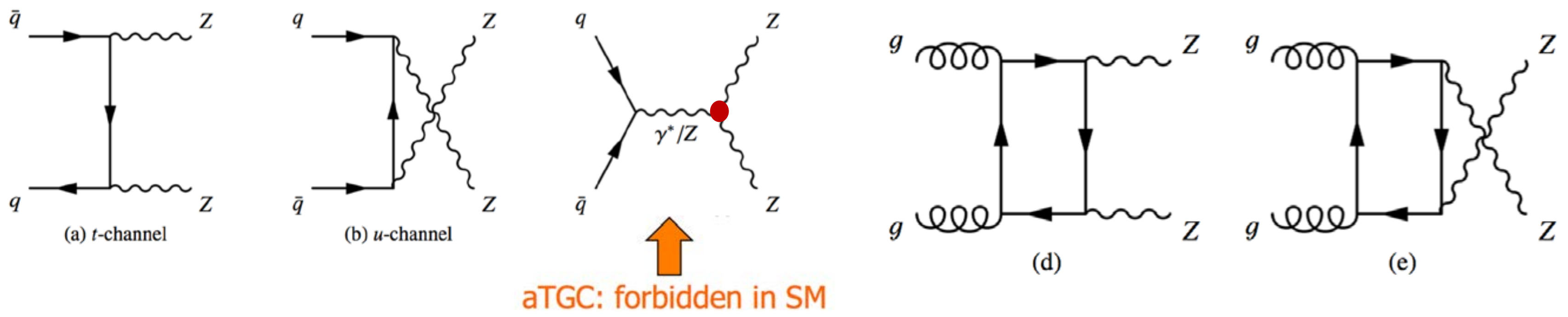
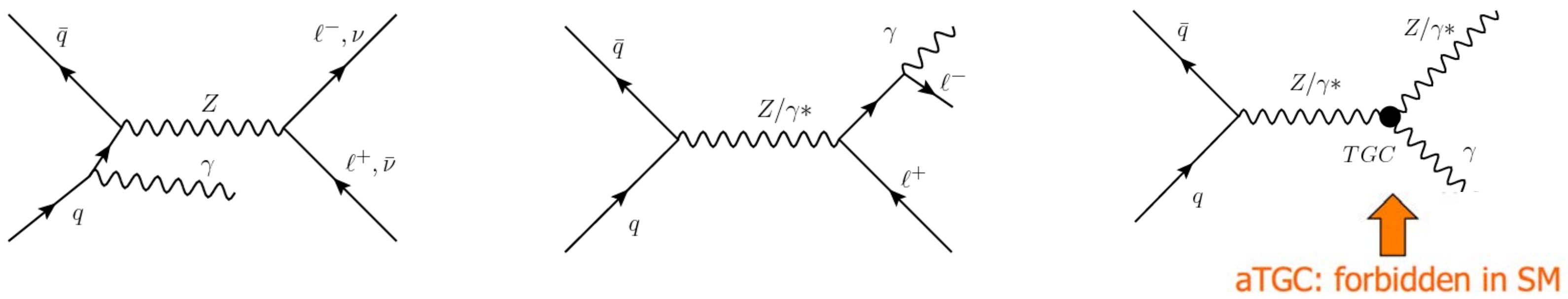
Measurement of the ZZ(*) and Zγ production cross section at 8 TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector

ZZ



Zγ



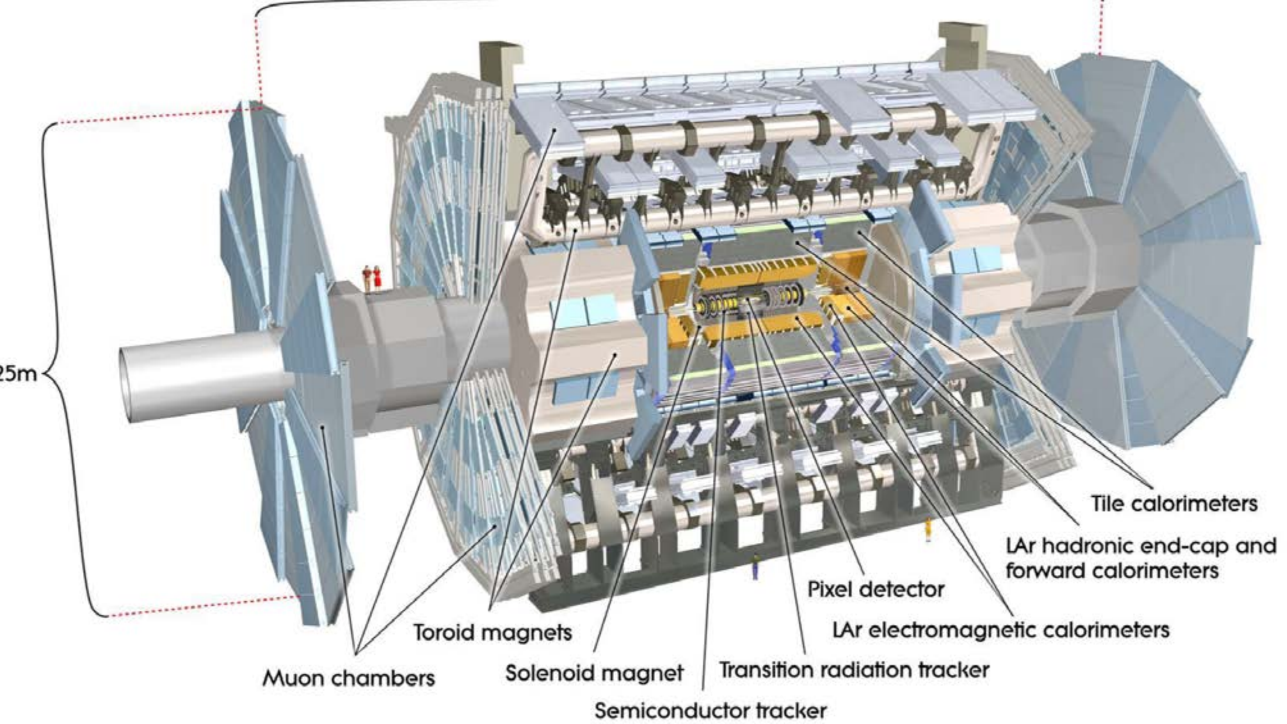
Bing Zhou (the University of Michigan)

On behalf of the ATLAS Collaboration, ICHEP at Chicago (Aug. 5, 2016)

ZZ and Zγ Physics and Measurements in ATLAS

Test SM at energy frontier; search for new physics with anomalous triple-gauge couplings

- **ZZ, Zγ (7TeV, L = 4.6 fb^{-1}):**
  - Phys.Rev. D87 (2013) no.11, 112003
  - JHEP 1303 (2013) 128
  - ATLAS-CONF-2016-036
- **ZZ, Zγ (8TeV, L = 20.3 fb^{-1}):**
  - Phys. Rev. D93 (2016) no.11, 112002
  - Phys. Lett. B753 (2016) 552-572
  - ATLAS-CONF-2013-020 (paper to be submitted to JHEP)
- **ZZ (13 TeV, L = 3.2 fb^{-1})**
  - Phys.Rev.Lett. 116 (2016) no.10, 101801



Measurements of σ^{total}, σ^{diff}, and couplings with leptonic final states: 4ℓ, $\ell\ell\nu\nu$, and $\ell\ell\gamma$, $\nu\nu\gamma$

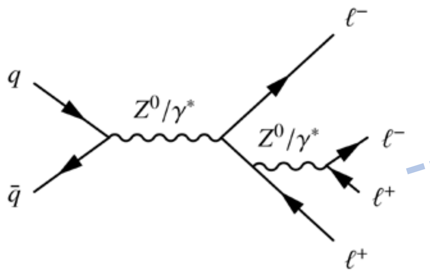
$ZZ^{(*)} \rightarrow 4l$ Lineshape Measurement at 8 TeV

4l lineshape is measured in mass range of 80 → 1000 GeV

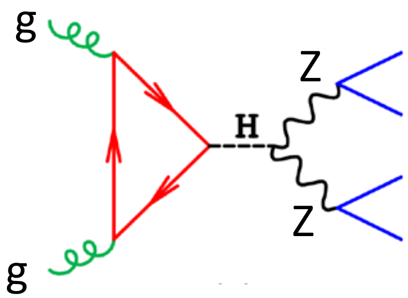
Phys. Lett. B753 (2016) 552-572

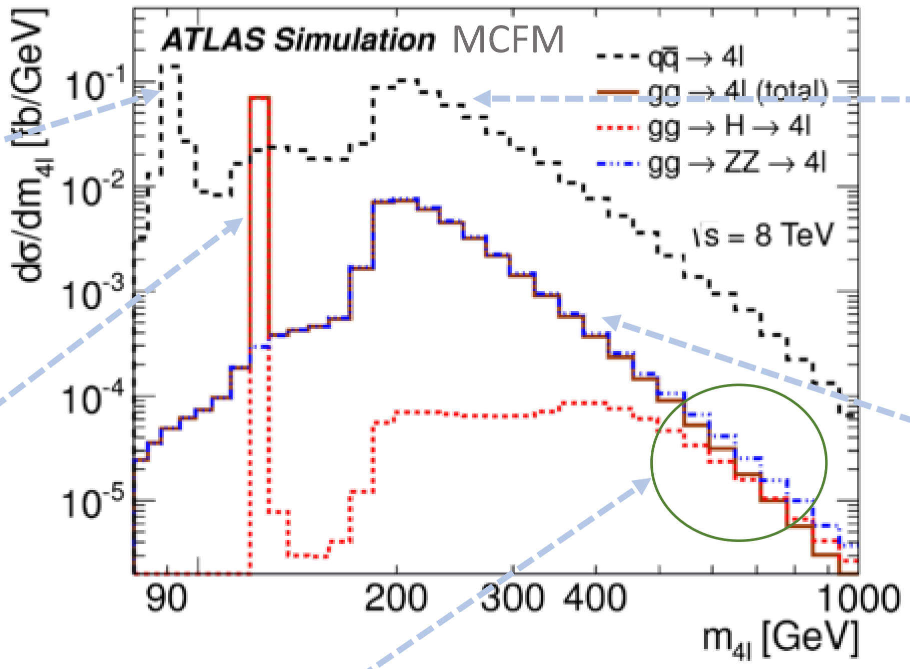
- Multiple processes involved in 4l productions; Measure at once give consistent look into missing corners not covered by dedicated analyses with certain mass ranges
- Test the validity of the SM through the interplay of QCD and EW effects for different 4l production mechanisms

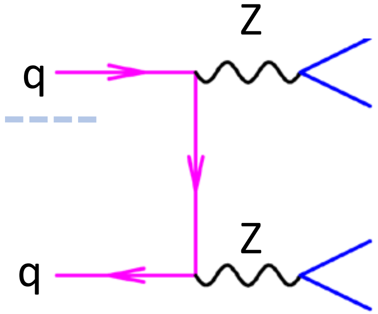
Calculated
NLO QCD
LO EW



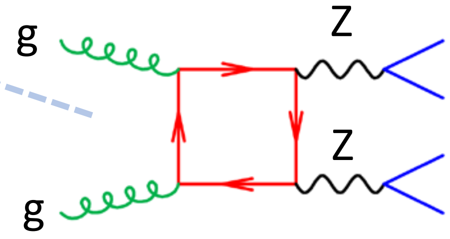
Calculated
NNLO QCD
NLO EW







Calculated
NNLO QCD
NLO EW

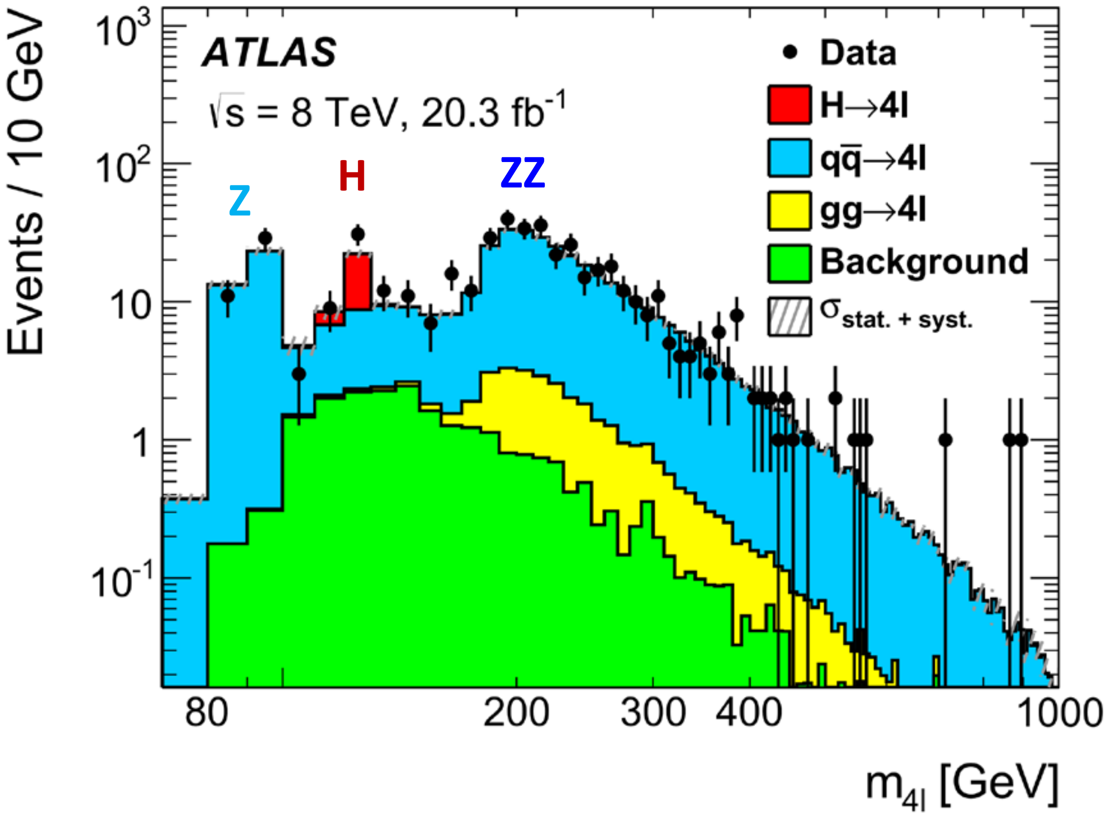


Calculated
LO QCD

Interference between gg→4l and off-shell Higgs→4l; Region for Higgs width study

4l Event Selection to Measure the Lineshape

Lepton selection	
Muons:	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton $p_T^{\ell_1,\ell_2,\ell_3}$:	$> 20, 15, 10(8 \text{ if } \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV
	$12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1\,000$ GeV



Observed 476 candidate, estimate <5% backgrounds

In phase space: $80 < m_{4l} < 1000$ GeV, $m_{2l} > 4$ GeV, $p_T^Z > 2$ GeV, $p_T^\ell > 5$ GeV, and $|\eta^\ell| < 2.8$

Measured σ^{ext} [fb]	SM σ^{ext} [fb]
73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

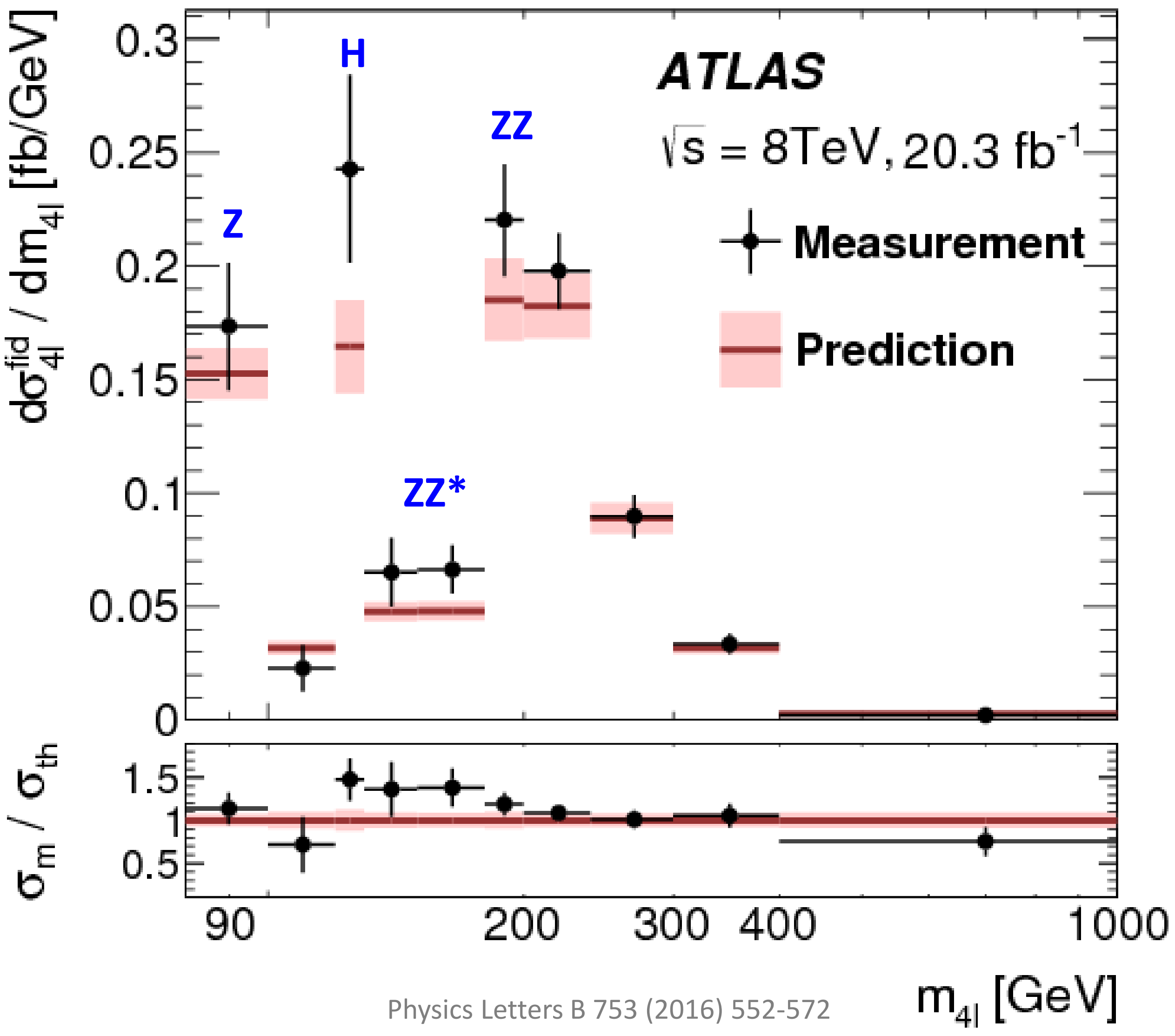
Note: σ(SM) calculation for diff processes includes diff. higher-order corrections (State-of-Art prediction)

Unfolded 4l Spectrum in Fiducial Phase Space

- **Compared with state-of-art MC prediction**
  - PowHeg MC (NLO+PS) predicts acceptance
  - Higgs pole and on-shell ZZ scaled to NNLO predictions
  - NLO EWK correction applied to high mass
- Statistical uncertainty O(10%)
- Systematic uncertainty O(5%)
  - lepton reconstruction

Remarks

1) Good agreement In the **Z** and **H** resonances with dedicated measurements
2) Data excess between H pole and on-shell ZZ – no NNLO correction available
3) Data excess around ZZ on-shell (no higher-order correction for continuum gg→4l)



Physics Letters B 753 (2016) 552-572

Extract the gg→ZZ→4l Contribution

- Study of gg→4l contribution in m_{4l} > 200 GeV region

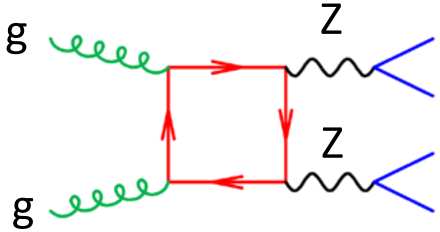
Physics Letters B 753 (2016) 552-572

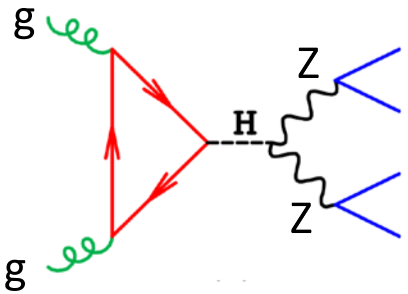
- Derived $\mu = \sigma_{gg}^{meas} / \sigma_{gg}^{LO}$

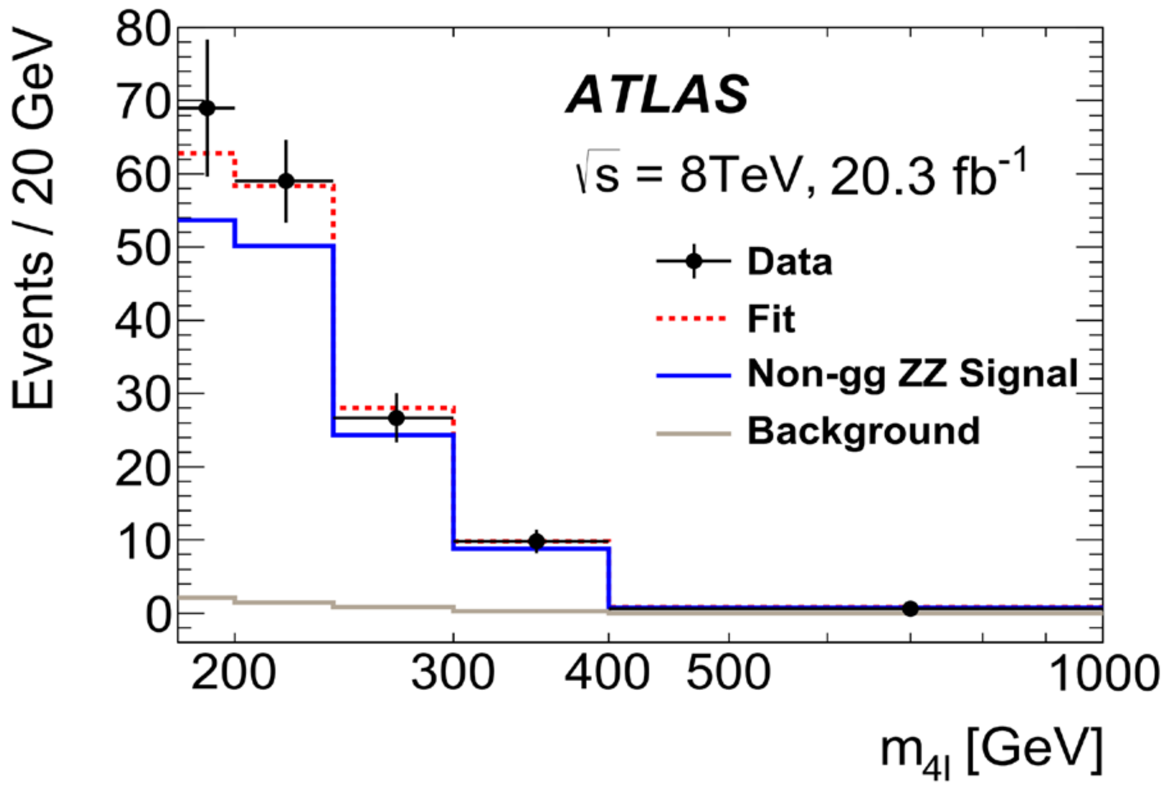
$$\mu_{gg} = 2.4 \pm 1.0\,(\text{stat.}) \pm 0.5\,(\text{syst.}) \pm 0.8\,(\text{theory})$$

- Compatible to recent calculation of NLO/LO k-factor of 1.5-2 (PhysRevD.92.094028)

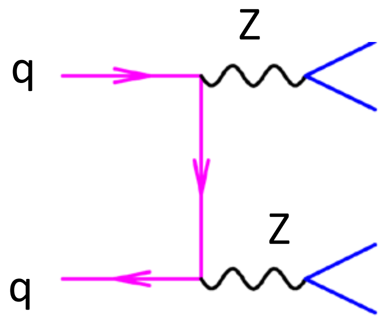
gg→ ZZ signal (including interference) is calculated at **LO QCD**





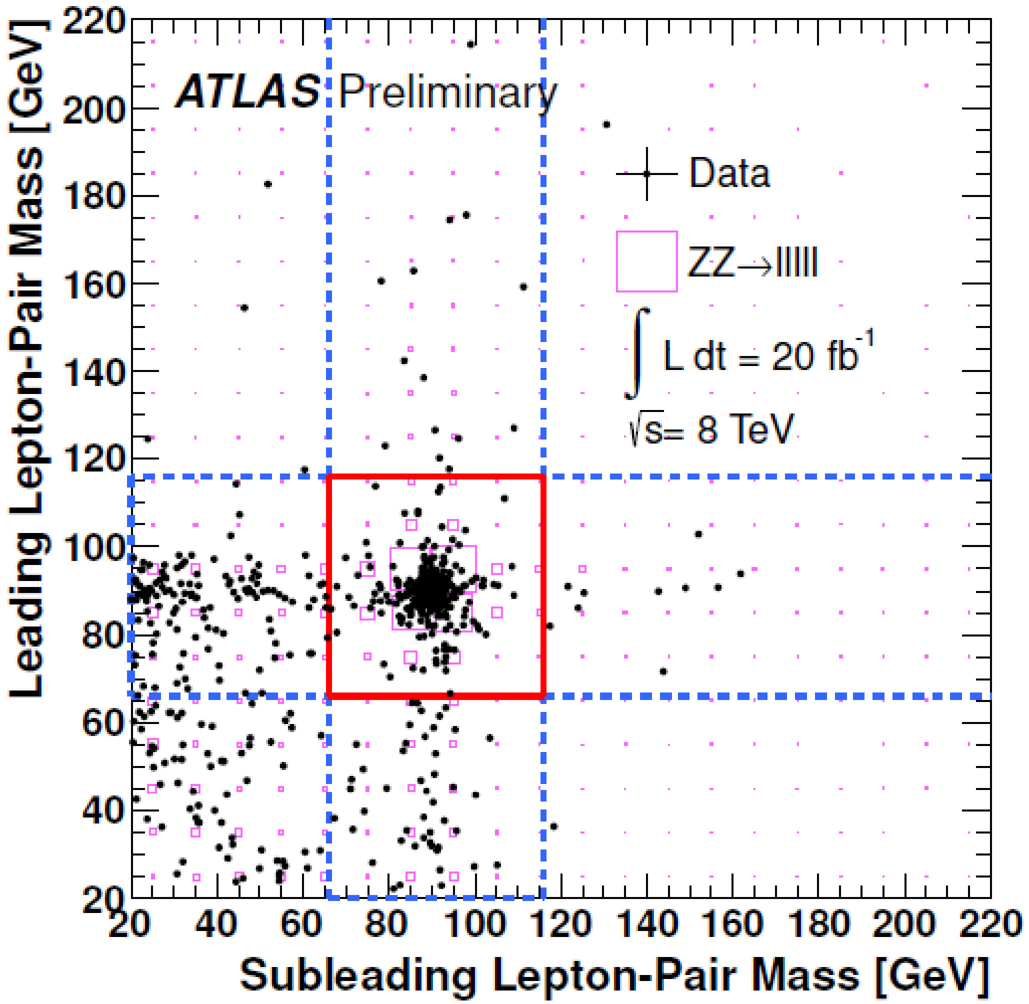


Non-gg ZZ signal s is calculated at **NNLO QCD, NLO EW**



Study of On-shell ZZ Production at 8 TeV

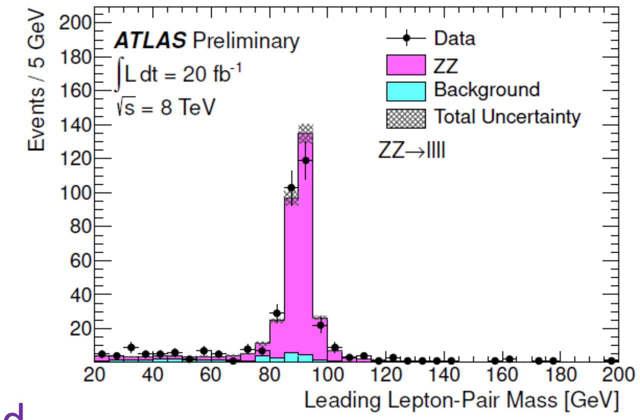
ATLAS-CONF-2013-020

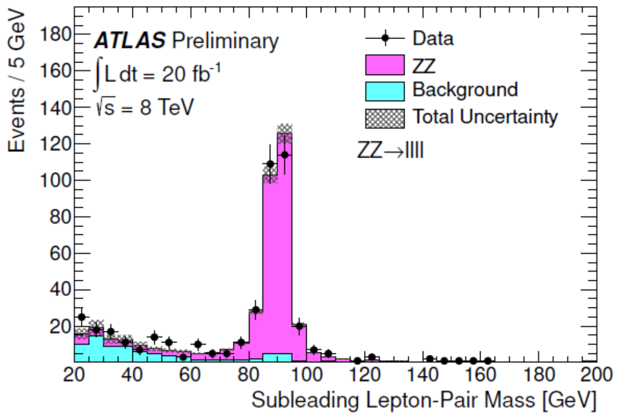


Observed **305** candidate, estimate 20.5±5.5 background

Measure the total cross section in a phase space: for both Z in mass window: **66 GeV < m_Z < 116 GeV** (with 4e, 4μ, 2e2μ)

Fiducial cross section is measured with $p_T^{\ell} > 7$ GeV, $|\eta\ell| < 2.7$, $\Delta R(\ell, \ell') > 0.2$ and 66 GeV < m_Z < 116 GeV





Measurements of ZZ Production Cross Section at 8 TeV

ATLAS-CONF-2013-020

The observation compared with predictions

Final state	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Observed	62	85	158	305
Signal (MC)	59.5±4.0	90.2±2.7	142.7±5.6	292.5±10.6
Background	10.0±1.8±1.4	1.1±1.4±0.5	9.3±2.1±3.1	20.4±2.9±5.0

Measured and predicted

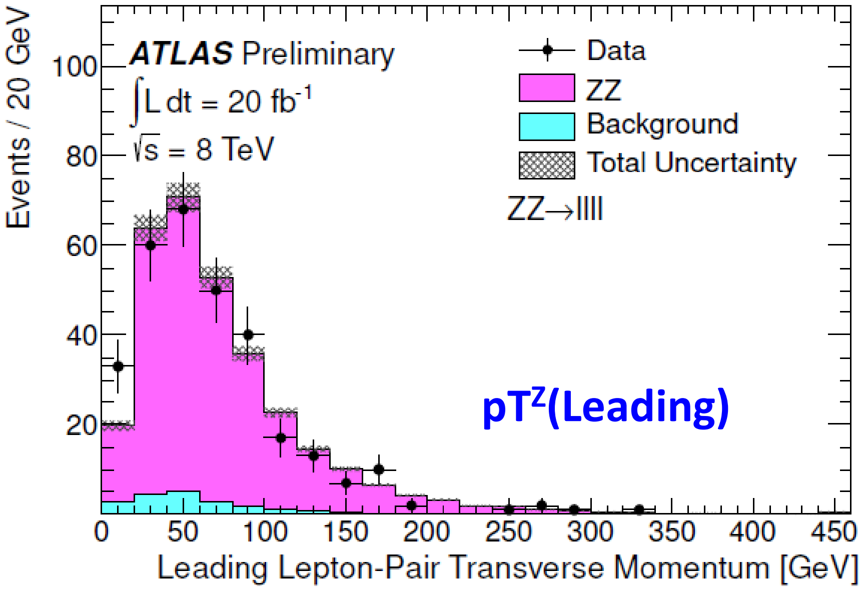
Total cross sections and **fiducial cross sections**

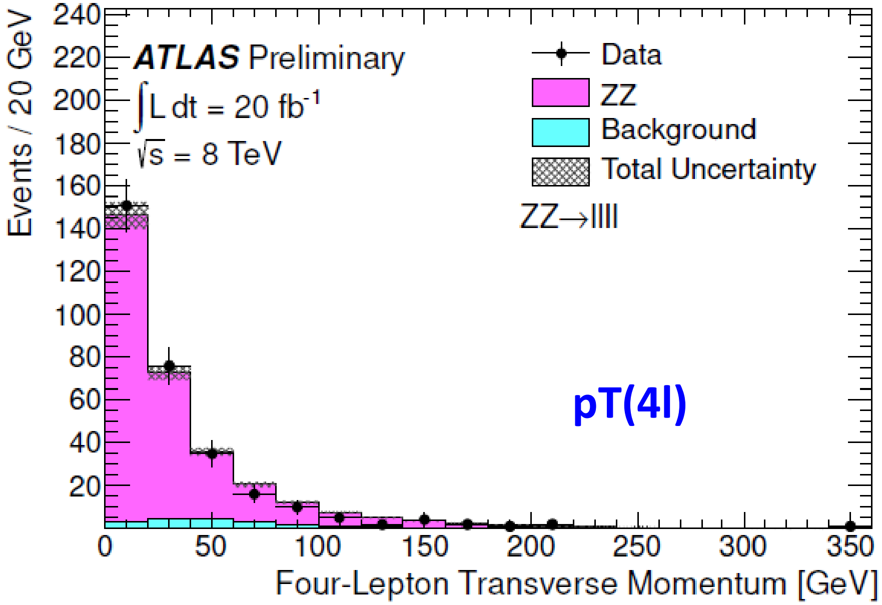
$$7.1^{+0.5}_{-0.4}(\text{stat.})\pm0.3(\text{syst.})\pm0.2(\text{lumi.})\ \text{pb}$$

Standard Model expectation of $6.6^{+0.7}_{-0.6}$ pb

$$20.7^{+1.3}_{-1.2}(\text{stat.})\pm0.8(\text{syst.})\pm0.6(\text{lumi.})\ \text{fb}$$

Standard Model expectation of $19.1^{+0.9}_{-0.7}$ fb





ZZ Production Cross Section Measurement at 13 TeV

Phys. Rev. Lett. 116, 101801 (2016)

⇒ **With ZZ→4l channel; Each lepton pT>20 GeV, each Z pairs with 66 < mass < 116 GeV**

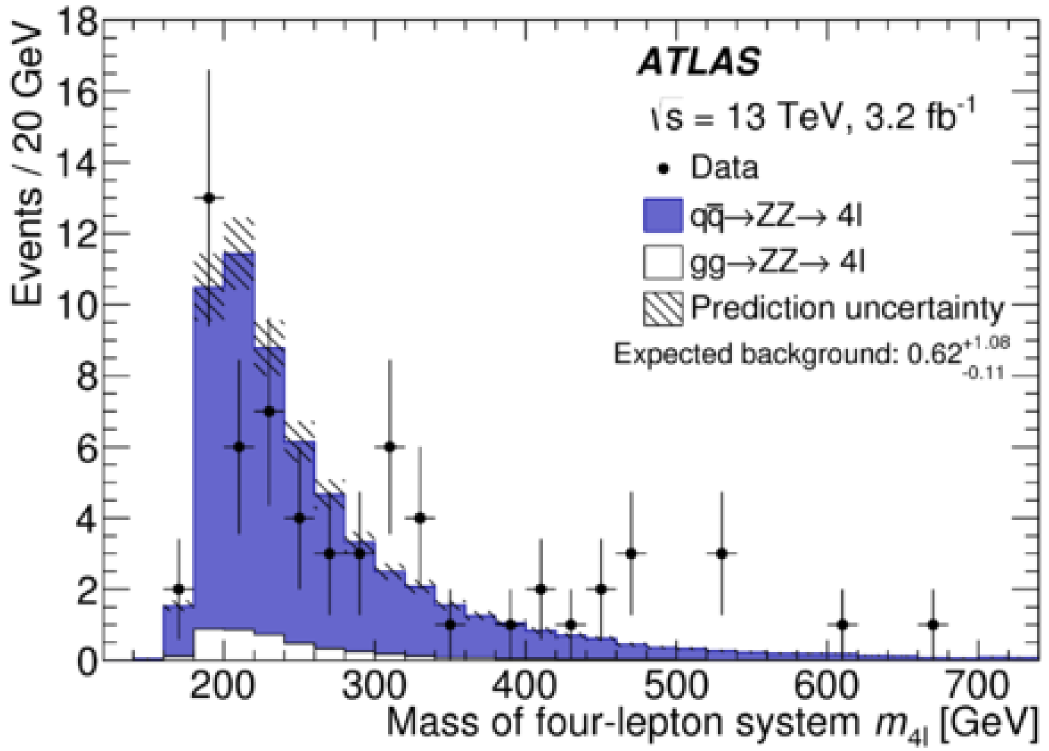
⇒ **Observed 63 ZZ→ 4l candidate events (3.2 fb^{-1}), estimate 1% from backgrounds**

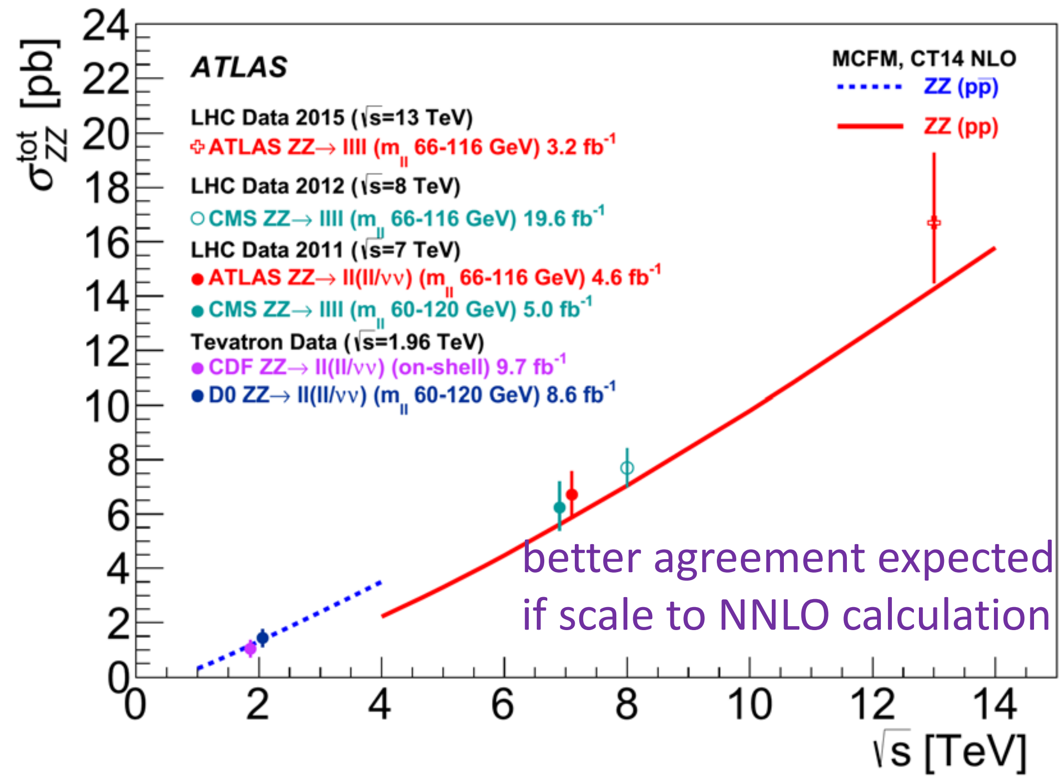
Measured σ in phase space of 66<m_Z<116 GeV

$$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})\ \text{pb}$$

SM prediction (NNLO) (PLB 750 (2015) 407)

$$15.6^{+0.4}_{-0.4}\ \text{pb}$$





Zγ Measurements at 8 TeV (L = 20.3 fb^{-1})

Phys. Rev. D 93, 112002 (2016)

Measurement of Zγ production with Z→ll (l=e,μ) and Z→νν channels

- **Event selection and major background**
  - **Z→ll** channels (two leptons pT>25 GeV, one or two γ E_T>15 GeV)
    - Major background from Z+jets (estimated from data)
  - **Z→νν** channels (hard cut on MET (>100 GeV), harder cut on γ E_T (>130 GeV) due to photon trigger threshold
    - Major backgrounds from γ+jet and W+γ (estimated from data)
  - **Exclusive channel defined with jet veto (for jet pT>30 GeV)**
    - Study high order calculation on Zγ channel

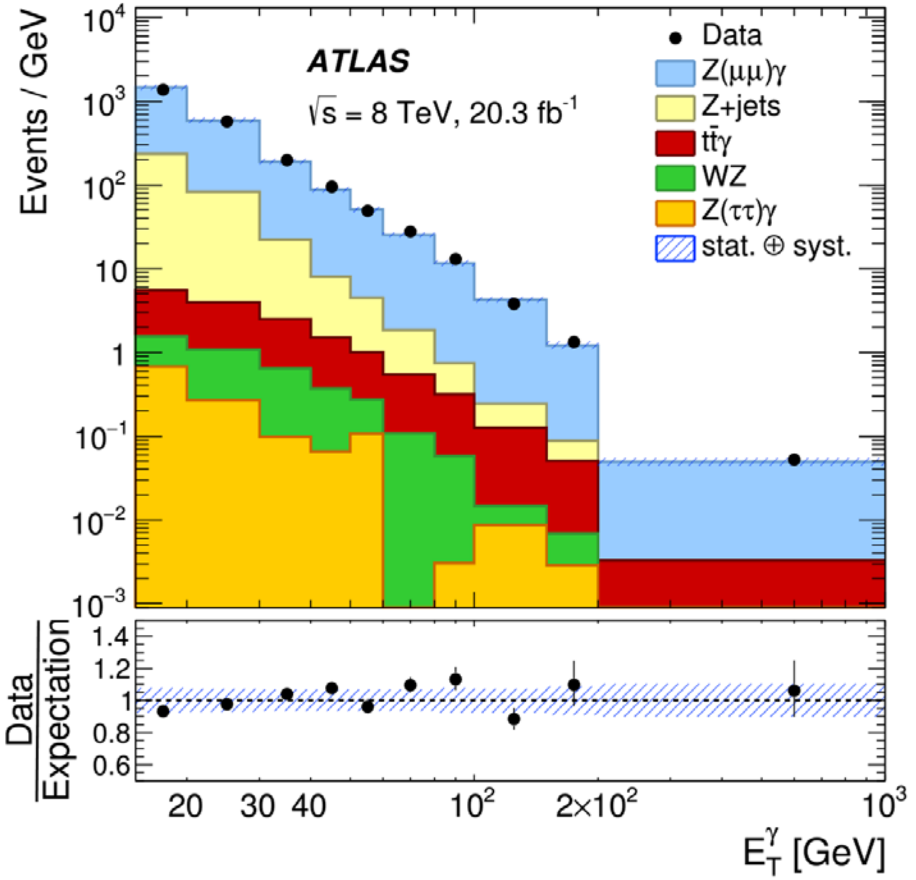
Selected numbers of candidates, and estimated bkg

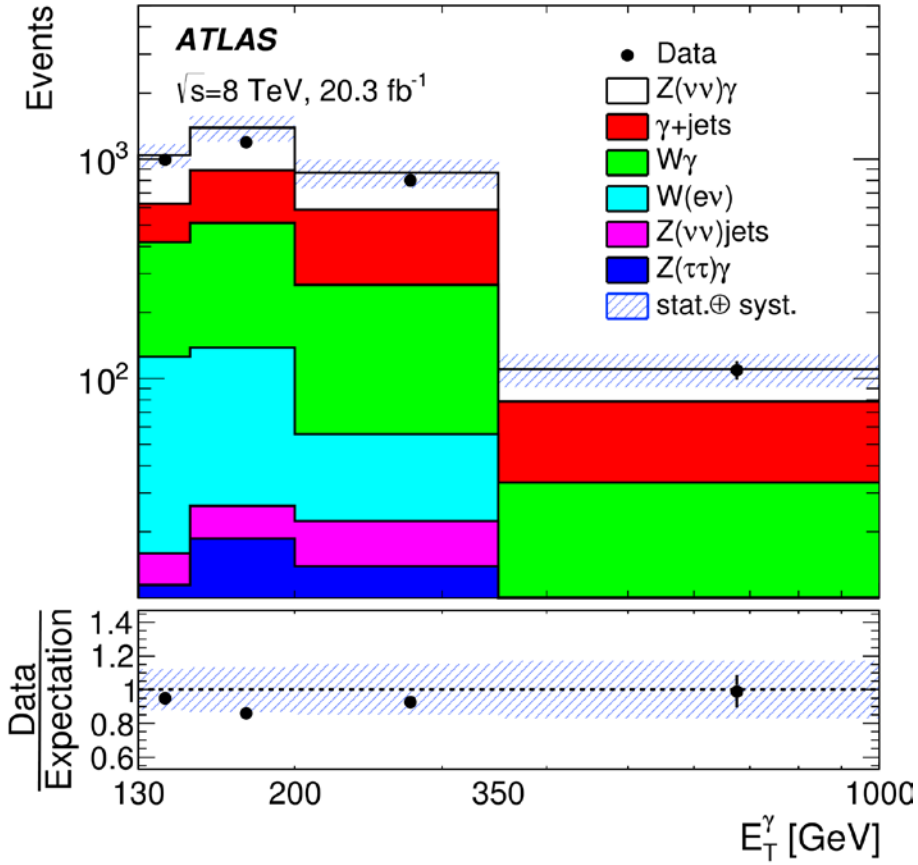
Zγ→llγ	$e^+e^-\gamma$ ($N_{jets} \geq 0$)	$\mu^+\mu^-\gamma$ ($N_{jets} \geq 0$)	$e^+e^-\gamma$ ($N_{jets} = 0$)	$\mu^+\mu^-\gamma$ ($N_{jets} = 0$)
$N_{Z\gamma}^{obs}$	13807	17054	10268	12738
$N_{Z\gamma}^{j\to\gamma}$	1840 ± 90 ± 480	2120 ± 90 ± 560	1260 ± 80 ± 330	1510 ± 80 ± 400
$N_{Z\gamma}^{\text{Other BKG}}$	143 ± 3 ± 26	146 ± 2 ± 28	30.8 ± 1.6 ± 3.9	26.9 ± 1.5 ± 3.4

Zγ→ννγ	$N_{jets} \geq 0$	$N_{jets} = 0$
$N_{Z\gamma}^{obs}$	3085	1039
$N_{Z\gamma}^{\gamma+\text{jets}}$	950 ± 30 ± 300	9.2 ± 3.5 ± 0.7
$N_{Z\gamma}^{W(\ell\nu)\gamma}$	900 ± 50 ± 300	272 ± 14 ± 92
$N_{Z\gamma}^{W(e\nu)}$	258 ± 38 ± 18	147 ± 21 ± 10
$N_{Z\gamma}^{Z(\nu\bar{\nu})+\text{jets}}$	22.9 ± 0.5 ± 6.1	11.1 ± 0.4 ± 3.4
$N_{Z\gamma}^{Z(\tau^+\tau^-)\gamma}$	46.2 ± 0.9 ± 3.2	10.23 ± 0.43 ± 0.72

E_T^γ Distributions of the Selected Zγ Events

Spectra sensitive to aTGC measurement   Phys. Rev. D 93, 112002 (2016)





Z(→ll)γ: Clean
observed $3x10^4$ candidates,
expected 4000 backgrounds

Z(→νν)γ: better statistics in high E_T
observed 4000 candidates,
expected 2200 backgrounds

Zγ Total and Differential Cross Section Measurements

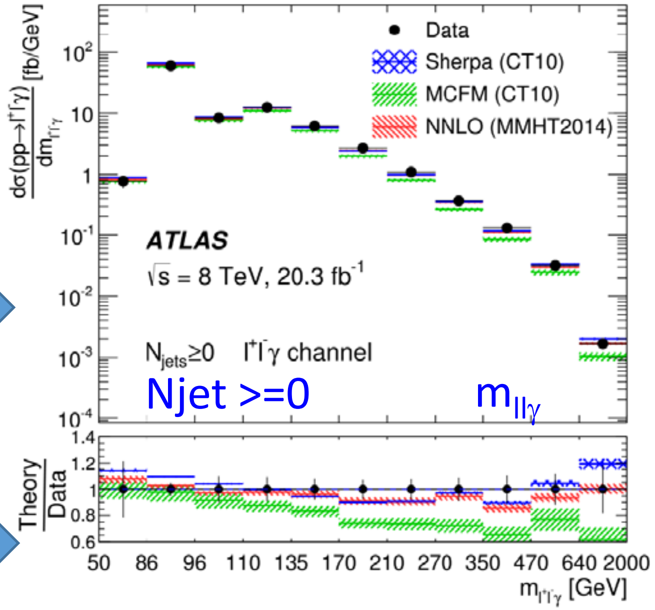
JHEP 1507 (2015) 085

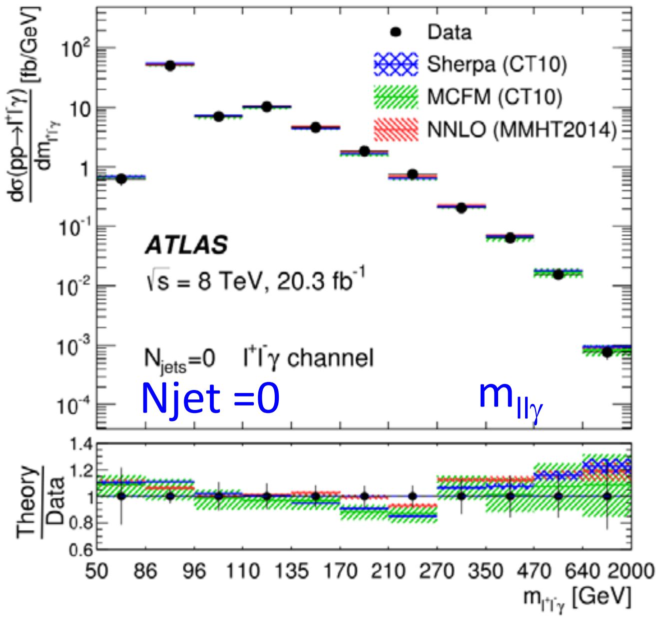
Channel	Measurement [fb]	MCFM Prediction [fb]	NNLO Prediction [fb]
	$N_{\text{jets}} \geq 0$	σ(NLO)	**σ(NNLO)**
$e^+e^-\gamma$	$1510 \pm 15(\text{stat.})^{+91}_{-84}(\text{syst.})^{+30}_{-28}(\text{lumi.})$	1345^{+66}_{-82}	1483^{+19}_{-37}
$\mu^+\mu^-\gamma$	$1507 \pm 13(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1507 \pm 10(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat.})^{+33}_{-32}(\text{syst.}) \pm 1(\text{lumi.})$	68.2±2.2	$81.4^{+2.4}_{-2.2}$
	$N_{\text{jets}} = 0$		
$e^+e^-\gamma$	$1205 \pm 14(\text{stat.})^{+84}_{-75}(\text{syst.}) \pm 23(\text{lumi.})$	1191^{+71}_{-89}	1230^{+10}_{-18}
$\mu^+\mu^-\gamma$	$1188 \pm 12(\text{stat.})^{+68}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1189 \pm 9(\text{stat.})^{+69}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat.}) \pm 10(\text{syst.}) \pm 1(\text{lumi.})$	$51.0^{+2.1}_{-2.3}$	$49.21^{+0.61}_{-0.52}$

- About 6% uncertainty from combined llγ fiducial σ
  - Main systematics: photon, backgrounds
  - Consistent with NNLO

Phys. Rev. D 93, 112002 (2016)

differential cross sections measurements of $m_{ll\gamma}$ for Njet >=0 and Njet = 0 categories

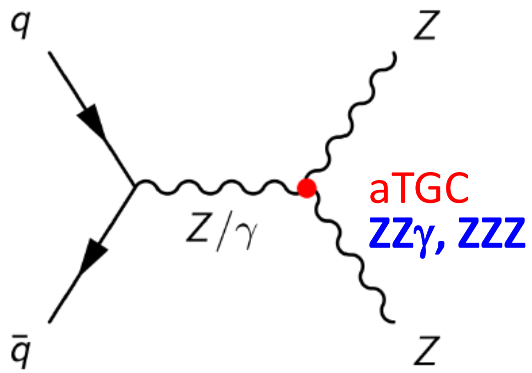




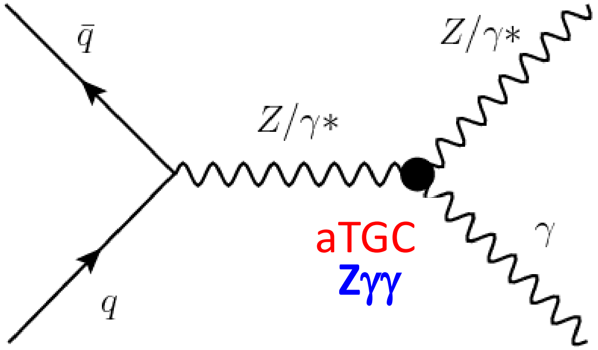
Start being sensitive to NNLO effect

Explore Anomalous Neutral Gauge Boson Couplings

- Vector boson self-couplings arise in the SM from the non-Abelian nature of the $SU(2)_L x U(1)_Y$ gauge symmetry; Only charged TGCs are allowed in SM
- In the SM the vertices of neutral gauge bosons are forbidden →anomalous neutral gauge boson couplings would indicate the existence of new physics.
  - For example, exotic, high mass particles can affect the observed properties of SM particles at low energy through virtual effects.



ZZ detect with
4l and 2l2ν



Zg detect with
2l γ and 2ν γ

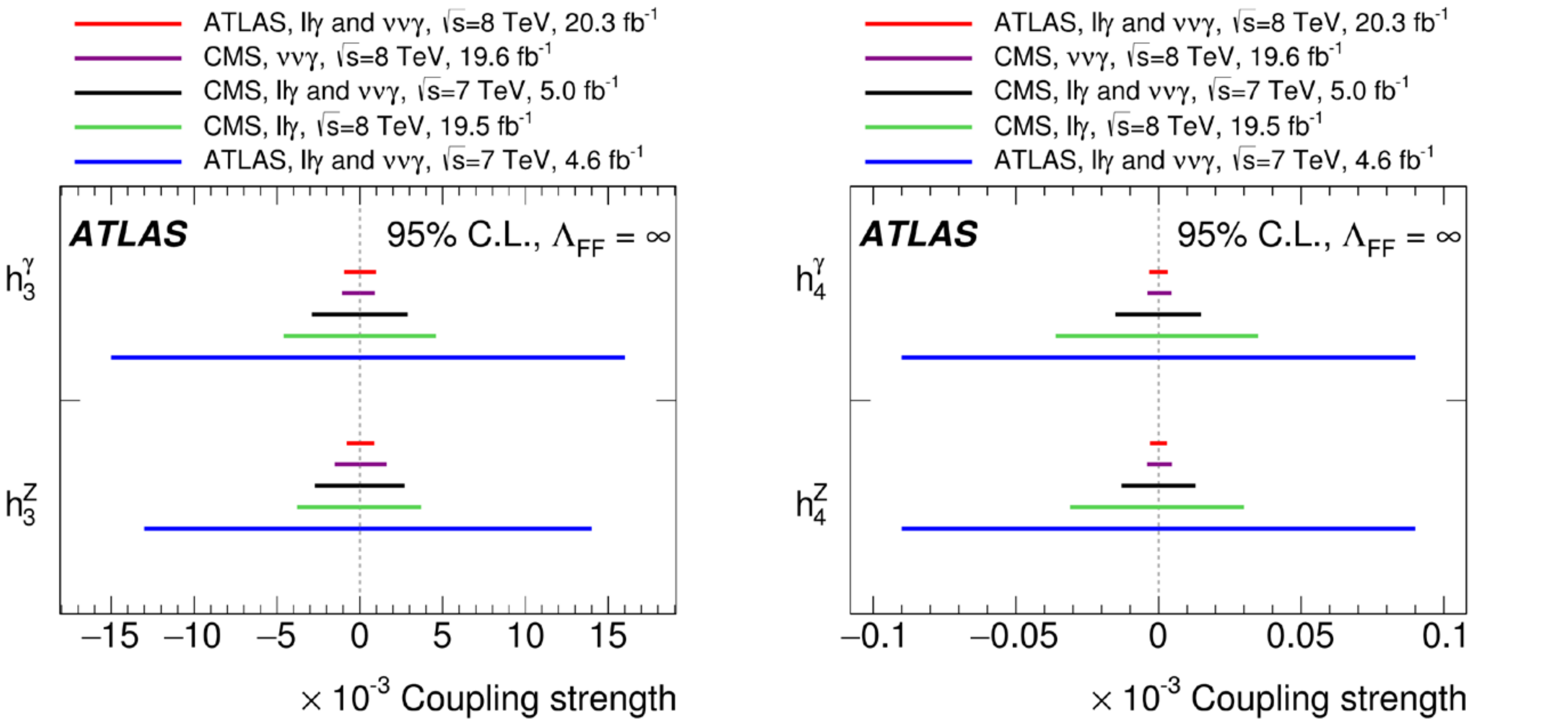
- Effective Langrangian approach is used to extend the SM Lagrangian with new operators in a generic way to accommodate physics beyond the SM
- Leading Z pT and γ $E_T$spectra are used to explore the aTGC in analysis

Explore aTGC in Zγ production

Using effective lagrangian approach: aTGC parameters $h_3^Z, h_3^\gamma, h_4^Z, h_4^\gamma$

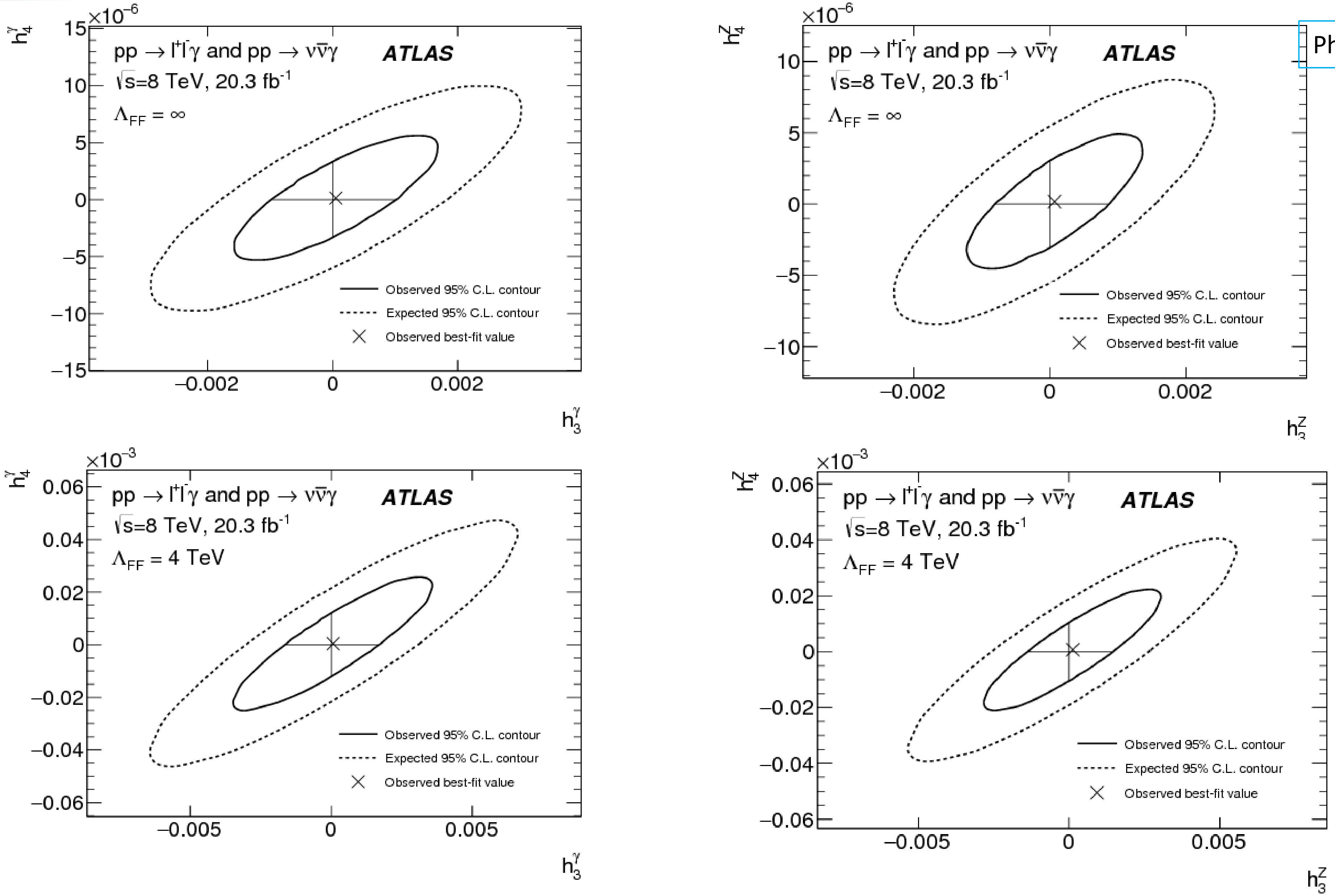
Phys. Rev. D 93, 112002 (2016)

- Use the event yield with photon $E_T > 250$ $(\ell\ell\gamma)$ and 400 $(\nu\nu\gamma)$ GeV with exclusive selection ($N_{Jets} = 0$) for the limit setting.
- Set limit on the CP-conserving couplings : h_3^Z and h_4^Z from $ZZ\gamma$ vertex and h_3^γ and h_4^γ from $Z\gamma\gamma$ vertex



2D aTGC limit at 95% CL extracted from Zγ production

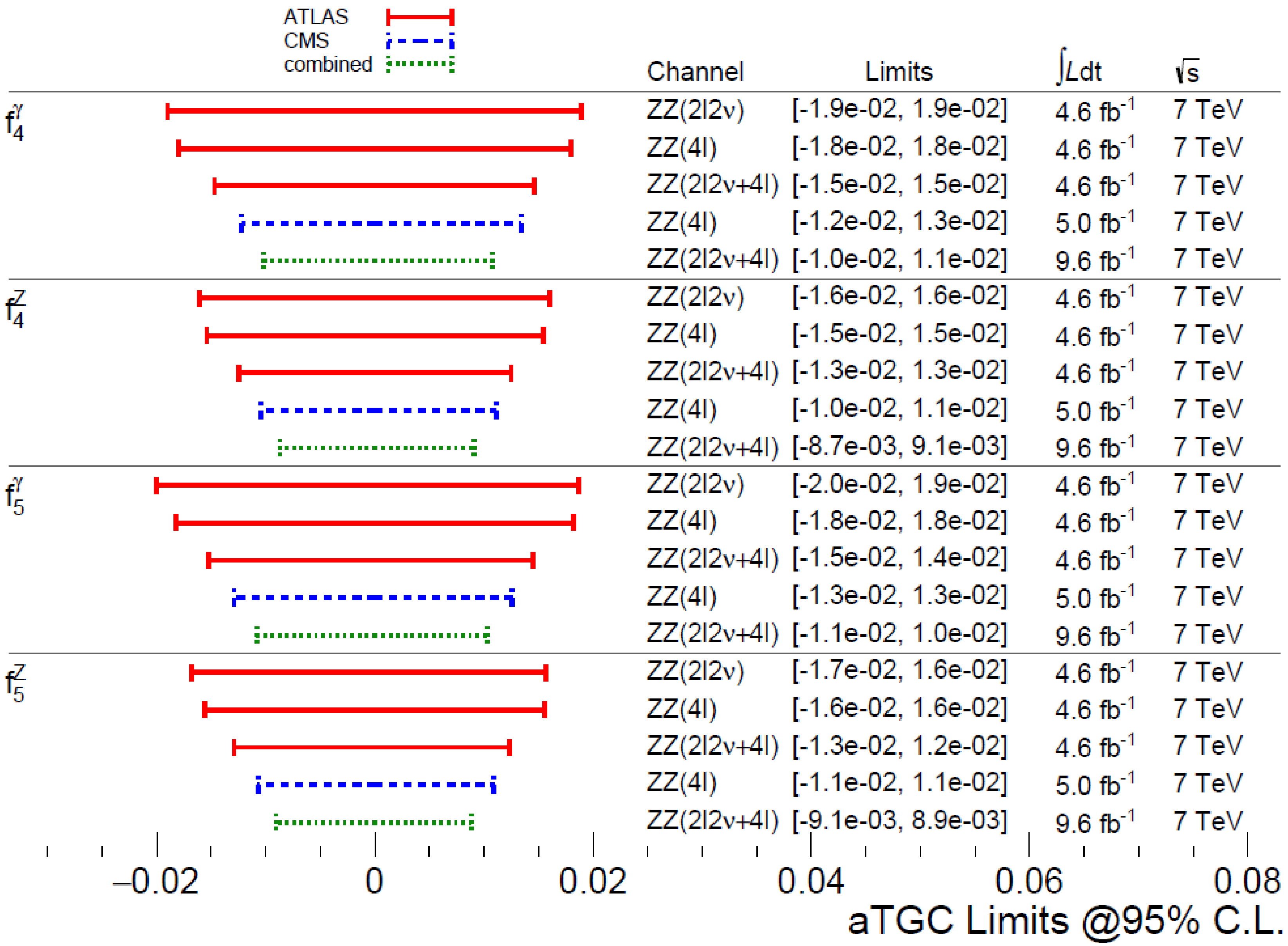
Phys. Rev. D 93, 112002 (2016)



aTGC Limits at 95% C.L. from ZZ Production at 7 TeV

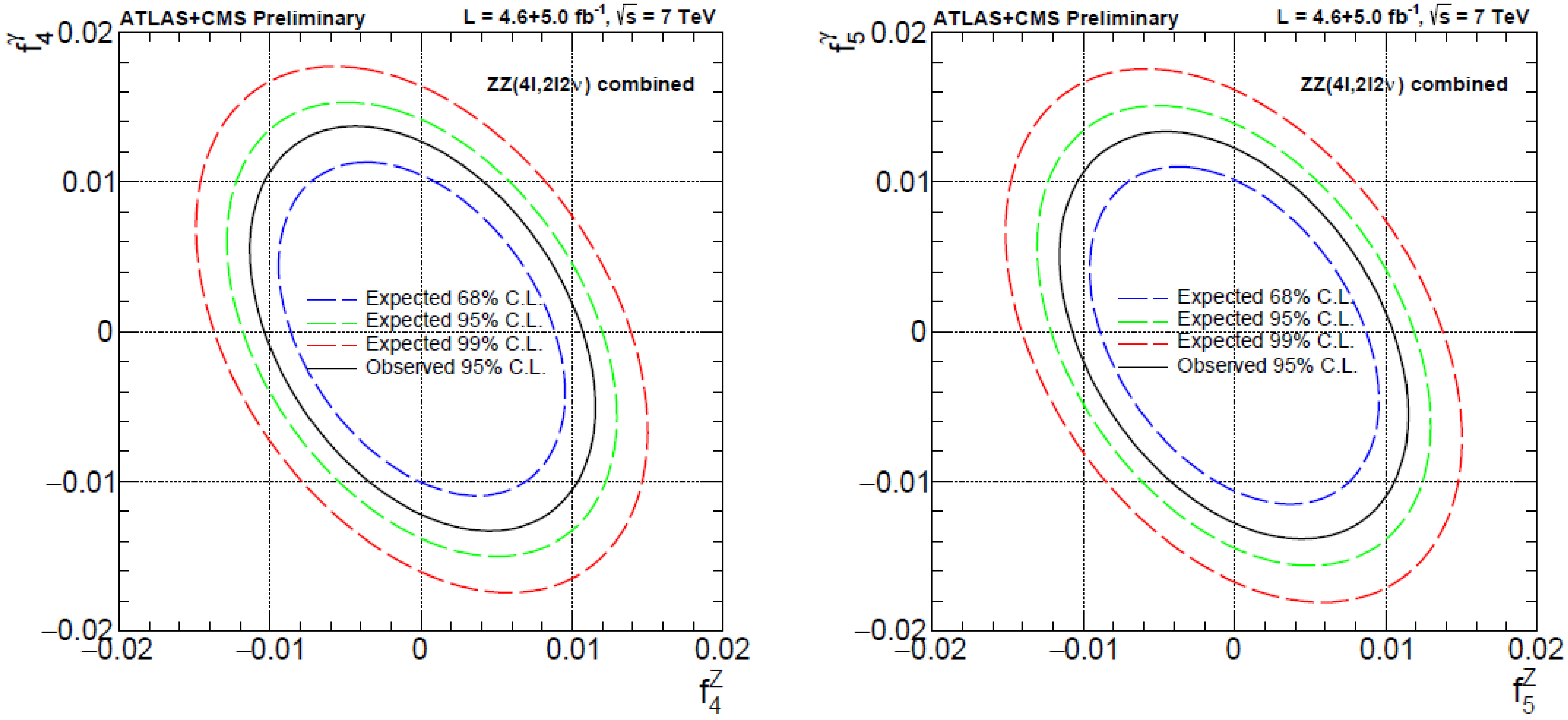
ATLAS-CONF-2016-036
CMS-PAS-SMP-15-001

- Search for aTGC from pTZ spectra with 4l, and 2l2ν final states;
- SHERPA MC is used by both ATLAS and CMS to model the anomalous coupling (ZZγ, and ZZZ) signals with parameters: $f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z$



2D aTGC Limit at 95% C.L. from ZZ production

ATLAS-CONF-2016-036
CMS-PAS-SMP-15-001



Summary

- The measured ZZ(*) and Zγ production cross sections (including integrated total and differential cross sections) at 7, 8 and 13 TeV by the ATLAS experiment are consistent within the uncertainties with the SM predictions calculated at NNLO QCD
- The stringent limits on anomalous neutral triple-gauge couplings are set by comparing the pT^V (V=Z, or γ) spectra of data with the theoretical predicted spectra in anomalous neutral triple-gauge-boson coupling space.

Back up slides

Explore aTGC from ZZ (ATLAS and CMS combined)

ATLAS-CONF-2016-036
CMS-PAS-SMP-15-001

- Data used to explore neutral aTGC (ZZZ, ZZγ) are ZZ→4l, 2l2ν at 7 TeV collected by ATLAS (4.6 fb^{-1}) and CMS (5.0 fb^{-1})
- SHERPA is used by both ATLAS and CMS to model the anomalous coupling signals (aTGC parameters: f_4^{γ}, f_4^{Z}, f_5^{γ}, f_5^{Z})

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left\{\left[f_4^{\gamma}\left(\partial_\mu F^{\mu\alpha}\right) + f_4^{Z}\left(\partial_\mu Z^{\mu\alpha}\right)\right] Z_\beta\left(\partial^\beta Z_\alpha\right) - \left[f_5^{\gamma}\left(\partial^\mu F_{\mu\alpha}\right) + f_5^{Z}\left(\partial^\mu Z_{\mu\alpha}\right)\right]\tilde{Z}^{\alpha\beta} Z_\beta\right\}$$

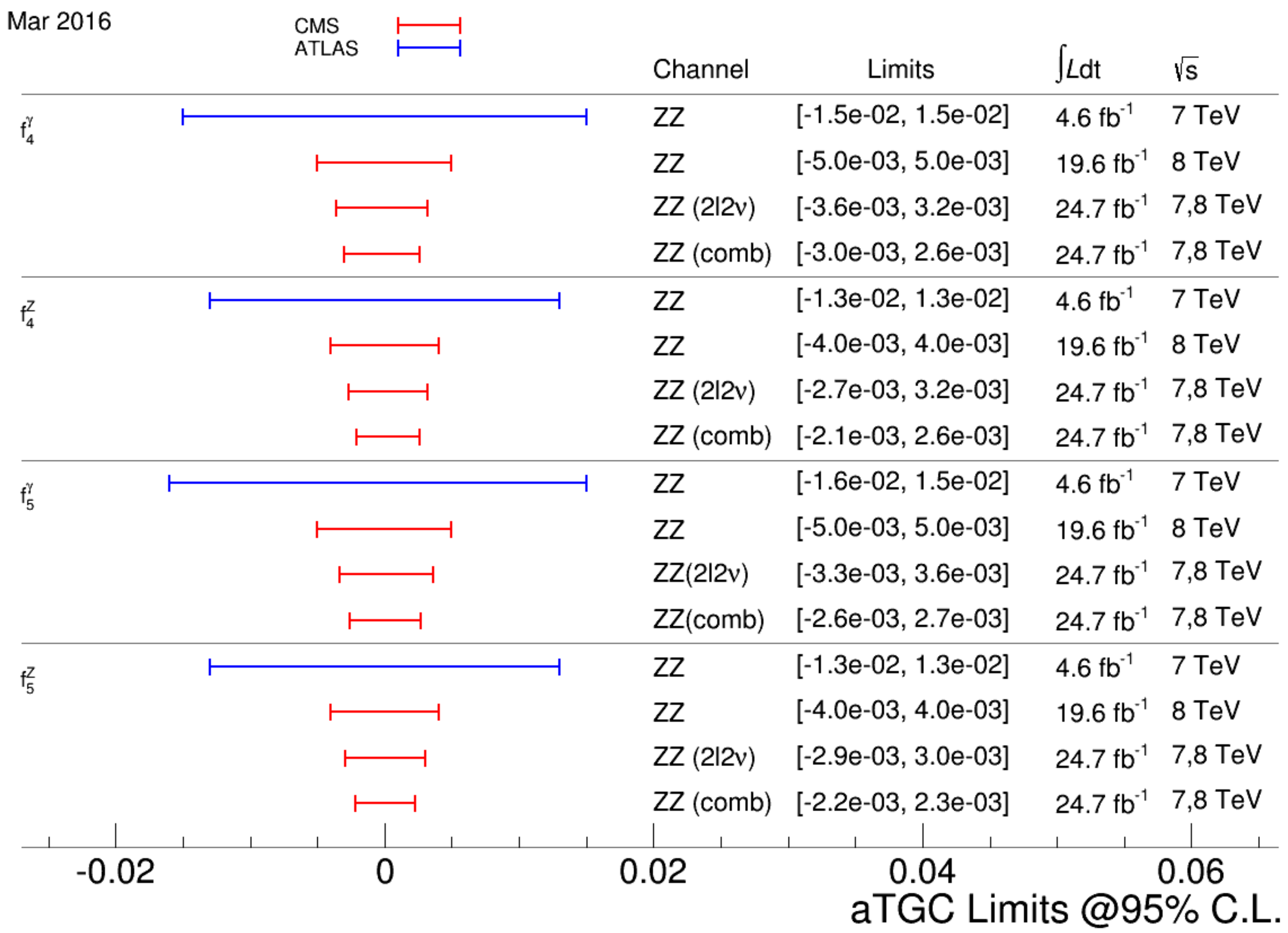
Source	CMS (4l)	Yield
Data		54.0
ZZ SM signal		53.2
Background estimate		1.4

ATLAS (4l)	Observed events	Expected ZZ signal events	Background events
$50 < p_T^Z < 90$ GeV	42	$13.6 \pm 0.2 \pm 1.3$	$26.0 \pm 4.5 \pm 1.1$
$90 < p_T^Z < 130$ GeV	29	$15.7 \pm 0.3 \pm 1.7$	$16.0 \pm 2.8 \pm 0.7$
$p_T^Z > 130$ GeV	16	$10.1 \pm 0.1 \pm 1.5$	$4.9 \pm 1.8 \pm 0.2$

ATLAS (2l2ν)	Observed events	Expected ZZ signal events	Background events
$0 < p_T^Z < 60$ GeV	28	$27.9 \pm 0.2 \pm 2.0$	$0.6 \pm 0.8 \pm 0.5$
$60 < p_T^Z < 100$ GeV	25	$14.6 \pm 0.2 \pm 1.2$	$0.2 \pm 0.2 \pm 0.2$
$100 < p_T^Z < 200$ GeV	11	$9.3 \pm 0.1 \pm 0.9$	$0.1 \pm 0.1 \pm 0.1$
$p_T^Z > 200$ GeV	2	$1.6 \pm 0.1 \pm 0.3$	$0.01 \pm 0.01 \pm 0.01$

JHEP 03 (2013) 128

Neutral aTGC limits from **ZZ** (ATLAS and CMS)

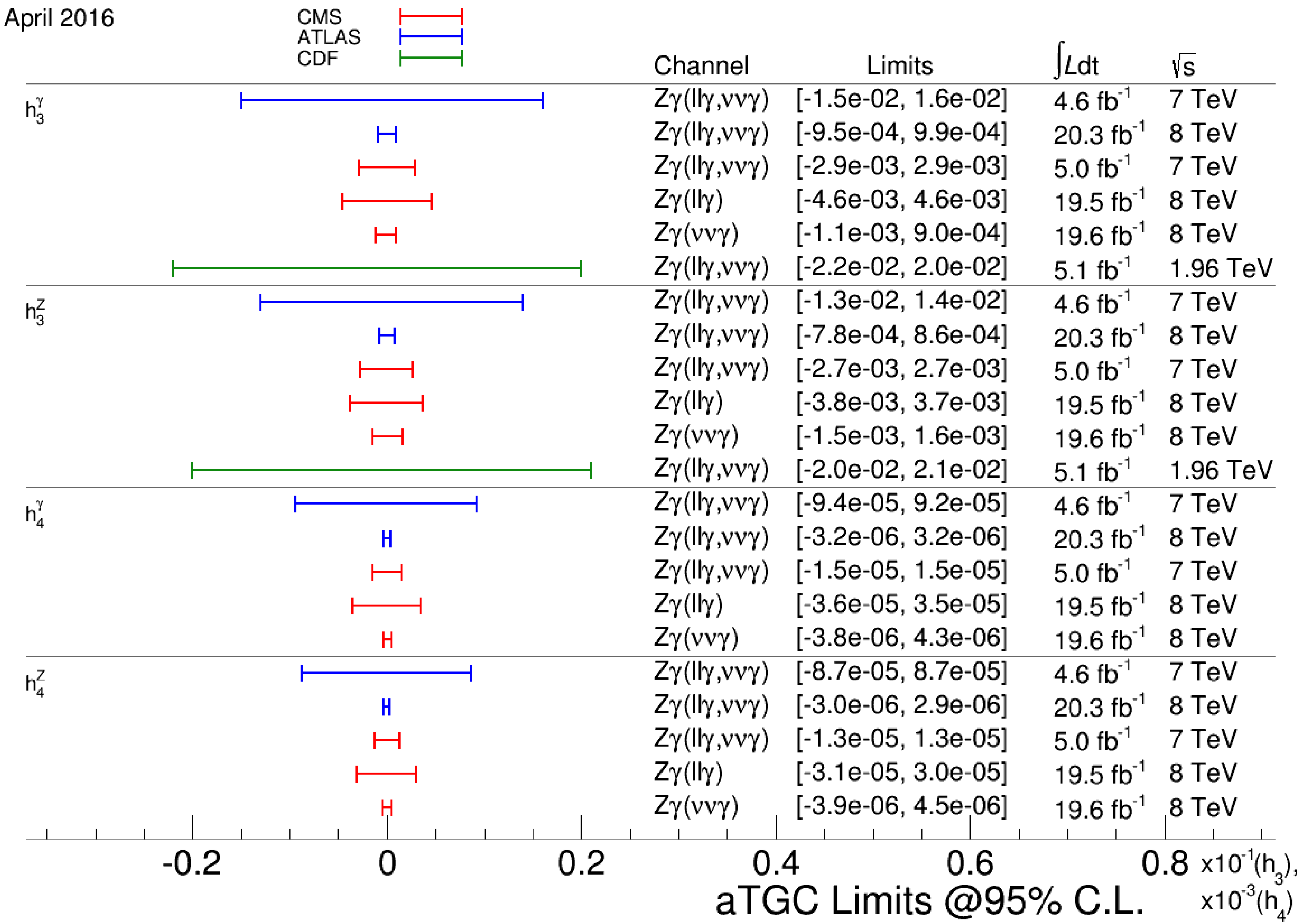


JHEP 03 (2013) 128

Phys. Lett. B 740 (2015) 250

Eur. Phys. J. C 75 (2015) 511

Neutral aTGC limits from Zγ (ATLAS and CMS)



	Channel	Limits	$\int L dt$	$\sqrt{s}$
h_3^γ	Zγ(llγ,ννγ)	[-1.5e-02, 1.6e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-9.5e-04, 9.9e-04]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.9e-03, 2.9e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-4.6e-03, 4.6e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.1e-03, 9.0e-04]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.2e-02, 2.0e-02]	5.1 fb^{-1}	1.96 TeV
h_3^Z	Zγ(llγ,ννγ)	[-1.3e-02, 1.4e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-7.8e-04, 8.6e-04]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.7e-03, 2.7e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.8e-03, 3.7e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.5e-03, 1.6e-03]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.0e-02, 2.1e-02]	5.1 fb^{-1}	1.96 TeV
h_4^γ	Zγ(llγ,ννγ)	[-9.4e-05, 9.2e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-3.2e-06, 3.2e-06]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-1.5e-05, 1.5e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.6e-05, 3.5e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.8e-06, 4.3e-06]	19.6 fb^{-1}	8 TeV
h_4^Z	Zγ(llγ,ννγ)	[-8.7e-05, 8.7e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-3.0e-06, 2.9e-06]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-1.3e-05, 1.3e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.1e-05, 3.0e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.9e-06, 4.5e-06]	19.6 fb^{-1}	8 TeV

Phys. Rev. D 87, 112003 (2013)

Phys. Rev. D 89 (2014) 092005

J. High Energy Phys. 10 (2013) 164

JHEP 04 (2015) 164