# A search for the electroweak production of $Z\gamma$ with two jets and aQGC couplings in p-p collisions at $\sqrt{s}$ = 13 TeV

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**Ying AN**, Meng Lu, Qiang Li, Andrew Michael Levin, Jie Xiao, Junho Lee, Qianming Huang, Yong Ban, Yajun Mao
Peking University(CN)

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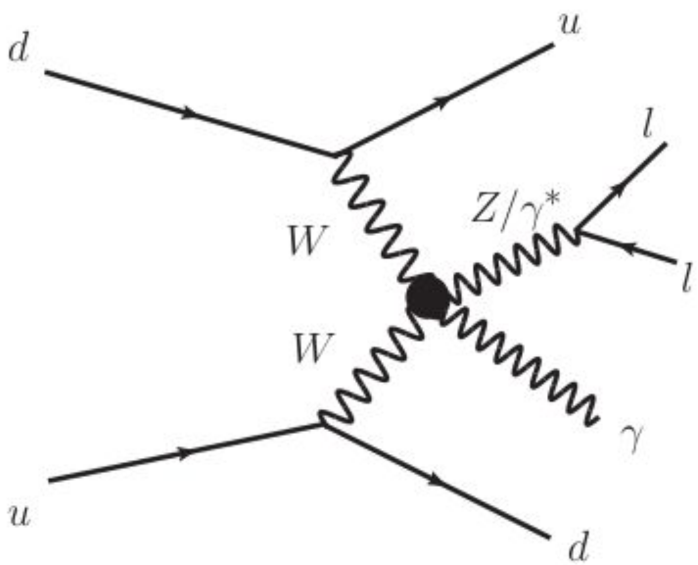
# Introduction and motivation

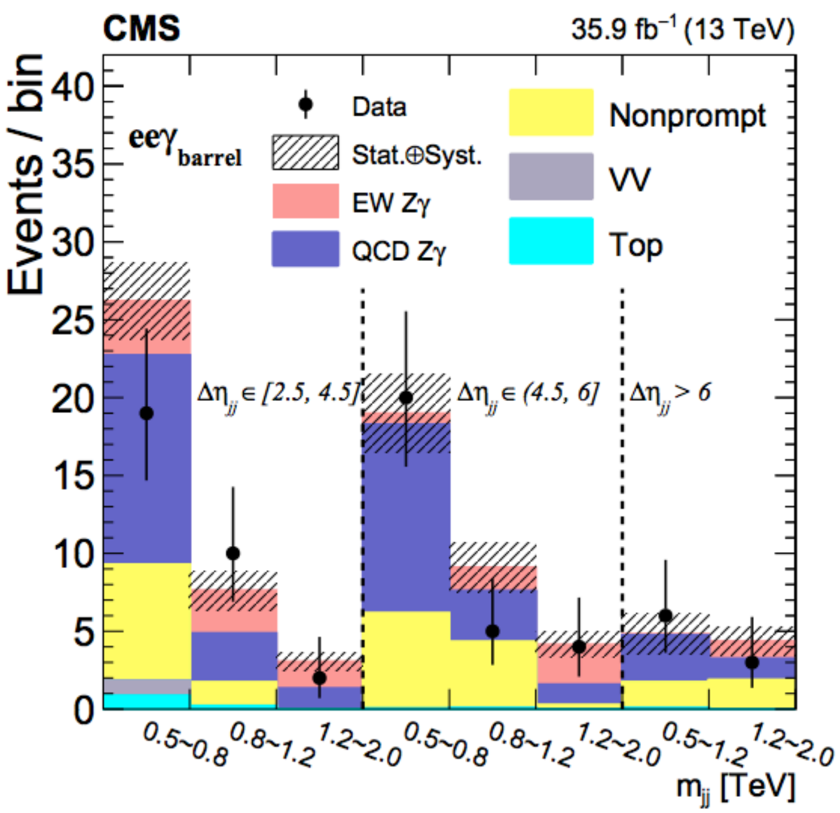



Final states: Z to ee and Z to μμ plus a photon with two jets.

VBS Signature: large dijet mass and large η separation between the jets.

- We have observed charged vector boson scattering final states, but not yet a neutral gauge boson scattering final state
- Probe standard model triple and quartic gauge couplings
- Constrain anomalous couplings model parameters in combination with other analyses
- Provide fiducial cross section measurement for theorists/people outside CMS to play with

# Introduction and motivation

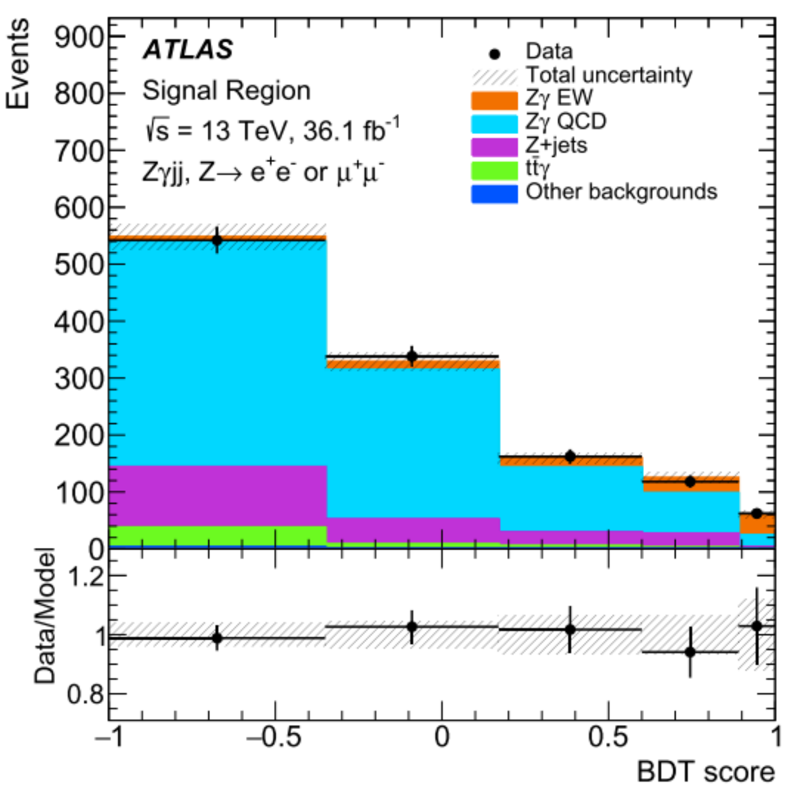



CMS: **8 TeV**(19.7 fb-1): observed(expected) significance is **3.0(2.1)** standard deviations.

**13TeV**(35.9fb-1): observed(expected) significance is **3.9(5.2)** standard deviations.

Combined: observed(expected) significance is **4.7(5.5)** standard deviations.

aQGC limits and fiducial cross section are also reported




ATLAS: **8 TeV**(20.2 fb−1)**:** observed(expected) significance is **2.0(1.8)** standard deviations.

**13 TeV**(36.1fb−1)**:** observed(expected) significance is **4.1(4.1)** standard deviations

Fiducial cross section is also reported

# Samples and selection

**Data:** collected in 2016 with integrated luminosity: 35.9 $fb^{-1}$

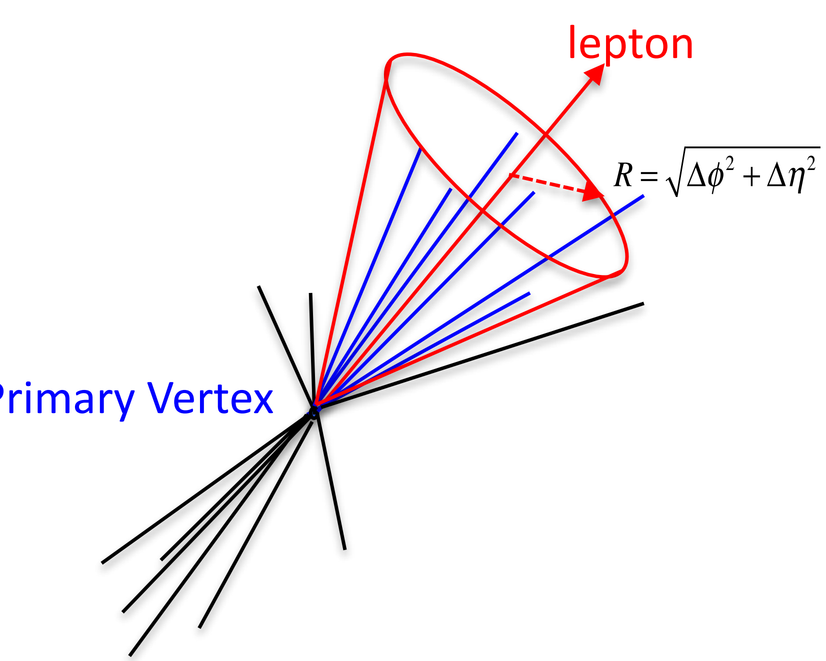
**MC Signal:** Electroweak production of Z and $\gamma$.

- Generate by MADGRAPH5 aMC@NLO, simulated at leading order (LO) in QCD with dilepton mass larger than 50 GeV
- The parton shower and hadronization are held by pythia8 using CUETP8M1
- NNPDF 3.0 parton distribution functions is used

**MC Background:**

- **Z$\gamma$ plus QCD jets** estimated from simulation
  - Generate by MADGRAPH5 aMC@NLO using FxFx jet merging scheme
  - The matrix element include 0/1 jets at NLO
  - The parton shower and hadronization are held by pythia8 using CUETP8M1
  - NNPDF 3.0 parton distribution functions is used
- **Non-prompt photon** contributions estimated from Data
- **Di-boson,** $t\bar{t}\gamma$ and **single top** estimated from simulation
  - simulated using PYTHIA 8.212,
  - simulated at NLO with MADGRAPH5 aMC@NLO using the FxFx jet matching scheme
  - simulated at NLO using POWHEG

# Samples and selection




**Muon:**

- A highly restrictive working points with average efficiency 70%
- $R_{iso} = \frac{\sum_i E_T^i}{p_T^l} < 0.15$
- pT > 20 GeV, $|\eta| < 2.4$

A loose WP with efficiency 90% are used to **veto the third lepton**

**Electron**

- A medium working point with average efficiency 80%
- pT > 25 GeV, $|\eta| < 2.5$

**Good Photon**

- A medium WP with efficiency 80%
- Conversion-safe electron veto
- pT > 20 GeV and $|\eta sc| < 1.4442$ or $1.566 < |\eta sc| < 2.5$

**Jets**

- Particle flow candidates
- anti-kT jet clustering algorithm within a distance 0.4.
- pT>30 GeV
- $|\eta| < 4.7$

# Sample and selection

- Two and only two same-flavor good leptons
- Third lepton veto
- One good photon with pT > 20 GeV
- Two jets with pT > 30 GeV
- 70 GeV < $M_{ll}$ < 110 GeV

Basic event selection

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

Suppress FSR

- 150 GeV < $M_{jj}$ < 400 GeV

Low $M_{jj}$ control region

- $M_{jj}$ > 500 GeV
- $\Delta\eta(j_1, j_2) > 2.5$

VBS signal region

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

Optimization cuts

# Background estimation

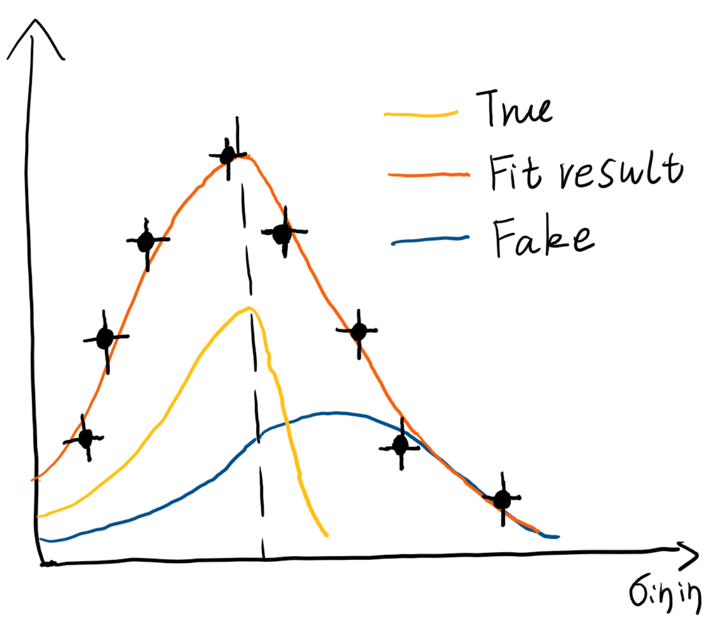
- Background processes estimated from simulation are normalized to the best theoretical cross section prediction and all of them are reweighted to correct pileup, lepton, photon and trigger efficiencies.
- Irreducible background QCD $Z\gamma$ normalization is significantly constrained by data in a low $M_{jj}$ control region.
- A data-driven method is used to estimation non-prompt photon contribution.


From Data

By inverting one of cut in the photon WP

$$n_{fake}^{weighted} = n_{tot} \times \epsilon = N_{fake}^{unweighted} \times weights$$

**Template fit**




True photon is from QCD $Z\gamma$ with medium photon working points and matched to generator-level

Fake photon is from data by inverting charged isolation between 5 and 10 GeV
*Closure test was done to select a best charged isolation sideband*

Data is from data with medium working points photon

$$W_{p_T^\gamma} = \frac{h_{data} -> GetBinContent(p_T^\gamma)}{h_{plj} -> GetBinContent(p_T^\gamma)} \times FakeFraction(p_T^\gamma)$$

# Uncertainties

Factorization and renormalization scale uncertainty

- Exclude the two variations where $(2\mu_R, 0.5\mu_F)$ and $(0.5\mu_R, 2\mu_F)$
- Nuisance parameter 1: (Largest yield – smallest yield)/2
- Nuisance parameter 2: up = scale7 and down = scale4
- Calculated bin-by-bin, correlated between bins and categories and regions

PDF uncertainty

Theoretical uncertainties

- Standard deviation of the around 100 NNPDF3.0 PDF set variations
- Calculated bin-by-bin, correlated between bins and categories and regions

Interference between EWK and QCD Zγ

- Evaluated at LHE-level as $(\sigma(QCD + EWK) - \sigma(QCD) - \sigma(EWK))/\sigma(EWK)$

JER and JES uncertainty

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

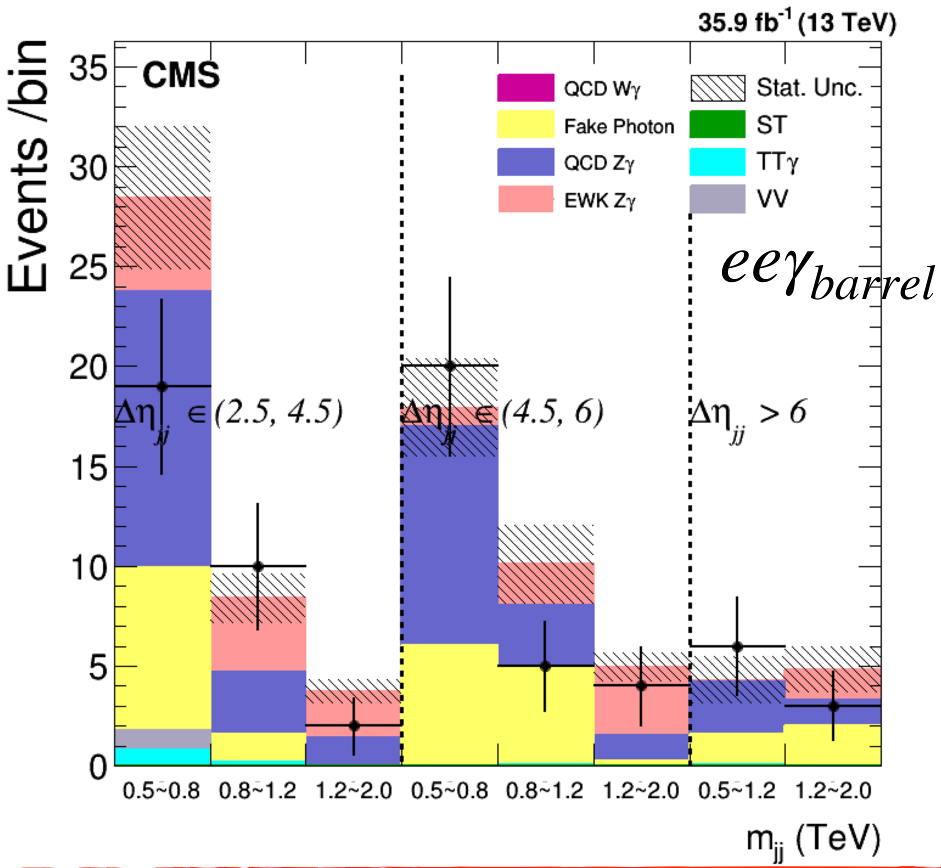
Fake photon uncertainty

Experimental uncertainties

- Propagate fake photon fraction uncertainties (next slide) through analysis
- Calculated bin-by-bin, correlated between bins and categories and regions

Efficiencies, pileup and etc.

# Significance




- Extract signal via the feature of VBS process, large invariant mass and $\Delta\eta_{jj}$ of two jets.
- Add optimization cuts Zepp = $|\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2| < 2.4$ and dphi = $|\phi_{Z\gamma} - \phi_{j1,j2}| > 1.9$ by a scanning

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

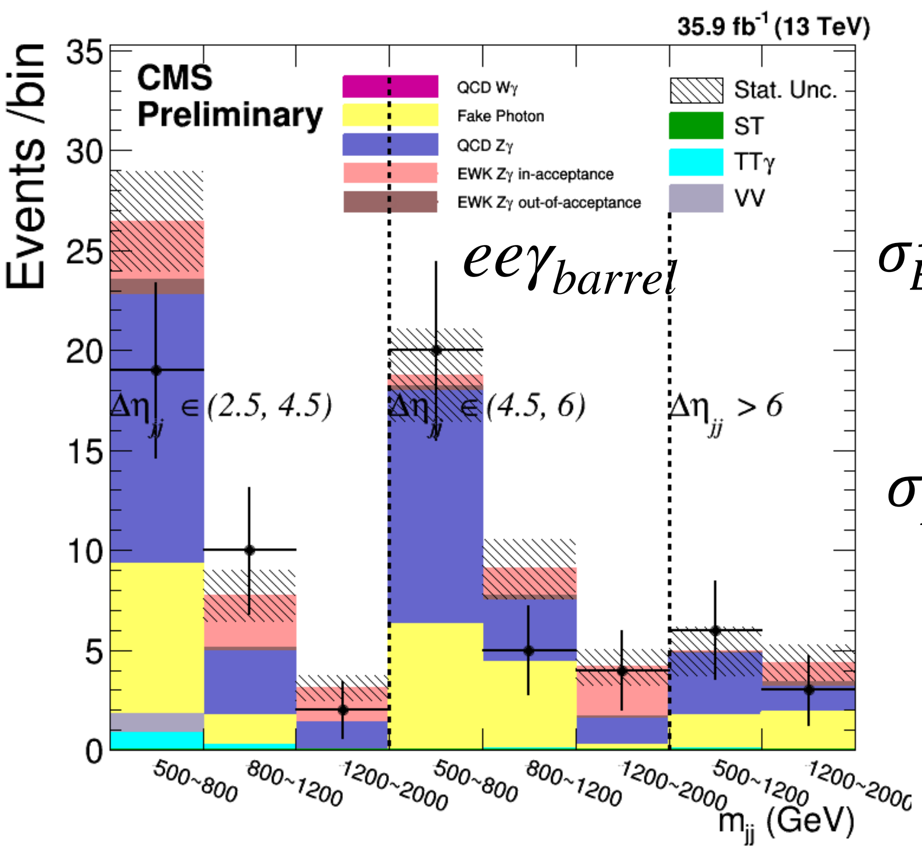
- The expected significance based on 2016 data is 5.2 σ and the observed significance is 3.9 σ
- After the combination with 8 TeV data, the significance is 5.5 σ (expected) and 4.7 σ (observed)

In the combination of the 13 TeV and 8 TeV results, the theoretical uncertainties are treated as correlated, the experimental uncertainties are uncorrelated.

# Fiducial cross section

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

- $\mu_{\text{signal-strength}}$ is the best-fit signal strength which is 0.65 ±0.24 for EWK and 0.91 ± 0.19 for EWK+QCD.
- $\sigma_{\text{generator}}$ is the cross section computed by the generator (MadGraph5_aMC@NLO) which is 4.97 ± 0.25 (scale) ± 0.14 (PDF) for EWK and 15.7 ± 1.7 (scale) ± 0.2 (PDF) fb for EWK+QCD within the fiducial region acceptance.
- $\varepsilon_{\text{generated to fiducial}}$ is the efficiency to go from the generator cuts to the fiducial cuts




$$\sigma^{fid}_{EW+QCD} = 14.3 \pm 0.4(\text{lumi}) \pm 1.1(\text{stat}) \pm 2.7(\text{syst})\ \text{fb} = 14.3 \pm 3.0\ \text{fb}$$

$$\sigma^{fid}_{EW} = 3.2 \pm 0.2(\text{lumi}) \pm 1.1(\text{stat}) \pm 0.6(\text{syst})\ \text{fb} = 3.2 \pm 1.2\ \text{fb}$$



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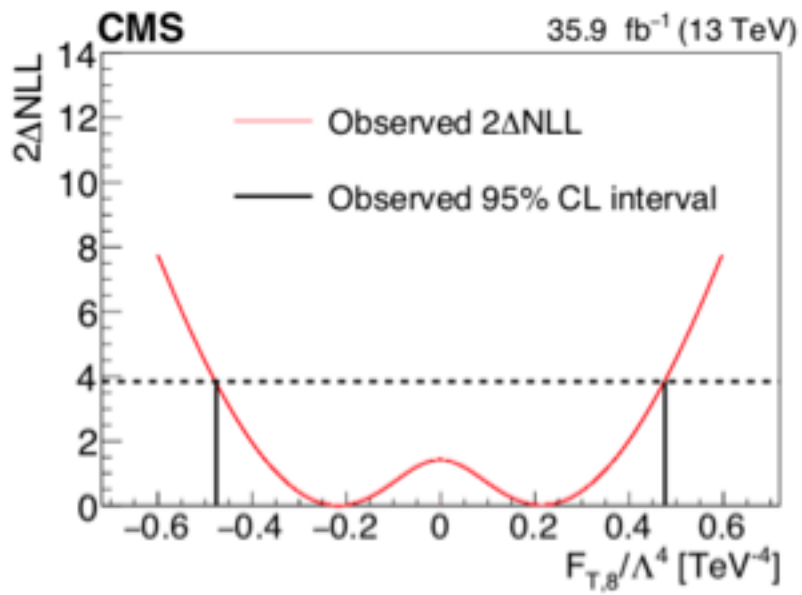
# aQGC limits

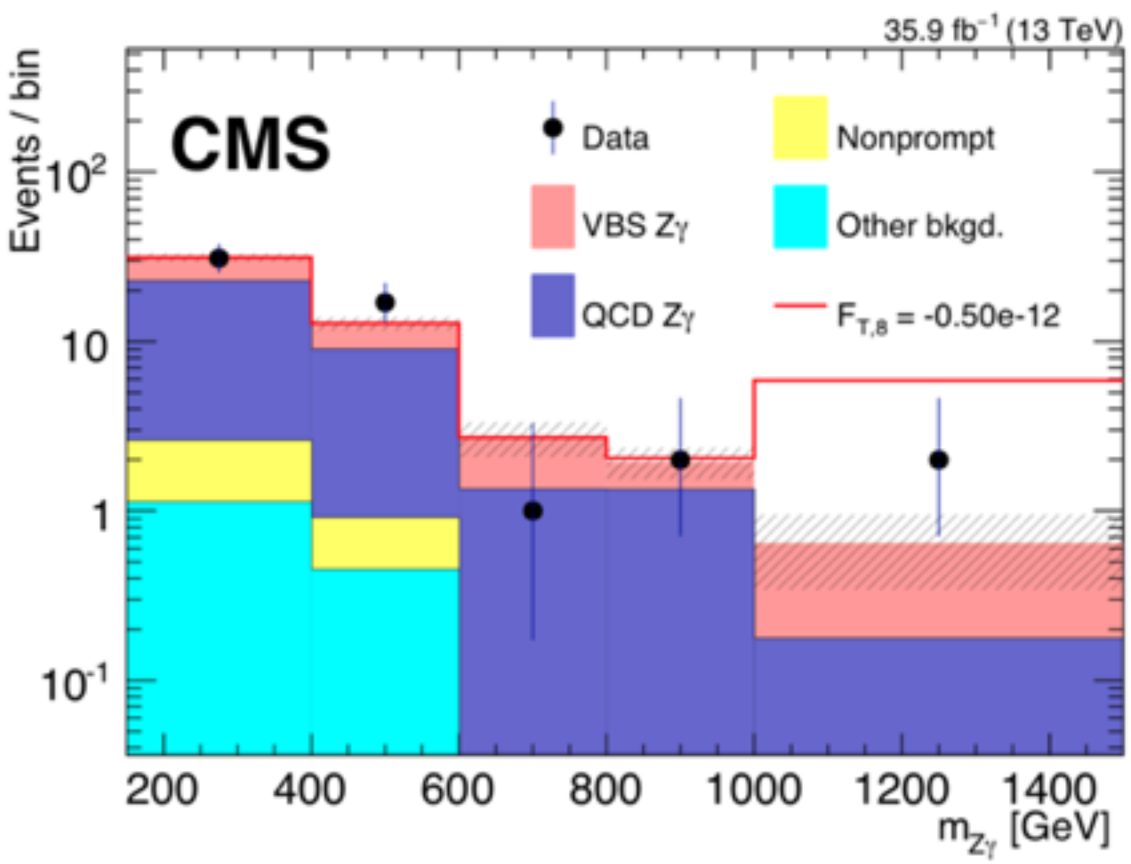
SM lagrangian can be extended with higher dimensional operators maintainng SU(2)×U(1) gauge symmetry:

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} \mathscr{O}_n$$

- Operator: $LT_{0\text{-}2}$, $LT_{5\text{-}9}$ and $LM_{0\text{-}7}$ were considered.
- For each aQGC value, the ratio of AQGC/SM was computed for every $m_{Z\gamma}$ bin and a fit was performed.
- Considering a test statistics test: $t_{\alpha_{test}} = -2ln\frac{\mathcal{L}(\alpha_{test},\hat{\hat{\theta}})}{\mathcal{L}(\hat{\alpha},\hat{\theta})}$ follows $\chi^2$ distribution.
- Extract the limits directly using the delta log-likelihood function $\Delta NLL = t_{\alpha test}/2$.
- The 95% CL limit on a one dimensional aQGC parameter corresponds a value of 3.84.

# aQGC limits




| Observed Limits [TeV$^{-4}$] | Expected Limits [TeV$^{-4}$] | Unitarity Bound |
|---|---|---|
| $-19.5 < f_{M0}/\Lambda^4 < 20.3$ | $-15.0 < f_{M0}/\Lambda^4 < 15.0$ | 1.0 |
| $-40.5 < f_{M1}/\Lambda^4 < 39.5$ | $-30.0 < f_{M1}/\Lambda^4 < 29.9$ | 1.2 |
| $-8.22 < f_{M2}/\Lambda^4 < 8.10$ | $-6.09 < f_{M2}/\Lambda^4 < 6.06$ | 1.3 |
| $-17.7 < f_{M3}/\Lambda^4 < 17.9$ | $-13.1 < f_{M3}/\Lambda^4 < 13.2$ | 1.4 |
| $-15.3 < f_{M4}/\Lambda^4 < 15.8$ | $-11.7 < f_{M4}/\Lambda^4 < 11.7$ | 1.4 |
| $-25.1 < f_{M5}/\Lambda^4 < 24.5$ | $-19.0 < f_{M5}/\Lambda^4 < 18.1$ | 1.8 |
| $-38.9 < f_{M6}/\Lambda^4 < 40.6$ | $-29.9 < f_{M6}/\Lambda^4 < 30.0$ | 1.0 |
| $-60.3 < f_{M7}/\Lambda^4 < 62.5$ | $-45.9 < f_{M7}/\Lambda^4 < 46.1$ | 1.3 |
| $-0.74 < f_{T0}/\Lambda^4 < 0.69$ | $-0.56 < f_{T0}/\Lambda^4 < 0.51$ | 1.4 |
| $-0.98 < f_{T1}/\Lambda^4 < 0.96$ | $-0.72 < f_{T1}/\Lambda^4 < 0.72$ | 1.4 |
| $-1.97 < f_{T2}/\Lambda^4 < 1.86$ | $-1.47 < f_{T2}/\Lambda^4 < 1.37$ | 1.4 |
| $-0.70 < f_{T5}/\Lambda^4 < 0.75$ | $-0.51 < f_{T5}/\Lambda^4 < 0.57$ | 1.7 |
| $-1.64 < f_{T6}/\Lambda^4 < 1.68$ | $-1.23 < f_{T6}/\Lambda^4 < 1.26$ | 1.6 |
| $-2.59 < f_{T7}/\Lambda^4 < 2.82$ | $-1.91 < f_{T7}/\Lambda^4 < 2.12$ | 1.7 |
| $-0.47 < f_{T8}/\Lambda^4 < 0.47$ | $-0.36 < f_{T8}/\Lambda^4 < 0.36$ | 1.5 |
| $-1.27 < f_{T9}/\Lambda^4 < 1.27$ | $-0.94 < f_{T9}/\Lambda^4 < 0.94$ | 1.5 |

the most stringent limits on the aQGC parameters fT8 and fT9 before 2019

# Summary and future plan

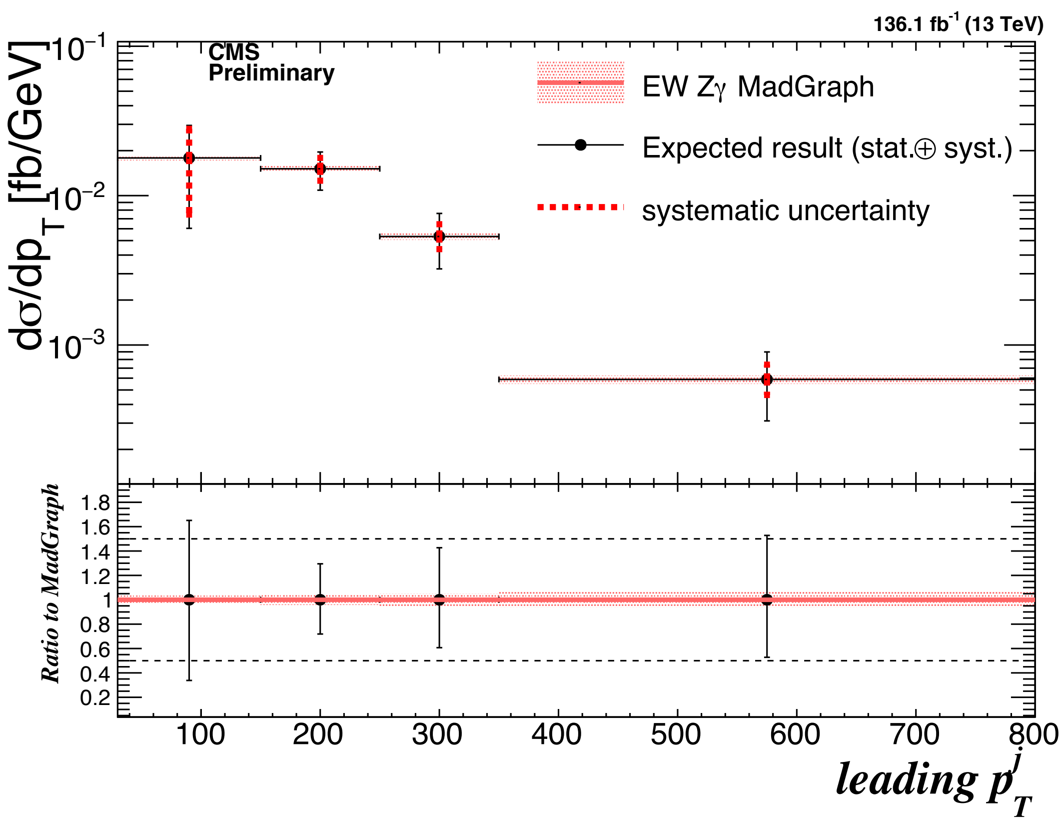
Measurements of electroweak $Z\gamma jj$ analysis using 2016 data

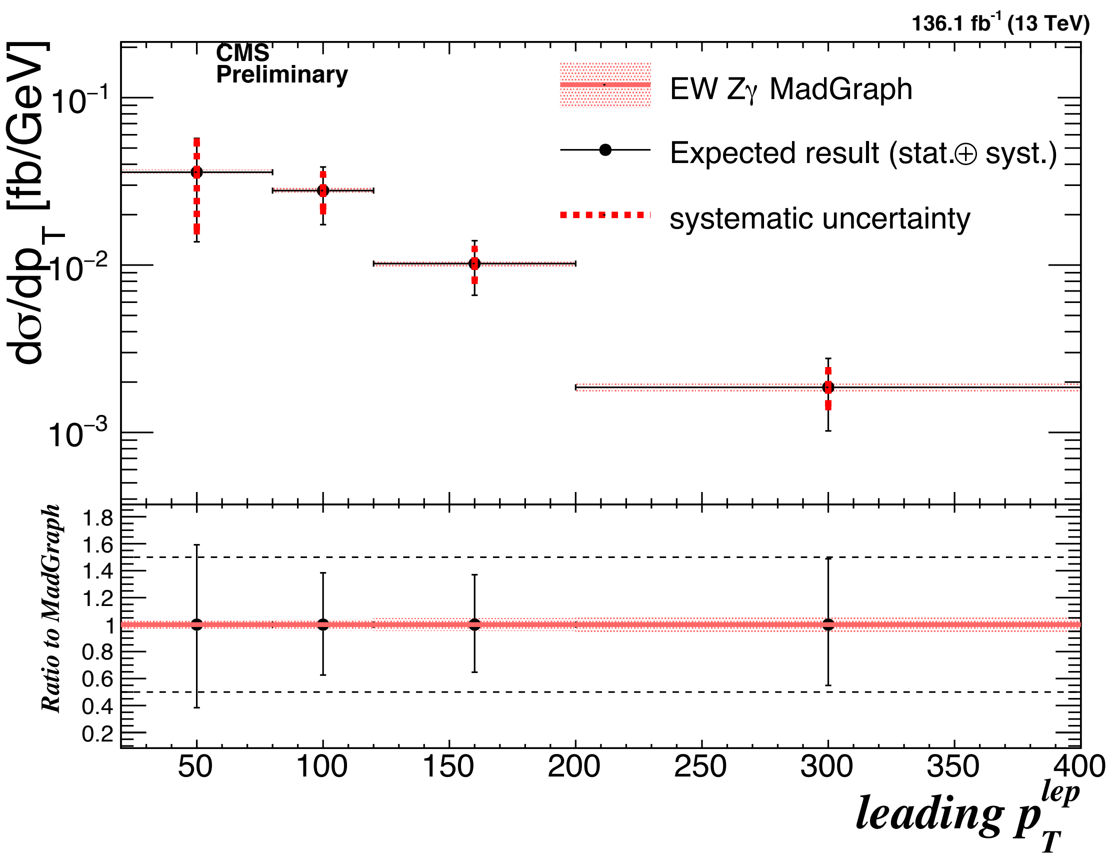
- Observed (expected) significance after combination with previous analysis of 2012 data: 4.7 σ (5.5 σ)
- Observed (expected) significance with only 2016 data: 3.9 σ (5.2 σ)
- Limits on anomalous couplings, the results are competitive or more stringent than previous constraints
- Fiducial cross section measurement

# Summary and future plan

The full RunII VBS Zgamma analysis is being done now and have results of significance and cross section for three years.

Besides previous measurements, the unfolded differential cross section measurements are added.



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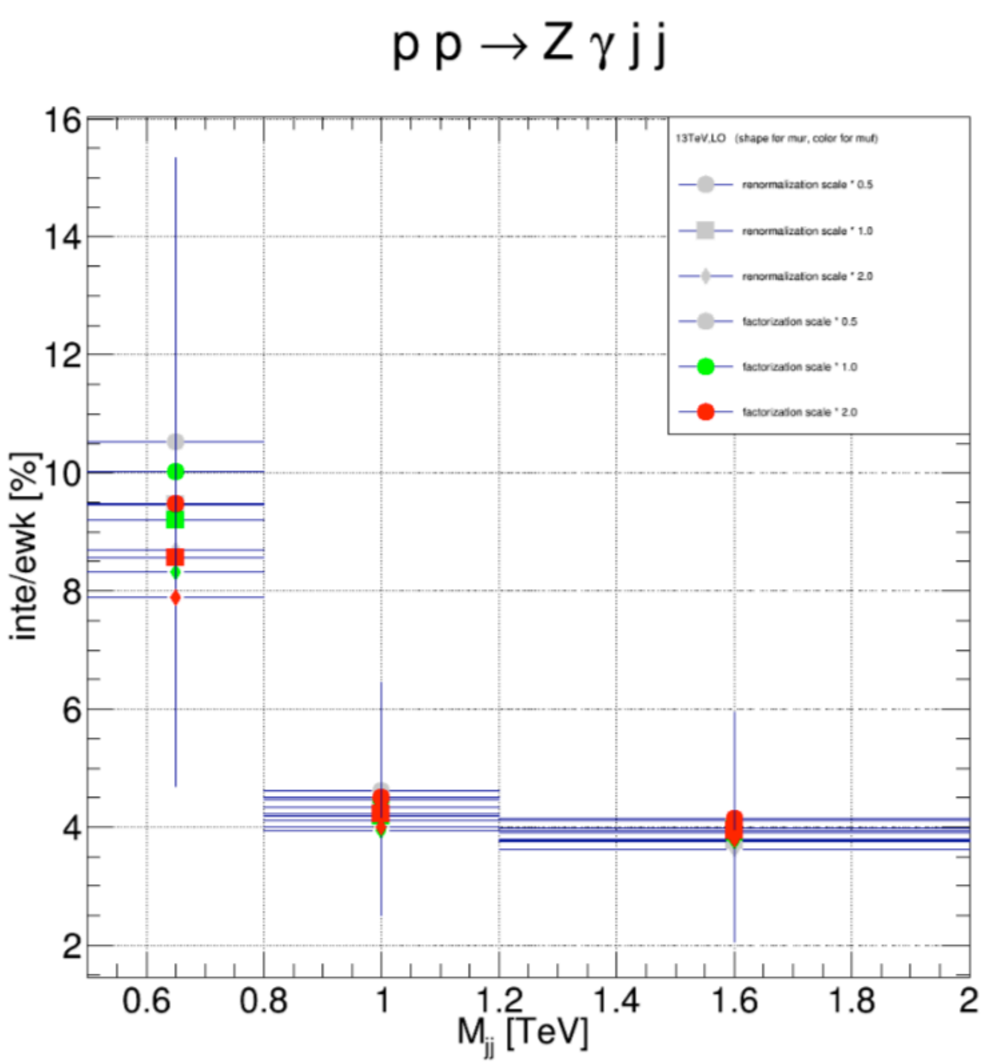
# Backup interference

Generated by `generate p p > lep+ lep- a j j QCD^2==2.`

Defined by $$[\sigma(\mathrm{QCD}+\mathrm{EWK})-\sigma(\mathrm{QCD})-\sigma(\mathrm{EWK})]/\sigma(\mathrm{EWK}),$$

the cross section of the pure interference process is 0.0045pb, while the cross section of EW $Z\gamma$ is 0.1097pb, which lead to a interference 4.1%. The result is consistent with the one we used in the analysis.



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# Backup fiducial

- $P_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$,
- $M_{jj} > 500$ GeV, $\Delta\eta_{jj} >2.5$,
- $P_T^{l1,l2} > 20(25)$ GeV, $|\eta^{l1,l2}| < 2.4(2.5)$, for muon(electron)
- 70 GeV $< M_{ll} <$ 110 GeV,
- $P_T^{\gamma} > 20$ GeV,
- $|\eta^{\gamma}| < 1.4442$ or $1.566 < |\eta^{\gamma}| < 2.5$,
- $\Delta R_{jj}$, $\Delta R_{j\gamma}$, $\Delta R_{jl} > 0.5$,$\Delta R_{l\gamma} > 0.7$,

where "l1" and "l2" denote the lepton and anti-lepton decayed from Z boson, the angular separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, the leptons are dressed with photon whose $\Delta R_{l\gamma} < 0.1$. In this definition, $Z \to \tau\tau$ and $\tau \to \mu/e\nu$ decay are included.

The $\sigma_{generator}$ is 0.1097 pb, $\epsilon_{generated\_to\_fiducial}$ is 0.0453.