Triboson ZZγ production in the 4lγ channel in pp collisions with the CMS experiment at 13 TeV

Antonio Vagnerini (Univ. Lincoln-Nebraska)

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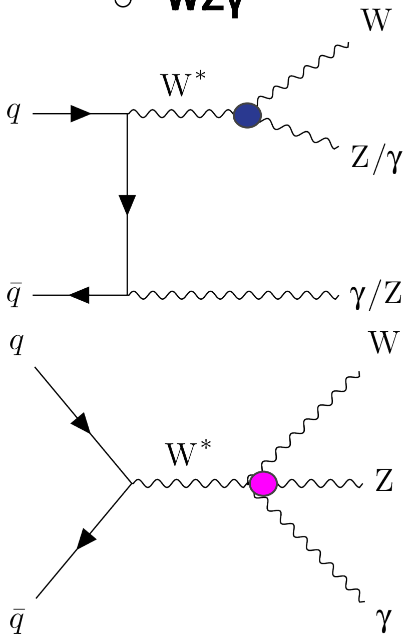
Outline

- Theoretical introduction
- Event selection
- Signal definition
- Background estimation
- Results
- Summary

Triboson production

- Study the **EW** sector to **high precision**
  - Probe the non-Abelian triple **(TGC)** and quartic **(QGC)** gauge couplings
  - Complementary to Higgs measurements at an energy scale larger than Higgs mass $\sqrt{s} > m_H$
- **VZγ** processes sensitive to Beyond Standard Model **(BSM)** effects on gauge couplings
  - **WZγ** has **Leading Order** (LO) contributions from **TGC and QGC**
  - **ZZγ** does **not** have TGC/QGC **LO diagrams** in SM → sensitive to anomalous couplings

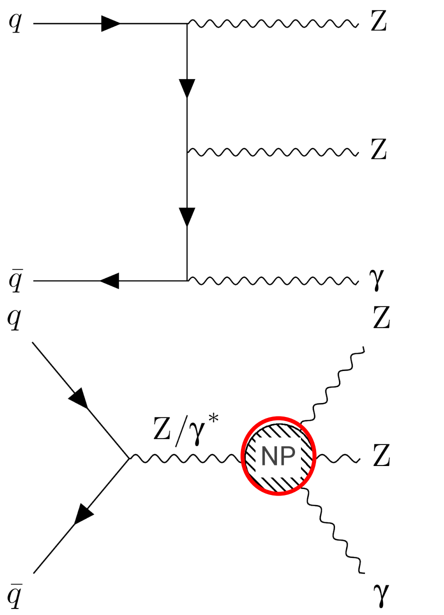
- **WZγ**



σ(pp→WZγ→3ℓ ν γ) = 1.5 fb
σ(pp→WZγ→2j 2ℓ γ) = 4.8 fb

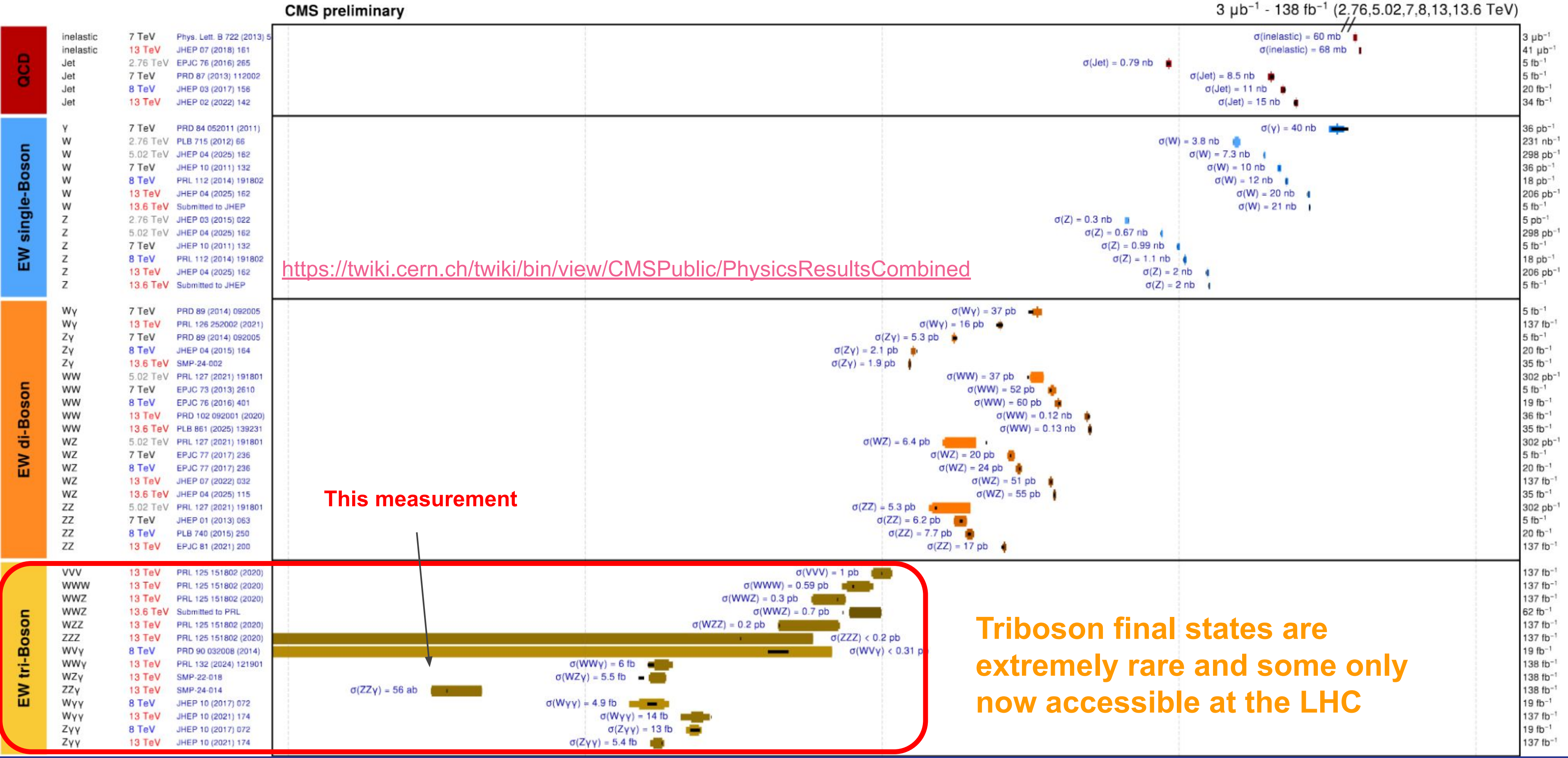
MadGraph5_aMC@NLO

- **ZZγ**



σ(pp→ZZγ→4ℓ γ) = 0.20 fb
σ(pp→ZZγ→2j 2ℓ γ) = 3.9 fb

Overview of CMS cross section results

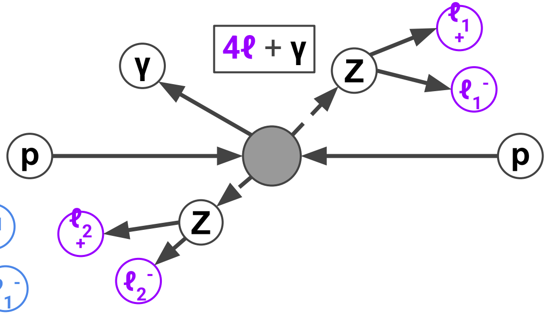


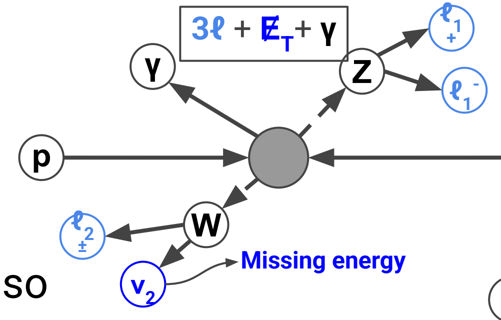
Triboson final states are extremely rare and some only now accessible at the LHC

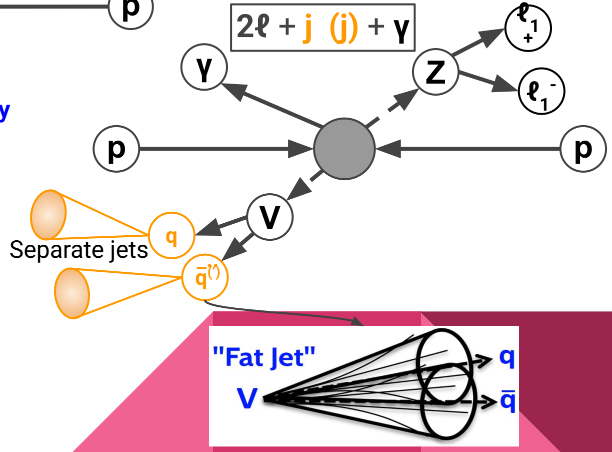
VZγ triboson channels and their signature

VZγ processes can be studied in different **channels** based on **# charged leptons: 4,3,2**

- **4ℓ: ZZγ** → $\ell_1^{\pm}\ell_1^{\mp}+\ell_2^{\pm}\ell_2^{\mp}+\gamma$
- **3ℓ: WZγ** → $\ell_1^{\pm}\ell_1^{\mp}+\ell_2^{\pm}+\gamma$ + **MET**
- **2ℓ: VZγ** → $\ell_1^{\pm}\ell_1^{\mp}+j(j)+\gamma$







- **Leptonic final state** relatively **clean**, but also **smaller Branching Ratio** (BR)

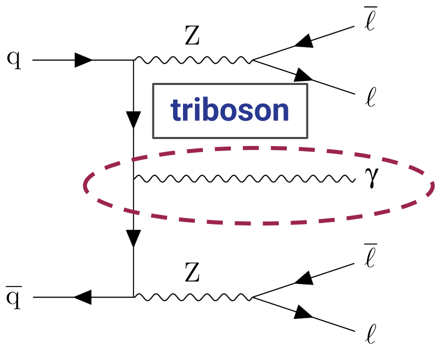
- **Hadronic** decay **larger BR** but huge background
  - study **resolved** or **merged jet topology**

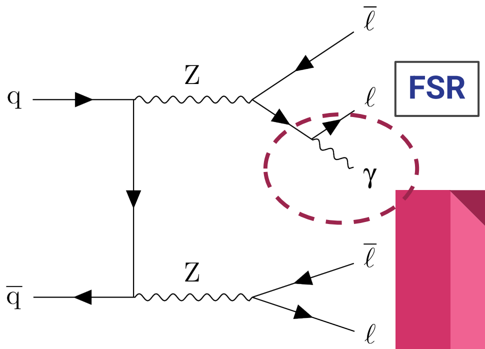
ZZγ leptonic measurement

- **First LHC result** on triboson $ZZ\gamma$ production!
- **Inclusive EWK $pp \to 4\ell\gamma$**
  - Not all analyses distinguish between **FSR** and **triboson**
- Very **challenging** analysis due to small section, but very **clean final state**

	ATLAS	CMS
$W\gamma\gamma$	13 TeV $\ell^{\pm}\nu\,\gamma\,\gamma$: **5.6 σ** (PUB)	13 TeV $\ell^{\pm}\nu\,\gamma\,\gamma$: **3.1 σ** (PUB)
$Z\gamma\gamma$	13 TeV $\ell^{+}\ell^{-}\nu\,\gamma\,\gamma$ (PUB)	13 TeV $\ell^{+}\ell^{-}\nu\,\gamma\,\gamma$: **4.8 σ** (PUB)
$WW\gamma$	8 TeV $\ell^{\pm}\nu\,\ell'^{\pm}\nu\,\gamma$ + $\ell^{\pm}\nu\,jj\,\gamma$ (PUB)	13 TeV $\ell^{\pm}\nu\,\ell'^{\pm}\nu\,\gamma$: **5.6 σ** (PUB)
$WZ\gamma$	13 TeV $\ell'^{\pm}\nu\,\ell^{+}\ell^{-}\,\gamma$: **6.3 σ** (PUB)	13 TeV $\ell'^{\pm}\nu\,\ell^{+}\ell^{-}\,\gamma$: **5.4 σ** (PAS)
$ZZ\gamma$	-	**This work** (PAS)

Search for $ZZ\gamma$ production
CMS Run 2 data (138 fb^{-1})





Reconstruction and identification e/μ

Electrons

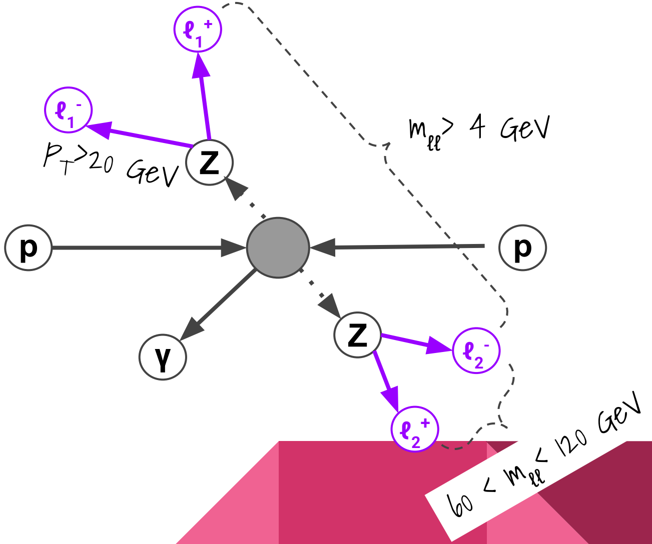
- **Track** in the **silicon tracker + ECAL clusters** (+ **bremsstrahlung**)
- **Loose selection**:
  - $p_T > 7$ GeV (**VB decay**)
  - $|\eta| < 2.5$ (**tracker acceptance**)
  - Isolation (**VB vs e.g. hadronic activity**)
  - **Vertex-track**: $d_{xy} < 0.5$ cm, $d_z < 1$ cm
- **Tight selection**: (high purity)
  - **Significance of Impact Parameter: SIP_{3D}** < 4 and MVA discriminant

Muons

- **Tracker track** + match in the **muon system** (track OR **single segment**)
- **Loose selection:**
  - $p_T > 5$ GeV (**VB decay**)
  - $|\eta| < 2.4$ (**muon system acceptance**)
  - Isolation (**VB vs e.g. heavy flavour decay**)
  - **Vertex-track**: $d_{xy} < 0.5$ cm, $d_z < 1$ cm
- **Tight selection:** (high purity)
  - $SIP_{3D} = IP_{3D}/\sigma_{IP,3D} < 4$ and MVA discriminant

Z reconstruction from leptons

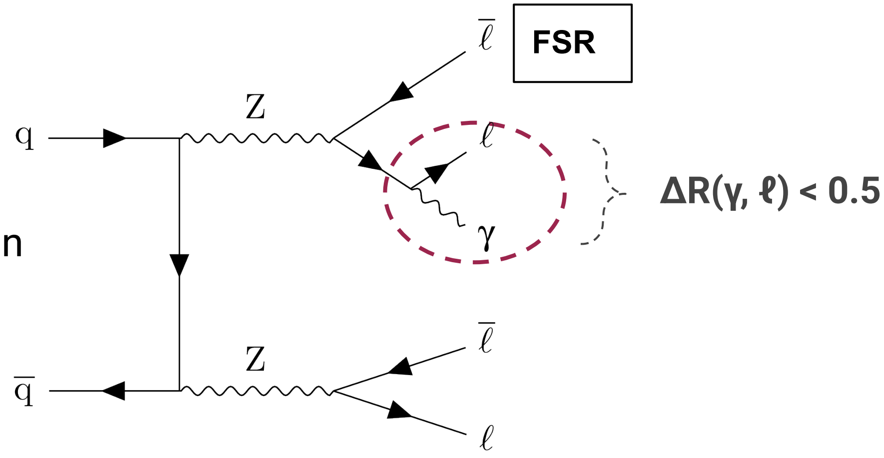
- **Z** candidates: **S**ame **F**lavour **O**pposite **S**ign (**SFOS) pairs** of leptons passing loose selection (low purity)
  - 60 GeV < $m_{\ell\ell}$ < 120 GeV
  - $|m_{Z1} - m_Z| < |m_{Z2} - m_Z|$
- Veto opposite-sign leptons that have $m_{\ell\ell}$ < 4 GeV
- **ZZ**: pair of non overlapping Z candidates
  - **Z_1**: closest in mass to the nominal Z peak
  - **Z_2**: with the highest scalar sum p_T of its daughters



FSR recovery for charged leptons

- **Algorithm** to recover **F**inal **S**tate **Radiation photons** in the **vicinity** of **charged** leptons
  - same method as in H->ZZ->4l analysis JHEP08(2023)040

1. FSR candidate **preselection**:
   a. $p_T > 2$ GeV; $|\eta| < 2.4$
   b. $I^\gamma \stackrel{\text{def}}{=} \frac{1}{p_T^\gamma}\left(\sum p_T^\gamma + \sum_{i \in \text{neutral}} p_T^i + \sum_{j \in \text{charged}} p_T^j\right) < 1.8$
   c. Exclude γ used in electron reconstruction
2. Assigned to the **closest lepton** (e, μ)
3. Accepted (at most 1 per ℓ) if:
   a. $\Delta R(\gamma, \ell) < 0.5$
   b. $\Delta R(\gamma, \ell)/E_{T,\gamma}^2 < 0.012\ \text{GeV}^{-2}$
4. Add **vectorially four-momentum** of FSR candidate to the lepton



Reconstruction and identification of signal γ

Signal photon **kinematic** selection:

- $\Delta R(\gamma, \ell) > 0.5$ – suppresses **FSR photon**
- **$p_T > 20$ GeV, $|\eta| < 1.4442 \vee 1.566 < |\eta| < 2.4$**
- **electron conversion** veto

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

Photon identification:

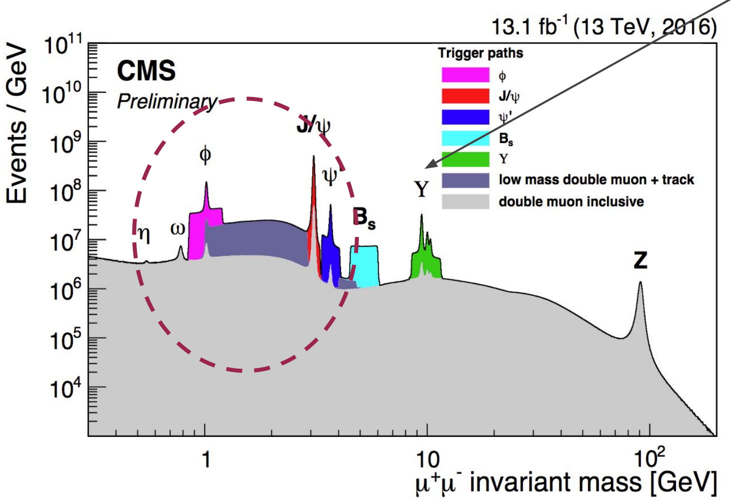
cut-based with thresholds on 5 variables

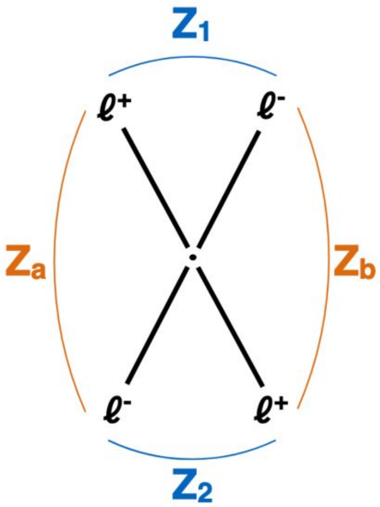
- **shower shape $\sigma_{i\eta i\eta}$**
- **energy ratio** in **HCAL** to **ECAL H/E**
- **isolation** : photon, neutral and charged

$$\text{Iso}_{\text{ch}} = \sum_{\text{charged hadrons}} p_T \quad \text{within } \Delta R < R_{\text{iso}}$$

Search region(s)

- **Inclusive Electroweak $4\ell\gamma$**:
  - Exactly 4 leptons passing **high purity** $p_T^{\ell 1, \ell 2} > 20, 10$ GeV
  - **“Smart-cut”**: **reject** $4e$ and 4μ candidates where alternative pairing satisfies $|m_{Za} - m_Z| < |m_{Z1} - m_Z| \wedge m_{Zb} < 12\ \mathrm{GeV/c^2}$
  - **1 good photon**





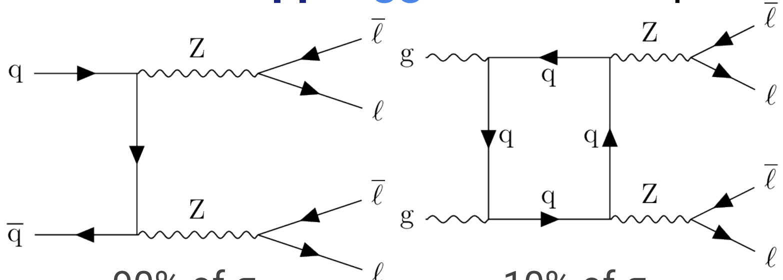
- **Triboson $ZZ\gamma$**:
  in addition **min($m_{\ell^+\ell^-\gamma}$) > 100 GeV** , $\ell^+\ell^-$ from a Z candidate to suppress FSR

Backgrounds: irreducible vs reducible

Two main categories of background:

- **Irreducible rare VVV**, *$t\bar{t}Z$* estimated from simulation
- **Main reducible bkg:** $(qq/gg) \rightarrow ZZ \rightarrow 4\ell$ $(+\gamma$ **fake**/FSR) **(non-prompt photon)** estimated with data-driven method and simulation
- **Small fake-lepton bkg** estimated with data-driven method

ZZ: from **qq** or **gg**-initiated loop



90% of σ_{ZZ} | 10% of σ_{ZZ}

Fake ℓ from data		
	ℓ pass	ℓ fail
γ pass	SR	ℓ AR
γ fail		ℓ AR

× ℓ-TF

Fake γ from data		
	ℓ pass	ℓ fail
γ pass	SR	
γ fail	γ AR	

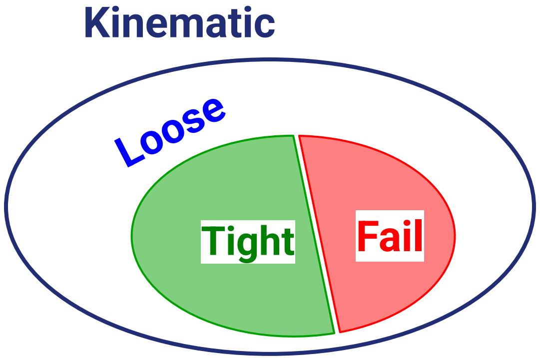
× γ-TF

Non-prompt/misidentified photons

- Origin of **fake photons** (instrumental bkg):
  - **non-prompt**, from **light meson** decays, e.g. $\pi^0 \rightarrow \gamma\gamma$
  - **mis-identified** electrons / light quark jets

- Subset of **Z+ℓ** Control Region + **1 loose γ** (enriched in fake γ)
  - Subtract **prompt photons** from MC (**Zγ**)

- **"Tight-to-loose" method** to measure fake rate: **FR(p_T, η) = Tight/Loose**
  - Loose: ≥ **3 cuts** (H/E, $Iso_{neutral}$, Iso_{photon})
  - Tight: all **5 cuts** of cut-based ID

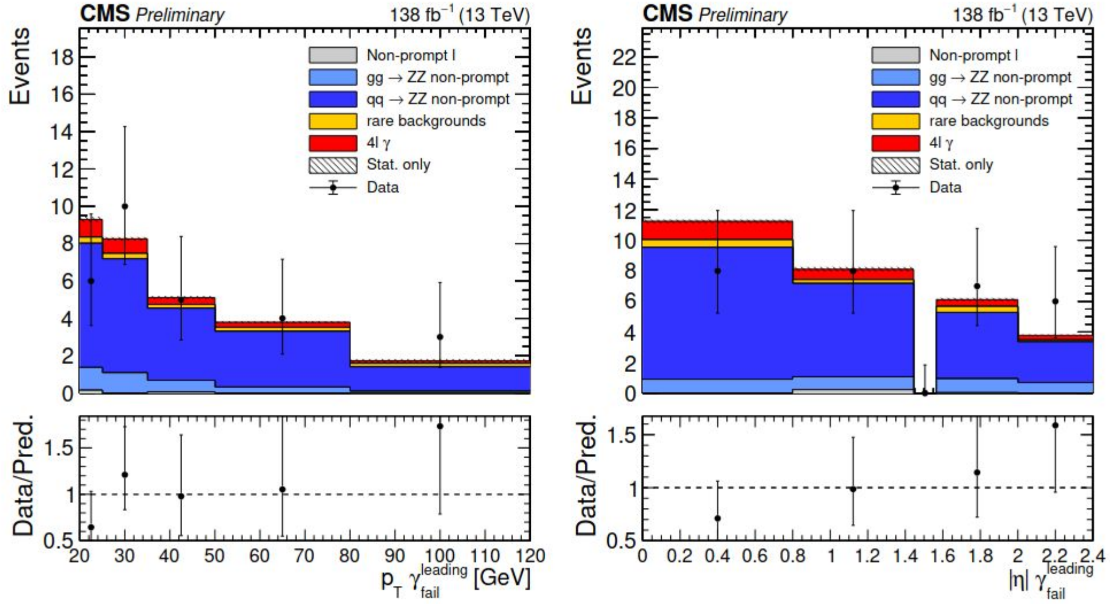


Application of photon fake rate

- **A**pplication **R**egion used to estimate **fake γ** yield in **S**ignal **R**egion
  - **4 leptons** pass the Tight selection
  - **1 γ** passes the **Loose selection** but **fails** tight

γ-FR from Z+l control region

$$N_{SR}^{bkg} = \sum \frac{f_i}{1-f_i} N_{AR}$$

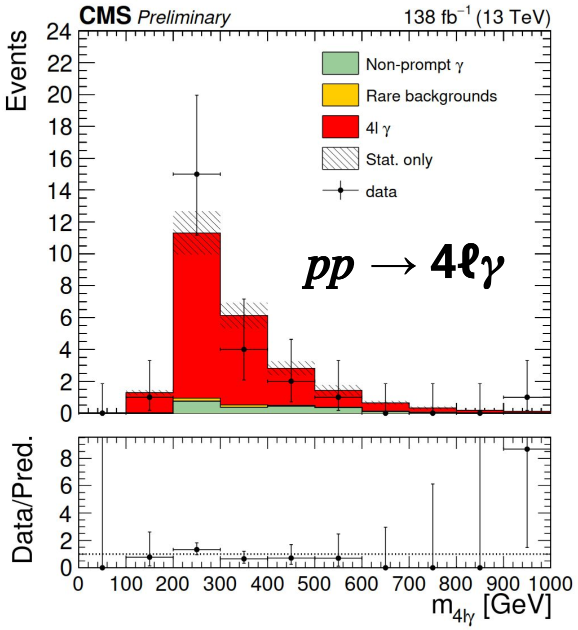


(a) p_T^γ (b) $|\eta^\gamma|$

- Good **agreement** between **data-driven** approach and **MC** for non **prompt γ**
  - used for **inclusive 4ℓγ**
- Use MC for **non-prompt γ** in ***ZZγ* region** due to low stat in AR

First observation of inclusive $pp \rightarrow 4\ell\gamma$

- Perform ML fit using $\mathbf{m_{4\ell\gamma}}$ as observable and **non-prompt-γ** estimate from **data**



- Observation of pp→ $4\ell\gamma$: 5.1σ obs. (4.1σ exp.)

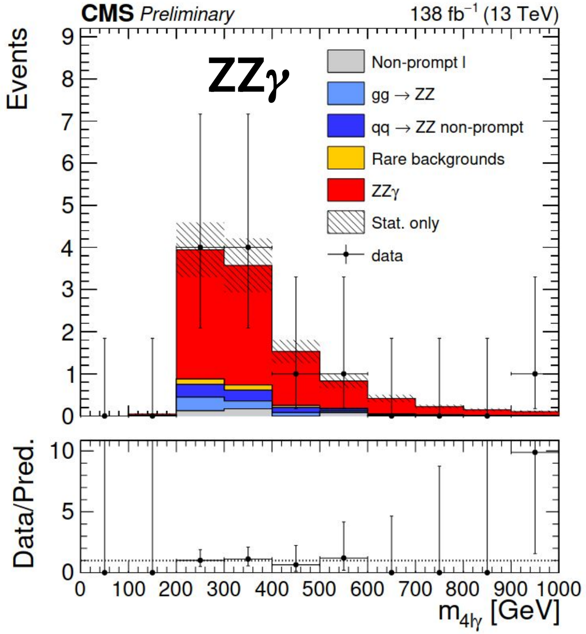
	2016	2017	2018	Run 2
$pp \rightarrow 4\ell\gamma$	5.83 ± 0.91	6.35 ± 1.40	9.32 ± 2.04	21.51 ± 2.64
Non-prompt γ	0.81 ± 0.70	0.42 ± 0.35	0.82 ± 0.72	2.05 ± 1.07
Rare backgrounds	0.09 ± 0.04	0.12 ± 0.04	0.22 ± 0.03	0.44 ± 0.07
$pp \rightarrow 4\ell\gamma$ OOA	0.07 ± 0.02	0.08 ± 0.02	0.09 ± 0.01	0.24 ± 0.02
Predicted number of events	6.81 ± 1.06	6.98 ± 1.41	10.45 ± 2.09	24.24 ± 2.74
Observed number of events	7	6	11	24

nonpr.-ℓ already included in the the "data-driven" non-prompt γ

$$\sigma_{\text{fid}}(\text{pp} \rightarrow 4\ell\gamma) = 161^{+64}_{-56}\,(\text{stat})^{+7}_{-9}\,(\text{theo})^{+5}_{-4}\,(\text{lumi})^{+15}_{-14}\,(\text{syst})\,\text{ab} = 161^{+66}_{-58}\,\text{ab}$$

First evidence of triboson $ZZ\gamma$

- Perform ML fit using $\mathbf{m_{4\ell\gamma}}$ as observable and **non-prompt-γ** estimate from **MC**



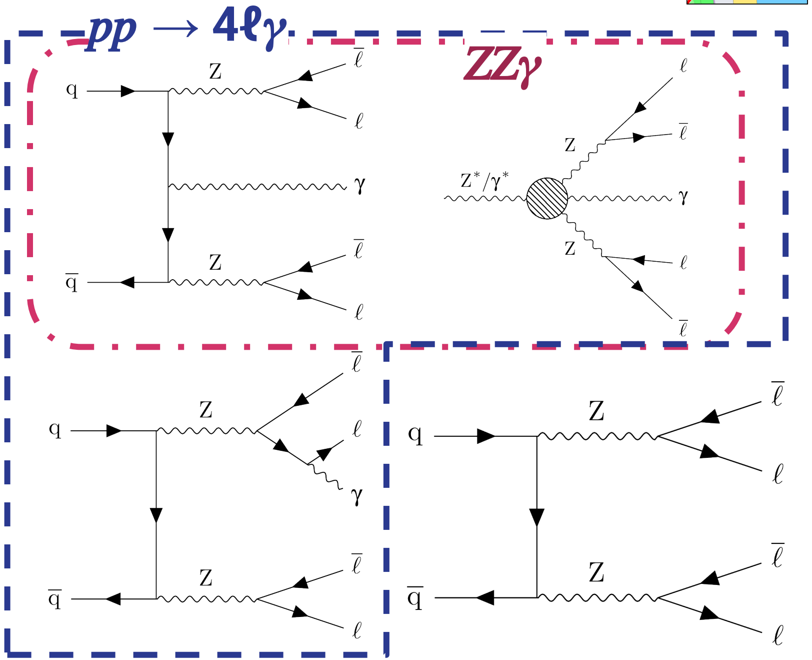
- Evidence of pp→ZZγ→4ℓγ: <u>3.7σ obs</u>. (3.0σ exp.)

	2016	2017	2018	Run 2
$ZZ\gamma \to 4\ell\gamma$	2.18 ± 0.61	2.52 ± 0.99	3.58 ± 1.41	8.28 ± 1.83
$q\bar{q} \to ZZ$	0.18 ± 0.04	0.24 ± 0.06	0.34 ± 0.09	0.76 ± 0.12
$gg \to ZZ \to \ell\ell$	0.19 ± 0.03	0.20 ± 0.04	0.28 ± 0.05	0.67 ± 0.07
$ZZ\gamma \to 4\ell\gamma$ OOA	0.12 ± 0.02	0.12 ± 0.01	0.14 ± 0.02	0.38 ± 0.03
Non-prompt ℓ	0.17 ± 0.15	0.12 ± 0.11	0.08 ± 0.09	0.37 ± 0.21
Rare backgrounds	0.04 ± 0.01	0.13 ± 0.03	0.18 ± 0.04	0.35 ± 0.05
Predicted number of events	2.87 ± 0.64	3.34 ± 1.00	4.60 ± 1.41	10.80 ± 1.84
Observed number of events	2	3	6	11

$$\sigma_{\text{fid}}(pp \to ZZ\gamma \to 4\ell\gamma) = 56^{+34}_{-28}\,(\text{stat})^{+1}_{-1}\,(\text{theo})^{+2}_{-1}\,(\text{lumi})^{+6}_{-5}\,(\text{syst})\,\text{ab} = 56^{+34}_{-28}\,\text{ab}$$

Summary

- Full **Run 2** analysis with **{4e;2e 2μ;4μ} γ FS**
- **First observation of inclusive $pp \rightarrow 4\ell\gamma$**
  - significance: **5.1 σ observed (4.1 σ expected)**
- **First evidence for triboson $ZZ\gamma$ @13 TeV**
  - significance: **3.7 σ observed (3.0 σ expected)**
- Both results are in **agreement** with the **SM**
  - Signal strengths are slightly **> 1**
  - **NLO EW** corrections may be needed



Measurement of the most rare tri-boson channel to date!

- $\sigma_{fid}(pp \rightarrow ZZ\gamma \rightarrow 4\ell\gamma)$ = 56 ± 30 ab   CMS PAS SMP-24-014

Thanks for your attention

Backup

Triboson searches @LHC

	8 TeV		13 TeV	
	ATLAS	CMS	ATLAS	CMS
Zγγ	Observation	Observation	Cross-section	Evidence
Wγγ	Evidence	Evidence	Observation	Evidence
ZZγ	–	Study	–	–
WZγ	Study		Observation	Observation
WWγ	Study	–	–	–

Source of systematic uncertainty	Type	Impact on $4\ell\gamma$	Impact on $ZZ\gamma$
QCD scale	norm.	5.0 %	1.0 %
α_S	norm.	1.3 %	0.3 %
pdf	norm.	1.4 %	0.9 %
Trigger	norm.	1.0 %	1.0 %
Pileup	norm.	2.5 %	2.3 %
Luminosity	norm.	2.7 %	2.7 %
Muon efficiency	norm.	1.0 %	1.0 %
Electron efficiency	norm.	4.4 %	4.4 %
Photon efficiency	norm.	2.0 %	2.1 %
Photon energy scale	norm.	0.2 %	0.1 %
γ misidentif. rate	norm.	2.2 %	-
Non-prompt ℓ norm.	norm.	-	1.8 %
Non-prompt γ norm.	norm.	3.7 %	4.7 %
Non-prompt γ shape	shape	3.6 %	-

Table 1: Sources of systematic uncertainty and their impact on the cross section measurement for the inclusive $pp \to 4\ell\gamma$ final state and for the triboson $ZZ\gamma$ final state.

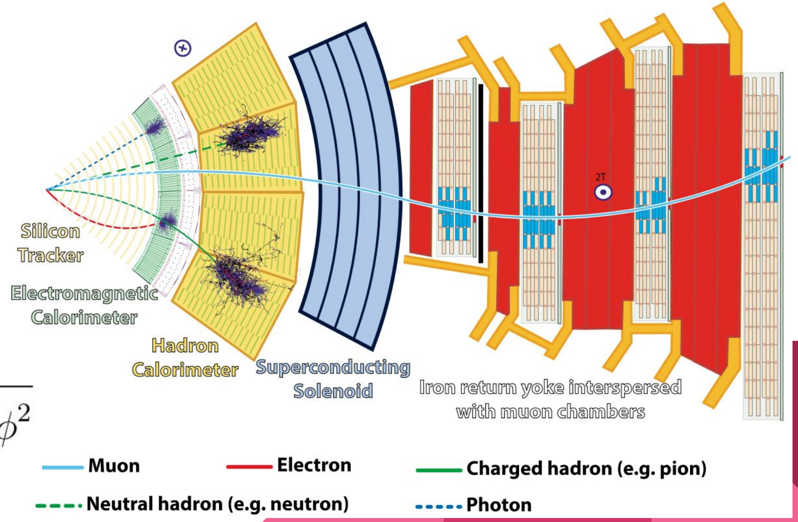
The Large Hadron Collider and CMS

- High energies for triboson → **LHC**
- Need to detect the collision products → **Compact Muon Solenoid** experiment
  - Silicon tracker (**pixel+strip**)
  - Electromagnetic calorimeter (**ECAL**)
  - Hadron calorimeter (**HCAL**)
  - Superconducting solenoid (**3.8 T**)
  - Muon system (**DT** + **CSC** + **RPC** [+ GEM])
- **Particle Flow (PF)** algorithm gives a consistent **global event description**
- Right handed coordinates:
  - **z = beam** axis , **x** = →**center** , **y = vertical**

pseudo-rapidity: $\eta = -ln\left(\tan\frac{\theta}{2}\right)$ distance: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Run 2 (2016–2018) - 13 TeV

@CMS	2016	2017	2018	**Run2**
<interactions/BX>	20	27	38	**37**
$\int\mathcal{L}\,dt$ [fb^{-1}]	36.3	41.5	59.8	**137.6**



Vector boson self-interactions

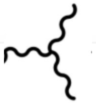
- The **production** of **three electroweak (EW) bosons** (W,Z,γ) in high energy collisions probes the **EW symmetry breaking** in the SM**,** in particular the **gauge boson self-interactions**

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\epsilon^{abc}W^b_\mu W^c_\nu$
- $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

After electroweak symmetry breaking and rotation into the physical fields **W±,Z, A**

Triple WWV



Quartic WWVV

Interaction	Lagrangian Term
WWγ	$-ie\left[(W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)A_\nu + W^+_\mu W^-_\nu F^{\mu\nu}\right]$
WWZ	$-ig\cos\theta_W\left[(W^{+\mu\nu}W^-_\mu - W^{-\mu\nu}W^+_\mu)Z_\nu + W^+_\mu W^-_\nu Z^{\mu\nu}\right]$
WWWW	$-\frac{1}{2}g^2\left[W^+_\mu W^{-\mu}W^+_\nu W^{-\nu} - W^+_\mu W^+_\nu W^{-\mu}W^{-\nu}\right]$
WWγγ	$-e^2\left[W^+_\mu W^{-\mu}A_\nu A^\nu - W^+_\mu A^\mu W^-_\nu A^\nu\right]$
WWZZ	$-g^2\cos^2\theta_W\left[W^+_\mu W^{-\mu}Z_\nu Z^\nu - W^+_\mu Z^\mu W^-_\nu Z^\nu\right]$
WWZγ	$-eg\cos\theta_W\left[W^+_\mu W^{-\mu}Z_\nu A^\nu - W^+_\mu Z^\mu W^-_\nu A^\nu + \text{h.c.}\right]$

$ZZ\gamma$ analysis strategy

- Rows: photon selection
- Columns: number of tight leptons

$ZZ\gamma$ (4ℓ) channel		Lepton selection			
γ selection		4P		3P1F	2P2F
kinematic	**γ tight ID PASS**	**SR4P_1P** $\rightarrow 4\ell\gamma$ inclusive	**SR4P_1P _triboson** $\rightarrow ZZ\gamma$	Nonpr. leptons AR	Nonpr. leptons AR
kinematic	**γ FAIL**	CR4P_1F (fake γ AR)			
kinematic	**γ fails loose**				
No γ kinem.					

4P – $ZZ \rightarrow 4\ell$ (SMP-22-001)

CR3P1F | CR2P2F

Signal/background regions:

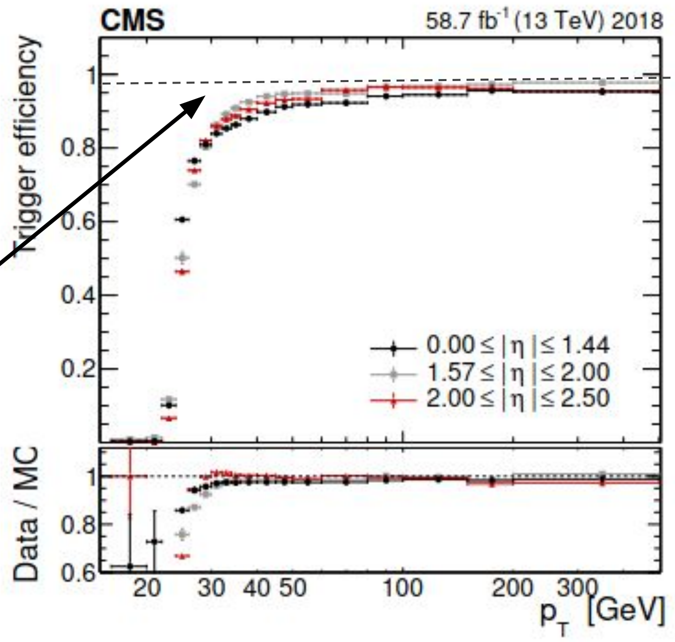
- **4P**: $4\ell_{tight}$, no requests on photons (historically SR4P)
- CR**3P1F**: $3\ell_{tight}1\ell_{fail}$
- CR**2P2F**: $2\ell_{tight}2\ell_{fail}$
- CRLFR: $2\ell_{tight}1\ell_{loose}$
- CR**4P_1F**: $4\ell_{tight}$ + $1\gamma_{fail}$
- SR**4P_1P**: $4\ell_{tight}$ + $1\gamma_{tight}$
- SR4P_1P_triboson
  - min($m_{\ell\ell\gamma}$) > 100 GeV

CRLFR: p_T^{miss} < 30 GeV

Trigger and samples

- CMS uses a two-stage trigger (LHC **collisions: 40 MHz**)
  - **L1 trigger** (custom FPGA): **100 kHz (-98%)**, latency < 4μs
  - **High Level Trigger** (software): ~**1kHz (-99%)**, < 50 ms/event
- This analysis uses several **trigger paths** :
  - inclusive **OR** of triggers requiring **1**, **2** or **3 electrons** at least one **muon**
- This analysis requires that $p_T^{\ell 1}, p_T^{\ell 2} > 20, 10$ **GeV**
  - close to trigger efficiency plateau **Ɛ >95**%
- Run 2 data split in **4 periods**: $\mathcal{L}_{int}$ **= 137.6 fb**$^{-1}$ at **13 TeV**

HLT Ele23 Ele12 trigger



Non-prompt leptons

- **Non-prompt ℓ** are difficult to model form simulation (instrumental background)
- **Misidentified** light-flavour jets, **non-prompt** from heavy quark decays
- **Tight-to-loose** method to estimate fake **ℓ**
  - Measure Fake Rate in a **dedicated CR:** $\mathbf{Z_{PP} + \ell_L} \rightarrow \mathbf{f(p_T^{\ell}, \eta^{\ell}) = N_{PASS}/N_{FAIL}}$
  - Use it to **reweight events** in application regions

Small contribution to the signal region from non-prompt lepton

$$N^{bkg}_{4P} = \sum \frac{f_i}{1-f_i}\left(N_{3P1F} - N^{bkg}_{3P1F} - N^{ZZ}_{3P1F}\right) + \sum \left(\frac{f_i}{1-f_i}\frac{f_j}{1-f_j}\right) N_{2P2F}$$

TF(f^Y) TF(f^Y)

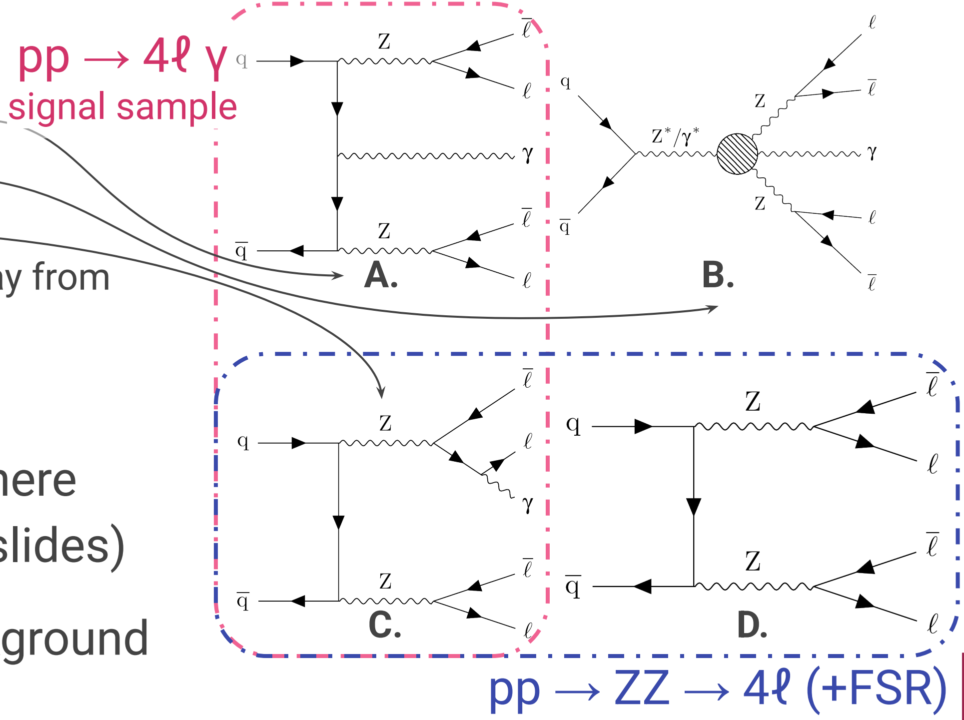
SR CR, 3lep CR, 2lep

Overlap between samples

- The γ can be emitted from:
  - A. an **initial state fermion** (this includes ISR)
  - B. a **TGC** or **QGC** vertex (not for SM ZZγ)
  - C. a lepton from a Z/W decay, as **FSR**
  - D. an unrelated process, e.g. light hadron decay from another collision ("nonprompt"), or "fake"

- Only (A.) and (B.) are "triboson"
- Defined a **triboson fiducial region** where these diagrams are enhanced (next slides)

- Both the ZZG signal and the ZZ background samples **include FSR** diagrams (c.)
- **Remove** events with **prompt γ** from ZZ to avoid double counting



Electron MVA

Observable type	Observable name
Cluster shape	RMS of the energy-crystal number spectrum: $\sigma_{i\eta i\eta}$, $\sigma_{i\varphi i\varphi}$
	Super cluster width along η and ϕ
	Ratio of the hadronic energy behind the SC to the SC energy, H/E
	Circularity $(E_{5\times5} - E_{5\times1})/E_{5\times5}$
	Sum of the seed and adjacent crystal over the SC energy R_9
	For endcap training bins: energy fraction in pre-shower $E_{\mathrm{PS}}/E_{\mathrm{raw}}$
Track-cluster match	Energy-momentum agreement E_{tot}/p_{in}, E_{ele}/p_{out}, $1/E_{tot} - 1/p_{in}$
	Position matching $\Delta\eta_{in}$, $\Delta\varphi_{in}$, $\Delta\eta_{seed}$
Tracking	Fractional momentum loss $f_{brem} = 1 - p_{out}/p_{in}$
	Reduced χ^2 of the KF and GSF track χ^2_{KF}, χ^2_{GSF}

Muon high-p_T ID

Requirement	Technical description
Muon station matching	Muon is matched to segments in at least two muon stations
Good p_{T} measurement	$\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}} < 0.3$, $\sigma_{p_{\mathrm{T}}}$ is the p_{T} uncertainty
Vertex compatibility (xy)	$d_{xy} < 2\,\mathrm{mm}$
Vertex compatibility (z)	$d_z < 5\,\mathrm{mm}$
Pixel hits	At least one pixel hit
Tracker hits	Hits in at least six tracker layers

Photon ID

Variable	Barrel (tight WP)	Endcap (tight WP)
H/E	<0.021	<0.032
$\sigma_{i\eta i\eta}$	<0.0099	<0.027
I_{ch}	$<0.65\,\text{GeV}$	$<0.52\,\text{GeV}$
I_{n}	$<0.32\,\text{GeV} + 0.015E_T +$ $2.26 \times 10^{-5} E_T^2/\text{GeV}$	$<2.72\,\text{GeV} + 0.012E_T +$ $2.3 \times 10^{-5} E_T^2/\text{GeV}$
I_{γ}	$<2.04\,\text{GeV} + 0.0040E_T$	$<3.03\,\text{GeV} + 0.0037E_T$

Signal definition (GEN)

- Leptons:
  - electron or muon (|ID| = 11, 13)
  - $p_T > 5$ GeV
  - $|\eta| < 2.5$
- Photons
  - isPrompt (generator status bit)
  - min $\Delta R(\gamma_{GEN}, \ell_{GEN}) > 0.5$
  - $p_T > 20$ GeV
  - $|\eta| < 1.4442 \lor 1.566 < |\eta| < 2.4$
  - Frixione isolation
- Jets AK4 (AK8)
  - $p_T > 30$ (150) GeV
  - $|\eta| < 4.7$

- SR4P_1P ($ZZ\gamma \rightarrow 4\ell\ \gamma$)
  - 2 SFOS with $|m_{\ell\ell} - m_Z^{PDG}| < 30$ GeV
  - ≥ 1 prompt γ
- SR3P_1P ($ZW\gamma \rightarrow 3\ell\ \nu\ \gamma$)
  - 1 SFOS with $|m_{\ell\ell} - m_Z^{PDG}| < 30$ GeV
  - $1\ \ell + 1\nu$ with $|m^T_{\ell\ell} - m^T{}_W{}^{PDG}| < 30$ GeV
  - ≥ 1 prompt γ
- SR2P_1P ($ZV \rightarrow 2\ell\ 2j\ \gamma$)
  - 1 SFOS with $|m_{\ell\ell} - m_Z^{PDG}| < 30$ GeV
  - EITHER 2 j / minDM(m_{jj}) < 30 GeV (*)
  - OR 1 J / minDM(m_J) < 30 GeV (*)
  - ≥ 1 prompt γ

minDM(x) = min($|x - m_Z^{PDG}|$, $|x - m_W^{PDG}|$)

Trigger paths

2016

Trigger description	Requirements	Primary Dataset
Double isolated electron	$p_T^{e_1}, p_T^{e_2} > 17, 12\,\mathrm{GeV}$	DoubleEG
Double isolated electron	$p_T^{e_1}, p_T^{e_2} > 23, 12\,\mathrm{GeV}$	
Double isolated GSF electron	$p_T^{e_1}, p_T^{e_2} > 33, 33\,\mathrm{GeV}$	
Triple isolated electron	$p_T^{e_1}, p_T^{e_2}, p_T^{e_3} > 16, 12, 8\,\mathrm{GeV}$	
Double isolated muon	$p_T^{\mu_1}, p_T^{\mu_2} > 17, 8\,\mathrm{GeV}$	DoubleMuon
Double isolated muon[1]	$p_T^{\mu_1}, p_T^{\mu_2} > 17, 8\,\mathrm{GeV}$	
Triple isolated muon	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{\mu_3} > 12, 10, 5\,\mathrm{GeV}$	
Tracker muon + isolated electron	$p_T^{\mu}, p_T^{e} > 8, 17$	MuonEG
Tracker muon + isolated electron	$p_T^{\mu}, p_T^{e} > 8, 23$	
Tracker muon + isolated electron	$p_T^{\mu}, p_T^{e} > 17, 12$	
Tracker muon + isolated electron	$p_T^{\mu}, p_T^{e} > 23, 12$	
Tracker muon + isolated electron	$p_T^{\mu}, p_T^{e} > 23, 8$	
Tracker muon + double electron	$p_T^{\mu}, p_T^{e_1}, p_T^{e_2} > 8, 12, 12\,\mathrm{GeV}$	
Double tracker muon + electron	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{e} > 9, 9, 9\,\mathrm{GeV}$	
Single tight ID central electron	$p_T^{e} > 25,\ \lvert\eta^{e}\rvert < 2.1$	SingleElectron
Single tight ID electron	$p_T^{e} > 27$	
Single tight ID GSF electron	$p_T^{e} > 27,\ \lvert\eta^{e}\rvert < 2.1$	
Single isolated muon	$p_T^{\mu} > 20$	SingleMuon
Single isolated muon	$p_T^{\mu} > 22$	

1: μ_1 is global, μ_2 is tracker muon

2017

Trigger description	Requirements	Primary Dataset
Double isolated electron	$p_T^{e_1}, p_T^{e_2} > 23, 12\,\mathrm{GeV}$	DoubleEG
Double GSF electron	$p_T^{e_1}, p_T^{e_2} > 33, 33\,\mathrm{GeV}$	
Triple electron	$p_T^{e_1}, p_T^{e_2}, p_T^{e_3} > 16, 12, 8\,\mathrm{GeV}$	
Double isolated muon	$p_T^{\mu_1}, p_T^{\mu_2} > 17, 8\,\mathrm{GeV},\ m_{\mu\mu} > 3.8\,\mathrm{GeV}$	DoubleMuon
Double isolated muon	$p_T^{\mu_1}, p_T^{\mu_2} > 17, 8\,\mathrm{GeV},\ m_{\mu\mu} > 8\,\mathrm{GeV}$	
Triple muon	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{\mu_3} > 12, 10, 5\,\mathrm{GeV}$	
Triple muon	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{\mu_3} > 10, 5, 5\,\mathrm{GeV}$	
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 23, 12\,\mathrm{GeV}$	MuonEG
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 8, 23\,\mathrm{GeV}$	
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 12, 23\,\mathrm{GeV}$	
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 23, 12\,\mathrm{GeV}$	
Double muon + electron	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{e} > 9, 9, 9\,\mathrm{GeV}$	
Muon + double electron	$p_T^{\mu}, p_T^{e_1}, p_T^{e_2} > 8, 12, 12\,\mathrm{GeV}$	
Muon + double electron	$p_T^{\mu}, p_T^{e_1}, p_T^{e_2} > 8, 12, 12\,\mathrm{GeV}$	
Single tight ID electron	$p_T^{e} > 35\,\mathrm{GeV}$	SingleElectron
Single tight ID electron	$p_T^{e} > 38\,\mathrm{GeV}$	
Single tight ID electron	$p_T^{e} > 40\,\mathrm{GeV}$	
Single isolated muon	$p_T^{\mu} > 27\,\mathrm{GeV}$	SingleMuon

2018

Trigger description	Requirements	Primary Dataset
Double isolated electron	$p_T^{e_1}, p_T^{e_2} > 23, 12\,\mathrm{GeV}$	EGamma
Double electron	$p_T^{e_1}, p_T^{e_2} > 25, 25\,\mathrm{GeV}$	
Single isolated electron	$p_T^{e} > 32\,\mathrm{GeV}$	
Double isolated muon	$p_T^{\mu_1}, p_T^{\mu_2} > 17, 8\,\mathrm{GeV},\ m_{\mu\mu} > 3.8\,\mathrm{GeV}$	DoubleMuon
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 23, 12\,\mathrm{GeV}$	MuonEG
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 8, 23\,\mathrm{GeV}$	
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 12, 23\,\mathrm{GeV}$	
Iso muon + iso electron	$p_T^{\mu}, p_T^{e} > 23, 12\,\mathrm{GeV}$	
Double muon + electron	$p_T^{\mu_1}, p_T^{\mu_2}, p_T^{e} > 9, 9, 9\,\mathrm{GeV}$	
Single isolated muon	$p_T^{\mu} > 24\,\mathrm{GeV}$	SingleMuon

MC simulations

Process	Generator	σ [pb]
Signal samples		
$ZZ\gamma \to 4\ell\,\gamma$	MadGraph (NLO)	0.02202
$WZ\gamma \to 3\ell\,\nu\,\gamma$	MadGraph (NLO)	0.03844
$ZZ\gamma \to 2\ell\,2j\,\gamma$	MadGraph (NLO)	0.04978
$WZ\gamma \to 2\ell\,2j\,\gamma$	MadGraph (NLO)	0.08044
Main background samples		
$ZZ \to 4\ell$ + 0,1 jets	MadGraph (NLO)	1.256
$gg \to ZZ \to 4\mu$	MCFM (LO)	0.001586
$gg \to ZZ \to 4e$	MCFM (LO)	0.001586
$gg \to ZZ \to 2e\,2\mu$	MCFM (LO)	0.003191
Z + 0,1,2 jets	MadGraph (NLO)	6225.2
$Z\gamma$ + 0,1 jets	MadGraph (NLO)	55.48
$WZ \to 3\ell\,\nu$	MadGraph (NLO)	5.213
$t\bar{t} \to 2\ell\,\nu$ + jets	Powheg	87.3
Rare background samples		
$t\bar{t}Z$ + 0,1 jets	MadGraph (NLO)	0.5407
$t\bar{t}W$ + 0,1 jets	MadGraph (NLO)	0.2161
$t\bar{t}ZZ$	MadGraph (LO)	0.001572
$t\bar{t}WW$	MadGraph (LO)	0.007883
ZZZ	MadGraph (NLO)	0.01398
WZZ	MadGraph (NLO)	0.05565
WWZ	MadGraph (NLO)	0.1651
WWW	MadGraph (NLO)	0.08058

Statistical model

- Perform maximize likelihood fit to assess presence of signal and significance
  - **μ**: "**signal strength**", multiplicative factor for the **signal** cross section; **unconstrained**
  - **ϑ$_i$**: i-th "**nuisance** parameter", models a **systematic** uncertainty; constrained by a **prior**

$$\mathcal{L}(data\,|\,\mu,\vec{\theta}) = \prod_c \mathcal{L}_c(data\,|\,\mu\cdot s(\vec{\theta}) + b(\vec{\theta}))\cdot\prod_i p_i(\tilde{\theta}_i\,|\,\theta_i)$$

Poisson distribution for yield

- Systematic uncertainty can affect only **yield** or also **alter** the shape of signal/bkg process

$$p(\tilde{\theta}\,|\,\theta) = \frac{1}{\sqrt{2\pi}\ln k}\cdot\frac{1}{\tilde{\theta}}\cdot\exp\left(-\frac{(\ln(\tilde{\theta}/\theta_m))^2}{2\ln^2 k}\right)$$

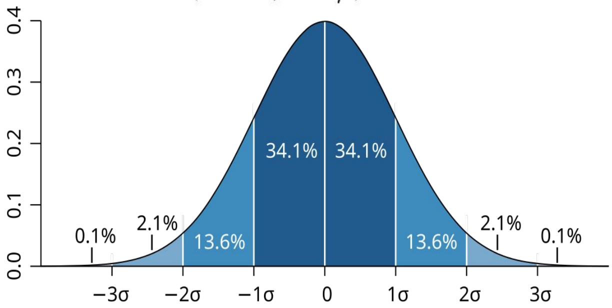
- Excess quantified with **test-statistic** on **log-likelihood**

$$t_0 = -2\ln\frac{\mathcal{L}(data\,|\,0,\hat{\vec{\theta}}_0)}{\mathcal{L}(data\,|\,\hat{\mu},\hat{\vec{\theta}}_{\hat{\mu}})},\quad \text{with } \hat{\mu}\geq 0$$

$$p_0 = p(t_0 \geq t_0^{obs}\,|\,\mu = 0)$$

expressed in terms of **Z**

$$p_0 = \int_Z^\infty \frac{1}{\sqrt{2\pi}}e^{-x^2/2}dx$$



- **Z-significance**: **3σ** (evidence); **5σ** discovery

EFT interpretation dimension-6

- **Triboson** measurements can be used to set limits on **EFT operators**
  - **dimension 6 operators**: triple/quartic gauge **O$_W$** and Higgs-gauge **HVV** coupling **O$_{HX}$**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_k c_k^6 O_k^6 + o\left(\frac{1}{\Lambda^3}\right)$$

$$\sigma_{SMEFT} \propto |A_{SM}|^2 + 2c_W Re(A_{SM}A^*_{OW}) + c_W^2|A_{OW}|^2$$

Introducing **O$_W$**-amplitude and **squaring** it

- **Warsaw basis**

$$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_p) \qquad Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$$

$$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_p) \qquad Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$$

$$Q_{qq}^{(1)} = (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r) \qquad Q_{qq}^{(1,1)} = (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$$

$$Q_{qq}^{(3)} = (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r) \qquad Q_{qq}^{(3,1)} = (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$$

$$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H) \qquad Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

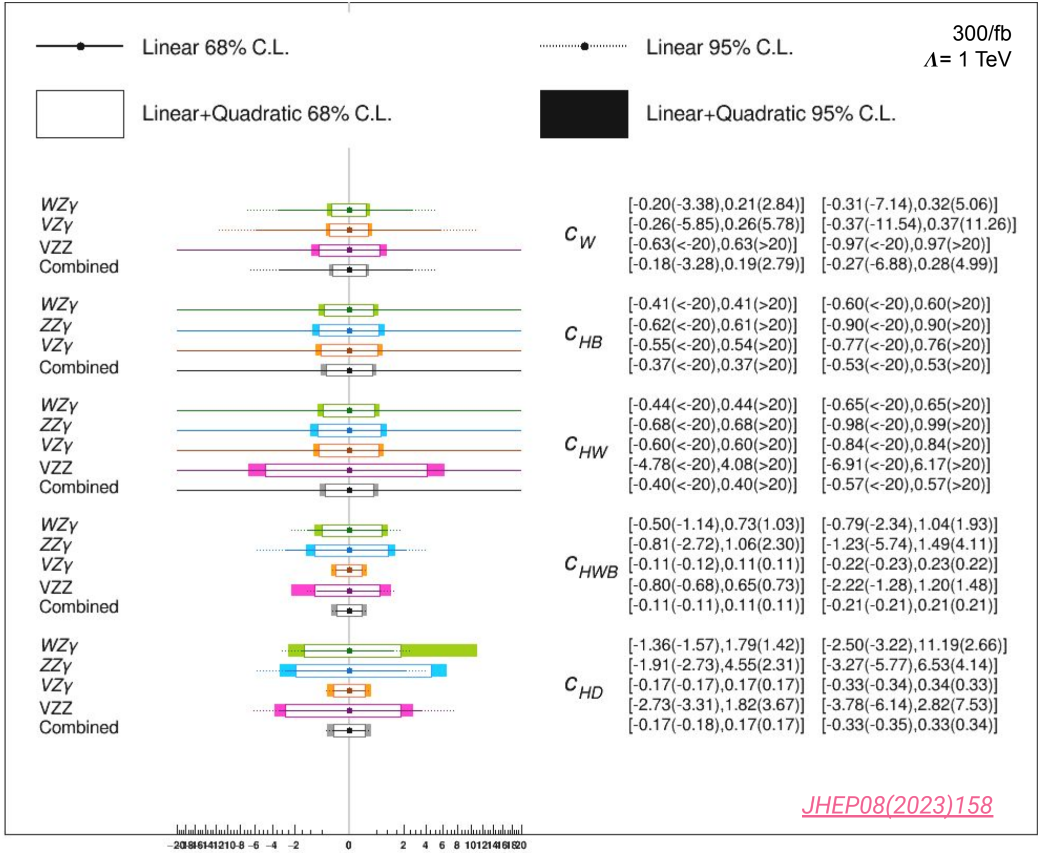
$$Q_{HWB} = (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu} \qquad Q_{HW} = (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}$$

$$Q_W = \varepsilon^{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho \qquad Q_{ll}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

- **VZγ sensitivity** to **bosonic operators**

Operators → / ↳ Processes	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}	$Q_{H\Box}$
WZγ	✓	✓	✓	✓	✓	
ZZγ		✓	✓	✓	✓	
VZγ	✓	✓	✓	✓	✓	
QCD-Zγjj				✓	✓	
VZZ	✓	(✓)	✓	✓	✓	(✓)
QCD-ZZjj				✓	✓	

Dimension-six EFT study



Interpretation of triboson results *traditionally* in terms of **dim-8 SMEFT** operators (aQGCs)

- **Dim-6 EFT operators have an impact too**!! [10.1007/JHEP08(2023)158.]
- proof of **quadratic** terms importance!
- very **competitive** constraints!
- identification of the **most sensitive variables**
- fundamental role of **combination** of the analyses

Next step:

- CMS Detector-level analysis
- dim. 6 vs dim. 8 operators effects
- Coordination role in the combination of several EFT analyses