# Electroweak Multiboson Production in CMS

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**On behalf of the CMS collaboration**

**Multi-boson Interactions Workshop 2023**

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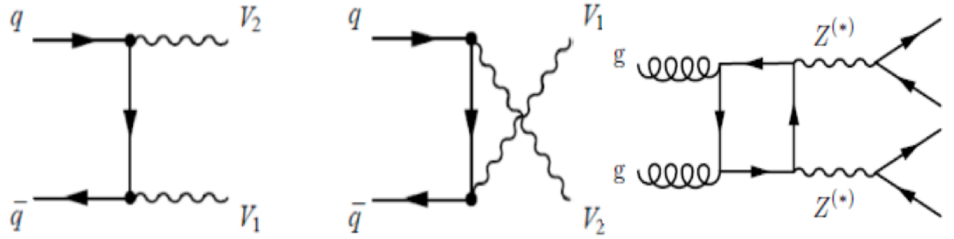
UC San Diego

# Multi-boson Measurements

**Test the SM at TeV scale:**

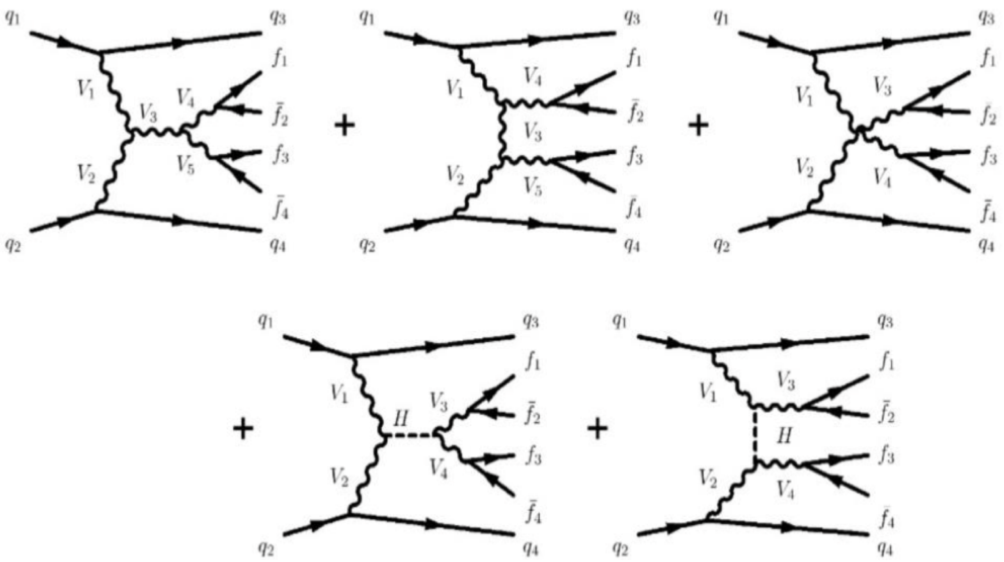
**Differential cross-section**:

- measurement in validation of current models




**Vector boson scattering/fusion (VBS/F):**

- processes **probe the mechanism of electroweak symmetry breaking**

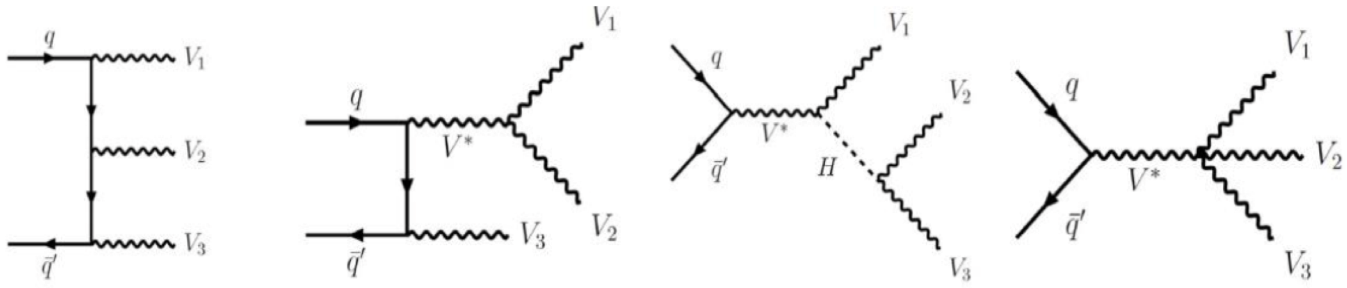



**Triple/Quatric Gauge Couplings (T/QGC):**

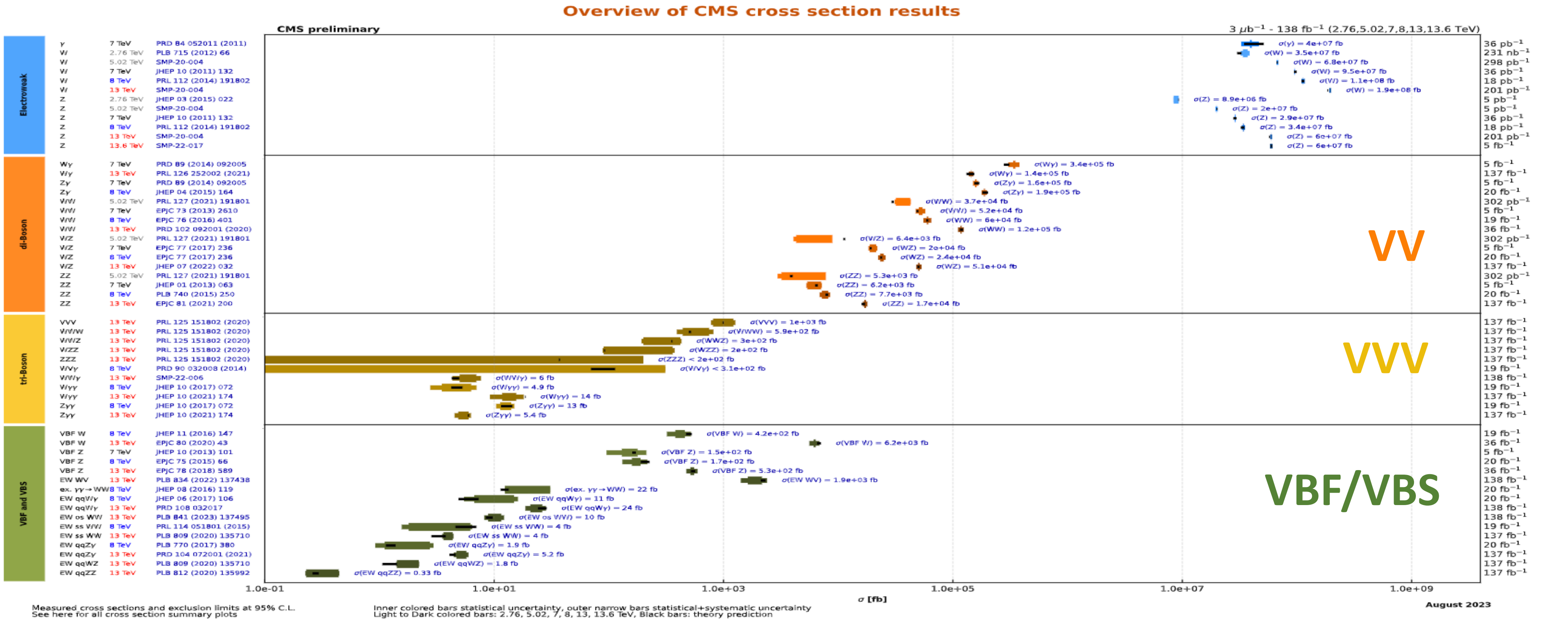
- search for anomalous couplings
- sensitive to new physics

EFT interpretation:

$$\mathcal{L}_{\text{SMEFT}} \approx \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} O_j^{(8)}$$



# EWK results from CMS




Run3 of the LHC is ongoing. We expect to have doubled Run2 lumi by mid-2024
I will focus today on **new EWK CMS results with full Run2 dataset**

[CMS Public Results]()

# Diboson Production

## Precision Measurements

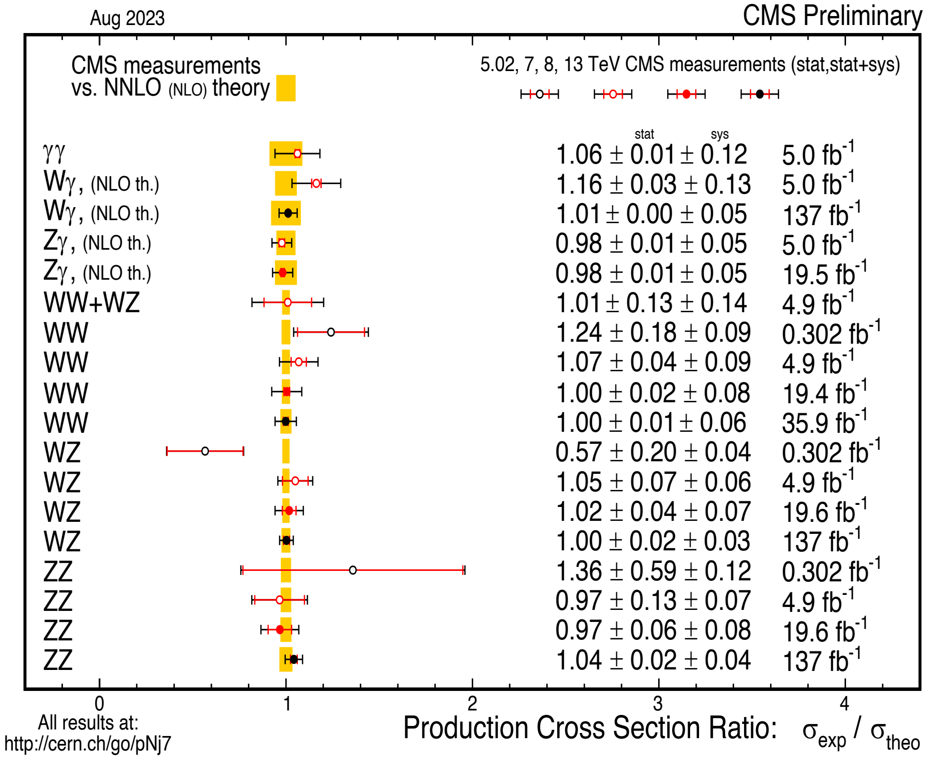
- Cross-section measure in fiducial volumes and extrapolated to total phase space
- Differential measurements performed to provide kinematic distributions of data subtracted from backgrounds and corrected form detector effect

## EFT interpretation

- Anomalous triple/ quartic gauge couplings (aTGCs and aQGCs)
- Limits provided as functions of operators

**Analyses presented today:**

- ZZ(4ℓ +jets)
- ssWW to τh (VBS)
- Wγ+2jets (VBS)
- osWW (VBS)
- Polarized WW

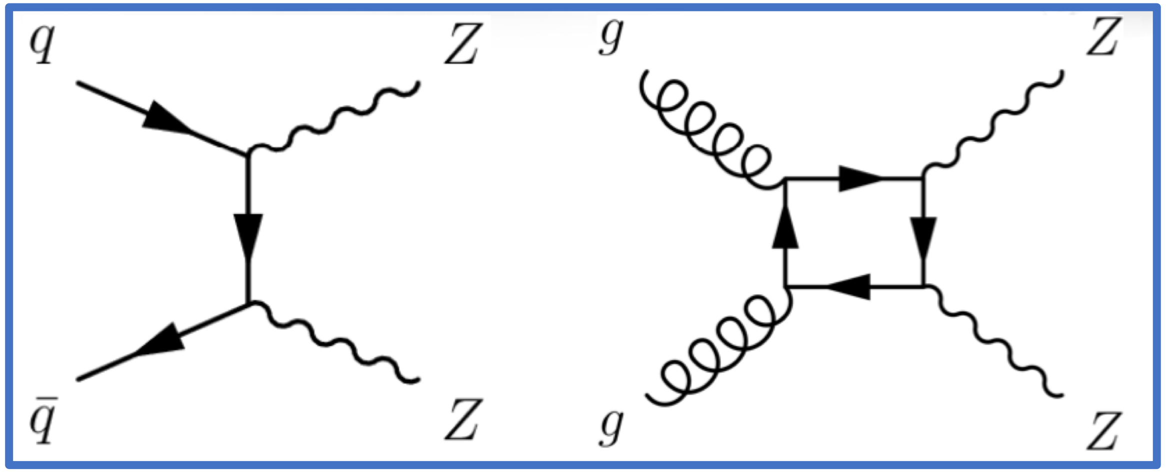


# ZZ(4ℓ)+jets analysis

CMS-PAS-SMP-22-001

## Measurement of ZZ production

- Process allows precision studies in the SM
- LO t-channel: s-channel forbitten in SM
- Gluon-gluon fusion via box diagram: 10% contribution




Differential distributions and normalized differential cross sections are measured as a function of:

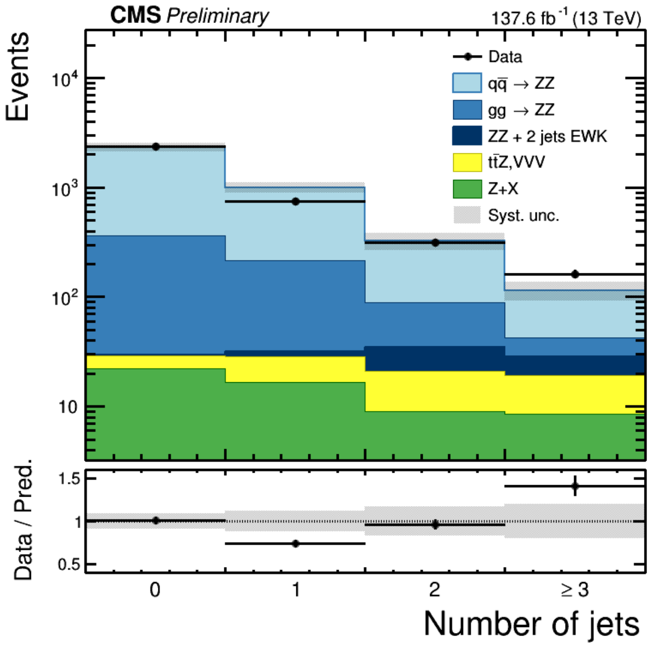
- Number of jets
- Kinematic variables of jets
- M4ℓ as a function of jet multiplicity

# ZZ(4ℓ)+jets analysis

CMS-PAS-SMP-22-001

## Selection

- on-shell leptonically decaying Z bosons
- Require 60 *GeV* < *m4ℓ* < 120 *GeV*
- ZZ → 2ℓ2ℓ' (ℓ, ℓ'= e or μ)




- Discrepancy at 1-jet bin
- >=3 jets requires NNLO and even higher order corrections, thus **the discrepancy at high jets bin is expected.**

Background extremely suppress by 4-lepton requirement

- processes with 4 prompt leptons (ttZ,VVV): **estimated with MC**
- processes with fakes: jets or non-prompt leptons misidentified as signal leptons: **estimated from the data**

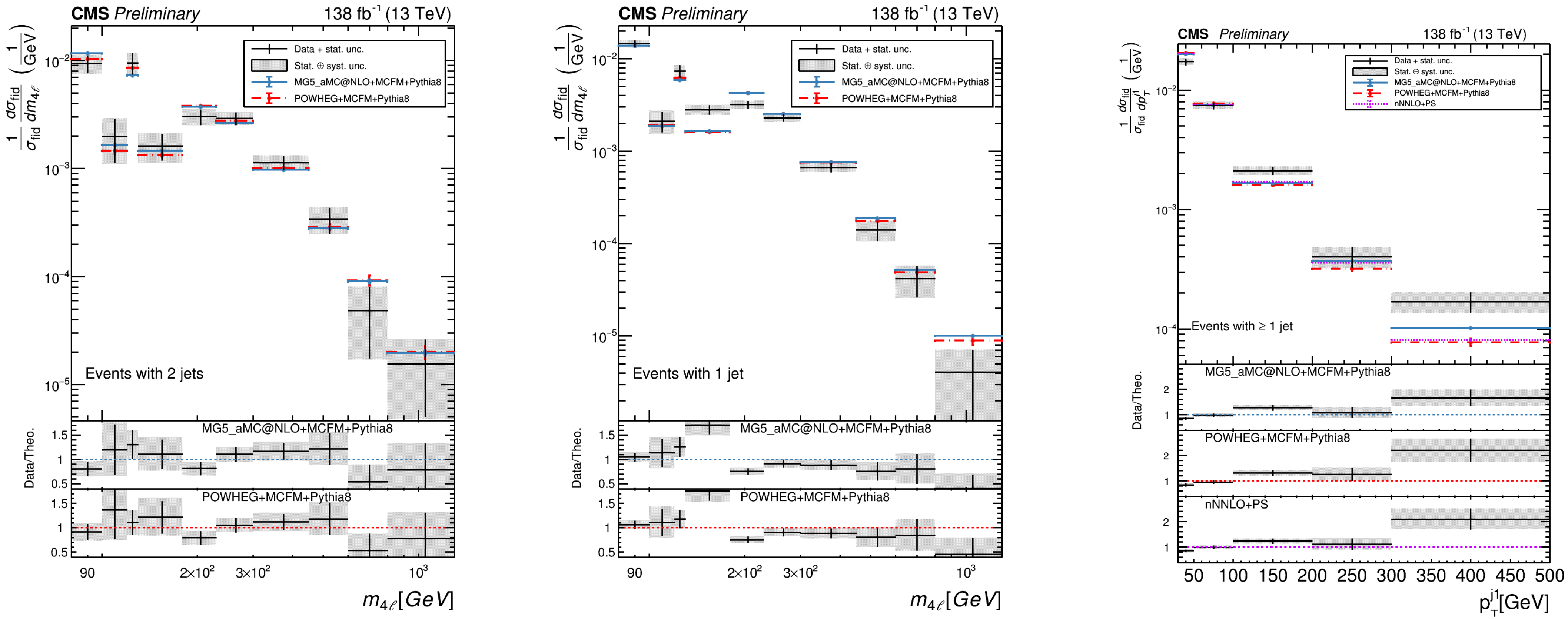
Main systematic uncertainties: jets, QCD scales

| Systematic source | $m_{4\ell}$ with all jets | 0 jet | 1 jet | 2 jets | 3 and more jets |
|---|---|---|---|---|---|
| Trigger | - | - | - | - | - |
| Electron Efficiency | 0.42 % | 0.38 % | 0.66 % | 0.36 % | 0.26 % |
| Muon Efficiency | 0.05 % | 0.06 % | 0.07 % | 0.09 % | 0.08 % |
| Jet energy resolution | 0.0 | 0.07 % | 1.72 % | 1.65 % | 0.8 % |
| JES correction | 0.0 | 0.17 % | 1.77 % | 1.95 % | 0.97 % |
| Reducible background | 0.18 % | 0.18 % | 0.32 % | 0.33 % | 0.96 % |
| Pileup | 0.02 % | 0.05 % | 0.11 % | 0.13 % | 0.35 % |
| Luminosity | 0.01 % | 0.01 % | 0.02 % | 0.02 % | 0.05 % |
| Monte Carlo choice | 0.35 % | 0.65 % | 0.94 % | 0.48 % | 0.35 % |
| gg cross section | 0.02 % | 0.03 % | 0.09 % | 0.06 % | 0.09 % |
| QCD Scales | 0.15 % | 0.16 % | 0.58 % | 0.54 % | 0.62 % |
| PDF | 0.05 % | 0.05 % | 0.15 % | 0.15 % | 0.21 % |
| $\alpha_S$ | 0.02 % | 0.01 % | 0.05 % | 0.03 % | 0.02 % |

# ZZ(4ℓ)+jets analysis

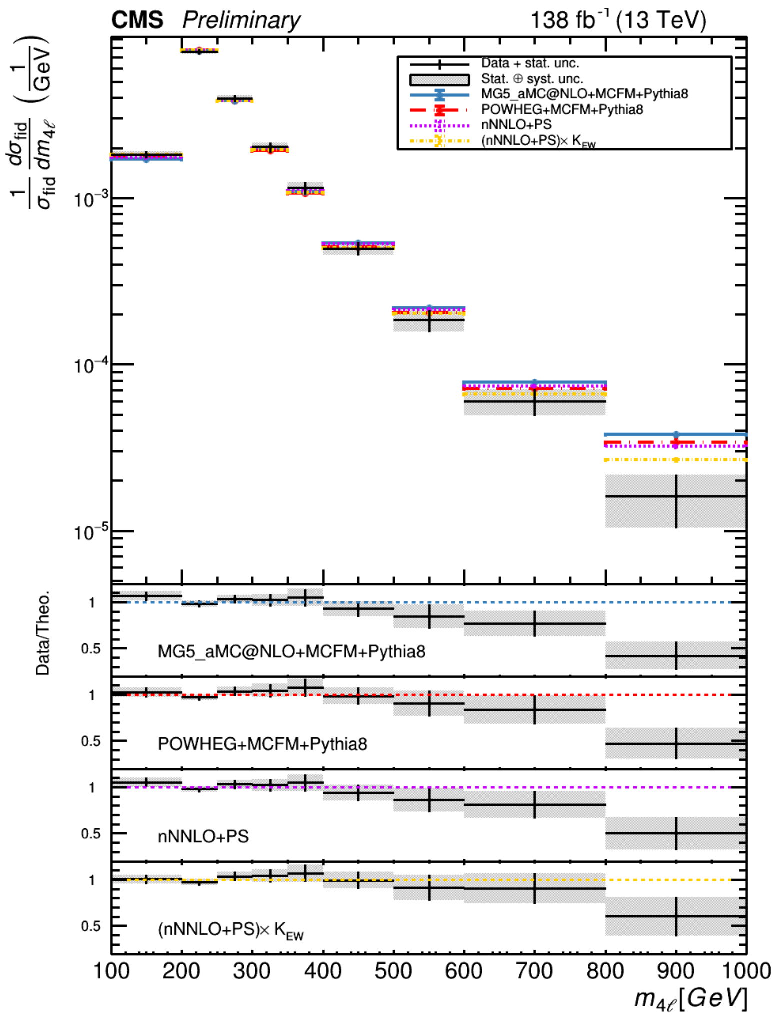
CMS-PAS-SMP-22-001

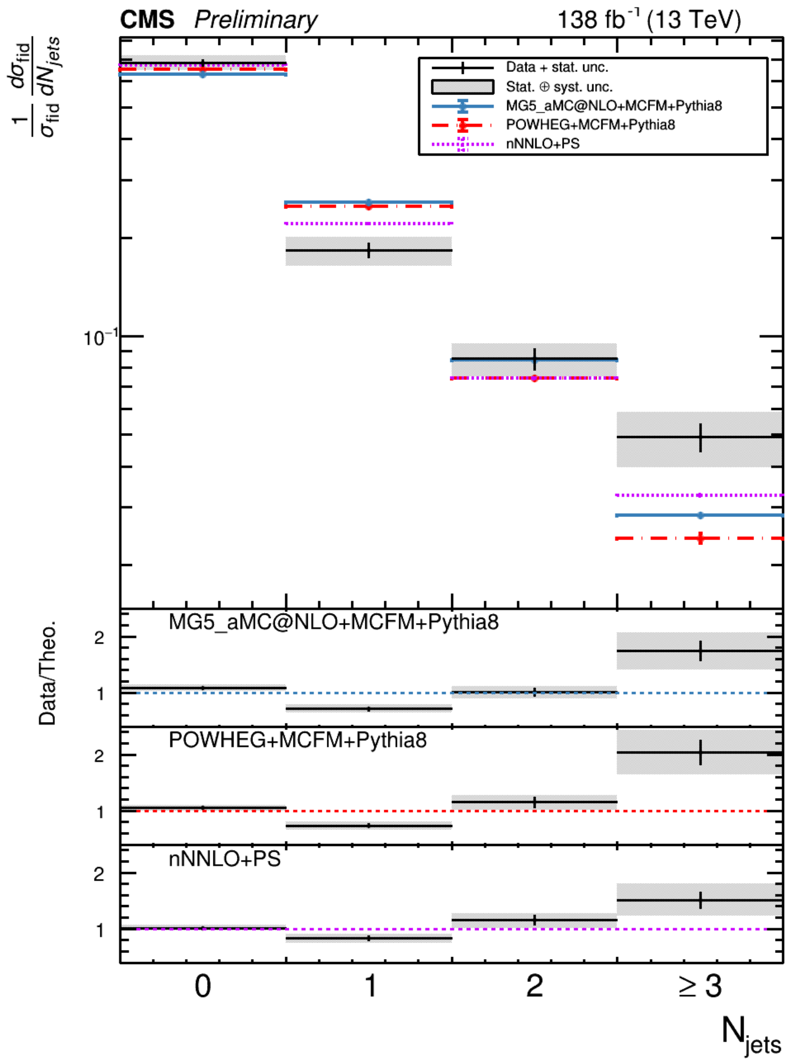
- Differential cross sections normalized to the fiducial cross sections
- Theory predictions over-estimate data in some regions
- Large discrepancy at high jet $p_T$ region



# ZZ(4ℓ)+jets analysis

CMS-PAS-SMP-22-001




- the modeling at higher jet multiplicities is not great but it improved when using nNNLO+PS MCs instead of NLO MCs
- the EW corrections help with modeling the high energy behavior

# Vector (V) Boson (B) Scattering (S)

**VBS: scattering between two vector bosons radiated from incoming partons.**

**Unique topologies:**

- two very forward jets, with large eta separation and invariant mass
- low hadronic activity in central region
- possible couplings: WWWW/WWZZ/WWZ$\gamma$/WW$\gamma\gamma$ ...

**Why is VBS interesting?**

- very rare process (~ fbs), precision test of SM
- VBS with longitudinally polarized massive vector bosons is connected to the Higgs mechanism, help us have a better understanding on Higgs mechanism
- the SM could be extended with higher operators (dimension-8, typically studied in VBS) standing for anomalous couplings between vector bosons, model independent search of BSM

**Present results from 4 VBS analyses**

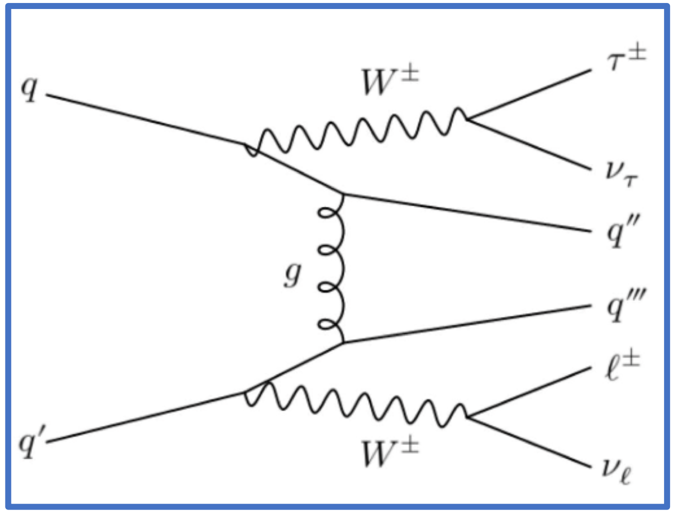
# ssWW to $\tau_h$

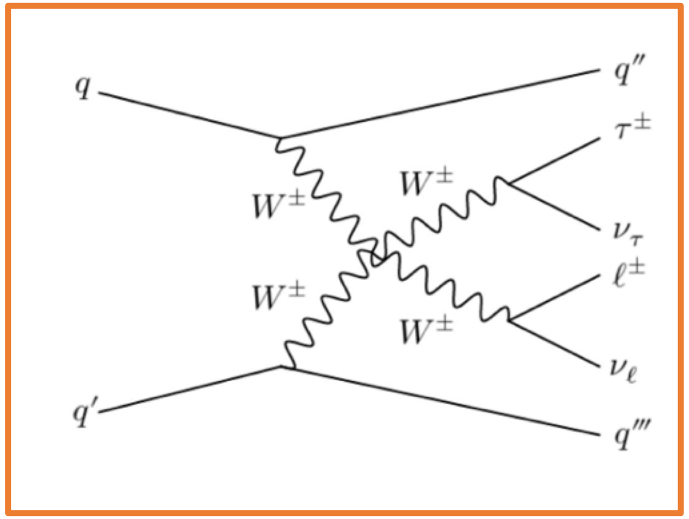
CMS-PAS-SMP-22-008

NEW

- Vector boson scattering (VBS) processes are crucial to understanding EWK symmetry breaking
- Possibility to access **tau decay channel in ssWW VBS** for the **first time**
- Same-charge W pair scattering (ssWW VBS): **largest cross-section among the EW-mediated processes**
- Possible **Beyond-SM effects** in EW vertices: Indirect search with SM Effective Field Theory (not covered for this PAS)

**qq’ → WWq’’q’’’ → $\ell^\pm \tau^\pm jj \nu \nu$**




**QCD interactions between partons**

**Pure EWK process**

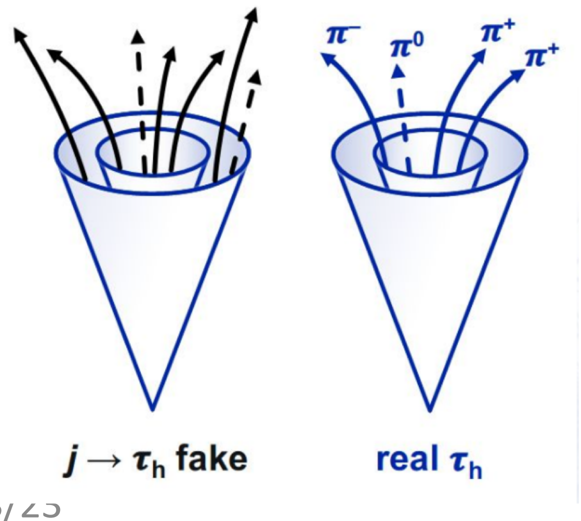
# *ssWW to $\tau_h$*

[CMS-PAS-SMP-22-008](CMS-PAS-SMP-22-008)

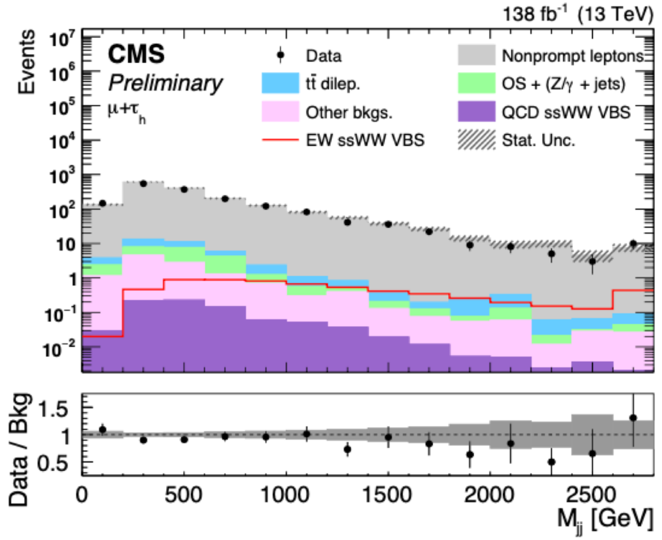
**NEW**

- Final state: $\ell^\pm \tau^\pm jj$ + MET ($\ell$ = e, μ)
- two very energetic forward-backward jets → VBS jets
- large large **dijet mass** ($m_{jj}$) and large **η separation** ($\Delta\eta_{jj}$ )between the jets
- DNN discriminators to enhance signal sensitivity: 9 kinematic quantities describing of the ssWW VBS process

**Main background:** no-prompt lepton/tau: jets are mis reconstructed as e,μ, or τh




estimated from the data and validate in a CR close to SR



# ssWW to $\tau_h$

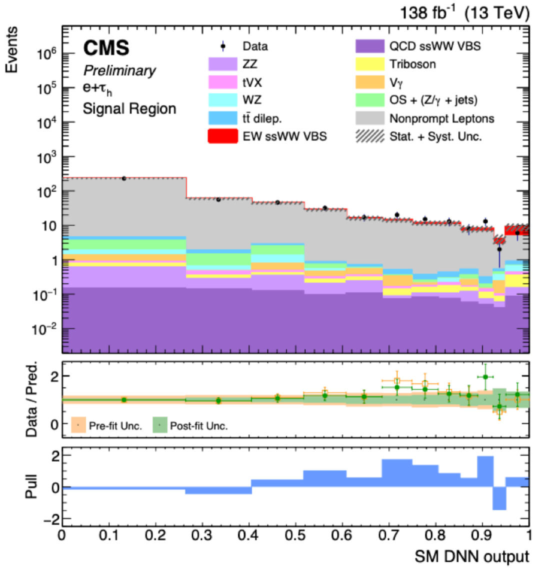
CMS-PAS-SMP-22-008

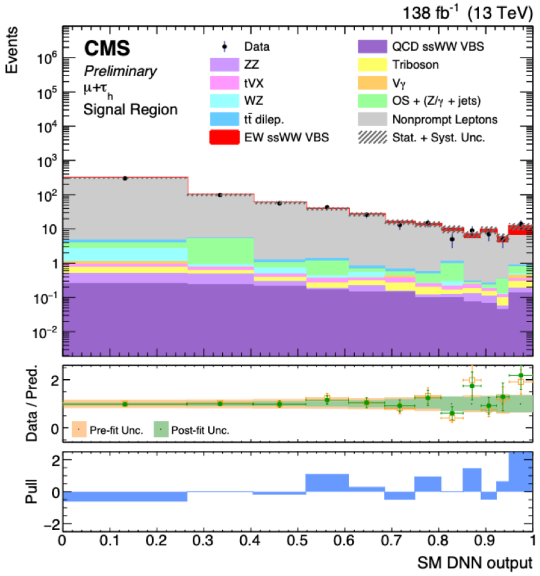
NEW

- dedicated DNN trained and tested to classify the events in signal and background categories
- ML fit using DNN templates from **SR** and **two enriched background CRs** to control opposite-sign, ZZ and tt rates
- **ssWW purely-EW signal strength**
- **Simultaneous EW and QCD ssWW signal strength**

| Signal | Significance $[\sigma]$ Expected | Significance $[\sigma]$ Observed |
|---|---|---|
| pure EW ssWW VBS | 1.94 | 2.74 |
| EW + QCD ssWW VBS | 2.04 | 2.87 |

- Dominant uncertainty: data statistics and theoretical uncertainties

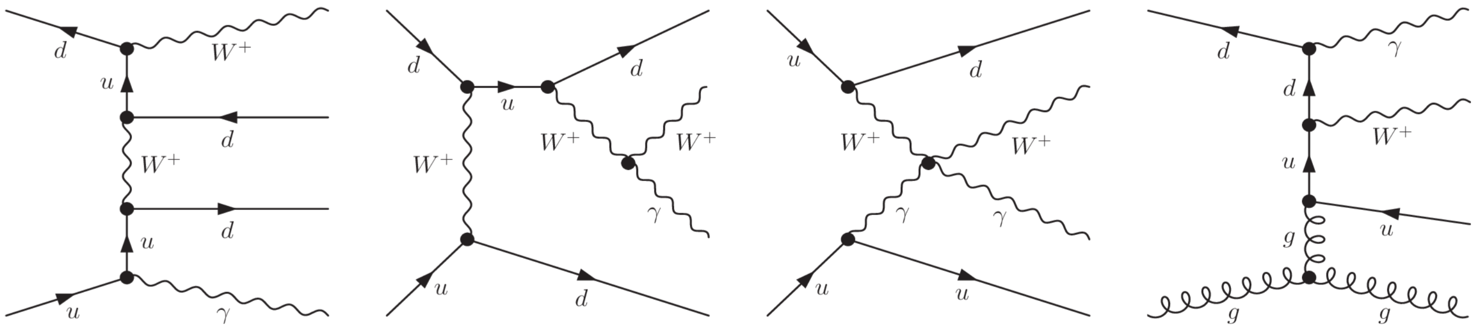


# Electroweak Wγjj production

[CMS-SMP-21-011](#)
[Phy.Ref.D](#)

Electroweak production of a W boson, a photon (γ), and two jets (j)




**Final states**: eνγ +2 jets and μνγ + 2jets

**VBS Signature**: Large **dijet mass** ($m_{jj}$) and large **η separation** ($\Delta\eta_{jj}$) between the jets

**Main results:**

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

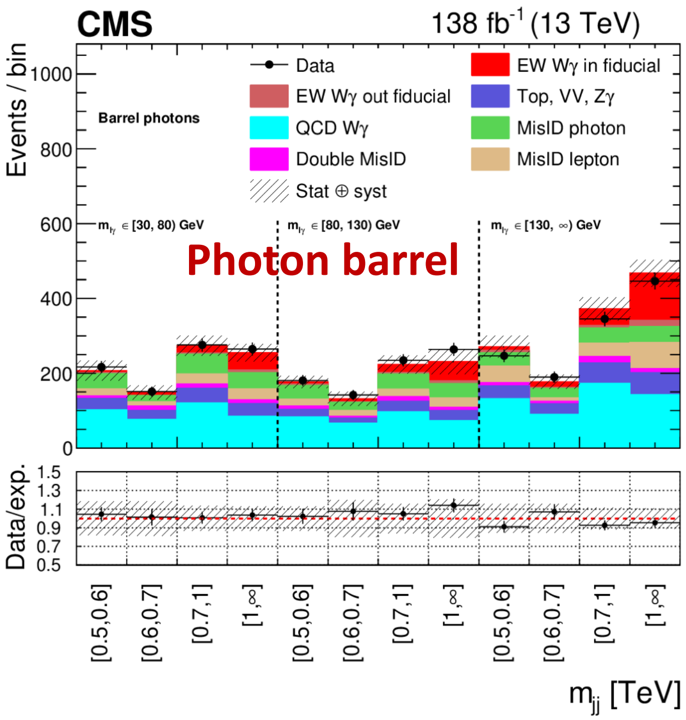
# Electroweak Wγjj production

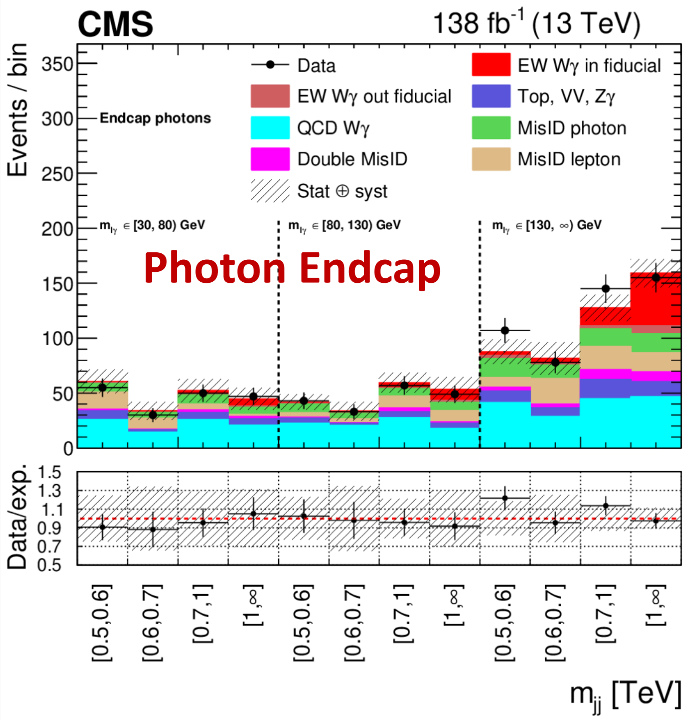
CMS-SMP-21-011
Phy.Ref.D

Major backgrounds from W+jets and processes where the jet constituents is misidentified as a photon

Data-driven method for background estimate:

- Template fit: non-prompt (fake) photon
- Tight-loose method: non-prompt lepton



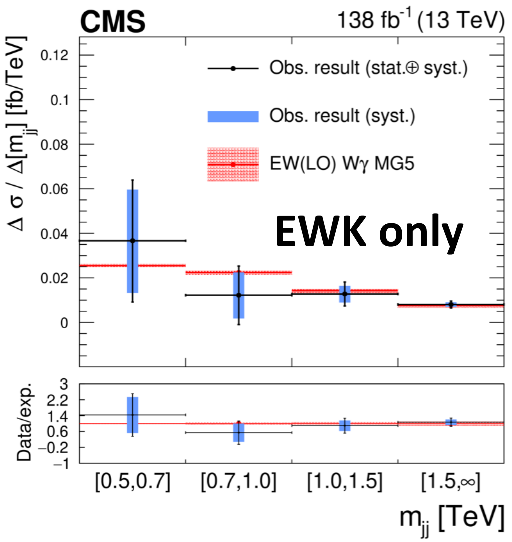



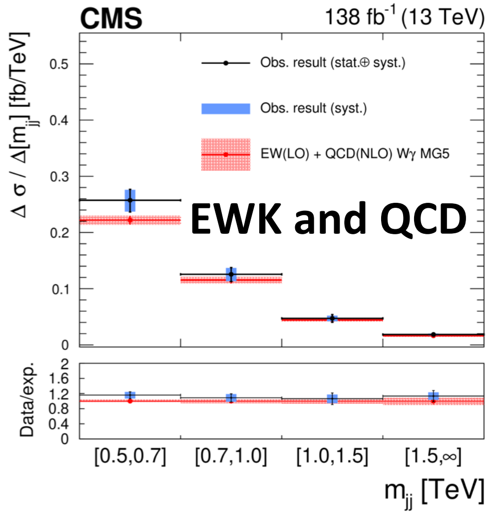

- measurement of the total EW Wγ production rate is performed with a binned likelihood fit to the data of the two-dimensional (2D) distribution in $m_{jj}$ and $m_{\gamma\gamma}$
- Separated into barrel and endcap to account for differences in photon performance

# Electroweak Wγjj production

[CMS-SMP-21-011](#)
[Phy.Ref.D](#)

- Measure EWK-only and EWK+QCD fiducial and differential cross sections and observe good agreement with SM
- The EWK $W\gamma jj$ production is observed with 6.03 $\sigma$ (6.79 $\sigma$ expected).




VBS very powerful to study anomalous quartic gauge couplings (aQGC)

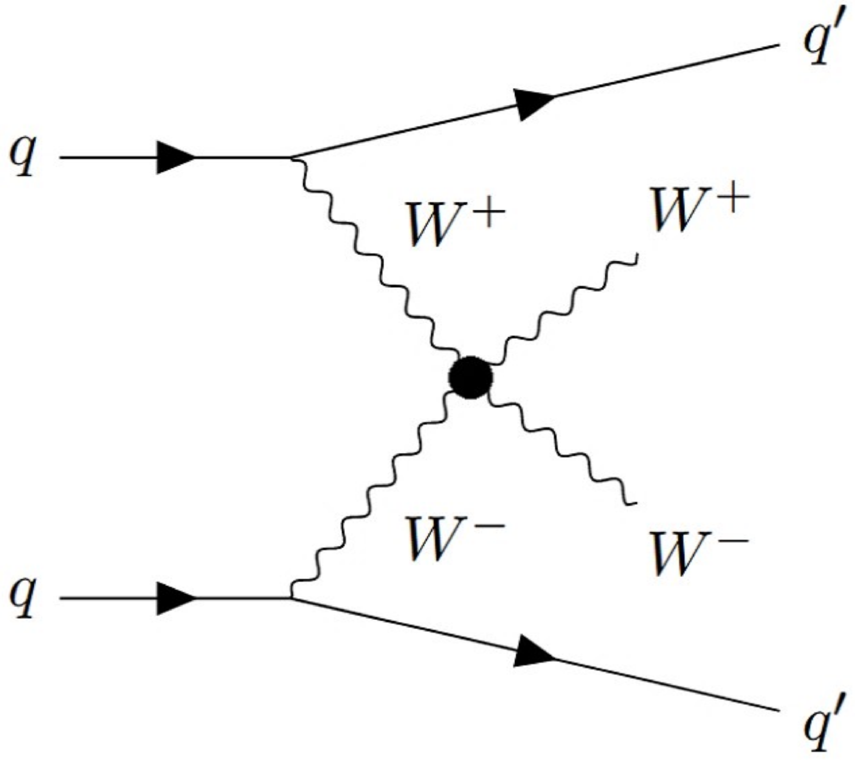
- Exploration of dim-8 operators possible due to presence of SM quartic coupling
- Invariant mass of the Wγ system is sensitive to presence of dim-8 operators
- Sets most stringent limits on $fM,2–4/\Lambda^4$ and $fT,6–7/\Lambda^4$

| Expected limit | Observed limit | |
|---|---|---|
| $-5.1 < f_{M,0}/\Lambda^4 < 5.1$ | $-5.6 < f_{M,0}/\Lambda^4 < 5.5$ | |
| $-7.1 < f_{M,1}/\Lambda^4 < 7.4$ | $-7.8 < f_{M,1}/\Lambda^4 < 8.1$ | |
| $-1.8 < f_{M,2}/\Lambda^4 < 1.8$ | $-1.9 < f_{M,2}/\Lambda^4 < 1.9$ | |
| $-2.5 < f_{M,3}/\Lambda^4 < 2.5$ | $-2.7 < f_{M,3}/\Lambda^4 < 2.7$ | BEST |
| $-3.3 < f_{M,4}/\Lambda^4 < 3.3$ | $-3.7 < f_{M,4}/\Lambda^4 < 3.6$ | |
| $-3.4 < f_{M,5}/\Lambda^4 < 3.6$ | $-3.9 < f_{M,5}/\Lambda^4 < 3.9$ | |
| $-13 < f_{M,7}/\Lambda^4 < 13$ | $-14 < f_{M7}/\Lambda^4 < 14$ | |
| $-0.43 < f_{T,0}/\Lambda^4 < 0.51$ | $-0.47 < f_{T,0}/\Lambda^4 < 0.51$ | |
| $-0.27 < f_{T,1}/\Lambda^4 < 0.31$ | $-0.31 < f_{T,1}/\Lambda^4 < 0.34$ | |
| $-0.72 < f_{T,2}/\Lambda^4 < 0.92$ | $-0.85 < f_{T,2}/\Lambda^4 < 1.0$ | |
| $-0.29 < f_{T,5}/\Lambda^4 < 0.31$ | $-0.31 < f_{T,5}/\Lambda^4 < 0.33$ | |
| $-0.23 < f_{T,6}/\Lambda^4 < 0.25$ | $-0.25 < f_{T,6}/\Lambda^4 < 0.27$ | BEST |
| $-0.60 < f_{T,7}/\Lambda^4 < 0.68$ | $-0.67 < f_{T,7}/\Lambda^4 < 0.73$ | |

# Observation of opposite Sign WW VBS

SMP-21-001
PLB

First observation of the electroweak production of a leptonically decaying $W^{+}W^{-}$ pair in association with two jets




**final state**: 2 opposite-sign leptons, 2 jets and moderate missing $p_T^{miss}$

**VBS topology**: 2 jets with large pseudorapidity gap $\boldsymbol{\Delta\eta_{jj}}$ and invariant mass $\boldsymbol{m_{jj}}$

**Lepton-flavour-based event categories**

- eμ: background dominated by ttbar
- ee/μμ: background mostly dominated by DY

# Observation of opposite Sign WW VBS

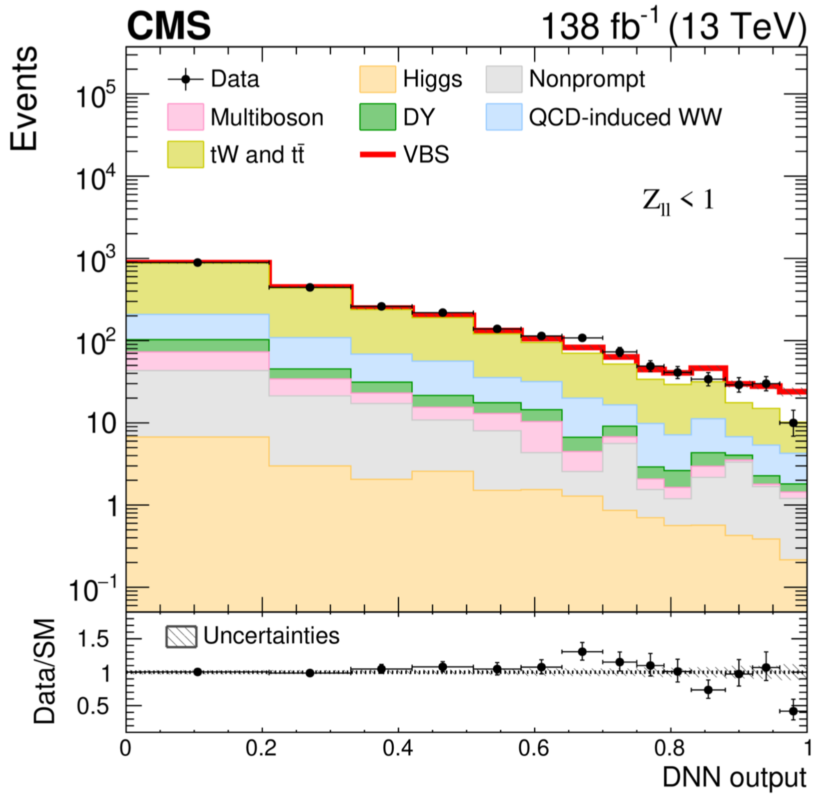
SMP-21-001
PLB

Deep Neural-Network selection based on lepton/jets kinematic variables was used to disentangle signal from top and QCD induced WW background

| Variable | Description |
|---|---|
| $m_{jj}$ | Invariant mass of the two tagging jets pair |
| $p_T^{j_1}$ | $p_T$ of the highest $p_T$ jet |
| $\lvert\Delta\eta_{jj}\rvert$ | Pseudorapidity separation between the two tagging jets |
| $p_T^{j_2}$ | $p_T$ of the second-highest $p_T$ jet |
| $Z_{\ell_2}$ | Zeppenfeld variable of the second-highest $p_T$ lepton |
| $p_T^{\ell\ell}$ | $p_T$ of the lepton pair |
| $\Delta\phi_{\ell\ell}$ | Azimuthal angle between the two leptons |
| $Z_{\ell_1}$ | Zeppenfeld variable of the highest $p_T$ lepton |
| $m_T^{\ell_1}$ | Transverse mass of the $(p_T^{\ell_1}, p_T^{miss})$ system |

**2 models implemented:**

- $Z_{\ell\ell} < 1$ phase space
- $Z_{\ell\ell} \geq 1$ phase space




centrality of the dilepton system with respect to the tagging jets is quantified as:

**Zeppenfeld variable:** $Z_{\ell\ell} = \frac{1}{2}\lvert Z_{\ell\,1} + Z_{\ell\,2}\rvert$, where $Z_{\ell} = \eta_{\ell} - \frac{1}{2}(\eta_{j1} + \eta_{j2})$

# Observation of opposite Sign WW VBS

SMP-21-001
PLB

## Background estimation

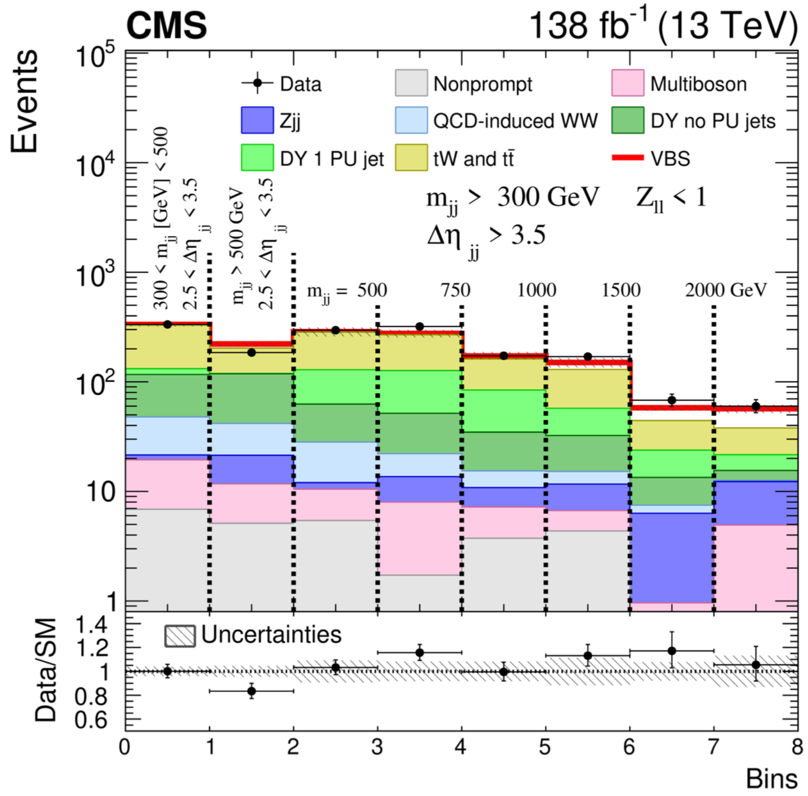
- Non-prompt leptons: data-driven
- DY and ttbar: estimates from CR is the data
- minor backgrounds ( tW and Z→ee/μμ) are estimated from simulation

## Signal Extraction

- Combined binned maximum likelihood fit of the most discriminating variable distributions with signal and background templates
- Lepton-flavour dependent signal extraction

  eμ: DNN output

  ee/μμ: bins in $m_{jj}$, $\Delta\eta_{jj}$, Zeppenfeld variables
- Simultaneously in all signal regions and control regions




**Largest systematic uncertainties**: theory, b-jet veto

# Observation of opposite Sign WW VBS

SMP-21-001
PLB

- **Observed (expected) significance w.r.t. the background-only hypothesis is 5.6 σ (5.2 σ)**
- The cross section measurement of the $W^+W^-$ EW production is performed in two fiducial volumes

## Inclusive Volume

Loose requirements
- $p_T(q) > 10$ GeV
- $m_{qq'} > 100$ GeV

**Inclusive**: 99 ± 20 fb (theory: 89 ± 5)
**Tight**: 10.2 ± 2.0 fb (theory: 9.1 ± 0.6)

**Good agreement with SM predictions!**

## Exclusive (Tight) volume

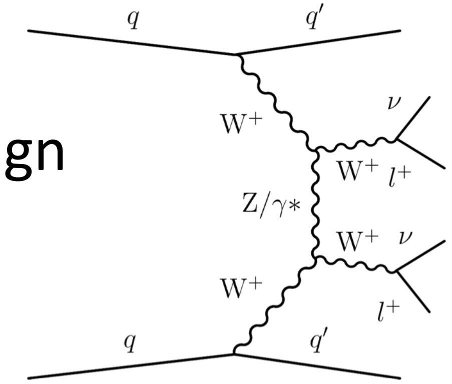
| Objects | Requirements |
|---|---|
| Leptons | e$\mu$, ee, $\mu\mu$ (not from $\tau$ decay), opposite charge<br>$p_T^{\text{dressed } \ell} = p_T^{\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$<br>$p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 13\,\text{GeV}$, $p_T^{\ell_3} < 10\,\text{GeV}$<br>$\lvert\eta\rvert < 2.5$<br>$p_T^{\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$ |
| Jets | $p_T^{j} > 30\,\text{GeV}$<br>$\Delta R(j, \ell) > 0.4$<br>At least 2 jets, no b jets<br>$\lvert\eta\rvert < 4.7$<br>$m_{jj} > 300\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$ |
| $p_T^{\text{miss}}$ | $p_T^{\text{miss}} > 20\,\text{GeV}$ |

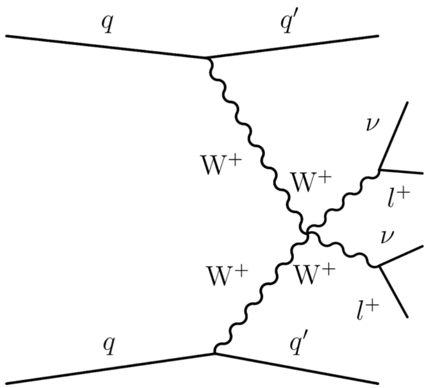
**more signal-like**

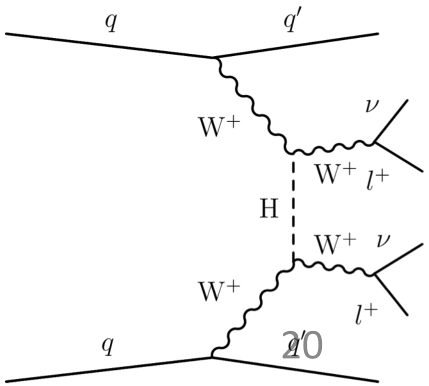
# Polarized $W^{\pm}{}_{L} W^{\pm}{}_{L}$ extraction

SMP-20-006
PLB

- the first measurements of production cross sections of polarized same-sign WW
- gauge boson polarization in VBS production, which can target diagrams with intermediate Higgs mediation instead of the quadruple gauge coupling
- the analysis uses all data from the Run II to target doubly polarized final states: $W_LW_L$ , $W_TW_T$ , $W_LW_T$
- measurements are also provided for $W_LW_X$ and $W_TW_X$ production



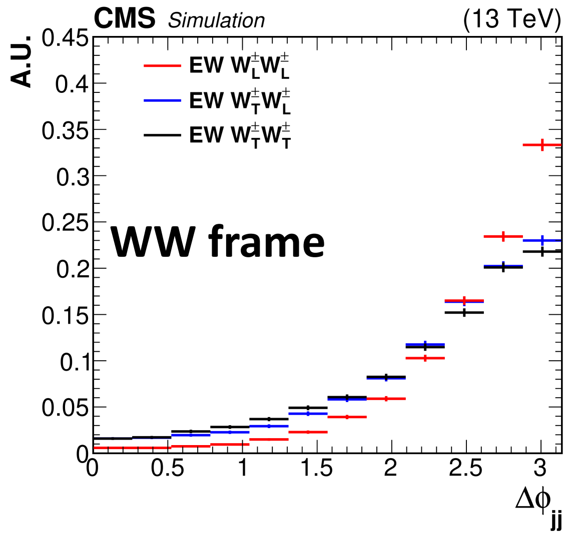



# Polarized $W^{\pm}_{L}W^{\pm}_{L}$ extraction

SMP-20-006
PLB

Angular variables powerful for polarization components extraction

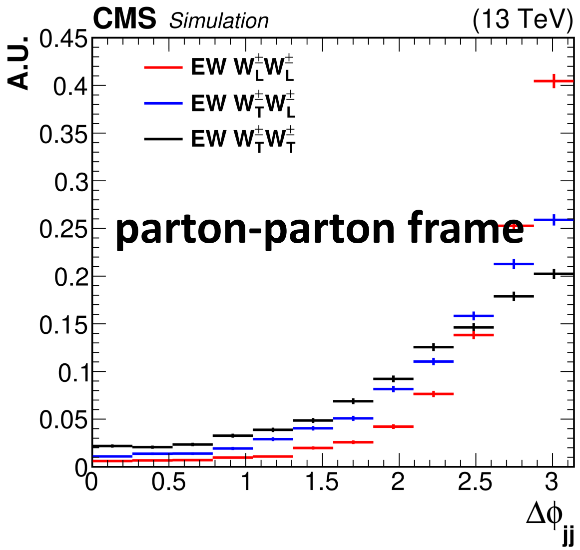



**Backgrounds:**

- control regions to measure WZ, ZZ, tZq backgrounds
- Non-prompt data-driven and mis-charge ID
- Results are reference-frame-dependent:

**WW frame**: based on the center of mass frame of the WW pair

**Parton frame**: based on the center of mass frame of the incoming partons




**Strategy**

Inclusive BDT to extract WW same-sign signal

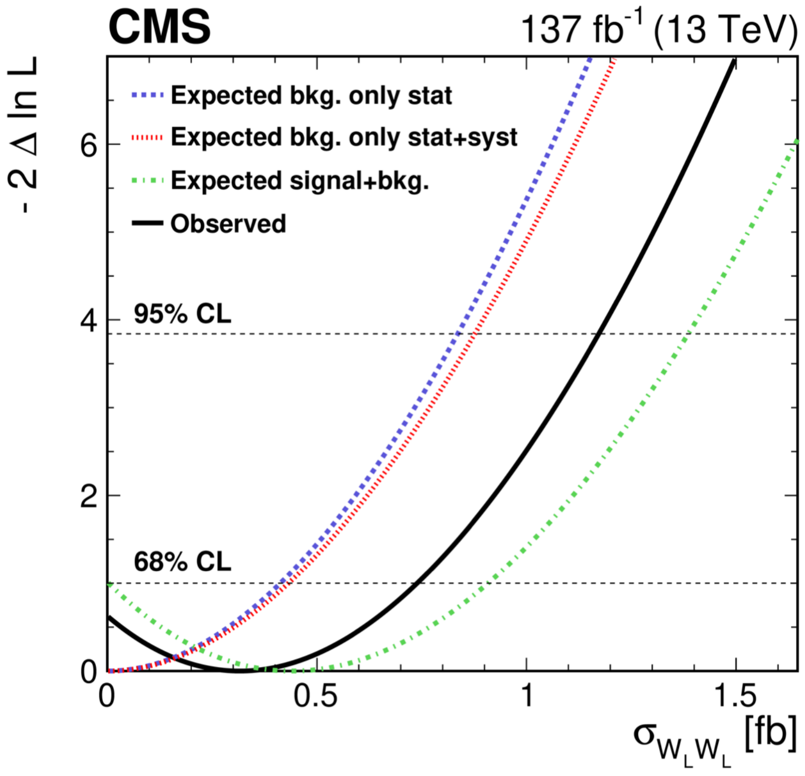
specific signal BDT for ( $W_L W_L$ vs $W_X W_T$ ) and ( $W_T W_T$ vs $W_X W_L$ )

The final signal extraction uses a 2D fit based on a binning of both BDTs

# Polarized $W^{\pm}_{L}W^{\pm}_{L}$ extraction

SMP-20-006
PLB

- the significance of the measured $W_LW_X$ yield is 3.1 σ expected, 2.3 σ observed
- exclude > ~2 x SM $W_LW_L$ production at 95% confidence-level
- fiducial cross-sections extracted for all the polarizations → agrees with SM within uncertainties




**WW center of mass reference frame**

| Process | $\sigma\mathcal{B}$ (fb) | Theoretical prediction (fb) |
|---|---|---|
| $W^{\pm}_{L}W^{\pm}_{L}$ | $0.32^{+0.42}_{-0.40}$ | $0.44 \pm 0.05$ |
| $W^{\pm}_{X}W^{\pm}_{T}$ | $3.06^{+0.51}_{-0.48}$ | $3.13 \pm 0.35$ |
| $W^{\pm}_{L}W^{\pm}_{X}$ | $1.20^{+0.56}_{-0.53}$ | $1.63 \pm 0.18$ |
| $W^{\pm}_{T}W^{\pm}_{T}$ | $2.11^{+0.49}_{-0.47}$ | $1.94 \pm 0.21$ |

**parton-parton reference frame**

| Process | $\sigma\mathcal{B}$ (fb) | Theoretical prediction (fb) |
|---|---|---|
| $W^{\pm}_{L}W^{\pm}_{L}$ | $0.24^{+0.40}_{-0.37}$ | $0.28 \pm 0.03$ |
| $W^{\pm}_{X}W^{\pm}_{T}$ | $3.25^{+0.50}_{-0.48}$ | $3.32 \pm 0.37$ |
| $W^{\pm}_{L}W^{\pm}_{X}$ | $1.40^{+0.60}_{-0.57}$ | $1.71 \pm 0.19$ |
| $W^{\pm}_{T}W^{\pm}_{T}$ | $2.03^{+0.51}_{-0.50}$ | $1.89 \pm 0.21$ |

# Summary

- **Recent results on EW multiboson production were presented from CMS using the full Run2 dataset**
- Differential cross sections on **diboson ZZ** in association with jets from CMS
- first **observation of VBS ssWW to $\tau_h$**
- **Wγ +2j** analysis: sets most stringent limits on some aQGC operators
- first observation of opposite sign WW VBS
- first measurements of production cross sections of polarized same-sign $W^{\pm}W^{\pm}$
- **Run2**: many interesting results from Run 2 are yet to come
- **Run3 ahead**: increased statistics are promising for new measurements and BSM interpretations!

# Back Up