

Measurement of VBS $W\gamma$ with the CMS detector

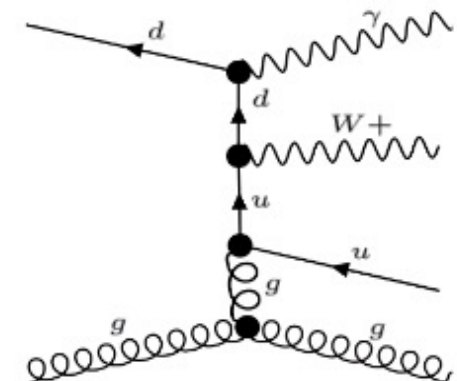
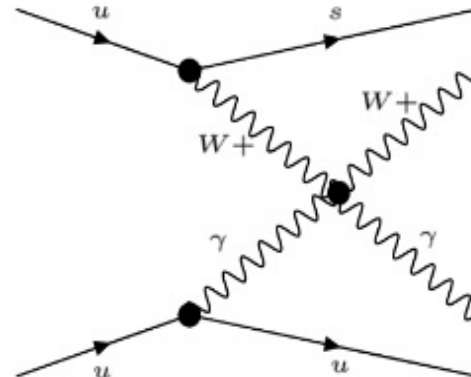
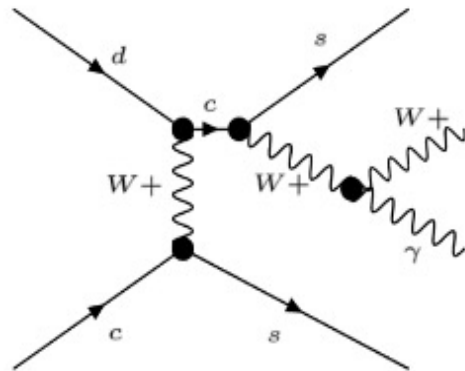
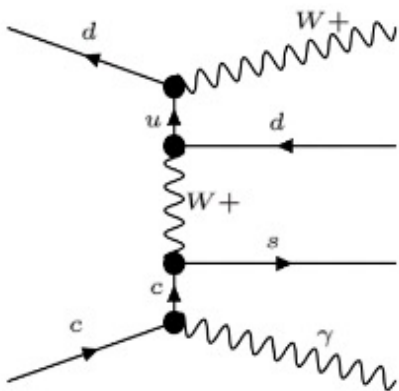
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on behalf of the CMS Collaboration
CLHCP2023, Shanghai Jiao Tong University



Introduction

2

- To deeply examine the SM and probe quartic/triple gauge couplings, we study the vector-boson-scattering (VBS) produced $W\gamma$
- The final states include $e\nu jj$ and $\mu\nu jj$ using the leptonic decay of W bosons
- The VBS signature would be large dijet mass and large η separation between the jets
- Publication: [PRD 108 \(2023\) 032017](#)



Object definition

3

- Muon selection

- Cut-based tight ID
- $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$

- Electron selection

- Cut-based tight ID
- $p_T > 20 \text{ GeV}$, $|\eta| < 2.5$, $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

- Photon selection

- Cut-based medium ID
- Conversion-safe electron veto
- $p_T > 25 \text{ GeV}$ and $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

- Jet selection

- Anti-kT R=0.4 jet
- $p_T > 20 \text{ GeV}$, $|\eta| < 4.7$

- Veto on additional leptons:

- Muon veto

- Cut-based loose ID
- $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$

- Electron veto

- Cut-based veto ID
- $p_T > 20 \text{ GeV}$
- $|\eta| < 2.5$, $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

Event selections

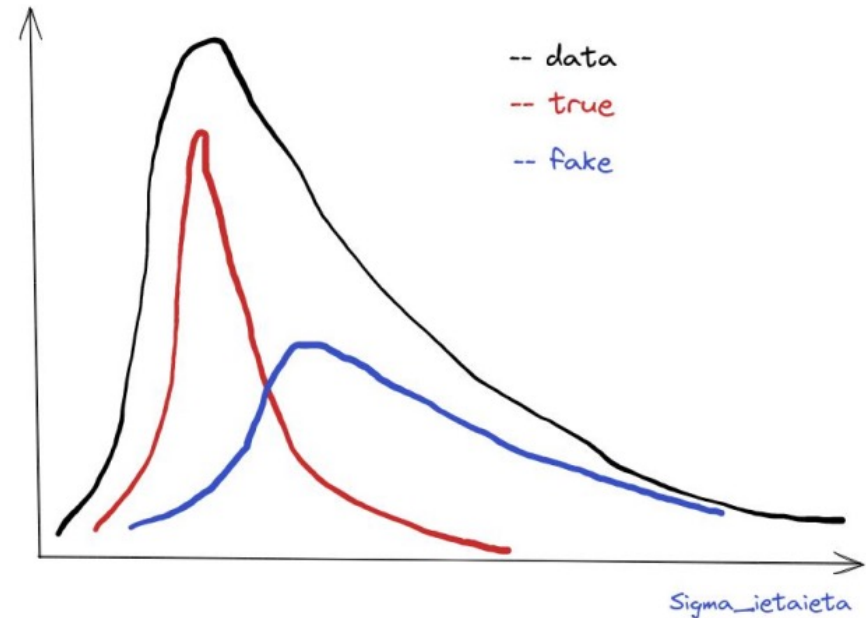
- Trigger with leptons
- Basic selection
 - **One** muon (electron) in muon (electron) channel, **veto** second lepton
 - **Two** reconstructed jets, $p_T^{j1} > 50\text{GeV}$, $|\eta^{j1}| < 4.7$, $p_T^{j2} > 50\text{GeV}$, $|\eta^{j2}| < 4.7$
 - $E_T^{\text{miss}} > 30\text{GeV}$, $M_T(W) > 30\text{GeV}$, $p_T^\ell > 35\text{GeV}$, $|\eta^\ell| < 2.4/2.5(\text{muon/electron})$
 - $p_T^\gamma > 25\text{GeV}$, $|\eta^\gamma| < 1.4442(\text{barrel})$, $1.556 < |\eta^\gamma| < 2.5(\text{endcap})$, $|M_{\ell\gamma} - M_Z| > 10\text{GeV}(\text{electron})$
 - B-tagged jets veto, $\Delta R_{j\gamma} > 0.5$, $\Delta R_{\ell\gamma} > 0.5$, $\Delta R_{j\ell} > 0.5$, $|\Delta\phi_{j,\text{met}}| > 0.5$
- Control region
 - $200\text{GeV} < M_{jj} < 500\text{GeV}$
- Signal region
 - $M_{jj} > 500\text{GeV}$, $M_{W\gamma} > 100\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$
 - $|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$ $|\phi_{W\gamma} - \phi_{j1,j2}| > 2$

Fitting strategy:

Extract signal from 2D fit of $M_{jj} - M_{\ell\gamma}$

Background estimations

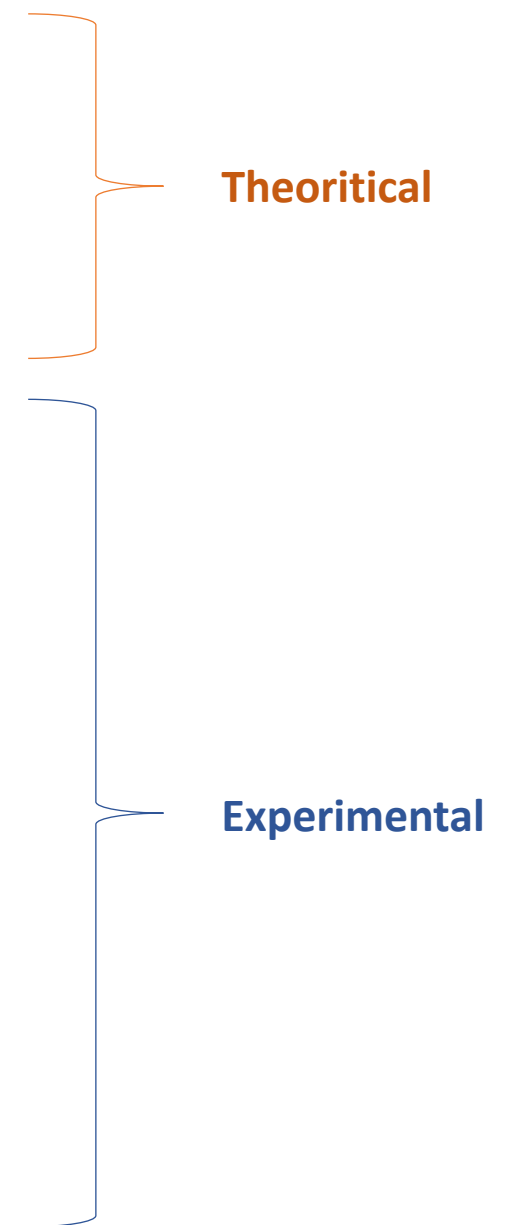
- Reducible backgrounds are estimated using MC (QCD $W\gamma$, top VV , $Z\gamma$ etc.)
- Irreducible background mainly comes from fake photons (**non-prompt photons**) and fake leptons
 - Mainly π^0 s mis-reconstructed as photons
 - Estimated using template method
 - Make 'TRUE', 'FAKE', and 'DATA' templates



Template	True	Fake	Date
Sample	QCD $W\gamma$	Data	Data
Basic selection	lepton and photon cut		
Individual selection	photon isolation required	photon isolation inverted	photon isolation required
Fit	fit on $\sigma_{i\eta i\eta}$		

Systematic uncertainties

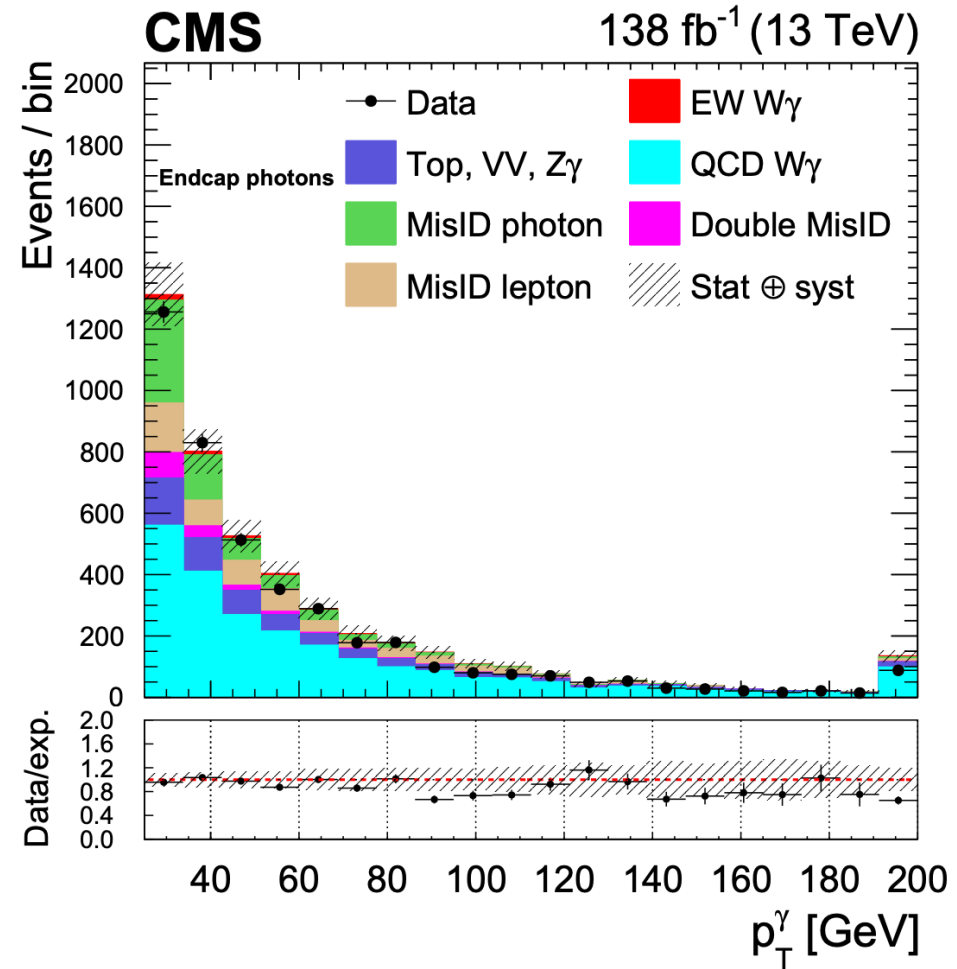
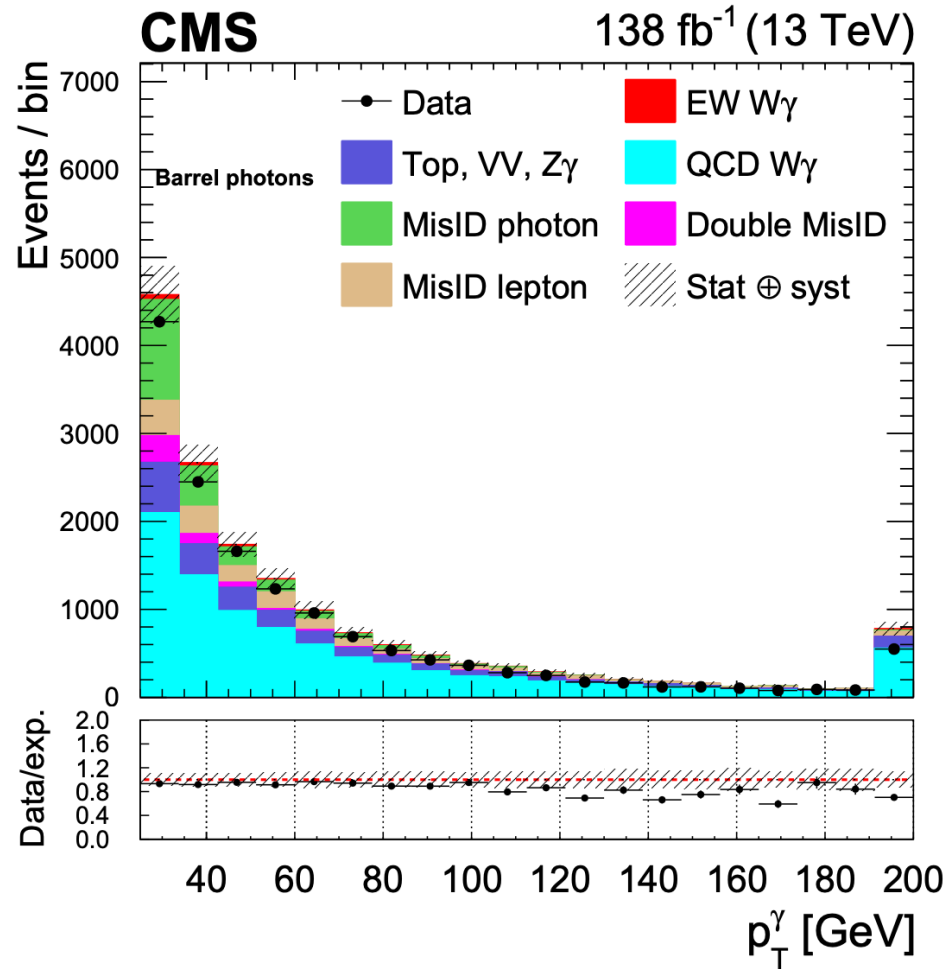
- **Factorization and renormalization scale uncertainty**
 - Calculated bin-by-bin, correlated between bins, channels, and years
- **PDF uncertainty**
 - Standard deviation of the NNPDF3.0 set variations
 - Calculated bin-by-bin, correlated between bins, channels, and years
- **Fake photon uncertainty**
 - 3 sources of uncertainty are added in quadrature
 - Uncertainty due to charged isolation sideband selection
 - Uncertainty due to non-closure of MC closure test
 - Uncertainty due to fit error
 - Calculated bin-by-bin, correlated between bins, channels, and years
- **Fake lepton uncertainty**
 - 30% normalization uncertainty for each lepton flavor
- **Jet energy scale and resolution**
 - Choose the largest deviation of up/down to the central
 - Calculated bin-by-bin, correlated between bins, channels, and years
 - **JES** is the largest uncertainty and is broken into 12 sub-uncertainties
- **Other systematic uncertainties**
 - Pileup, prefiring, luminosity, lepton and photon scale factors



Theoretical

Experimental

Kinematics in control region



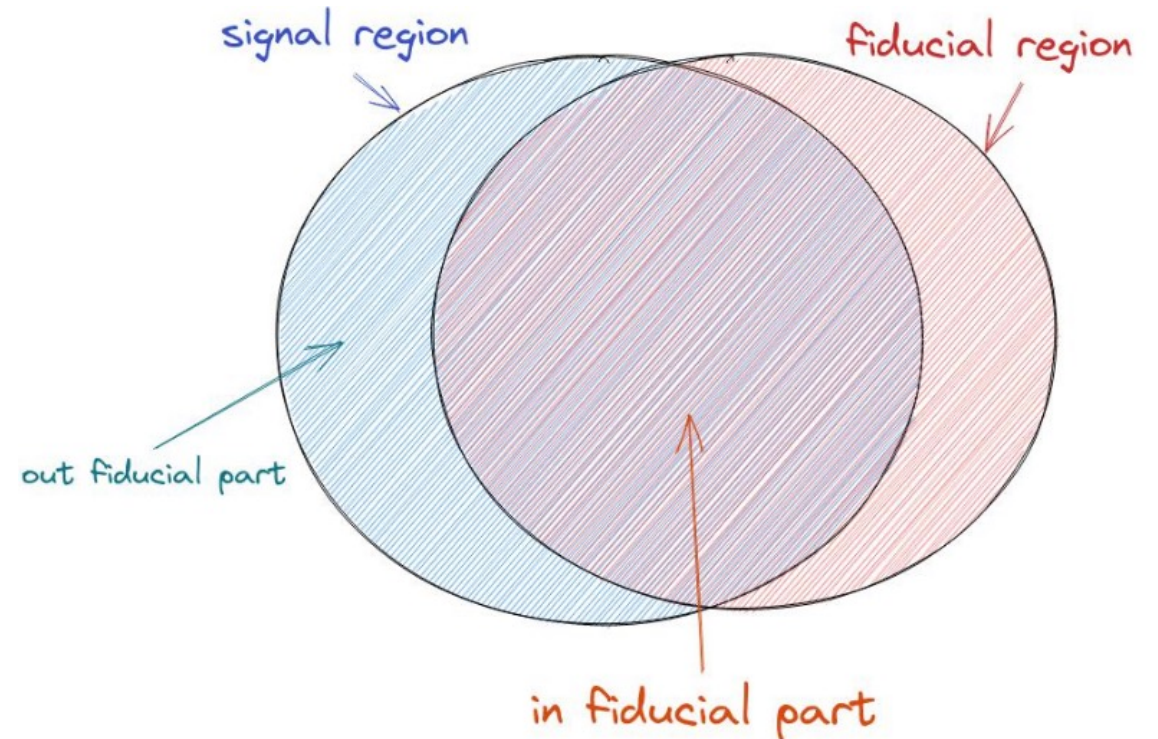
- ★ Pre-fit plot for photon p_T in control region. The left is for barrel and the right for edcap.
- ★ Data and MC have decent agreement within uncertainties (stat + syst).

Fiducial cross section

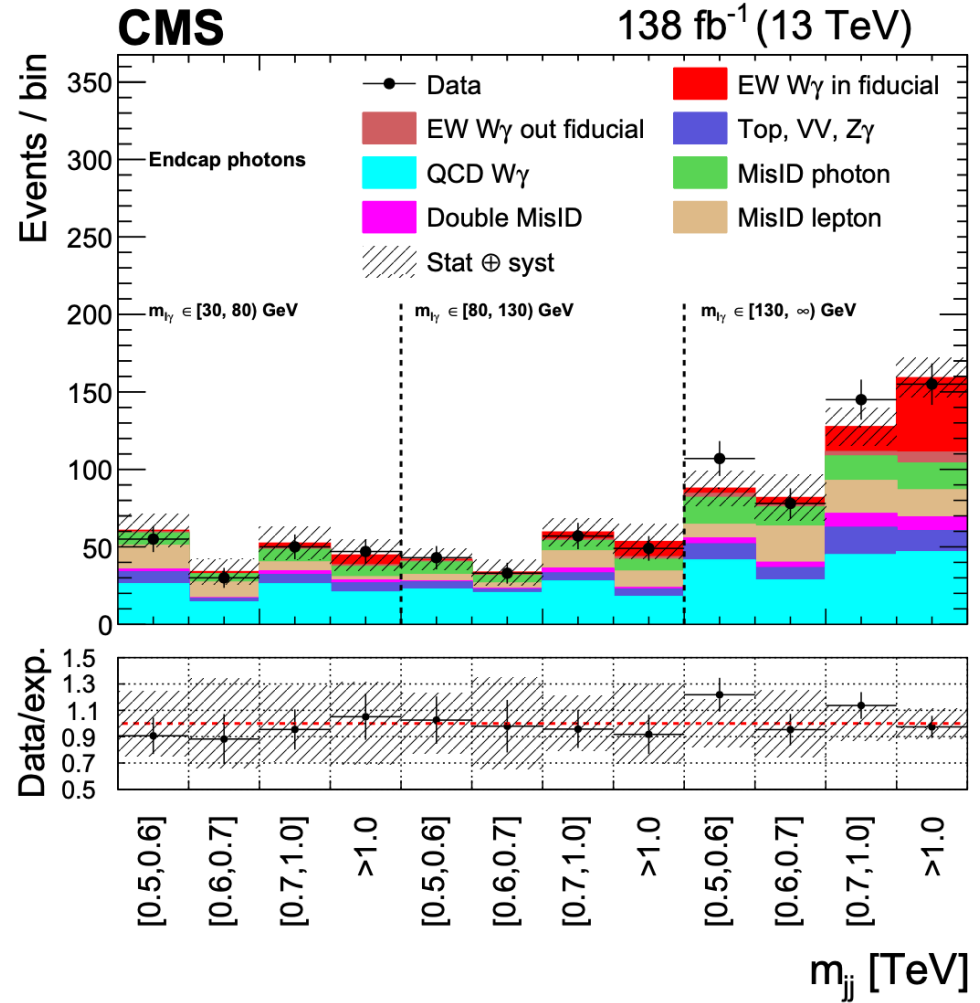
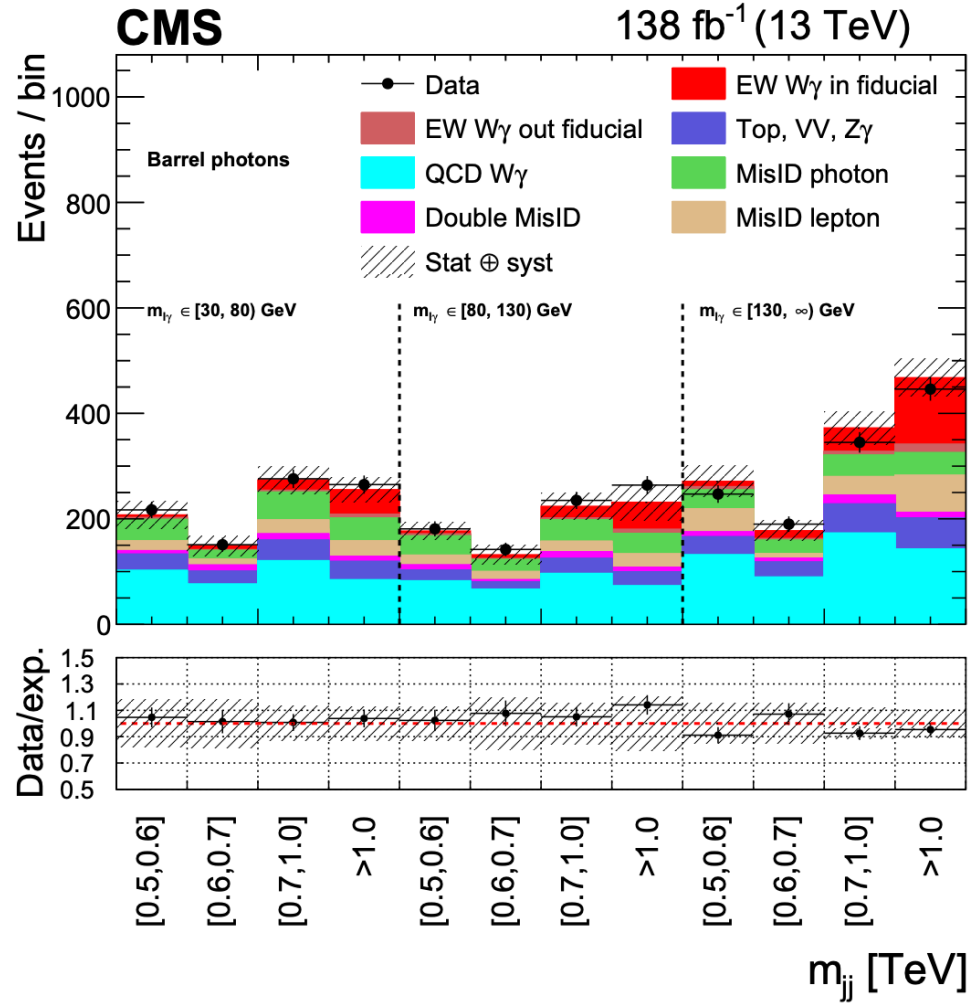
- The fiducial region is defined at “particle level” (“generator level”).
- The component of the signal that doesn't pass the fiducial region is treated as a background.

★ Fiducial region selections :

- Jet $p_T > 50$ GeV and $|\eta| < 4.7$
- Photon $p_T > 25$ GeV
- Photon $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$
- Lepton $p_T > 35$ GeV and $|\eta| < 2.4$
- $m_{jj} > 500$ GeV, $|\eta_{jj}| > 2.5$
- $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{jl}, \Delta R_{l\gamma} > 0.5$
- Leptons are dressed with photons within $\Delta R = 0.1$



Fiducial cross section measurements



Fiducial cross section

$$\sigma_{fiducial_{XS}} = \sigma \cdot \mu \cdot \epsilon$$

- σ is the cross section of the Monte Carlo signal sample.
- μ is the signal strength from fitting.
- ϵ is the fraction of the generated signal events passing the fiducial region selection

★ Fiducial cross section

- EW

- Acceptance = 0.034

- $\sigma_{EW}^{fid} = 23.5_{-4.7}^{+4.9} = 23.5_{-2.8}^{+2.8} \text{ (stat)}_{-1.7}^{+1.9} \text{ (theo)}_{-3.4}^{+3.5} \text{ (syst) fb}$

- EW +QCD

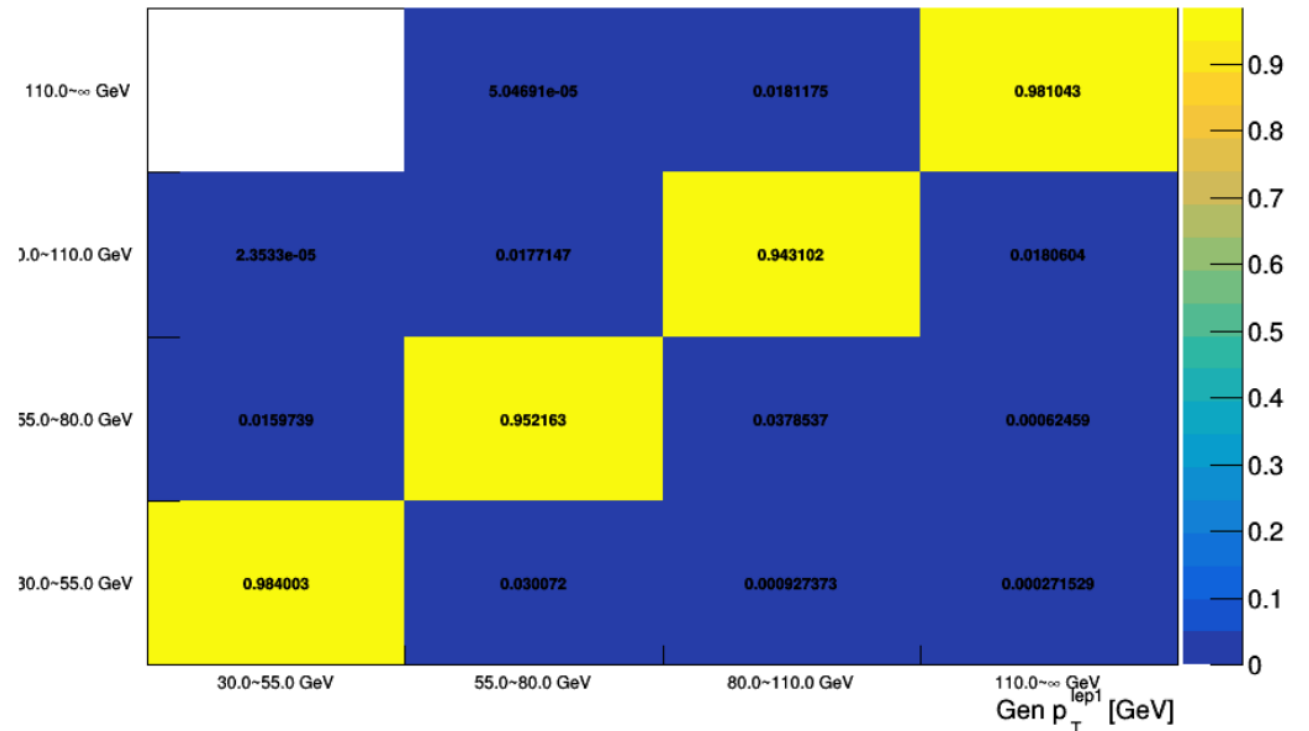
- Acceptance = 4.6e-4

- $\sigma_{EW+QCD}^{fid} = 113_{-13}^{+13} = 113_{-2.0}^{+2.0} \text{ (stat)}_{-2.3}^{+2.5} \text{ (theo)}_{-13}^{+13} \text{ (syst) fb}$

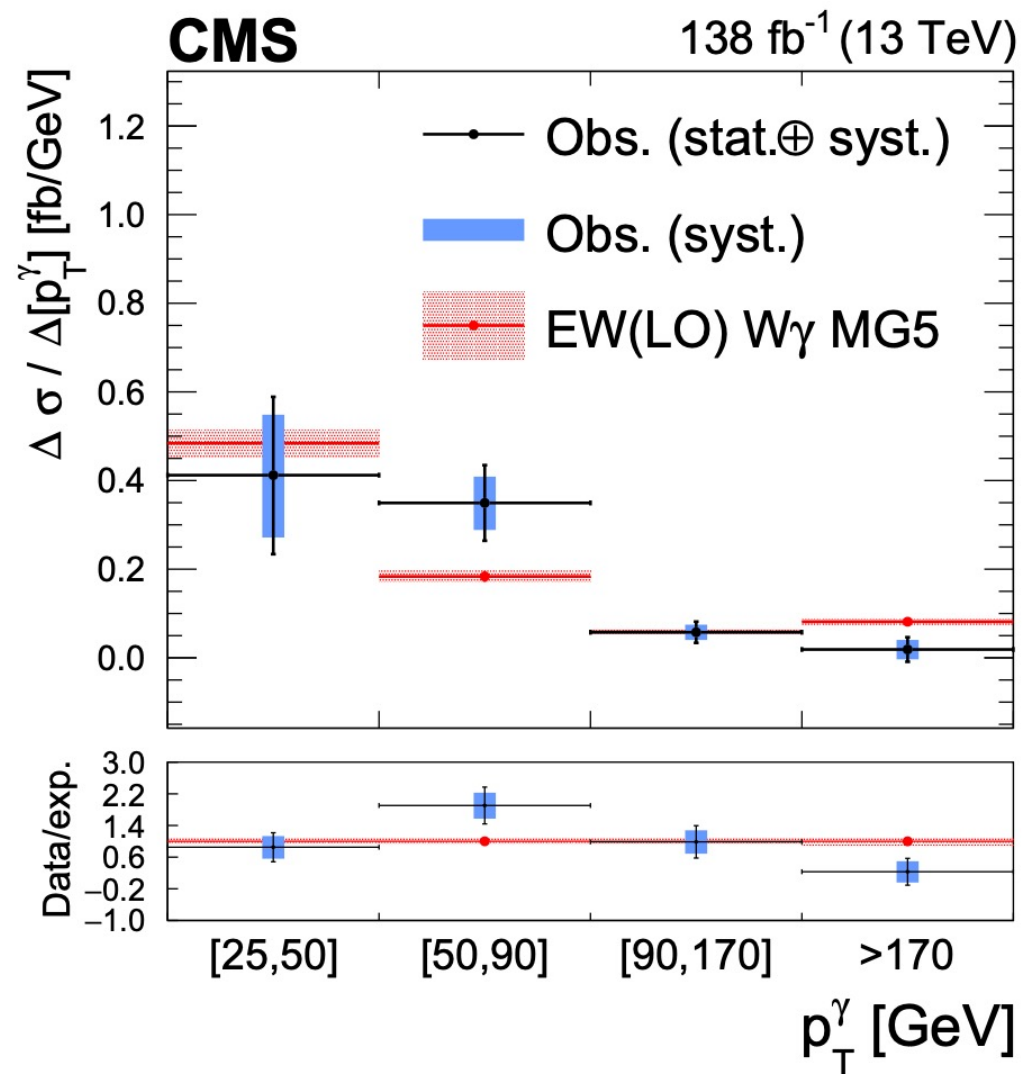
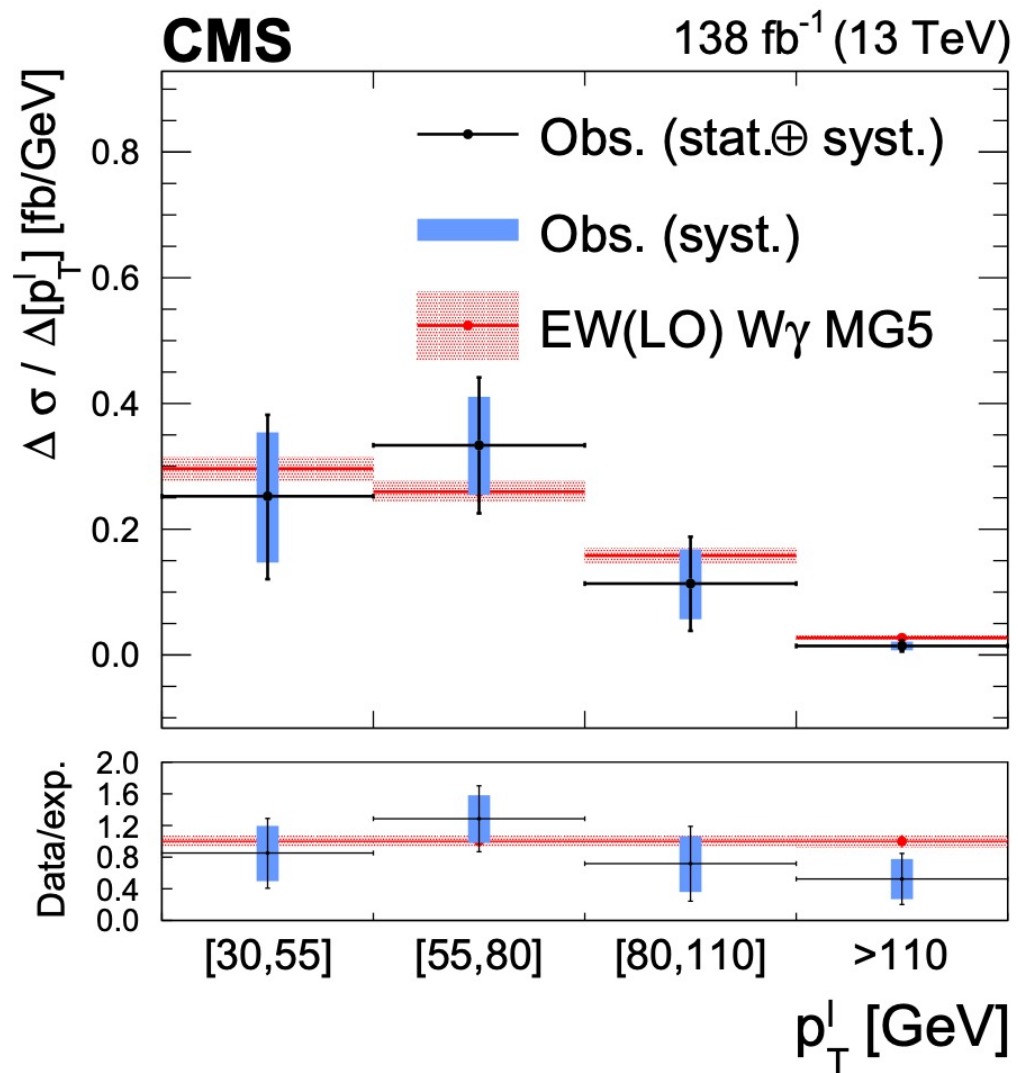
Differential cross section

- The full Run2 data has larger statistic for possible extraction of differential information
- Perform 'unfolding' to revert the 'detector smearing' on the data to get the 'True' distribution.
- Same uncertainties with fiducial cross section measurement.
- Differential cross section are measured :
 - EW and EW+QCD
 - $p_T^l, p_T^\gamma, p_T^{j1}, m_{l\gamma}, m_{jj}, \Delta\eta_{jj}$

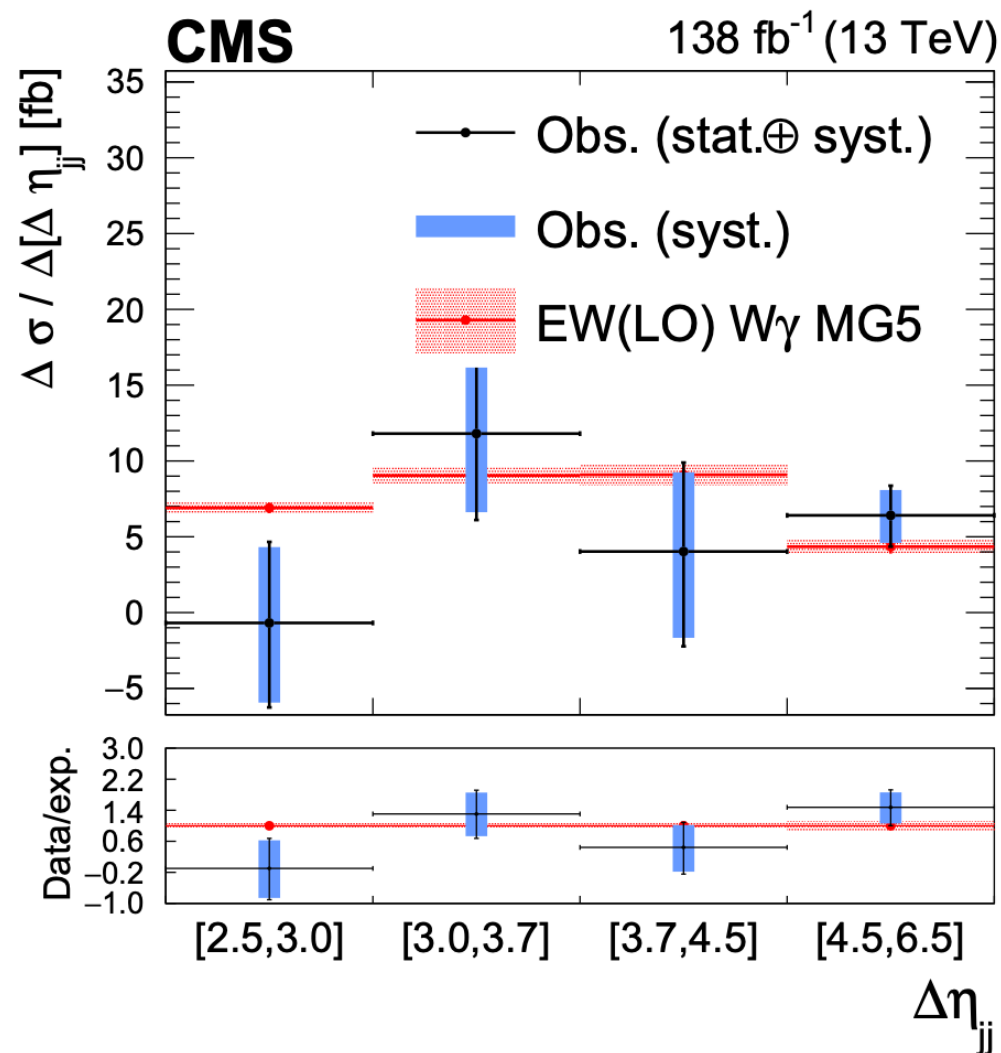
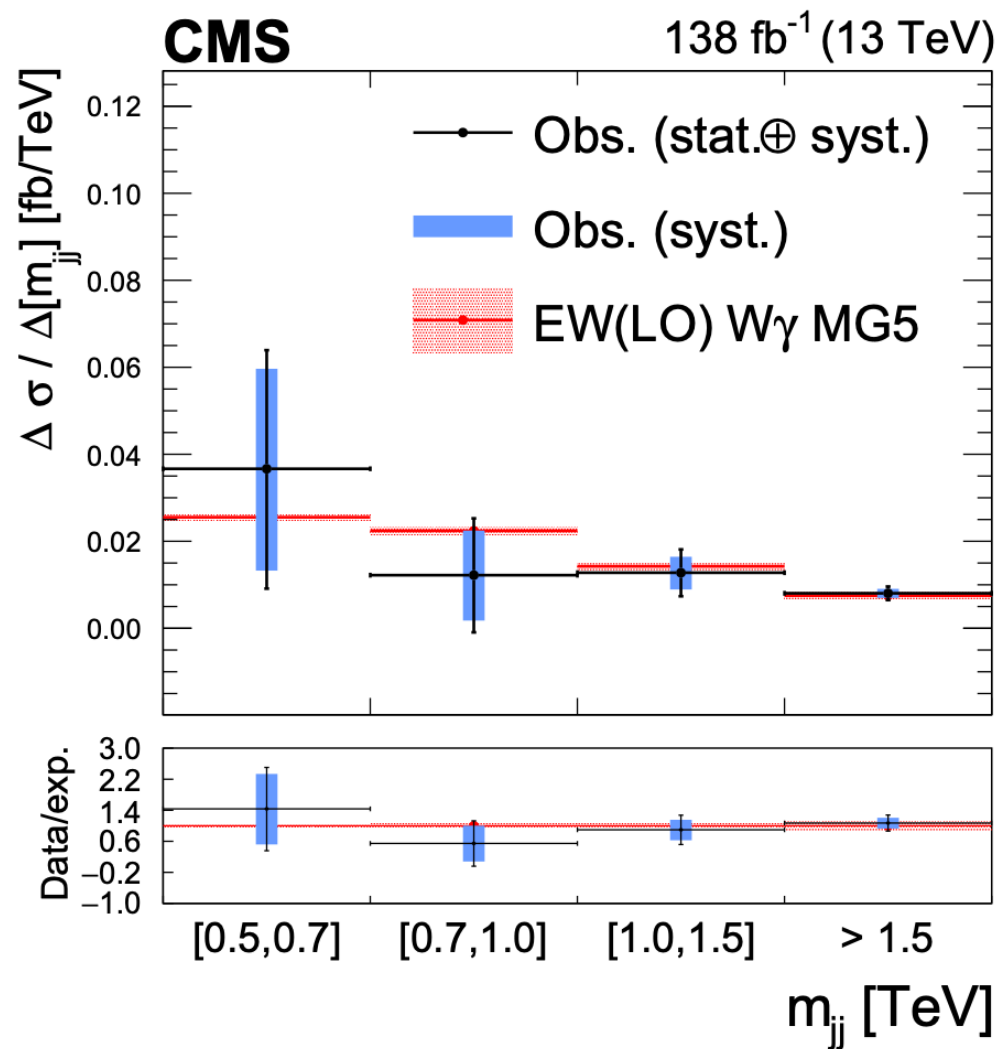
Response matrix



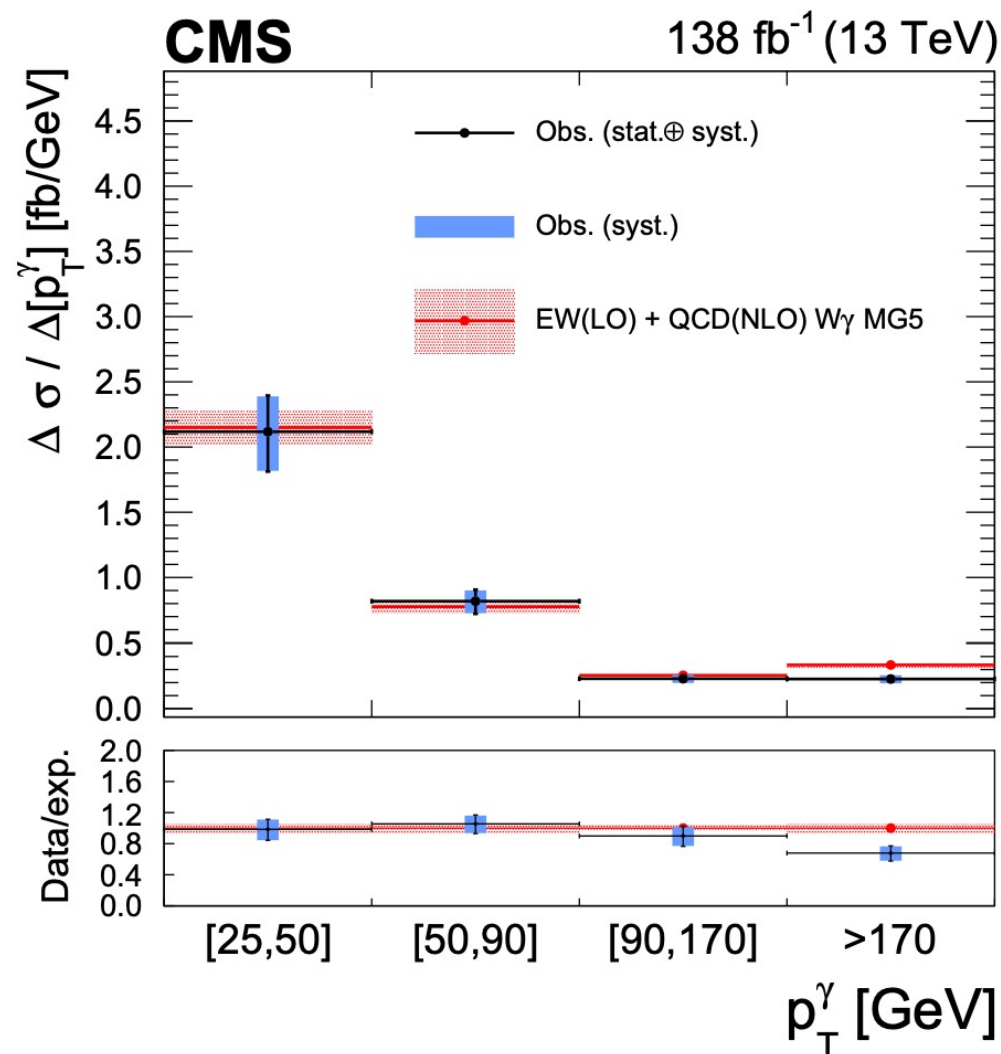
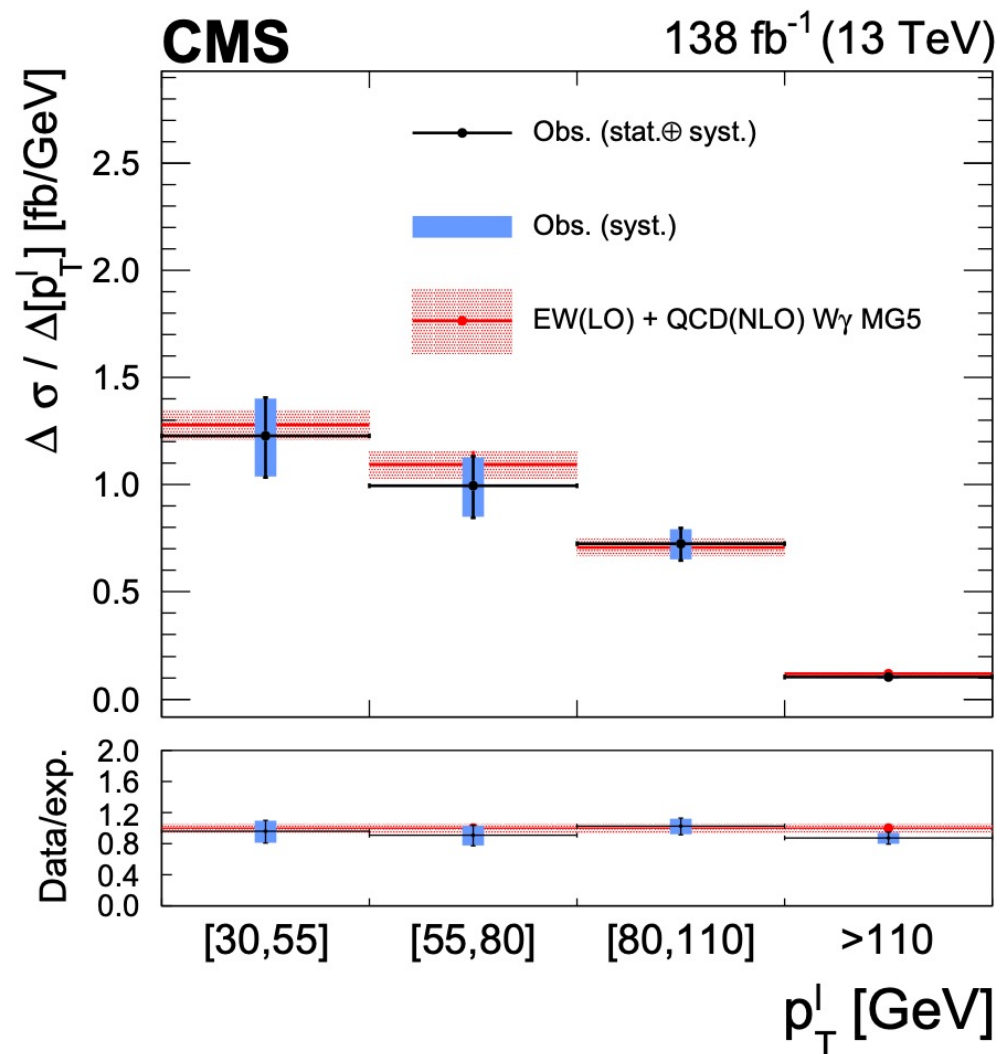
Differential cross section of EW $W\gamma$



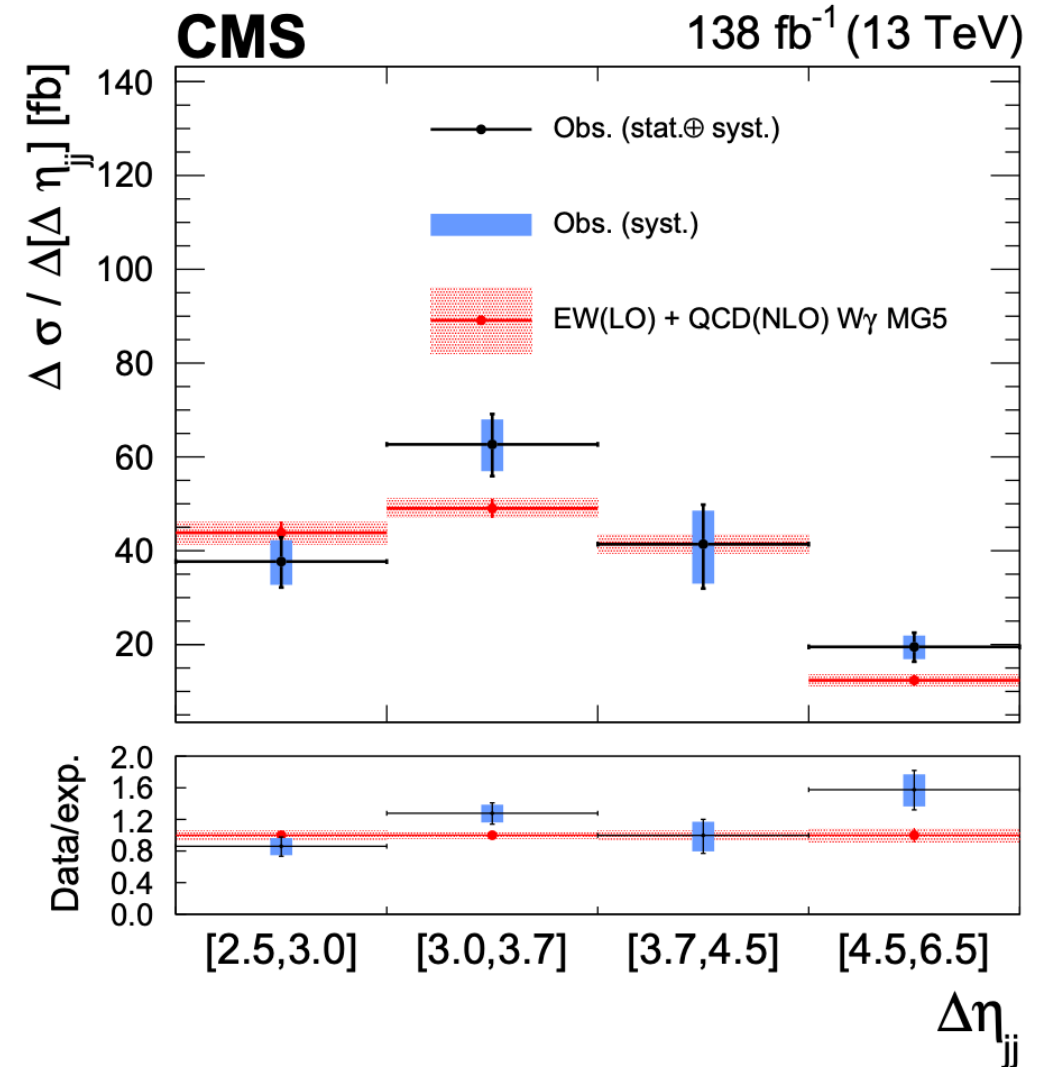
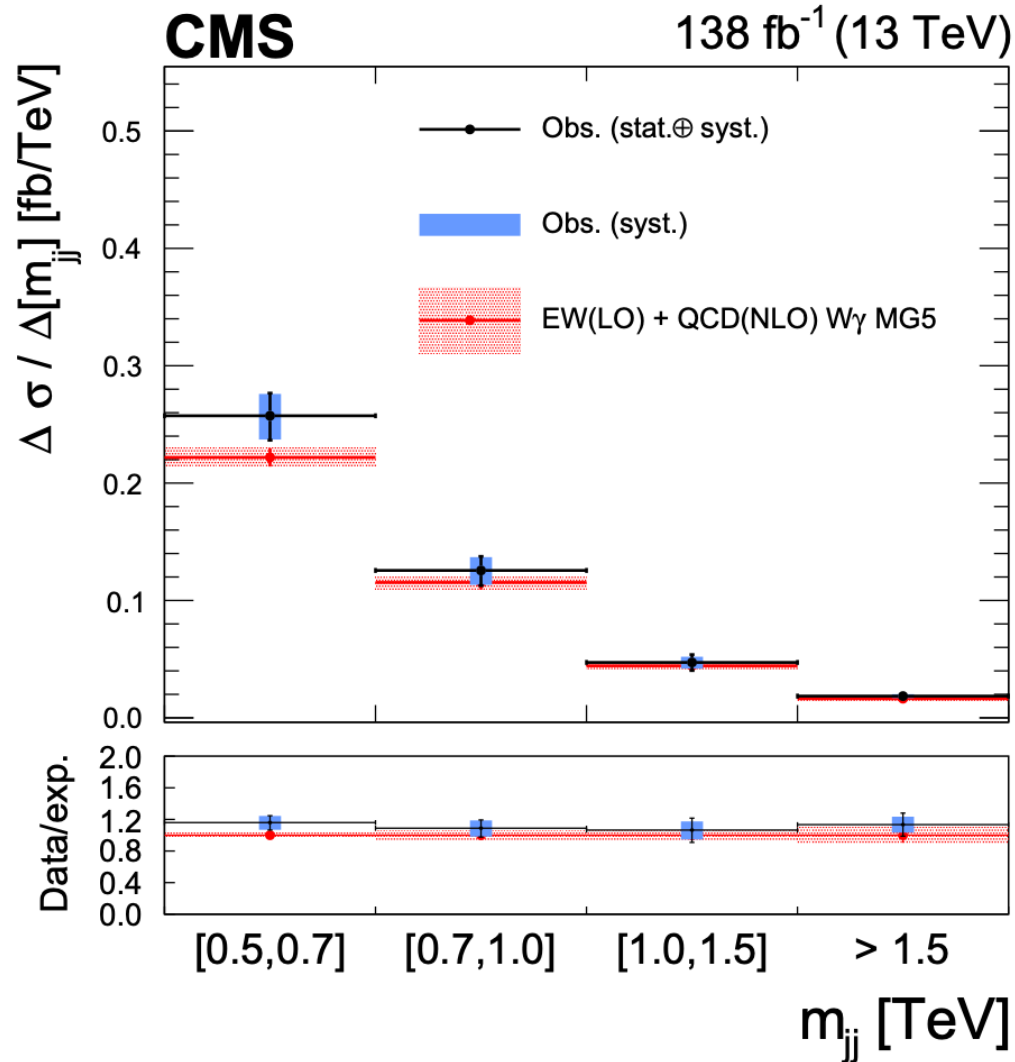
Differential cross section of EW $W\gamma$



Differential cross section of EW+QCD $W\gamma$



Differential cross section of EW+QCD $W\gamma$



Limits on dimension 8 EFT coefficients

16

- **Portal to BSM effects** in a model independent approach, usually parametrized as

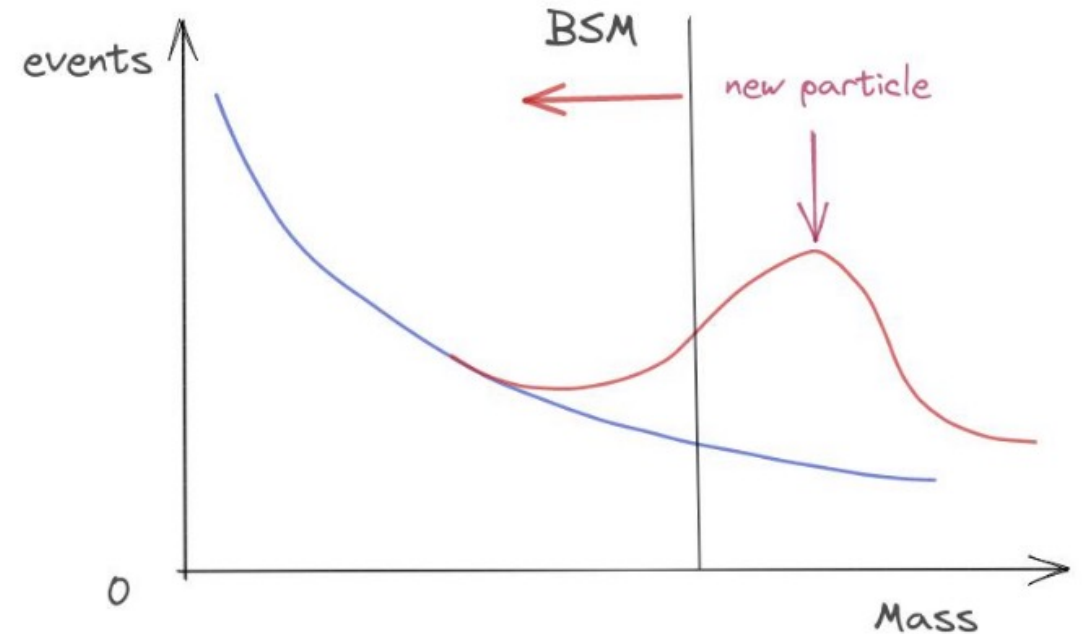
Effective Field Theory (EFT)

- Effective field theory with cutoff energy scale Λ

- $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$

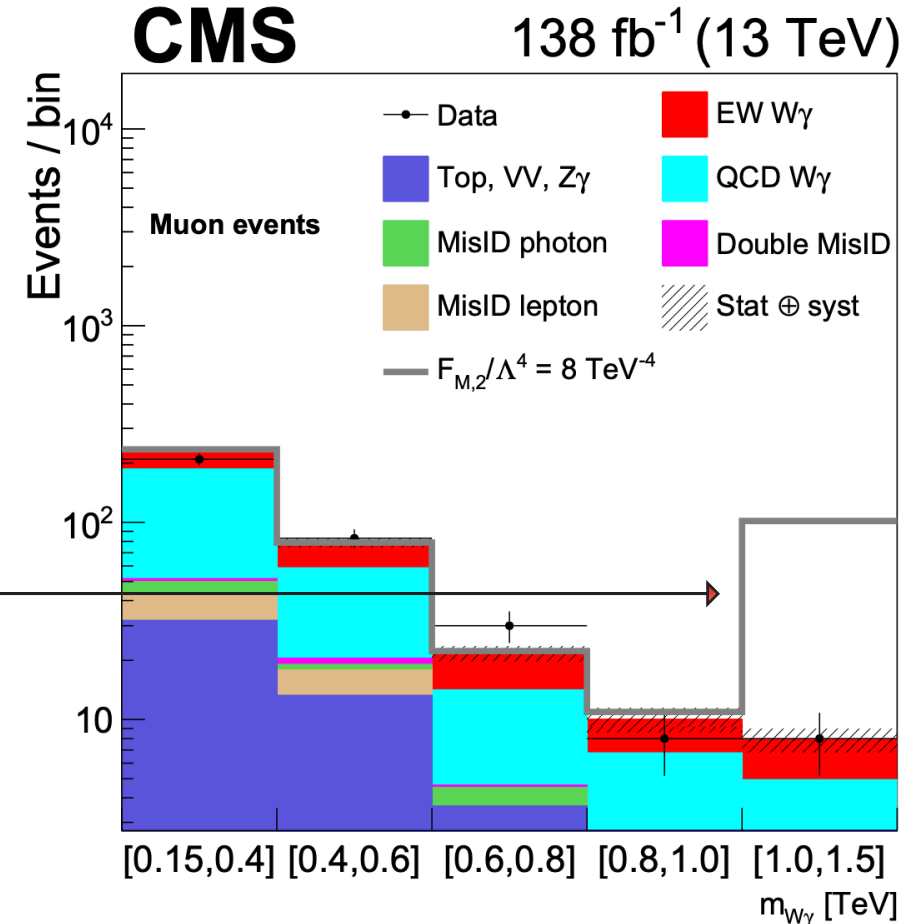
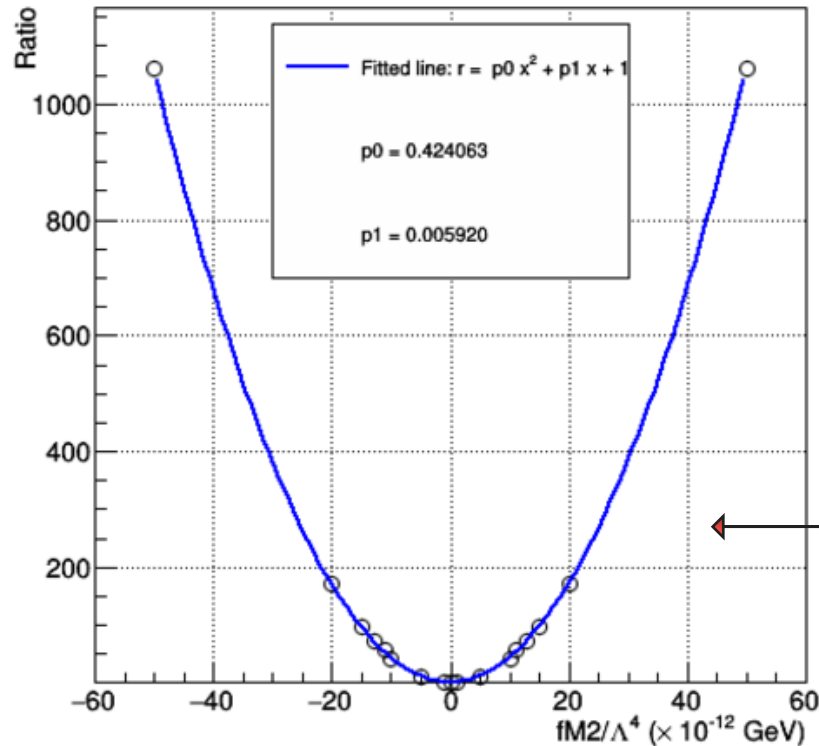
- Dimension 8 EFT operators under tests

- Operators : LM0-7, LT0-2, LT5-7



Limits on dimension 8 EFT coefficients

- EFT operator modifications on the EW signal are inserted into the fits to data



The yield ratio between SM and AQC following the quadratic function! ★

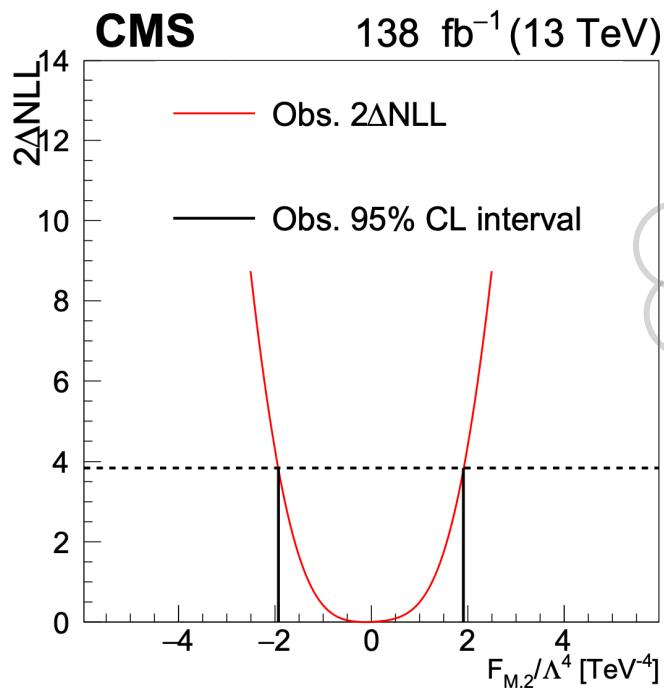
Limits on dimension 8 EFT coefficients

18

- Dimension 8 EFT model
- Effective field theory with cutoff energy scale Λ

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$$

Operators : LM0-7, LT0-2, LT5-7



World's
leading
limits to
date

Coef	Exp Low(TeV ⁻⁴)	Exp High(TeV ⁻⁴)	Obs Low(TeV ⁻⁴)	Obs High(TeV ⁻⁴)
F_{M0}/Λ^4	-5.1	5.1	-56	5.5
F_{M1}/Λ^4	-7.1	7.4	-7.8	8.1
F_{M2}/Λ^4	-1.8	1.8	-1.9	1.9
F_{M3}/Λ^4	-2.5	2.5	-2.7	2.7
F_{M4}/Λ^4	-3.3	3.3	-3.7	3.6
F_{M5}/Λ^4	-3.4	3.6	-3.9	3.9
F_{M7}/Λ^4	-13	13	-14	14
F_{T0}/Λ^4	-0.43	-0.51	-0.47	0.51
F_{T1}/Λ^4	-0.27	0.31	-0.31	0.34
F_{T2}/Λ^4	-0.72	0.92	-0.85	1.0
F_{T5}/Λ^4	-0.29	0.31	-0.31	0.33
F_{T6}/Λ^4	-0.23	0.25	-0.25	0.27
F_{T7}/Λ^4	-0.60	0.68	-0.67	0.73

Summary

19

- At CMS, VBS $W\gamma$ is studied using full Run2 data at 13 TeV
- Observation
 - The signal is **observed for the first time** under 13 TeV at the LHC
 - 6.03 σ observed, 6.79 σ expected
- Fiducial cross section measurements, agreeing well with SM:
 - $\sigma_{EW}^{fid} = 23.5_{-4.7}^{+4.9} = 23.5_{-2.8}^{+2.8} \text{ (stat)}_{-1.7}^{+1.9} \text{ (theo)}_{-3.4}^{+3.5} \text{ (syst) fb}$
 - $\sigma_{EW+QCD}^{fid} = 113_{-13}^{+13} = 113_{-2.0}^{+2.0} \text{ (stat)}_{-2.3}^{+2.5} \text{ (theo)}_{-13}^{+13} \text{ (syst) fb}$
- Differential cross section measurements, showing no significant deviation wrt current predictions:
 - EW and EW+QCD
 - $p_T^l, p_T^\gamma, p_T^{j1}, m_{l\gamma}, m_{jj}, \Delta\eta_{jj}$
- Anomalous coupling limits, providing constraints for dimension 8 EFT coefficients
 - **World leading limits for FM2-5, FT5-7**
- Publication: [PRD 108 \(2023\) 032017](#)

Back Up

20

$$\sigma_{i\eta i\eta} = \sqrt{\frac{\sum_i^{5 \times 5} w_i (\eta_i - \bar{\eta}_{5 \times 5})^2}{\sum_i^{5 \times 5} w_i}}$$

$w_i \neq 0$, if $E_i > 0.9\%$ of $E_{5 \times 5}$

