Diboson Results from CMS

Nate Woods

University of Wisconsin—Madison

On behalf of the CMS Collaboration

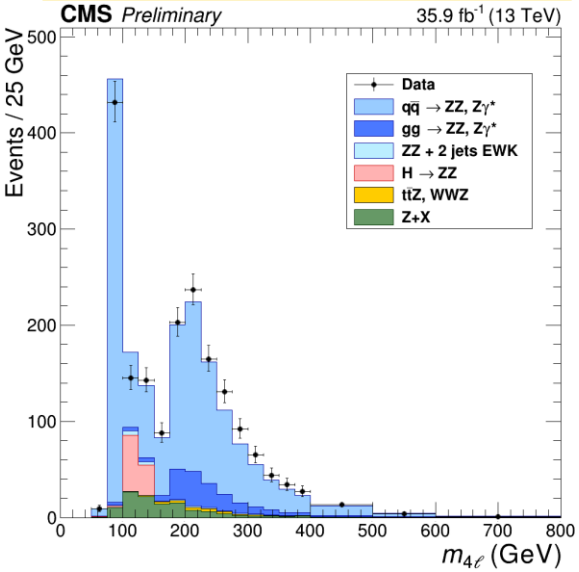
Motivation

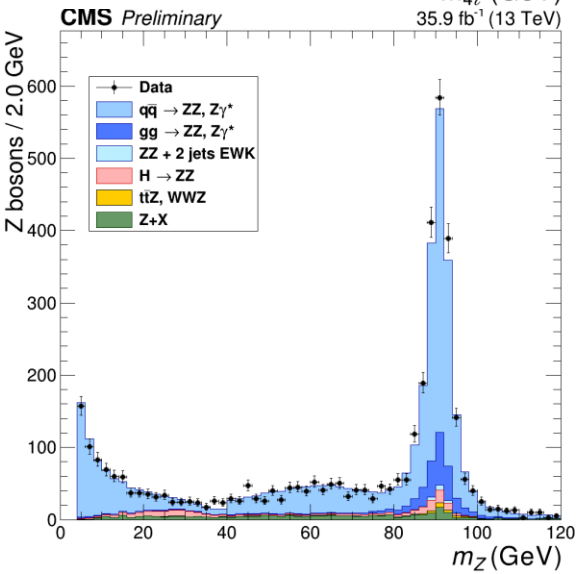
- **Multi-V (V ∈ Z, W$^{\pm}$, γ) final states are an important probe of the SM electroweak (EWK) sector**
  - Sensitive to deviations from SM
  - Insight into gauge boson (self-)couplings
    - Natural first search channels for anomalous couplings (aTGCs and aQGCs)
  - Is the Higgs we found enough to preserve unitarity?
- **Impressive theoretical progress: NNLO available for most states**
- **Run I analyses wrapping up**
  - Today: WZ→3$\ell\nu$ differential+aTGC, WV→$\ell\nu q\bar{q}$ aTGC
- **Enough data ⊗ time for some mature 13 TeV results**
  - Today: WZ→3$\ell\nu$ inclusive, ZZ→4ℓ differential+aTGC, Zγ→$\nu\bar{\nu}\gamma$

ZZ→4ℓ (2016 13 TeV)

CMS-PAS-SMP-16-017

- **Motivation**
  - Very clean, fully reconstructed final state
  - Sensitive to higher-order QCD corrections
  - Good channel for neutral aTGC search
  - Background to Higgs and searches
- **Inclusive and differential cross sections and aTGC limits with full 13 TeV dataset**
- **Selections**
  - Lepton ID, isolation optimized for efficiency
  - Full spectrum: $m_{Z_1}(m_{Z_2})$ in 40(4)-120 GeV
    - Z→4ℓ: $m_{4\ell}$ in 80-100 GeV
  - On-shell: Both Z masses in 60-120 GeV

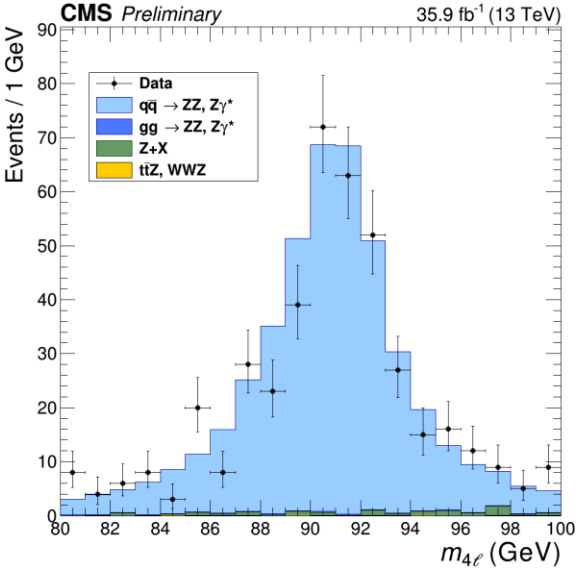


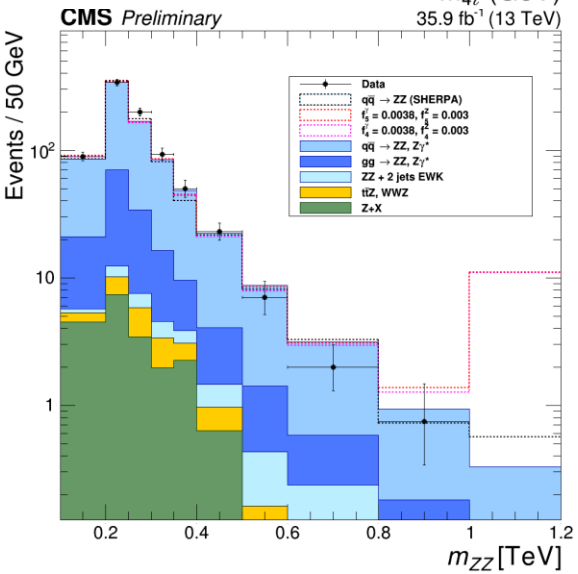


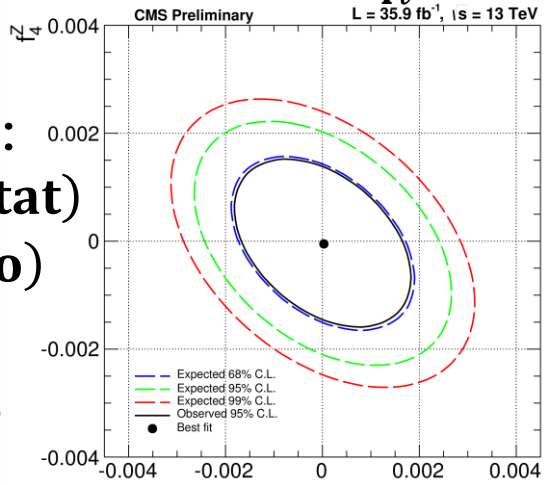
$ZZ \to 4\ell$ and $Z \to 4\ell$

CMS-PAS-SMP-16-017

- **Backgrounds small, Z+jets and $t\bar{t}$ from data**
  - $Z+\ell'\ell'$ control regions with one or both ℓ' failing ID or isolation
  - Derive per-lepton transfer factors from $Z+\ell_{fake}$ sample
- **VVV, $t\bar{t}V$ and Higgs backgrounds from MC**
- **World-best neutral aTGC limits from $m_{4\ell}$ fit with SHERPA samples**
- **$Z \to 4$ branching fraction:**
  $\mathfrak{B}(4\ell) = 4.74 \pm 0.16(\text{stat}) \,^{+0.18}_{-0.17}(\text{syst}) \pm 0.08\,(\text{theo}) \pm 0.12\,(\text{lumi}) \times 10^{-6}$
  - MG5_aMC: 4.6×10^{-6}







$ZZ \rightarrow 4\ell$

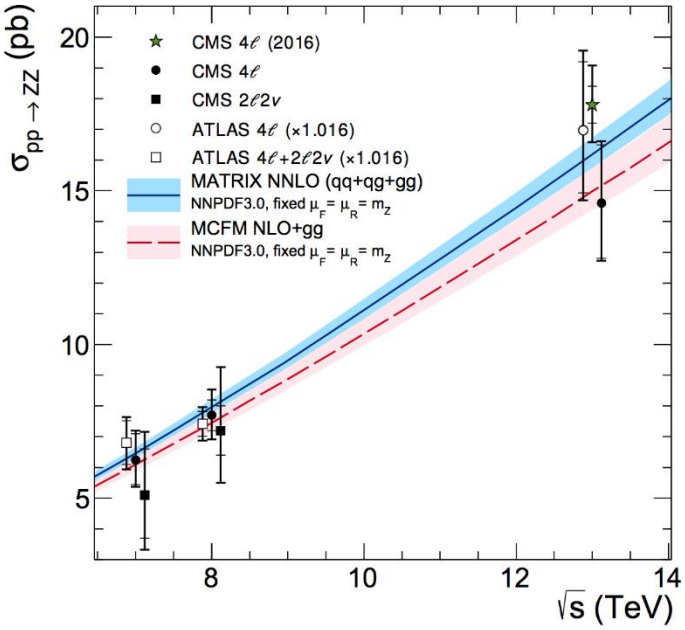
CMS-PAS-SMP-16-017

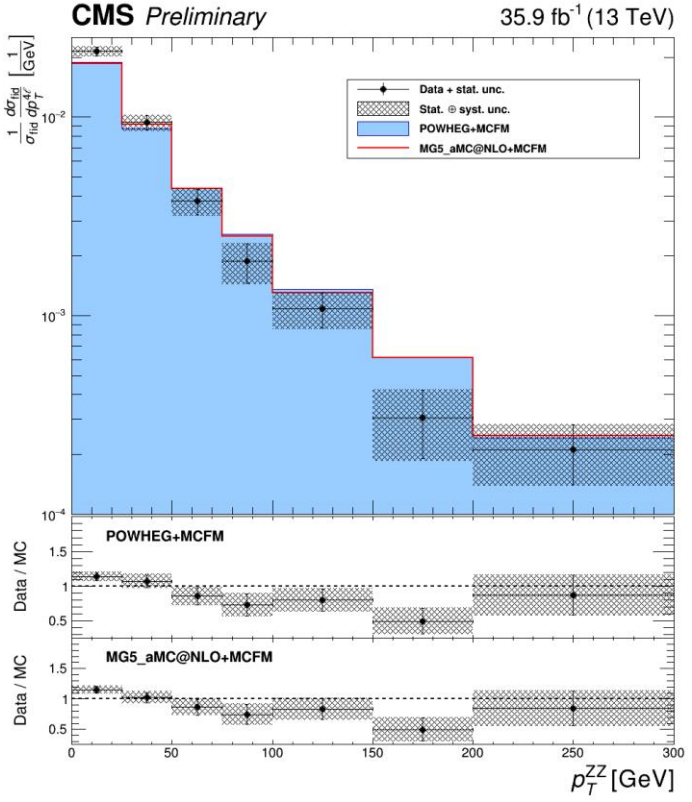
- **Total inclusive cross section (m_Z 60-120 GeV):**

$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 17.8 \pm 0.6\,(\mathrm{stat})^{+0.7}_{-0.6}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.5\,(\mathrm{lumi})\,\mathrm{pb}$$

  - NNLO: $16.2^{+0.6}_{-0.4}$ pb [arXiv:1507.06257]
  - Compatible with ATLAS

- **Largest systematic is lepton efficiency**
- **Differential cross sections unfolded with D'Agostini method (4 iterations)**

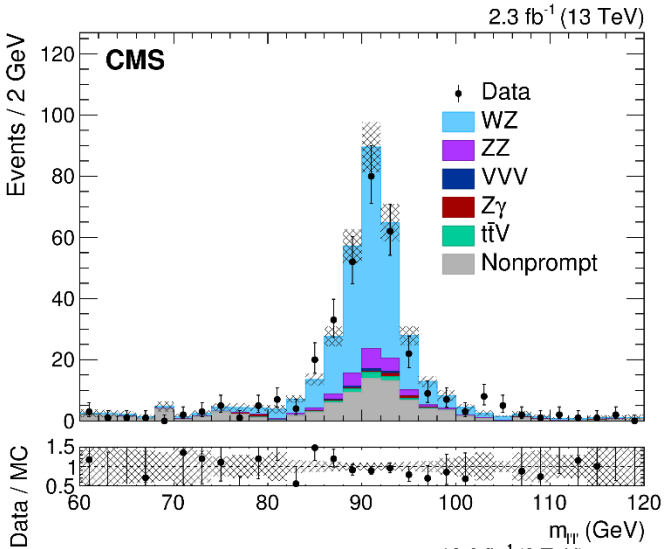


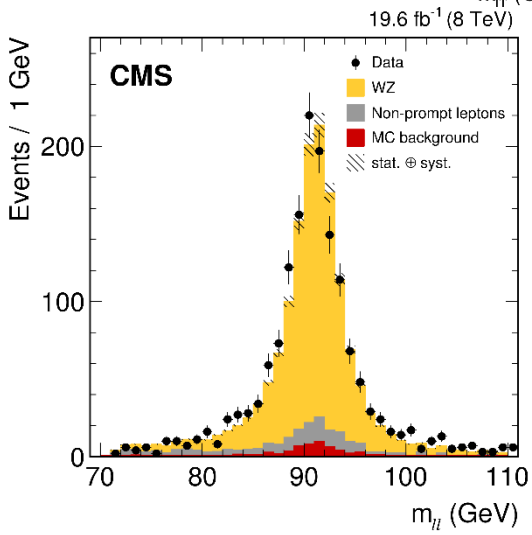


WZ→3ℓν (7+8 TeV, 2015 13 TeV)

CMS-SMP-16-002 (PLB)
CMS-SMP-14-014 (EPJC)

- **Motivation**
  - Clean leptonic final state
  - Very sensitive to higher-order QCD corrections
  - Sensitive to charged aGC
  - Background to searches (e.g. $H^{\pm}$)
- **Differential cross sections+aTGC at 8TeV, inclusive cross section at 13 TeV**
- **Selections**
  - Three good, isolated leptons + E_{T}^{miss}
  - $76 < m_{\mathrm{Z}} < 106$ GeV, $m_{3\ell} > 100$ GeV
  - Veto on extra lepton or b jet (13 TeV)

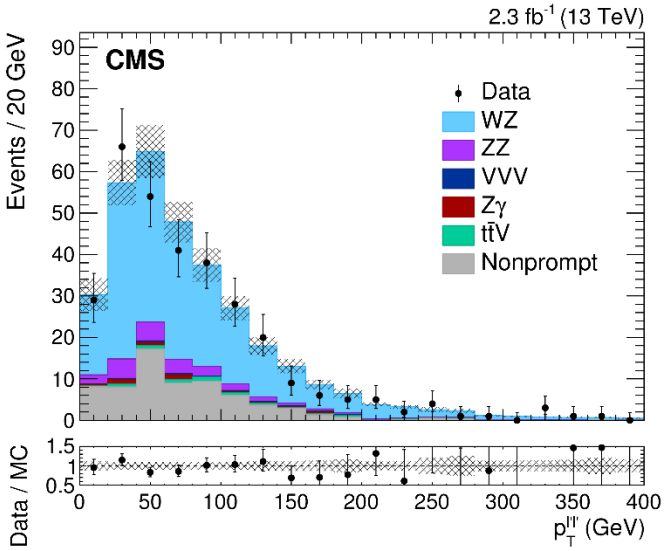


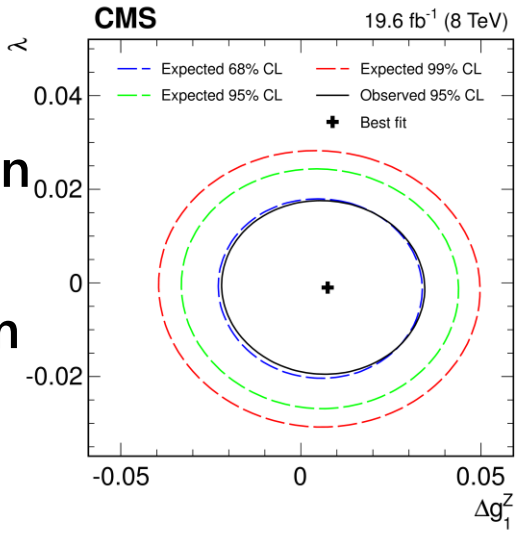


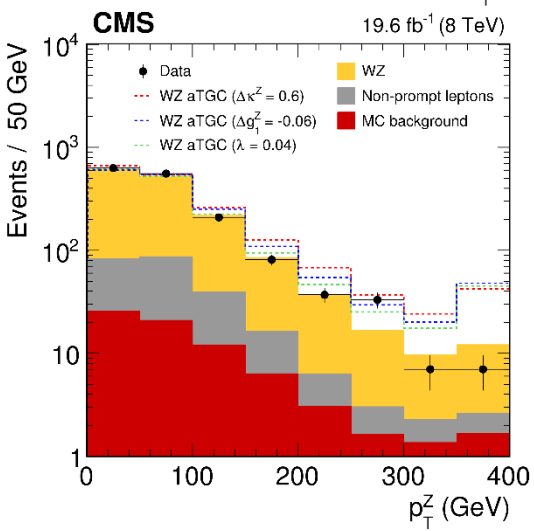
WZ→3ℓν

CMS-SMP-16-002 (PLB)
CMS-SMP-14-014 (EPJC)

- **Background**
  - Zγ, ZZ, VVV, V+top from MC
  - Nonprompt (largest) from data control region like signal except with 1, 2, or 3 leptons failing ID or isolation
    - Calculate per-lepton transfer factors in dijet events
- **Largest systematics are nonprompt background estimation and E_T^{miss}**
- **8 TeV aTGC limits from fit to Z p_T**







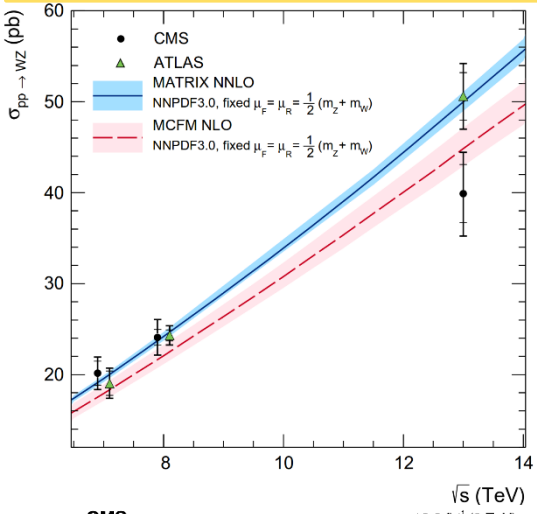
WZ→3ℓν

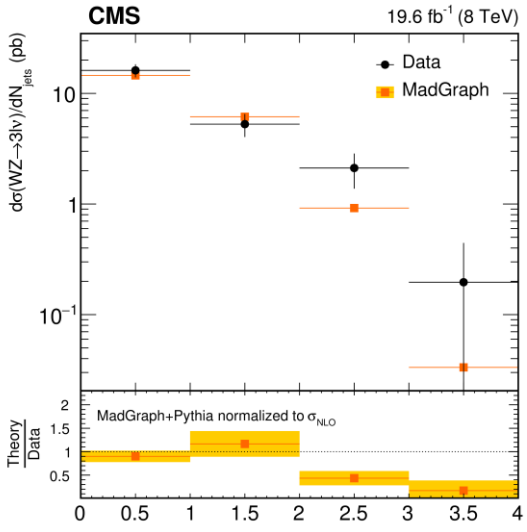
CMS-SMP-16-002 (PLB)
CMS-SMP-14-014 (EPJC)

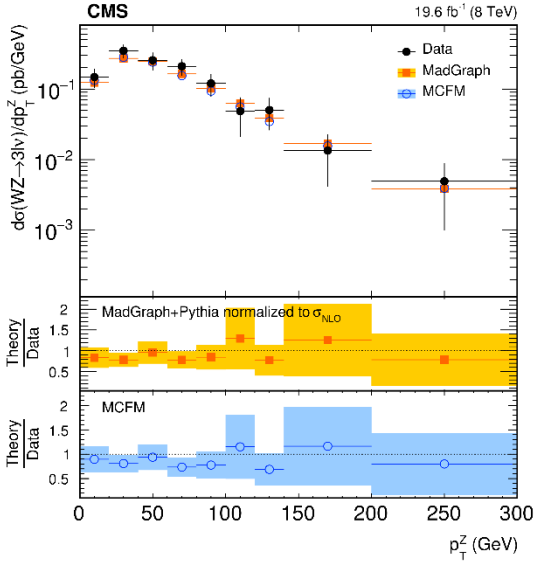
- **13 TeV total inclusive cross section:**

$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 39.9 \pm 3.2\,(\mathrm{stat})^{+2.9}_{-3.1}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 1.3\,(\mathrm{lumi})\,\mathrm{pb}.$$

  - Theory: NLO ($46.1^{+4.9\%}_{-3.9\%}$), NNLO ($51.1^{+2.2\%}_{-2.0\%}$) [arXiv:1604.08576]
  - Difference with ATLAS statistically significant
- **8 TeV differential cross sections**
  - D'Agostini unfolding (5 iterations)
  - Compare with LO MadGraph and fixed-order NLO MCFM



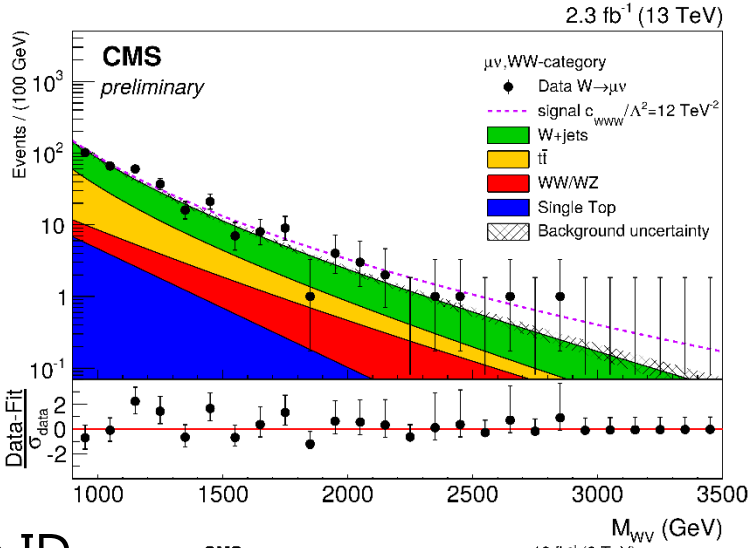


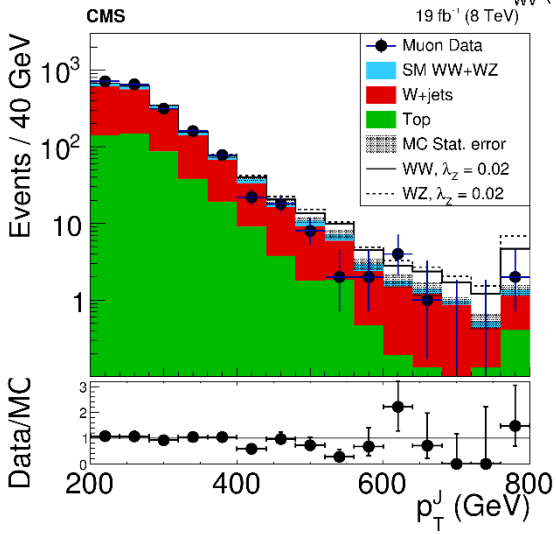


WV→ℓνqq̄ (8TeV+ 2015 13 TeV)

CMS-PAS-SMP-16-012
CMS-SMP-13-008 (PLB)

- **Motivation**
  - Large V(W/Z)→ qq̄ branching fraction
  - Similar to high-mass resonance search
- **V boosted to BSM-sensitive "fat" jet**
- **Selections at 13 (8) TeV**
  - Standard leptonic W, $p_T > 200$ GeV
  - V_{had} an AK8 (CA8) jet with substructure ID
    - N-subjettiness $\tau_2/\tau_1 <$ 0.6 (0.55)
    - $40 < m_{pruned} <$ 150 (140), $p_T > 200$ GeV
  - Veto additional jets (tighter cut for b jets)
  - $\Delta R(\ell, j) > \pi/2$, $\Delta\phi(E_T^{miss}, j) > 2.0$, $\Delta\phi(W_{lep}, j) > 2.0$

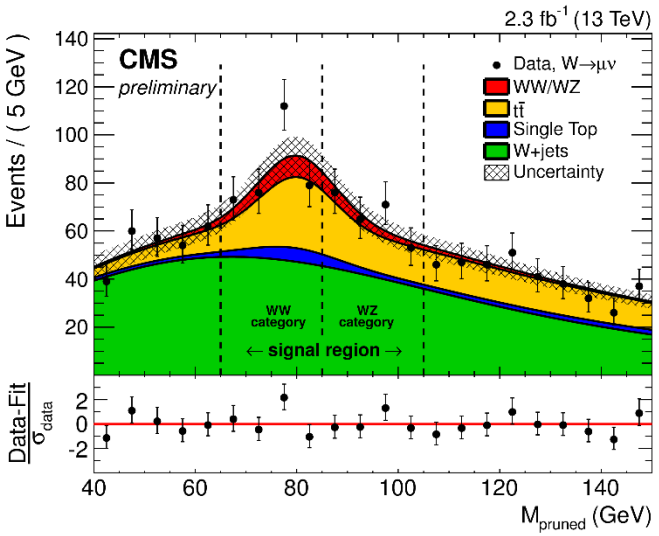


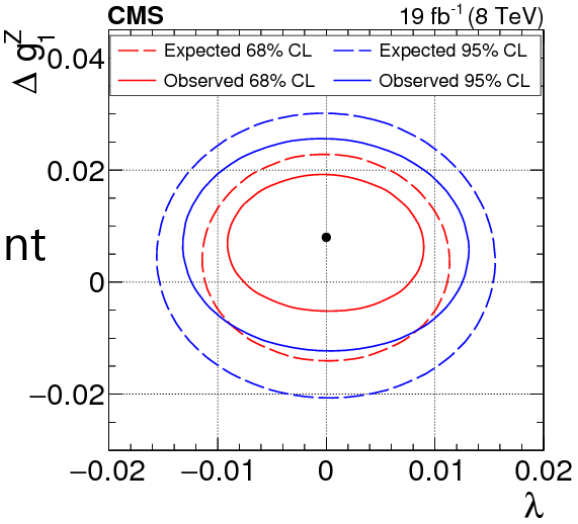


WV→ℓνqq̄

CMS-PAS-SMP-16-012
CMS-SMP-13-008 (PLB)

- **Backgrounds: W+jets, tt̄, single-t**
  - Shapes from analytical functions fit to MC
  - Normalizations from m_{pruned} distributions
- **Largest systematic (12%) is V-tag efficiency**
- **Method at 13 (8) TeV**
  - aTGC signal from MG5_aMC via ME reweighting (MCFM without reweighting)
  - Extract yields and significance with simultaneous fit to $m_{WV} > 900$ GeV $\left(p_T^j\right)$
    - Full ν momentum found with W mass constraint
- **Tighter WWZ aC limits than leptonic channels**
  - 8 TeV $\lambda_{z/\gamma}$ and Δg_1^Z limits tightest to date

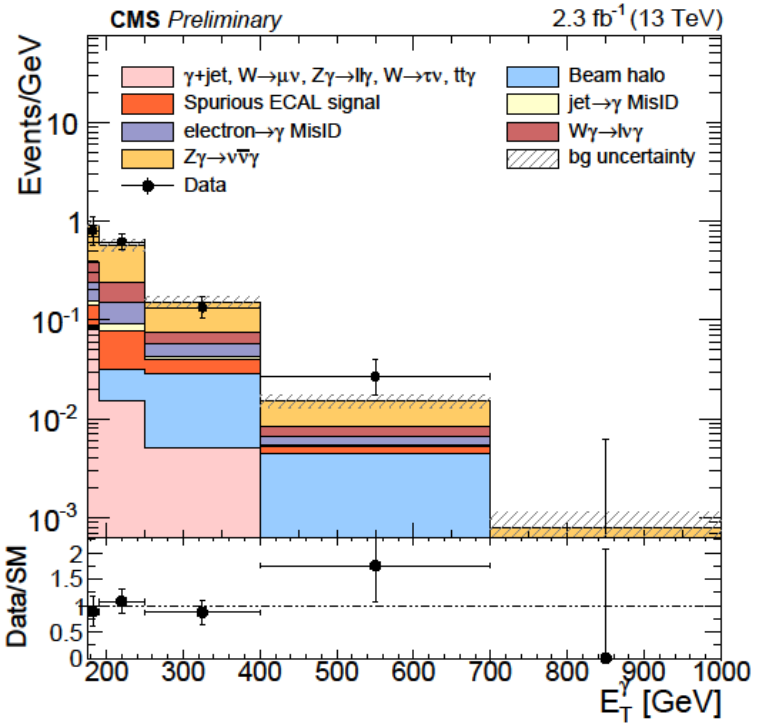




$Z\gamma \rightarrow \nu\bar{\nu}\gamma$ (2015 13 TeV)

CMS-PAS-SMP-16-004

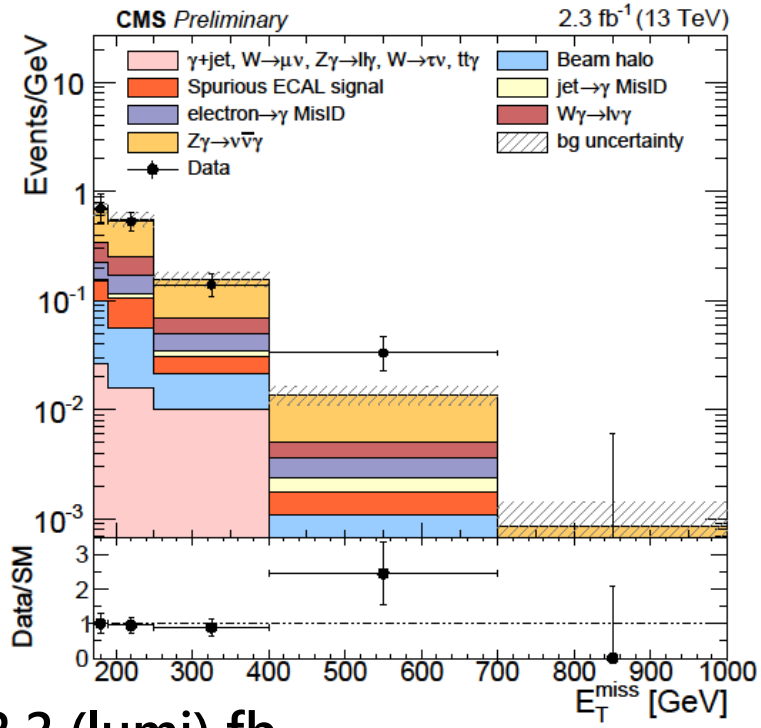
- **Motivation**
  - Tree-level SM production only through ISR
    - Sensitive to anomalous $Z\gamma$ couplings
  - Background to monophoton search
- **Selection**
  - Tight photon ID and isolation
  - $E_{\mathrm{T}}^{\gamma} > 175$ GeV, $|\eta^{\gamma}| < 1.44$,
  - $E_{\mathrm{T}}^{miss} > 170$ GeV
  - Tight lepton veto, $\Delta\phi\left(\gamma, \vec{E}_{\mathrm{T}}^{miss}\right) > 2$, $\Delta\phi\left(\mathrm{j}, \vec{E}_{\mathrm{T}}^{\gamma}\right) < 0.5$
  - ECAL timing cut and shape requirement to reject halo and detector effects



$Z\gamma \rightarrow \nu\bar{\nu}\gamma$

CMS-PAS-SMP-16-004

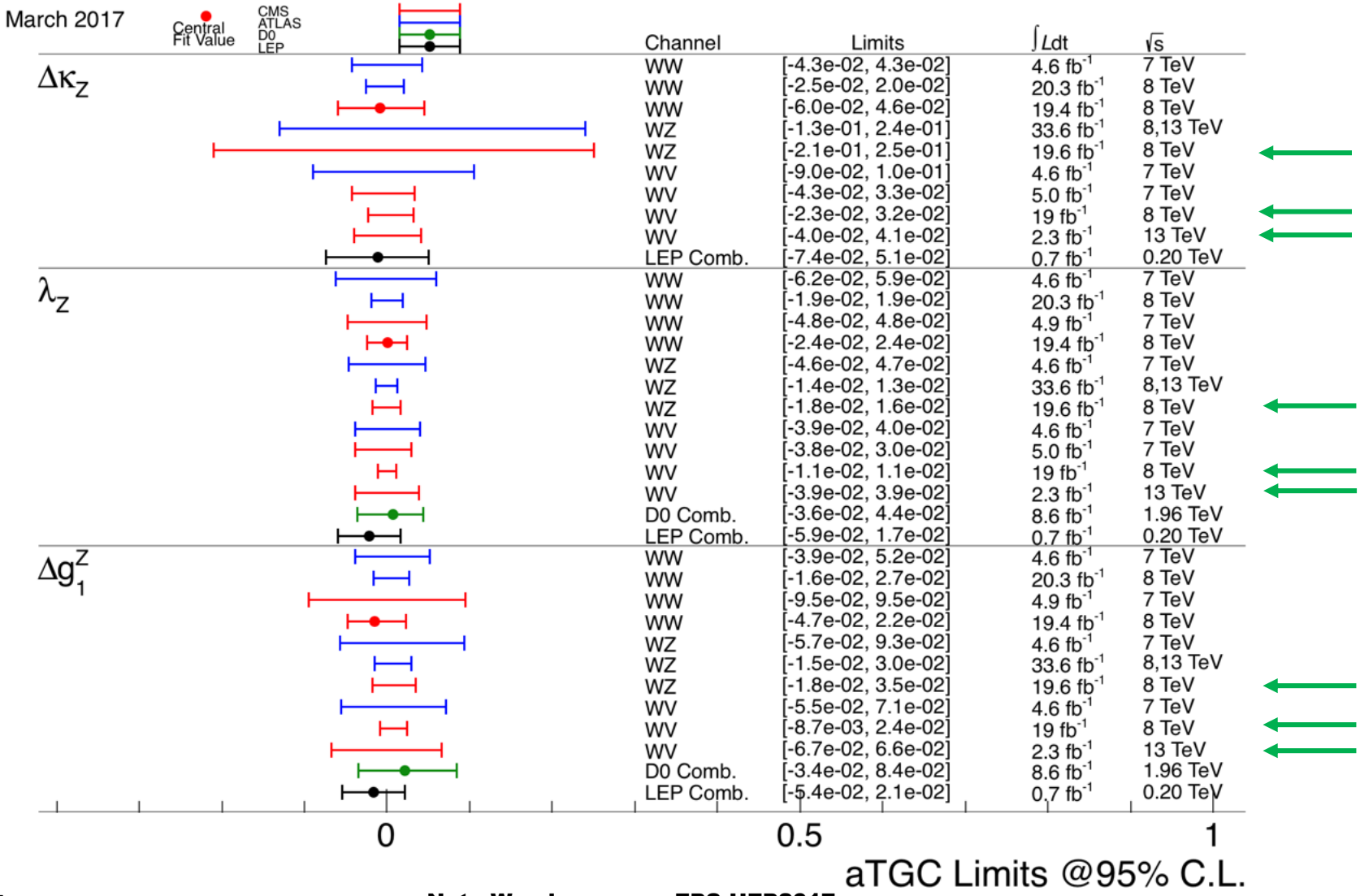
- **Signal MC: LO MadGraph5_aMC@NLO**
- **Background estimation**
  - $W\gamma \rightarrow \ell\nu\gamma$ and small others: MC
  - $W \rightarrow e\nu$: CR with inverted pixel veto
    - Transfer function from pixel efficiency
  - Cosmics+ECAL spikes: ECAL timing fit
- **Largest systematics: energy scales, background estimation, EWK theory**



- $\sigma_{\text{fid}} = 66.5 \pm 13.6\ (\text{stat}) \pm 14.3\ (\text{syst}) \pm 2.2\ (\text{lumi})$ fb
  - $E_{\text{T}}^{\gamma} > 175$ GeV, $|\eta^{\gamma}| < 1.44$
  - NNLO theory: 65.5 ± 3.3 fb [arXiv:1504.01330]

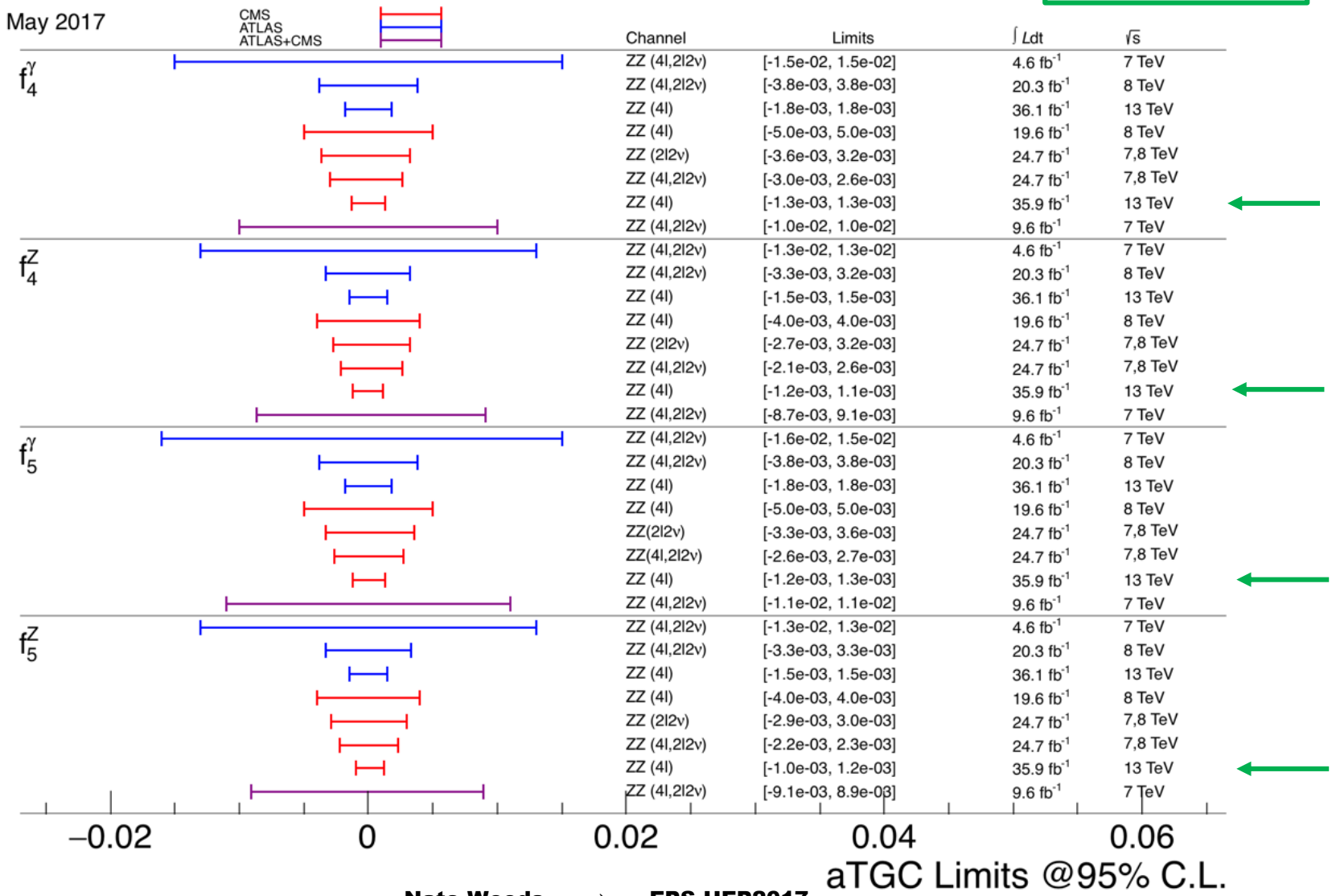
State of the Field: WWZ aTGC

Shown today



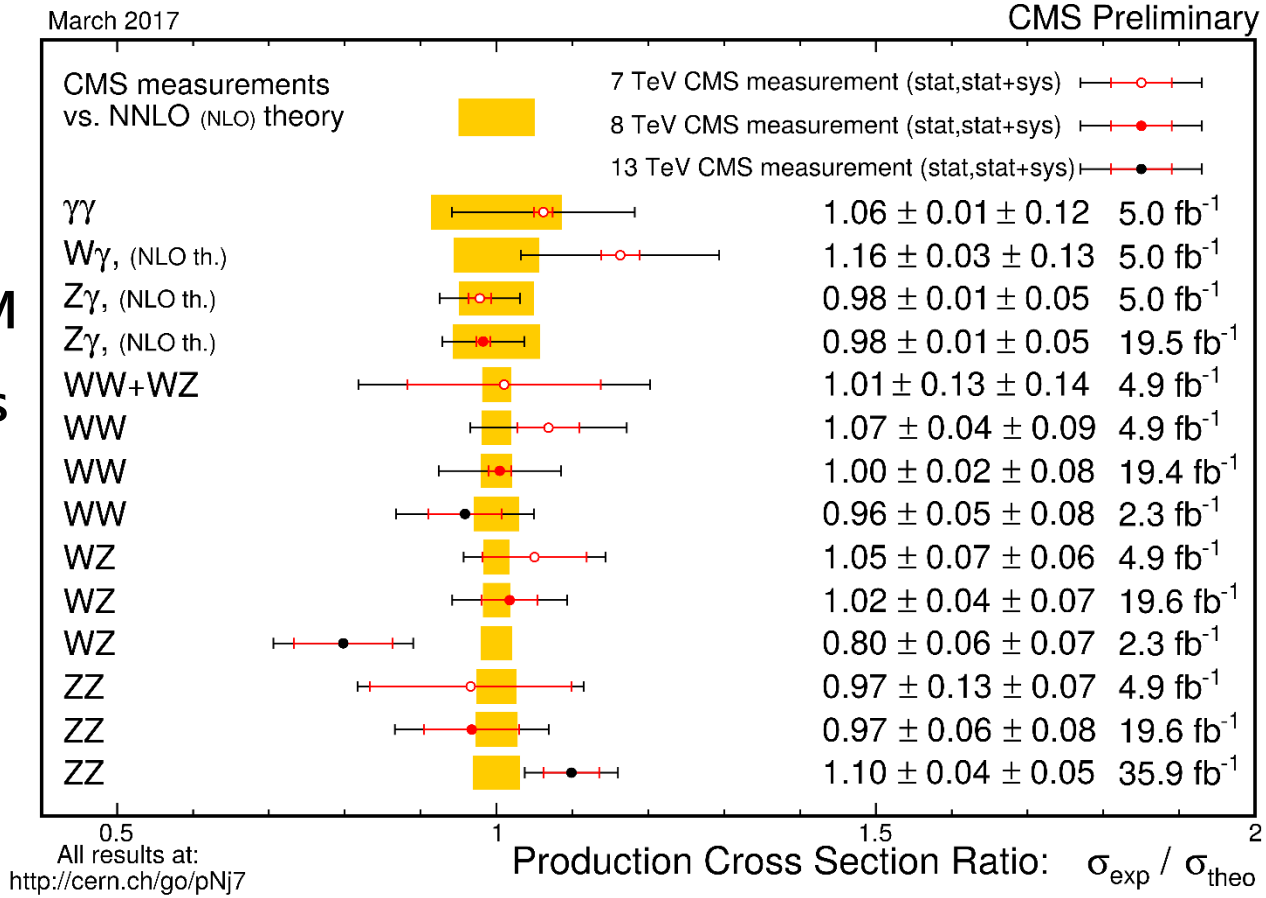
State of the Field: ZZγ/ZZZ aTGC

Shown today



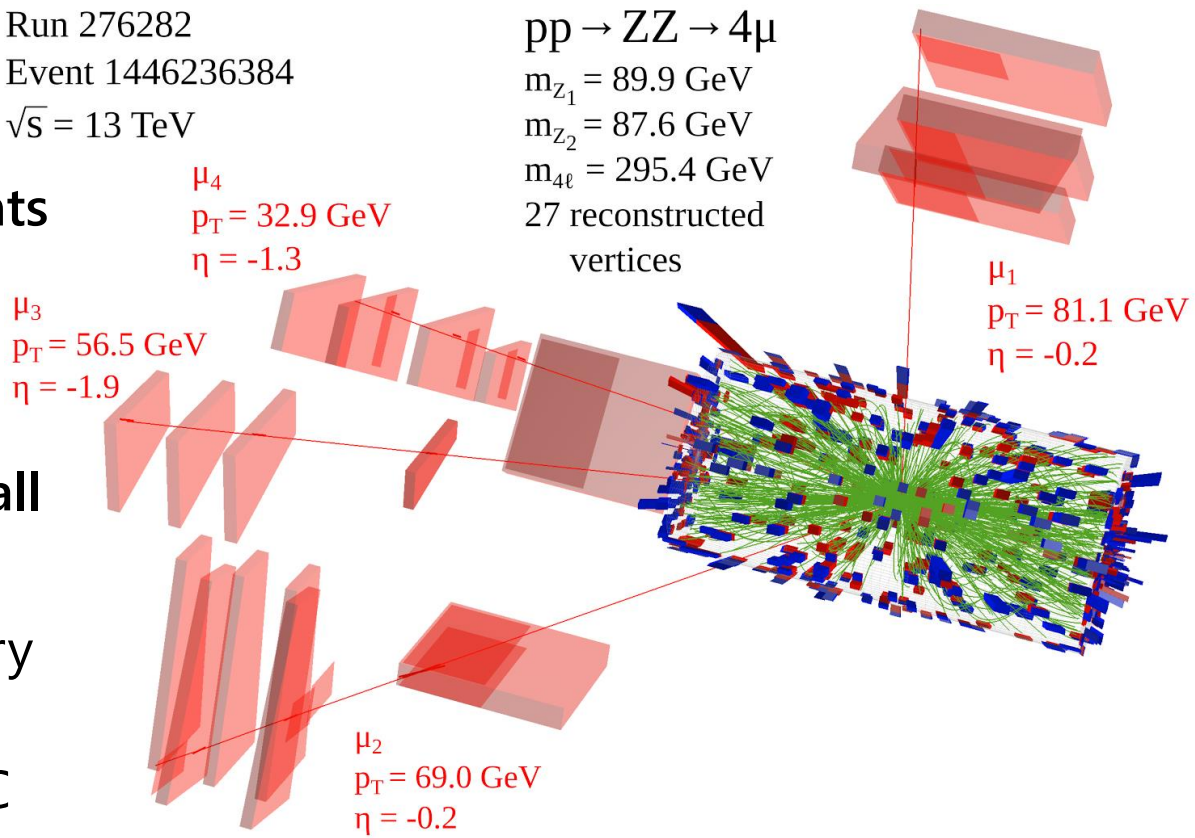
State of CMS Measurements: Diboson Cross Sections

- NNLO calculations now the default
- Overall good agreement with SM
- Many uncertainties are or will soon be systematics dominated
  - Challenges for experimentalists and theorists
- The "precision measurements" dream will soon be reality



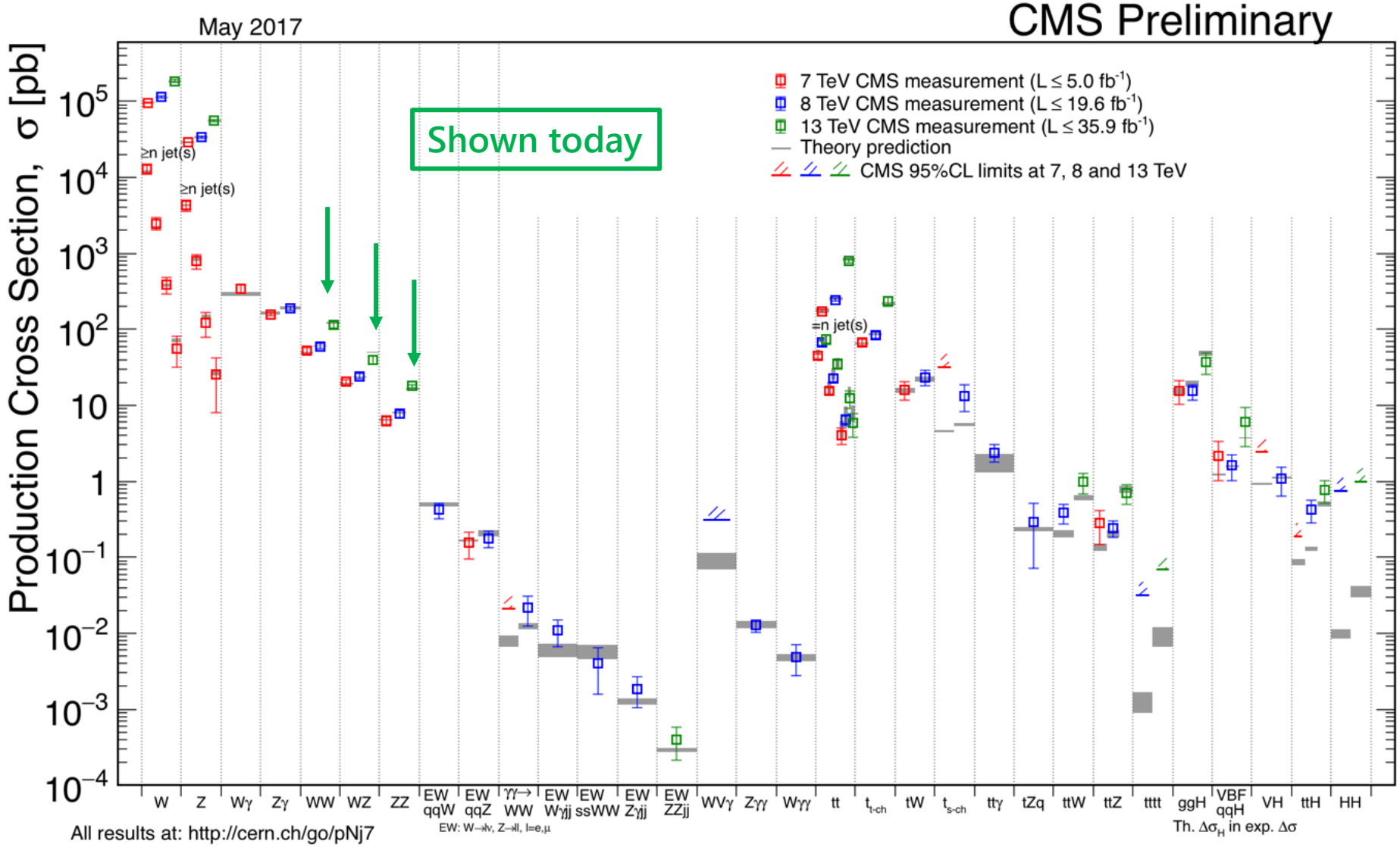
Conclusions

- **Diboson measurements are important for SM and BSM physics**
- **CMS results in $Z\gamma$, WV, WZ, and ZZ overall consistent with SM**
  - Confirm latest theory calculations
  - Place limits on aTGC parameters
- **Large, mature datasets allow detailed measurements even for low cross section processes**



Backup

The Whole SM


May 2017
CMS Preliminary
Production Cross Section, σ [pb]
Shown today
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 35.9 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW Wγjj
EW ssWW
EW Zγjj
EW ZZjj
WVγ
Zγγ
Wγγ
tt
t t-ch
tW
t s-ch
ttγ
tZq
ttW
ttZ
tttt
ggH
VBF qqH
VH
ttH
HH
All results at: http://cern.ch/go/pNj7
EW: W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ

$Z\gamma$ Yields and Systematics

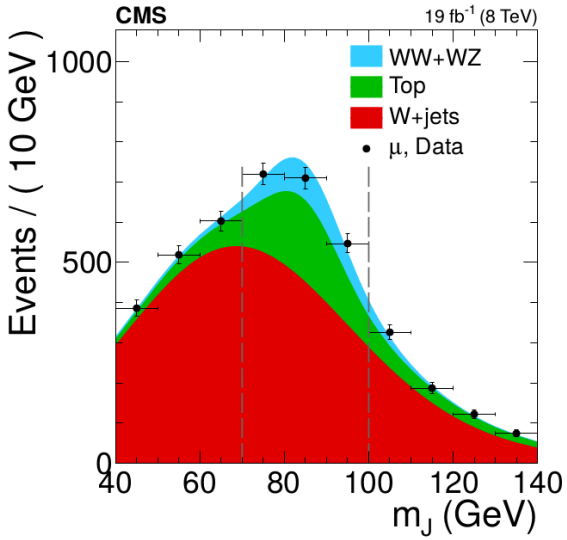
- **Systematics**

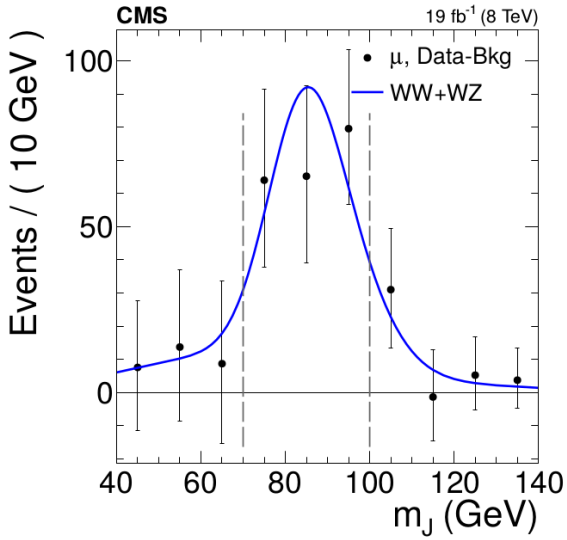
Sources	Effect on cross section (%)
Luminosity	3.3
PDF and QCD scale	6.8
Electroweak corrections	11.3
Jets misidentified as γ	1.3
Electron misidentified as γ	3.6
Beam halo	11.0
Spurious ECAL signals	5.0
$E_{\mathrm{T}}^{\mathrm{miss}}$, photon energy scales, pileup	7.1
Data/sim. scale factors	9.7

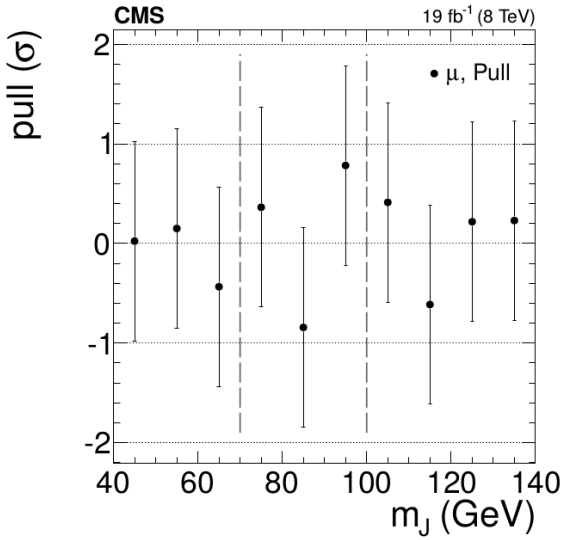
- **Yields**

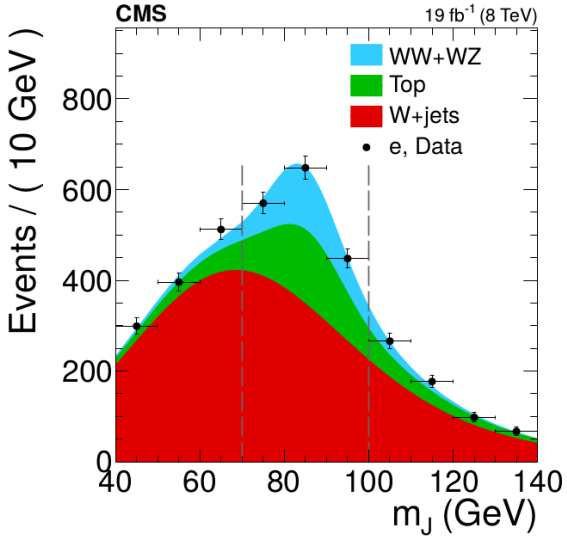
Process	Estimate
$Z\gamma \to \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \to \ell\nu\gamma$	10.60 ± 1.58
$W \to e\nu$	7.80 ± 1.78
Jet $\to \gamma$ misidentified	1.75 ± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77

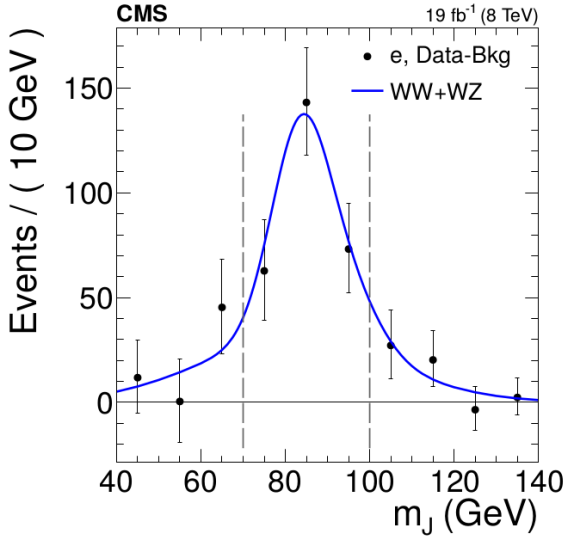
More WV Plots

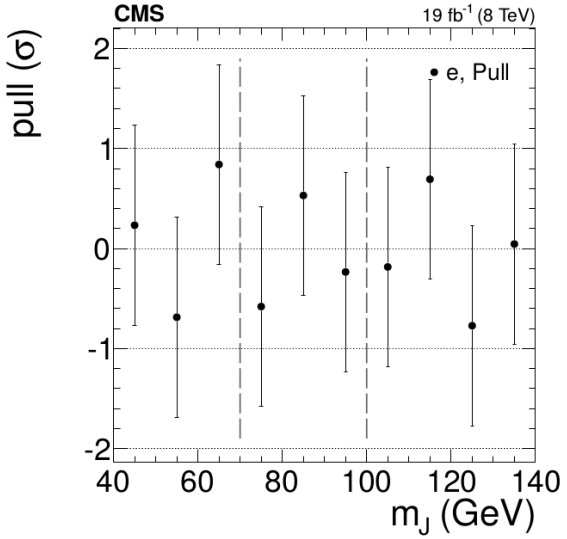




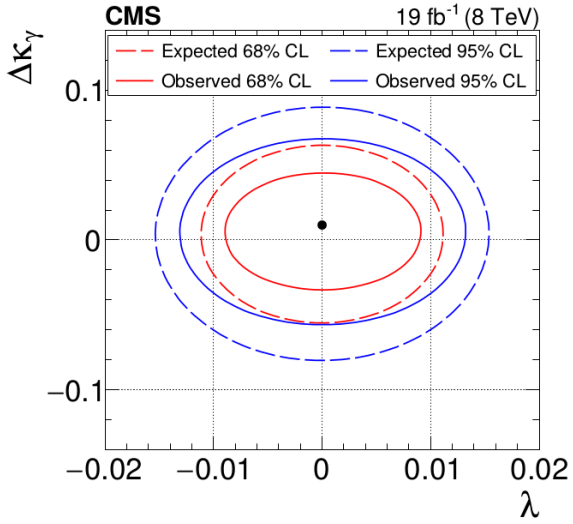


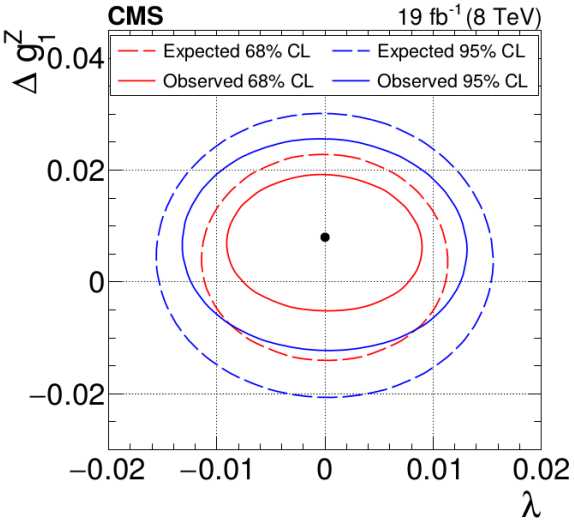


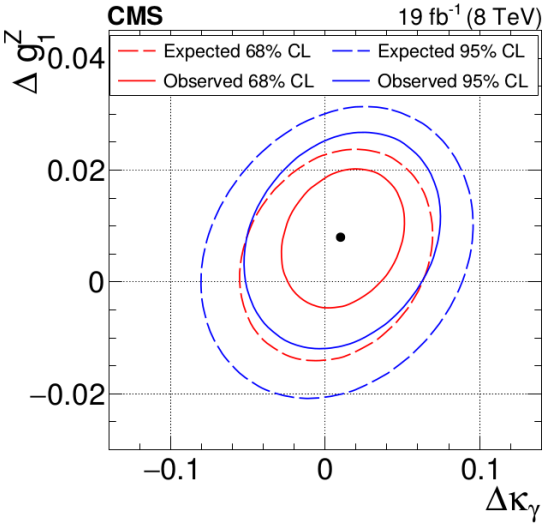


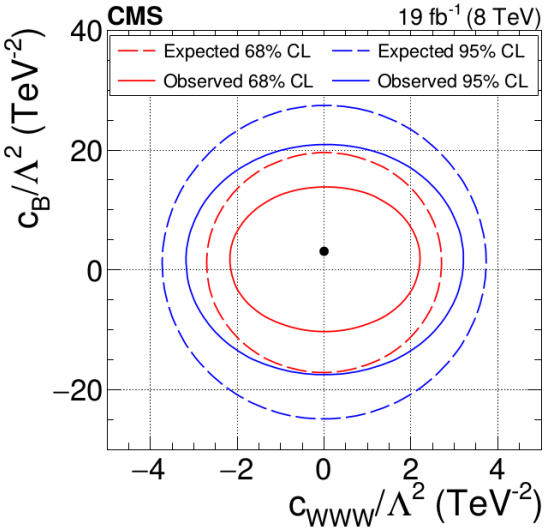


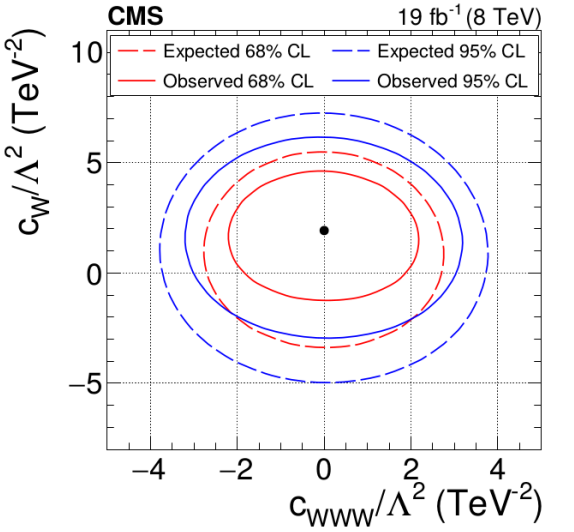
All WV Limits (8 TeV)

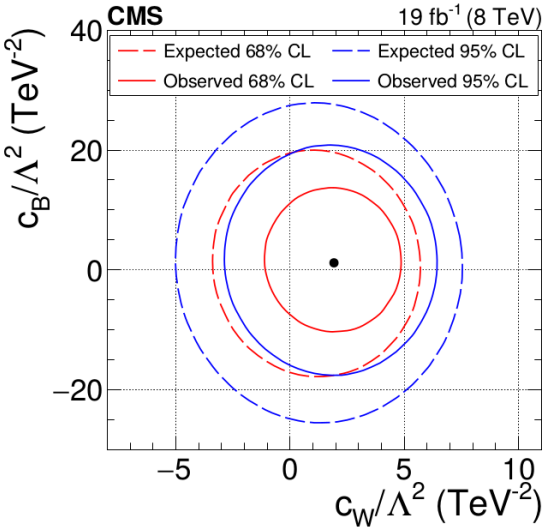




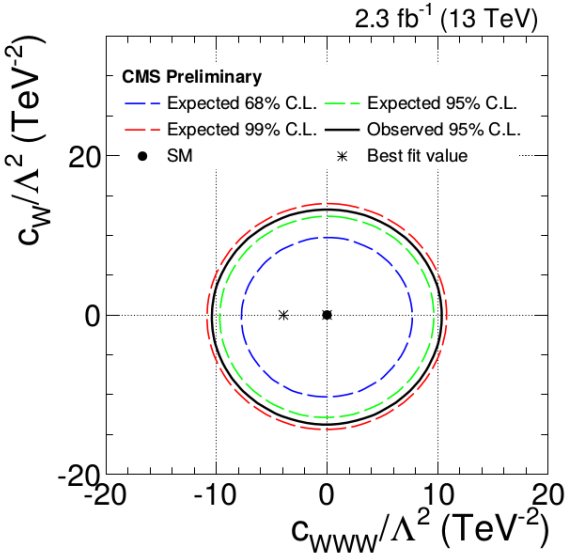


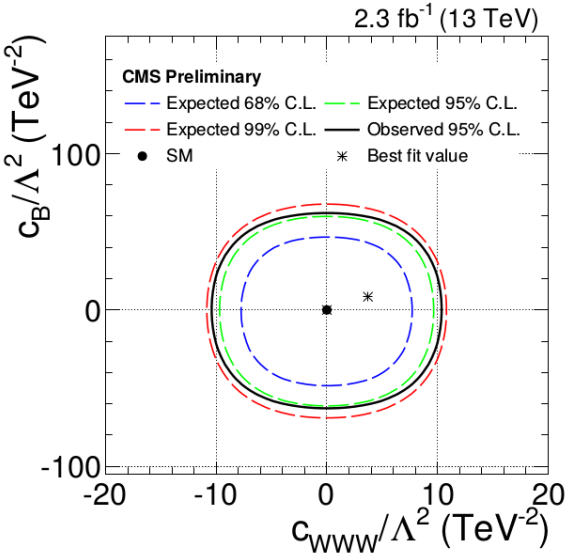


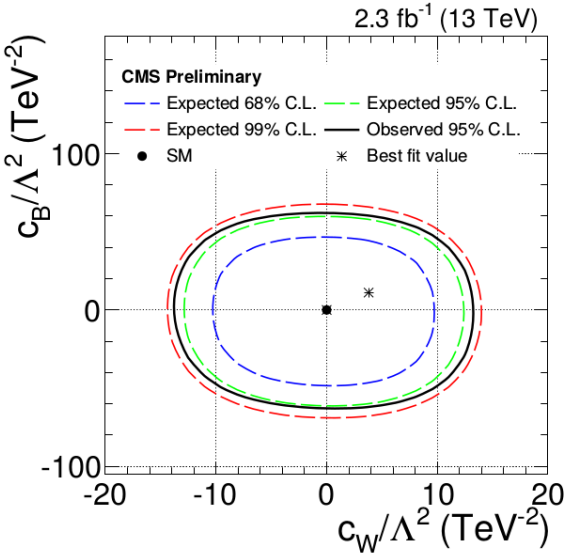




All WV Limits (13 TeV)







WZ Yields and Systematics (8TeV)

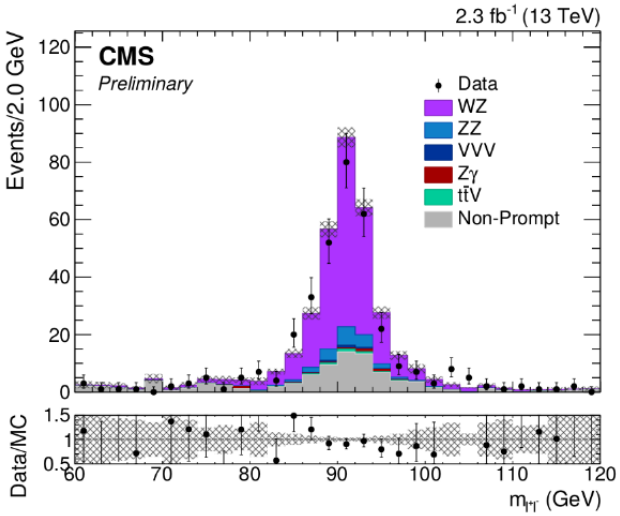
Sample	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Total
$\sqrt{s} = 7$ TeV; $\mathcal{L} = 4.9$ fb^{-1}					
Nonprompt leptons	2.2 ± 2.1	$1.5^{+4.8}_{-1.5}$	$2.4^{+5.1}_{-2.4}$	$1.8^{+7.5}_{-1.8}$	$7.9^{+13.0}_{-5.0}$
ZZ	2.0 ± 0.3	3.5 ± 0.5	2.7 ± 0.4	5.1 ± 0.7	13.3 ± 1.9
Zγ	0	0	0.5 ± 0.5	0	0.5 ± 0.5
VVV	1.6 ± 0.8	2.0 ± 1.0	2.4 ± 1.2	3.0 ± 1.5	9.0 ± 4.5
Total background (N_{bkg})	3.8 ± 2.3	$6.0 \pm ^{+4.9}_{-1.9}$	$8.0^{+5.1}_{-2.4}$	$9.9^{+7.7}_{-2.4}$	$30.7^{+13.9}_{-7.0}$
WZ	44.7 ± 0.5	49.8 ± 0.5	56.0 ± 0.5	73.8 ± 0.6	224.3 ± 1.1
Total expected	50.5 ± 2.3	$56.8^{+5.0}_{-1.9}$	$64.0^{+5.3}_{-2.8}$	$83.7^{+7.7}_{-2.5}$	$255^{+14.0}_{-7.0}$
Data (N_{obs})	64	62	70	97	293
$\sqrt{s} = 8$ TeV; $\mathcal{L} = 19.6$ fb^{-1}					
Nonprompt leptons	18.4 ± 12.7	32.0 ± 21.0	54.4 ± 33.0	62.4 ± 37.7	167.1 ± 55.8
ZZ	2.1 ± 0.3	2.4 ± 0.4	3.2 ± 0.5	4.7 ± 0.7	12.3 ± 1.0
Zγ	3.4 ± 1.3	0.4 ± 0.4	5.2 ± 1.8	0	9.1 ± 2.2
Wγ^*	0	0	0	2.8 ± 1.0	2.8 ± 1.0
VVV	6.7 ± 2.2	8.7 ± 2.8	11.6 ± 3.8	14.8 ± 5.1	41.9 ± 7.3
Total background (N_{bkg})	30.6 ± 13.0	43.5 ± 21.2	74.4 ± 33.3	84.7 ± 38.1	233.2 ± 56.3
WZ	211.1 ± 1.6	262.1 ± 1.8	346.7 ± 2.1	447.8 ± 2.4	1267.7 ± 4.0
Total expected	241.6 ± 13.1	305.7 ± 21.3	421.0 ± 33.3	532.4 ± 38.2	1500.8 ± 56.5
Data (N_{obs})	258	298	435	568	1559

Source	$\sqrt{s} = 7$ TeV				$\sqrt{s} = 8$ TeV			
	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Renorm. and fact. scales	1.3	1.3	1.3	1.3	3.0	3.0	3.0	3.0
PDFs	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Pileup	0.3	0.5	1.0	0.6	0.2	0.4	0.3	0.2
Lepton and trigger efficiency	2.9	2.7	2.0	1.4	3.4	2.5	2.5	3.2
Muon momentum scale	–	0.6	0.4	1.1	–	0.5	0.8	1.3
Electron energy scale	1.9	0.8	1.2	–	1.4	0.8	0.8	–
$E_{\text{T}}^{\text{miss}}$	3.7	3.4	4.3	3.7	1.5	1.5	1.6	1.2
ZZ cross section	0.5	0.9	0.6	0.9	0.1	0.1	0.1	0.1
Zγ cross section	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0
$\mathrm{t\bar{t}}$ and Z+jets	2.7	6.5	6.3	6.0	4.6	7.2	6.1	7.7
Other simulated backgrounds	0.2	0.2	0.9	0.2	1.0	1.1	1.1	1.0
Total systematic uncertainty	6.1	7.8	8.1	7.2	7.0	8.6	7.7	9.2
Statistical uncertainty	13.5	13.9	13.1	11.0	7.7	7.2	6.4	5.2
Integrated luminosity uncertainty	2.2	2.2	2.2	2.2	2.6	2.6	2.6	2.6

WZ Yields (13 TeV)

Decay channel	N_{WZ}^{exp}	Background Non-prompt	Background Prompt	Total expected	Observed
eee	$35.88 \pm 0.63^{+1.84}_{-1.78}$	$10.64 \pm 1.73^{+3.19}_{-2.46}$	$6.08 \pm 0.59^{+0.73}_{-0.66}$	$52.60 \pm 1.93^{+3.91}_{-3.29}$	49
eeμ	$50.23 \pm 0.77^{+2.41}_{-2.35}$	$14.83 \pm 3.56^{+3.88}_{-2.98}$	$7.57 \pm 0.47^{+1.00}_{-0.87}$	$72.63 \pm 3.67^{+4.89}_{-4.14}$	78
$\mu\mu$e	$56.02 \pm 0.80^{+2.47}_{-2.42}$	$21.56 \pm 3.21^{+5.01}_{-3.86}$	$8.43 \pm 0.55^{+1.17}_{-1.04}$	$86.01 \pm 3.35^{+5.90}_{-4.89}$	83
$\mu\mu\mu$	$83.96 \pm 0.99^{+3.35}_{-3.27}$	$20.16 \pm 4.91^{+6.05}_{-4.65}$	$11.13 \pm 0.49^{+1.47}_{-1.28}$	$115.25 \pm 5.03^{+7.30}_{-6.09}$	108
Total	$226.09 \pm 1.61^{+9.46}_{-9.25}$	$67.19 \pm 7.08^{+14.43}_{-11.10}$	$33.21 \pm 1.05^{+4.32}_{-3.80}$	$326.50 \pm 7.33^{+18.66}_{-15.90}$	318

More WZ Plots



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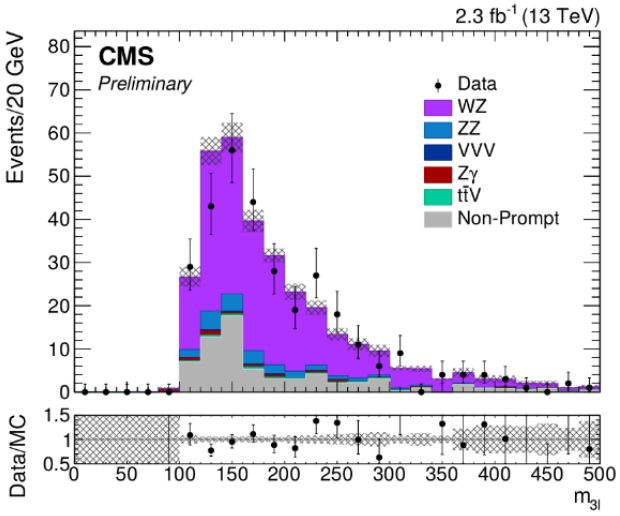

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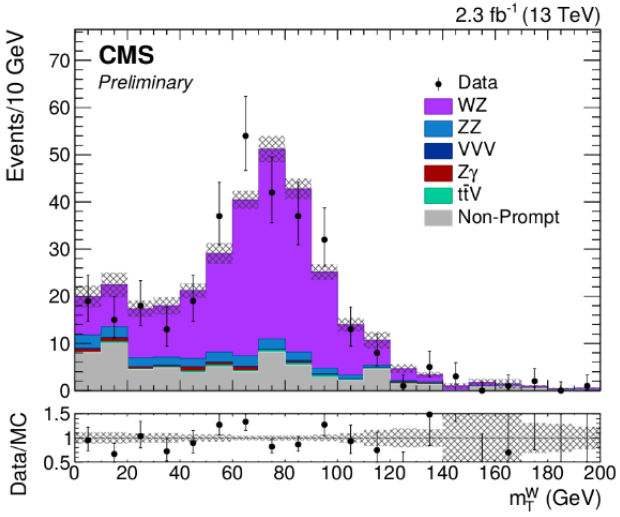
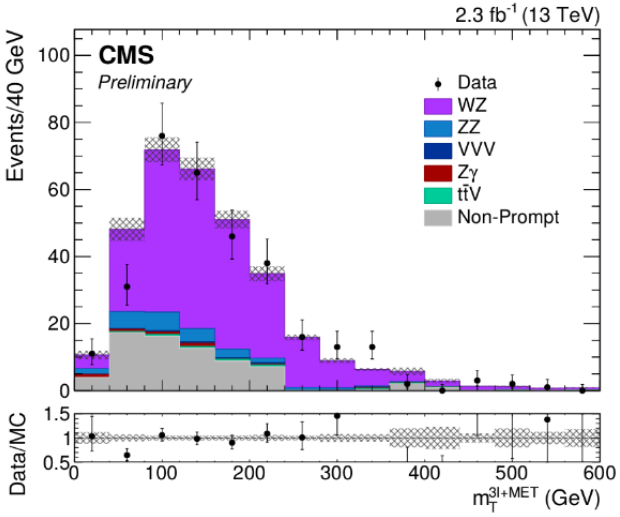
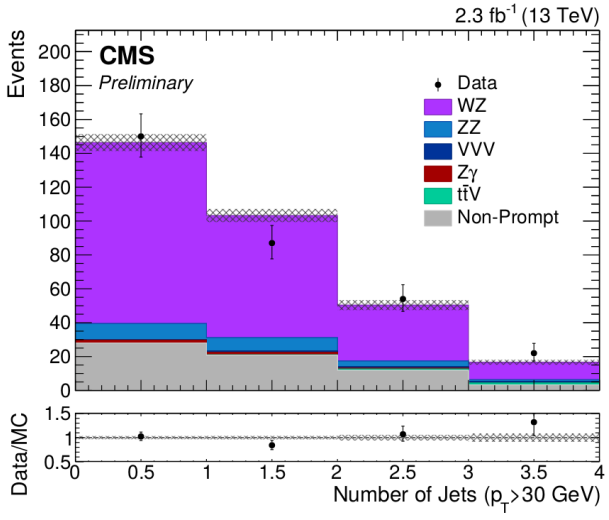




More WZ Plots



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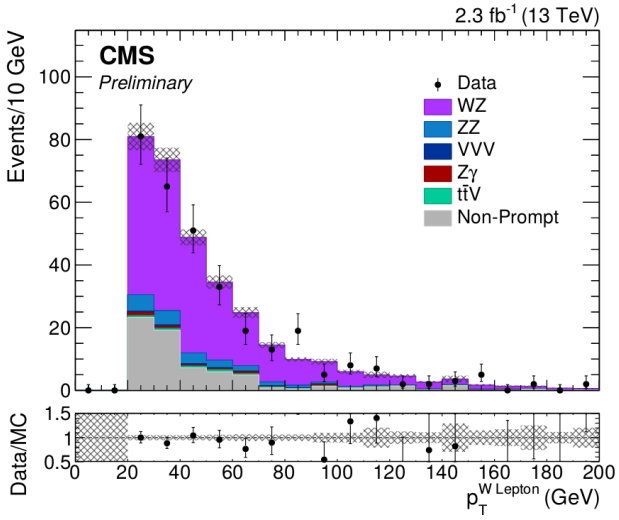

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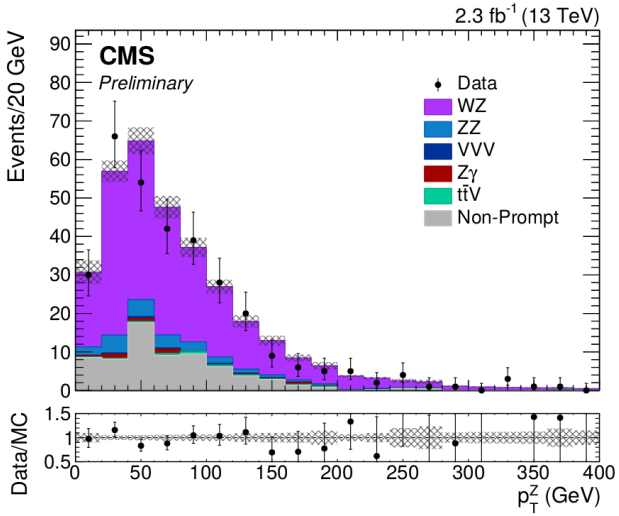
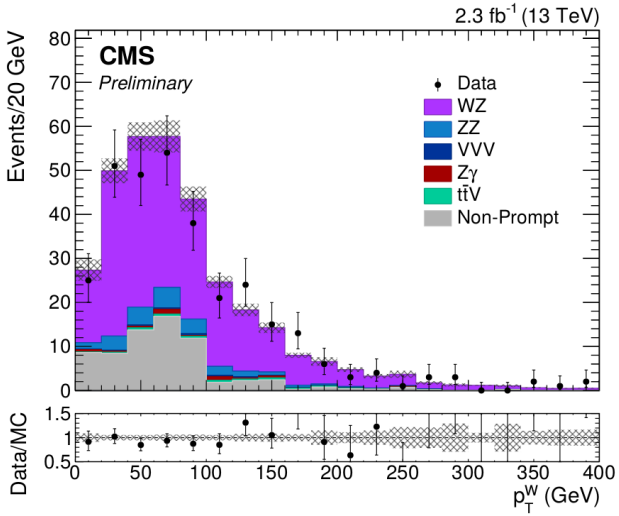




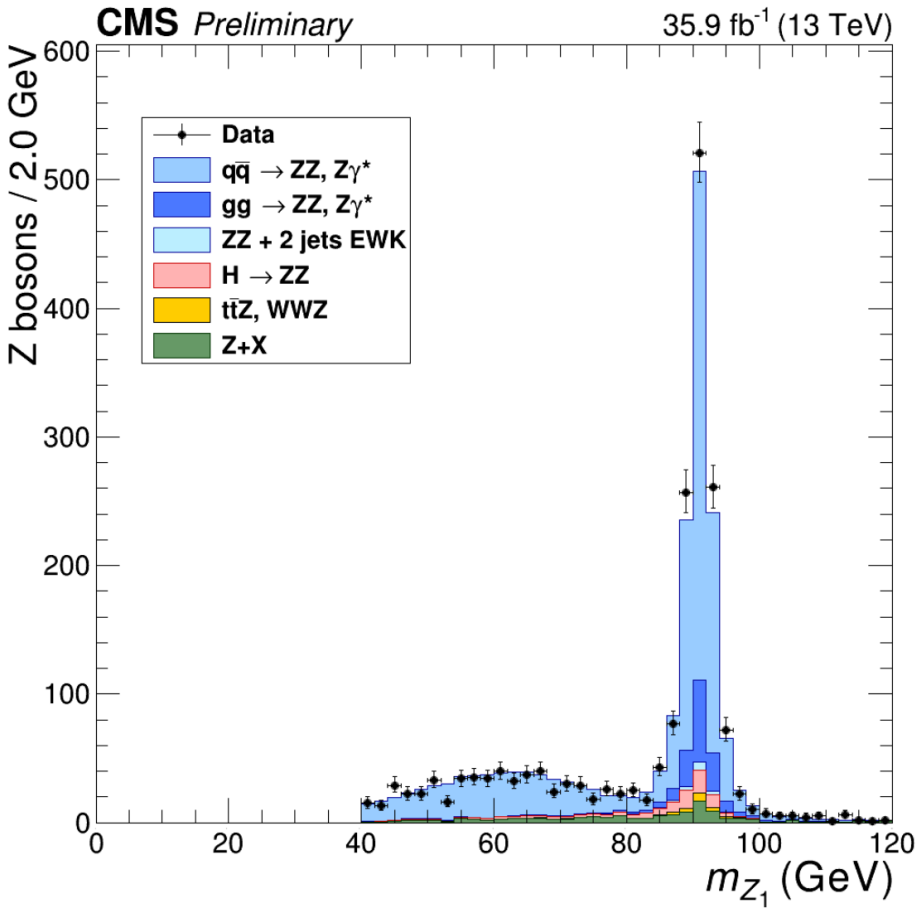
ZZ Yields and Systematics

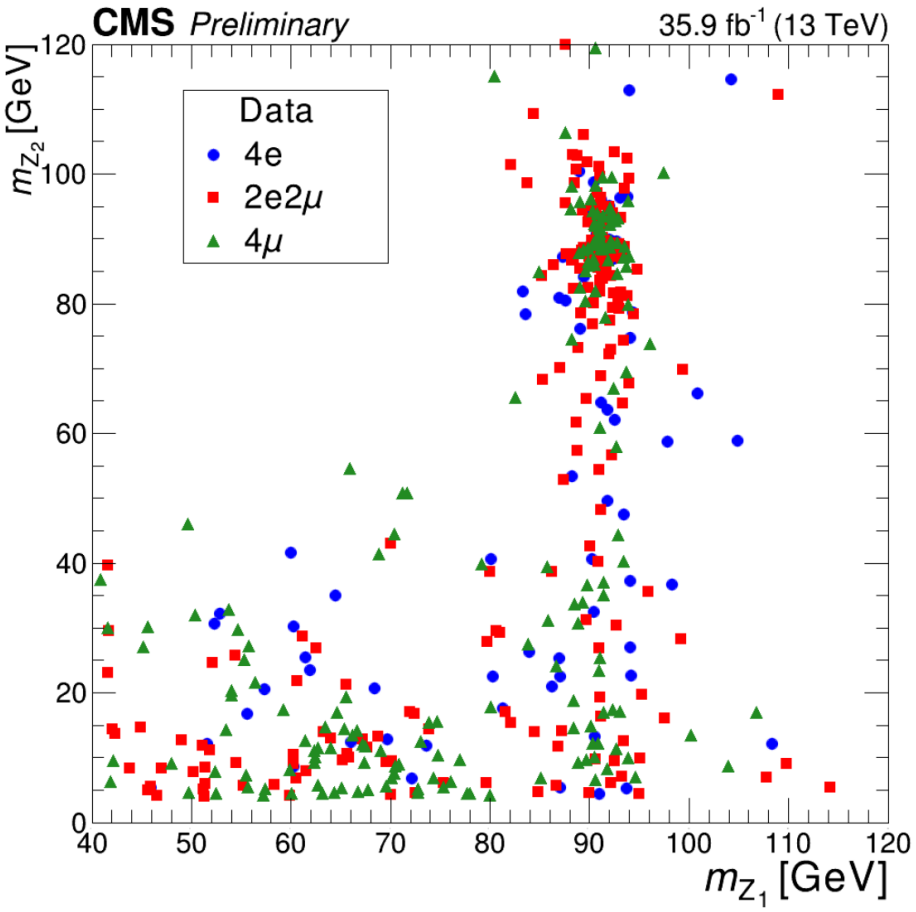
Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
Lepton efficiency	6–10%	2–6%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	0.5%
Background	0.6–1.3%	0.5–1%
Pileup	1–2%	1%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.6%	2.6%

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

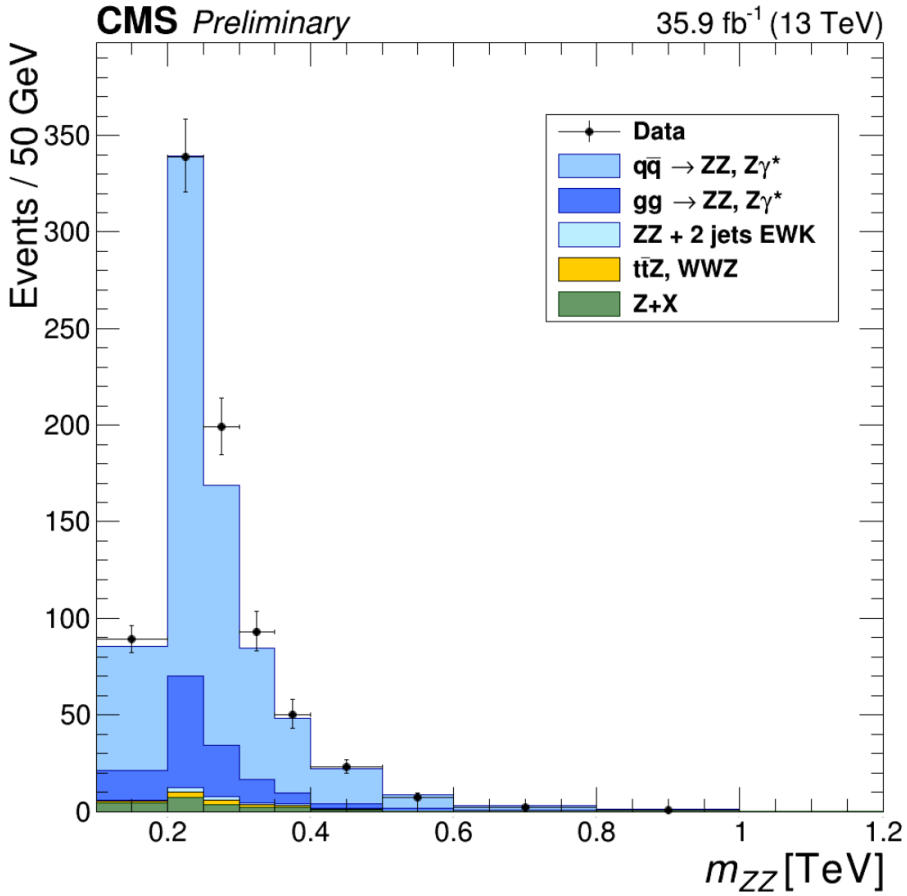
Decay channel	Expected $N_{4\ell}$	Background	Total expected	Observed
4μ	$265.5 \pm 1.3 \pm 8.4$	$5.2 \pm 0.8 \pm 1.5$	$270.7 \pm 1.5 \pm 8.6$	290
$2e2\mu$	$425.4 \pm 1.6 \pm 17.5$	$19.0 \pm 1.8 \pm 3.4$	$444.4 \pm 2.4 \pm 18.1$	465
4e	$165.3 \pm 1.0 \pm 10.9$	$11.8 \pm 1.5 \pm 2.2$	$177.2 \pm 1.8 \pm 11.4$	175
Total	$856.2 \pm 2.3 \pm 33.3$	$36.0 \pm 2.5 \pm 6.4$	$892.2 \pm 3.4 \pm 34.4$	930

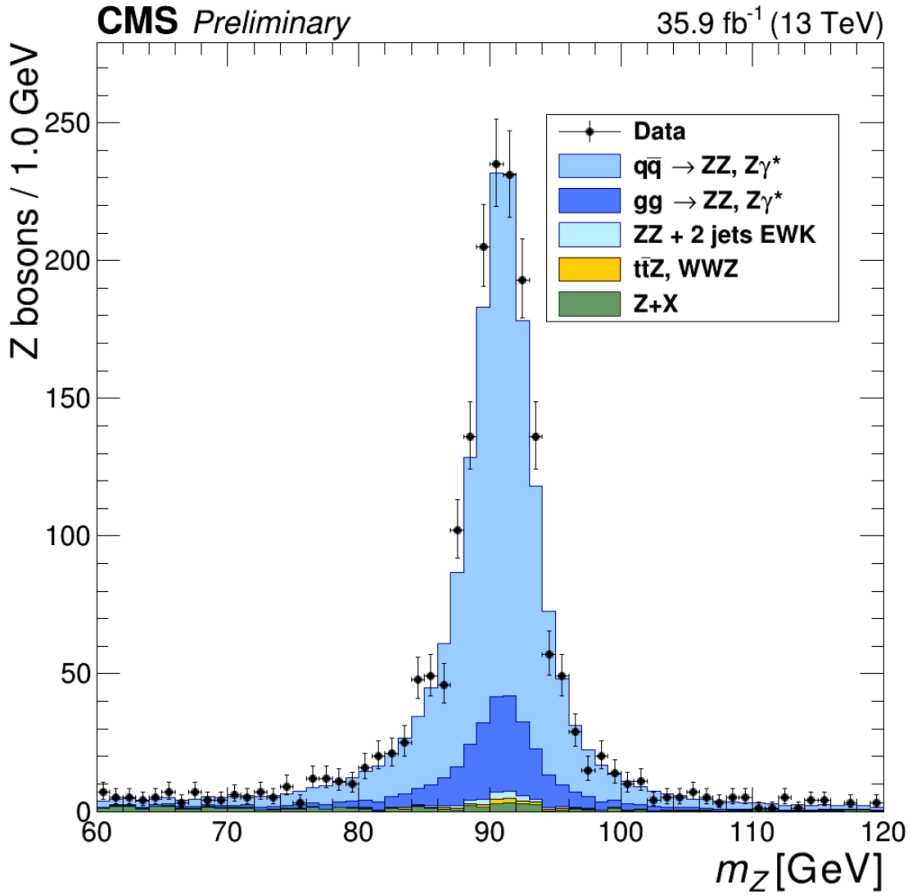
More ZZ Plots



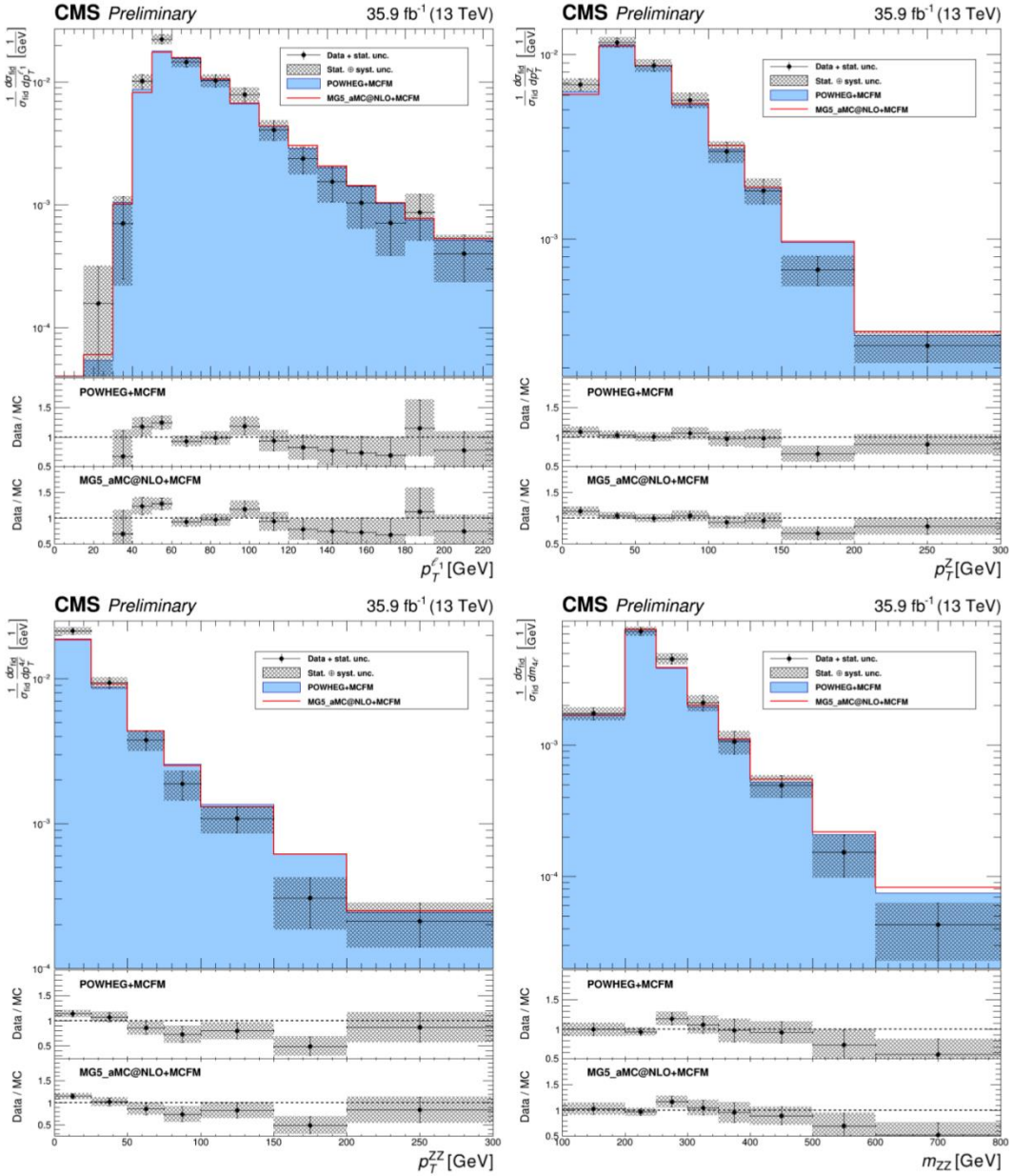


More ZZ Plots





More ZZ Differential Cross Sections



More ZZ Differential Cross Sections