Vector boson scattering results in CMS

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On behalf of the **CMS** Collaboration

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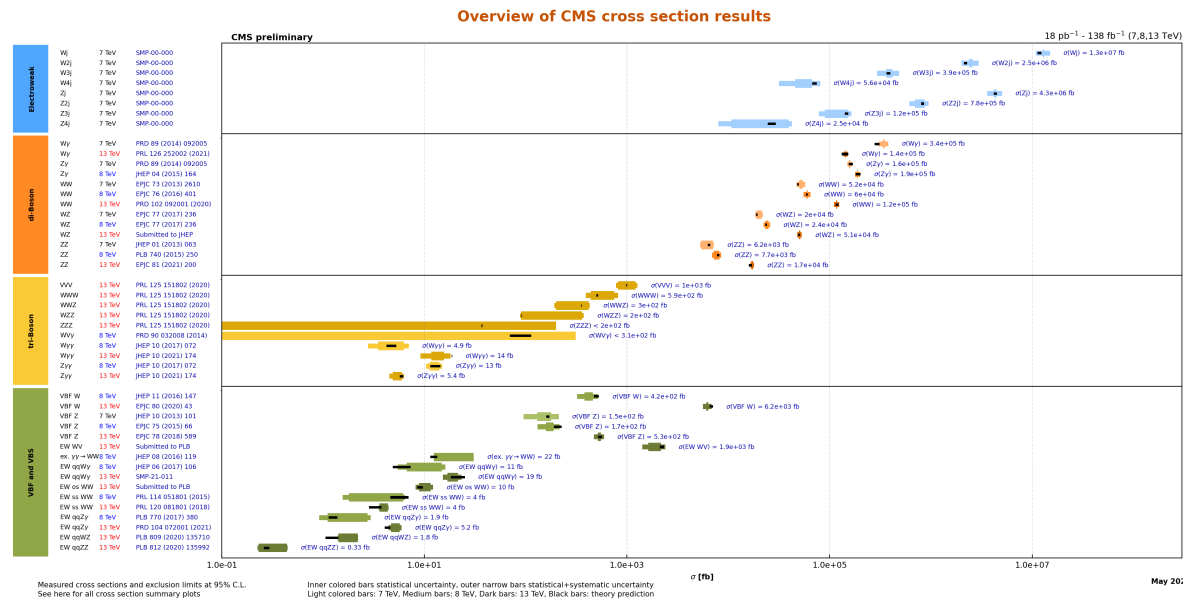
The journey is in full swing

- Standard Model cross sections successfully tested over **10 orders of magnitude**
- We **discovered** **a Higgs boson**
- ***Still*** we have to understand **<u>in detail</u>** **the Electroweak Symmetry Breaking Mechanism** (EWSB)

It is a ***<u>long journey</u>***, but **several milestones of the path have been posed**:



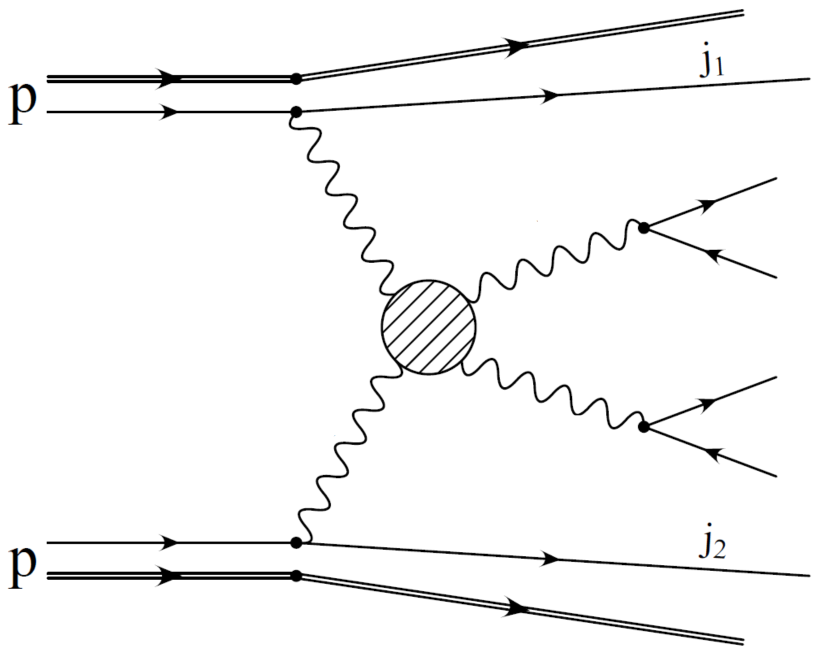
- The observation of the production of EW bosons through **vector boson fusion**
- The detailed measurement of the **diboson productions**
- The observation of the **electroweak production of vector bosons and jets, i.e., the vector boson scattering**
- The observation of several **triboson production**
- The first attempt to measure the **vector boson polarization** in diboson intermediate states

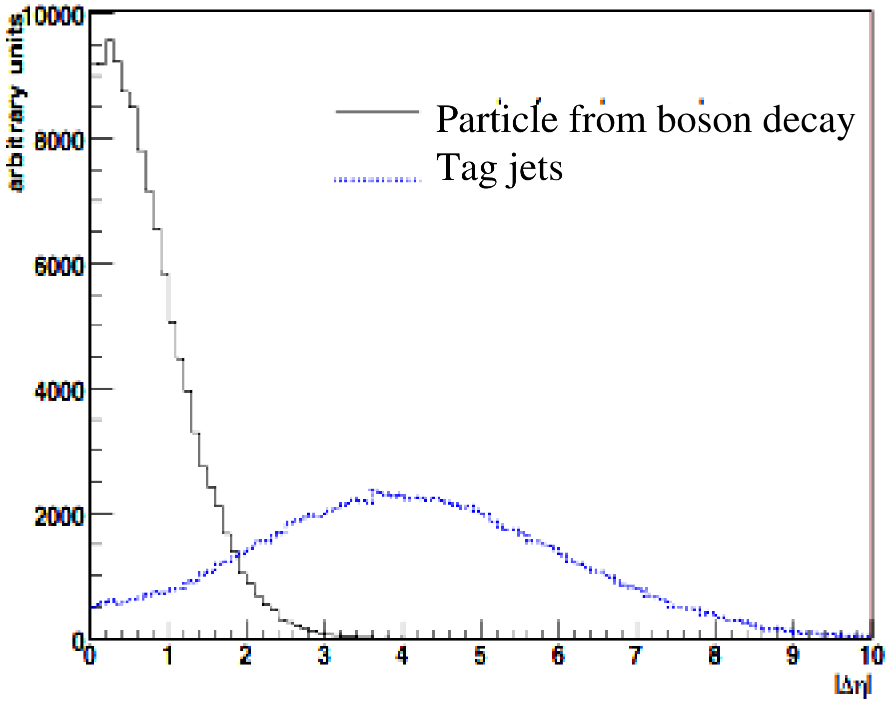
We are on the road to study the most intimate part of the EWSB: the acquisition of the longitudinal degree of polarization of the massive electroweak bosons

Vector boson scattering topology

… has **a distinctive signature**

- **Two jets in the forward-background region w/o color connection → Large pseudorapidity gap**
- Decay products of the outgoing vector bosons tend to be **in-between the tag-jet pseudorapidity gap**

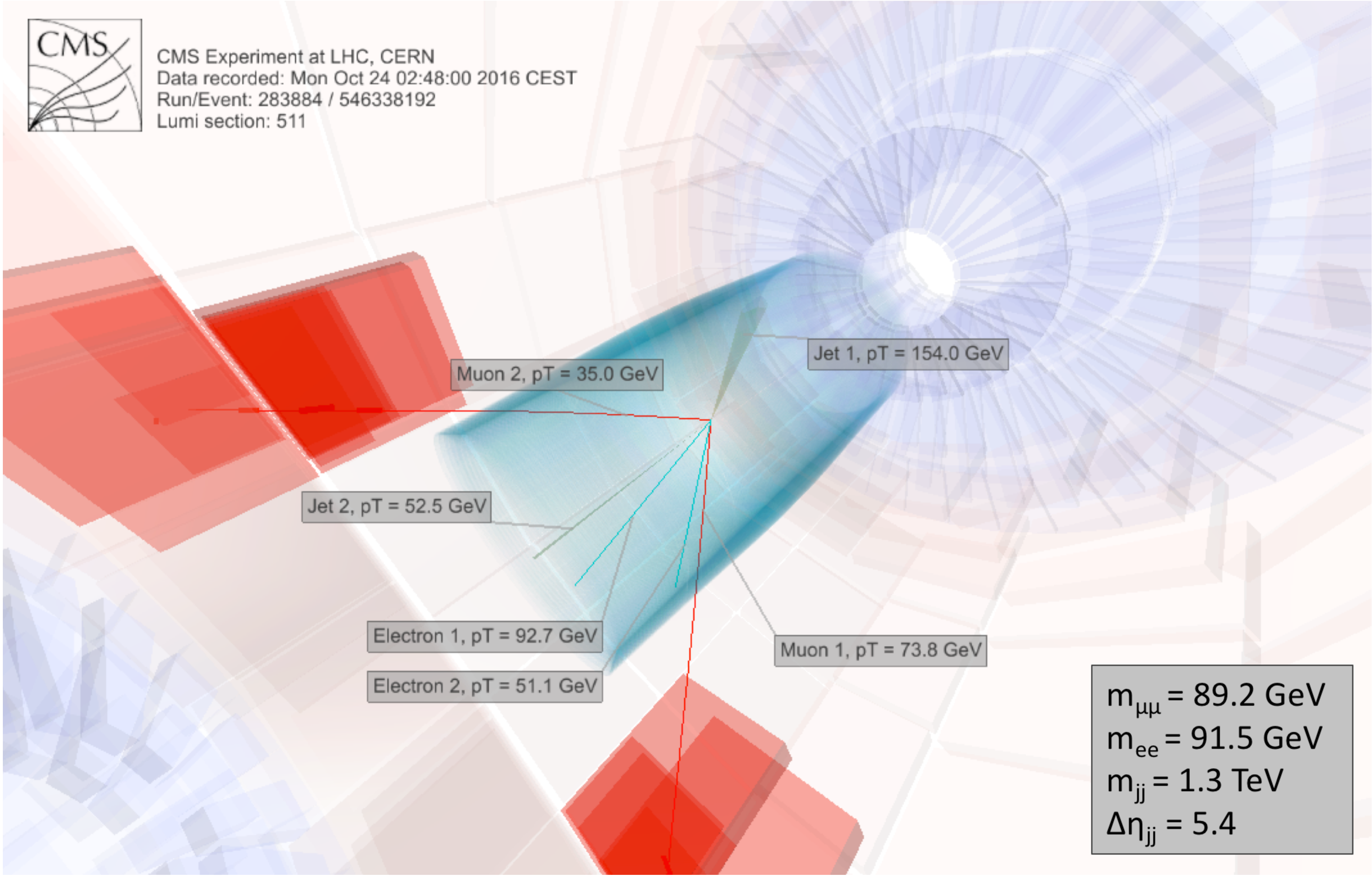




- Other key variables are: the **invariant mass of the dijet system (m_{jj})** and the **Zeppenfeld variable (z*)**, usually defined as $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})|/2$ or $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})/2|/|\Delta\eta_{jj}|$

VBS event candidate

CMS-PAS-SMP-16-019



Menu, for today: Vector boson scattering

Most updated results ($\sqrt{s}$ = 13 TeV and full lumi), other results w/ lower $\sqrt{s}$ or $\mathscr{L}$ exist

See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

$pp \rightarrow W^{\pm}W^{\pm}jj$ CMS-SMP-19-012 CMS-SMP-20-013 CMS-SMP-20-006 **Polarization studies**

$pp \rightarrow W^{\pm}Zjj$ CMS-SMP-19-012 CMS-SMP-20-013

$pp \rightarrow W^{\pm}W^{\mp}jj$ CMS-SMP-21-001 CMS-SMP-20-013

$pp \rightarrow ZZjj$ CMS-SMP-20-001

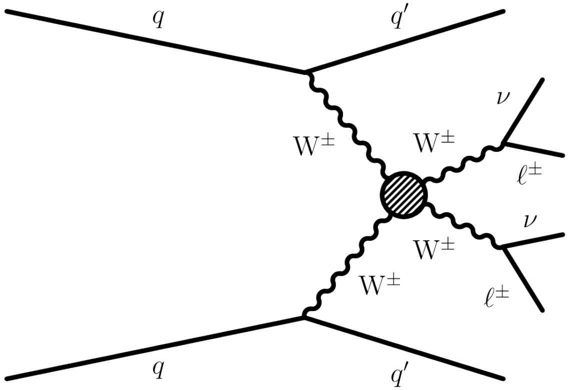
$pp \rightarrow W^{\pm}\gamma jj$ CMS-SMP-21-011

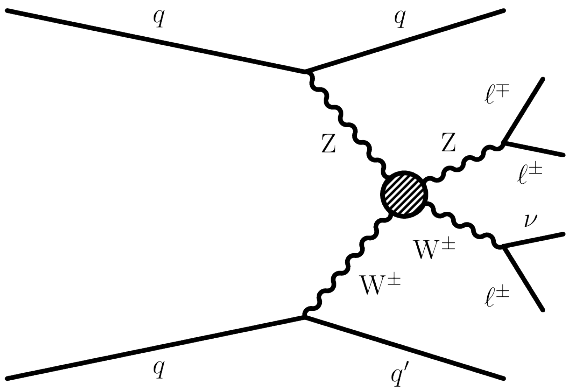
$pp \rightarrow Z\gamma jj$ CMS-SMP-20-016

$pp \rightarrow p(*)VVp(*)$ CMS-SMP-21-014 $\mathscr{L}$ = 100 fb^{-1}

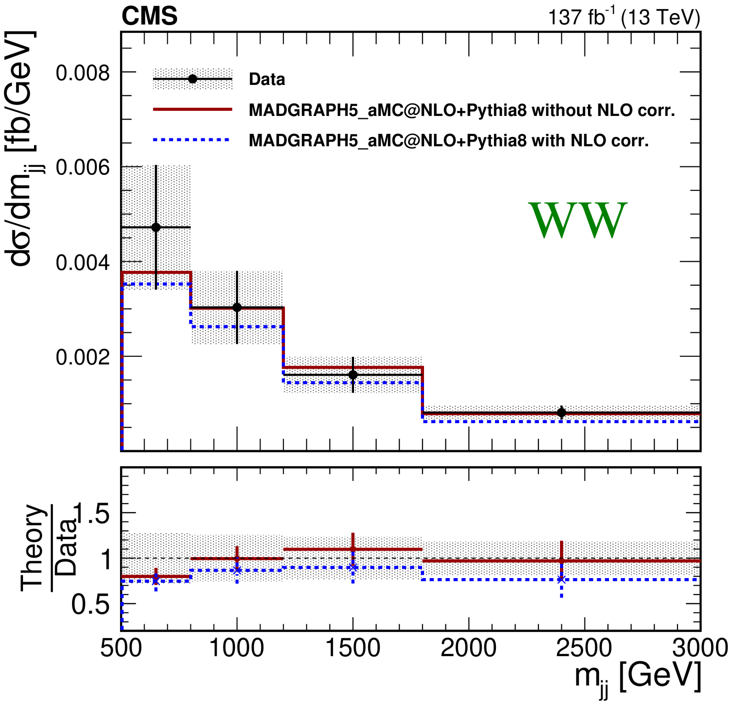
Fully leptonic
Semileptonic (W→lep & V → had)
Fully hadronic

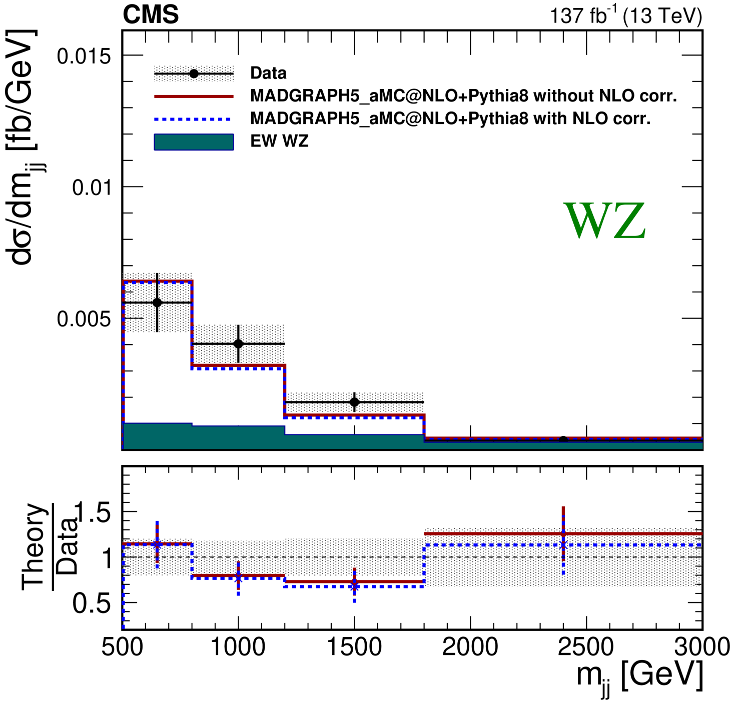
$pp \to W^{\pm}W^{\pm}jj + pp \to WZjj$ CMS-SMP-19-012



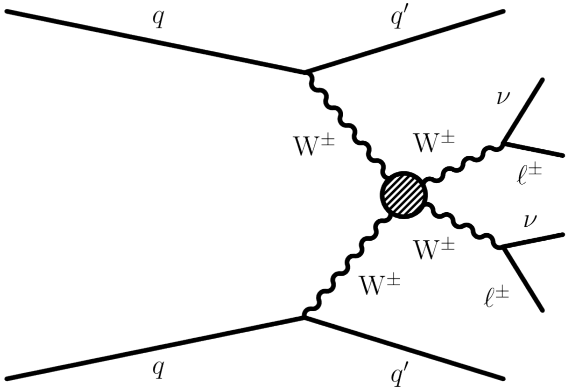


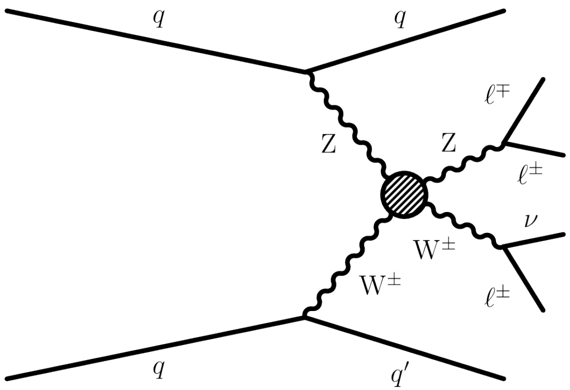
Unique analysis that **combines the 2 and 3 charged leptons final states**. A **simultaneous fit** is performed to both constrain the **signal**, the **background** and **possible deviations from the SM predictions**





$pp \rightarrow W^{\pm}W^{\pm}jj + pp \rightarrow WZjj$ CMS-SMP-19-012





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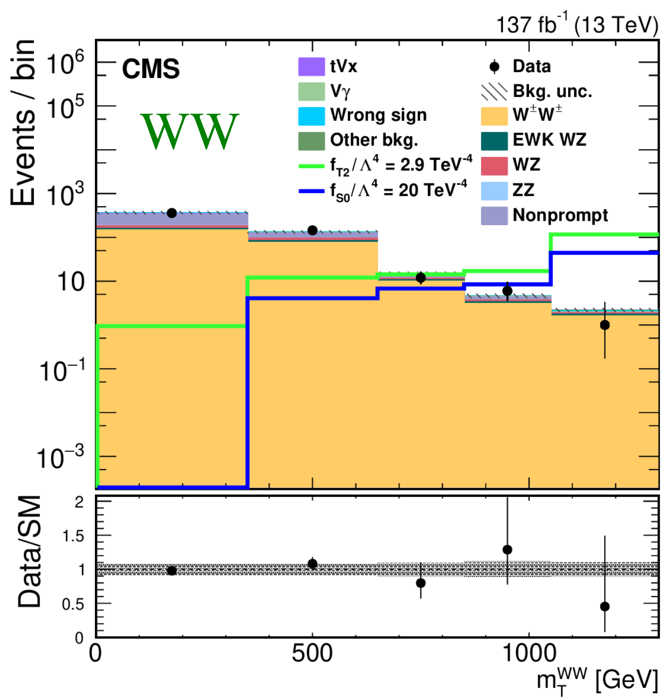
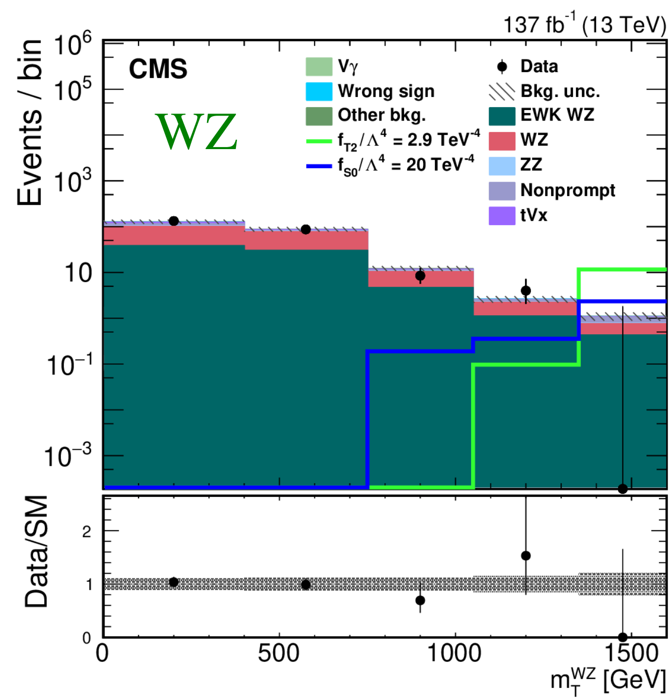
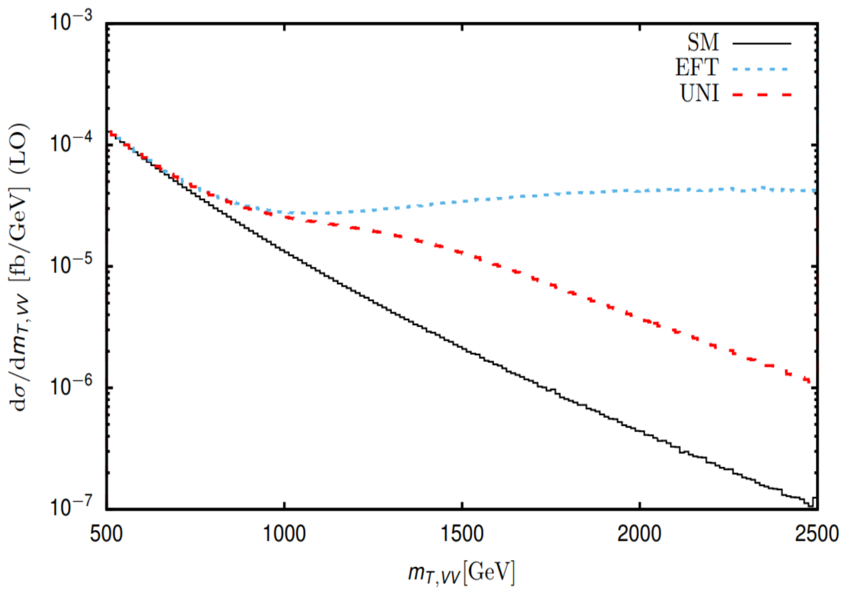




The analysis adopts a tecnique (clipping) that takes into account the possible violation of the unitarity (not physical) that can be induced by large Wilson coefficients

$qq \to W^+Zjj \to l^+l^-l^+\nu_l jj,$



	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

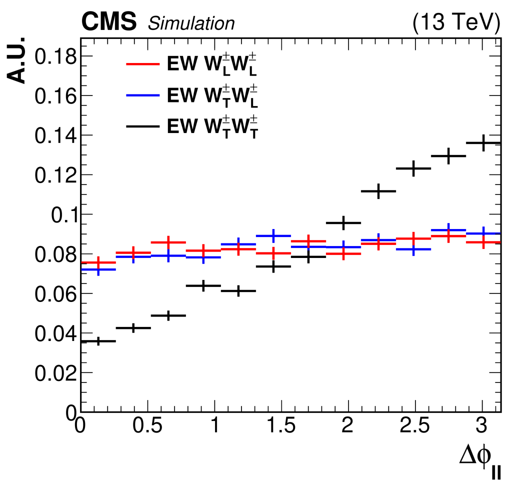
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

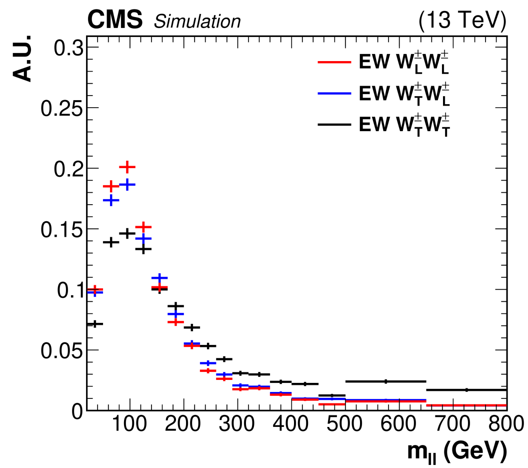
Limits worsen by a factor of 5 in comparison with limits without unitarity constraints

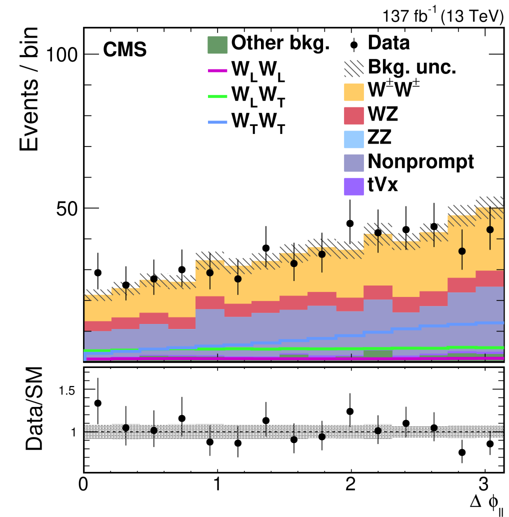
$W^{\pm}_{L}W^{\pm}_{L} \rightarrow W^{\pm}_{L}W^{\pm}_{L}$ scattering

CMS-SMP-20-006

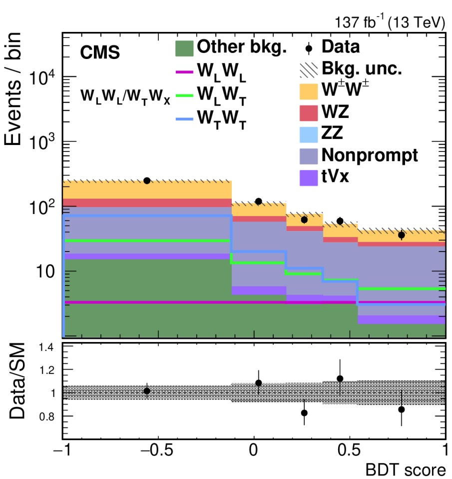
- First attempt to **measure the different polarization contribution** to the total pp → WWjj cross section

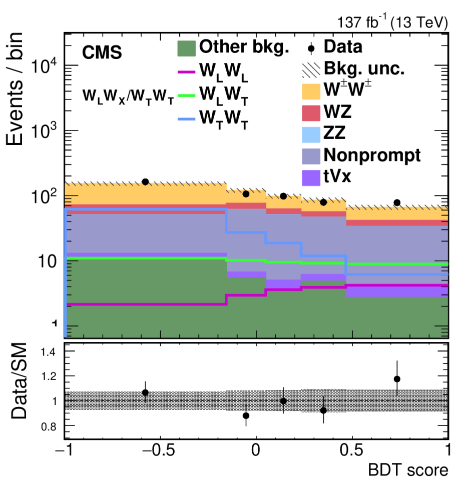






- Make use of boosted decision tree technique and perform two separate fits to extract either the **scattering of two longitudinally polarized Ws or at least one** longitudinal polarized W.

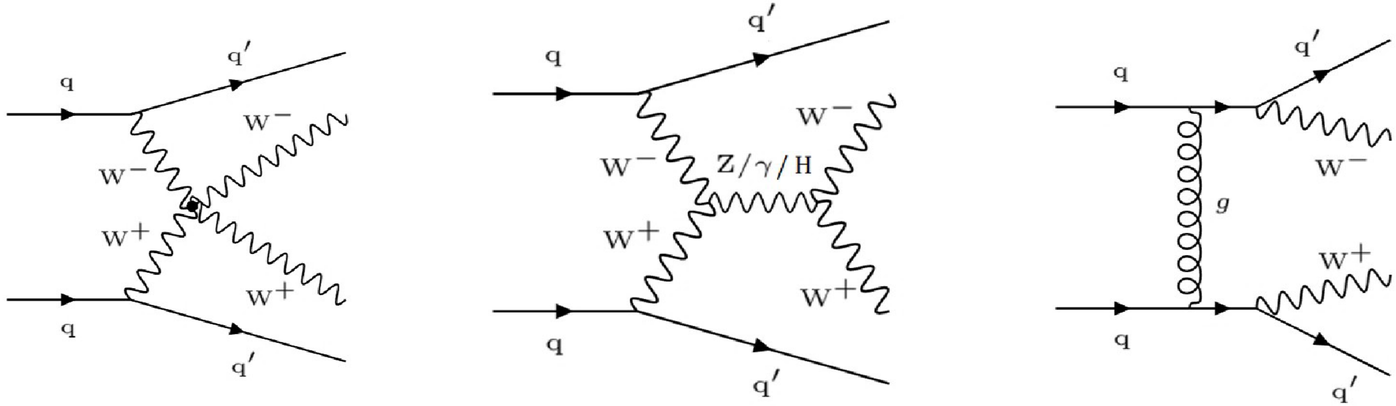




Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

PLB 812 (2020) 136018

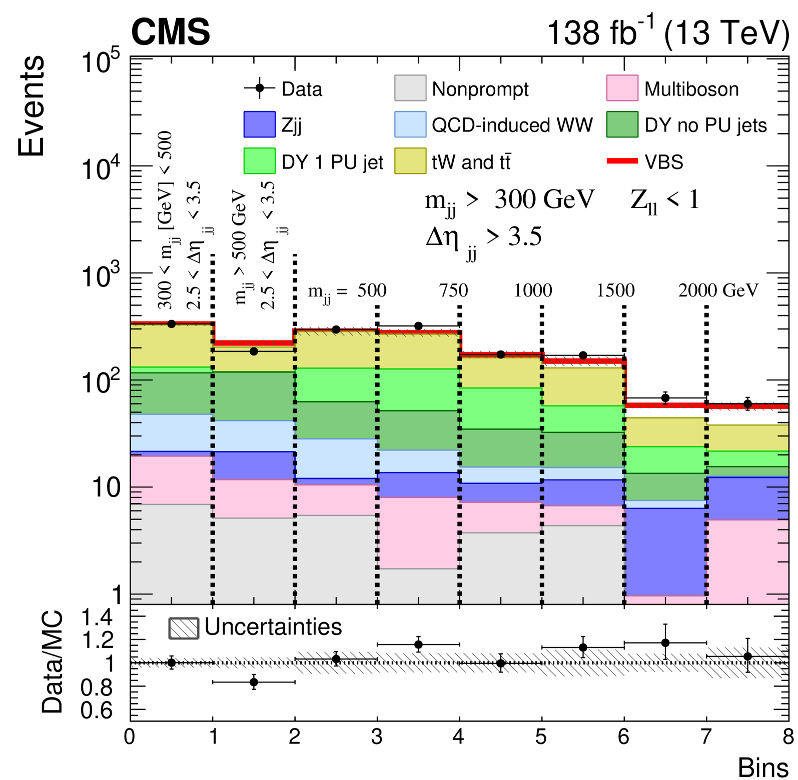
$pp \to W^{\pm}W^{\mp}jj$



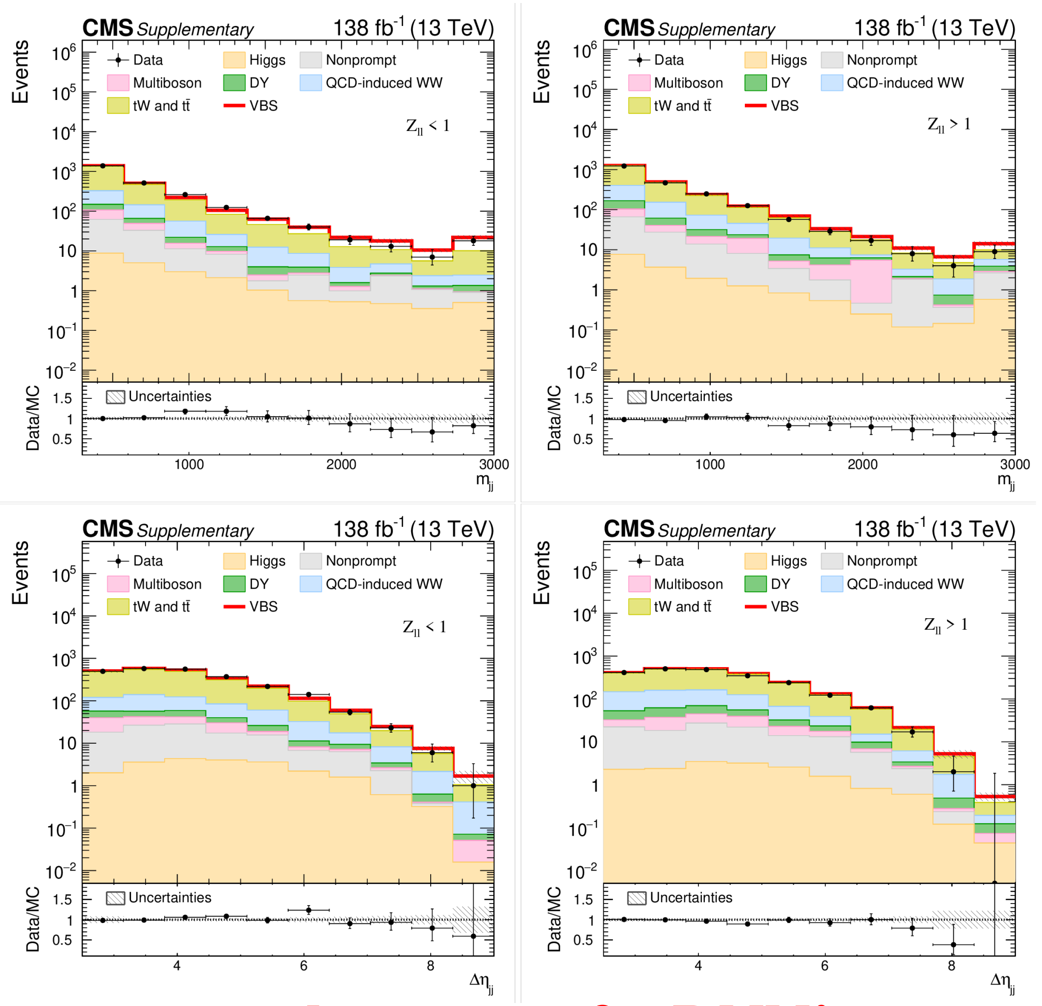
Opposite sign WW production in fully leptonic final states (e,μ)

- **Largest background from $t\bar{t}$ and tW** production and decay (~10x the signal in the SR), **followed by QCD-induced WWjets** (2.5x).
- Two SRs for each final state, based on a **Zeppenfeld variable** (< or > 1)

$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}| \qquad Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$



The most disciminating variables, m_{jj} and $\Delta\eta_{jj}$, are not enough to disentangle the signal from the background, although in the $Z_{ll} < 1$ SR the EW WWjj production is pretty visible at large values



→ **make usage of a DNN!**

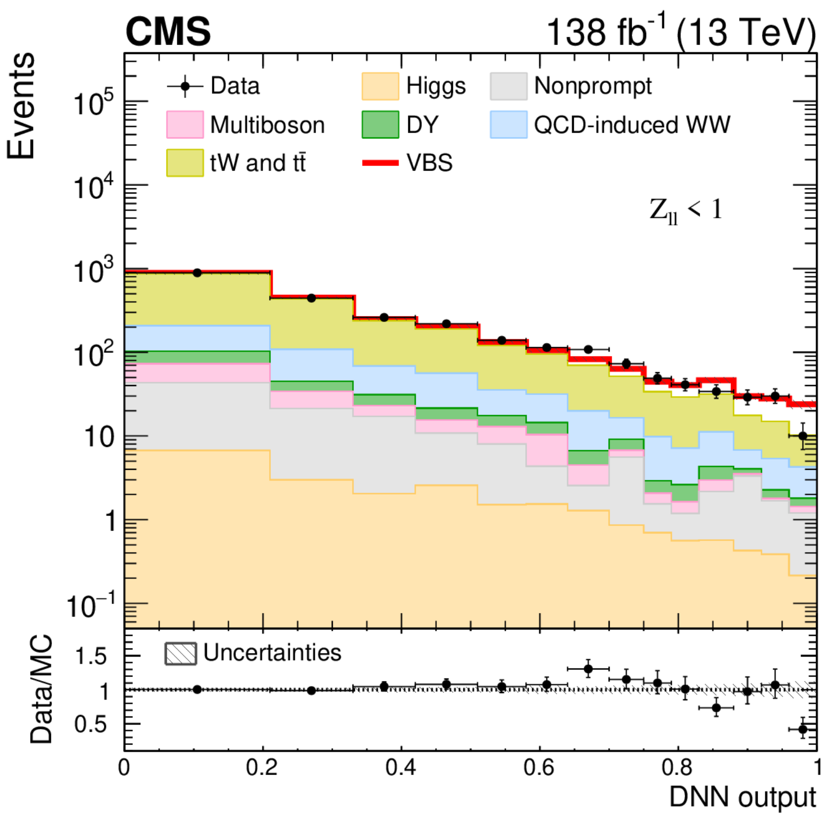
$pp \to W^{\pm}W^{\mp}jj$

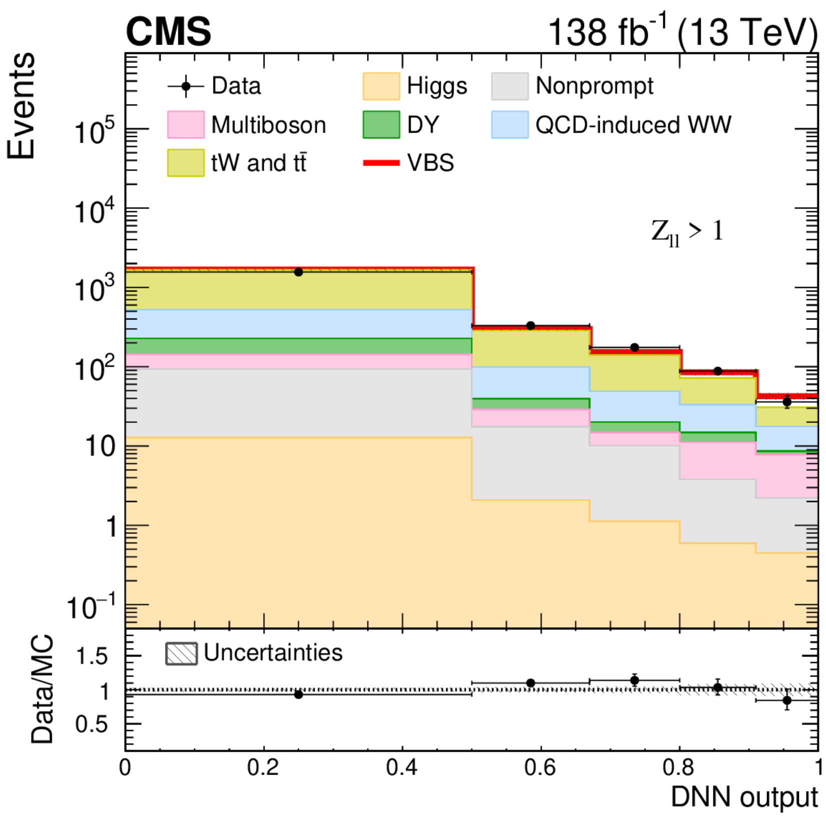
SMP-21-001

Variable	Description
m_{jj}	Invariant mass of the two tagging jets pair
$\Delta\eta_{jj}$	Pseudorapidity separation between the two tagging jets
$p_T^{j_1}$	p_T of the highest p_T jet
$p_T^{j_2}$	p_T of the second-highest p_T jet
$p_T^{\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest p_T lepton
Z_{ℓ_2}	Zeppenfeld variable of the second-highest p_T lepton
$m_T^{\ell_1}$	Transverse mass of the $(p_T^{\ell_1}, p_T^{miss})$ system

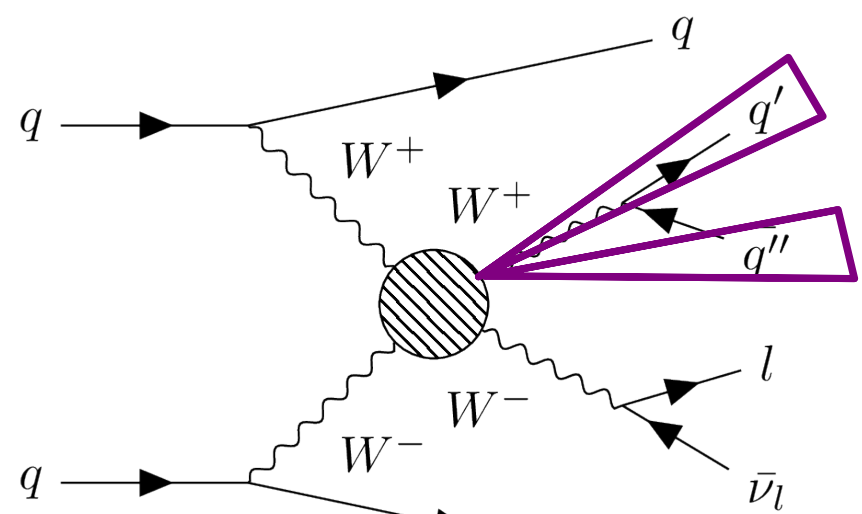
- EW $W^{\pm}W^{\mp}jj$ fiducial cross-section:
  - Measured: σ_{EW} **= (10.2±2.0) fb**
  - LO predicition: $\sigma_{EW} = (9.1 \pm 0.6)$ fb
- With an **observed** (*expected*) significance of **5.6σ** (*5.2σ*)

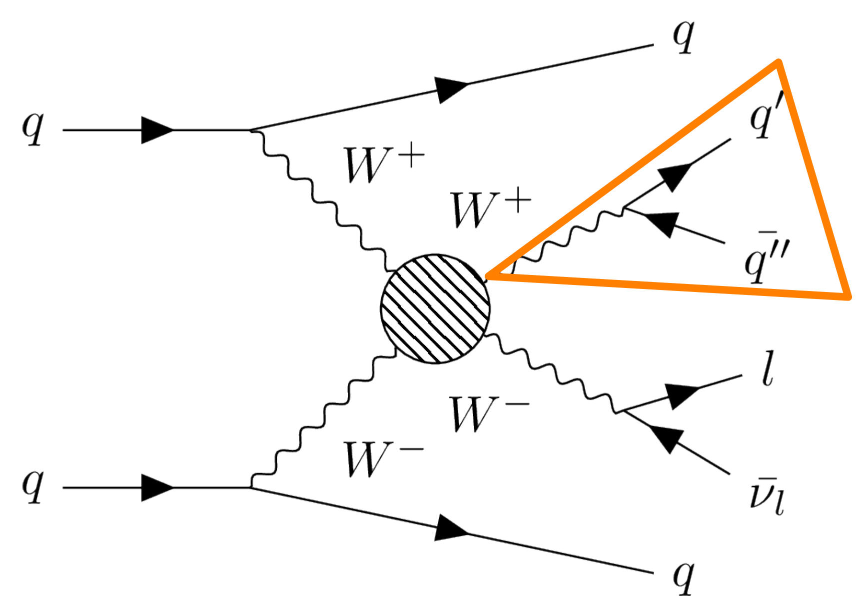
→ **first observation ever!**





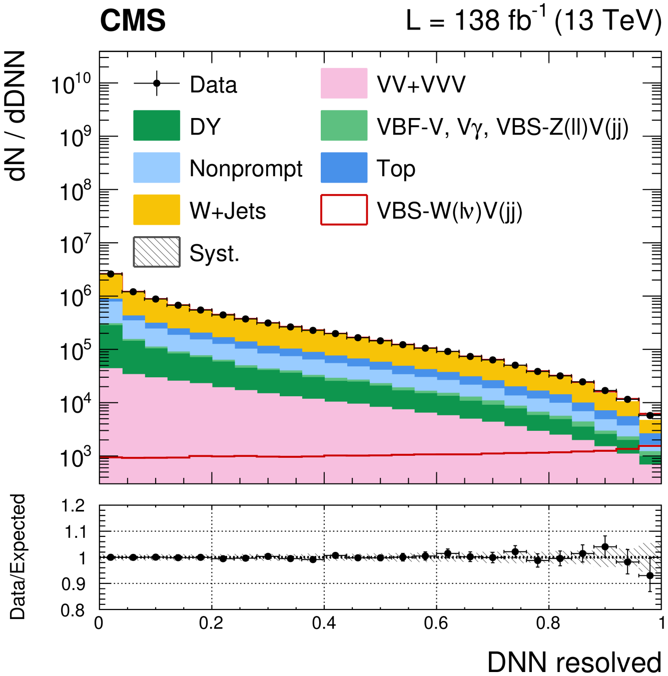
- **First evidence** of the pp → $WVj_{tag}j_{tag}$ → $\ell\nu$ 2j $2j_{tag}j_{tag}$ process at LHC
- Searched it in **two topologies**:
  - **Resolved**: search the vector boson decay in two separate ΔR = 0.4 jets
  - **Boosted**: look for the vector boson reconstructed in a unique ΔR = 0.8 jet
- **Contribution from QCD-induced process is very large**. A careful estimation has been done.
  - Dedicated control regions to costrain main sources of backround
- Make use of a DNN discriminator in both categories

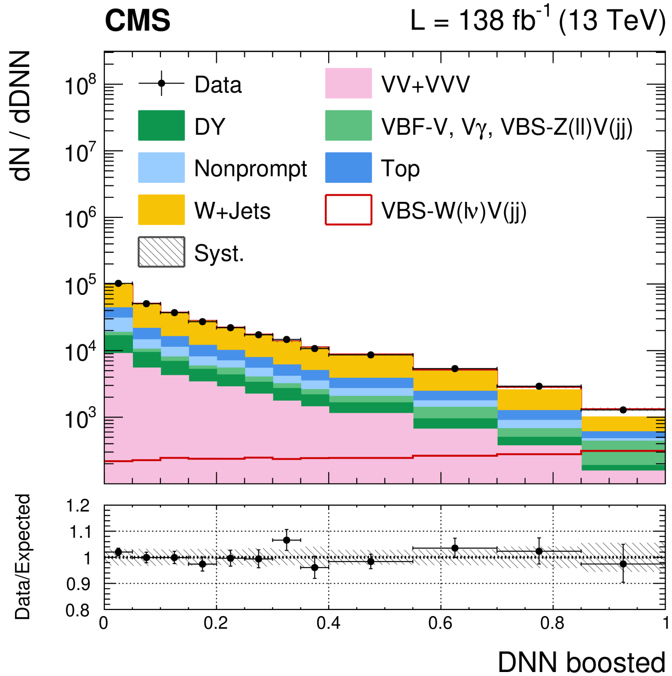


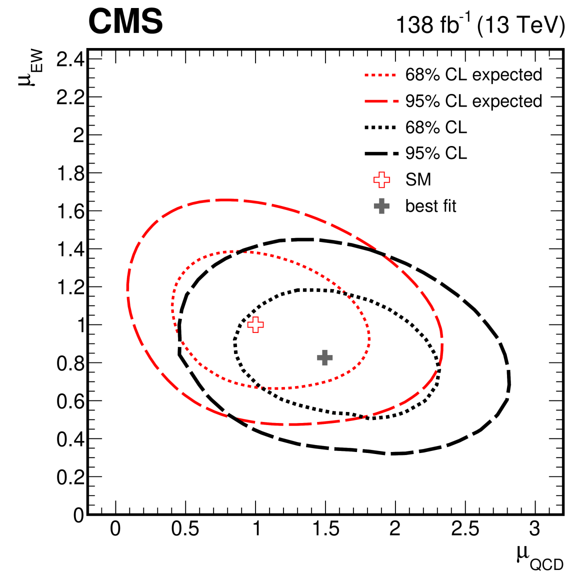


pp → $W^{\pm}Vjj$, V=W,Z

SMP-20-013







- **Simultaneous fit** of the **SRs** and the dedicated **CRs** fot W+jets and $t\bar{t}$
- **Extract separately** EW WVjj and EW+QCD WVjj signal strenght (μ)
- Extract the μ_{EW} and μ_{QCD} with a **2D simultanous fit**

Observed (expected) significance = **4.4σ** (5.1σ)

$$\sigma_{EW+QCD} = 16.4^{+3.5}_{-2.8}\ pb$$

$$\sigma_{EW} = 1.90^{+0.53}_{-0.46}\ pb$$

ZZ+jets analysis

Search for two **on-shell** (**60 < $m_{\ell\ell}$ < 120 GeV**) **Z** bosons decaying into **electrons** or **muons** pairs, consider jets if their p_T is > 30 GeV

Pros

- Final state can be **fully reconstructed**

  → **all kinematic variables are accessible**

- **Very clean** final state

  → **low reducible background**

Cons

- **Low σxBR** compared to other channels

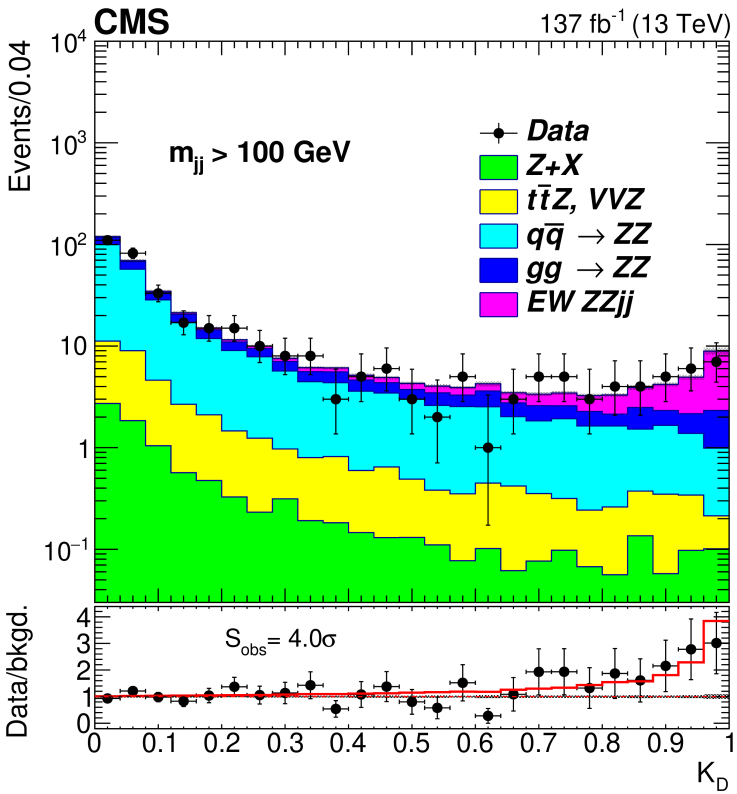
  → **maximize the selection efficiency** (minimal cuts on lepton mainly driven by trigger thresholds, detector acceptance)

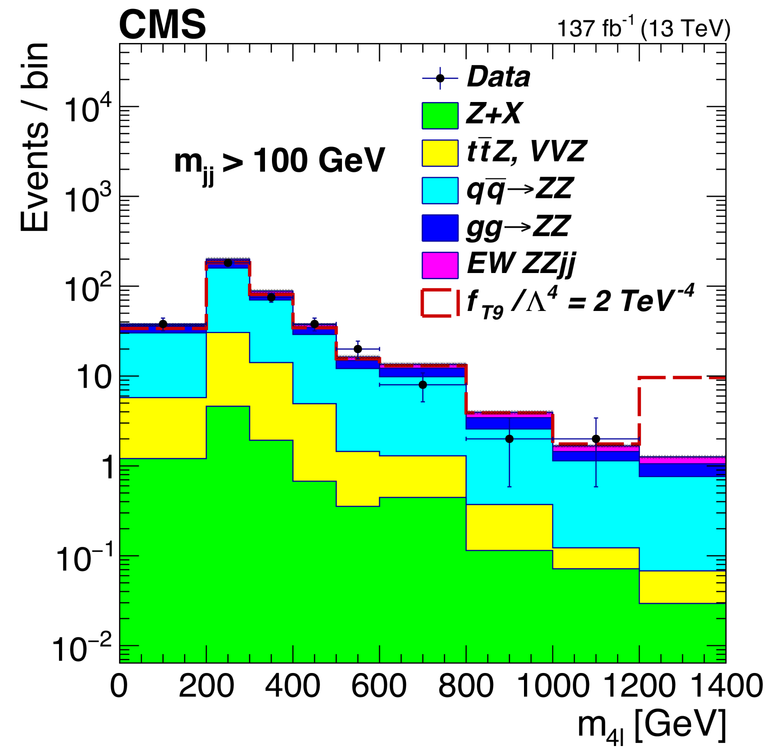
- **ZZ + QCD-induced jets** (irreducible background) **highly dominant** compared to pure EW production

  → **understanding of the irreducible background is paramount**

pp → ZZjj

SMP-20-001





Evidence of the electroweak production of ZZ+jets with **4.0** (3.5) σ obs (exp)

$$\sigma_{\mathrm{EW}} = 0.33^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.04}_{-0.03}\,(\mathrm{syst})\,\mathrm{fb}$$

Among the lowest cross sections measured so far at LHC!

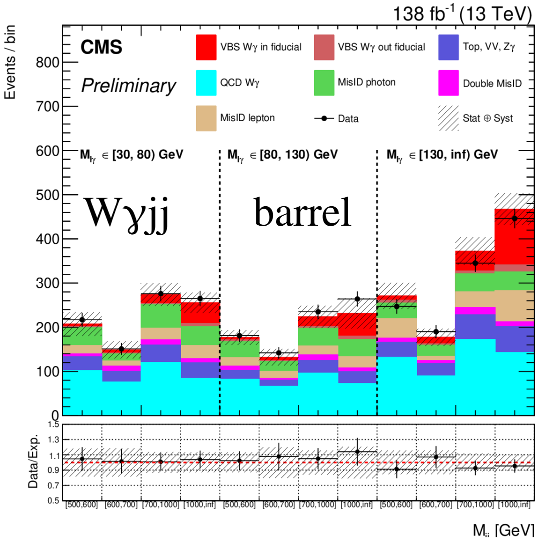
- **Access to neutral dim-8 operators** T8 and T9, not accessible in other VBS processes with massive bosons only

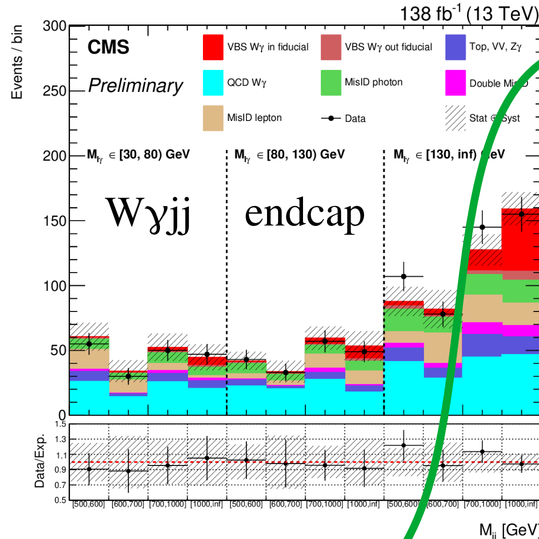
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

- Set **strict bounds** on these sets of operators, inaccessible in charged gauge boson final states
- Results take into account the **unitarity bounds**

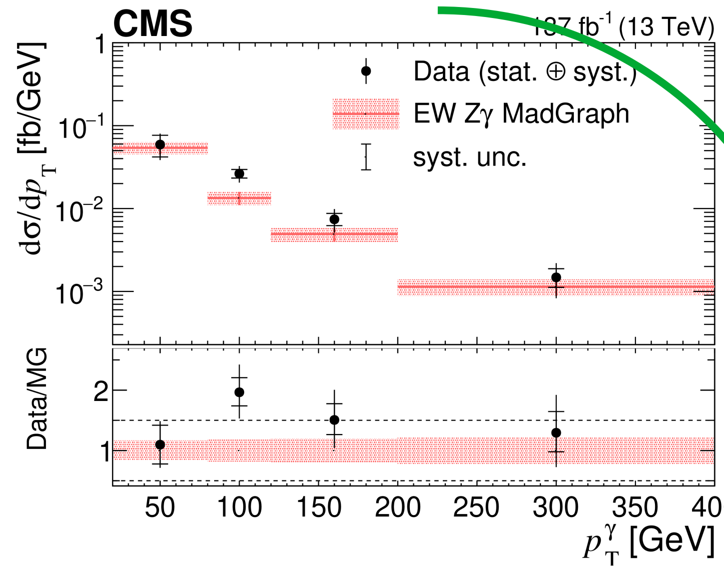
pp → Zγjj and pp → Wγjj

SMP-20-016
SMP-21-011

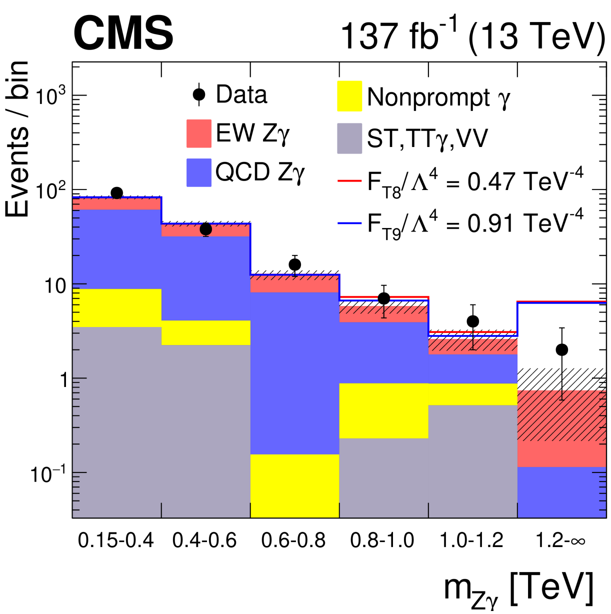




Allows the measurement of differential cross sections



Clear evidence of the process



and stringent limits on dim-8 operators.

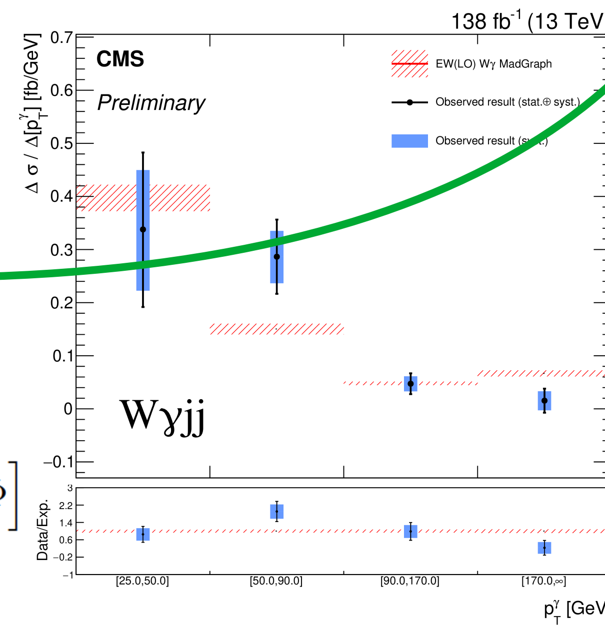
Zγjj:

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Wγjj:

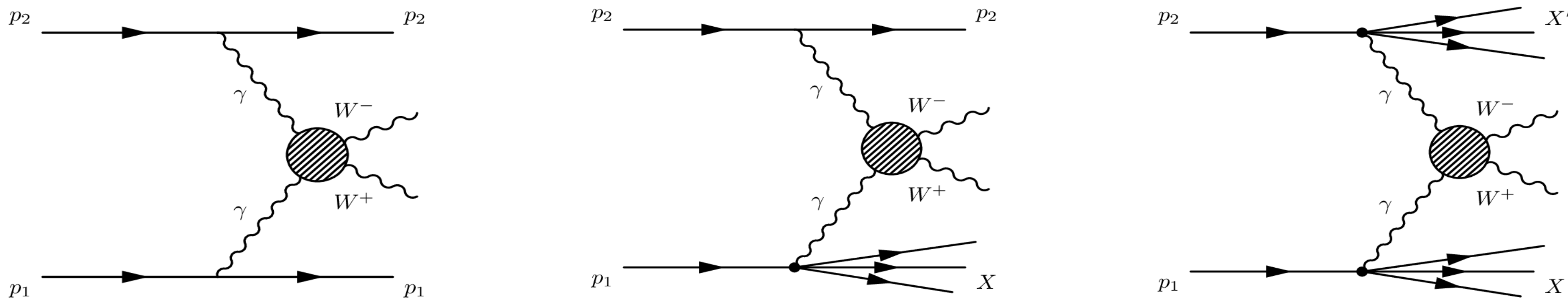
$$\mathcal{L}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$



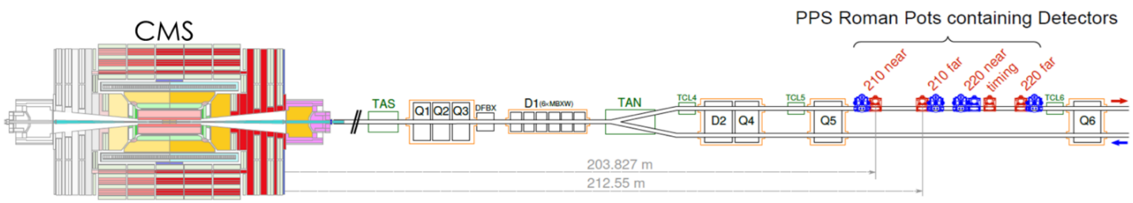
$pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)}VVp^{(*)}$

SMP-21-014

- **Single and double proton** channel detected in the very forward-backward regions



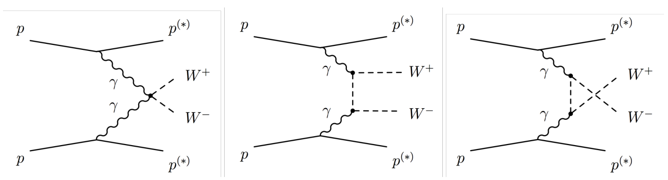
- Interaction of **quasi-real photons** (very low q^2)
- Search for one or two **intact protons** in PPS in central events with 2 jets



- Access to the full kinematics of the event!

  → **Can directly access the EW gauge boson interactions**

- Very rare process: $\boldsymbol{\sigma_{qq\rightarrow WW} \approx O(10^3)\, \sigma_{\gamma\gamma\rightarrow WW}}$

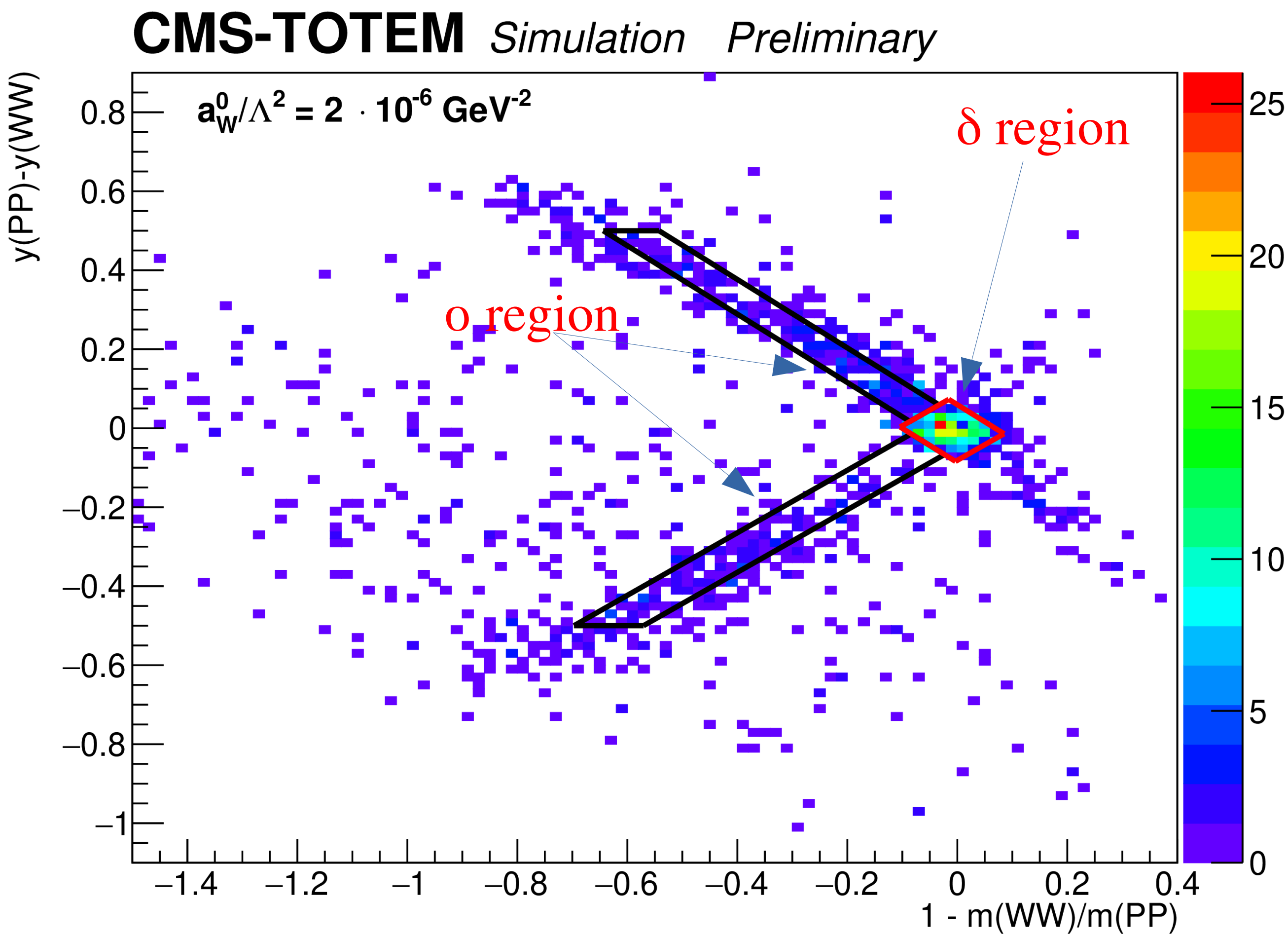


$pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)}VVp^{(*)}$

SMP-21-014

$\xi = \Delta p_p/p_p$ is measured with PPS and it is used to cumpute the **rapidity** and the **invariant mass of the pp system**

$$y(pp)=\frac{1}{2}\log\frac{\xi_1}{\xi_2} \qquad m(pp)=\sqrt{s\,\xi_1\,\xi_2}$$



Signal regions:

- In the **red** diamond (δ):
  m(VV) = m(pp)
  y(VV) = y(pp)

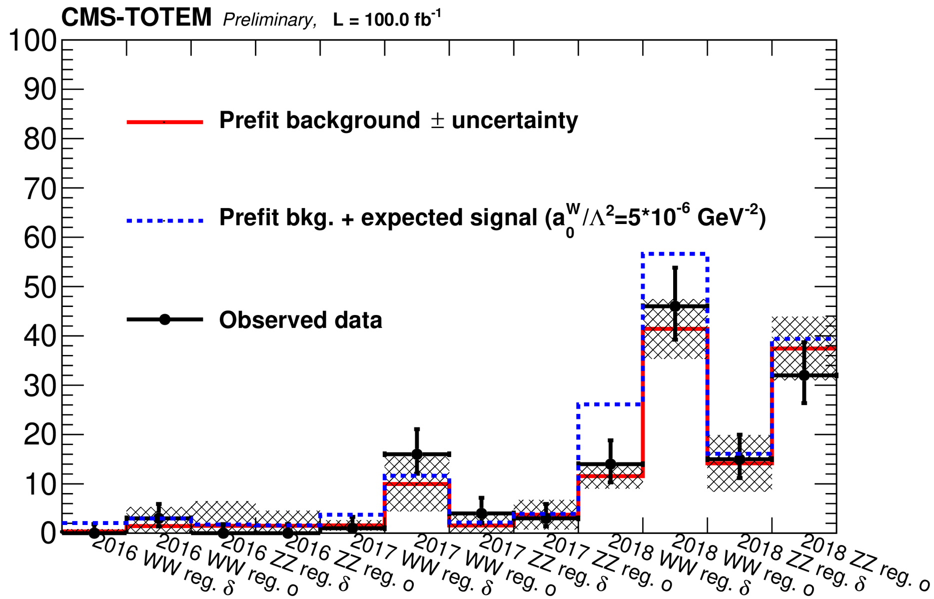
- the **black** diagonal bands (o):
  one proton is correctly matched, the other comes ***from pileup events***
  → **Still considered as signal**

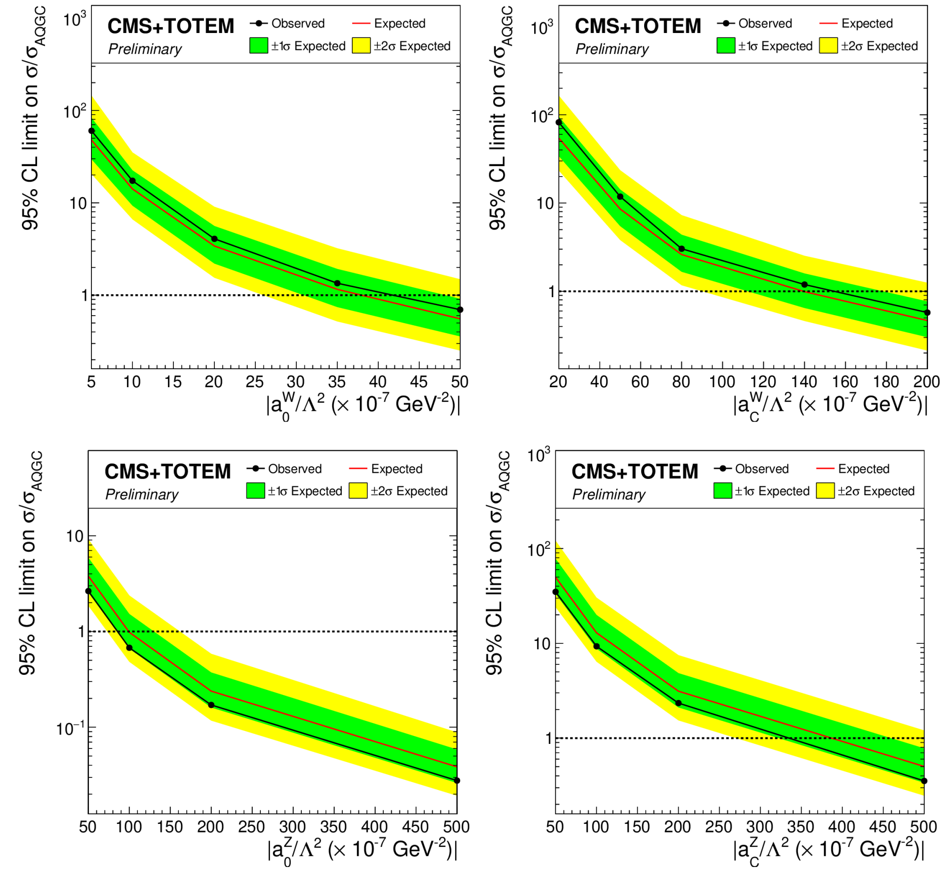
Key selection:
At least two fat jets, with $|\eta| < 2.5$, $p_T > 200$ GeV, $|\eta(j1) - \eta(j2)| < 1.3$.
m_{jj} range: 1126 - 2500 GeV, both jets V-tagged.

Main background from QCD dijet production, estimated with 'ABCD' method

$pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)}VVp^{(*)}$

SMP-21-014





- **Dim-6 γγWW aQGC limits ~15 – 20x more stringent** than the unitarized limits obtained from the γγ → WW without proton tag in Run 1
- **Dim-8 limits close** to CMS same-sign WW and WZ scattering analyses at 13 TeV after unitarization
- **First γγZZ limits through the exclusive γγ → ZZ**
- New **limits on the fiducial cross section** for TeV-scale

Limits on the fiducial cross sections

$$\sigma(pp \rightarrow pWWp)_{0.04<\xi<0.20,\, m>1000\,GeV} < 67\left(53^{+34}_{-19}\right) fb$$

$$\sigma(pp \rightarrow pZZp)_{0.04<\xi<0.20,\, m>1000\,GeV} < 43\left(62^{+33}_{-20}\right) fb$$

Conclusions

- We discovered a Higgs boson, yet **the comprehension of the Electroweak Symmetry Breaking <u>is not completed</u>**

  → Understanding the Multi-boson production in association with jets is the key point!

  – **Complementary** to Higgs boson properties studies and high mass searches

- **Observation/evidence of all VVjj electroweak production processes**

Time to enter in the differential cross section measurements,
Especially those sensitive to the <u>vector boson polarization</u>

→ they will be ones of the hot topic of LHC Run III data analysis!

Details on results can be found in the public pages of the CMS experiments
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Instructions to directly access the analysis page

CMS

- For pubblications

  http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-YY-XXX/index.html

- For PAS

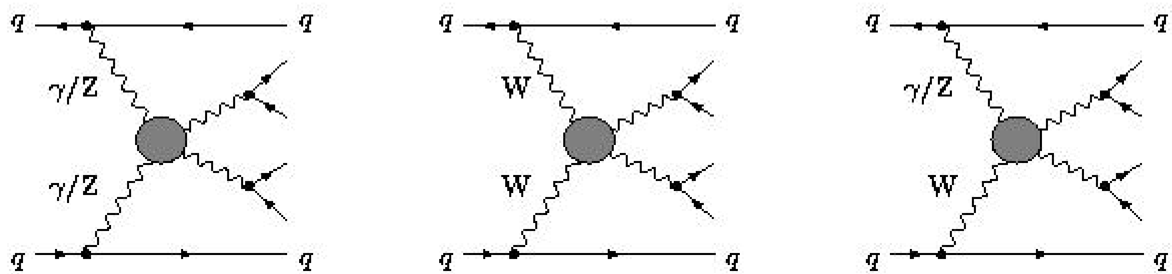
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-YY-XXX/index.html

Additional material

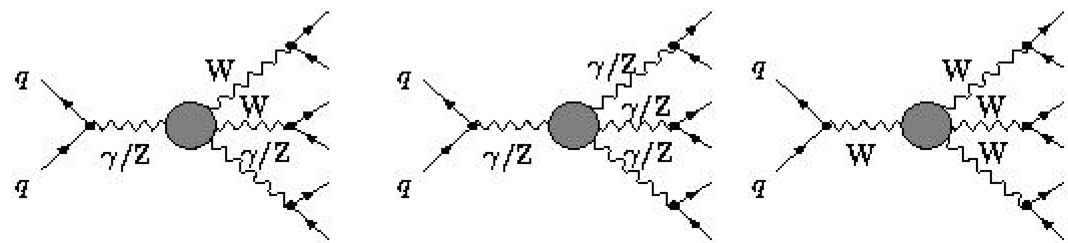
VBS, where to find it

Six-fermions final state at leading order α^6, or **four-fermions** and a photon at $\mathcal{O}(\alpha^5)$

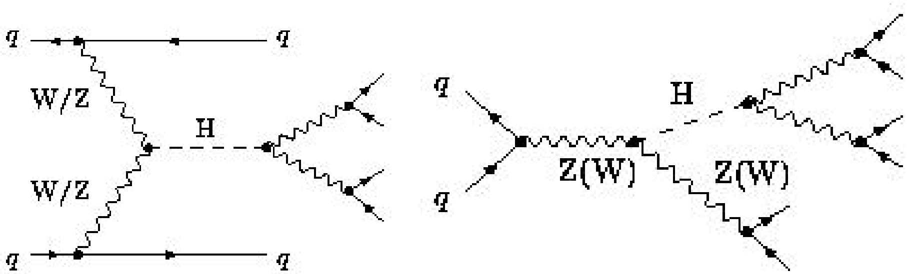
VV scattering →



Triboson →

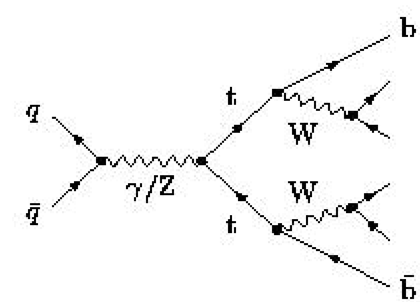


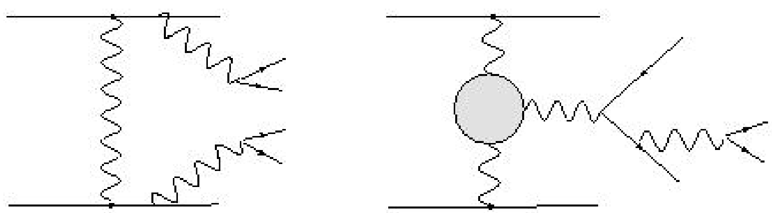
… however, also this diagrams are present and **cannot be neglected**



← Higgs

top-top (EW) →



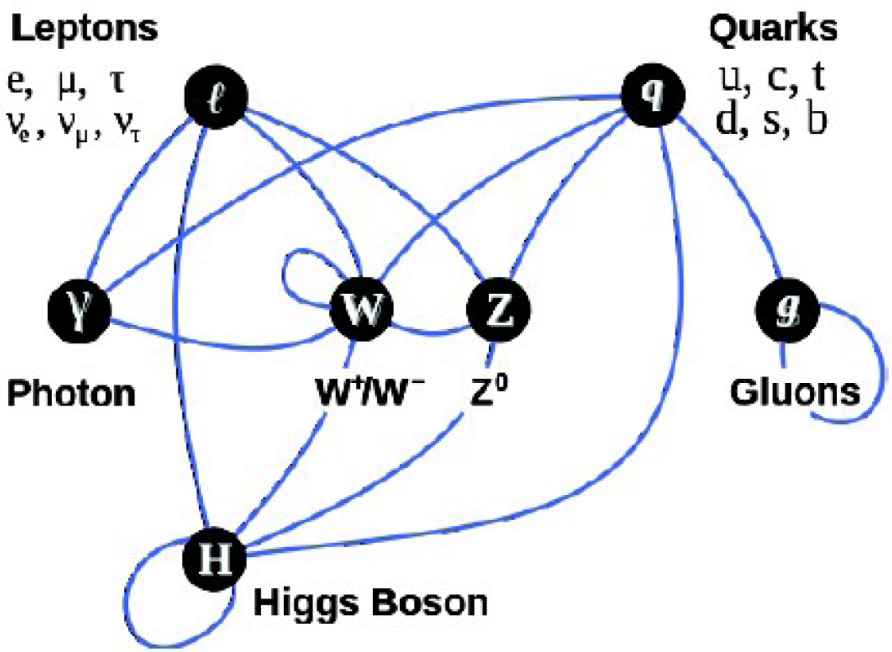


← VV and non resonant

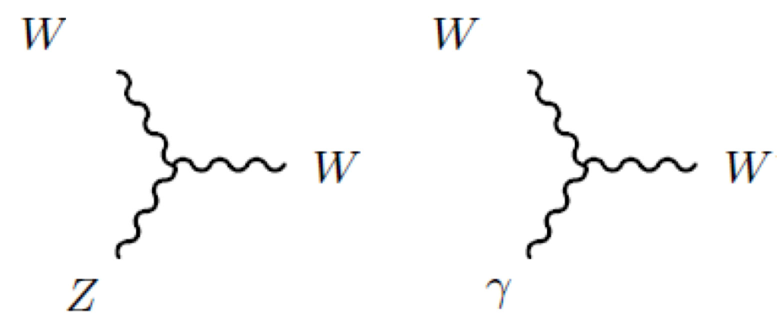
Why multiboson interaction is so important?

- **Test of the non-Abelian structure of the Electroweak theory** of the Standard Model
- **Validation of the perturbative calculations**
- **Test of standard model couplings**
  - In vector boson scattering processes, the unitarity is preserved via Higgs contributions, if not the **cross section rise as a function of the invariant mass of the $V_L V_L$ system**
  - **Test the gauge structure of the EW interactions**, as it is sensitive at three level to quartic gauge couplings
  - **Test the couplings** between the Higgs and gauge bosons
- Search for **new physics**
  - Through **resonances**, if the new particle mass is accessible w/ LHC
  - Through **deviations** if the energy scale of new physics is higher than those reachable at the LHC

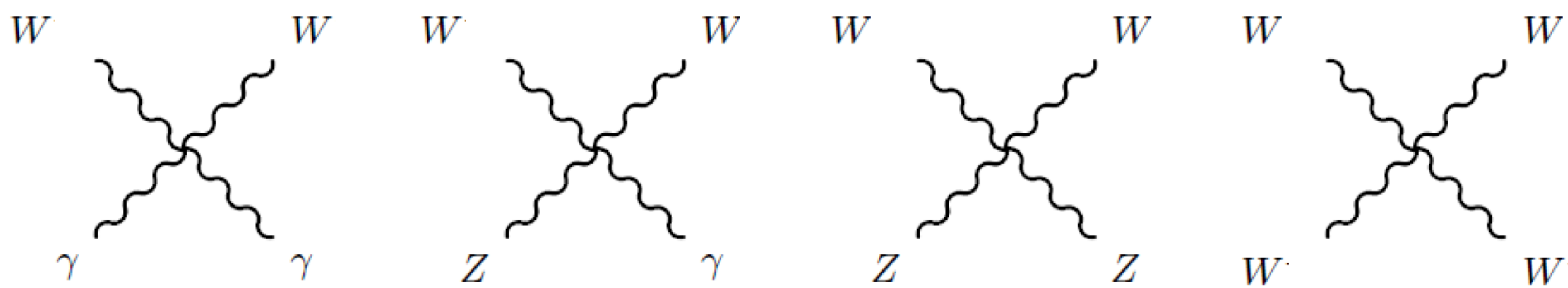
What do we mean with Triple and Quartic Gauge Couplings?

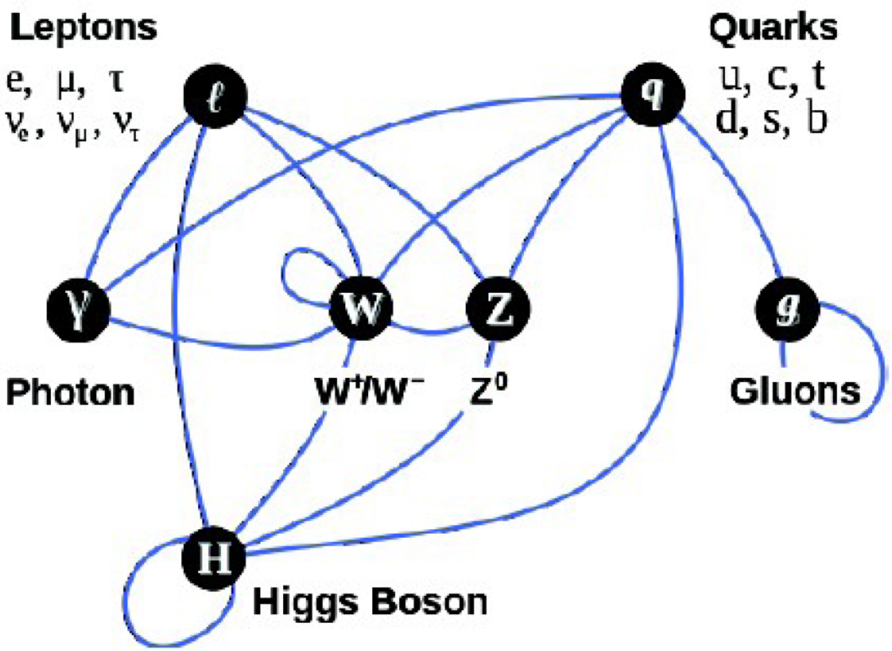


- **Triple gauge couplings (TGC)**

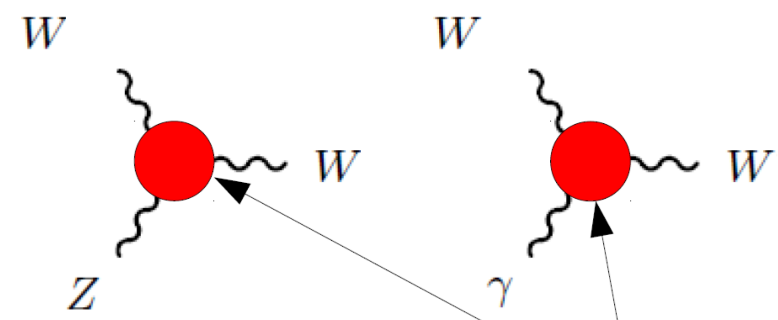


- **Quartic gauge couplings (QGC)**



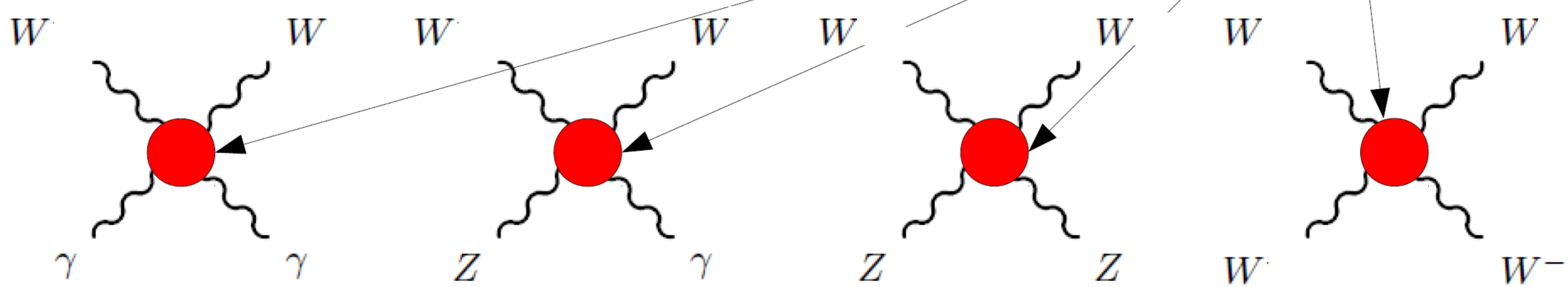


- Triple gauge couplings (TGC)

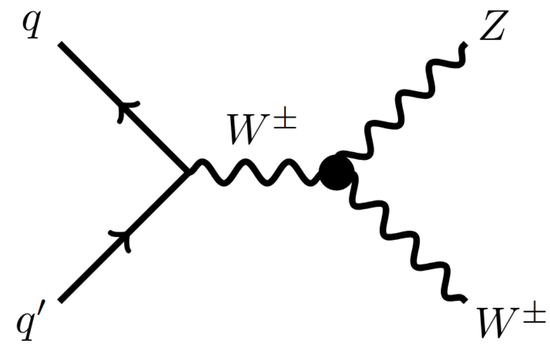


Anomalous couplings
+ what forbidden in SM

- Quartic gauge couplings (QGC)



Parametrization of new physics: Anomalous Gauge Couplings



Traditional parametrization for diboson production

(assuming CP conservation, Lorentz invariance, U(1)EM gauge invariance)

$$\mathcal{L}_{WWZ} = -ig\cos\theta_W \Big[g_1^Z (W^+_{\mu\nu} W^{-\mu} Z^\nu - W^-_{\mu\nu} W^{+\mu} Z^\nu) + \kappa^Z W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W^+_{\rho\mu} W^{-\mu}_{\ \ \nu} Z^{\nu\rho} \Big]$$

$$\mathcal{L}_{WW\gamma} = -ie \Big[(W^+_{\mu\nu} W^{-\mu} A^\nu - W^-_{\mu\nu} W^{+\mu} A^\nu) + \kappa^\gamma W^+_\mu W^-_\nu F^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^+_{\rho\mu} W^{-\mu}_{\ \ \nu} F^{\nu\rho} \Big]$$

with

$$g_1^Z = 1 + \delta g_1^Z, \;\; \kappa^{Z,\gamma} = 1 + \delta\kappa^{Z,\gamma}$$

and from SU(2) invariance

$$\delta g_1^Z = \delta\kappa^Z + \frac{s_W^2}{c_W^2}\delta\kappa^\gamma$$

$$\lambda^\gamma = \lambda^Z$$

See,e.g., C. Degrande et al, 10.1016/j.aop.2013.04.016

Parametrization of new physics: SM Effective Field Theory (SMEFT)

- We can add to the SM lagrangian a series of dimension > 4 operators with a "new physics" cutoff Λ:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,k} \frac{C_k^d}{\Lambda^{d-4}} \mathcal{O}_k^d$$

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- For example, for d = 6, we can have operators like

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
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Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
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Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
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Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

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Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
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Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
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Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

In case we truncate the series to **d = 6**, then we have a simple relation with the aGC view

$$\delta\kappa^\lambda = -\frac{v^2}{\Lambda^2}\frac{c_W}{s_W}C_{HWB}, \quad \lambda^Z = \frac{v}{\Lambda^2}3M_W C_W$$

e.g., see I. Brivio and M. Trott, Phys. Rep. 793 (2019) 1

The EFT is more general and in present days is the preferred framework for the interpretation of the experimental results

Few key points in SMEFT

- The effective field theory reveals high energy physics through precise measurements at low energies . **Its validity is for E << Λ**.
- It allows us to **compute precise cross sections** starting from the lagrangian

from Lagrangian …

$$\underbrace{\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}}_{\text{SM}} + \sum_{m=1}^{N_6} \underbrace{\frac{c_m}{\Lambda^2}\mathscr{O}_i^{(6)}}_{\text{EFT}_{d6}} + \sum_{n=1}^{N_8} \underbrace{\frac{b_j}{\Lambda^4}\mathscr{O}_i^{(8)}}_{\text{EFT}_{d8}} + \dots$$

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Linear EFT cross-sections: interference SM-EFT$_{d6}$

Quadratic EFT cross-sections: squares EFT$_{d6}$

R. Ruiz

to cross-sections ....

$$\sigma_{\mathrm{SMEFT}}\left(c,\Lambda\right) \simeq \sigma_{\mathrm{SM}} \times \left(1 + \sum_{m=1}^{N_6}\frac{c_m}{\Lambda^2}\sigma_m^{(\mathrm{eft})} + \sum_{m,n=1}^{N_6}\frac{c_m c_n}{\Lambda^4}\sigma_{m,n}^{(\mathrm{eft})}\right)$$

evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD with **SMEFT@NLO**

The **quadratic d6 cross section** contains both **pure** (i.e., m=n) and **mixed** contributions
When considering **d6 quadratic** term **one should include the d8 linear term**, unless the measurement is **proven to be insensitive** to the addition of the d6 quadratic term

Relevant dim-8 operators fo QGC

Relevant Operators	WWWW	WWZZ	ZZZZ	ZZZγ
$\mathcal{L}_{S,1}$ $\mathcal{L}_{S,2}$	✅	✅	✅	0
$\mathcal{L}_{M,0}$ $\mathcal{L}_{M,1}$ $\mathcal{L}_{M,6}$ $\mathcal{L}_{M,7}$	✅	✅	✅	✅
$\mathcal{L}_{M,2}$ $\mathcal{L}_{M,3}$ $\mathcal{L}_{M,4}$ $\mathcal{L}_{M,5}$	0	✅	✅	✅
$\mathcal{L}_{T,0}$ $\mathcal{L}_{T,1}$ $\mathcal{L}_{T,2}$	✅	✅	✅	✅
$\mathcal{L}_{T,5}$ $\mathcal{L}_{T,6}$ $\mathcal{L}_{T,7}$	0	✅	✅	✅
$\mathcal{L}_{T,8}$ $\mathcal{L}_{T,9}$	0	0	✅	✅

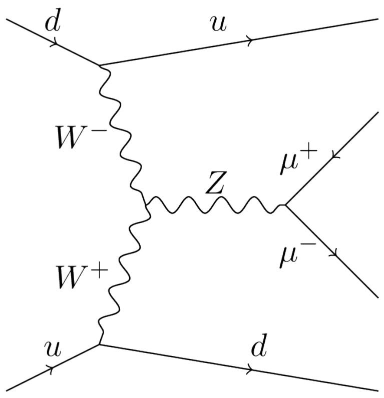
$pp \to Z\gamma jj$ and $pp \to ZZjj$

$$-0.24 < f_{T0}/\Lambda^4 < 0.22$$
$$-0.31 < f_{T1}/\Lambda^4 < 0.31$$
$$-0.63 < f_{T2}/\Lambda^4 < 0.59$$
$$-0.43 < f_{T8}/\Lambda^4 < 0.43$$
$$-0.92 < f_{T9}/\Lambda^4 < 0.92$$

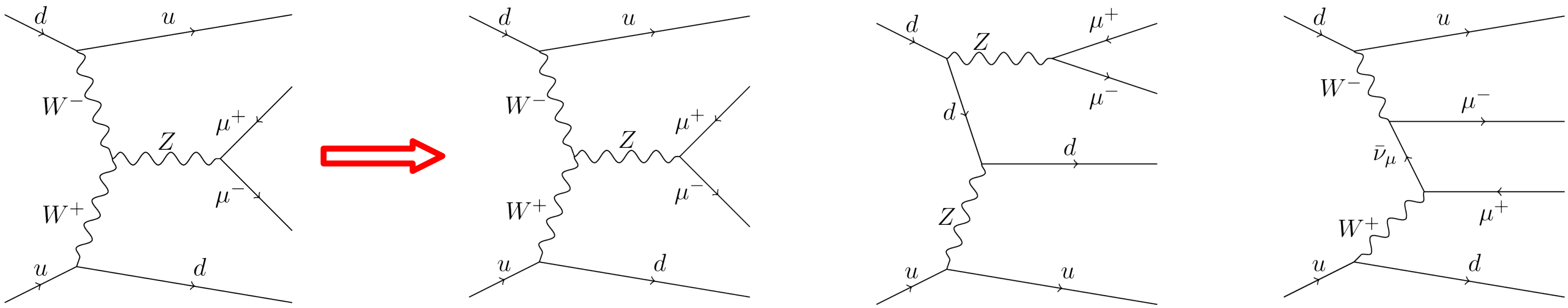
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

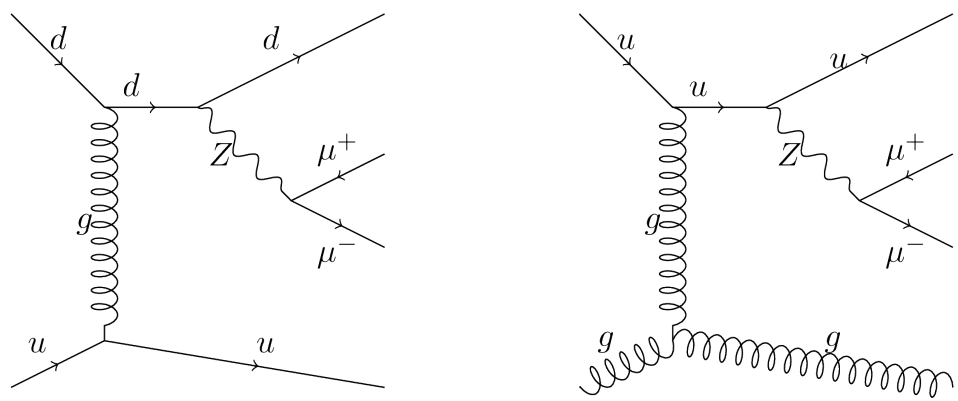
Production of W/Z via VBF

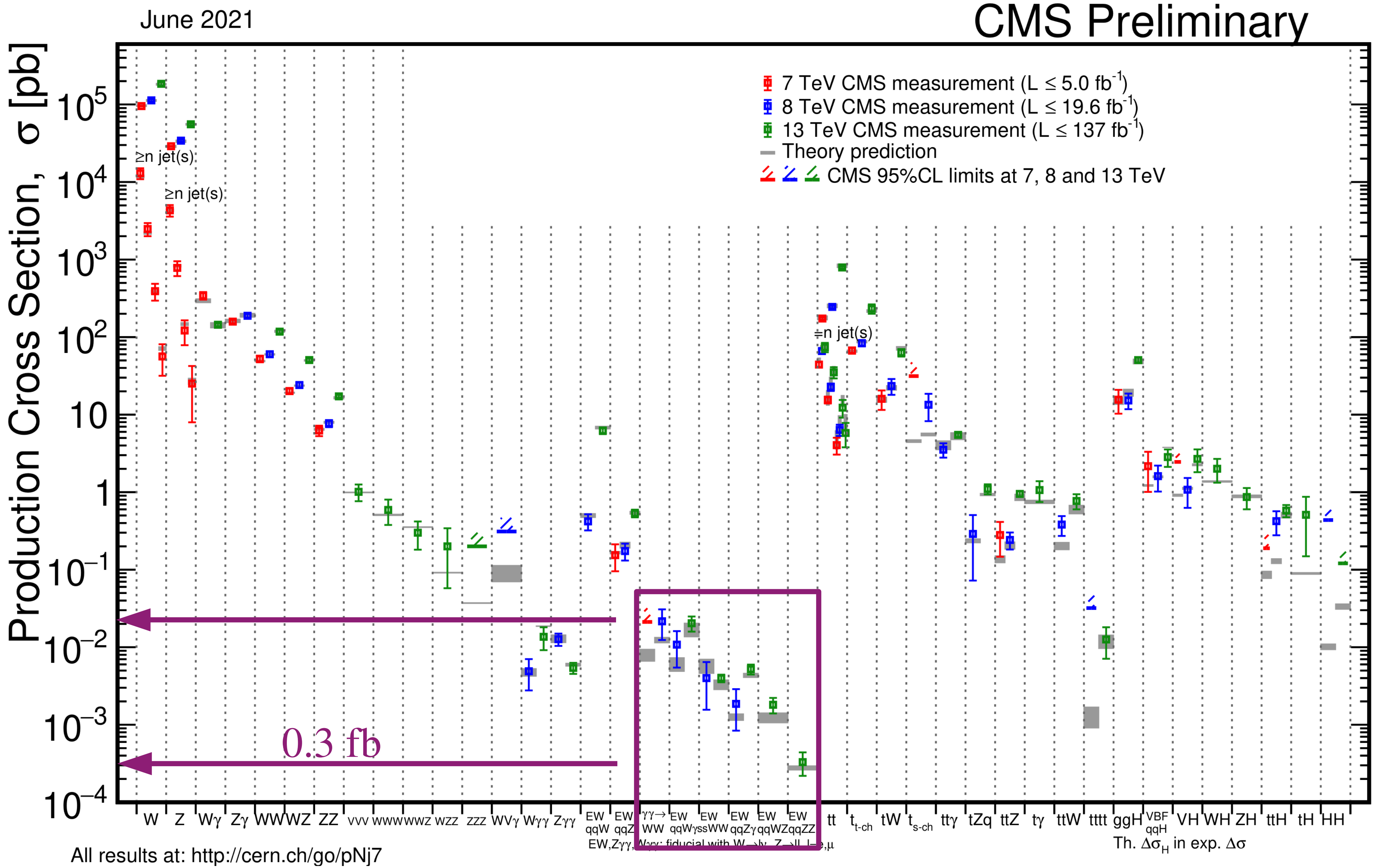


Production of W/Z via VBF

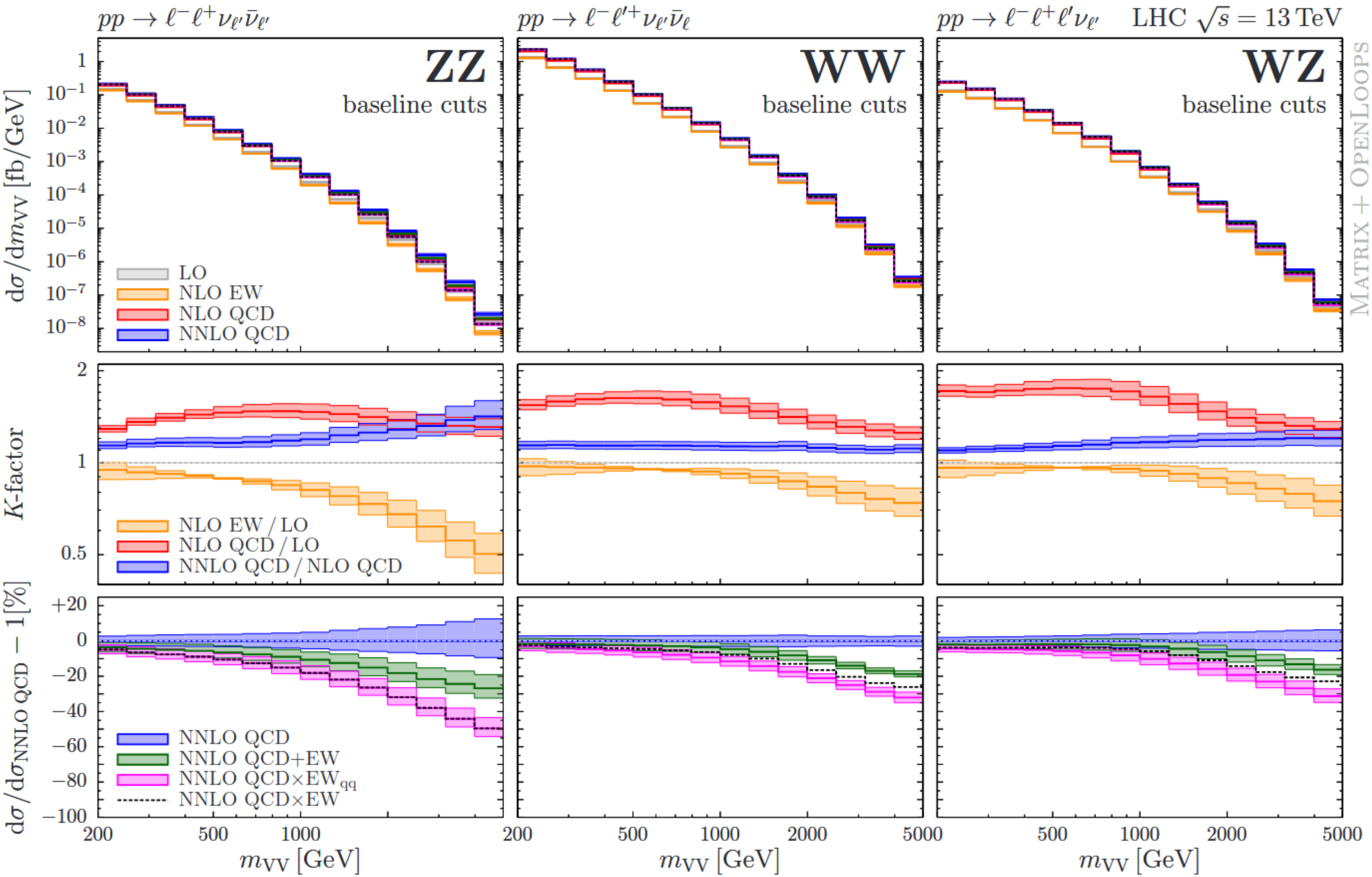


- The EWK V+2jets process - **Important SM benchmark**
  - Cross check and validate other VBF productions
- VBF V process:
  - **Central V decay associated with energetic forward-backward jets**
  - **Large invariant dijet mass and large η separation** between the tagging jets
- Pure EWK process :
  - **Suppressed color flow** between the quark-jets



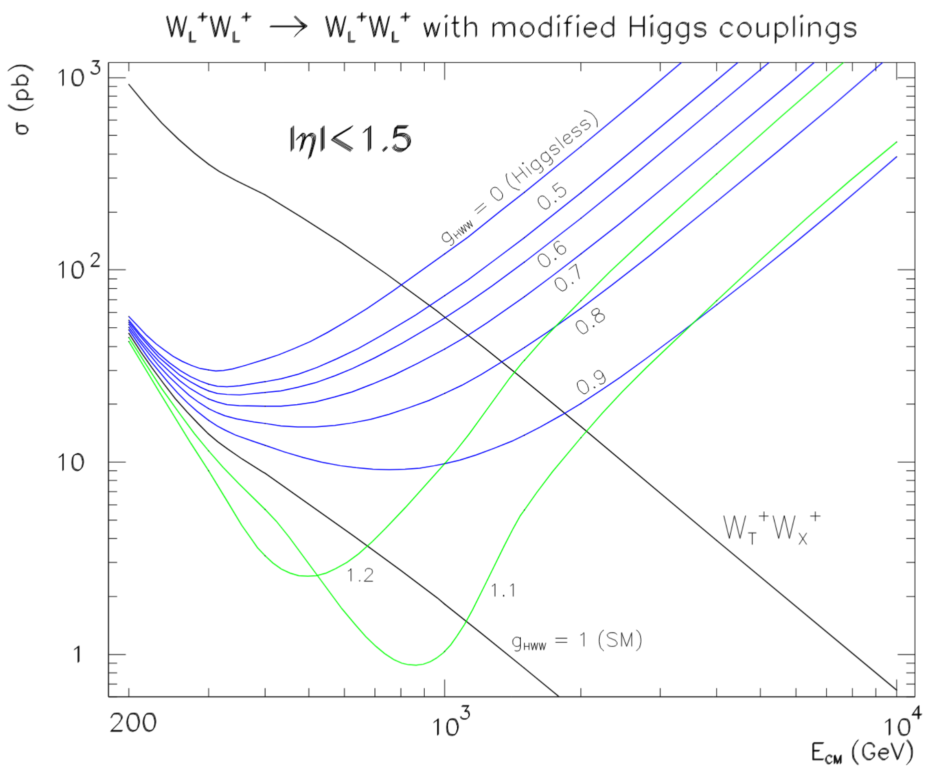

June 2021
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
0.3 fb
W Z Wγ Zγ WW WZ ZZ VVV WWW WWZ WZZ ZZZ WVγ Wγγ Zγγ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ tt t-ch tW s-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

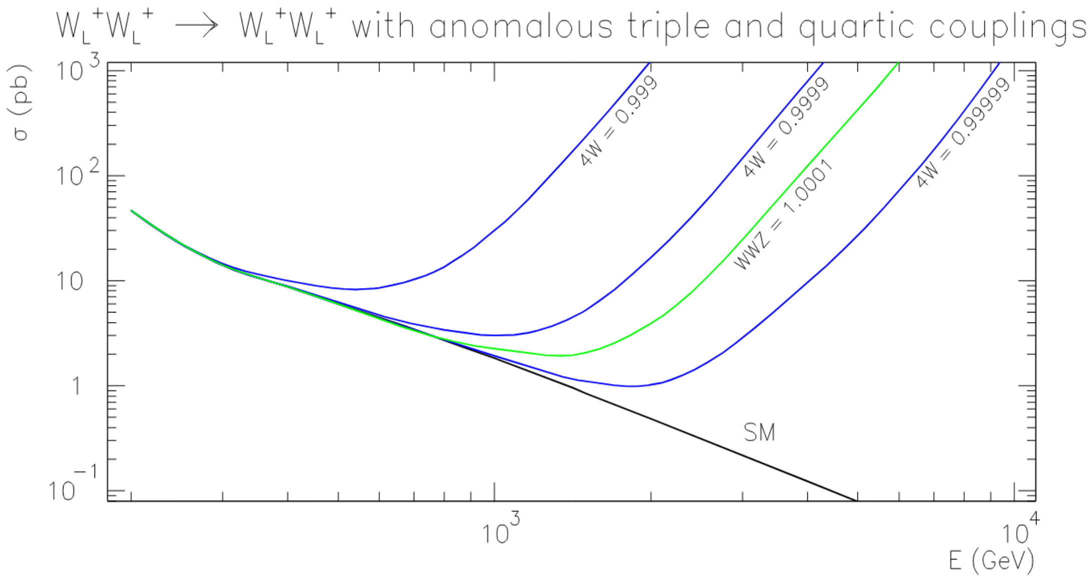
Validation of the perturbative calculations

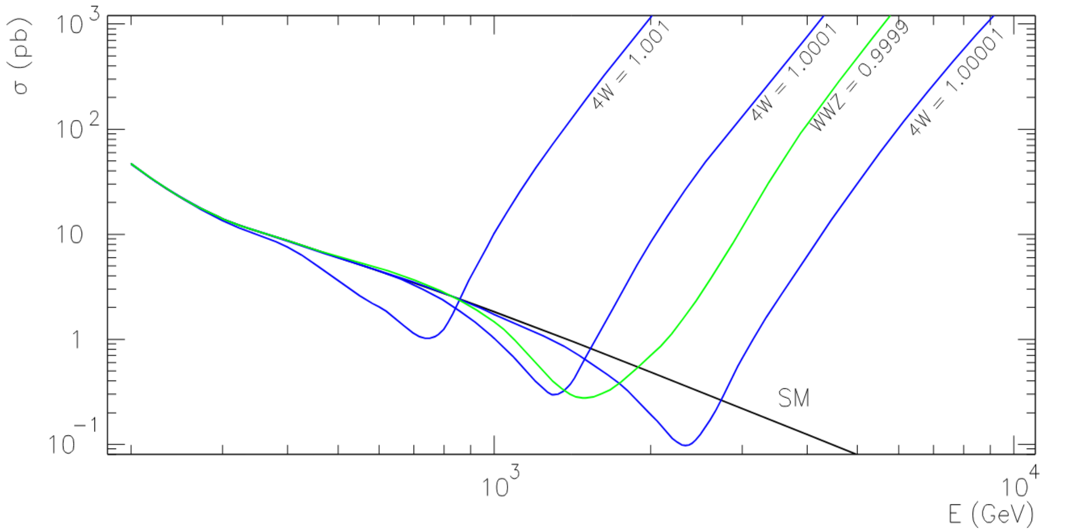


M. Grazzini et al, 10.1007/JHEP02(2020)087

If the cancellation of the Higgs diagrams is not complete, **then the $W_L W_L$ cross section will grows** as a function of √s, up to a new physics scale Λ







M. Szleper, arXiv:1412.8367

Electroweak production of Zjj

STDM-2017-27

Process	Generator	ME accuracy	PDF	Shower and hadronisation	Parameter set
EW Zjj	Powheg-Box v1	NLO	CT10nlo	Pythia8 + EvtGen	AZNLO
	Herwig7 + Vbfnlo	NLO	MMHT2014lo	Herwig7 + EvtGen	default
	Sherpa 2.2.1	LO (2–4j)	NNPDF3.0nnlo	Sherpa	default
Strong Zjj	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default
	MadGraph5_aMC@NLO	NLO (0–2j), LO (3–4j)	NNPDF2.3nlo	Pythia8 + EvtGen	A14
	MadGraph5	LO (0–4j)	NNPDF3.0lo	Pythia8 + EvtGen	A14
VV	Sherpa	NLO (0–1j), LO (2–3j)	NNPDF3.0nnlo	Sherpa	default
$t\bar{t}$	Powheg-Box v2 hvq	NLO	NNPDF3.0nnlo	Pythia8 + EvtGen	A14
VVV	Sherpa	LO (0–1j)	NNPDF3.0nnlo	Sherpa	default
W+jets	Sherpa	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default

Anomalous vector boson couplings

- Search for **new physics** *while doing* **EW measurements**
- Look for deviations from SM in tail of distributions (**m_{VV}, m_{ll}, m_{jj}, $p_{T,V}$**, …)
- Parametrize the new physics **adding terms to the SM lagrangian**
- Several possibilities, for the analyses presented here we made use of the **Effective field theory approach** [Phys. Rev. D 48(1993) 2182, Phys. Rev. D 74 (2006) 073005] to extract limits on **anomalous quartic gauge couplings**
- Parameters are varied ***one-by-one***, with the exception of the WZjj analysis in which we varied two parameters at a time
- Designed an analysis (SMP-18-006) **specifically to search for aQGC in WW/WZ/ZZ + jets production**, in final states where the vector bosons have been decayed semileptonically

Anomalous Quartic Gauge Couplings Modelling

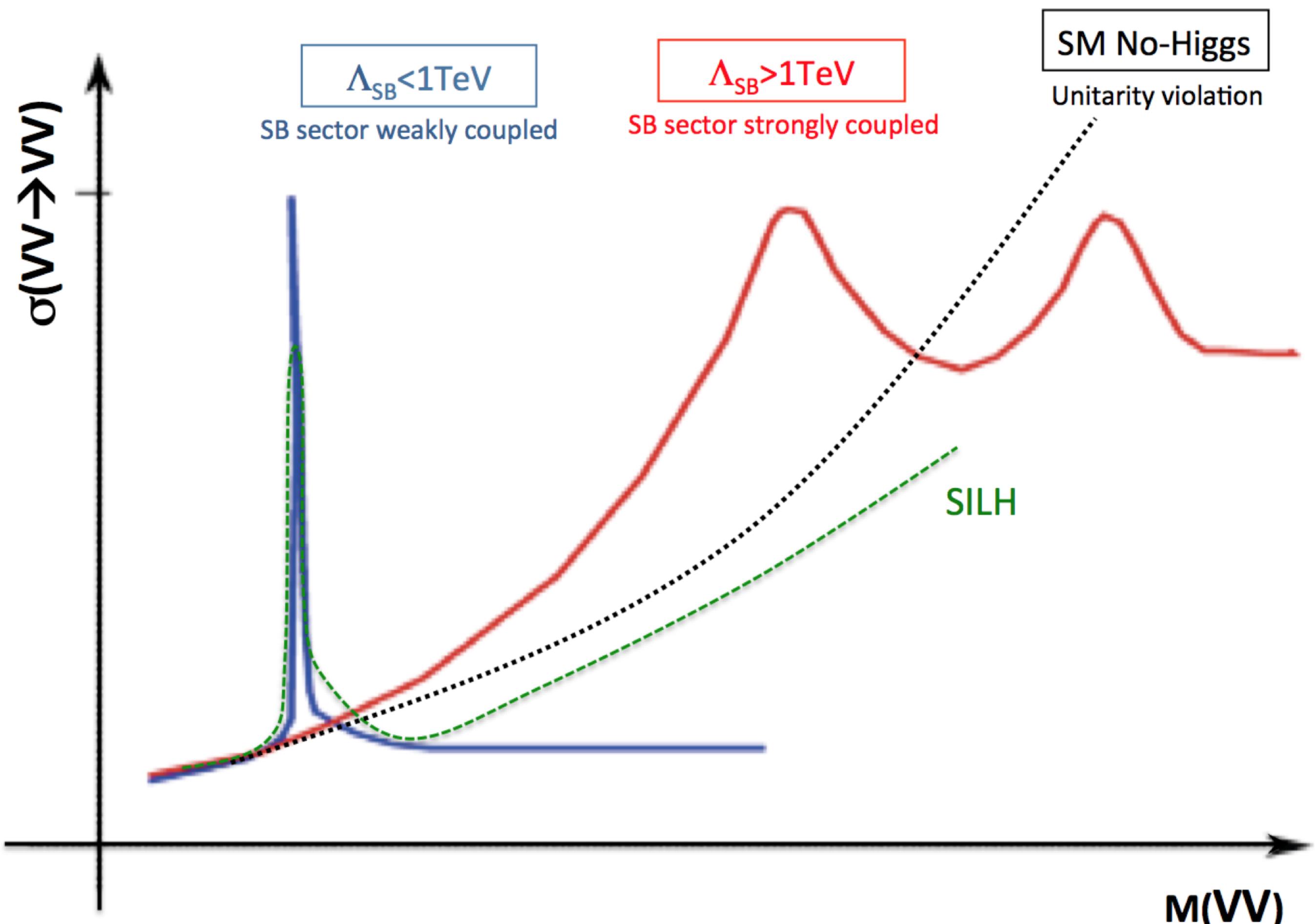
- Extension of the SM Lagrangian by introducing additional **dimension-8 (or 6) operators**:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$

desideratum: Λ ~ 1-2 TeV

- **Effective field theory** is useful as a methodology for studying possible new physics effects from massive particles that are **not directly detectable**.
  - Underlying assumption: scale **Λ is large compared with the experimentally-accessible energy**
  - These operators have **coefficients of inverse powers of mass** (Λ), and hence are suppressed if this mass is large compared with the experimentally-accessible energy
  - **Limit**: Λ so large that the effect is comparable to missing higher order corrections from SM
  - An effective field theory is the **low-energy approximation of the new physics**
- coefficients in **dimension-6** (i.e. c_i/Λ^2) (e.g., hep-ph/9908254), **may affects 3 boson vertices too**:
  - **$C_{\varphi W}/\Lambda^2$ (VBFNLO), a_0^W/Λ^2, a_C^W/Λ^2 (CALCHEP)…**
- coefficients in **dimension-8** (i.e. c_i/Λ^4) (e.g., hep-ph/0606118), **modifies 4 boson vertices only**:
  - **$f_{S,0}/\Lambda^4$, $f_{T,0}/\Lambda^4$…**

VV Scattering to test the EWSB



$$g_h \to g_h / \sqrt{1+\xi c_H}, \xi = v^2 / f^2$$

SILH :

Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

Modified higgs coupling $h \to h/\sqrt{1+\xi c_H},\ \xi = v^2/f^2$

SILH Giudice et al arXiv:hep-ph/0703164v2