Triboson production in CMS

Alberto Mecca (Università and INFN Torino)
on behalf of the CMS Collaboration

Young Scientist Forum

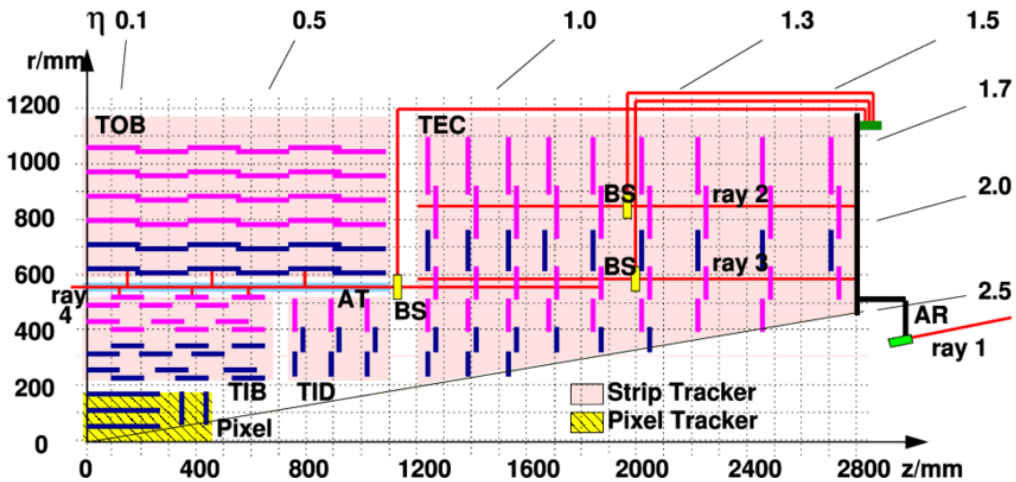
Multi-Boson Interactions 2021, Milano - Bicocca

Overview

- **VVV** $\rightarrow 2\ell\, 2q \,/\, 3\ell \,/\, 4\ell \,/\, 5\ell \,/\, 6\ell$ SMP-19-014
  - CMS Collaboration, "Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV", Phys. Rev. Letters (2020), doi:10.1103/physrevlett.125.151802, arXiv:2006.11191v2
- **Vγγ** , $W \rightarrow \ell\nu$, $Z \rightarrow 2\ell$ SMP-19-013
  - CMS Collaboration, "Measurements of the pp to Wγγ and pp to Zγγ cross sections at $\sqrt{s} = 13$ TeV and limits on anomalous quartic gauge couplings", 2021, arXiv:2105.12780

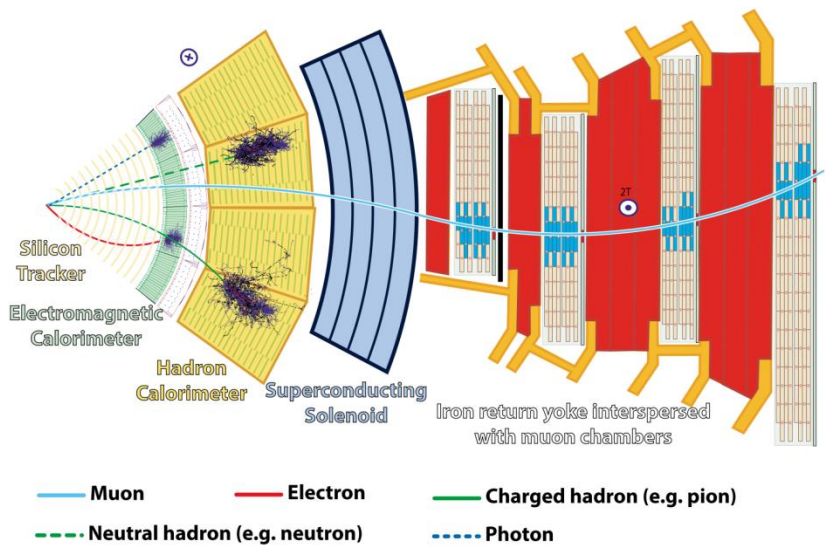
The CMS detector

Silicon Tracker

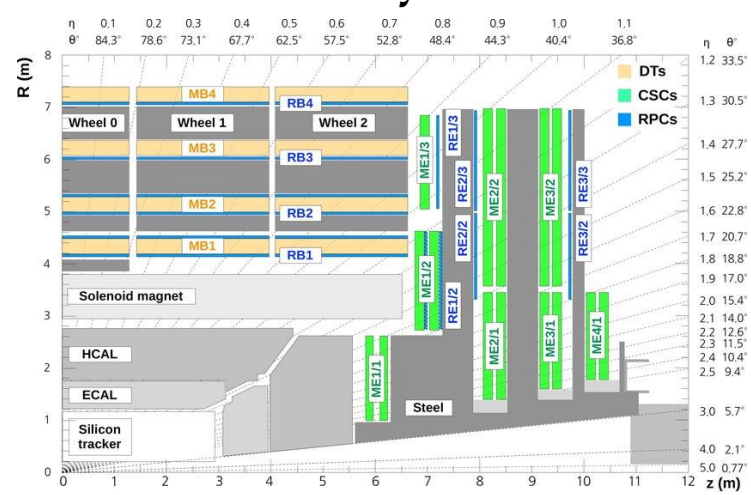


$$\eta = -\ln\left(\tan\left(\theta/2\right)\right)$$

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$



Muon system



SMP-19-014

Three massive gauge bosons at 13 TeV

Process	Theoretical cross section (NLO)	σ_{TOT} x BR	Expected events for 137 fb^{-1}
WWW	509 fb	54.0 fb *	7 400
WWZ	354 fb	4.12 fb	560
WZZ	91.6 fb	0.36 fb	50
ZZZ	37.1 fb	0.05 fb	6.9

- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\ell^{\pm}\, 2\nu\, q\bar{q}'$ **2 charged leptons**
- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\ell^{\pm}\ell^{\mp}\, 3\nu$ **3 charged leptons**
- $W^{\pm}W^{\mp}Z \rightarrow \ell^{\pm}\ell^{\mp}\, 2\nu\, \ell^{\pm}\ell^{\mp}$ **4 charged leptons**
- $W^{\pm}Z\,Z \rightarrow \ell^{\pm}\, \nu\, 2(\ell^{\pm}\ell^{\mp})$ **5 charged leptons**
- $Z\,Z\,Z \rightarrow 3(\ell^{\pm}\ell^{\mp})$ **6 charged leptons**

* Sum of 2 and 3 charged leptons channels

SMP-19-014

Backgrounds

- Same sign dilepton (SS-2ℓ):
  - Lost lepton: mostly WZ with a lost lepton from the Z
  - Nonprompt lepton: 1 prompt + 1 nonprompt from hadronic decays
  - Irreducible background: $W^{\pm}W^{\pm}$ from VBS, double parton scattering
  - Charge misidentification: a lepton from Z is assigned the wrong charge; negligible for μ
- Three-lepton (3ℓ):
  - WZ with off-shell Z
  - Nonprompt lepton: 2 prompt + 1 nonprompt from hadronic decays
  - Irreducible: $t\bar{t} + W$
- Four-lepton: ZZ, $t\bar{t}Z$, tWZ, WZ+fake, Higgs
- Five-lepton: ZZ + fake lepton
- Six-lepton: negligible

SMP-19-014

Reconstruction

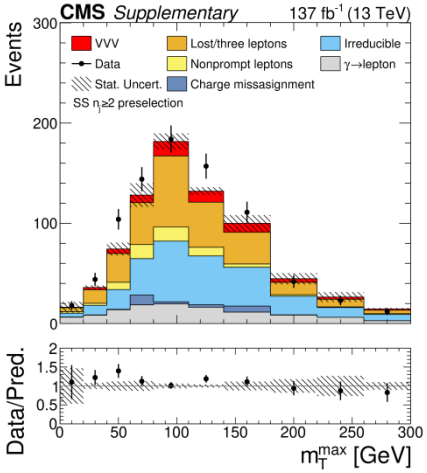
- Particle Flow
- Leptons
  - Common veto ID (η, d_z, d_{xy}, isolation) for all final states
  - Thigh selection for 2 lep channel, slightly looser for the others. Loose for fake lepton background prediction
- Jets
  - anti-kt, $\Delta R < 0.4$, $p_T > 20$ GeV, $|\eta| < 2.4$

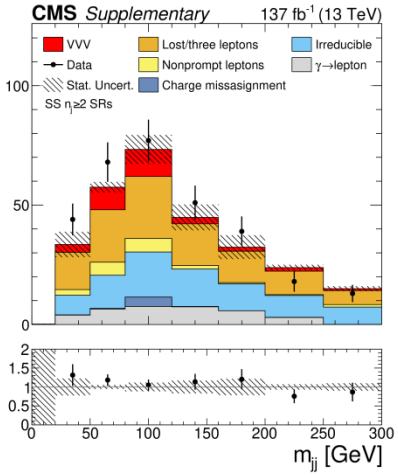
SFOS: A pair of Same Flavour, Opposite Sign (leptons)
$\vec{p}_T^{miss}$: negative vector sum in the transverse plane of jets associated with the primary vertex
m_T^{max}: Largest transverse mass from $\vec{p}_T^{miss}$ and any lepton

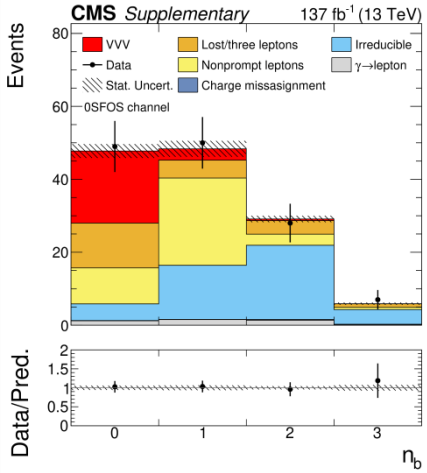
SMP-19-014

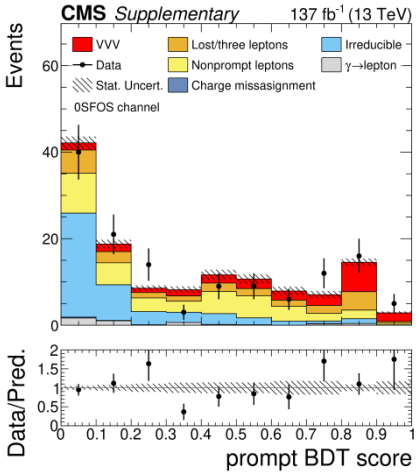
Boosted Decision Tree: 2ℓ and 3ℓ

- Variables used for SS-1J and SS-2J: p_T^{miss}, m_T^{max}, m_T^{min}, $m_{\ell j}^{min}$, $\Delta R_{\ell j}^{min}$, p_T^{j1}, $p_T^{\ell 1,2}$, $ID^{\ell 1,2}$, $m_{\ell\ell}$
  - Additional for SS-2J: $p_T^{j2,3}$, N_j, m_{jj}^{lead}, $m_{jj}^{min\,\Delta R}$, ΔR_{jj}, $\Delta\eta_{jj}$









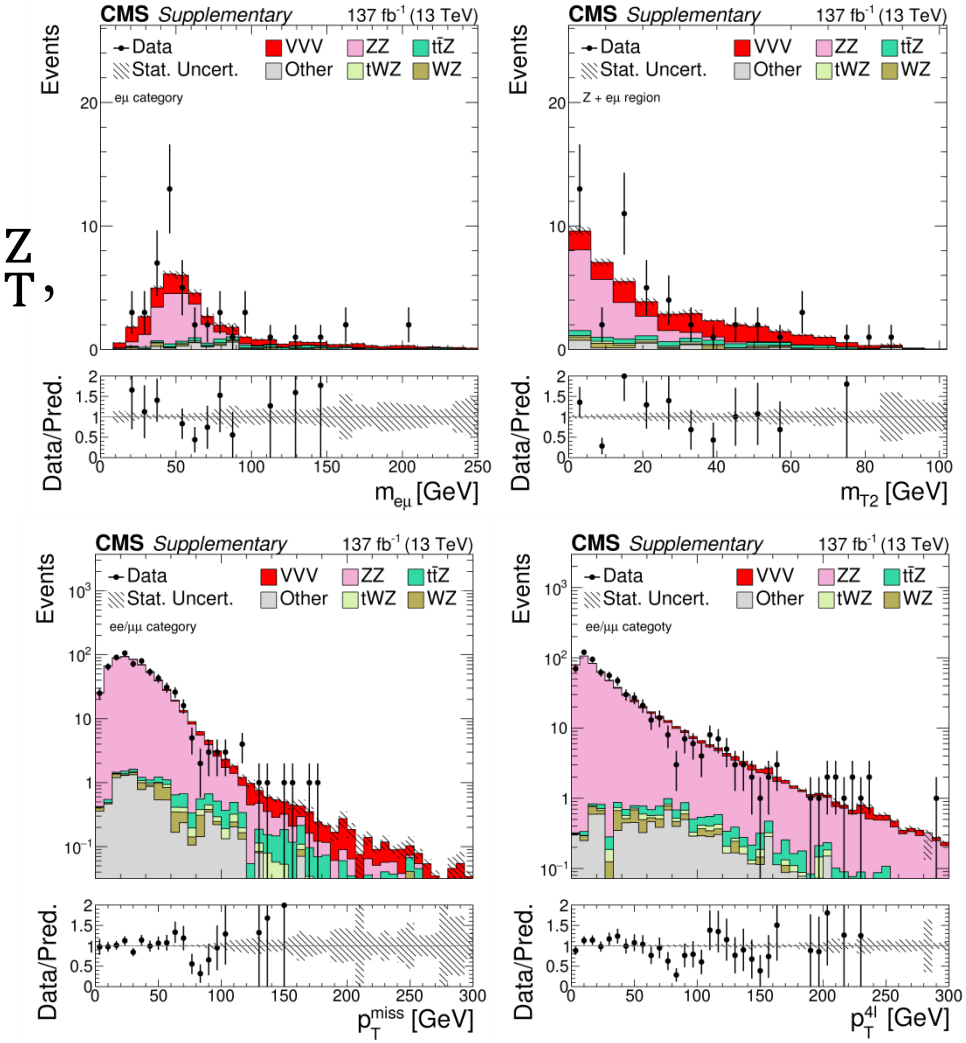
- Variables for 3ℓ: $p_T^{\ell 1,2,3}$, $ID^{\ell 1,2,3}$, $p_T^{j1,2,3}$, p_T^{miss}, $\Delta\phi(\vec{p}_T^{\ell\ell\ell}, \vec{p}_T^{miss})$, $p_T^{\ell\ell\ell}$, $m_{\ell\ell}^{SF}$, $m_{\ell\ell\ell}$, n_b

SMP-19-014

Boosted Decision Tree: 4ℓ

- Two BDTs, one for $t\bar{t}Z$ and one for ZZ
- Input variables: $m_{\ell\ell}$, $m_{\ell\ell}^{34}$, p_T^Z, m_{T2}, $p_T^{\ell 3,4}$, $p_T^{\ell\ell\ell\ell}$, $\sum_{i=1}^{4} p_T^{\ell i}$
  - Additional against $t\bar{t}Z$: p_ζ, p_ζ^{vis}, $m_T^{\ell 3,4}$, $m^{\ell\ell\ell\ell}$
  - Additional against ZZ: $\min \Delta R(j, \ell_{3,4})$, $p_T^{lead\ j}$

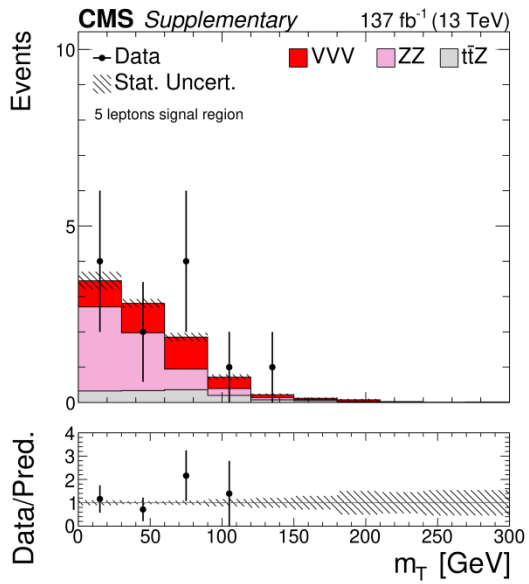
$$P_\zeta = \left(\vec{p}_T^{miss} + \vec{p}_T^{\ell 1} + \vec{p}_T^{\ell 2}\right) \cdot \hat{\zeta}$$
$$P_\zeta^{vis} = \left(\vec{p}_T^{\ell 1} + \vec{p}_T^{\ell 2}\right) \cdot \hat{\zeta}$$
$\hat{\zeta}$ = unit vector, bisector of ℓ_1 and ℓ_2

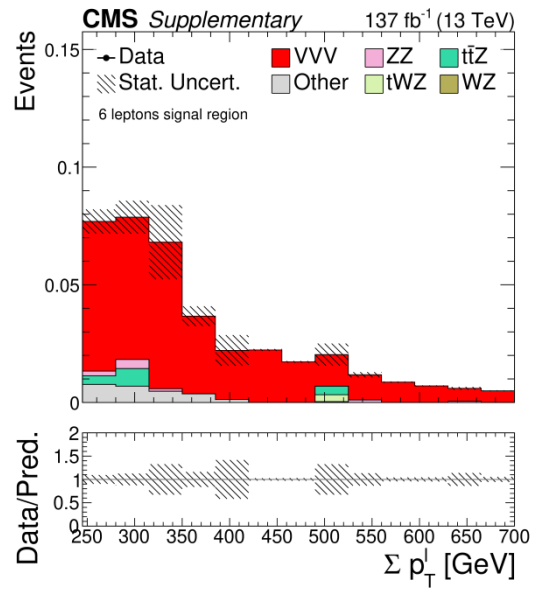


Sequential cuts (5ℓ, 6ℓ)

SMP-19-014

5ℓ (WZZ)	6ℓ (ZZZ)
$p_T^{\ell 1,2} > 25$ GeV/c , $p_T^{\ell >2} > 10$ GeV/c , no b-tagged jets	
2 SFOS pairs $\lvert m_{SFOS} - m_Z \rvert < 15$ GeV	3 SFOS pairs $\lvert m_{SFOS} - m_Z \rvert < 15$ GeV
ZZ+ℓ_{fake} $m(\vec{p}_T^{miss} + \vec{p}_T^{e5}) > 50$ GeV	$\sum_{i=1}^{6} \lvert \vec{p}_T^{\ell i} \rvert > 250$ GeV $t\bar{t}H$ ZZ+$\ell\ell$

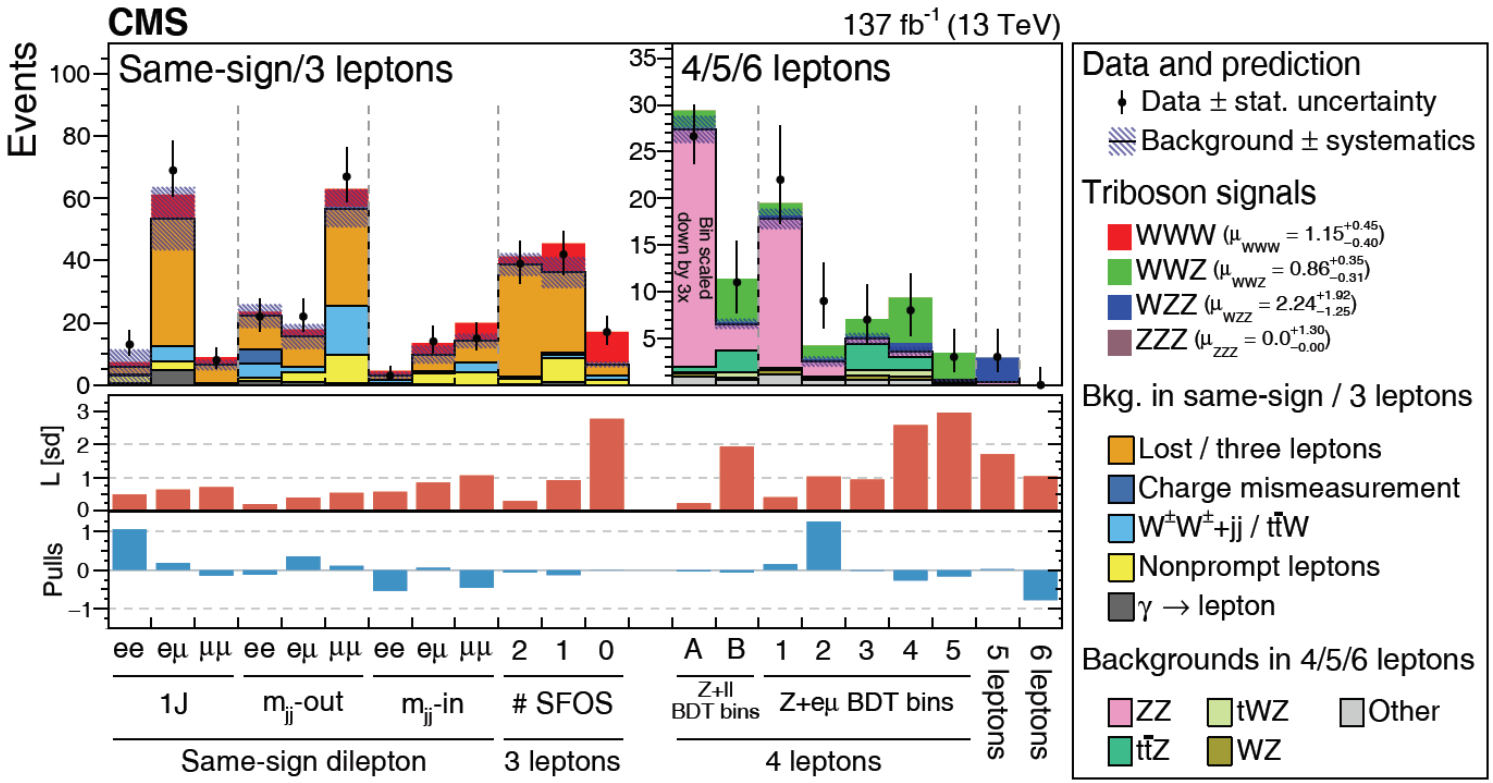




Combination

SMP-19-014

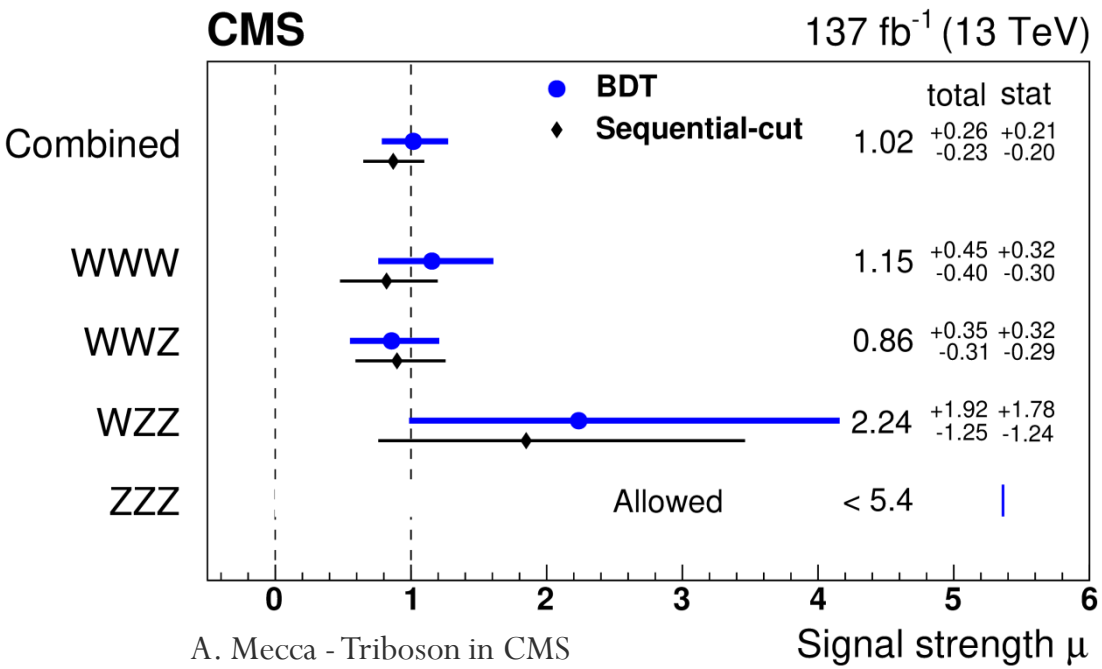
- Each sub analysis targets a different production channel, with cross contamination.



SMP-19-014

Results

- Two fits of all the channels:
  - Combined signal strength μ_{comb}
  - Four independent signal strengths μ_{WWW} , μ_{WWZ}, μ_{WZZ}, μ_{ZZZ}



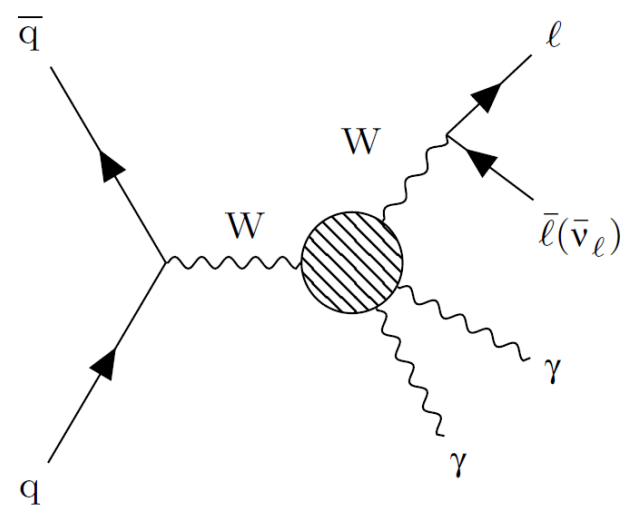
Process	VH as signal	
	cut-based	BDT-based
WWW	2.54 (2.94)	3.33 (3.09)
WWZ	3.53 (3.62)	3.35 (4.09)
WZZ	1.55 (0.70)	1.71 (0.69)
ZZZ	0.00 (0.90)	0.00 (0.89)
combined	5.02 (5.37)	5.67 (5.88)

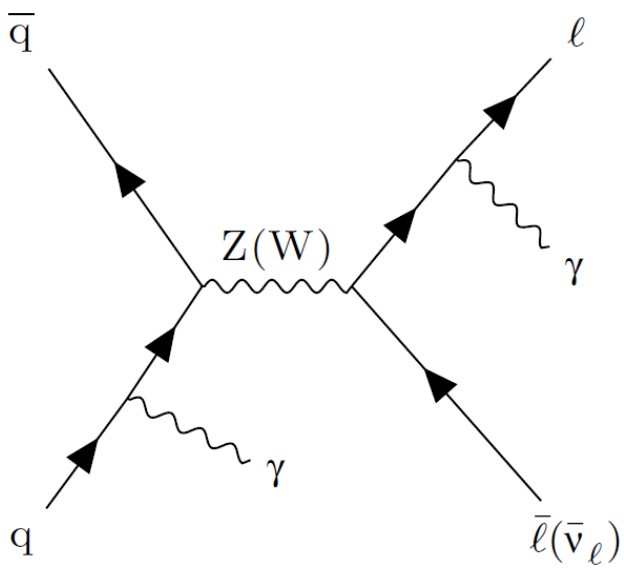
Process	Cross section (fb)
Treating Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}{}^{+150}_{-120}$
WWW	$590^{+160}_{-150}{}^{+160}_{-130}$
WWZ	$300^{+120}_{-100}{}^{+50}_{-40}$
WZZ	$200^{+160}_{-110}{}^{+70}_{-20}$
ZZZ	<200
Treating Higgs boson contributions as background	
VVV	$370^{+140}_{-130}{}^{+80}_{-60}$
WWW	$190^{+110}_{-100}{}^{+80}_{-70}$
WWZ	$100^{+80}_{-70}{}^{+30}_{-30}$
WZZ	$110^{+100}_{-70}{}^{+30}_{-10}$
ZZZ	<80

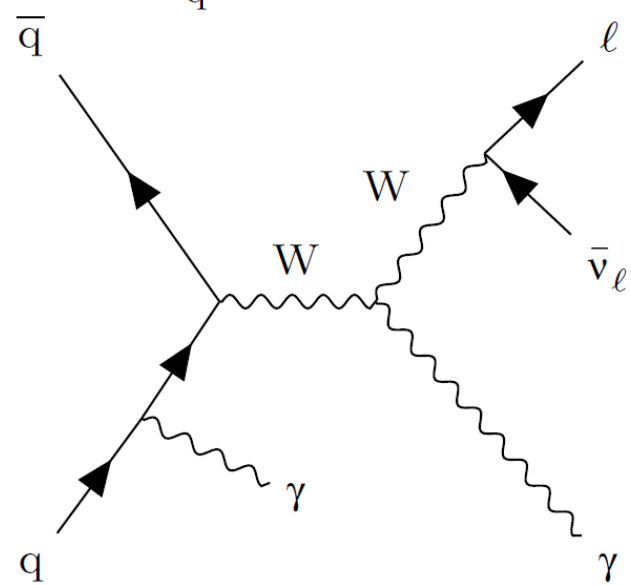
SMP-19-013

Wγγ and Zγγ at 13 TeV

Process	Theo. Cross section (NLO)
Wγγ	2 000 fb
Zγγ	680 fb





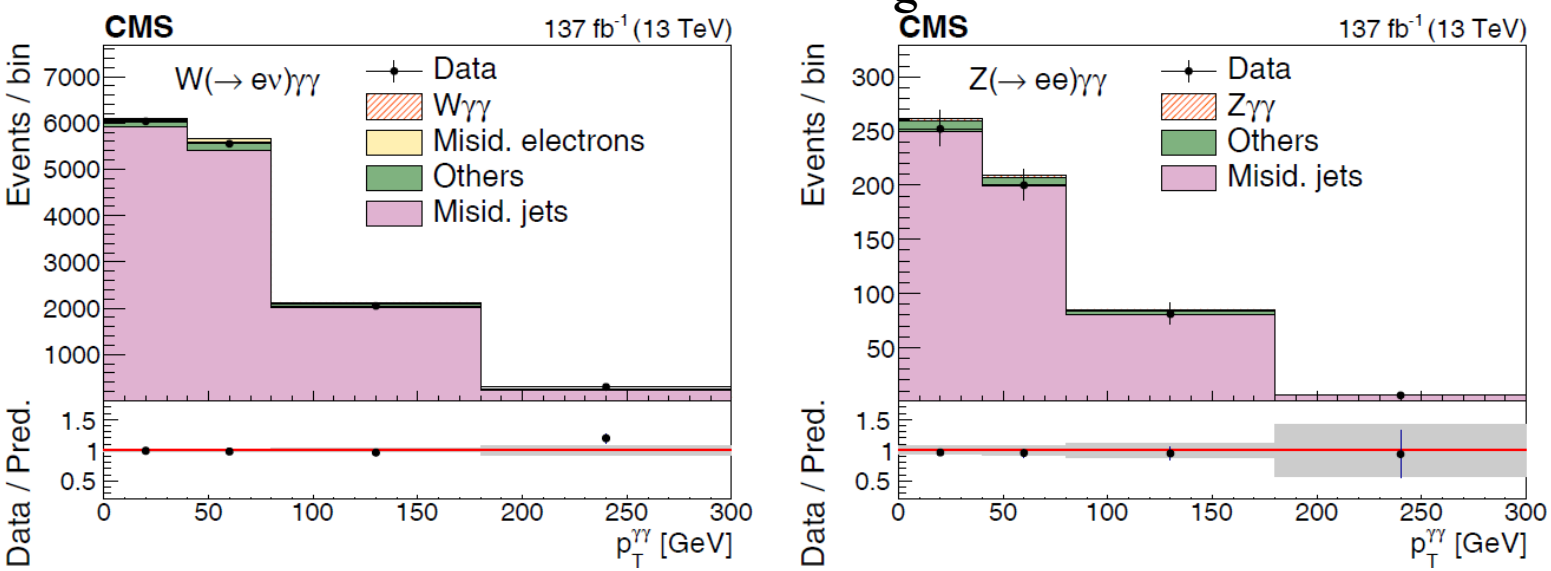


SMP-19-013

Backgrounds

- Major sources estimated from data control regions
  - Jets misidentified as photons
  - Electrons as photons (e.g. $Z\gamma \rightarrow ee\gamma$ where an e is misclassified as γ)
- QCD: $t\gamma$, $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$, $VV\gamma$ $\rightarrow$ from MC

Data control region



SMP-19-013

Selection cuts for Wγγ and Zγγ

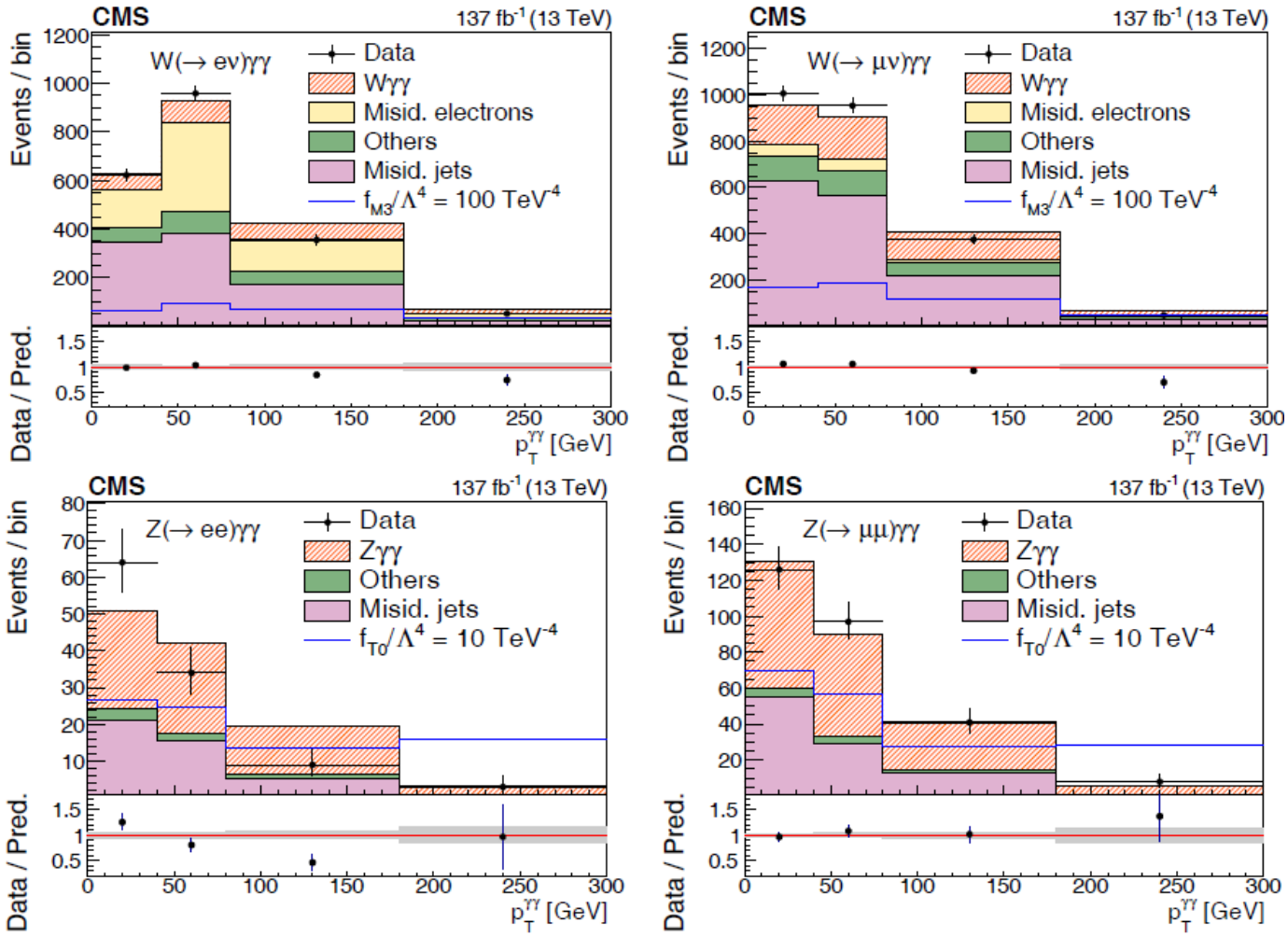
- Trigger: single $e^{\pm}$ with p_T > 27-32 GeV or $\mu^{\pm}$ with p_T > 24 GeV

Basic selection	Electrons	Muons
	$p_T > 15$ GeV $\lvert\eta\rvert < 1.442$ or $1.566 < \lvert\eta\rvert < 2.5$ Cut based Tight ID Impact parameter cuts	$p_T > 15$ GeV $\lvert\eta\rvert < 2.4$ Cut based Tight ID Rochester corrections
	photons	
	$p_T > 20$ GeV $\lvert\eta\rvert < 1.442$ or $1.566 < \lvert\eta\rvert < 2.5$ Cut based Medium ID Pixel seed veto $\lvert m_{e,\gamma} - 91.2\rvert > 5$ $\Delta R(\gamma, \gamma/l) > 0.4$	
Event selection	$W\gamma\gamma$	$Z\gamma\gamma$
	Exactly one selected lepton $p_{T,\,\mathrm{lead}}^{e(\mu)} > 35(30)$ GeV At least two photons	At least two selected same flavour leptons $p_{T,\,\mathrm{lead}}^{e(\mu)} > 35(30)$ GeV At least two photons $m_Z > 55$ GeV

$Z\gamma \to ee\gamma\ (e\gamma\gamma)$

SMP-19-013

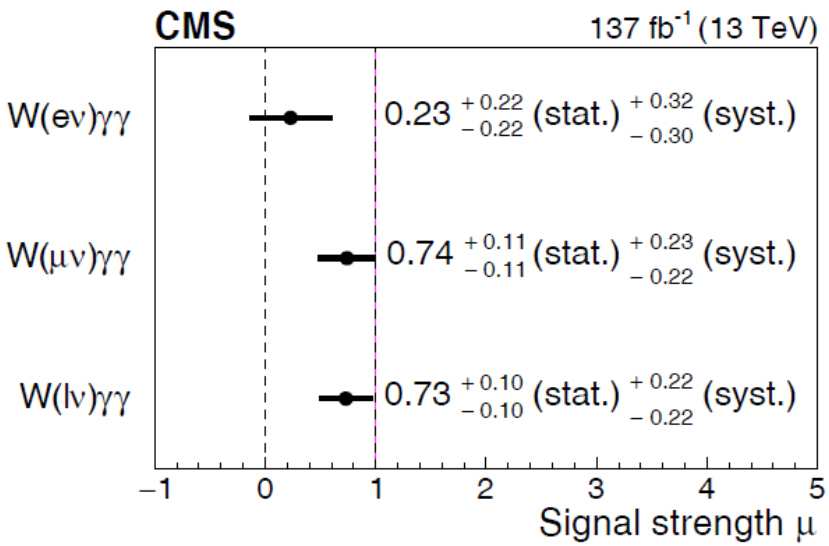
Pre-fit: p_T of diphoton

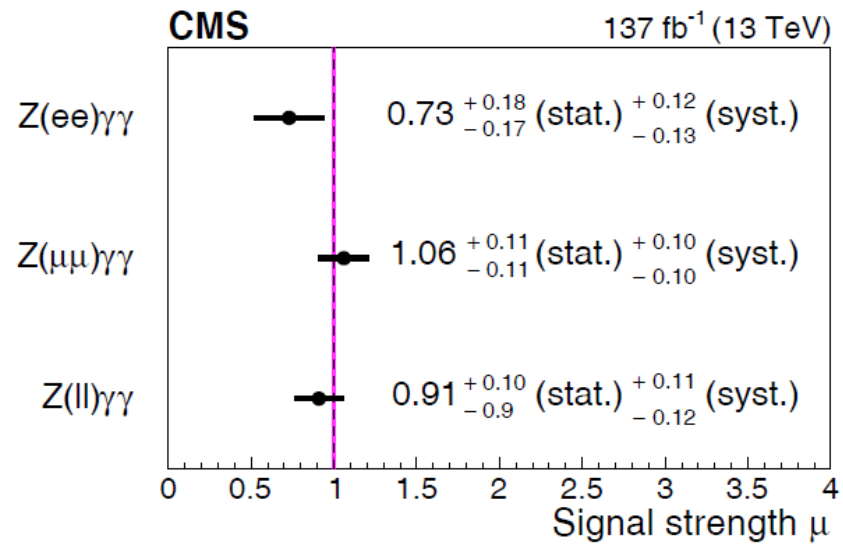


SMP-19-013

Results

- $\sigma(W\gamma\gamma)_{SR} = \mathbf{13.6}^{+1.9}_{-1.9}$ (stat) $^{+4.0}_{-4.0}$(syst) ± 0.08 (PDF+scale) fb
- $\sigma(Z\gamma\gamma)_{SR} = \mathbf{5.41}^{+0.58}_{-0.55}$ (stat) $^{+0.64}_{-0.70}$(syst) ± 0.06 (PDF+scale) fb





References

SMP-19-014

- CMS Collaboration, "Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV", Phys. Rev. Letters (2020), doi:10.1103/physrevlett.125.151802, arXiv:2006.11191v2
- CMS Collaboration, "Measurements of the pp to $W\gamma\gamma$ and pp to $Z\gamma\gamma$ cross sections at $\sqrt{s} = 13$ TeV and limits on anomalous quartic gauge couplings", 2021, arXiv:2105.12780

SMP-19-013

- Chatrchyan, S. and Khachatryan, V. and Sirunyan et al., "Search for $WW\gamma$ and $WZ\gamma$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 8$ TeV", Phys. Rev. D (2014), doi:10.1103/physrevd.90.032008, arXiv:1404.4619

SMP-13-009

Thanks for your attention

Backup

SMP-19-014

Selection: sequential cuts (2ℓ, 3ℓ)

Features	Selections		
	SS + $\geq$2j	SS + 1j	3ℓ
Triggers	Select events passing dilepton triggers		
Number of leptons	Select events with 2 (3) leptons passing SS-ID (3ℓ-ID) for SS (3ℓ) final states		
Number of leptons	Select events with 2 (3) leptons passing veto-ID for SS (3ℓ) final states		
Isolated tracks	No additional isolated tracks		—
b-tagging	no b-tagged jets and soft b-tag objects		
Jets	$\geq$2 jets	1 jet	$\leq$1 jet
m_{JJ} (leading jets)	$<$500 GeV		—
$\Delta\eta_{\mathrm{JJ}}$ (leading jets)	$<$2.5		—
$m_{\ell\ell}$	$>$20 GeV		—
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert > 20$ GeV if $e^{\pm}e^{\pm}$		—
m_{SFOS}	—	—	$m_{\mathrm{SFOS}} > 20$ GeV
m_{SFOS}	—	—	$\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert > 20$ GeV
$m_{\ell\ell\ell}$	—	—	$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}}\rvert > 10$ GeV

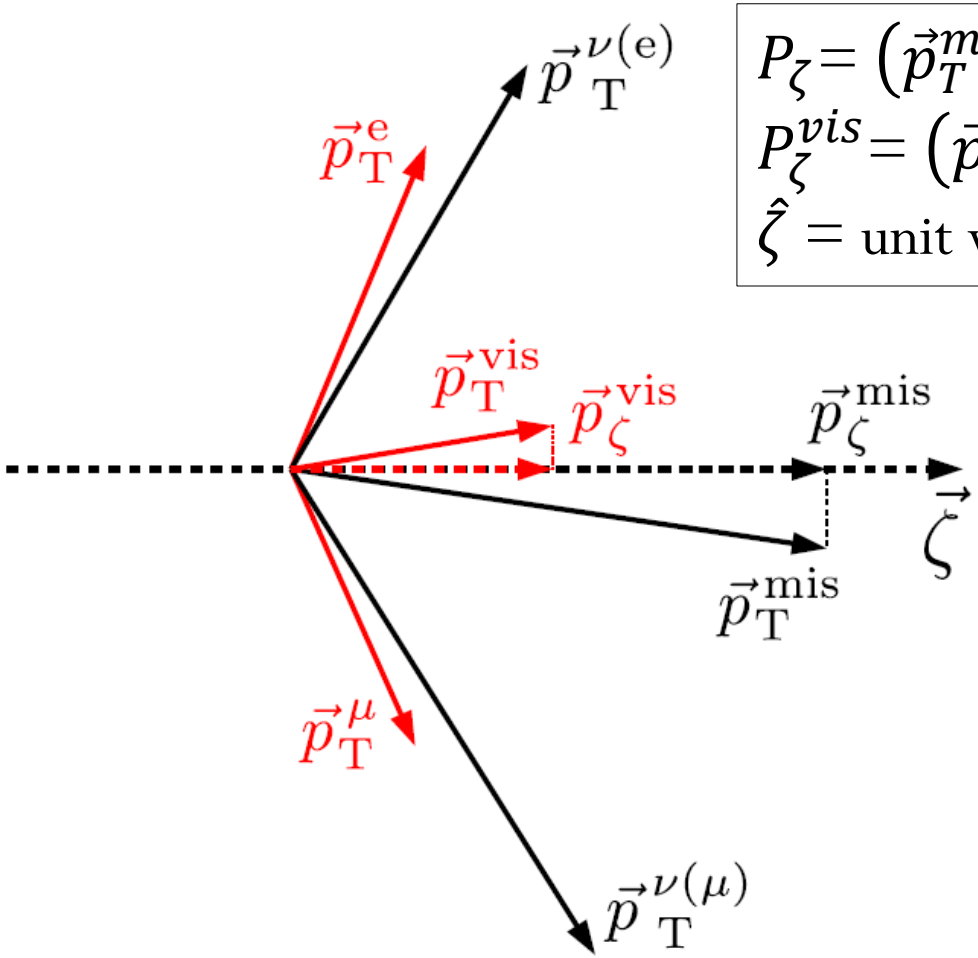
SMP-19-014

Selection: sequential cuts (4ℓ)

- 4ℓ (ZWW)
  - 1 SFOS with
    - $|m_{SFOS} - m_Z| < 10$ GeV/c^2
    - $p_T^{\ell 1} > 25$ GeV, $p_T^{\ell 2} > 10$ GeV/c
  - If the other 2 leptons have same flavour:
    - $|m_{\ell\ell} - m_Z| > 10$ GeV/c^2
  - Any $m_{SFOS} > 12$ GeV/c^2

$$m_{T2} = \min_{\vec{p}_T^{\nu 1} + \vec{p}_T^{\nu 2} = \vec{p}_T^{miss}} \left[\max\left(m_T(\vec{p}_T^{\nu 1}, \vec{p}_T^{e}), m_T(\vec{p}_T^{\nu 2}, \vec{p}_T^{\mu}) \right) \right]$$

P_ζ and P_ζ^{vis}



$$P_\zeta = \left(\vec{p}_T^{miss} + \vec{p}_T^{\ell 1} + \vec{p}_T^{\ell 2}\right) \cdot \hat{\zeta}$$

$$P_\zeta^{vis} = \left(\vec{p}_T^{\ell 1} + \vec{p}_T^{\ell 2}\right) \cdot \hat{\zeta}$$

$\hat{\zeta}$ = unit vector, bisector of ℓ_1 and ℓ_2

SMP-19-014

Electron and muon Common veto ID

Lepton Flavor	Electron	Muon
ID	MVA POG Loose NoIso	Loose
$\lvert\eta\rvert$	< 2.5	< 2.4
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm
$I_{rel,R=0.3,EA,Lep}$	< 0.4	< 0.4

The isolation is computed including other leptons, in additions to hadrons and photons

SMP-19-014

Electron definitions

	SS-ID	Loose-SS-ID	3ℓ-ID	Loose-3ℓ-ID
Veto ID see Table 7	Common Veto ID		Common Veto ID	
POG MVA wp	MVA POG 80% No Iso		MVA POG 90% No Iso	
p_T	> 25 GeV		> 20 GeV	
$\|\eta\|$ (veto $1.4 < \|\eta\| < 1.6$)	< 2.4		< 2.4	
IP_{3D}	< 0.01 cm		< 0.015 cm	
$\|d_{xy}\|$	< 0.05 cm		< 0.05 cm	
$\|d_z\|$	< 0.1 cm		< 0.1 cm	
$I_{\mathrm{rel,R=0.3,EA,Lep}}$	< 0.05	< 0.4	< 0.10	< 0.4
3-charge agreement	yes		not required	
Trigger safe cuts	yes		yes	

SMP-19-014

Muon definitions

	SS-ID	Loose-SS-ID	3ℓ-ID	Loose-3ℓ-ID
Veto ID see Table 7	Common Veto ID		Common Veto ID	
POG ID	Medium		Medium	
p_T	> 25 GeV		> 20 GeV	
$\|\eta\|$	< 2.4		< 2.4	
IP_{3D}	< 0.015 cm		< 0.015 cm	
$IP_{3D}/\sigma_{IP_{3D}}$	< 4		< 4	
$\|d_{xy}\|$	< 0.05 cm		< 0.05 cm	
$\|d_z\|$	< 0.1 cm		< 0.1 cm	
$I_{rel,R=0.3,EA,Lep}$	< 0.04	< 0.4	< 0.15	< 0.4
$\sigma(p_T)/p_T^{track}$	< 0.2		< 0.2	

SMP-19-014

Triboson production

Process	Theoretical cross section (NLO)	BR for selected final state	σ_{TOT} x BR	Expected events for 137 fb^{-1}
WWW	509 fb	2ℓ 7.42 %	36.4 fb	5 000
		3ℓ 3.46 %	17.6 fb	2 400
WWZ	354 fb	1.16 %	4.12 fb	560
WZZ	91.6 fb	0.39 %	0.36 fb	50
ZZZ	37.1 fb	0.13 %	0.05 fb	6.9

* Sum of 2 and 3 leptons channels

Process	sample name	σ (pb)
QCD Multijet	QCD_Pt-20toInf_MuEnrichedPt15_TuneCUETP8M1_13TeV_pythia8	$7.2\ 10^8$
	/QCD_Pt-*_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8	variable
	/QCD_Pt-*_EMEnriched_TuneCUETP8M1_13TeV_pythia8	variable
	/QCD_Pt-*_bcToE_TuneCUETP8M1_13TeV_pythia8/	variable
$gg \to ZZ$	GluGluToContinToZZTo(2e2mu/2e2tau/2mu2tau)_13TeV_MCFM701_pythia8	0.005423
	GluGluToContinToZZTo(4e/4mu/4tau)_13TeV_MCFM701_pythia8	0.002703
$qq \to ZZ$	ZZTo2L2Nu_13TeV_powheg_pythia8	0.5644
	ZZTo2L2Q_13TeV_powheg_pythia8	3.221
	ZZTo4L_13TeV_powheg_pythia8_ext1	1.3816
$gg \to H \to ZZ$	GluGluHToZZTo4L_M125_13TeV_powheg2_JHUgenV6_pythia8	0.011814
Single top	ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.6818
	ST_t-channel_antitop_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1	80.95
	ST_t-channel_top_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1	136.02
	ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.559
	ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1	19.559
	ST_tWll_5f_LO_13TeV-MadGraph-pythia8	0.01123
$t\bar{t}$	TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	87.315
	TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	114.6
	TTJets_SingleLeptFromT_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	114.6
Rare Top + X	TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.2043
	TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2728
	TTZToLL_M-1to10_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	0.0493
	tZq_ll_4f_13TeV-amcatnlo-pythia8	0.0758
	ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8	0.215
	TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	3.697
V + jets	WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	61335
	WJetsToLNu_HT-*_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	variable
	DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	20657
	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	6025.3
	DYJetsToLL_HT-*_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	variable
	DYnJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8 (n = 0, ..., 3)	variable
V + γ + jets	WGToLNuG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	512.6
	ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	123.9
Diboson (+ γ)	WWTo2L2Nu_13TeV-powheg	12.178
	WWToLNuQQ_13TeV-powheg	49.997
	WWTo2L2Nu_DoubleScattering_13TeV-pythia8	0.170
	WpWpJJ_EWK-QCD_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0539
	WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	5.52
	WZTo3LNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.4297
	WWG_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2147
	WZG_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.04123
VH	VHToNonbb_M125_13TeV_amcatnloFXFX_madspin_pythia8	0.952
	HZJ_HToWWTo2L2Nu_ZTo2L_M125_13TeV_powheg_pythia8	0.0186
	GluGluZH_HToWWTo2L2Nu_ZTo2L_M125_13TeV_powheg_pythia8	0.000891^2
Triboson	WWW_4F_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2086
	WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651
	WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565
	ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398

DRAFT

SMP-19-013

Monte Carlo

Process	Generator (NLO)	Notes
$V\gamma\gamma$	MADGRAPH5 aMC@NLO 2.2.2 / 2.2.6	
Inclusive W, Z		
$t\gamma$		
$t\bar{t}\gamma(\gamma)$		
VVV		
γ + jets		Generated at LO
$V\gamma$		Main backgr. estimated with control regions
$V\gamma$	SHERPA 2.26	
t	POWHEG v2	Decay with MadSpin
VV	PYTHIA 8.219 / 8.226	

Hadronization: PHITHIA 8.226/8.230 tune CUETP8M1 / CP5
PDF set: NLO NNPDF 3.0 / 3.1

SMP-19-013

Selection for electrons

Variable	Barrel	Endcap
$\lvert\eta\rvert$	≤ 1.442	≥ 1.566 && ≤ 2.5
d_{xy}	< 0.05	< 0.10
d_z	< 0.10	< 0.20
$\sigma_{i\eta i\eta}$	< 0.0104	< 0.0353
$\lvert\Delta\eta\rvert$	< 0.00255	< 0.00501
$\lvert\Delta\phi\rvert$	< 0.022	< 0.0236
H/E	$< 0.026 + 1.15/E_{SC} + 0.0324\rho/E_{SC}$	$< 0.0188 + 2.06/E_{SC} + 0.183\rho/E_{SC}$
Iso_{rel}	$< 0.0287 + 0.506/p_T$	$< 0.0445 + 0.963/p_T$
$\lvert 1/E - 1/p\rvert$	< 0.159	< 0.0197
Missing hits	≤ 1	≤ 1
Pass conversion veto	Yes	Yes

DRAFT

SMP-19-013

Selections for muons

Variable	Cut
Global muon	Yes
Particle-flow muon	Yes
Track fit $\chi^2/\text{ndof} < 10$	Yes
Muon chamber hits	≥ 1
Muon station segments	≥ 2
d_{xy}	< 0.2
d_z	< 0.5
Pixel hits	> 1
Tracker layers hits	> 5

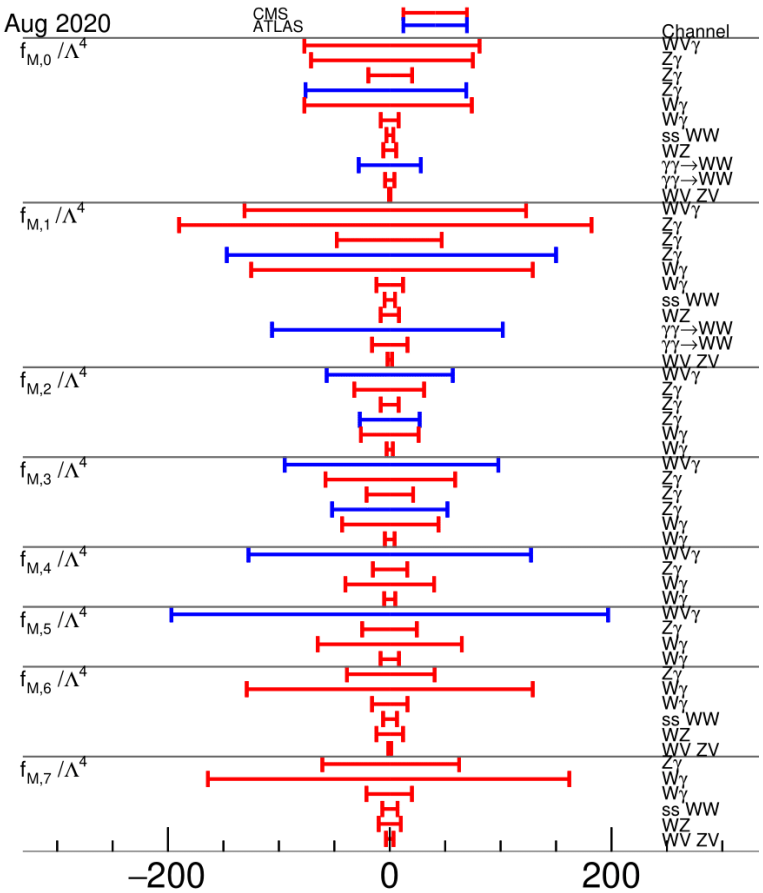
SMP-19-013

Systematics

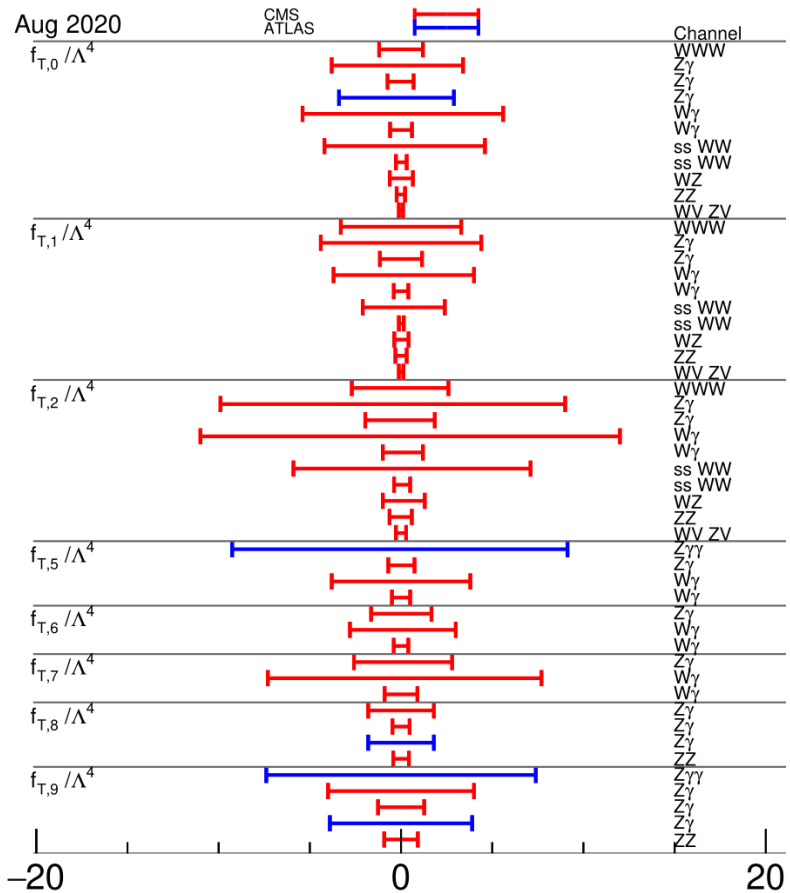
Systematic source	$\ell\nu\gamma\gamma$ [%]	$\ell\ell\gamma\gamma$ [%]
Integrated luminosity	2	3
Pile-up	<1	1
Electron efficiencies	<1	1
Muon efficiencies	<1	1
Photon efficiencies	12	5
Jet-photon misid.	21	6
Electron-photon misid.	<1	—
$W\gamma$ theoretical cross section	3	<1
$Z\gamma$ theoretical cross section	<1	6
Other bkgs theoretical cross section	2	<1
Simulated sample event count	8	4

Status: limits on dimension 8

Mixed transverse and longitudinal parameters



Transverse parameters



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

SMP-19-013

Limits on anomalous couplings

Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]