Diboson and Multiboson Results with CMS

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On behalf of the CMS Collaboration

Multiboson Physics

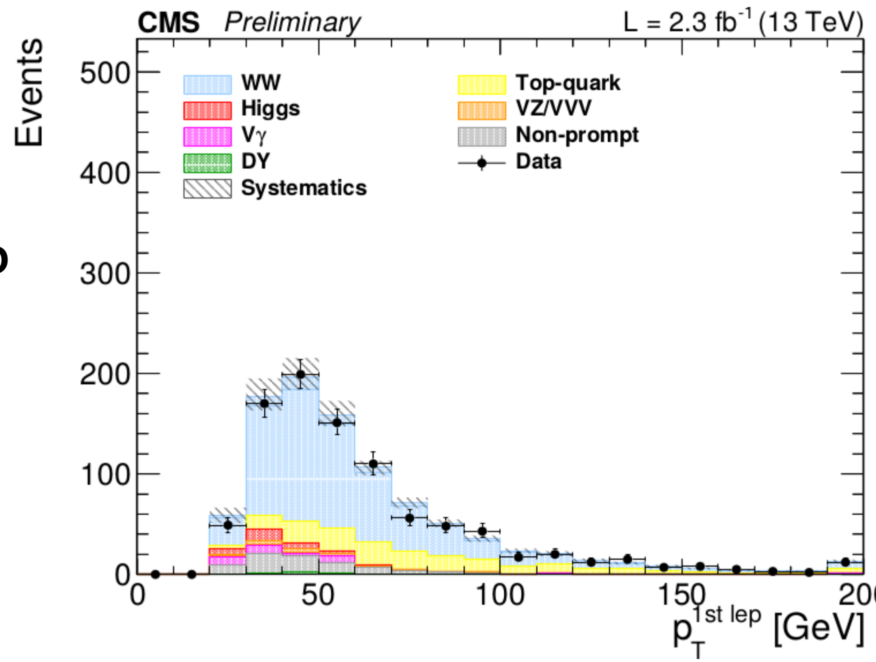
For similar ATLAS results, see talk by S. Barnes

- **Multi-V (V ∈ Z,$W^{\pm}$,γ) production is an important probe of SM electroweak (EWK) gauge boson interactions**
  - Sensitive to deviations from the SM
  - Is the Higgs we found enough to preserve unitarity?
  - Multi-V final states are the natural first search channels for anomalous gauge couplings (aTGCs and aQGCs)
- **2015 datasets permit measurements of some 13 TeV inclusive cross sections**
  - NNLO predictions now available for many processes
  - Today: W^+W^-, $W^{\pm}Z$ and ZZ
- **Run-I datasets allowed measurements of all diboson and several triboson states**
  - Today: EWK Zγ+jets and Wγ+jets; Zγγ and Wγγ; γγ→WW

W^+W^- at 13 TeV

- Good channel for studies of charged gauge boson couplings
- Primary irreducible background to important Higgs decay
- $e\nu\mu\nu$ decay channel avoids large Drell-Yan background
- Large top-quark backgrounds suppressed with b-jet veto and $N_{jets} < 2$ cut
- $E_T^{miss} > 30$ GeV, $\vec{E}_T^{miss} \cdot \vec{p}_T^{\ell_1} > 20$ GeV

CMS-PAS-SMP-16-006

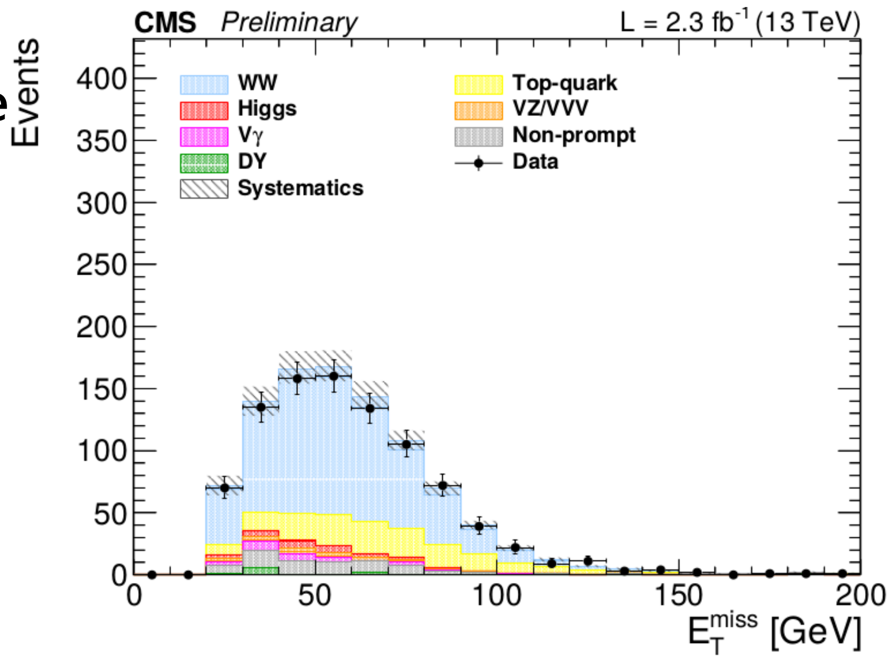


Brand new!

W^+W^- at 13 TeV

CMS-PAS-SMP-16-006

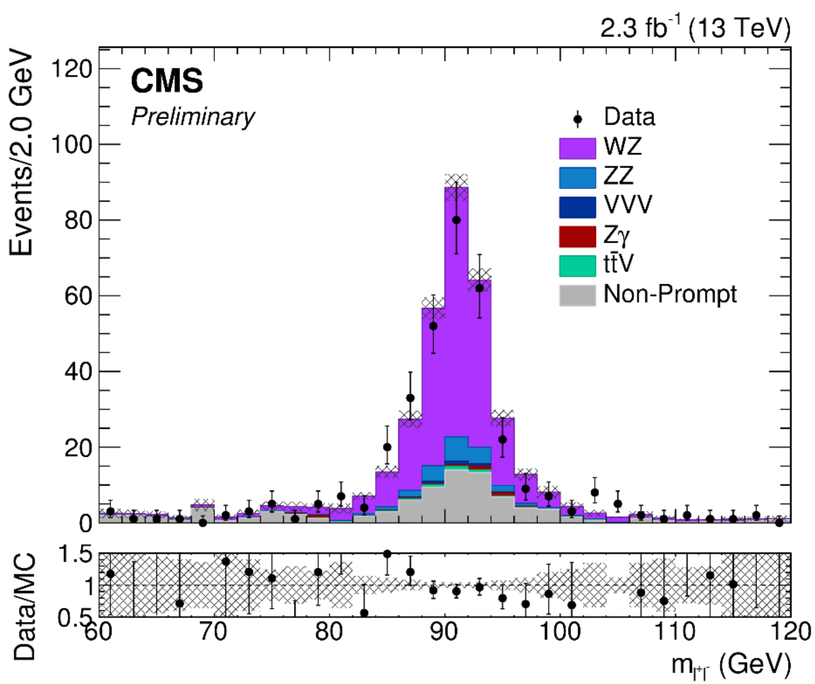
- **Jet veto makes efficiency sensitive to higher-order QCD corrections**
  - POWHEG signal sample reweighted to results of NNLL p_T^{WW} resummation
- **Also sensitive to underlying event and parton shower modeling**
- $\boldsymbol{\sigma_{W^+W^-} = 115.2 \pm 5.8(\mathrm{stat}) \pm 5.7\ (\mathrm{syst}) \pm 6.4(\mathrm{theo}) \pm 3.6(\mathrm{lumi})\ \mathrm{pb}}$
- NNLO prediction: $\mathbf{120.3 \pm 3.6\ pb}$

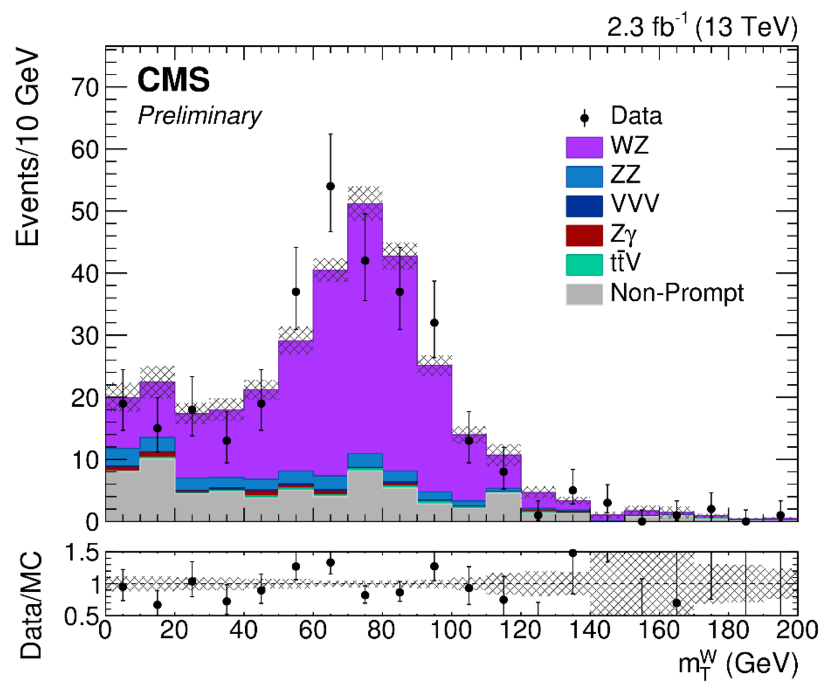


WZ at 13 TeV

CMS-PAS-SMP-16-002

- WZ→3ℓν ($\ell \in \mathbf{e}, \boldsymbol{\mu}$) signal is clean enough to measure cross section with 2015 dataset despite modest cross section
- Good channel to investigate charged TGCs with more data
- NNLO predictions recently produced by Grazzini et al.

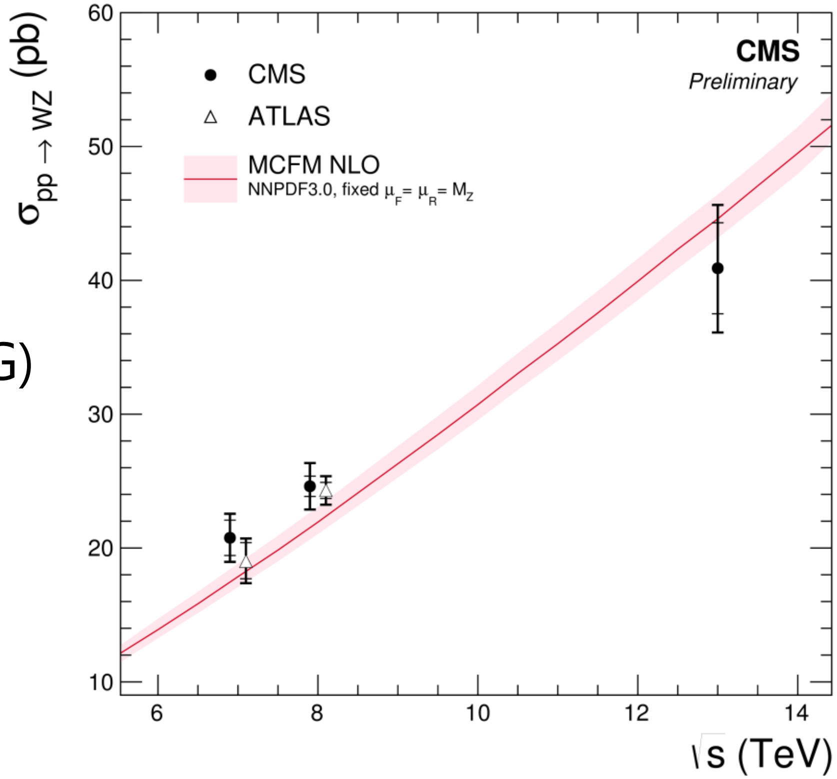




WZ at 13 TeV

CMS-PAS-SMP-16-002

- Total cross section found for $60 < m_Z < 120$ GeV
- $\sigma_{WZ} = 40.9 \pm 3.4(\text{stat})^{+3.1}_{-3.3}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi})$ pb
  - Acceptance $45.0 \pm 0.4\%$ (POWHEG)
  - Branching ratios from PDG
- MCFM NLO: $42.6^{+1.6}_{-0.8}$ pb
- New since this plot: NNLO from Grazzini et al. (arXiv:1604.08576)
  - $50.0^{+1.1}_{-1.0}$ pb

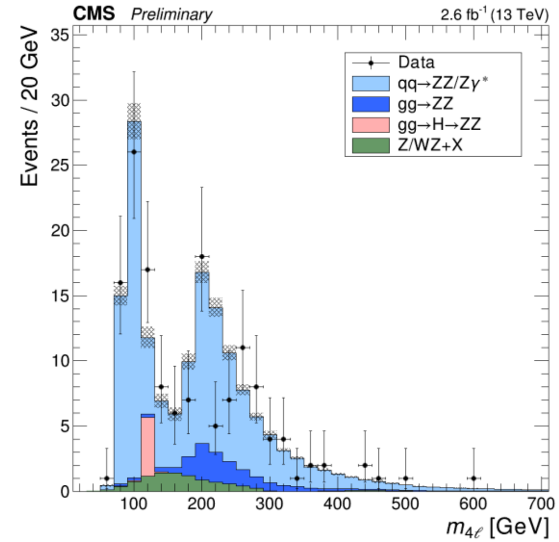


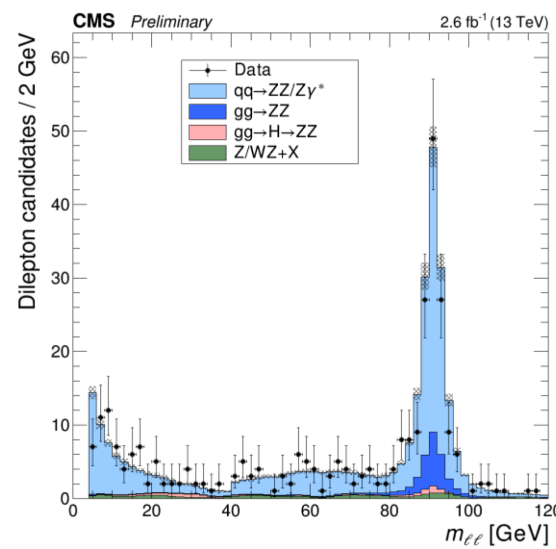
More data needed to exceed 2012 precision

ZZ at 13 TeV

CMS-PAS-SMP-16-001

- ZZ→4ℓ ($\ell \in \mathbf{e}, \boldsymbol{\mu}$) virtually zero-background
- Only irreducible background to Higgs "golden channel"
- NNLO predictions available
  - Gluon-fusion "box diagrams" have large effect
- Extend to low mass for Z→4ℓ branching ratio measurement
- Full spectrum (further restricted for cross section and branching ratio measurements):
  - $40 < m_{Z_1} < 120$ GeV ($\ell^+\ell^-$ closer to nominal m_Z)
  - $4 < m_{Z_2} < 120$ GeV



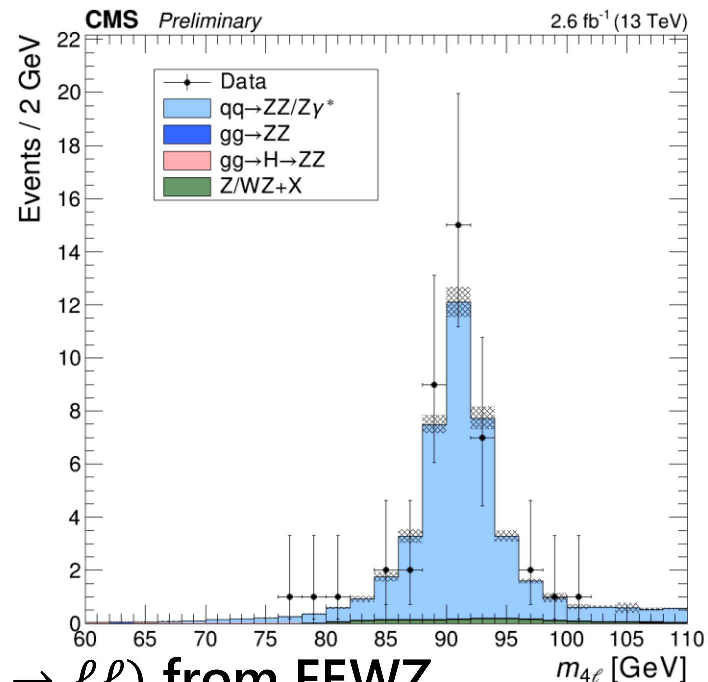


$Z \to 4\ell$ Branching Fraction

CMS-PAS-SMP-16-001

- Measure Z cross section by restricting phase space to $80 < m_{4\ell} < 100$ GeV
  - 4% correction for non-resonant γ*γ*
- We already know the Z cross section; natural to interpret as branching fraction

$$\frac{\mathcal{B}(Z \to 4\ell)}{\mathcal{B}(Z \to \ell\ell)} = \frac{\sigma(pp \to Z \to 4\ell)}{\sigma(pp \to Z \to \ell\ell) \cdot \mathcal{C}_{80-100}^{60-120}}$$



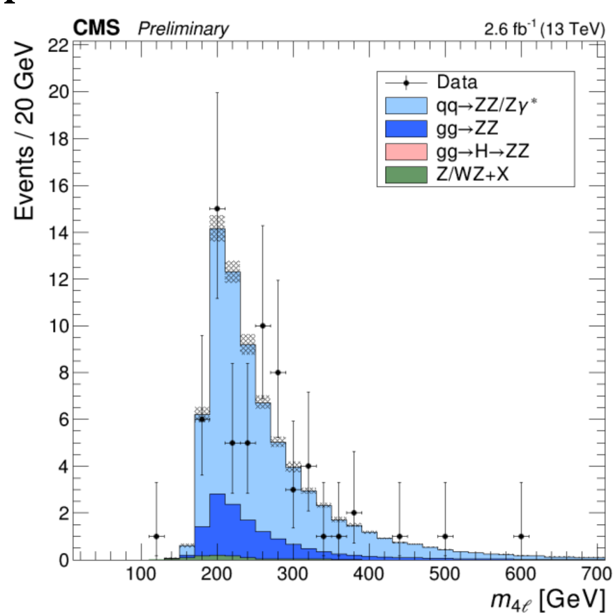
- $\sigma(pp \to Z \to 4\ell)$ measured here, $\sigma(pp \to Z \to \ell\ell)$ from FEWZ
- $\mathcal{C}_{80-100}^{60-120}$ corrects for different mass window
- $\mathcal{B}(Z \to 4\ell) = 4.9^{+0.8}_{-0.7}(\text{stat})^{+0.3}_{-0.2}(\text{syst})^{+0.2}_{-0.1}(\text{theo}) \pm 0.1(\text{lumi}) \times 10^{-6}$
  - Theory (MCFM or MadGraph5_aMC@NLO): 4.6×10^{-6}

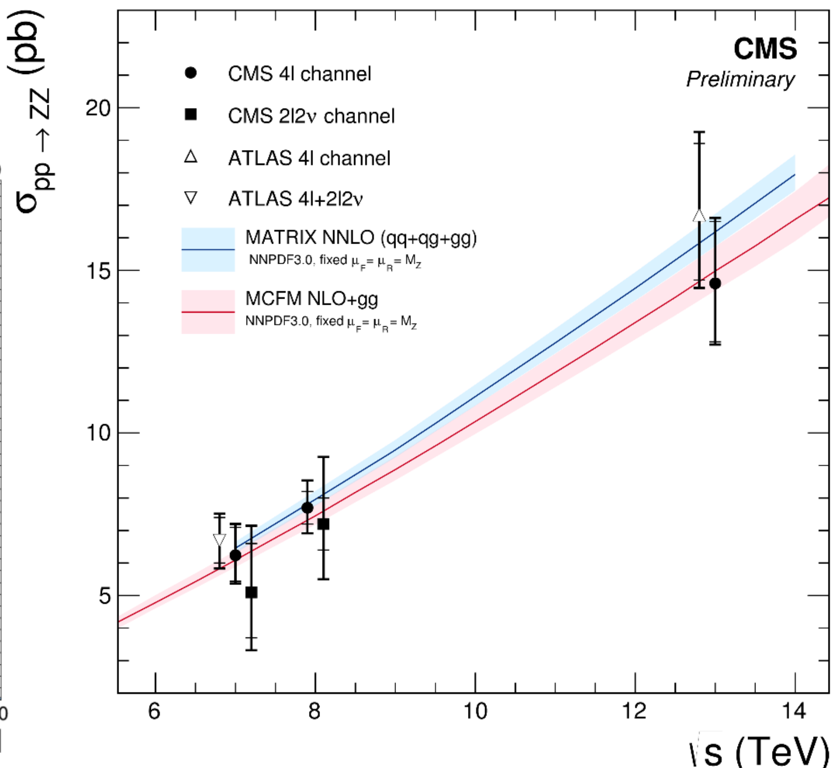
ZZ Cross Section at 13 TeV

CMS-PAS-SMP-16-001

- Require both Zs on-shell (60-120 GeV)
- $\sigma_{ZZ} = 14.6^{+1.9}_{-1.8}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \pm 0.2(\text{theo}) \pm 0.4(\text{lumi})\ \text{pb}$
  - MCFM NLO+gg: $15.0^{+0.8}_{-0.6}$ pb
  - New NNLO from Grazzini et al.: $16.2^{+0.6}_{-0.4}$ pb

Results already approaching precision from 2012 despite smaller dataset

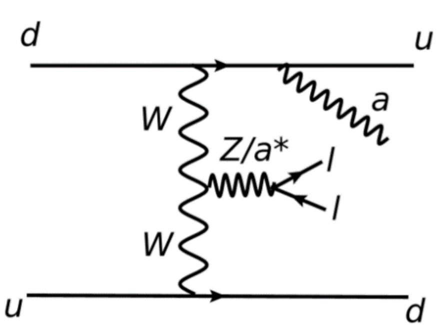




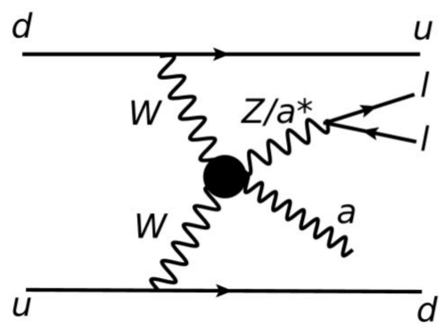
EWK Zγ+2jets and Wγ+2jets at 8 TeV

CMS-PAS-SMP-14-018
CMS-PAS-SMP-14-011

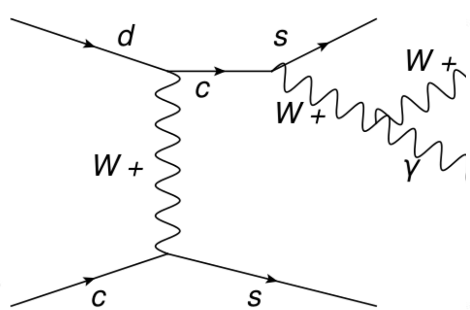
- **Vector Boson Scattering (VBS) processes at $\mathcal{O}(\alpha_{EWK}^5 \alpha_s^0)$ probe multi-V interactions**
- **Distinctive 2-jet topology**
  - Cuts on m_{jj} and $\Delta\eta_{\mathrm{jj}}$ select VBS phase space
  - Background from ZV with V→jj also removed by m_{jj} cut



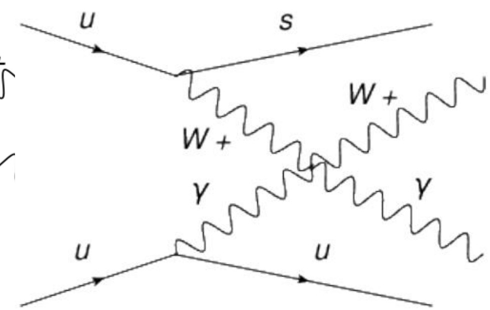
Zγ with TGC



Zγ with QGC



Wγ with TGC

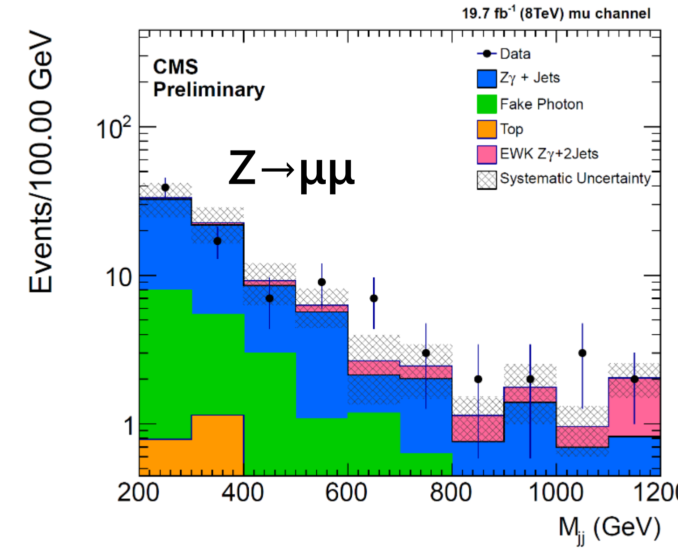


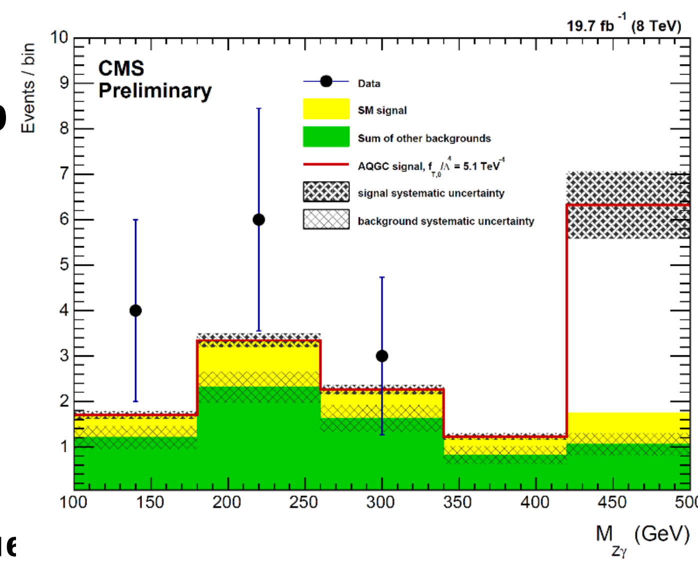
Wγ with QGC

EWK Zγ+2jets at 8 TeV

CMS-PAS-SMP-14-018

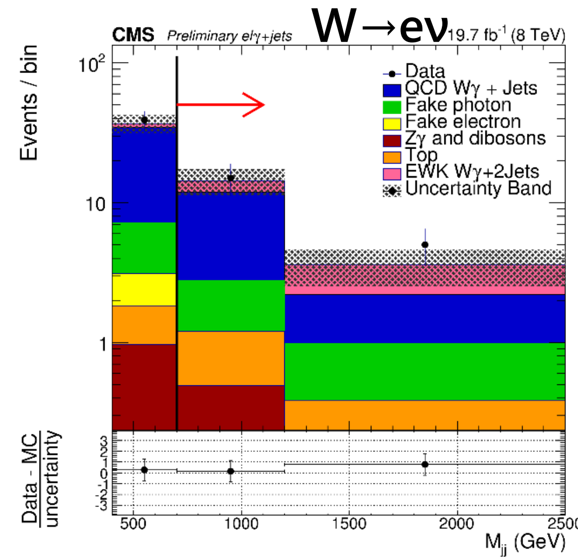
- Selection
  - Z→e⁺e⁻ or μ⁺μ⁻, $70 < m_{\ell\ell} < 110$ GeV
  - $m_{jj} > 400$ GeV, $\Delta\eta_{jj} > 1.6$, $\Delta\phi_{Z\gamma,jj} > 2.0$, $\left|y_{Z\gamma} - \frac{(y_{j_1}+y_{j_2})}{2}\right| < 1.2$
- Evidence of VBS: significance of 3.0σ over background (2.1σ expected)
- EWK cross section: $\mathbf{1.86^{+0.89}_{-0.75}(stat)^{+0.41}_{-0.27}(syst) \pm 0.05(lumi)\ fb}$
- MadGraph LO: $\mathbf{1.26 \pm 0.11(scale) \pm 0.05(PDF)\ fb}$
- Most stringent limits to date on several dimension-8 aQGC parameters



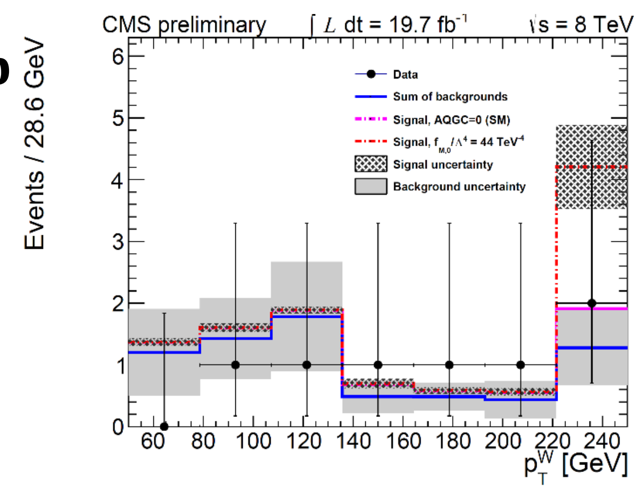


EWK Wγ+2jets at 8 TeV

CMS-PAS-SMP-14-011



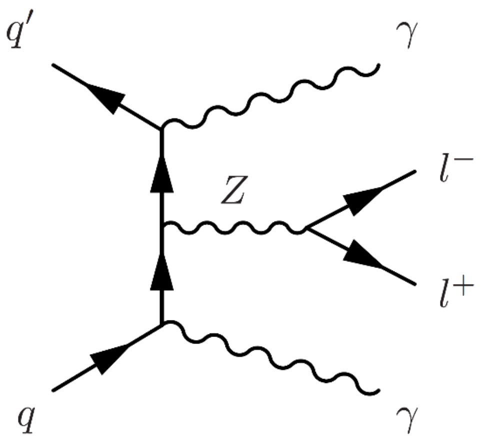
- **Selection:**
  - W→eν or μν, $E_T^{miss} > 35$ GeV
  - $m_{jj} > 700$ GeV, $\Delta\eta_{jj} > 1.6$, $\Delta\phi_{W\gamma,jj} > 2.6$, $\left|y_{W\gamma} - \frac{(y_{j_1}+y_{j_2})}{2}\right| < 0.6$
- **Excess consistent with EWK production with significance of 2.7σ (1.5σ expected)**
- **EWK-only fiducial cross section:** $\mathbf{10.8 \pm 4.1(stat) \pm 3.4(syst) \pm 0.3(lumi)\ fb}$
- **MadGraph NLO:** $\mathbf{6.1 \pm 1.2(scale) \pm 0.2(PDF)\ fb}$
- **Most stringent limits to date on several dimension-8 aQGC parameters**

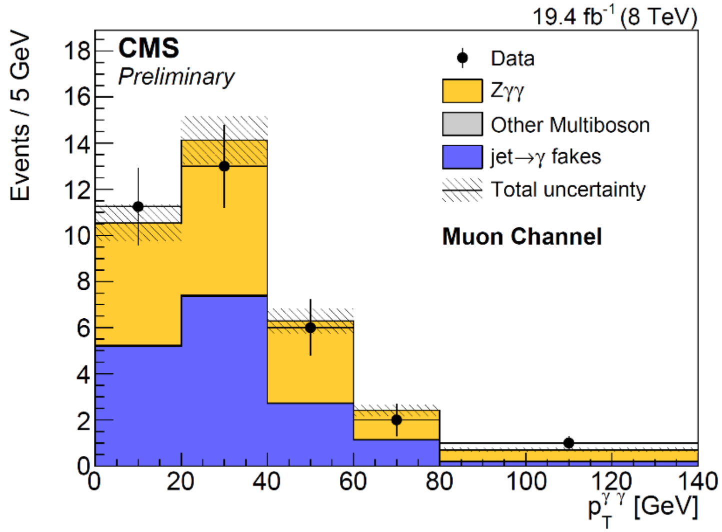


Zγγ at 8 TeV

CMS-PAS-SMP-15-008

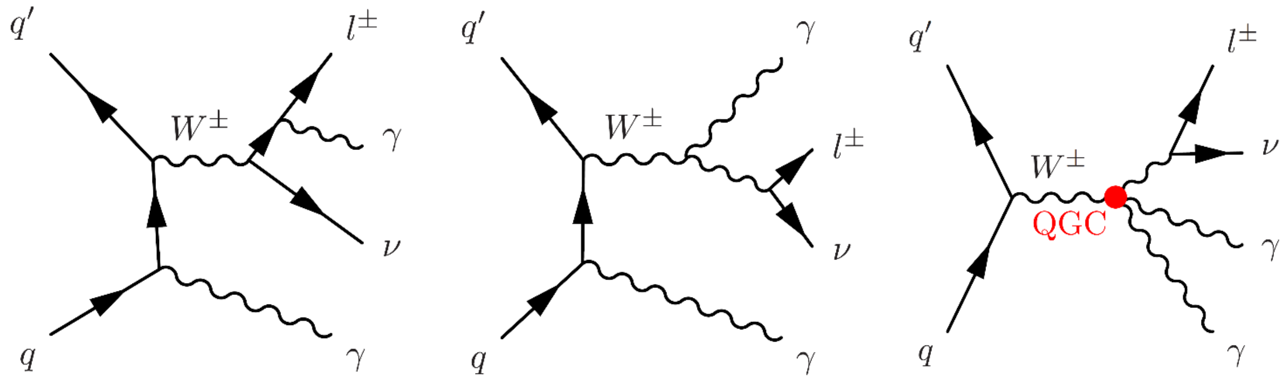
- Unique view of aQGC: 3/4 bosons in potential vertex identified and measured well
- Observation: 5.9σ above background
- $\sigma^{\mathrm{fid}}_{Z\gamma\gamma} \times \mathcal{B}(Z \to \ell\ell) = 12.7 \pm 1.4(\mathrm{stat}) \pm 1.8(\mathrm{syst}) \pm 0.3(\mathrm{lumi})$ fb
  - MadGraph NLO: 12.95 ± 1.47 fb
- Largest systematic is jet→photon misidentification rate
- Also used to obtain aQGC limits



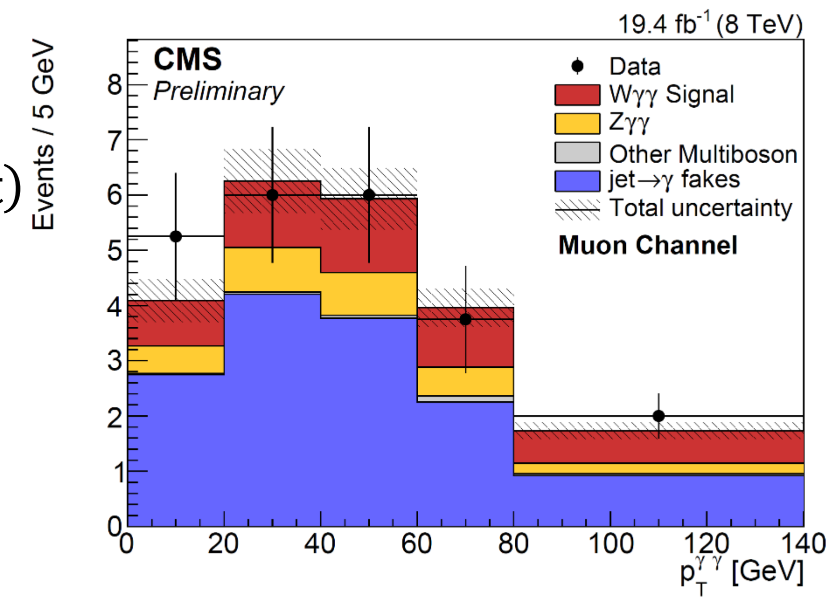


Wγγ at 8 TeV

CMS-PAS-SMP-15-008



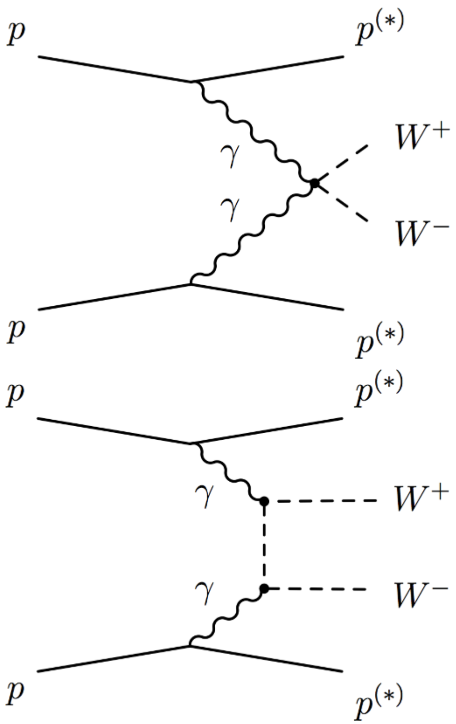
- Photons may be ISR/FSR, TGC or QGC
- Significance over background: 2.4σ
- $\sigma^{\mathrm{fid}}_{W^\pm\gamma\gamma} \times \mathcal{B}(W \to \ell\nu) = 6.0 \pm 1.8(\mathrm{stat}) \pm 2.3(\mathrm{syst}) \pm 0.2(\mathrm{lumi})\ \mathrm{fb}$
  - MadGraph NLO: 4.76 ± 0.53 fb
- As for Zγγ, largest systematic is from photon fake rate



$\gamma\gamma \to W^+W^-$ at 8 TeV

CMS-PAS-FSQ-13-008
Submitted to JHEP

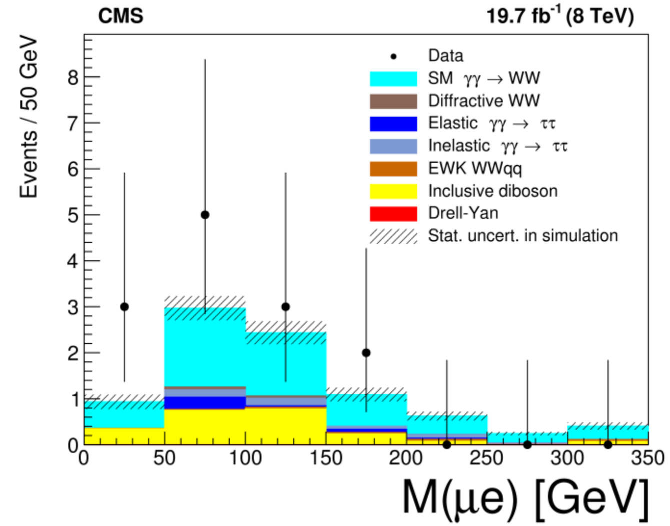
- **Useful to examine gauge couplings with initial and final states fully specified**
  - Direct sensitivity to $\gamma\gamma WW$ quartic coupling
- **Idea: use LHC as a photon-photon collider**
- **Protons scatter elastically or break up, but either way are too forward to see**
  - Signature: coplanar $e^{\pm}\mu^{\mp}$ from vertex with no other charged tracks
- **$\gamma\gamma \to \ell^+\ell^-$ events used to understand efficiency, background, and nonperturbative effects**

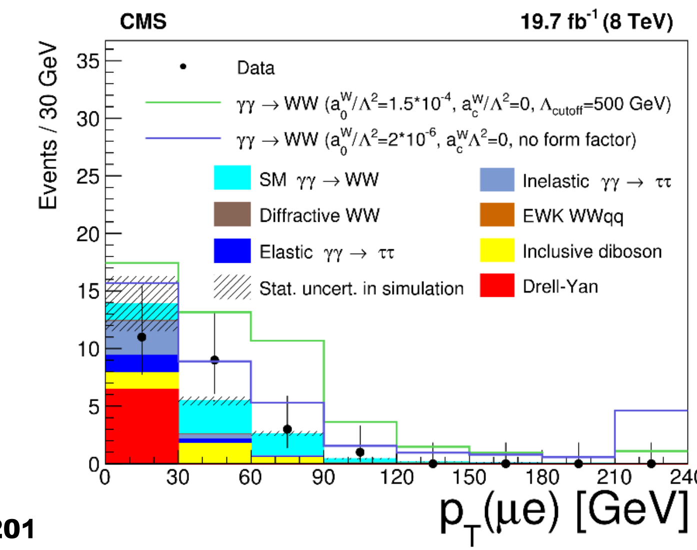


$\gamma\gamma \rightarrow W^+W^-$ at 8 TeV

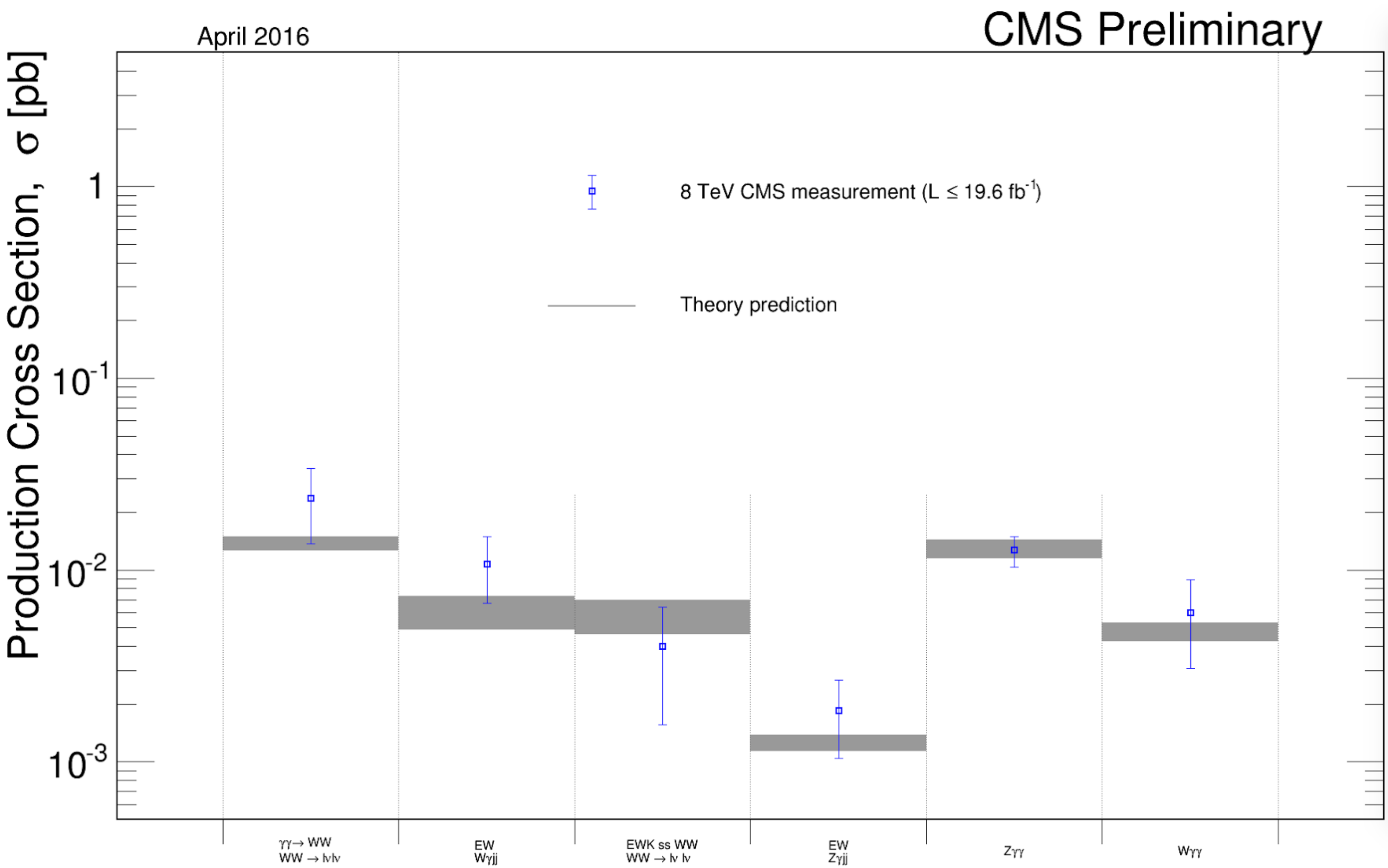
CMS-PAS-FSQ-13-008
Submitted to JHEP

- Combination of 7 and 8 TeV shows evidence of process with significance of 3.4σ (2.8σ expected)
- $\sigma\left(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}\right) = 11.9^{+5.6}_{-4.5}\ \mathrm{fb}$
- MadGraph: $6.9 \pm 0.6\ \mathrm{fb}$
- Primary uncertainties are statistics and effect of proton dissociation
- Most stringent limits to date on several dimension-6 and dimension-8 aQGC parameters



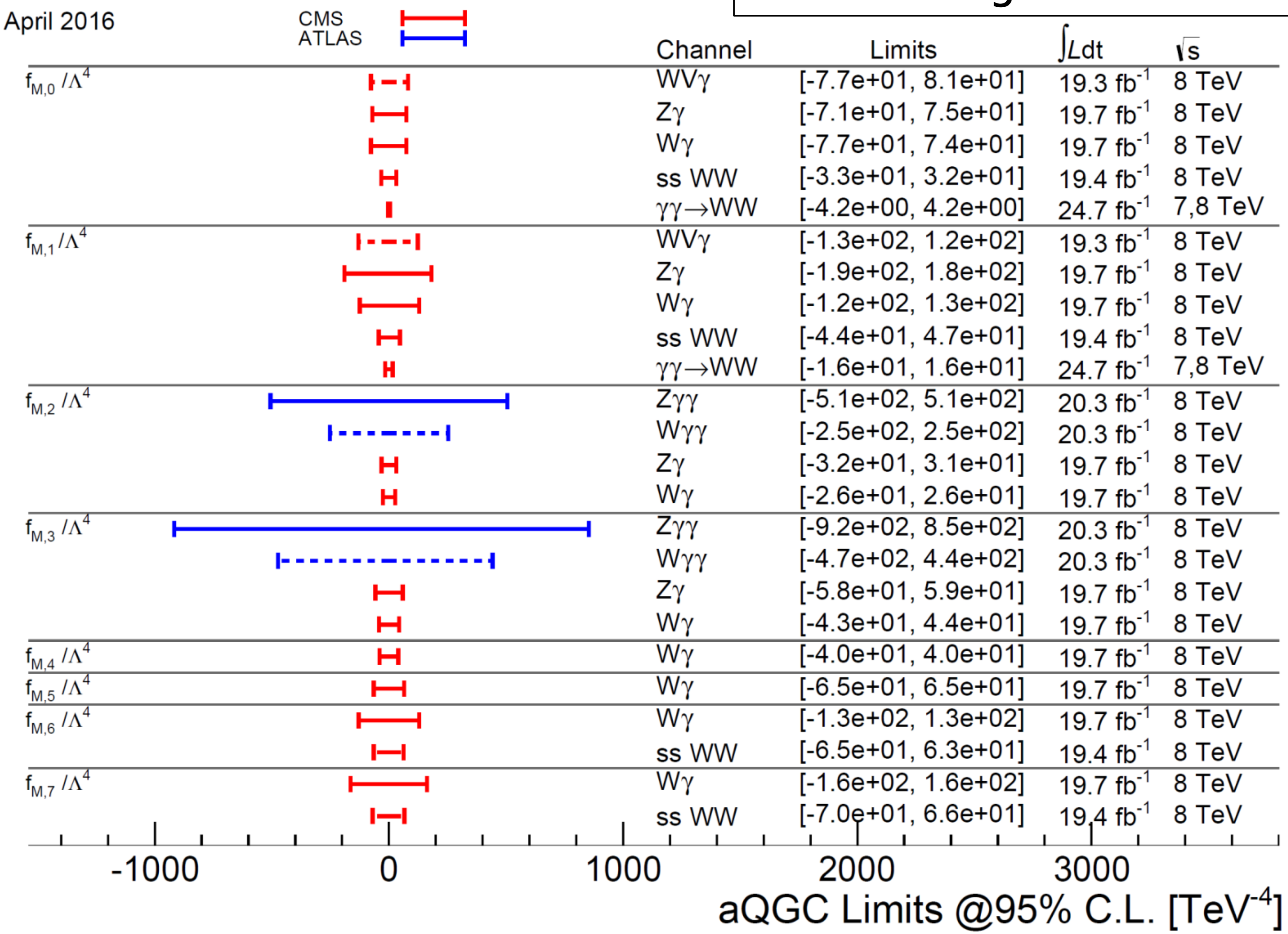


8 TeV Cross Section Summary



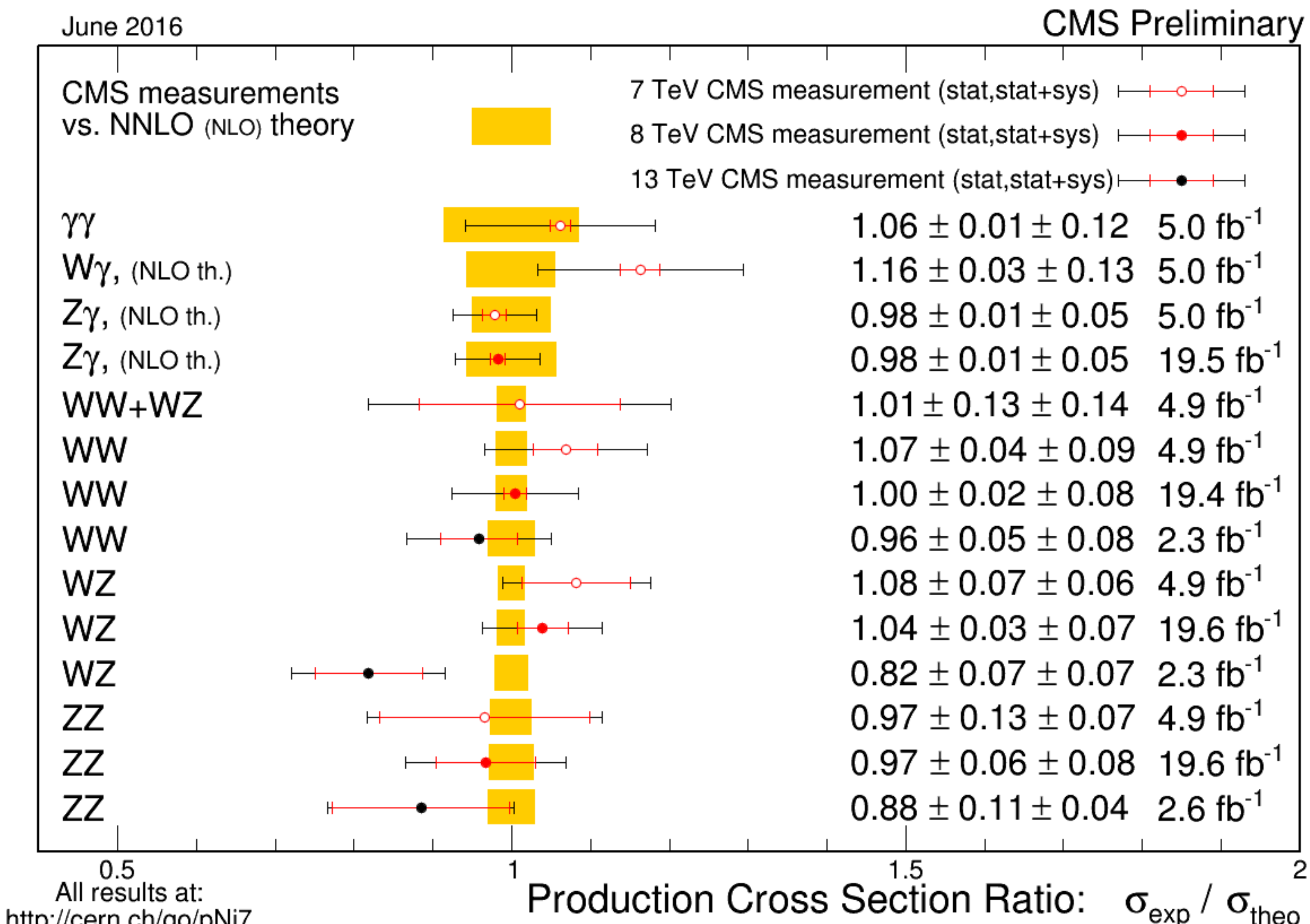
aQGC Limits—Longitudinal + Transverse

Limits on longitudinal terms in backup



Coupling	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-3.3e+01, 3.2e+01]	19.4 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.4e+01, 4.7e+01]	19.4 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
$f_{M,2}/\Lambda^4$	Zγγ	[-5.1e+02, 5.1e+02]	20.3 fb^{-1}	8 TeV
	Wγγ	[-2.5e+02, 2.5e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	Zγγ	[-9.2e+02, 8.5e+02]	20.3 fb^{-1}	8 TeV
	Wγγ	[-4.7e+02, 4.4e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.5e+01, 6.3e+01]	19.4 fb^{-1}	8 TeV
$f_{M,7}/\Lambda^4$	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-7.0e+01, 6.6e+01]	19.4 fb^{-1}	8 TeV

CMS VV Cross Section Summary



Summary

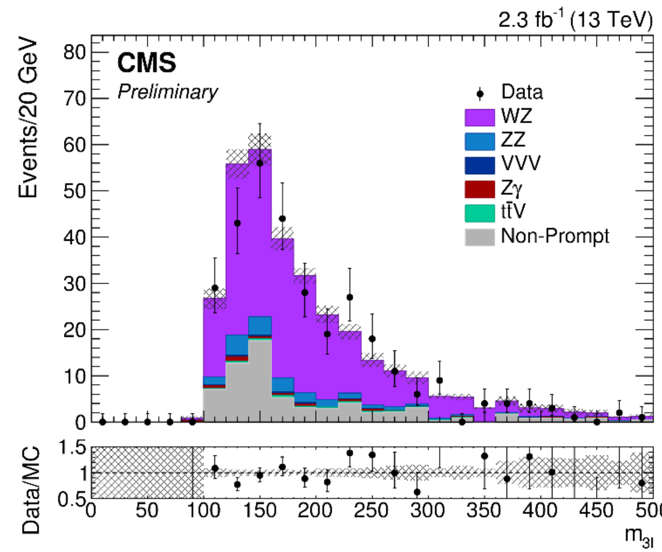
- Multiboson measurements at CMS continue to shed light on the electroweak sector of the Standard Model
- 13 TeV WW, WZ, and ZZ cross sections are measured and compared to NNLO predictions
- $Z \rightarrow 4\ell$ branching ratio is measured in 13 TeV four-lepton data
- Evidence of 8 TeV EWK $Z\gamma$+2 jets production seen with significance of 3.0σ; search for EWK $W\gamma$+2 jets performed
- 8 TeV $Z\gamma\gamma$ observed with significance of 5.9σ; $W\gamma\gamma$ search performed
- Evidence of $\gamma\gamma \rightarrow WW$ seen at 8 TeV with significance of 3.4σ
- Run-I results are used to place stringent new limits on anomalous quartic gauge couplings

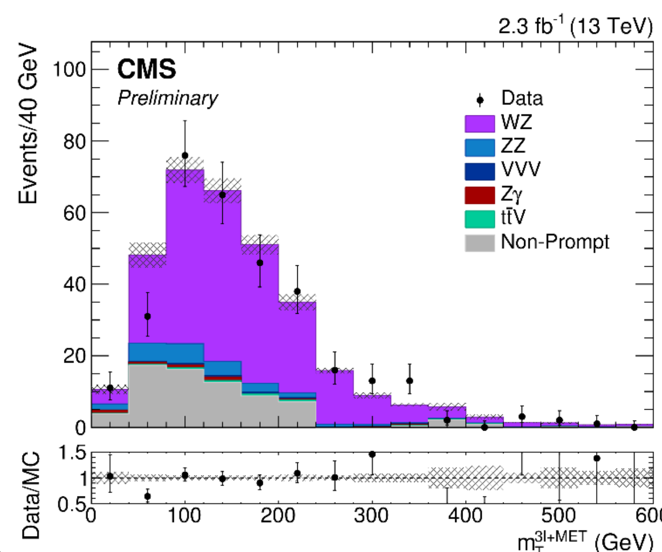
Backup

More on WZ

CMS-PAS-SMP-16-002

- $76 < m_{\ell\ell} < 106$ **GeV**, $E_T^{miss} > 30$ **GeV**
- **Background control**
  - Veto events with extra leptons or b-tagged jets with $|\eta| < 2.4$
  - Derive jet→lepton misidentification probability in dijet control region
  - Apply mis-ID rate to control regions where 1,2, or 3 leptons fail ID or isolation
- **Largest systematic is background estimation, ~6% on the final cross section**

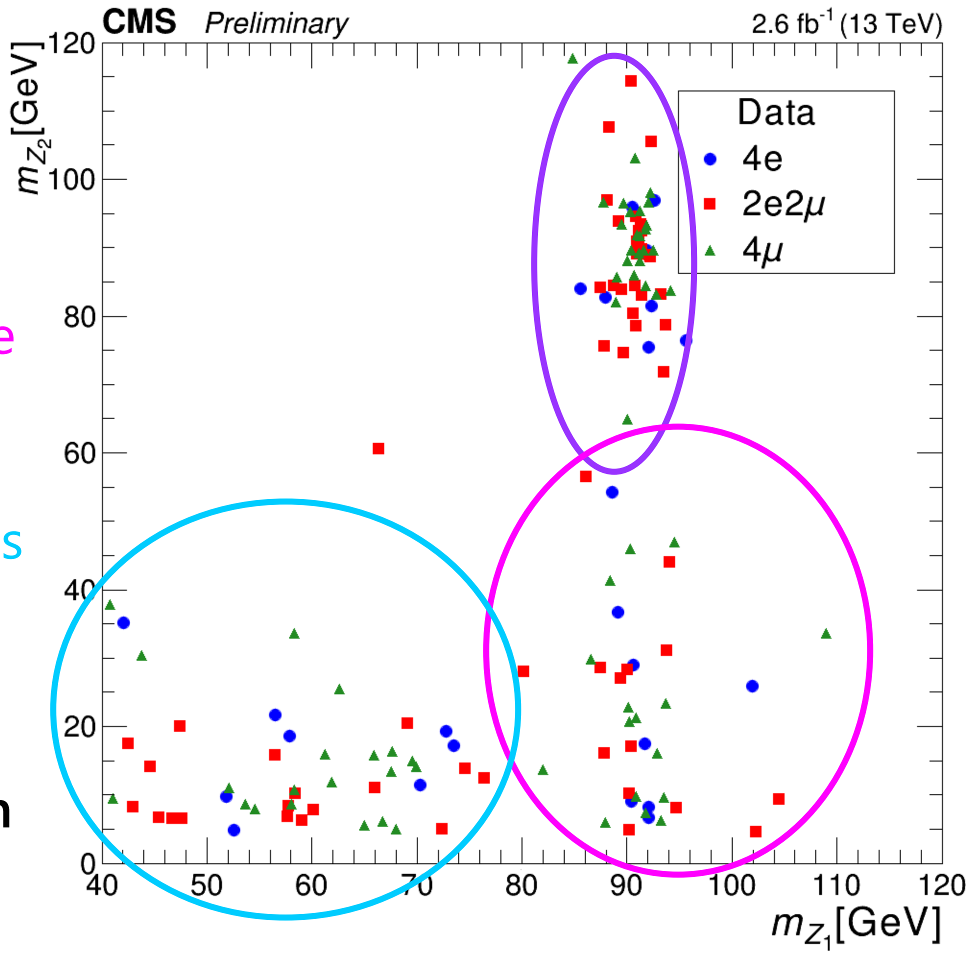




4ℓ Production Mechanisms

CMS-PAS-SMP-16-001

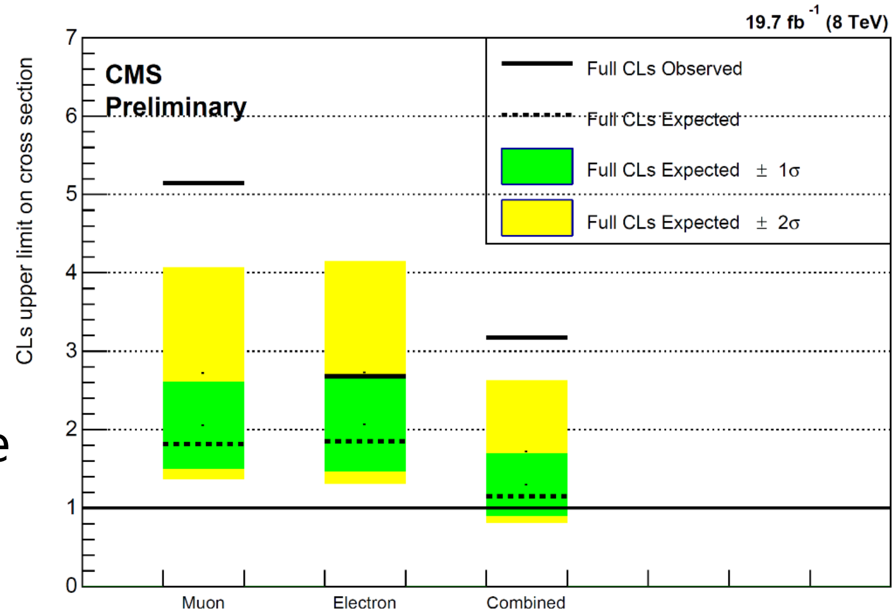
- **4ℓ production mechanisms fall in distinct regions of dilepton mass space**
  - ZZ: both on-shell
  - Zγ*, H→ZZ*: one on-shell, one at lower mass
  - Z→4ℓ: lepton from Z radiates γ*, both lepton pairs low-mass
- **Small backgrounds estimated with lepton mis-ID rate applied to Z+ℓℓ control regions where one or both ℓ fail ID or isolation**



More on EWK Zγ+2jets

CMS-PAS-SMP-14-018

- **Backgrounds**
  - Zγ+QCD jets shape from Monte Carlo, normalization from low-m_{jj} control region in data
  - Z+fake γ estimated from data with fits to photon shower shape variables
- **Limits on EWK cross section shown here**

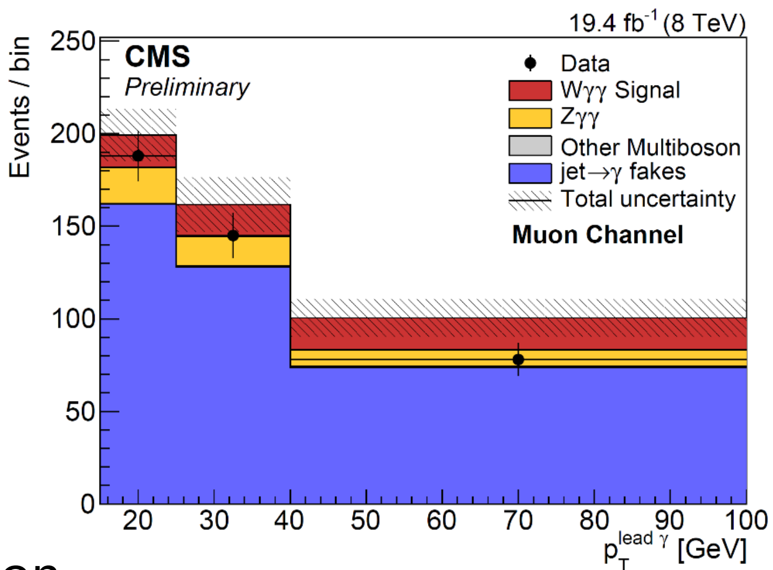


- **EWK+QCD, $m_{jj} > 800$ GeV: 4.5σ observed (4.3σ expected)**
  - $1.00 \pm 0.43(\text{stat}) \pm 0.26(\text{syst}) \pm 0.03(\text{lumi})$ fb
  - MadGraph LO: $0.78 \pm 0.09(\text{scale}) \pm 0.02(\text{PDF})$ fb

More on Wγγ & Zγγ

CMS-PAS-SMP-15-008

- Zγγ: Z→e^+e^- or $\mu^+\mu^-$, $m_{\ell\ell} > 40$ GeV
- Wγγ: W→μν, $m_T(\mu, E_T^{miss}) > 40$ GeV
- Background from jets faking photons large and difficult to estimate
  - Cross-contamination between events with zero, one, and two fake photons estimated with a template normalization method to apply fake rates to data events
  - Correlations between pairs of fakes require use of a separate V+jets sideband

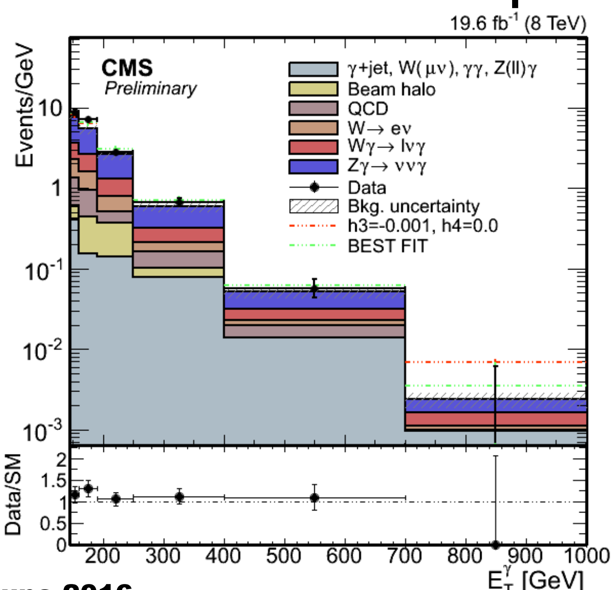


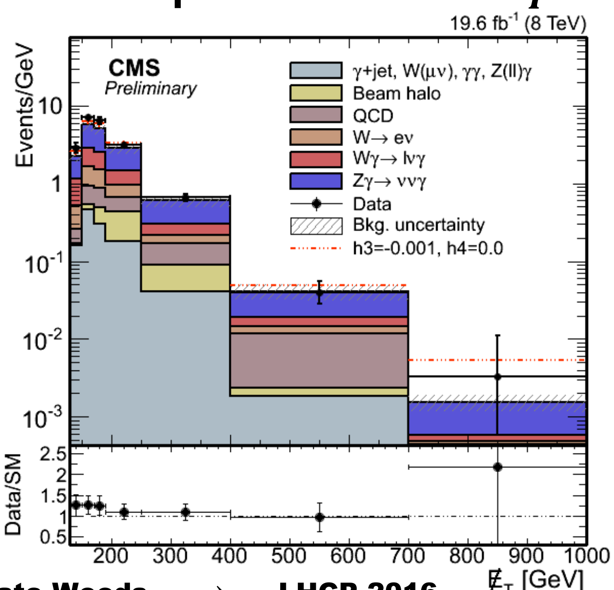
Simulation and data in dijet control region (for background validation)

Z(νν)γ

CMS-PAS-SMP-14-019
Submitted to PLB

- Invisible Z decays have a larger branching ratio and acceptance than leptonic decays, and can be used to set more stringent limits on neutral aTGCs
- Require $E_T^{\gamma} > 145$ GeV, $E_T^{miss} > 140$ GeV, $\Delta\phi(\gamma, E_T^{miss}) > 2$
- Significant non-collision backgrounds in addition to events with lost leptons or fake photons and E_T^{miss}

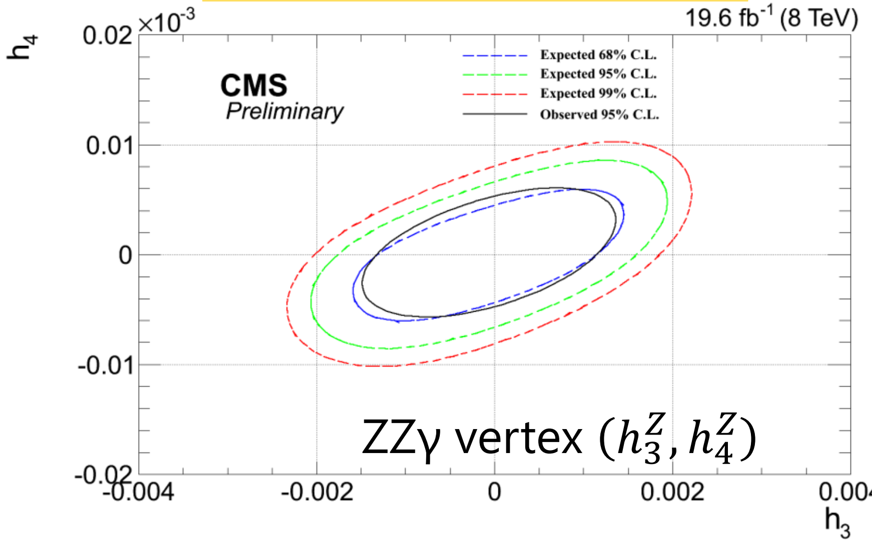


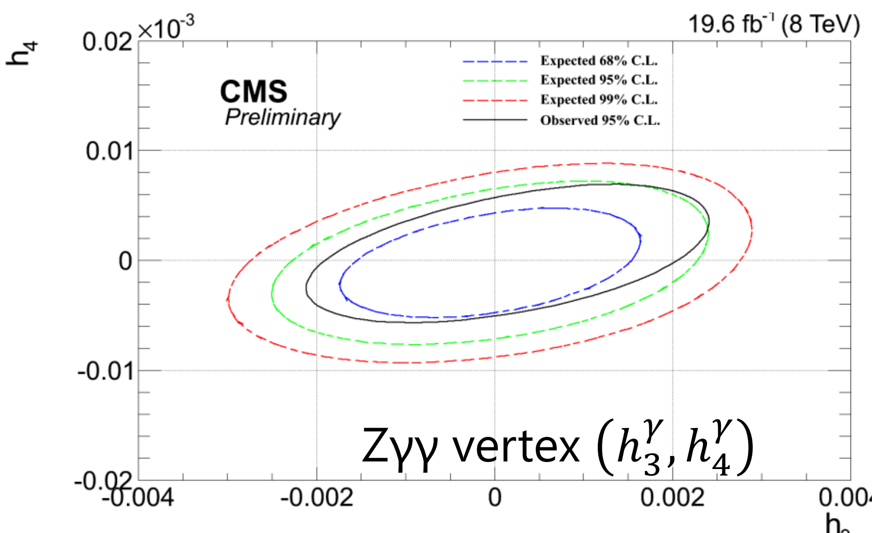


Z(νν)γ

CMS-PAS-SMP-14-019
Submitted to PLB

- Cross section is measured for $E_T^{\gamma} > 145\ GeV, |\eta^{\gamma}| < 1.44$
- $\sigma_{Z\gamma} \times \mathcal{B}(Z \rightarrow \nu\nu) = 52.7 \pm 2.1(\text{stat}) \pm 6.4(\text{syst}) \pm 1.4(\text{lumi})\ \text{fb}$
  - MCFM NLO: 40.7 ± 4.9 fb
  - Grazzini et al. NNLO: $50.0^{+2.4}_{-2.2}$ fb
- Limits set on aTGC parameters governing ZZγ and Zγγ vertices are the most stringent to date





Anomalous Quartic Gauge Coupling Details

- **Treat SM as a low-energy effective theory and add terms with new dimension-8 operators to represent new physics**
  - Lowest dimension that gives aQGC without aTGC
- **Parameterize search in coefficients of these new terms**
- **Non-unitary without model-dependent form factor or cutoff**

		Couplings modified								
	Terms	WWWW	WWZZ	ZZZZ	WWZγ	WWγγ	ZZZγ	ZZγγ	Zγγγ	γγγγ
Longitudinal + transverse	$f_{M0}, f_{M1}, f_{M6}, f_{M7}$	✓	✓	✓	✓	✓	✓	✓		
	$f_{M2}, f_{M3}, f_{M4}, f_{M5}$		✓	✓	✓	✓	✓	✓		
Transverse	f_{T0}, f_{T1}, f_{T2}	✓	✓	✓	✓	✓	✓	✓	✓	✓
	f_{T5}, f_{T6}, f_{T7}		✓	✓	✓	✓	✓	✓	✓	✓
	f_{T8}, f_{T9}			✓			✓	✓	✓	✓

Table modified from here

aQGC Limits—Transverse Only