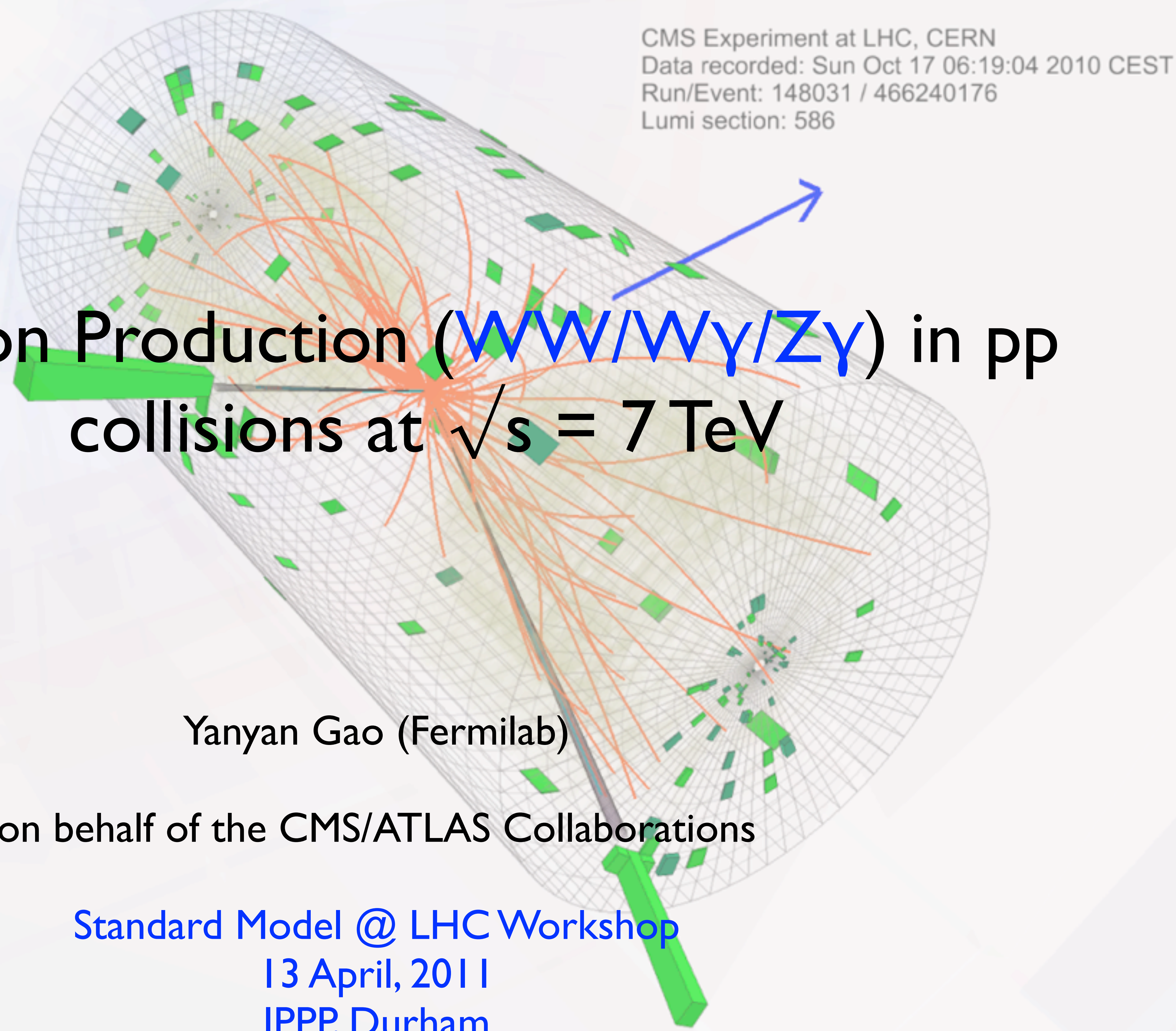

Diboson Production (WW/Wγ/Zγ) in pp collisions at $\sqrt{s}$ = 7 TeV

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on behalf of the CMS/ATLAS Collaborations

Standard Model @ LHC Workshop
13 April, 2011
IPPP, Durham

Outline

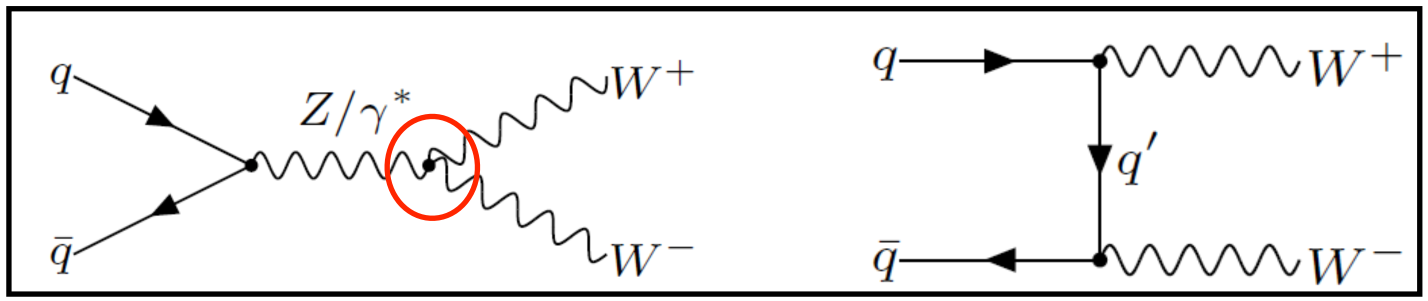
- Introduction to Diboson Production
- WW Production Cross-section Measurement
  - Analysis strategy* (signal selection and background estimation)
  - WW production cross-section determination
  - Limits on WWγ/WWZ anomalous triple gauge-boson couplings (aTGC)
- Wγ/Zγ Production Cross-section Measurements
  - Analysis strategy (signal selection and background estimation)
  - Wγ/Zγ production cross-section determination
  - Limits on WWγ/ZZγ/Zγγ anomalous triple gauge-boson couplings (aTGC)
- Summary and Conclusion

** Both CMS and ATLAS adopt similar analysis strategies with minor differences in the implementation details. It will be noted in the cases when different strategies are taken.*

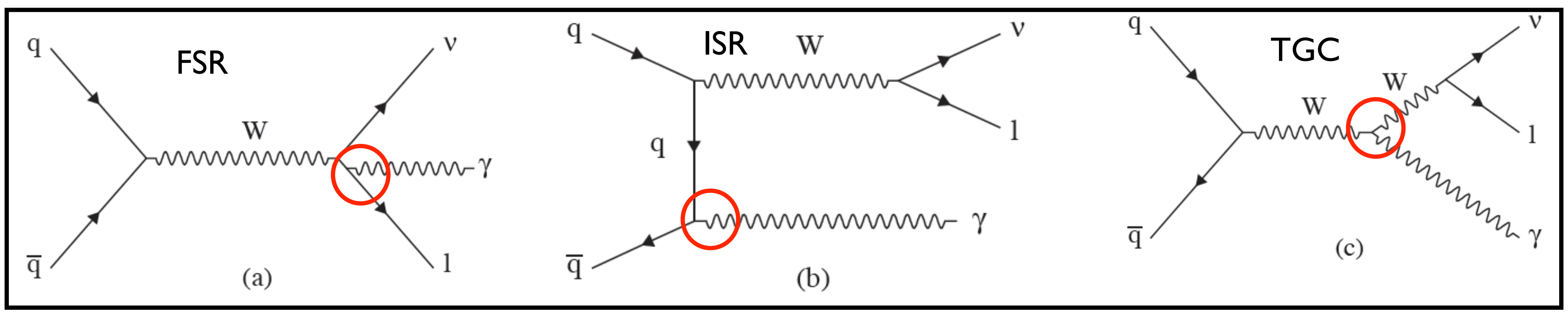
Introduction to Diboson Production (I)

- Diboson production such as WW/WZ/Wγ/Zγ/ZZ in pp collisions at LHC provides important tests to SM in the EWK sector
  - The processes have much smaller rates compared to V+jets in SM. It is crucial to demonstrate our experimental understanding of them in a new energy region, even with only ~40/pb data
  - Leading order productions in SM

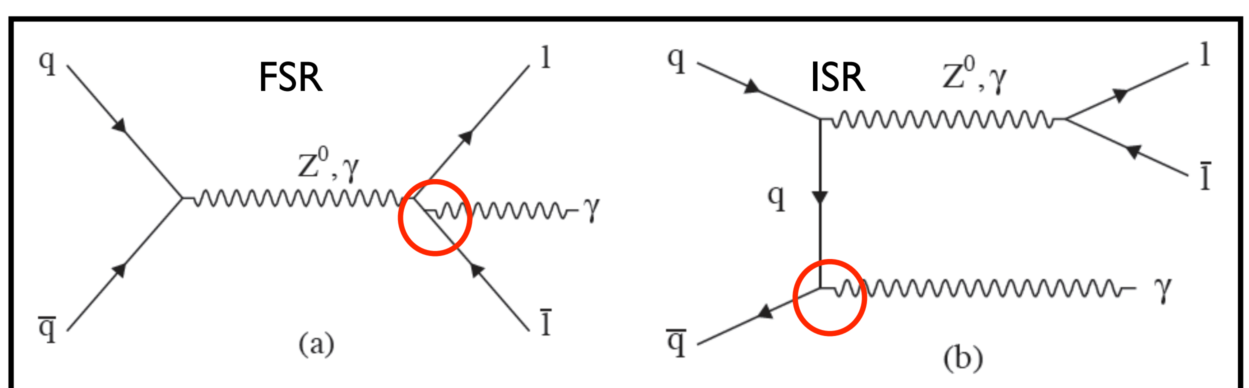
WW



Wγ

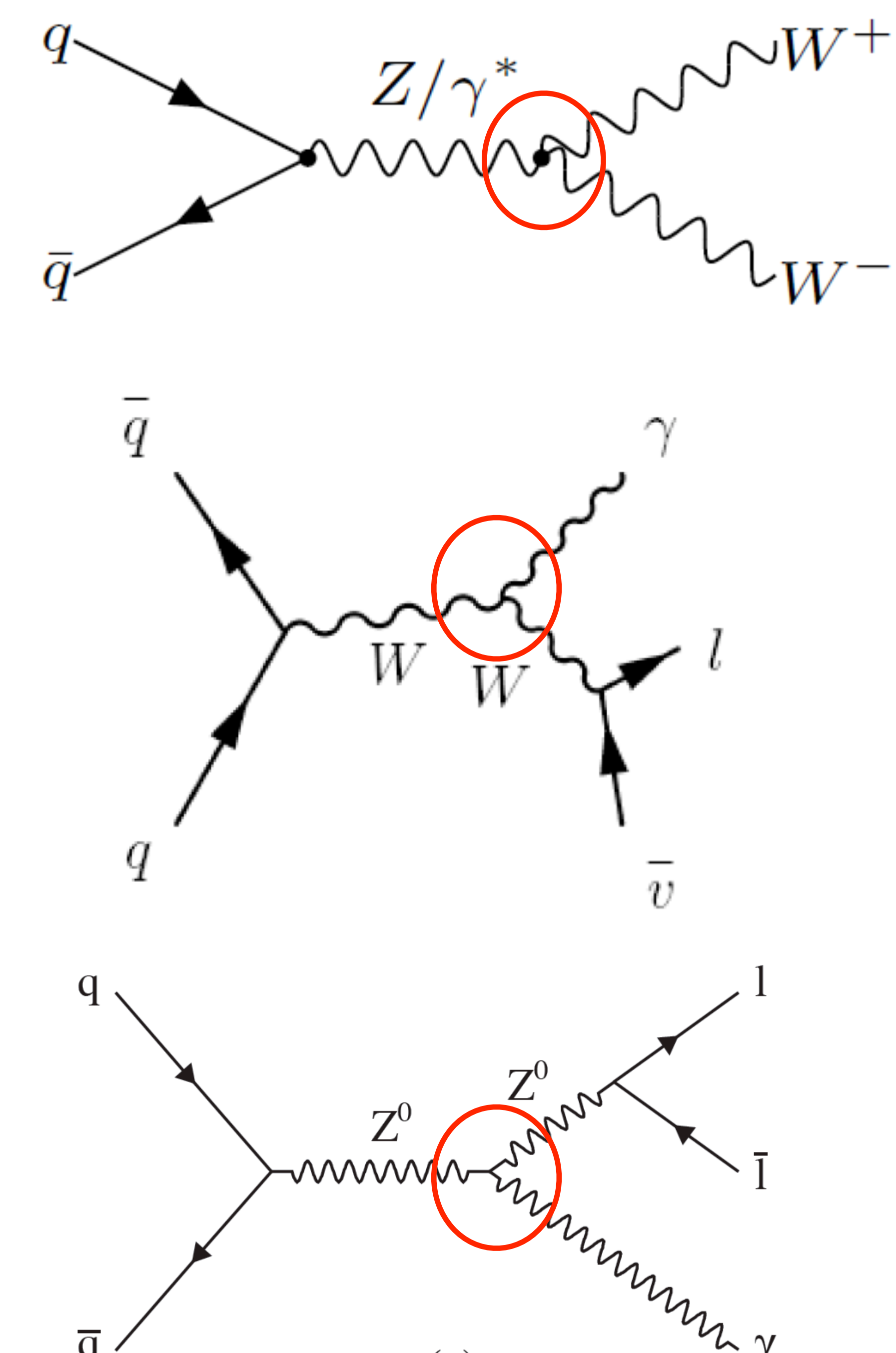


Zγ



Introduction to Diboson Production (II)

- Precise measurement of diboson production is a prerequisite for physics searches beyond SM
  - WW production is the dominant and irreducible background to Higgs→WW searches
  - Anomalous triple-gauge-boson couplings (aTGC) from new physics would lead to different cross-section and kinematics in diboson production in WW/Wγ/Zγ compared to SM expectations
    - CMS: place limits on anomalous TGCs averaged for s-hat
  - These processes thus become the testing-ground to catch surprising new physics in the early LHC data



(c)

WW Cross-section

WW Candidate Selections

- Reconstruct WW candidates in fully leptonic channels, selecting events
  - passing single lepton trigger requiring the presence of at least one high pT lepton (e or μ)
  - two prompt oppositely-charged isolated leptons (electron or muon) with large pT (>20 GeV)
  - large MET (neutrinos)
  - low hadronic activity
- A number of SM processes can lead to a similar final state

process	cross-section (pb)
WW	43.0
W(lν)+jets	31314.0
Drell-Yan (ee, μμ, ττ)	4998.0
ttbar	157.5
single-top (tW)	10.6
WZ	18.2
ZZ	5.9

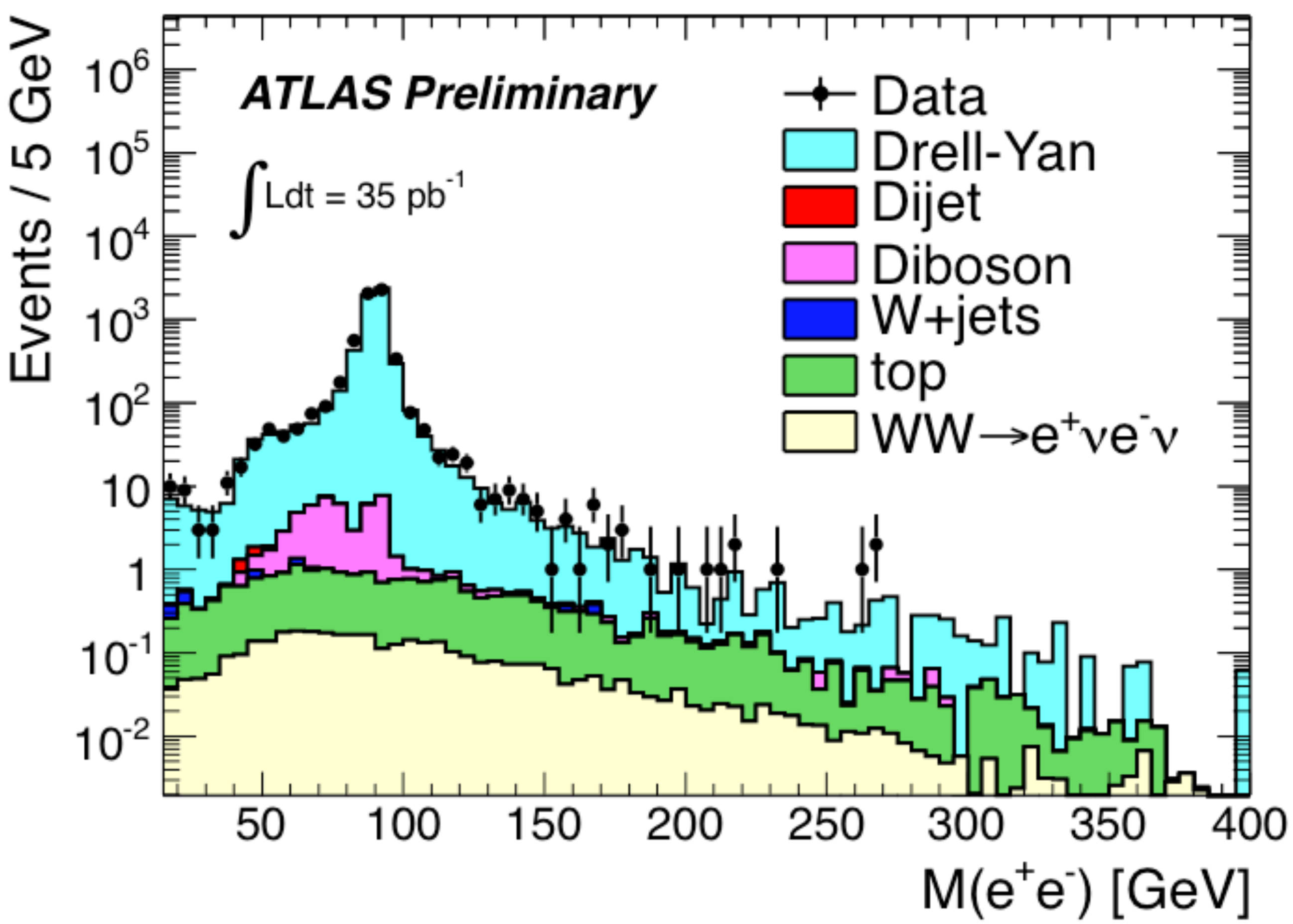
  - Detailed event selections are designed to maximize signal over background (see references)
  - A number of data-driven techniques are used estimate the background contribution in data

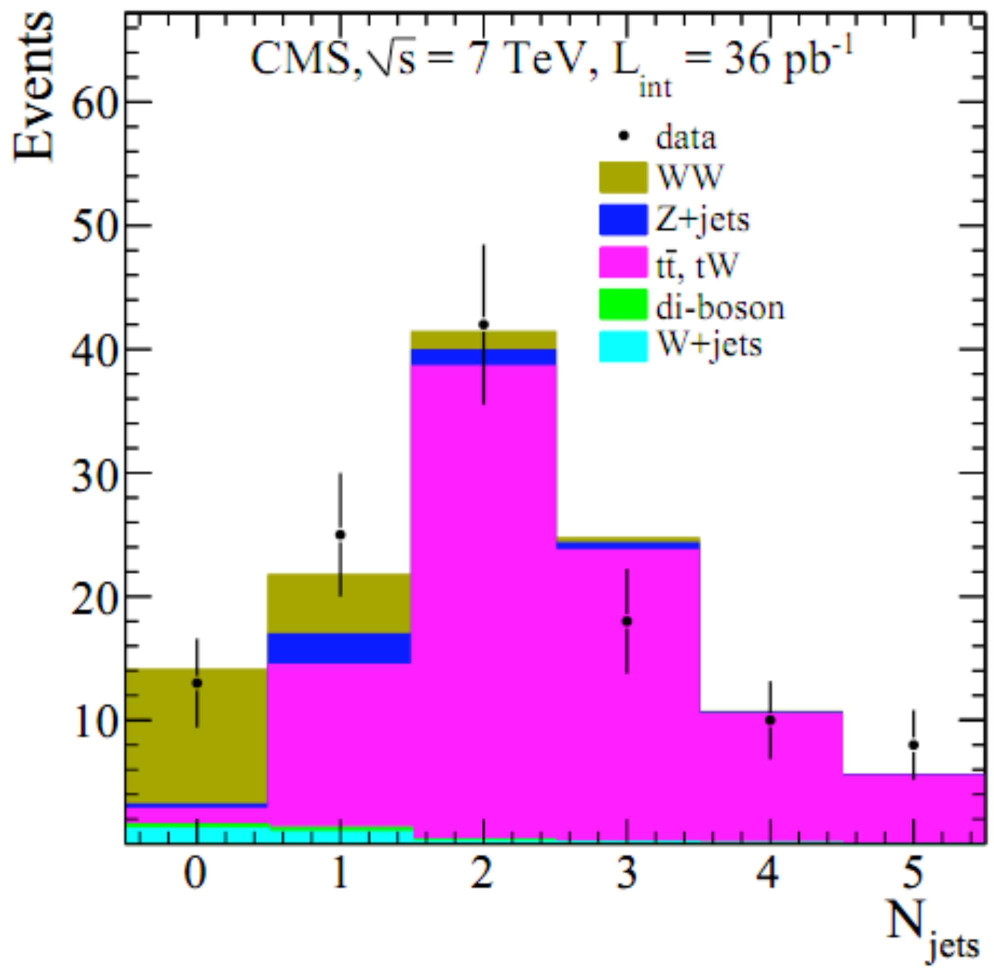
Background Estimations

- W→l+Jets background can fake signal if a jet "fakes" a lepton
  - This background is reduced by the stringent lepton identification and isolation requirements
  - The remaining background in the signal region is estimated from data in both CMS/ATLAS
  - Take the CMS approach as an example
    - We extract the rate for lepton candidates passing a looser-than-analysis cut to pass the tighter analysis cut from a fake enriched sample
    - We then count the number of events in the signal region replacing tight-tight lepton selections with tight-loose selections and weight them by this rate
- Drell-Yan background contains no MET at leading order
  - This background is reduced by applying a tight cut on MET and vetoing events with dilepton mass within 15 GeV of the nominal Z mass (Z-veto)
  - The residual DY with fake MET is estimated from data-driven method (CMS) or MC (ATLAS)
- Top backgrounds (ttbar, tW) differ from signal by the presence of jets
  - This background is suppressed by vetoing events with high pT jets (jet-veto)
  - For events surviving jet-veto, CMS applies further top-veto to rejects events consistent with top-decay indicated by the presence of either additional soft muon or with jets tagged as b

Data/Simulation Validations

- Background enriched datasets are used to validate data/simulation performance in both background normalization and kinematics





<u>DY enriched Region</u>
Events passing the dilepton selections

<u>Top enriched Region</u>
Events passing all selections except for jet-veto and top-veto

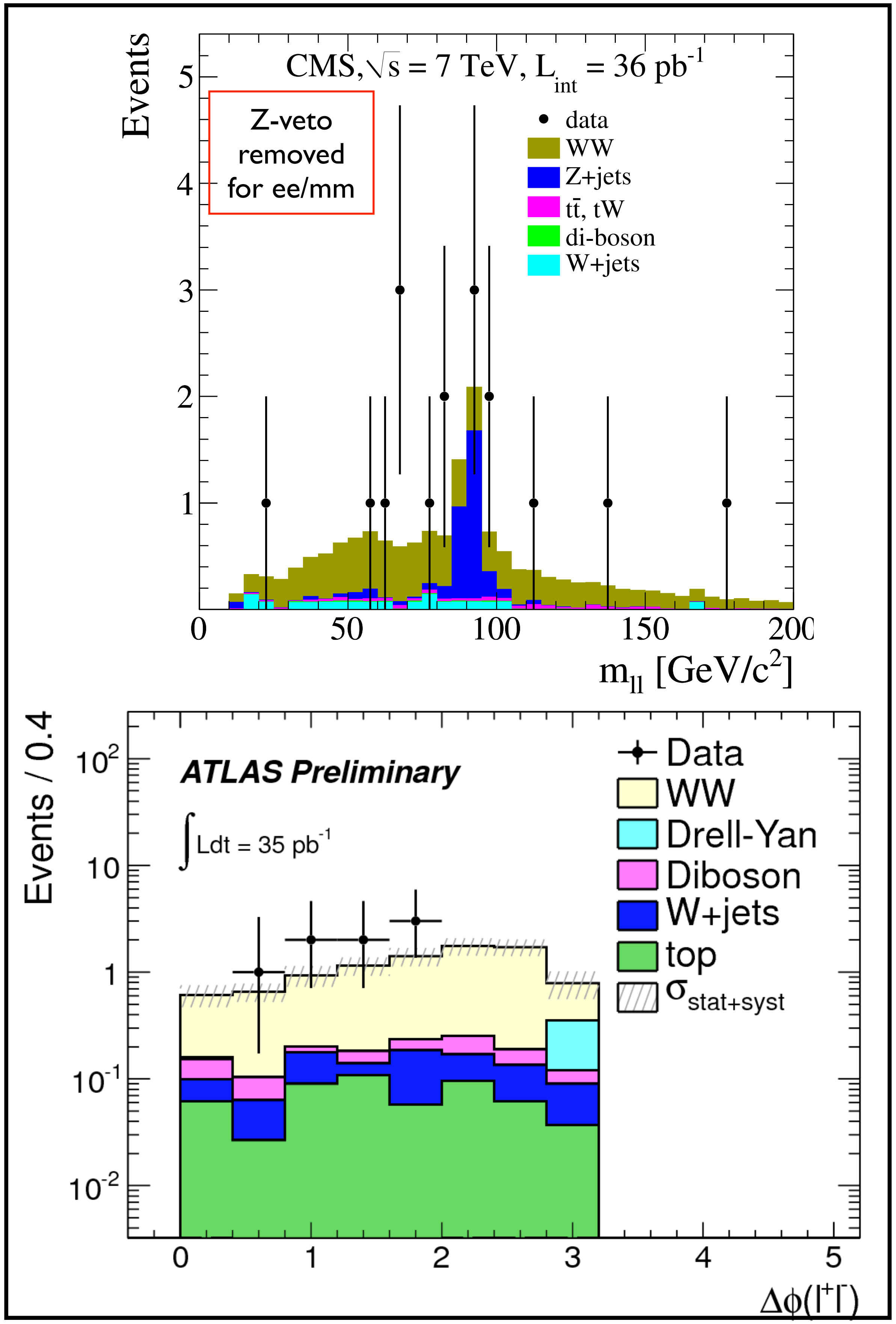
WW Candidates in the Signal Region

- CMS

Observed Events	13
Total background	3.3 ± 0.5(stat) ± 1.1(syst)
Dominant Backgrounds	
W+jets+QCD	1.7 ± 0.4(stat) ± 0.7(syst)
top	0.8 ± 0.1(stat) ± 0.8(syst)

- ATLAS

Observed Events	8
Total background	1.7 ± 0.6 (stat⊕syst)
Dominant Backgrounds	
W+jets+QCD	0.5 ± 0.3(stat) ± 0.2(syst)
top	0.6 ± 0.1(stat) ± 0.3(syst)



WW Cross-section Measurement

- The number of WW events in the signal region N_{sig} is determined
  - using simple counting technique in CMS as (N_{data} - N_{bkg})
  - through a maximum likelihood fitting method in ATLAS
- The cross-section is calculated as

$$\sigma = \frac{N_{sig}}{\varepsilon \mathcal{L}}$$

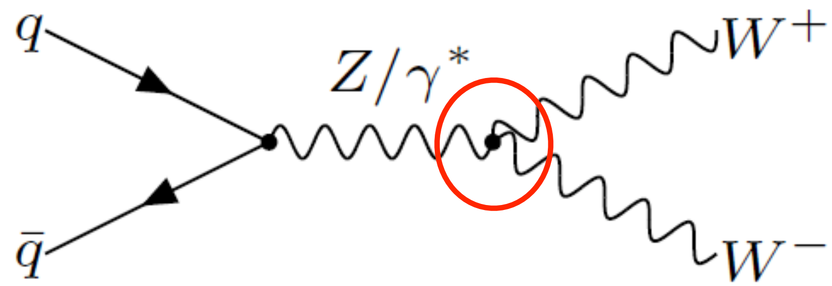
  - Signal efficiencies are determined from MC, with appropriate data/MC scale factors derived from Z events to account for data/MC differences
    - Z events: trigger, lepton selection and jet-veto efficiency data/MC scale factors
  - Systematic effects such as jet-veto requirements, lepton selections and luminosity uncertainties etc. are accounted for
- WW Cross-section Results (NLO prediction 43±2 pb from MCFM)
  - CMS: 41.1 ± 15.3 (stat) ± 5.8 (syst) ± 4.5 (lumi) pb
  - ATLAS: 40 (+20, -16) (stat) ± 7 (syst including lumi) pb

Anomalous TGCs

- WWZ/γ TGC vertex in s-channel WW production is sensitive to NP
  - TGCs in SM are a direct consequence of the non-Abelian nature of SU(2)⊗U(1)
  - NP involving TGCs could lead to enhancement in WW production rate and different kinematic distributions from SM
- Imposing EM/C/P and SU(2)⊗U(1) gauge invariance, the effective $\mathcal{L}$ of a general WWZ/γ vertex can be written in HISZ Parameterization
  - The TGCs can be described in terms of the deviations of g, κ and λ from their SM expectations

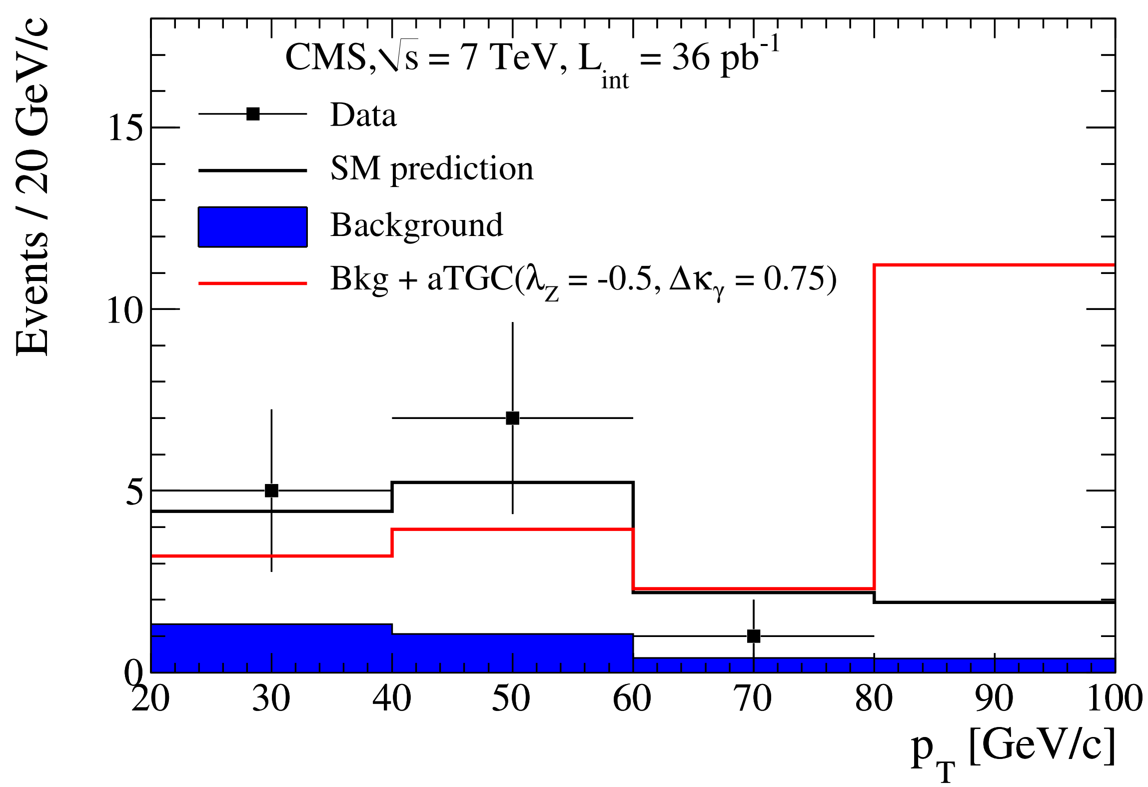
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W,$$
$$\lambda = \lambda_\gamma = \lambda_Z.$$

  - CMS places limits on these aTGCs without assuming any explicit form factors, thus representing the values averaged over s-hat



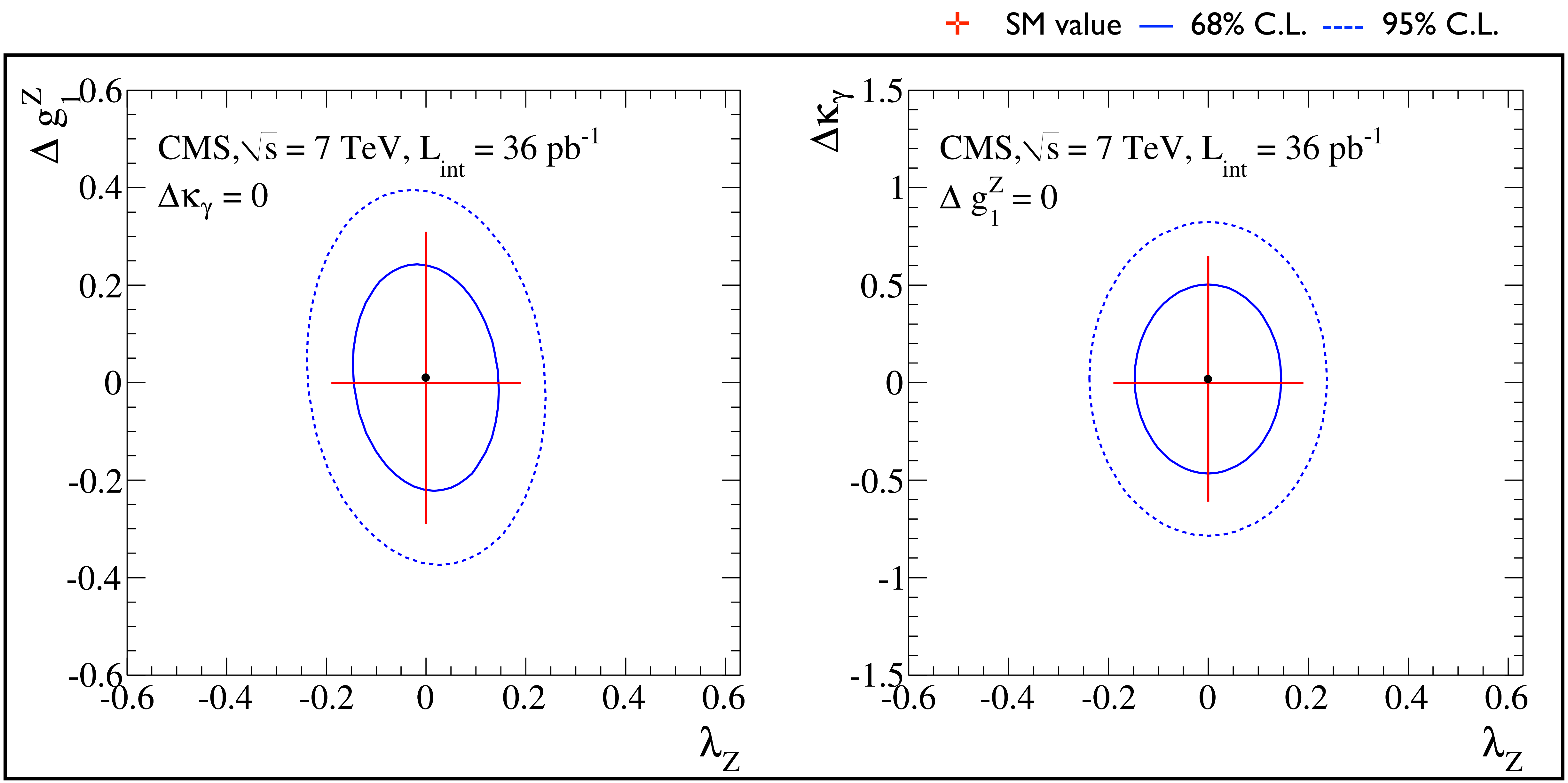
WWV effective $\mathcal{L}$ (Phys. Rev. D 48, 2182–2203 (1993))

$$\mathcal{L}_{\text{eff}}^{WWV} = i\, g_{WWV} \left(g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} V_\rho{}^\mu \right), \quad (2.8)$$



Limits on Anomalous TGCs

- To extract aTGCs, CMS fits the overall WW cross-section and leading lepton pT distribution simultaneously
  - The results agree with SM and limits at 68% and 95% CL are set
  - In probing the 2D limits, the third parameter is fixed to SM values



Wγ/Zγ Cross-section

$W\gamma$ and $Z\gamma$ Candidate Selections

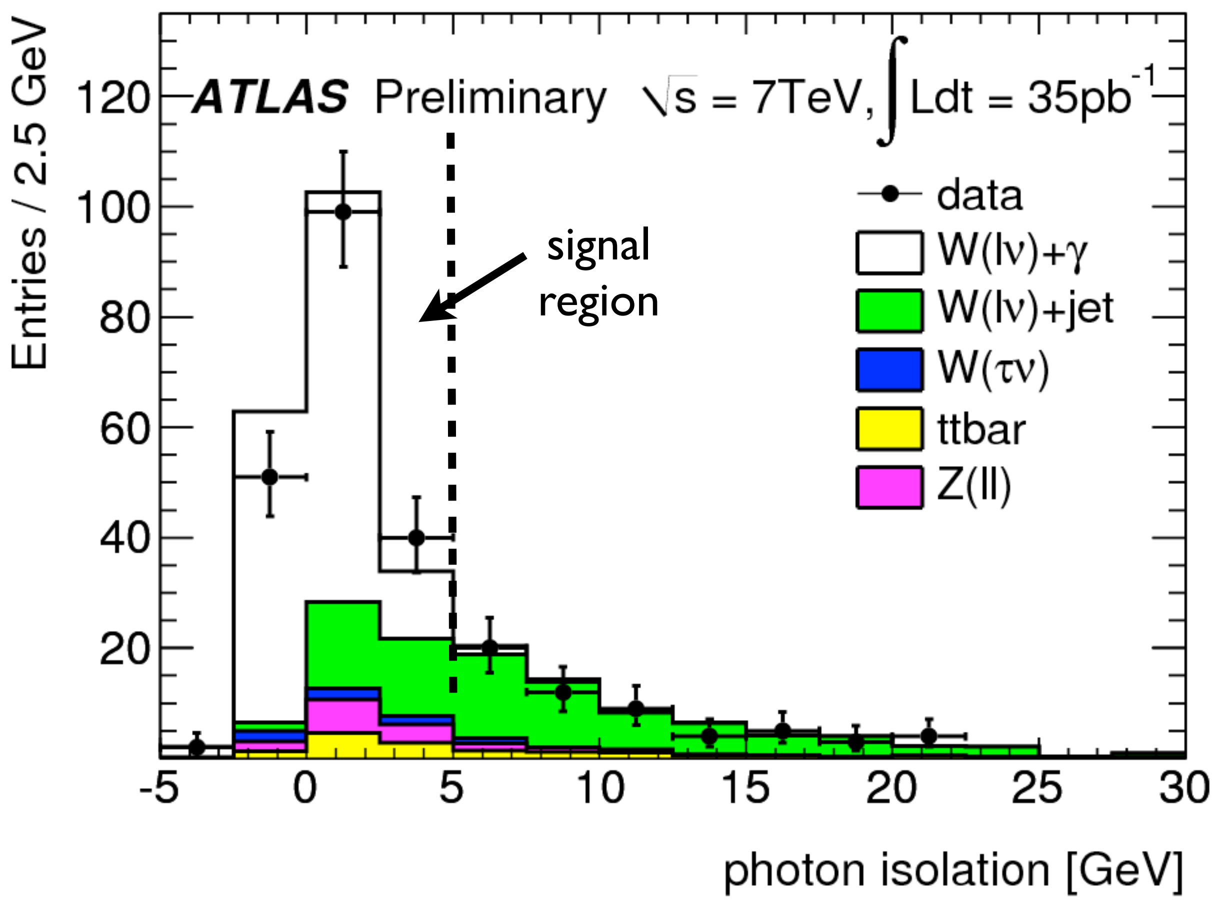
- The dominate background in both analyses is V+jets
  - To suppress these background, select events with an isolated high pT photon with
    - pT > 10 GeV (CMS) pT >15 GeV (ATLAS)
    - $\Delta R(l,\gamma) > 0.7$ (suppress FSR)
- $W\gamma$ candidates are further selected by requiring the event to have
  - one prompt isolated high pT (> 20 GeV) lepton (electron or muon)
  - large MET (neutrinos)
  - ATLAS also requires the transverse W mass > 40 GeV
- $Z\gamma$ candidates are further selected by requiring the event to have
  - two high pT isolated leptons (electron or muon)
  - di-lepton mass M(ll) > 50(40) GeV in CMS (ATLAS)
- A number of data-driven techniques are used estimate the residual background contribution in the signal region of data

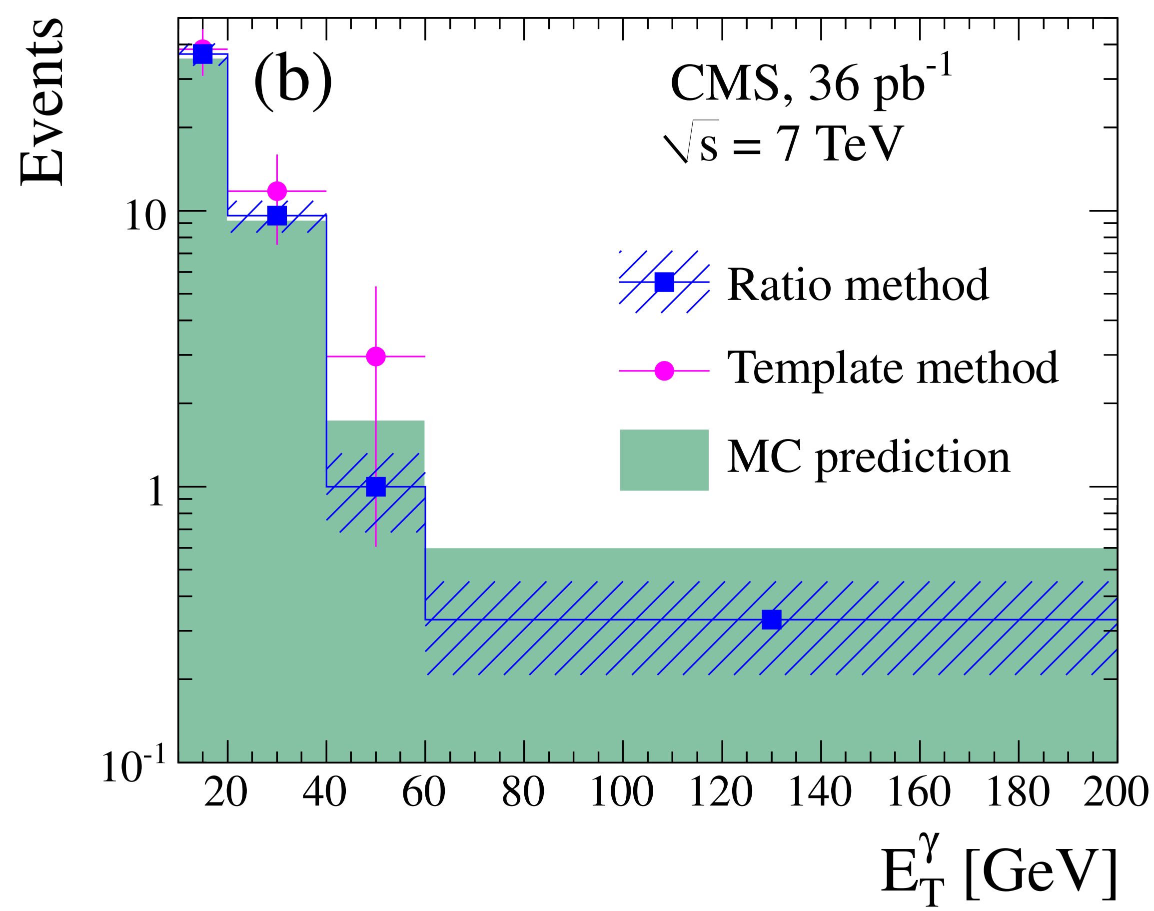
Background Estimations

- Dominant background to W(Z)γ is from W(Z)+jets
  - W(Z)+jets background fakes signal, where the photon candidate originates in a jet
    - This background is reduced first by requiring the photon to be isolated
    - The remaining contribution in the signal region can be estimated from data with various data-driven methods in both CMS and ATLAS
    - For example, one of the methods CMS uses is the "ratio method"
      - Measure Et-dependent ratio of non-isolated photon candidates to isolated ones in a QCD-enriched sample, correcting for γ+jet contamination using MC
      - Fold the Et-dependent ratio in W(Z) + non-isolated photon samples to obtain the W(Z)+jets background
      - The results are cross checked with alternative data-driven methods using shower templates and MC simulation
- Other backgrounds such as top or multi-jets are much smaller
  - Their contributions are estimated from MC

Data/Simulation Validations

- Background enriched datasets are used to validate the data/simulation performance in both background normalization and key kinematic shapes





<u>W+Jets enriched Region</u>
Events with photon with relaxed isolation requirement

<u>Z+jet background Region</u>
Excellent agreement between various data-driven methods and the predictions from simulation

Wγ Candidates in the Signal Region

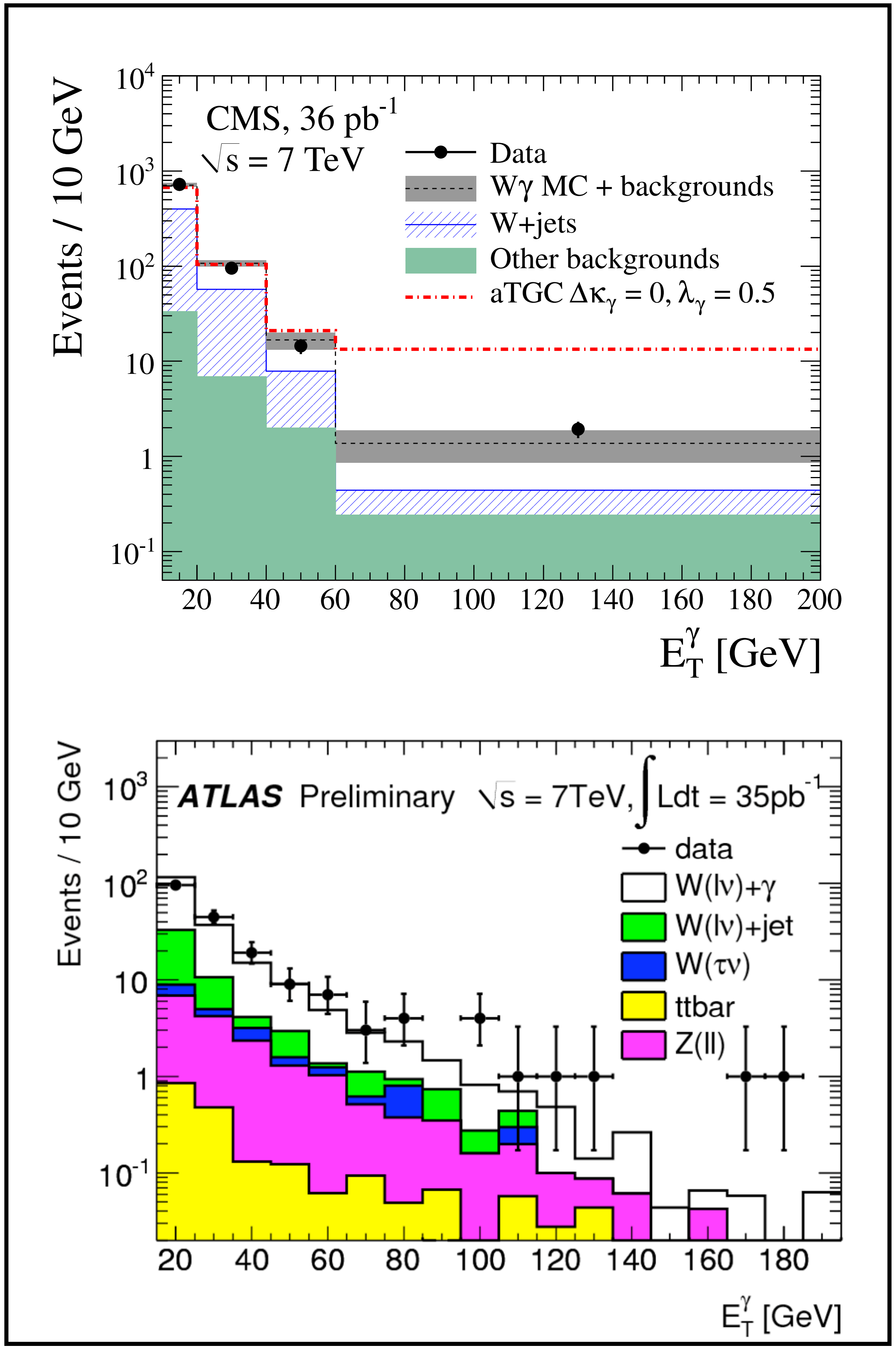
- CMS

process	Observed Events	non W+jet background	W+jet background
eνγ	452	7.7 ± 0.5	220 ± 16 ± 14
μνγ	520	16.4 ± 1.0	261 ± 19 ± 16

- ATLAS

process	Observed Events	W+jets background	non W+jet background
eνγ	95	16.9±6.4±7.3	10.1±0.8±1.2
μνγ	97	16.8±4.7±7.3	12.4±0.9±1.4

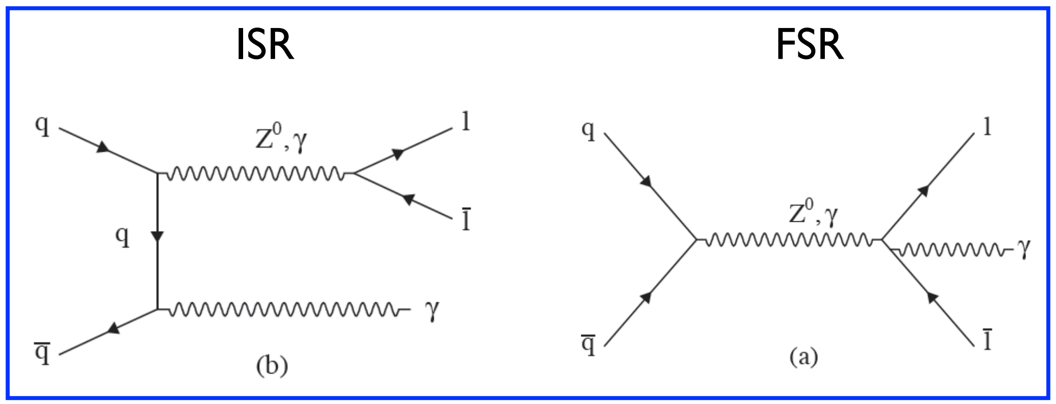
- Difference in yields are mainly due to the different cuts on the photon pT (10 GeV in CMS and 15 GeV in ATLAS)

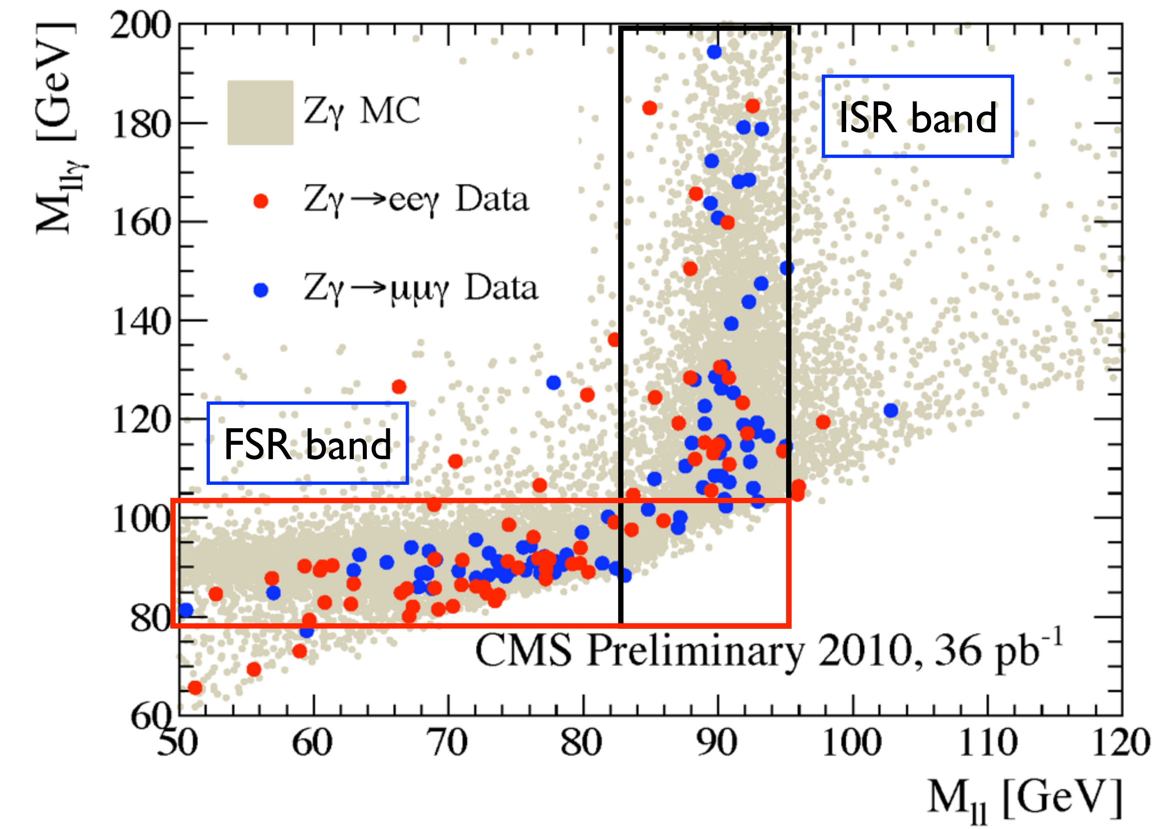


Zγ Candidates in the Signal Region

- CMS

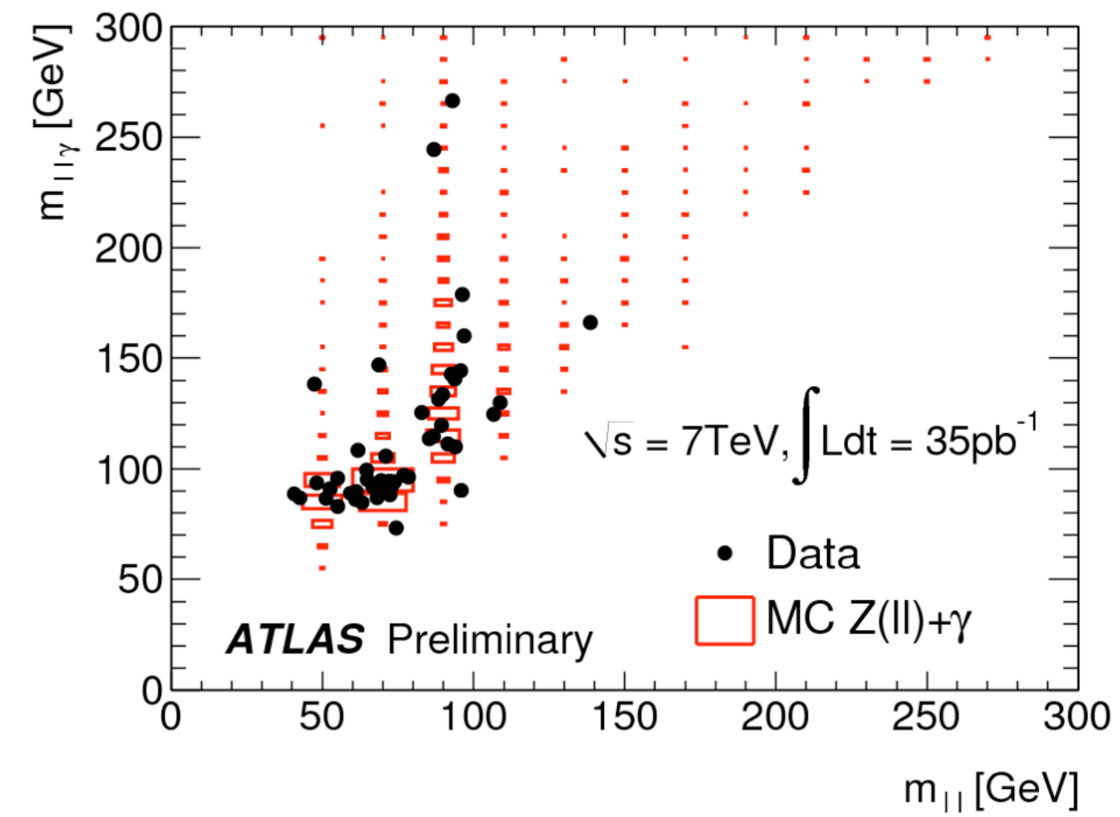
process	Observed Events	Z+jet background
eeγ	81	20.5 ± 1.7 ± 1.9
μμγ	90	27.3 ± 2.2 ± 2.3





- ATLAS

process	Observed Events	Total Background
eeγ	25	3.8 ± 3.8
μμγ	23	3.4 ± 3.4



- Difference in yields are mainly due to the different cuts on the photon pT (10 GeV in CMS and 15 GeV in ATLAS)

Wγ/Zγ Cross-section Measurements

- Both CMS and ATLAS measures the cross sections using a simple counting technique

$$\sigma = \frac{N_{data} - N_{bkg}}{A \cdot \epsilon \cdot \mathcal{L}},$$

  - Signal efficiencies are determined from MC, with appropriate data/MC scale factors derived from Z events to account for data/MC differences
  - Systematic effects such as uncertainties in trigger and e/μ/γ selections and luminosity σ etc. are accounted for

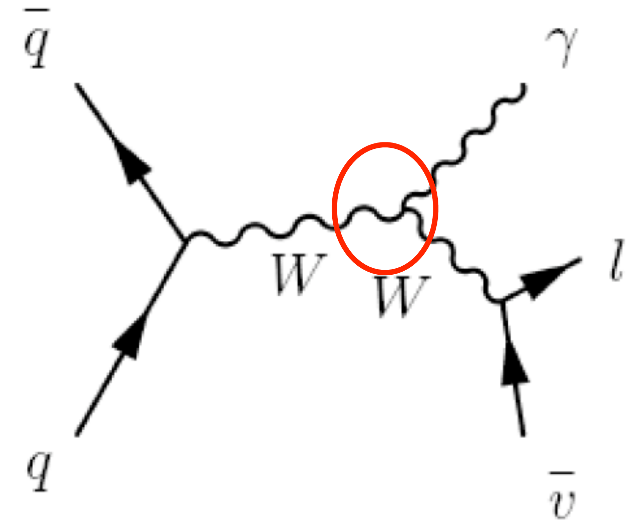
- Vγ cross-section are measured relative to pre-defined acceptance cuts
  - CMS: Et(γ)>10GeV, ΔR(l,γ)>0.7 and M(ll)>50GeV for Zγ
  - ATLAS: Et(γ)>10GeV, ΔR(l,γ)>0.5 and a generator level isolation criteria for the photon fragmentation component from parton ISR/FSR
  - NLO predicutions are from the Baur NLO program

	Wγ→eνγ (pb)	Wγ→μνγ (pb)	NLO prediction (pb)
CMS	56.7±6.9(stat)±5.1(syst)±6.2(lumi)	55.0±7.2(stat)±5.0(syst)±6.1(lumi)	49.4±3.8
ATLAS	73.9±10.5(stat)±14.6(syst)±8.1(lumi)	58.6±8.2(stat)±11.3(syst)±6.4	69.0±4.6
	Zγ→eeγ (pb)	**Zγ→μμγ (pb)**	**NLO prediction (pb)**
CMS	9.4±1.4(stat)±0.7(syst)±1.0(lumi)	9.2±1.4(stat)±0.6(syst)±1.0(lumi)	9.6±0.4
ATLAS	16.4±4.5(stat)±4.3(syst)±1.8(lumi)	10.6±2.6(stat)±2.5(syst)±1.2(lumi)	13.8±0.9

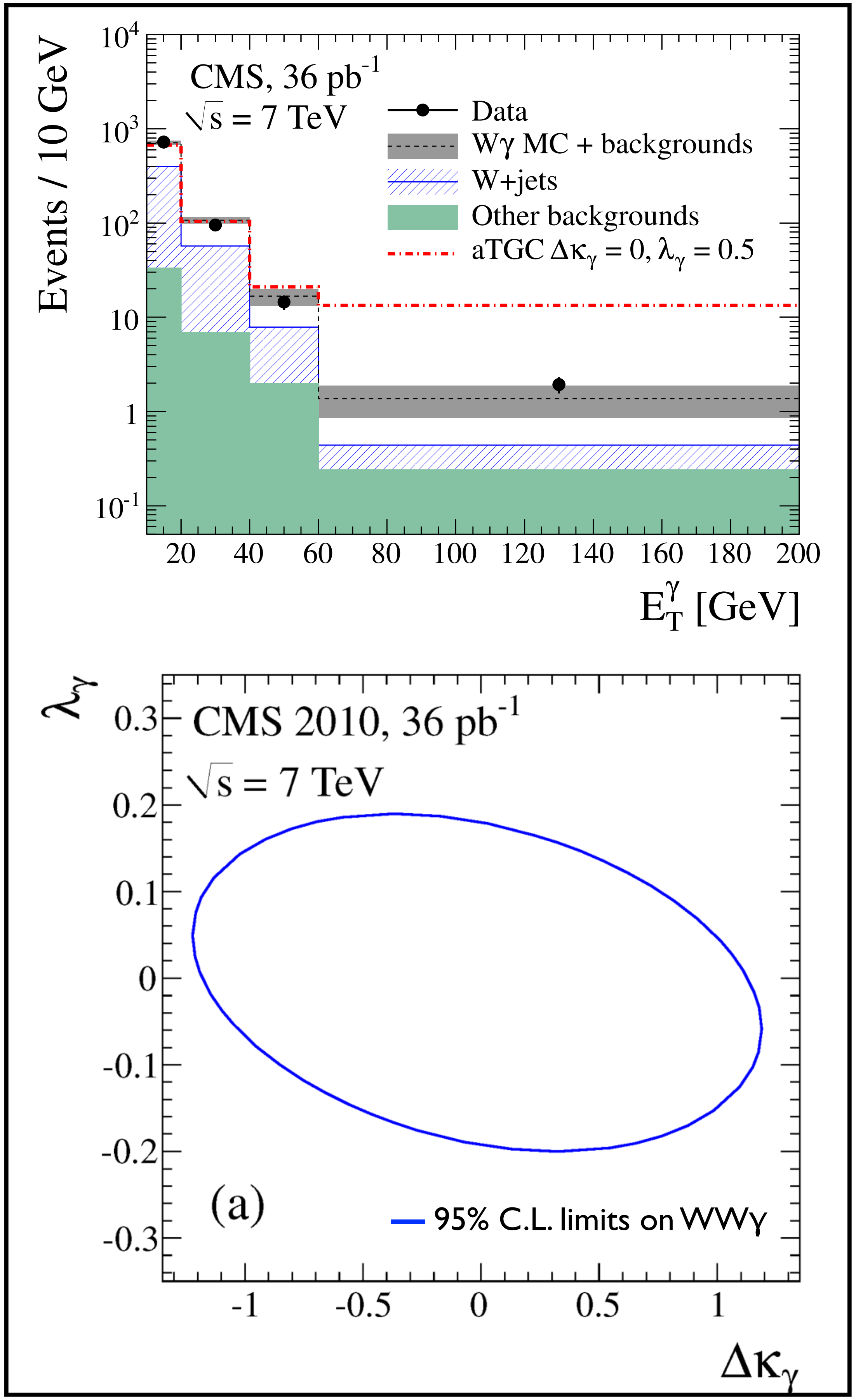
19

Limits on Anomalous TGCs (Wγ)

- NP involving WWγ vertex can lead to enhancement in Wγ rate and different leading photon Et distributions from SM

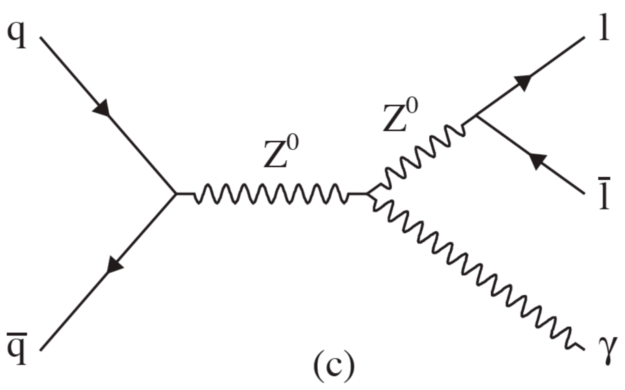


- To extract aTGCs, CMS fits the Wγ cross-section and leading γ Et distribution simultaneously
  - The aTGCs agree with SM expectations
  - 95% C.L. limits on aTGCs are set



Limits on Anomalous TGCs (Zγ)

- NP involving Zγγ or ZZγ vertexes can lead to enhancement in Zγ rate and different leading photon Et distributions from SM



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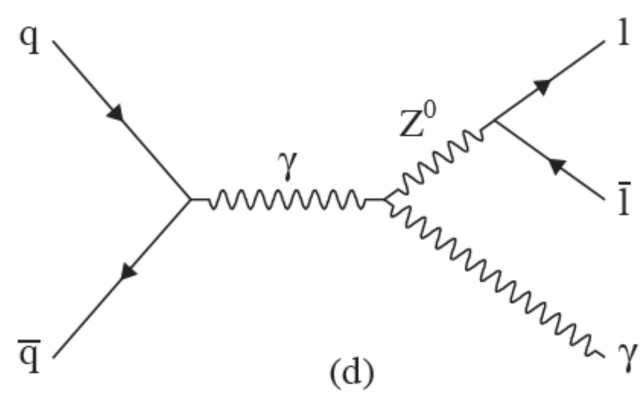

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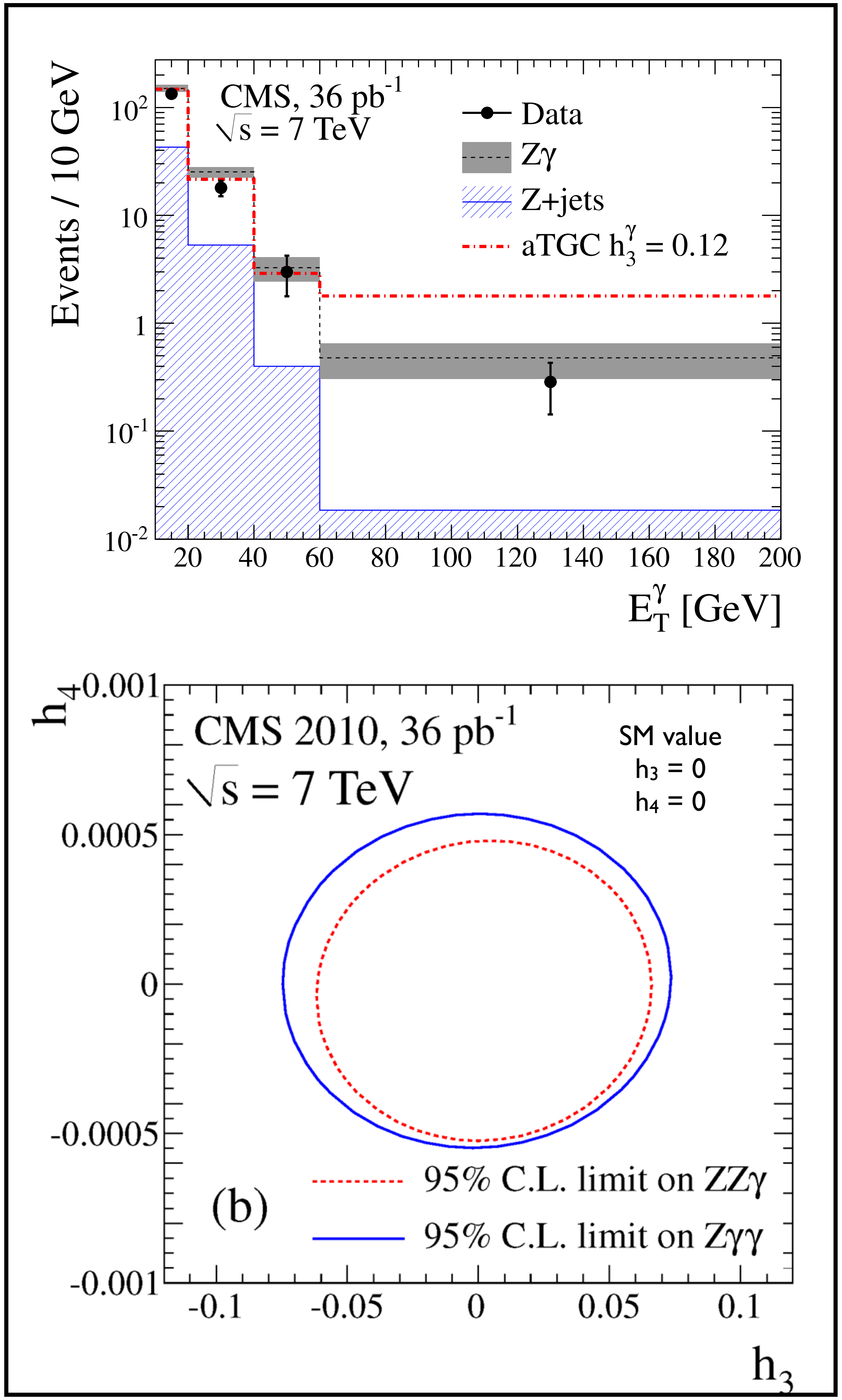

- To extract aTGCs, CMS fits the Zγ cross-section and leading γ Et distribution simultaneously
  - The aTGCs agree with SM expectations
  - 95% C.L. limits on aTGCs are set

Summary

- Both CMS and ATLAS measured diboson production cross-sections with 36/pb LHC data in pp collisions and the results all agree with the SM expectations
  - WW production cross-section (NLO prediction 43±2 pb)
    - CMS: 41.1 ± 15.3 (stat) ± 5.8 (syst) ± 4.5 (lumi) pb
    - ATLAS: 40 (+20, -16) (stat) ± 7 (syst) pb
  - Vγ production cross-section relative to a given acceptance (slide 19)

	$W\gamma\rightarrow e\nu\gamma$ (pb)	$W\gamma\rightarrow \mu\nu\gamma$ (pb)	NLO prediction (pb)
CMS	56.7±6.9(stat)±5.1(syst)±6.2(lumi)	55.0±7.2(stat)±5.0(syst)±6.1(lumi)	49.4±3.8
ATLAS	73.9±10.5(stat)±14.6(syst)±8.1(lumi)	58.6±8.2(stat)±11.3(syst)±6.4(lumi)	69.0±4.6
	$Z\gamma\rightarrow ee\gamma$ (pb)	$Z\gamma\rightarrow \mu\mu\gamma$ (pb)	NLO prediction (pb)
CMS	9.4±1.4(stat)±0.7(syst)±1.0(lumi)	9.2±1.4(stat)±0.6(syst)±1.0(lumi)	9.6±0.4
ATLAS	16.4±4.5(stat)±4.3(syst)±1.8(lumi)	10.6±2.6(stat)±2.5(syst)±1.2(lumi)	13.8±0.9

- CMS performed the first search on aTGCs in pp→WW/Wγ/Zγ decays at 7 TeV
  - The aTGCs measurements all agree with SM predictions and first limits on these couplings are set

Outlook

- The WW/Wγ/Zγ results presented here are just the beginning of the EWK precision measurements from LHC using only 36/pb
  - Currently, the statistical uncertainties dominate in all measurements
- With at least 1/fb data expected for 2011, diboson production measurements in LHC will enter the precision regime
  - Measure diboson production for more final states such as WZ and ZZ
  - Extend diboson production measurements to include lepton plus jets final states
  - Set better limits on or observe anomalous TGCs
- These diboson production measurements will provide the foundations for Higgs searches in many channels such $H \rightarrow WW$ and $H \rightarrow ZZ$

Supporting Material

24

Reference

- This talks focuses on discussing the basic experimental strategies and results in the di-boson production measurements
- For the details, please refer to the public documents listed here
  - CMS Public Documents
    - WW Production
      - Physics Letters B 699 (2011) 25–47 (http://arxiv.org/abs/1102.5429)
    - Wγ/Zγ Production
      - https://twiki.cern.ch/twiki/bin/view/CMSPublic/VGammaEWK10008
  - ATLAS Public Documents
    - WW Production
      - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-015/
    - Wγ/Zγ Production
      - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-013/