Observation of the electroweak production of Zγ and two jets at 13 TeV and constraints on EFTs

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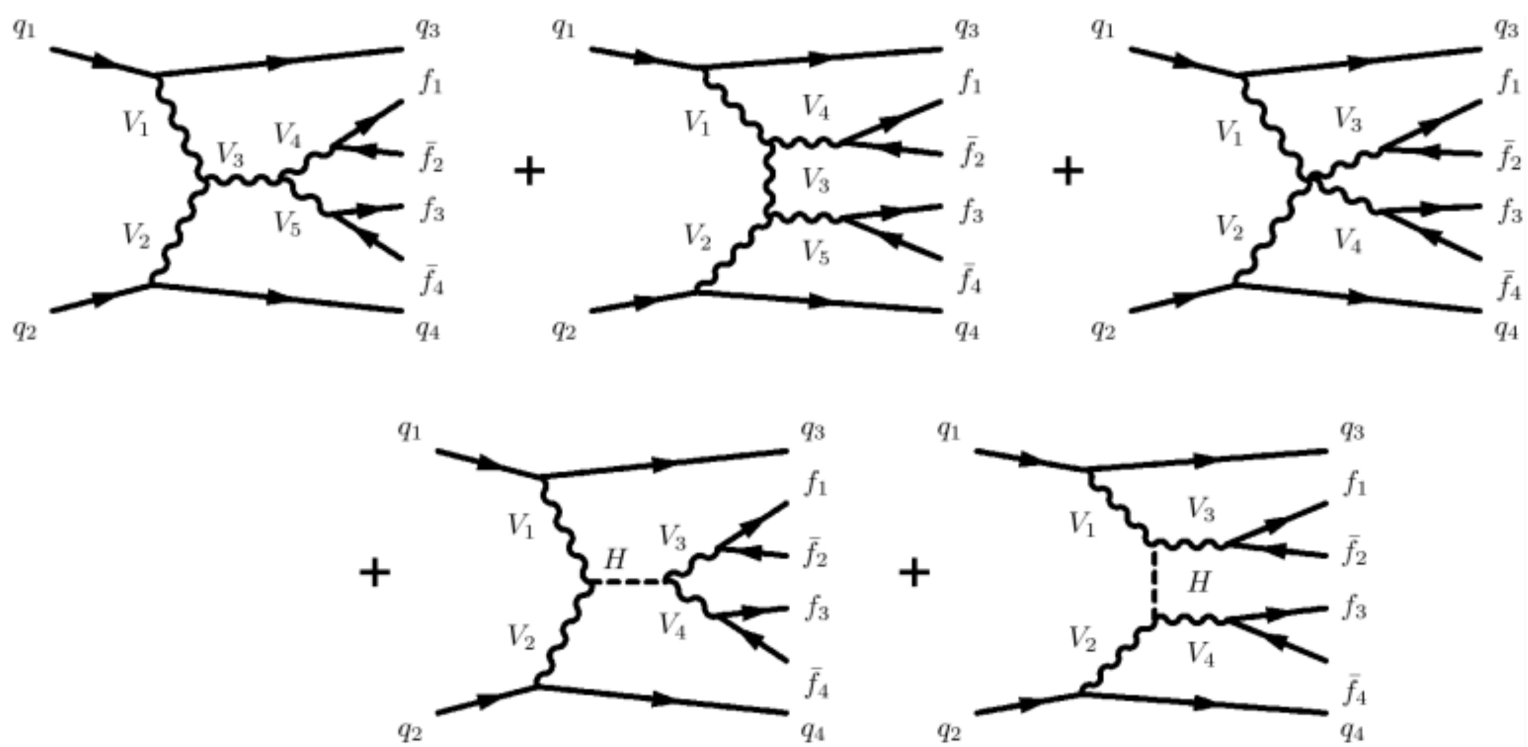
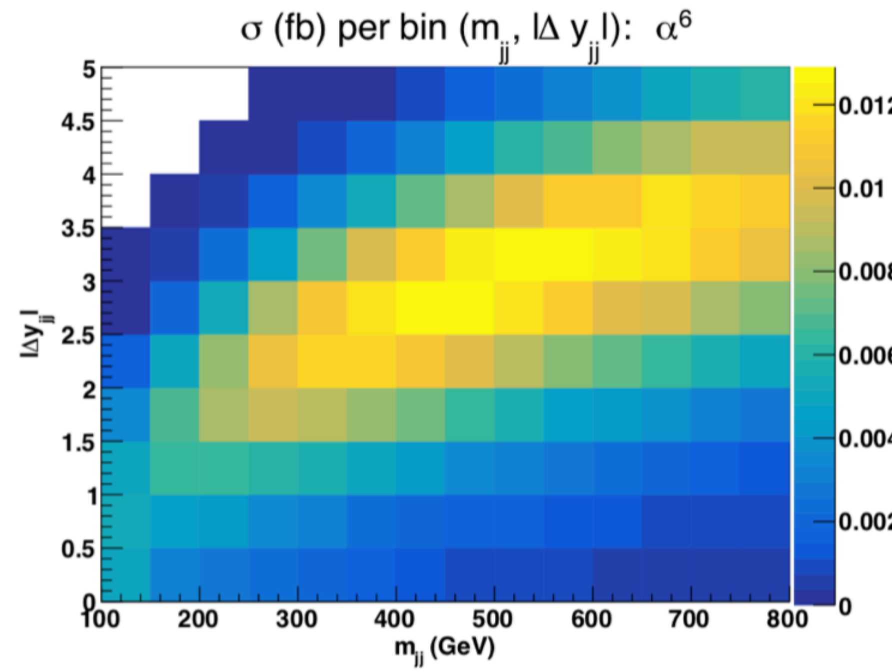
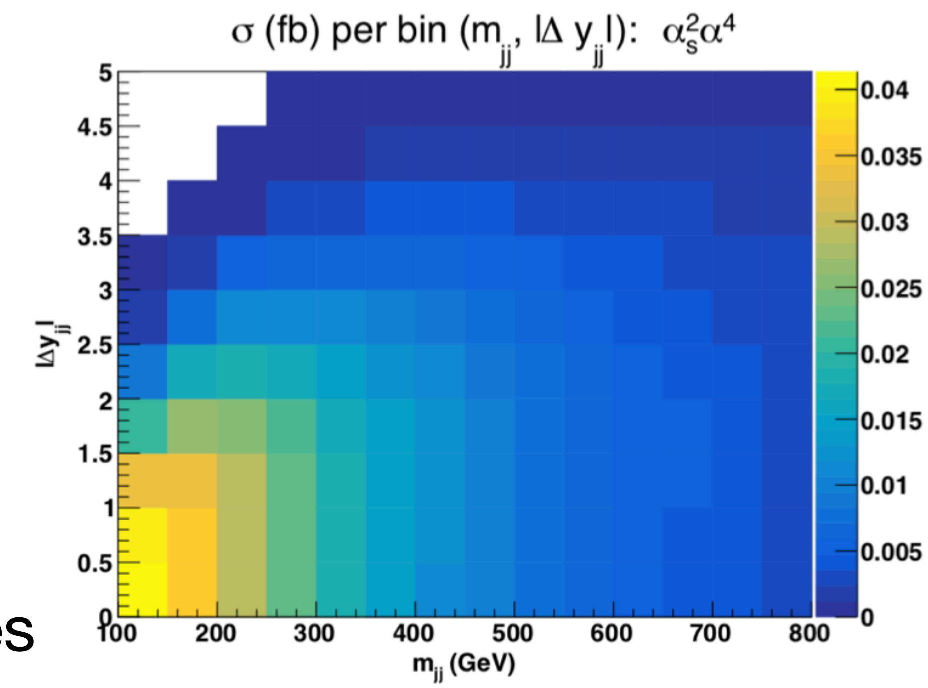
2021.08.17

Introduction & Motivation

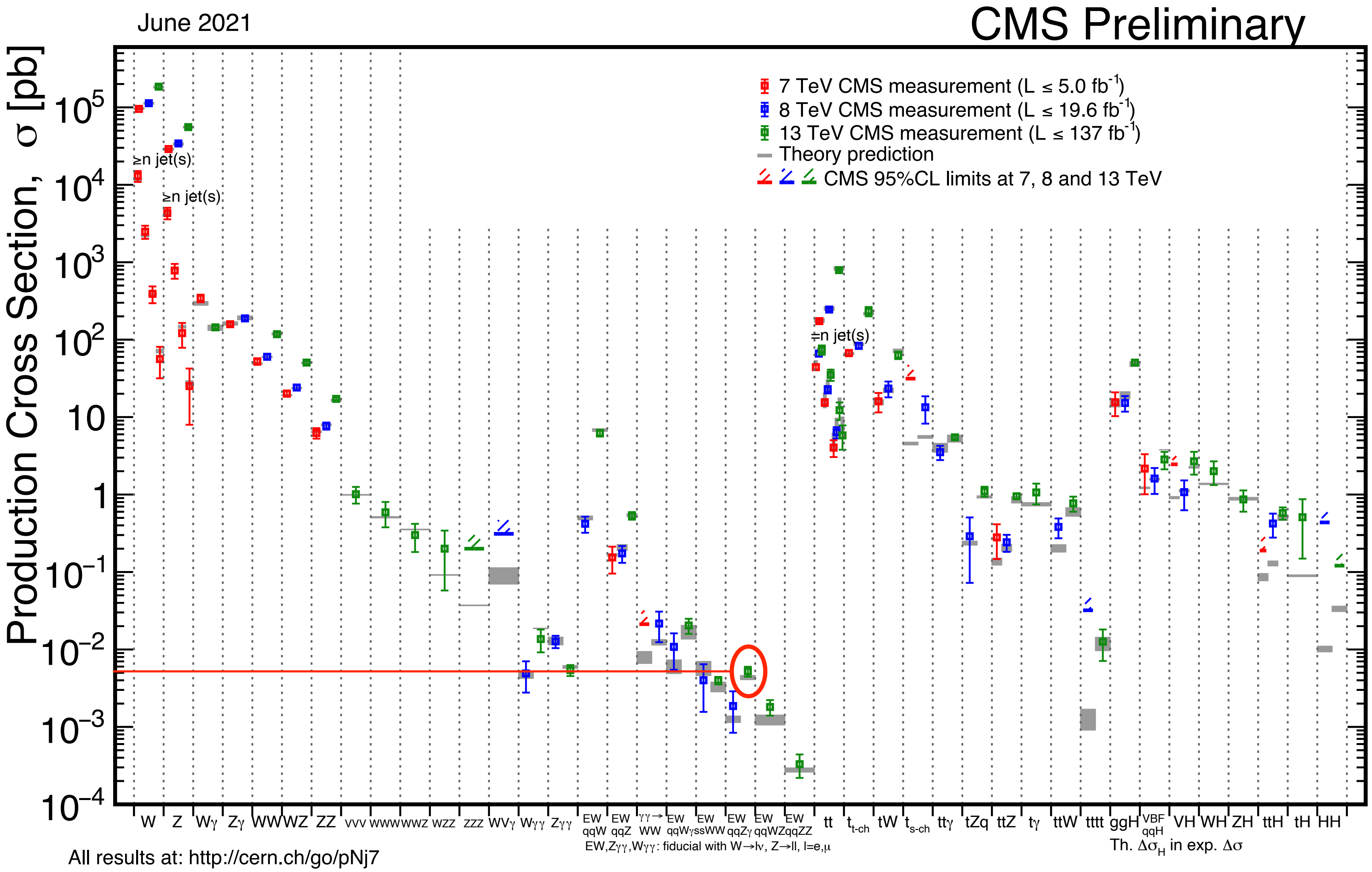




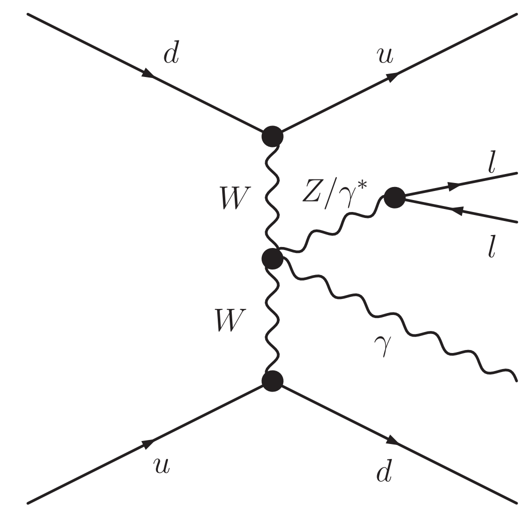


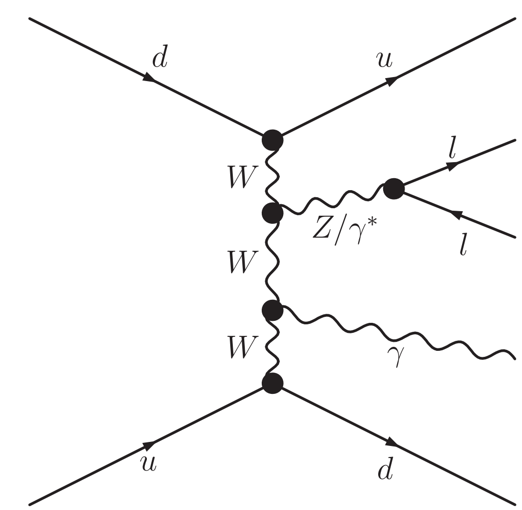
- **Signal:** six fermions final state at leading order $\mathcal{O}(\alpha^6)$
- **Irreducible background:** QCD-induced $\mathcal{O}(\alpha^4\alpha_s^2)$
- Interference: between EW and QCD $\mathcal{O}(\alpha^5\alpha_s)$
- **Reducible** background due to mis-ID of final state particles
- Significant systematic uncertainties from jet energy reconstruction and background modeling

Introduction & Motivation



arxiv.org/abs/2106.11082





Final states: Z to ee/μμ plus a photon with two additional jets.

Vector boson scattering (VBS) signature: large dijet mass and large η separation between the jets.

Main results:

- ✓ Signal significance
- ✓ Fiducial cross section
- ✓ Unfolded differential cross section
- ✓ Limits on anomalous couplings

Sample & Selection

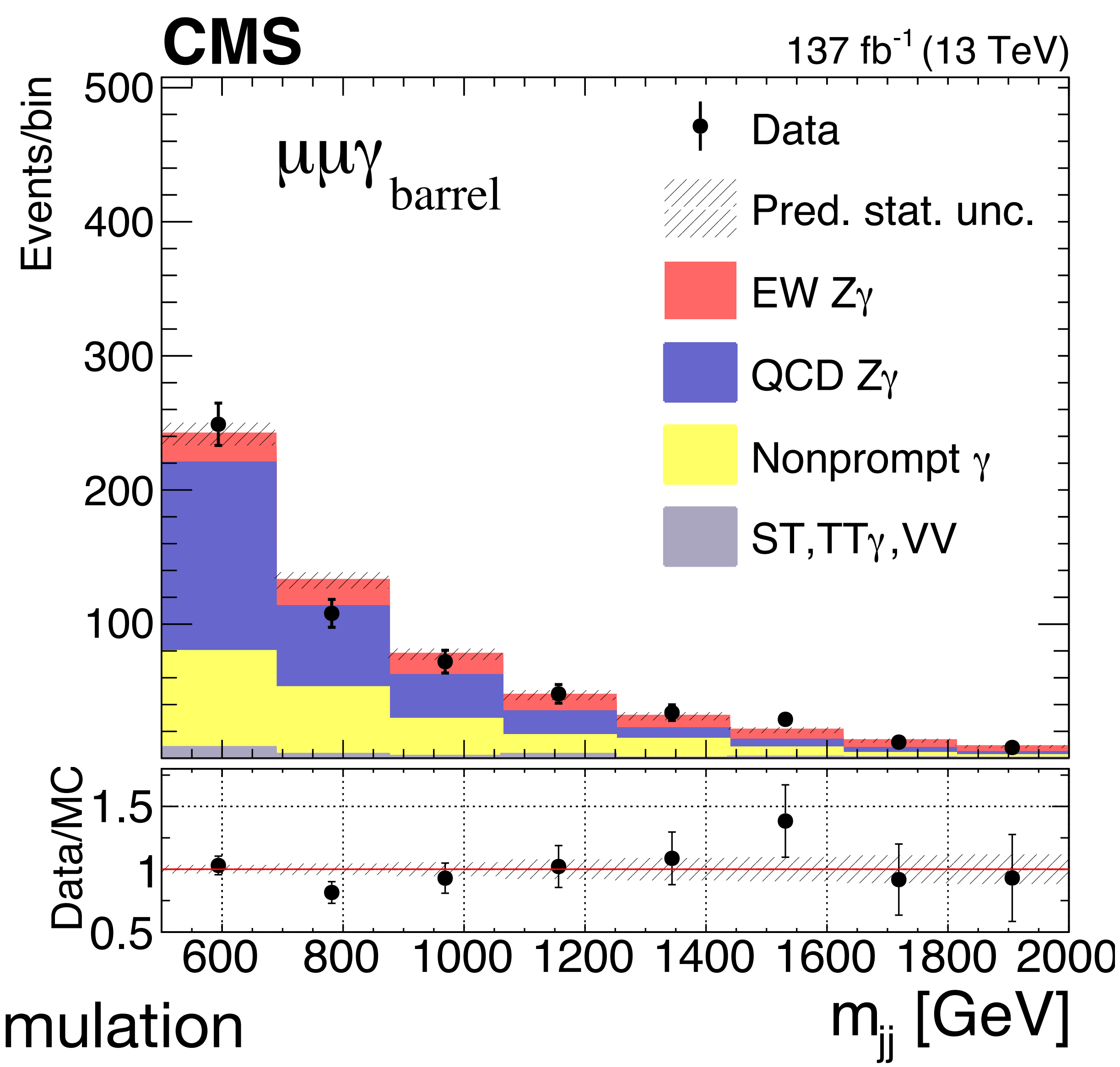
Data: collected from 2016 to 2018 with integrated luminosity: 137 fb^{-1}

Signal: EW Zγjj

- MadGraph_aMC@NLO (MG5) at LO
- Pythia8 with CP5 (CUETP8M1 for 2016)
- NNPDF 3.1(3.0 for 2016)
- $m_{ll} > 50$ GeV

Backgrounds:

- **Zγ plus QCD jets** from simulation
  - MG5 with FxFx jet merging scheme at NLO
  - Pythia8 with CP5 (CUETP8M1 for 2016)
  - NNPDF 3.1(3.0 for 2016)
- **Nonprompt photon** from data
- **EW/QCD Interference** from simulation
- **Di-boson,** $t\bar{t}\gamma$ and **single top** from MG5 simulation
  - di-boson: Pythia8 at LO
  - $t\bar{t}\gamma$: MG5 at NLO with FxFx jet merging scheme
  - single top: POWHEG at NLO



Sample & Selection

Working points (WP): a series of variables reflecting the properties of the particle are optimized to identify the particle.

Tight Medium Loose

← High quality → High efficiency

Good Muon

- Tight muon WP
- Relative PF-isolation (0.4 cone) <0.15
- $p_T > 20$ GeV, $|\eta| < 2.4$

Veto Muon

- Loose muon WP
- Relative PF-isolation (0.4 cone) <0.25
- $p_T > 20$ GeV, $|\eta| < 2.4$

Veto Electron

- Loose electron WP
- $p_T > 20$ GeV, $|\eta| < 2.5$, $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

For third lepton veto

Good Electron

- Medium electron WP
- $p_T > 25$ GeV, $|\eta| < 2.5$

Good Photon

- Medium photon WP
- Electron veto
- $p_T > 20$ GeV and $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

Jets

- Particle-flow jets and AK4CHS (0.4 cone; charged particles from pileup are removed)
- Tight jet WP and pileup jet WP ($p_T < 50$ GeV)
- p_T>30 GeV
- $|\eta| < 4.7$

Sample & Selection

- Two same-flavor opposite-sign tight leptons ★
- Double muon/electron HLT paths
- Third lepton veto
- 70 GeV $< m_{ll} <$ 110 GeV ★
- One good photon in barrel/endcap ★
- Two jets with $p_T > 30$ GeV, $|\eta| < 4.7$ ★

Basic event selection

- $m_{ll\gamma} > 100$ GeV

Suppress FSR

- 150 GeV $< m_{jj} < 500$ GeV

Low m_{jj} control region

- $m_{jj} > 500$ GeV ★
- $\Delta\eta_{jj} > 2.5$ ★

VBS Signal region

- $p_T^{\gamma} > 120$ GeV

Special cut added for aQGC

- zepp $= |\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2| < 2.4$
- dphi $= |\phi_{Z\gamma} - (\phi_{j1} + \phi_{j2})| > 1.9$

EW signal extraction
for signal significance

Selection with ★ in the generator-level defines the **fiducial volume**

Background estimation

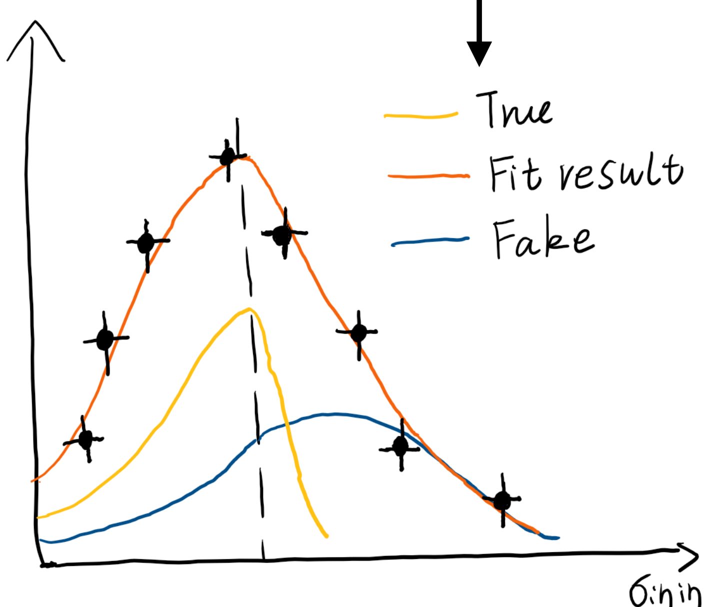
- Background processes estimated from simulation are normalized to the best theoretical cross section prediction.
- Irreducible background QCD Zγ normalization is constrained by data in the low m_{jj} control region.
- A data-driven method is used to estimate nonprompt photon contribution.

From Data

Fake photon enriched sample by inverting one of cut in the photon WP with data

$$n_{fake}^{weighted} = n_{tot} \times \epsilon_{\text{fake-fraction}} = N_{fake}^{unweighted} \times weights$$

Shape as the PDF



A shower shape variable

True photon is from QCD Zγ with medium photon WP and matched to generator-level

Fake photon is from data by inverting charged isolation with an appropriate sideband.
Closure test was done to select a best charged isolation sideband

Data is from data with medium photon WP

$$\textbf{weight}(p_T^{\gamma}) = \frac{n_{data}(p_T^{\gamma})}{N_{fake}^{unweighted}(p_T^{\gamma})} \times \epsilon_{\text{fake-fraction}}(p_T^{\gamma})$$

Systematic uncertainties

QCD Factorization and renormalization scale uncertainty

- Exclude the two variations where $(2\mu_0, 0.5\mu_0)$ and $(0.5\mu_0, 2\mu_0)$. μ_0 is the nominal scale.
- Nuisance parameter 1: μ_F only, $(2\mu_0, \mu_0)$ and $(0.5\mu_0, 1\mu_0)$
- Nuisance parameter 2: μ_R only, $(\mu_0, 2\mu_0)$ and $(1\mu_0, 0.5\mu_0)$
- Nuisance parameter 3: $\mu_R + \mu_F$ fully correlated, $(2\mu_0, 2\mu_0)$ and $(0.5\mu_0, 0.5\mu_0)$
- Calculated bin-by-bin, correlated between bins, categories, and years

Theoretical

PDF uncertainty

- Standard deviation of the around 100 NNPDF PDF set variations
- Calculated bin-by-bin, correlated between bins, categories, and years

Jet energy resolution&scale uncertainty

Experimental

- Calculated bin-by-bin, correlated between bins and categories, uncorrelated between years

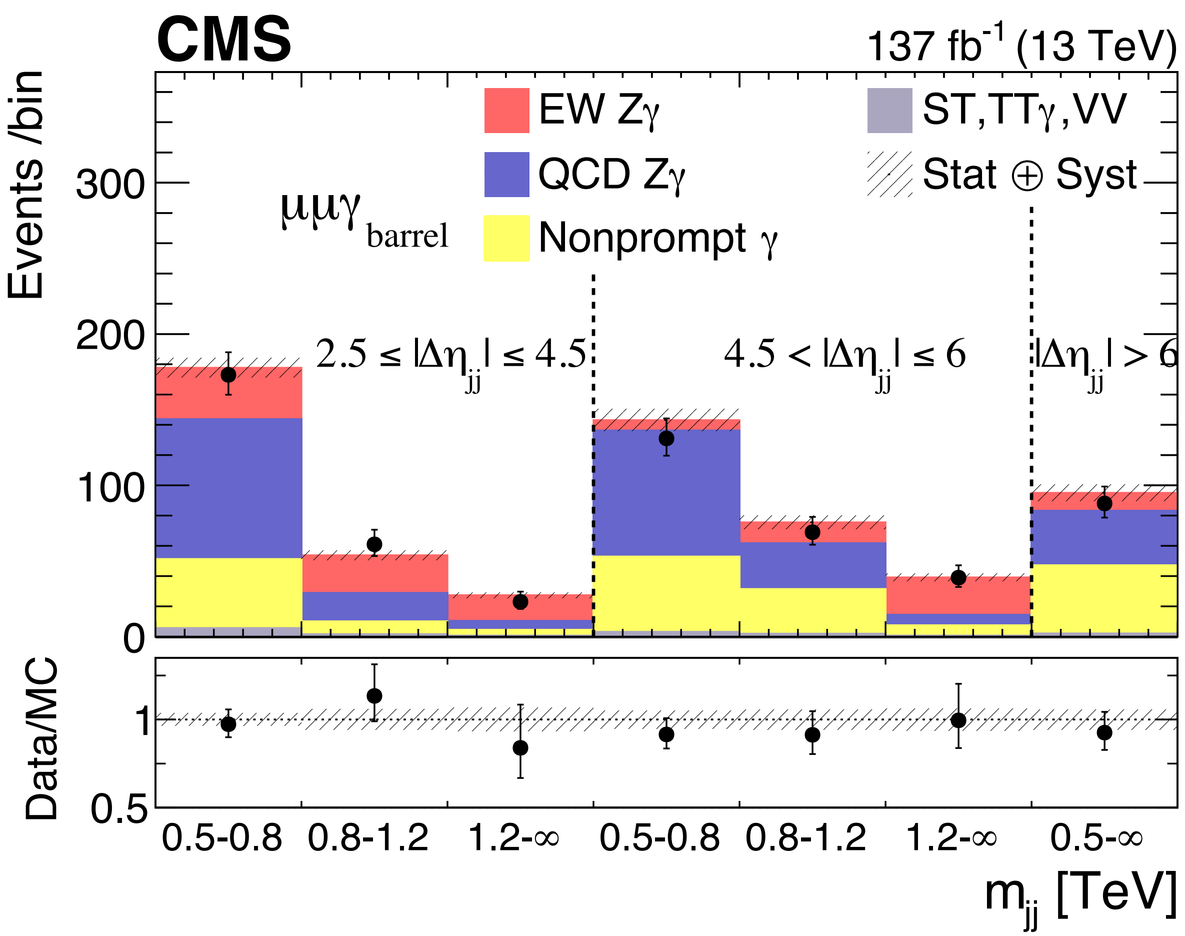
Nonprompt photon uncertainty

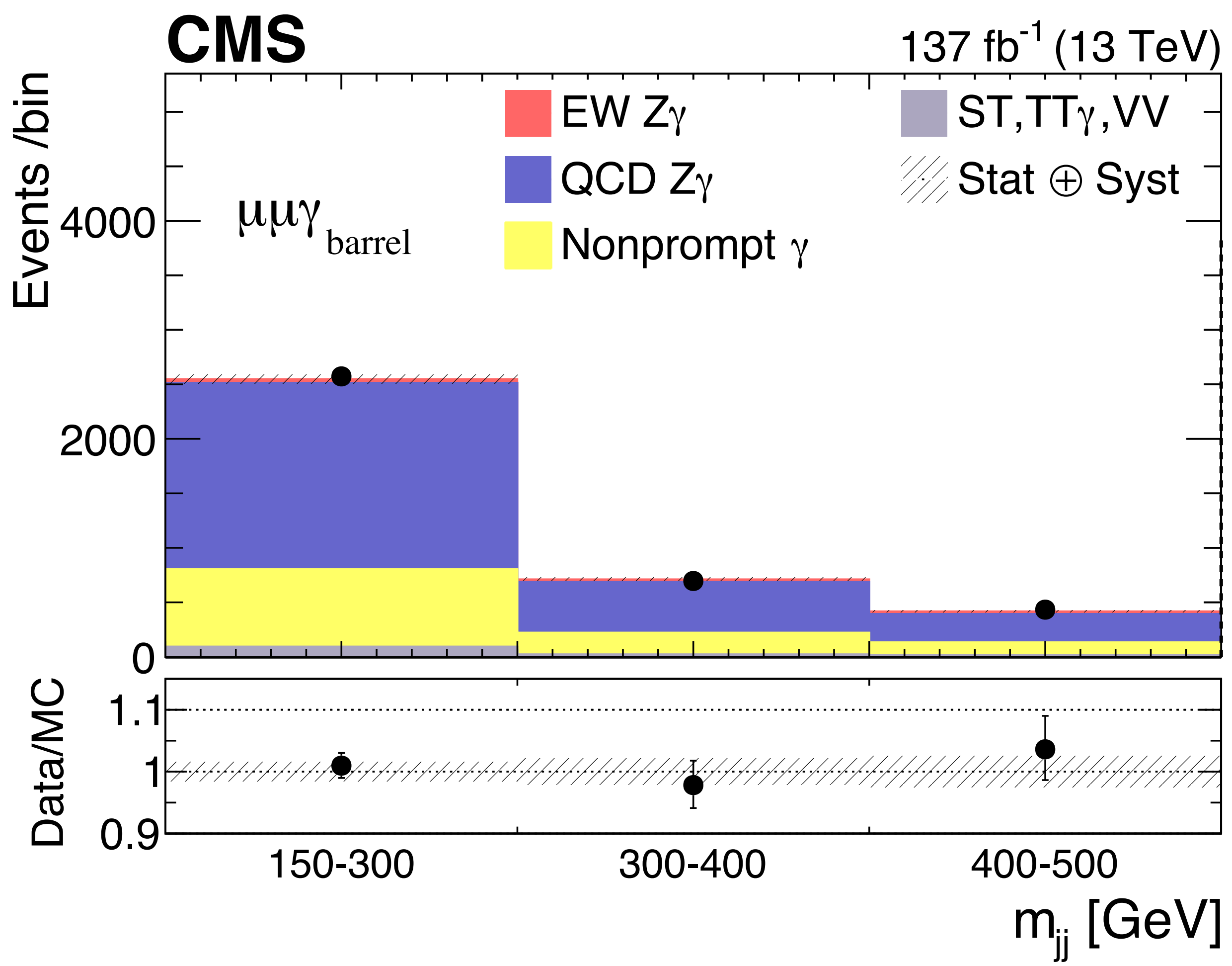
- Closure test + Sideband choice + True template choice
- Calculated bin-by-bin, correlated between bins, uncorrelated between categories and years

MC Statistical uncertainty

Efficiencies of lepton/photon ID/ISO/Reco, HLT, pileup, L1prefiring and luminosity.

Signal significance





The significance is calculated using a **simultaneous fit** in the signal region with **2D mjj-Δηjj** binning and the control region with **1D mjj binning** in 4 categories for muon/electron choice and barrel photon/endcap photon choice.

- The observed (expected) significance is 9.4 σ (8.5 σ).

Fiducial cross section

$$\sigma_{fiducial-region} = \sigma_{generator} \cdot \mu_{signal-strength}$$

- $\mu_{\text{signal-strength}}$ is the best-fit signal strength, representing the ratio of observed to expected signal yields, which is
  - ☑ $\mu = 1.20^{+0.12}_{-0.12}\,(\text{stat})\,^{+0.14}_{-0.12}\,(\text{syst}) = 1.20^{+0.18}_{-0.17}$ for EW
  - ☑ $\mu = 1.11^{+0.06}_{-0.06}\,(\text{stat})\,^{+0.10}_{-0.09}\,(\text{syst}) = 1.11^{+0.12}_{-0.11}$ for EW+QCD.
- $\sigma_{\text{generator}}$ is the cross section computed by the generator (MadGraph5_aMC@NLO) in the fiducial region which is
  - ☑ $\sigma_{\text{generator}} = 4.34 \pm 0.26\,(\text{scale}) \pm 0.06\,(\text{PDF})$ fb for EW
  - ☑ $\sigma_{\text{generator}} = 13.3 \pm 1.72\,(\text{scale}) \pm 0.10\,(\text{PDF})$ fb for EW+QCD
- $\sigma_{\text{fiducial-region}}$ and its uncertainty is the calculated
  - ☑ $\sigma_{fid} = 5.21 \pm 0.52\,(\text{stat}) \pm 0.56\,(\text{syst}) = 5.21 \pm 0.76$ fb for EW
  - ☑ $\sigma_{fid} = 14.7 \pm 0.80\,(\text{stat}) \pm 1.26\,(\text{syst}) = 14.7 \pm 1.53$ fb for EW+QCD

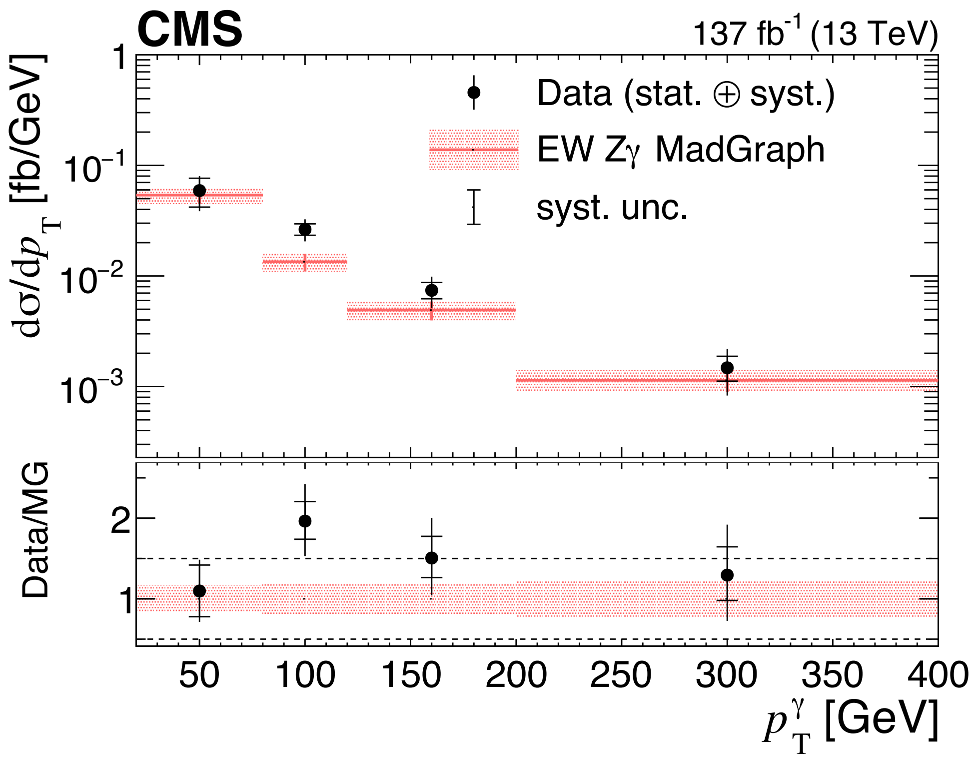
Unfolded differential cross section

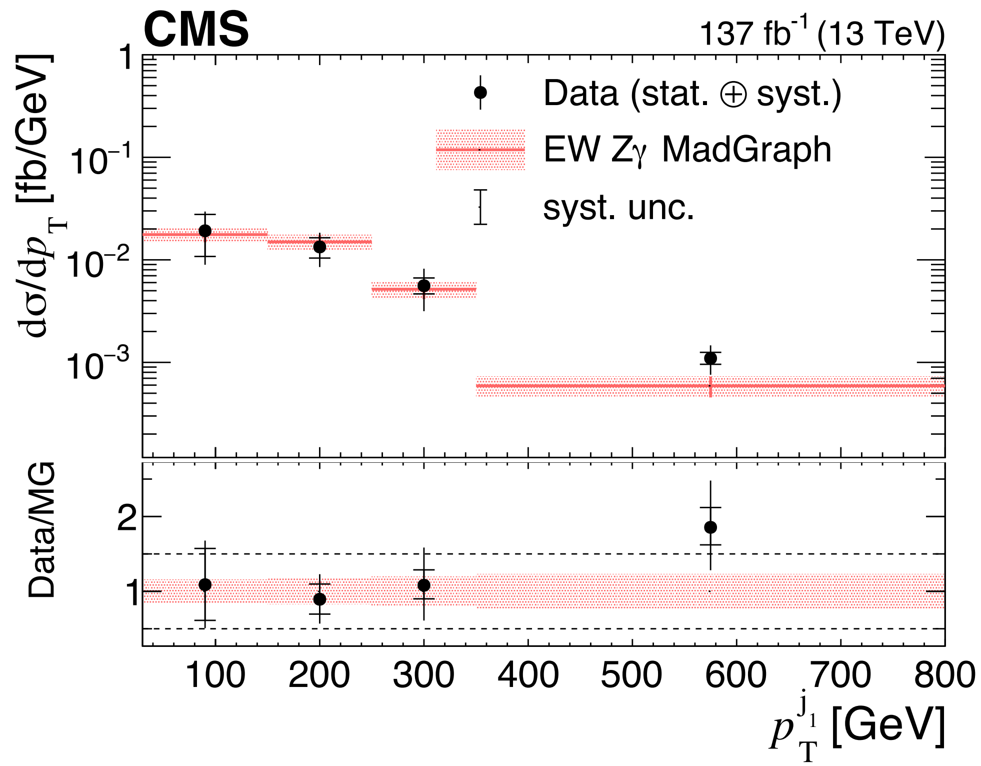
Similar with the fiducial cross section measurement, 'unfolding' was performed to revert the 'detector smearing' on the data to get the 'True' distribution.

$$\mathscr{L}(\vec{\mu};\vec{\theta}) = \prod_j \textbf{Poisson}(n_j; \sum_i R_{ji}(\vec{\theta})\mu_i s_i(\vec{\theta}) + b_j(\vec{\theta})) \cdot \mathcal{N}(\vec{\theta})$$

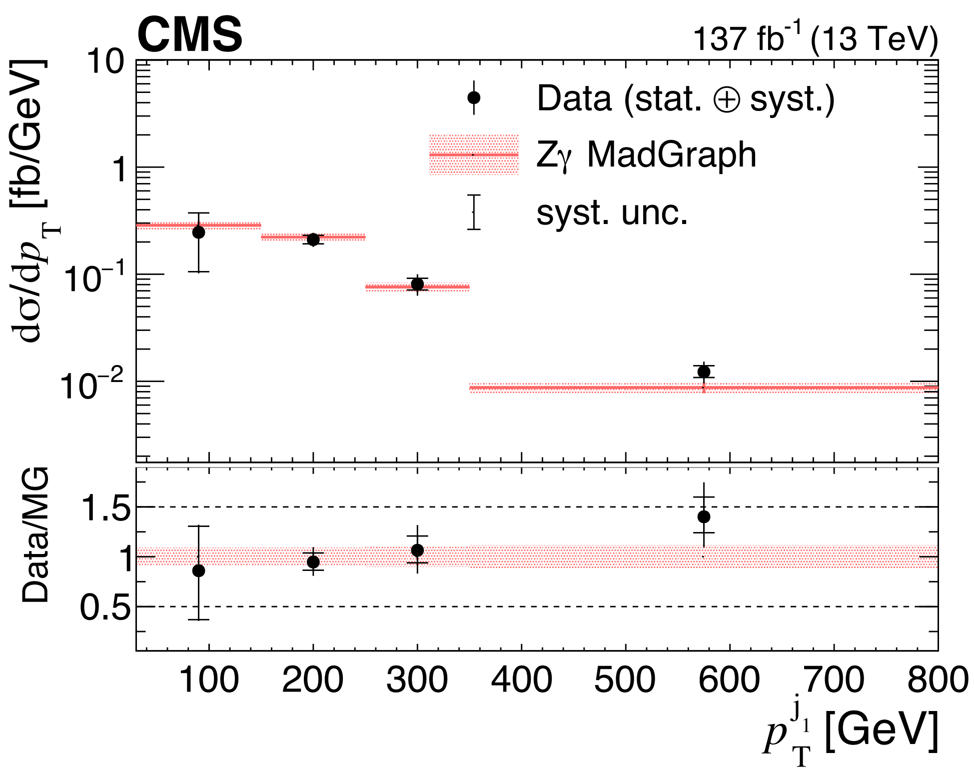
- Each reconstructed bin (j) describes the contribution from each truth bin (i) - this is the R_{ji} (response matrix).
  - ☑ Condition number of the R is smaller than about 10, so the regularization is not needed
- Same uncertainties with significance measurement are applied
- 1D variables of leading lepton, photon and jet, and 2D variable $m_{jj} - \Delta\eta_{jj}$ are measured

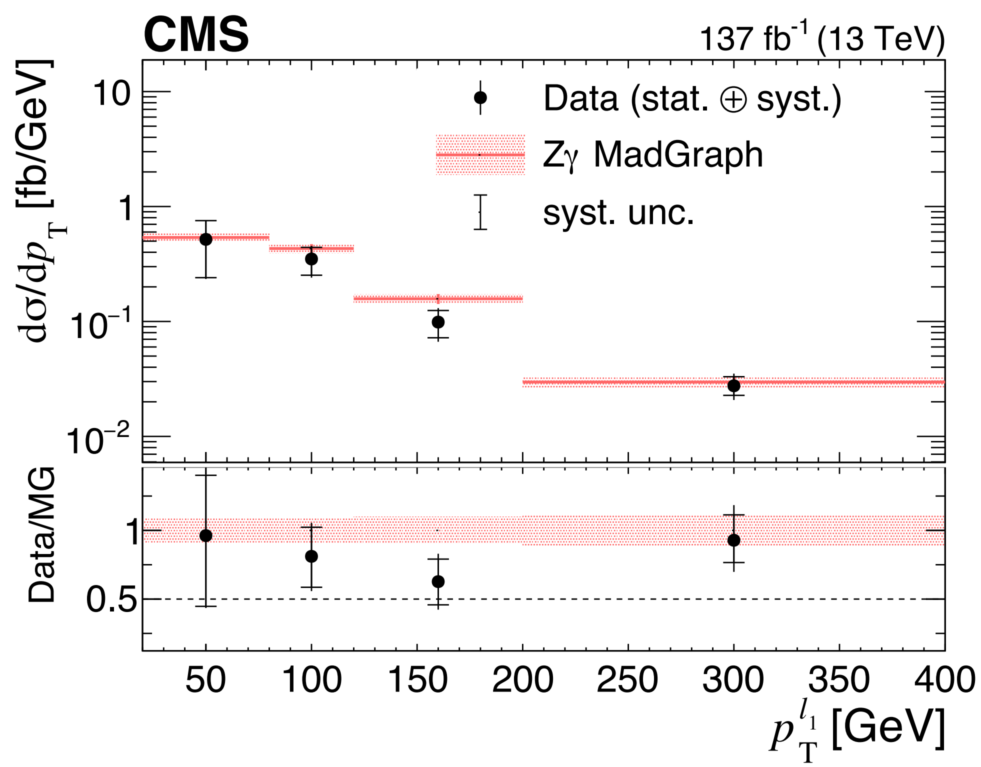
Unfolded differential cross section





EW





EW+QCD

Within the uncertainties, the measurements agree with the SM predictions.

aQGC limits

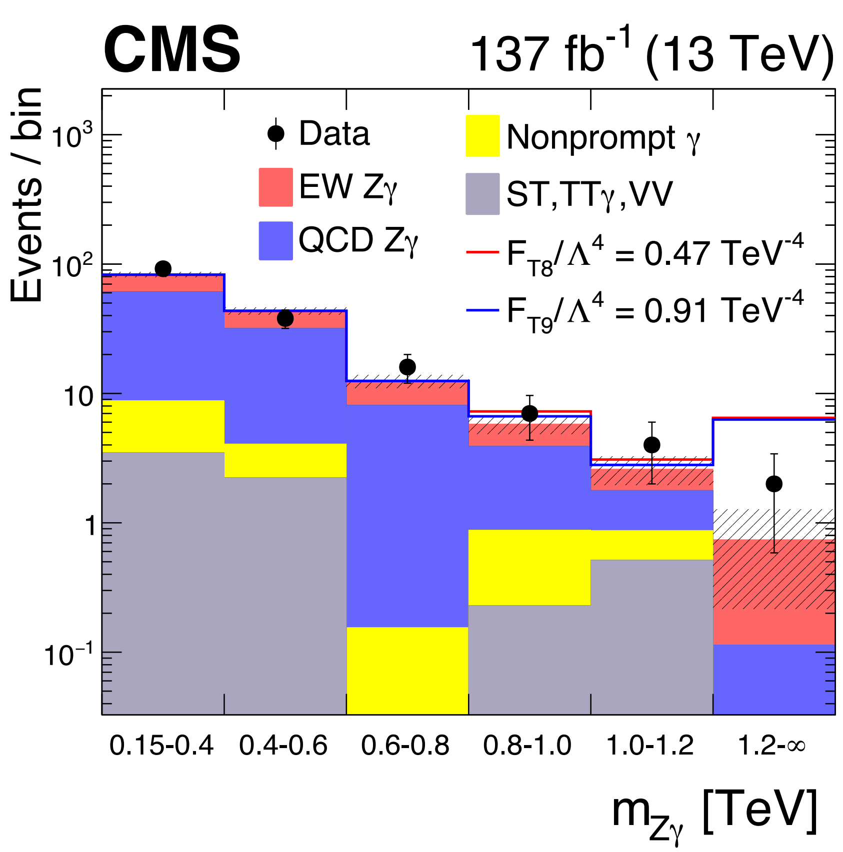
SM Lagrangian can be extended with higher dimensional operators maintaining SU(2)×U(1) gauge symmetry:

$$L_{EFT} = L_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^2}\mathcal{O}^{(8)} + \ldots.$$

Test statistic $t_{\alpha_{test}} = -2ln\frac{\mathscr{L}(\alpha, \hat{\hat{\theta}})}{\mathscr{L}(\hat{\alpha}, \hat{\theta})}$: follows χ^2 distribution;

Extract the limits directly using the profiling log likelihood ratio ΔNLL $= t_{\alpha_{test}}/2$;

The 95% CL limit corresponds 2ΔNLL=3.84.



The most stringent limit for operator T_9

aQGC limits

As the sensitivity on the T_i operators of VBS Zγ, we show the comparison of the limits of T_i from recent public VBS results with the full Run2 data

Operator	SMP-20-016 VBS Zγ	SMP-20-001 VBS ZZ	SMP-19-012 VBS W±W±
f_{T0}	-0.64 , 0.57	-0.24 , 0.22	-0.28 , 0.31
f_{T1}	-0.81 , 0.90	-0.31 , 0.31	-0.12 , 0.15
f_{T2}	-1.68 , 1.54	-0.63 , 0.59	-0.38 , 0.50
f_{T5}	-0.58 , 0.64	—	—
f_{T6}	-1.30 , 1.33	—	—
f_{T7}	-2.15 , 2.43	—	—
f_{T8}	-0.47 , 0.47	-0.43 , 0.43	—
f_{T9}	-0.91 , 0.91	-0.92 , 0.92	—

Similar sensitivity on T_8 and T_9 between VBS Zγ and VBS ZZ, which is expected, as the T_8 and T_9 give rise to QGCs only containing the neutral gauge bosons.

Summary

- ✓ Overall significance is far more 5σ.
- ✓ Fiducial cross section measurement reported
- ✓ Unfolded differential cross section as functions of leading lepton/jet/ photon pT and m_{jj}-$\Delta\eta_{jj}$
- ✓ AQGC limits for operator M_{0-7}, T_{0-2}, and T_{5-9} .
  - ✓ Limit for T_9 is the most stringent limit to date

Backup

variables	2016	2017	2018
p_T^{γ}	1.08	1.12	1.21
$p_T^{j_1}$	1.35	1.41	1.44
$p_T^{l_1}$	1.09	1.09	1.11
m_{jj}-$\Delta\eta jj$	1.87	1.97	1.95

Condition Number of R for EW

variables	2016	2017	2018
p_T^{γ}	1.16	1.41	1.37
$p_T^{j_1}$	1.33	1.41	1.39
$p_T^{l_1}$	1.10	1.35	1.16
m_{jj}-$\Delta\eta jj$	1.93	2.32	2.09

Condition Number of R for EW+QCD

If the condition number is small (~10), then the problem is well-conditioned and can most likely be solved using the unregularized maximum likelihood estimate (MLE). This happens when the resolution effects are small and R is almost diagonal. If on the other hand, the condition number is large (~10^5) then the problem is ill-conditioned and the unfolded estimator needs to be regularized.

Backup

Building blocks:

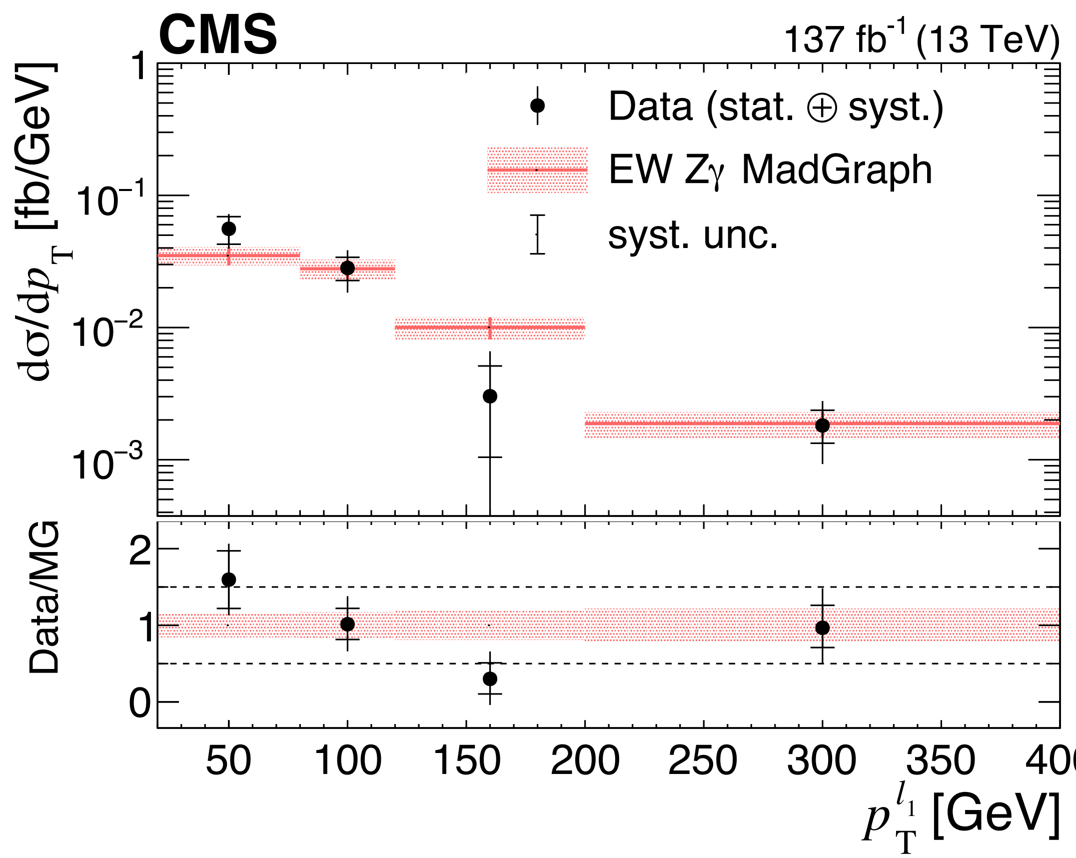
- $D_\mu \Phi$: Higgs doublet field, affects the coupling of longitudinal modes of the gauge bosons.
- $\hat{W}_{\mu\nu}$, $\hat{B}_{\mu\nu}$: Field strength tensors

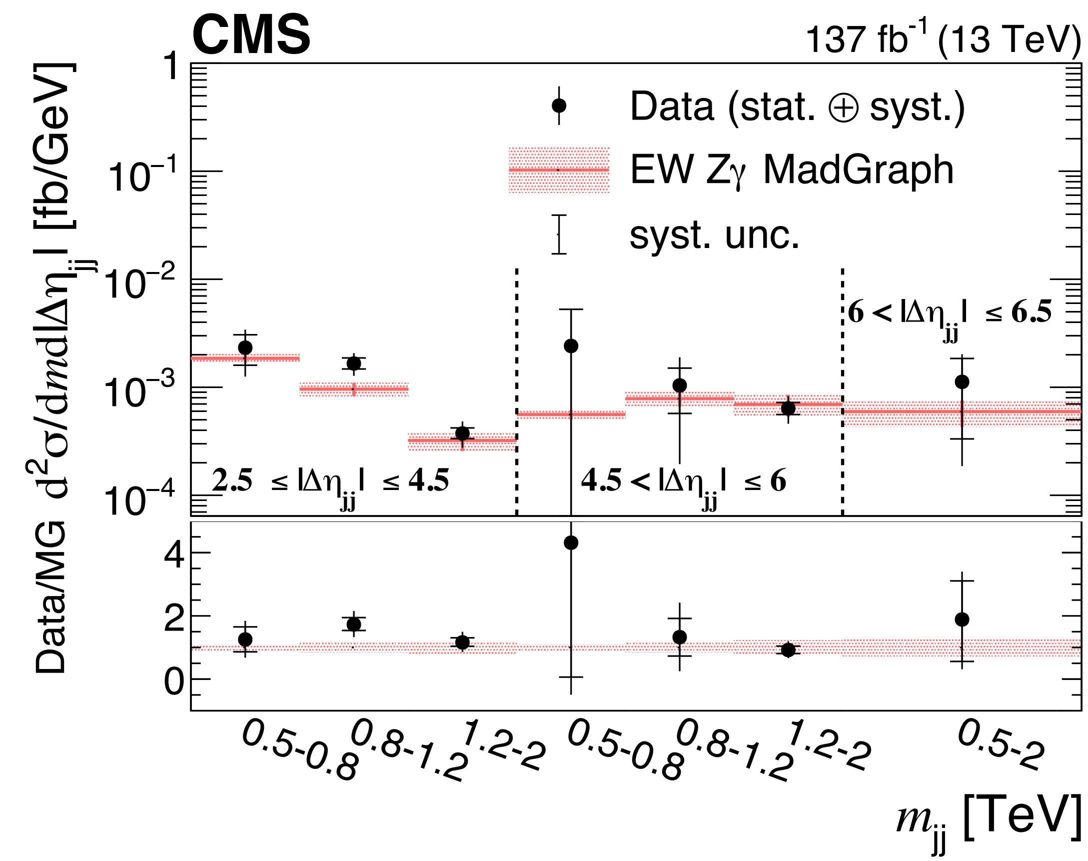
Dimension-8 operators (only field strength/mixed)

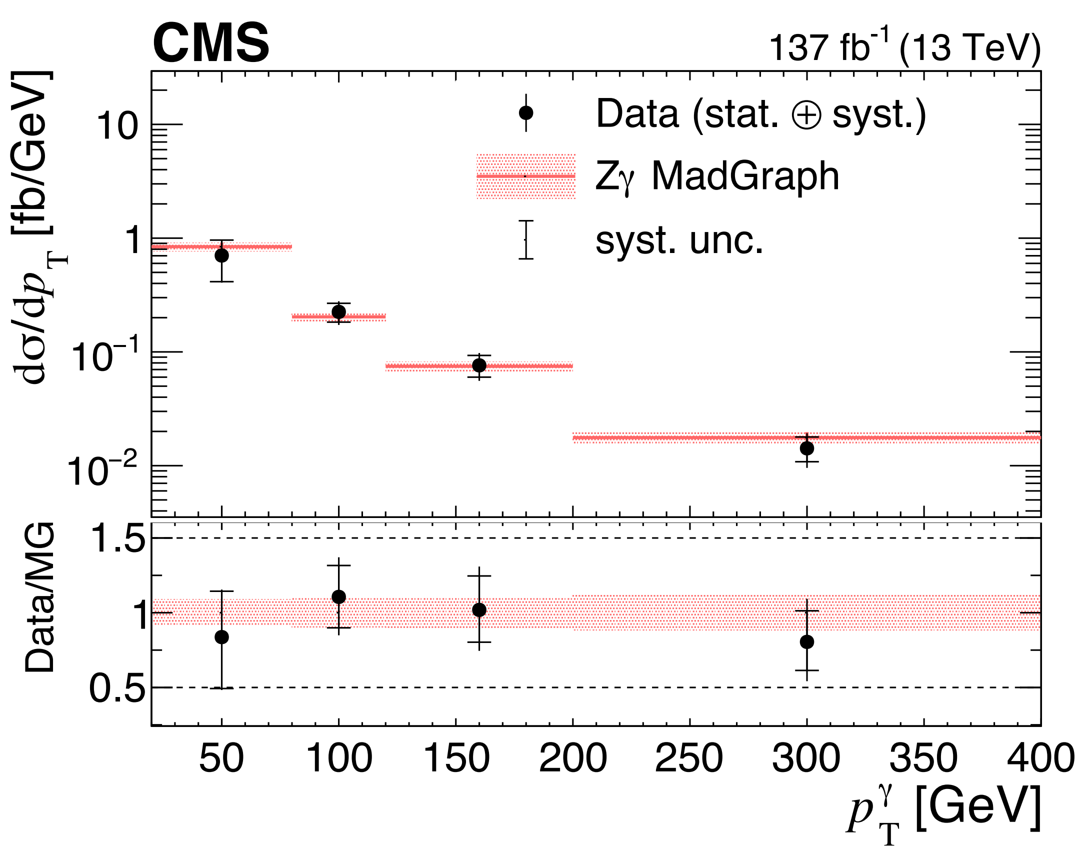
$$\begin{aligned}
\mathcal{O}_{T,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right]\cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] , \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right]\cdot \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] , \\
\mathcal{O}_{T,2} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right]\cdot \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] , \\
\mathcal{O}_{T,5} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right]\cdot B_{\alpha\beta}B^{\alpha\beta} , \\
\mathcal{O}_{T,6} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right]\cdot B_{\mu\beta}B^{\alpha\nu} , \\
\mathcal{O}_{T,7} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right]\cdot B_{\beta\nu}B^{\nu\alpha} , \\
\mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} .
\end{aligned}$$

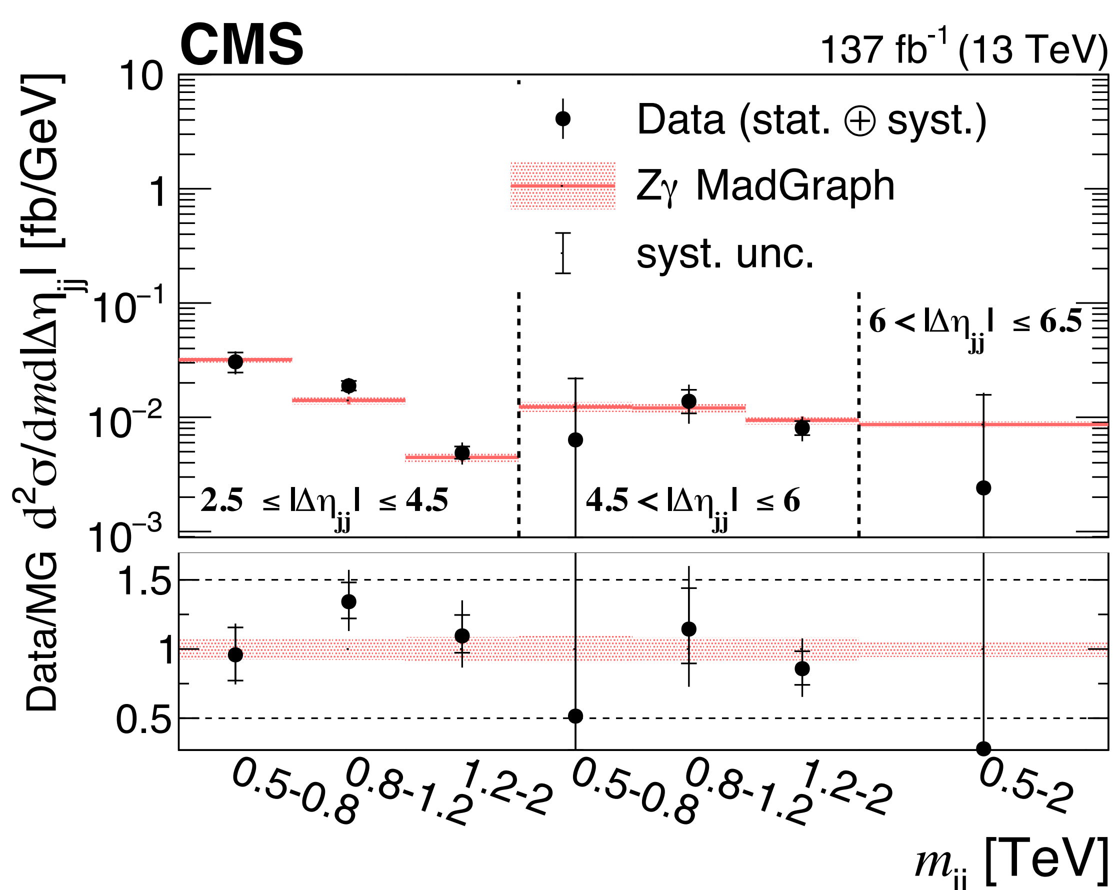
$$\begin{aligned}
\mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right]\cdot\left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,1} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right]\cdot\left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right]\cdot\left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] , \\
\mathcal{O}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right]\cdot\left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] , \\
\mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right]\cdot B^{\beta\nu} , \\
\mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right]\cdot B^{\beta\mu} , \\
\mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] , \\
\mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] ,
\end{aligned}$$

Backup— Unfolding for EW+QCD









Backup

- sigmaIEtaIEta is the log energy weighted RMS of the shower in units of crystals
  - $\sigma_{i\eta i\eta} = \sqrt{\left(\frac{\Sigma_i^{5\times 5} w_i (\eta_i - \overline{\eta}_{5\times 5})^2}{\Sigma_i^{5\times 5} w_i}\right)}$
  - $w_i = 4.7 + \ln \frac{E_i}{E_{5\times 5}}$
    - this is effectively a noise cut, each crystal needs to have > 0.9% of 5x5 energy
    - means that very low energy electrons are sensitive to noise as 0.9% of a small number brings it below noise threshold
  - E_i = energy of crystal, $E_{5\times 5}$ energy of 5x5
    - likewise for η
  - η is in units of crystals, not absolute η
    - endcap uses $(ix^2 + iy^2)^{1/2}$ to get η in terms of crystals
  - normalised to 0.01745 in barrel and 0.0447 in endcap
  - cut effectively means that all the energy is within two crystals