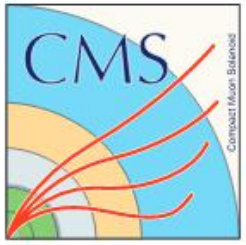
Measurement of WWγ and VBS Wγ production

Jing Peng on behalf of the CMS Collaboration

MBI2022



OUTLINE

★WWγ

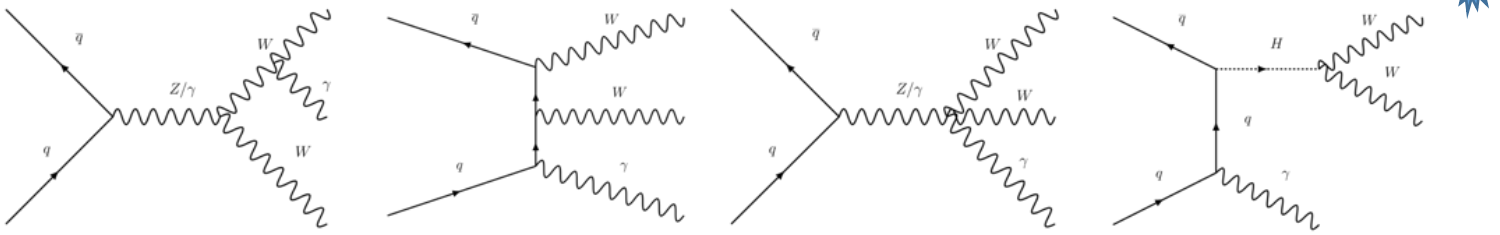
- WWγ Brief Introduction
- Previous WWγ study at CMS/ATLAS
- Probing Higgs boson couplings in H+γ production at the LHC

★VBS Wγ

- Introduction and objects definition
- Data and Simulated samples
- Nonprompt photon and nonprompt lepton
- Selection definitions and uncertanties
- Comparison plot in control region
- Fiducial cross section and differential cross section
- Limits on dimension 8 EFT coefficients
- Summary

Measurement of WWγ production

WWγ Brief Introduction



WWγ Representative Feynman Diagrams

- CMS in 2014 at $\sqrt{s}$ = 8 TeV with 19.3/fb
- Focus on WWγ semileptonic channel

- Atlas in 2014 at $\sqrt{s}$ = 8 TeV with 20.2/fb
- Focus on WWγ $e\mu$ channel

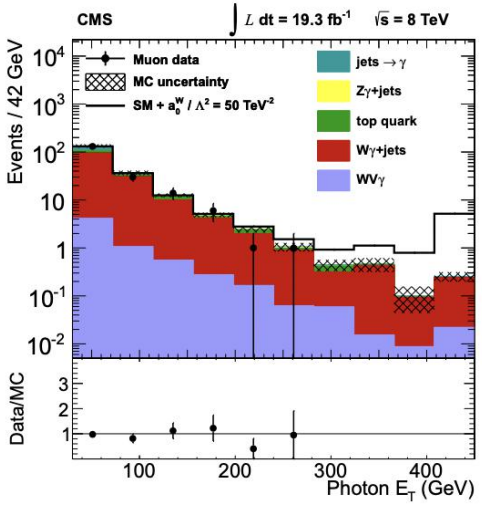
- Atlas in 2014 at $\sqrt{s}$ = 8 TeV with 20.2/fb
- Focus on WWγ semi-leptonic channel

- **Direct measurement of gauge boson self-couplings and precision test of SM**
  - CMS studied semi-leptonic WWγ and anomalous quartic gauge couplings at $\sqrt{s}$ = 8 TeV with 19.3/fb in 2014 [1]
  - ATLAS studied $e\mu$ and semi-leptonic channel at $\sqrt{s}$ = 8 TeV with 20.2/fb and significance is 1.4(1.6)σ [2]
  - **NOW: at CMS, $e\mu$ channel at $\sqrt{s}$ = 13 TeV with 138/fb is under study.**
- **Beyond SM study**
  - CMS studied WWγ anomalous quartic gauge couplings at $\sqrt{s}$ = 8 TeV in 2014
  - ATLAS studied WWγ anomalous quartic gauge couplings at $\sqrt{s}$ = 8 TeV with 20.2/fb in 2017
  - **NOW: at CMS,**

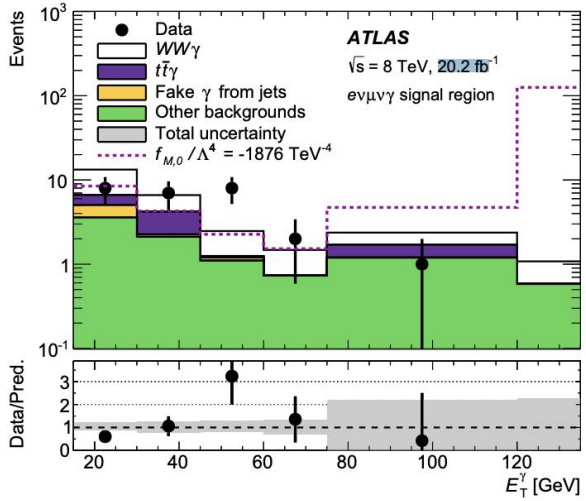
    based on SM WWγ study, rare Hγ process and/or anomalous coupling between Higgs and quarks can be studied

[1] Eur. Phys. J. C, 2017, 77(9): 646
[2] Phys. Rev. D, 2014, 90(3): 032008

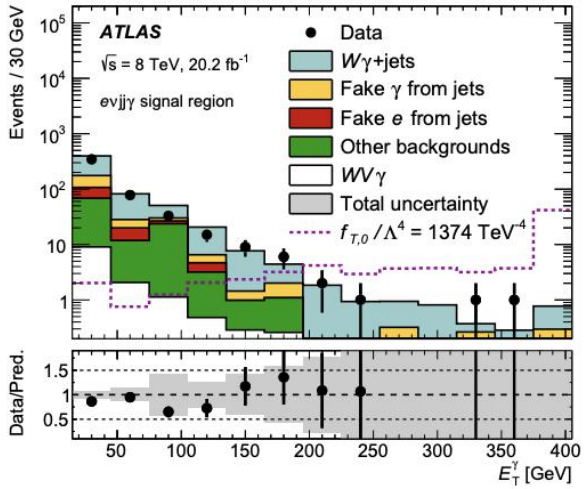
Previous WWγ study at CMS/ATLAS



CMS semileptonic channel



ATLAS $e\mu$ channel



ATLAS semileptonic channel

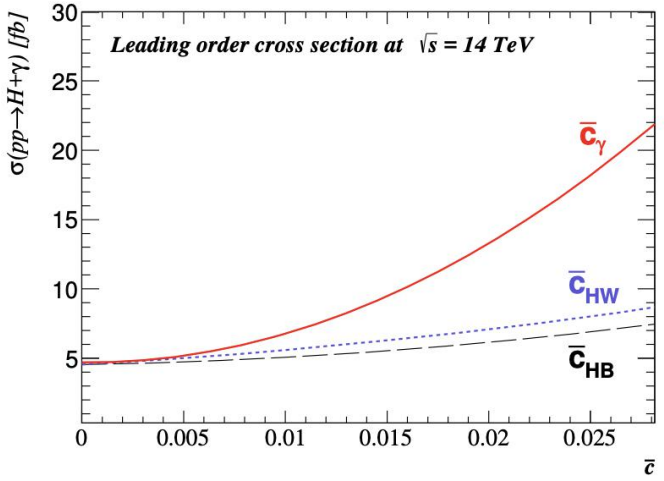
	Channel	Lepton	Photon	Jets	Other
CMS	semileptonic	1 electron (pT > 30 GeV, |η| < 2.5) or 1 muon (pT > 25 GeV, |η| < 2.1) No additional leptons pT > 10 (20) GeV for mu(ele)	photon ET > 30 GeV and |η| < 1.44.	At least two jet pT > 30 GeV and |η| < 2.4 70 < mjj < 100 GeV |Δηjj| < 1.4	E_missT > 35 GeV
ATLAS	leptonic(emu)	1 electron and 1 muon pT > 20 GeV no 3rd lepton (pT > 7 GeV) |η| < 2.5 opposite charge leptons ΔR(l1,l2) > 0.1	≥ 1 isolated photon ET > 15 GeV |η| < 2.37 isolation fraction < 0.5 ΔR(l, γ) > 0.5	Njets = 0 pT > 25 GeV ΔR(jet, γ) > 0.5 |y| < 4.4 ΔR(jet, l) > 0.3	E_missT, rel > 15 GeV M_eμ > 50 GeV
ATLAS	semileptonic	1 electron or 1 muon pT > 25 GeV no 2nd lepton (pT > 7 GeV) |η| < 2.5	≥ 1 isolated photon ET > 15 GeV |η| < 2.37 isolation fraction < 0.5 ΔR(l, γ) > 0.5	Njets ≥ 2 and Nb-jets = 0 pT > 25 GeV |η| < 2.5 |Δηjj| < 1.2 ΔRj j < 3.0 70 GeV < mj j < 100 GeV ΔR(jet, γ) > 0.5 ΔR(jet, l) > 0.3	E miss T > 30 GeV mT > 30 GeV

Probing Higgs boson couplings in H+γ production at the LHC [3]

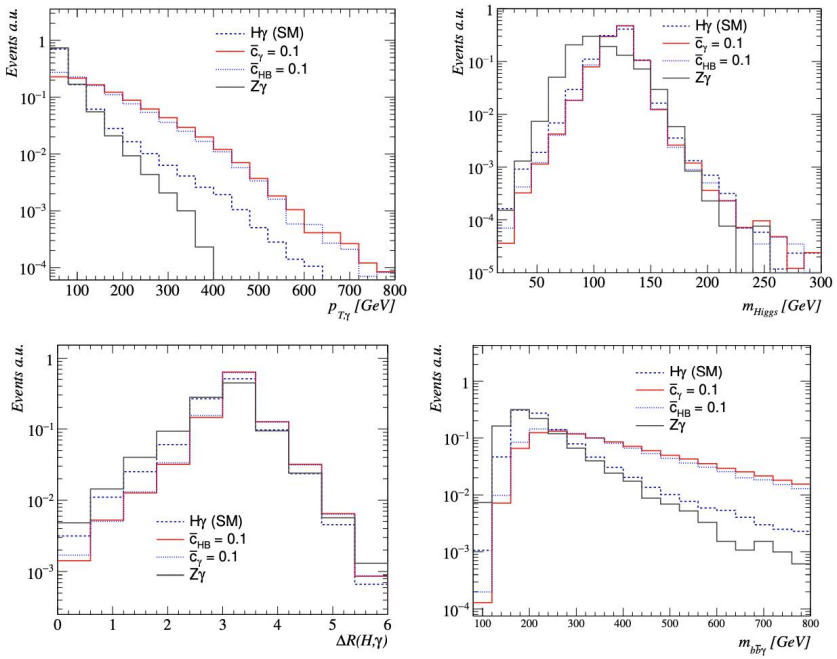
arXiv:1702.05753

Mass basis	Gauge basis
$g_{h\gamma\gamma}$	$a_H - \frac{8gs_W^2}{m_W}\bar{c}_\gamma$
$g^{(1)}_{hZ\gamma}$	$\frac{gs_W}{c_W m_W}(\bar{c}_{HW} - \bar{c}_{HB} + 8s_W^2\bar{c}_\gamma)$
$g^{(2)}_{hZ\gamma}$	$\frac{gs_W}{c_W m_W}(\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W)$
$\tilde{y}_u$	$y_u[1 - \frac{1}{2}\bar{c}_H + \frac{3}{2}\bar{c}_u]$
$\tilde{y}_d$	$y_d[1 - \frac{1}{2}\bar{c}_H + \frac{3}{2}\bar{c}_d]$
$g^{(\partial)}_{h\gamma uu}$	$\frac{\sqrt{2}gs_W}{m_W^2}y_u[\bar{c}_{uB} + \bar{c}_{uW}]$
$g^{(\partial)}_{h\gamma dd}$	$\frac{\sqrt{2}gs_W}{m_W^2}y_d[\bar{c}_{dB} - \bar{c}_{dW}]$

Higgs mass coupling and gauge basis relation



The LO cross section in H+γ versus the coefficients



The distributions with the corresponding coefficients

- Focus on the operators which are relevant to Higgs+γ process according to the strongly interacting light Higgs (SILH)
- There is a significant sensitivity to operator $\overline{C}_\gamma, \overline{C}_{HW}, \overline{C}_{HB}$.
- Consider γ+jets, tjγ + ttγ, Wγ + Zγ and SM (Hγ) as background.
- Cuts:

  One photon and lepton veto

  Only 2 b-jets, ΔR(i,j) > 0.4 i, j = γ, b

  90 < $m_{b\bar{b}}$< 160 GeV and ΔR(H, γ) > 2.4

  $m_{b\bar{b}\gamma}$ > 250 and $P_{T\gamma}$> 400 GeV (decreases fake photon)

With an integrated luminosity of 3000 fb−1:

$\overline{C}_\gamma, \overline{C}_{HW}, \overline{C}_{HB}$ can be down to 10^{-2} and 10^{-3}

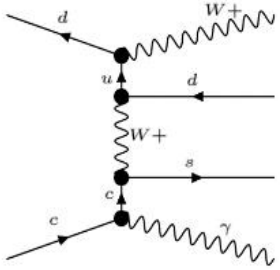
Coefficient	$\mathcal{L} = 300$ fb^{-1}	$\mathcal{L} = 3000$ fb^{-1}
$\bar{c}_\gamma$	$[-0.013, 0.023]$	$[-0.0042, 0.0075]$
$\bar{c}_{HB}$	$[-0.038, 0.050]$	$[-0.012, 0.016]$
$\bar{c}_{HW}$	$[-0.053, 0.038]$	$[-0.017, 0.012]$

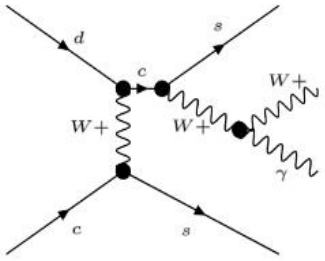
The predicted constraints at 95% CL

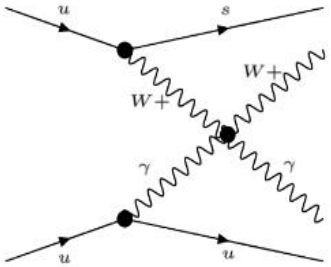
Measurement of VBS Wγ production

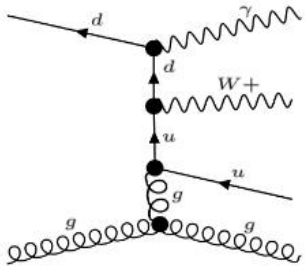
Introduction

- **Goal** : probe quartic gauge couplings and triple gauge couplings
- **Final states**: evγjj and μvγjj.
- **Signature** : large dijet mass and large η separation between the jets,the vector boson scattering topology
- Previous analysis: SMP-19-008









Main results:

- Signal strength and significance
- Fiducial and differential cross-section measurements
- Limits on dimension 8 EFT coefficients

OBJECT DEFINITION

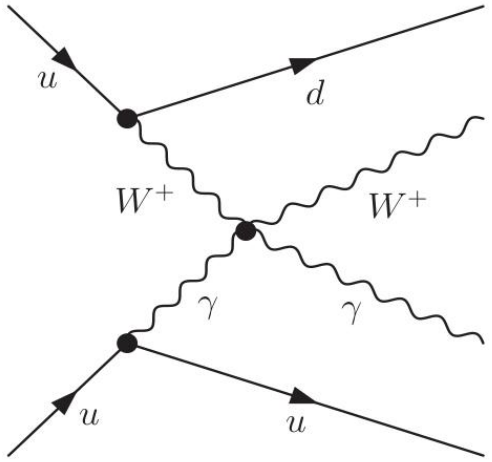
- Muon selection
  - Cut-based tight ID
  - Relative PF isolation with cone size = 0.4, δβ pileup correction < 0.15
  - pT > 20 GeV, |η| < 2.4
- Electron selection
  - Cut-based tight ID
  - pT > 20 GeV, |η| < 2.5, |η| < 1.4442 or 1.566 < |η|< 2.5
- Photon selection
  - Cut-based medium ID
  - Conversion-safe electron veto
  - pT > 25 GeV and |η| < 1.4442 or 1.566 < |η|< 2.5

- Jet selection
  - AK4CHS jet

- Muon veto
  - Cut-based loose ID
  - pT > 10 GeV and |η| < 2.4
  - Relative PF isolation with cone size = 0.4
  - δβ pileup correction < 0.25
- Electron veto
  - Cut-based veto ID
  - pT > 20 GeV
  - |η| < 2.5, |η| <1.4442 or 1.566 < |η|< 2.5

Data and Simulated samples

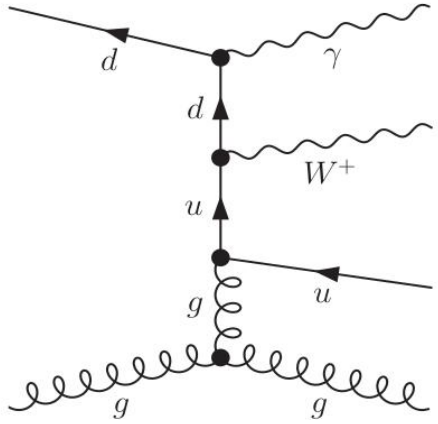
- Data
  - “SingleMuon” and “SingleElectron” collected from 2016 to 2018 with integrated luminosity: 138 /fb.
- MC Signal
  - Electroweak production of Wγjj : signal for VBS Wγ, Generated by MADGRAPH5_aMC@NLO (MG5), simulated at leading order.
  - process syntax
    - define lep = e+ e- mu+ mu- ta+ ta-
    - define nu = ve ve~ vm vm~ vt vt~
    - define p = p b b~
    - define j = j b b~
    - generate p p > lep nu a j j $$ t t~ QCD=0



  - Signature : large dijet mass and large η separation between the jets

Data and Simulated samples

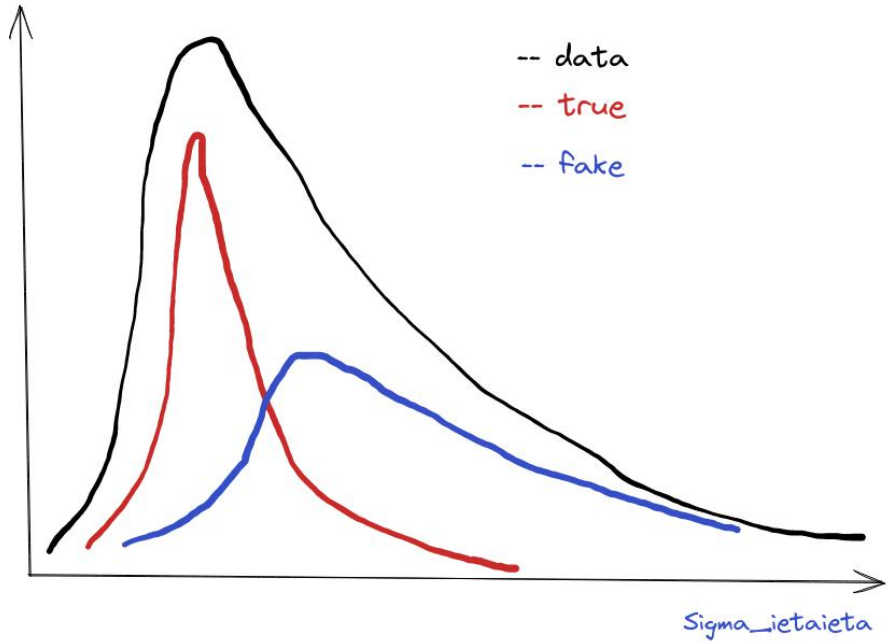
- MC Background
  - Wγ plus QCD jets : Main backbround for VBS Wγ, Generated by MG5 using FxFx jet merging scheme(0, 1 jets).
    - process syntax
      - define lep = e+ mu+ ta+ e- mu- ta-
      - define nu = ve vm vt ve~ vm~ vt~
      - generate p p > lep nu a [QCD] @0
      - add process p p > lep nu j a [QCD] @1



  - There are Top, $t\bar{t}\gamma$, $Z\gamma$, and VV background. All of them have the same or very similar final states to the signal. They are simulated by madgraph, pythia, and powheg.
- Nonprompt background estimation
  - Including the nonprompt photon, nonprompt lepton, and double nonprompt
  - They are estimated by data-driven methods and will be introduced in next few slides.

Nonprompt photon

- Where is the Nonprompt photon from?
  - Mainly π^0s mis-reconstructed as photons
- How to estimate it?
  - Template method
  - Make 'TRUE', 'FAKE', and 'DATA' templates
  - $\text{Weight}_{\text{fake photon}} = \frac{\text{h}_{\text{data}}}{\text{h}_{\text{plj}}} \times \text{fraction}$

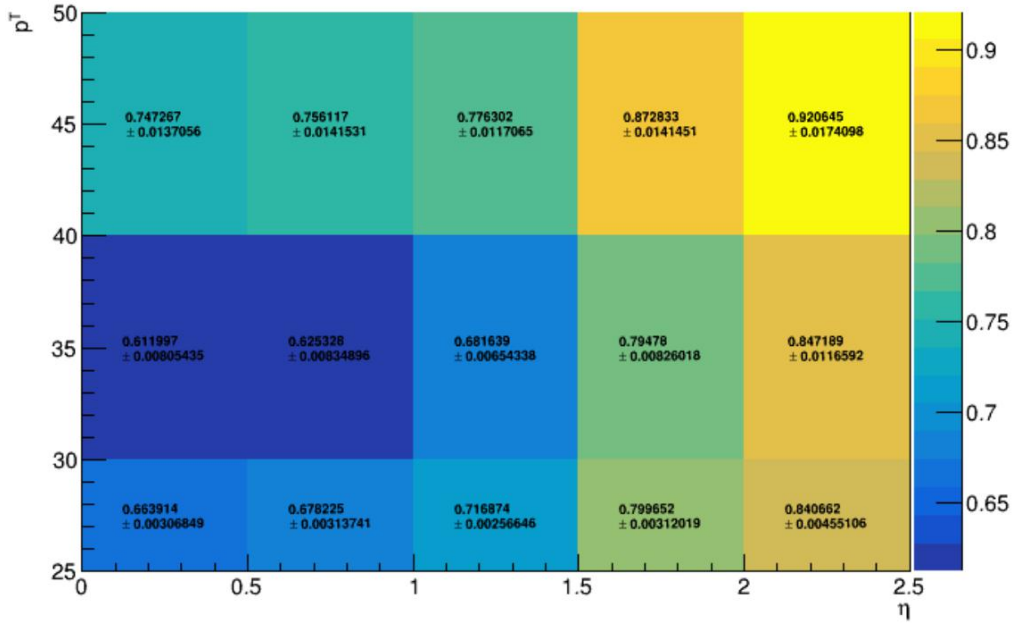


Template	True	Fake	Date
Sample	QCD Wγ	Data	Data
Basic selection	lepton and photon cut		
Individual selection	photon CHISO < 1.141	photon CHISO inverted (4 to 10)	photon CHISO < 1.141
Fit	fit on $\sigma_{i\eta i\eta}$		

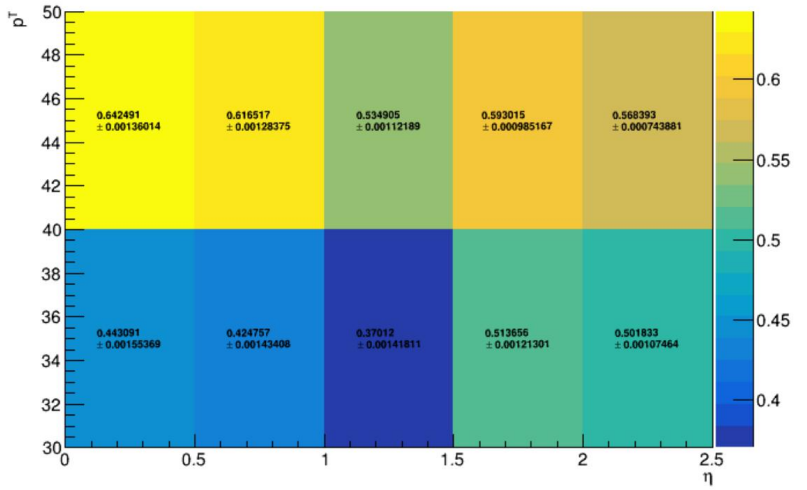
Nonprompt lepton

- Nonprompt Lepton
  - Mainly real electrons and muons inside of jets
  - tight-loose method
  - Subtract real lepton contamination using W+jets and Z+jets MC samples
  - $\text{fake\_rate} = \frac{\text{tight}}{\text{tight} + \text{loose}}$
  - $\text{Weight}_{\text{fake\_lepton}} = \frac{\text{fake\_rate}}{1 - \text{fake\_rate}}$
- Double nonprompt
  - Contain both a nonprompt photon and a nonprompt lepton

MUON



ELECTRON



SELECTION DEFINITIONS

- Basic selection
  - one muon(electron) in muon(electron) channel, second lepton veto
  - two reconstructed jets, $p_T^{j1} > 50GeV, |\eta^{j1}| < 4.7$, $p_T^{j2} > 50GeV, |\eta^{j2}| < 4.7$
  - $E_T^{miss} > 30GeV, M_T(W) > 30GeV,\ p_T^{\ell} > 35GeV, |\eta^{\ell}| < 2.4/2.5(muon/electron)$
  - $p_T^{\gamma} > 25GeV, |\eta^{\gamma}| < 1.4442(barrel), 1.556 < |\eta^{\gamma}| < 2.5(endcap), |M_{\ell\gamma} - M_Z| > 10GeV(electron)$
  - B-tagged jets veto, $\Delta R_{j\gamma} > 0.5, \Delta R_{\ell\gamma} > 0.5, \Delta R_{j\ell} > 0.5, |\Delta\varphi_{j,met}| > 0.5$
- Control region
  - $200\text{GeV} < M_{jj} < 500GeV$
- Signal region
  - $M_{jj} > 500GeV, M_{W\gamma} > 100GeV, |\Delta\eta_{jj}| > 2.5$
  - zepp<1.2, dphi>2.0

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

Significance : 6.0(6.8) standard deviations

UNCERTAINTIES

- Factorization and renormalization scale uncertainty
  - Calculated bin-by-bin, correlated across bins, channels, and years
- PDF uncertainty
  - Standard deviation of the NNPDF3.0 set variations
  - Calculated bin-by-bin, correlated across bins, channels, and years

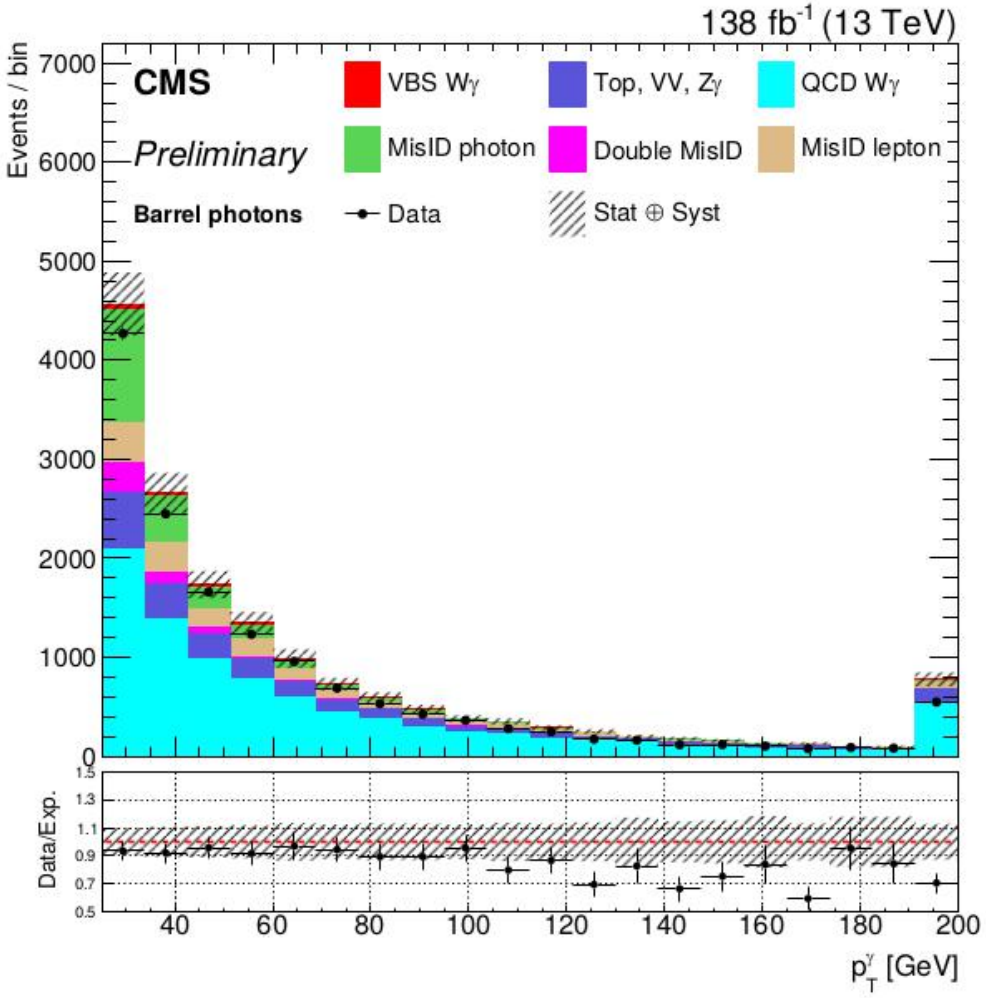
THEORETICAL

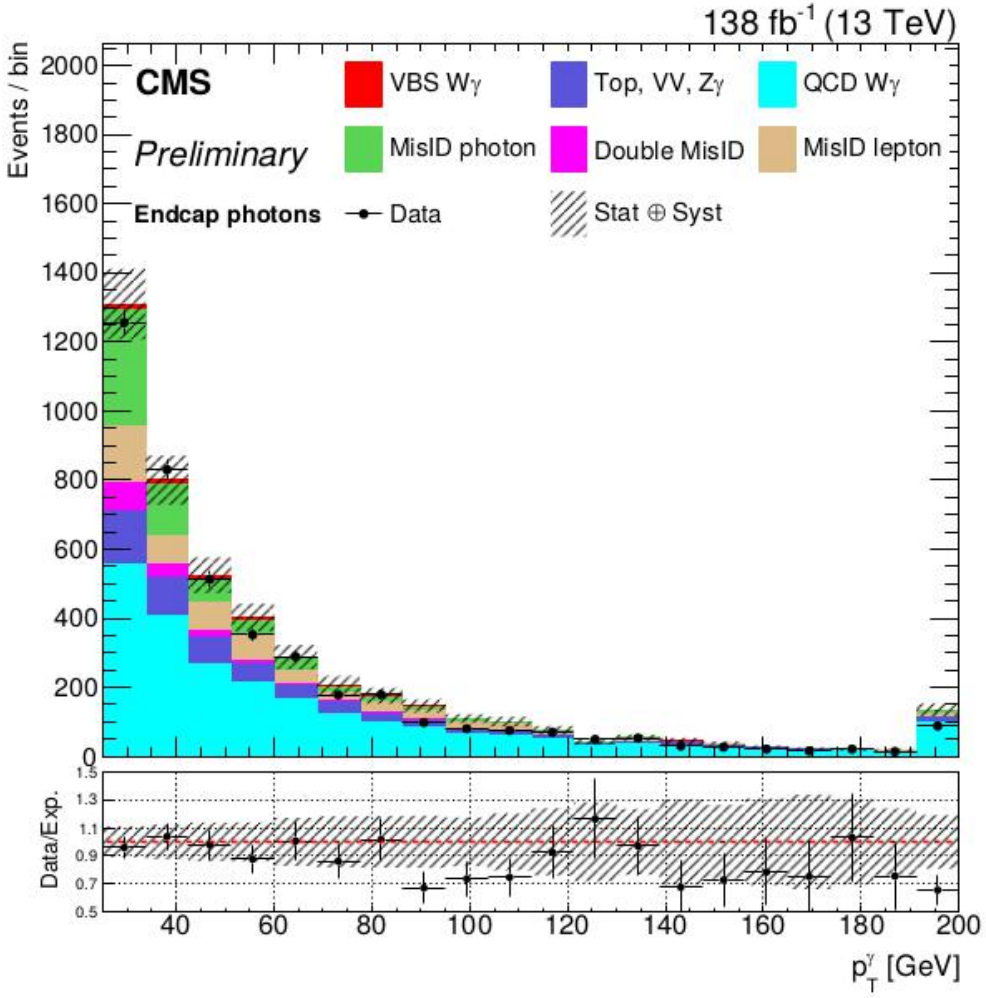
- Fake photon uncertainty
  - 3 sources of uncertainty are added in quadrature
    - Uncertainty due to charged isolation sideband selection
    - Uncertainty due to non-closure of MC closure test
    - Uncertainty due to fit error
  - Calculated bin-by-bin, correlated across bins, channels, and years
- Fake lepton uncertainty
  - 30% normalization uncertainty for each lepton flavor
- **Jet energy scale** and resolution(JES and JER)
  - Choose the largest deviation of up/down to the central
  - Calculated bin-by-bin, correlated across bins, channels, and years

  ★ **JES** is the largest uncertainty and is broken into 12 sub-uncertainties.
- Other systematic uncertainties
  - Pileup, L1 prefiring for 2016-2017, luminosity, lepton and photon scale factors

SYSTEMATIC

Comparison plot in control region





★ Pre-fit plot for photon pT in control region. The left is for barrel and the right for edcap.

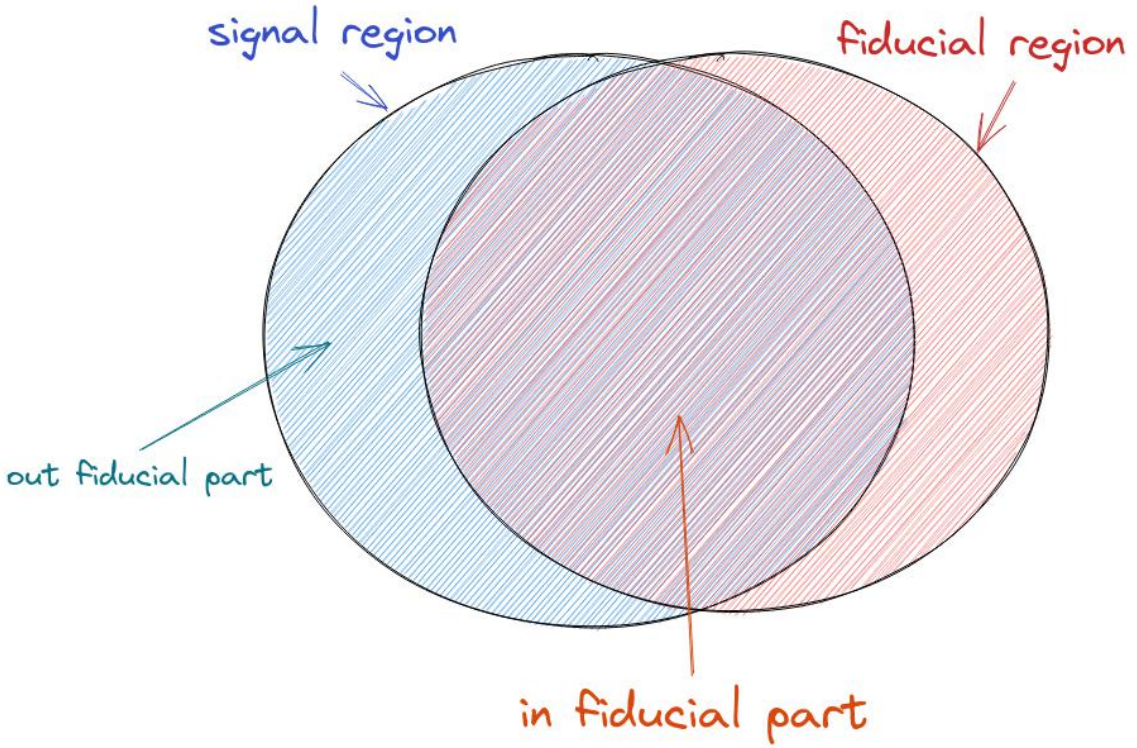
★ Data and MC have good agreement within uncertainties(stat + syst).

Fiducial cross section

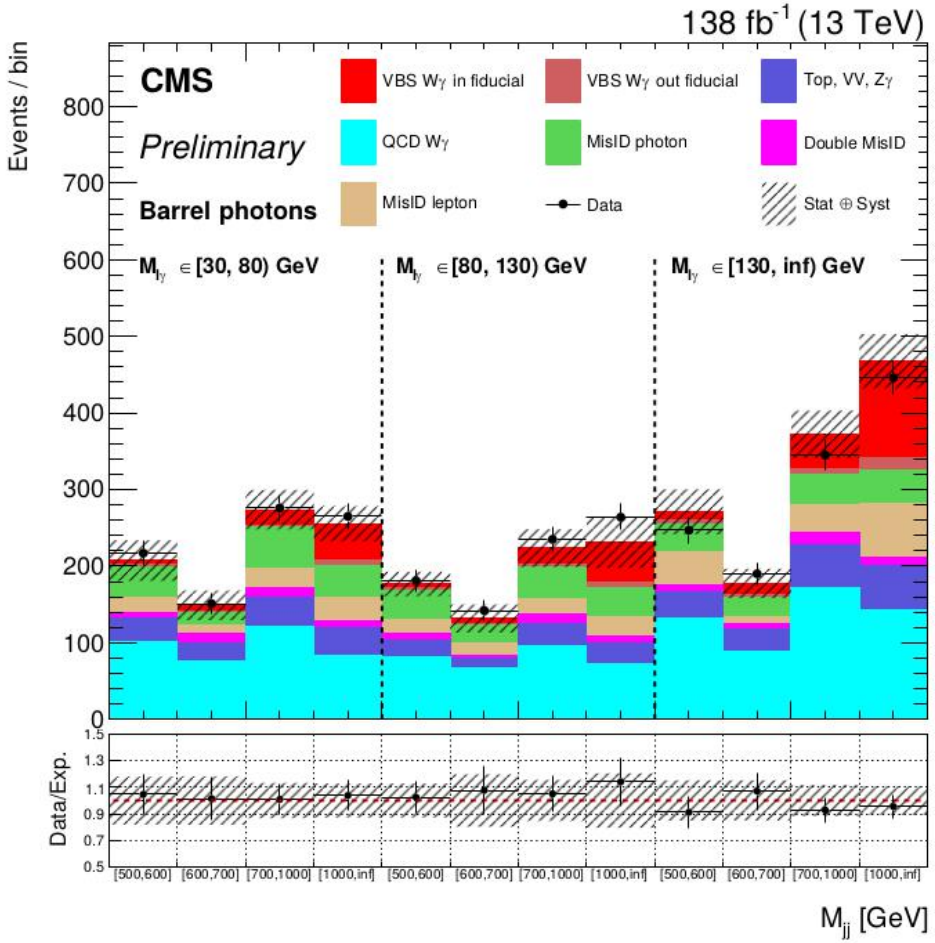
- The fiducial region is defined at “particle level” (“generator level”) .
- The component of the signal that doesn’t pass the fiducial region is treated as a background.

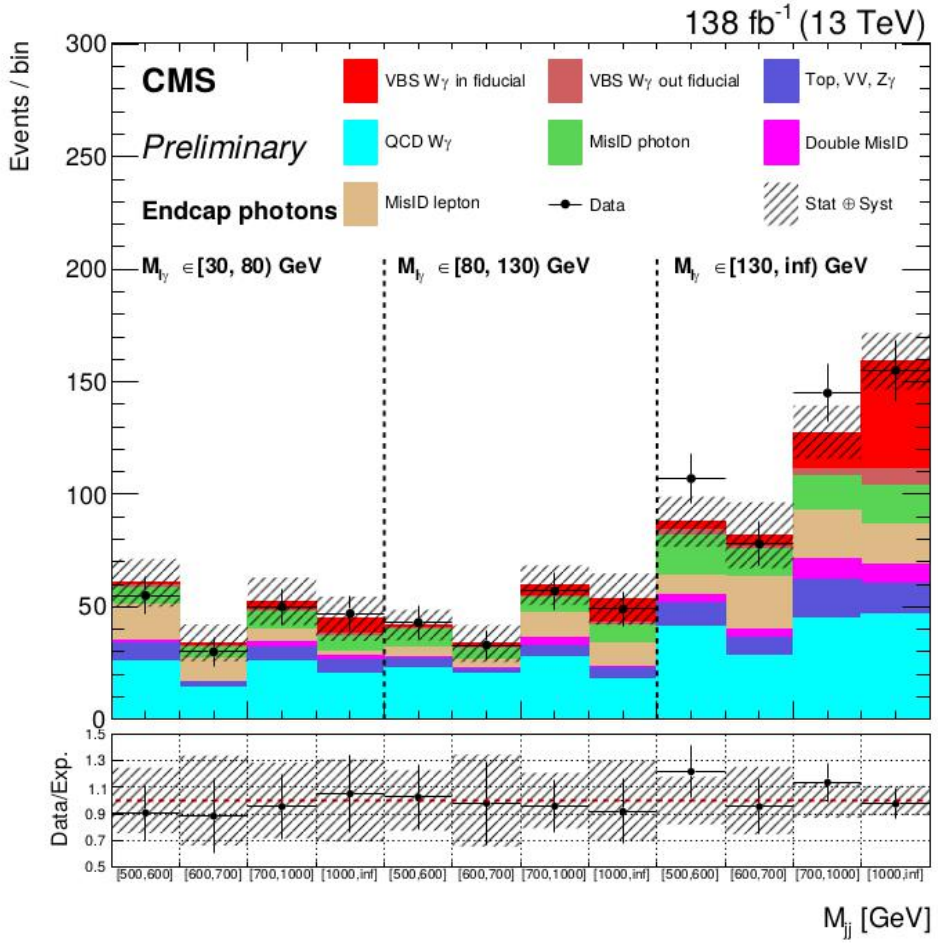
★Fiducial region selections :

- Jet pT > 50 GeV and |η| < 4.7
- Photon pT> 25 GeV
- Photon |η| < 1.4442 or 1.566 < |η|< 2.5
- Lepton pT > 35 GeV and |η| < 2.4
- mjj > 500 GeV, |ηjj|> 2.5
- ΔRjj, ΔRjγ, ΔRjl, ΔRlγ > 0.5
- Leptons are dressed with photons within ΔR = 0.1



Fiducial cross section





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 fracation of the generated signal events passing the fiducial region selection

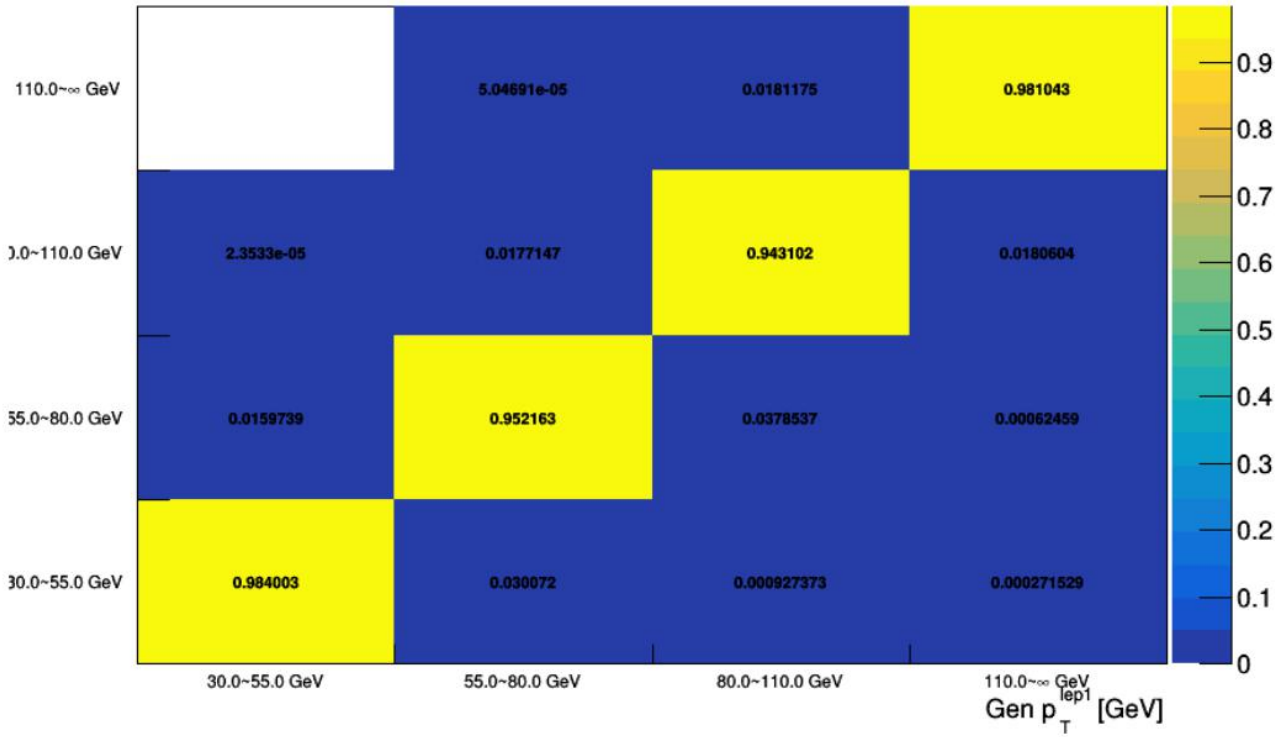
★Fiducial cross section

- EW
  - Acceptance = 0.034
  - $\sigma^{\text{fid}}_{\text{EW}} = 19^{+4.0}_{-3.9} = 19^{+2.3}_{-2.3}(\text{stat})^{+1.6}_{-1.4}(\text{theo})^{+2.9}_{-2.8}(\text{syst})\text{fb}$
- EW +QCD
  - Acceptance = 4.6e-4
  - $\sigma^{\text{fid}}_{\text{EW+QCD}} = 90^{+11}_{-10} = 90^{+1.6}_{-1.6}(\text{stat})^{+2.0}_{-1.8}(\text{theo})^{+10}_{-10}(\text{syst})\text{fb}$

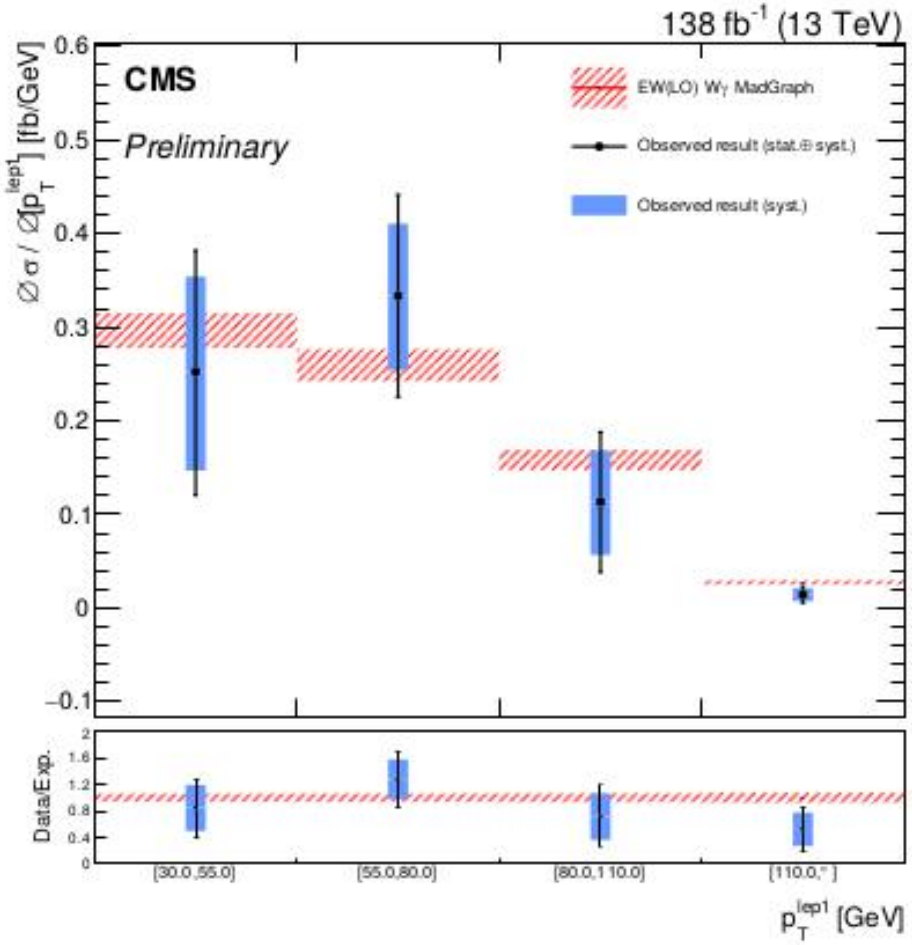
Differential cross section

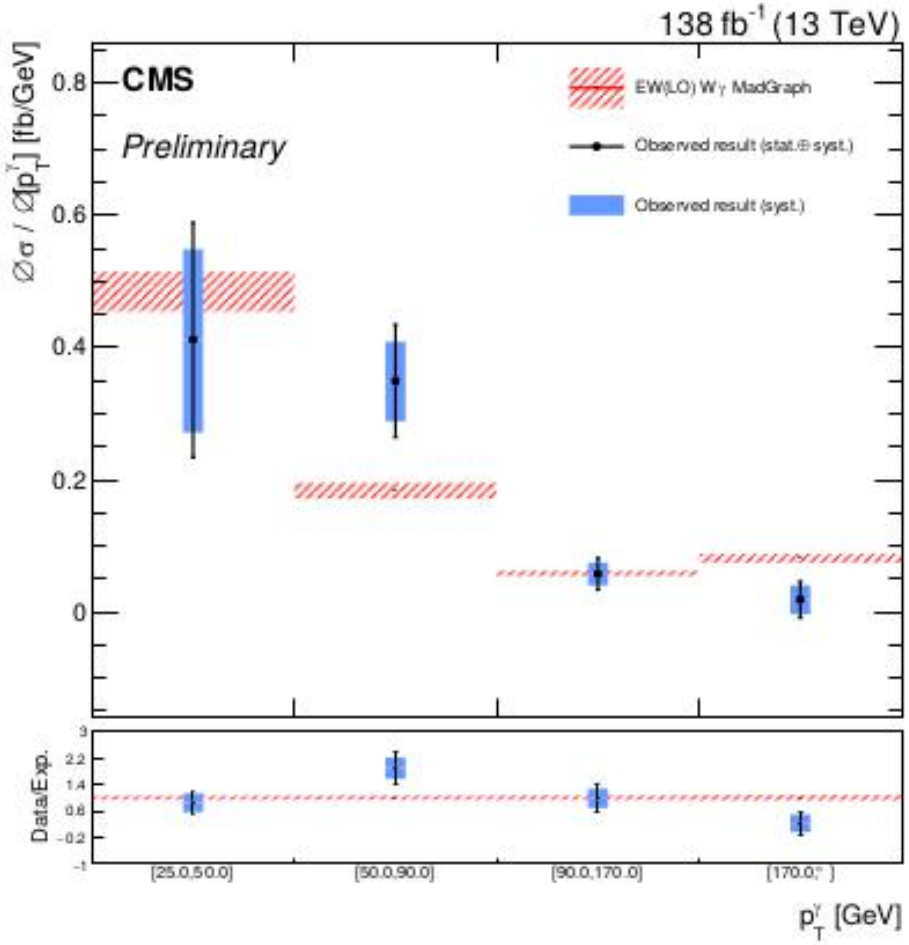
- The full run2 data collected on CMS has larger statistic.
- Perform ‘unfolding’ to revert the ‘detector smearing’ on the data to get the ‘True’ distribution.
- Same uncertainties with fiducial cross section measurement.
- Differential cross section are measured :
  - EW and EW+QCD
  - p_T^l, p_T^γ, p_T^{j1}, $m_{l\gamma}$, m_{jj}, $\Delta\eta_{jj}$

RESPONSE MATRIX



Differential cross section





Limits on dimension 8 EFT coefficients

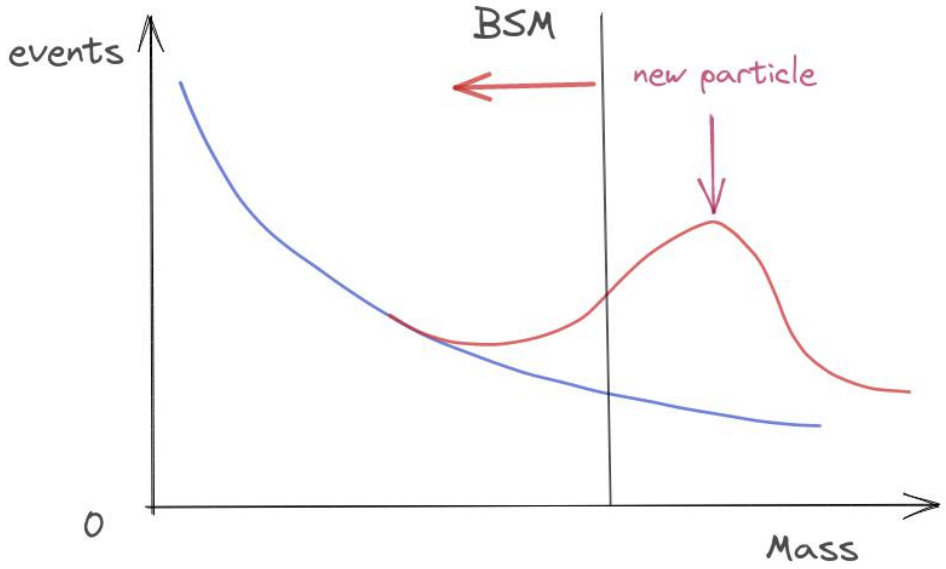
- **Powerful portal test to BSM effects** in a model independent approach, usually parametrized as Effective Field Theory (EFT)

- Dimention 8 EFT model

- Effective field theory with cutoff energy scale Λ

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

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



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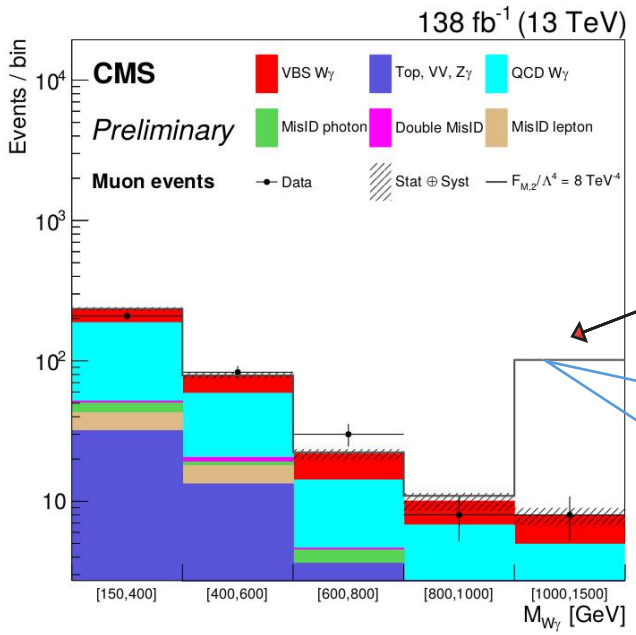
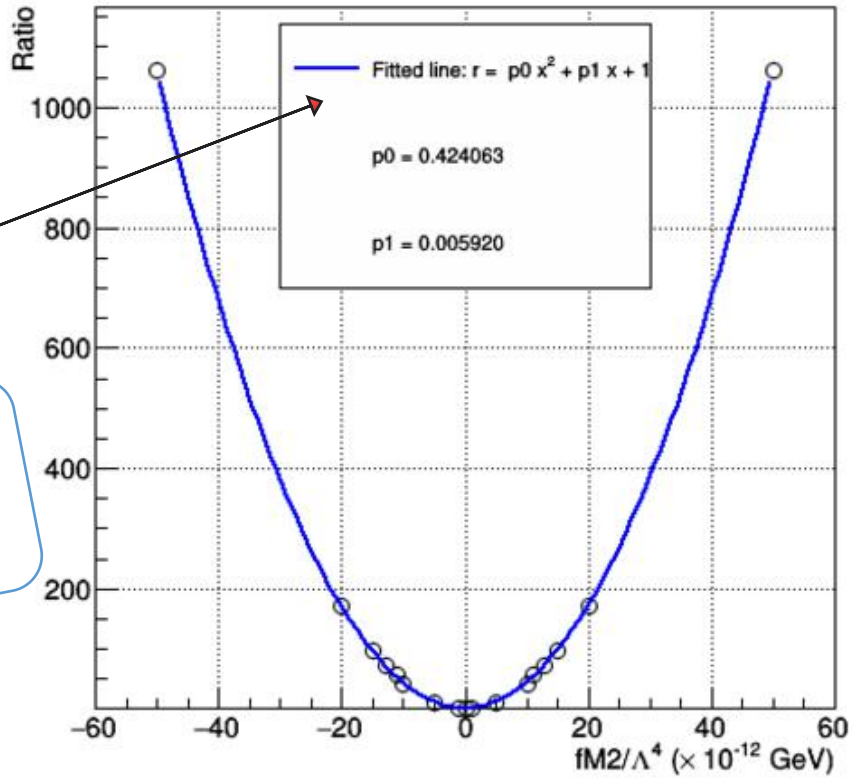
The yield ratio between SM and AQGC following the quadratic function! ★

Quadratic fitting



MODEL : QuarticCKM_5_Aug21



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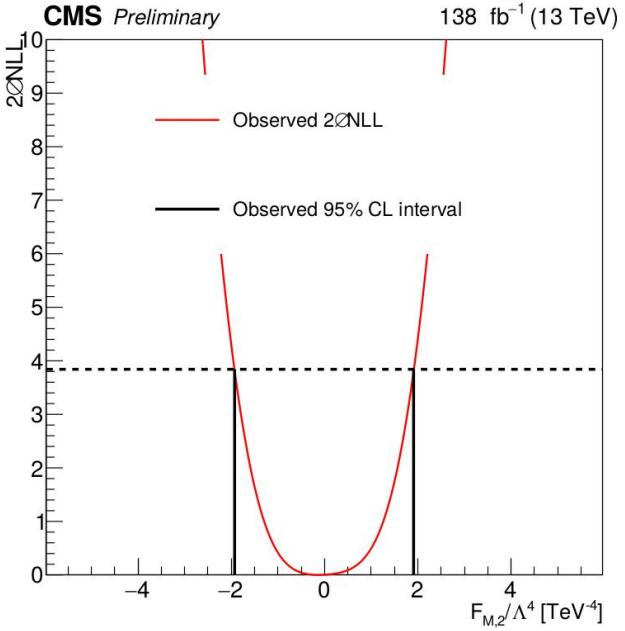
- $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} O_i$
- Operators : LM0-7, LT0-2, LT5-7



World's best limits

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	-.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

- Significance
  - First observation of VBS Wγ process based on only run2 data
  - 6.03 σ observed, 6.79 σ expected
- Fiducial cross section measurements:
  - $\boldsymbol{\sigma}^{\mathbf{fid}}_{\mathbf{EW}} = 19^{+4.0}_{-3.9} = 19^{+2.3}_{-2.3}(\mathrm{stat})^{+1.6}_{-1.4}(\mathrm{theo})^{+2.9}_{-2.8}(\mathrm{syst})\,\mathrm{fb}$
  - $\boldsymbol{\sigma}^{\mathbf{fid}}_{\mathbf{EW+QCD}} = 90^{+11}_{-10} = 90^{+1.6}_{-1.6}(\mathrm{stat})^{+2.0}_{-1.8}(\mathrm{theo})^{+10}_{-10}(\mathrm{syst})\,\mathrm{fb}$
- **Differential cross section** measurements:
  - EW and EW+QCD
  - $\mathrm{p}^{\mathrm{l}}_{\mathrm{T}},\ \mathrm{p}^{\gamma}_{\mathrm{T}},\ \mathrm{p}^{\mathrm{j1}}_{\mathrm{T}},\ \mathrm{m}_{\mathrm{l}\gamma}, \mathrm{m}_{\mathrm{jj}}, \Delta\eta_{\mathrm{jj}}$
- Anomalous coupling limits
  - We set limits for dimention 8 EFT coeffients
  - **We can get world's best limits for FM2-5, FT5-7)**

Back Up

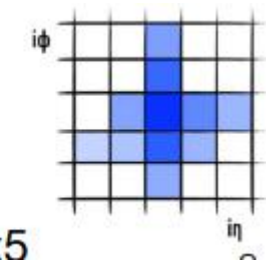
Prompt pileup photon estimation

- Record the event and luminosity block numbers of the selected events in the W+jets sample
- Using a DAS query, find the corresponding MINIAODSIM W+jets files
- Access each of the MINIAODSIM files, and record the event and luminosity block numbers of the minimum bias events that are mixed into the 0th bunch crossing of the W+jet sevent
- Using a DAS query, find the GENSIM minimum bias file that contains each of the minimum bias events
- Match the generator photons in the minimum bias files to the selected reconstructed photons in the W+jets events
- If there is a matched generator photon, determine whether it is prompt based on its

Selected W+jets events	Matched gen particles in pileup events that are mixed into the W+jet events			
Evt Num	ID	p_T	ΔR(gen part, reco γ)	Moth ID
1	22	12.5	0.002753	111
1	22	15.0	0.010083	111
2	22	28.2	0.0091	111
3	-211	5.5	0.146365	-213
3	22	24.9	0.065286	111
4	22	6.4	0.024246	111
4	22	18.6	0.019501	111
5	22	31.6	0.039385	22

$$\sigma_{i\eta i\eta} = \sqrt{\frac{\sum_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\sum_i^{5\times5} w_i}}$$

$w_i \neq 0$, if $E_i > 0.9\%$ of E_{5x5}



WWγ Object defination

Good Electron:

- ✓ mvaFall17V2Iso_WP80
- ✓ $p_T > 25$ GeV, $|\eta| < 2.5$,

Good Muon:

- ✓ Cut-Based Medium ID
- ✓ mvaTTH>-0.2 [1]
- ✓ miniPFRelIso_all < 0.4 [1]
- ✓ $p_T > 20$ GeV, $|\eta| < 2.4$

Good Photon:

- ✓ Cut-based Medium ID
- ✓ Pass pixel veto
- ✓ $p_T > 20$ GeV, $|\eta| < 2.5$, $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$

Jets

- ✓ PF tight ID
- ✓ AK4CHS
- ✓ JEC correction

MET

- ✓ PuppiMET
- ✓ JES/JER correction

Veto and Fake Electron:

- ✓ Cut-based Veto ID
- ✓ $p_T > 10$ (25) GeV, $|\eta| < 2.5$,
- ✓ $|\eta| < 1.4442$ or 1.566 or $|\eta| < 2.5$

Veto Muon:

- ✓ Cut-Based loose ID
- ✓ miniPFRelIso_all < 0.4
- ✓ $p_T > 10$ GeV, $|\eta| < 2.4$

Fake Muon:

- ✓ Cut-Based Medium ID
- ✓ mvaTTH<-0.2
- ✓ miniPFRelIso_all < 0.4
- ✓ $p_T > 20$ GeV, $|\eta| < 2.5$