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

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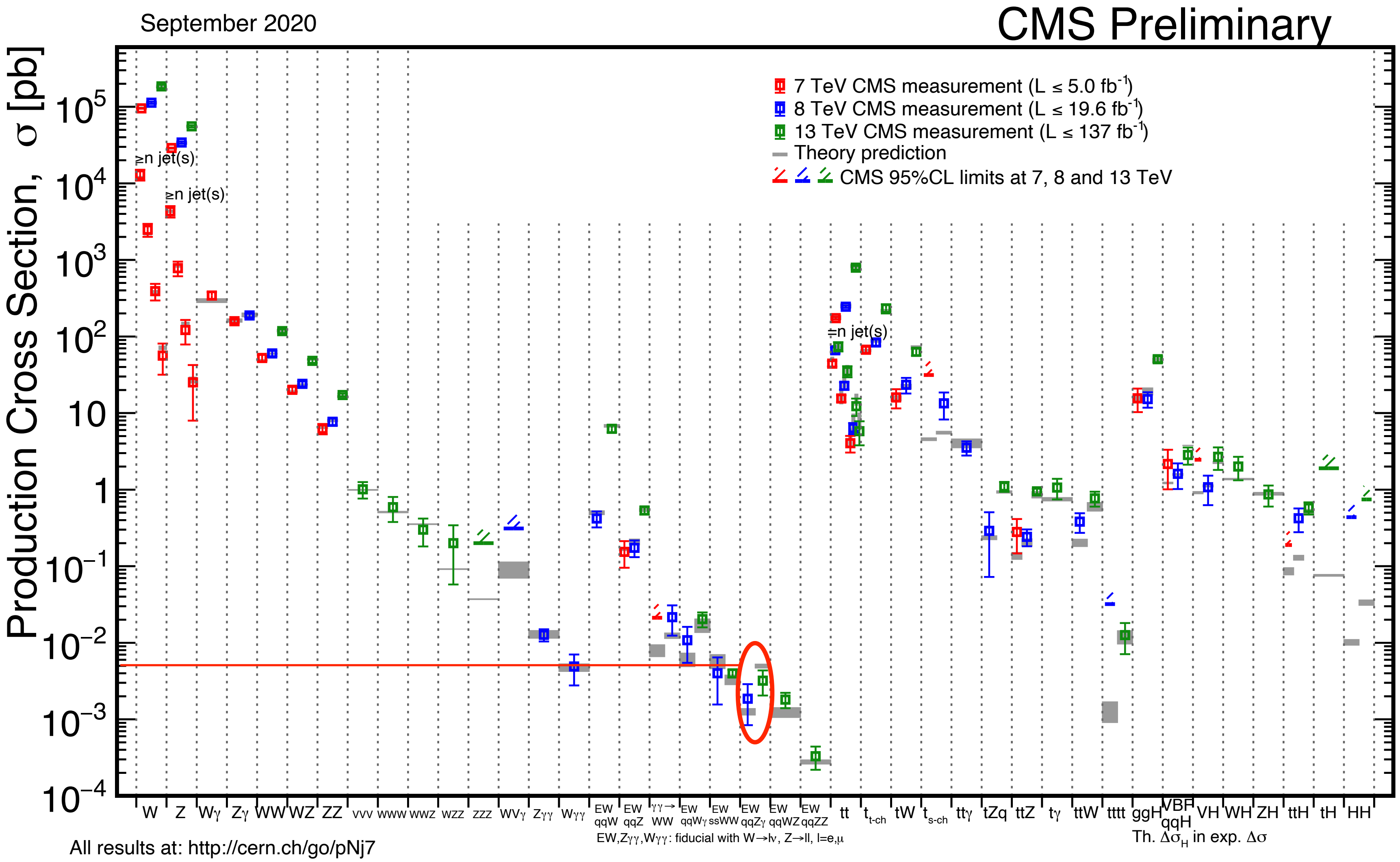
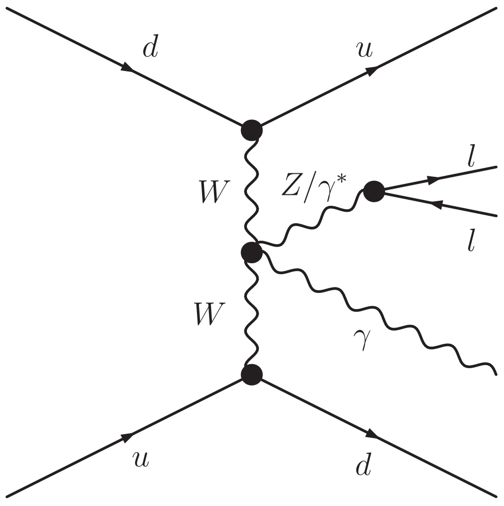
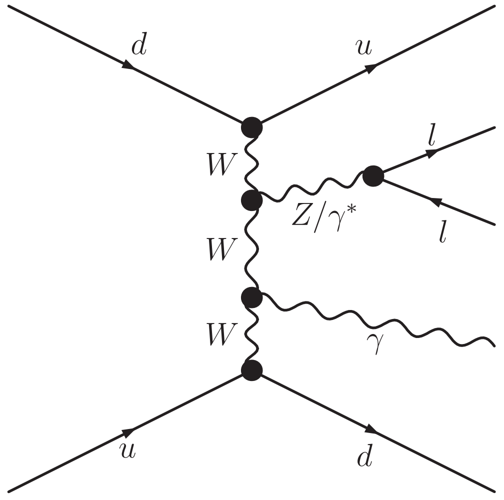
(on behalf of the CMS Collaboration)
Standard Model at LHC April 29 2021

Introduction & Motivation



All results at: http://cern.ch/go/pNj7





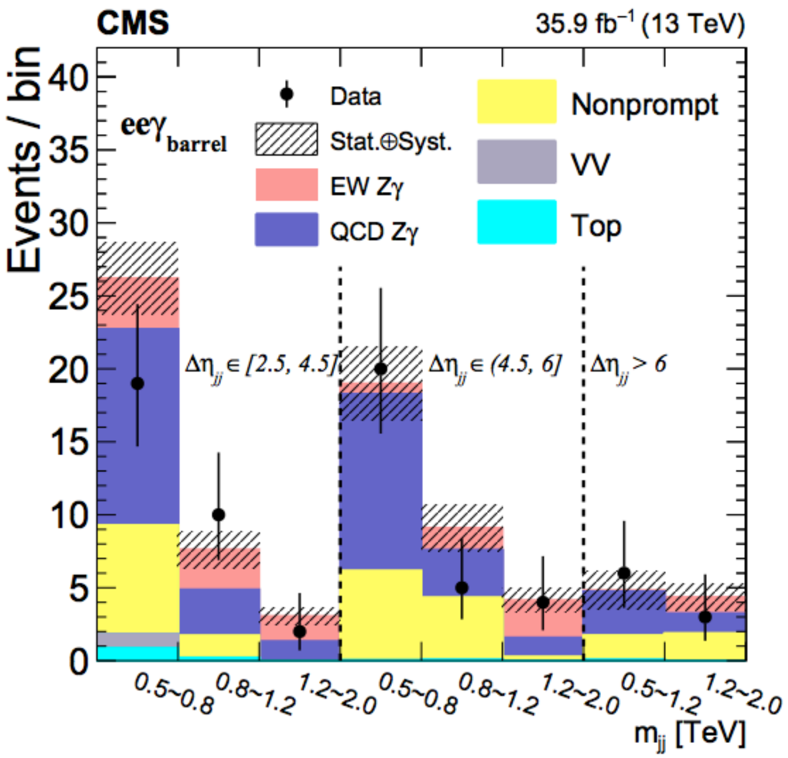
Final states: Z to ee/μμ plus a photon with two additional jets.

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

Introduction & Motivation



CMS: arxiv: 2002.09902 for 13 TeV

8 TeV (19.7 fb^{-1}):

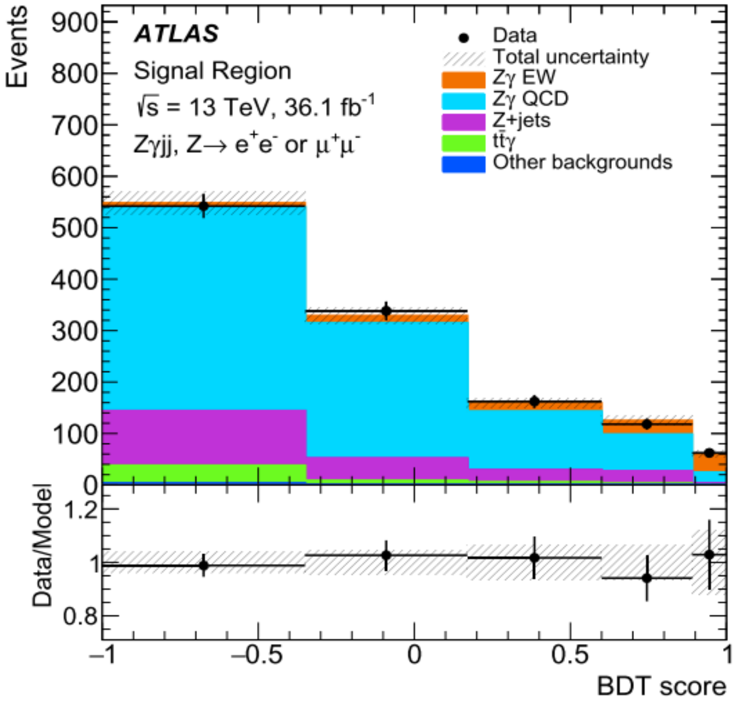
observed (expected) significance is **3.0σ (2.1σ)**.

13TeV (35.9 fb^{-1}):

observed (expected) significance is **3.9σ (5.2σ)**.

aQGC limits and fiducial cross section are also reported.

Combined observed(expected) significance is **4.7σ (5.5σ)**.



ATLAS: arxiv: 1910.09503 for 13 TeV

8 TeV (20.2 fb^{-1})**:**

observed (expected) significance is **2.0σ (1.8σ)**.

13 TeV (36 fb^{-1})**:**

observed (expected) significance is **4.1σ (4.1σ)**

Fiducial cross section is also reported

Sample & Selection

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

MC Signal: Electroweak production of Zγjj.

- Generated by MADGRAPH5_aMC@NLO (MG5), simulated at leading order (LO) with dilepton mass larger than 50 GeV
- The parton shower and hadronization are held by Pythia8 using CP5 (CUETP8M1 for 2016)
- NNPDF 3.1(3.0 for 2016) parton distribution functions is used

Backgrounds:

- **Zγ plus QCD jets** estimated from simulation
  - Generated by MG5 using FxFx jet merging scheme
  - The matrix element include 0/1 jets at NLO
  - The parton shower and hadronization are held by pythia8 using CP5 (CUETP8M1 for 2016)
  - NNPDF 3.1(3.0 for 2016) parton distribution functions is used
- **Nonprompt photon** estimated from data
- **EW/QCD Interference** estimated from simulation by MG5
- **Di-boson,** $t\bar{t}\gamma$ and **single top** estimated from simulation
  - di-boson is simulated using Pythia8
  - $t\bar{t}\gamma$ is simulated at NLO with MG5 using the FxFx jet matching scheme
  - single top is simulated at NLO using POWHEG

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

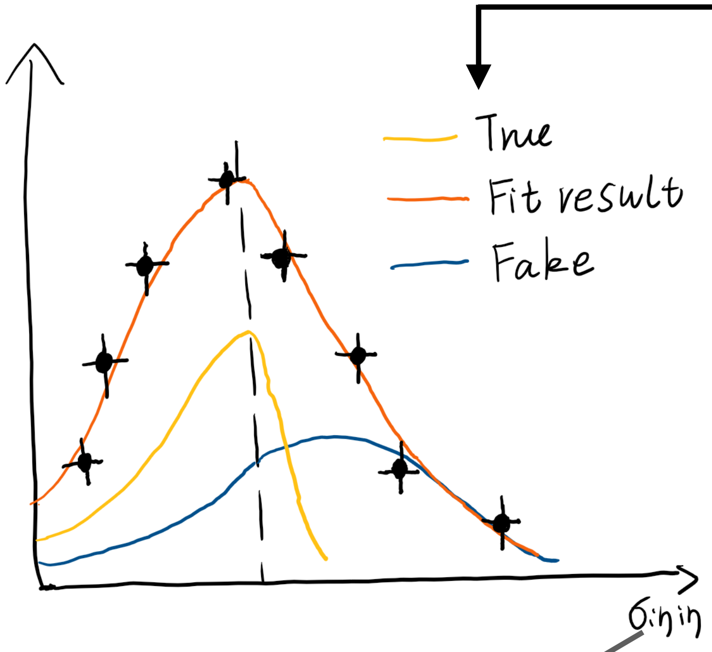
- Background processes estimated from simulation are normalized to the best theoretical cross section prediction.
- Irreducible background QCD Zγ normalization is constrained by data in the low m_{jj} control region.
- A data-driven method is used to estimate nonprompt photon contribution.

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 and categories and years

Theoretical

PDF uncertainty

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

Jet energy resolution&scale uncertainty

Experimental

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

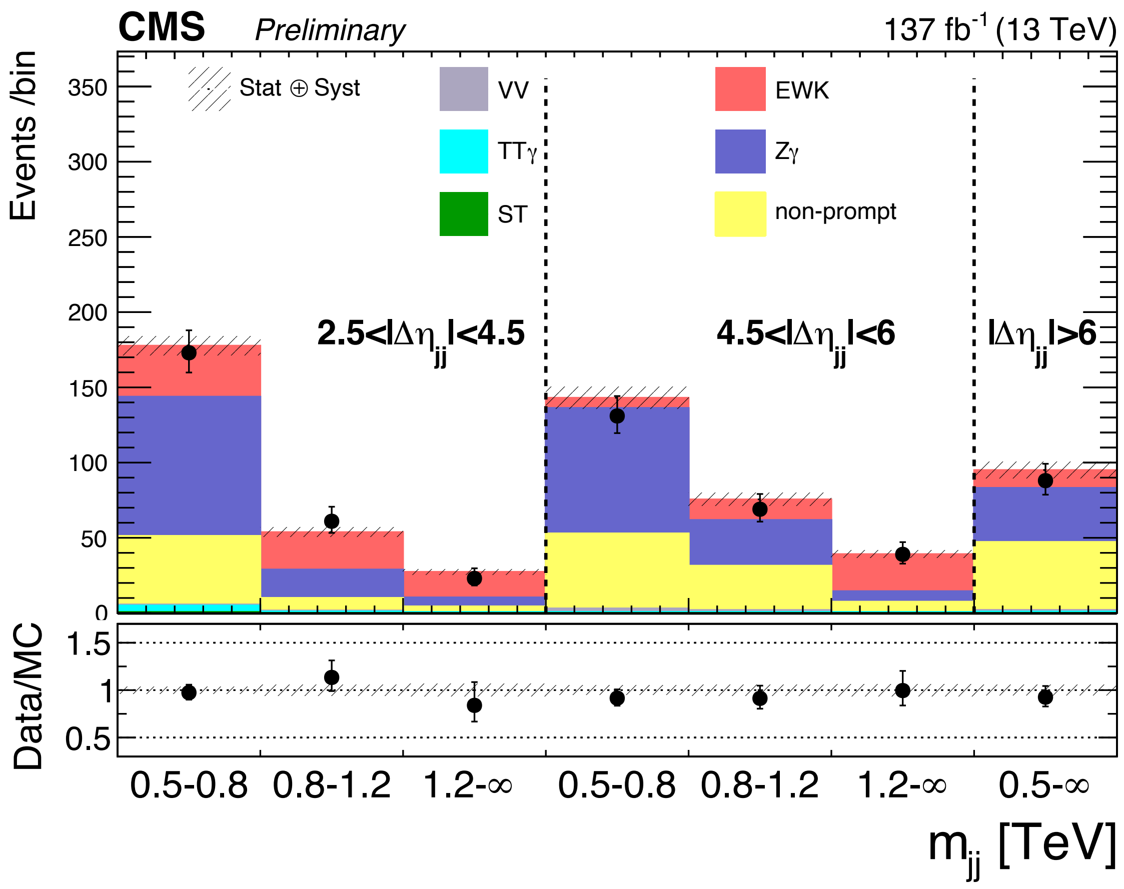
Fake photon uncertainty

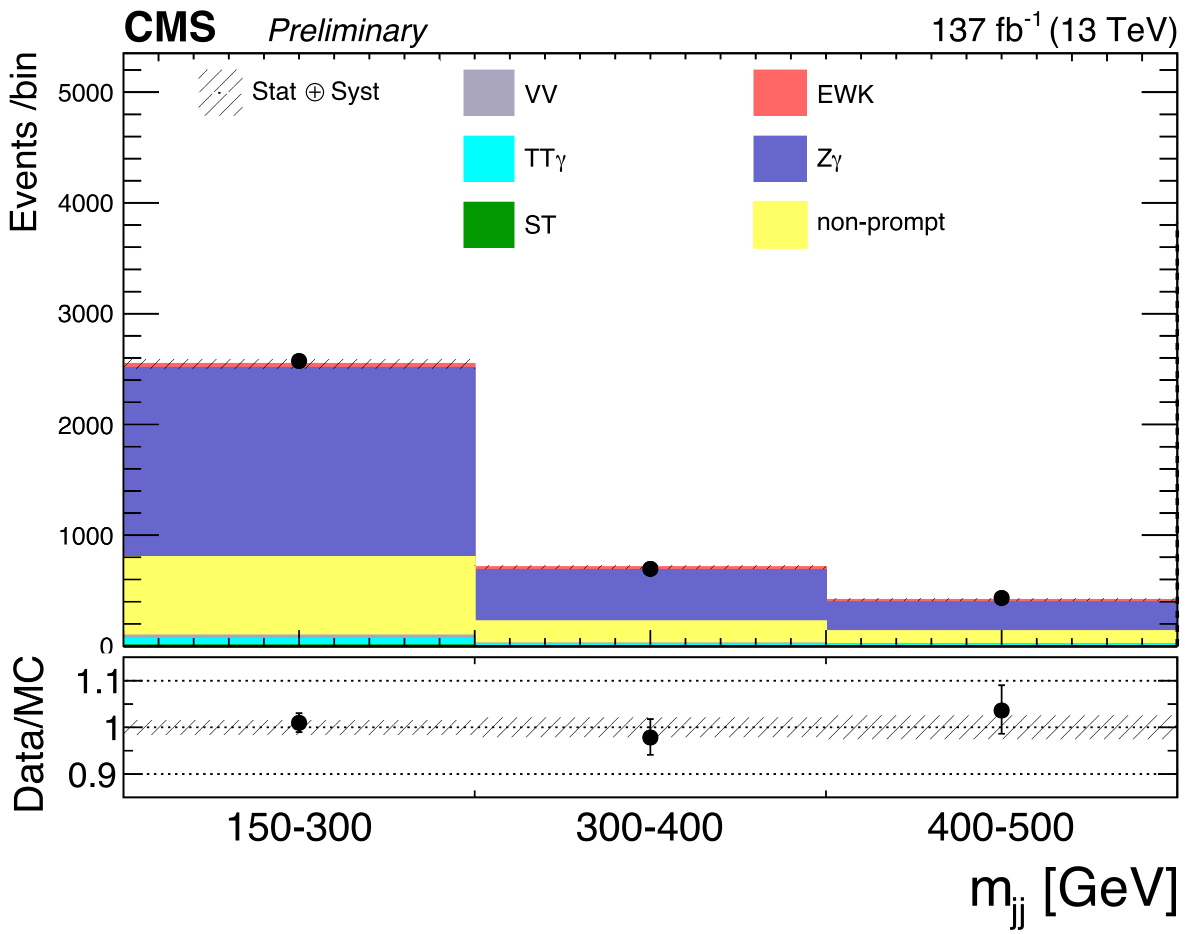
- Closure test + Sideband choice + True template choice
- Calculated bin-by-bin, correlated between bins and categories

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 9.6 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

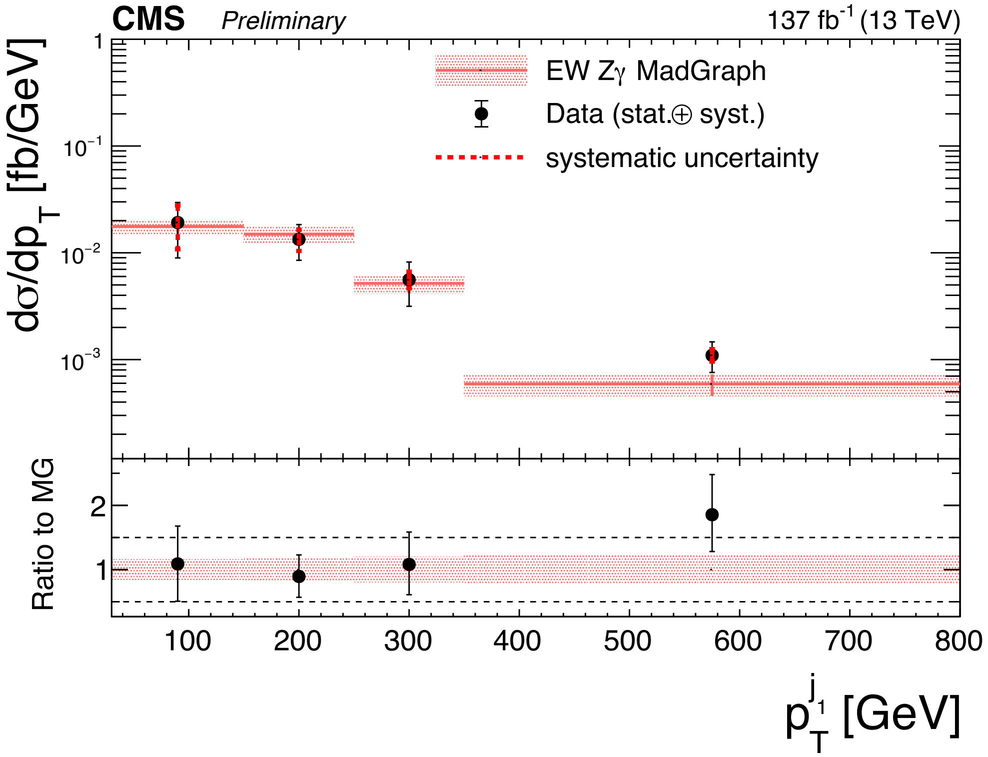
Unfolded differential cross section

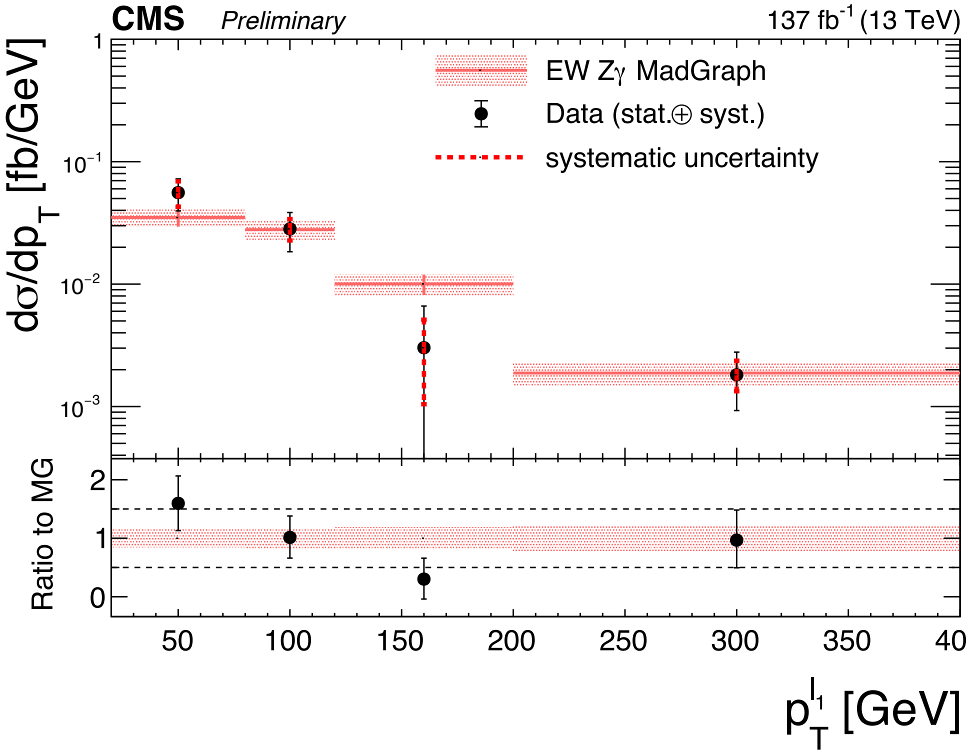
Similar with the fiducial XS measurement, we perform ‘unfolding’ to revert the ‘detector smearing’ on the data to get the ‘True’ distribution.

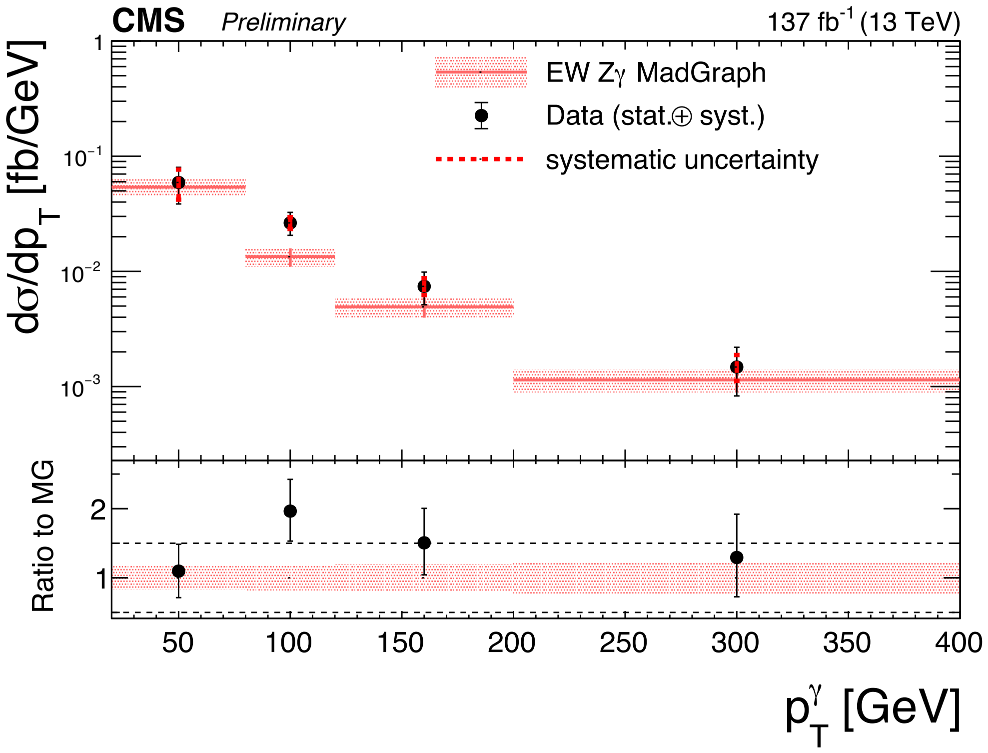
$$\mathscr{L}(\vec{\mu};\vec{\theta}) = \prod_j \textbf{Poisson}(n_j; \sum_i R_{ji}(\vec{\theta})\mu_i L_j(\sigma_i^{SM} + \sigma_i^{SM-out}) + b_j(\vec{\theta})\,) \cdot \mathscr{N}(\vec{\theta})$$

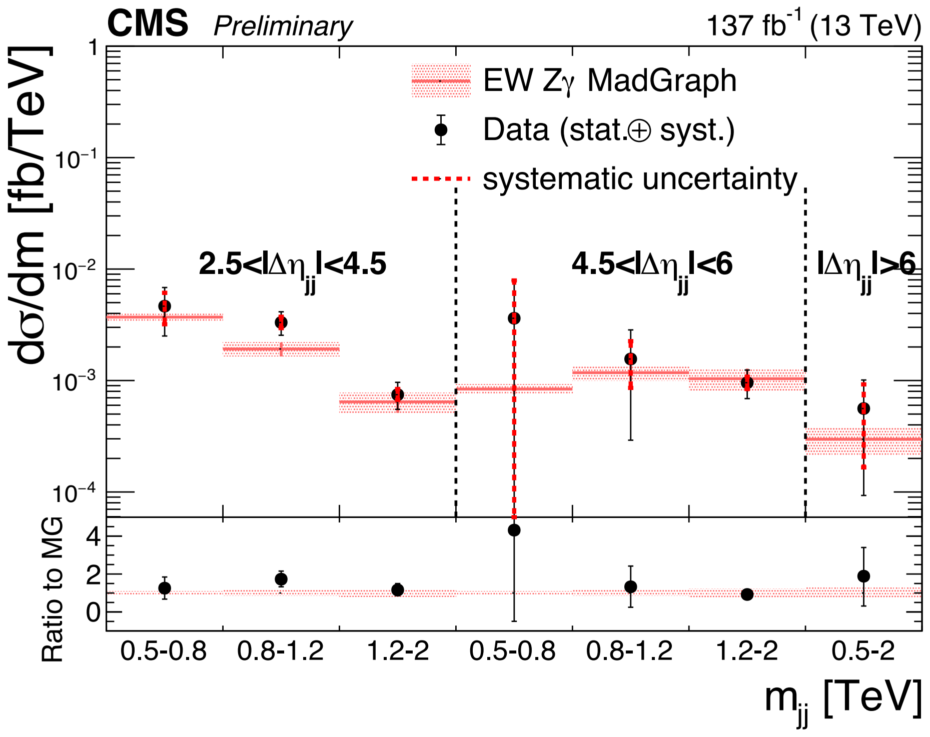
- Each reconstructed bin (j) describes the contribution from each truth bin (i) - this is the R_{ji} (response matrix).
  - ☑ Condition number of the R is smaller than about 10, so the regularization is not needed
- Same uncertainties with significance measurement are applied
- 1D variables of leading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

Unfolded differential cross section









Within the uncertainties, the measurements agree with the predictions.

aQGC limits

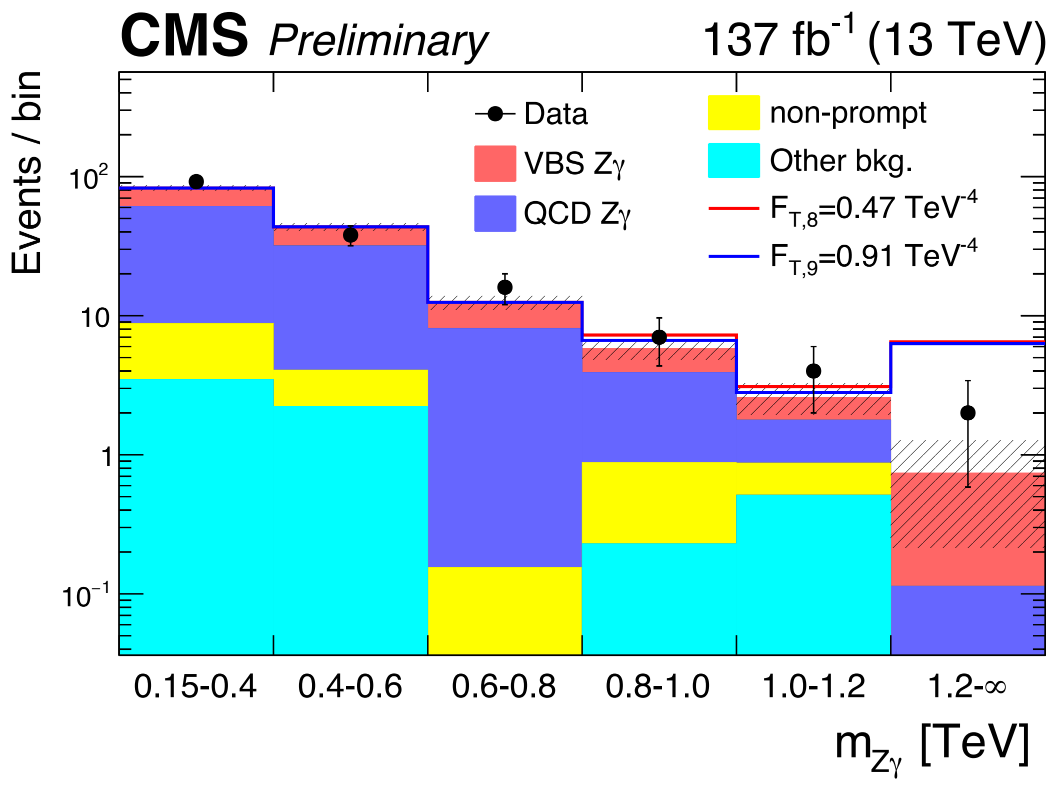
SM Lagrangian can be extended with higher dimensional operators maintaining SU(2)×U(1) gauge symmetry:

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

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

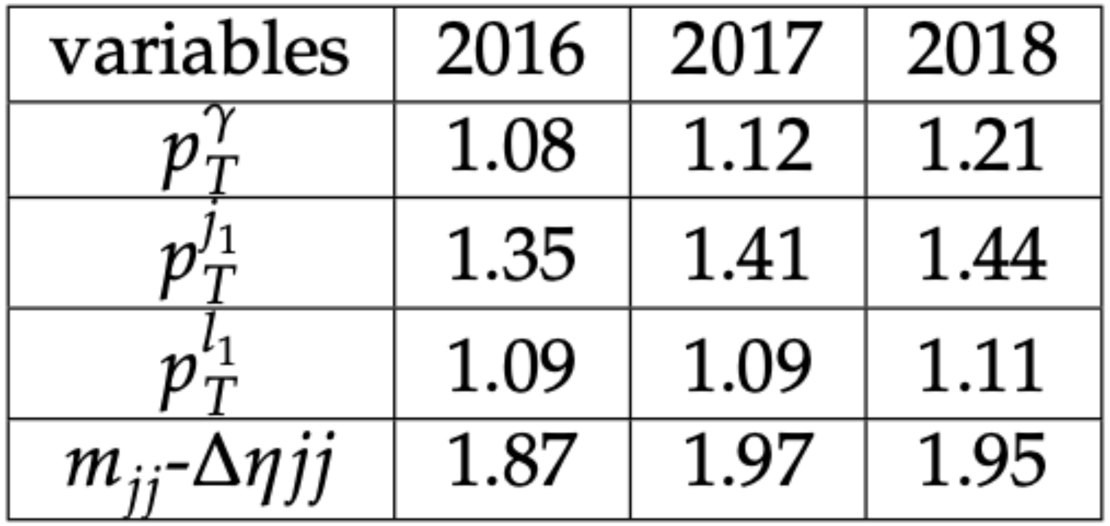
Operator	SMP-20-016 VBS Zγ	SMP-20-001 VBS ZZ	SMP-19-012 VBS $W^{\pm}W^{\pm}$
f_{T0}	-0.64 , 0.57	-0.24 , 0.22	-0.28 , 0.31
f_{T1}	-0.81 , 0.90	-0.31 , 0.31	-0.12 , 0.15
f_{T2}	-1.68 , 1.54	-0.63 , 0.59	-0.38 , 0.50
f_{T5}	-0.58 , 0.64	—	—
f_{T6}	-1.30 , 1.33	—	—
f_{T7}	-2.15 , 2.43	—	—
f_{T8}	-0.47 ,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

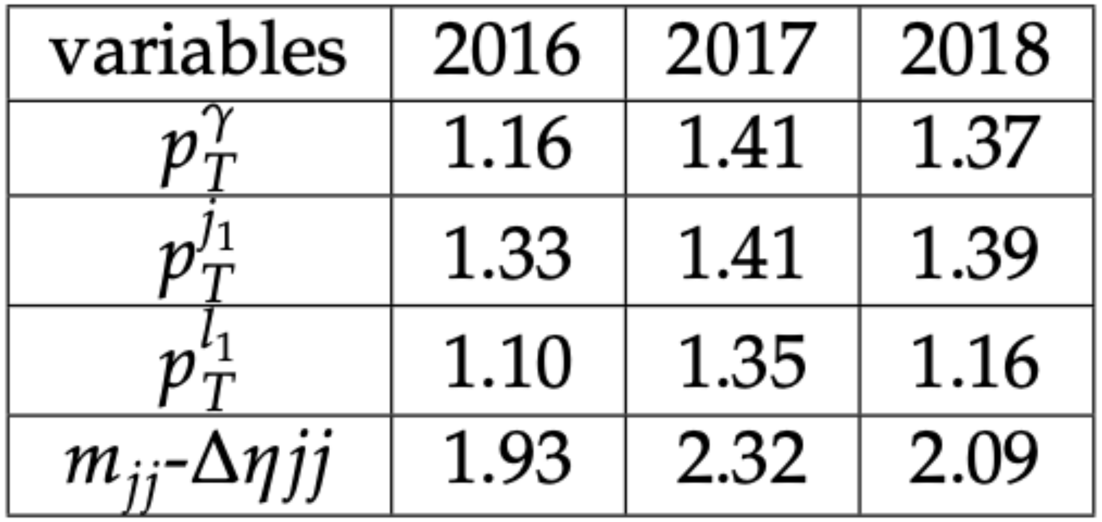
- ✓ Overall significance is far more 5σ.
- ✓ Fiducial cross-section measurement reported
- ✓ Unfolded differential cross section as functions of leading lepton/jet/photon pT and m_{jj}-$\Delta\eta_{jj}$
- ✓ AQGC limits for operator M_{0-7}, T_{0-2}, and T_{5-9} .
  - ✓ Limit for T_9 is the most stringent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

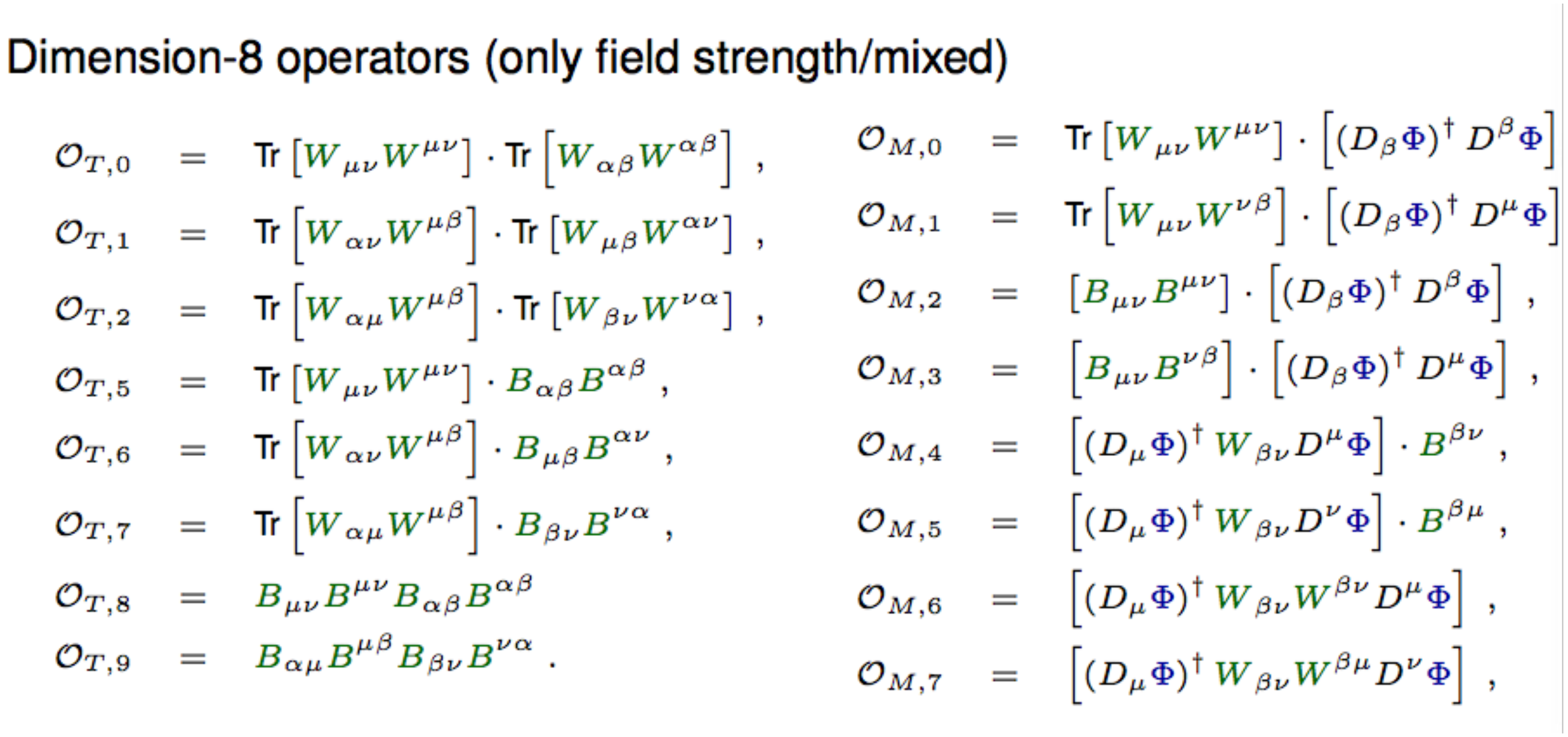
Condition Number of R for EW+QCD

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)

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

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