Electroweak production of vector bosons and jets at the CMS experiment

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On behalf of the **CMS** Collaboration

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VBS Analyses in CMS

Targetting the observation of the **Electroweak production** of dibosons in associations with at least two jets:

- $pp \rightarrow ZZjj \rightarrow 4\ell jj$ Phys. Lett. B 774 (2017) 682
- $pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow 2\ell^{\pm}2\nu jj$ Phys. Rev. Lett. 120, 081801 (2018)
- $pp \rightarrow WZjj \rightarrow 3\ell\nu jj$ arXiv:1901.04060 sub to PLB

Targetting strong limits on **anomalous quartic gauge couplings**:

- $pp \rightarrow ZVjj \rightarrow 2\ell jjjj$ and $pp \rightarrow WVjj \rightarrow \ell\nu jjjj$ arXiv:1905.07445 sub to PLB

In all cases, ℓ = e, μ, and $\mathscr{L} = 35.9\ \mathrm{fb}^{-1}$ (2016 data only).

ZZ+jets analysis

Phys. Lett. B 774 (2017) 682

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**

ZZ+jets Complete Cut List

Phys. Lett. B 774 (2017) 682

Fiducial region (baseline)

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

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

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

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

$m_{\ell^+\ell^-} > 4\,\text{GeV}$ (regardless of their flavour)

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

Fiducial region (VBS)

+ $m_{jj} > 100$ GeV

Search region (baseline)

- $|\eta_e| < 2.5$ $p_T^e > 7$ GeV, $|\eta_\mu| < 2.4$ $p_T^\mu > 5$ GeV, relative isolation < 0.35 in a cone of $\Delta R = 0.3$, CMS tight ID and SIP= $|IP/\sigma_{IP}| < 4$
- At least a lepton with $p_T > 20$ GeV and a μ(e) with $p_T > 10(12)$ GeV
- $60 < m_Z < 120$ GeV (On shell), $m_{ll\ \text{crossed(opposite sign)}} > 4$ GeV
- Loosely ID jets, reco with anti-k_T 0.4; $|\eta_{jet}| < 4.7$ and $p_T > 30$ GeV

Search region (VBS)

+ $m_{jj} > 100$ GeV

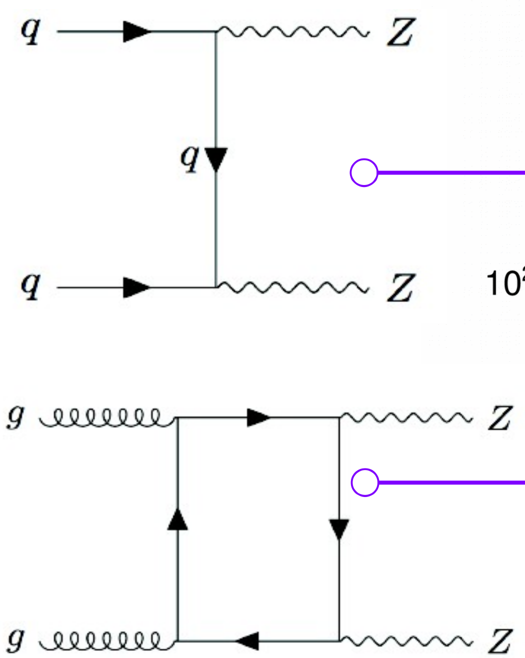
Relevant MC Simulations

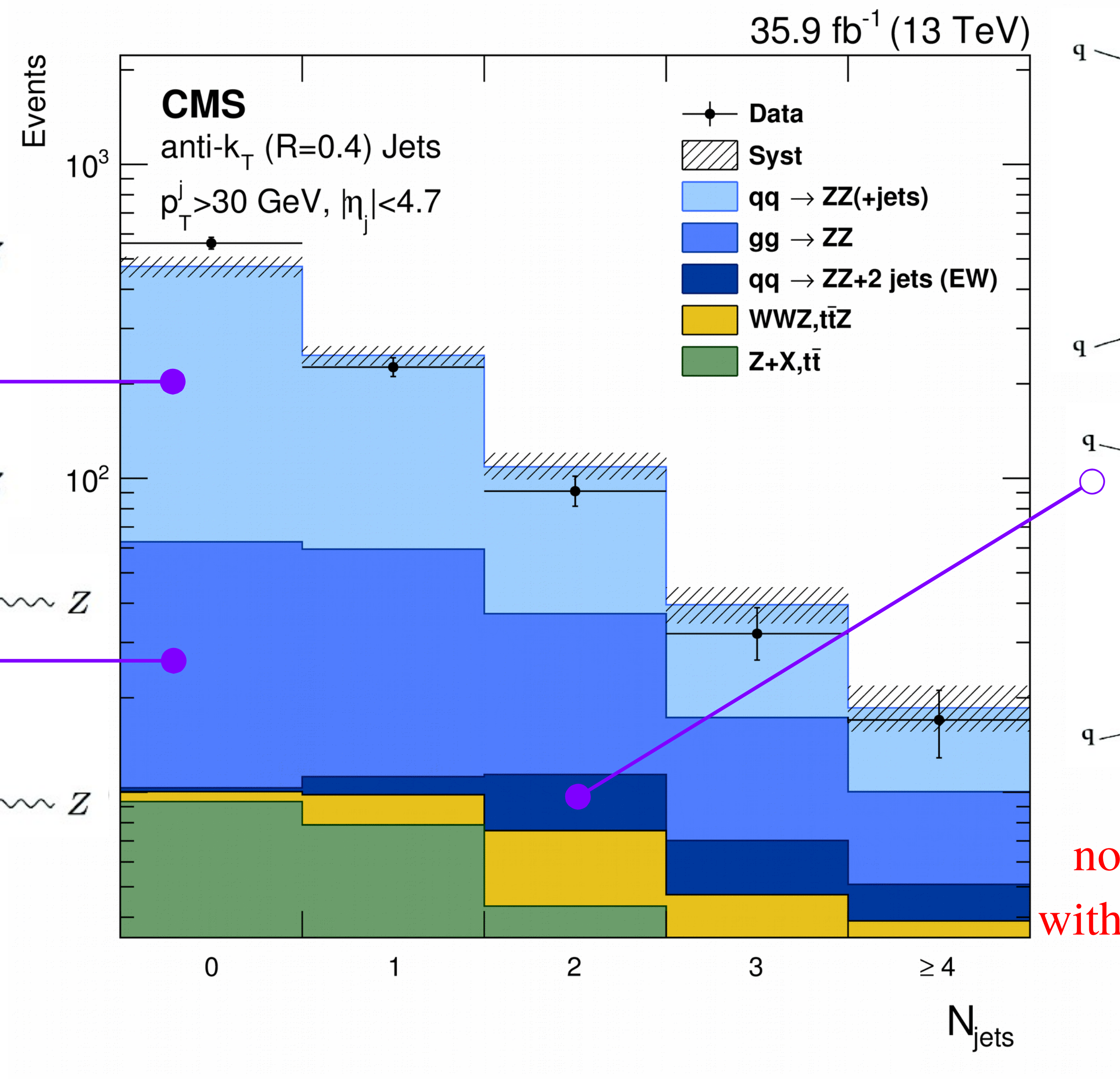
Phys. Lett. B 774 (2017) 682

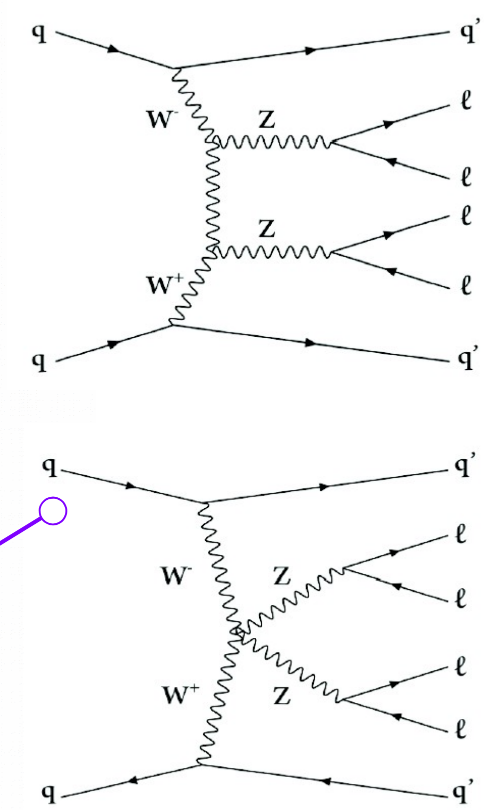
- **Signal**: MadGraph_aMC@NLO v2.3.3
  - Cross checked with Phantom v1.2.8
- **ZZ + QCD-induced jets** (0,1 at born level @NLO): MadGraph_aMC@NLO
  - Jets merged with FxFx scheme
- **Loop-induced ZZ production** (gg → ZZ): MCFM v7.0.1
  - Cross checked with MadGrap_aMC@NLO
- In all cases, PYTHIA v8.212 is used for parton showering, hadronization and underlying event simulation (CUETP8M1 tune), while we used the NNPDF3.0 PDF set.

Number of jets in association with two Zs

Phys. Lett. B 789 (2019) 19







+

non-VBS diagrams,

with ($\alpha_{EW}{}^6$) at tree level

ZZ+jets Cross sections

Phys. Lett. B 789 (2019) 19

Number of jets ($\|\eta_j\| < 4.7$)	Cross section [fb]	Theoretical cross section [fb]
0	$28.3 \pm 1.3\,(\text{stat})^{+1.7}_{-1.5}\,(\text{syst}) \pm 0.7\,(\text{lumi})$	$23.6^{+0.8}_{-0.9}$
1	$8.0 \pm 0.8\,(\text{stat})^{+0.7}_{-0.8}\,(\text{syst}) \pm 0.2\,(\text{lumi})$	$9.7^{+0.5}_{-0.5}$
2	$3.0 \pm 0.5\,(\text{stat})^{+0.3}_{-0.4}\,(\text{syst}) \pm 0.1\,(\text{lumi})$	$4.0^{+0.3}_{-0.3}$
≥ 3	$1.3 \pm 0.4\,(\text{stat})^{+0.2}_{-0.2}\,(\text{syst})$	$1.7^{+0.1}_{-0.1}$

Cross section of ZZ + ≥ 2 jets = (4.3 ± 0.8) fb [(5.7 ± 0.3) fb theo]

Applying *a further selection* on VBS-enanching variables, namely

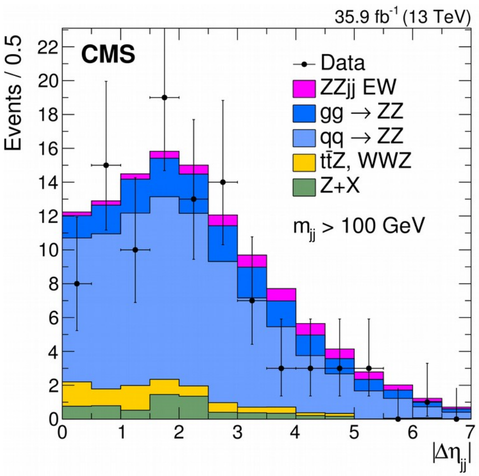
m_{jj} > 400 GeV and **$|\Delta\eta|$ > 2.4**, what we obtain is

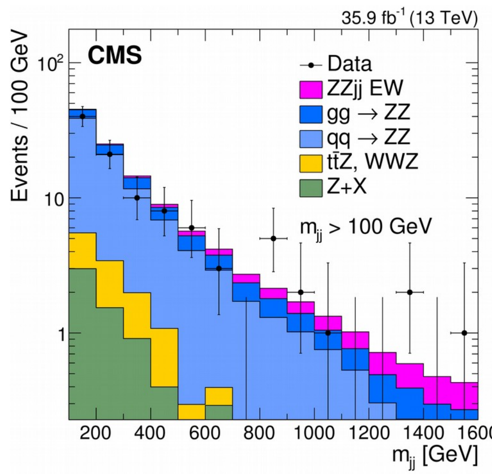
Selection	$t\bar{t}Z$ and WWZ	QCD ZZjj	Z + X	Total bkg.	EW ZZjj	Total expected	Data
ZZjj	7.1 ± 0.8	97 ± 14	6.6 ± 2.5	111 ± 14	6.2 ± 0.7	117 ± 14	99
VBS signal-enriched	0.9 ± 0.2	19 ± 4	0.7 ± 0.3	20 ± 4	4 ± 0.5	25 ± 4	19

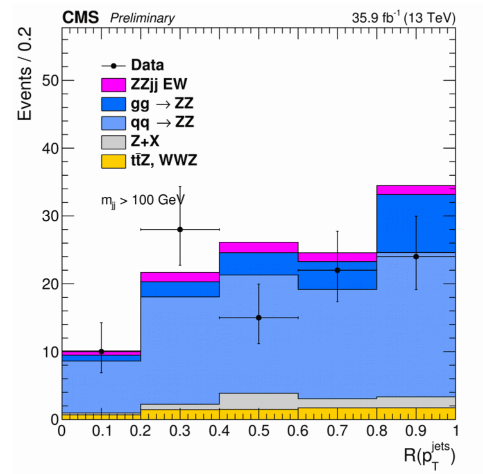
Celarly not enough to target for an evidence → move to a BDT-based analysis

ZZ+jets MVA input variables

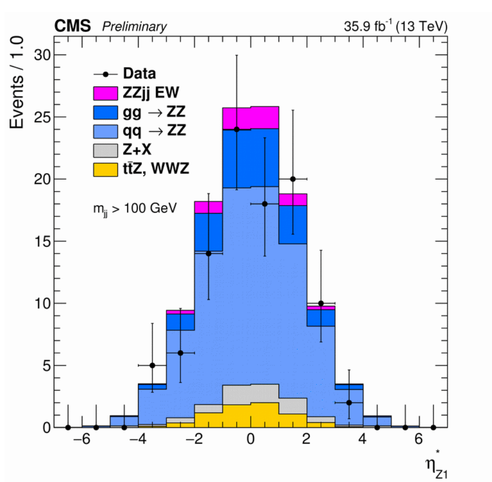
Phys. Lett. B 774 (2017) 682 and SMP-16-019

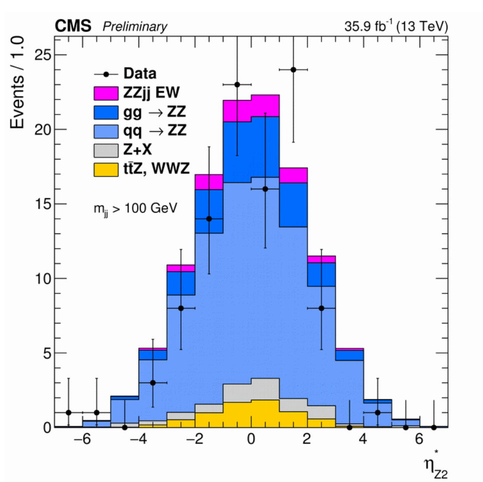


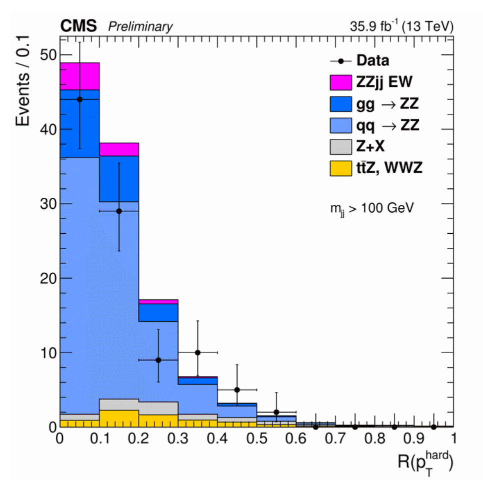




$$R(p_T^{hard}) = \frac{\|\mathbf{p}_T^{jet\,1} + \mathbf{p}_T^{jet\,2} + \mathbf{p}_T^{Z_1} + \mathbf{p}_T^{Z_2}\|}{p_T^{jet\,1} + p_T^{jet\,2} + p_T^{Z_1} + p_T^{Z_2}}$$







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

$$R(p_T^{jets}) = \frac{\|\mathbf{p}_T^{jet\,1} + \mathbf{p}_T^{jet\,2}\|}{p_T^{jet\,1} + p_T^{jet\,2}}$$

Search for the ZZ+jets EW production

Phys. Lett. B 774 (2017) 682

Overall **very good data-theory agreement**

Little discrimination on individual variables ⇨

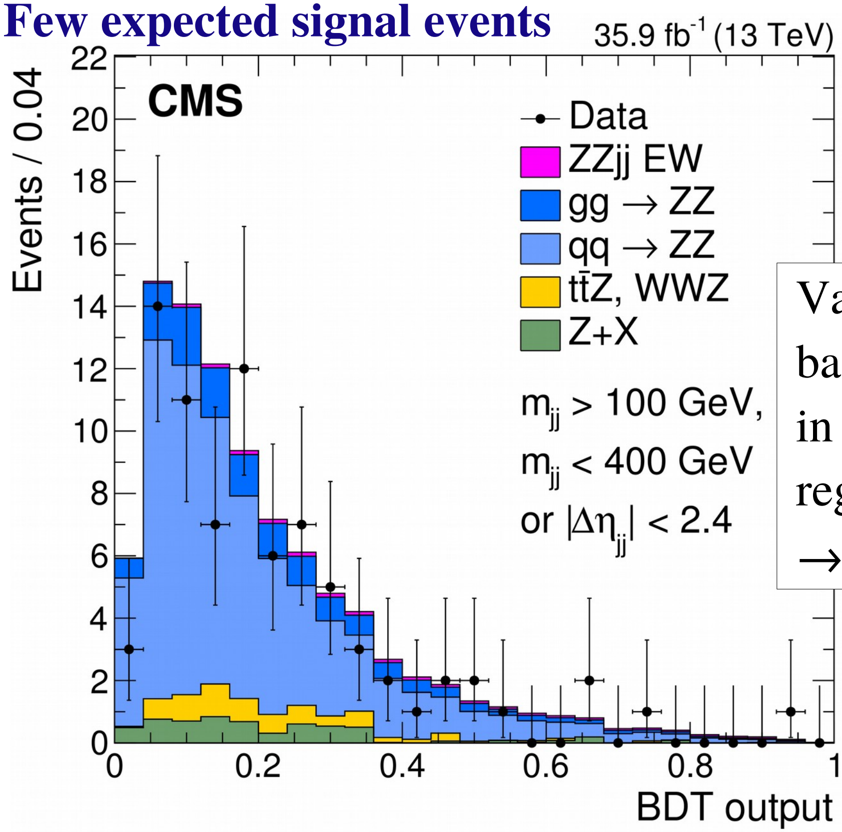
Few expected signal events

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

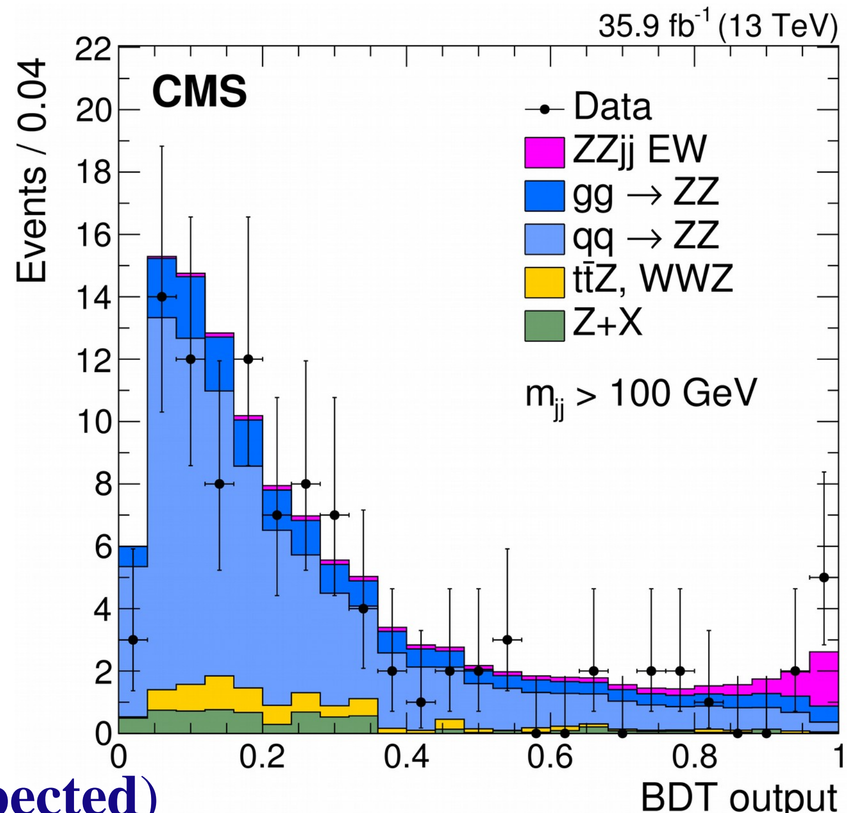
7 inputs: $\mathbf{m_{jj}}$, $\mathbf{\Delta\eta_{jj}}$, $\mathbf{z_1^*}$, $\mathbf{z_2^*}$, $\mathbf{R(p_T)}$, **dijet** $\mathbf{p_T}$ **balance**, $\mathbf{m_{4l}}$

Signal extracted via **template fit of full BDT spectrum**

Constrains **background normalization with data**



Validation of background model in a QCD-enriched region
→ **good** agreement

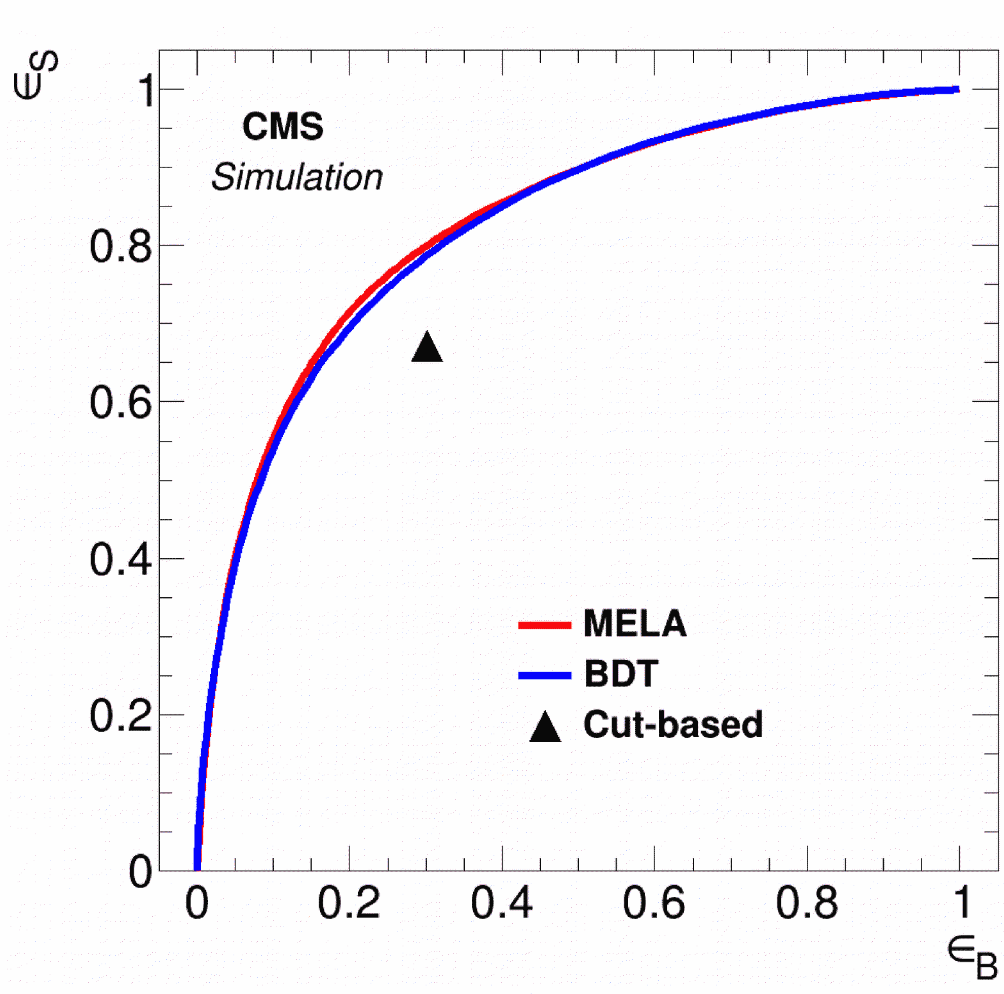


Measured signal strength: $\mu = 1.39^{+0.72}_{-0.57}(\text{stat})^{+0.46}_{-0.31}(\text{syst})$

With an **observed significance of 2.7 σ (1.6 σ, expected)**

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

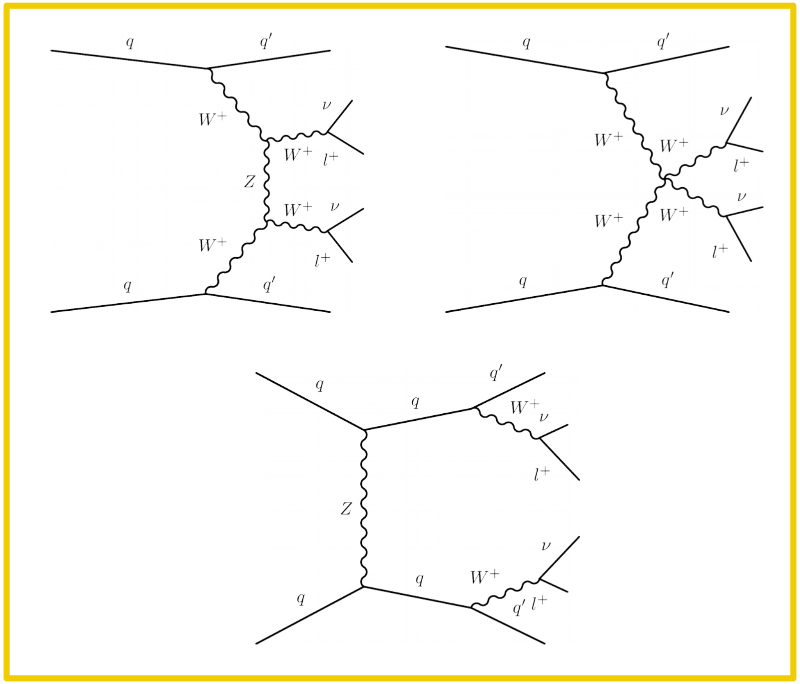
ZZ+jets: ROC Curve

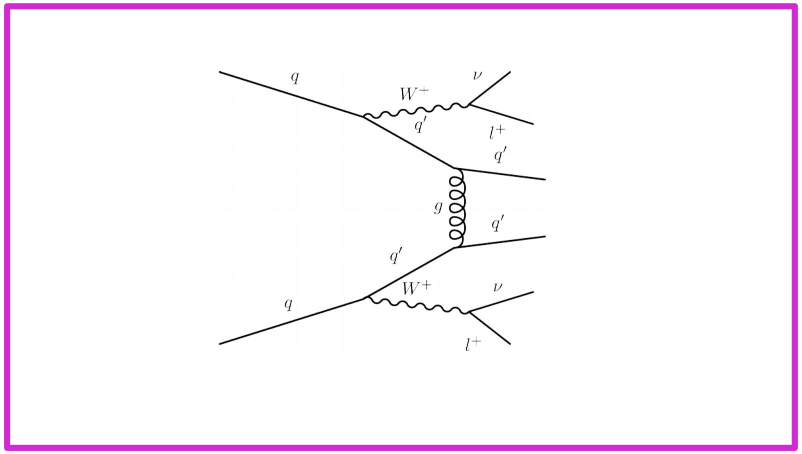


EW $pp \to W^{\pm}W^{\pm}jj \to l^{\pm}l^{\pm}\nu\nu jj$ production

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

- Search for a **pair of same charge lepton** (μ, e) with $p_{T,1(2)}$ > 25 (20) GeV m_{ll} > 20 GeV, **vetoing additional leptons** (including τ'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_l*) < 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 **→ # signal events ~ half of all background events**
- Background from **$W^{\pm}W^{\pm}$+jets induced by QCD** ***very small*** compared to the signal. **Main background** from **multi non-prompt leptons** in the event and **WZ → 3lυ** where a charged lepton is lost
  - To suppress DY → E_T^{miss} > 40 GeV and Z → e^+e^- veto
  - To reduce top background: anti b-tagging, m_{ll} > 20 GeV





$W^{\pm}W^{\pm}$+jets Complete Cut List

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

Search region

- **Two same charge lepton** (μ, 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 3rd loosely ID lepton is > 10 GeV or the p_T of an identified τ (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_l*) < 0.75 $Z_i^* = |\eta_l - (\eta_{jet,1} + \eta_{jet,2})/2| / |\Delta\eta_{jj}|$
- E_T^{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

Relevant MC Simulations

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

- **Signal and irreducible background**: MadGraph_aMC@NLO v2.3.3
  - Max $\mathcal{O}(\alpha_{QCD}^2)$ and up to $\mathcal{O}(\alpha_{EW}^6)$ diagrams
- **ZZ and WZ** are simulated at LO with MadGraph_aMC@NLO
- Tribosons are simulated at NLO with MadGraph_aMC@NLO
- In all cases, PYTHIA v8.205 is used for parton showering, hadronization and underlying event simulation (CUETP8M1 tune), while we used the NNPDF3.0 PDF set.

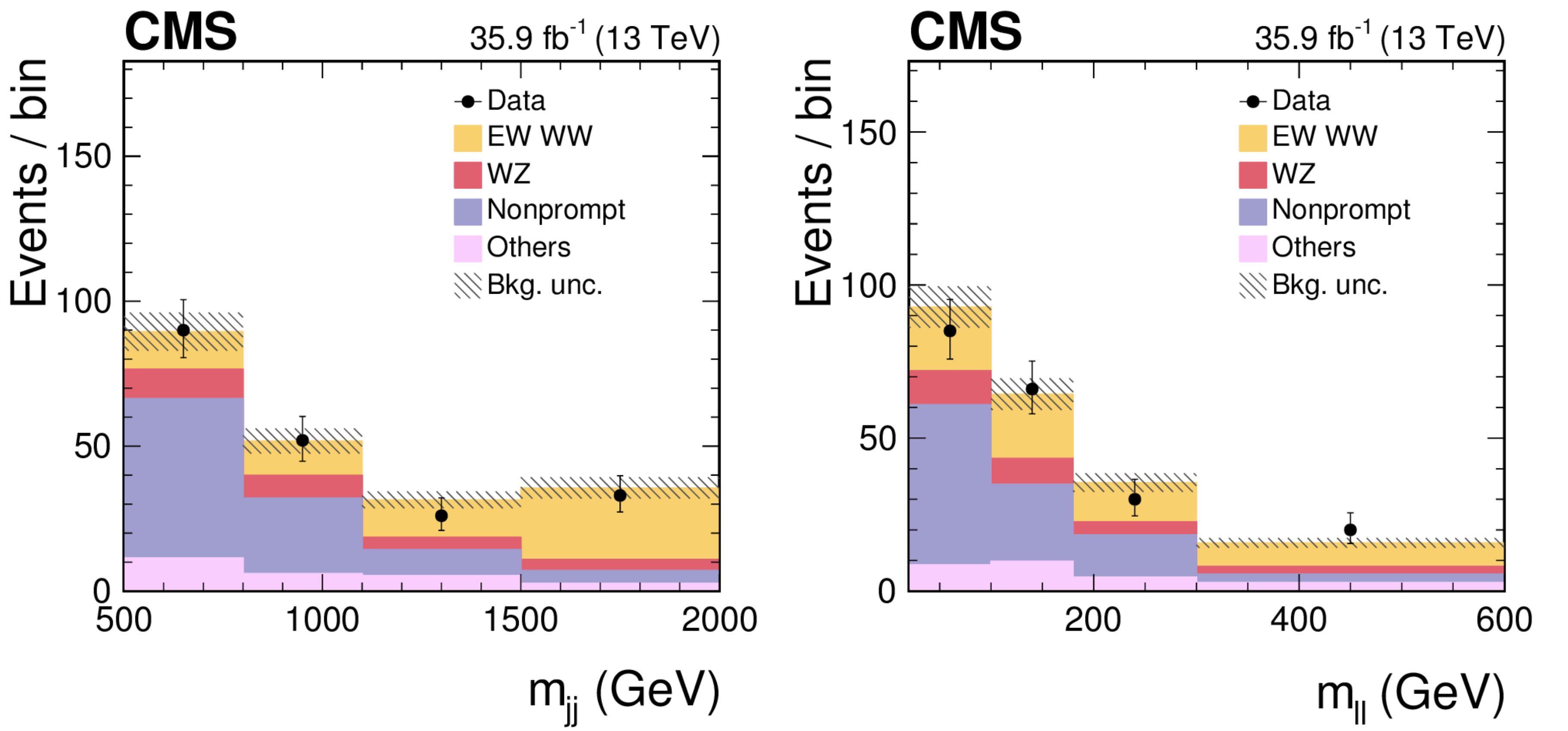
$W^{\pm}W^{\pm}$+jets: Yields

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

$W^{\pm}W^{\pm}$+jets m_{jj} and m_{ll} distributions

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



$W^{\pm}W^{\pm}$+jets result extraction

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 σ** (expected **5.7 σ**)

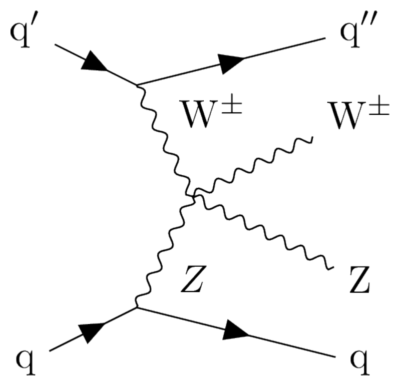
$$\sigma(\text{EW } pp \rightarrow W^{\pm} W^{\pm} + jets \rightarrow l^{\pm} l'^{\pm} \nu \nu + jets) = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\,\text{fb}$$

- Analysis also used to constrain the σxBR 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 → $W^{\pm}Zjj \to l^{\pm}\nu l^{\pm}l^{\mp}jj$ production

arXiv:1901.04060 sub to PLB

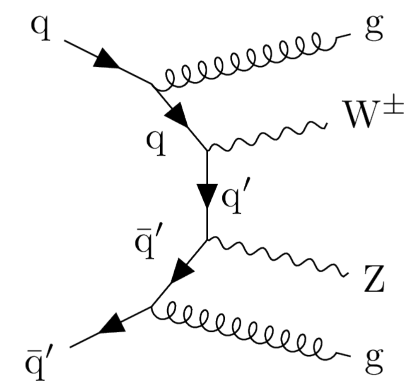
- Affected by more background than $W^{\pm}W^{\pm}$, but **cross section accessible with large dataset**



- Search for **three charged leptons** (μ, 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

$W^{\pm}Z$+jets 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^{ℓ} [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
$\|m_{\ell'\ell'} - m_Z\|$ [GeV]	<15	<15	<15	<15
$m_{3\ell}$ [GeV]	>100	>100	>100	>100
$m_{\ell\ell}$ [GeV]	>4	>4	>4	>4
p_T^{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	≥ 2	≥ 2	≥ 2	≥ 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
$\|\eta^{3\ell} - (\eta^{j_1} + \eta^{j_2})/2\|$	<2.5	—	<2.5	—

Relevant MC Simulations

arXiv:1901.04060 sub to PLB

- **Signal**: MadGraph_aMC@NLO v2.4.2
  - Cross checked with VBFNLO 3.0, SHERPA v2.2.4, and MOCANLO+RECOLA (at fixed order)
- **WZ + QCD-induced jets** (0,1,2 at born level @LO): MadGraph_aMC@NLO, Jets merged with MLM scheme
  - Cross checked wth MadGrap_aMC@NLO v2.3.3 (0,1 at born level @NLO, FxFx scheme) and with inclusive NLO simulation from POWHEG
- **Interference between EW-QCD WZjj** evaluated with a dedicated MadGraph_aMC@NLO v2.6.0 sample $\mathcal{O}(\alpha_{QCD}\alpha_{EW}{}^{5})$
- **Z, ttV and triboson** are generated at NLO with MadGraph_aMC@NLO v2.3.3
- In all cases, PYTHIA v8.212 is used for parton showering, hadronization and underlying event simulation (CUETP8M1 tune), while we used the NNPDF3.0 PDF set
  - Signal cross checked with PS and hadronization made with SHERPA and HERWIG v7.1

$W^{\pm}Z$+jets result extraction

arXiv:1901.04060 sub to PLB

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

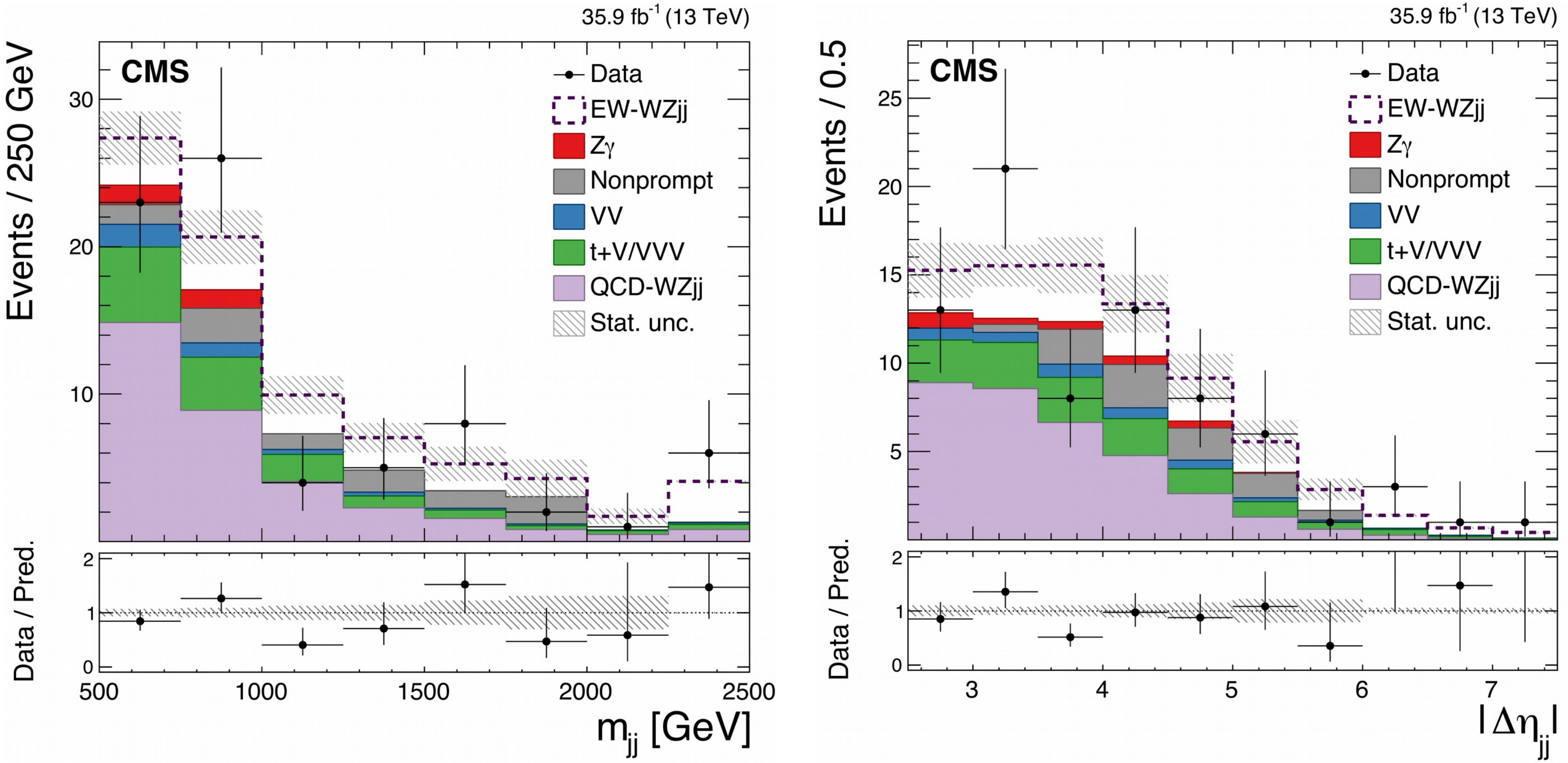
$$\sigma^{fid}(pp \rightarrow WZ + jets \rightarrow l \nu l' l' + jets) = 3.18^{+0.57}_{-0.52}(\text{stat})^{+0.43}_{-0.36}(\text{syst})\,\text{fb}$$

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

- 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 $\Delta\eta_{jj}$

$W^{\pm}Z$+jets m_{jj} and $|\Delta\eta_{jj}|$ (pre-fit yields)

arXiv:1901.04060 sub to PLB



$W^{\pm}Z$+jets result extraction

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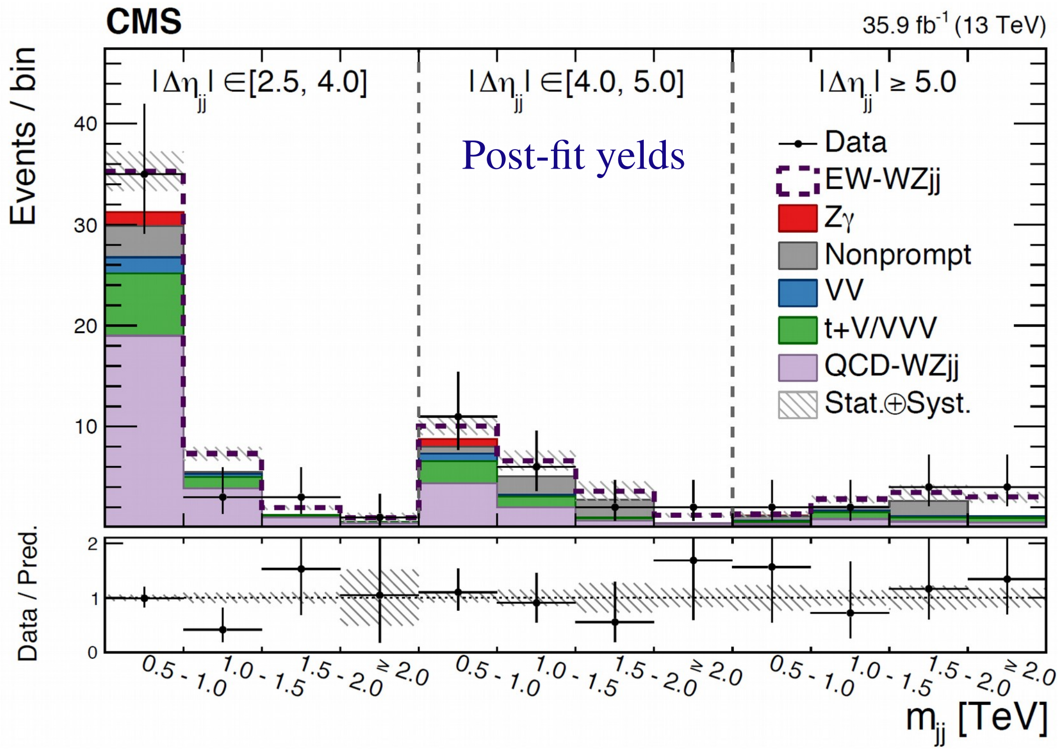
- To **extract the EW component** (~38% of the tight fid xsection) simultaneously fit yield from background control region and 2D distribution of m_{jj} and $\Delta\eta_{jj}$



Measured **signal strength**: $\mu=0.82^{+0.51}_{-0.43}$ with an expected **EW WZjj cross** section of $\sigma=1.25^{+0.11}_{-0.09}(\text{scale})\pm0.15(\text{PDF})\,\text{fb}$ and an observed significance of **2.2σ** (**2.7σ**, expected)

Analysis also used to constrain the σxBR 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

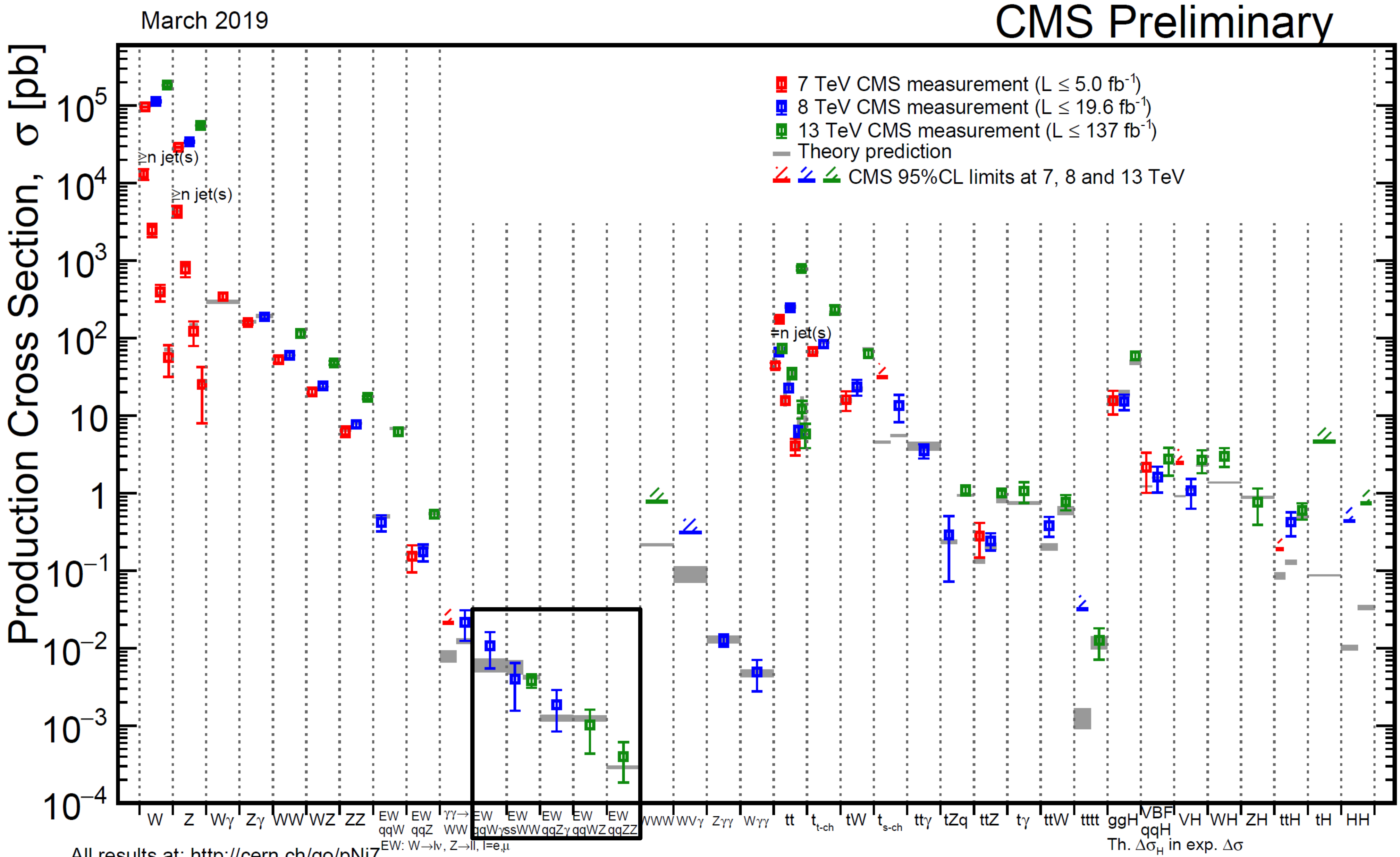
$W^{\pm}Z$+jets yields

arXiv:1901.04060 sub to PLB

Post-fit yelds

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

Cross sections summary

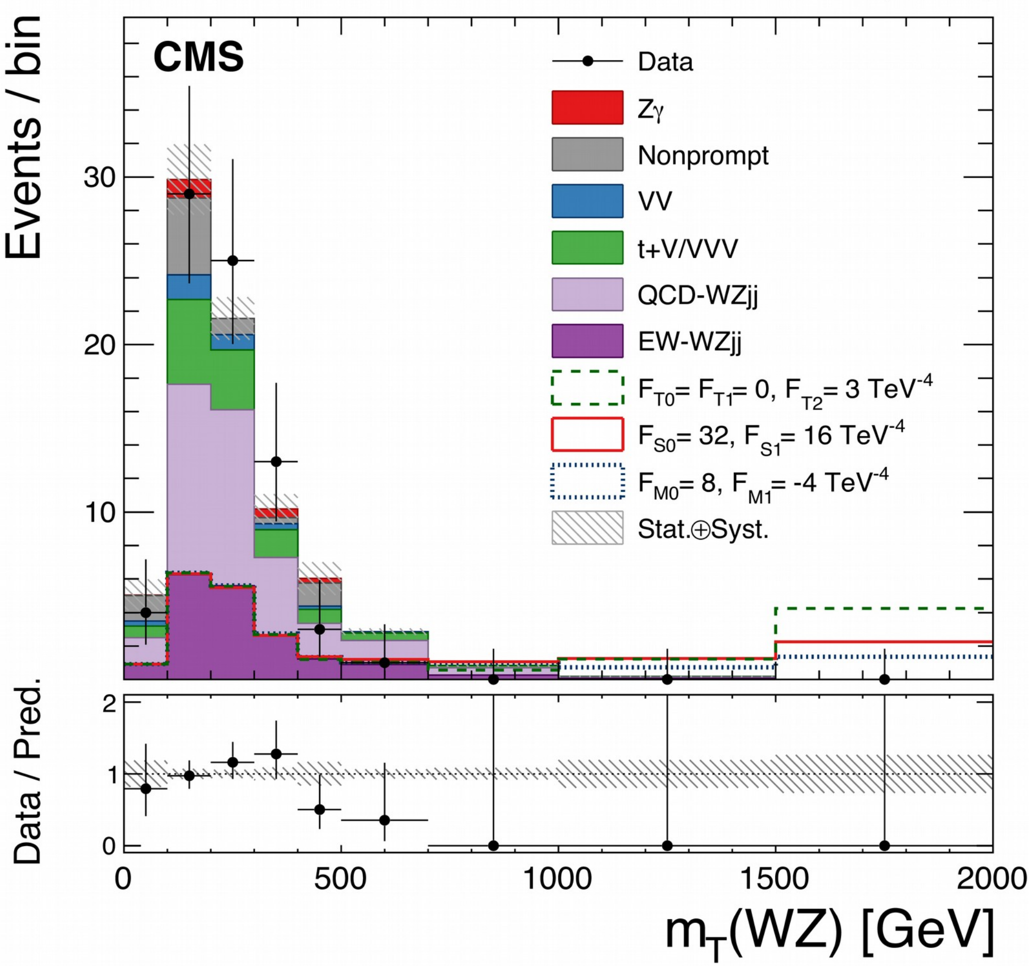


Anomalous vector boson couplings

- Search for **new physics** *while doing* **EW measurements**
- Look for deviations from SM in tail of distributions ($\mathbf{m_{VV}}$, $\mathbf{m_{ll}}$, $\mathbf{m_{jj}}$, $\mathbf{p_{T,V}}$, …)
- 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



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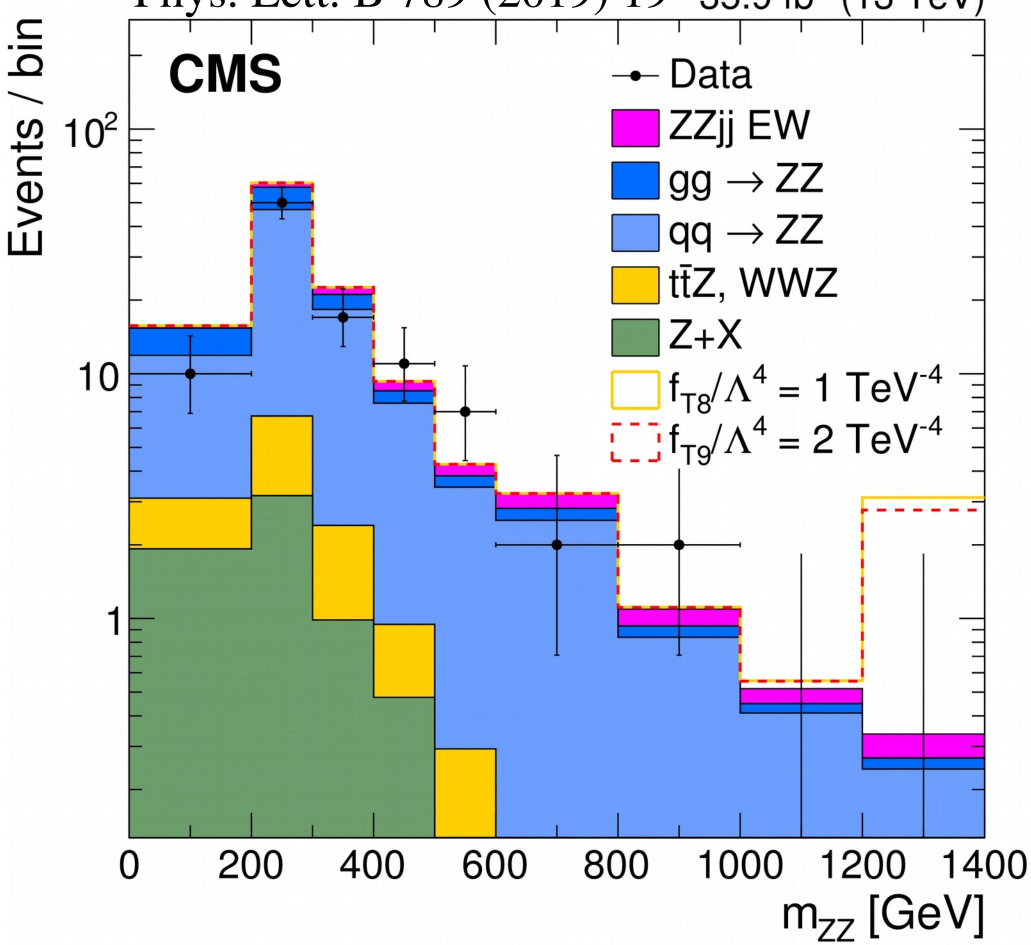


Main variables for the search of anomalous quartic gauge couplings

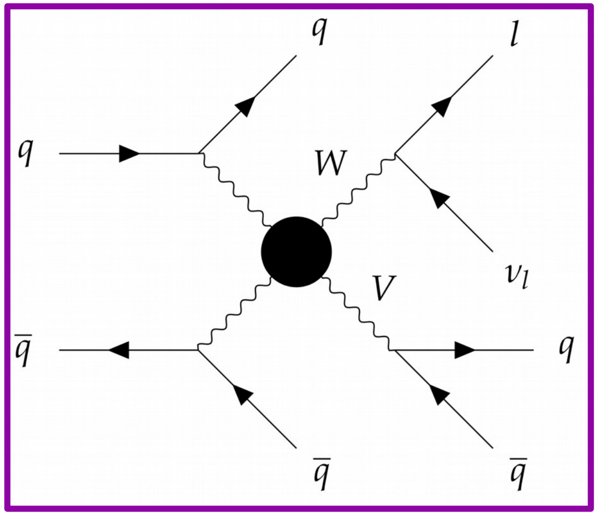
→ no evidence found so far

Search for anomalous EW production of WW/WZ/ZZ + jets

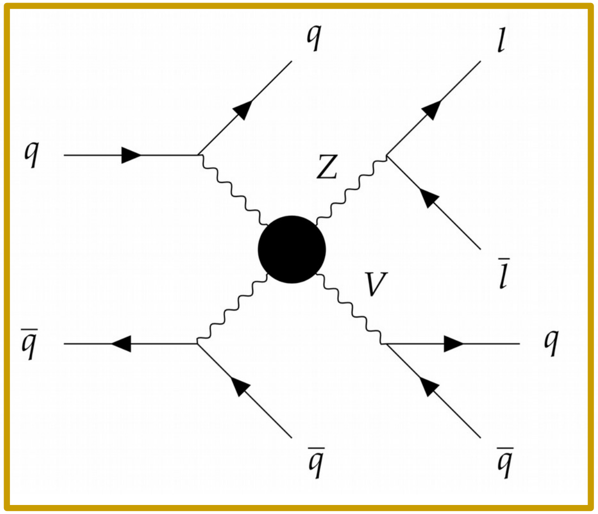
arXiv:1905.07445

sub to PLB

- Two final states: **pp → WVjj → lνjjjj** and **pp → ZVjj → lljjjj**



- Select events with
  - **One or two leptons** with $p_T > 30$ GeV
  - **WVjj**: $p_T^{miss} > 50$ (80) GeV for final state with μ (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

WW/WZ/ZZjj semileptonic: cuts

arXiv:1905.07445 sub to PLB

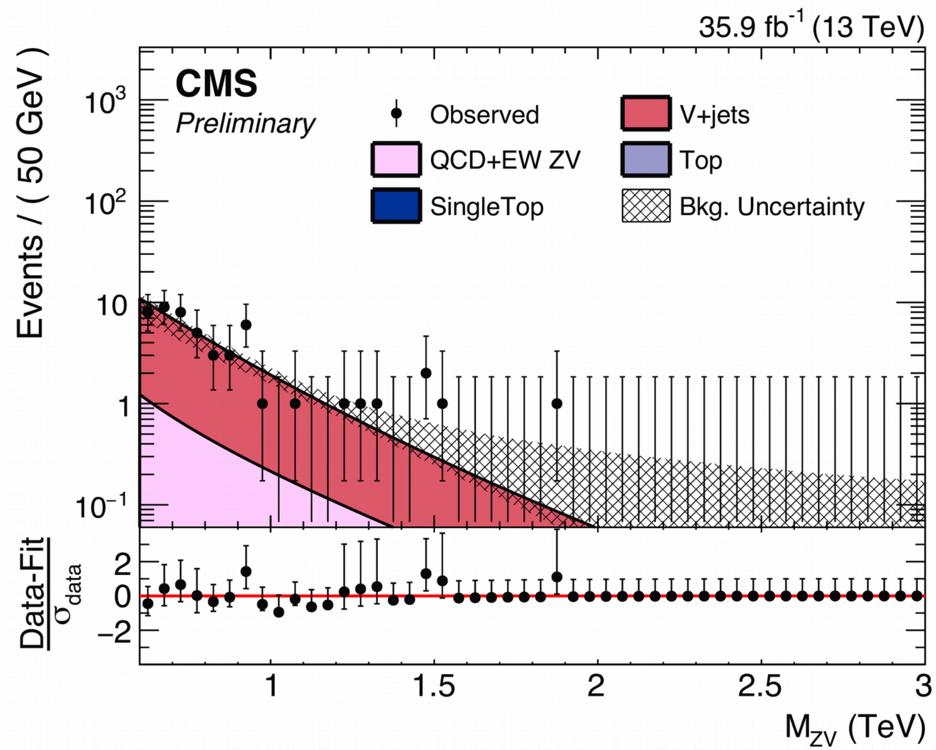
- Select events with
  - **One or two leptons** with $p_T > 30$ GeV, $R_{iso} < 0.3$ (0.4) for e (μ)
  - **WVjj**: $p_T^{miss} > 50$ (80) GeV for final state with μ (e)
  - **ZVjj**: $|m_{ll} - m_Z| < 15$ GeV
  - **No b-tagged jets**
- Hadronically decaying boson reconstructed in **boosted topology** (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 $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})/2| / |\Delta\eta_{jj}|$
  - $\theta = \min(\min(\eta_W, \eta_V) - \min(\eta_{jet,1}, \eta_{jet,2}), \max(\eta_{jet,1}, \eta_{jet,2}) - \max(\eta_W, \eta_V)) > 1.0$

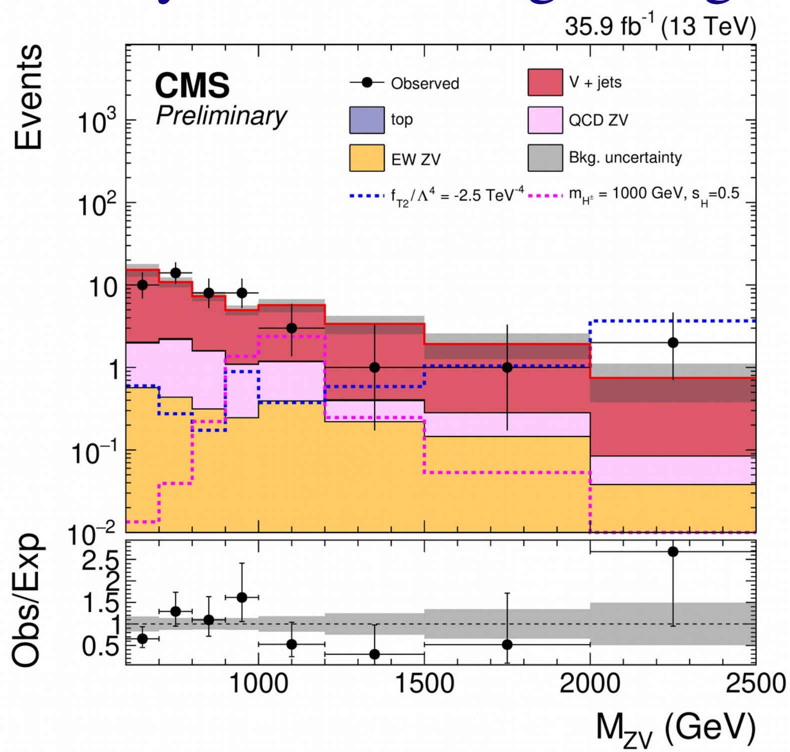
Search for anomalous EW production of WW/WZ/ZZ + jets

arXiv:1905.07445

sub to PLB

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

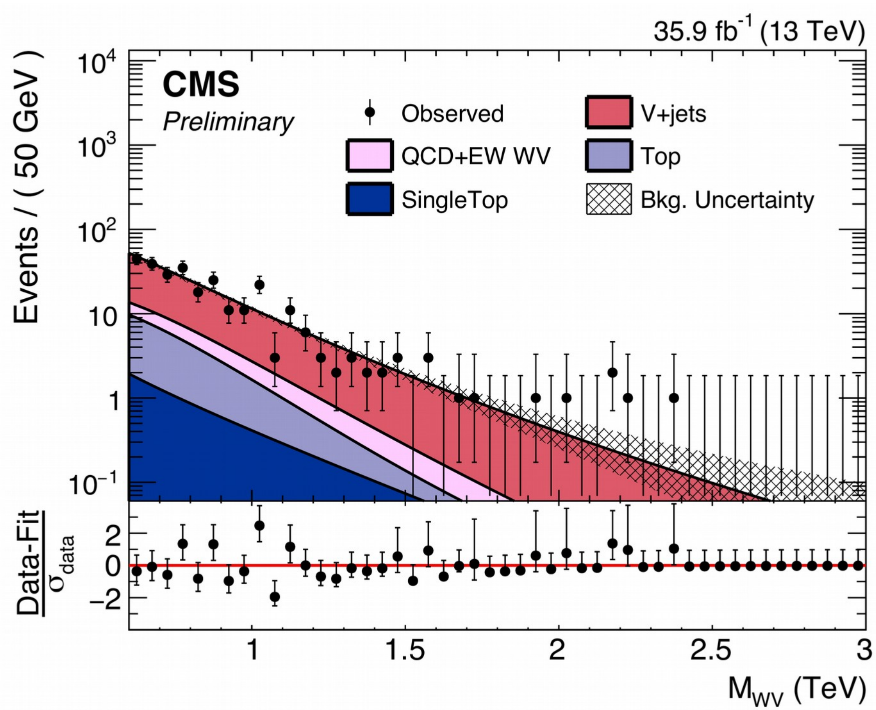


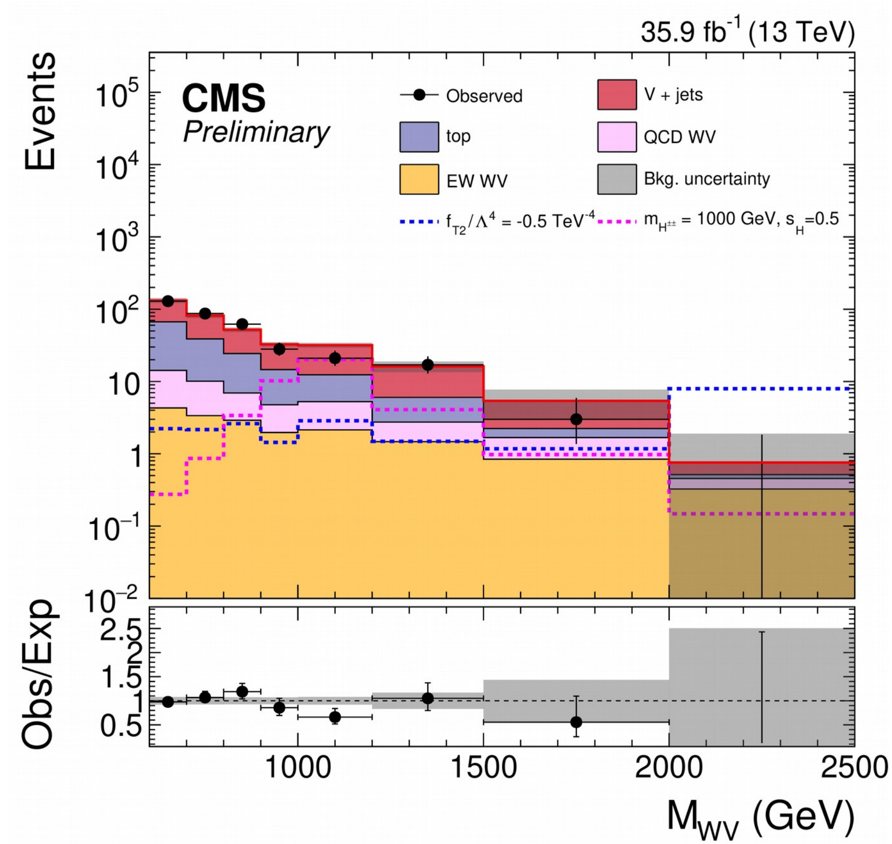


Set also stringent limits on $H^{\pm}$ and $H^{\pm\pm}$ production cross section

WW/WZ/ZZjj: WV analysis

arXiv:1905.07445 sub to PLB



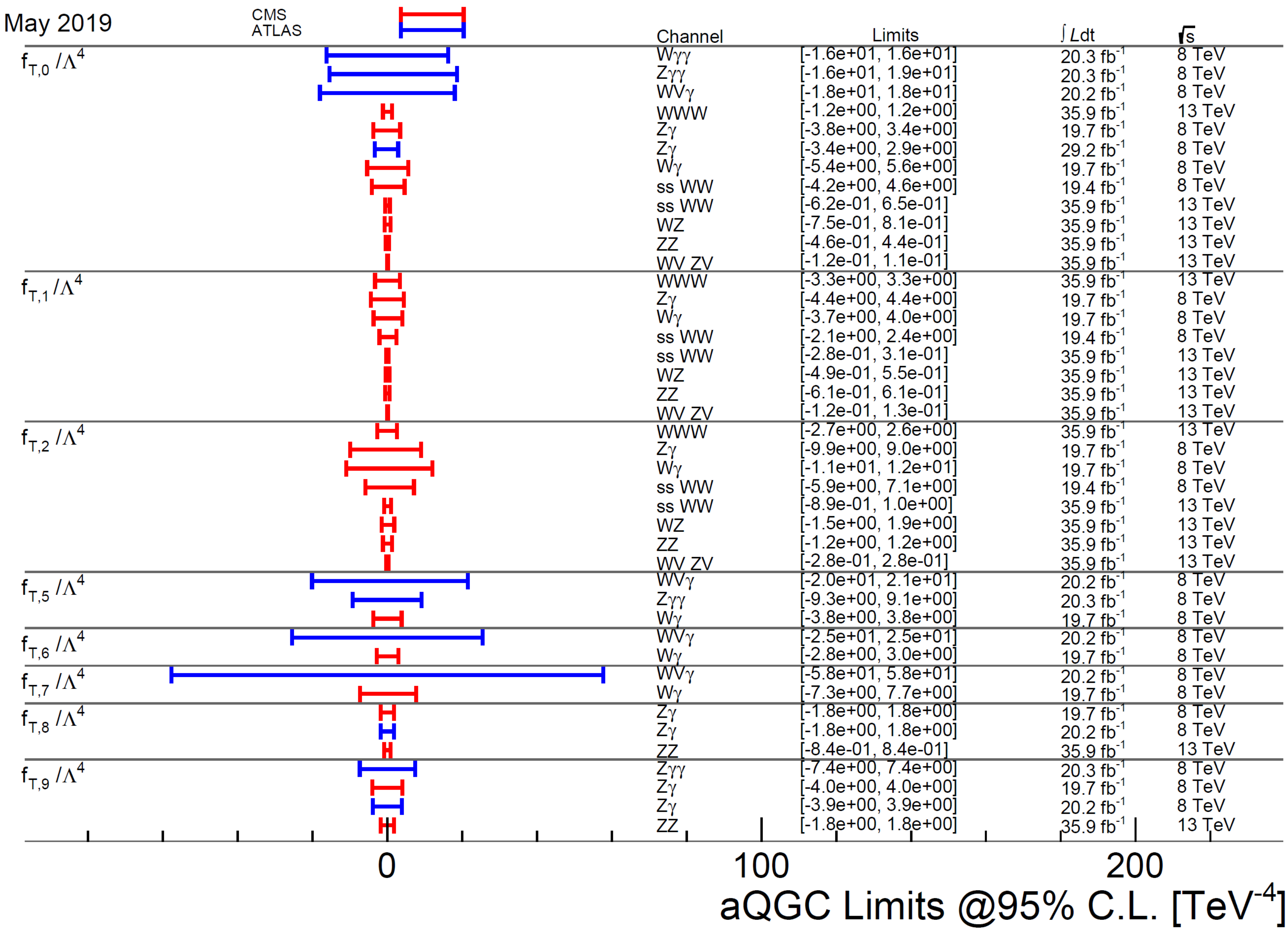


WW/WZ/ZZjj semileptonic: yields

arXiv:1905.07445 sub to PLB

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

aQGC summary table



Coupling	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	Zγγ	[-1.6e+01, 1.9e+01]	20.3 fb^{-1}	8 TeV
	WVγ	[-1.8e+01, 1.8e+01]	20.2 fb^{-1}	8 TeV
	WWW	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-7.5e-01, 8.1e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WWW	[-3.3e+00, 3.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.9e-01, 5.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.3e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WWW	[-2.7e+00, 2.6e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-1.5e+00, 1.9e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	WV ZV	[-2.8e-01, 2.8e-01]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	WVγ	[-2.0e+01, 2.1e+01]	20.2 fb^{-1}	8 TeV
	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	WVγ	[-2.5e+01, 2.5e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	WVγ	[-5.8e+01, 5.8e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

Conclusions

- **CMS explored several VBS-like final states**, using **2016 data**
- So far, we have **Observation of Electroweak production of two same sign W and two jets** and **Hint** (at CMS) of the production of ZZ+jets and WZ+jets through EW processes
- For VBS studies, CMS is pretty **MadGraph_aMC@NLO and PYTHIA** oriented
- **VBS fiducial region are not homogeneous** through the analyses. **VBSCan community should give an advice on a standard fiducial region**

  → Could be an addition one to other fiducial regions already quoted by the experiments

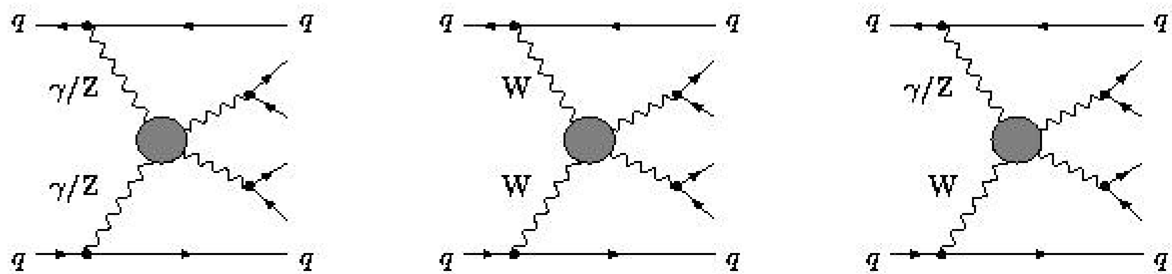
Details on results can be found in the public pages of the CMS experiment:
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

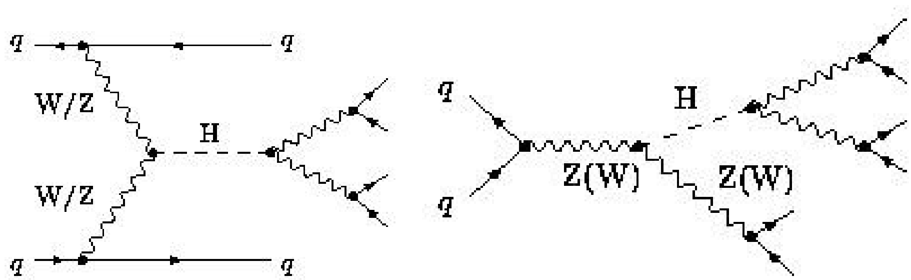
More Material

What is the electroweak production of vector bosons + jets?

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

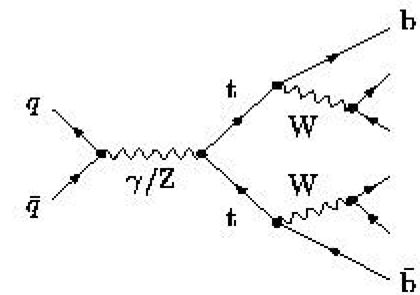
VV scattering →



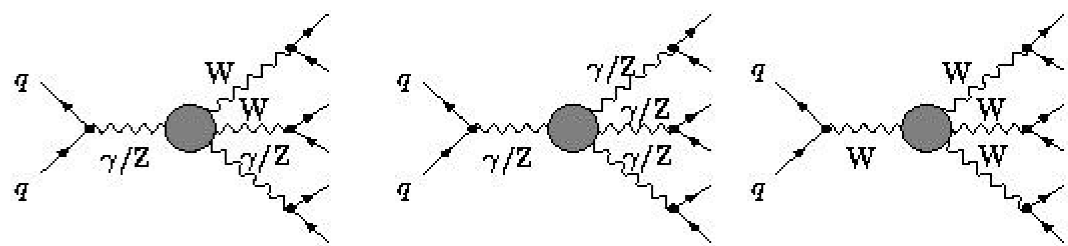


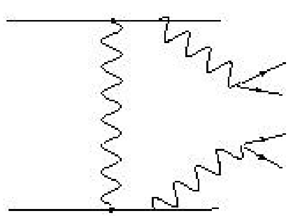
← Higgs

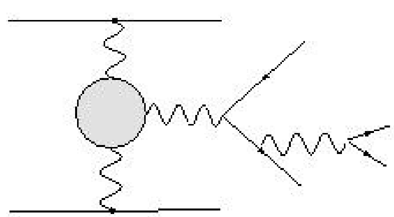
top-top (EW) →



TGC & QGC →



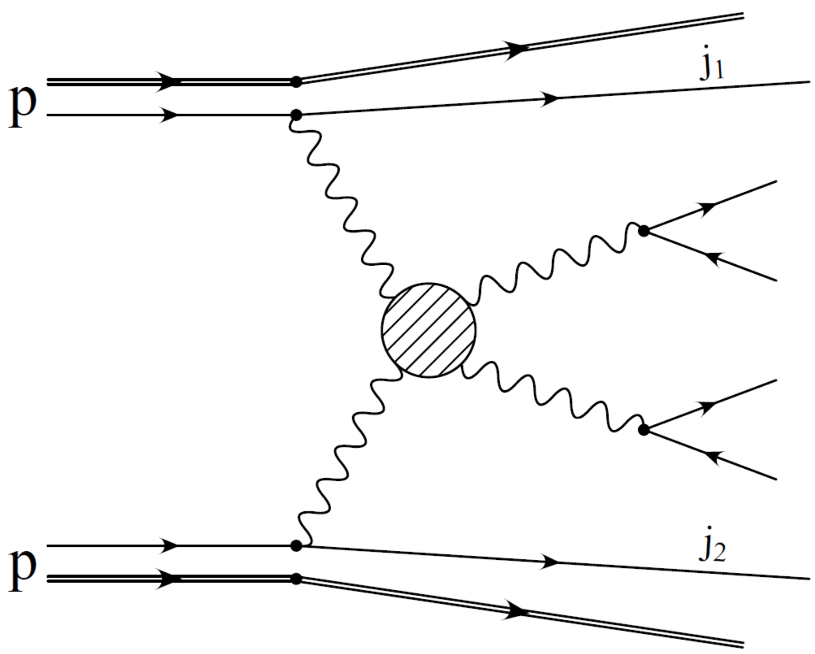


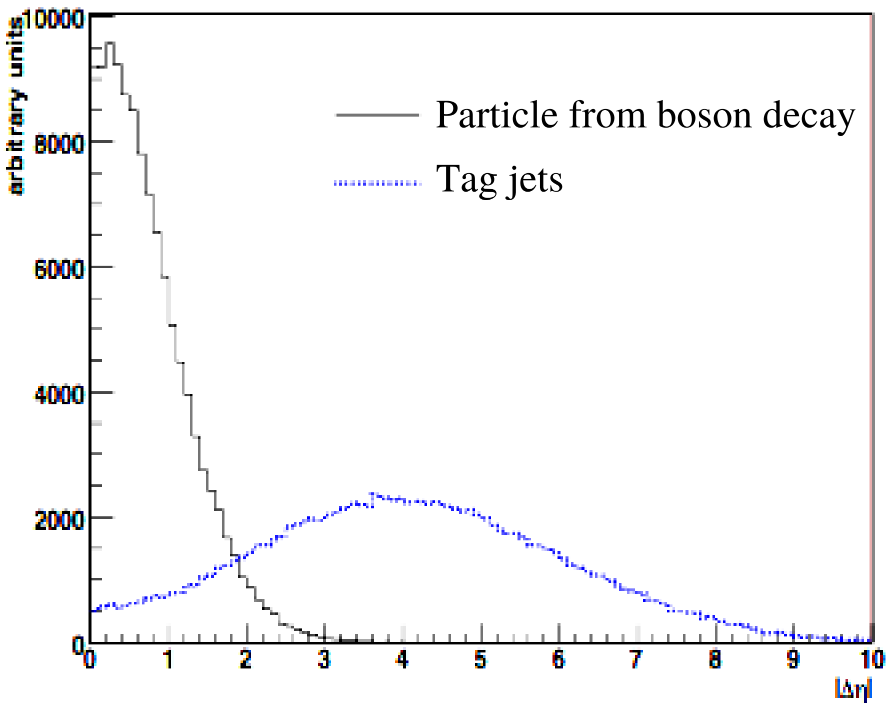


← VV and non resonant

… 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**

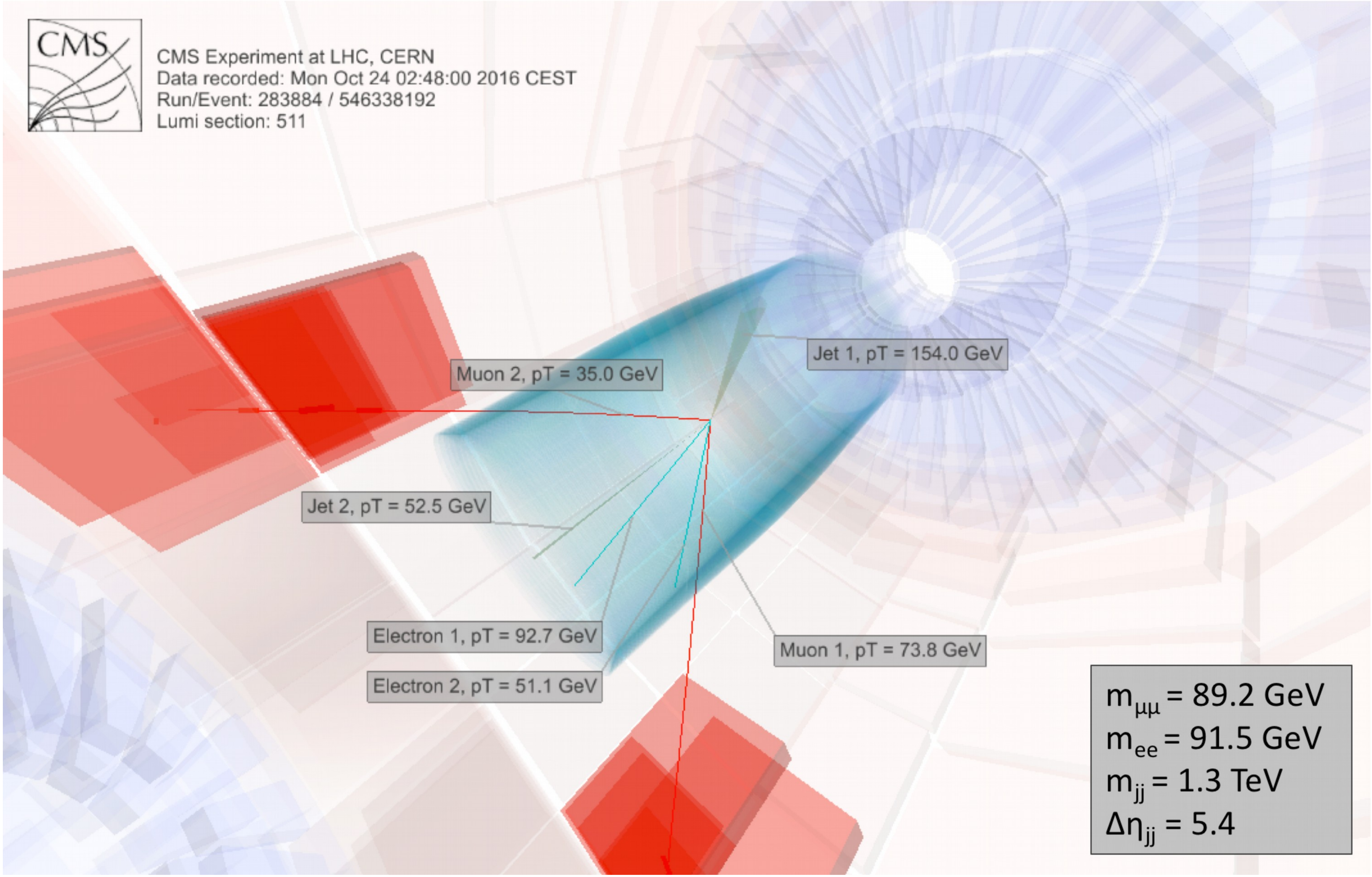




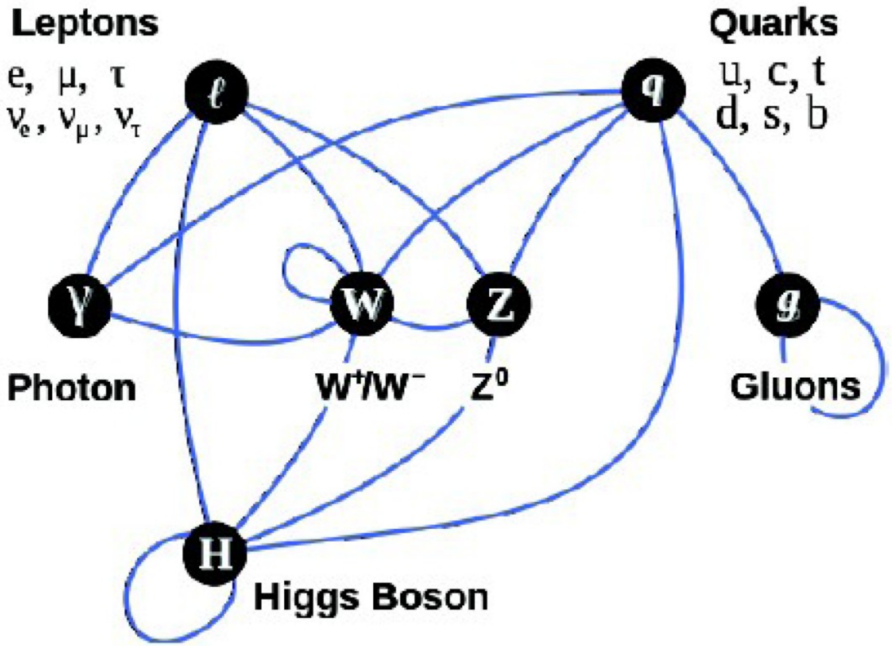
- Other key variables are: the **invariant mass of the dijet system (m_{jj})** and the **Zeppenfeld variable (z*)**, usually defined as $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})|/2$ or $Z_X^* = |\eta_X - (\eta_{jet,1} + \eta_{jet,2})/2|/|\Delta\eta_{jj}|$

VBS Candidate Event

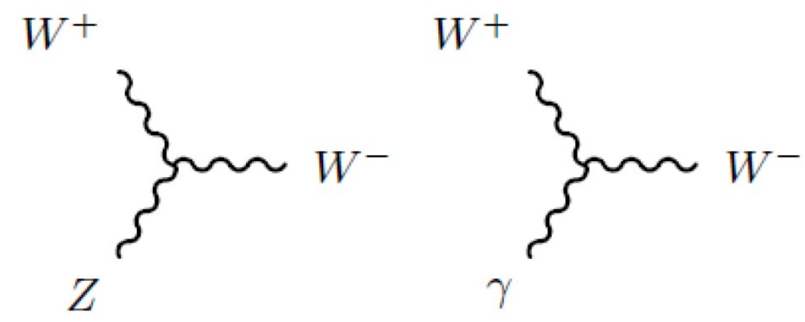
SMP-16-019



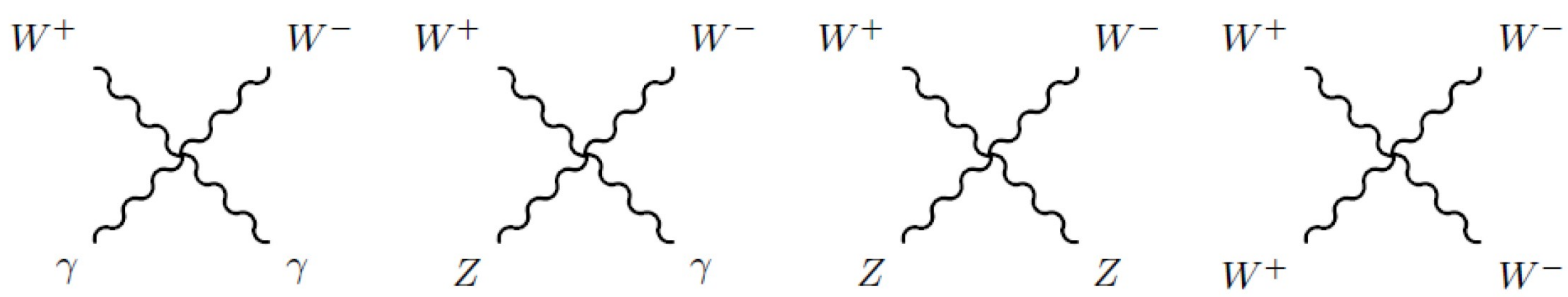
What interesting EW features can the VV production probe?



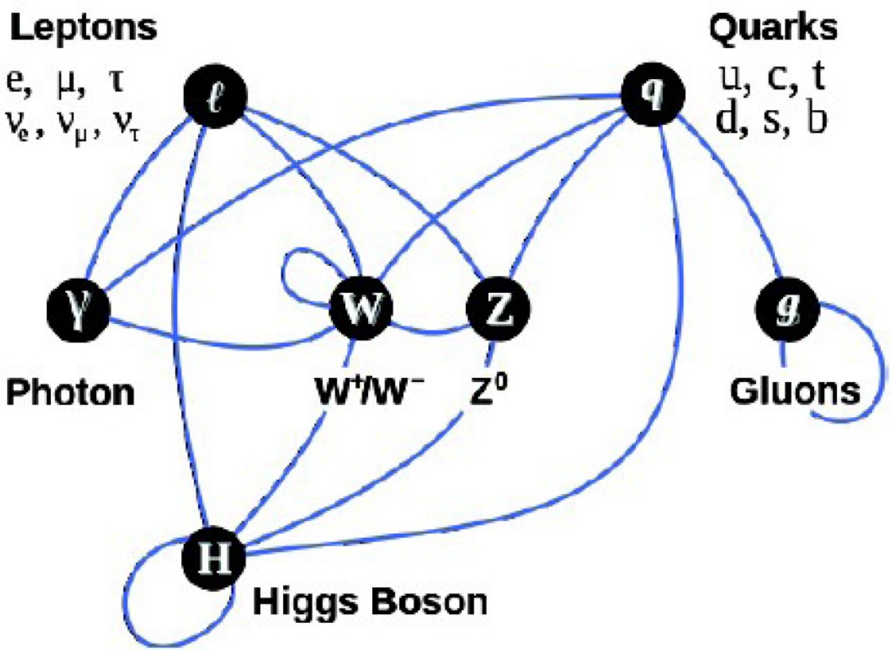
- **Triple gauge couplings (TGC)**



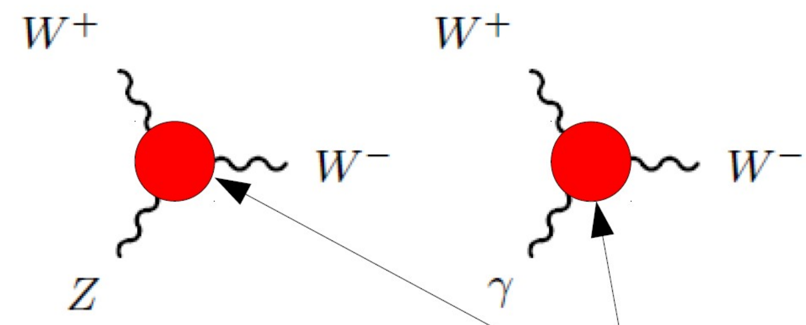
- **Quartic gauge couplings (QGC)**



What interesting EW features can the VV production probe?

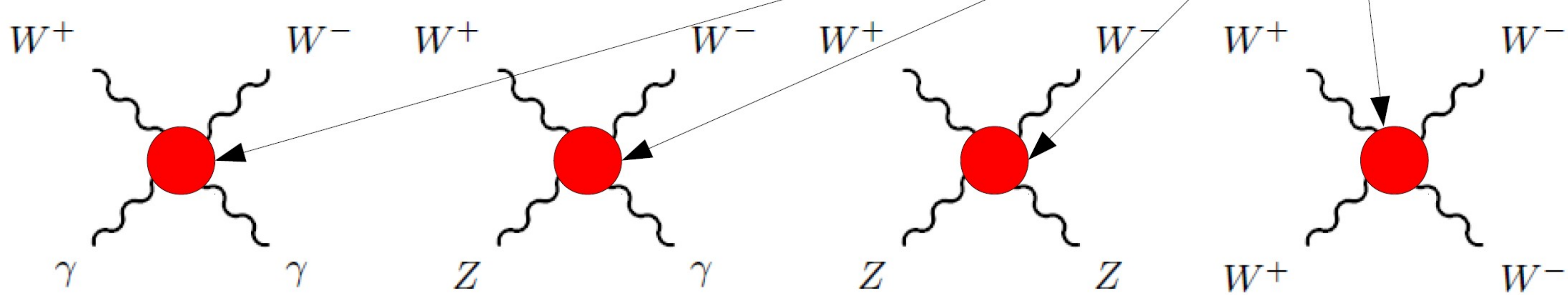


- **Triple gauge couplings (TGC)**



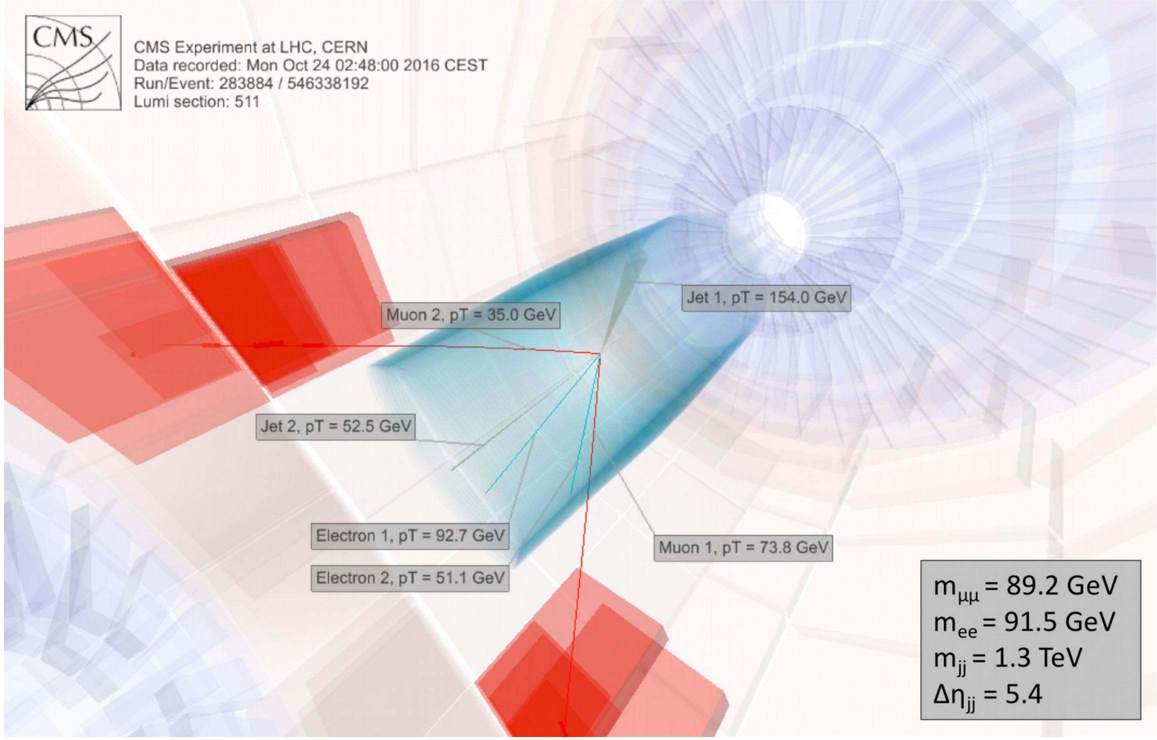
Anomalous couplings
+ what forbidden in SM

- **Quartic gauge couplings (QGC)**



ZZ+jets: Event Display

SMP-16-019



$m_{4\ell}$ [GeV]	m_{Z1} [GeV]	m_{Z2} [GeV]	m_{jj} [GeV]	$\lvert\Delta\eta_{jj}\rvert$	$\eta^{\star}_{Z_1}$	$\eta^{\star}_{Z_2}$	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

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

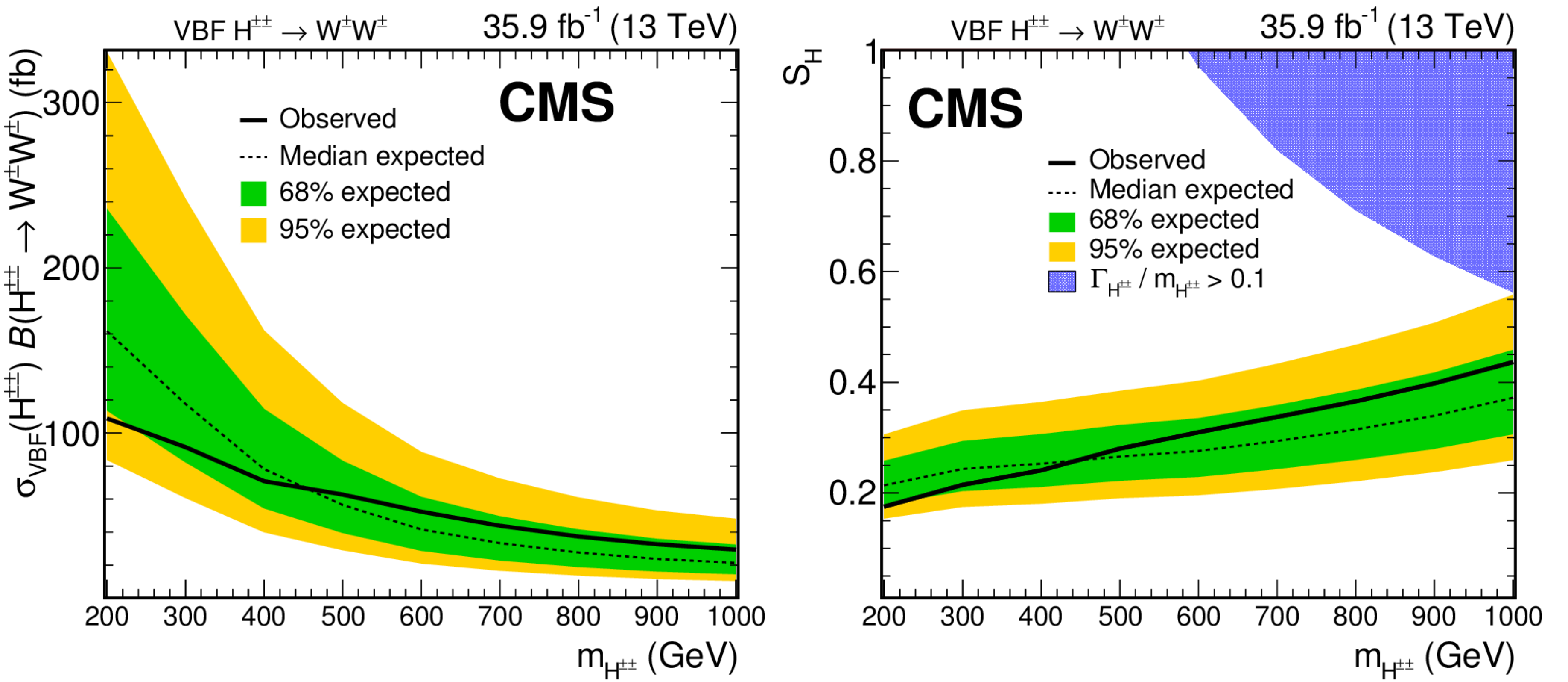
ssWW+jets: aQGC limits

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

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

ssWW+jets: charged Higgs limits

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



WZjj systematic uncertainties

arXiv:1901.04060 sub to PLB

Source of syst. uncertainty	Relative uncertainty [%]	
	σ_{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

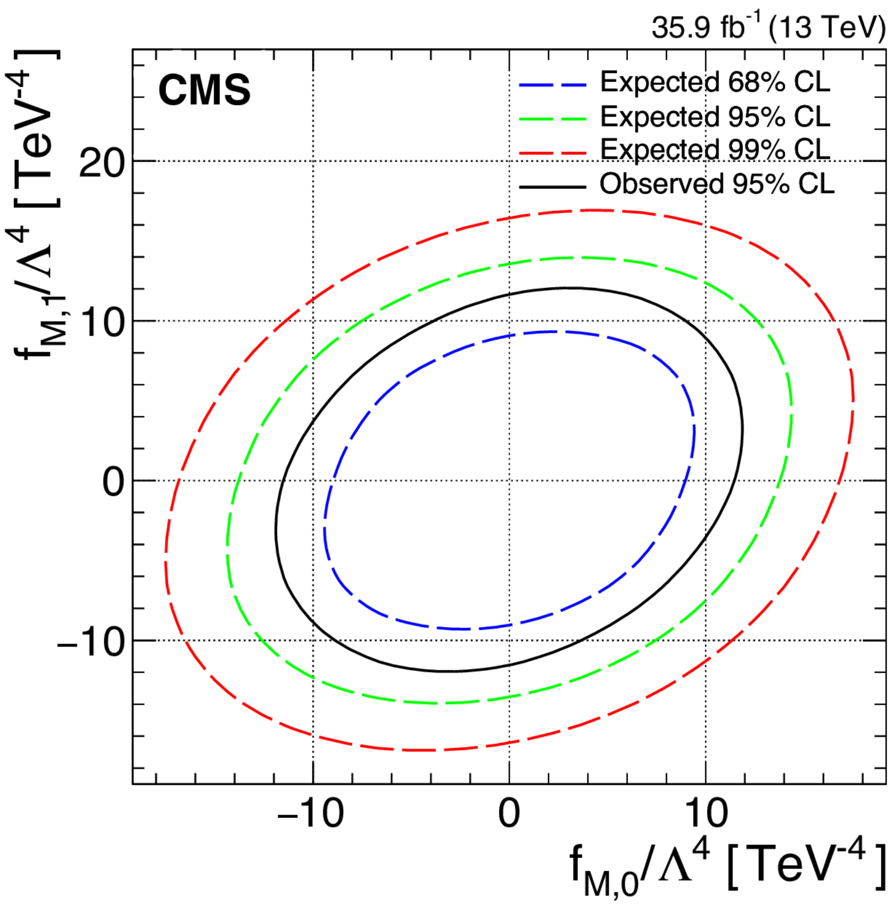
WZjj aQGC

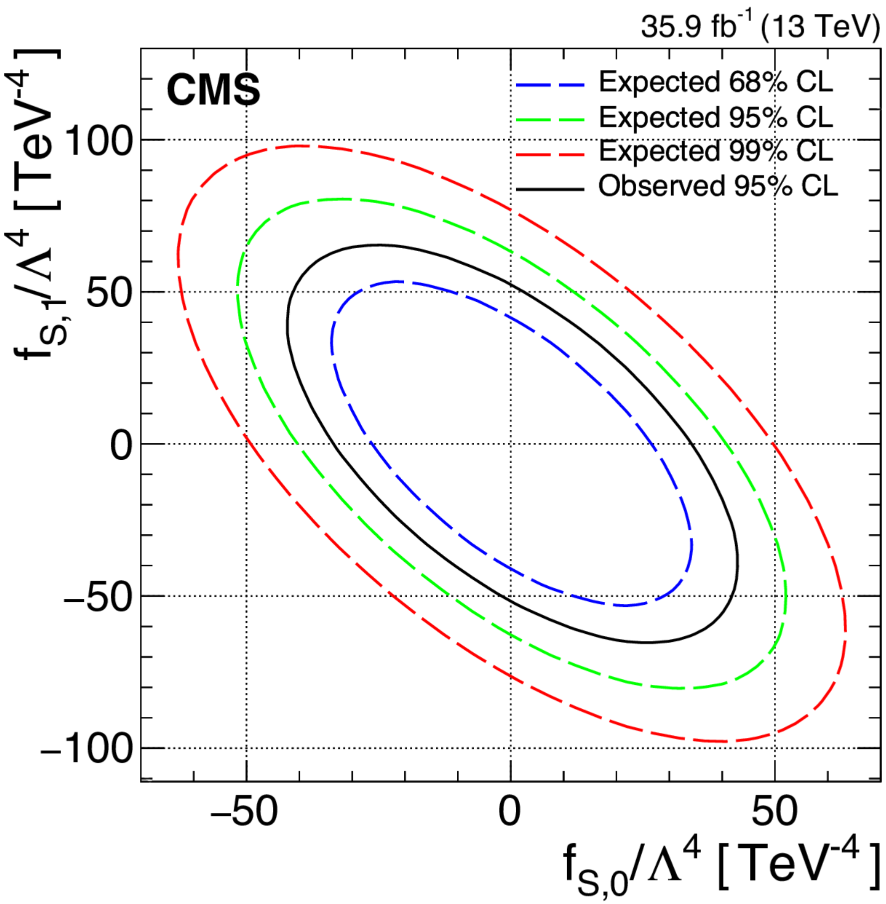
arXiv:1901.04060 sub to PLB

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

WZjj aQGC

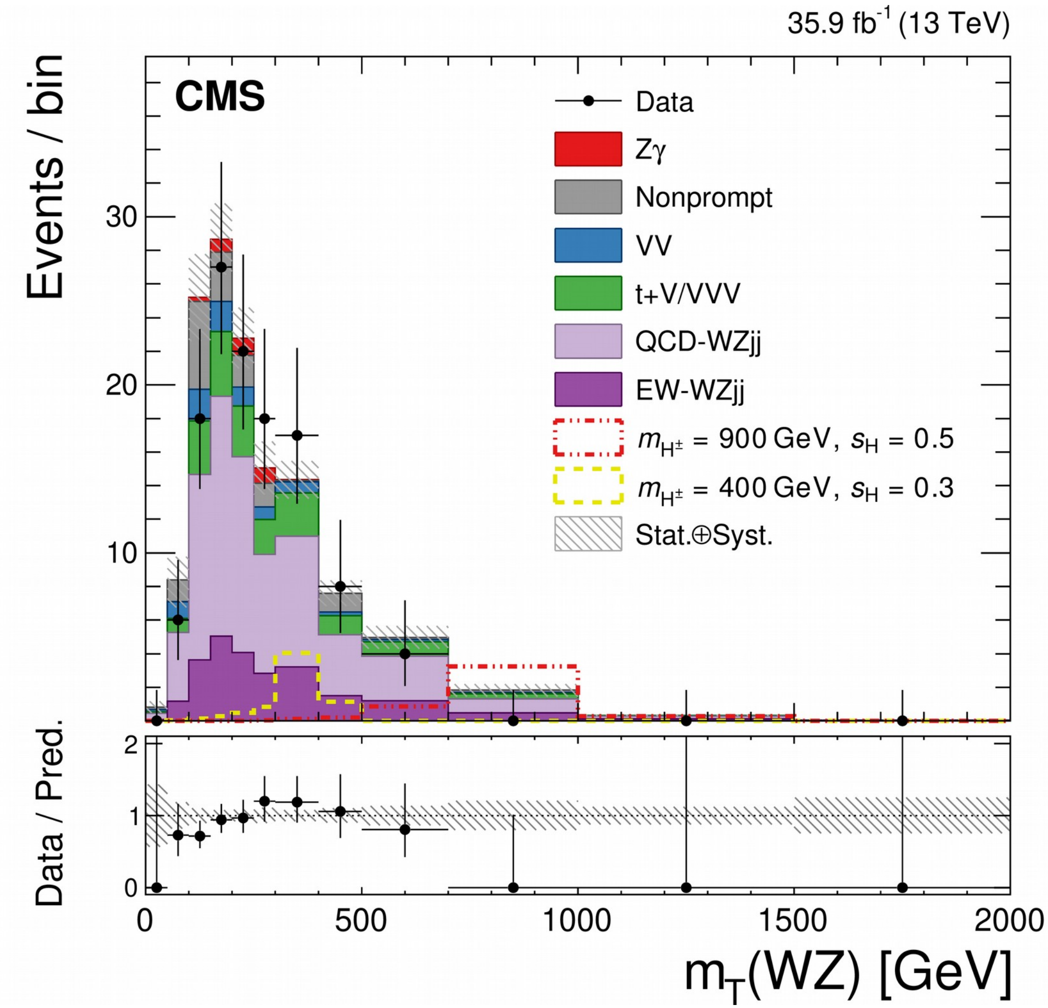
arXiv:1901.04060 sub to PLB





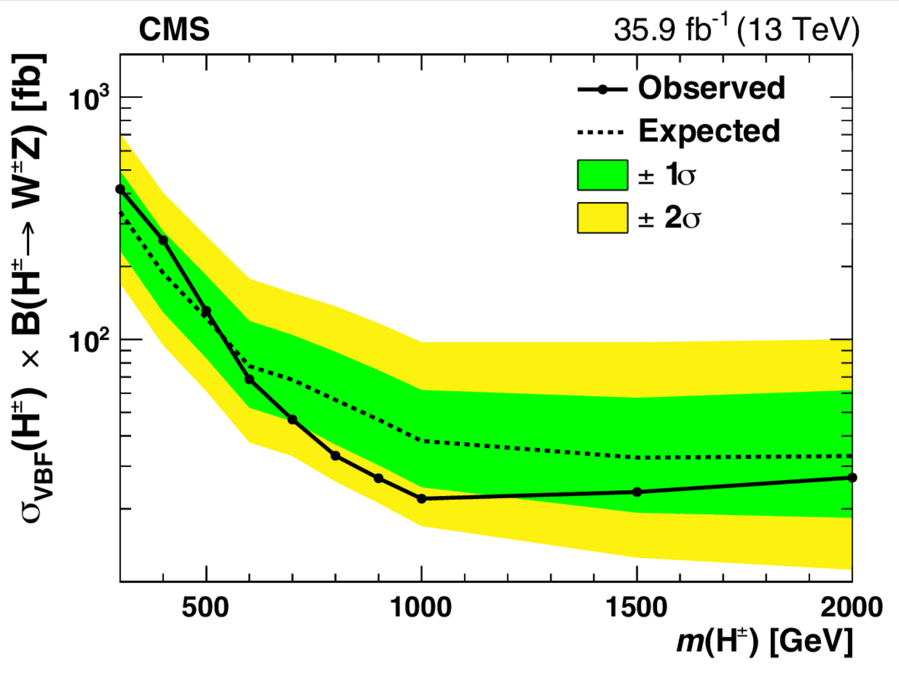
WZjj Charged Higgs search region

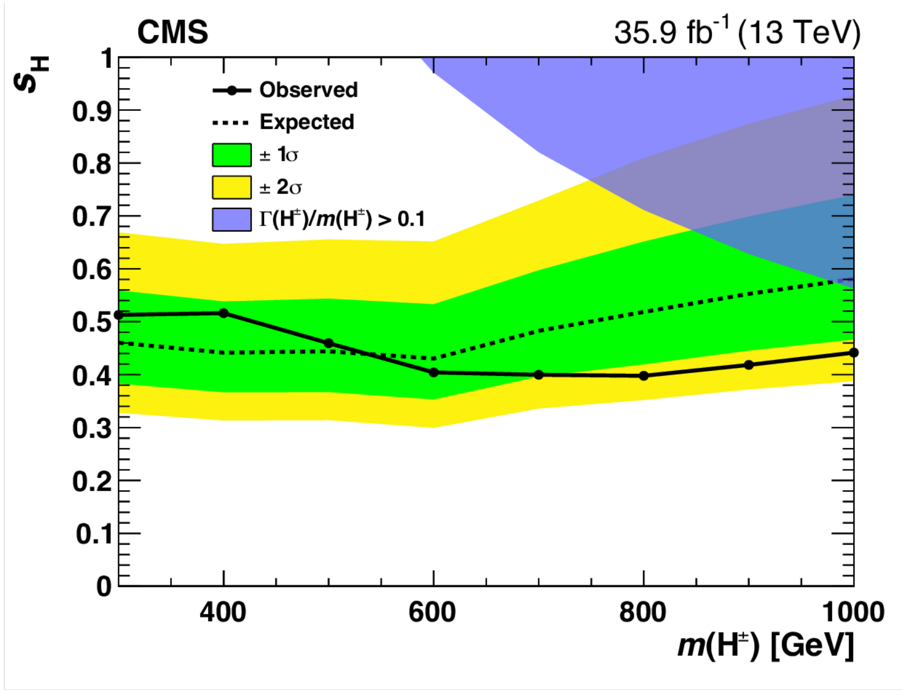
arXiv:1901.04060 sub to PLB



WZjj Cahrged Higgs limits

arXiv:1901.04060 sub to PLB





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

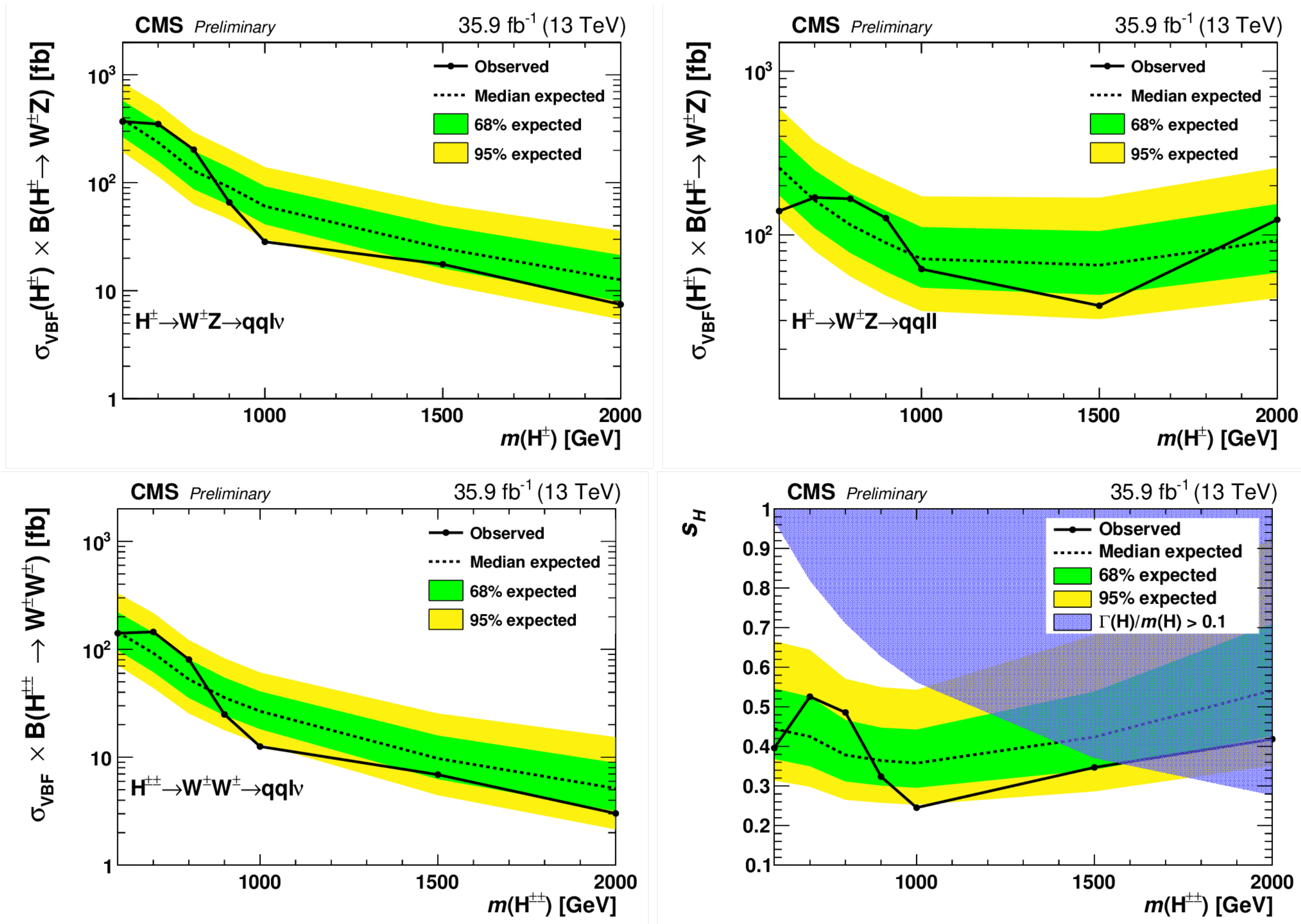
WW/WZ/ZZjj semileptonic: aQGC

SMP-18-006

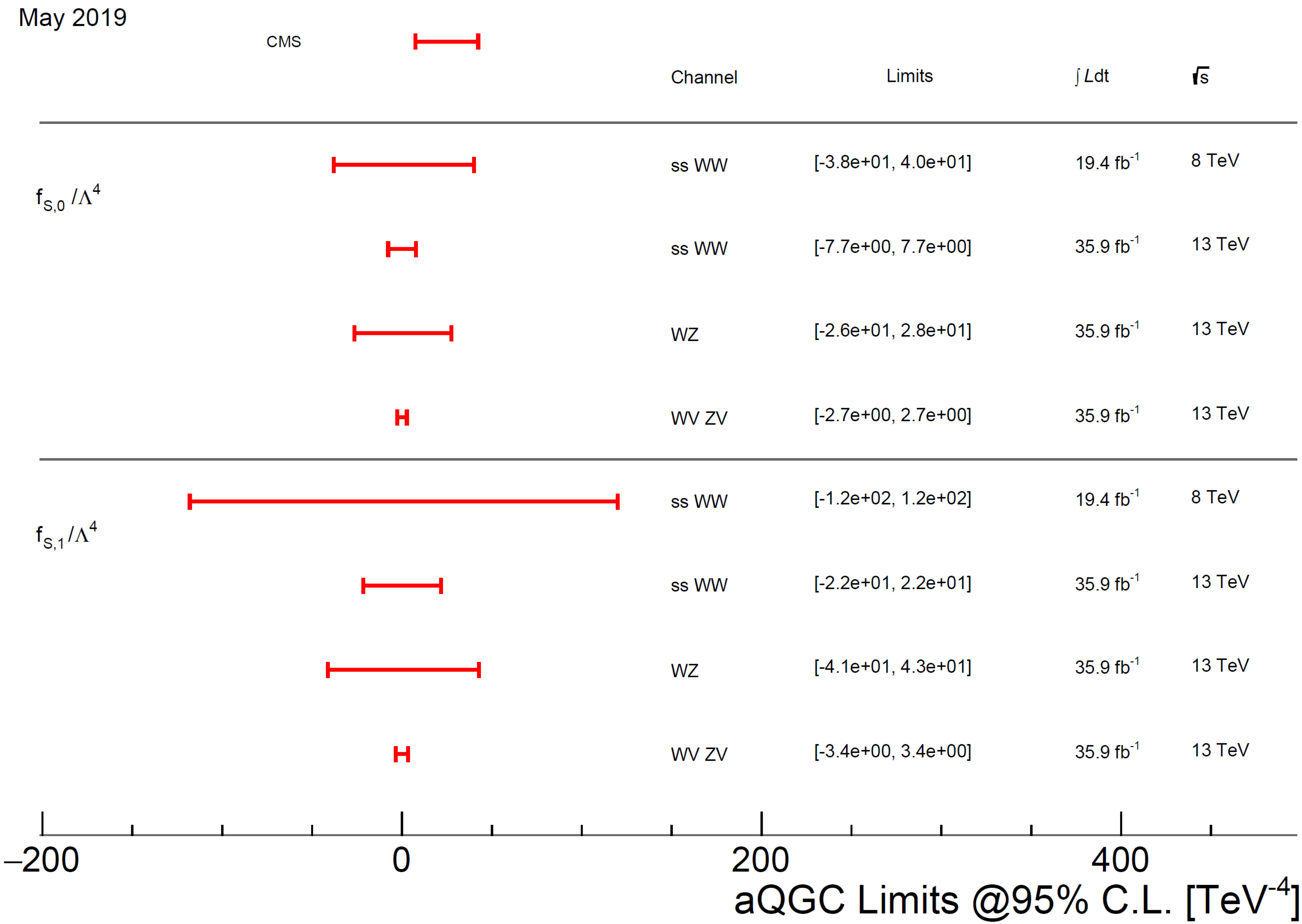
	Observed (WV) (TeV $^{-4}$)	Expected (WV) (TeV $^{-4}$)	Observed (ZV) (TeV $^{-4}$)	Expected (ZV) (TeV $^{-4}$)	Observed (TeV $^{-4}$)	Expected (TeV $^{-4}$)
f_{S0}/Λ^4	$[-2.6, 2.7]$	$[-4.0, 4.0]$	$[-37, 37]$	$[-29, 29]$	$[-2.6, 2.7]$	$[-4.0, 4.0]$
f_{S1}/Λ^4	$[-3.2, 3.3]$	$[-4.9, 4.9]$	$[-30, 30]$	$[-23, 23]$	$[-3.3, 3.3]$	$[-4.9, 4.9]$
f_{M0}/Λ^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}/Λ^4	$[-1.9, 2.0]$	$[-2.8, 2.8]$	$[-21, 21]$	$[-15, 15]$	$[-1.9, 2.0]$	$[-2.8, 2.8]$
f_{M6}/Λ^4	$[-1.3, 1.3]$	$[-1.9, 1.9]$	$[-14, 14]$	$[-10, 10]$	$[-1.3, 1.3]$	$[-1.9, 1.9]$
f_{M7}/Λ^4	$[-3.3, 3.2]$	$[-4.8, 4.8]$	$[-33, 33]$	$[-24, 24]$	$[-3.3, 3.3]$	$[-4.8, 4.8]$
f_{T0}/Λ^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}/Λ^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}/Λ^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: Cherged Higss limits

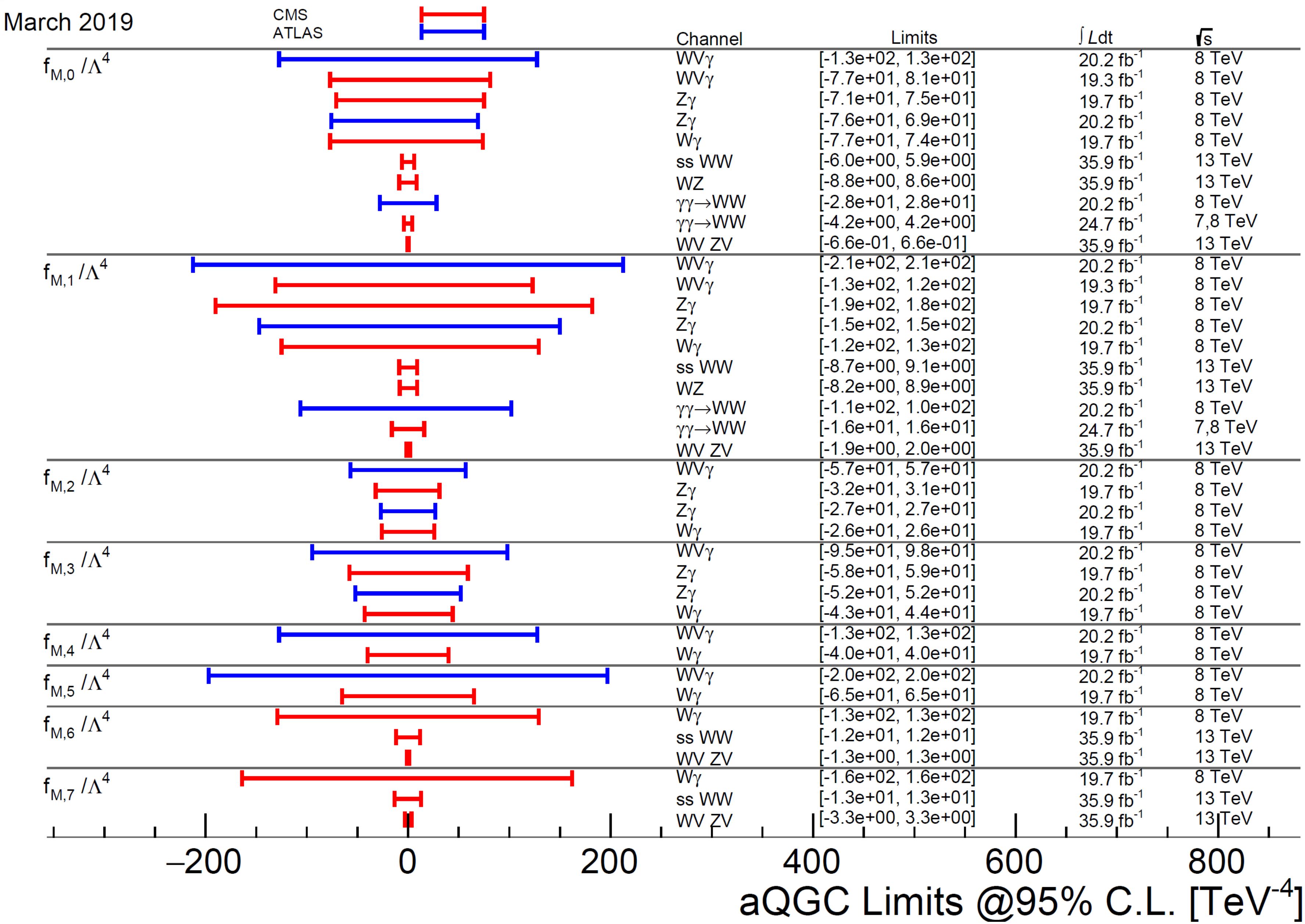
SMP-18-006



Limits on scalar aQGC operators



Limits on mixed aQGC operators



Operator	Channel	Limits	∫Ldt	√s
$f_{M,0}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 5.9e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-8.8e+00, 8.6e+00]	35.9 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.6e-01, 6.6e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-2.1e+02, 2.1e+02]	20.2 fb^{-1}	8 TeV
	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-8.7e+00, 9.1e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.9e+00]	35.9 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-1.9e+00, 2.0e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-1.3e+01, 1.3e+01]	35.9 fb^{-1}	13 TeV
	WV ZV	[-3.3e+00, 3.3e+00]	35.9 fb^{-1}	13 TeV

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

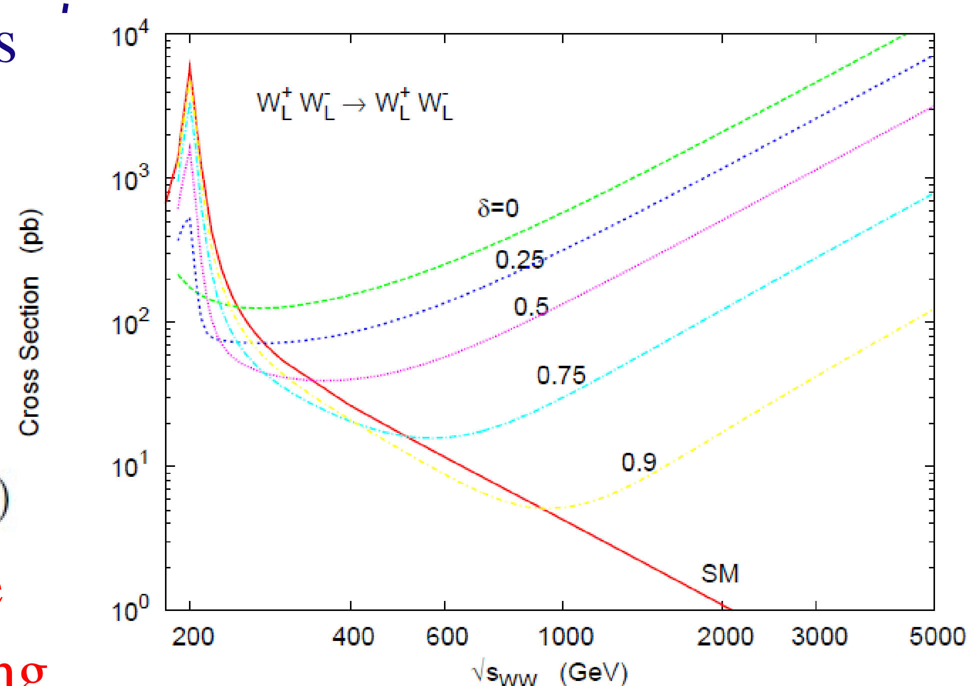
- If the cancellation of the **Higgs diagrams is not complete**, then we expect a **g_{HWW} coupling smaller than the SM**.
- The **$W_L W_L$ will keep growing with √s**, up to the the new resonance, or more generally to the **new physics scale Λ**.
- Suppose the Higgs-WW coupling is amplitudes become

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

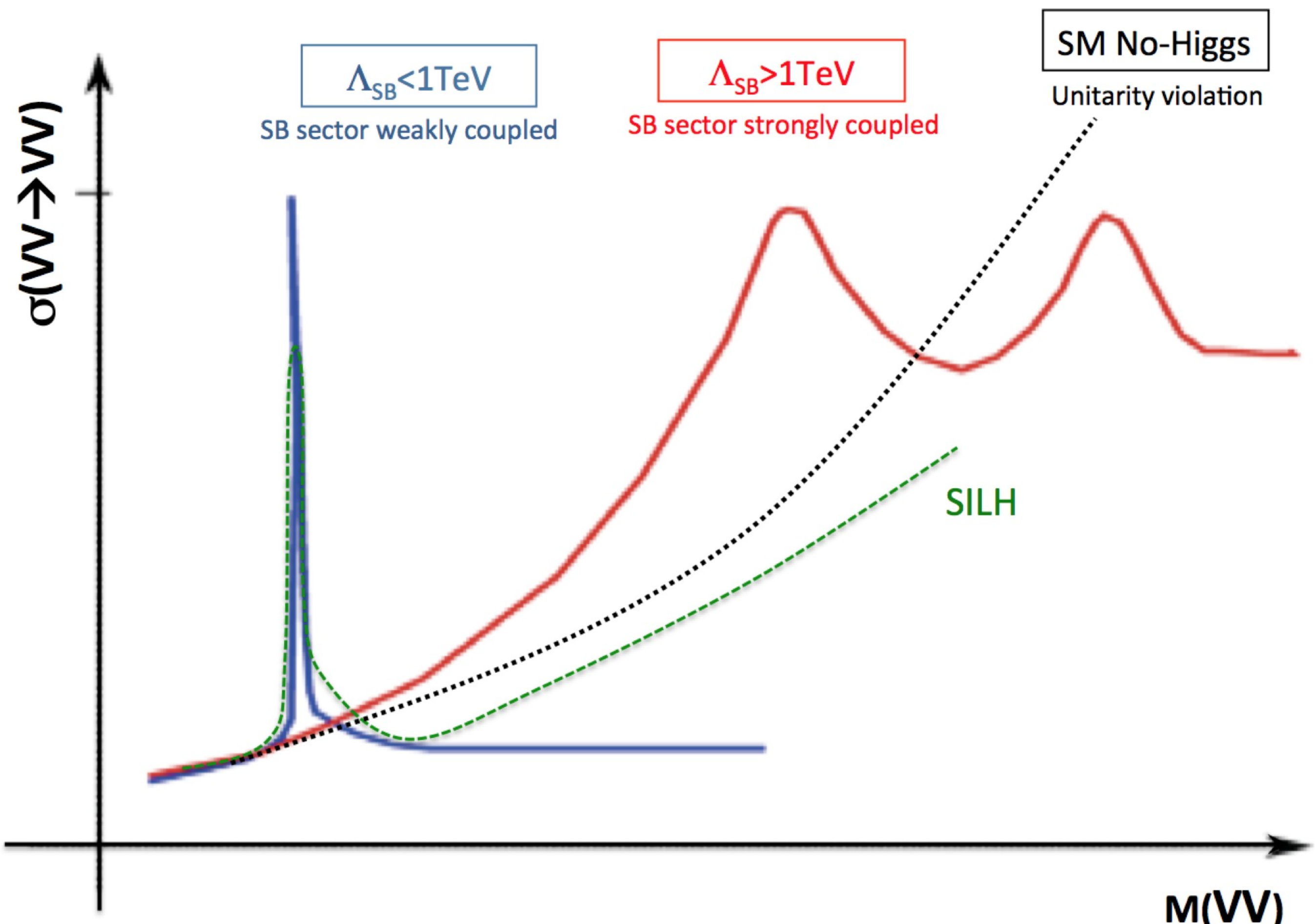
$$i\mathcal{M}^{\text{higgs}} = i\frac{g^2}{4m_W^2}\,u\,\delta + \mathcal{O}((E/m_W)^0)$$

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

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



Cheung, Chiang, Yuan



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

SILH :

Higgs a pseudo Goldstone Boson of a new strong sector

Both a light Higgs and Bosons strongly coupled

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

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**:

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

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**:
  - **$f_{S,0}/\Lambda^4$, $f_{T,0}/\Lambda^4$…**

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

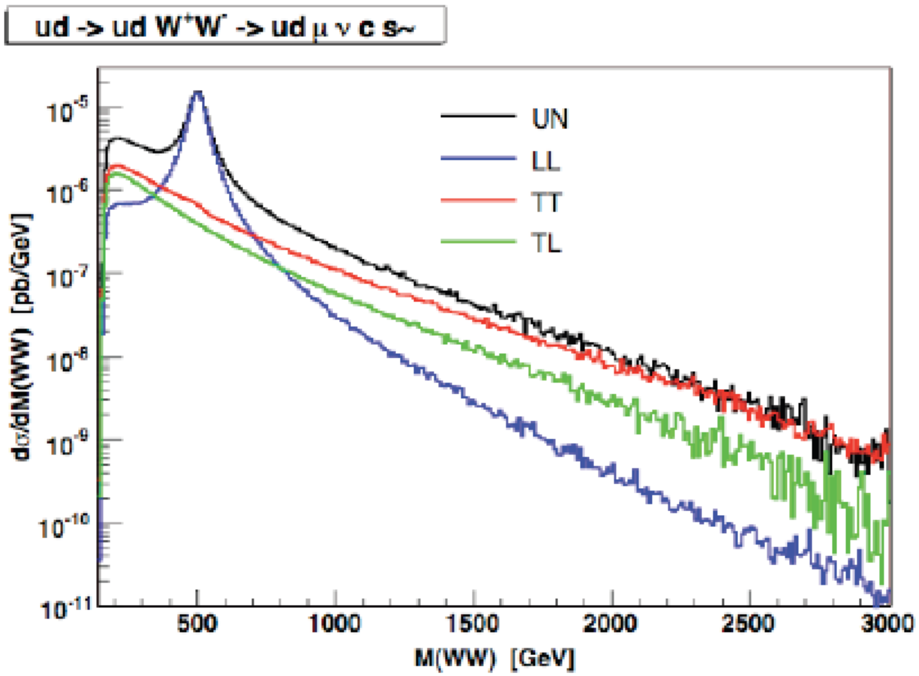
- Cross Sections for $\sqrt{s}$ = 14 TeV from Phantom Monte Carlo Generator:
full simulation of $2 \rightarrow 6$ @ $\mathcal{O}(\alpha_{EW}{}^6) + \mathcal{O}(\alpha_{EW}{}^4\alpha_{QCD}{}^2)$

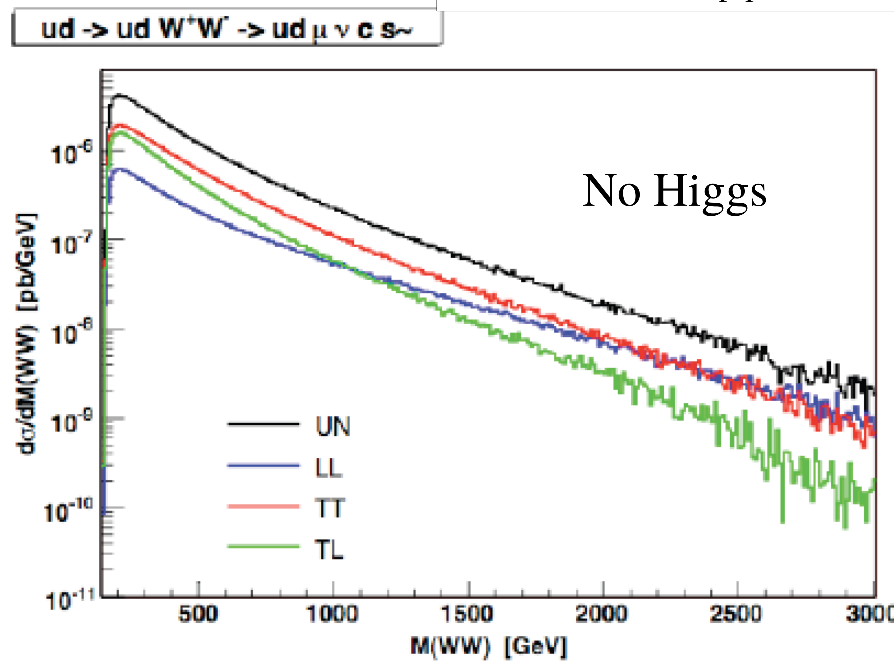
	$qqqq\mu\nu/e\nu$				$qqqq\mu\mu/ee$			
	no-Higgs		500 GeV		no-Higgs		500 GeV	
	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.	σ (pb)	perc.
total	0.689	100%	0.718	100%	0.0305	100%	0.0350	100%
signal	0.158	23%	0.184	26%	0.0125	41%	0.0165	47%
top	0.495	72%	0.494	69%	0.0137	45%	0.0137	39%
non resonant	0.020	3%	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	
	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (fb)	perc.	σ (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



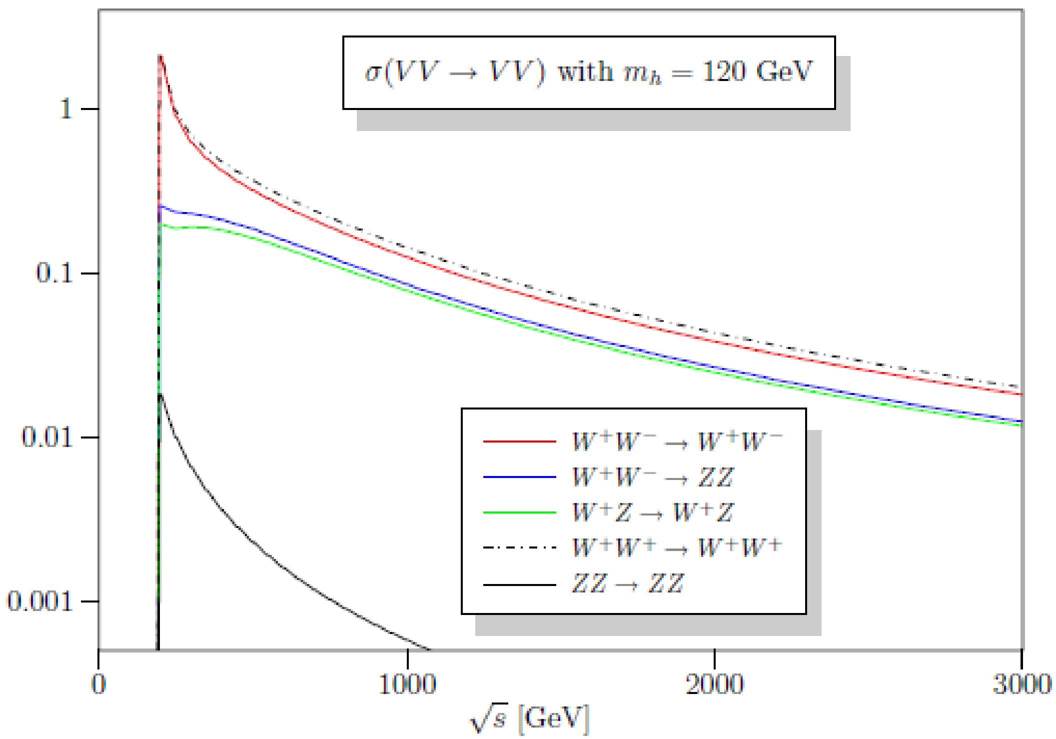


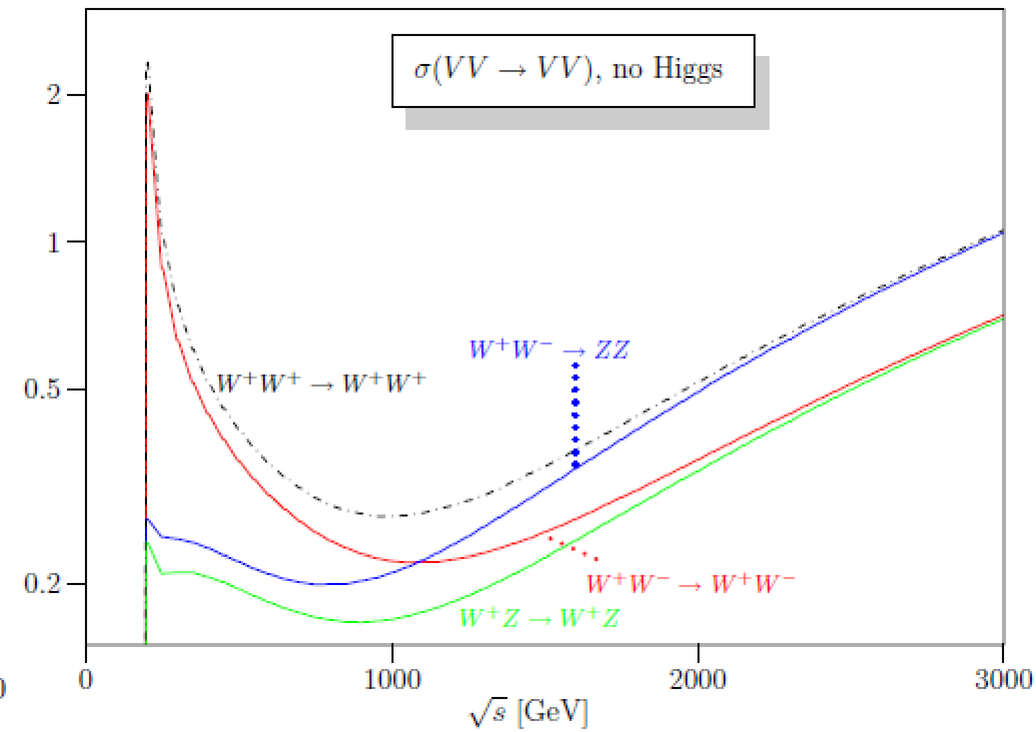
- The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
- The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
- At large M(VV) the TT cross section is of the same order as the LL (in the no-Higgs case)

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

- 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