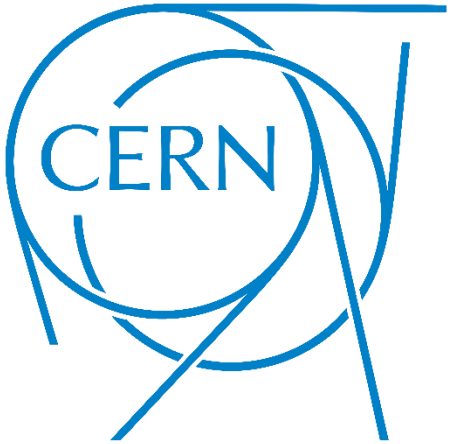


Measurements of inclusive neutral diboson production with ATLAS

Cong GENG

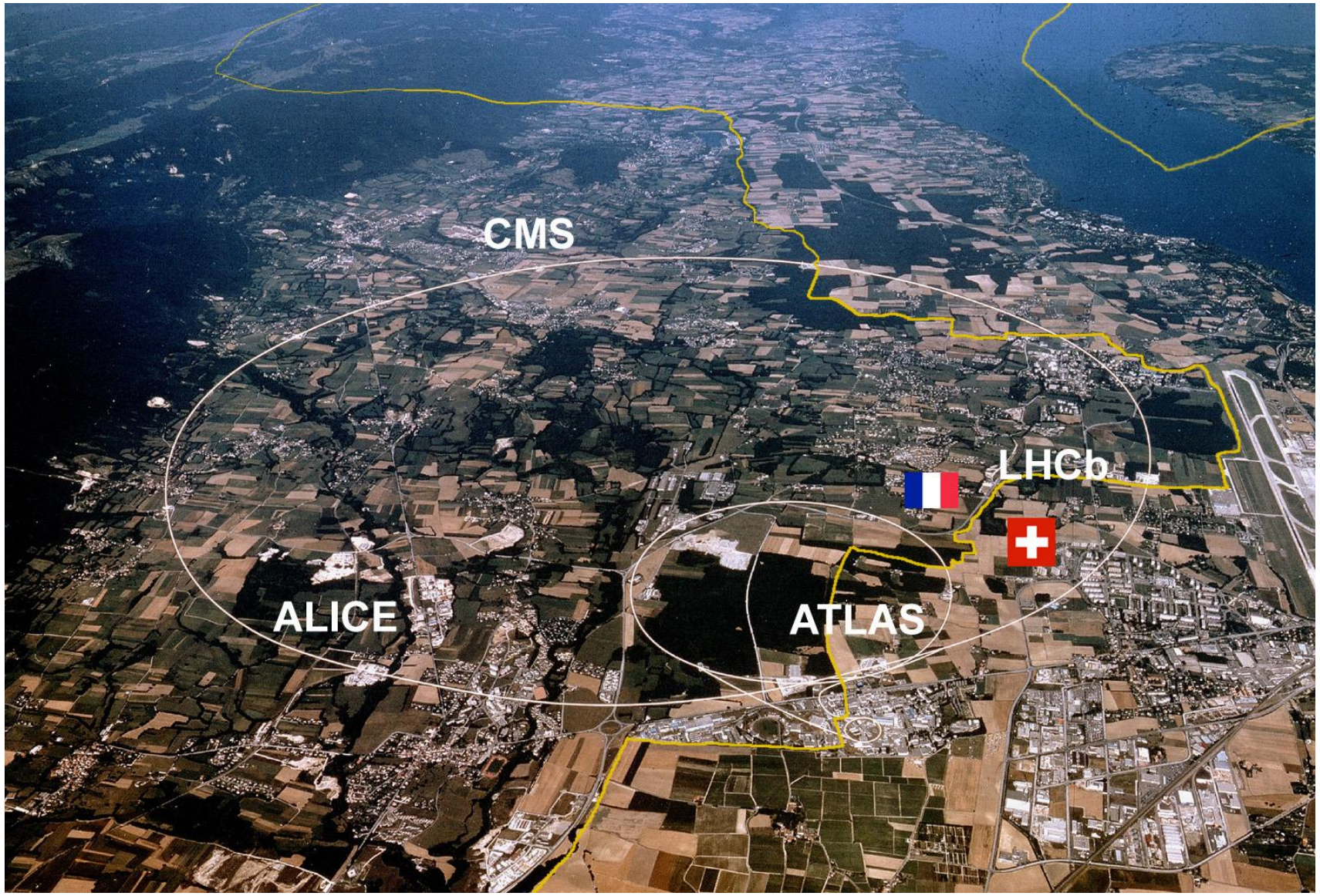
University of Michigan

On behalf of ATLAS collaboration

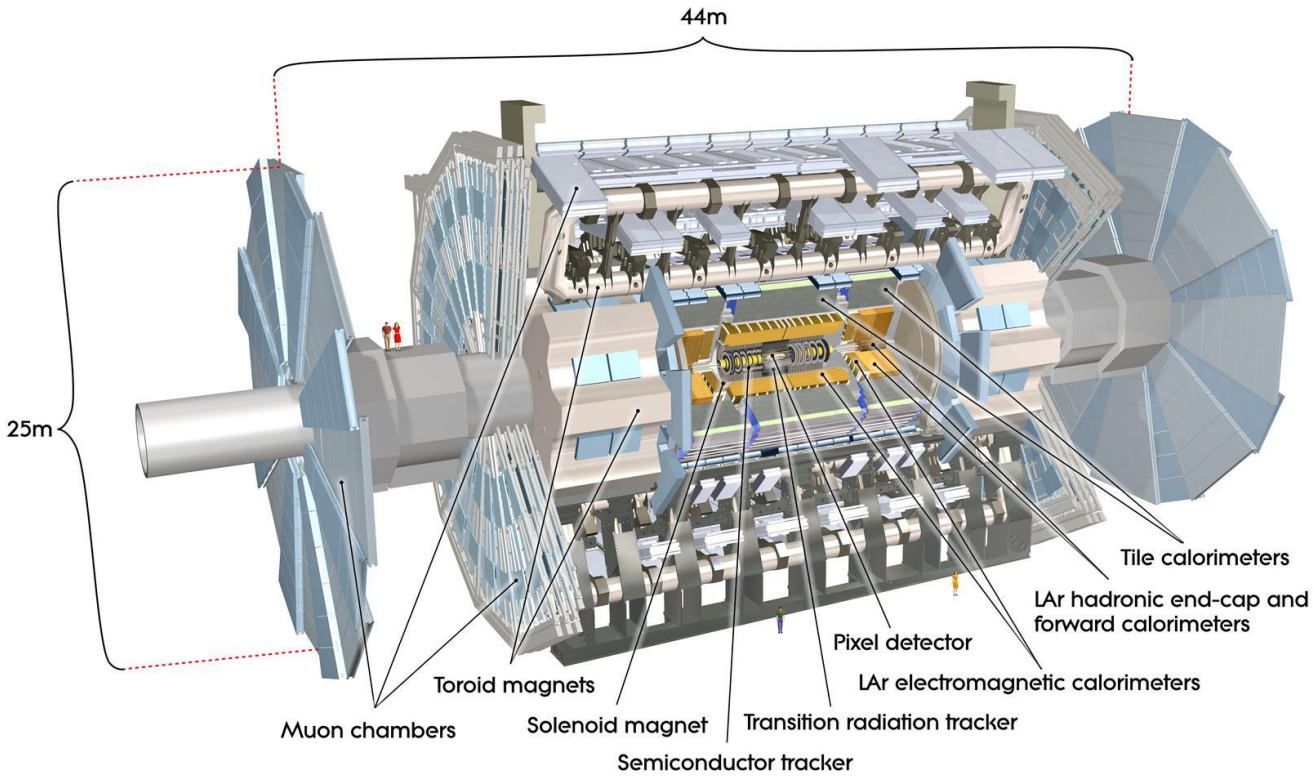
Outline

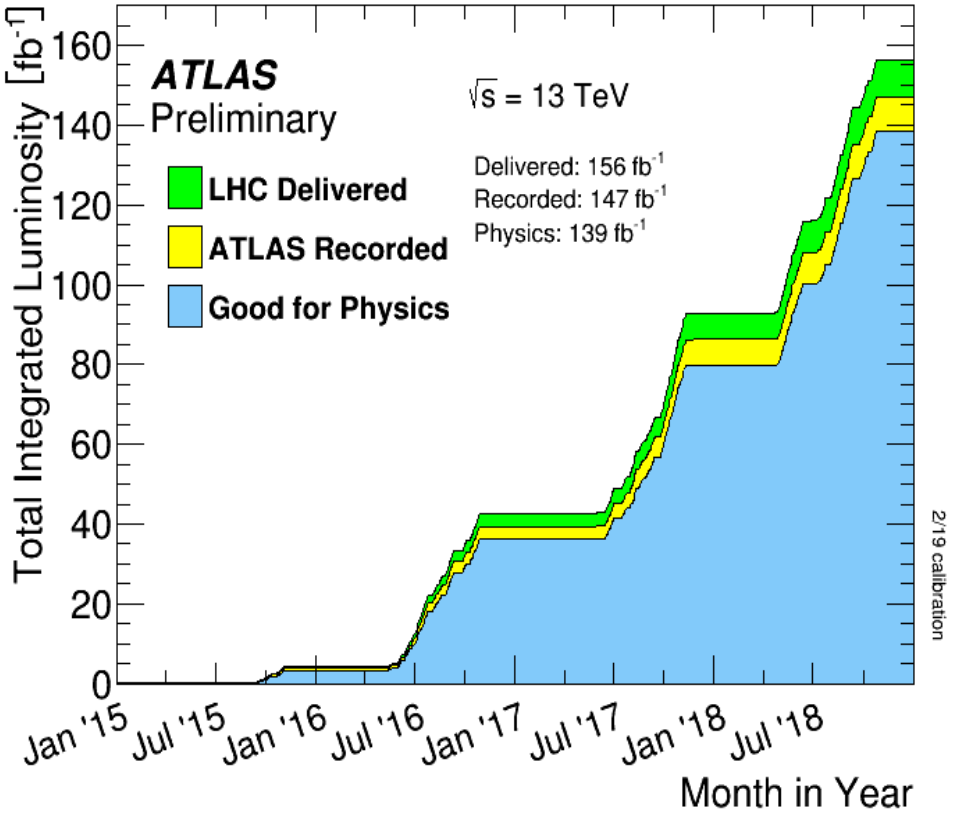
- Introduction to ATLAS
- Physics motivation
- Measurement of unfolded invariant mass of 4-leptons at 13 TeV
- Measurement of $Z\gamma$ with $Z \rightarrow \nu\nu$ at 13TeV
- Summary

CERN and LHC



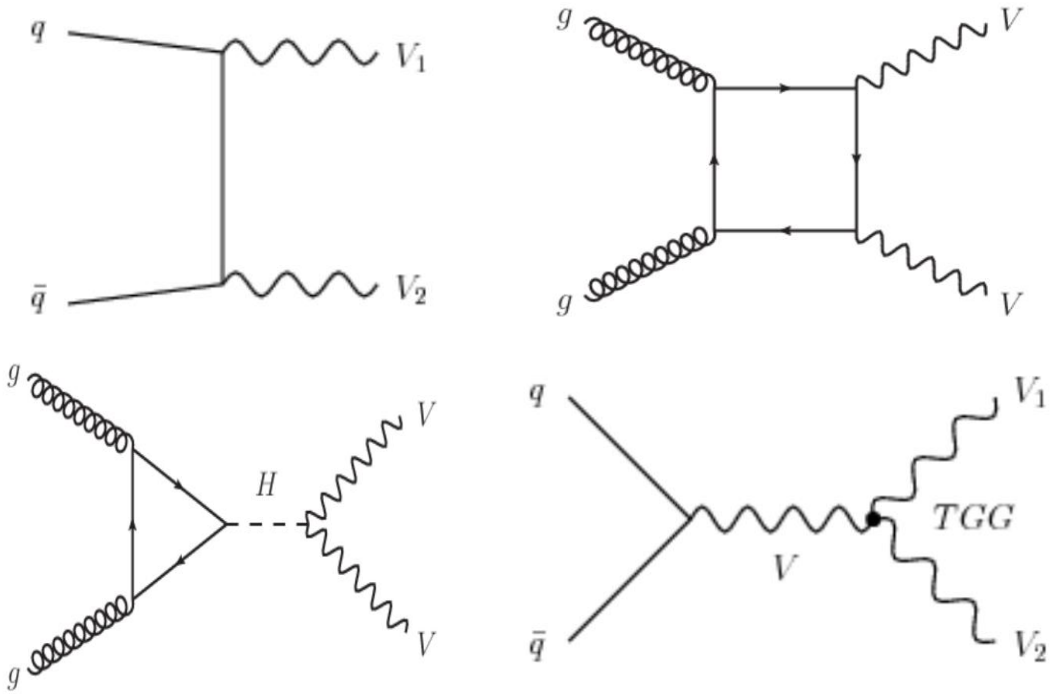
ATLAS detector and data taking

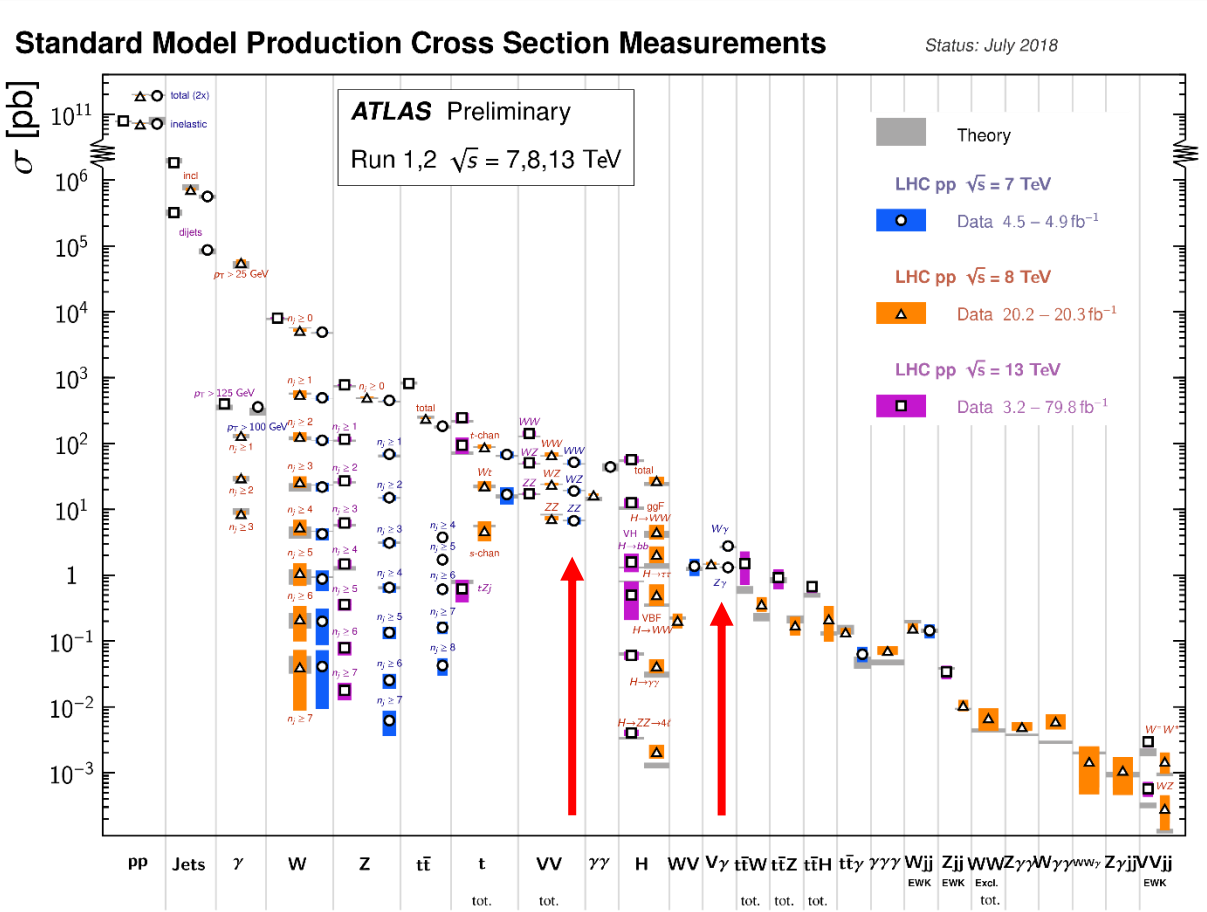




The analysis presented in this talk use the 36.1 fb^{-1}.

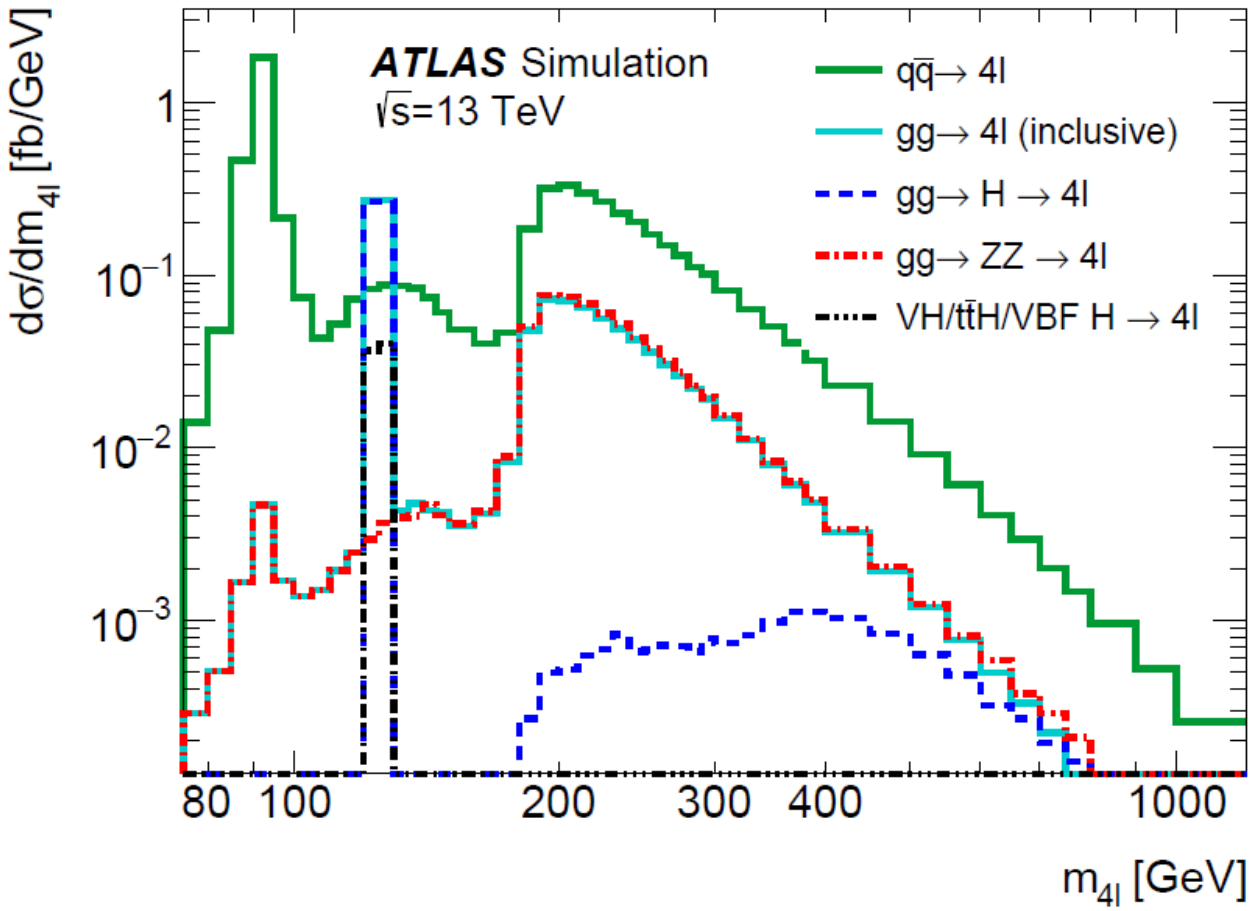
Physics motivation





- Search for the neutral TGC coupling which is forbidden in SM
- Sensitive to gluon induced process ; potential BSM hint in the quark-loop
- Important channel for constraint on Higgs property.

Measurement of unfolded m(4l) at 13 TeV



arXiv:1902.05892

Interesting topics:

- Behavior of full m(4l) spectrum.
- Measurement of gg→4l signal strength: K-factor w.r.t current LO/NLO simulation.
- Branching ratio of Z→4l
- Measurement of off-shell Higgs production: indirect constraint on Higgs width
- BSM searches in the higher energy region: anomalous neutral TGC (aTGC), BSM Higgs coupling …

Modelling of each process

- **Quark induced 4l (q→4l) process**
  - Nominal: modelled by "*Sherpa-2.2.2 + NNPDF3.0-NNLO*", and reweighted with virtual NLO EW effects as function of m(4l).
  - Cross checked with : "Powheg-Box v2 (NLO) + CT10 PDF" interfaced with Pythia 8, correction to higher-order precision (NNLO QCD and NLO EW)
- **Gluon induced 4l (g→4l) process**
  - Off-Higgs region three components: gg→H*→4l, continuum gg→4l, interference term.
  - Nominal: modelled by "*Sherpa-2.2.2 + NNPDF3.0-NNLO*", and reweighted to the NLO QCD precision as function of m(4l) ; An additional 1.2 factor is further applied to account for potential NNLO/NLO effects.
  - Cross checked with : "MCFM (LO) + CT10 PDF" interfaced with Pythia 8, correction to NNLO QCD precision

Analysis strategy

Matrix-element discriminant

$$D_{\mathrm{ME}} = \log_{10} \frac{\tilde{M}^2_{gg\to H^{(*)}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}{\tilde{M}^2_{gg(\to H^{(*)})\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right) + 0.1\cdot \tilde{M}^2_{q\bar{q}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}$$

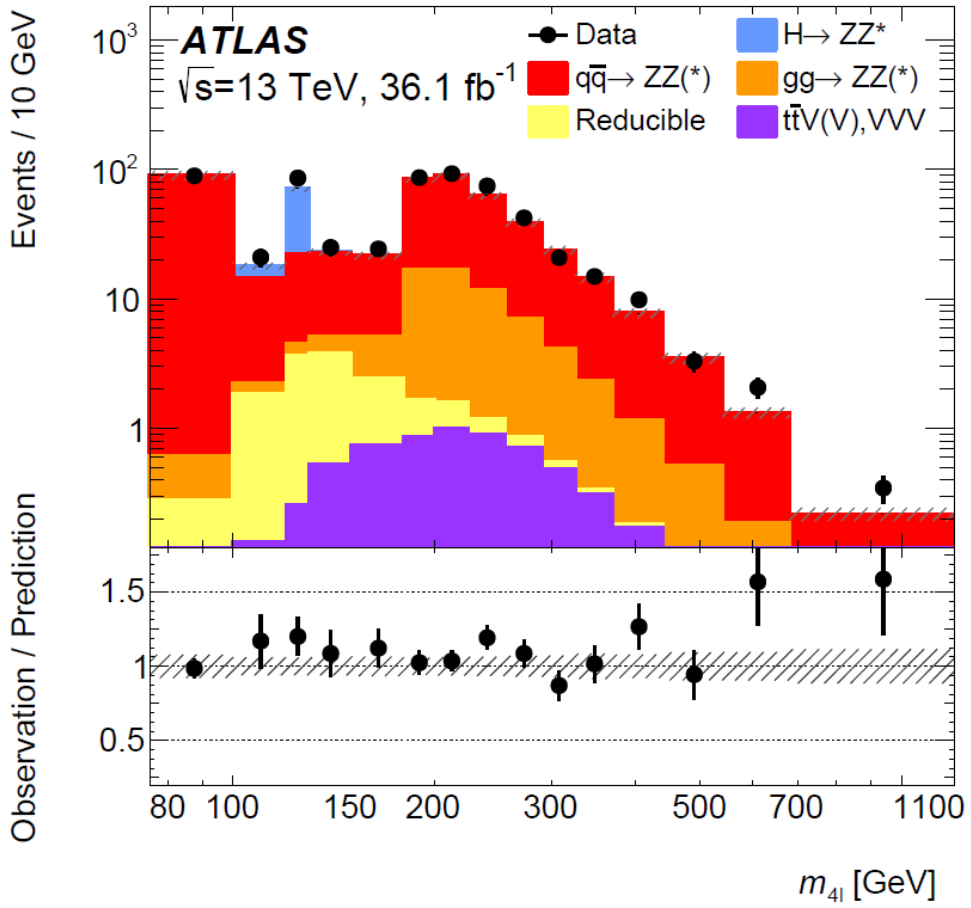
Reco-level SR selections

Object selection	
Electron	**Muon**
Loose working point $E_T > 7$ GeV and $\lvert\eta\rvert < 2.47$ $\lvert z_0 \cdot \sin\theta \rvert < 0.5$ mm	*Loose* working point $p_T > 5$ GeV and $\lvert\eta\rvert < 2.7$ [$p_T > 15$ GeV if calorimeter-tagged] $\lvert z_0 \cdot \sin\theta \rvert < 0.5$ mm, $\lvert d_0 \rvert < 1$ mm
Event level selections	
Quadruplet Selection: • SFOS lepton pairs with smallest and second-smallest $\lvert m(ll)-mZ \rvert$ as primary and secondary lepton pair; • $p_T > 20/15/10$ GeV for leading three leptons; Mass window for 2l pairs. J/ψ veto; Lepton isolation; Lepton transverse impact parameter; 4-lepton vertex fit	

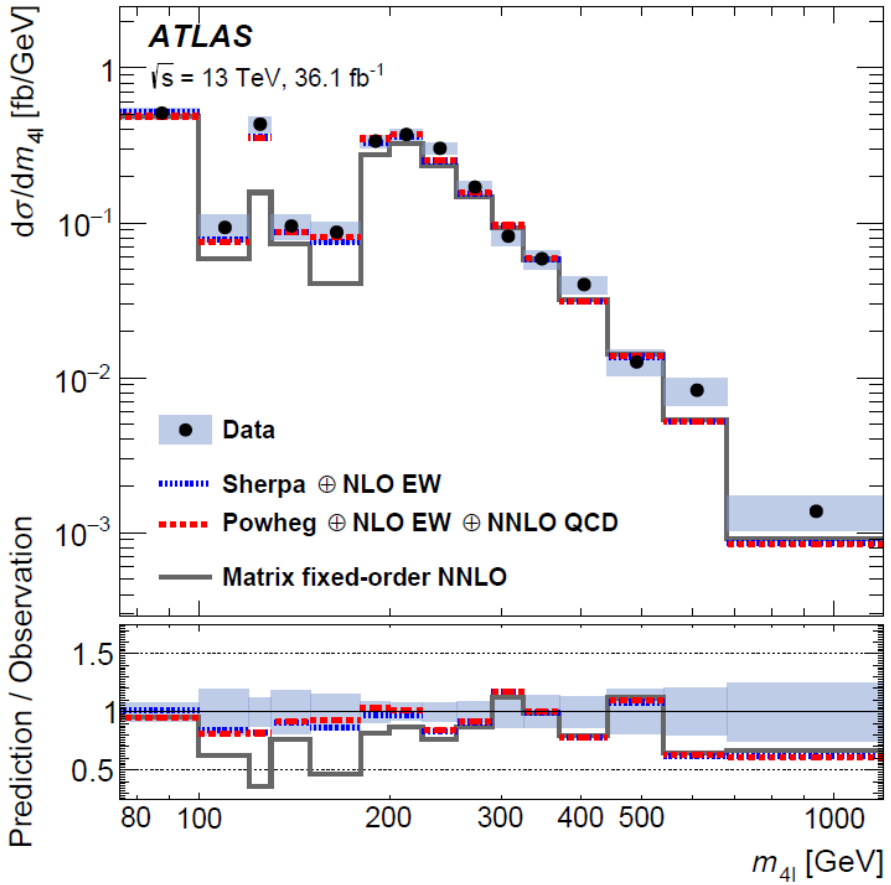
- Quite pure 4-lepton signal events
  - On-shell Higgs signal S/B ~ 1:2
  - < 5% contamination (non-ZZ) in the m4l>180 GeV region
- Major backgrounds:
  - Fake background → Zjets, ttbar
  - 4 prompt leptons → VVV, ttV
- Fiducial phase space definition is close to the reco-level SR selections at particle level.

Unfolded inclusive m(4l)

Reco-level distribution in SR



Differential cross section in Fid region



Interpretation: gg→4l signal strength, Br(Z→4l)

All the interpretations are done at the particle level

- **gg→4l signal strength ($\mu_{gg\to 4l}$)**
  - A likelihood scan in the range m4l ~ [180, 1200] GeV.

Generator	Observed $\mu_{gg\to 4l}$	Predicted $\mu_{gg\to 4l}$
Sherpa 2.2.2 with K-factor	1.3 ± 0.5	1.0 ± 0.4
MCFM, LO QCD	2.7 ± 0.9	2.2 ± 0.9

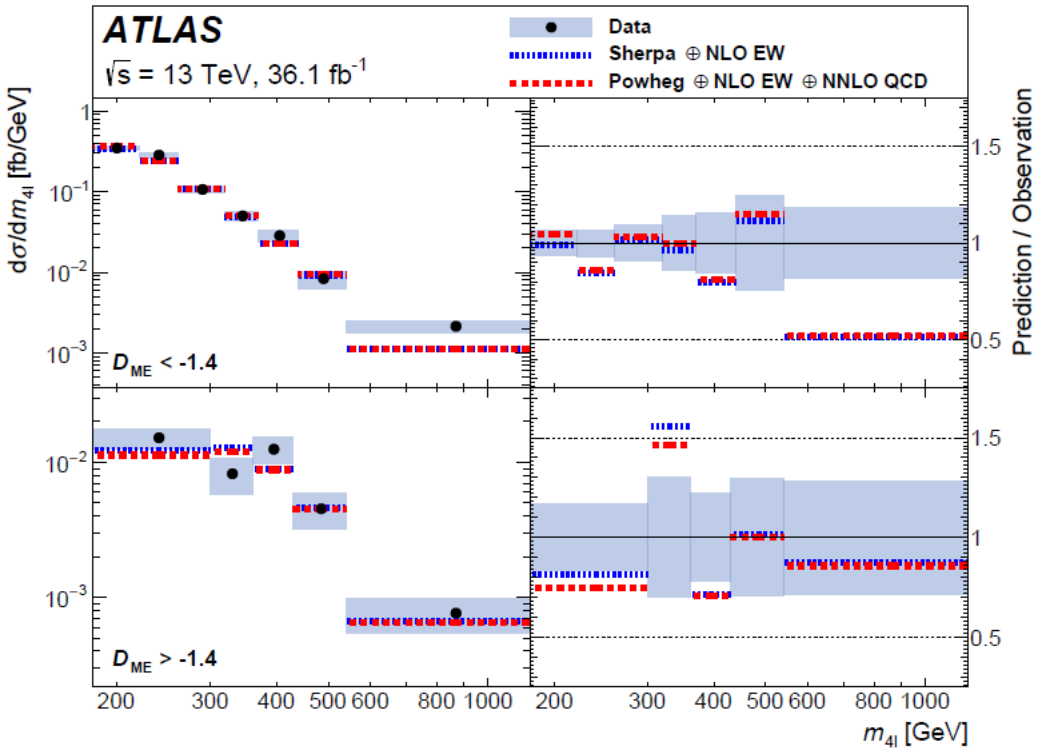
- **Measurement of Br(Z→4l)**
  - Lowest m(4l) bin [75, 100] GeV
  - All the uncertainties are treated uncorrelated.

$$\mathcal{B}_{Z\to 4\ell} = \frac{N_{\text{fid}} \times (1 - f_{\text{non-res}})}{\sigma_Z \times A_{\text{fid}} \times \mathcal{L}}$$

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV	4.31±0.34(stat)±0.17(syst)
CMS, $\sqrt{s}$ = 13 TeV	$4.83\ ^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}$ = 13 TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**

Interpretation: off-shell Higgs signal strength

- The double-differential distribution for "m4l-D_{ME}" is used to constrain the off-shell Higgs production process at high mass (m4l>180 GeV)
- Assuming that the contribution of the box diagram is as predicted by the SM.



- Interference is quite significant between off-shell signal and continuum ggZZ production

SBI = S + I + B

S : signal (gg→H*→ZZ); B : background (gg→ZZ);
I : interference term

- Interference is varied with signal strength. The signal related distribution built (**signal strength, μ_{off}**):

$$\mu_{off} \cdot S + \sqrt{\mu_{off}} \cdot I + B$$

Observed μ_{off}	Predicted
< 6.5 @ 95% C.L.	< 5.4 @ 95% C.L.

Consistent with recent reco-level results PLB 786 (2018) 223

Interpretation: modified Higgs couplings

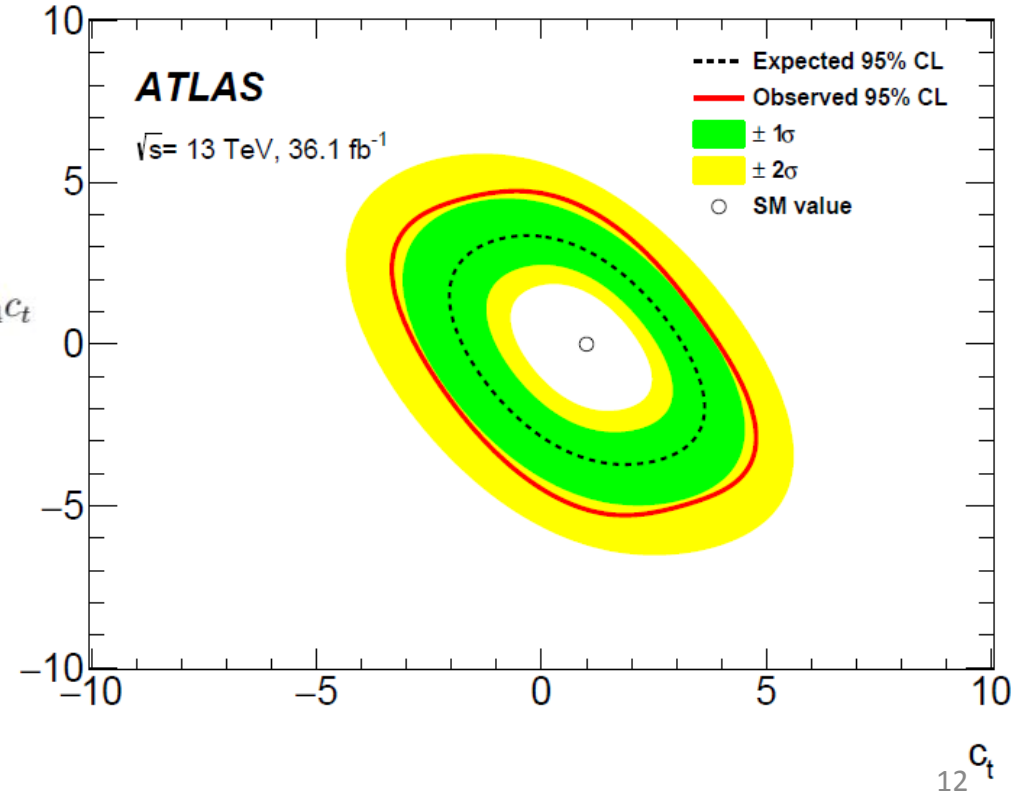
- Constrain possible BSM modifications of the couplings of H to top quarks (c_t) and gluons (c_g, 0 in the SM).
- Measurements at higher mass (> 180 GeV) can decouple c_t and c_g, as the partonic centre-of-mass energy of the process becomes larger than the top-quark mass.

- The yield from gg→4l is parameterised as a function of c_t and c_g [J. Exp. Theor. Phys. **120** (2015) 354] .

$$\frac{d\sigma(c_t, c_g)}{dm_{4\ell}} = F_0 + F_1 \left(c_t + c_g \frac{F_\Delta(\infty)}{\mathrm{Re}\, F_\Delta(m_t)} \right)^2 + F_3 \left(c_t + c_g \frac{F_\Delta(\infty)}{\mathrm{Re}\, F_\Delta(m_t)} \right) + F_2 c_t^2 + F_4 c_t$$

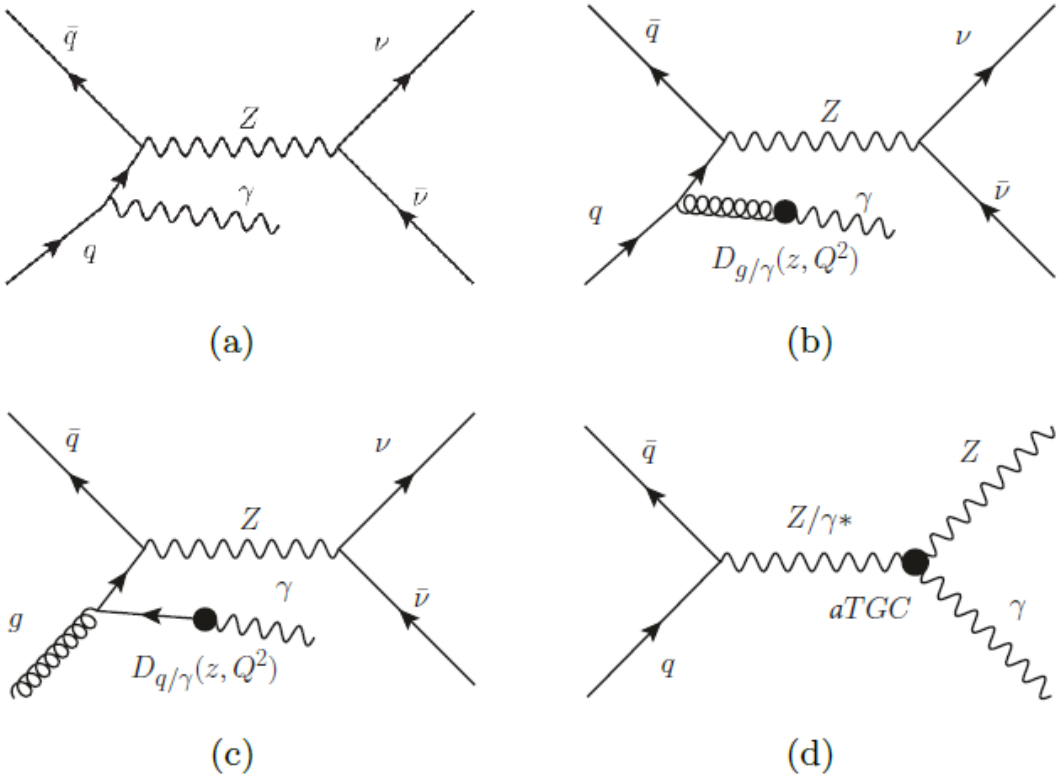
SM : c_t =1, c_g=0

- First interpretation with ATLAS data → improved the sensitivity compared to previous LHC result (CMS)



Zγ production with Z→νν at 13TeV

JHEP 12 (2018) 010



- Advantage of Zγ with Z→νν:
  - Higher branching ratio than Zγ with Z→ll (e or μ); more sensitive in higher energetic region.
  - Less contamination than Zγ with Z→qq.
- Measurement in this analysis:
  - Integrated and differential cross section in a dedicated fiducial phase space.
  - Inclusive (no Njets requirement) and exclusive (Njets=0) results.
- Searches : anomalous neutral TGC coupling.

Signal region definition

Signal topology: one high-pT and isolated γ, and a large E_T^{miss}

Photons	Leptons	Jets
$E_{\mathrm{T}} > 150$ GeV	$p_{\mathrm{T}} > 7$ GeV	$p_{\mathrm{T}} > 50$ GeV
$\lvert\eta\rvert < 2.37$,	$\lvert\eta\rvert < 2.47(2.7)$ for $e(\mu)$,	$\lvert\eta\rvert < 4.5$
excluding $1.37 < \lvert\eta\rvert < 1.52$	excluding $1.37 < \lvert\eta^e\rvert < 1.52$	$\Delta R(\mathrm{jet}, \gamma) > 0.3$
Event selection		
$N^\gamma = 1$, $N^{e,\mu} = 0$, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ signif. > 10.5 GeV$^{1/2}$, $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \gamma) > \pi/2$		
Inclusive : $N_{\mathrm{jet}} \geq 0$, Exclusive : $N_{\mathrm{jet}} = 0$		

- Lepton number = 0 : suppress events with leptons, e.g. Wγ with W->lv
- E_T^{miss} >150 GeV and E_T^{miss} -signif >10.5 : suppress the events with fake E_T^{miss}
- Δϕ(E_T^{miss} ,γ) : suppress pp→W(ev)+X

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

Signal and backgrounds

❖ Modelling of signal

- Sherpa 2.2.2 + NNPDF3.0-NNLO
- Alternative for systematic uncertainty : Sherpa 2.1.1, MG5_aMC@NLO

❖ Backgrounds components

- Wγ with W→lν : 60% arises from τ hadronic decay in W→τν ; misdetection of e/μ
- γ+jet : large E_T^{miss} due to mismeasurement of jet resolution.
- e/jet → γ : misidentified photon.

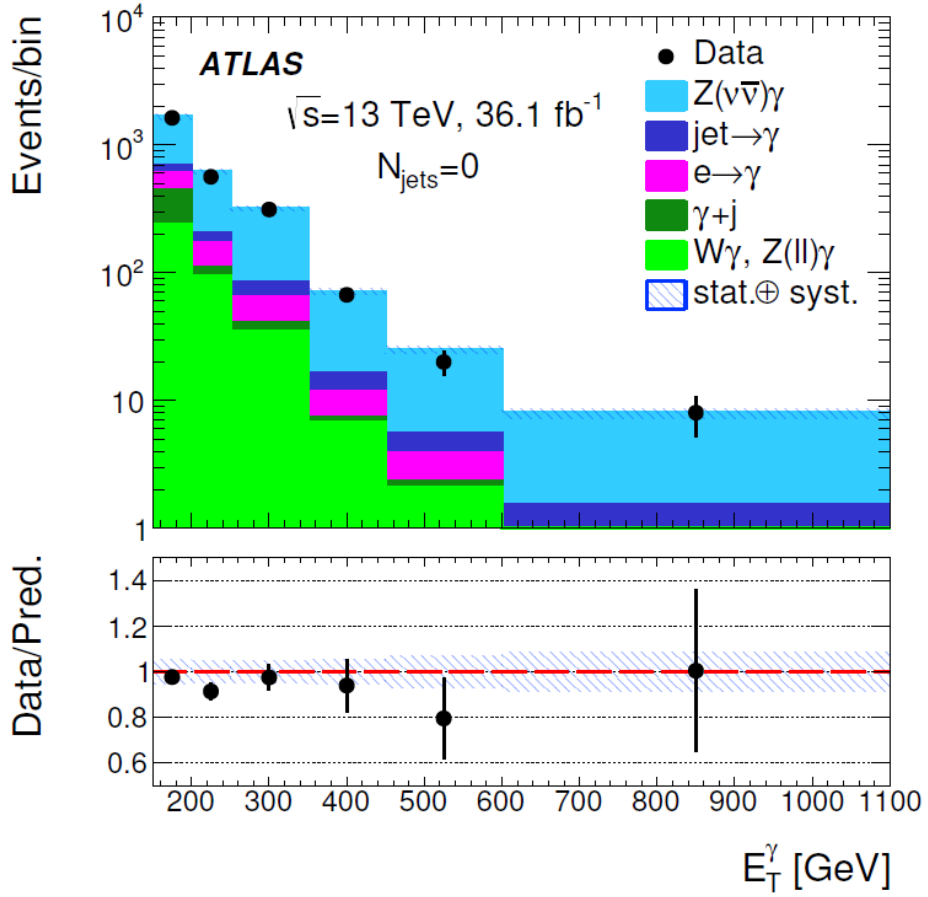
❖ Background estimation

- Wγ and γ+jet : 2 CRs with reversing SR definition (1 lepton, or small E_T^{miss} -sig value);
- e → γ : fake factor of e→ γ
- jet→ γ : 2D sideband, defined with photon isolation and identification.

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

Result of integrated cross section

Fiducial region is defined at particle level which is close to reco-level SR definition.



$$\sigma_{\text{ext-fid}} = \frac{N - B}{A_{Z\gamma} \cdot C_{Z\gamma} \cdot \int L \mathrm{d}\, t}$$

The likelihood function is defined as

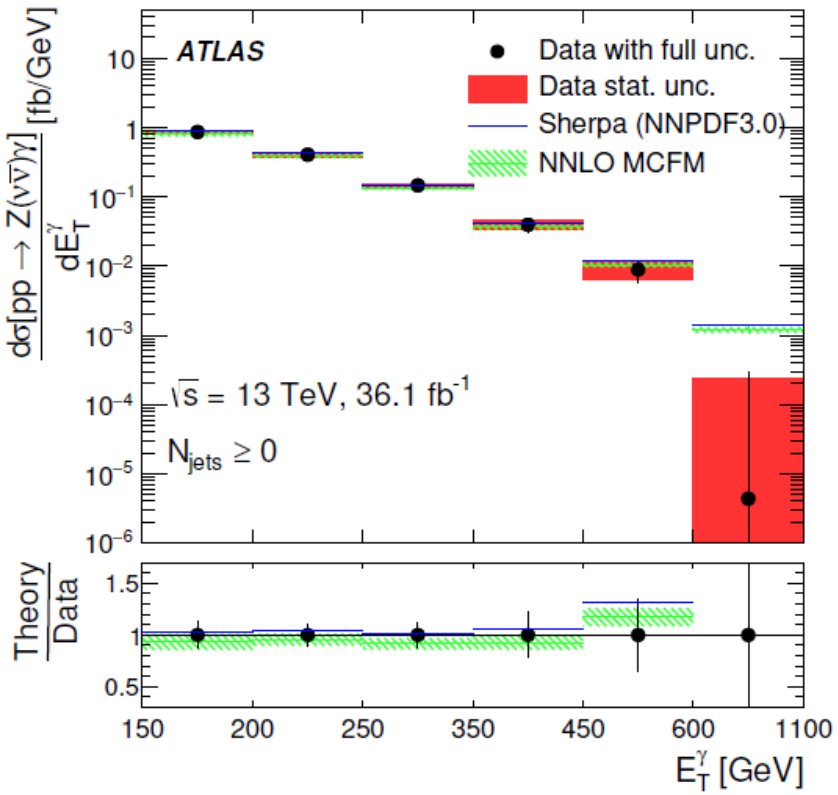
$$\mathcal{L}(\sigma, \boldsymbol{\theta}) = \text{Poisson}(N \mid S(\sigma, \boldsymbol{\theta}) + B(\boldsymbol{\theta})) \cdot \text{Gaussian}(\boldsymbol{\theta_0} \mid \boldsymbol{\theta})$$

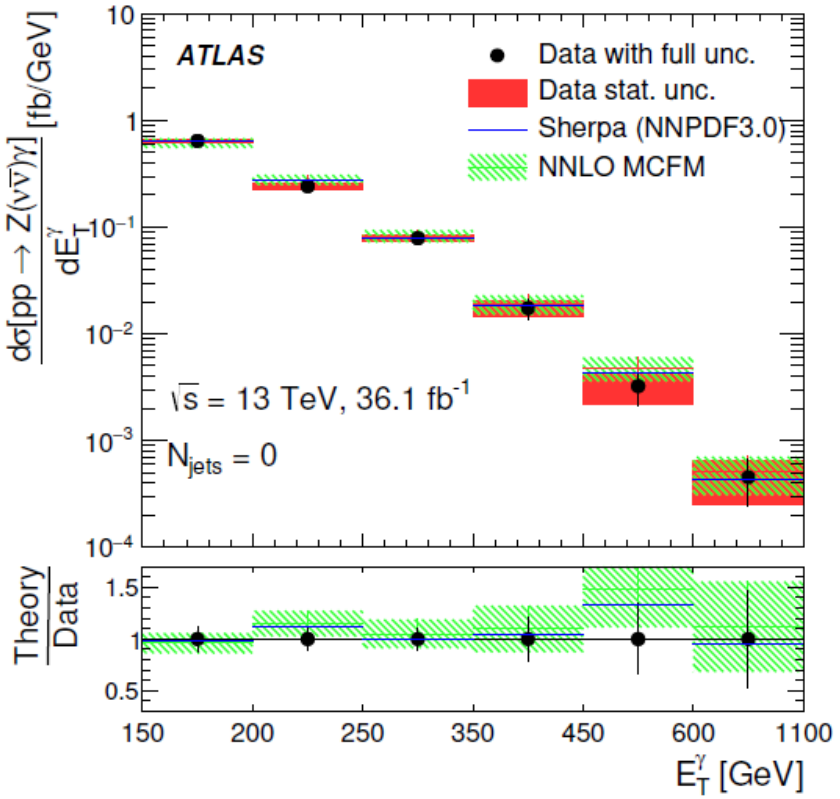
Good agreement between measurements and NNLO predictions!

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

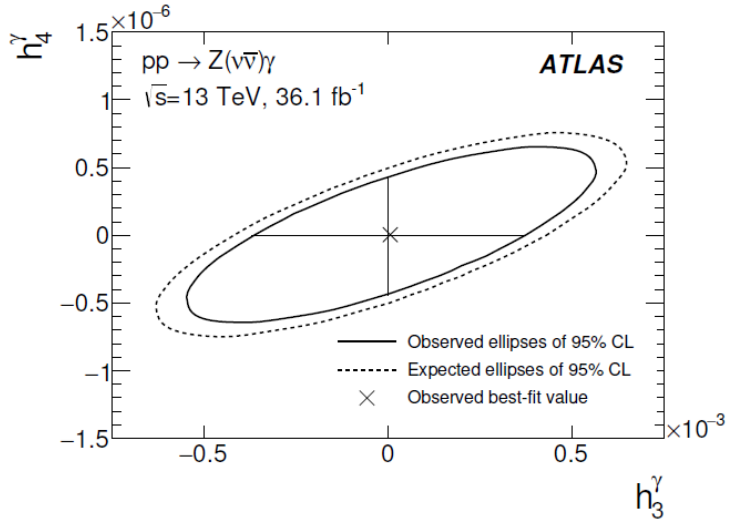
Differential cross sections

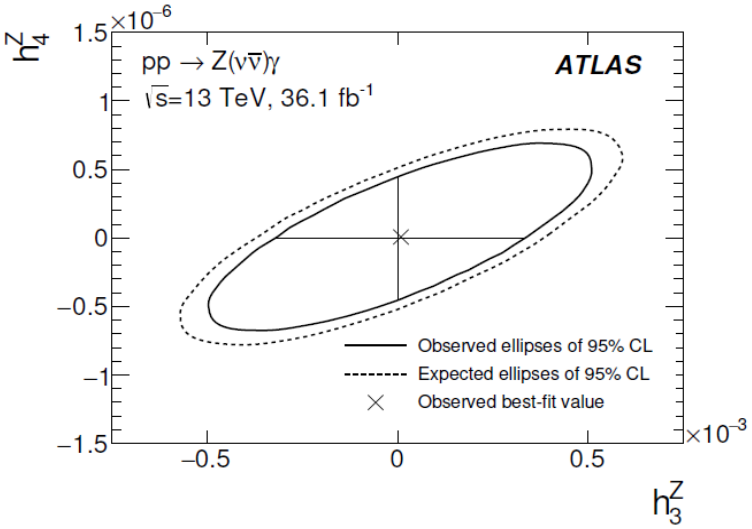
- Good agreement is also observed in the differential measurements w.r.t Sherpa and NNLO MCFM.
- Besides variable E_T^γ, differential cross section results of $p_T(\nu\nu)$ and Njets are provided in publication.
- The last bin in E_T^γ (>600 GeV) is also used for aTGC searches.





Constraint on aTGC parameter





- The framework of the effective vertex function approach: four CP-violating (h^V1 , h^V2) and four CP-conserving (h^V3, h^V4)
- These parameters would influence the event yield of **Zγ** , especially behaving quite significant in higher energetic region.

$$N_{Z\gamma}^{\mathrm{aTGC}}(h_3^V, h_4^V) = \sigma_{Z\gamma}^{\mathrm{aTGC}}(h_3^V, h_4^V) \cdot C_{Z\gamma} \cdot A_{Z\gamma} \cdot C^{*(\mathrm{parton}\to\mathrm{particle})} \cdot \int L\,\mathrm{d}t$$

- Higher E_T^{γ} bin (>600 GeV) is used for the aTGC searches.
- 3-7 times improved limits w.r.t. ATLAS 8TeV measurement

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}	$(-4.5 \times 10^{-7}, 4.4 \times 10^{-7})$	$(-5.3 \times 10^{-7}, 5.1 \times 10^{-7})$

Summary

- 4l (mainly ZZ production) and Zγ productions are reported with latest results (using **36.1 fb^{-1}**) : gg→4l signal strength, Br(Z→4l), BSM Higgs coupling, and aTGCs (ZZγ, Zγγ) searches.
- Looking forward more results with full Run-2 dataset !

Thanks !