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VBS $ZZ \rightarrow 2\ell 2\nu$ in RUN 2 with CMS detector

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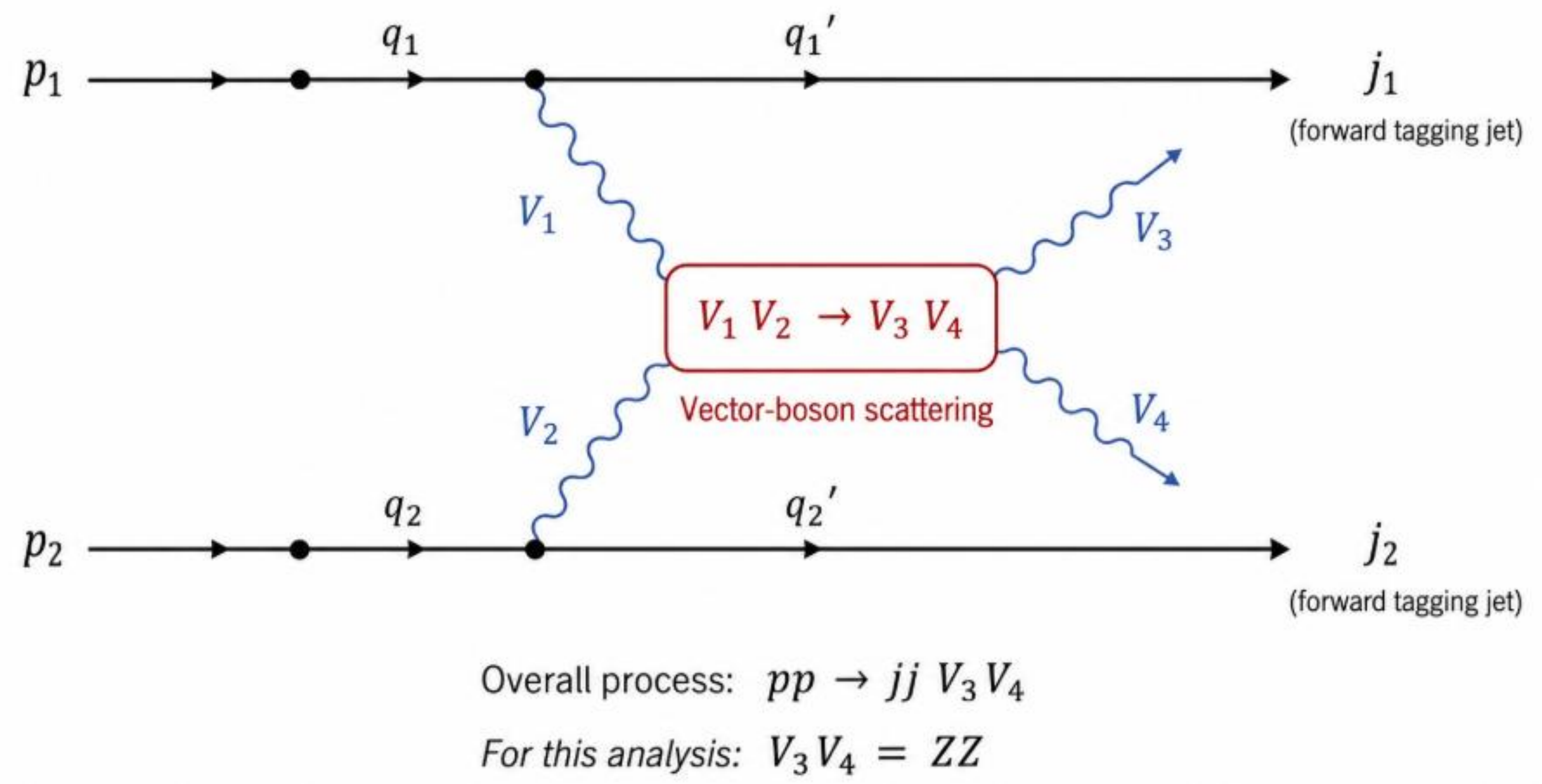
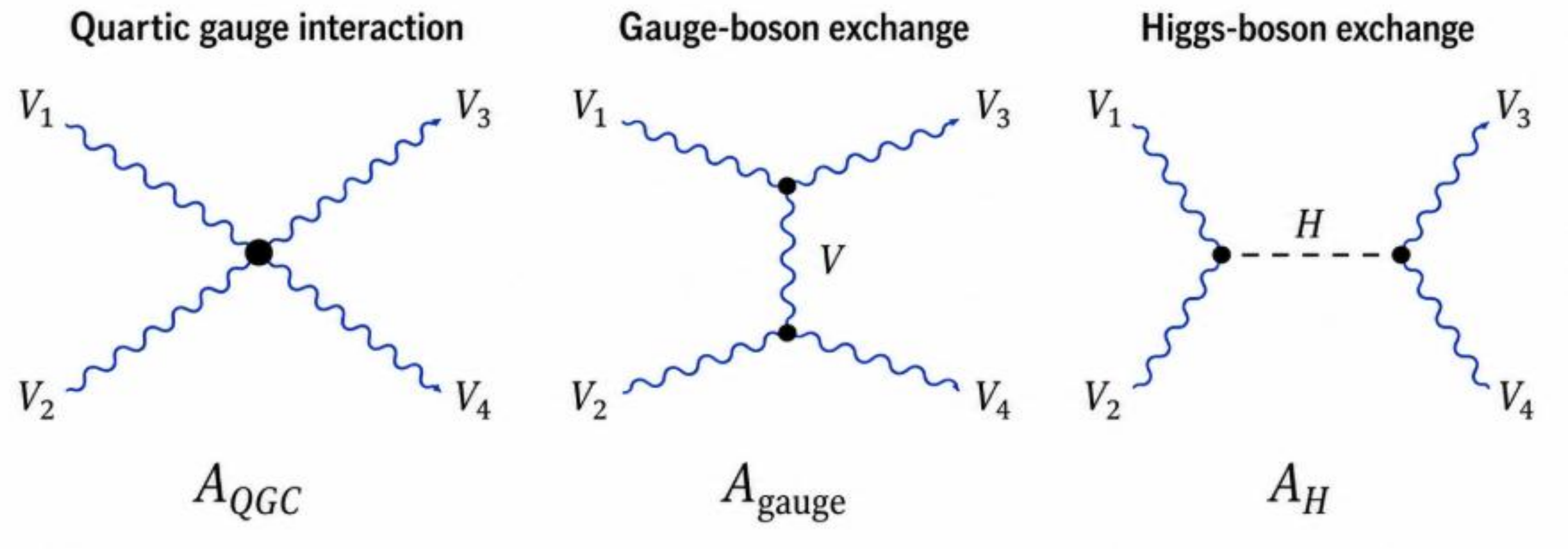
WHY VBS?

Vector boson scattering (VBS) :





$$\mathcal{A}_{\text{SM}} = \mathcal{A}_{\text{QGC}} + \mathcal{A}_{\text{gauge}} + \mathcal{A}_H$$

- **Probe electroweak symmetry breaking:**
  - For longitudinal VBS at high energy:

$$\left.\begin{aligned} \mathcal{A}_{\text{QGC}} + \mathcal{A}_{\text{gauge}} &\sim \frac{E^2}{v^2} \\ \mathcal{A}_H &\sim -\frac{E^2}{v^2}, \end{aligned}\right\} \Rightarrow \mathcal{A}_{\text{SM}} \sim \mathcal{O}(E^0)$$

    - The cancellation relying on the SM Higgs–gauge structure established by EWSB prevents the total SM amplitude from growing with energy.
    - Longitudinal VBS provides a direct test of the Higgs mechanism and the EWSB sector.

- **Probe anomalous quartic gauge couplings:**
  - VBS is directly sensitive to quartic gauge interactions. Possible new contributions can be parameterized using dimension-8 SMEFT operators:

$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^4} \mathcal{A}_i^{(8)} \quad \delta\mathcal{A}_i^{(8)} = \frac{f_i}{\Lambda^4} \mathcal{A}_i^{(8)} \sim f_i \left(\frac{E}{\Lambda}\right)^4$$

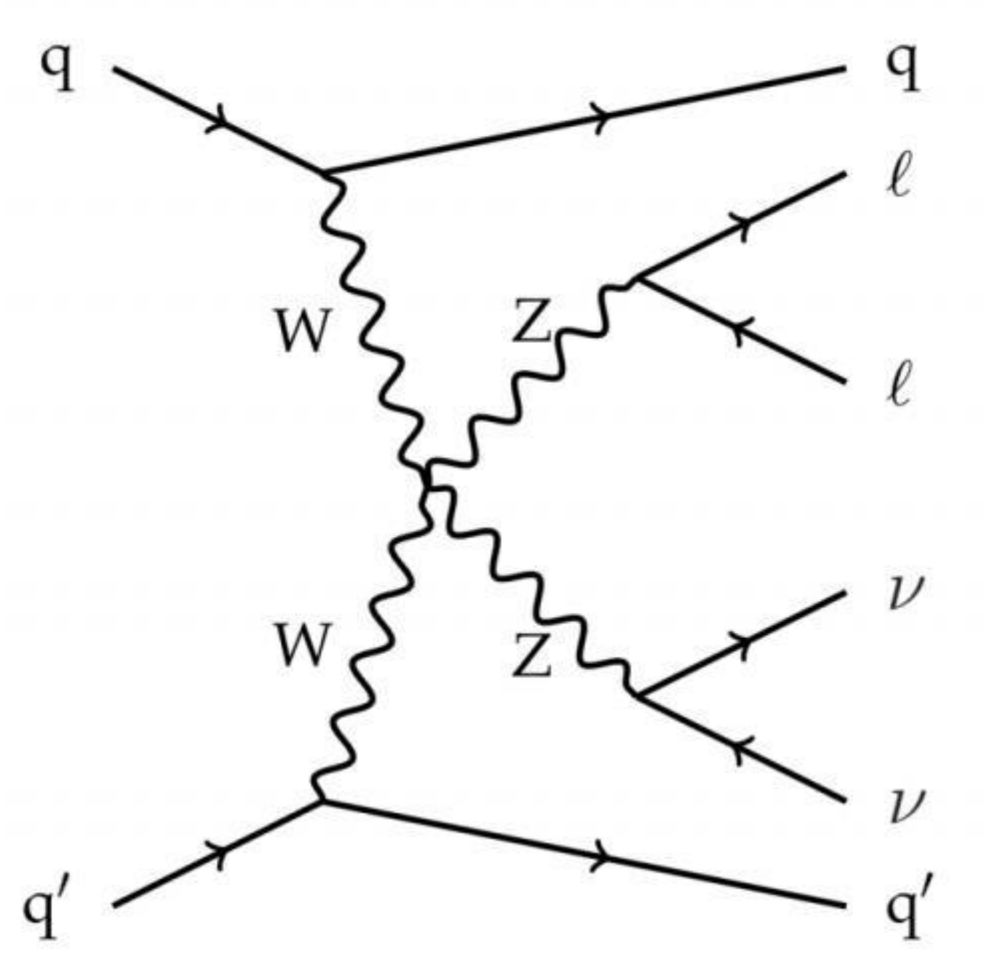
    - High-energy VBS provides enhanced sensitivity to aQGCs and BSM physics.

WHY $ZZ \to 2\ell 2\nu$?

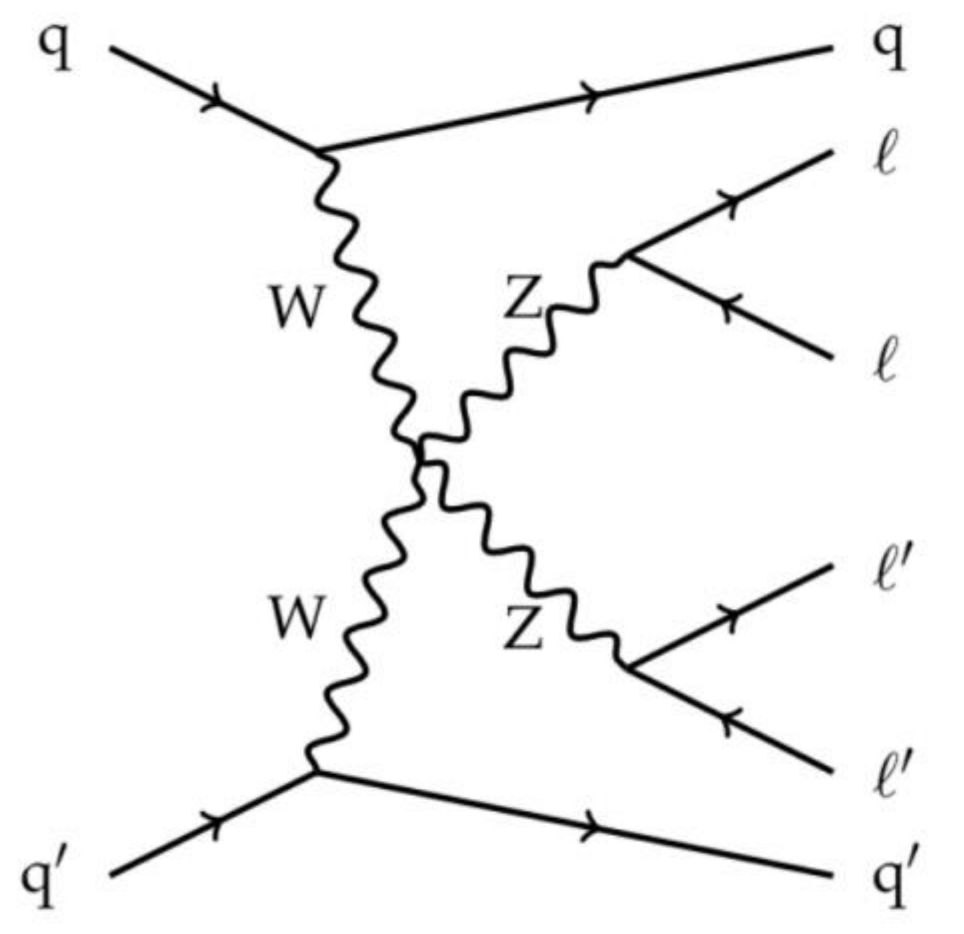
- Among all electroweak diboson VBS processes, VBS ZZ is one of the rarest process, with O(0.1 fb) fiducial cross section

Comparison of ZZ Final States: 4ℓ vs 2ℓ2ν

Channel	Advantages	Challenges	Previous Results
4ℓ	Extremely clean; fully reconstructable final state	Very limited statistics	CMS: 4.0**σ** (Phys. Lett. B 812 (2021)) ATLAS: 5.5**σ** (Nature Physics (2023))
2ℓ2**ν**	Higher branching fraction (~6×) compared to 4ℓ channel.	Neutrinos in final state (large MET); more complex backgrounds	ATLAS: 1.3**σ** (Nature Physics (2023))



$ZZ \to 2\ell 2\nu$



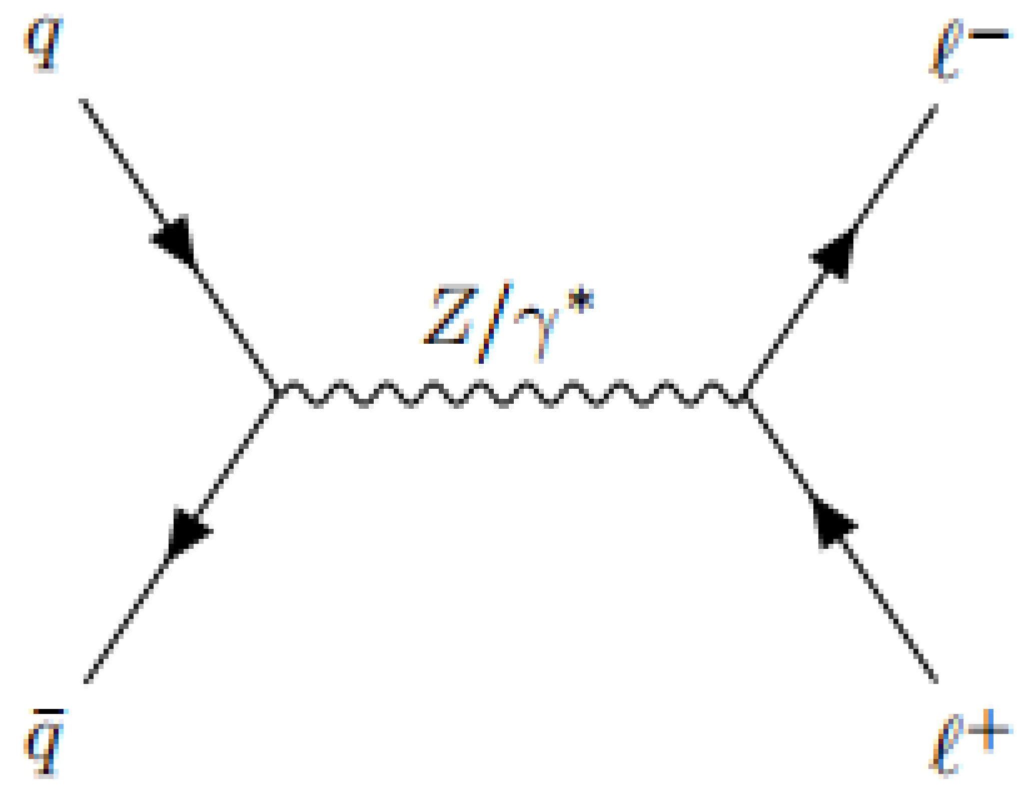
$ZZ \to 4\ell$

EWK ZZ ANALYSIS: IN SHORT

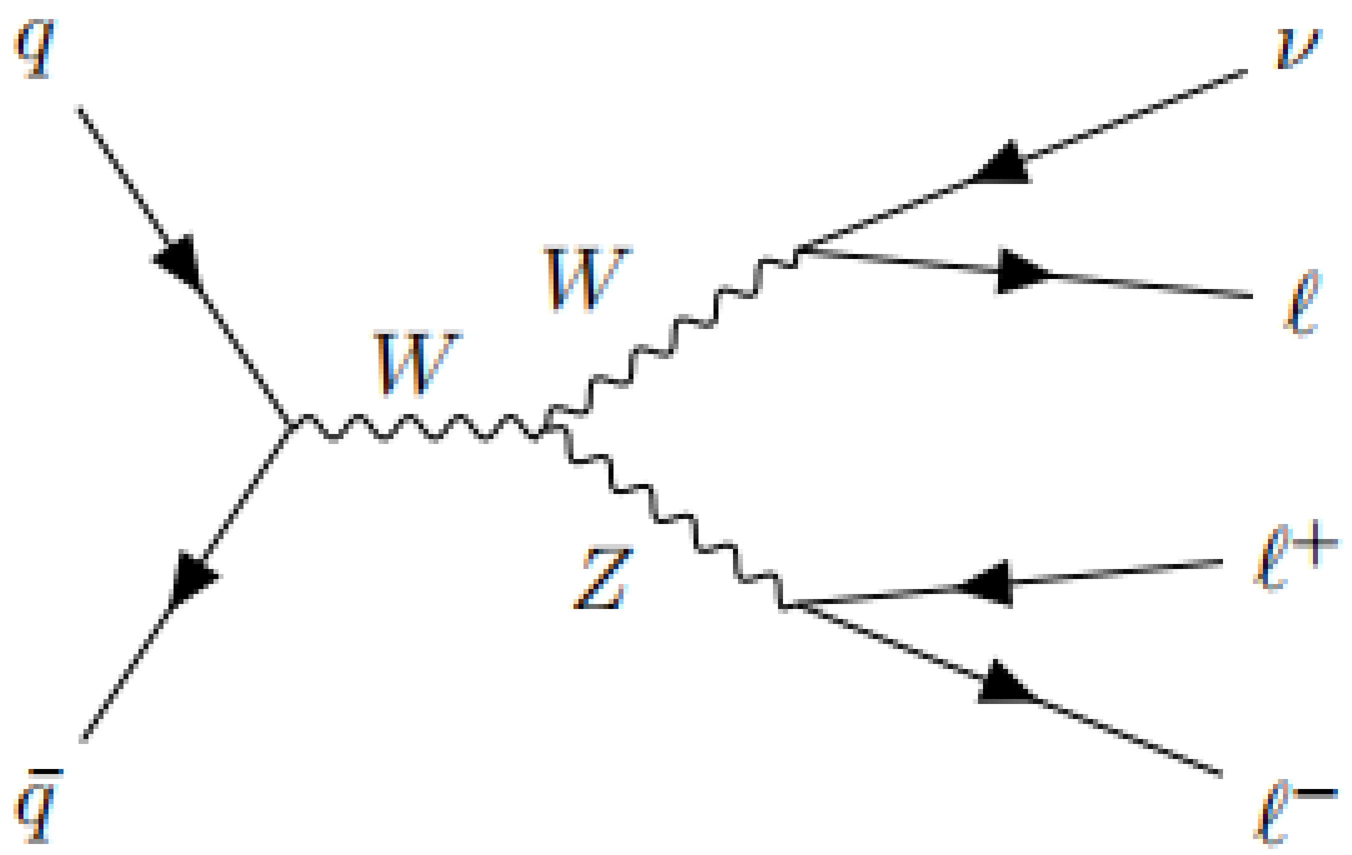
- **Working on full CMS run-2(2016-2018) data with 138 fb^{-1}**
- **Signal signature:**
  - 2 OSSF leptons consistent with a Z boson + large MET + 2 jets with a large $\Delta\eta jj$
  - Z boson recoil against MET, limited hadronic activity, no b-jets
- **Discriminant variable:**
  - Graph Neural Network (GNN) as the main discriminant for EWK ZZjj production
- **Statistical analysis:**
  - A simultaneous binned maximum-likelihood fit is performed using the CMS Combine framework, including both the signal and control regions.
- **Measurements:**
  - VBS ZZ signal strength/significance, fiducial volume cross-section and limits on dimension-eight EFT operators

DOMINANT BACKGROUNDS

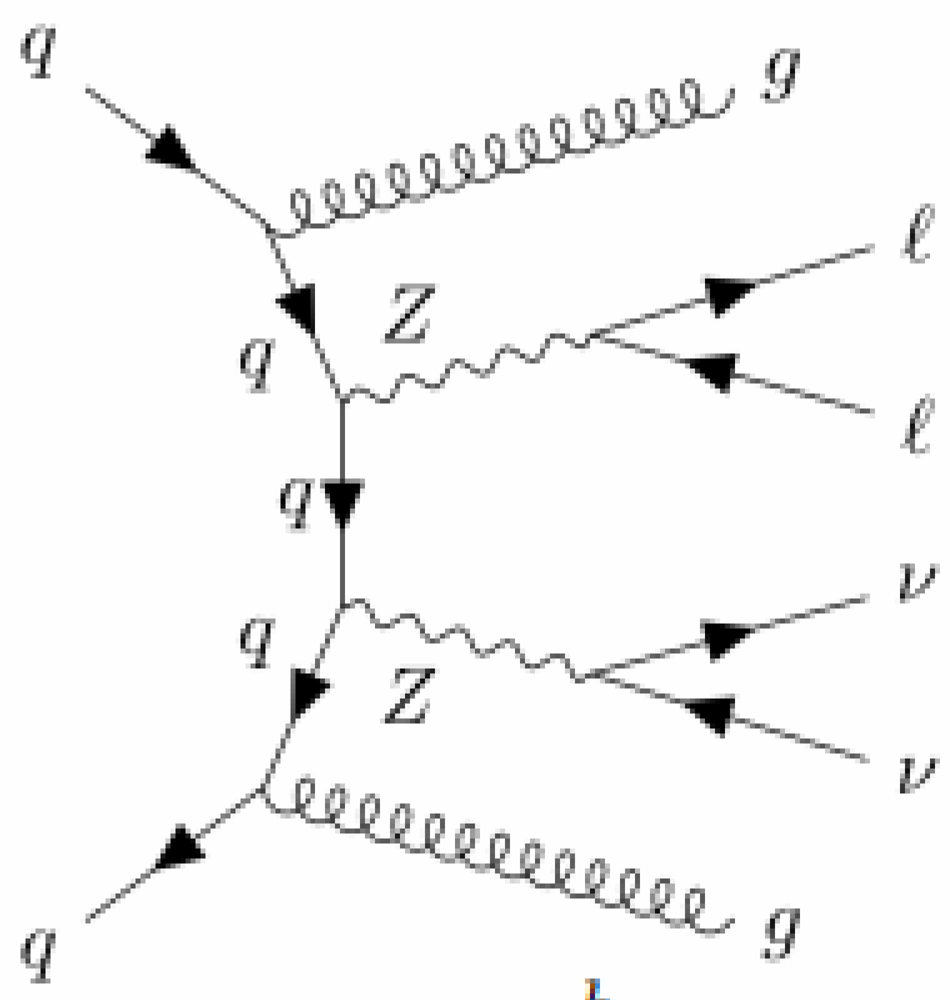
1. Z+jets (Drell-Yan)



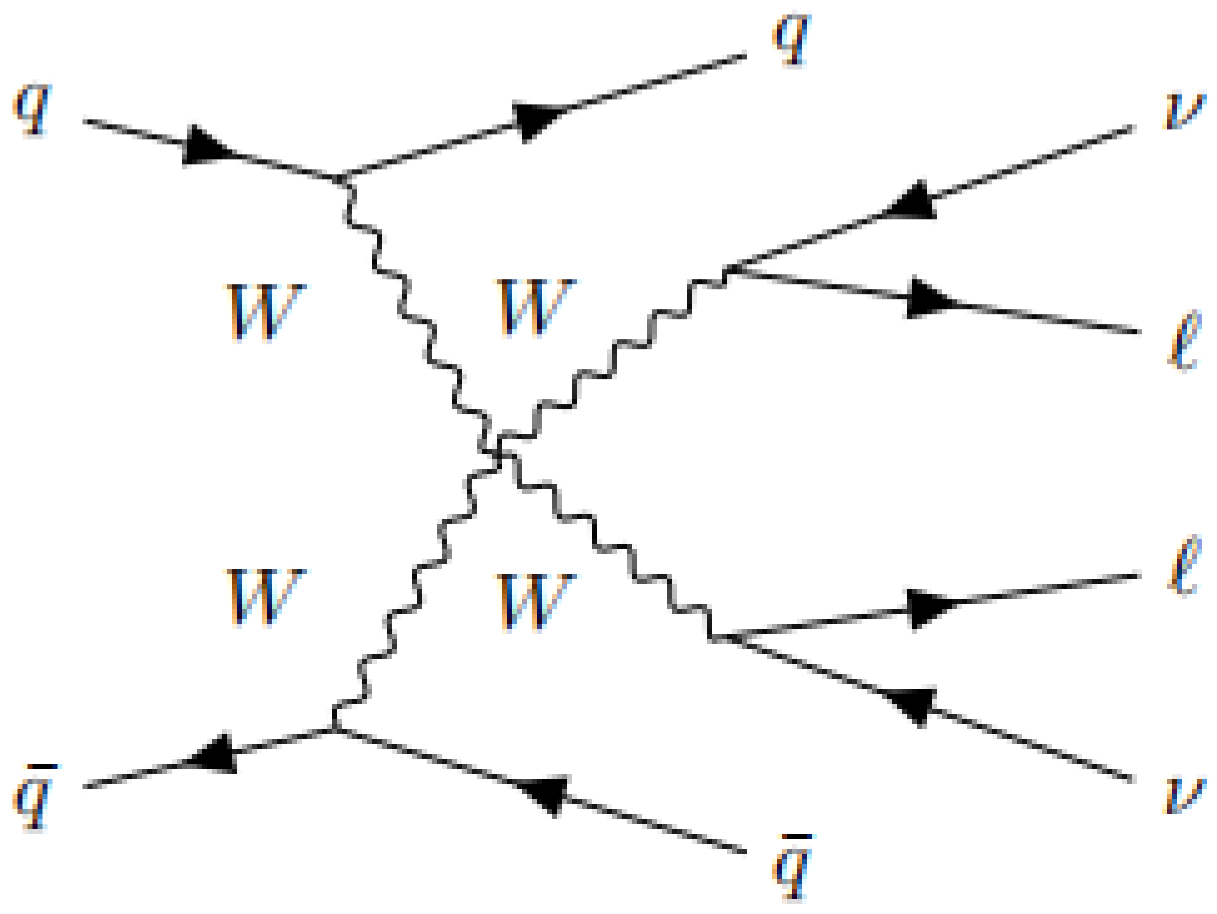
2. WZ



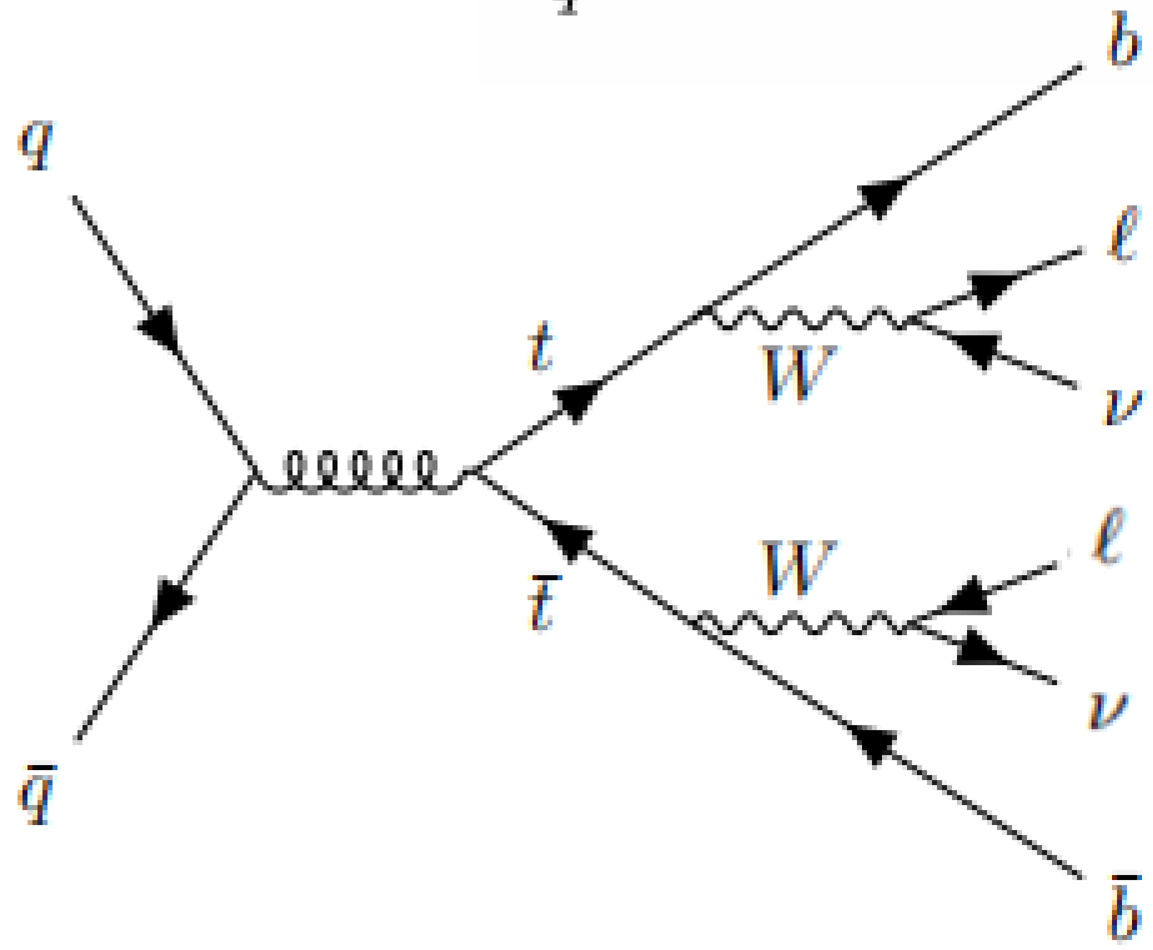
3. ZZ (QCD)



4. WW

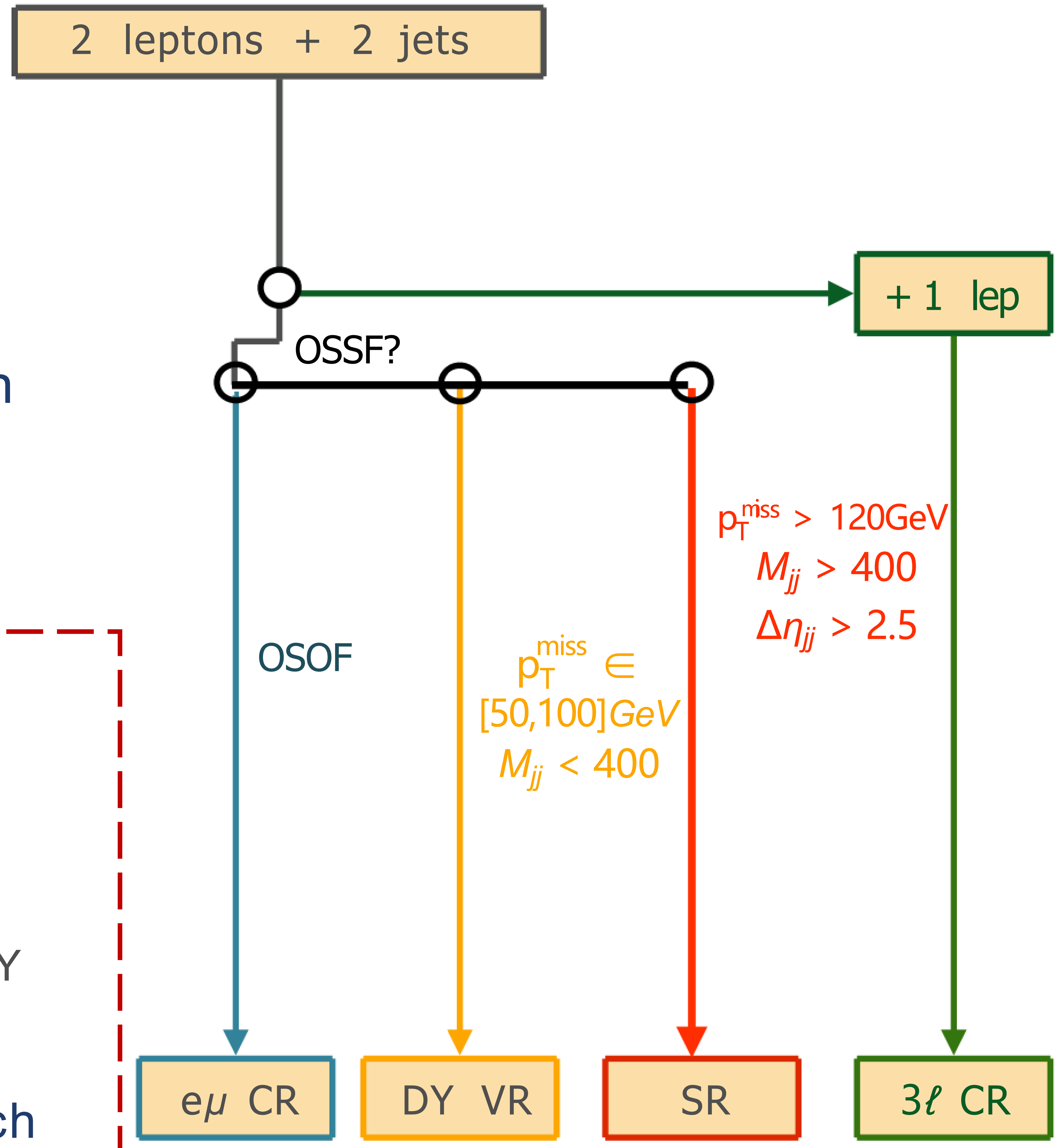


5. $t\bar{t}$ (Top)



SIGNAL & CONTROL REGIONS

- Irreducible background: ggZZ, qqZZ
- Reducible background: DY, WZ, $t\bar{t}$ and WW
- Two main control regions designed to simulate the signal region:
  - **WZ: 3 lepton region** (one additional lepton)
  - **Non-resonant bkgs (WW、top):** $e\mu$ **region** (OSOF)
- DY events contain no genuine large p_T^{miss},but their very large production cross section makes the small instrumental high- p_T^{miss} tail from detector mismeasurement a non-negligible background in the SR.



- Data-driven estimate of the DY fake- p_T^{miss} tail
  - A high-statistics γ+jets data sample with hadronic recoil and jet activity similar to Z+jets events, is used to model the response.
  - low-p_T^{miss} γ+jets: reweighting factors are derived to match the Z+jets kinematics.
  - *high*-p_T^{miss} γ+jets: the weights are applied to obtain a data-driven estimate of the DY fake- p_T^{miss} tail
  - The data-driven estimate is then used to correct the DY simulation, which retains the complete event kinematics needed to construct the final analysis templates.

SYSTEMATIC UNCERTAINTIES

Category	Source	Description	
Experimental	Luminosity	Per-year normalization	
	Trigger & lepton efficiencies	Selection efficiency	
	Lepton energy scale	Momentum calibration	
	Jet energy scale & resolution (JES/JER)	Affects jets and propagated to MET	★★
	Unclustered MET	Soft activity contribution	
	b-tagging SF	Efficiency and mistag rate	
	Pileup reweighting	PU modeling	★
	L1 pre-firing	L1 Trigger-related	
Theory	QCD scale variations (μ_f, μ_r)	Signal & background normalization/shape	★★★
	PDF + α_s	choice of PDF and strong coupling constant	
	VV QCD–EW corrections	NNLO / NLO-EW effects	
	Parton shower (Pythia8)	Modeling uncertainty	
	EW–QCD interference	~8% assigned to signal	
DY Data-driven	Genuine MET subtraction	From γ+jets control region	
	Zγ contribution	~20–55% of yields ±(2.1%–2.8%)	
	Wγ contribution	~15–20% of yields ±(19.0%–21.4%)	

SIMULTANEOUS FIT

- We perform a binned maximum likelihood estimation using CMS Combine framework

$$\mathcal{L}(\mu,\boldsymbol{\theta}) = \prod_i \mathrm{Pois}\left[n_i^{\mathrm{data}} \mid \mu S_i(\boldsymbol{\theta}) + \sum_b B_{i,b}(\boldsymbol{\theta})\right] \mathcal{L}_{\mathrm{syst}}(\boldsymbol{\theta}) \qquad \mathcal{L}_{\mathrm{total}} = \mathcal{L}_{\mathrm{SR}} \times \mathcal{L}_{3\ell\,\mathrm{CR}} \times \mathcal{L}_{e\mu\,\mathrm{CR}} \times \mathcal{L}_{\mathrm{syst}}$$

- The five-bin flattened GNN output is used as the final discriminating variable in the 2ℓ2v signal region.
- The fit is performed for the 2ℓ2v channel alone and in combination with the 4ℓ channel.

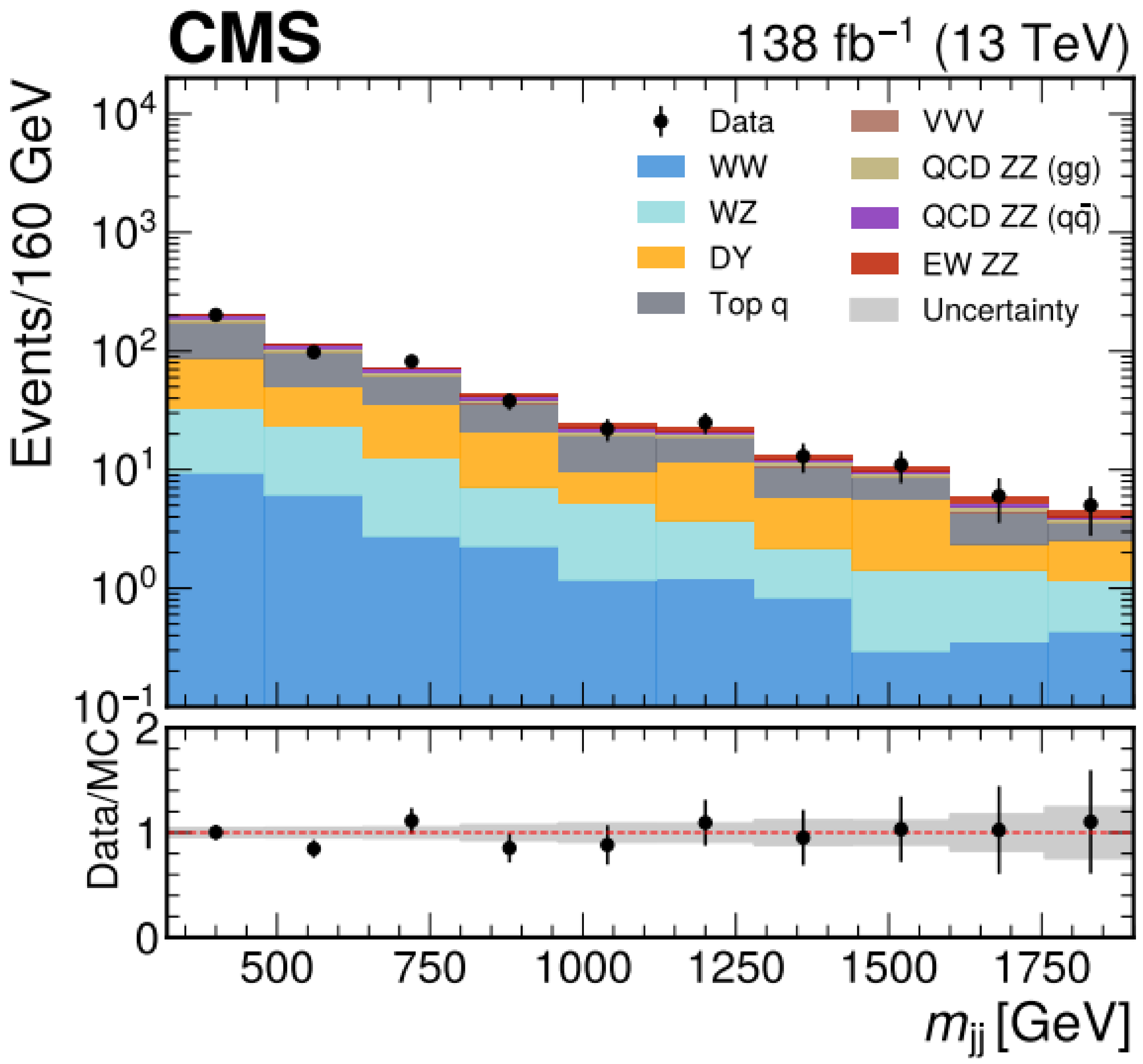
	μ		significance	
	Expected	**Observed**	**Expected**	**Observed**
$\ell\ell\ell\ell$	$1.0^{+0.45}_{-0.37}$	$1.21^{+0.50}_{-0.41}$	3.5σ	4.0σ
$\ell\ell\nu\nu$	$1.0^{+0.50}_{-0.42}$	$0.93^{+0.43}_{-0.35}$	$2.8\,\sigma$	3.1σ
$\ell\ell\ell\ell + \ell\ell\nu\nu$	$1.0^{+0.32}_{-0.28}$	$1.06^{+0.31}_{-0.28}$	4.5σ	5.0σ

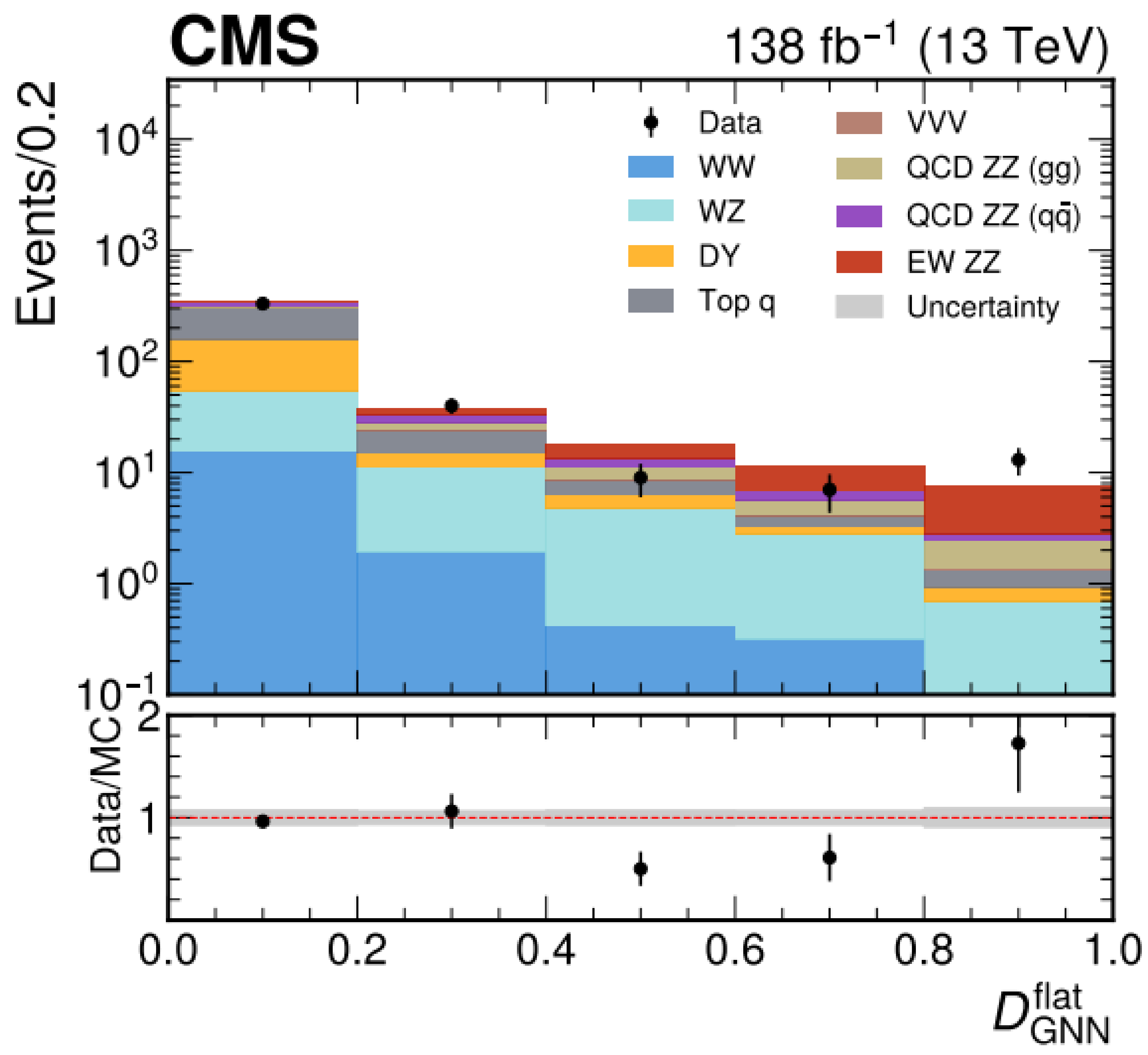
Table 26: Results for **combine 4l + 2l2**ν.

- **Evidence** is obtained for EW ZZjj production in the 2ℓ2v channel, while the combination with the 4ℓ channel reaches the **observation** level.

POST FIT PLOTS

- Postfit distributions of the dijet_mass and GNN flattened (years combined)





FIDUCIAL CROSS – SECTION

- The Fiducial Volume Cross-section is extracted using a modified version of the simultaneous fit:
  - Only signal events inside the fiducial volume are treated as the signal to be measured.
  - Signal events outside the fiducial volume are included separately as a background-like contribution.

Fiducial Volume Definition

Object	Selection
Leptons	$p_T(\ell_1) > 25$ GeV
	$p_T(\ell_2) > 20$ GeV
	$\lvert\eta(\ell)\rvert < 2.5$
	γ with $\Delta R(\ell,\gamma) < 0.1$ added to ℓ 4-vector
Z boson	$\lvert m(\ell\ell) - 91.1873\rvert < 15$ GeV
	$p_T(\ell\ell) > 60$ GeV
GenJet	at least 2 jets
	$p_T(j) > 30$ GeV
	$\lvert\eta(j)\rvert < 4.7$
	$m_{jj} > 400$ GeV
	$\Delta\eta(j_1, j_2) > 2.5$
	$\Delta R(\ell, j) > 0.4$ for each ℓ, j
GenMET	$E_T^{\text{miss}} > 120$ GeV

Predicted fiducial cross-section

$$\sigma_{\text{fid}}^{EWK} = 0.39^{+0.05}_{-0.06}\,(\text{syst})\text{fb}$$

$$\sigma_{\text{fid}}^{EWK+QCD} = 0.85^{+0.12}_{-0.10}\,(\text{syst})\text{fb}$$

Measured fiducial cross-section

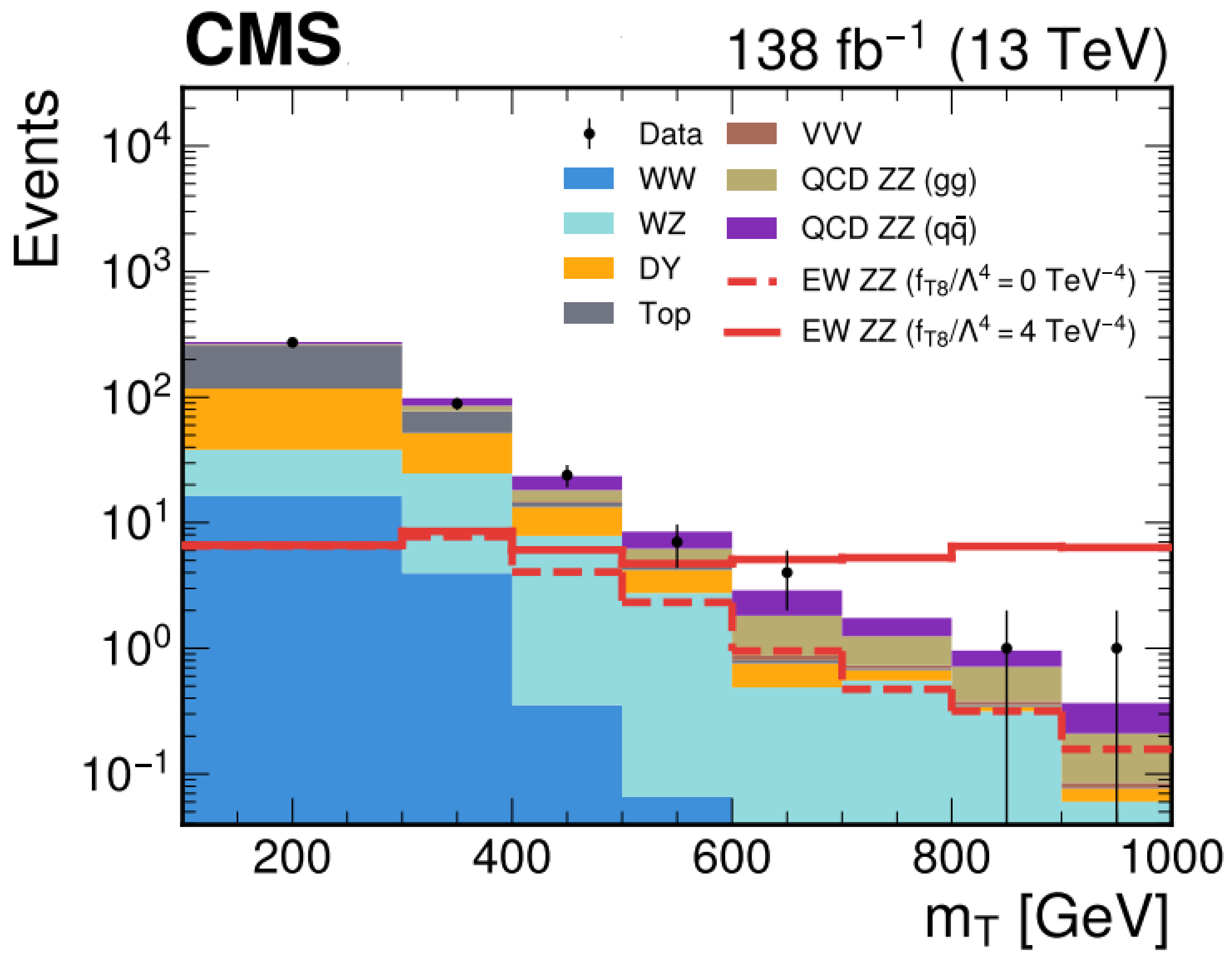
$$\sigma_{\text{fid}}^{EWK} = 0.37^{+0.14}_{-0.12}\,(\text{stat})^{+0.06}_{-0.06}\,(\text{syst})\text{fb}$$

$$\sigma_{\text{fid}}^{EWK+QCD} = 0.70^{+0.16}_{-0.15}\,(\text{stat})^{+0.12}_{-0.10}\,(\text{syst})\text{fb}$$

EFT ANALYSIS

- Dimension-8 operators are grouped into:
  - **S (longitudinal):** sensitive to Higgs/EWSB sector
  - **T (transverse):** pure gauge interactions
  - **M (mixed):** interference between gauge and Higgs sectors
- These operators lead to amplitudes growing with energy
  - Enhanced high m_T tail

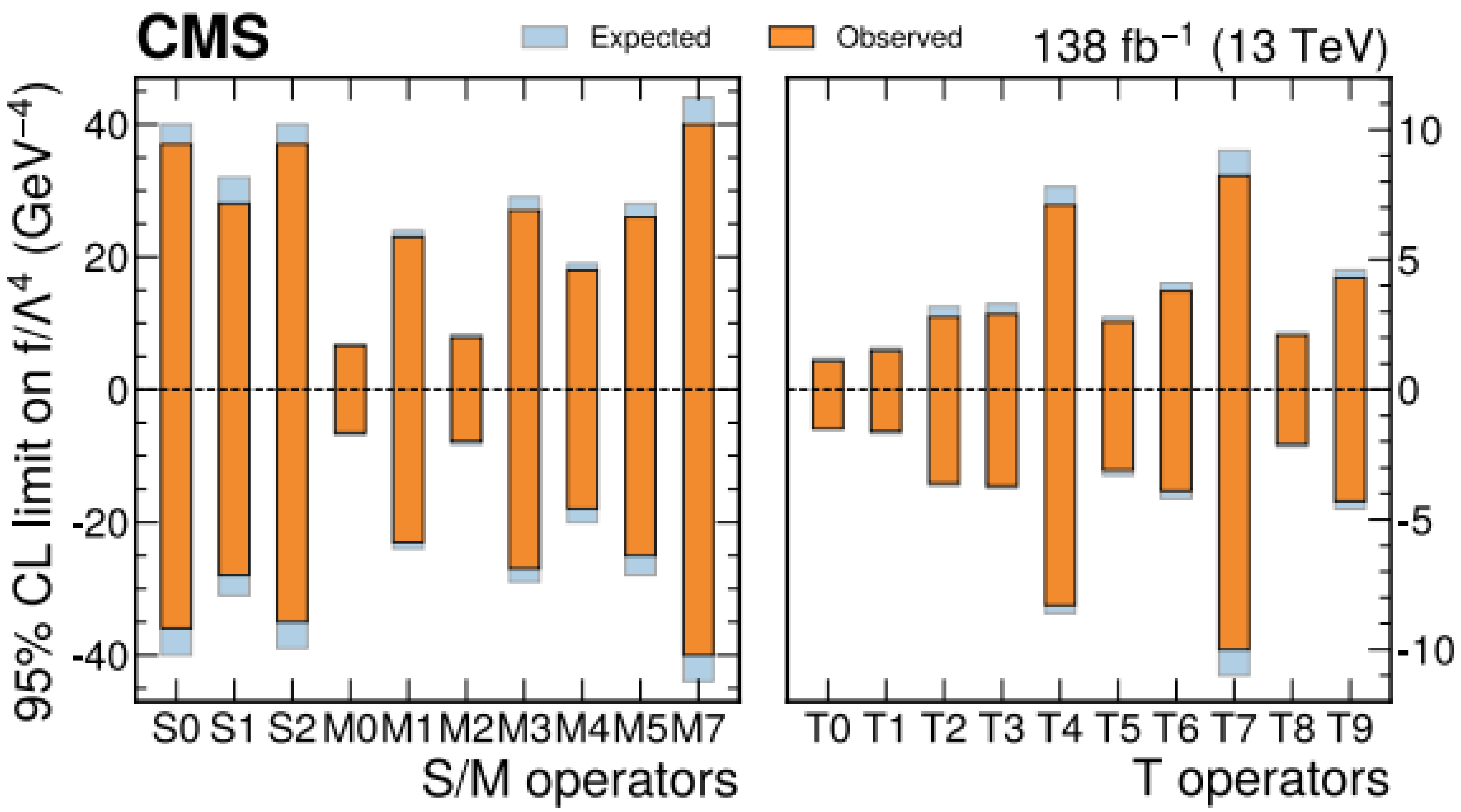
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{Z} p_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos \Delta\phi(\vec{p}_{\mathrm{T}}^{Z}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]}$$



S0	$[(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$	T0	$Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}]$
S1	$[(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$	T1	$Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$
S2	$[(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$	T2	$Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\beta\nu}\hat{W}^{\mu\alpha}]$
M0	$Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$	T5	$Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta}$
M1	$Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\nu\Phi]$	T6	$Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \hat{B}_{\mu\beta}\hat{B}^{\alpha\nu}$
M2	$[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$	T7	$Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times \hat{B}_{\beta\nu}\hat{B}^{\mu\alpha}$
M3	$[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$	T8	$\boxed{\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta}}$
M4	$[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi] \times \hat{B}^{\beta\nu}$	T9	$\boxed{\hat{B}_{\alpha\mu}\hat{B}^{\mu\beta}\hat{B}_{\beta\nu}\hat{B}^{\mu\alpha}}$
M5	$[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi] \times \hat{B}^{\beta\mu}$	M7	$[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi]$

longitudinal (S), transverse (T), and mixed (M) operators

- Observed limits are close to the expected limits



SUMMARY AND OUTLOOK

- The **first search** for VBS ZZ ($2\ell\, 2\nu$) production in CMS using the full Run 2 data
- CMS Evidence in $2\ell\, 2\nu$(Stat. limited) at level of 3.1σ (2.8σ exp)
  - ATLAS $1.3\ \sigma$ (2.1σ exp)
- Combined with ZZ 4ℓ we claim **observation** of the last electroweak production of vector diboson processes in CMS
- Fiducial cross-section measurements
- We place limits on several EFT operators sensitive to (anomalous) Quartic Gauge Couplings
- A team from the University of Wisconsin has already begun a Run3 study of VBS ZZ $2\ell\, 2\nu$

THANK YOU !