Results and Prospects in VV Production involving Neutral Dibosons including aTGC : ZZ, $Z\gamma$

ATLAS EXPERIMENT

CMS
Compact Muon Solenoid

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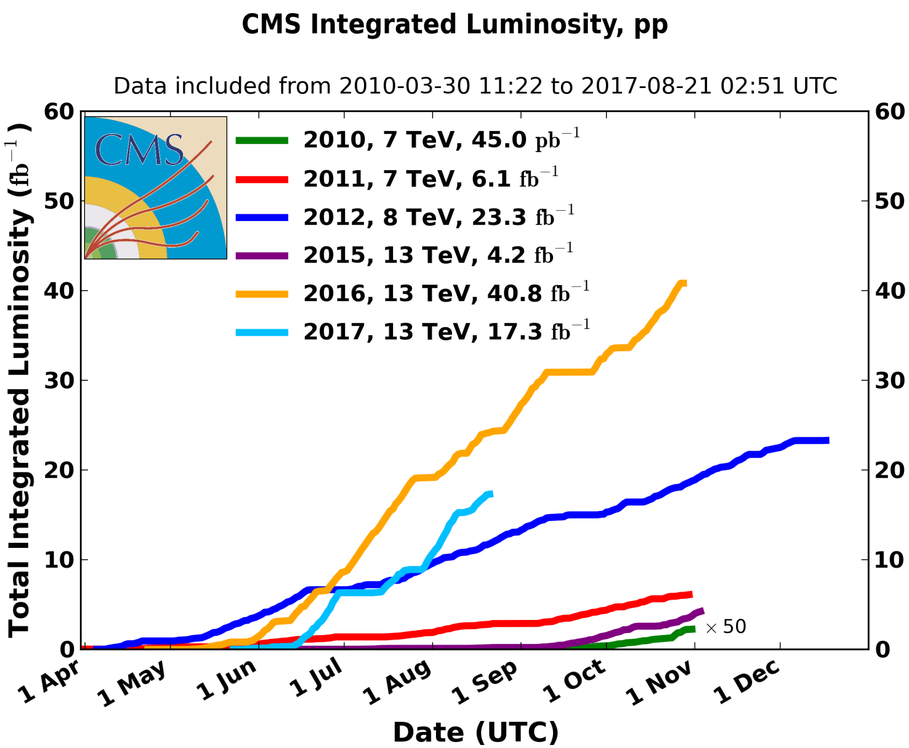
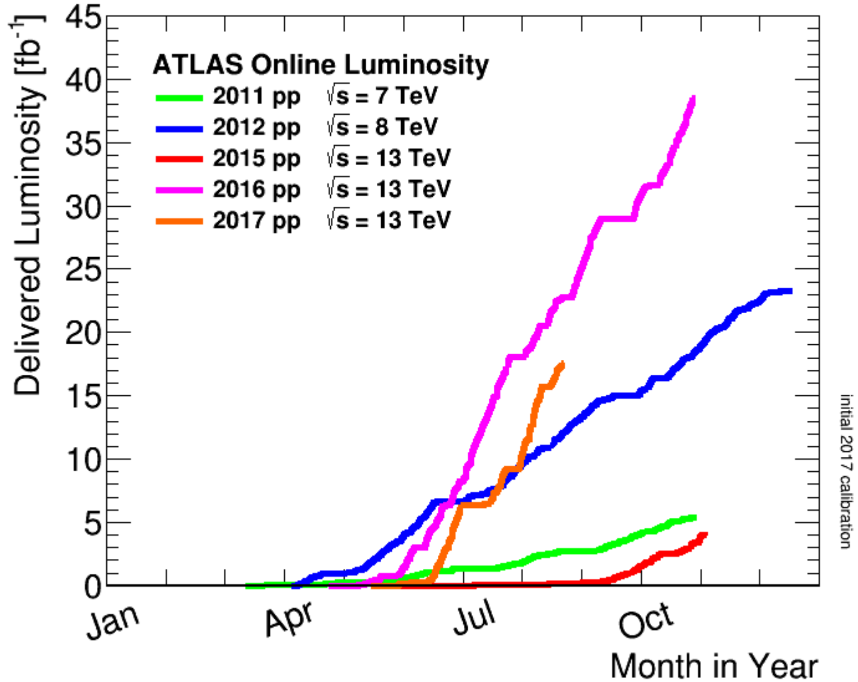
University of Wisconsin-Madison

Multi-Boson Interactions (MBI) 2017
Karlsruhe, Germany

+ LHC Performance



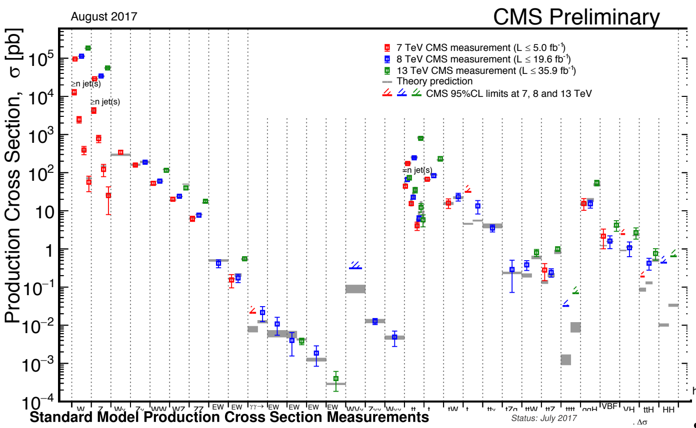


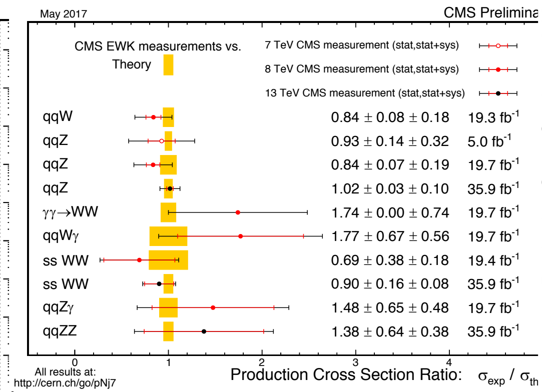
✓ LHC accelerator has been performing well in past years

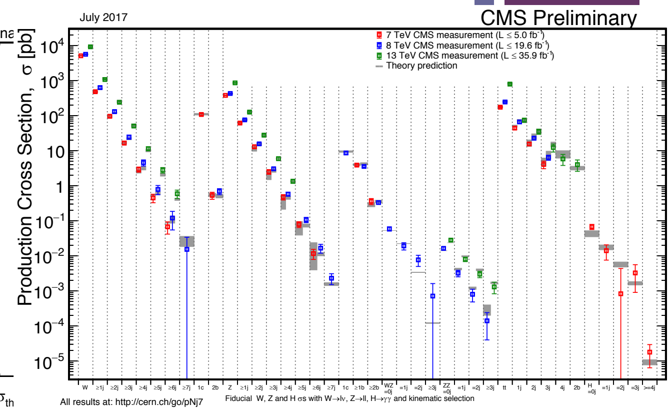
✓ Large amount of data collected by CMS and ATLAS experiments in proton-proton collisions at a center-of-mass energies of 7, 8 and 13 TeV

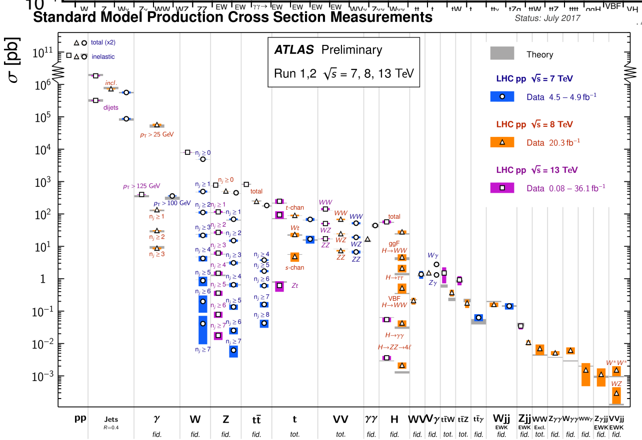
✓ Different Standard Model (SM) measurements are performed, alongside Higgs boson discovery!

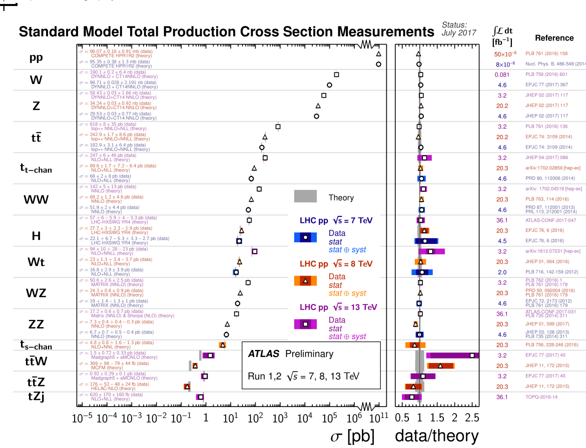
+ Summary of CMS and ATLAS results

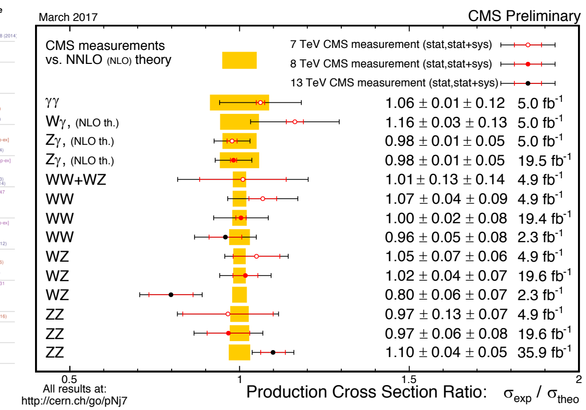


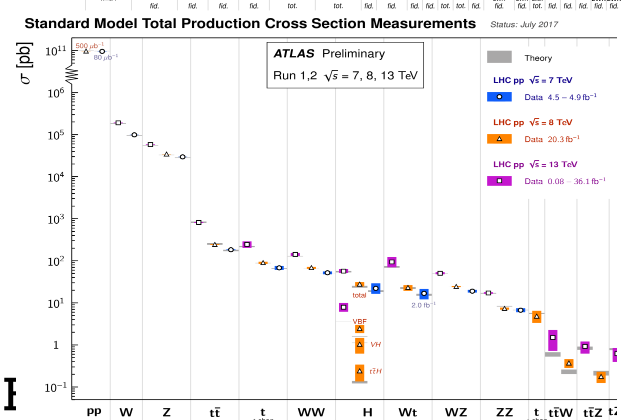


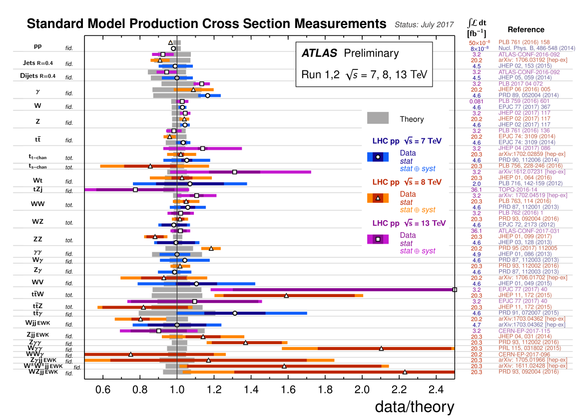


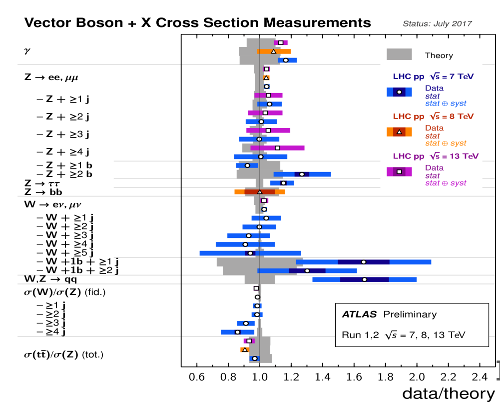












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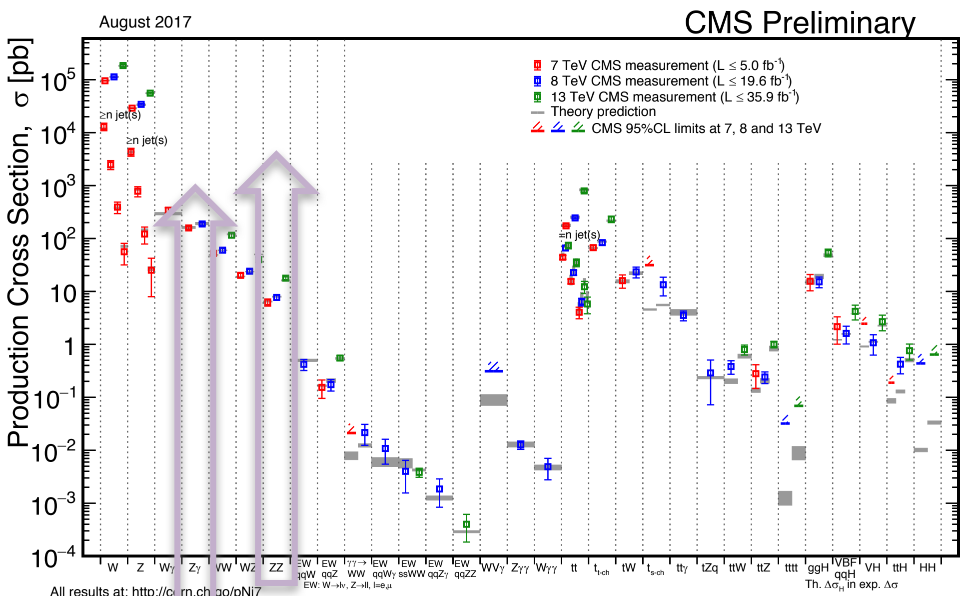
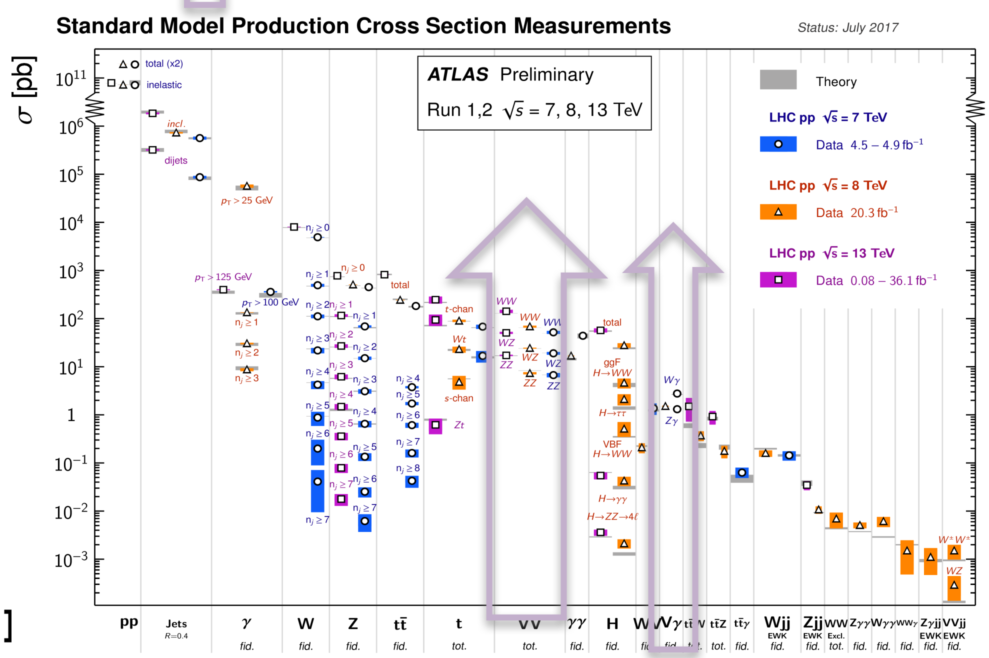
+ What I will present :





- ✓ ATLAS and CMS results
- ✓ Neutral diboson including aTGC
  - ✓ ZZ : 4l and 2l2ν
  - ✓ Zgamma : 2l+γ, 2ν+γ

- ✓ Other Talks covering related topics
  - ✓ Charged dibosons : Claire Lee
  - ✓ VBF-V Production : Darren Price
  - ✓ VBS-VV charged dibosons : Md Naimuddin
  - ✓ VBS-VV neutral dibosons : Narei Lorenzo Martinez
  - ✓ Triboson : Louis Helary's

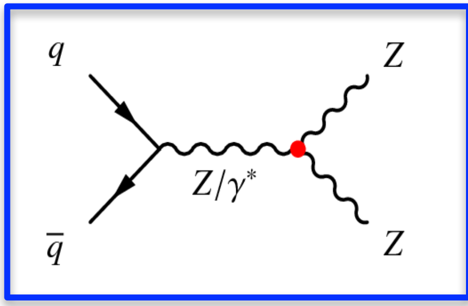
+ Diboson production at LHC

- Test the eletroweak sector of the standard model (SM)
  - Large cross section of multiboson production at LHC in pp collisions
- Clean signature and small branching ratio for vector bosons decaying leptonically
- Major background in searches for new physics and Higgs measurements
- Sensitive to theoretical calculation
  - Large NLO QCD corrections at high center-of-mass energy
  - Non-negligible NNLO QCD and NLO QED corrections
- Sensitive to anomalous triple gauge couplings (aTGCs)
  - Consequence of the non-Abelain nature of the SU(2) X U(1) symmetry
  - Value of couplings are fixed in SM
    - Any measured deviation from the SM prediction would be indication of new physics

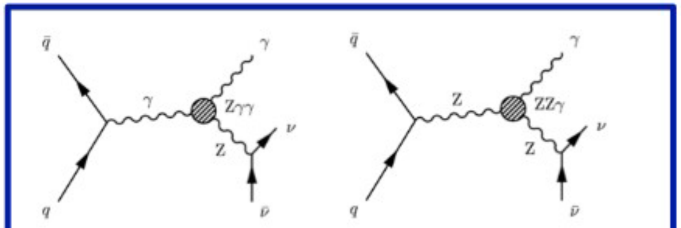
ZZ and Zg : Anomalous coupling parameterization

- Effective Vertex Parameterization
  - Add higher order operators that respect symmetries
  - Nucl. Phys. B282 (1987) 253

- ZZ channel
  - Electromagnetic gauge invariance and Lorentz invariance
  - Two ZZZ and two ZZγ couplings are allowed
  - Described by two CP-violating (f_4^V) and two CP-conserving (f_5^V) parameters, where V = Z, γ



- Zγ channel : Lorentz and gauge-invariant ZVγ vertex
  - 4 coupling parameters h_i^V (i = 1,…4).
  - h_1, h2 : CP-violating ; h_3, h_4 : CP-conserving
  - At tree level individual values of these couplings are zero
  - p_T pf photon has similar sensitivity to CP-conserving and CP-violating
    - Results are presented in terms of h_3^V, h_4^V



TGC

ZZγ, Z$\gamma\gamma$ are not allowed in SM

+ Anomalous coupling signature

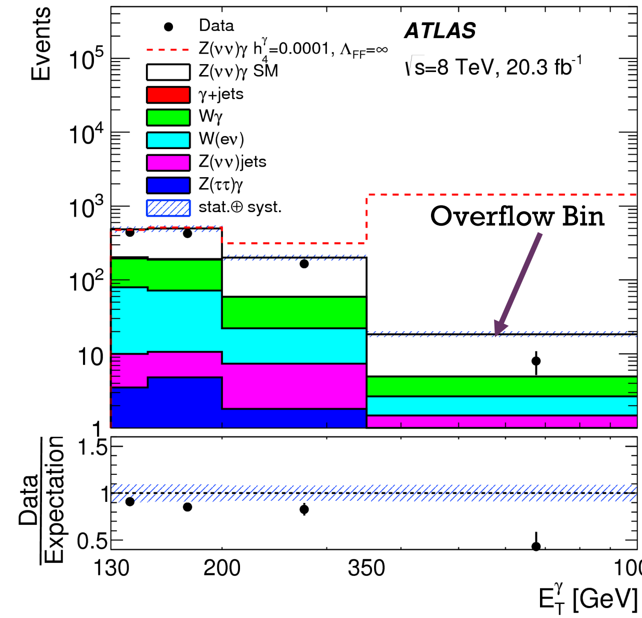
- Anomalous couplings result in an increase of cross section high energies ($\hat{s}$)
  - Observables dependent on the invariant mass of the diboson system and the boson p_T are particularly sensitive

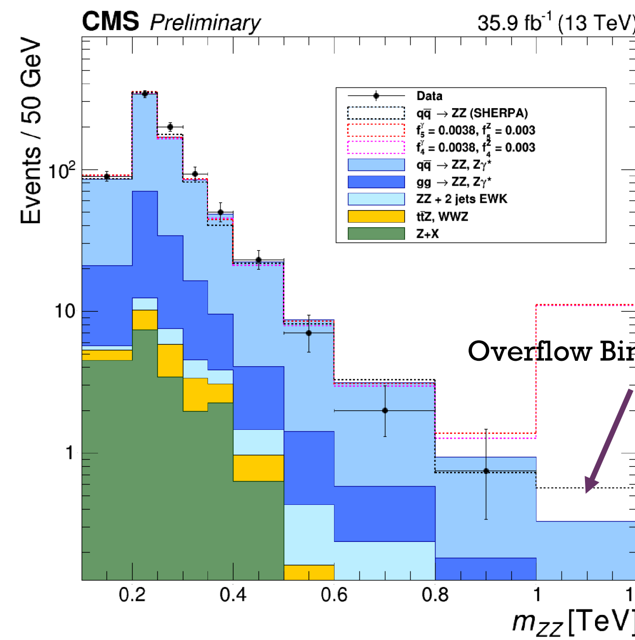
- Couplings are measured (or limits are set) by performing binned fit in single sensitive observable

- Sensitivity mostly in highest bin
  - Last bin is always overflow bin
  - Limiting factor
    - Primary : Observed statistics in the tail
    - Secondary : Systematic and statistical uncertainty

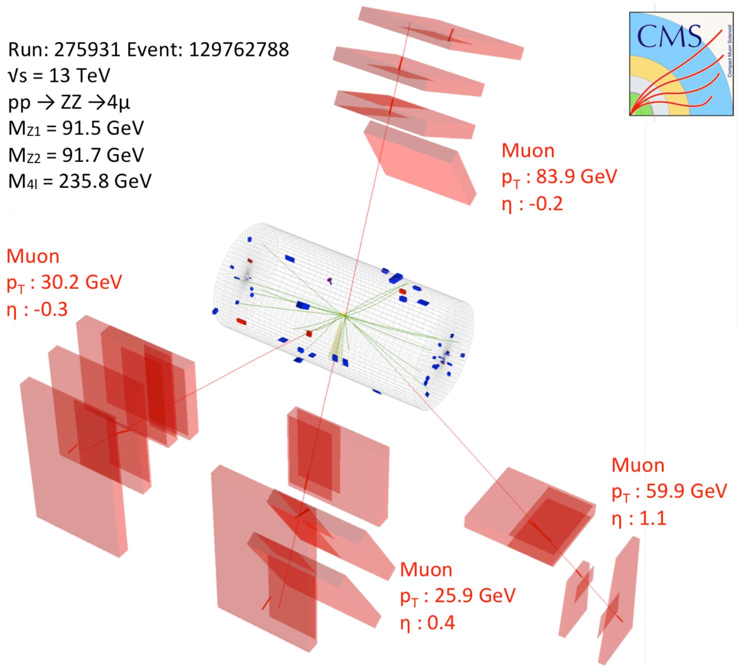
- Binning is optimized to reach highest expected sensitivity

- Sensitivity depends on
  - Absolute size of expected background
  - Absolute size of anomalous coupling signal
  - Uncertainties





ZZ Production at LHC



New

CMS Results ZZ (4l)

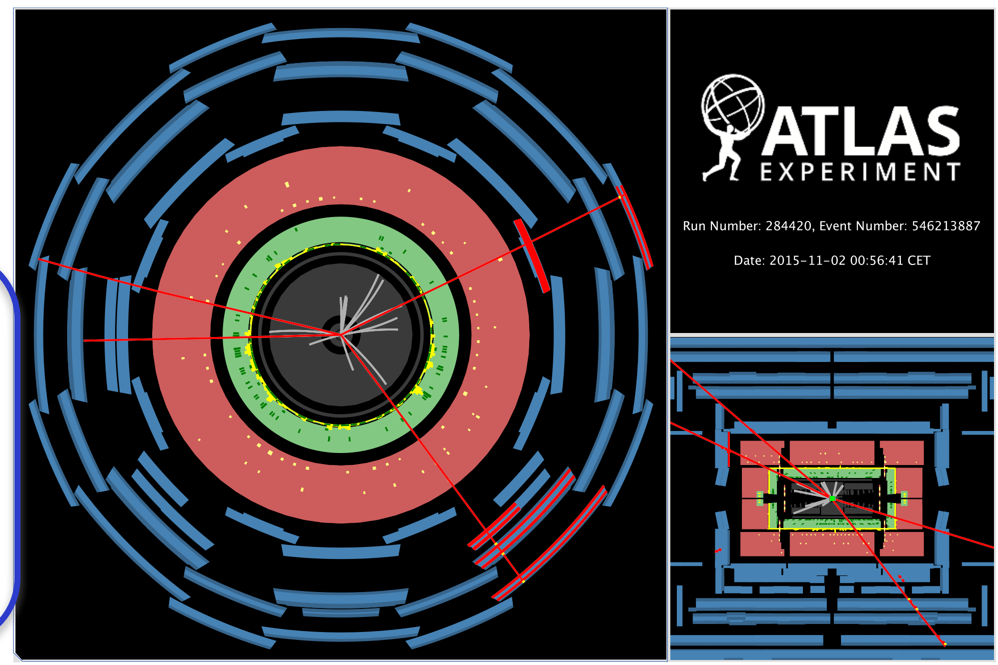
13 TeV (36 fb^{-1}): CMS-PAS-SMP-16-017

13 TeV (2.6 fb^{-1}) : [Phys. Lett. B 763 (2016) 280]

8 TeV (19.5 fb^{-1}) : [PLB 740 (2015) 250]

CMS Results ZZ (2l2ν)

7+ 8 TeV (5.1+19.6 fb-1) : [EPJC 75 (2015) 511]



New

ATLAS Results ZZ (4l)

13 TeV (36 fb^{-1}): ATLAS-CONF-2017-031

13 TeV (3.2 fb^{-1}) : [PRL 116, 101801 (2016)]

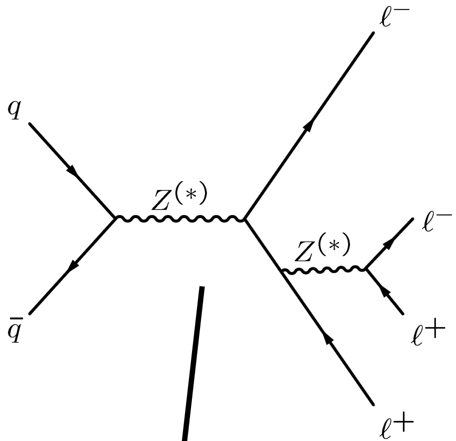
8 TeV (20.3 fb^{-1}) : [PLB 753 (2016) 552-572]

ATLAS Results ZZ (2l2ν)

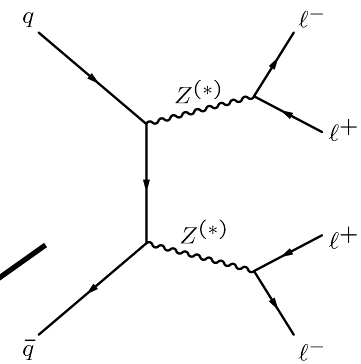
8 TeV (20.3 fb-1) : [JHEP 01 (2017) 099]

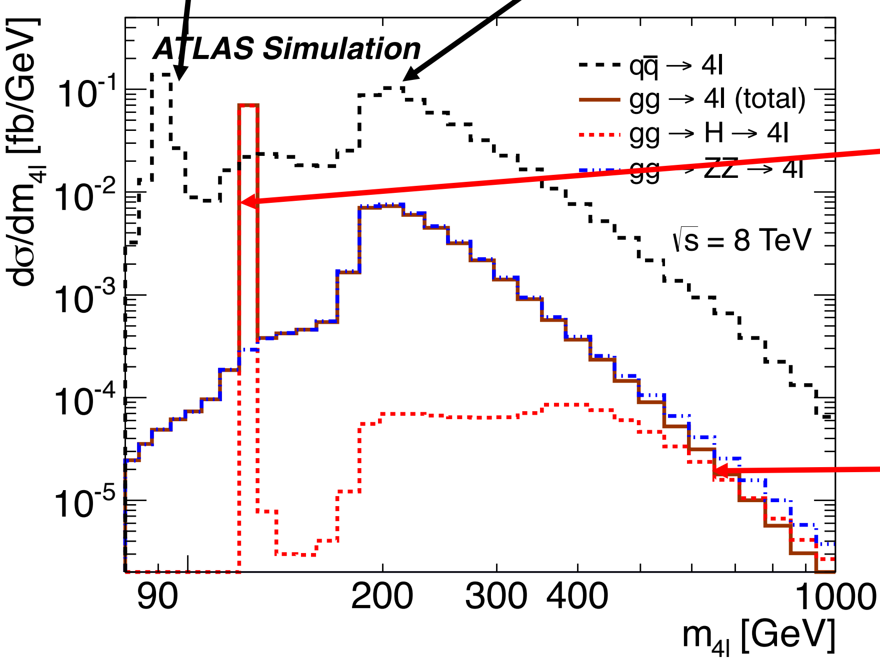
+ ZZ Production Modes

Dominant 4l production at Z resonance



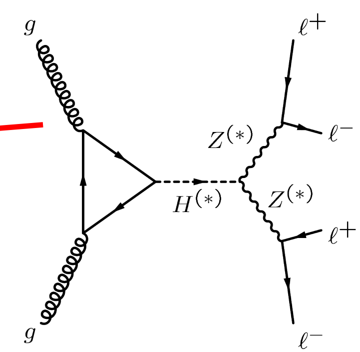
Dominant 4l production above the Z resonance





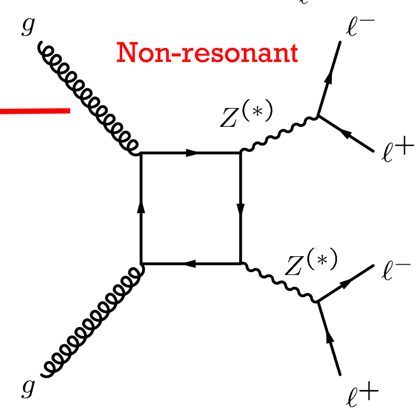
M_{4l} spectrum is essential for the study of different production mechanisms

Higgs boson production



+VBF, VH, ttH Higgs production (<15% to total Higgs production)

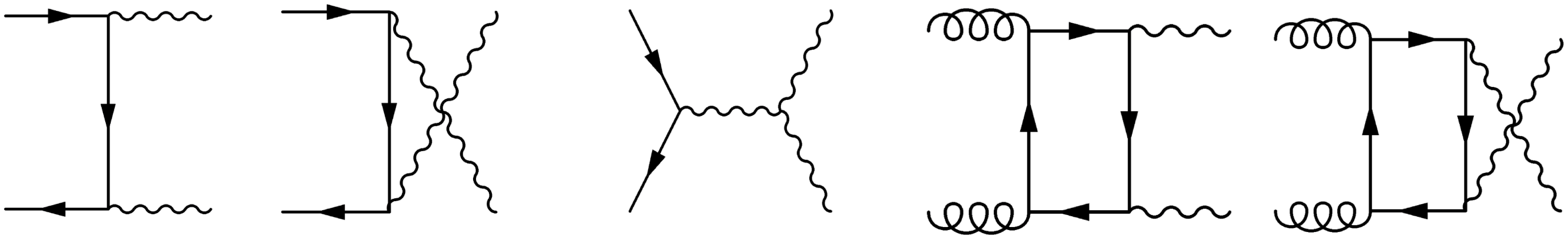
Non-resonant



Large destructive interference of ggH with ggF process at high mass m_{4l}

+ ZZ Production at LHC

Leading order Feymann diagram for ZZ production



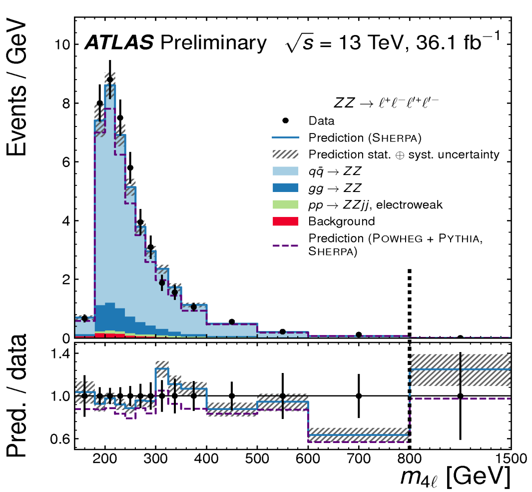
(a) t-channel (b) u-channel (c) s-channel (not in SM) (d) (e)

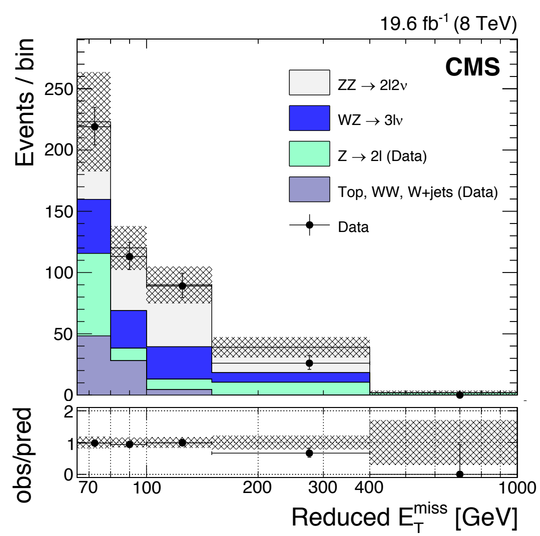
+ EWK production…

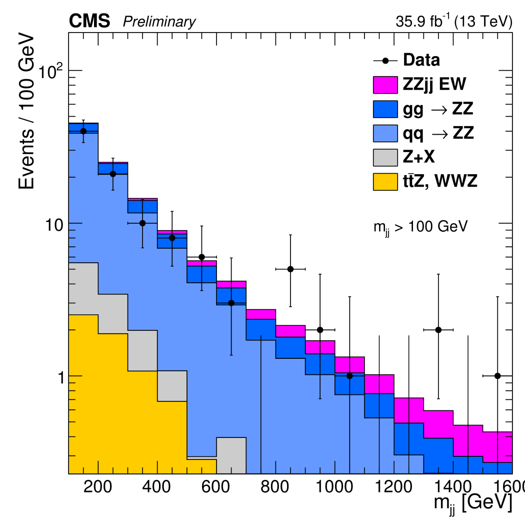
- ZZ -> 4l
- Clean signal signature
- Low background
- Small BR

ZZ-> 2l2ν
Clean signal signature
Larger background
Large BR

ZZ–> 2l2j
Not clean signal signature
Large background
Large BR



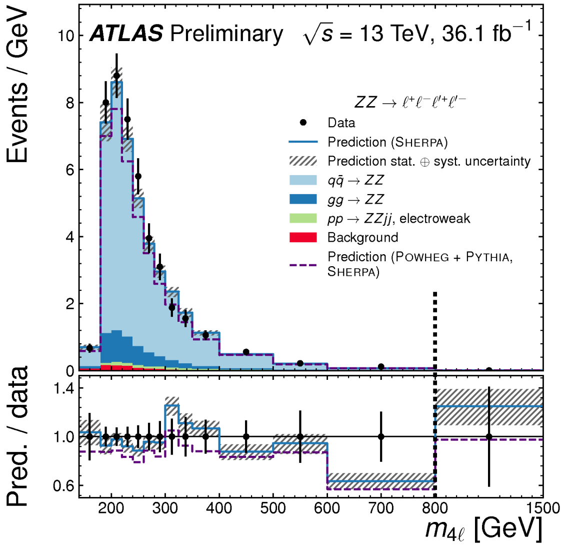


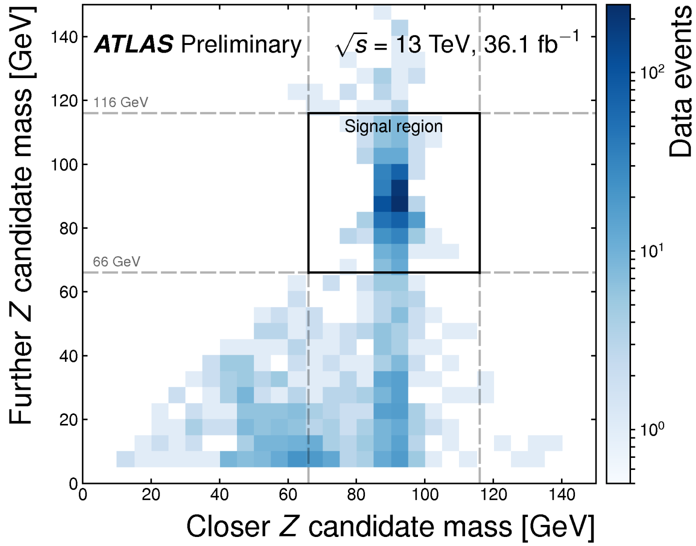


Signal Generation

- ATLAS
  - Signal for ZZ -> 4l
    - qq-initiated procss
      - Using Sherpa 2.1.1 at NLO up-to 1 additional jet
      - At LO matrix elements with up-to two or three additional jets
      - Powheg+Pythia at NLO
    - gg-inititated process
      - Sherpa 2.1.1 at LO using NLO PDFs up-to 1 additional jet
      - Cross section is multiplied by NLO/LO k-factor of 1.67 +/- 0.15
- CMS
  - Signal for ZZ -> 4l :
    - qq-initiated process
      - Powheg 2.0 at NLO in QCD
      - Cross section is multiplied by NNLO/NLO k-factor of 1.1
    - gg-initiated process
      - MCFM v7.0 at LO
      - Cross section is multiplied by NLO/LO k-factor of 1.7
    - Higgs boson produced in the gluon-gluon fusion process with Powheg2.0 in NLO QCD approx.
- Measurements are compared to SM predictions
  - Sherpa NLO upto 1 additional jet
  - Powheg+Pythia for qq process, where gg-initiated process is from Sherpa
  - MATRIX NNLO

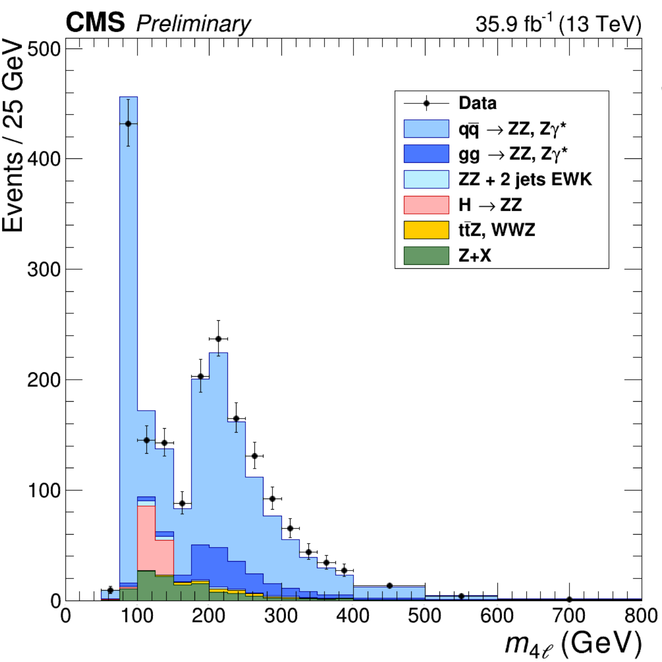
ZZ (4l) Measurement Results (13 TeV)

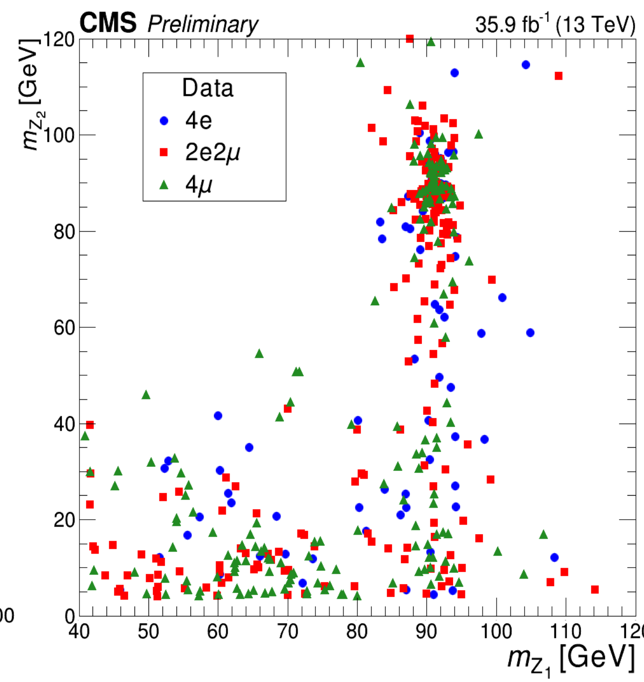


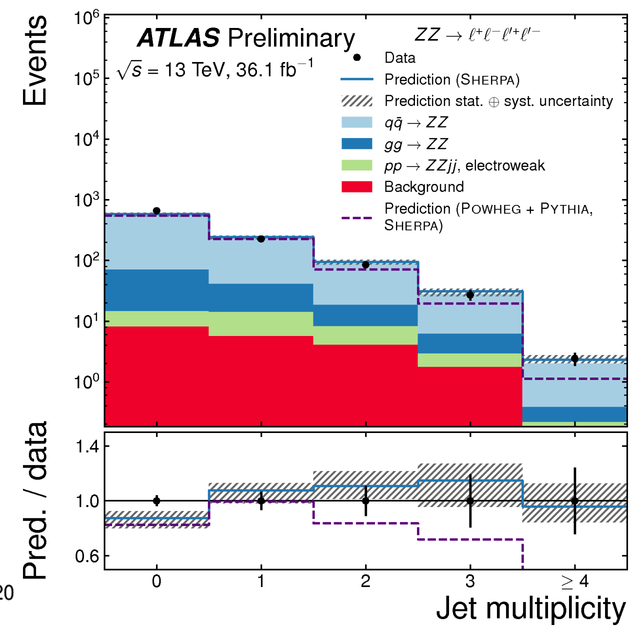


Measurement Strategy

Background from jets faking lepton estimated from data using fake rate/template method in CMS/ATLAS







Z-> 4l Measurement Results (13 TeV)

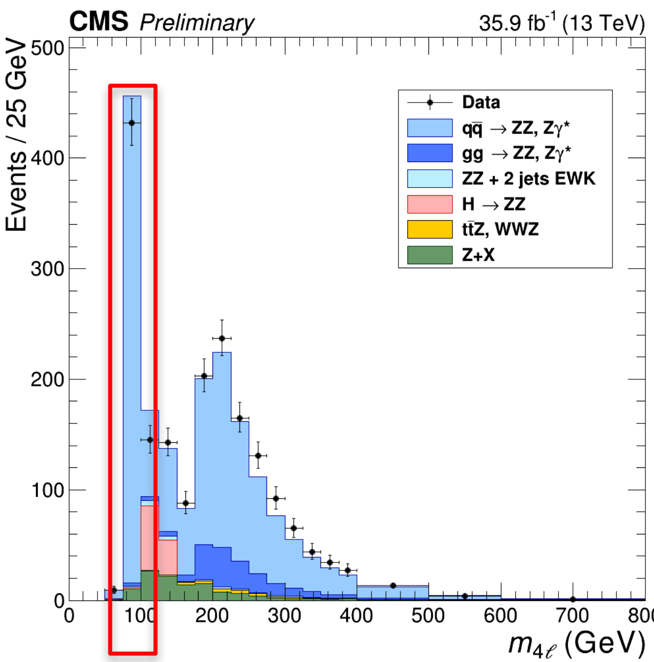
Expected/Oberved table with 80<M_{4l}<100

Final state	Expected $N_{4\ell}$	Background	Total expected	Observed
4μ	$196.0 \pm 1.2 \pm 14.9$	$3.9 \pm 1.0 \pm 1.5$	$199.9 \pm 1.6 \pm 15.0$	196
$2e2\mu$	$179.1 \pm 1.1 \pm 12.3$	$3.6 \pm 0.8 \pm 0.8$	$182.7 \pm 1.4 \pm 12.3$	167
4e	$59.1 \pm 0.6 \pm 6.7$	$2.4 \pm 0.4 \pm 1.0$	$61.4 \pm 0.8 \pm 6.8$	64
Total	$434.2 \pm 1.8 \pm 28.9$	$9.9 \pm 1.4 \pm 2.5$	$444.1 \pm 2.3 \pm 29.1$	427

CMS Fiducial cuts

Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\mathrm{GeV}$, $p_T^{\ell_2} > 10\,\mathrm{GeV}$, $p_T^{\ell_{3,4}} > 5\,\mathrm{GeV}$, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell^+\ell^-} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair)
$Z \to 4\ell$	$m_{Z_1} > 40\,\mathrm{GeV}$, $80 < m_{4\ell} < 100\,\mathrm{GeV}$
$ZZ \to 4\ell$	$60 < m_{Z_1}, m_{Z_2} < 120\,\mathrm{GeV}$

Including measurement of Z->4l



$$\sigma_{\mathrm{fid}}(pp \to Z \to 4\ell) = 29.7 \pm 1.4\,(\mathrm{stat})^{+2.0}_{-1.8}\,(\mathrm{syst}) \pm 0.8\,(\mathrm{lumi})\,\mathrm{fb},$$

Expected (NLO Powheg) = $27.9^{+1.0}_{-1.5} \pm 0.6$ fb

$$\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = \frac{\sigma(pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-)}{C^{60-120}_{80-100}\,\sigma(pp \to Z \to \ell^+\ell^-)/\mathcal{B}(Z \to \ell^+\ell^-)}$$

Correction for Z mass window, estimated using POWHEG

Calculated at NNLO with FEWZ v2.0

PDG value

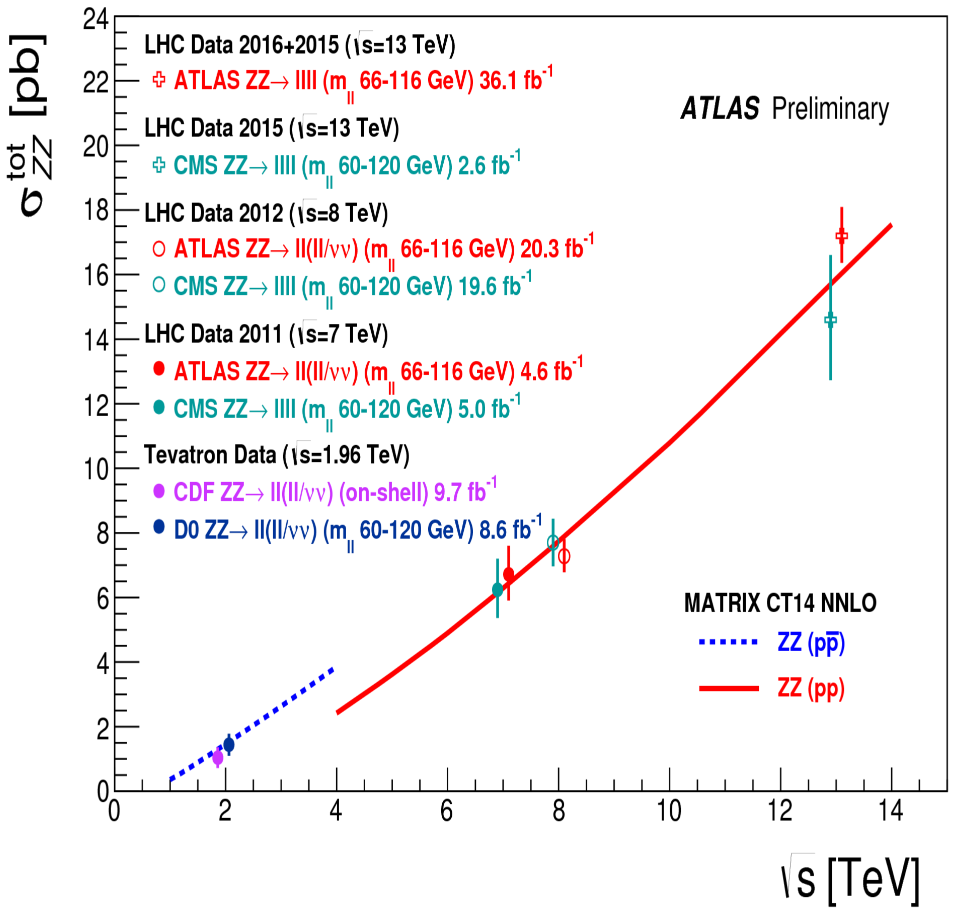
$$\mathcal{B}(Z \to 4\ell) = 4.74^{+0.16}_{-0.16}\,(\mathrm{stat})^{+0.18}_{-0.17}\,(\mathrm{syst}) \pm 0.08\,(\mathrm{theo}) \pm 0.12\,(\mathrm{lumi}) \times 10^{-6},$$

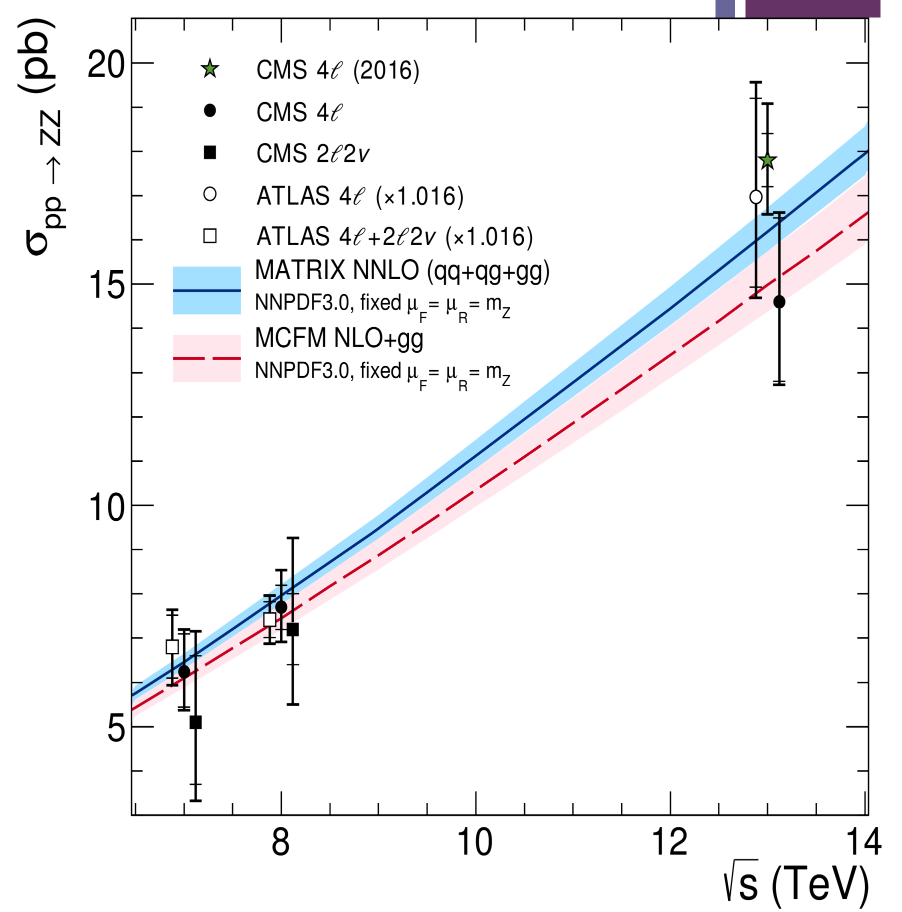
Expected (MG5_aMC@NLO) = 4.6×10^{-6}

Good agreement with SM expectation!

Statistic and systematic uncertainties are getting comparable!

ZZ Total Production cross section





Good agreement with NLO and NNLO calculation across sqrt(s)

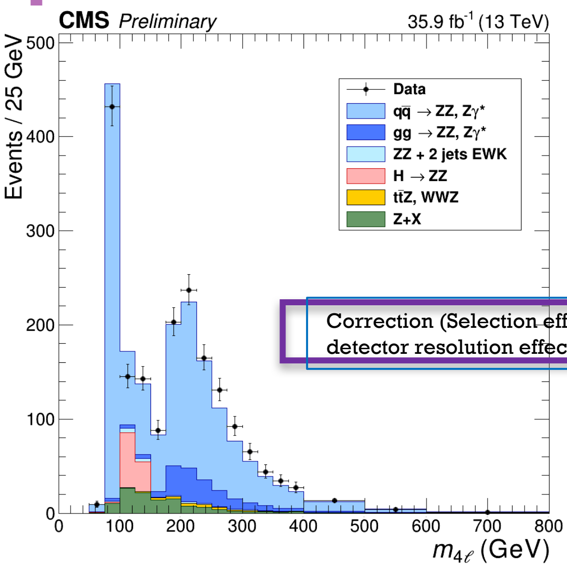
Uncertainty dominated by systematic uncertainty!

ZZ Differential Measurement

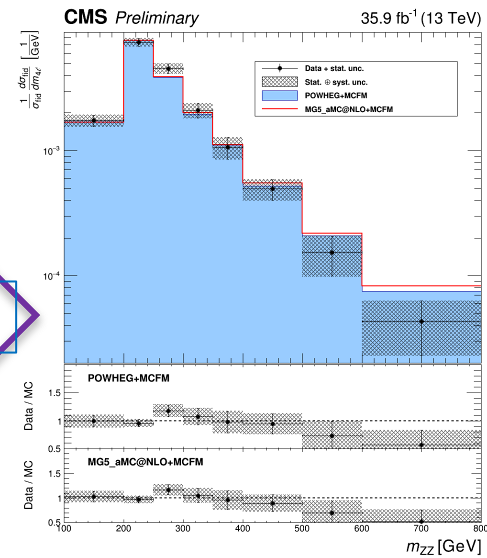
- Differential measurements provide detailed description of the kinematics in ZZ events
  - p_T, 4l measure the recoil against all other particles produced in the collision
    - Provides information about QCD and electroweak radiation across the entire region of scales
  - Rapidity of 4l system sensitive to the total momentum In the z-direction of the intial-state partons
    - Senstive to PDF
  - The azimuthal-angle separation and rapidity difference between the Z boson candidate
    - Help extract the contribution of double parton scattering ZZ production
    - Also sensitive to radiation of photons and partons produced in association with ZZ pair
  - $|\delta y(jet_1, jet_2)|$ and $m(jet_1, jet_2)$
    - Sensitive to EWK-ZZjj process
    - Both tend to have larger values in weak-boson scattering than in other ZZ production channels

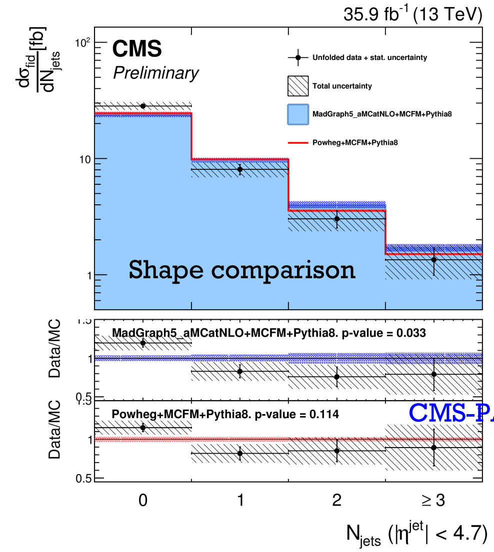
ZZ Differential Measurement

New differential measurement for ZZ+jets

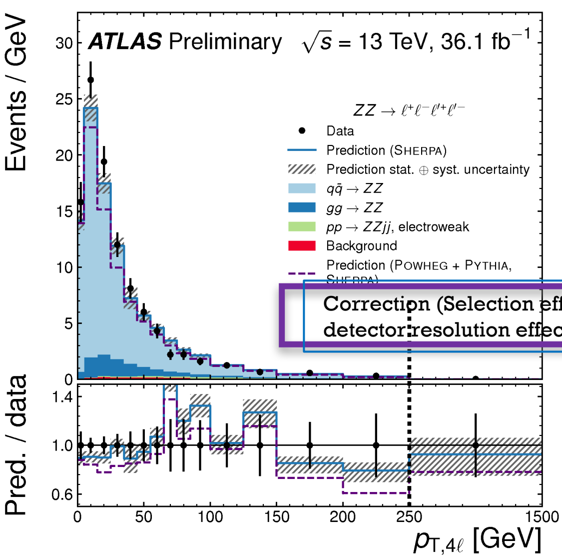


Correction (Selection efficiency, detector resolution effects)





CMS-PAS-SMP-16-019



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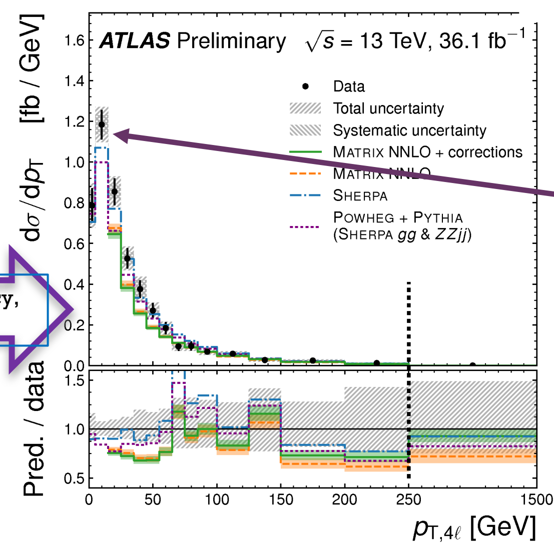
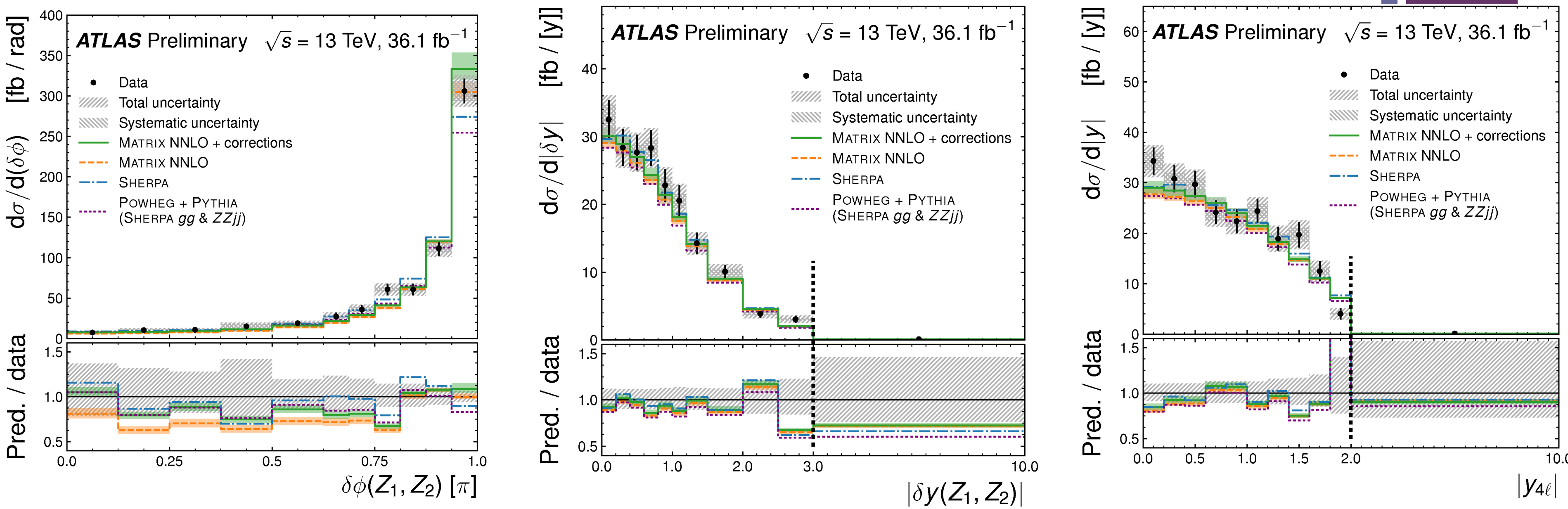


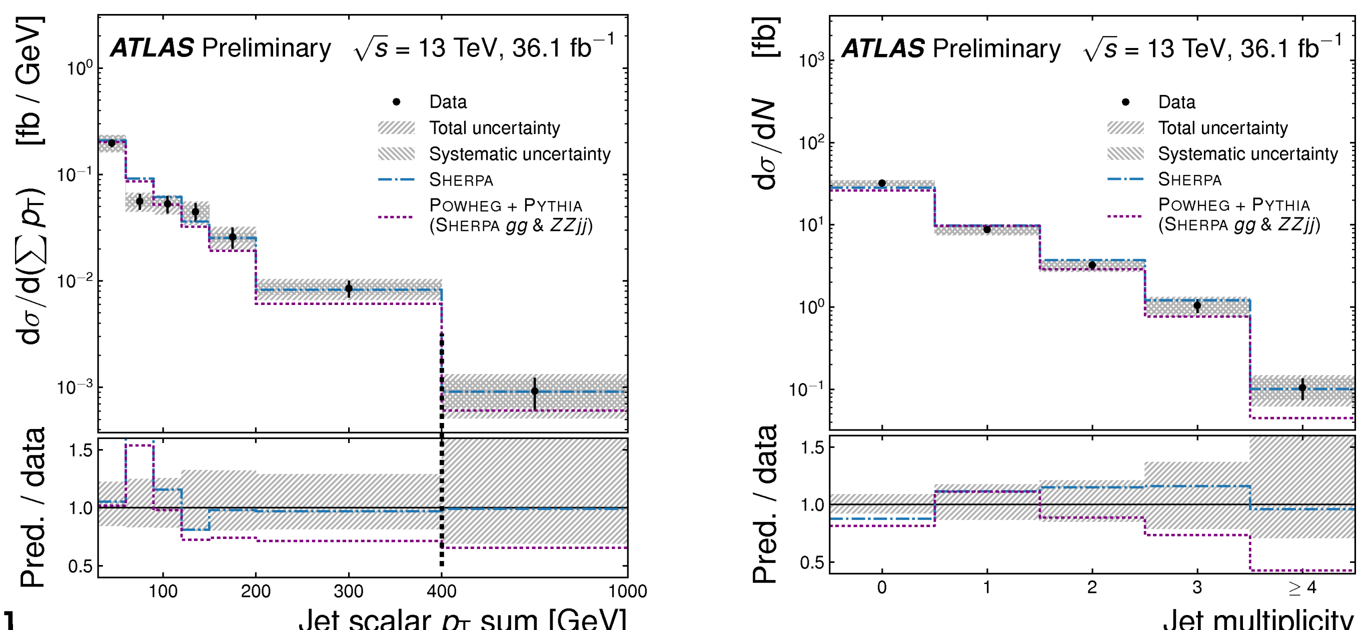
$p_T(4l)$ spectrum is sensitive to

- Higher order QCD corrections
- QCD resummation effects at small p_T
- Sensitive to top-loop effects in gg->H production as well to the anomalous triple gauge boson coupling at high $p_T(4l)$

Uncertainties dominated by the statistical uncertainties!

ZZ Differential Measurement

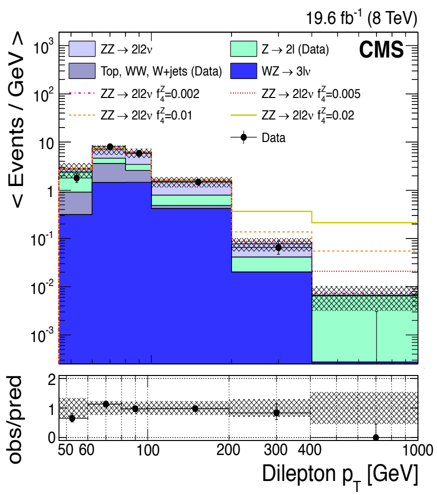


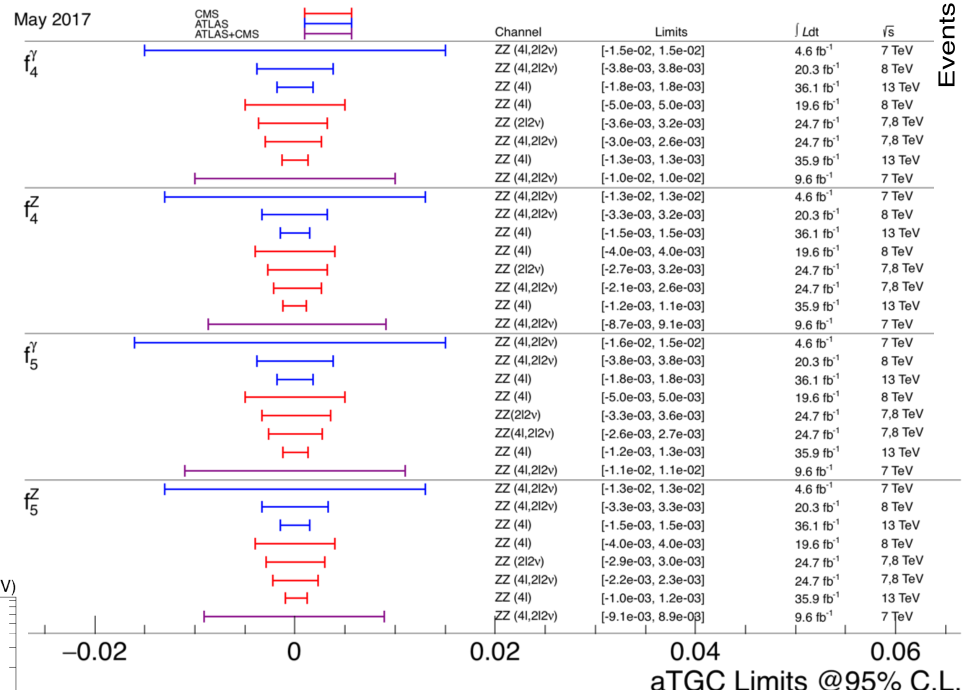


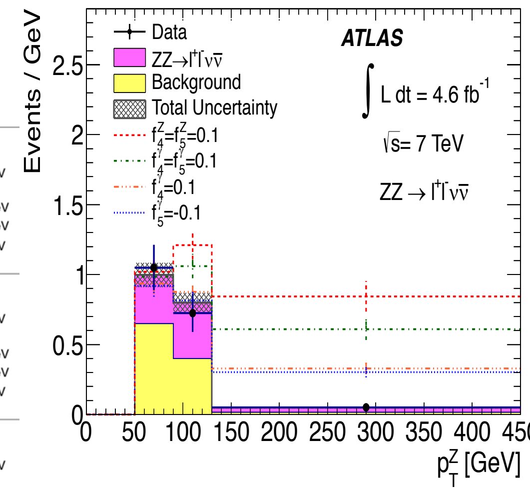
ZZ aTGC limits

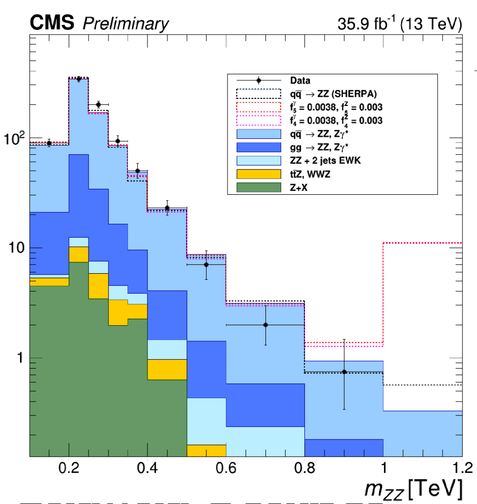
Limits derived from binned fit to M_{4l} (p_T^{ll}) distribution in 4l (2l2νυ) final state

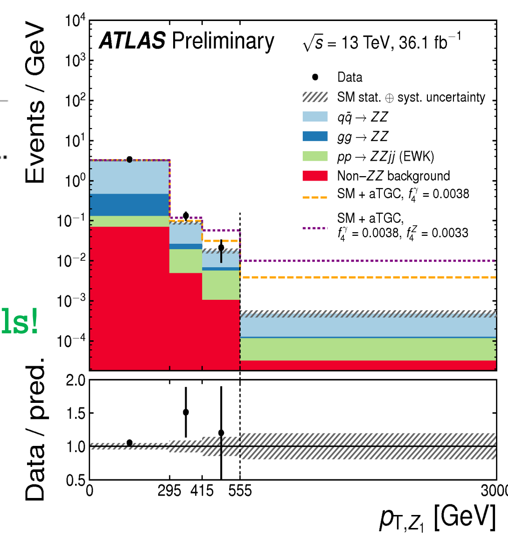
No significant deviation in the high M_{4l} (p_T^{ll}) tail







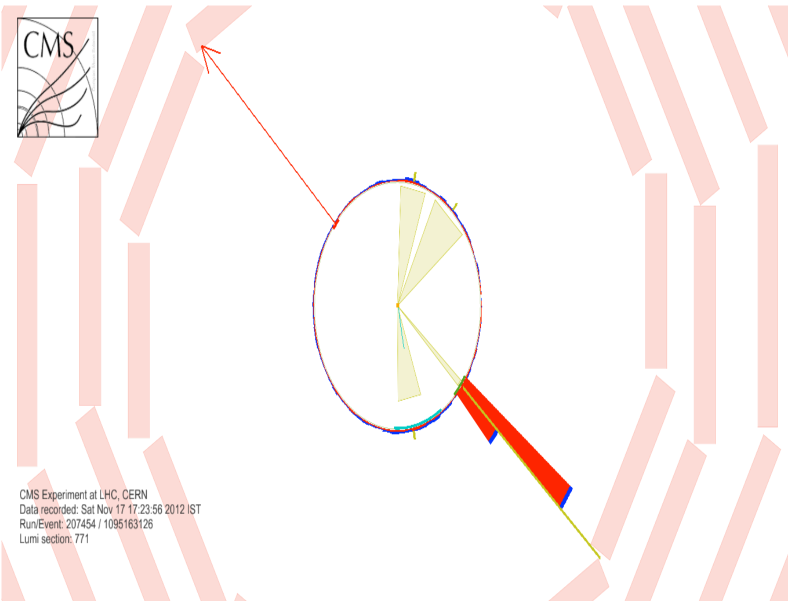




Similar sensitivity from ZZ->4l and ZZ->2l2nu channels!

First aTGC limits with full 2016 data!

+ Zγ Production at LHC



CMS Results Zγ (ννγ) New

13 TeV (2.3 fb^{-1}): CMS-PAS-SMP-16-004

8 TeV (19.6 fb^{-1}) : *PLB 760 (2016) 448*

CMS Results Zγ (llγ)

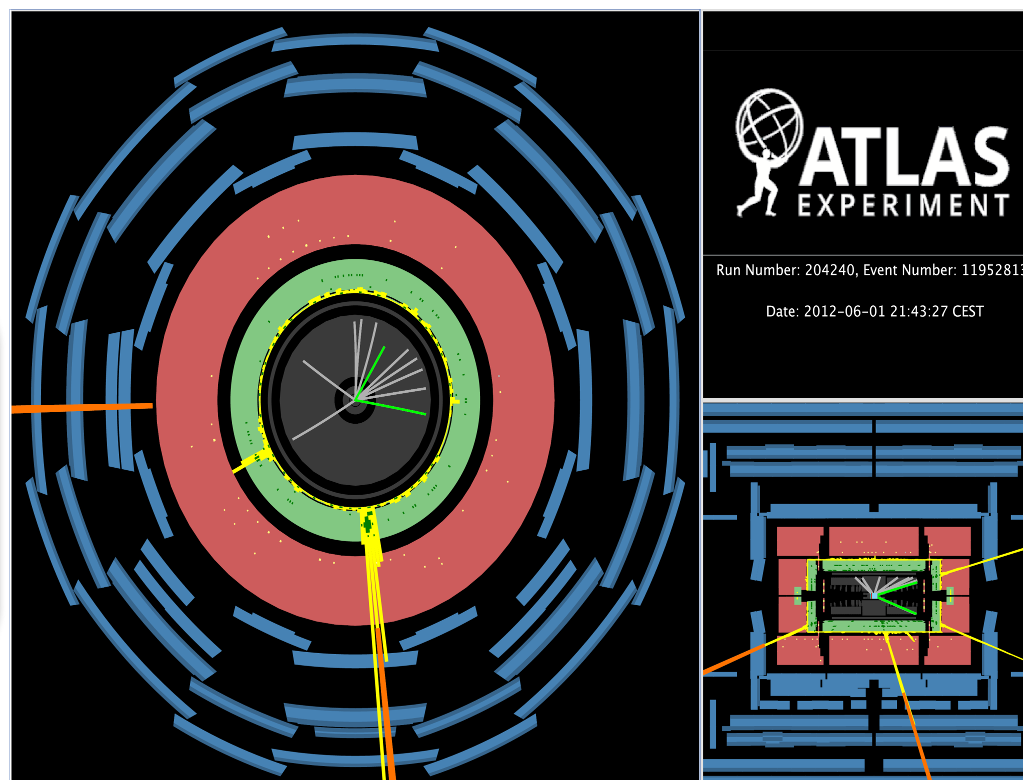
8 TeV (19.6 fb-1) : *JHEP 04 (2015) 164*

ATLAS Results Zγ (ννγ)

8 TeV (20.3 fb^{-1}) : *PRD 93, 112002 (2016)*

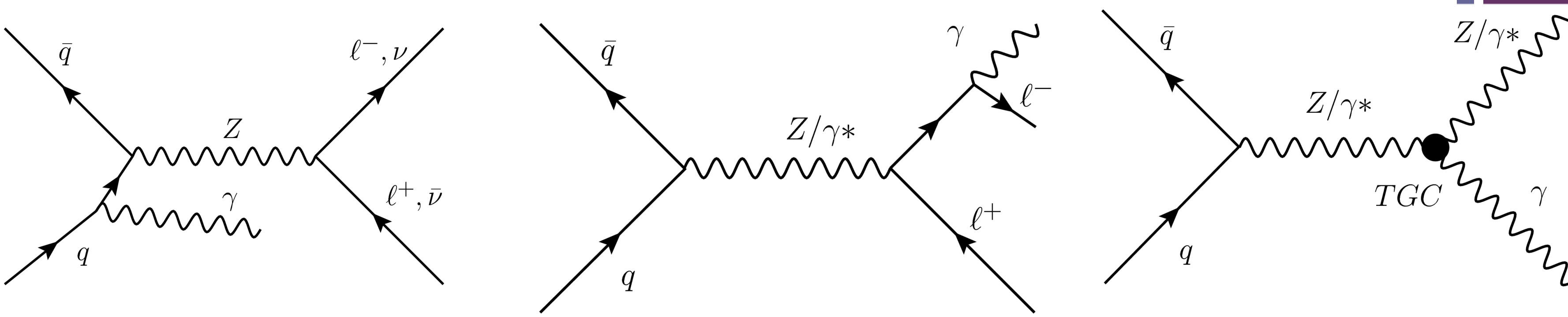
ATLAS Results Zγ (llγ)

8 TeV (20.3 fb-1) : *PRD 93, 112002 (2016)*



+ Zγ Production at LHC

Leading order Feymann diagram for Zγ production



- Zγ-> ννγ
- Small S/B
- Larger BR
- Significant instrumental bkg

Zγ-> llγ
Large S/B
Clean signal signature
Good precision for cross-section measurement

Neutrino channel has the highest sensitivity to aTGC

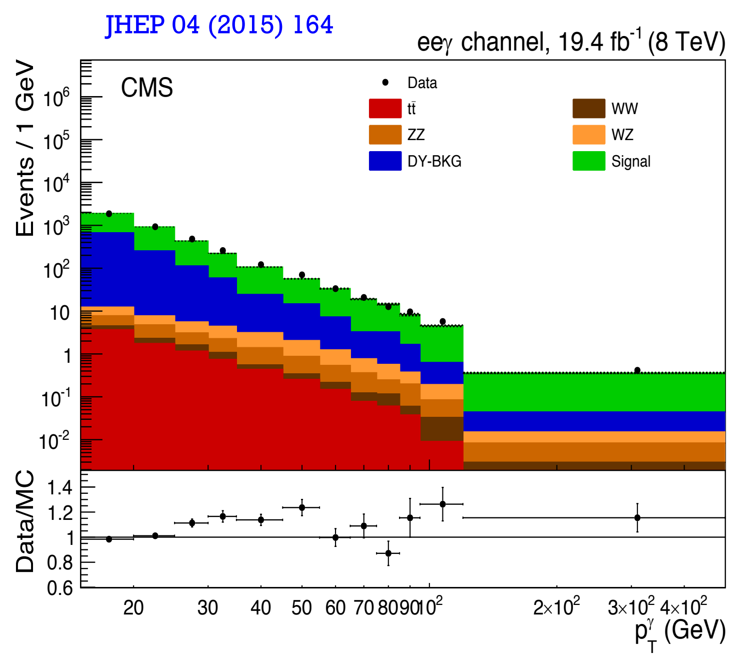
Signal Generation

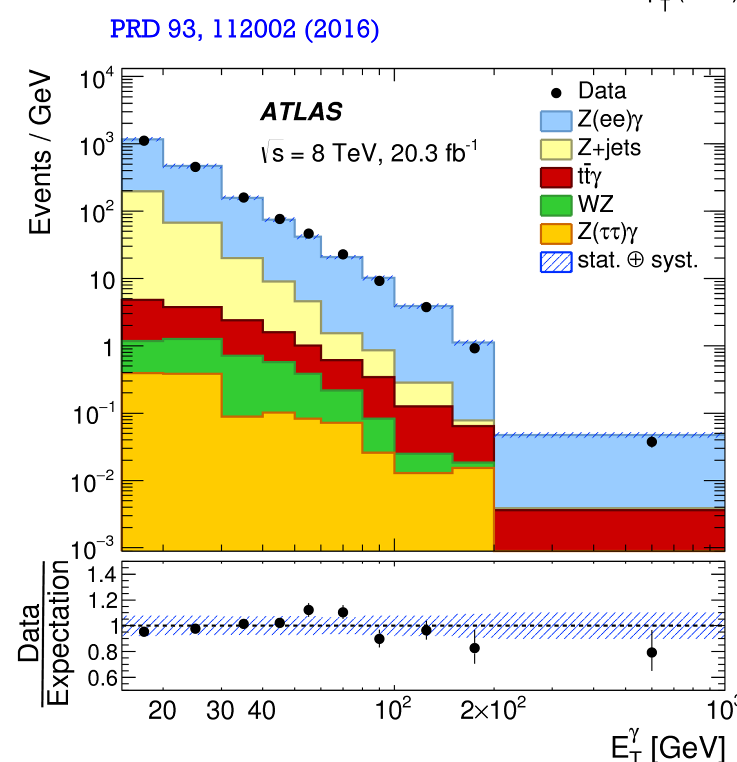
- ATLAS
  - Signal for Z(ll)γ and Z(νν)γ
    - Sherpa 1.4 with CT10 parton distribution function (PDF)
    - LO matrix elements with up-to three additional final-state partons
    - Multi-leg ensures first few hardest emissions are modeled by real-emission matrix elements
- CMS
  - Signal for Z(ll)γ :
    - Sherpa 1.4 with CT10 parton distribution function (PDF)
    - LO matrix element with up-to 2 additional partons
  - Signal for Z(νν)γ
    - Madgraph5v1.3.30 at LO with up-to 2 additional partons
    - aTGC samples using Sherpa v1.2.2 and cross section is corrected using K-factor obtained from MCFM to account for NLO effects

- Measurements are compared to SM predictions
  - Sherpa LO with 3 additional final-state partons
  - MCFM NLO using CT10 PDF
  - Parton level NNLO using MMHT2014 PDF (M Grazzini. et.al)
    - *J. High Energy Phys. 07 (2015) 085*

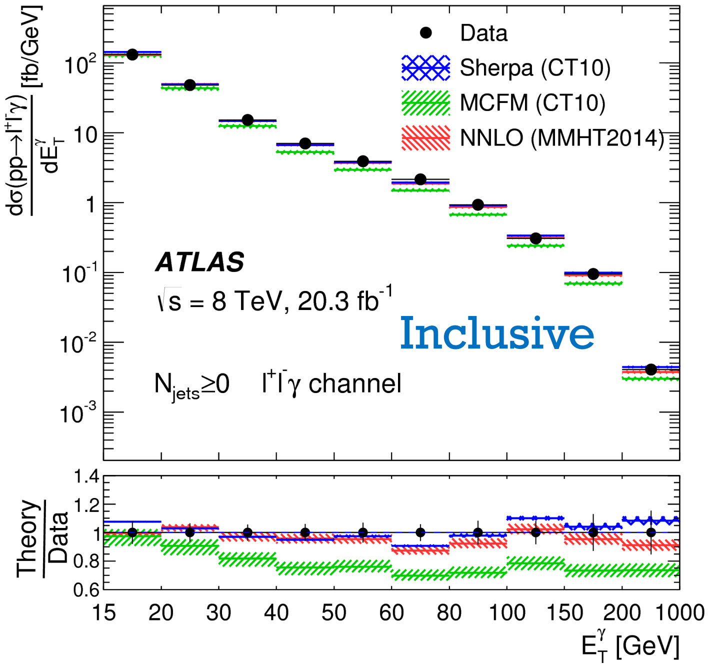
Z(ll)γ Production (8 TeV)

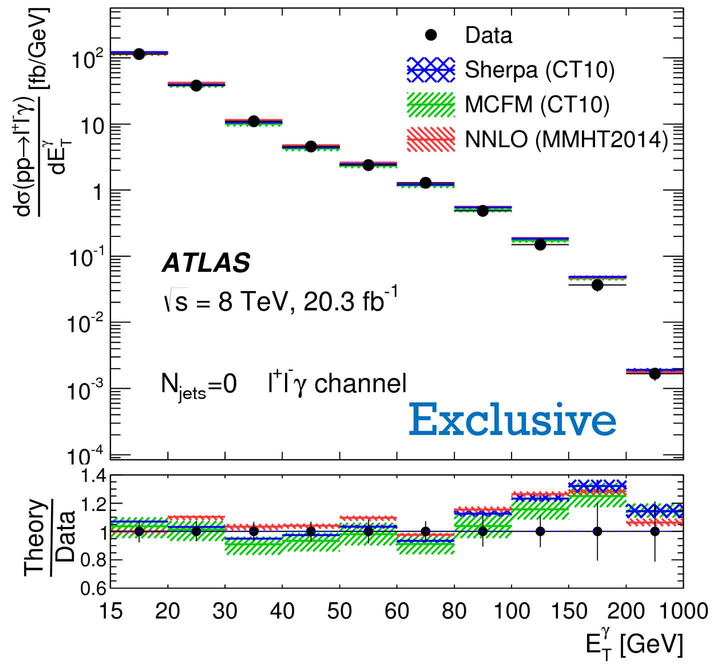
- **Basic Selection**
  - Two isolated leptons with significant p_T (ll)
  - Opposite sign same flavor pair within Z mass window
  - Isolated photon with significant $p_T(\gamma)$
- **Backgrounds**
  - Z+ Jets: hadronic jets which contains photons from π^0 or ρ decays are mis-identified as prompt photons
  - Estimated from data
    - ATLAS : two-dimensional sideband method (ABCD)
    - CMS : Template method from two shower-shape observables
  - Other backgrounds estimated from MC
- Systematics dominated measurement: uncertainty in the template method, photon energy scale and lepton isolation

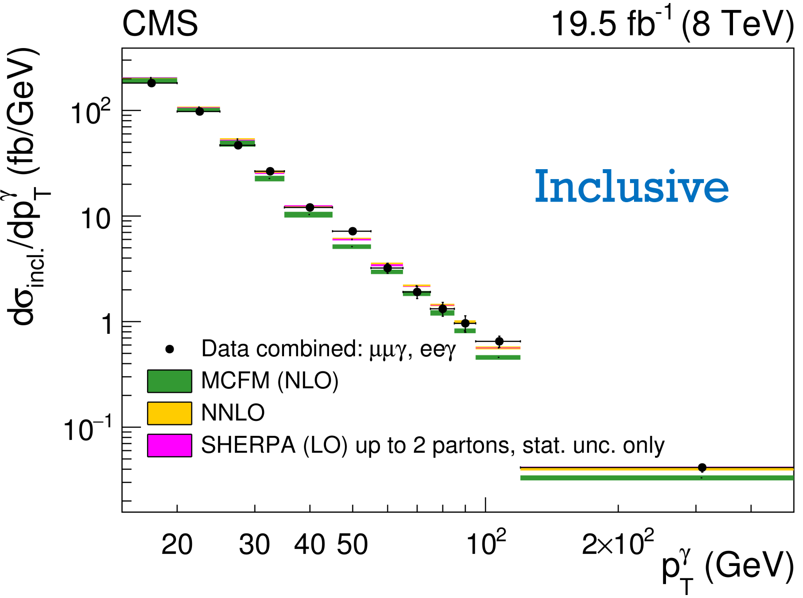


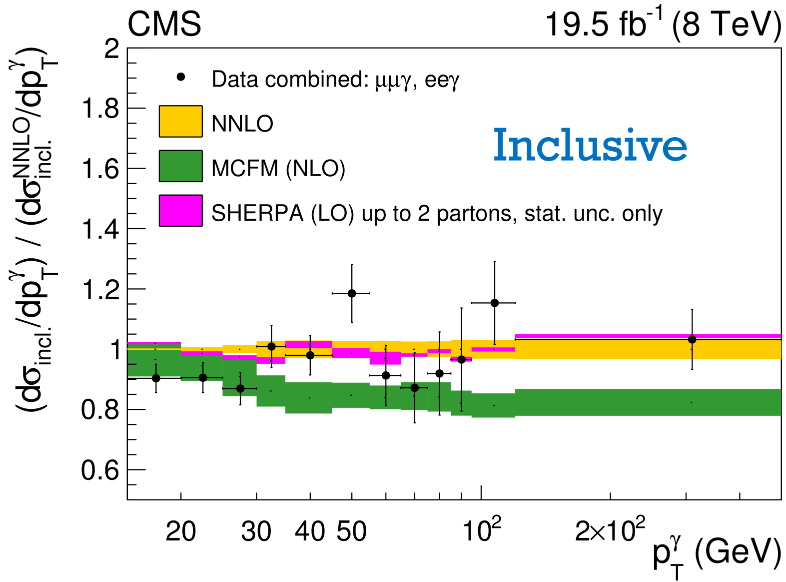


Differential Measurement for Z(ll)γ









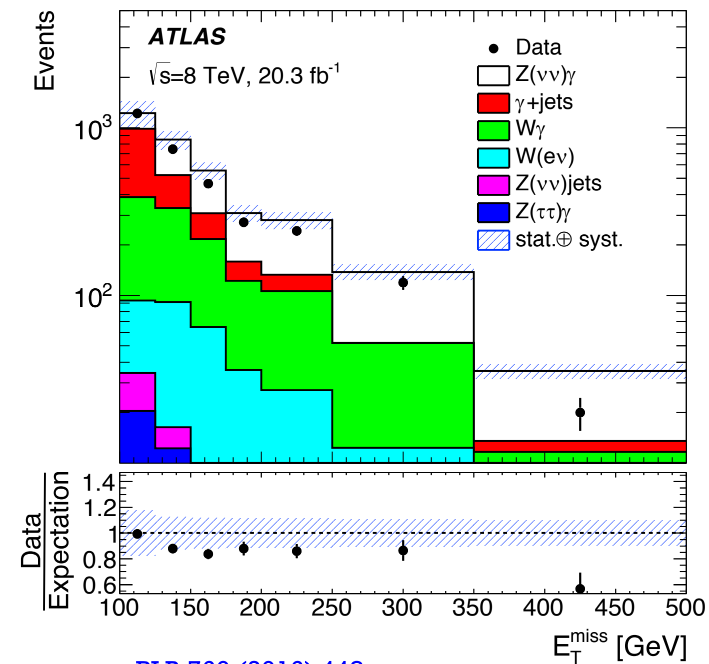
+ Z(νν)γ Production (8 TeV)

- Basic Selection, CMS(ATLAS)
  - One energetic photon, P_T > 145 (130) GeV & |η| < 1.44
  - MET > 140 (100) GeV
  - Azimuthal separation b/w photon & MET, ΔΦ(γ, MET) > 2.0 (pi/2)
  - Reject backgrounds with leptons and jets
    - ✓ Lepton veto & jet veto.

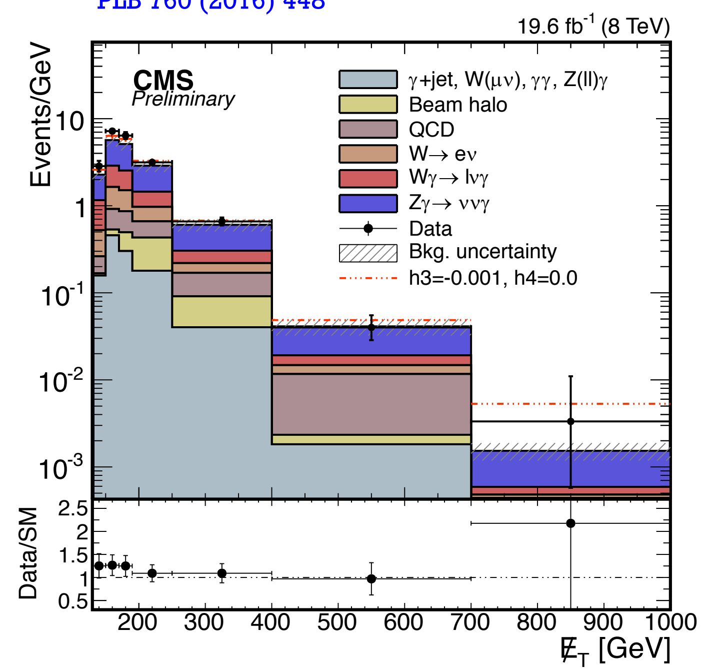
- Backgrounds
  - Wγ → (ℓ)ν γ (ℓ not reconstructed
  - W → eν (e mis-identified as a photon)
  - QCD multijet (jet misidentified as a photon)
  - Non-collision background (mostly beam halo)

- The most sensitive channel for ZZγ, Zγγ vertices aTGC measurement due to higher Z->νν BR giving access to more events with a high p_T^{γ}

PRD 93, 112002 (2016)



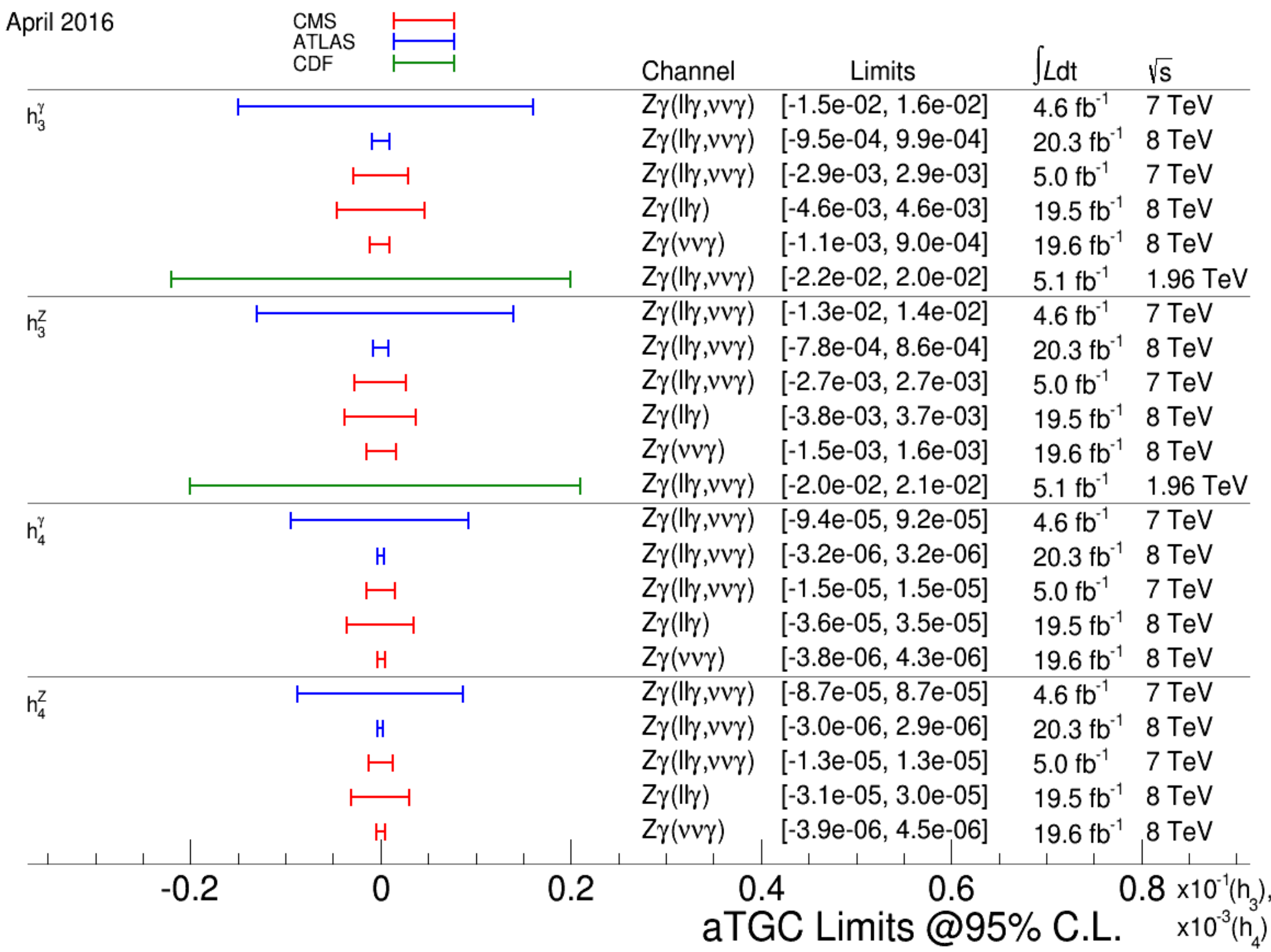
PLB 760 (2016) 448



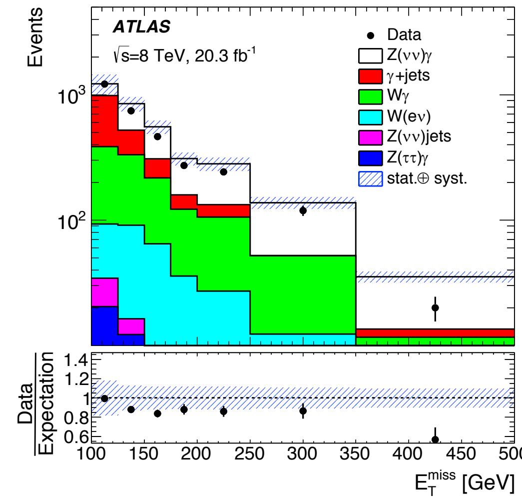
Bhawna Gomber

aTGC Limits Summary 7+8 TeV

- The most sensitive channel for ZZγ, Zγγ vertices aTGC measurement is Zννγ due to access to high p_T^{γ}



PRD 93, 112002 (2016)



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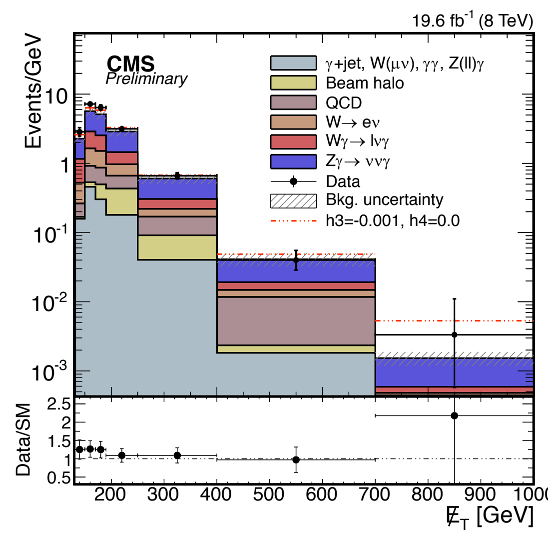


Bhawna Gomber

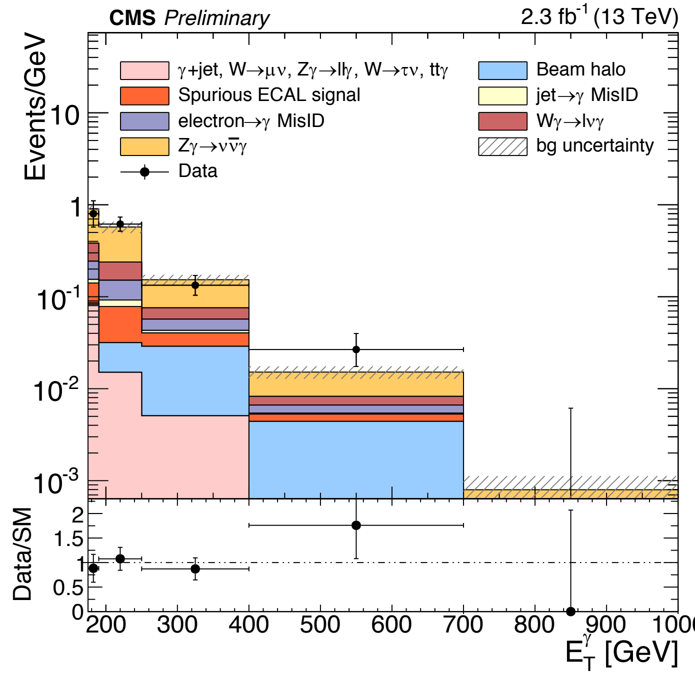
Z(νν)γ Production (13 TeV)

CMS-PAS-SMP-16-004

- Basic Selection wrt to Run1
  - High photon P_T > 175 GeV & |η| < 1.44
  - High MET > 170 GeV
- Backgrounds same as Run-1

Sources	Effect on cross section (%)
Luminosity	3.3
PDF and QCD scale	6.8
Electroweak corrections	11.3
Jets misidentified as γ	1.3
Electron misidentified as γ	3.6
Beam halo	11.0
Spurious ECAL signals	5.0
E_T^{miss}, photon energy scales, pileup	7.1
Data/sim. scale factors	9.7

Process	Estimate
$Z\gamma \to \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \to \ell\nu\gamma$	10.60 ± 1.58
$W \to e\nu$	7.80 ± 1.78
Jet → γ misidentified	1.75± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77



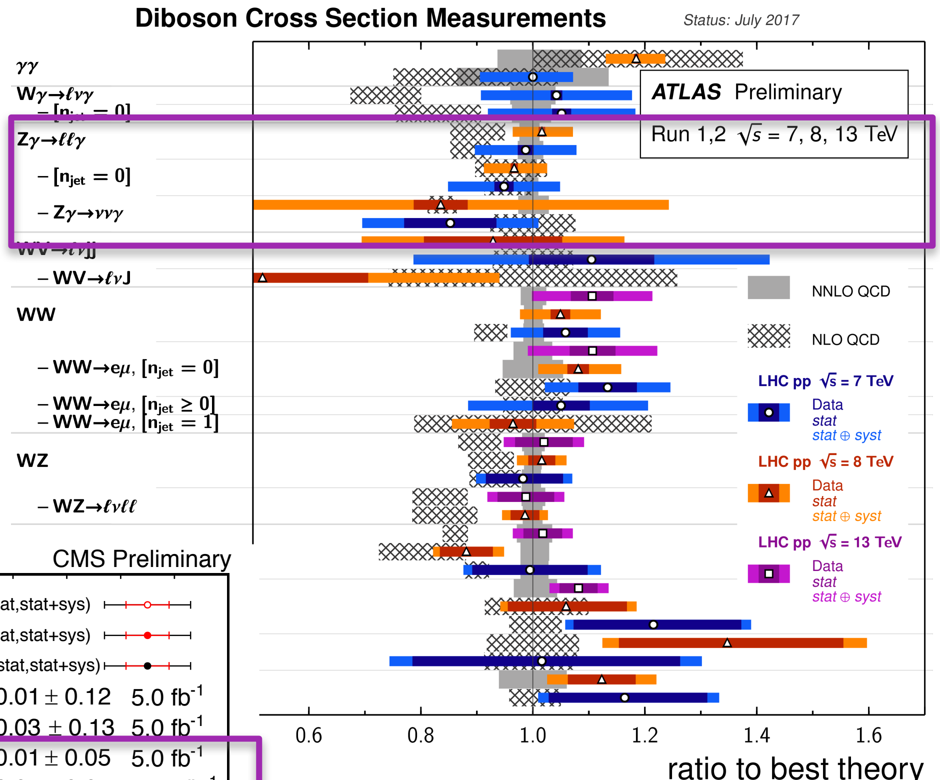
	σ(Zγ->ννγ) [fb]
	13 TeV
CMS	66.5 ± 13.6 (stat) ± 14.3 (syst) ± 2.2 (lumi) σNNLO = 65.5±3.3

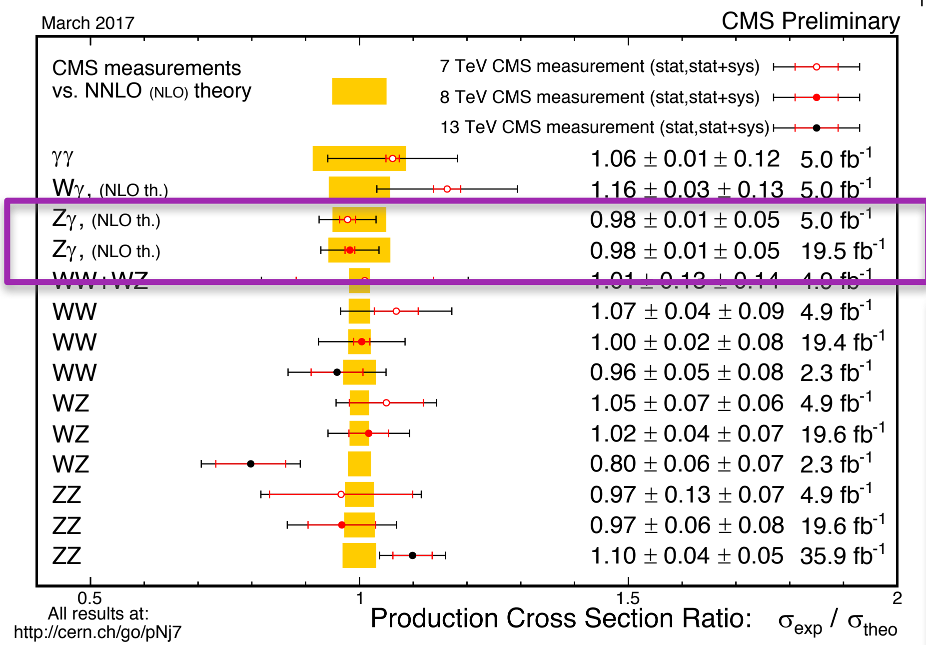
- Good agreement with SM expectation
- Dominant uncertainty : theory uncertainty, non-collision background estimate

- *Analysis with Run2 2015 (2.3 fb^{-1}), need more Run-2 data to supersede Run1 aTGC sensitivity*

Zγ Cross Section Summary

- No significant discrepancy is observed between data and SM expectations
- Systematic dominant measurements





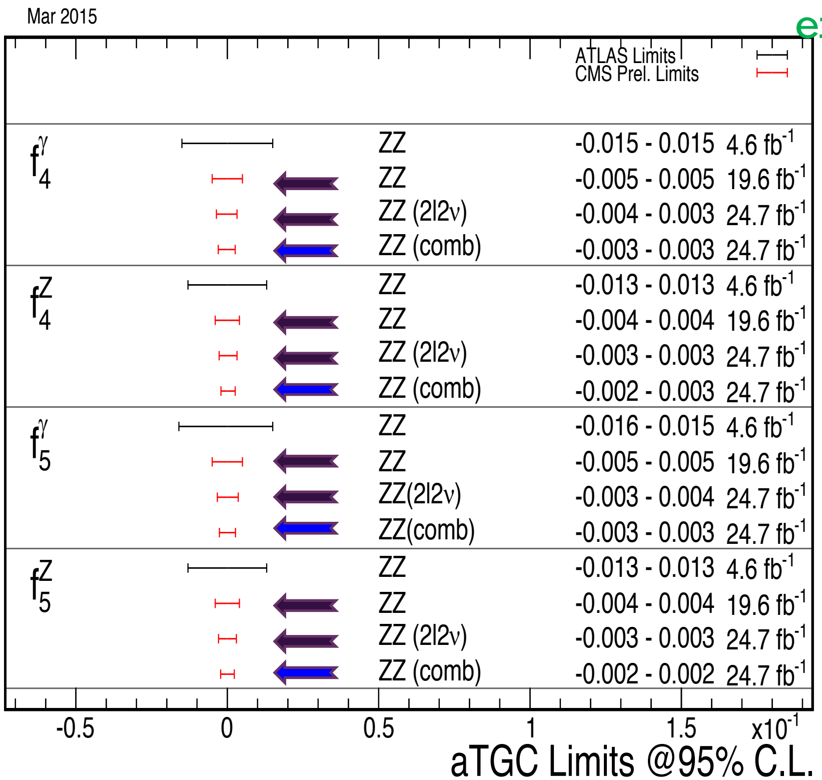
- **Prospects for Cross Section Measurement**
- More statistics at 13 TeV (with 2017/2018 data) will allow us to probe higher p_T/mass of diboson system which provides access to phase space with high sensitivity to higher order corrections

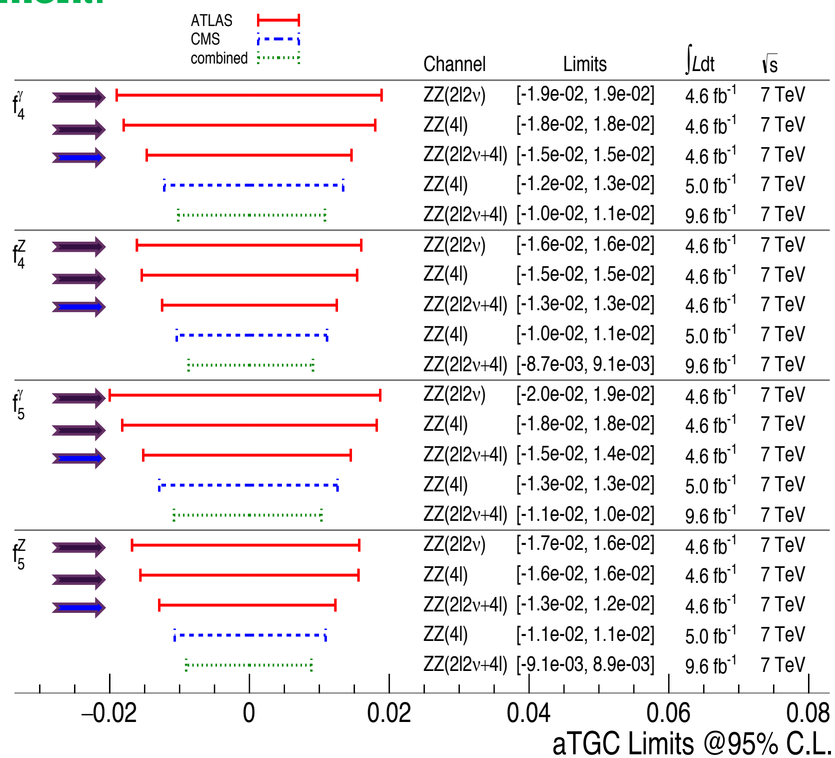
aTGC Sensitivity and Combinations

Combination within experiments CMS, ATLAS (7 TeV)

Combination between channels with similar aTGC sensitivity: ZZ->4l and ZZ->2l2ν channels.

The sensitivity to aTGC parameters is improved by about 20% compared to the sensitivity of a single experiment.

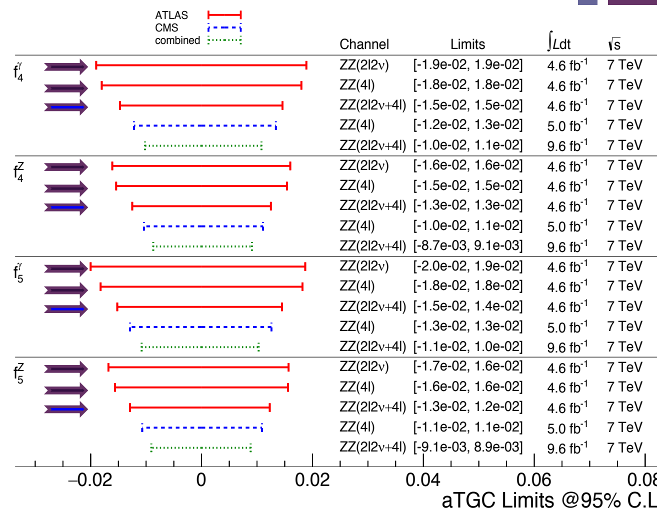




ATLAS-CONF-2016-036 ; CMS-PAS-SMP-15-001

Combination within experiments CMS, ATLAS (7 TeV)

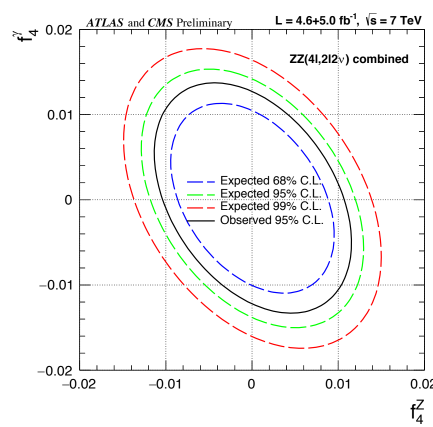
Observed limit	f_4^γ	f_4^Z	f_5^γ	f_5^Z
deltaNLL ATLAS	[-0.015, 0.015]	[-0.013, 0.013]	[-0.015, 0.015]	[-0.013, 0.012]
deltaNLL CMS	[-0.012, 0.013]	[-0.010, 0.011]	[-0.013, 0.013]	[-0.011, 0.011]
deltaNLL combined	[-0.010, 0.011]	[-0.0087, 0.0091]	[-0.011, 0.010]	[-0.0091, 0.0089]
F-C combined	[-0.010, 0.011]	[-0.0089, 0.0092]	[-0.011, 0.010]	[-0.0092, 0.0089]

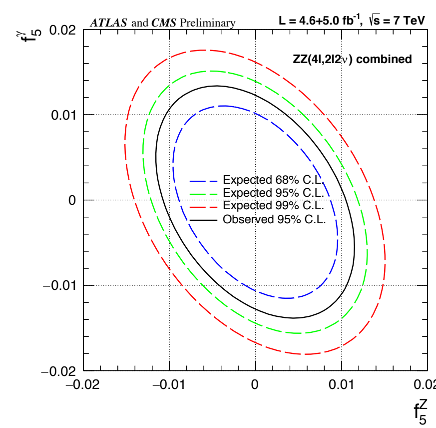


The sensitivity to aTGC parameters is improved by about 20% compared to the sensitivity of a single experiment.

First effort to combine ATLAS and CMS aTGC results

- ✓ **Synchronization of the ATLAS and CMS limit setting tools and statistical procedure**
- ✓ Requiring a good agreement between results of different tools is required to ensure consistency
- ✓ For the deltaNLL (FC) the results are in relative agreement at the 1% (5%) level

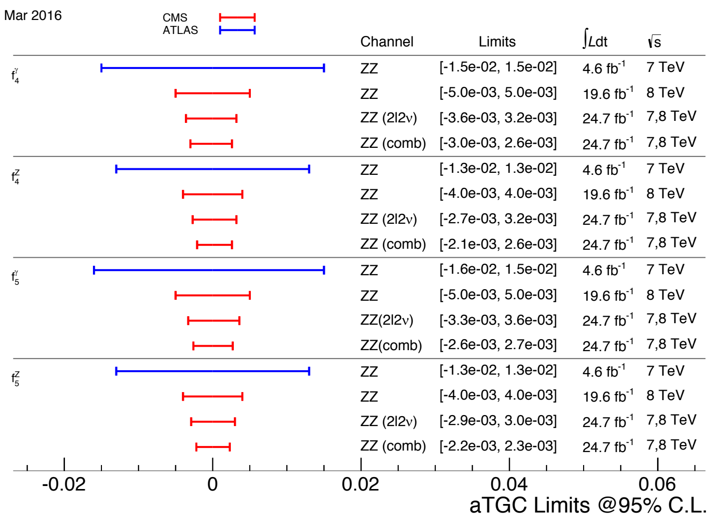


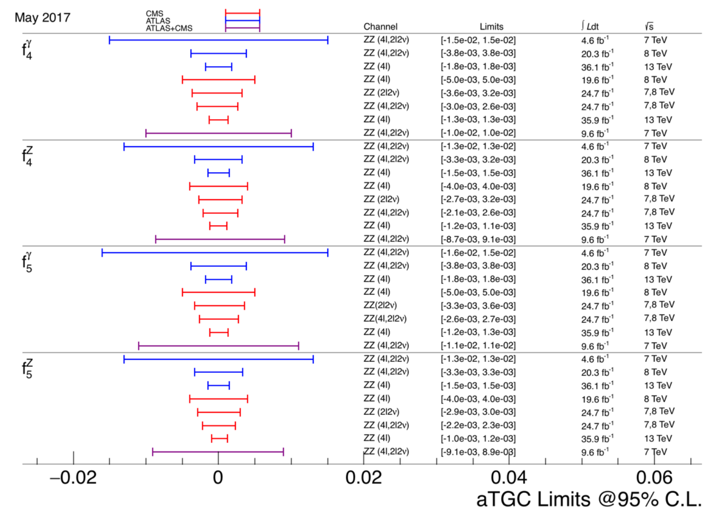


Combination procedure that can serve as guidance for future combinations of aTGC parameters at the LHC !

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

+ aTGC sensitivity vs time





Limits with 7/8 TeV → Limits with 7/8/13 TeV

- Collision energy increasing
- Integrated luminosity increasing
- Accessing higher diboson system mass / p_T
  - aTGC sensitivity increasing
- More challenging conditions for measurements (higher pileup etc)

- *Upcoming analysis with Run2 2016+2017 data will provide world's best limits*

+ aTGC Summary

- No significant discrepancy is observed between data and SM background expectations in high mass or p_T tails
  - Limits on aTGC parameters are set
- Results with Run2 data will provide more precise measurements/limits of anomalous couplings
  - Combination prospects: ATLAS+CMS results, diboson + higgs production channels

+ Backup

Statistical Methods : Anomalous coupling Measurement

$\vec{\theta}$ = nuisance parameters

$\vec{\alpha}$ = **anomalous coupling parameters**

L = likelihood function

$\lambda(\vec{\alpha})$ = profile likelihood ratio

maximizes L in θ, for specified α

$$\lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}_{\vec{\alpha}})}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

maximize L in α and θ

test statistics: $t(\vec{\alpha}) = -2\ln\lambda(\vec{\alpha})$

- Limit Setting Criteria for anomalous coupling
- "deltaNLL" limit
  - Use of Wilks theorem, distribution of t_α, under assumption α, is approximated with χ^2 distribution
  - Asymptotic, high statistics approximation
  - Fast but coverage is not guaranteed
- "Feldman-Cousins (F-C)" limit
  - Distribution of t_α, under assumption α, is determined by throwing toys
  - Computing time consuming but guaranties coverage
- *Usually the two methods agree within 10%.*

- Systematic Uncertainties covered by Nuisance paramaters
  - Nuisance parameters are profiled
  - Using logNormal (lnN), following CMS statistics committee recommendation

- For expected limits, we use pre-fit Asimov dataset

+ ATlAS fiducial cuts ZZ

Type	Input or requirement
Leptons (e, μ)	Prompt Dressed with prompt photons within $\Delta R = 0.1$ $> 5\ GeV$ $\lvert\eta\rvert < 2.7$
Quadruplets	Two same-flavor opposite-charge lepton pairs Three leading- leptons satisfy $>$ 20 GeV, 15 GeV, 10 GeV
Events	Only quadruplet minimizing $\lvert m_{\ell\ell} - m_Z\rvert + \lvert m_{\ell'\ell'} - m_Z\rvert$ is considered Any same-flavor opposite-charge dilepton has mass $m_{\ell\ell} >$ 5 GeV $\Delta R > 0.1$ (0.2) between all same-flavor (different-flavor) leptons Dileptons minimizing $\lvert m_{\ell\ell} - m_Z\rvert + \lvert m_{\ell'\ell'} - m_Z\rvert$ are taken as Z boson candidates Z boson candidates have mass $66\ GeV < m_{\ell\ell} <$ 116 GeV
Jets	Clustered from all non-prompt particles Anti-k_t algorithm with $R = 0.4$ $> 30\ GeV$ $\lvert\eta\rvert < 4.5$ Rejected if within $\Delta R = 0.4$ of a fiducial lepton

+ ATlAS fiducial cuts Zgamma

TABLE V. Definition of the extended fiducial regions where the cross sections are measured. The variable $p_T^{\nu\bar{\nu}}$ is the transverse momentum of the Z boson decaying to a neutrino pair. The variable ϵ_h^p is the transverse energy carried by the closest particle-level jet in a cone of $\Delta R = 0.4$ around the photon direction, excluding the photon and divided by the photon transverse energy.

Cuts	$\ell^+\ell^-\gamma$	$\ell^+\ell^-\gamma\gamma$	$\nu\bar{\nu}\gamma$	$\nu\bar{\nu}\gamma\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	...	...
	$\lvert\eta^\ell\rvert < 2.47$	$\lvert\eta^\ell\rvert < 2.47$	...	...
Boson	$m_{\ell^+\ell^-} > 40$ GeV	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 100$ GeV	$p_T^{\nu\bar{\nu}} > 110$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 130$ GeV	$E_T^\gamma > 22$ GeV
	$\lvert\eta^\gamma\rvert < 2.37$			
	$\Delta R(\ell,\gamma) > 0.7$	$\Delta R(\ell,\gamma) > 0.4$	...	...
	...	$\Delta R(\gamma,\gamma) > 0.4$	...	$\Delta R(\gamma,\gamma) > 0.4$
	$\epsilon_h^p < 0.5$			
Jet	$p_T^{\text{jet}} > 30$ GeV, $\lvert\eta^{\text{jet}}\rvert < 4.5$			
	$\Delta R(\text{jet},\ell/\gamma) > 0.3$	$\Delta R(\text{jet},\ell/\gamma) > 0.3$	$\Delta R(\text{jet},\gamma) > 0.3$	$\Delta R(\text{jet},\gamma) > 0.3$
	Inclusive: $N_{\text{jet}} \geq 0$, Exclusive: $N_{\text{jet}} = 0$			

+ CMS and ATLAS Systematics ZZ

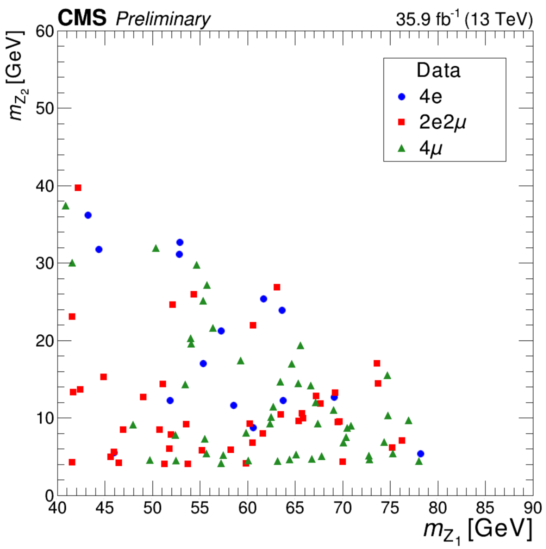
CMS Systematics

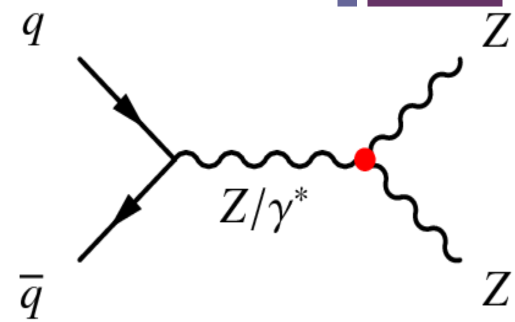
Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
Lepton efficiency	6–10%	2–6%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	0.5%
Background	0.6–1.3%	0.5–1%
Pileup	1–2%	1%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.6%	2.6%

ATLAS Systematics

Source	**Effect on total predicted yield [%]**
MC signal sample statistics	1.2
Electron efficiency	0.9
Electron energy scale & resolution	< 0.1
Muon efficiency	1.7
Muon momentum scale & resolution	$^{+0.1}_{-0.0}$
Pileup modeling	0.7
Luminosity	3.2
QCD scales	$^{+2.3}_{-2.2}$
PDFs	$^{+2.0}_{-1.7}$
Background prediction	0.9
Total	$^{+5.0}_{-4.9}$

+ ZZ and Zg : Anomalous coupling parameterization





channel	couplings	parametrization	parameters	Dimensionality of operator
Zγ	ZZγ, Zγγ	Effective vertex	h_3	dim6
			h_4	dim8
ZZ	ZZZ, ZZγ		f_4	dim6
			f_5	dim6

Cross Section Zllgamma 8 TeV (CMS)

p_T^γ (GeV)	σ_{incl} (fb)	σ_{incl}^{MCFM} (fb)	σ_{incl}^{NNLO} (fb)
15–20	$908 \pm 12 \pm 39 \pm 24$	972 ± 57	1005.6 ± 2.6
20–25	$489 \pm 9 \pm 21 \pm 13$	510 ± 27	540.1 ± 3.7
25–30	$234 \pm 7 \pm 11 \pm 6$	245 ± 17	269.2 ± 3.6
30–35	$132.8 \pm 4.8 \pm 7.0 \pm 3.5$	113.4 ± 6.8	131.6 ± 3.5
35–45	$120.7 \pm 4.0 \pm 6.2 \pm 3.1$	103.2 ± 6.4	123.2 ± 3.6
45–55	$71.8 \pm 3.0 \pm 4.6 \pm 1.9$	51.3 ± 2.5	60.6 ± 1.6
55–65	$32.2 \pm 2.3 \pm 2.5 \pm 0.8$	29.6 ± 1.4	35.2 ± 1.0
65–75	$19.1 \pm 1.8 \pm 1.7 \pm 0.5$	18.5 ± 1.0	21.89 ± 0.56
75–85	$13.2 \pm 1.5 \pm 1.2 \pm 0.3$	12.10 ± 0.70	14.38 ± 0.38
85–95	$9.6 \pm 1.2 \pm 1.2 \pm 0.3$	8.19 ± 0.41	9.98 ± 0.31
95–120	$16.3 \pm 1.3 \pm 1.4 \pm 0.4$	11.47 ± 0.57	14.10 ± 0.44
>120	$15.8 \pm 1.0 \pm 1.0 \pm 0.4$	12.59 ± 0.68	15.29 ± 0.51

p_T^γ (GeV)	σ_{excl} (fb)	σ_{excl}^{MCFM} (fb)
15–20	$832 \pm 12 \pm 49 \pm 22$	873 ± 51
20–25	$432 \pm 9 \pm 25 \pm 11$	450 ± 23
25–30	$196 \pm 6 \pm 12 \pm 5$	211 ± 10
30–35	$100.5 \pm 5.3 \pm 7.4 \pm 2.6$	89.5 ± 7.9
35–45	$89.2 \pm 3.7 \pm 6.2 \pm 2.3$	77.2 ± 5.6
45–55	$49.5 \pm 2.8 \pm 4.9 \pm 1.3$	39.0 ± 2.4
55–65	$25.4 \pm 2.0 \pm 3.1 \pm 0.7$	22.4 ± 1.6
65–75	$11.4 \pm 1.5 \pm 1.7 \pm 0.3$	13.83 ± 0.98
75–85	$9.3 \pm 1.3 \pm 1.6 \pm 0.2$	8.85 ± 0.48
85–95	$6.3 \pm 1.2 \pm 1.4 \pm 0.2$	5.83 ± 0.70
95–120	$9.9 \pm 1.0 \pm 1.3 \pm 0.3$	7.83 ± 0.48
>120	$8.6 \pm 0.8 \pm 1.1 \pm 0.2$	7.81 ± 0.58