Recent Results from CMS on the Production of Multiboson States

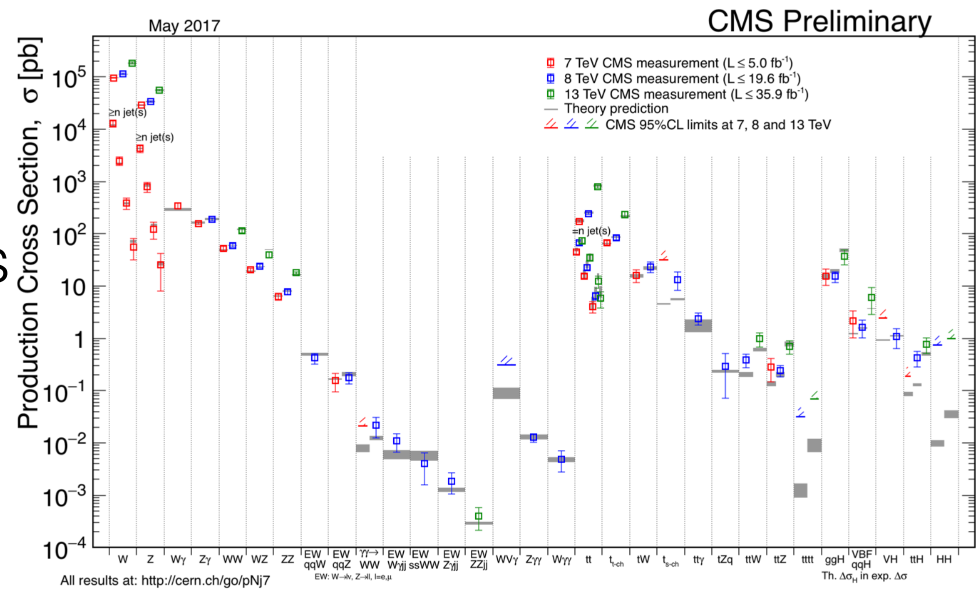
Kenneth Long
University of Wisconsin — Madison
for the CMS Collaboration

Outline

- Introduction and Motivation
- Cross section measurements and unfolded distributions
  - Z(vv)gamma at 13 TeV
  - WZ at 8 and 13 TeV
  - ZZ at 13 TeV
- Anomalous Coupling Searches
  - WV at 8 and 13 TeV
  - Limits from 8 TeV WZ and 13 TeV ZZ
- Summary and Conclusions

Introduction and Motivation

- Multiboson measurements
  - Direct probe of EWK sector of the SM
  - Insight into self couplings of gauge bosons



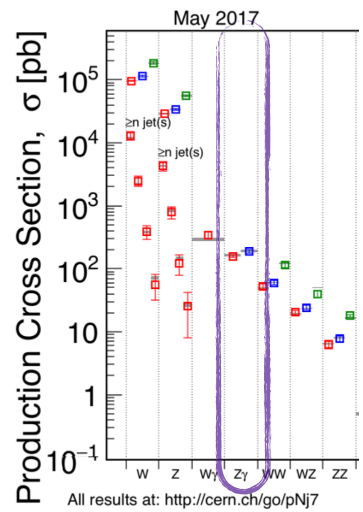
- Important background to SM Higgs and many BSM models with new gauge bosons

- Area of intense theoretical advancement
  - Known large NLO QCD corrections from LO
  - NNLO cross sections now known (many differential)
    - Several outside NLO uncertainties
  - Substantial differential effects from NLO EWK

Z(⟶ νν)γ: Measurement Overview

CMS-PAS-SMP-16-004

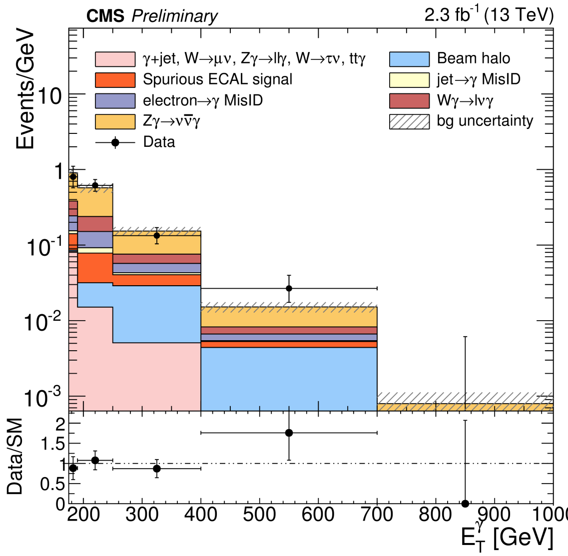
- Why Zγ ⟶ ννγ?
  - No direct Zγ coupling in the Standard Model
    - SM production only via initial state radiation
  - Important background for DM searches (monophoton)
- Selection
  - High p_T photon, high MET (>175, 170 GeV)
  - Tight γ ID and isolation requirements (avoid j/e fakes)
  - $\Delta\varphi$(MET, γ) > 2, $\Delta\varphi$(j, γ) > 0.5 ⟹ reduce γ+jets
- Primary Backgrounds
  - Purely experimental ⟹ estimated from data
    - Beam halo, spurious ECAL signals, cosmic rays
      - Removed via fit to characteristic shape, timing
  - Misidentification / Acceptance
    - γ+jets, Z(⟶ ℓℓ)γ, W ⟶ μν/τν, W(⟶ ℓν)γ ⟹ estimated from MC
      - LO MC with NNLO QCD + NLO EWK corrections
    - W ⟶ eν, QCD ⟹ from data
      - fake rates measured by inverting ID criteria, applied to data



Z(νν)γ: Measurement Overview

CMS-PAS-SMP-16-004

- Fiducial cross section
  - $p_T(\gamma) > 175$ GeV
  - $|\eta^\gamma| < 1.44$
- $A \cdot \varepsilon = 0.279 \pm 0.002$ (stat) ± 0.042 (syst)
  - via MG5_aMC@NLO (LO) with corrections



$$\sigma_{\rm fid} = 66.5 \pm 13.6\,({\rm stat}) \pm 14.3\,({\rm syst}) \pm 2.2\,({\rm lumi})\ {\rm fb}$$

➡ Excellent agreement with NNLO prediction from JHEP07(2015)085

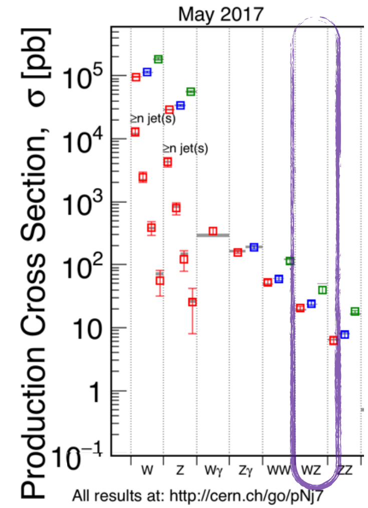
$$\sigma_{NNLO} = 65.5^{+3.3}_{-3.3}\ {\rm fb}$$

- Dominant uncertainties
- Estimation of backgrounds
- Theory uncertainties
  - Wγ and Zγ shape and normalization
  - ➡ Conservatively taken with LO PDF/scale + magnitude of higher order corrections on final yield

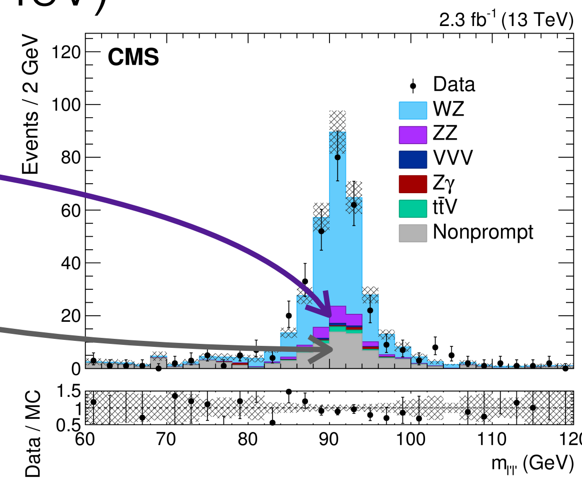
Sources	Effect on cross section (%)
Luminosity	3.3
PDF and QCD scale	6.8
Electroweak corrections	11.3
Jets misidentified as γ	1.3
Electron misidentified as γ	3.6
Beam halo	11.0
Spurious ECAL signals	5.0
E_T^{miss}, photon energy scales, pileup	7.1
Data/sim. scale factors	9.7

WZ ⟶ 3ℓν: Analysis Overview

- Why WZ ⟶ 3ℓν?
  - Insight into charged gauge interactions
  - Background to charged resonance searches (e.g. H±)
  - Cleanly reconstructed leptons, + σ within reach
- Selection
  - 3 isolated, well identified leptons + MET
  - Additional cuts target specific backgrounds
    - e.g. $m_{3\ell}$ > 100 GeV (Zγ), b-jet veto (tt - 13 TeV)



- Major backgrounds
- ≥ 3 prompt leptons, Zγ ⟹ from Monte Carlo
  - ZZ, t(t)+V/γ, VVV, Zγ
- Non-prompt backgrounds ⟹ data driven
  - Define "loose" ID with identification+ isolation relaxed from "tight" (analysis selection) ID
  - Measure ratio of tight/loose in dijet events
  - Apply loose ⟶ tight factors to events passing full analysis selection but failing analysis ID (tight)



PLB 766 (2017) 268

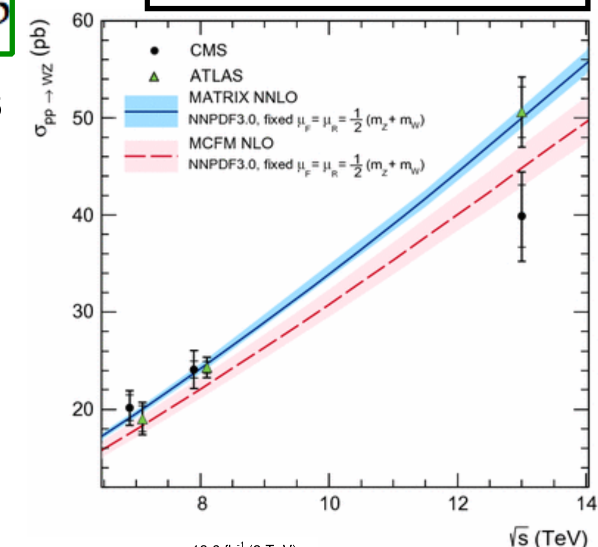
WZ ⟶ 3ℓν: Results

EPJ C (2017) 77: 236
PLB 766 (2017) 268

- Cross sections at 8, 13 TeV consistent with SM

$$\sigma_{\text{fid}}(\text{pp} \to \text{WZ} \to \ell\nu\ell'\ell') = 258 \pm 21\,(\text{stat})^{+19}_{-20}\,(\text{syst}) \pm 8\,(\text{lumi})\,\text{fb}$$

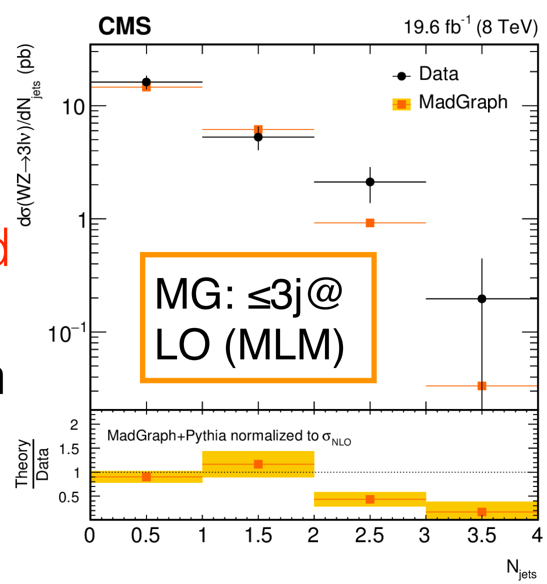
13 TeV $\sigma_{NNLO} = 334.3^{+7.7}_{-7.0}$ fb **PLB 761 (2016) 179-183**

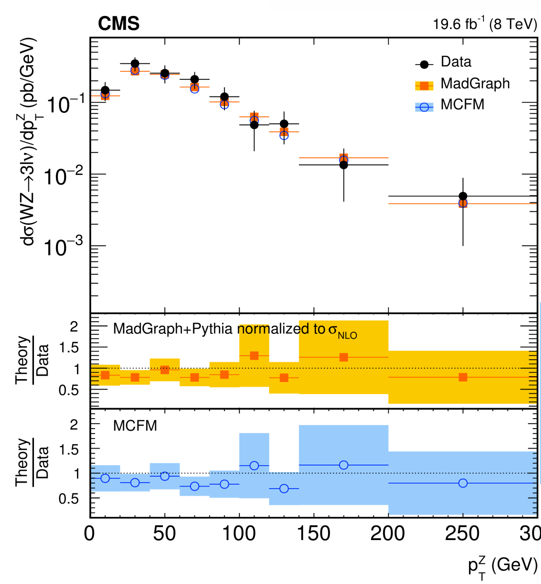


- **Unfolding** ⟹ remove detector smearing
  - Unfolding matrix (**R**) from simulation
  - ➡ Transfer between true (**μ**) and smeared (**ν**) distributions (after removing background **β**)

$$\vec{\nu} = R\vec{\mu} + \vec{\beta}$$

- Directly using R^{-1}
- ➡ large effect from stat variations
- D'Agostini Method
  - Regularize to obtain smooth spectrum



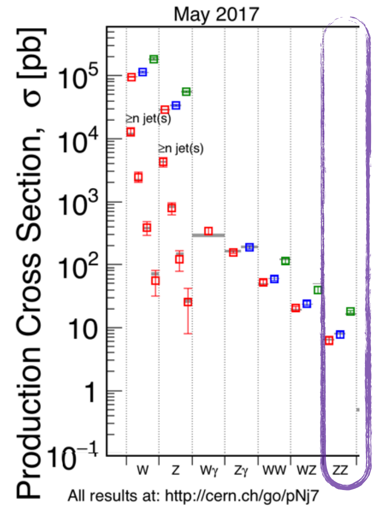


A·ε from MG, MCFM

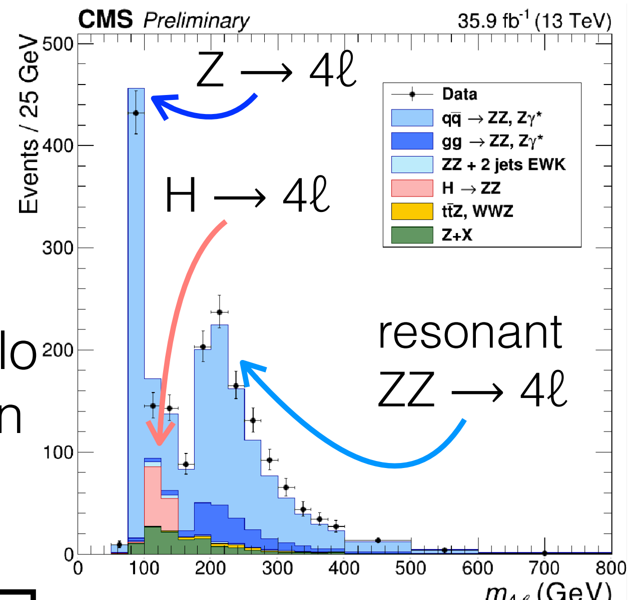
MCFM (NLO) Fixed Order

Z and ZZ $\longrightarrow 4\ell$: Overview

- Why ZZ $\longrightarrow 4\ell$?
  - Smallest diboson cross section but…
  - Completely reconstructed state with little background
    - ➡Very clean signal, good resolution
  - Primary background to standard model Higgs $\longrightarrow 4\ell$
    - Measurement of Z $\longrightarrow 4\ell$ reflective of H$\longrightarrow 4\ell$



- Selection
  - 4 leptons, 2 Z candidates with $m_{\ell^+\ell^-} \in [60, 120]$ GeV
  - Extended for Z $\longrightarrow 4\ell$ measurement
    - Z_1 (closest to $M_{PDG}(Z)$) in [40, 120] GeV
    - $Z_2 \in [4,120]$ GeV
    - $m_{4\ell} \in [80, 100]$ GeV
- Major backgrounds
  - ≥ 4 prompt leptons (ttV, VVV) $\Longrightarrow$ from Monte Carlo
  - Non-prompt backgrounds (Z+jets) $\Longrightarrow$ data driven
    - same approach as for WZ
      - tight/loose from Z+jets selection

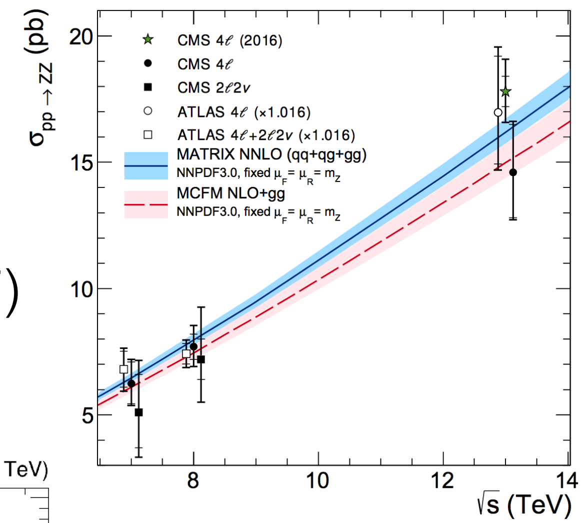


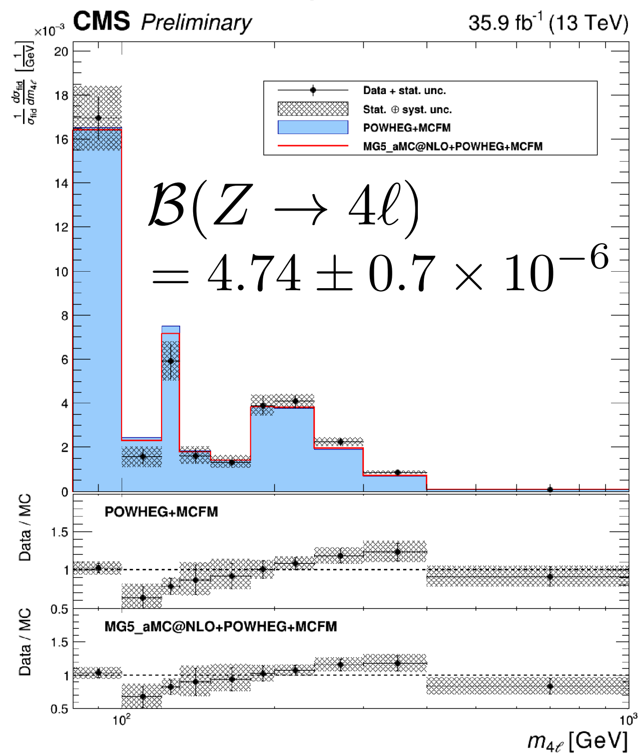
Kenneth Long

CMS-PAS-SMP-16-017

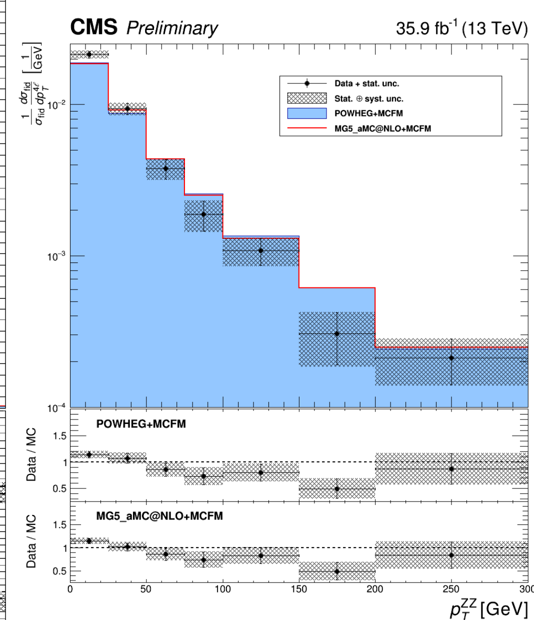
Z and ZZ → 4ℓ: Inclusive results

- Improved precision from 2015 measurement
  - Good agreement with NNLO prediction
  - Stat and syst uncertainties comparable
- First unfolded distributions at 13 TeV
  - qq → ZZ, gg → H scaled to NNLO (x1.1, x1.7)
  - gg → ZZ to NLO (x1.7)
  - Normalized distributions reduce experimental uncertainties.
  - Many sensitive to higher order corrections (QCD, EWK)
- MC differences, but modeling conclusions limited by stats





$$\mathcal{B}(Z \to 4\ell) = 4.74 \pm 0.7 \times 10^{-6}$$

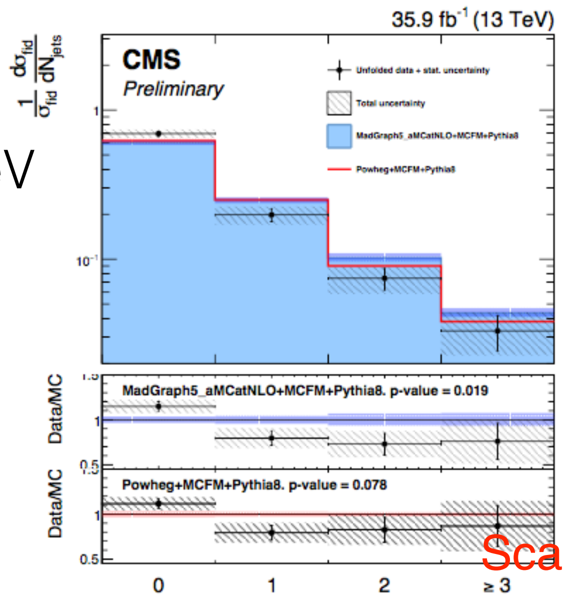


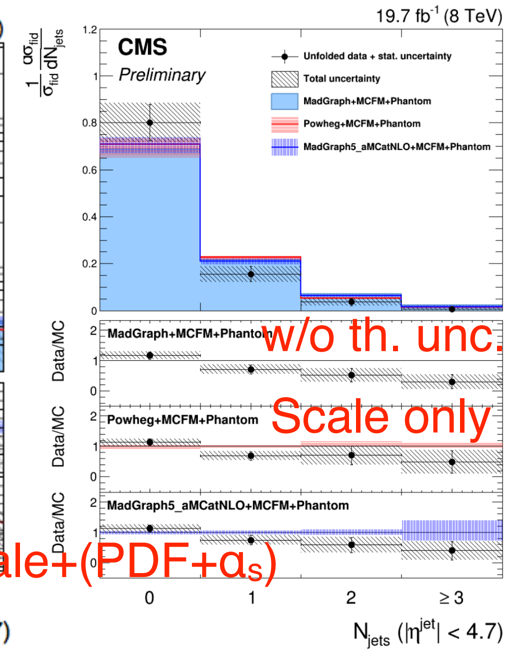
CMS-PAS-SMP-16-017

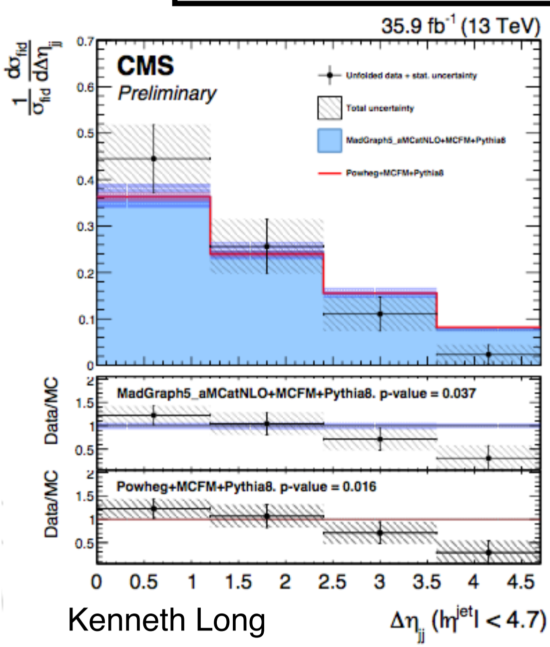
ZZ+jets ⟶ 4ℓ+jets: Results

- Extend inclusive analysis to distributions exclusive in n_{jets}
  - Data softer in n_{jets} at 8,13 TeV (limited by stats)
  - η_{jj}, mjj important for distinguishing EWK ZZjj

CMS-PAS-SMP-15-012
CMS-PAS-SMP-16-019







Setup at 13 (8) TeV

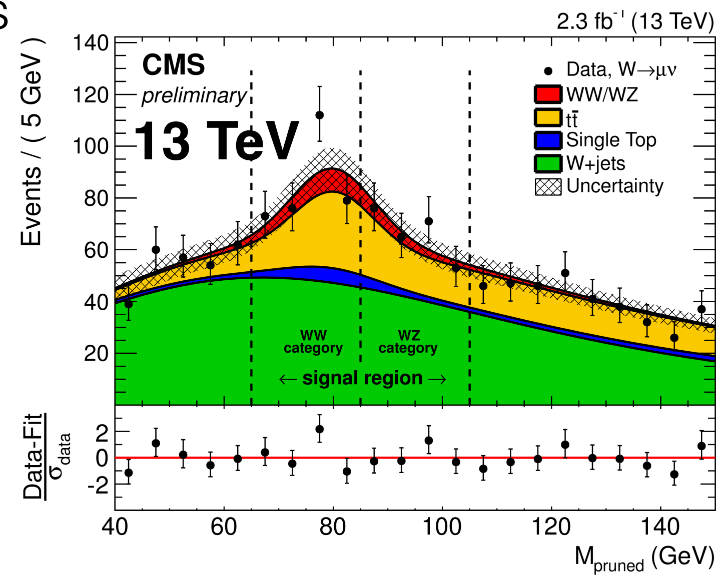
Process	ME Generator	Order/Merging	PS+Had+UE
qq/qg/gg ⟶ 4ℓ+nj	POWHEG v2	NLO inc.	PYTHIA 8 (6)
	MG5_aMC@NLO	≤1j@NLO FxFx	PYTHIA 8
	(MadGraph 5.1)	(≤2j@LO MLM)	(PYTHIA 6)
gg ⟶ 4ℓ	MCFM 7.0 (6.7)	LO inc.	PYTHIA 8 (6)
qq/qg/gg ⟶ 4ℓ+2j (EWK)	PHANTOM	LO inc.	PYTHIA 8 (6)

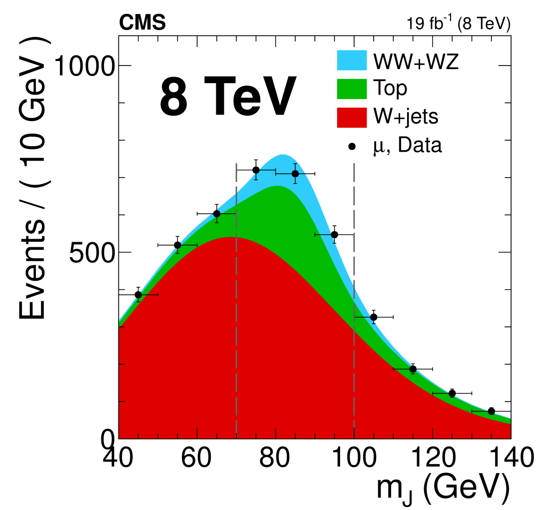
Anomalous Coupling Searches

$WV \longrightarrow \ell\nu q\bar{q}$: Overview

CMS-PAS-SMP-16-012

- Why $WV \longrightarrow \ell\nu qq$?
  - Larger branching ratios to hadronic states
  - Ability to reconstruct system p_T for WW
- Only boosted $V \longrightarrow qq$ considered
  - Most sensitive to BSM physics
- Selection and Backgrounds at 13 (8) TeV
  - High p_T lepton + MET (W)
  - Assign neutrino $p_T(\nu)$ using m_W constraint
  - $p_T(W_{lep}) > 200$ GeV
  - 1 $p_T > 200$ GeV ak8 (CA8) jet with V-like substructure
    - (N-subjettiness) $\tau_2/\tau_1 < 0.6$ (0.55)
    - $40 < m_{pruned} < 150$ (140) GeV
  - Reject further b-tagged ak4(5) jets
  - Jet ~back to back with lepton, MET, and leptonic W (Reduce W+jets)



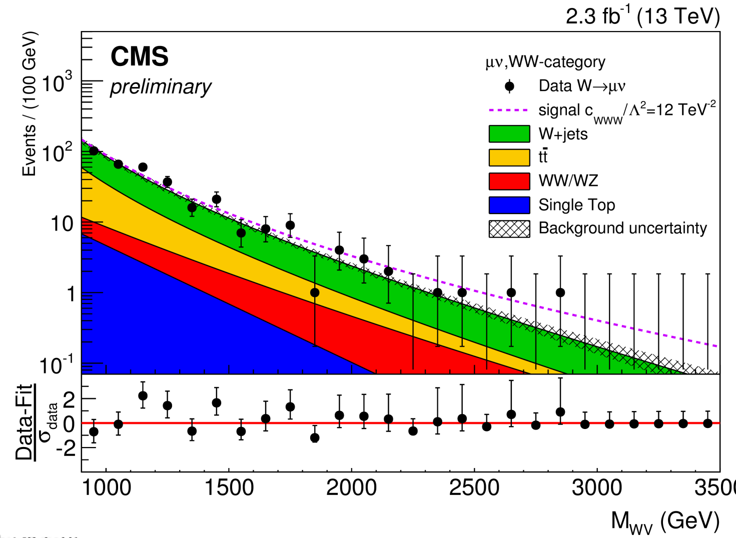


WV⟶ ℓvqq̄: Results

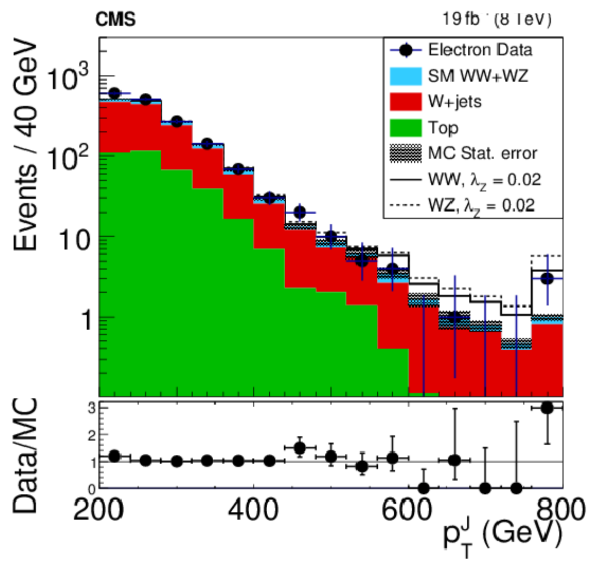
CMS-PAS-SMP-16-012
arXiv:1702.06095

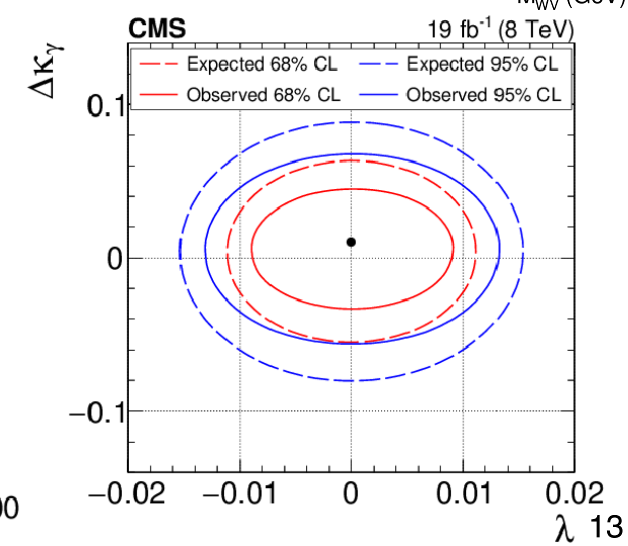
- Backgrounds modeled with analytic functions
  - Fit to m_{pruned} distribution
  - Normalization constrained in ttbar control region
- aTGC limits via unbinned fit

Energy	Generator for aC	Fit distribution
8	MCFM	$p_T(J)$
13	MG5_aMC LO via ME reweighting	m_{WV} (> 900 GeV)



- Consistent with SM
  - Improved sensitivity from leptonic results

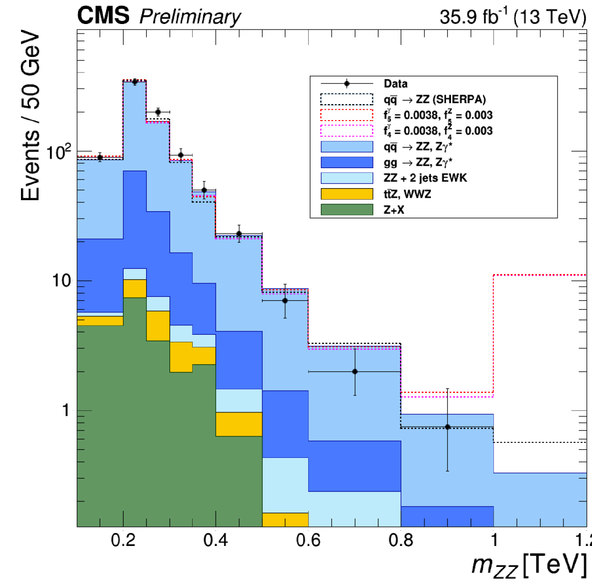




aC Limits from WZ and ZZ

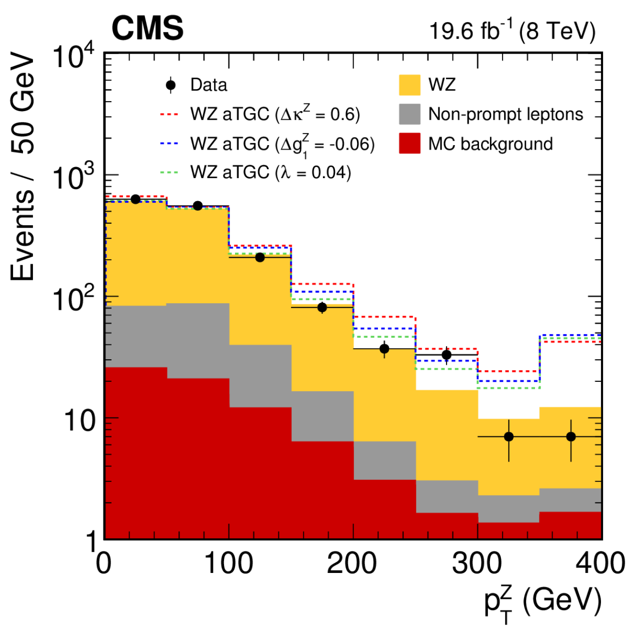
- Limits also obtained in leptonic states with aC formulation for ZZ and WZ

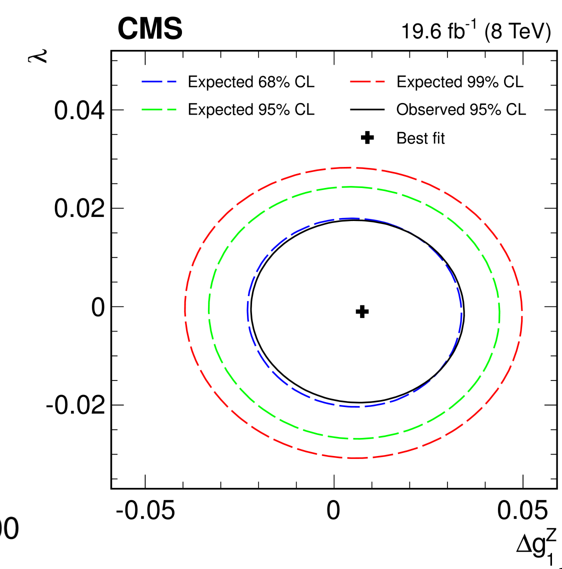
Process	Generator for aC	Fit distribution
ZZ	Sherpa 2.1	m_{ZZ}
WZ	MCFM	$p_T(Z)$



- Consistent with SM
  - Limits from ZZ exceed previous CMS limits by factor of 3-4

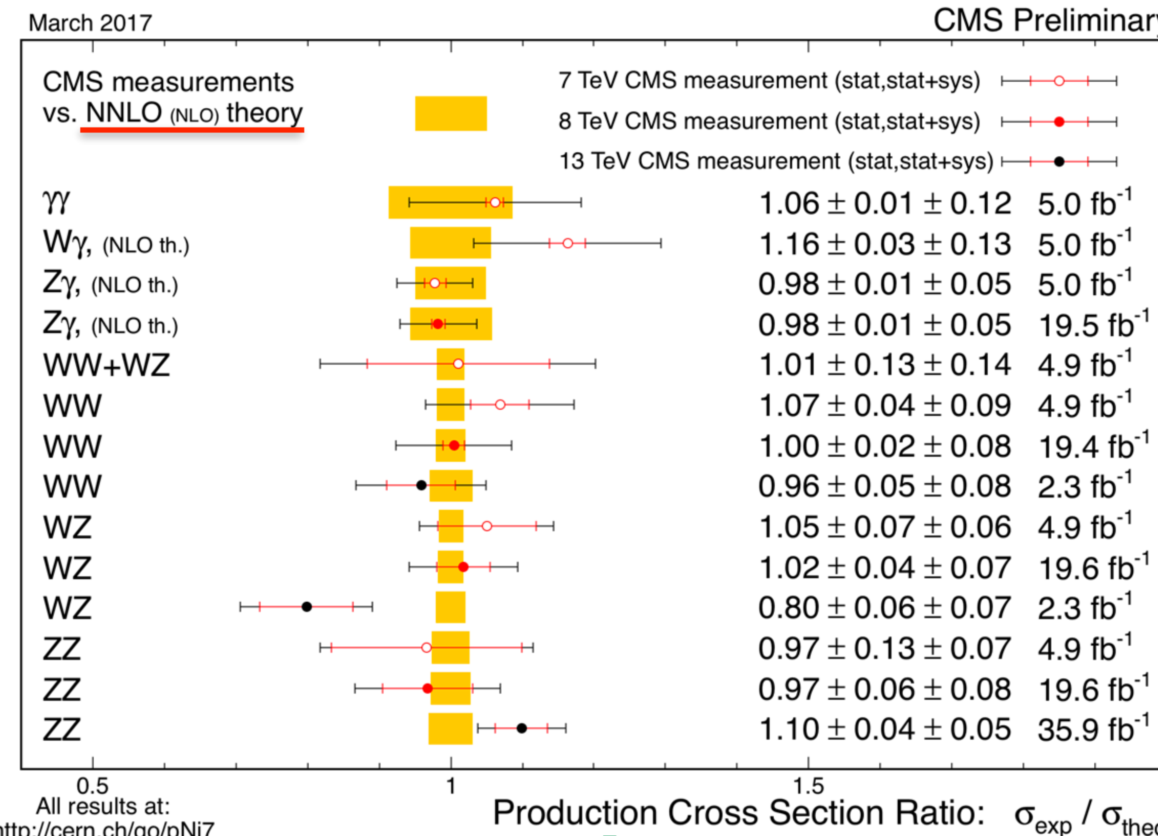
EPJ C (2017) 77: 236
PLB 766 (2017) 268
CMS-PAS-SMP-16-017

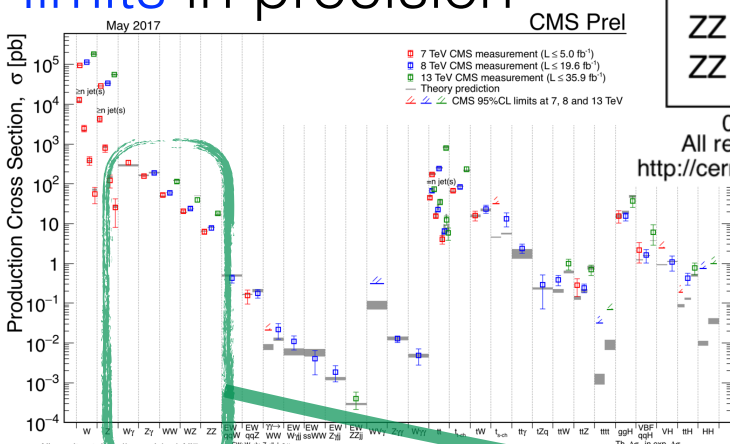




Multibosons and the Standard Model

- The Standard Model is alive and well
- ➡ And more complete than ever!
- Finding cracks requires pushing theory and experiment to new limits in precision

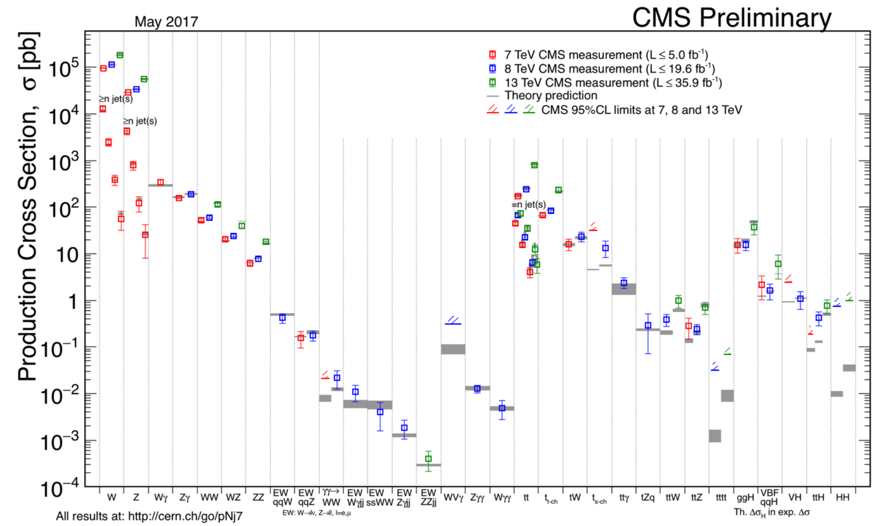




- Many measurements syst. limited
- Comparison to NNLO theory now the standard

Summary and Conclusions

- Multiboson physics an important probe of SM and BSM
- Results from CMS on Zγ, WZ, ZZ, and WV consistent with SM
  - Demonstrate energy dependence of SM production
  - Confirm state of the art theoretical predictions



  - Place limits on BSM physics in generalized language of aC/EFT

- Analyses at 13 TeV have greater reach to deviations from SM
  - Extension of analyses to full 2016 (+ 2017) dataset begins new era of precision measurements at the LHC

Backup

Overview of Inclusive Measurements

	ATLAS		CMS	
	8 TeV	13 TeV	8 TeV	13 TeV
Z->4l	PRL 112, 231806 (2014)	-	-	PLB 763 (2016) 280, CMS-PAS-SMP-16-017 ,019 Cross section, differential and aTGC
ZZ->4l	PLB 753 (2016) 552-572, JHEP01 099 (2017) Cross section, differential, aTGC	PRL 116, 101801 (2016) Cross section	PLB 740 (2015) 250, CMS-PAS-SMP-15-012 Cross section, differential and aTGC measurement	
ZZ->2l2ν	JHEP01, 099 (2017) Cross section, differential, aTGC	-	EPJC 75 (2015) 511 Cross section and aTGC measurement	-
Zγ->llγ	PRD 93, 112002 (2016) Cross section, differential and aTGC measurement	-	JHEP 04 (2015) 164 Cross section and aTGC measurement	-
Zγ->ννγ			PLB 760 (2016) 448 Cross section and aTGC measurement	CMS-PAS-SMP-16-004 Cross section
WW->lνlν	JHEP 09 (2016) 029 (WW+0jet) Cross section, differential and aTGC measurement PLB 763 (2016) 114 (WW+1jet) Cross section measurement	arXiv:1702.04519 Cross section	EPJC 76 (2016) 401 (WW+0- or 1-jet) Cross section, differential and aTGC measurement	CMS-PAS-SMP-16-006 Cross section
WZ->3lν	PRD 93, 092004 (2016) Cross section, differential, upper limit on EWK WZ, aTGC, aQGC measurement	PLB 762 (2016) 1 (3.2 fb-1) Cross section, differential (Njets) ATLAS-CONF-2016-043 (13.3 fb-1) Cross section, differential and aTGC!	CMS-SMP-14-014, EPJ C (2017) 77: 236 Cross section, differential and aTGC measurement	arXiv:1607.06943 (CMS-PAS-SMP-16-002) (2.3 fb-1) Cross section
WV->lνjj	-	-	arXiv:1703.06095 aTGC measurement	CMS-PAS-SMP-16-012 aTGC measurement

S. Duric, DIS 2017

Multiboson Measurements: Procedure

- Cross sections
  - Total production rate

$$\sigma \times \mathcal{B} = \frac{N_{\rm data} - N_{\rm bg}}{\mathcal{A} \times \epsilon \times \mathcal{L}}$$

A = Acceptance (theoretical)
ε = Efficiency (experimental)
$\mathcal{L}$ = Luminosity

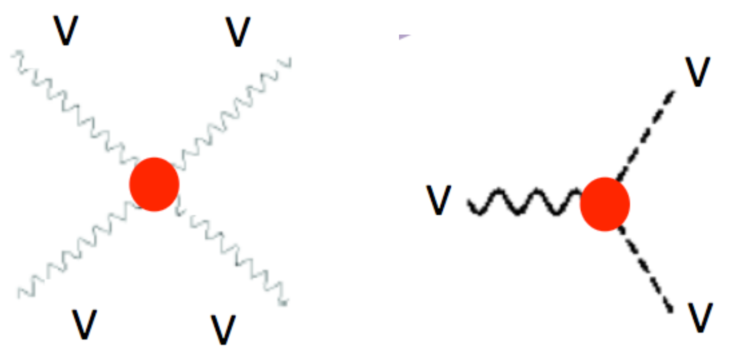
  - Fiducial cross section
    - Minimize extrapolation ⟹ minimize theoretical uncertainty
    - Most interesting comparison as theory tools become more flexible (differential + full decays)
- Unfolded distributions
  - "True" distributions from data ⟹ remove detector smearing
    - Unfolding matrix (R) to transfer between true (μ) and smeared (ν) distributions (after removing background β) from simulation

$$\vec{\nu} = \mathrm{R}\vec{\mu} + \vec{\beta}$$

  - Directly using μ^{-1} ⟹ large affect from statistical variations
  - D'Agostini Method — Regularize to obtain smooth spectrum

Overview of Anomalous Couplings / EFT

- Generalized language for new physics in multiboson interactions
- Anomalous couplings (triple and quartic)
  - Observed as deviations at high mass
  - Defined by modifying SM lagrangian or effective vertices



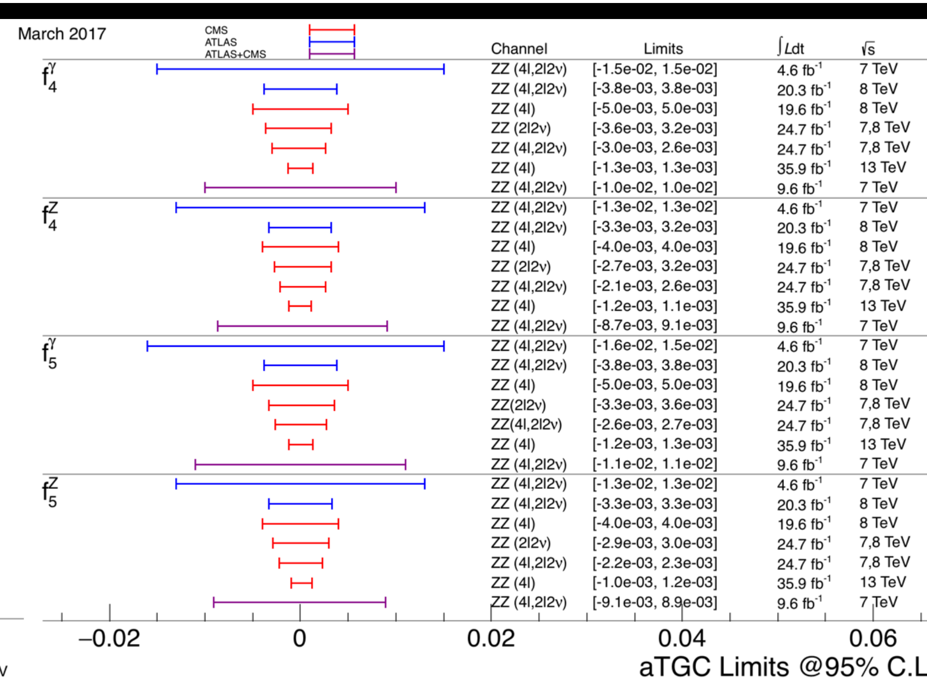
  - Alternatively… expand in effective field theory (EFT)
    - in terms of Wilson coefficients c_i and New Physics scale Λ

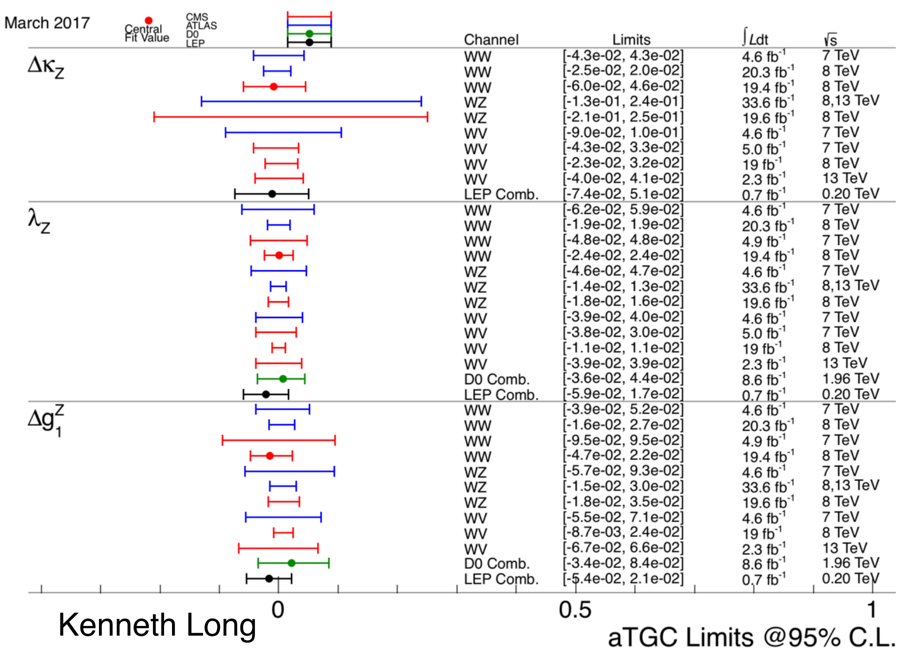
$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

  - Non-unitary as $\sqrt{\hat{s}} \longrightarrow \Lambda$ without form factor
    - Often presented without form factor for simplicity
    - Inclusion of form factor decreases limits

Anomalous Couplings (aTGC) Summary

- Limits (without form factors) comparable to LEP in many cases
  - LHC and LEP probing different energies
  - Form factors decrease LHC limits





WW → ℓνℓν (Presented at LHCP 2016)

CMS-PAS-SMP-16-006

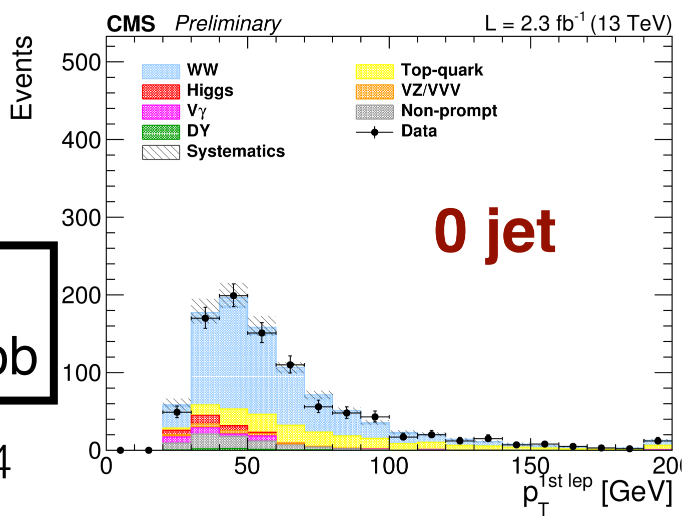
- Only OF state (eμ) considered
- p_T(WW) distribution reweighted to NNLO+NNLL[1]
  - Jet p_T strongly correlated with p_T(WW)
    - Affects jet categorization
- Background
  - VV and VVV — from MC, Higgs removed using simulation (~4% of final yield)
  - Top (mostly ttbar and tW) — inverting jet vetos
  - Drell-Yan (inverting mass and MVA vetoes)
  - Non-prompt background (from mis-ID in W+jets) — "Tight-to-loose" method

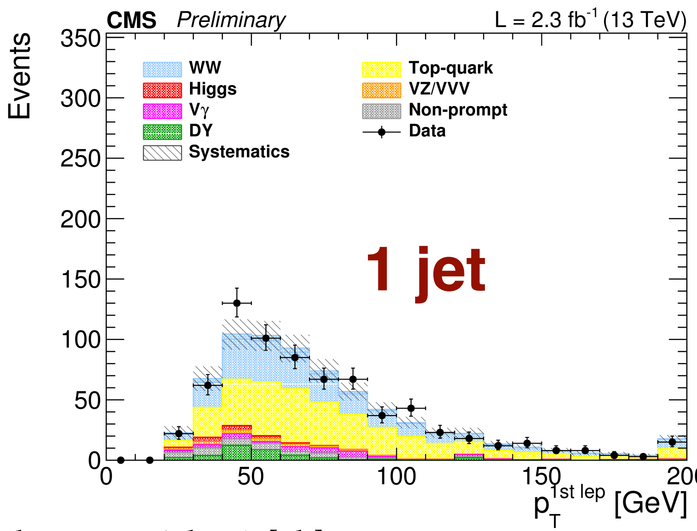
[1] JHEP08(2015)154

Fit using 0 and 1 jet regions

$\sigma_{NNLO+NNLL}$ = 120.3 ± 3.0 pb

Phys. Lett. B754 (2016) 275-280





Category	Value ± stat. ± exp. syst. ± theo. syst. ± lumi. [pb]
0-jet	113.6 ± 6.3 ± 5.1 ± 6.5 ± 3.3
1-jet	135.3 ± 15.4 ± 34.0 ± 14.4 ± 6.0
Combination	115.3 ± 5.8 ± 5.7 ± 6.4 ± 3.6

Systematic Uncertainties: WZ

EPJ C (2017) 77: 236

Source of uncertainty	Uncertainty in the cross section
Background with nonprompt μ	5.4%
Background with nonprompt e	3.9%
b tagging	2.1%
E_T^{miss}	2.0%
Electron efficiency	1.9%
Muon efficiency	1.5%
Pileup	0.8%
ZZ cross section	0.4%
$t\bar{t}V$ cross section	negligible
$Z\gamma$ cross section	negligible
VVV cross section	negligible
Integrated luminosity	3.2%
PDF and scales	1.0%

PLB 766 (2017) 268

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_T^{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
$Z\gamma$ cross section	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0
$t\bar{t}$ 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

Systematic Uncertainties: ZZ

CMS-PAS-SMP-16-017

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%

CMS-PAS-SMP-16-019

Systematic source	Absolute	Normalized
Trigger	2.0 %	-
Muon ID, ISO and Tracking	0.9 - 1.0 %	<0.1 - 0.1 %
Electron ID, ISO and Tracking	2.8 - 3.5 %	0.1 - 0.7 %
Jet energy resolution	2.1 - 8.4 %	2.1 - 8.4 %
JES correction	4.6 - 17.6 %	4.6 - 17.6 %
Reducible background	0.5 - 2.5 %	0.3 - 1.8 %
Irreducible background	<0.1 - 1.2 %	<0.1 - 1.1 %
Pileup	0.3 - 1.9 %	0.6 - 1.8 %
Luminosity	2.5 %	-
Monte Carlo choice	0.5 - 5.1 %	0.8 - 4.8 %
qq/gg cross section	<0.1 - 0.3 %	0.1 - 0.2 %
PDF	<0.1 - 0.2 %	<0.1 - 0.2 %
α_S	<0.1 - 0.1 %	<0.1 - 0.1 %