



# Electroweak production of Vector Bosons and jets at the experiment

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On behalf of the **CMS** Collaboration

**LHCP2019: 7<sup>th</sup> Edition of the Large Hadron Collider Physics Conference**

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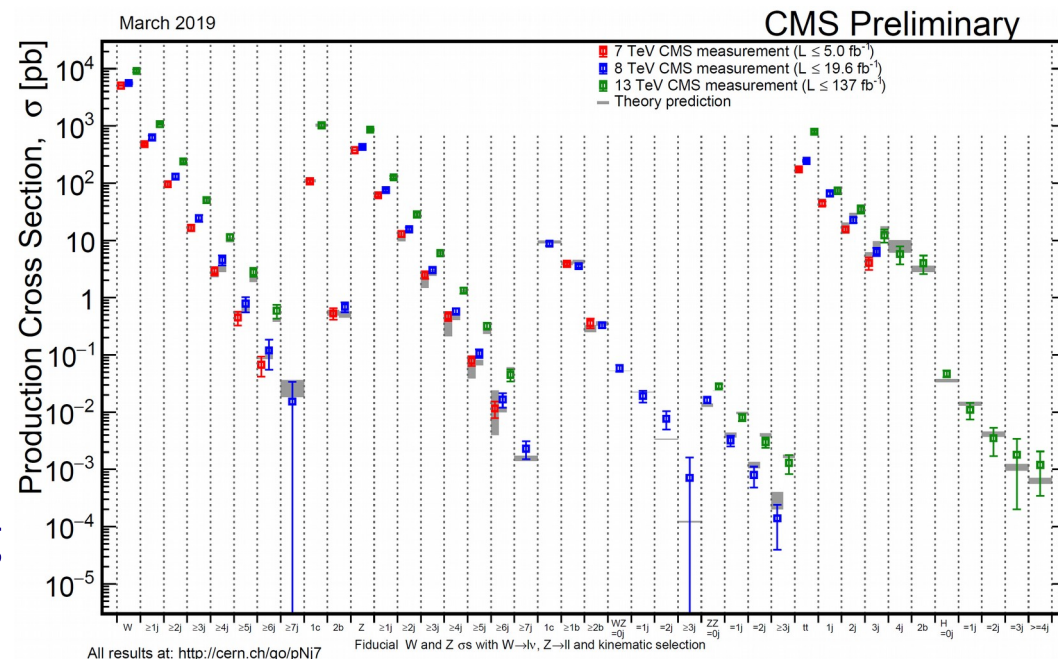
*Electroweak physics session*



# The journey is started



- Standard Model cross sections successfully tested over **9 orders of magnitude**
- We discovered **a Higgs boson**
- *Still* we have to understand in detail the **Electroweak Symmetry Breaking Mechanism (EWSB)**



It is a long journey, but it is finally started and **the first milestones of the path have been posed**: the study and the first measurement and observation of the **electroweak production of vector bosons and jets**

We just *scratched the surface* that covers the processes which are sensitive to the most intimate part of the EWSB, **the acquisition of the longitudinal degree of polarization of the massive electroweak bosons**

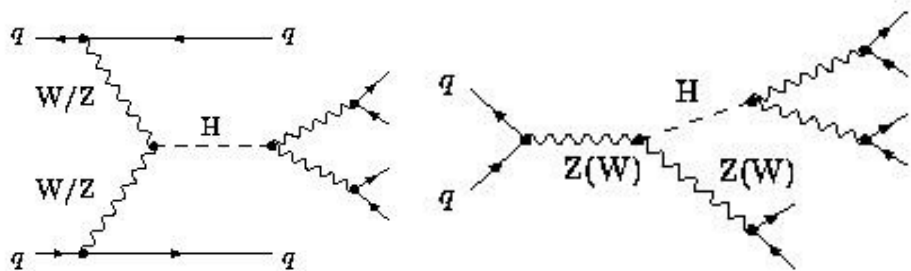
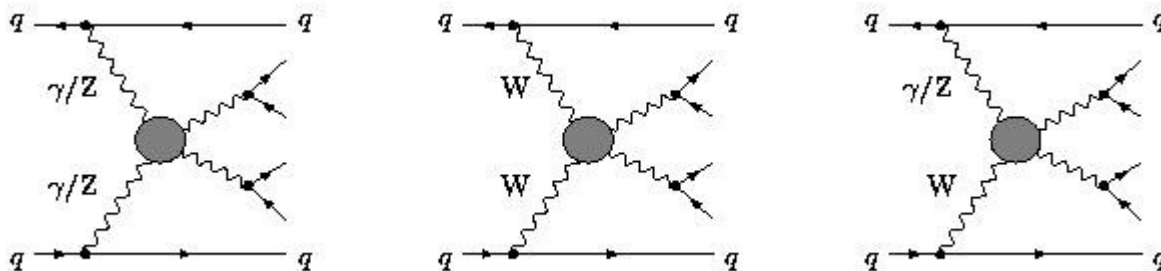


# What is the electroweak production of vector bosons + jets?



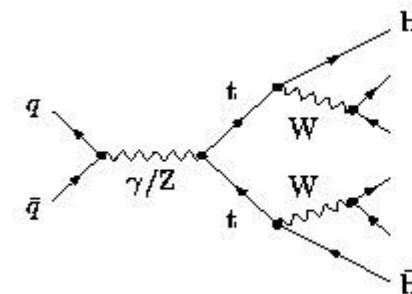
Six-fermions final state at leading order  $\alpha^6$ , or four-fermions and a photon at  $\mathcal{O}(\alpha^5)$

**VV scattering**

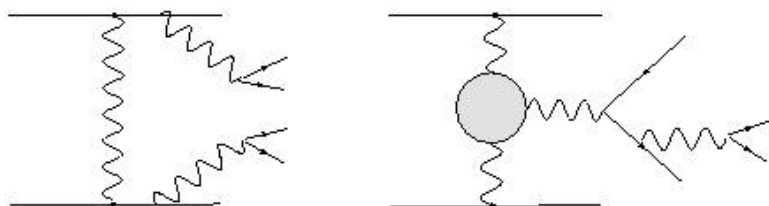
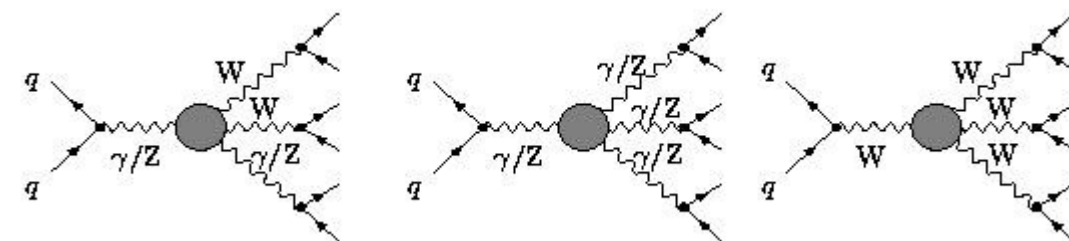


**Higgs**

**top-top (EW)**



**TGC & QGC**



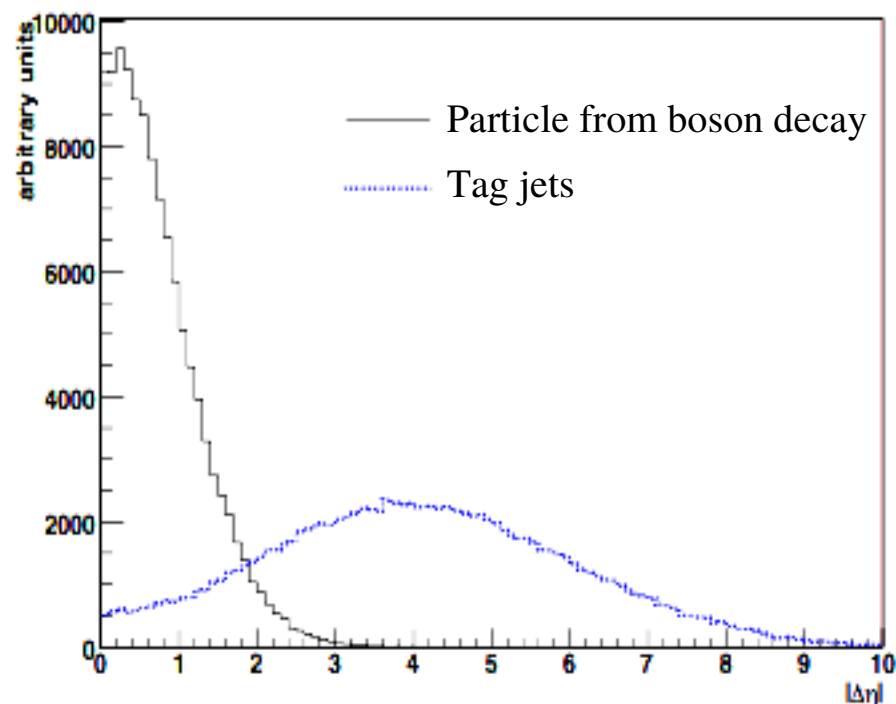
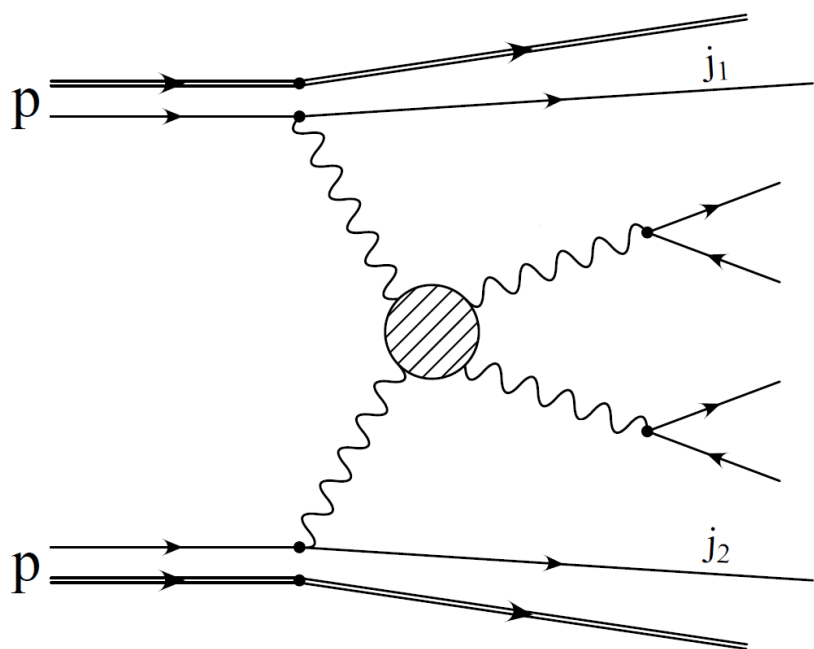
**VV and non resonant**



# However, our target is VBS

... which has **a distinctive signature**

- **Two jets in the forward-background region → 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  $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})/2|/|\Delta\eta_{jj}|$



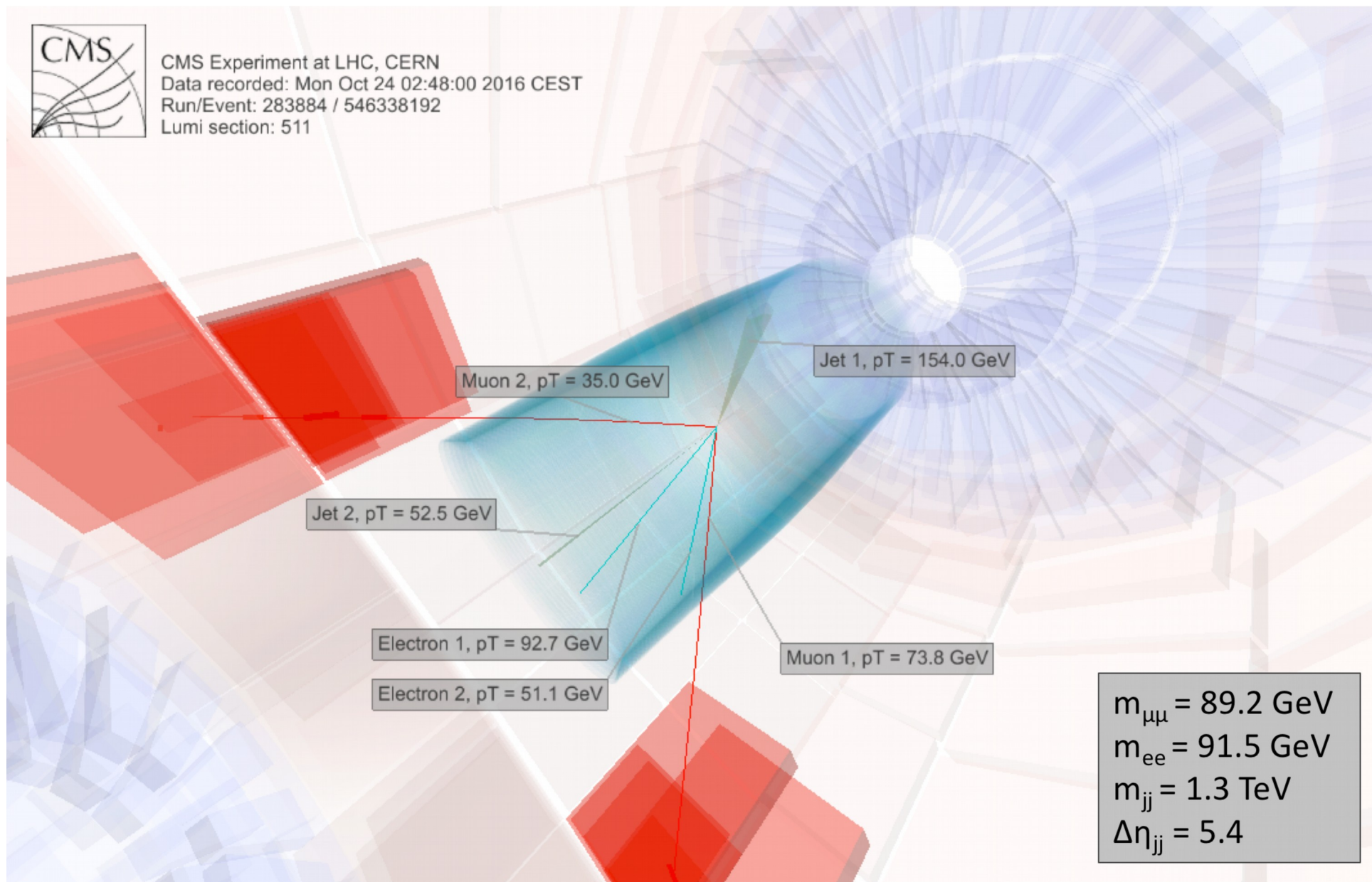


# VBS Candidate Event

SMP-16-019



CMS Experiment at LHC, CERN  
Data recorded: Mon Oct 24 02:48:00 2016 CEST  
Run/Event: 283884 / 546338192  
Lumi section: 511





# What interesting EW features can the VV production probe?

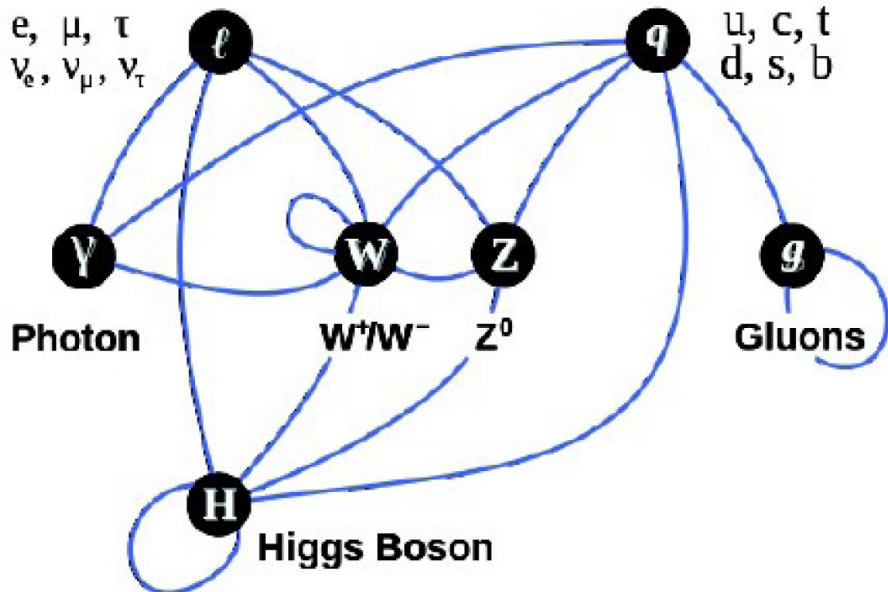


Leptons

$e, \mu, \tau$   
 $\nu_e, \nu_\mu, \nu_\tau$

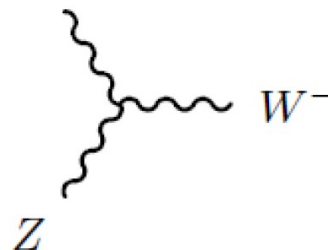
Quarks

$u, c, t$   
 $d, s, b$

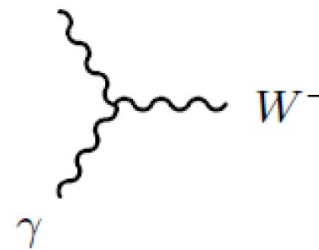


- **Triple gauge couplings (TGC)**

$W^+$

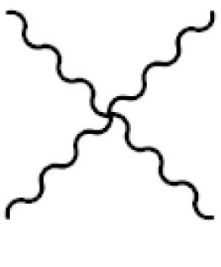


$W^+$



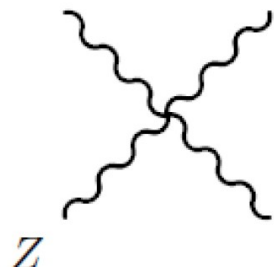
- **Quartic gauge couplings (QGC)**

$W^+$



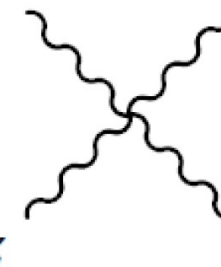
$W^-$

$W^+$



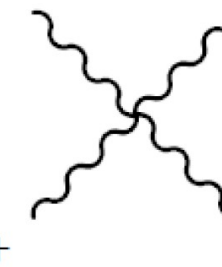
$W^-$

$W^+$



$W^-$

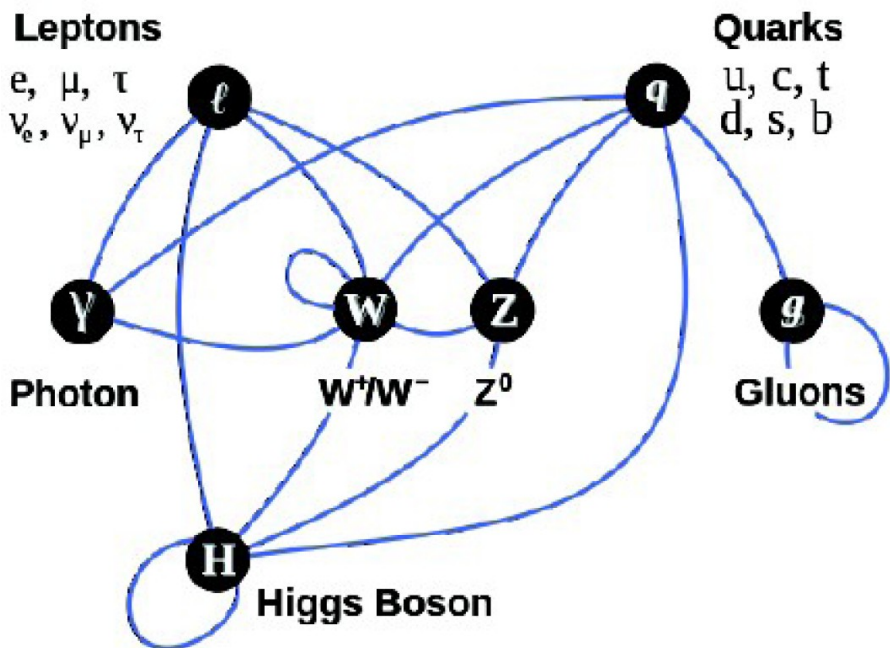
$W^+$



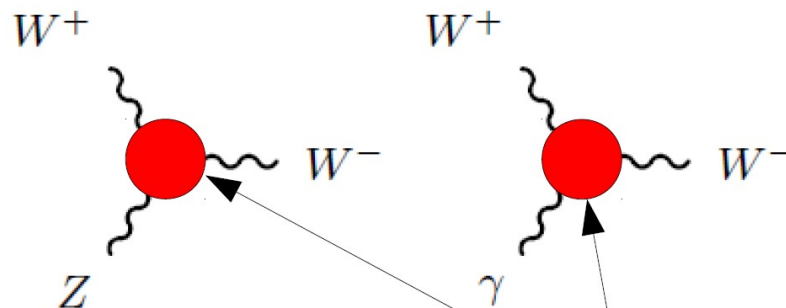
$W^-$



# What interesting EW features can the VV production probe?

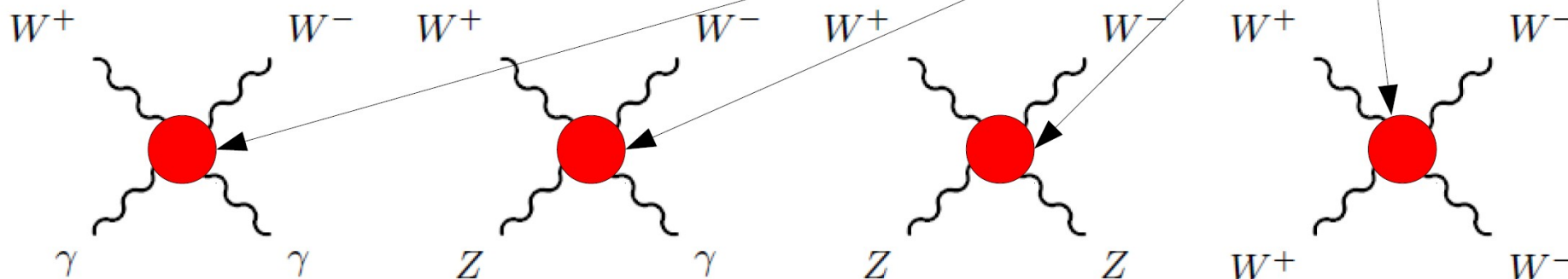


## • Triple gauge couplings (TGC)



Anomalous couplings  
+ what forbidden in SM

## • Quartic gauge couplings (QGC)





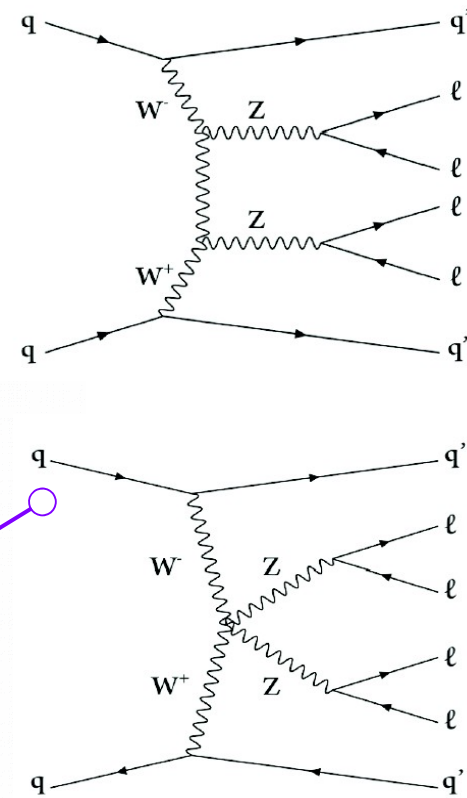
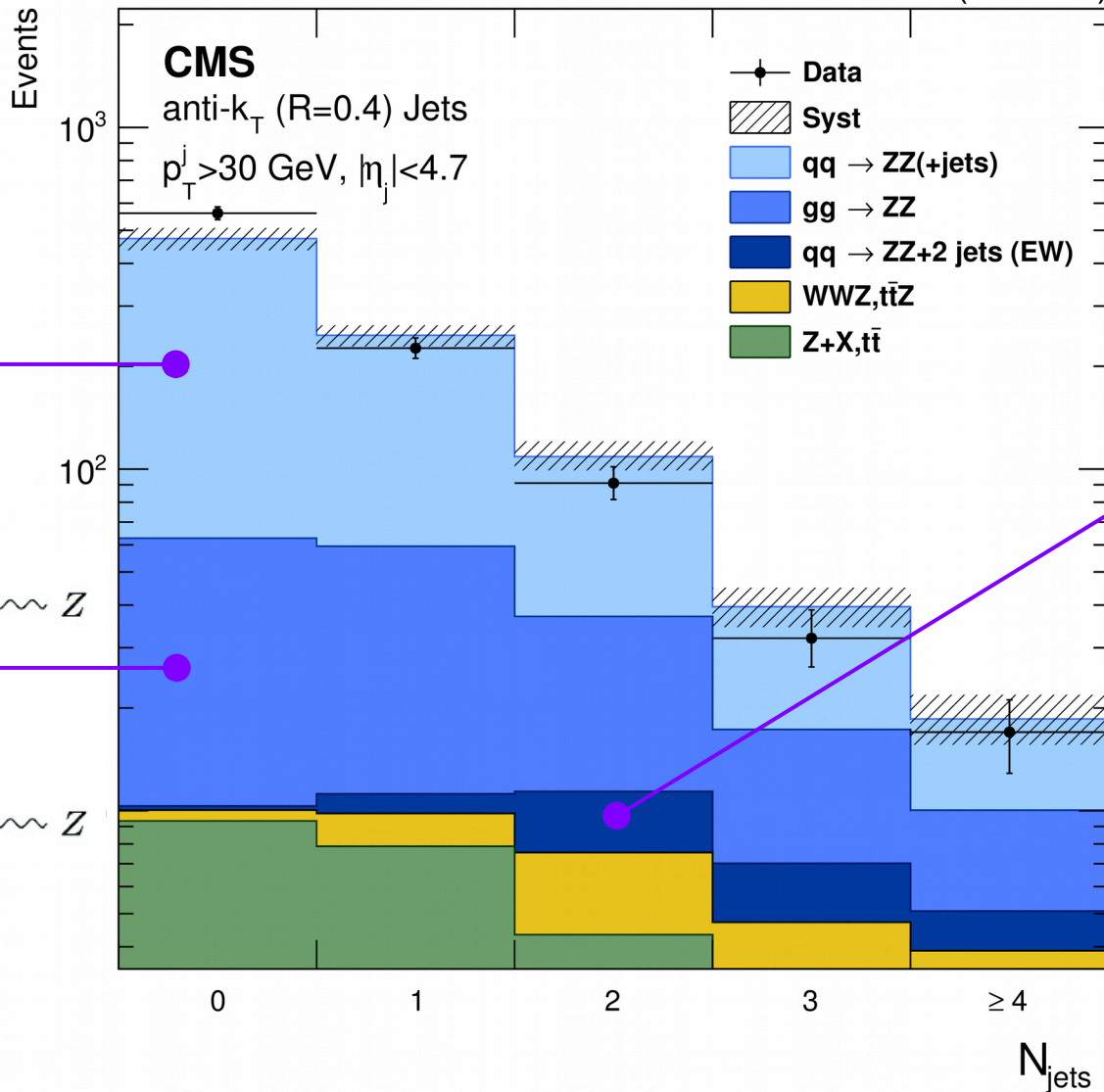


# Experimental and theoretical challenges

Phys. Lett. B 789 (2019) 19



35.9 fb<sup>-1</sup> (13 TeV)



+  
non-VBS diagrams,  
with ( $\alpha_{EW}^6$ ) at tree level



# ZZ+jets analysis

Phys. Lett. B 774 (2017) 682



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

## Pros

- Final state can be **fully reconstructed**  
→ **all kinematic variables are accessible**
- **Very clean** final state  
→ **low reducible background**

## Cons

- **Low  $\sigma \times \text{BR}$**  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**





# Search for the ZZ+jets EW production

Phys. Lett. B 774 (2017) 682



Overall very good data-theory agreement

Little discrimination on individual variables

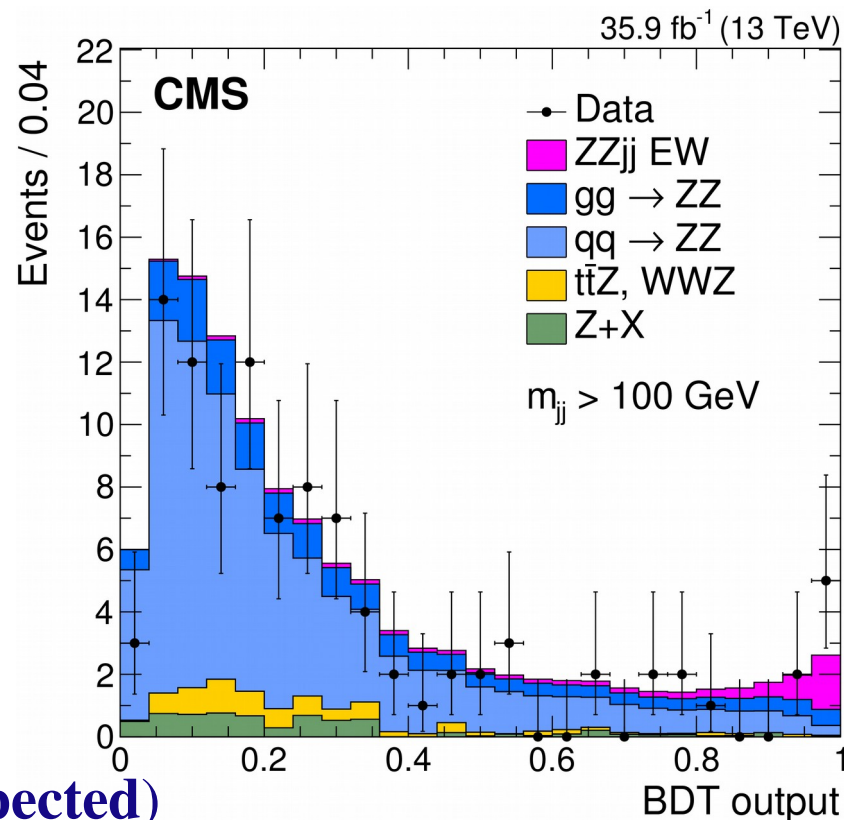
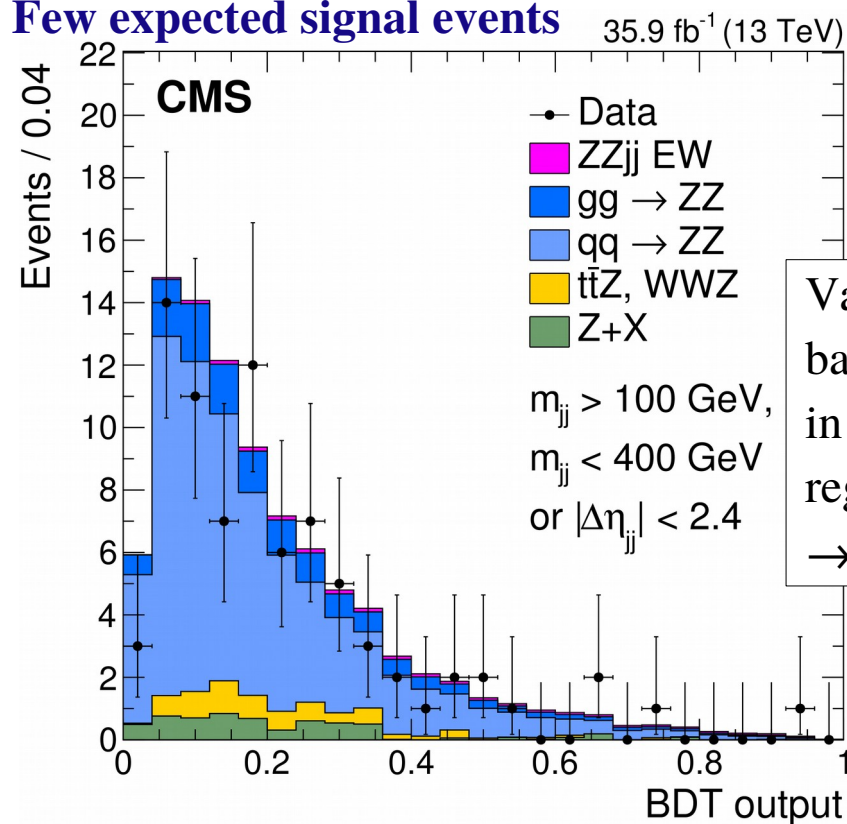
Few expected signal events

BDT optimized to separate EW ZZ+jets from QCD-induced jet production

7 inputs:  $m_{jj}$ ,  $\Delta\eta_{jj}$ ,  $z_1^*$ ,  $z_2^*$ ,  $R(p_T)$ , dijet  $p_T$  balance,  $m_{4l}$

Signal extracted via template fit of full BDT spectrum

Constrains background normalization with data



Measured signal strength:  $\mu = 1.39^{+0.72}_{-0.57} (\text{stat})^{+0.46}_{-0.31} (\text{syst})$

With an observed significance of  $2.7 \sigma$  ( $1.6 \sigma$ , expected)

Measured fiducial cross section  $\sigma(\text{EW } pp \rightarrow ZZ + \text{jets} \rightarrow ll'l' + \text{jets}) = 0.40^{+0.21}_{-0.16} (\text{stat})^{+0.13}_{-0.09} (\text{syst}) \text{ fb}$

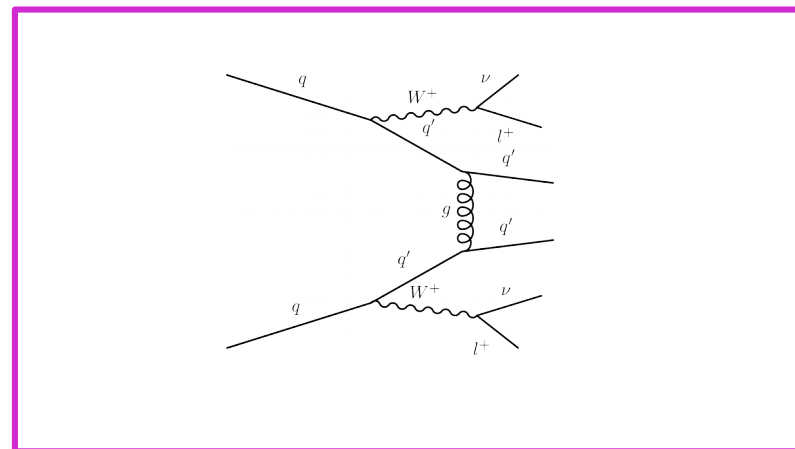
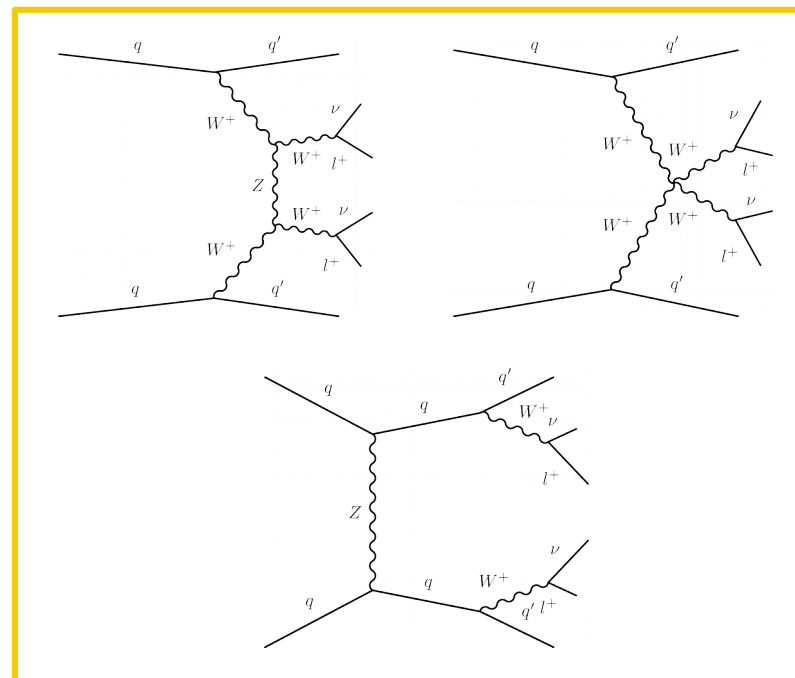


# EW $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm l^\pm \nu \nu jj$ production

Phys. Rev. Lett. 120, 081801 (2018)



- Search for a **pair of same charge lepton** ( $\mu, e$ ) with  $p_{T,1(2)} > 25$  (20) GeV  $m_{ll} > 20$  GeV, **vetoing additional leptons** (including  $\tau$ 's) in the event
- **Two jets** with  $p_T > 30$  GeV, leading jets taken as tagging jets,  $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$ ,  $\max(z_1^*) < 0.75$
- **Low background contamination** compared to other VBS search channels, because processes with two true high- $p_T$  same-sign lepton are pretty rare  $\rightarrow$  **# signal events ~ half of all background events**
- Background from  **$W^\pm W^\pm + \text{jets}$  induced by QCD** *very small* compared to the **signal**. Main background from **multi non-prompt leptons** in the event and  **$WZ \rightarrow 3l\nu$**  where a charged lepton is lost
  - To suppress DY  $\rightarrow E_T^{\text{miss}} > 40$  GeV and  $Z \rightarrow e^+e^-$  veto
  - To reduce top background: anti b-tagging,  $m_{ll} > 20$  GeV





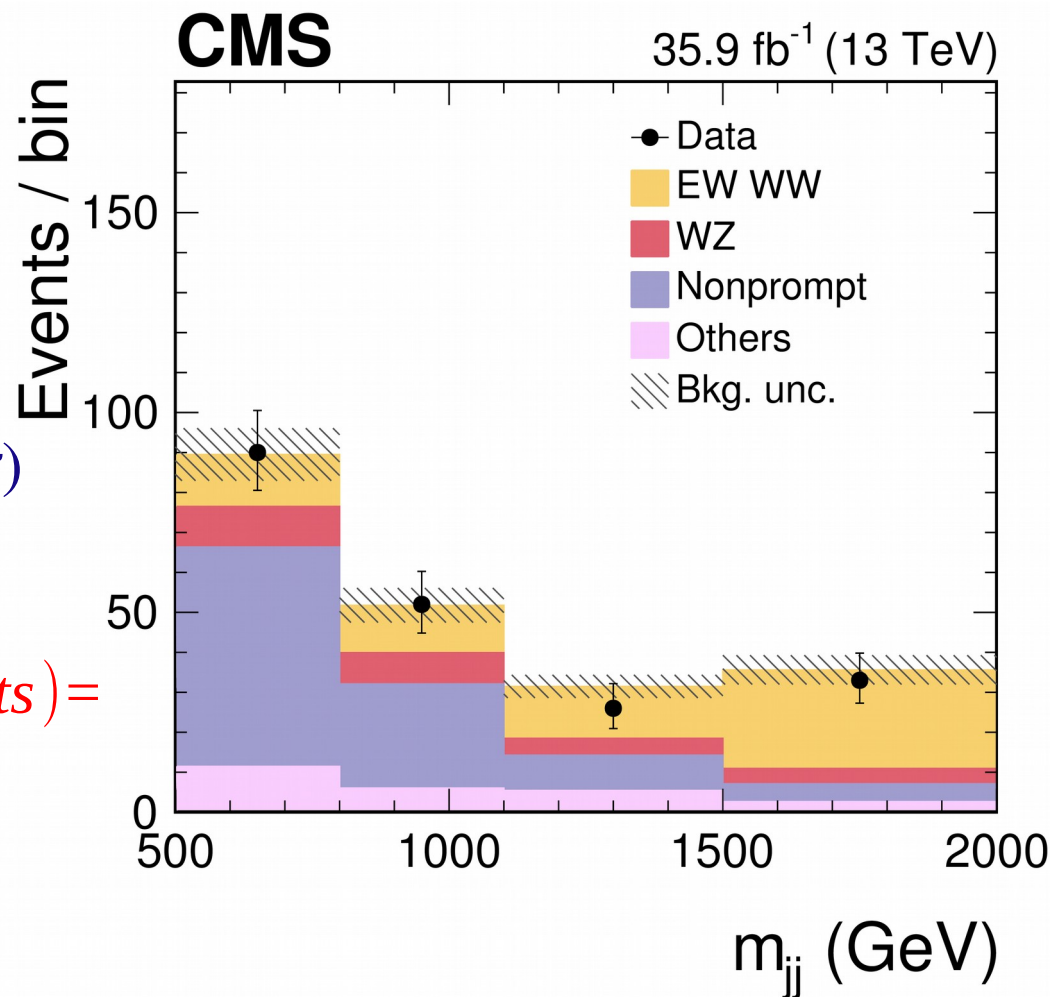
# EW $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm l'^\pm \nu \nu jj$ production

Phys. Rev. Lett. 120, 081801 (2018)



- Signal event yield extracted using a **2D fit of  $m_{jj}$  and  $m_{ll}$**
- EW production observed with a significance of  **$5.5 \sigma$**  (expected  **$5.7 \sigma$** )

$$\sigma(\text{EW } pp \rightarrow W^\pm W^\pm + \text{jets} \rightarrow l^\pm l'^\pm \nu \nu + \text{jets}) = 3.83 \pm 0.66 (\text{stat}) \pm 0.35 (\text{syst}) \text{ fb}$$



- Analysis also used to constrain the  $\sigma \times \text{BR}$  for the production of **doubly charged Higgs boson** decaying into two same sign W, resulting in a **limit at 95% CL well below 100 fb** for a large range of the  **$H^{\pm\pm}$  mass**



# EW $pp \rightarrow W^\pm Z jj \rightarrow l^\pm \nu l^\pm l^\mp jj$ production

arXiv:1901.04060 sub to PLB



- Affected by more background than  $W^\pm W^\pm$ , but **cross section accessible with large dataset**

- Search for **three charged leptons** ( $\mu, e$ ) in the final state, with  $p_T(l_Z, 1) > 25$  GeV,  $p_T(l_Z, 2) > 15$  GeV and  $p_T(l_W) > 20$  GeV

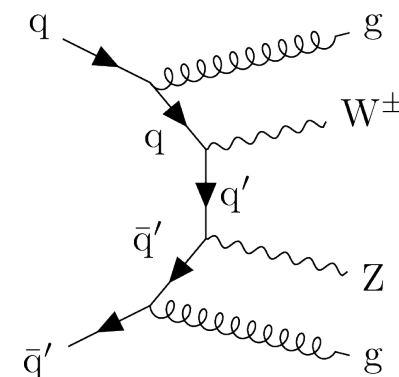
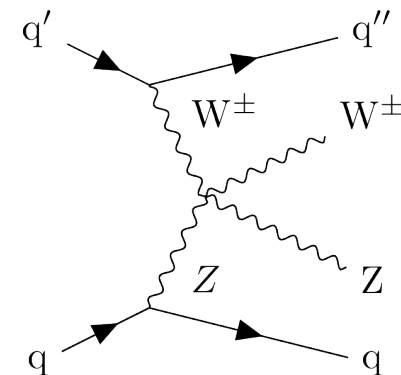
- Two jets** with  $p_T > 50$  GeV, leading jets taken as tagging jets,  $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$ ,  $|\eta_{3l} - (\eta_{j1} + \eta_{j2})/2| < 2.5$

- QCD production of WZ+jets is the dominant background**

→ Use **MC and data control regions** to predict it and all the other background with three prompt leptons

– **Nonprompt lepton background estimated from data**

- Robust analysis** that uses only variable that are theoretically well understood for both QCD WZjj and EW WZjj processes







# EW $pp \rightarrow W^\pm Z jj \rightarrow l^\pm \nu l^\pm l^\mp jj$ production

arXiv:1901.04060 sub to PLB



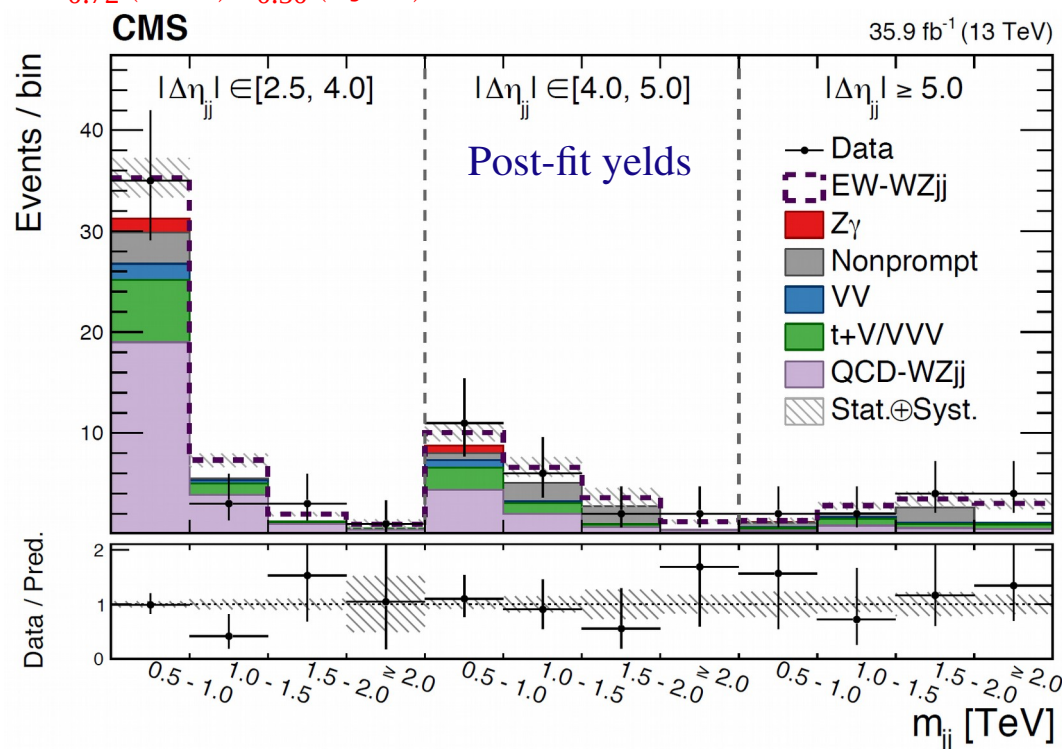
- First, measure the **WZjj (QCD+EW) cross section** in the EW WZjj enhanced regions (tight, and loose)

$$\sigma^{fid} (pp \rightarrow WZ + jets \rightarrow l \nu l' l' + jets) = 3.18_{-0.52}^{+0.57} (\text{stat})_{-0.36}^{+0.43} (\text{syst}) \text{ fb}$$

$$\sigma^{fid, loose} (pp \rightarrow WZ + jets \rightarrow l \nu l' l' + jets) = 4.39_{-0.72}^{+0.78} (\text{stat})_{-0.50}^{+0.60} (\text{syst}) \text{ fb}$$

- To extract the **EW component** (~38% of the tight fid xsection) simultaneously fit yield from background control region and 2D distribution of  $m_{jj}$  and  $\Delta\eta_{jj}$

Measured **signal strength**:  $\mu = 0.82_{-0.43}^{+0.51}$   
 with an expected **EW WZjj cross section** of  $\sigma = 1.25_{-0.09}^{+0.11} (\text{scale}) \pm 0.15 (\text{PDF}) \text{ fb}$   
 and an observed significance of  **$2.2\sigma$**   
**( $2.7\sigma$ , expected)**



Analysis also used to constrain the  $\sigma_{\text{BR}}$  for the production of **charged Higgs boson**, resulting in a **limit at 95% CL** well **below 100 fb** for a large range of the  $H^\pm$  mass



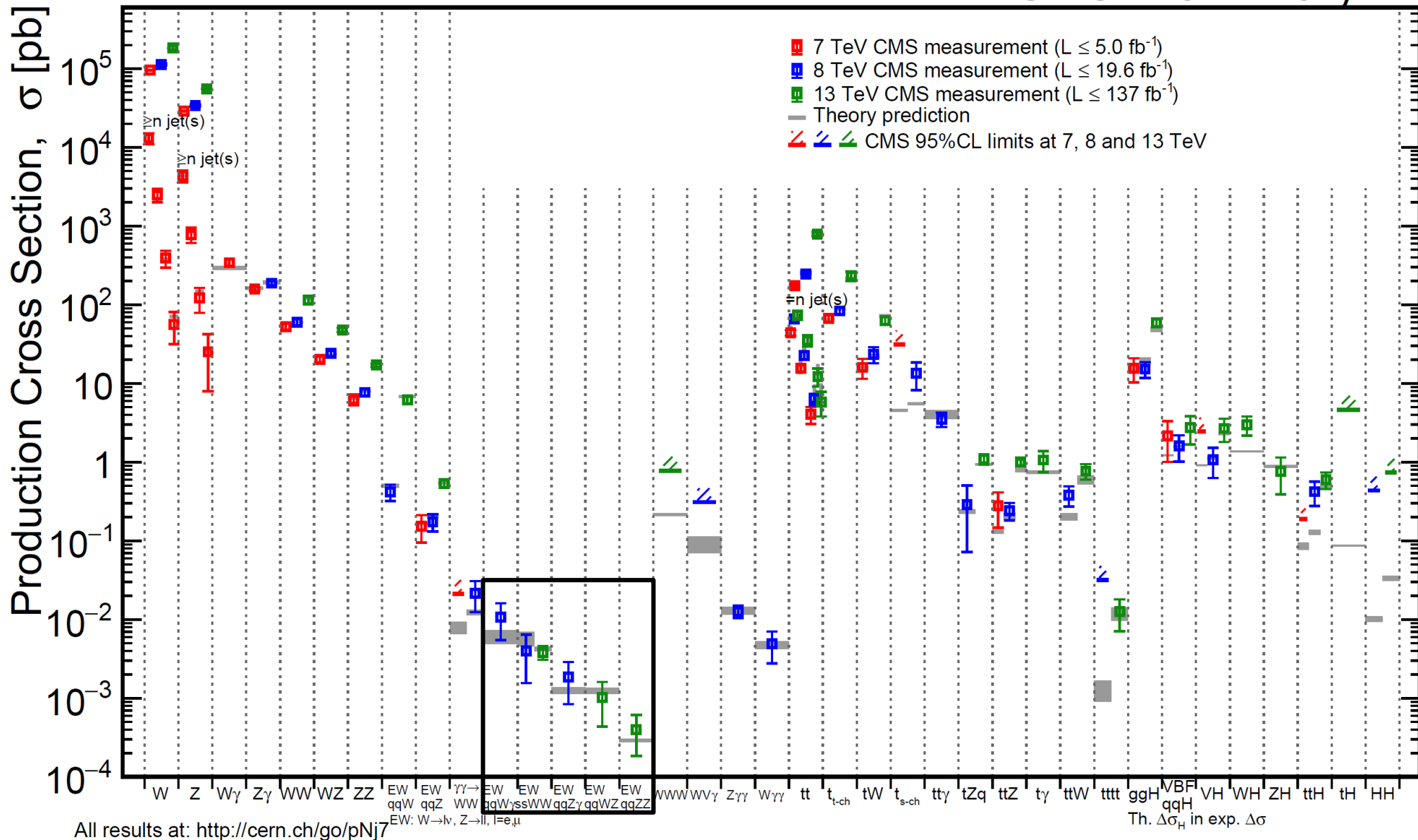


# Cross sections summary



March 2019

CMS Preliminary





# 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

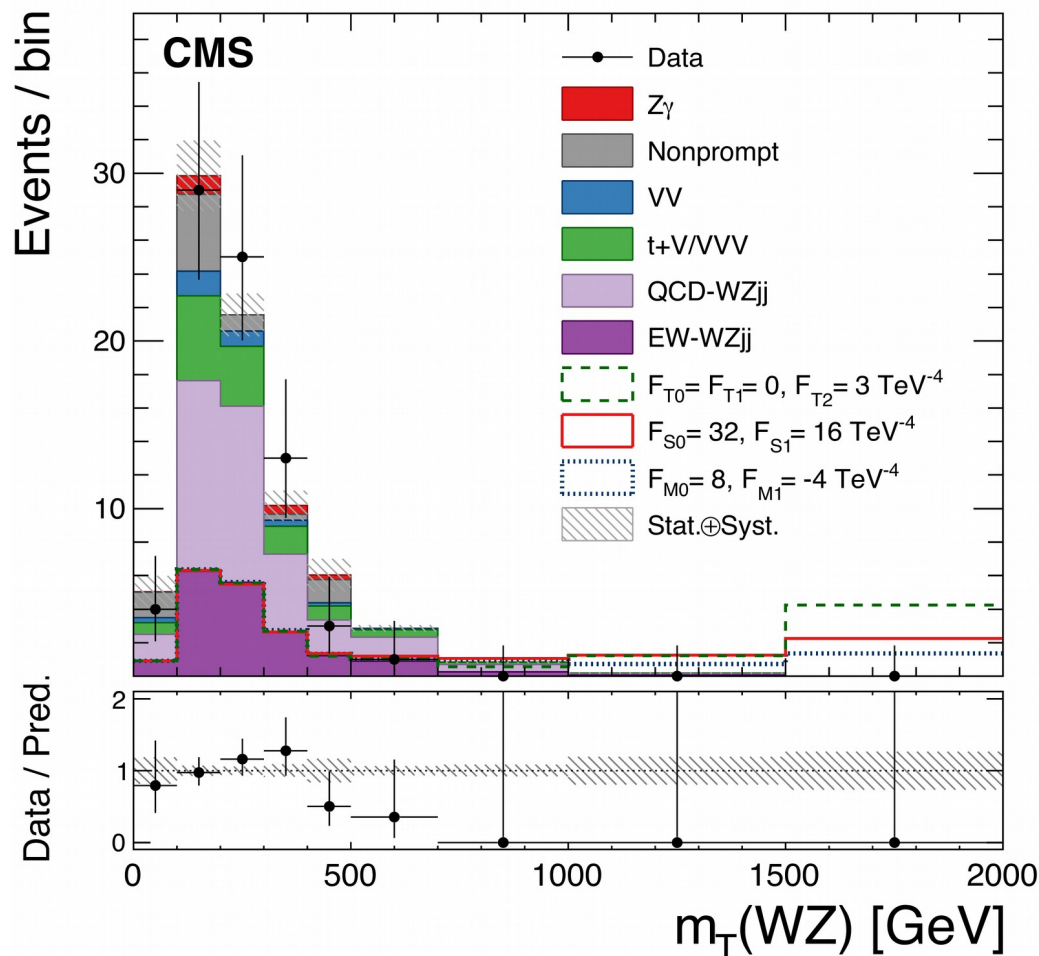


# Anomalous quartic gauge couplings

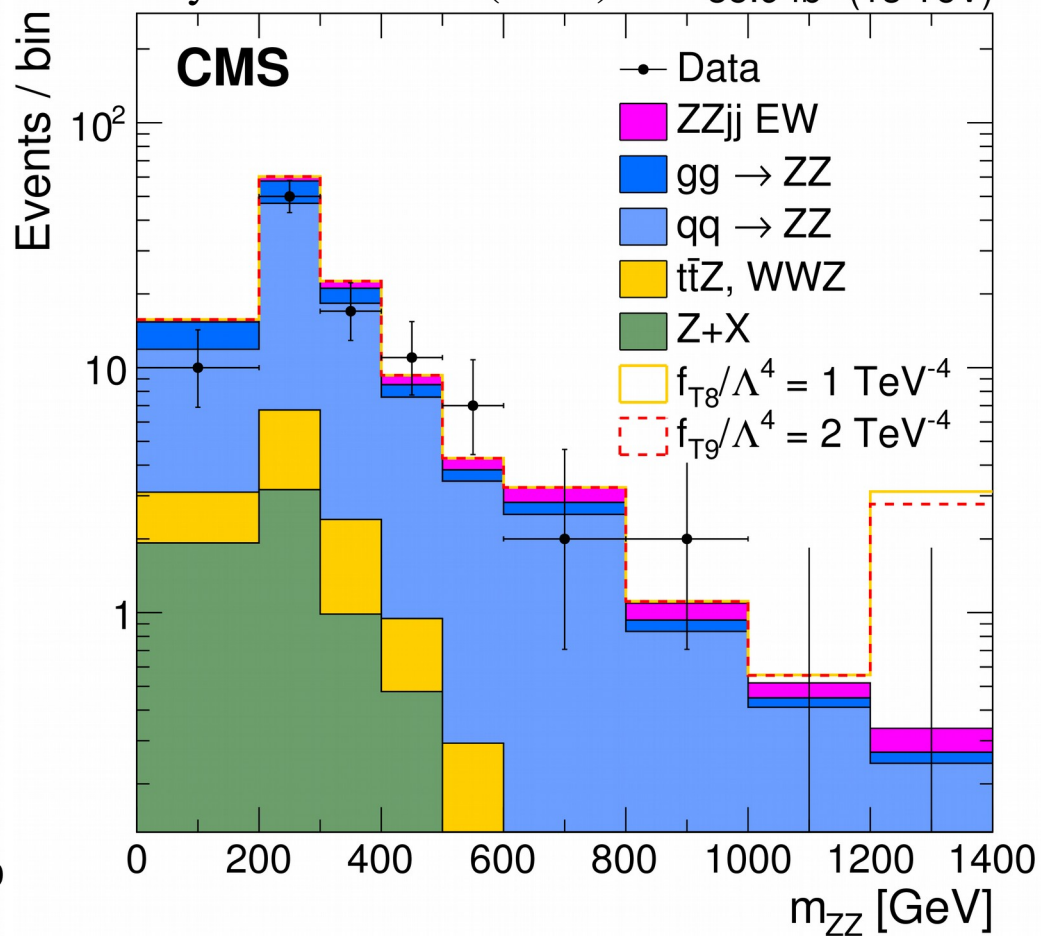


arXiv:1901.04060

35.9 fb<sup>-1</sup> (13 TeV)



Phys. Lett. B 774 (2017) 682 35.9 fb<sup>-1</sup> (13 TeV)



Main variables for the search of anomalous quartic gauge couplings

→ no evidence found so far



# Search for anomalous EW production of $WW/WZ/ZZ + \text{jets}$

SMP-18-006



- Two final states:  $pp \rightarrow WVjj \rightarrow lvjjjj$  and  $pp \rightarrow ZVjj \rightarrow lljjjj$

- Select events with

- **One or two leptons** with  $p_T > 30$  GeV
- **WVjj**:  $p_T^{\text{miss}} > 50$  (80) GeV for final state with  $\mu$  (e)
- **ZVjj**:  $|m_{ll} - m_Z| < 15$  GeV

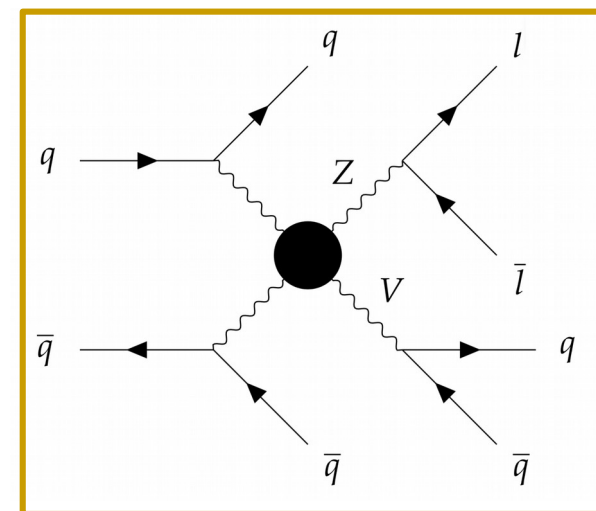
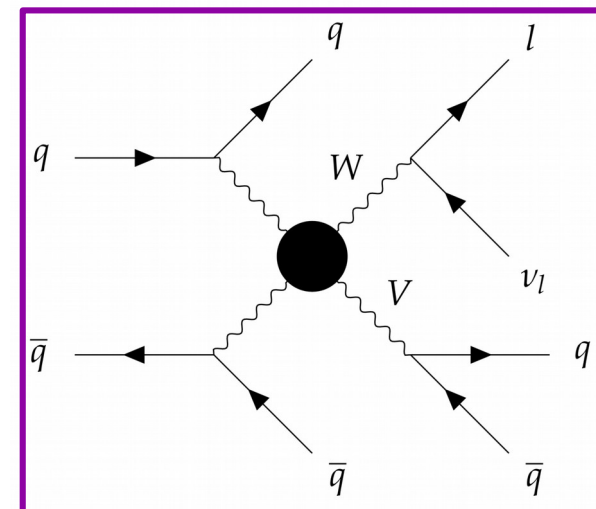
- Hadronically decaying boson reconstructed in **boosted topology** (anti- $k_T$  w/  $R = 0.8$ )

- $p_{T,V} > 200$  GeV,  $65$  GeV  $< m_V < 105$  GeV

- **Stringent VBS requirements:**

- **Two jets** with  $p_T > 30$  GeV,  $m_{jj} > 800$  GeV,  $|\Delta\eta_{jj}| > 4$

- Requirement on **Zeppenfeld variables** ( $< 0.3$ ) and **boson centrality** ( $> 1$ ) for WVjj





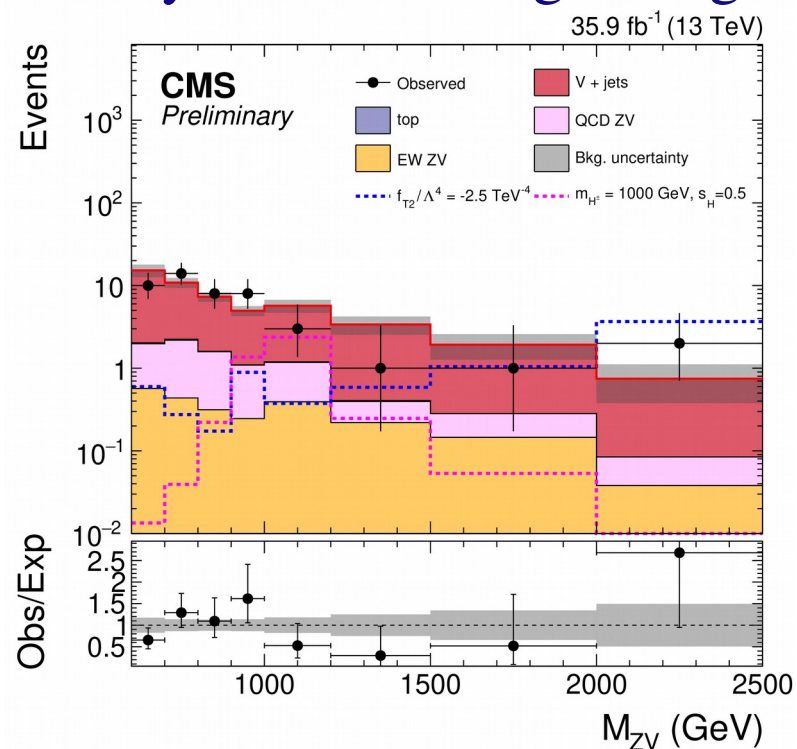
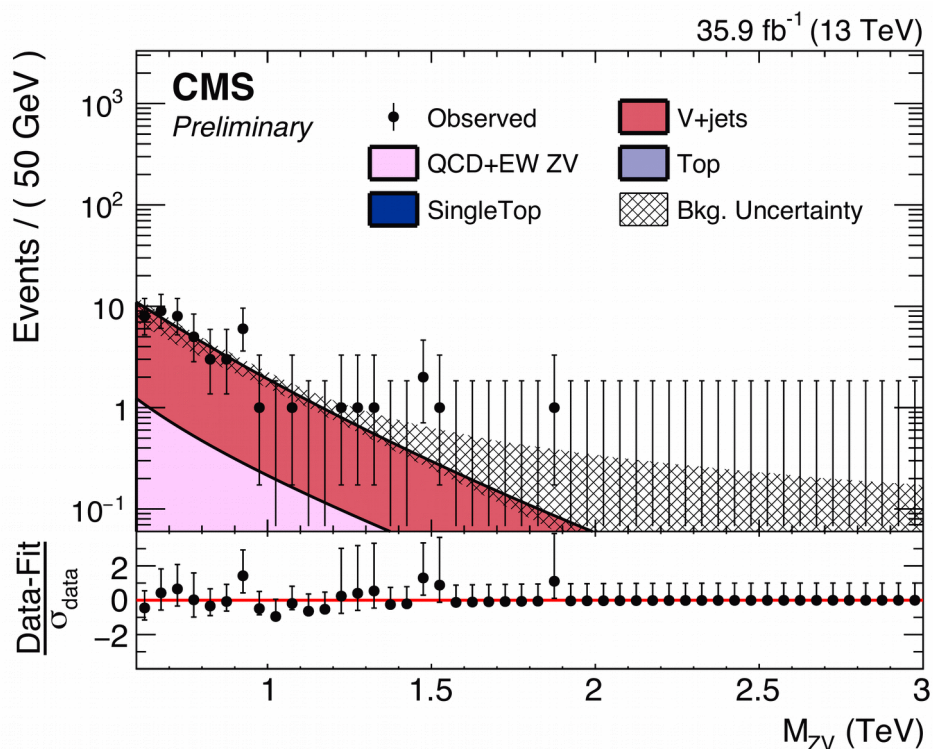


# Search for anomalous EW production of $WW/WZ/ZZ + \text{jets}$



SMP-18-006

- **Laegest bakground is V+jets**  $\rightarrow$  estimated yield and shape from **sidebands** of the signal region ( $40 \text{ GeV} < m_V < 65 \text{ GeV}$  and  $105 \text{ GeV} < m_V < 150 \text{ GeV}$ )
- **Fit mass the distribution of the  $WV$  or  $ZV$  system in the signal region**



Set also stringent limits on  $H^\pm$  and  $H^{\pm\pm}$  production cross section



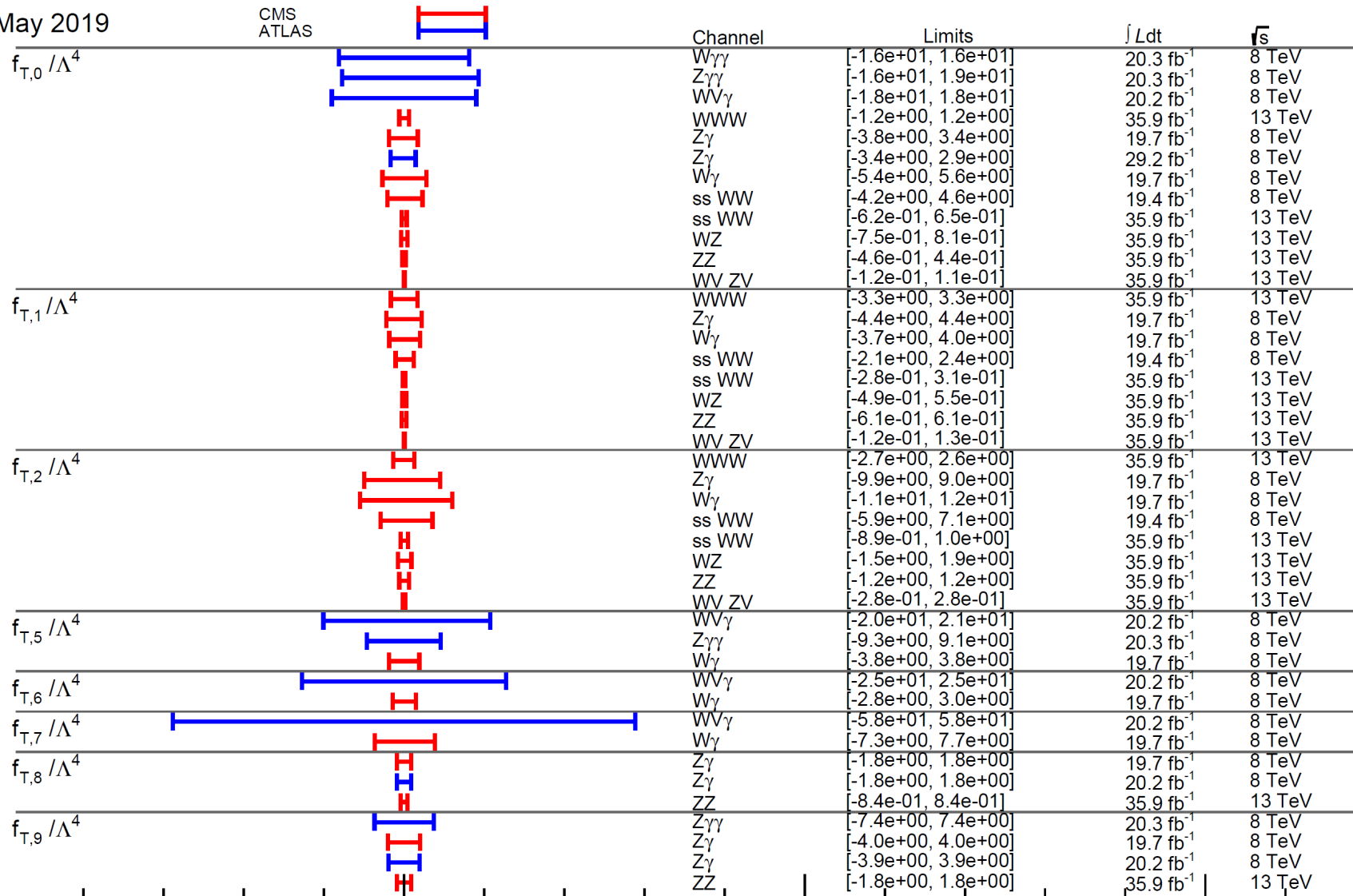


# aQGC summary table



May 2019

CMS  
ATLAS



100 200  
aQGC Limits @95% C.L. [TeV<sup>-4</sup>]



# Conclusions



- We discovered a Higgs boson, yet the **comprehension of the Electroweak Symmetry Breaking is not completed**
  - **Understanding the Multi-boson production in association with jets is the key point!**
    - **Complementary** to Higgs boson properties studies and high mass searches
- **Observation of Electroweak production of two same sign W and two jets**
  - **Hint** at CMS of the production of ZZ+jets and WZ+jets through EW processes

**Time of multi-boson production is now, the New Frontier is:**

**VV + jets, Vector Boson Scattering and triboson production**

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

**Details on results** can be found in the public pages of the CMS experiment:

<http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html>



## More Material



# ZZ+jets Complete Cut List

Phys. Lett. B 774 (2017) 682



## Fiducial region (baseline)

$$p_T^e > 5 \text{ GeV}, |\eta^e| < 2.5$$

$$p_T^\mu > 5 \text{ GeV}, |\eta^\mu| < 2.5$$

$$p_T^{\ell_{3,4}} > 5 \text{ GeV}$$

$$p_T^{\ell_1} > 20 \text{ GeV}, p_T^{\ell_2} > 10 \text{ GeV}$$

$$m_{\ell^+\ell^-} > 4 \text{ GeV (any opposite-sign same-flavor pair)}$$

$$60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$$

## Fiducial region (VBS)

$$+ m_{jj} > 100 \text{ GeV}$$

## Search region (baseline)

- $|\eta_e| < 2.5$   $p_T^e > 7 \text{ GeV}$ ,  $|\eta_\mu| < 2.4$   $p_T^\mu > 5 \text{ GeV}$ , relative isolation  $< 0.35$  in a cone of  $\Delta R = 0.3$ , CMS tight ID and SIP =  $|\text{IP}/\sigma_{\text{IP}}| < 4$

- At least a lepton with  $p_T > 20 \text{ GeV}$  and a  $\mu(e)$  with  $p_T > 10(12) \text{ GeV}$   $+ m_{jj} > 100 \text{ GeV}$

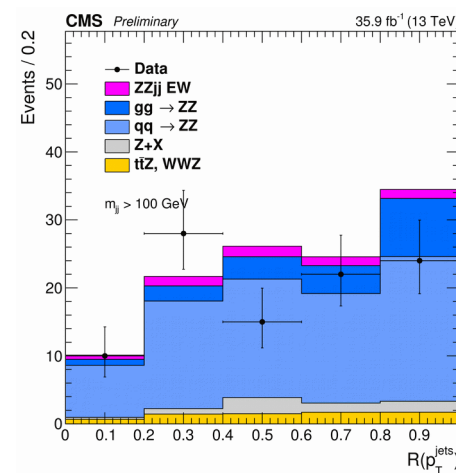
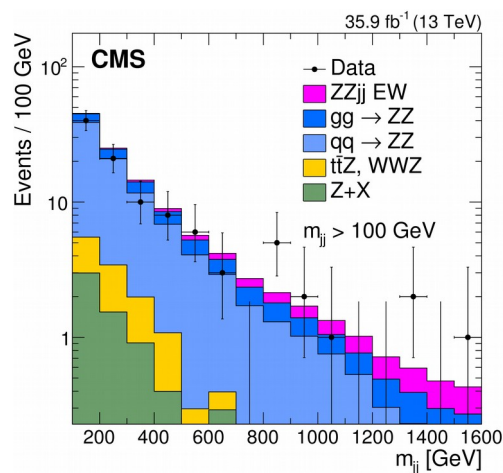
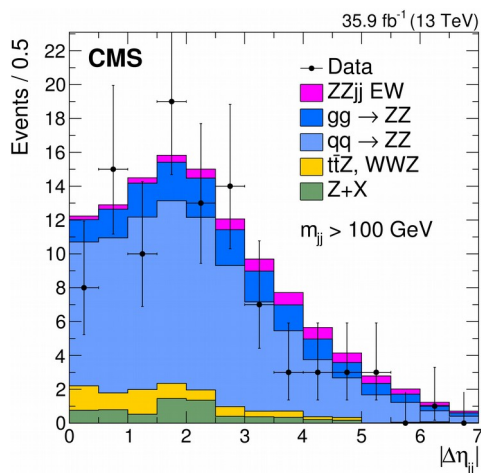
- $60 < m_Z < 120 \text{ GeV}$  (On shell),  $m_{\text{ll crossed (Opposite sign same flavour)}} > 4 \text{ GeV}$

- Loosely ID jets, reco with anti- $k_T$  0.4;  $|\eta_{\text{jet}}| < 4.7$  and  $p_T > 30 \text{ GeV}$

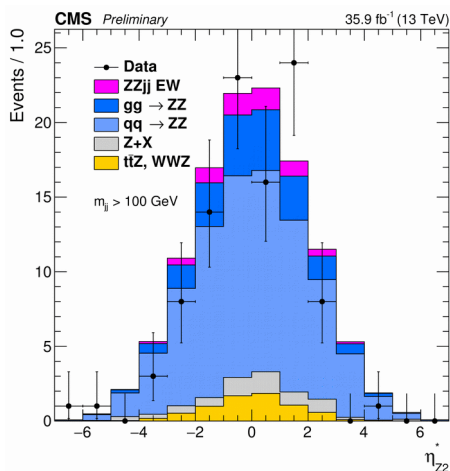
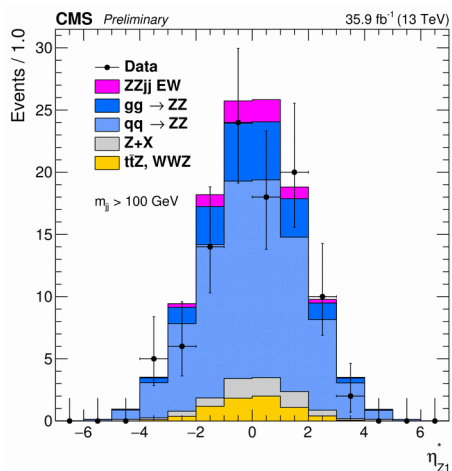


# ZZ+jets MVA input variables

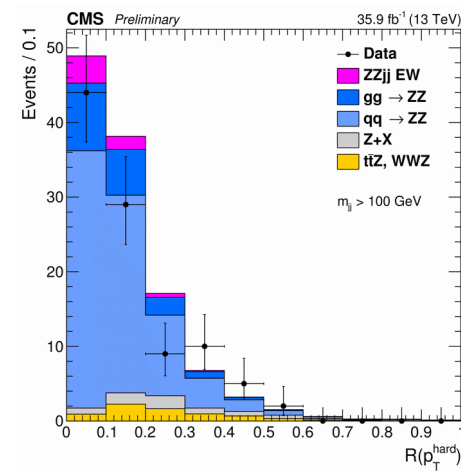
Phys. Lett. B 774 (2017) 682 and SMP-16-019



$$R(p_T^{hard}) = \frac{\| \mathbf{p}_T^{jet1} + \mathbf{p}_T^{jet2} + \mathbf{p}_T^{Z_1} + \mathbf{p}_T^{Z_2} \|}{p_T^{jet1} + p_T^{jet2} + p_T^{Z_1} + p_T^{Z_2}}$$



$$Z_i^* = \eta_{Z_i} - (\eta_{jet,1} + \eta_{jet,2})/2$$



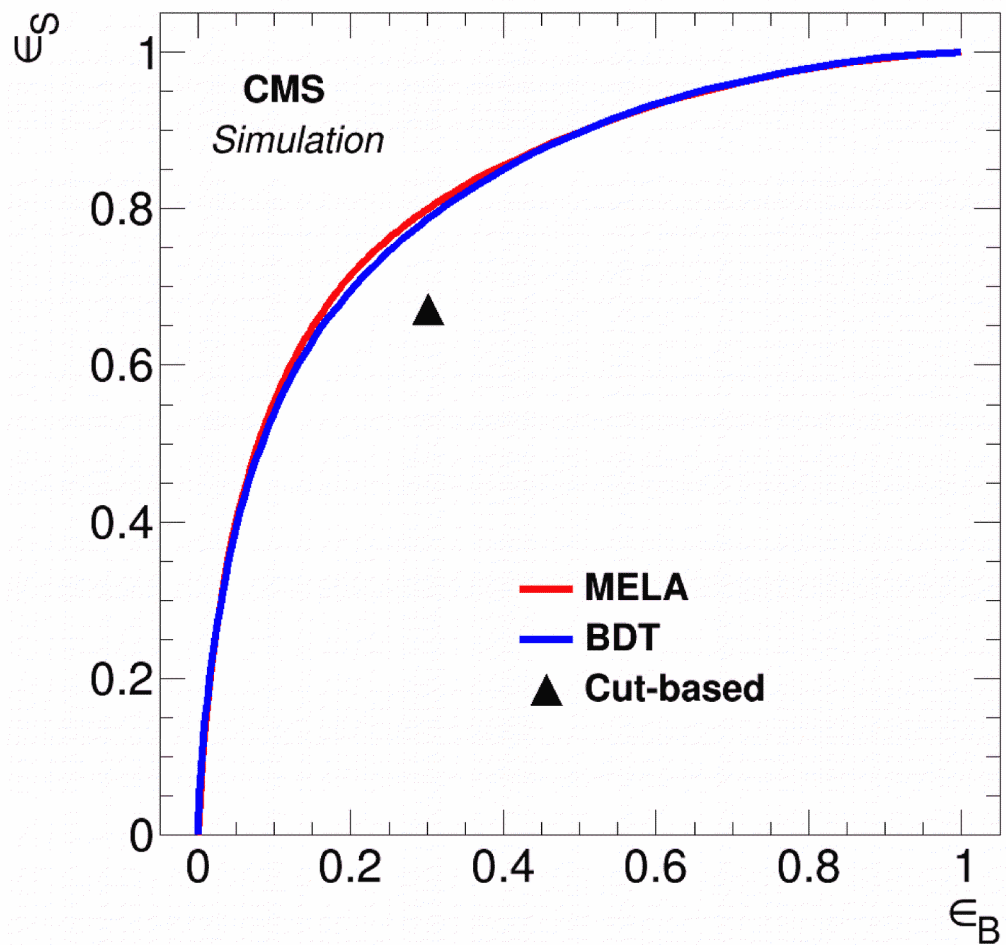
$$R(p_T^{jets}) = \frac{\| \mathbf{p}_T^{jet1} + \mathbf{p}_T^{jet2} \|}{p_T^{jet1} + p_T^{jet2}}$$





# ZZ+jets: ROC Curve

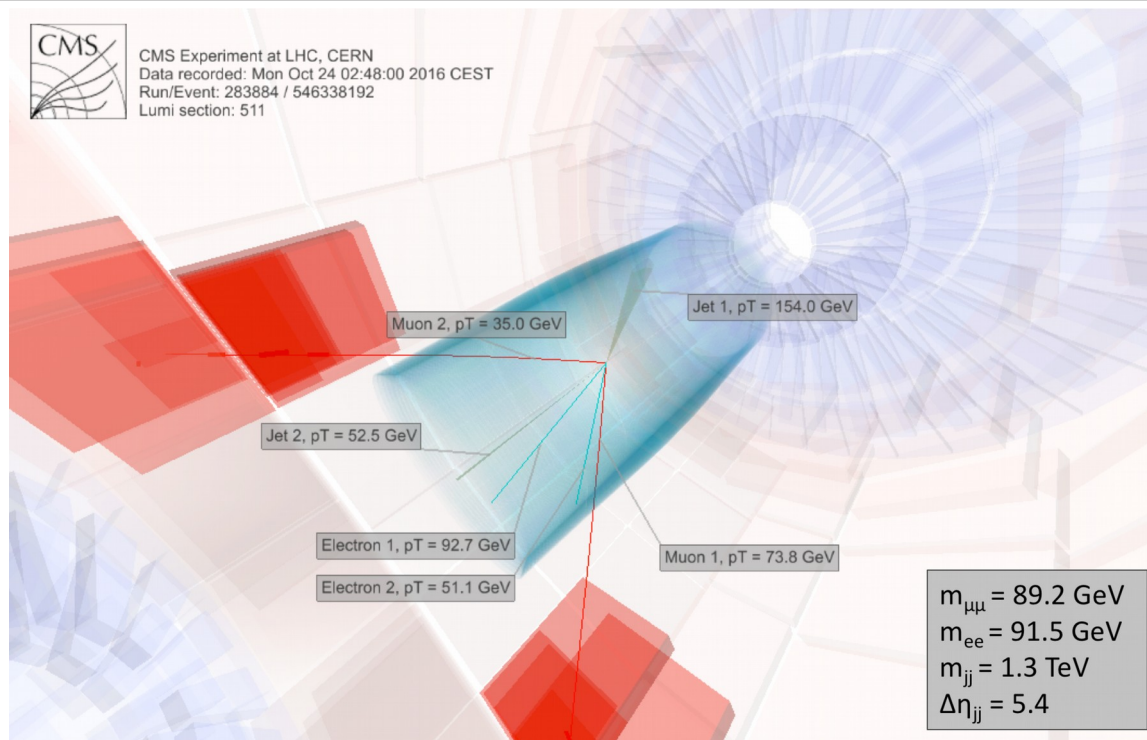
SMP-16-019





# ZZ+jets: Event Display

SMP-16-019



$m_{4\ell}$ [GeV]	$m_{Z1}$ [GeV]	$m_{Z2}$ [GeV]	$m_{jj}$ [GeV]	$ \Delta\eta_{jj} $	$\eta_{Z1}^*$	$\eta_{Z2}^*$	BDT score
365.8	91.4	101.1	844.1	3.4	-0.7	0.0	0.97
325.1	93.1	96.3	1332.9	5.2	0.0	-1.8	0.98
263.8	91.9	88.0	829.7	2.2	-0.5	1.1	0.94
562.8	93.7	88.0	947.3	2.8	0.6	0.6	0.93
248.8	91.5	89.2	1340.9	5.4	-0.5	0.2	0.98
375.2	89.4	98.5	1052.5	3.8	0.7	-0.2	0.96
482.1	95.0	95.6	1543.1	4.8	-1.6	2.5	0.99



# ZZ+jets: aQGC Limits

Phys. Lett. B 774 (2017) 682



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
$f_{T0}/\Lambda^4$	-0.53	0.51	-0.46	0.44	2.5
$f_{T1}/\Lambda^4$	-0.72	0.71	-0.61	0.61	2.3
$f_{T2}/\Lambda^4$	-1.4	1.4	-1.2	1.2	2.4
$f_{T8}/\Lambda^4$	-0.99	0.99	-0.84	0.84	2.8
$f_{T9}/\Lambda^4$	-2.1	2.1	-1.8	1.8	2.9



# ss WW+jets Complete Cut List

Phys. Rev. Lett. 120, 081801 (2018)



## Search region

- **Two same charge lepton** ( $\mu, e$ ) with  $p_{T,1(2)} > 25$  (20) GeV,  $|\eta| < 2.4$  (2.5),  $m_{ll} > 20$  GeV
- **Veto events with additional leptons** if  $p_T$  of a 3<sup>rd</sup> loosely ID lepton is  $> 10$  GeV or the  $p_T$  of an identified  $\tau$  (to hadrons) is  $> 18$  GeV
- **Two jets** (anti- $k_T$  0.4) with  $p_T > 30$  GeV,  $|\eta| < 5$  leading jets taken as tagging jets,  $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$ ,  $\max(z_1^*) < 0.75$   $z_i^* = |\eta_l - (\eta_{jet,1} + \eta_{jet,2})/2| / |\Delta\eta_{jj}|$
- $E_T^{\text{miss}} > 40$  GeV,  $Z \rightarrow e^+e^-$  veto (requiring  $|m_{ll} - m_Z| > 15$  GeV), anti b-tag,  $m_{ll} > 20$  GeV

## Fiducial region

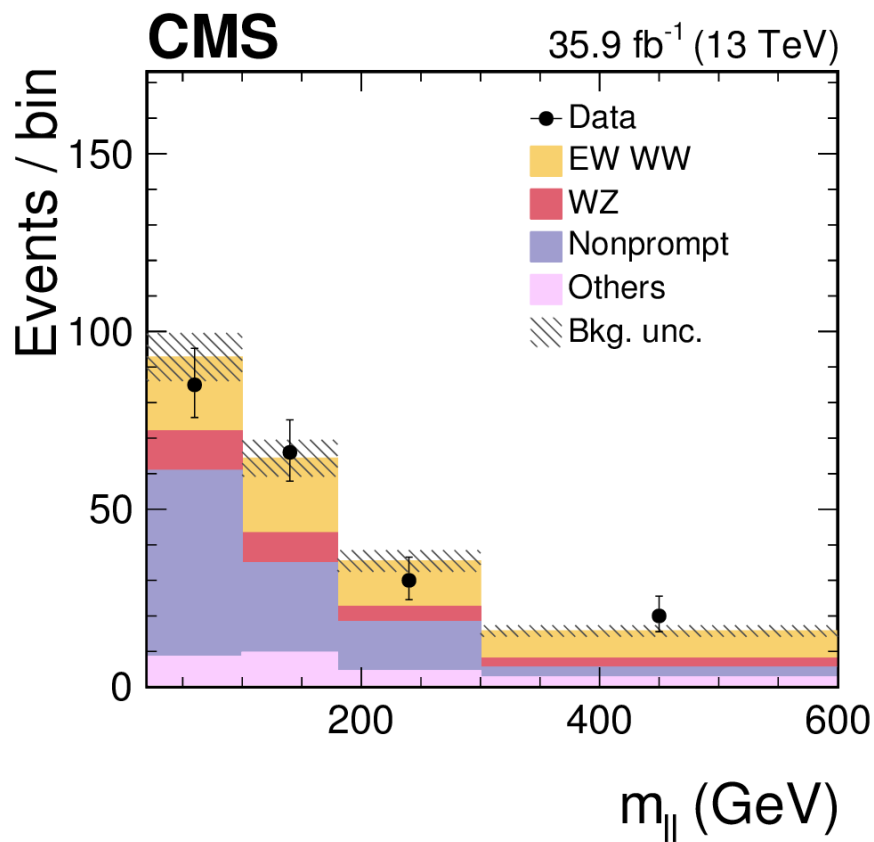
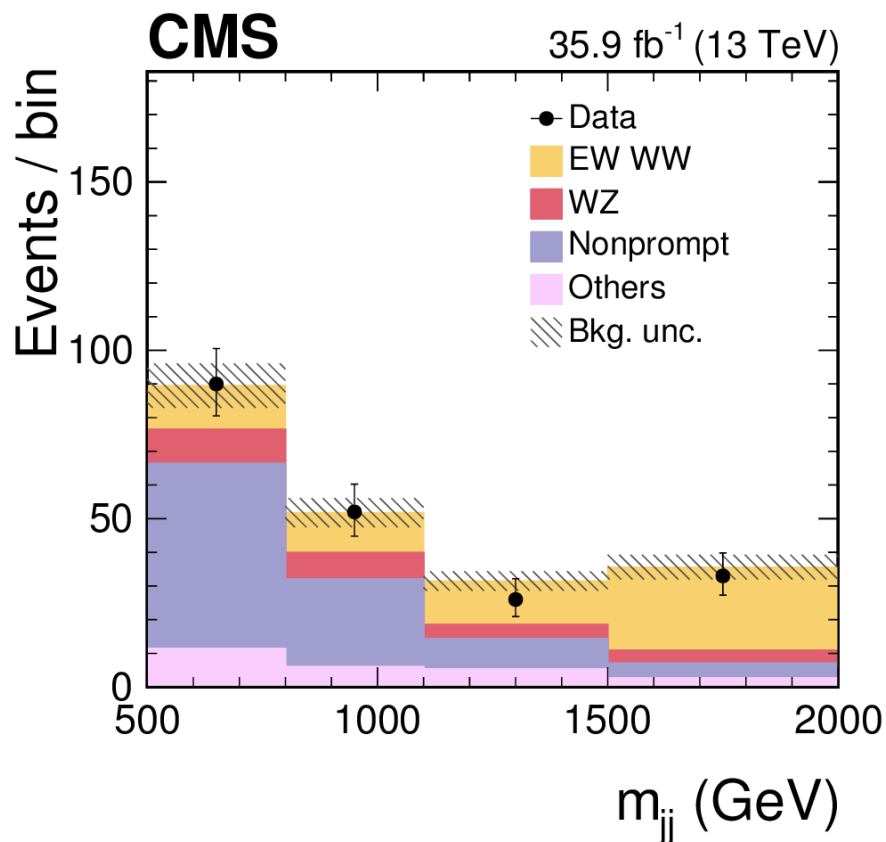
- $p_T > 20$  GeV,  $|\eta| < 2.5$ , for both leptons
- $p_T > 30$  GeV,  $|\eta| < 5$  for the two leading jets and  $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$
- Taus decay into leptons are excluded from this definition





# ss WW+jets $m_{jj}$ and $m_{ll}$ distributions

Phys. Rev. Lett. 120, 081801 (2018)





# ssWW+jets: Yields

Phys. Rev. Lett. 120, 081801 (2018)



	$e^+e^+$	$e^+\mu^+$	$\mu^+\mu^+$	$e^-e^-$	$e^-\mu^-$	$\mu^-\mu^-$	Total
Data	14	63	40	10	48	26	201
Signal + total bkg.	$19.0 \pm 1.9$	$67.6 \pm 3.8$	$44.1 \pm 3.4$	$11.8 \pm 1.8$	$38.9 \pm 3.3$	$23.9 \pm 2.8$	$205 \pm 13$
Signal	$6.2 \pm 0.2$	$24.7 \pm 0.4$	$18.3 \pm 0.4$	$2.5 \pm 0.1$	$8.7 \pm 0.2$	$6.5 \pm 0.2$	$66.9 \pm 2.4$
Total bkg.	$12.8 \pm 1.9$	$42.9 \pm 3.8$	$25.7 \pm 3.4$	$9.4 \pm 1.8$	$30.2 \pm 3.3$	$17.4 \pm 2.8$	$138 \pm 13$
Nonprompt	$5.6 \pm 1.7$	$24.9 \pm 3.6$	$18.4 \pm 3.3$	$5.0 \pm 1.6$	$19.9 \pm 3.2$	$14.2 \pm 2.8$	$88 \pm 13$
WZ	$3.0 \pm 0.2$	$8.5 \pm 0.3$	$4.4 \pm 0.2$	$1.9 \pm 0.2$	$5.2 \pm 0.3$	$2.2 \pm 0.1$	$25.1 \pm 1.1$
QCD WW	$0.6 \pm 0.1$	$1.7 \pm 0.1$	$1.3 \pm 0.1$	$0.2 \pm 0.1$	$0.6 \pm 0.1$	$0.4 \pm 0.1$	$4.8 \pm 0.4$
$W\gamma$	$1.4 \pm 0.5$	$3.6 \pm 0.9$	$0.2 \pm 0.2$	$0.8 \pm 0.4$	$2.3 \pm 0.7$	—	$8.3 \pm 1.6$
Triboson	$0.8 \pm 0.2$	$2.2 \pm 0.4$	$1.2 \pm 0.3$	$0.3 \pm 0.1$	$0.9 \pm 0.3$	$0.5 \pm 0.2$	$5.8 \pm 0.8$
Wrong sign	$1.5 \pm 0.6$	$1.4 \pm 0.4$	—	$1.1 \pm 0.5$	$1.2 \pm 0.4$	—	$5.2 \pm 1.1$



# ss WW+jets: aQGC limits

Phys. Rev. Lett. 120, 081801 (2018)

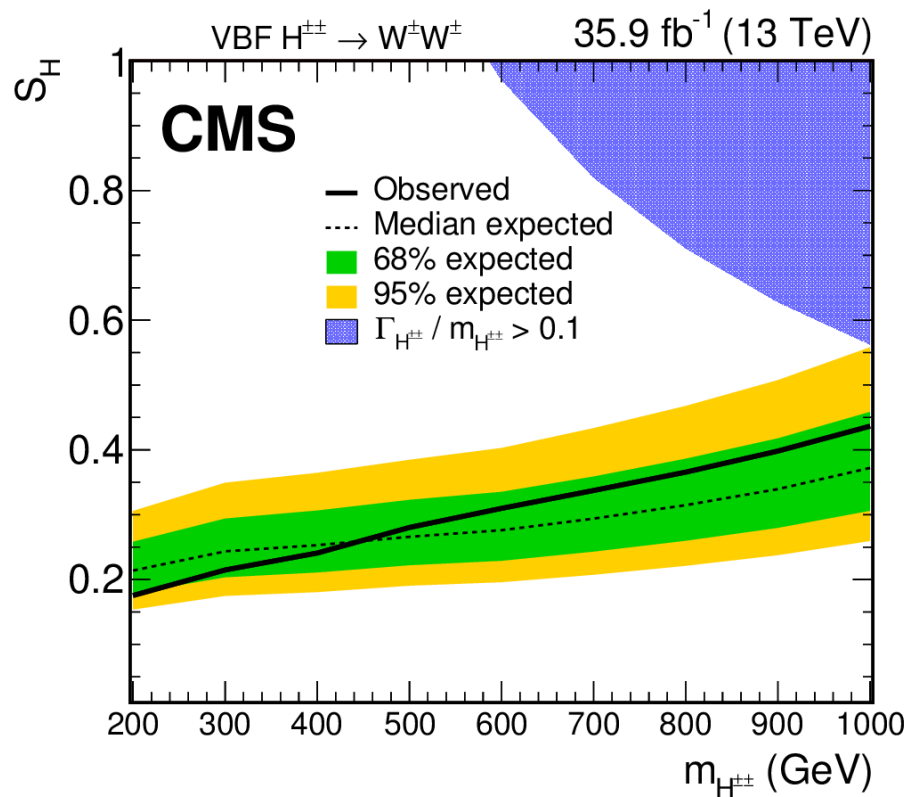
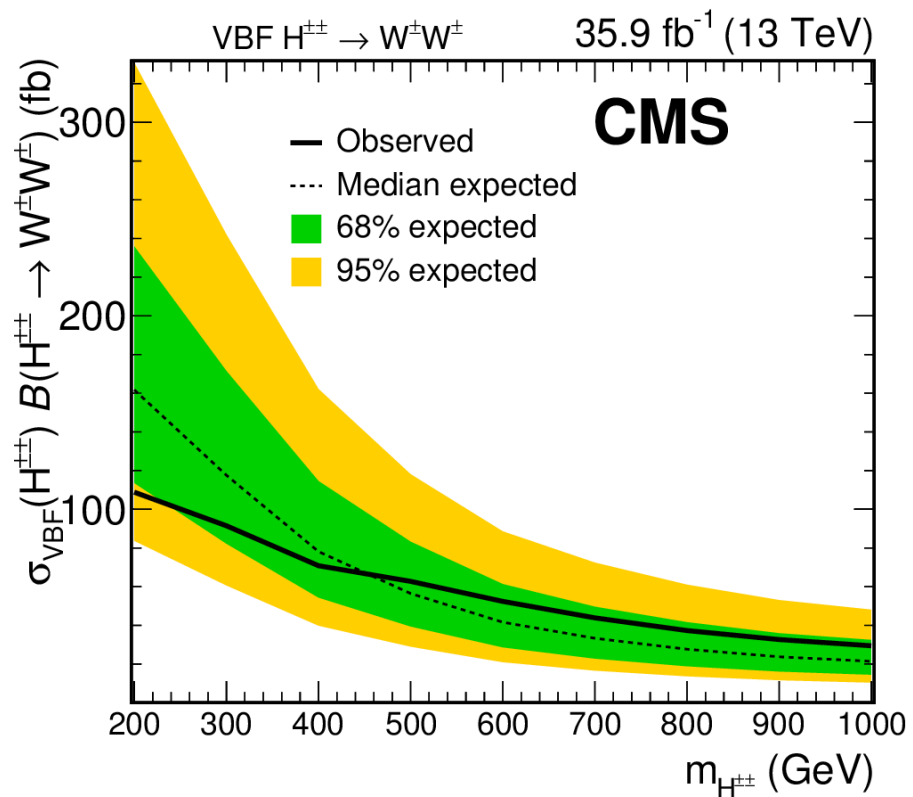


	Observed limits ( $\text{TeV}^{-4}$ )	Expected limits ( $\text{TeV}^{-4}$ )	Previously observed limits ( $\text{TeV}^{-4}$ )
$f_{S0} / \Lambda^4$	$[-7.7, 7.7]$	$[-7.0, 7.2]$	$[-38, 40]$ , [11]
$f_{S1} / \Lambda^4$	$[-21.6, 21.8]$	$[-19.9, 20.2]$	$[-118, 120]$ , [11]
$f_{M0} / \Lambda^4$	$[-6.0, 5.9]$	$[-5.6, 5.5]$	$[-4.6, 4.6]$ , [36]
$f_{M1} / \Lambda^4$	$[-8.7, 9.1]$	$[-7.9, 8.5]$	$[-17, 17]$ , [36]
$f_{M6} / \Lambda^4$	$[-11.9, 11.8]$	$[-11.1, 11.0]$	$[-65, 63]$ , [11]
$f_{M7} / \Lambda^4$	$[-13.3, 12.9]$	$[-12.4, 11.8]$	$[-70, 66]$ , [11]
$f_{T0} / \Lambda^4$	$[-0.62, 0.65]$	$[-0.58, 0.61]$	$[-0.46, 0.44]$ , [37]
$f_{T1} / \Lambda^4$	$[-0.28, 0.31]$	$[-0.26, 0.29]$	$[-0.61, 0.61]$ , [37]
$f_{T2} / \Lambda^4$	$[-0.89, 1.02]$	$[-0.80, 0.95]$	$[-1.2, 1.2]$ , [37]



# ss WW+jets: charged Higgs limits

Phys. Rev. Lett. 120, 081801 (2018)







# WZjj complete set of cuts

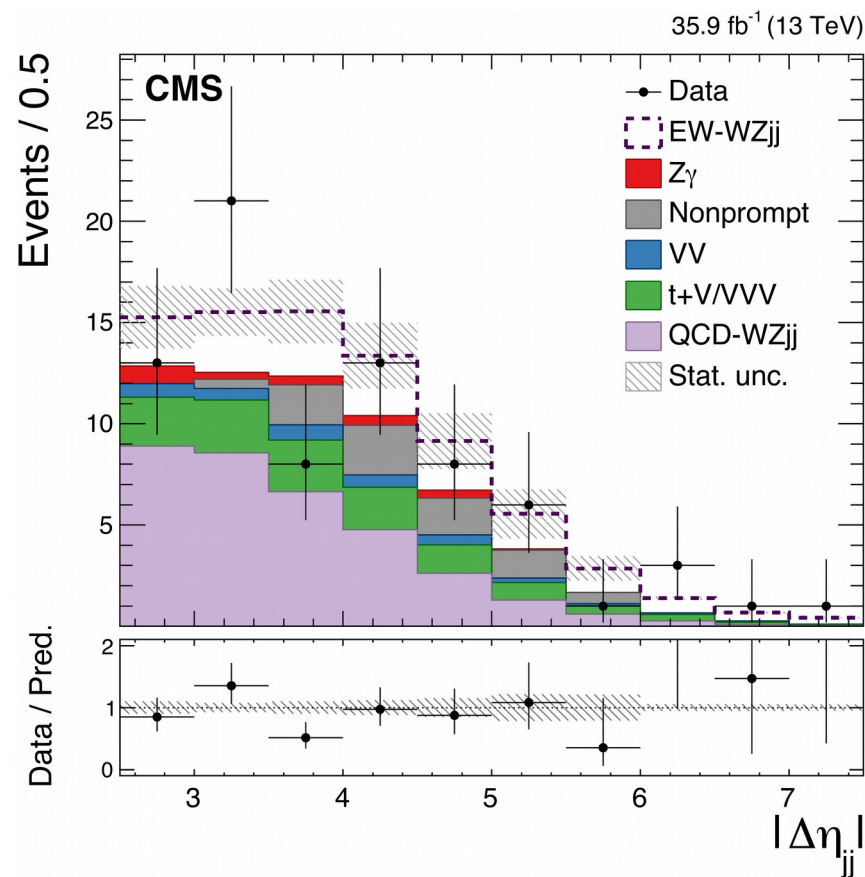
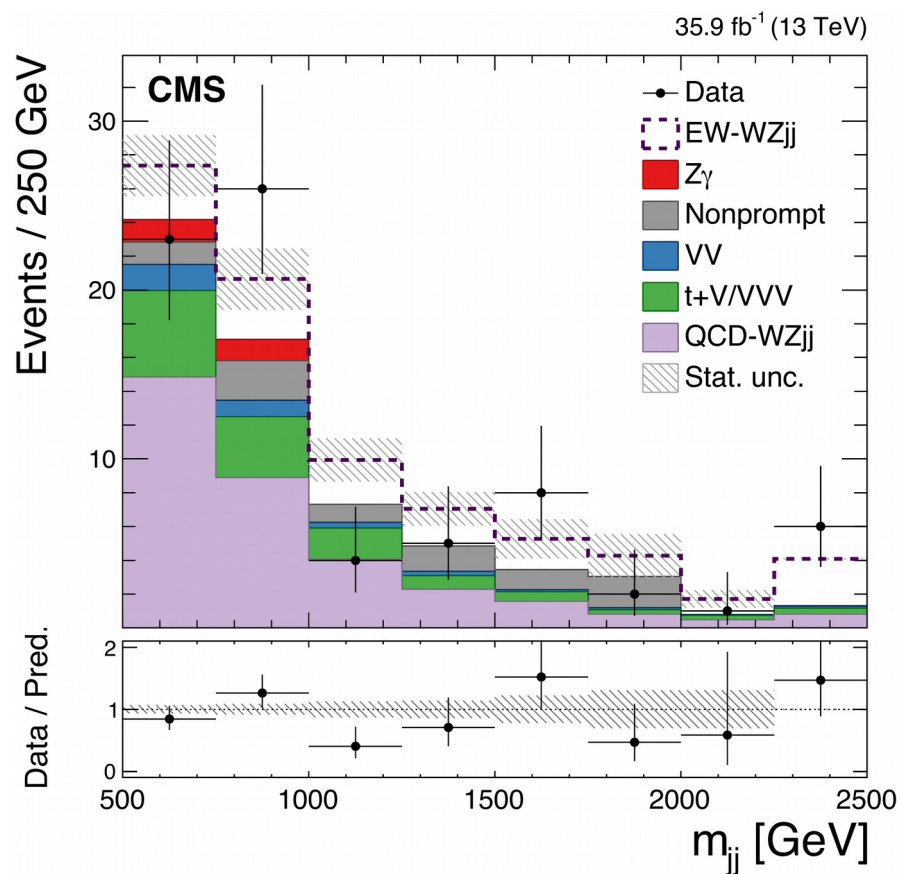
arXiv:1901.04060 sub to PLB



	EW signal	Higgs boson	Tight fiducial	Loose fiducial
$p_T^{\ell'1}$ [GeV]	>25	>25	>25	>20
$p_T^{\ell'2}$ [GeV]	>15	>15	>15	>20
$p_T^{\ell}$ [GeV]	>20	>20	>20	>20
$ \eta^\mu $	<2.4	<2.4	<2.5	<2.5
$ \eta^e $	<2.5	<2.5	<2.5	<2.5
$ m_{e'e'} - m_Z $ [GeV]	<15	<15	<15	<15
$m_{3\ell}$ [GeV]	>100	>100	>100	>100
$m_{\ell\ell}$ [GeV]	>4	>4	>4	>4
$p_T^{\text{miss}}$ [GeV]	>30	>30	—	—
$ \eta^j $	<4.7	<4.7	<4.7	<4.7
$p_T^j$ [GeV]	>50	>30	>50	>30
$ \Delta R(j, \ell) $	>0.4	>0.4	>0.4	>0.4
$n_j$	$\geq 2$	$\geq 2$	$\geq 2$	$\geq 2$
$p_T^b$ [GeV]	>30	>30	—	—
$ \eta^b $	<2.4	<2.4	—	—
$n_b$	=0	=0	—	—
$m_{jj}$	>500	>500	>500	>500
$ \Delta\eta_{jj} $	>2.5	>2.5	>2.5	>2.5
$ \eta^{3\ell} - (\eta^{j1} + \eta^{j2})/2 $	<2.5	—	<2.5	—



# WZjj $m_{jj}$ and $|\Delta\eta_{jj}|$ (pre-fit yields)





# WZjj yields

arXiv:1901.04060 sub to PLB



Post-fit yields

Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	$eee$	Total yield
QCD WZ	$13.5 \pm 0.8$	$9.1 \pm 0.5$	$6.8 \pm 0.4$	$4.6 \pm 0.3$	$34.1 \pm 1.1$
t+V/VVV	$5.6 \pm 0.4$	$3.1 \pm 0.2$	$2.5 \pm 0.2$	$1.7 \pm 0.1$	$12.9 \pm 0.5$
Nonprompt	$5.2 \pm 2.0$	$2.4 \pm 0.9$	$1.5 \pm 0.6$	$0.7 \pm 0.3$	$9.9 \pm 2.3$
VV	$0.8 \pm 0.1$	$1.6 \pm 0.2$	$0.4 \pm 0.0$	$0.7 \pm 0.1$	$3.5 \pm 0.2$
Z $\gamma$	$<0.1$	$2.1 \pm 0.8$	$<0.1$	$<0.1$	$2.1 \pm 0.8$
Pred. background	$25.2 \pm 2.1$	$18.3 \pm 1.6$	$11.2 \pm 0.8$	$7.7 \pm 0.5$	$62.4 \pm 2.8$
EW WZ signal	$6.0 \pm 1.2$	$4.2 \pm 0.8$	$2.9 \pm 0.6$	$2.1 \pm 0.4$	$15.1 \pm 1.6$
Data	38	15	12	10	75



# WZjj systematic uncertainties

arXiv:1901.04060 sub to PLB



Source of syst. uncertainty	Relative uncertainty [%]	
	$\sigma_{WZjj}$	EW WZ sig.
Jet energy scale	+11 / - 8.1	7.0
Jet energy resolution	+1.9 / - 2.1	<0.1
QCD WZ modeling	—	2.2
Other background theory	+2.2 / - 2.2	0.3
Nonprompt normalization	+2.5 / - 2.5	0.3
Nonprompt event count	+6.0 / - 5.8	1.7
Lepton energy scale and eff.	+3.5 / - 2.7	<0.1
b tagging	+2.0 / - 1.7	<0.1
Integrated luminosity	+3.6 / - 3.0	<0.1





# WZjj aQGC

arXiv:1901.04060 sub to PLB

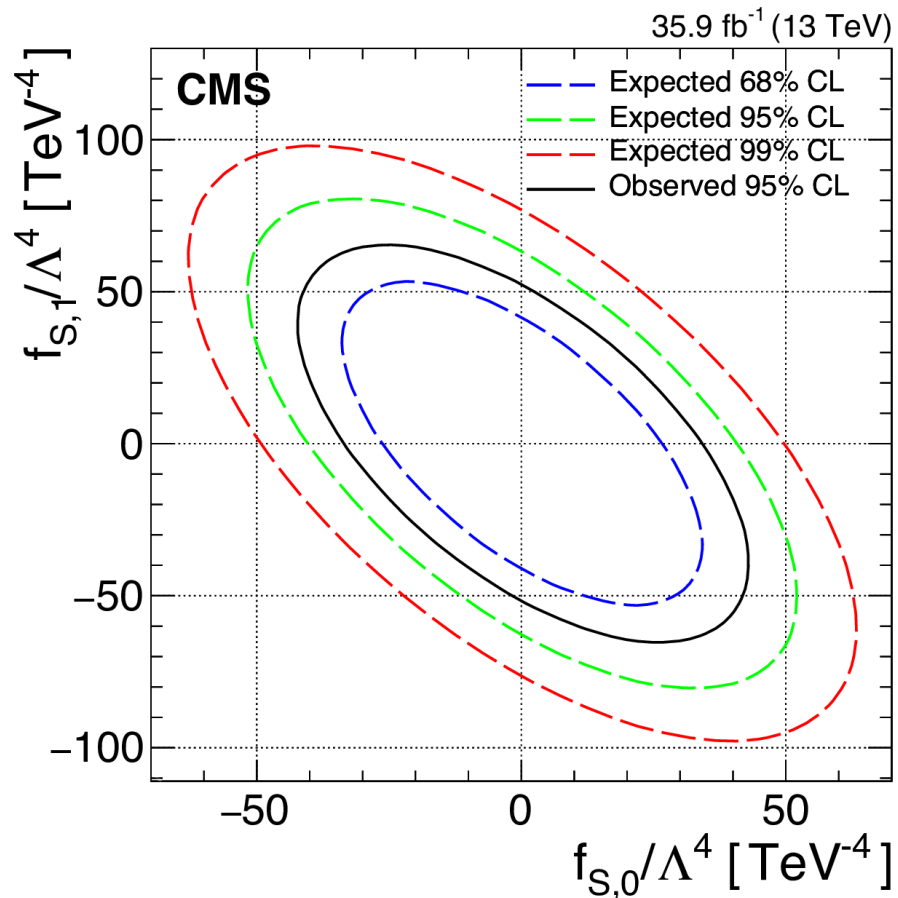
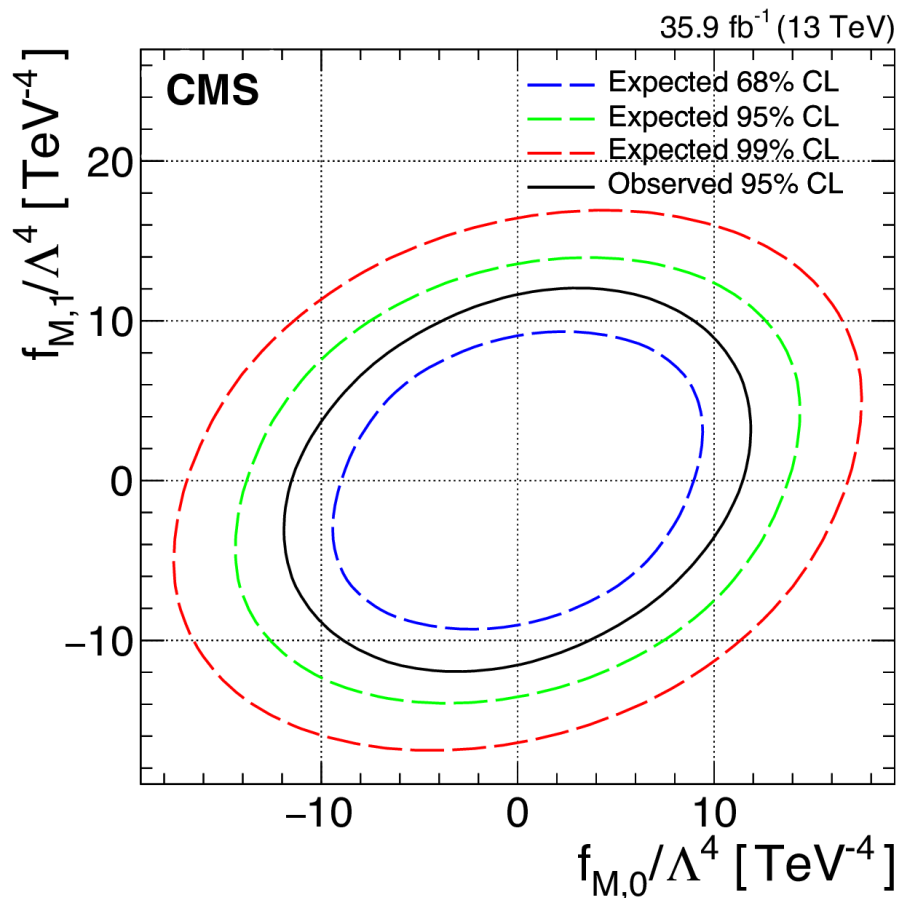


Parameters	Exp. limit	Obs. limit
$f_{M0} / \Lambda^4$	$[-11.2, 11.6]$	$[-9.15, 9.15]$
$f_{M1} / \Lambda^4$	$[-10.9, 11.6]$	$[-9.15, 9.45]$
$f_{S0} / \Lambda^4$	$[-32.5, 34.5]$	$[-26.5, 27.5]$
$f_{S1} / \Lambda^4$	$[-50.2, 53.2]$	$[-41.2, 42.8]$
$f_{T0} / \Lambda^4$	$[-0.87, 0.89]$	$[-0.75, 0.81]$
$f_{T1} / \Lambda^4$	$[-0.56, 0.60]$	$[-0.49, 0.55]$
$f_{T2} / \Lambda^4$	$[-1.78, 2.00]$	$[-1.49, 1.85]$



# WZjj aQGC

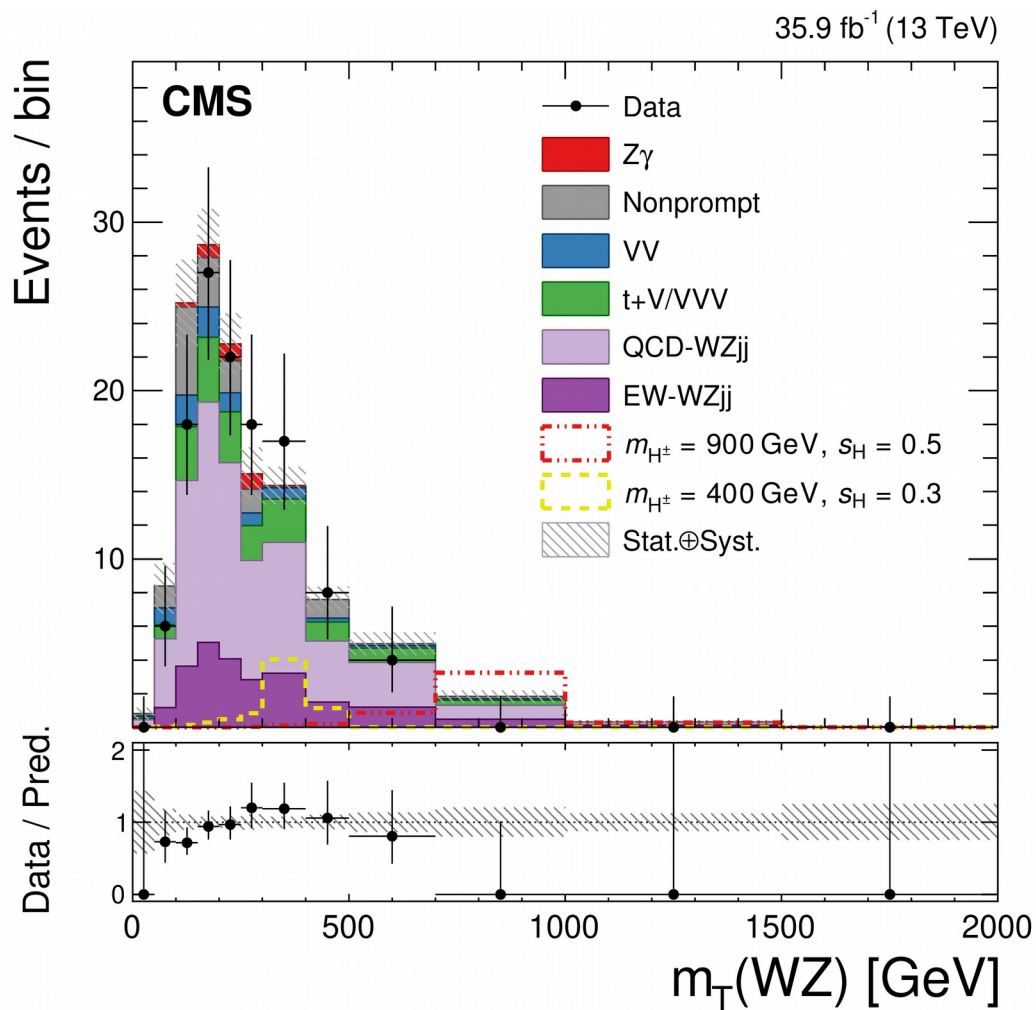
arXiv:1901.04060 sub to PLB





# WZjj Charged Higgs search region

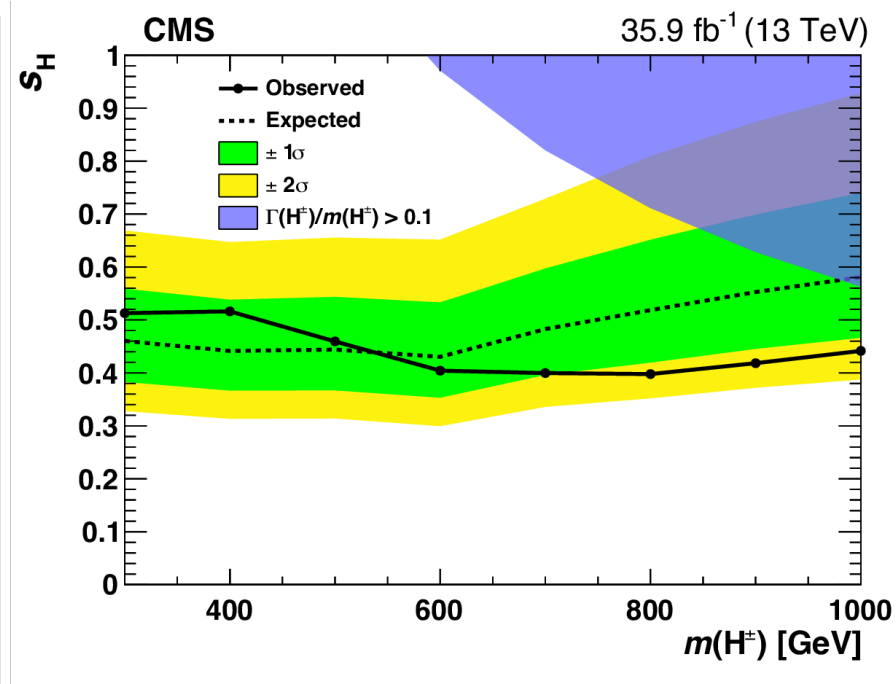
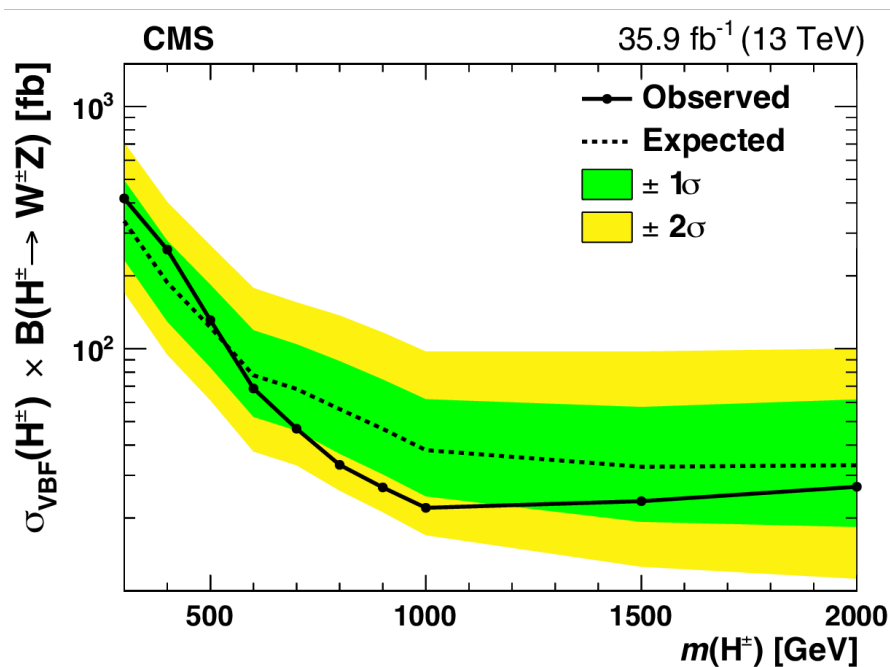
arXiv:1901.04060 sub to PLB





# WZjj Charged Higgs limits

arXiv:1901.04060 sub to PLB





# WW/WZ/ZZjj semileptonic: cuts

SMP-18-006



- Select events with
  - **One or two leptons** with  $p_T > 30$  GeV,  $R_{\text{iso}} < 0.3$  (0.4) for e ( $\mu$ )
  - **WVjj**:  $p_T^{\text{miss}} > 50$  (80) GeV for final state with  $\mu$  (e)
  - **ZVjj**:  $|m_{\text{ll}} - m_Z| < 15$  GeV
  - **No b-tagged jets**
- Hadronically decaying boson reconstructed in **boosted topology** (anti- $k_T$  w/  $R = 0.8$ )
  - $p_{T,V} > 200$  GeV,  $65$  GeV  $< m_V < 105$  GeV,  $\tau_2/\tau_1 < 0.55$
- **Stringent VBS requirements:**
  - **Two jets** with  $p_T > 30$  GeV,  $m_{jj} > 800$  GeV,  $|\Delta\eta_{jj}| > 4$
  - $Z_V^*, Z_W^*, Z_Z^* < 0.3$ , with  $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})/2| / |\Delta\eta_{jj}|$
  - $\theta = \min(\min(\eta_W, \eta_V) - \min(\eta_{jet,1}, \eta_{jet,2}), \max(\eta_{jet,1}, \eta_{jet,2}) - \max(\eta_W, \eta_V)) > 1.0$





# WW/WZ/ZZjj semileptonic: yields

SMP-18-006



Final state	WV	ZV
	347	47
V+jets	$187 \pm 21$	$41.2 \pm 6.1$
top	$120 \pm 18$	$0.16 \pm 0.04$
SM QCD VV	$28 \pm 10$	$6.4 \pm 2.2$
SM EW VV	$17 \pm 2$	$2.4 \pm 0.4$
Total bkg.	$352 \pm 21$	$50.1 \pm 5.9$
$f_{T2} / \Lambda^4 = -0.5, -2.5 \text{ TeV}^{-4}$	$22 \pm 1$	$7.6 \pm 0.6$
$m_{H_5} = 500 \text{ GeV}, s_H = 0.5$	$40 \pm 1$	$4.3 \pm 0.1$



# WW/WZ/ZZjj: systematic uncertainty

SMP-18-006

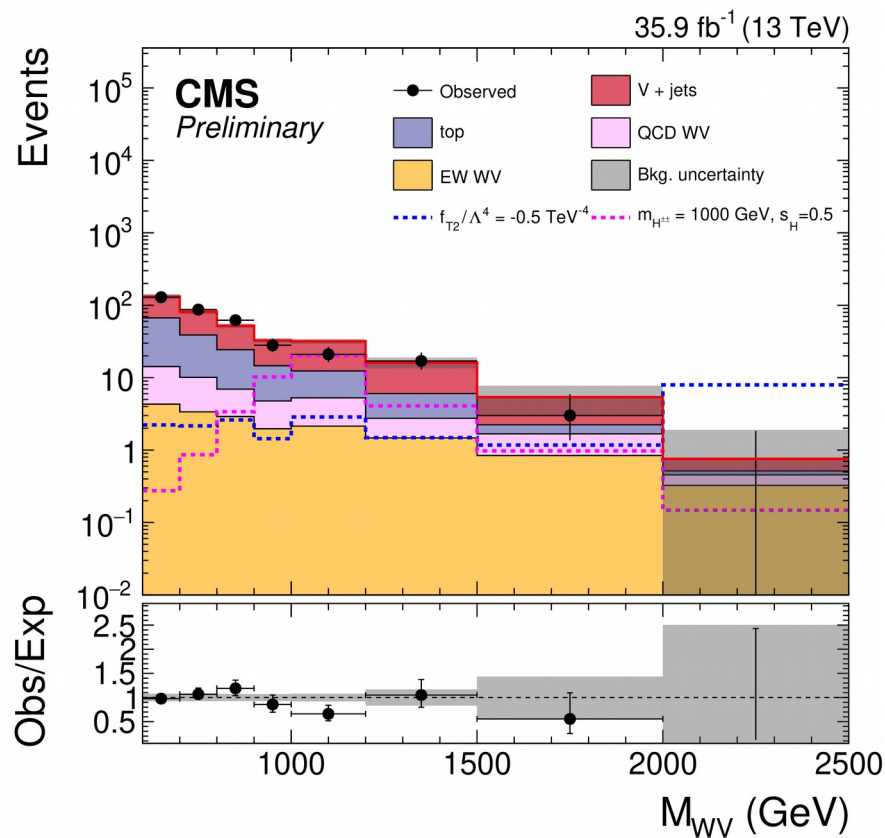
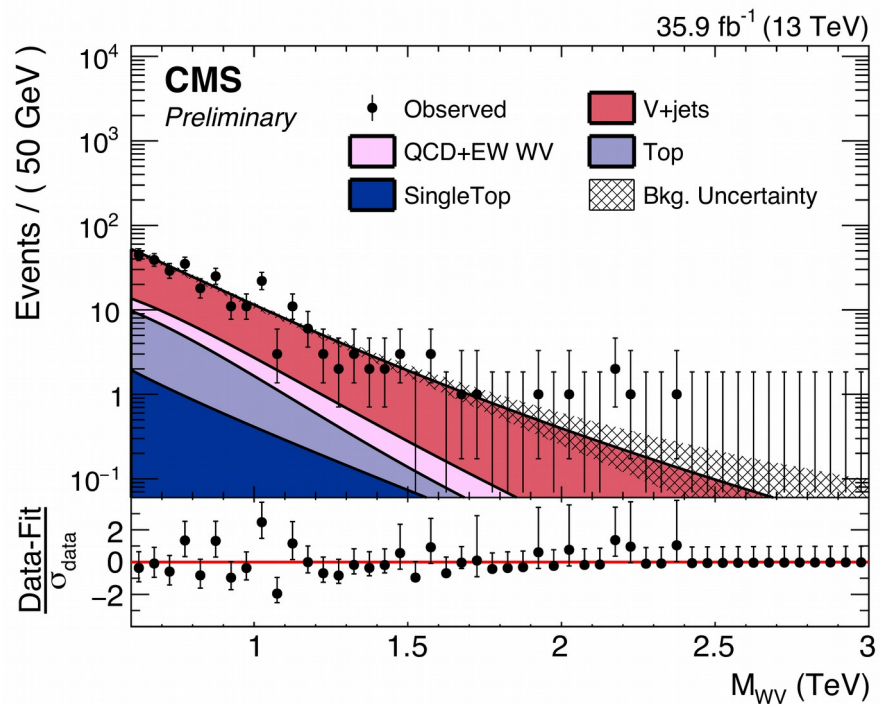


Source	Shape	Signal	V+jets	SM EW	SM QCD VV	top
QCD scale	✓	9-20	—	12	30	—
PDF unc.	✓	15	—	10	10	—
Jet momentum scale	✓	1-9	—	1-9	3.0-15	5.0-7.0
V-jet selection		8.0	—	8.0	8.0	—
GM model EW		7.0	—	—	—	—
bkg. normalization		—	7-16	—	—	2.0
V+jets shape	✓	—	shape	—	—	—
Integrated luminosity		2.5	—	2.5	2.5	—
Lepton efficiency		1.0-2.0	—	1.0-2.0	1.0-2.0	—
Lepton momentum scale	✓	0.2-0.4	—	0.5	1.0-1.3	1.0
b-quark jet efficiency		2.0	—	2.0	2.0	3.0
Jet/MET resolution		4.0	—	3.0	2.0	—
Pileup modeling		4.0	—	4.0	4.0	—
Limited MC stat.	✓	shape	—	shape	shape	shape



# WW/WZ/ZZjj: WV analysis

SMP-18-006





# WW/WZ/ZZjj semileptonic: aQGC

SMP-18-006

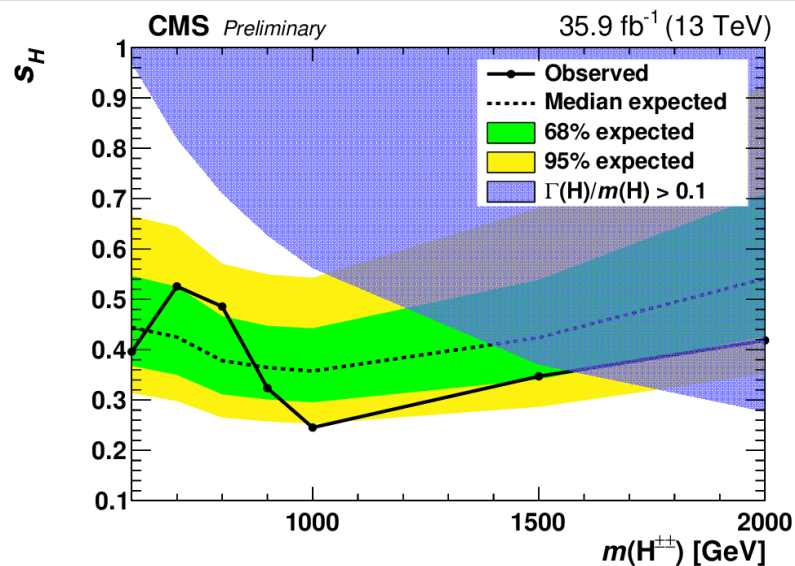
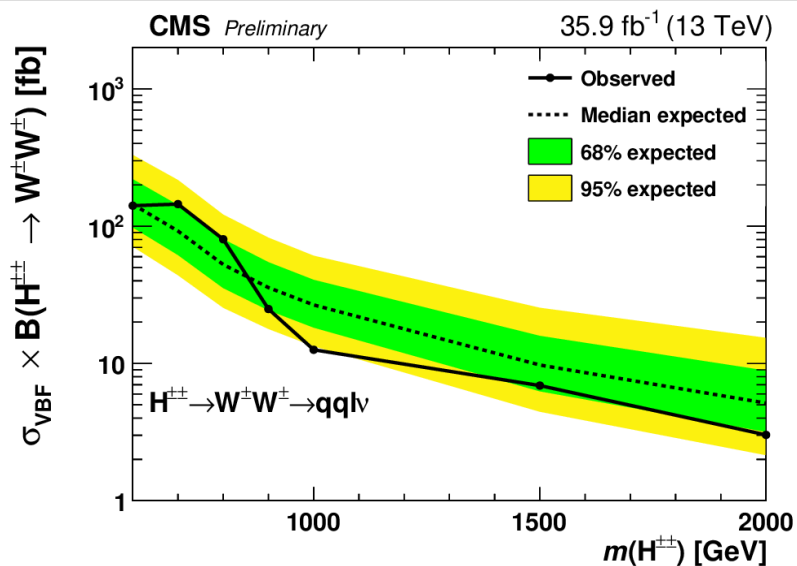
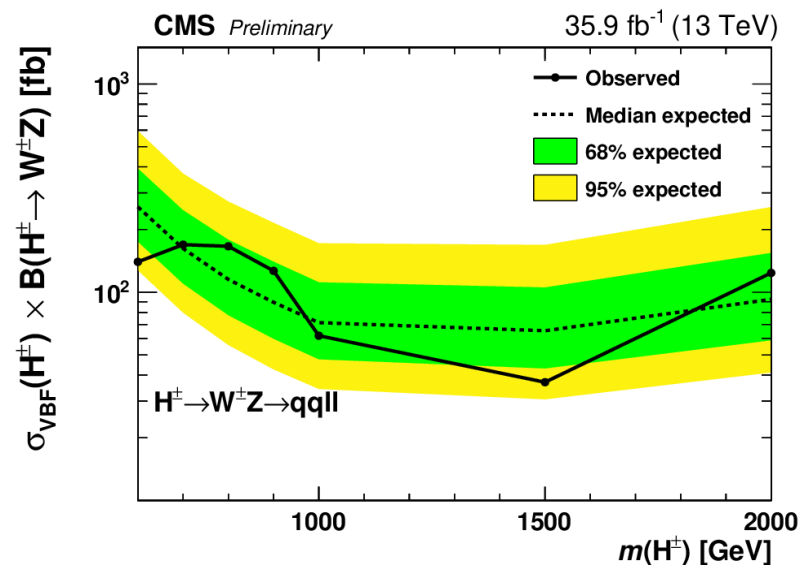
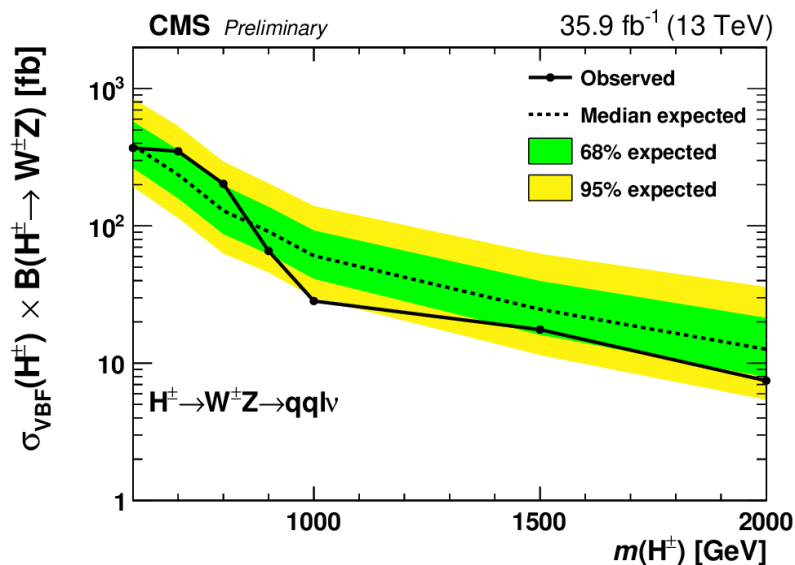


	Observed (WV) (TeV <sup>-4</sup> )	Expected (WV) (TeV <sup>-4</sup> )	Observed (ZV) (TeV <sup>-4</sup> )	Expected (ZV) (TeV <sup>-4</sup> )	Observed (TeV <sup>-4</sup> )	Expected (TeV <sup>-4</sup> )
$f_{S0}/\Lambda^4$	[-2.6, 2.7]	[-4.0, 4.0]	[-37, 37]	[-29, 29]	[-2.6, 2.7]	[-4.0, 4.0]
$f_{S1}/\Lambda^4$	[-3.2, 3.3]	[-4.9, 4.9]	[-30, 30]	[-23, 23]	[-3.3, 3.3]	[-4.9, 4.9]
$f_{M0}/\Lambda^4$	[-0.66, 0.66]	[-0.95, 0.95]	[-6.9, 6.9]	[-5.1, 5.1]	[-0.66, 0.66]	[-0.95, 0.95]
$f_{M1}/\Lambda^4$	[-1.9, 2.0]	[-2.8, 2.8]	[-21, 21]	[-15, 15]	[-1.9, 2.0]	[-2.8, 2.8]
$f_{M6}/\Lambda^4$	[-1.3, 1.3]	[-1.9, 1.9]	[-14, 14]	[-10, 10]	[-1.3, 1.3]	[-1.9, 1.9]
$f_{M7}/\Lambda^4$	[-3.3, 3.2]	[-4.8, 4.8]	[-33, 33]	[-24, 24]	[-3.3, 3.3]	[-4.8, 4.8]
$f_{T0}/\Lambda^4$	[-0.11, 0.10]	[-0.16, 0.15]	[-1.3, 1.3]	[-0.95, 0.95]	[-0.12, 0.10]	[-0.16, 0.15]
$f_{T1}/\Lambda^4$	[-0.11, 0.12]	[-0.17, 0.17]	[-1.4, 1.4]	[-0.98, 0.99]	[-0.11, 0.12]	[-0.17, 0.17]
$f_{T2}/\Lambda^4$	[-0.27, 0.27]	[-0.38, 0.38]	[-3.1, 3.2]	[-2.3, 2.3]	[-0.27, 0.27]	[-0.38, 0.38]



# WW/WZ/ZZjj: Charged Higgs limits

SMP-18-006







# Limits on scalar aQGC operators



May 2019

CMS



Channel

Limits

$\int L dt$

$\sqrt{s}$

$f_{s,0}/\Lambda^4$



ss WW

[-3.8e+01, 4.0e+01]

19.4 fb<sup>-1</sup>

8 TeV



ss WW

[-7.7e+00, 7.7e+00]

35.9 fb<sup>-1</sup>

13 TeV



WZ

[-2.6e+01, 2.8e+01]

35.9 fb<sup>-1</sup>

13 TeV

H

WV ZV

[-2.7e+00, 2.7e+00]

35.9 fb<sup>-1</sup>

13 TeV

$f_{s,1}/\Lambda^4$



ss WW

[-1.2e+02, 1.2e+02]

19.4 fb<sup>-1</sup>

8 TeV



ss WW

[-2.2e+01, 2.2e+01]

35.9 fb<sup>-1</sup>

13 TeV



WZ

[-4.1e+01, 4.3e+01]

35.9 fb<sup>-1</sup>

13 TeV

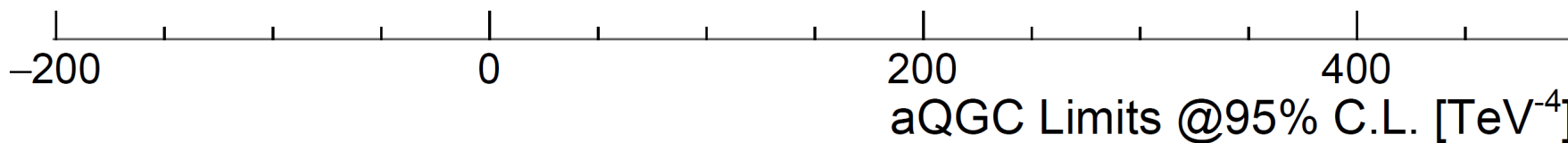
H

WV ZV

[-3.4e+00, 3.4e+00]

35.9 fb<sup>-1</sup>

13 TeV

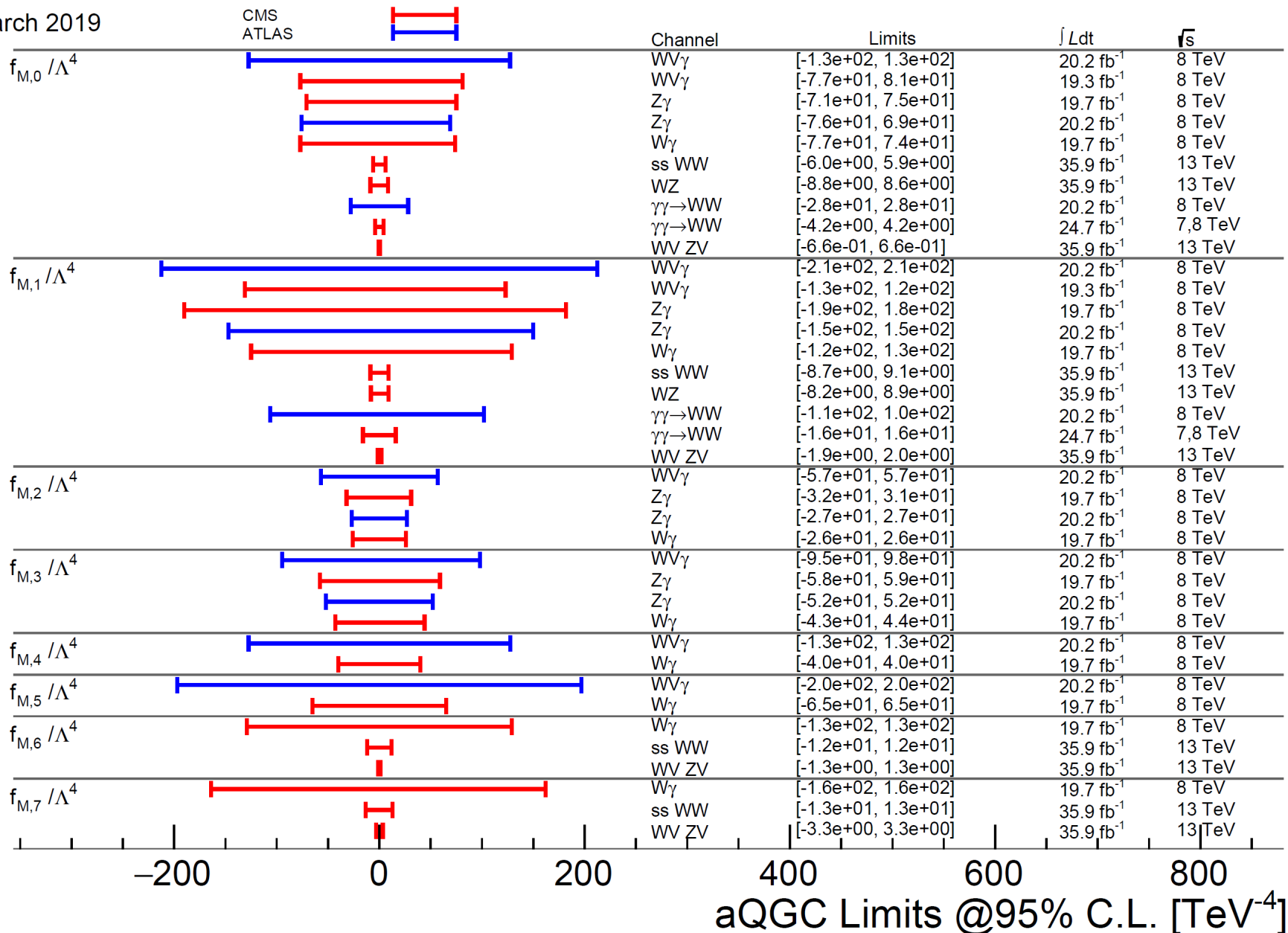




# Limits on mixed aQGC operators



March 2019





# Why VV Scattering



In the symmetry breaking (EWSB) mechanism the **W** and **Z** bosons get their **masses** and acquire a **longitudinal degree of polarization**.

The mechanism responsible for the EWSB has to **regulate the  $V_L V_L \rightarrow V_L V_L$  cross section** such that the unitarity is preserved above  $m_{VV} \sim 1-2$  TeV

**VV scattering is the key process to probe EWSB** and high energy vector boson scattering will play a central role:

- both as a **test of the Higgs boson nature**
  - If the discovered Higgs boson contributes **fully to the EWSB**, then most probably the interaction among longitudinal weak bosons would remain **weak** at high energy
- and as a **model independent research** of alternative theory to explain EWSB
  - if the 125.5 GeV Higgs boson is only **partially responsible for the EWSB**, then the VV interaction could get **strong** at high energy.
- Also **TGC** and **QGC** processes may carry **new physics phenomena**



# The Higgs Job



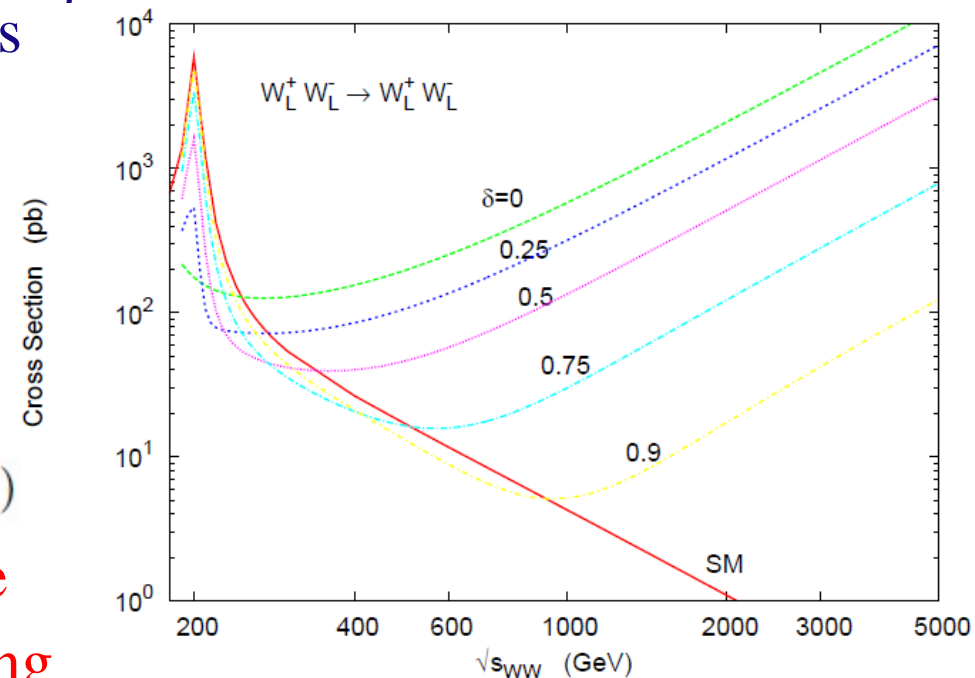
- If the cancellation of the **Higgs diagrams is not complete**, then we expect a  **$g_{HWW}$  coupling smaller than the SM**.
- The  **$W_L W_L$  will keep growing with  $\sqrt{s}$** , up to the the new resonance, or more generally to the **new physics scale  $\Lambda$** .
- Suppose the Higgs-WW coupling is amplitudes become

$$i\mathcal{M}^{\text{gauge}} = -i \frac{g^2}{4m_W^2} u + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{higgs}} = i \frac{g^2}{4m_W^2} u \delta + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{all}} = -i \frac{g^2}{4m_W^2} u(1 - \delta) + \mathcal{O}((E/m_W)^0)$$

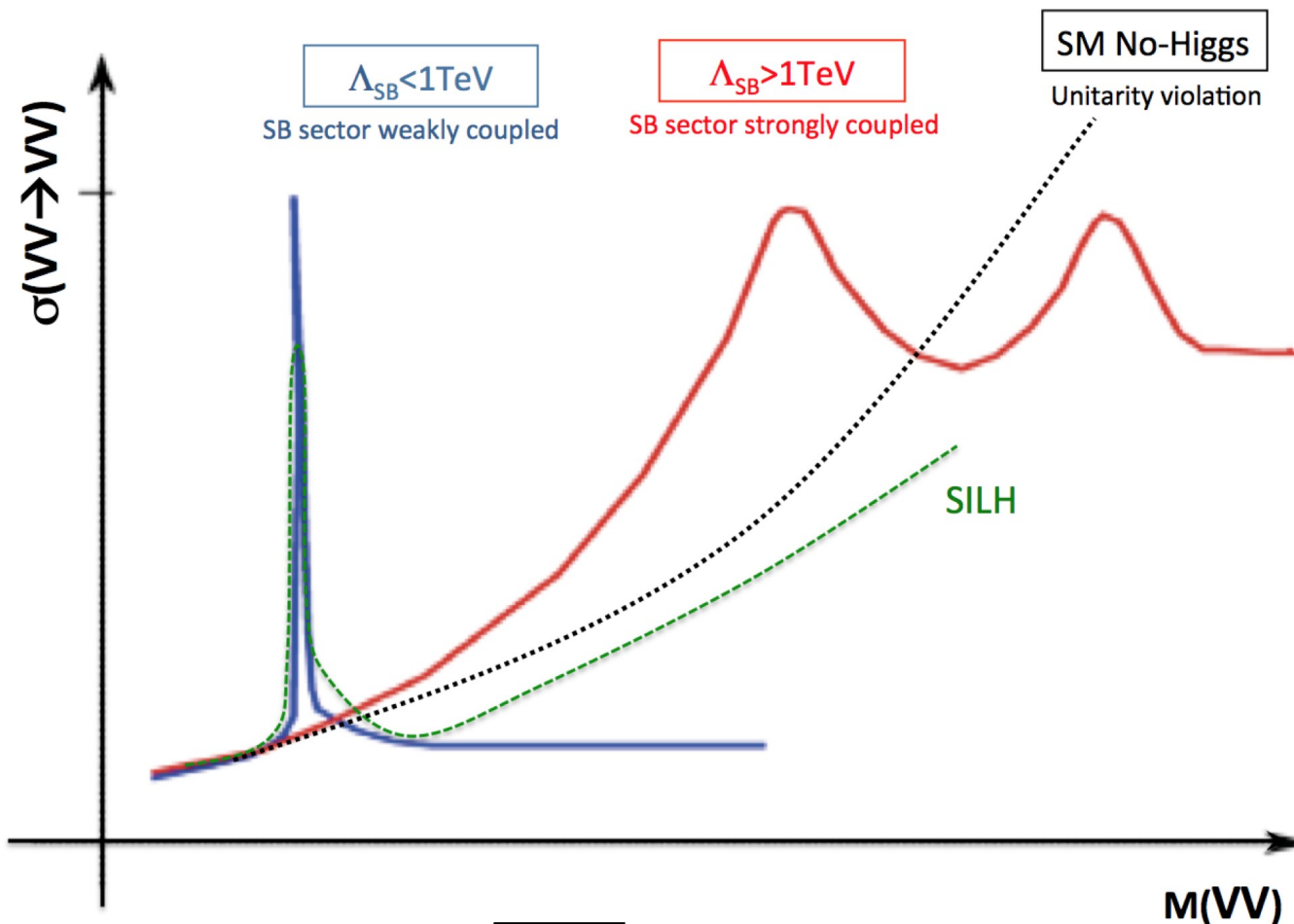
Measure with high precision both the HVV coupling and the  $V_L V_L$  scattering



Cheung, Chiang, Yuan



# VV Scattering to test the EWSB



**SILH :**

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

Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

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

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





# Anomalous Quartic Gauge Couplings Modelling



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

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \dots \quad \text{desideratum: } \Lambda \sim 1-2 \text{ TeV}$$

- **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  $\Lambda$  is large compared with the experimentally-accessible energy
  - These operators have **coefficients of inverse powers of mass** ( $\Lambda$ ), and hence are suppressed if this mass is large compared with the experimentally-accessible energy
  - **Limit**:  $\Lambda$  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.  $c_i/\Lambda^2$ ) (e.g., hep-ph/9908254), **may affects 3 boson vertices too**:
  - $C_{\phi W}/\Lambda^2$  (VBFNLO),  $a_0^W/\Lambda^2$ ,  $a_C^W/\Lambda^2$  (CALCHEP)...
- coefficients in **dimension-8** (i.e.  $c_i/\Lambda^4$ ) (e.g., hep-ph/0606118), **modifies 4 boson vertices only**:

–  $f_{S,0}/\Lambda^4, f_{T,0}/\Lambda^4 \dots$



# Final States and their Cross-sections



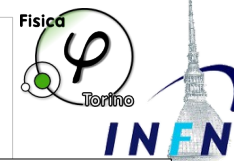
- Needs to simulate all  $2 \rightarrow 6$  processes at least at the order  $\mathcal{O}(\alpha_{EW}^6)$
- Large interference** among same order diagrams
- Signal has to be defined a posteriori**, using kinematic cuts arXiv:0801.3359
- Cross Sections for  $\sqrt{s} = 14$  TeV from Phantom Monte Carlo Generator:  
**full simulation of  $2 \rightarrow 6$  @  $\mathcal{O}(\alpha_{EW}^6) + \mathcal{O}(\alpha_{EW}^4\alpha_{QCD}^2)$**

	$qqqq\mu\nu/e\nu$				$qqqq\mu\mu/ee$			
	no-Higgs		500 GeV		no-Higgs		500 GeV	
	$\sigma$ (pb)	perc.	$\sigma$ (pb)	perc.	$\sigma$ (pb)	perc.	$\sigma$ (pb)	perc.
total	0.689	100%	0.718	100%	0.0305	100%	0.0350	100%
signal	0.158	23%	0.184	26%	0.0125	41%	0.0165	47%
top	0.495	72%	0.494	69%	0.0137	45%	0.0137	39%
non resonant	0.020	3%	0.023	3%	0.0030	10%	0.0035	10%
three bosons	0.016	2%	0.017	2%	0.0012	4%	0.0014	4%

	$qq\mu\mu\mu\mu/eeee$				$qq\mu\mu\mu\nu$				$qq\mu^\pm\nu\mu^\pm\nu$			
	no-Higgs		500 GeV		no-Higgs		500 GeV		no-Higgs		500 GeV	
	$\sigma$ (fb)	perc.	$\sigma$ (fb)	perc.	$\sigma$ (fb)	perc.	$\sigma$ (fb)	perc.	$\sigma$ (fb)	perc.	$\sigma$ (fb)	perc.
total	0.180	100%	0.310	100%	4.182	100%	4.152	100%	4.29	100%	4.16	100%
signal	0.120	66.4%	0.229	74.1%	1.317	31.5%	1.281	30.8%	3.26	76%	3.11	75%
top	0	0%	0	0%	1.817	43.5%	1.828	44.01%	0	0%	0	0%
non resonant	0.0364	20.2%	0.0533	17.2%	0.673	16.1%	0.651	15.7%	0.47	11%	0.46	11%
three bosons	0.0241	13.4%	0.0268	8.66%	0.375	8.9%	0.392	9.5%	0.56	13%	0.58	14%

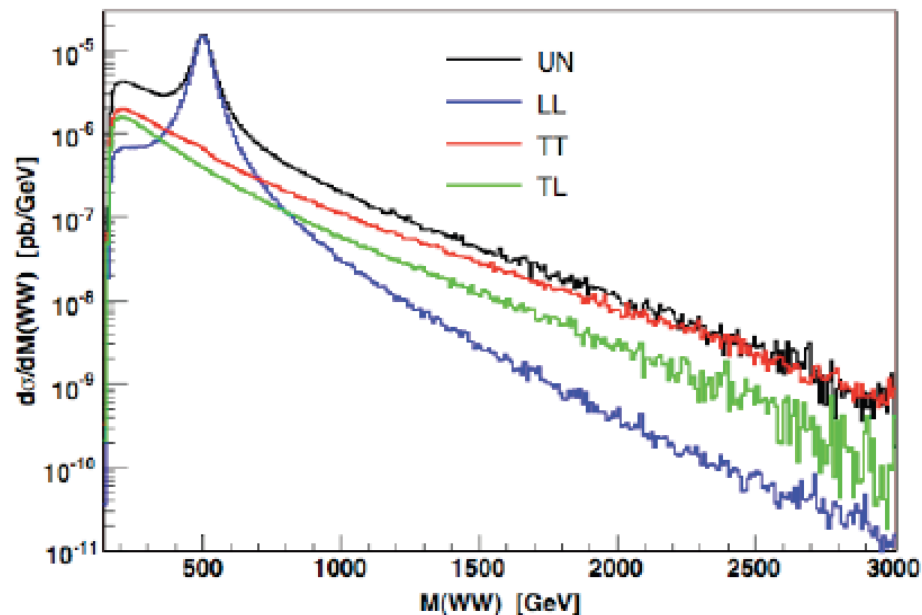


# Scattering of Polarized Vector Bosons

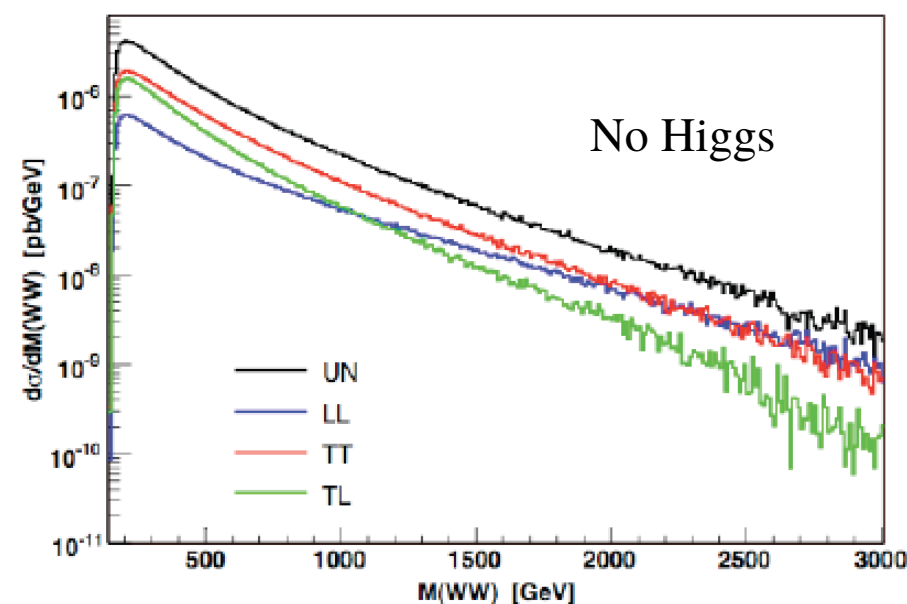


Accomando et al: hep-ph/0512219

$ud \rightarrow ud W^+W^- \rightarrow ud \mu \nu c s$



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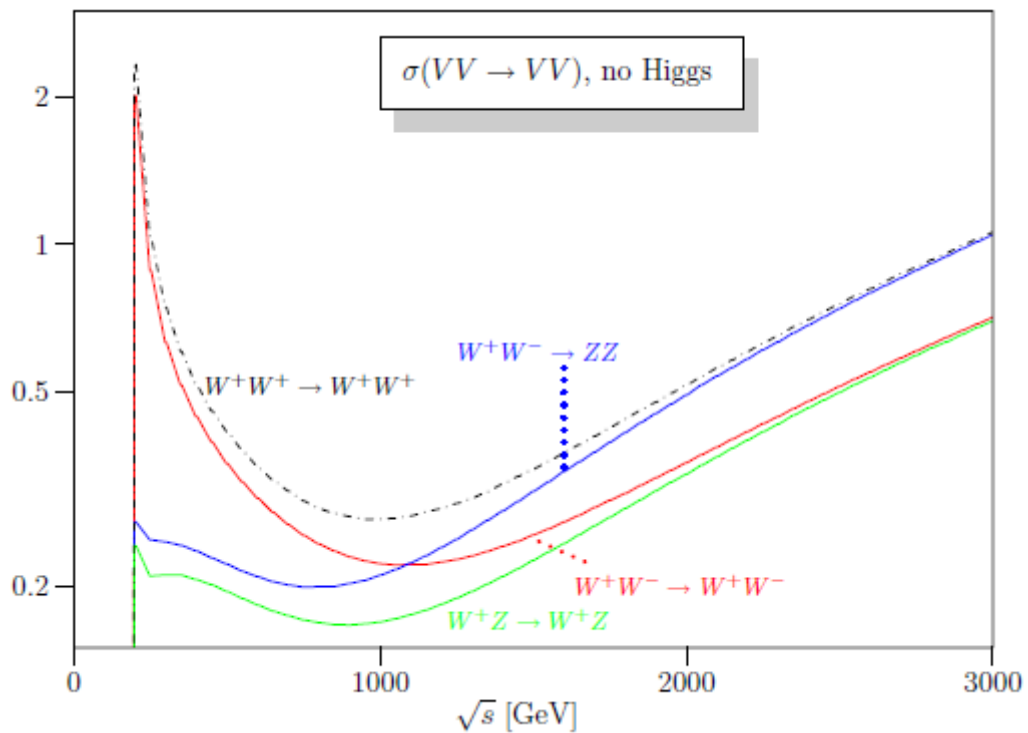
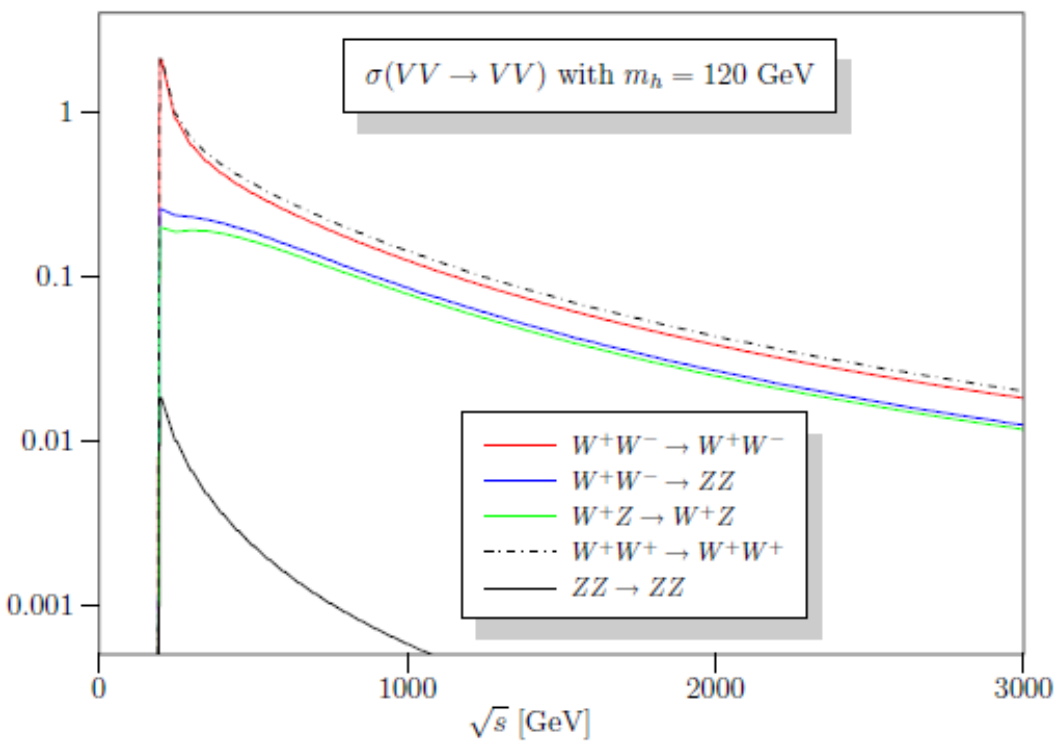


- The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
- The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
- At large  $M(VV)$  the TT cross section is of the same order as the LL (in the no-Higgs case)

If there is a new resonance at a scale  $\Lambda$ , the LL cross section will not decrease until  $\Lambda$ .

- Experimentally we should enhance LL wrt TT and measure XS at the highest  $M(VV)$

- The cross section decreases rapidly at high invariant masses due to PDF – Hard life for LHC @14 TeV !
- The invariant VV mass is the equivalent of the CM energy of the elastic VV scattering



arxiv:0806.4145