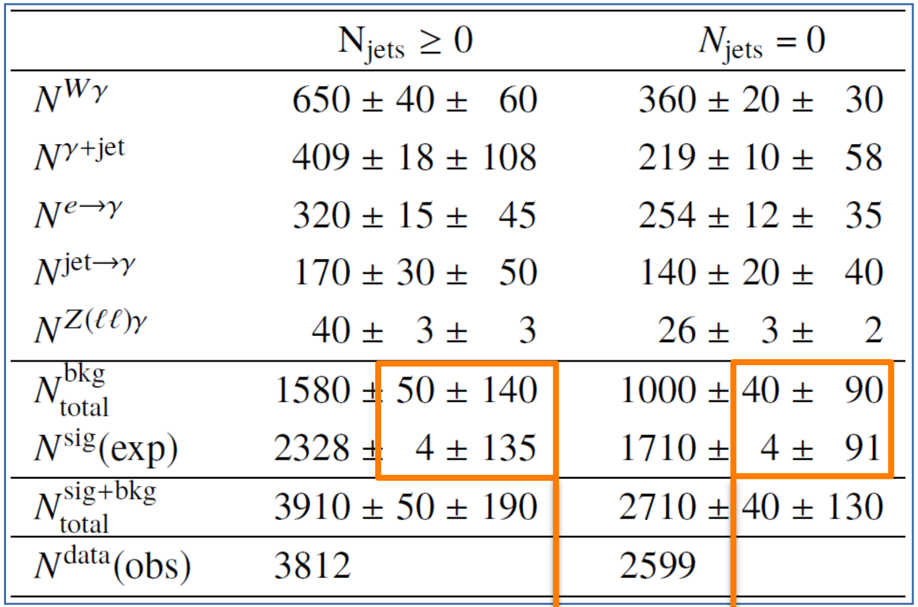
Estimated from MC.

Inclusive case:



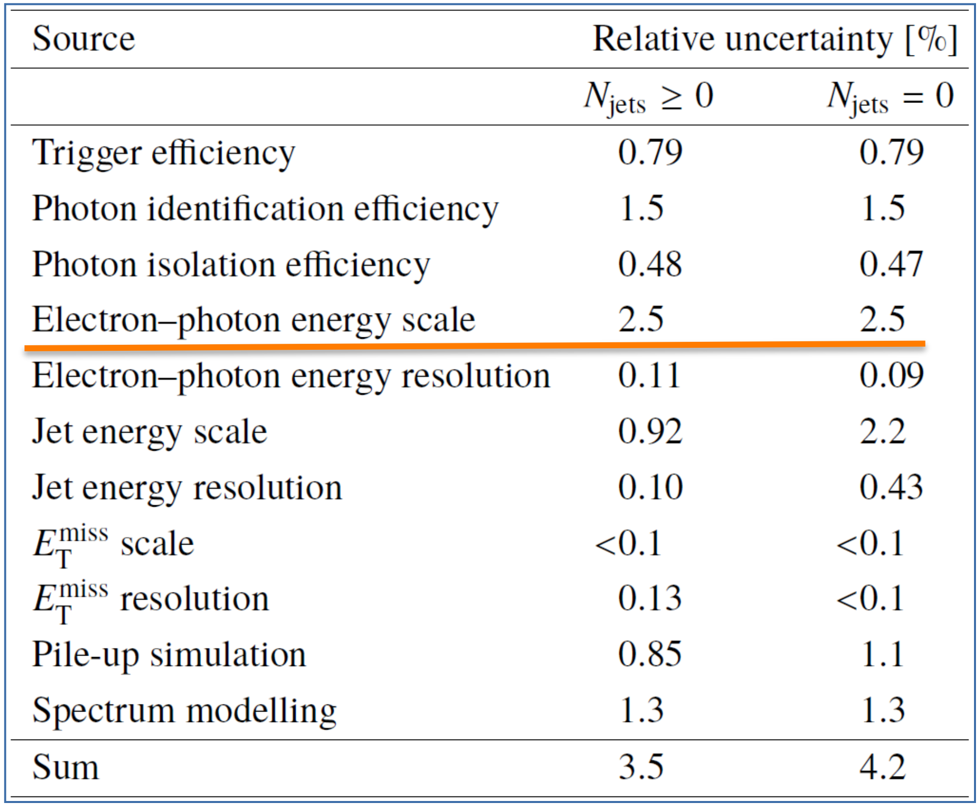
Event yields and signal systematics

Expected signal is modeled by Sherpa



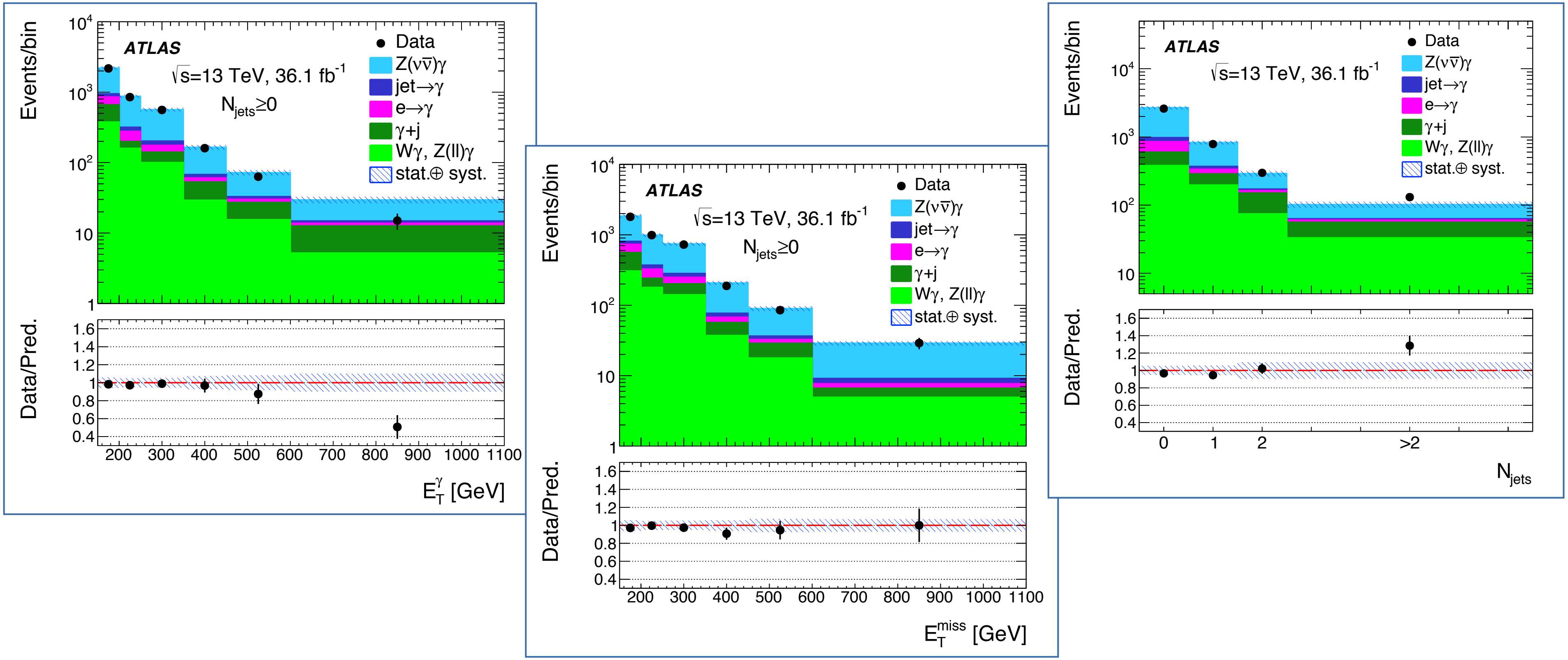
	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{W\gamma}$	650 ± 40 ± 60	360 ± 20 ± 30
$N^{\gamma+\text{jet}}$	409 ± 18 ± 108	219 ± 10 ± 58
$N^{e\to\gamma}$	320 ± 15 ± 45	254 ± 12 ± 35
$N^{\text{jet}\to\gamma}$	170 ± 30 ± 50	140 ± 20 ± 40
$N^{Z(\ell\ell)\gamma}$	40 ± 3 ± 3	26 ± 3 ± 2
$N^{\text{bkg}}_{\text{total}}$	1580 ± 50 ± 140	1000 ± 40 ± 90
$N^{\text{sig}}(\text{exp})$	2328 ± 4 ± 135	1710 ± 4 ± 91
$N^{\text{sig+bkg}}_{\text{total}}$	3910 ± 50 ± 190	2710 ± 40 ± 130
$N^{\text{data}}(\text{obs})$	3812	2599

Total uncertainty is around 9%



Source	Relative uncertainty [%]	
	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
Trigger efficiency	0.79	0.79
Photon identification efficiency	1.5	1.5
Photon isolation efficiency	0.48	0.47
Electron–photon energy scale	2.5	2.5
Electron–photon energy resolution	0.11	0.09
Jet energy scale	0.92	2.2
Jet energy resolution	0.10	0.43
$E_{\text{T}}^{\text{miss}}$ scale	<0.1	<0.1
$E_{\text{T}}^{\text{miss}}$ resolution	0.13	<0.1
Pile-up simulation	0.85	1.1
Spectrum modelling	1.3	1.3
Sum	3.5	4.2

Kinematic plots

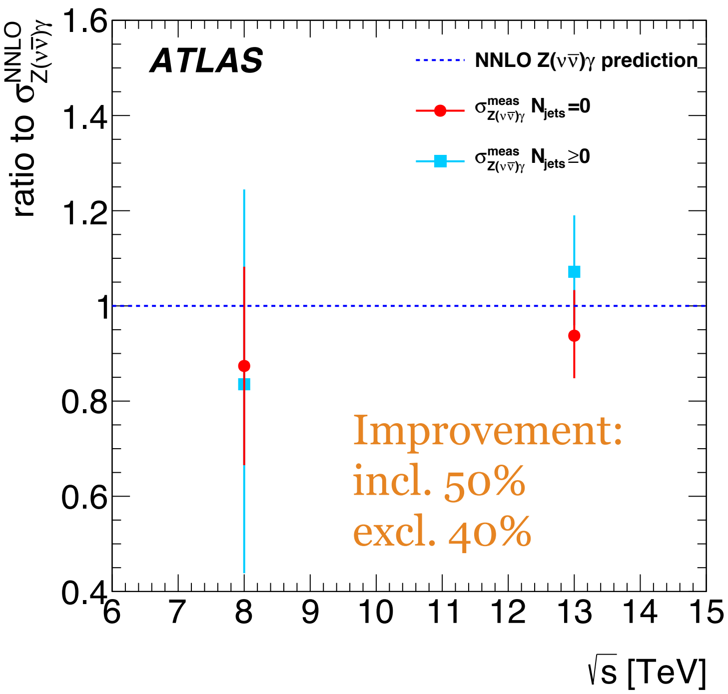


Agreement between data and the SM expectation within total error except bins with very low statistics.

Cross-section measurements

$$\sigma^{fid}_{pp\to Z(\nu\nu)\gamma} = \frac{N^{obs}_{Z(\nu\nu)\gamma} - N^{bkg}_{Z(\nu\nu)\gamma}}{C_{Z(\nu\nu)\gamma}\int L\,dt}$$

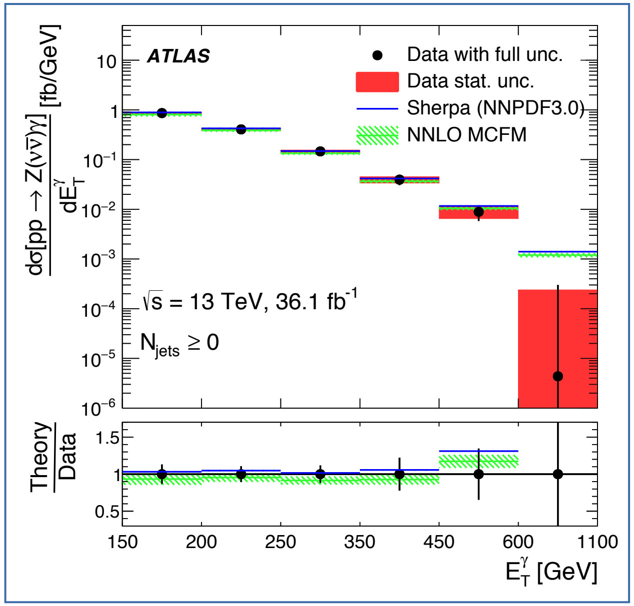
$\sigma^{\text{ext.fid.}}$ [fb] Measurement	$\sigma^{\text{ext.fid.}}$ [fb] NNLO MCFM Prediction
$N_{\text{jets}} \geq 0$	
$83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.)	78.1 ± 0.2(stat.)± 4.7(syst.)
$N_{\text{jets}} = 0$	
$52.4^{+2.4}_{-2.3}$ (stat.)$^{+4.0}_{-3.6}$ (syst.)$^{+1.2}_{-1.1}$ (lumi.)	55.9 ± 0.1(stat.)± 3.9(syst.)

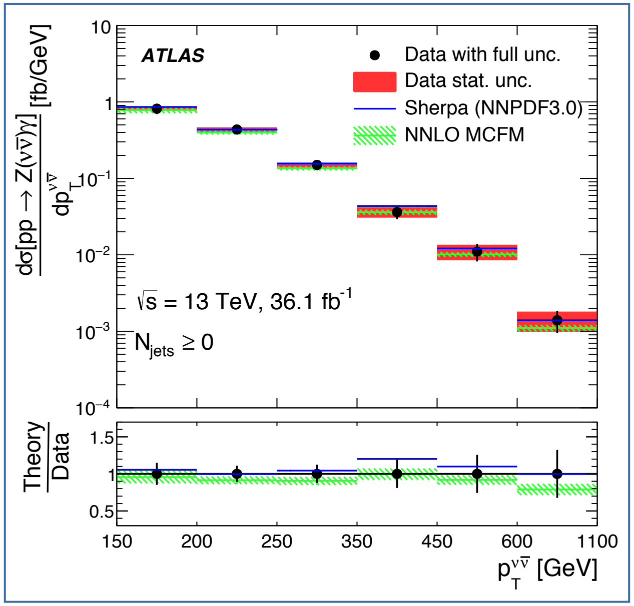


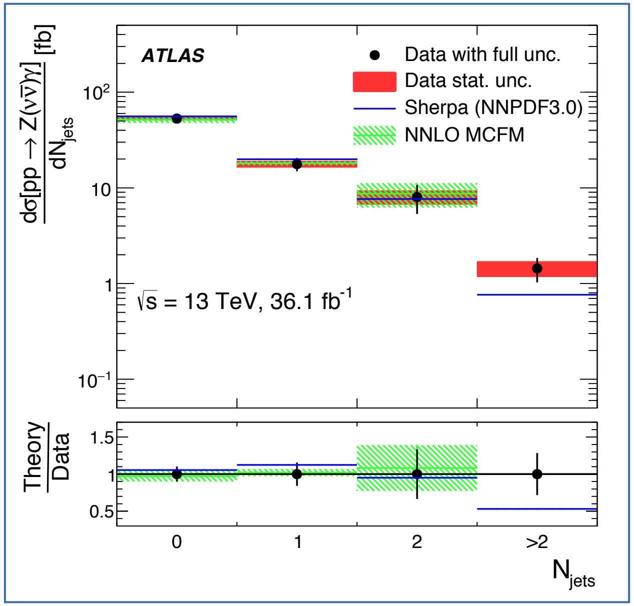
Improvement:
incl. 50%
excl. 40%

Measured cross sections are in an agreement with theory (MCFM or MATRIX)

Differential cross-section measurements







Good agreement with SM expectations is observed in all but the last bin of the photon ET inclusive distribution.

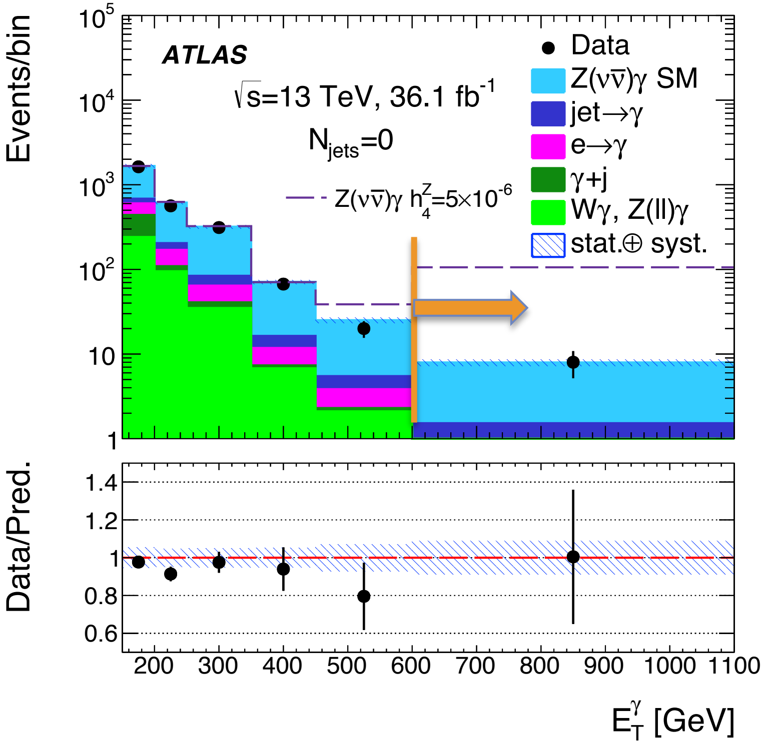
Triple gauge couplings

- ➢ Non-Abelian nature of $SU(2)_L \times U(1)_Y$ allows for couplings of the gauge bosons in fermions interactions: WWZ, WWγ.
- ➢ Neutral boson gauge couplings are forbidden at tree level in the SM, but can arise in theories beyond the SM via anomalous couplings. Limits on anomalous couplings will provide constraints on BSM theories.

- ❑ Couplings can be described by eight parameters in the vertex function: $\mathbf{h_1^V}$ - $\mathbf{h_4^V}$, where V = γ, Z.
- ❑ Anomalous values of the $\mathbf{h_i^V}$ couplings lead to increase of the Zγ cross section.

h_4^Z h_3^Z	$-5 \cdot 10^{-7}$	0	$5 \cdot 10^{-7}$
$-5 \cdot 10^{-4}$	0.439	0.696	1.42
0	0.477	$\boxed{0.243}$	0.483
$5 \cdot 10^{-4}$	1.40	0.674	0.424

SM



ATGC limits

Vertex approach

Parameter	Limit 95% CL	
	Measured	Expected
h_3^γ	$(-3.7 \times 10^{-4}, 3.7 \times 10^{-4})$	$(-4.2 \times 10^{-4}, 4.3 \times 10^{-4})$
h_3^Z	$(-3.2 \times 10^{-4}, 3.3 \times 10^{-4})$	$(-3.8 \times 10^{-4}, 3.8 \times 10^{-4})$
h_4^γ	$(-4.4 \times 10^{-7}, 4.3 \times 10^{-7})$	$(-5.1 \times 10^{-7}, 5.0 \times 10^{-7})$
h_4^Z	$(-4.5 \times 10^{-7}, 4.4 \times 10^{-7})$	$(-5.3 \times 10^{-7}, 5.1 \times 10^{-7})$

Improvement in 3-7 times vs 8 TeV results

EFT approach

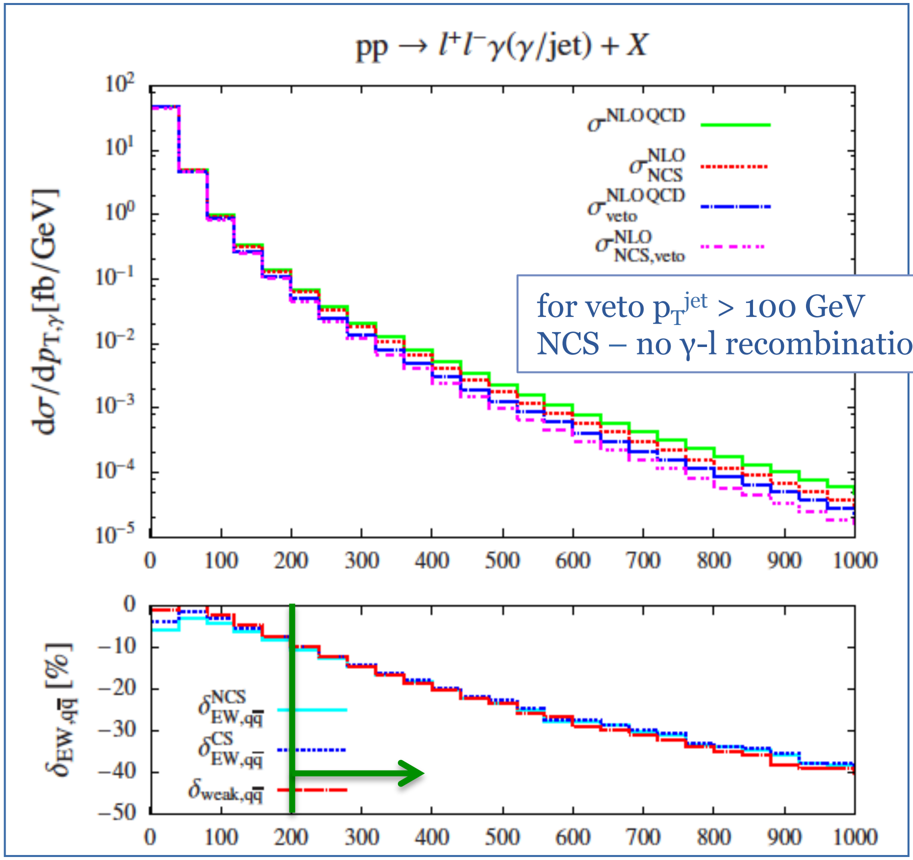
Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\widetilde{B}W}/\Lambda^4$	$(-1.1,\ 1.1)$	$(-1.3,\ 1.3)$
C_{BW}/Λ^4	$(-0.65,\ 0.64)$	$(-0.74,\ 0.74)$
C_{WW}/Λ^4	$(-2.3,\ 2.3)$	$(-2.7,\ 2.7)$
C_{BB}/Λ^4	$(-0.24,\ 0.24)$	$(-0.28,\ 0.27)$

Transformation formulas are in the backup

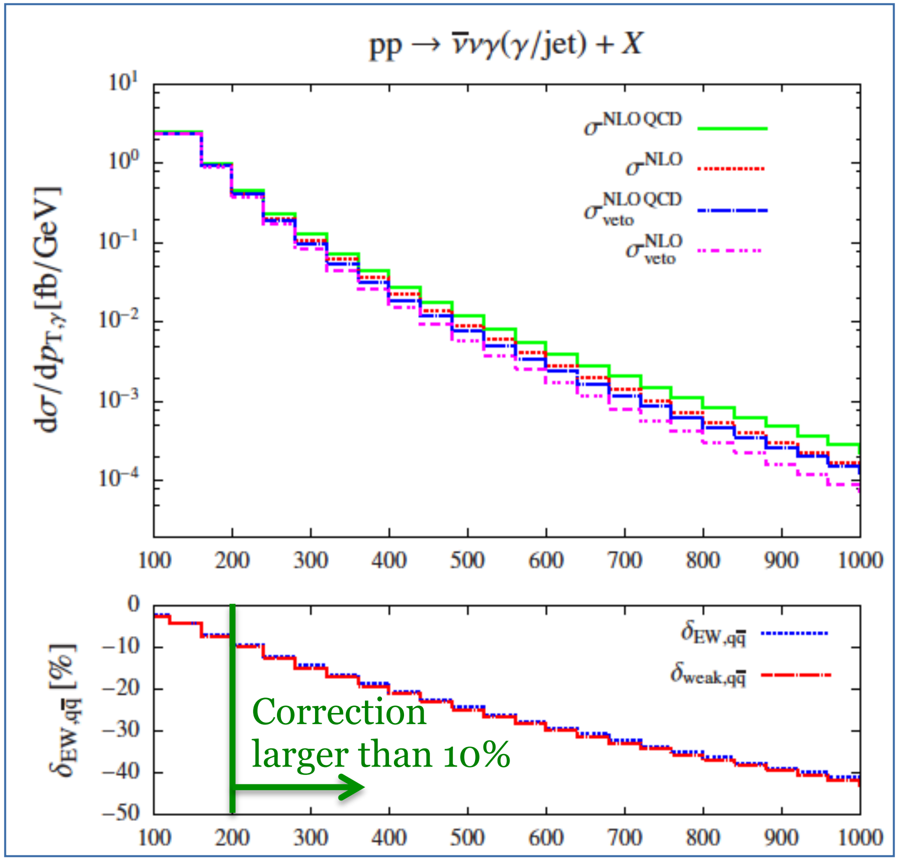
Prospects for full Run 2

Important goal is to probe NLO EW corrections.

arXiv:1510.08742v3



for veto $p_T^{\text{jet}} > 100$ GeV
NCS – no γ-l recombination



Correction larger than 10%

A total uncertainty smaller than 10% for photon energy larger 200 GeV is required.

Summary

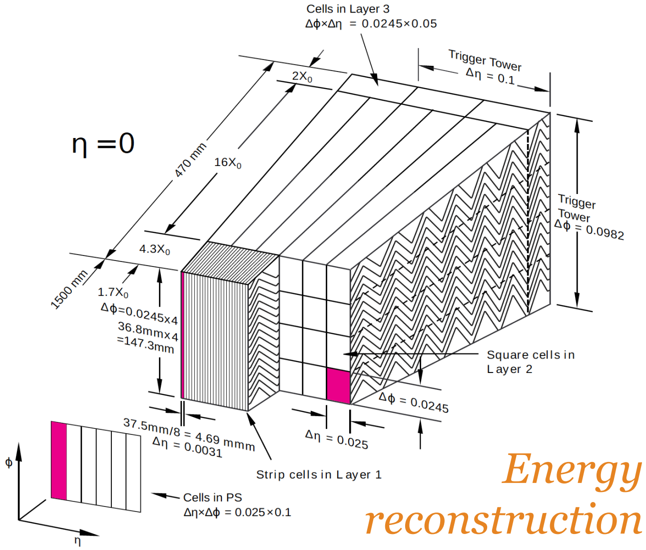
- ☐ The **first ATLAS measurements** for Zγ process with 13 TeV data.
- ☐ Integrated cross section measurements are performed with ≈10% precision and compared with QCD NNLO predictions. **Signal significance is higher than 5σ.**
- ☐ Differential cross section measurement are performed for E_T^{γ}, E_T^{miss} and N_{jets} distributions.
- ☐ No signs of new physics were observed and data is used to set limits **(the best in ATLAS and CMS for the moment)** on anomalous triple gauge couplings in both vertex and EFT formalisms.
- ☐ More Zγ results will arrive with the full Run 2 data.

The end, thank you.

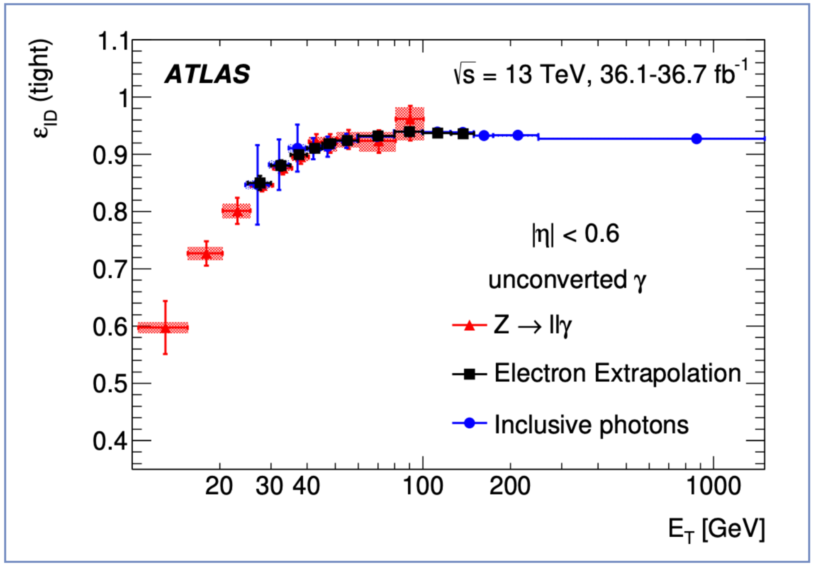
Backup

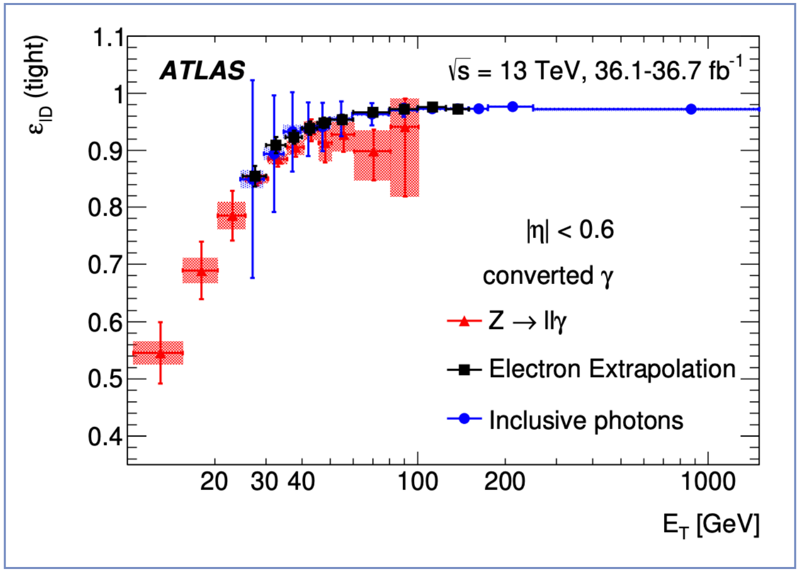
Photons in ATLAS

- ATLAS uses Electromagnetic calorimeter and Inner Detector system to reconstruct photons with high efficiencies. Both photons that do or do not convert to electron-positron pairs are reconstructed in ATLAS.
- The jet suppression is about 10^4 along with a high identification efficiency for photons:

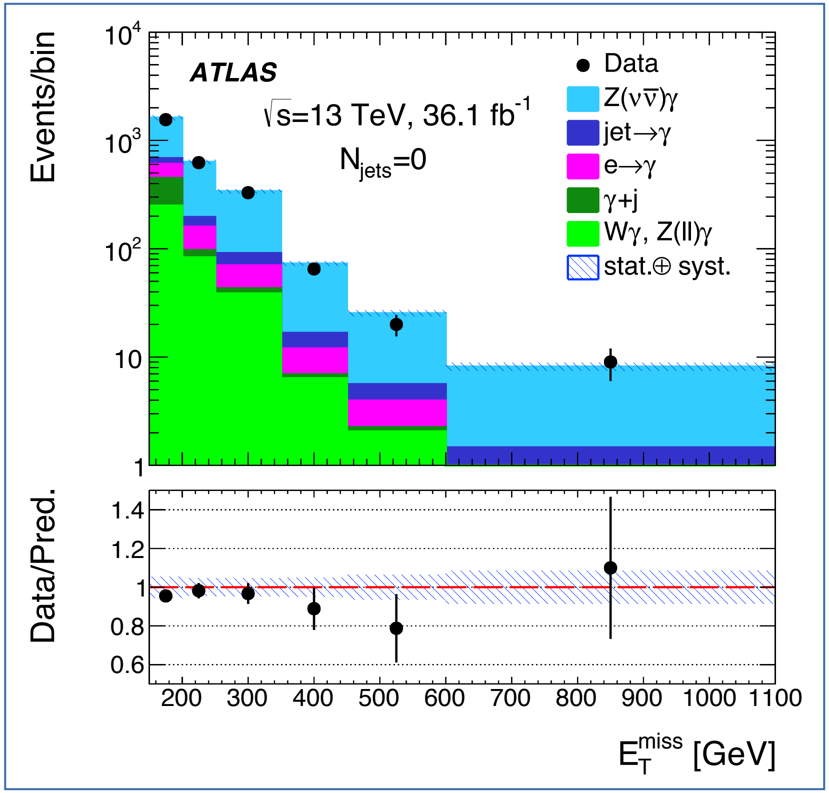


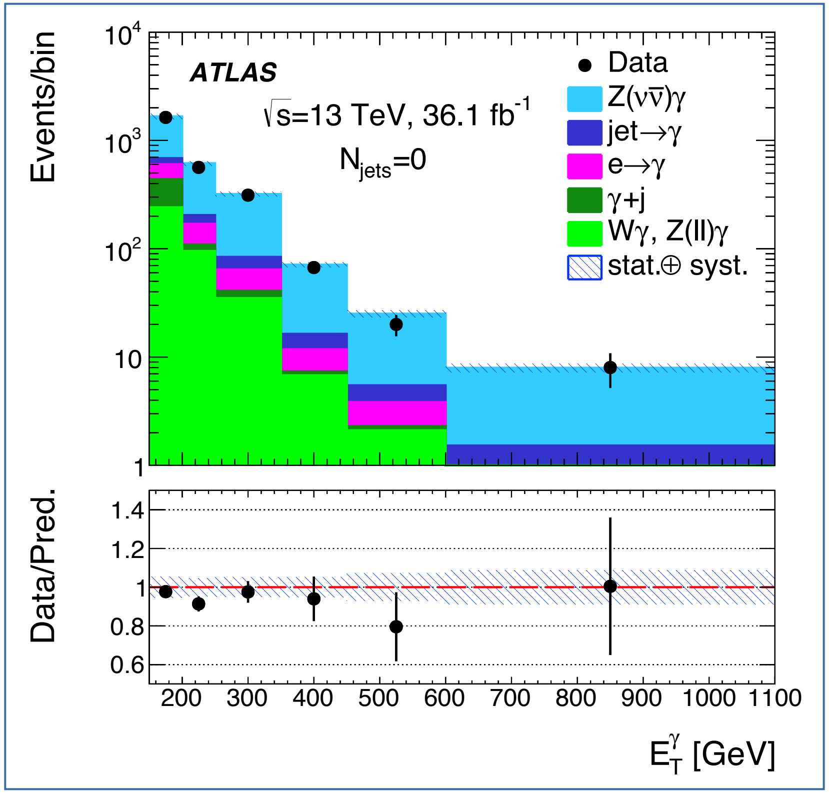
Energy reconstruction





Kinematic plots in SR (Njets=0)





Good agreement between data and the SM expectation

Fiducial region correction

$$\boxed{\sigma^{fid}_{pp\to Z(\nu\nu)\gamma} = \frac{N^{obs}_{Z(\nu\nu)\gamma} - N^{bkg}_{Z(\nu\nu)\gamma}}{C_{Z(\nu\nu)\gamma}\int L\,dt}}$$

$$\boxed{\sigma^{ext-fid}_{Z(\nu\nu)\gamma} = \frac{\sigma^{fid}_{Z(\nu\nu)\gamma}}{A_{Z(\nu\nu)\gamma}}}$$

Category	Requirement
Photons	$E_{\mathrm{T}}^{\gamma} > 150$ GeV $\lvert\eta\rvert < 2.37$
Jets	$\lvert\eta\rvert < 4.5$ $p_{\mathrm{T}} > 50$ GeV $\Delta R(\mathrm{jet}, \gamma) > 0.3$ Inclusive : $N_{\mathrm{jet}} \geq 0$, Exclusive : $N_{\mathrm{jet}} = 0$
Neutrino	$p_{\mathrm{T}}^{\nu\nu} > 150$ GeV

Cross section is measured in fiducial region and calculated in the extended fiducial region. The latter region is straightforward to apply in various MC generators for further comparison.

	$N_{\mathrm{jets}} \geq 0$	$N_{\mathrm{jets}} = 0$
$A_{Z\gamma}$	0.816 ± 0.029	$0.952 \pm \boxed{0.026}$
$C_{Z\gamma}$	0.904 ± 0.031	0.889 ± 0.037

- PDF, α_S
- QCD scale
- Parton showering

Conversion to EFT formalism

Straightforward

$$h_3^Z = \frac{v^2 M_Z^2}{4c_w s_w}\frac{C_{\tilde{B}W}}{\Lambda^4}$$

$$h_4^Z = 0$$

$$h_3^\gamma = 0$$

$$h_4^\gamma = 0$$

$$\boxed{h_1^Z = \frac{M_Z^2 v^2 \left(-c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4}\left(c_w{}^2 - s_w{}^2\right) + 4c_w s_w \frac{C_{BB}}{\Lambda^4}\right)}{4c_w s_w}}$$

$$h_2^Z = 0$$

$$\boxed{h_1^\gamma = -\frac{M_Z^2 v^2 \left(s_w{}^2 \frac{C_{WW}}{\Lambda^4} - 2c_w s_w \frac{C_{BW}}{\Lambda^4} + 4c_w{}^2 \frac{C_{BB}}{\Lambda^4}\right)}{4c_w s_w}}$$

$$h_2^\gamma = 0.$$

Hidden correlation between parameters

MCFM parameterization was redone for EFT parameters to get into account all effects:

$$\sigma_{Z\gamma}^{aTGC} = P_0^{XX} + P_1^{XX} * C_{XX}/\Lambda^4 + P_2^{XX} * (C_{XX}/\Lambda^4)^2,$$

ATGC 2D limits: vertex formalism