VBS Measurement at CMS with Run2 data

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outline

- Introduction
- Analysis based on RunII data
  - EW same-sign WW
  - VBS ZZ
- Summary

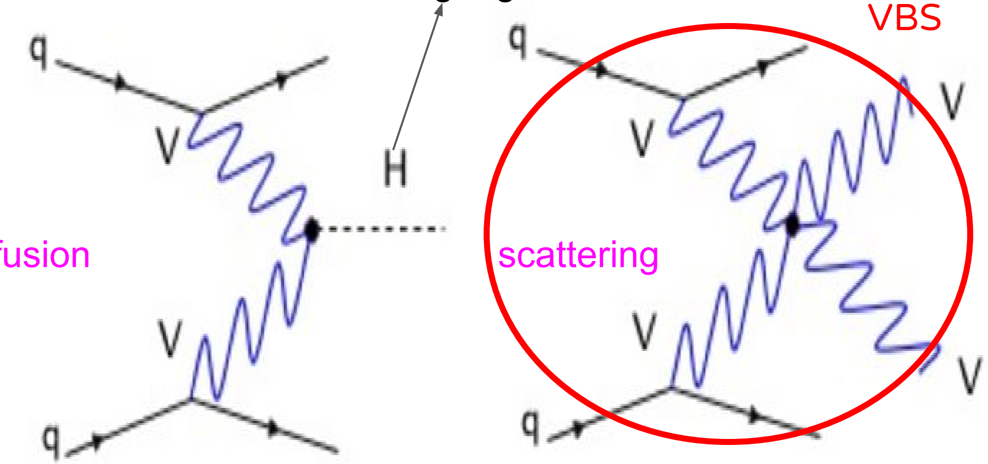
Introduction: VBS process

could be other gauge bosons

fusion

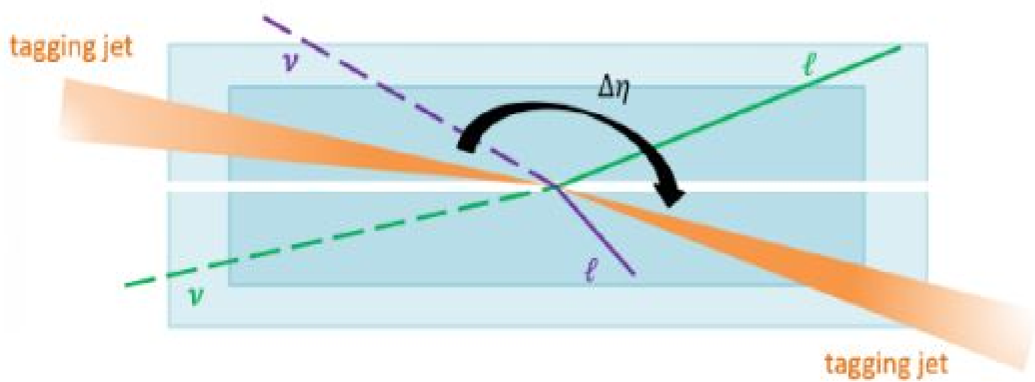
scattering

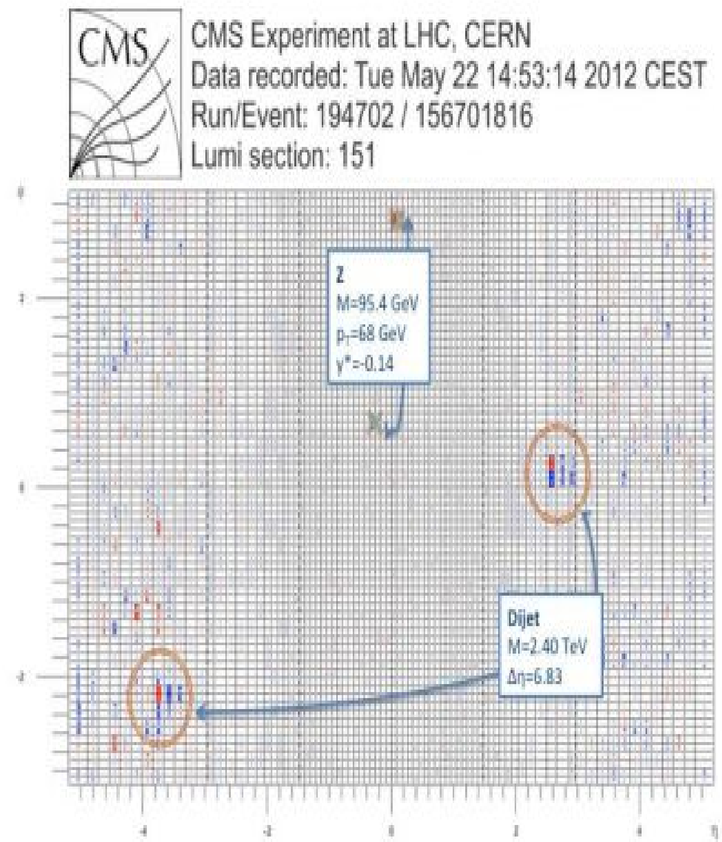
VBS



$V = W^{+}, W^{-}, Z, \gamma$

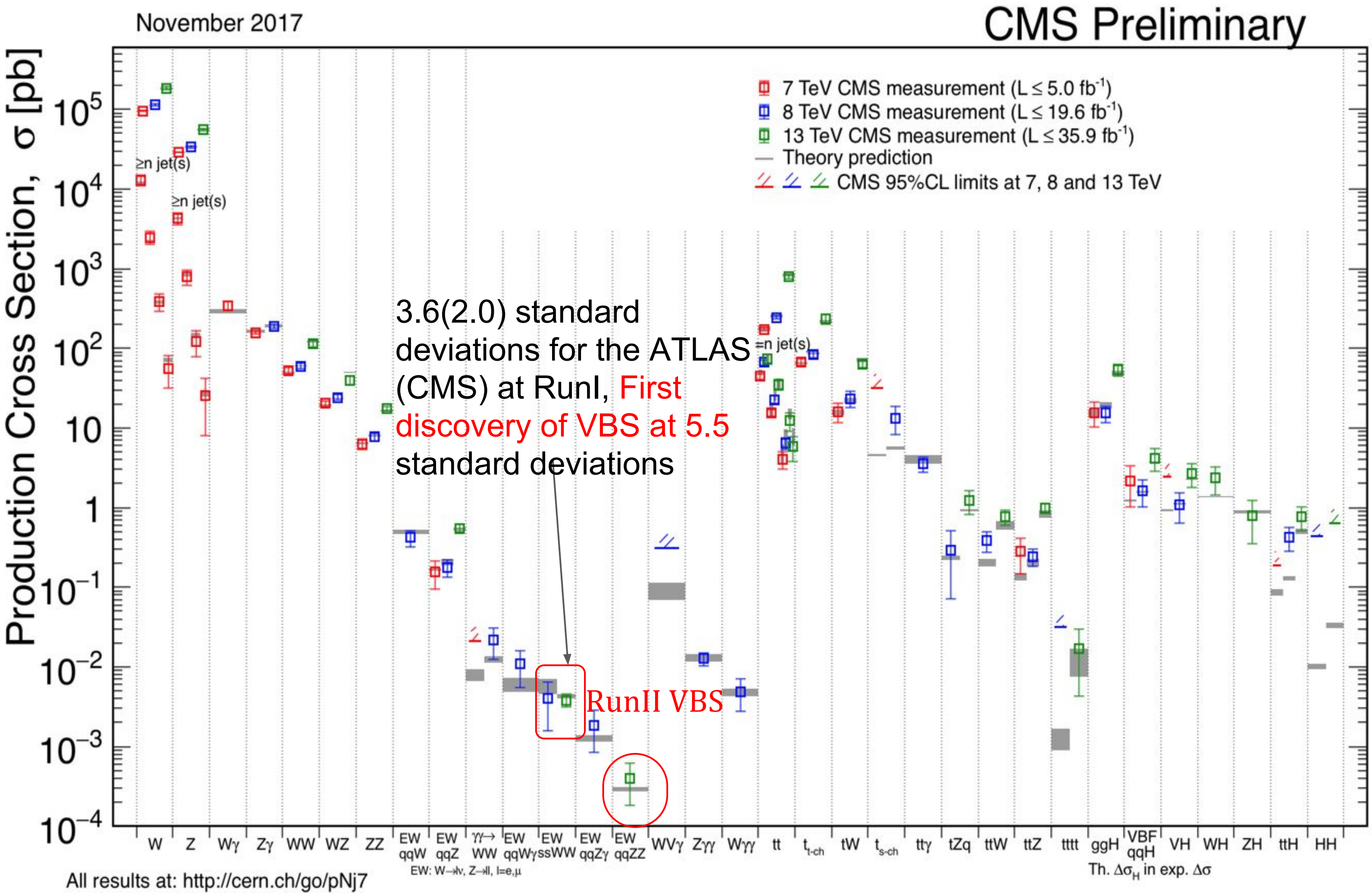
*two forward jets
*large $\Delta\eta$ between two jets
*lower central hadronic activity
*large M_{jj}



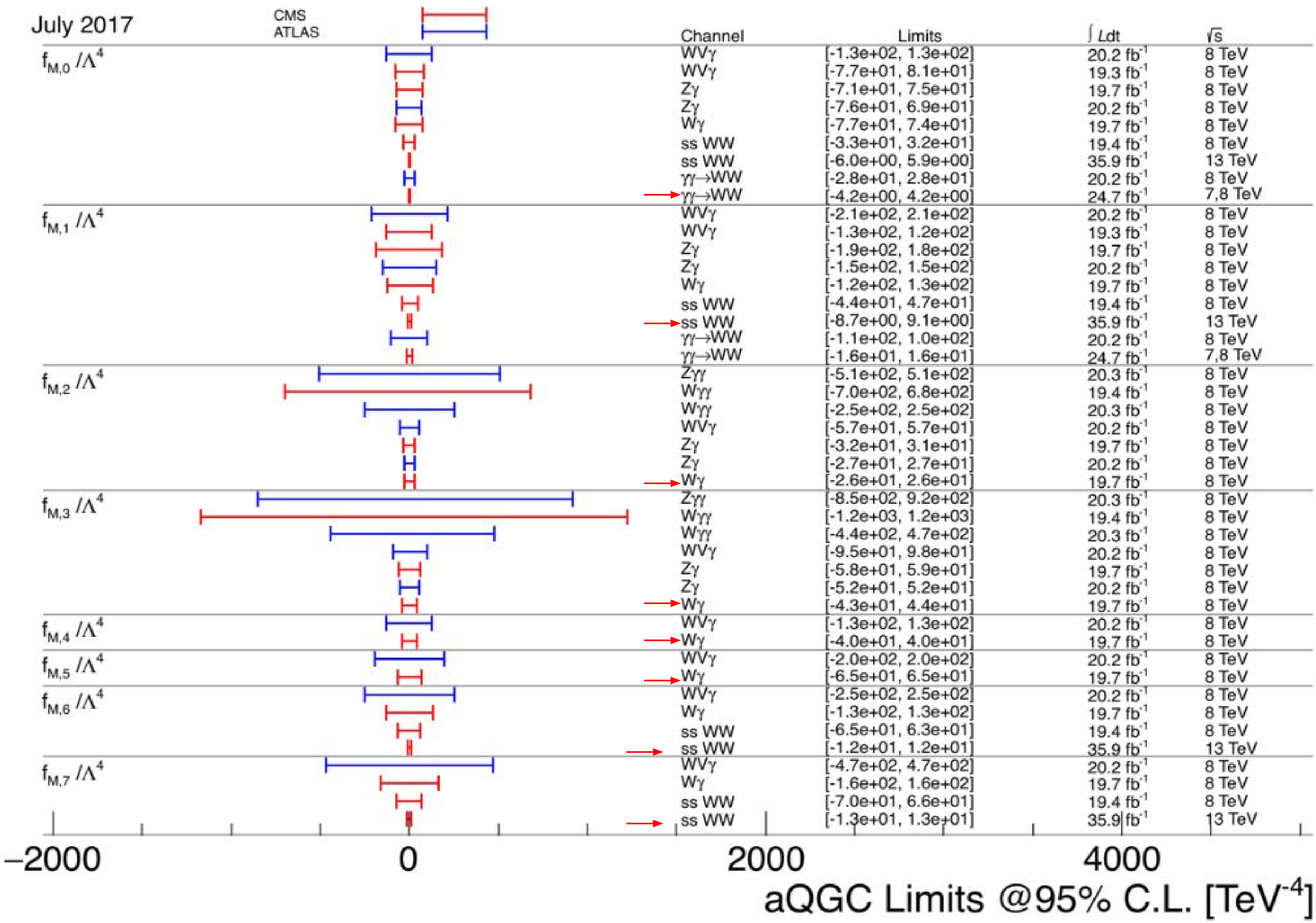


Introduction: cross section results

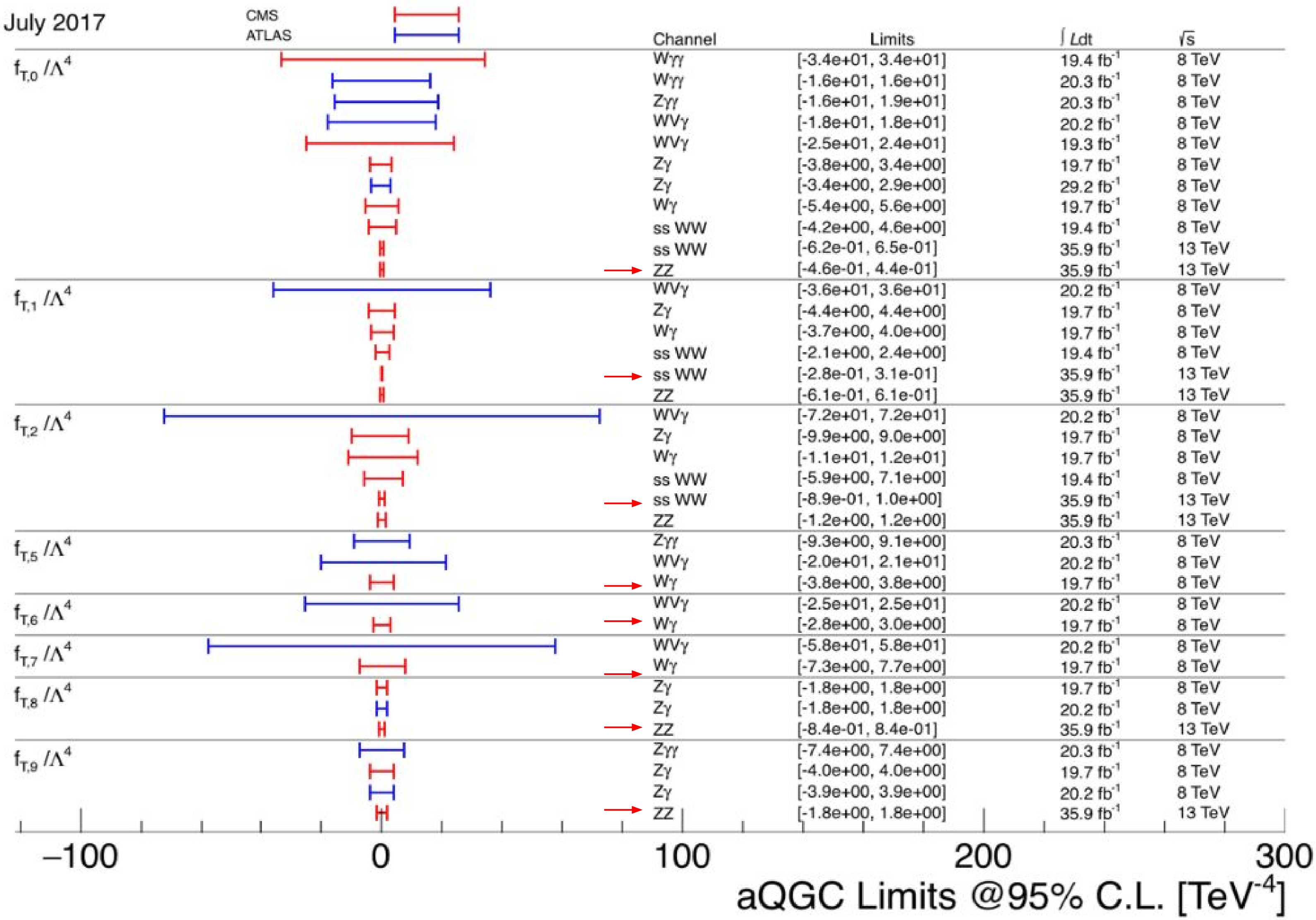
VBS analysis based on RunI data have shown lots of interesting results(talks from Daneng Yang), more and more attention have been paid on it now



Introduction: limits on dimension 8 mixed transverse and longitudinal parameters



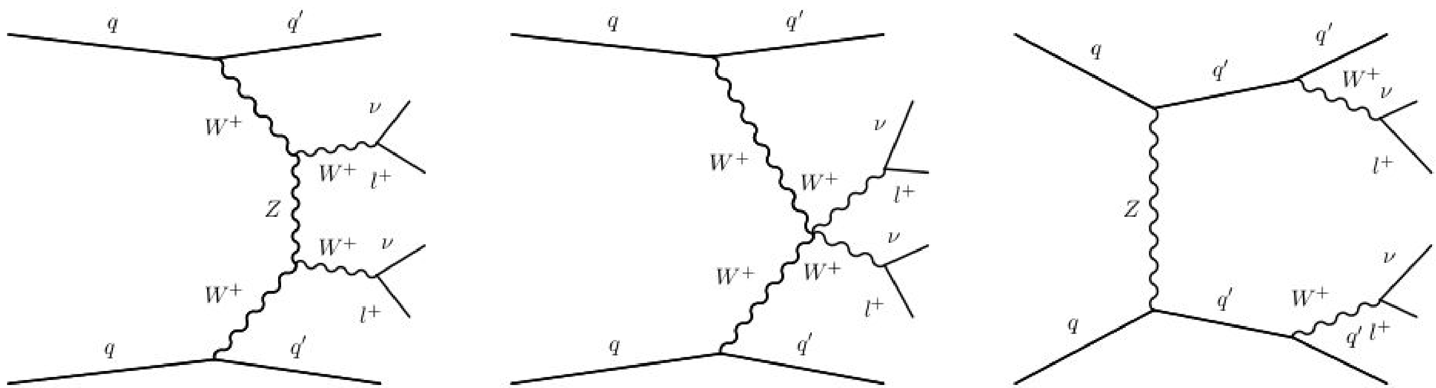
Introduction: limits on dimension 8 transverse parameters



EW same-sign WW: signal and background

arXiv:1709.05822

Representative Feynman diagrams for the electroweak ssWW process:



Signal process final states objects: two same-sign charged leptons, two forward jets, and moderate missing energy(6 channels).

Backgrounds and contribution(after event selection):

-Non-prompt:	60%	data-driven
Jets misidentified as leptons		Dominant two backgrounds
(semi-leptonic $t\bar{t}$, W+jets)		
-WZ/γ*	20%	from MC, data-driven normalized
-Vγ:		
Photon is converted in detector material	6%	
-WW QCD	3%	
-charge misassignment	3%	
-VVV	3%	
-ZZ, WW DPS	<1%	

EW same-sign WW: event selection and WZ control region

Event selection:

- two tight, same sign leptons (electron or muon) with $p_T > 25$, 20 GeV
- two jets with $p_T > 30$ GeV
- MET > 40 GeV
- $m_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 2.5$
- $max(z_l^*) < 0.75$,
  $z_l^* = |\eta_\ell - (\eta_{j1} + \eta_{j2})/2| / |\Delta\eta_{jj}|$
- 3th lepton veto:
  - loose lepton ($p_T > 10$ GeV)
  - hadronic tau ($p_T > 18$ GeV)
- $|m_{ee} - m_Z| > 15$ GeV
- $m_{ll} > 20$ GeV
- b veto (CSVv2M) + soft Muon veto

WZ background contribution comes from MC but normalised from data, the WZ control region is defined as:

- three and only three leptons with pT > 25/20/20 GeV and total charge equal to one
- $|m_{ll} - m_Z| < 15$ GeV for one opposite-sign same-flavor lepton pair
- $m_{ll} > 4$ GeV for all opposite-sign lepton pairs
- events are rejected if there is a b-jet with pT > 20 GeV passing the CSVv2 tight working point

EW same-sign WW: non-prompt

Non-prompt background estimation: Jet is misidentified as a lepton

- Measure Fake Rate($\varepsilon_{\text{fake}}$) in a QCD region in data(real lepton subtracted)

  $\varepsilon_{\text{fake}}$= #Tight lepton(flavor, pT, $|\eta|$)/#Loose lepton(flavor, pT, $|\eta|$)

- Data-driven estimation of non-prompt, weights are assigned to events pass all event selections except one(two) of the leptons pass loose lepton cuts but fail tight lepton cuts,

$$w_i = \frac{\varepsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \varepsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}$$

$$w_{ij} = \frac{\varepsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \varepsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)} \times \frac{\varepsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}{1 - \varepsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}$$

- Summing over all the weights to get the non-prompt background contribution.

EW same-sign WW: WZ scalefactor and significance

The scale factor of WZ comes from the simultaneous fit with the signal strength,

m_{jj} region [GeV]	WZ scale factor	Data	Expected WZ	Backgrounds
500-800	0.82 ± 0.20	45	37.1 ± 4.8	15.5 ± 3.6
800-1100	1.45 ± 0.35	32	20.0 ± 2.5	6.7 ± 1.9
1100-1500	1.11 ± 0.33	17	11.6 ± 1.7	3.9 ± 1.4
1500-∞	1.11 ± 0.34	19	13.2 ± 2.1	5.2 ± 2.0

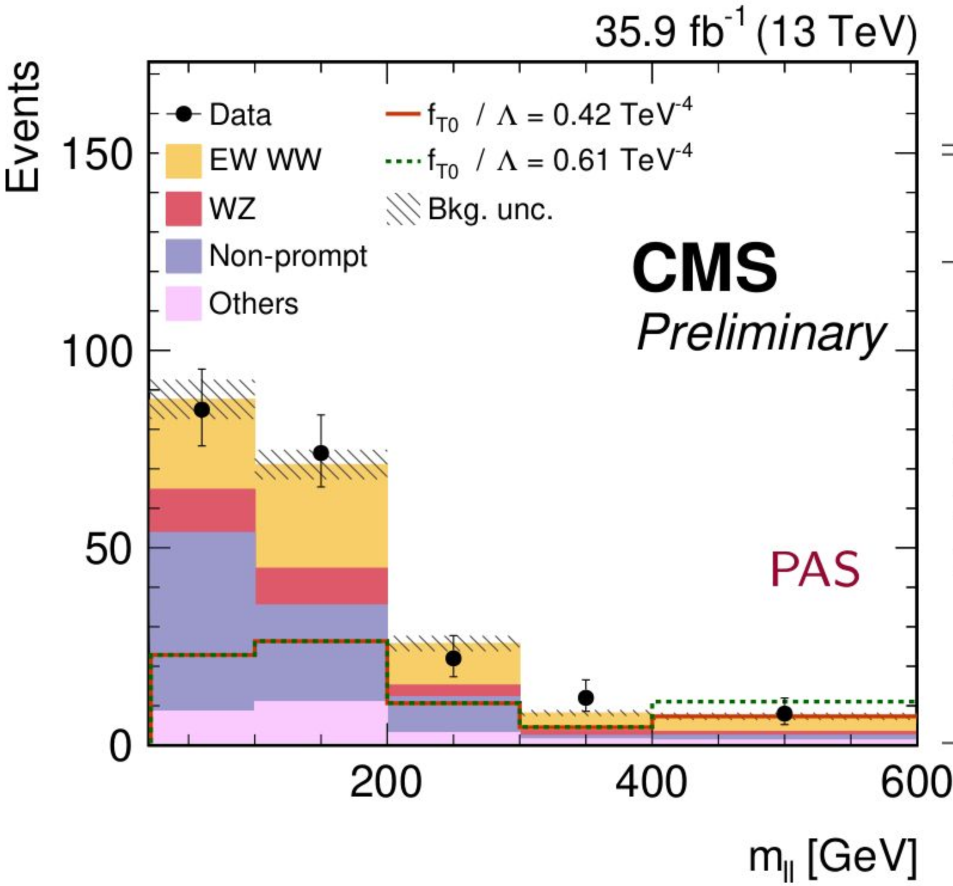
After full event selection cuts, the yields are

	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

The observed (expected) statistical significance of the signal is 5.5(5.7) using a profile likelihood ratio test statistics, first discovery.

EW same-sign WW: AQGC

Search for anomalous couplings: if exist, would promote the yields in high energy scale region, for ssWW, m_{ll} is the most sensitive variable.the limit set is based on the ATGCRooStats tool.



No evidence for anomalous is found, limits are set:

	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]

EW same-sign WW: Fiducial cross-section

Fiducial region:

- two tight, same sign leptons (electron or muon) with $p_T > 20$ GeV, $|\eta| < 2.5$
- two jets with $p_T > 30$ GeV and $|\eta| < 5.0$
- $m_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 2.5$
- $W \rightarrow \tau\nu \rightarrow l\nu\nu\nu$ decays are excluded.

Theoretical cross section and acceptance from MG5aMC

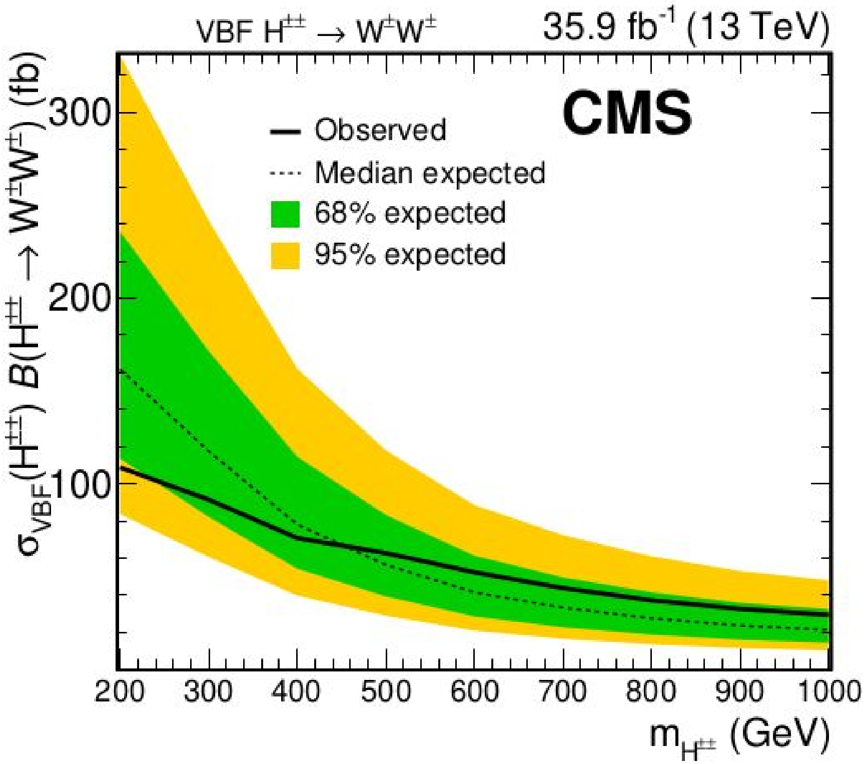
- Theoretical cross section $= 4.25 \pm 0.21$ fb
- $\sigma_{\text{fiducial}} = 3.83 \pm 0.66$ (stat.) ± 0.35 (syst.) ± 0.12 (lumi.) fb

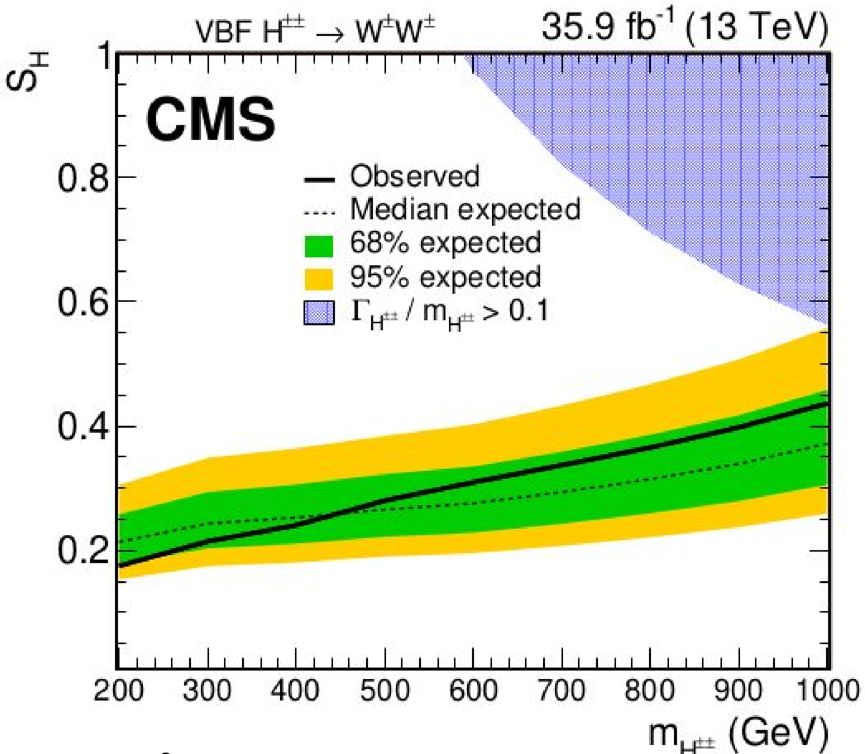
Acceptance x efficiency $= 34.8 \pm 0.3$ (stat.)%

Selected at analysis level but not in fiducial region $= 20.3 \pm 0.3$ (stat.)%
(Mostly $W \rightarrow \tau\nu \rightarrow l\nu\nu\nu$).

EW same-sign WW: Double charged Higgs boson search

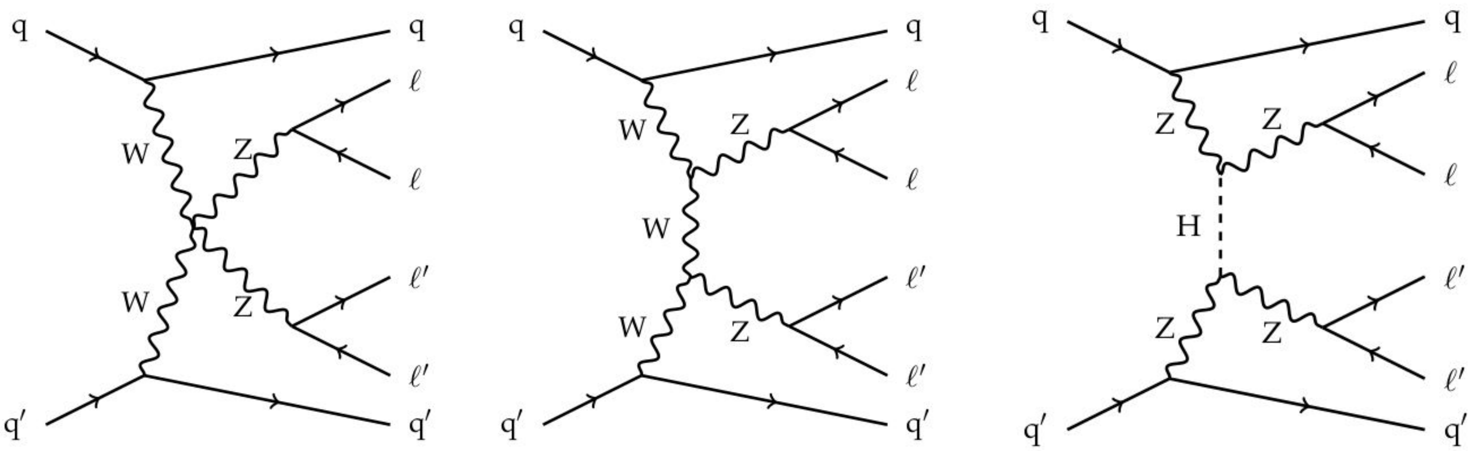
Some models that contain a Higgs triplet field predict same-sign lepton events from $W^{\pm}W^{\pm}$ decays with a VBF topology. Same analysis stratagy with EWK search but the signal sample, which is MG5aMC sample generated with fermiophobic Georgi–Machacek model.





s_H^2 denotes the fraction of the W boson mass generated by the vacuum expectation value of the triplets arXiv:1708.02812v2

Representative Feynman diagrams for the electroweak ZZ process:



Signal process final states objects: two pairs of oppositely charged isolated leptons and two forward jets. (MG, LO)

Backgrounds :

-no-loop QCD ZZ+0/1/2 jets	(MG,NLO)	irreducible
-loop-induced(gg-->ZZ) ZZ+jets	(MCFM, LO)	
-ttZ	(MG, LO)	
-WWZ	(MG, NLO)	
-Z+X(mainly Z+jets)	(MG, NLO)	reducible
-WZ	(MG, NLO)	
-tt+jets	(MG, NLO)	

VBS ZZ: ZZ selection

As there are four leptons in the final states, all permutations of four leptons giving a valid pair of Z pairs are considered.

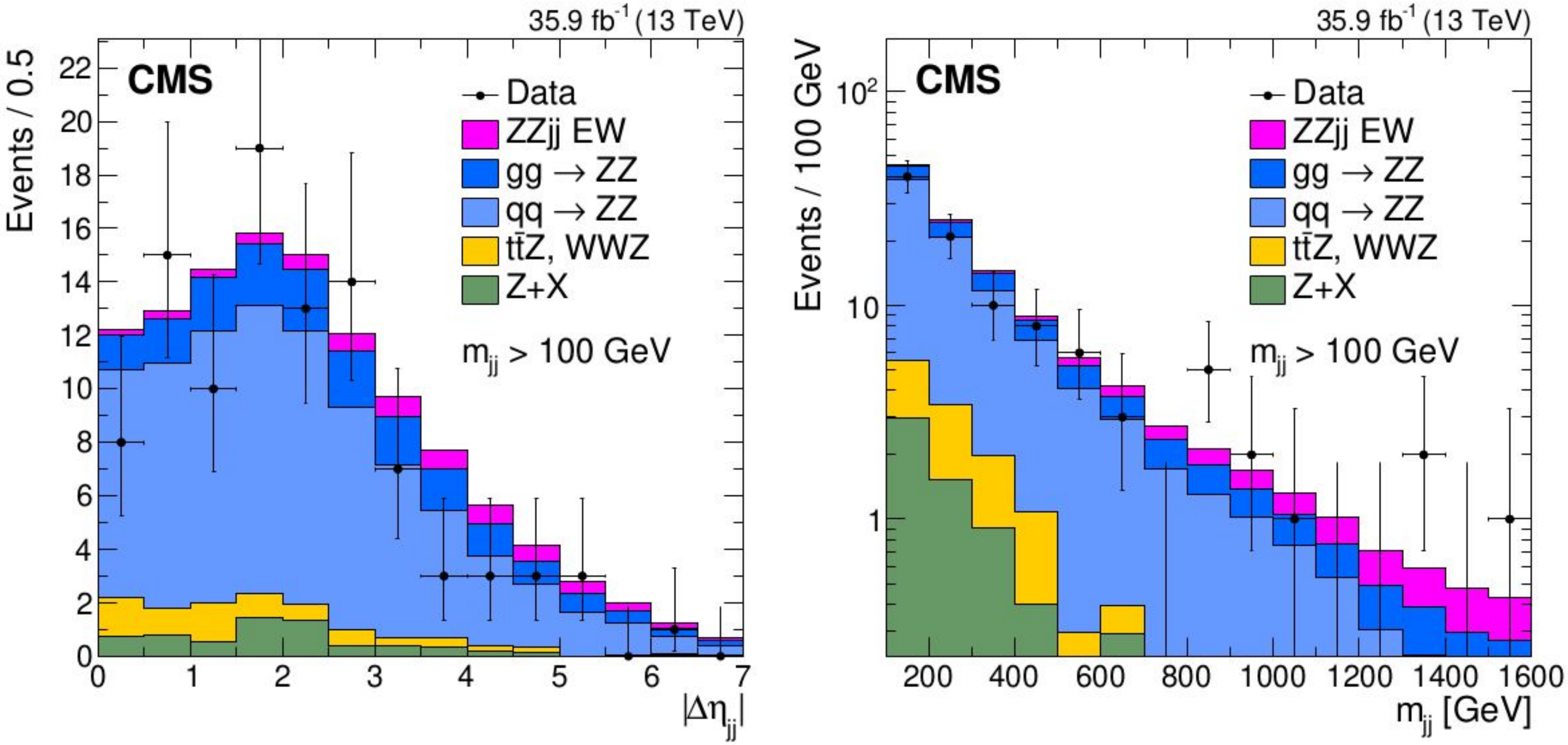
For each ZZ candidate, the lepton pair with the invariant mass closest to the nominal Z boson mass is denoted Z_1 and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2 . Both mass of Z_1 and Z_2 are required to be less than 120 GeV.

If multiple ZZ candidates in an event pass this selection, the candidate with mass Z_1 closest to the nominal Z boson mass is chosen.In the rare case (0.3%) of further ambiguity, which may arise in events with more than four leptons, the Z_2 candidate that maximizes the scalar pT sum of the four leptons is chosen.

Finally, the Z_1 and Z_2 candidates must have masses between 60 and 120 GeV. This selection is referred to as the ZZ selection

VBS ZZ: comparison between Data and MC

After ZZ selection and jets selection(mjj > 100 GeV && (mjj < 400 GeV || $|\Delta\eta_{jj}|$<2.4))



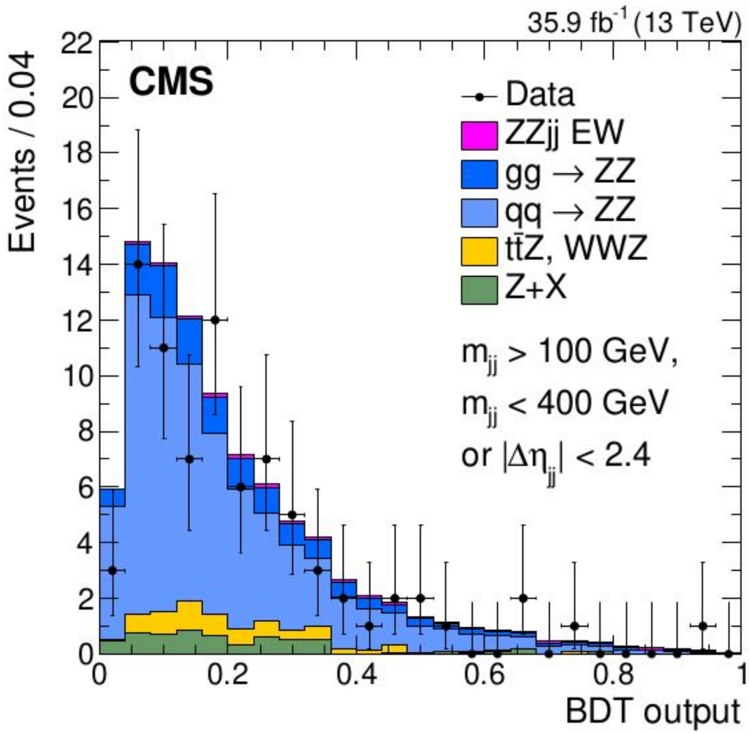
Selection	$t\bar{t}Z$ and WWZ	QCD ZZjj	Z + X	Total bkg.	EW ZZjj	Total expected	Data
ZZjj	7.1 ± 0.8	97 ± 14	6.6 ± 2.5	111 ± 14	6.2 ± 0.7	117 ± 14	99
VBS signal-enriched	0.9 ± 0.2	19 ± 4	0.7 ± 0.3	20 ± 4	4 ± 0.5	25 ± 4	19

VBS selection: mjj > 400 GeV && $|\Delta\eta_{jj}|$>2.4

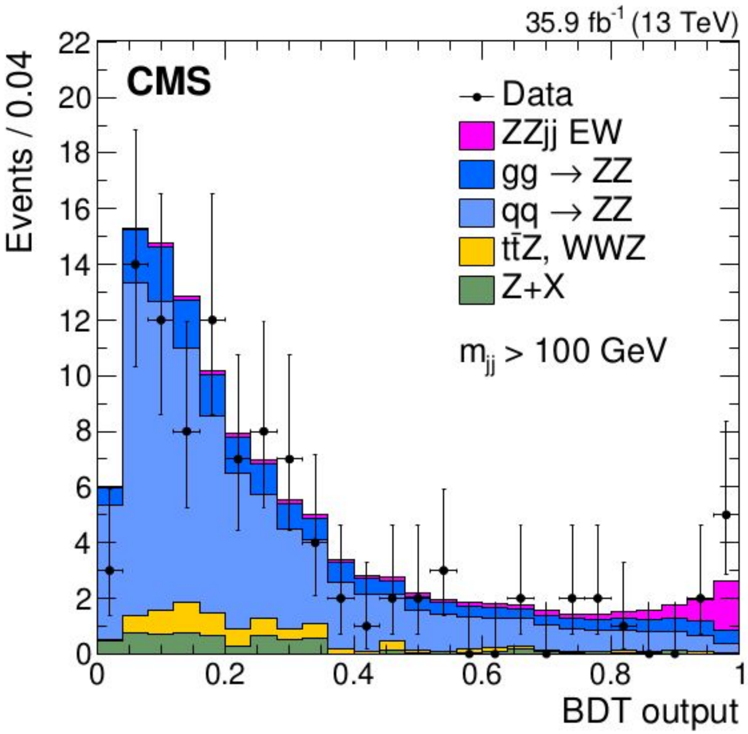
VBS ZZ: signal strength

As the small ratio of the signal process after final selection, multivariate discriminant is needed to optionally separate the signal and QCD background.

inputs for BDT: mjj ,$\Delta\eta_{jj}$, m_{ZZ}, zeppenfeld of two Z boson, ratio between the pT of the jet system and the scalar pT sum of jets.

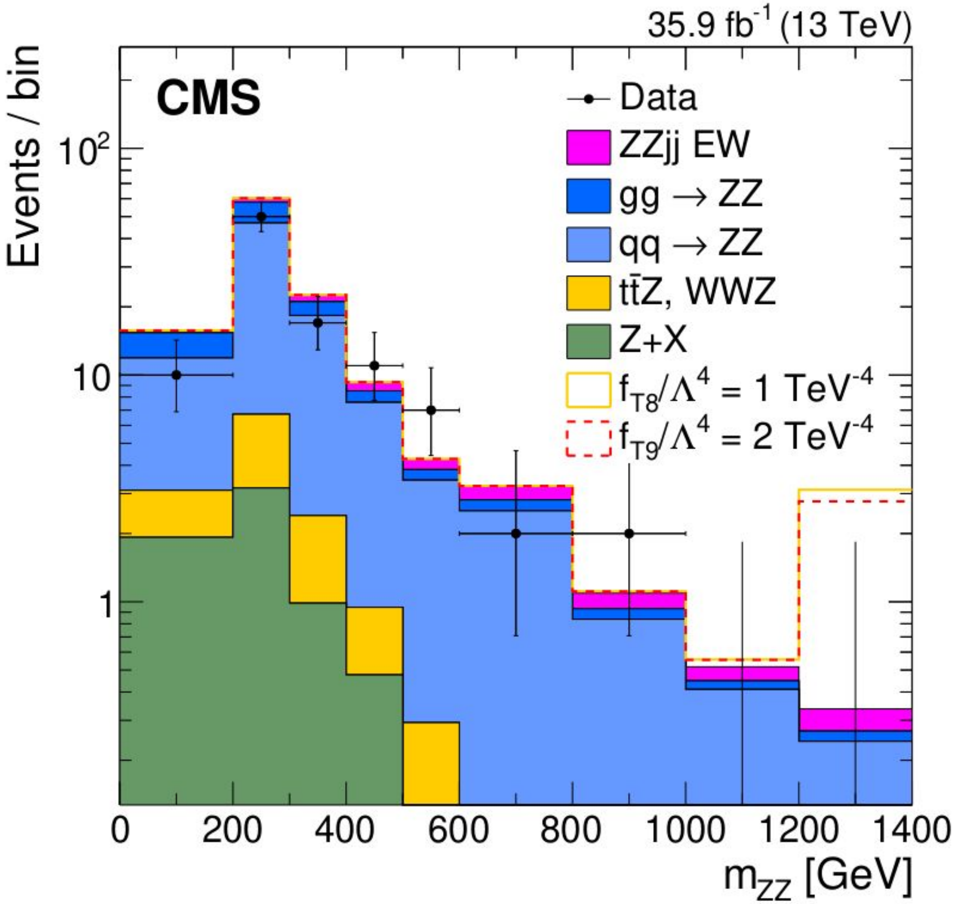


Control region(QCD-enriched):mjj < 400 GeV || $|\Delta\eta_{jj}$<2.4|, good agreement.



All events, signal strength is $1.39^{+0.86}_{-0.65}$
Significance: 2.7standard deviation(1.6 expected)

ZZjj channel is sensitive to T0, T1, T2, T8 and T9. the effect of non-zero AQGC is to enhance the production cross section at large masses of the ZZ system, thus m_{ZZ} distribution is used to constrain the AQGC parameters.



No evidence for anomalous is found, limits are set:

$$-0.46 < f_{T0}/\Lambda^4 < 0.44$$
$$-0.61 < f_{T1}/\Lambda^4 < 0.61$$
$$-1.2 < f_{T2}/\Lambda^4 < 1.2$$
$$-0.84 < f_{T8}/\Lambda^4 < 0.84$$
$$-1.8 < f_{T9}/\Lambda^4 < 1.8$$

Summary

ssWW have observed the first VBS process at 5.5 standard deviation, which give us strong confidence on the search of VBS process. What's more, stronger constraints on the AQGC parameters have been set from these RunII analysis, which may give us some new point to the new physics.

Apart from these two published analysis, there are several other VBS works based on RunII data are on-going, e.g. WGamma, ZGamma and WZ, more and more results would come in years.

Thanks for your attention!