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Electroweak physics in multiboson final states at CMS

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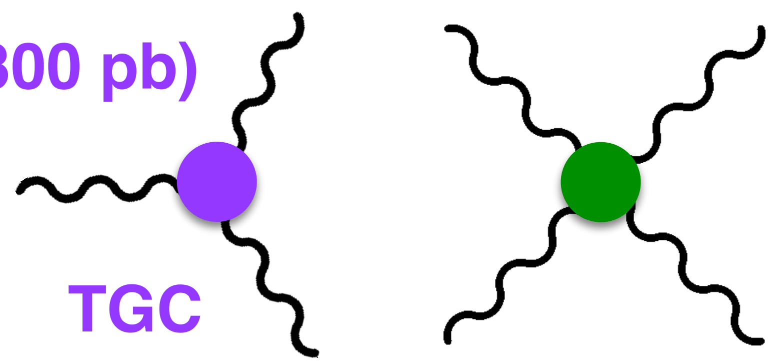
Why do we study multiboson physics ?

- electroweak gauge bosons carry weak charge → interaction vertices with three bosons (triple gauge coupling, TGC) or four bosons (quartic gauge coupling, QGC) are predicted in SM



- the measurements of multiboson production provide
  - an important test of SM
  - an indirect search for new physics
  - a detailed understanding of the background processes to the search of new physics

The measurements

number of major background events is estimated from data

number of events selected in the fiducial region

$$\sigma^{fid} = \frac{N_{obs} - N_{bkg}}{\epsilon \times SF \times L}$$

integrated luminosity

selection efficiencies (reconstruction, identification, trigger)

correct for differences of ε between data and MC

- σ^{tot} is obtained by correcting for acceptance and branching ratio
- low statistics → inclusive cross sections
- decent statistics → differential cross sections
- much higher statistics → triboson, vector boson scattering

higher order QCD and QED perturbative corrections

probe any deviation from SM prediction more closely

key process for exploring the SM nature of EWSB

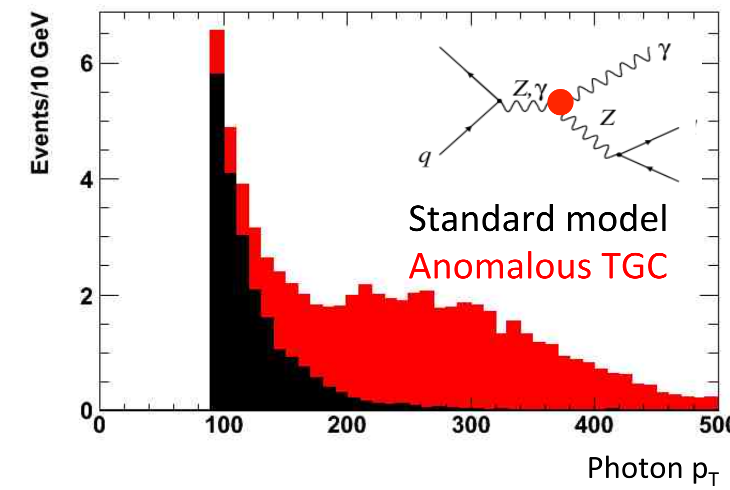
Interpretation of the results

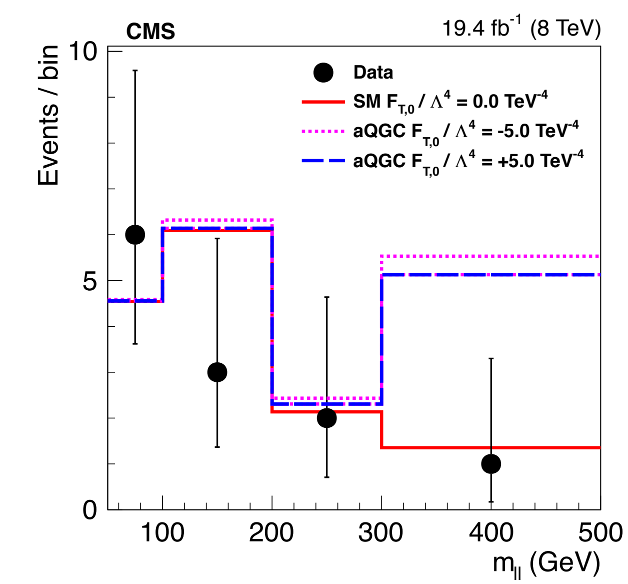
- values of TGCs and QGCs are fully fixed in the SM
- new phenomena can induce changes in TGCs/QGCs so that cross sections and kinematics deviate from SM prediction
  →**test SM gauge structure**
- anomalous couplings are constrained in the effective field theory (model independent) framework

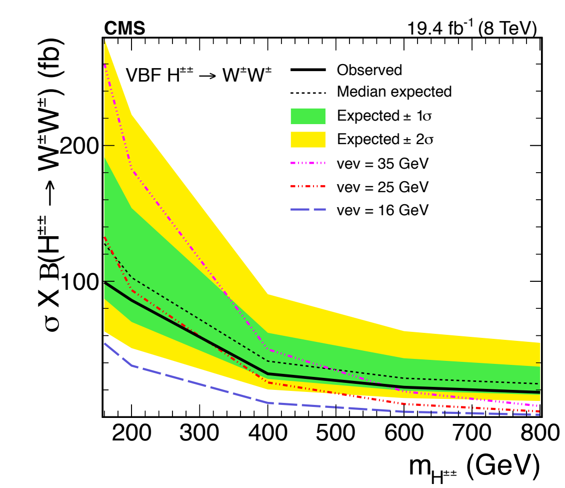
$$L_{EFT} = L_{SM} + \Sigma_i \frac{c_i}{\Lambda^2} O_i + \Sigma_j \frac{f_j}{\Lambda^4} O_j + \ldots$$

dim-6 **dim-8**

  - the gauge invariant operators O_i, O_j are built from SM fields
  - the coefficients c_i, f_j are unknown and treated as free parameters to be determined from data
- can also be used to **investigate various BSM models** such as H±, H±±…





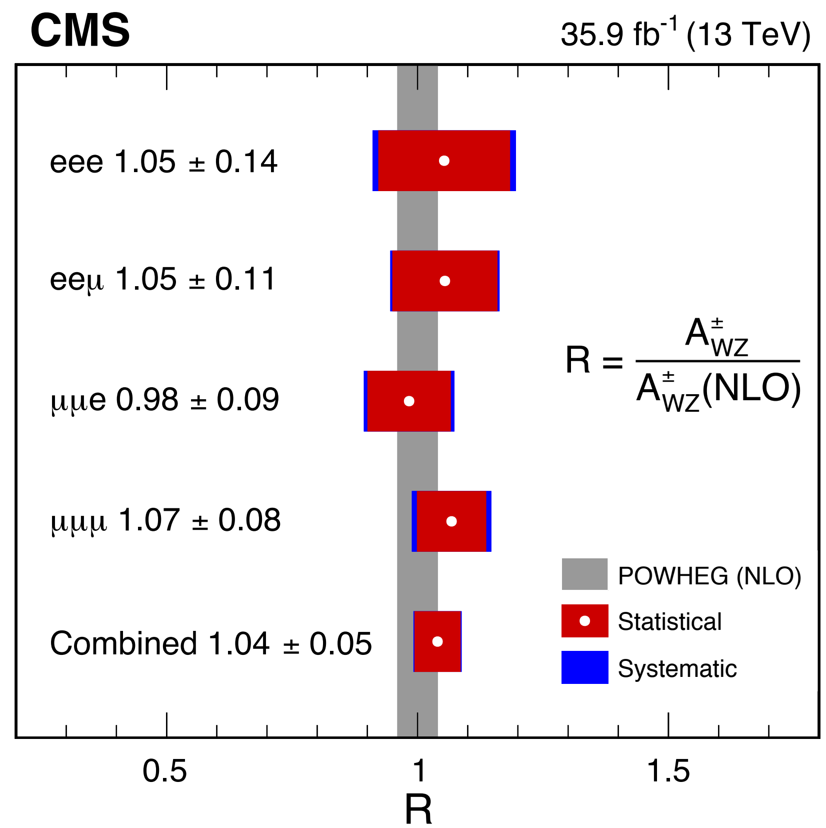


What will be covered

	Production mode	Final state	Dataset (13 TeV)	Documents
Diboson	WZ	lllv	35.9/fb	JHEP 04 (2019) 122
	ZZ	llll llll + jets	101.2/fb 35.9/fb	CMS SMP-19-001 PLB 789 (2019) 19
	WW/WZ	lvjj	35.9/fb	CMS SMP-18-008
Triboson	WWW	lll, SS ll+jj	35.9/fb	CMS SMP-17-013 arXiv:1905.04246
VBS	WW	SS ll	35.9/fb	PRL 120 (2018) 081801
	WZ	lllv	35.9/fb	CMS SMP-18-001 arXiv:1901.04060
	ZZ	llll	35.9/fb	PLB 774 (2017) 682
	WW/WZ/ZZ	lvjj, lljj	35.9/fb	CMS SMP-18-006 arXiv:1905.07445
	Zγ	llγ	35.9/fb	CMS SMP-18-007 NEW
DPS	WW	SS μμ, eμ	77.4/fb	CMS SMP-18-015

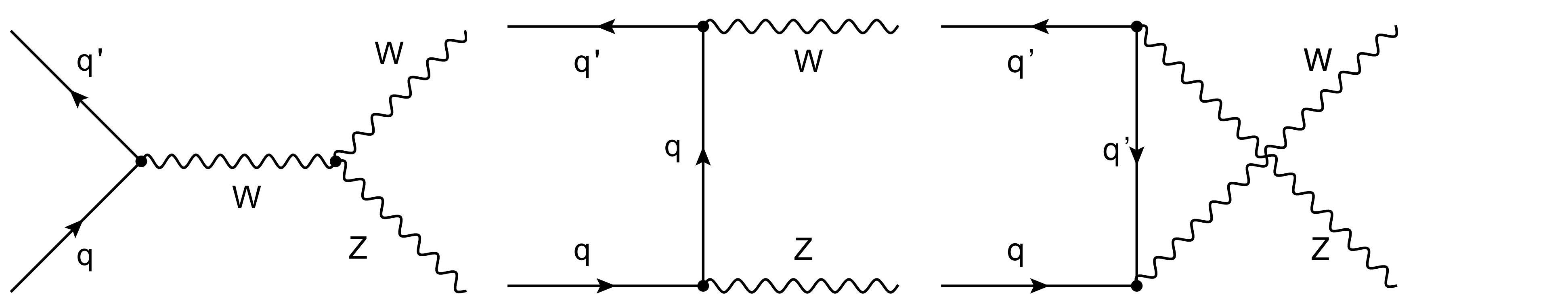
$WZ \rightarrow ll l\nu$

- only multiboson process directly sensitive to the WWZ coupling
- $Z \rightarrow ee/\mu\mu, W \rightarrow e\nu/\mu\nu$
- both of inclusive and differential cross sections are measured with increased precision wrt previous results
- $\sigma(W^+Z)/\sigma(W^-Z)$ is computed as well

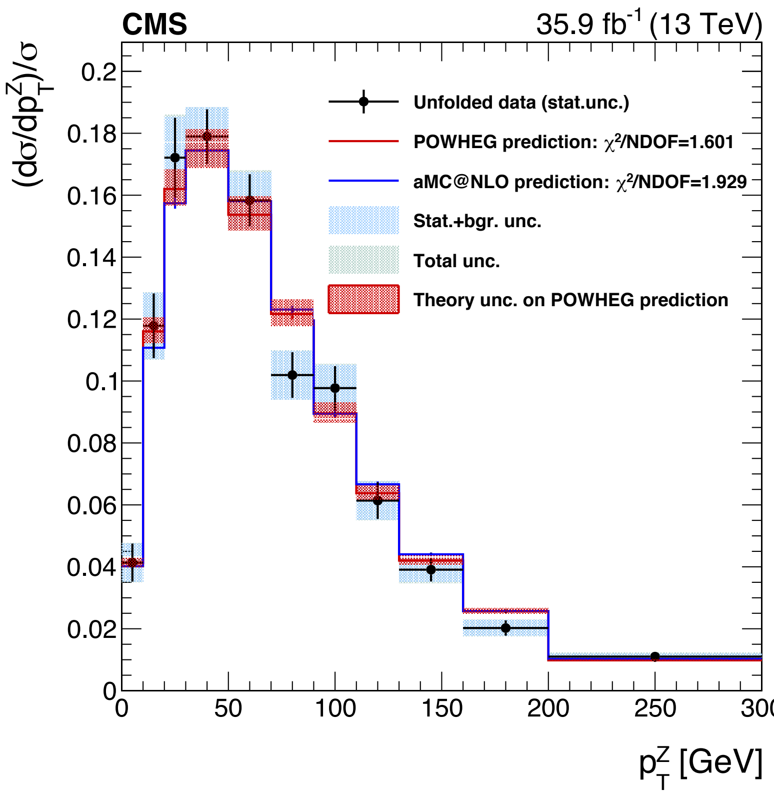


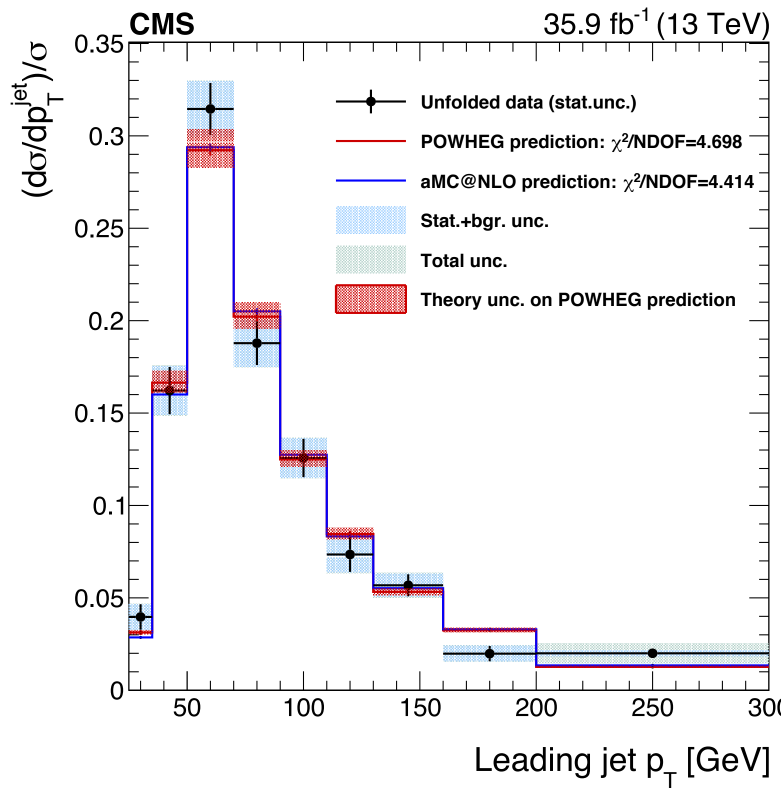
$$\sigma^{tot} = 48.09^{+1.00}_{-0.96}\,(stat)^{+0.44}_{-0.37}\,(theo)^{+2.39}_{-2.17}\,(syst) \pm 1.39\,(lumi)\;pb$$

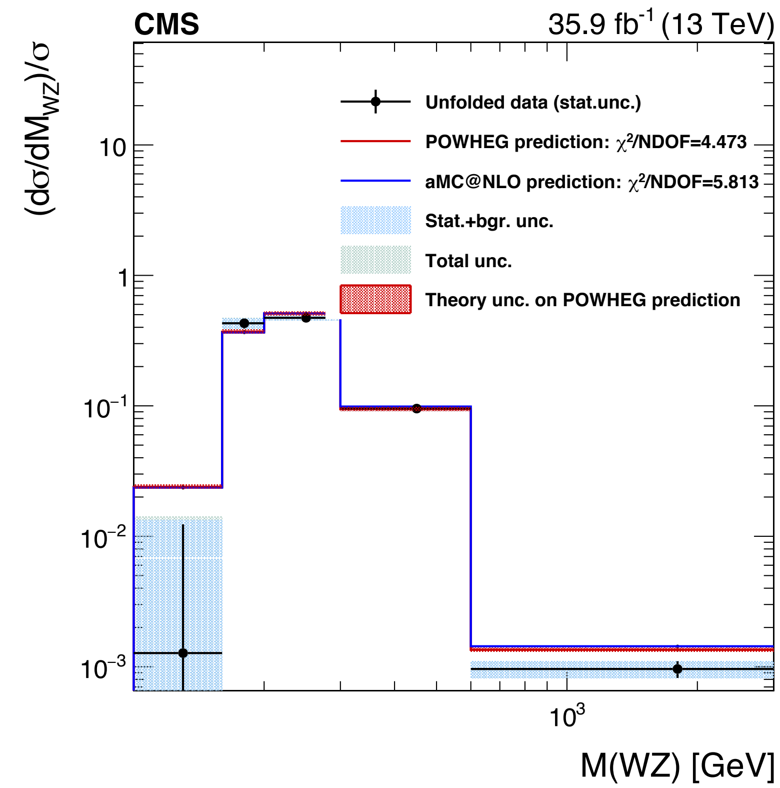
$$\sigma^{NNLO} = 49.98^{+1.10}_{-1.00}\;pb \quad \sigma^{NLO} = 45.09^{+2.21}_{-1.76}\;pb \quad \sigma^{NNLO} \approx 1.1 \times \sigma^{NLO}$$



WZ→lllν: differential cross sections



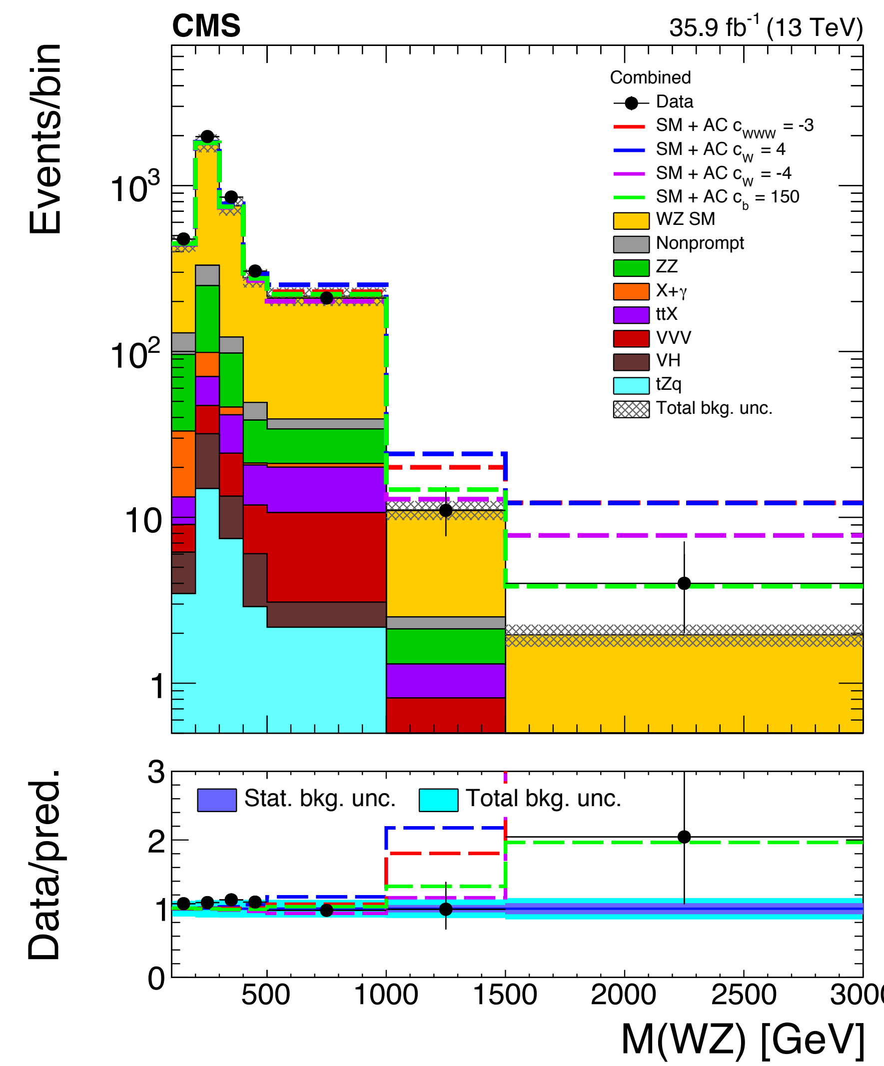


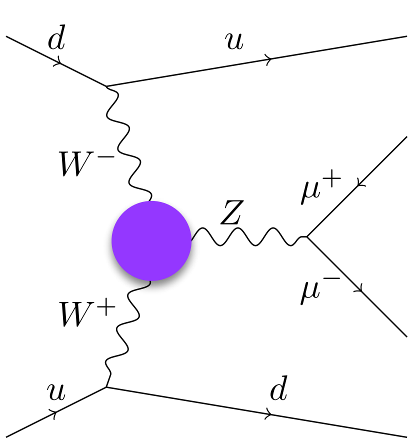


- p_T of the leading jet→a probe of the boost of the WZ system recoiling against ISR
- the differential cross sections are also measured for each sign of the W boson charge
- measurements and predictions agree well

WZ→lllν: aTGC

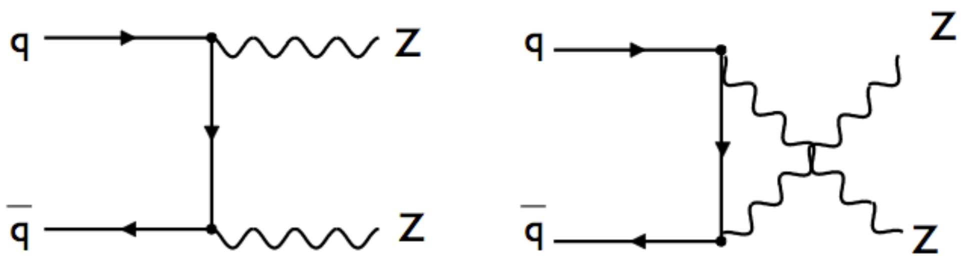
- M_{WZ} is used to derive the limits for contributions from dim-6 operators on aTGC
- WWZ TGC can be indecently checked with VBF Z production [EPJC 78 (2018) 589]



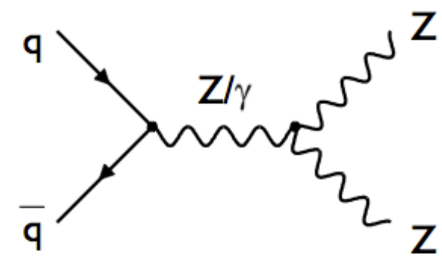


	Inclusive WZ		VBF Z	
	Exp.	Obs.	Exp.	Obs.
c_W/Λ^2	[-3.3, 2.0]	[-4.1, 1.1]	[-12.6, 14.7]	[-8.4, 10.1]
c_{WWW}/Λ^2	[-1.8, 1.9]	[-2.0, 2.1]	[-3.7, 3.6]	[-2.6, 2.6]
c_b/Λ^2	[-130, 170]	[-100, 160]		

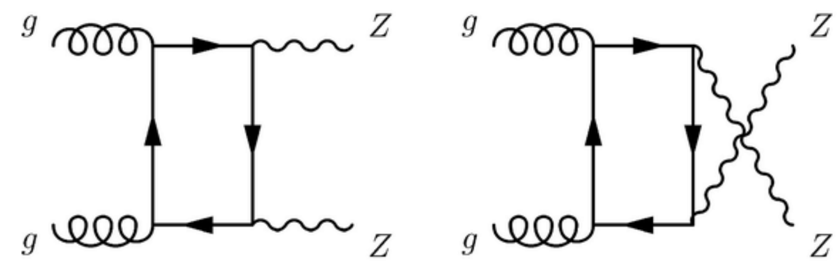
ZZ→llll



Major SM diagrams

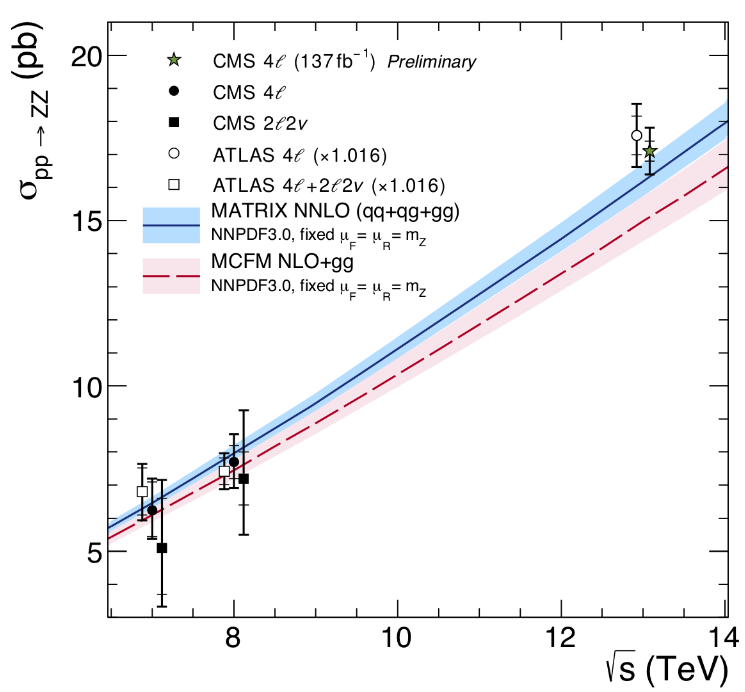


Not allowed in SM



One loop contributions

- non-resonant ZZ→llll production with 60 < m_{ll} < 120 GeV
- 3 final states：eeee, μμμμ, eeμμ



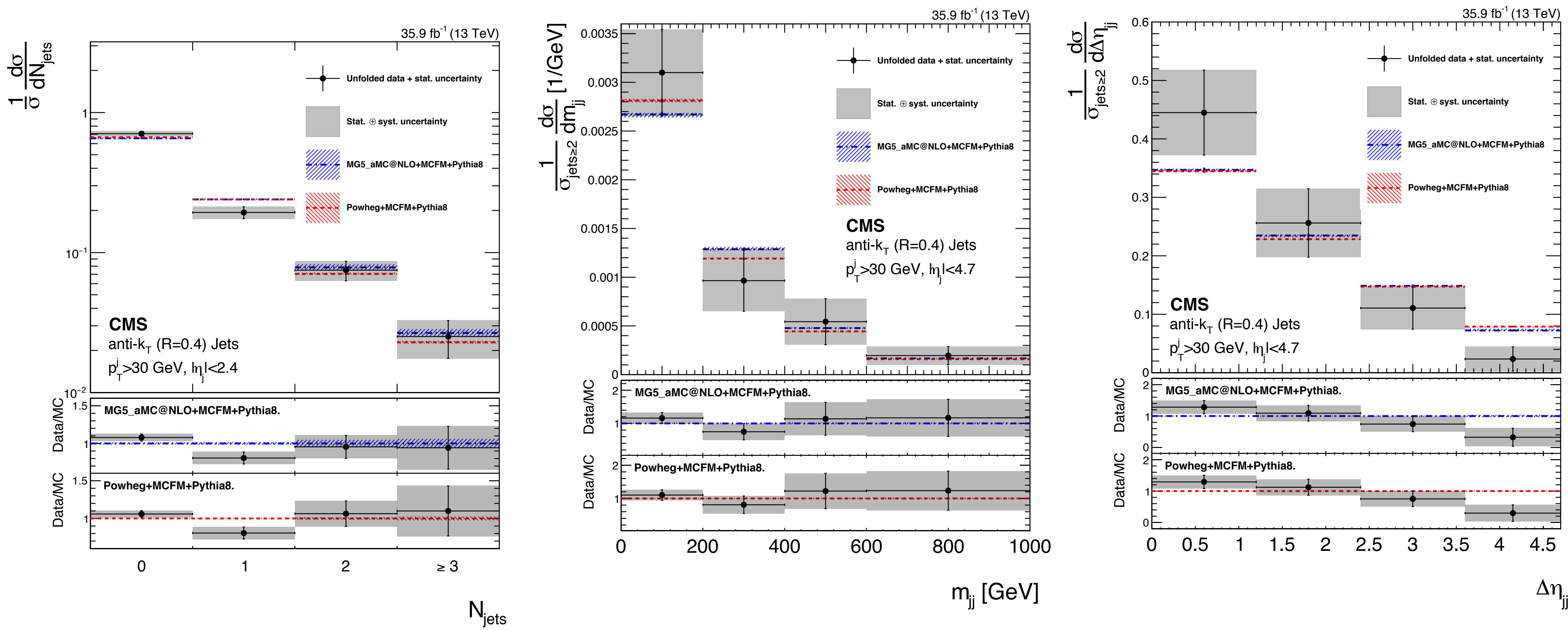
Year	Total cross section, pb
2016	$17.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2017	$16.8 \pm 0.5\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$16.8 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.1 \pm 0.3\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

$$\sigma^{NNLO\ QCD} = 16.2^{+0.6}_{-0.4}\ pb$$

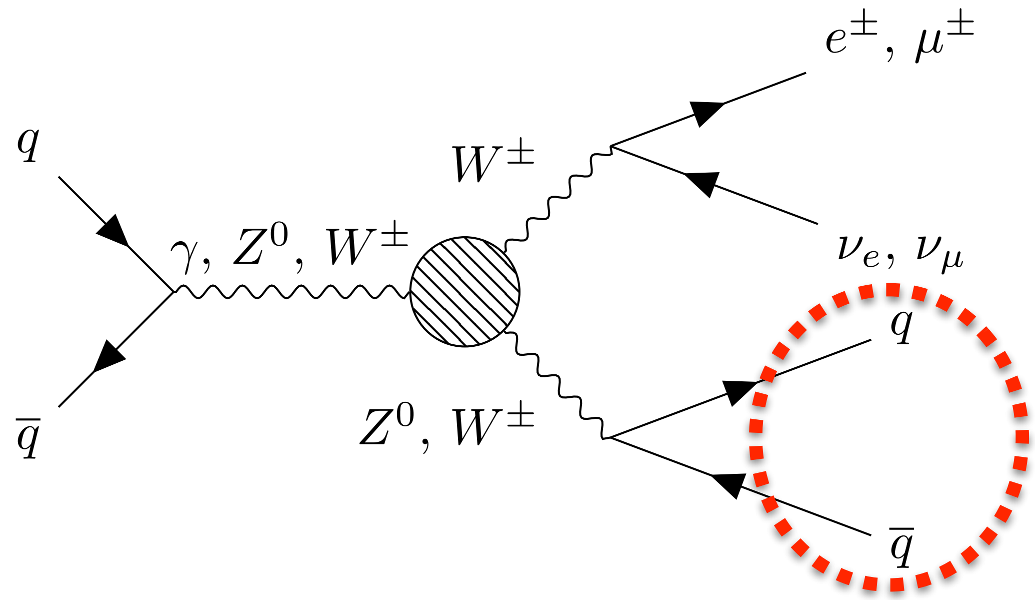
$$\sigma^{NLO\ QCD} = 15.0^{+0.7}_{-0.6}(PDF) \pm 0.2(scale)\ pb$$

ZZ→llll + jets

- σ(ZZ→llll) on the jet multiplicity and the kinematic properties of two p_T-leading jets
- provide an important test of the QCD corrections to ZZ production



WW/WZ→lν + jet



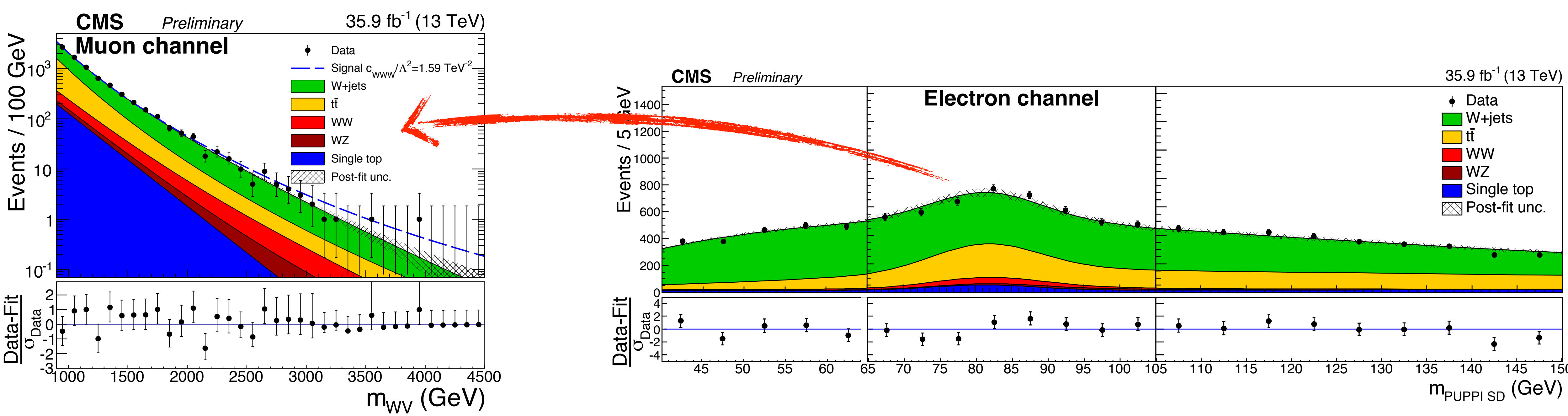
a single large-radius massive jet

	Electron channel		Muon channel	
	WW	WZ	WW	WZ
W+jets	1618 ± 66	1418 ± 57	2529 ± 99	2138 ± 83
$t\bar{t}$	600 ± 63	526 ± 56	1040 ± 106	938 ± 96
Single top quark	145 ± 16	97 ± 10	264 ± 25	185 ± 18
Diboson (SM)	144 ± 52	122 ± 52	265 ± 88	200 ± 79
Total expected (SM)	2507 ± 106	2163 ± 96	4098 ± 172	3461 ± 151
Diboson ($c_{WWW}/\Lambda^2 = 3.6\,\text{TeV}^{-2}$)	193 ± 15	185 ± 15	334 ± 26	287 ± 22
Diboson ($c_W/\Lambda^2 = 4.5\,\text{TeV}^{-2}$)	163 ± 14	154 ± 15	283 ± 23	237 ± 21
Diboson ($c_B/\Lambda^2 = 20\,\text{TeV}^{-2}$)	188 ± 21	144 ± 14	322 ± 33	221 ± 20
Data	2456	2235	3996	3572

- offers a good balance between efficiency at high p_T^V and purity
- improve the sensitivity to BSM signals
- major backgrounds: W+jets and tt
- WW and WZ final states are distinguished with the invariant mass of the jet and the jet substructure techniques so that different aTGC contributions (WWγ and WWZ) are discriminated

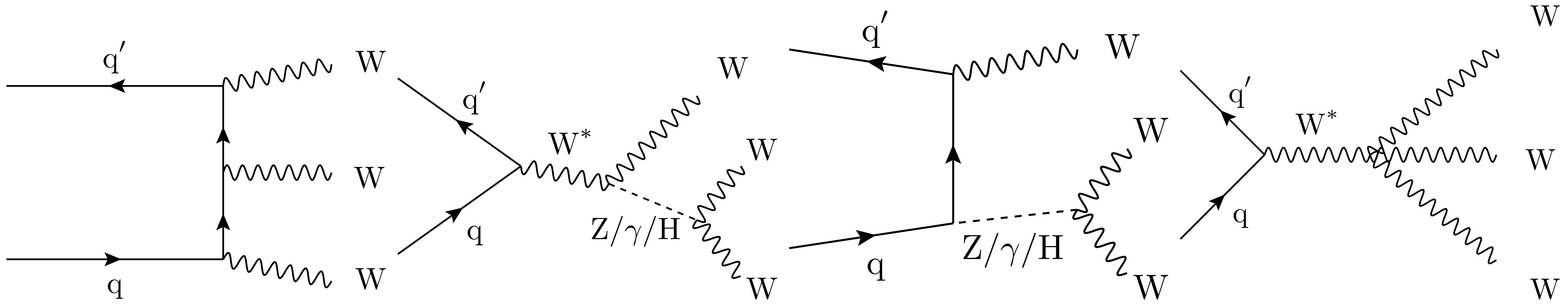
WW/WZ→lν + jet: aTGC

- focus on possible additional contributions by dim-6 operators
- limits are set with the mass of the resulting jet and M_{WV}
- most strictest bounds from direct measurements so far

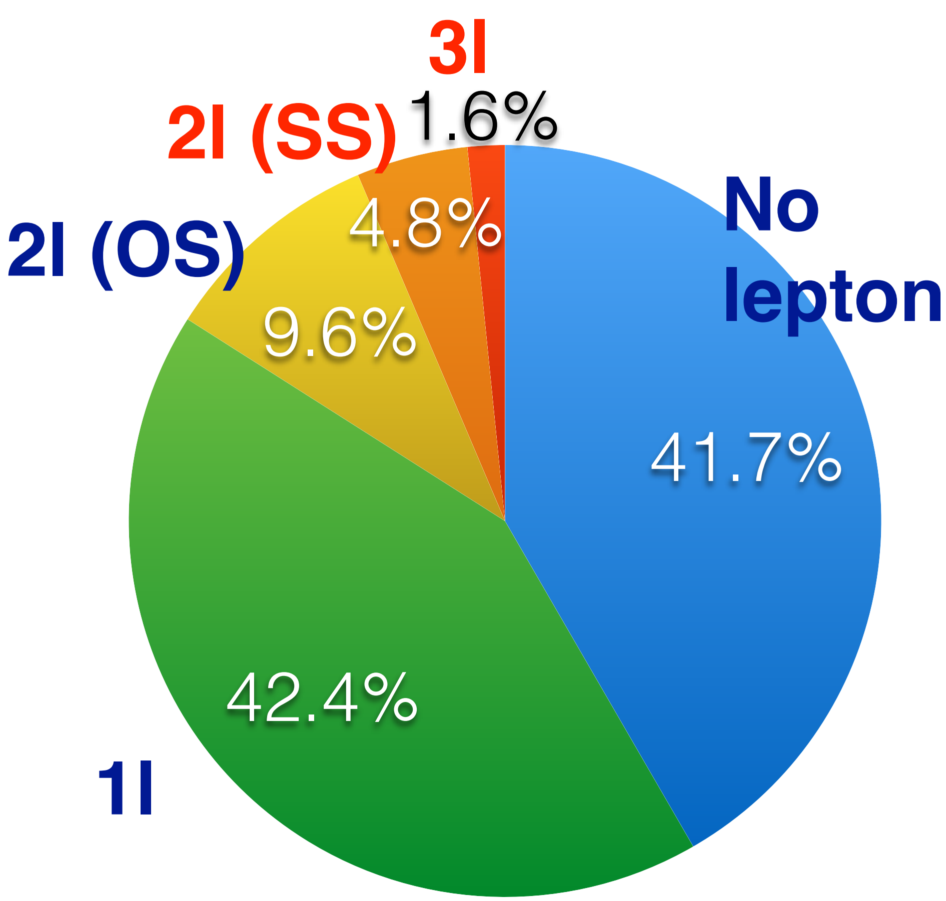


Parametrization	aTGC	Expected limit	Observed limit	Run I limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	[-14, 17]

WWW



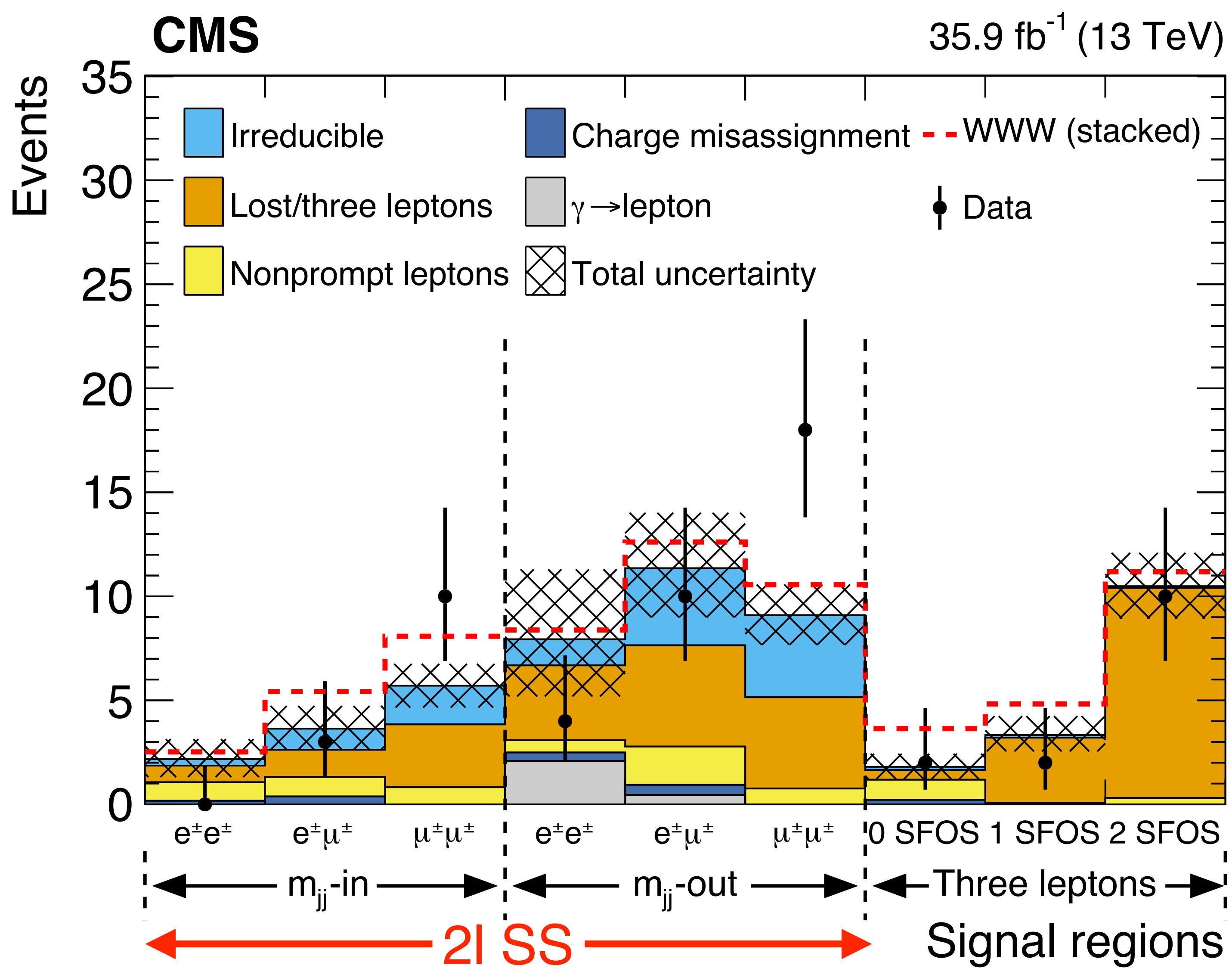
QED radiation | Higgs gauge coupling | Triple gauge coupling | Quartic gauge coupling



classification bases on the number of e or μ

- search for non-resonant WWW production (216±9 fb @ NLO) and WH→WWW* → σ^{tot} = 509±13 fb
- look into 2 SS leptons and 3l category
  - further divided into 9 signal regions depending on lepton flavor and dijet mass, and lepton flavor and charge
- focus on aQGCs as the constraints on aTGCs cannot be improved

WWW: inclusive cross section



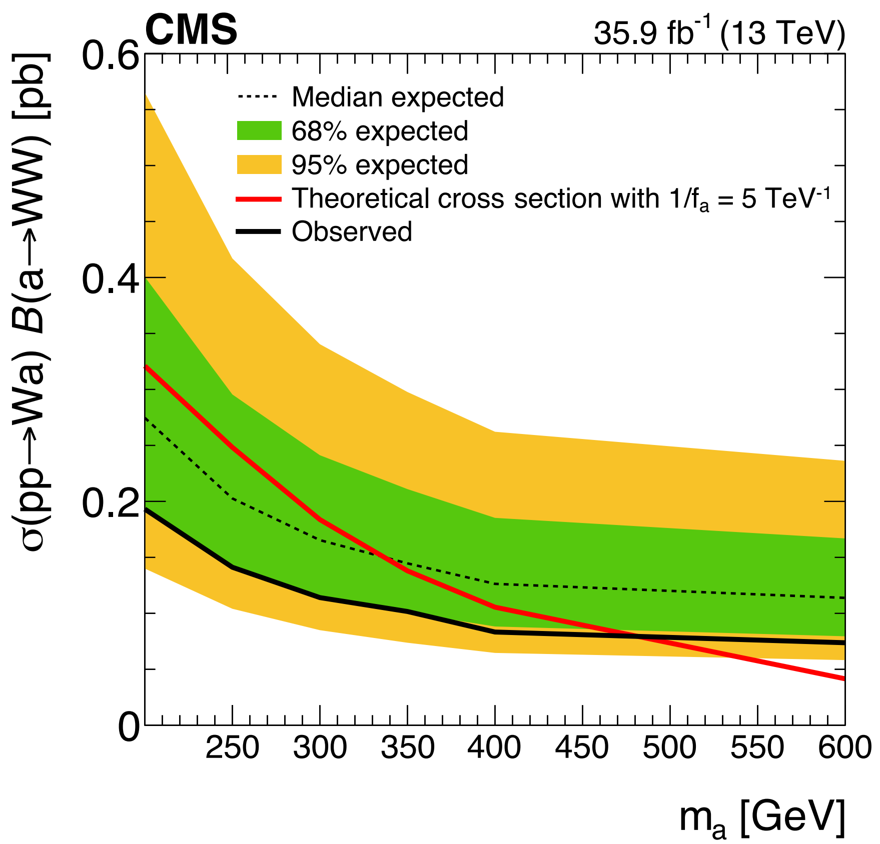
- significance : 0.6σ (obs.) and 1.78σ (exp.), assuming SM rate
- $\mu^{observed} = 0.34^{+0.62}_{-0.34} \quad \sigma^{measured} = 173^{+326}_{-173}\ fb$

WWW: aQGC & limits on BSM physics

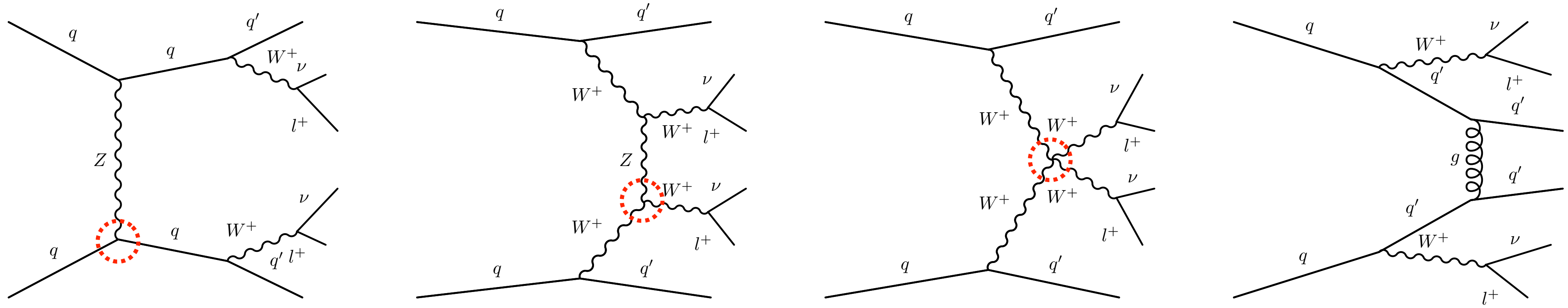
- focus on f_j of the dim-8 operators
- limits on aQGC are set with S_T, scalar sum of p_T of final state particles

Anomalous coupling	Allowed range (TeV^{-4}) Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

- limits on the production of axionlike particles (a→WW) in association with a W
- 200 < m_a < 480 GeV are excluded with $1/f_a = 5\ TeV^{-1}$



WW VBS



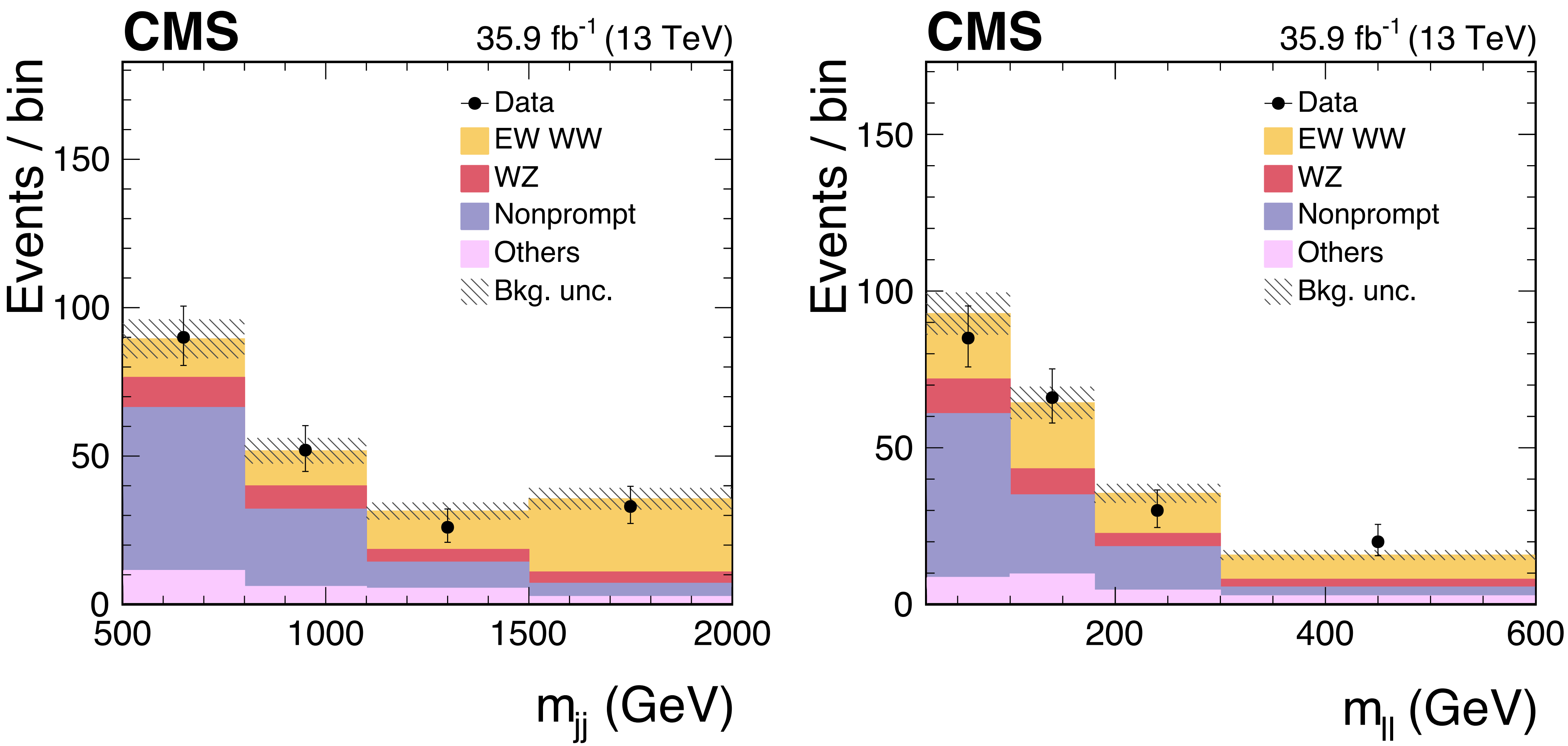
Electroweak-induced SS WW production

QCD-induced background

- the largest ratio of EW to QCD production comparing to other VBS processes
- signal：electroweak production of two SS charged leptons ($e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$) and two jets with a large $\Delta\eta_{jj}$ and m_{jj}
- major backgrounds：
  non-prompt lepton events, WZ

Data	201
Signal + total background	205 ± 13
Signal	66.9 ± 2.4
Total background	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD *WW*	4.8 ± 0.4
$W\gamma$	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

WW VBS: first observation



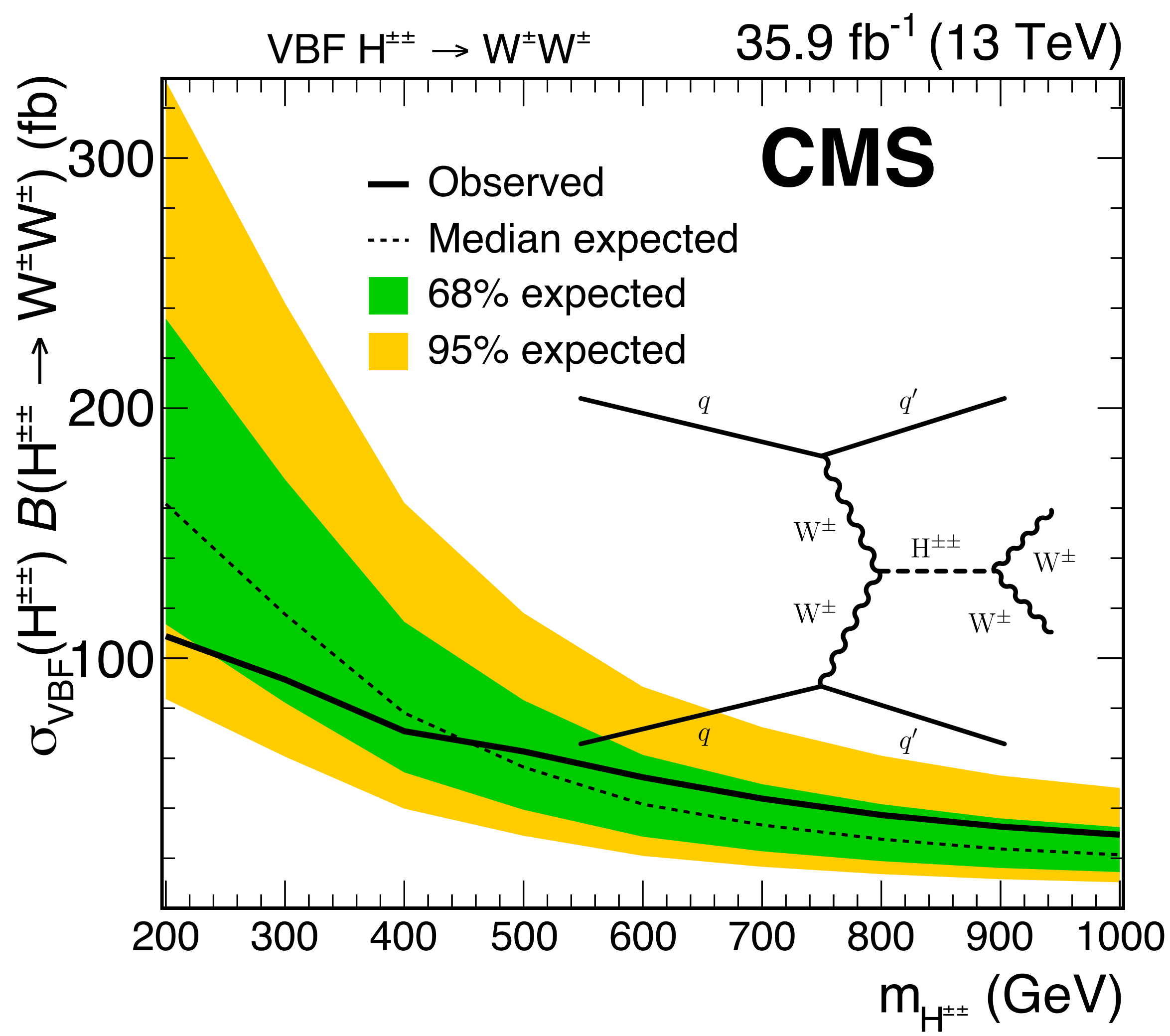
- significance : 5.5σ (obs.); 5.7σ (exp.) → first observation of EW $W^{\pm}W^{\pm}jj$
- $\sigma_{fid} = 3.83 \pm 0.66(stat) \pm 0.35(syst)\, fb$ (statistically dominated)
- $\sigma^{LO} = 4.25 \pm 0.27(scale + PDF)\, fb$

WW VBS: aQGC & limits on $H^{\pm\pm}$

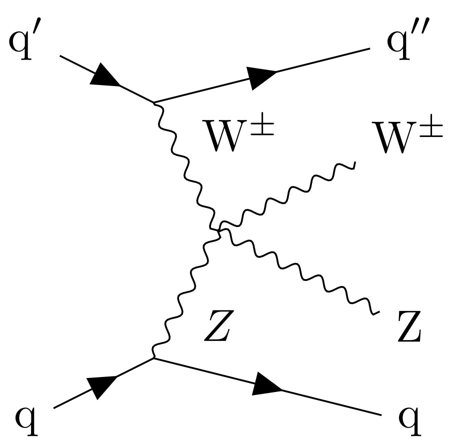
- focus on dim-8 operators
- limits are set with m_{ll} and improved by a factor up to 6 w.r.t. previous results

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

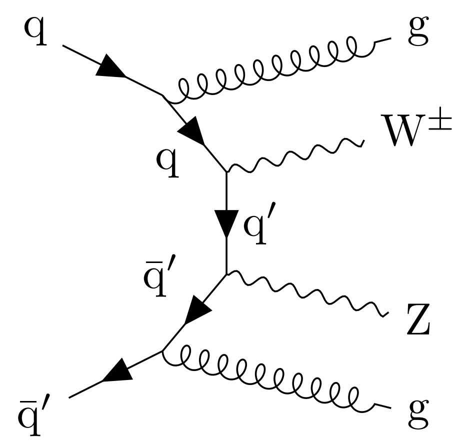
- limits on $\sigma \times BF$ for VBF production of $H^{\pm\pm}$



WZ VBS



Electroweak-induced

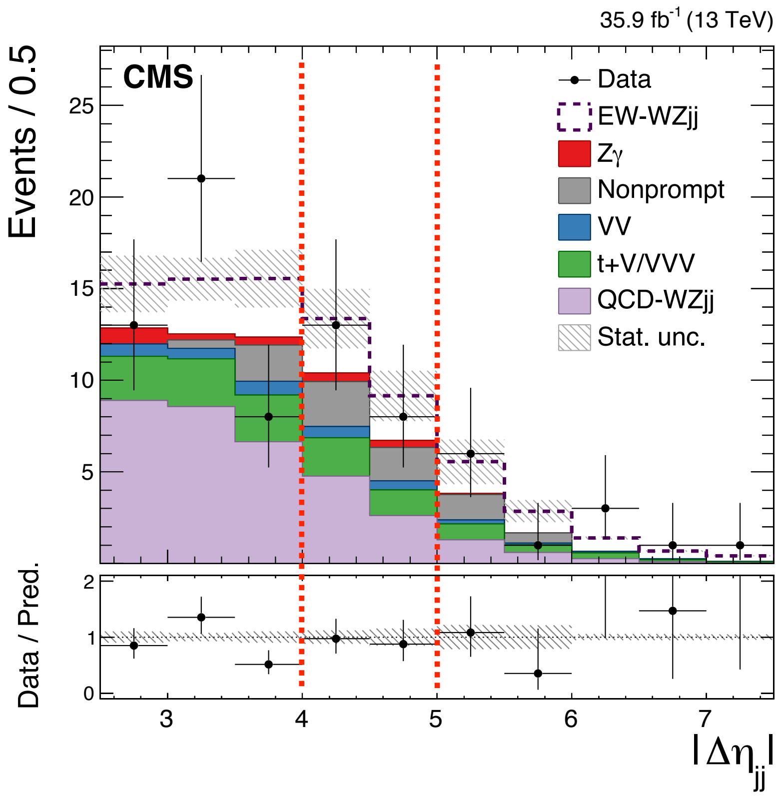


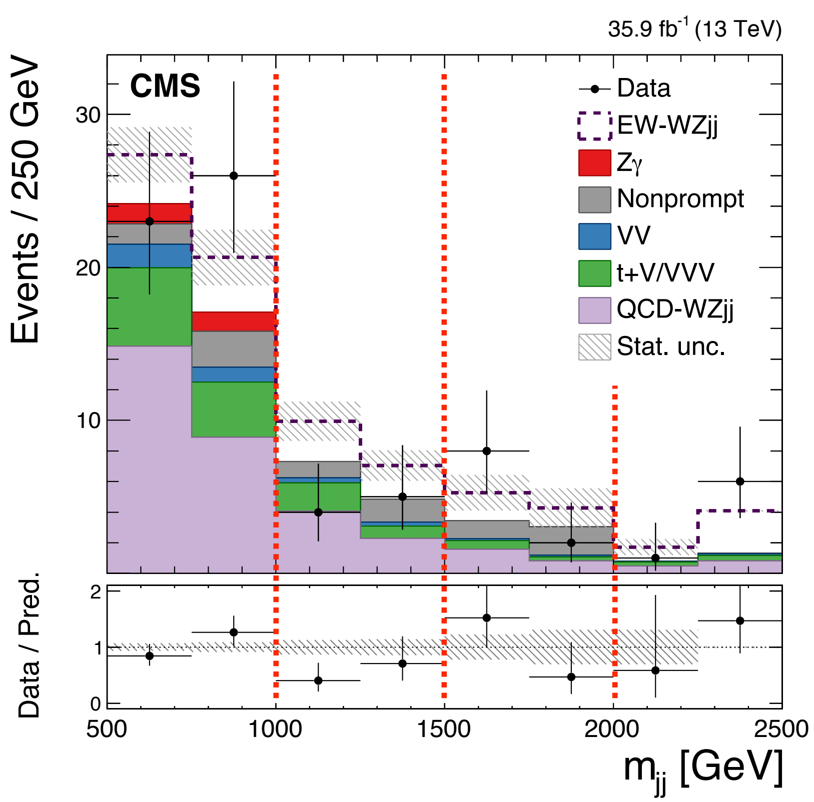
QCD-induced production

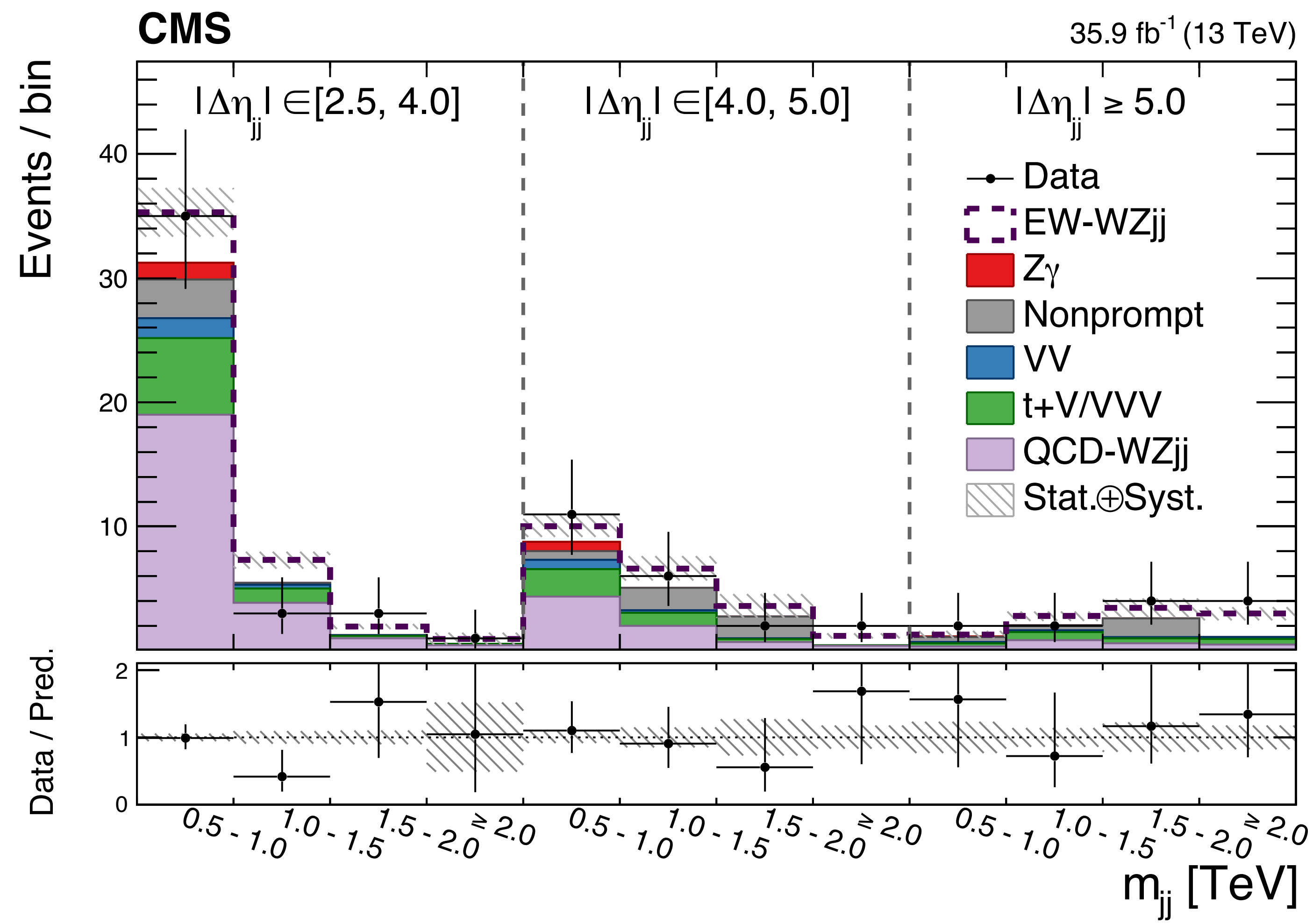
Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total yield
QCD WZ	13.5 ± 0.8	9.1 ± 0.5	6.8 ± 0.4	4.6 ± 0.3	34.1 ± 1.1
t+V/VVV	5.6 ± 0.4	3.1 ± 0.2	2.5 ± 0.2	1.7 ± 0.1	12.9 ± 0.5
Nonprompt	5.2 ± 2.0	2.4 ± 0.9	1.5 ± 0.6	0.7 ± 0.3	9.9 ± 2.3
VV	0.8 ± 0.1	1.6 ± 0.2	0.4 ± 0.0	0.7 ± 0.1	3.5 ± 0.2
$Z\gamma$	<0.1	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

- $WZ \rightarrow lll\nu$ ($l = e, \mu$), 2 jets with a large $\Delta\eta_{jj}$ and m_{jj}
- less clean signature than $W^{\pm}W^{\pm}jj$
- major backgrounds: QCD-induced production, t+V/VVV

WZ VBS: inclusive cross sections



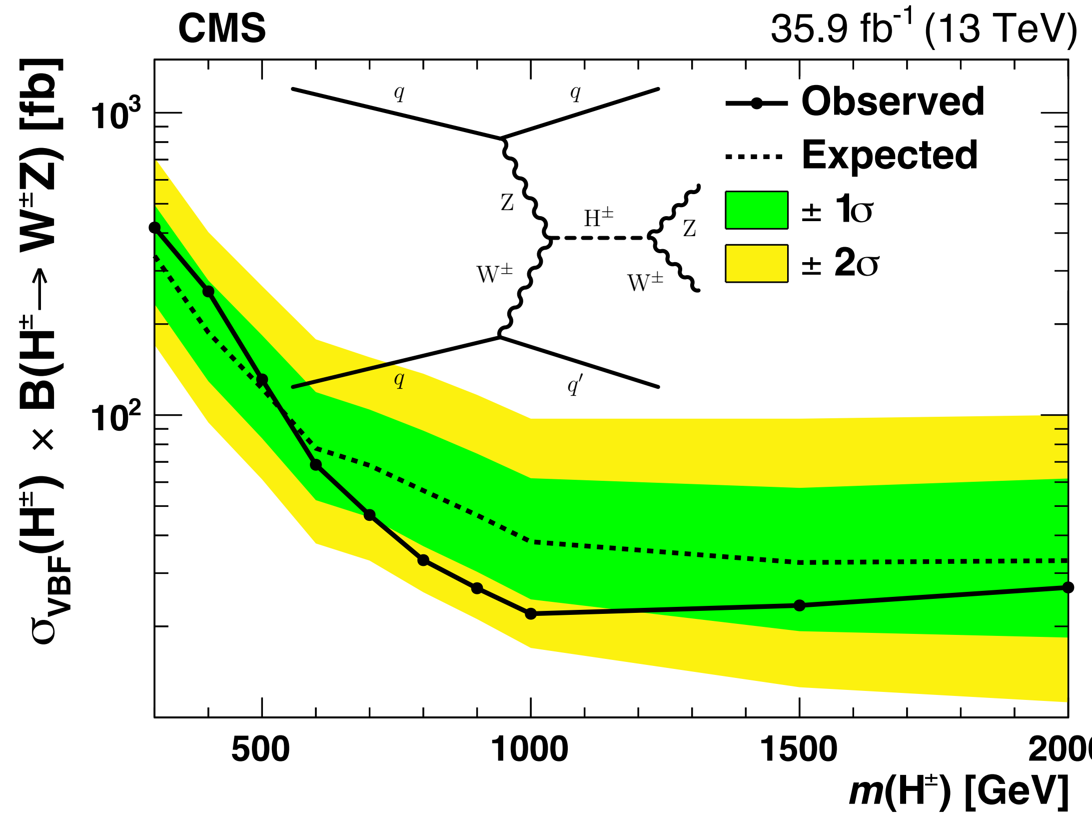


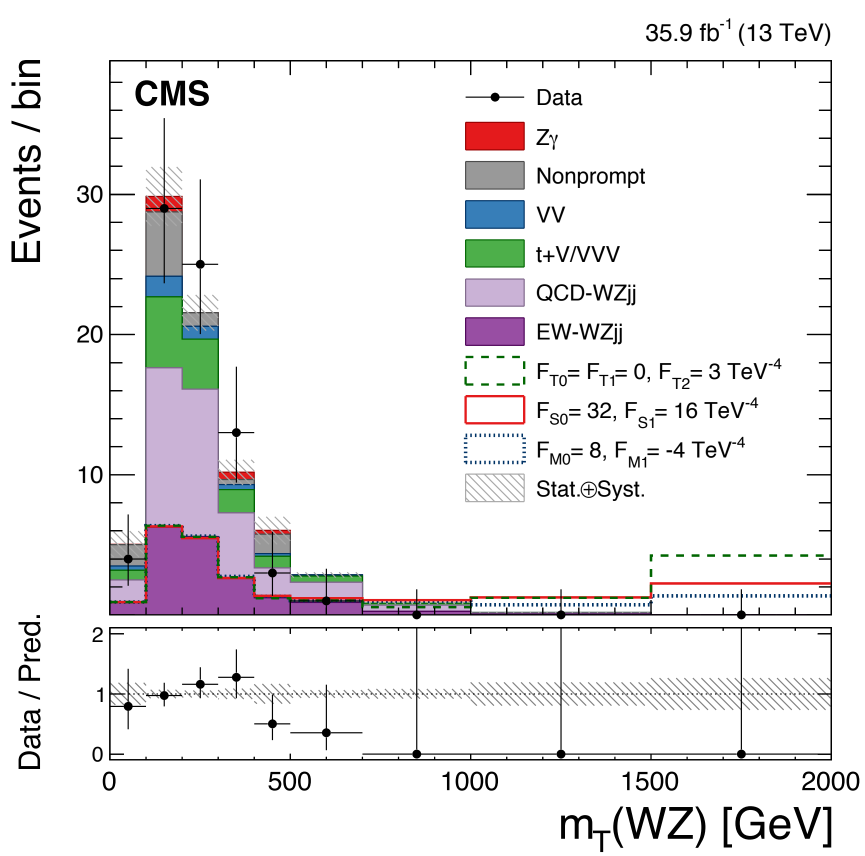


- $\sigma^{fid}_{WZjj} = 3.18^{+0.57}_{-0.52}\ (stat)\ ^{+0.43}_{-0.36}(syst)\ fb$
- $\sigma^{LO}_{WZjj} = 3.27^{+0.39}_{-0.32}\ (scale)\ \pm 0.15\ (PDF)\ fb$
- $\mu^{EW} = 0.82^{+0.51}_{-0.43}$
- significance of EW WZjj：2.2σ (obs.) 2.5σ (exp.)

WZ VBS: aQGC & limits on H±

- aQGCs are constrained with $m_T(WZ)$
- limits on $\sigma \times BF$ for VBF production of H±





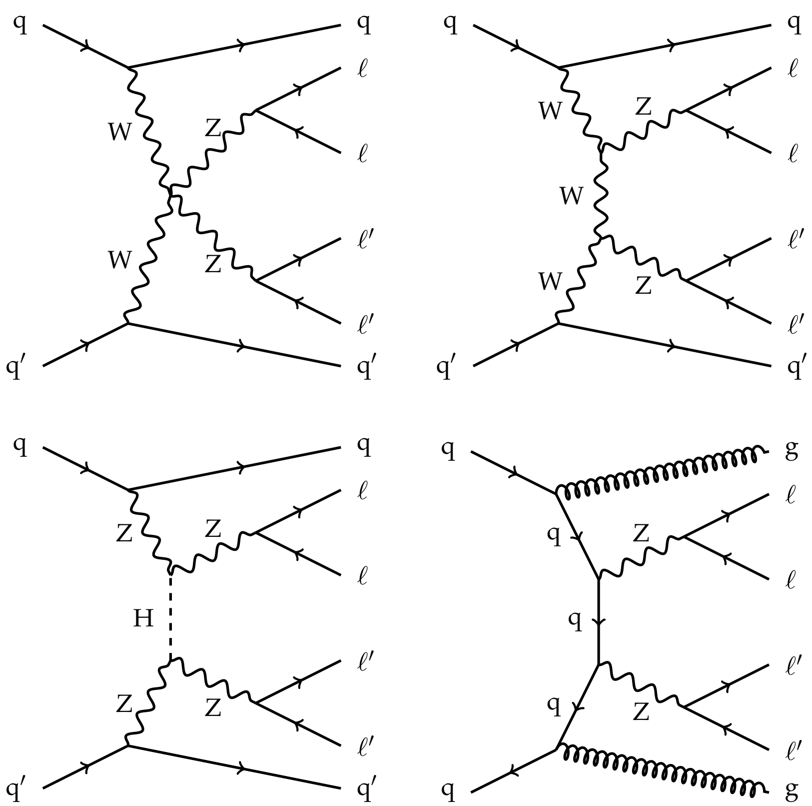
Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	$[-11.2, 11.6]$	$[-9.15, 9.15]$
f_{M1}/Λ^4	$[-10.9, 11.6]$	$[-9.15, 9.45]$
f_{S0}/Λ^4	$[-32.5, 34.5]$	$[-26.5, 27.5]$
f_{S1}/Λ^4	$[-50.2, 53.2]$	$[-41.2, 42.8]$
f_{T0}/Λ^4	$[-0.87, 0.89]$	$[-0.75, 0.81]$
f_{T1}/Λ^4	$[-0.56, 0.60]$	$[-0.49, 0.55]$
f_{T2}/Λ^4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

f_{M0}, f_{M1}: involve a mixture of gauge and Higgs field interactions

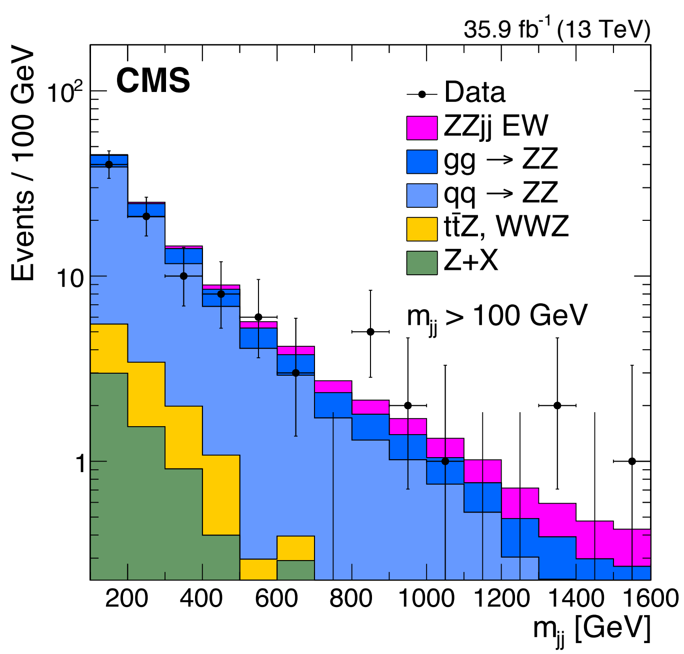
f_{S0}, f_{S1}: involve interactions with the Higgs field

f_{T0}, f_{T1}, f_{T2}: purely from the SU(2) gauge fields

ZZ VBS (1/2)

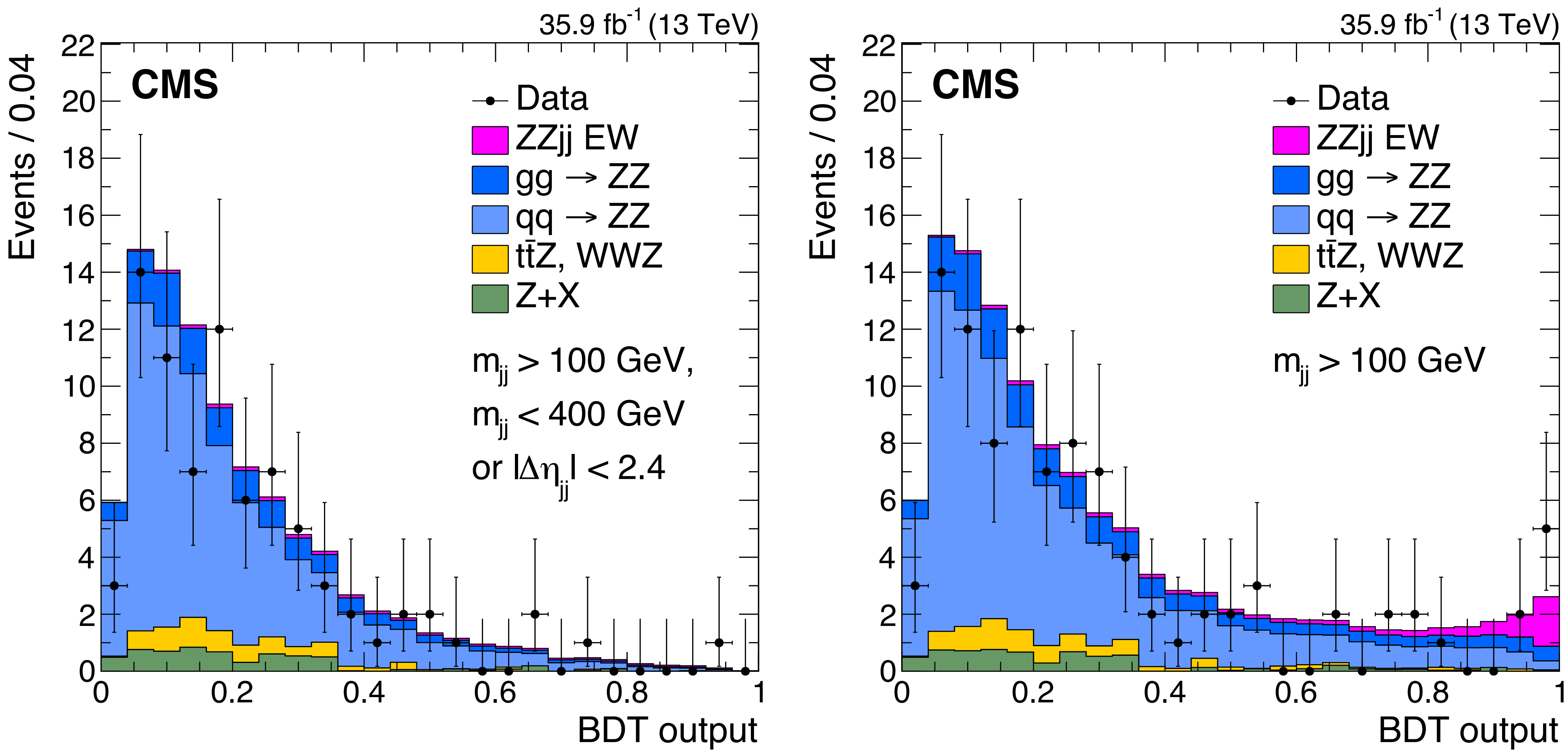


QCD-induced background



- fully leptonic final state ZZ→llll (l = e, μ)
- low σ, small BR, large irreducible QCD background → all final state particles can be reconstructed → favorable for EWSB study
- clean leptonic final state → small reducible background
- provide the precise understanding of the scattering energy
- the spin correlations of reconstructed fermions permit the extraction of the longitudinal contribution to VBS

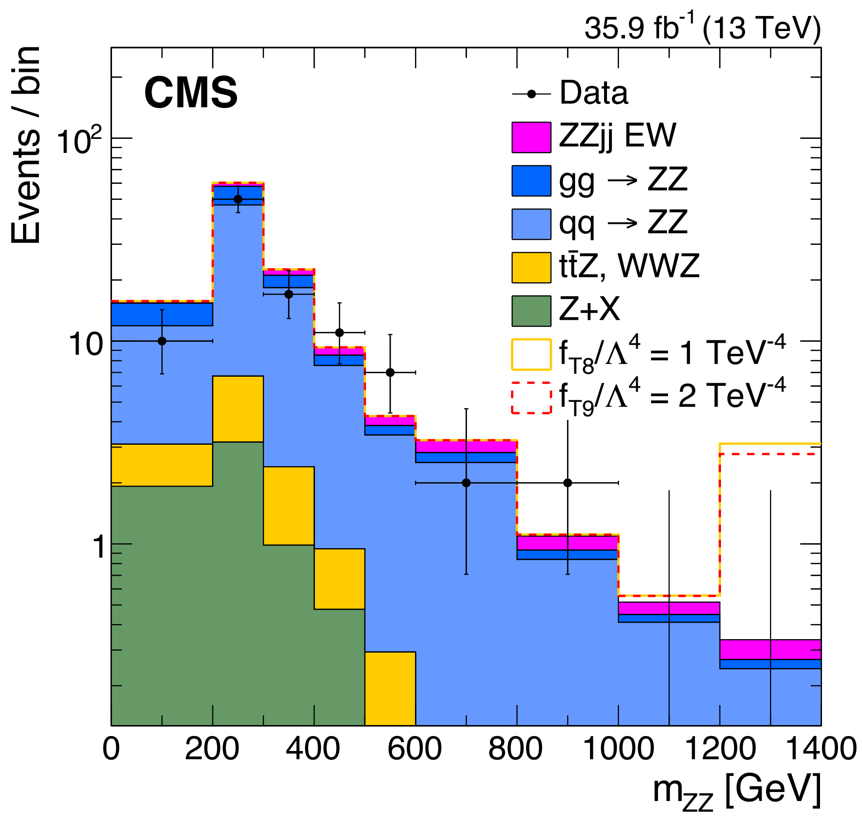
ZZ VBS (2/2)



- BDT used to separate EW- and QCD-induced production
- $\sigma_{ZZjj}^{fid} = 0.40^{+0.21}_{-0.16}\ (stat)\ ^{+0.13}_{-0.09}(syst)\ fb$
- $\sigma_{ZZjj}^{LO} = 0.29^{+0.02}_{-0.03}\ fb$
- significance of EW ZZjj：2.7σ (obs.) 1.6σ (exp.)

ZZ VBS: aQGC

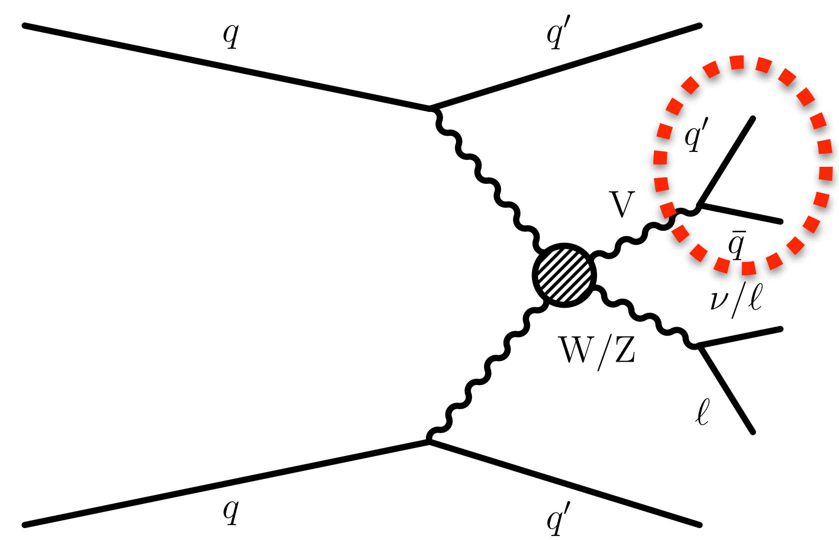
- M_{ZZ} is used to constrain the aQGCs
- the results are statistically limited so far



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

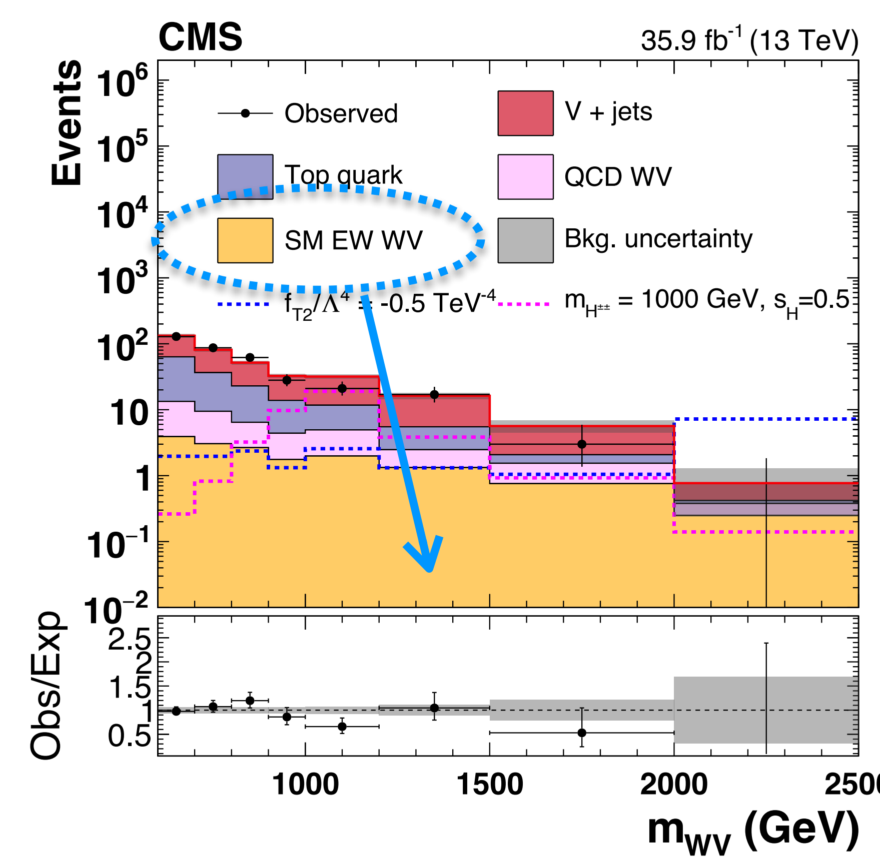
involve U(1) fields only accessible via the final state of neutral gauge bosons

WV, ZV VBS (V=W,Z)



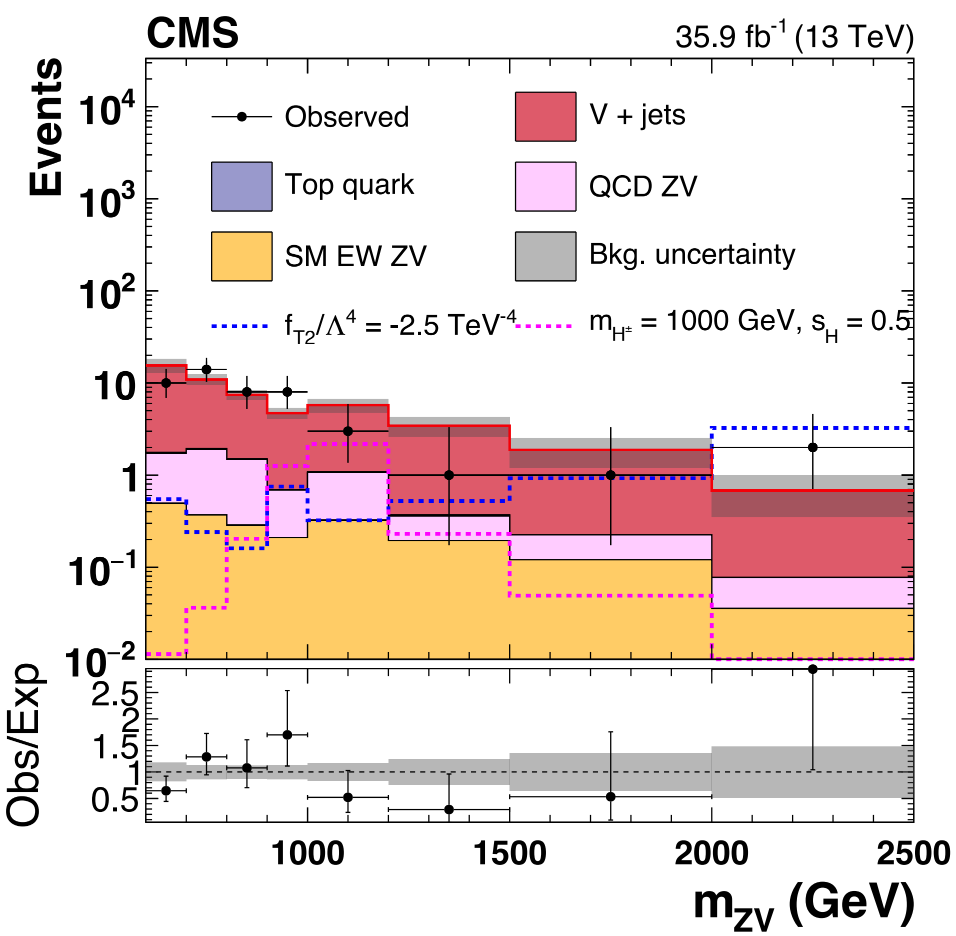
- WV→lν + a large radius jet
- ZV→ll + a large radius jet
- p_T^{jet} > 200 GeV
- sensitivity is enhanced by requiring tight dijet selections and centrality of leptonically decayed W/Z
- major backgrounds：V+jets and tt (for WV)
- not sensitive to SM yet

Final state	WV	ZV
Data	347	47
V+jets	196 ± 14	42.6 ± 6.1
Top quark	113 ± 15	0.14 ± 0.04
QCD VV	27 ± 8	5.5 ± 1.9
SM EW VV	16 ± 2	2.0 ± 0.4
Total bkg.	352 ± 19	50.3 ± 5.8

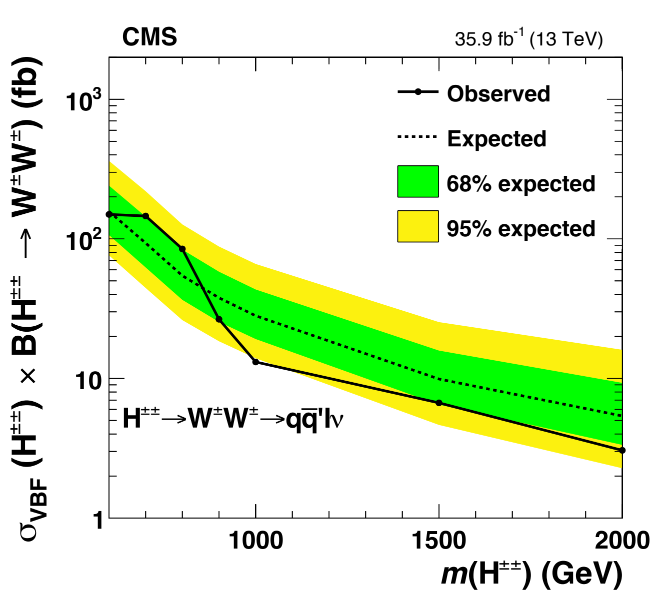


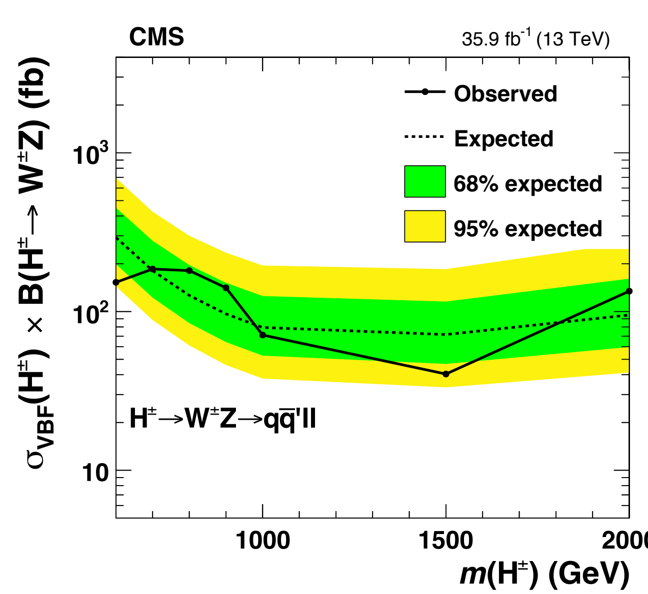
WV, ZV VBS (V=W,Z): aQGC & limits on $H^{\pm}$, $H^{\pm\pm}$

- M_{WV} and M_{ZV} are used to constrain aQGCs
- stringent limits are set and improve the results with fully leptonic final state by factors of up to seven
- limits on VBF produced charged Higgs boson extend the previous CMS results to higher mass region



	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	$[-2.7, 2.7]$	$[-4.2, 4.2]$	$[-40, 40]$	$[-31, 31]$	$[-2.7, 2.7]$	$[-4.2, 4.2]$
f_{S1}/Λ^4	$[-3.3, 3.4]$	$[-5.2, 5.2]$	$[-32, 32]$	$[-24, 24]$	$[-3.4, 3.4]$	$[-5.2, 5.2]$
f_{M0}/Λ^4	$[-0.69, 0.69]$	$[-1.0, 1.0]$	$[-7.5, 7.5]$	$[-5.3, 5.3]$	$[-0.69, 0.70]$	$[-1.0, 1.0]$
f_{M1}/Λ^4	$[-2.0, 2.0]$	$[-3.0, 3.0]$	$[-22, 23]$	$[-16, 16]$	$[-2, 0, 2.1]$	$[-3.0, 3.0]$
f_{M6}/Λ^4	$[-1.4, 1.4]$	$[-2.0, 2.0]$	$[-15, 15]$	$[-11, 11]$	$[-1.3, 1.3]$	$[-1.4, 1.4]$
f_{M7}/Λ^4	$[-3.4, 3.4]$	$[-5.1, 5.1]$	$[-35, 36]$	$[-25, 26]$	$[-3.4, 3.4]$	$[-5.1, 5.1]$
f_{T0}/Λ^4	$[-0.12, 0.11]$	$[-0.17, 0.16]$	$[-1.4, 1.4]$	$[-1.0, 1.0]$	$[-0.12, 0.11]$	$[-0.17, 0.16]$
f_{T1}/Λ^4	$[-0.12, 0.13]$	$[-0.18, 0.18]$	$[-1.5, 1.5]$	$[-1.0, 1.0]$	$[-0.12, 0.13]$	$[-0.18, 0.18]$
f_{T2}/Λ^4	$[-0.28, 0.28]$	$[-0.41, 0.41]$	$[-3.4, 3.4]$	$[-2.4, 2.4]$	$[-0.28, 0.28]$	$[-0.41, 0.41]$



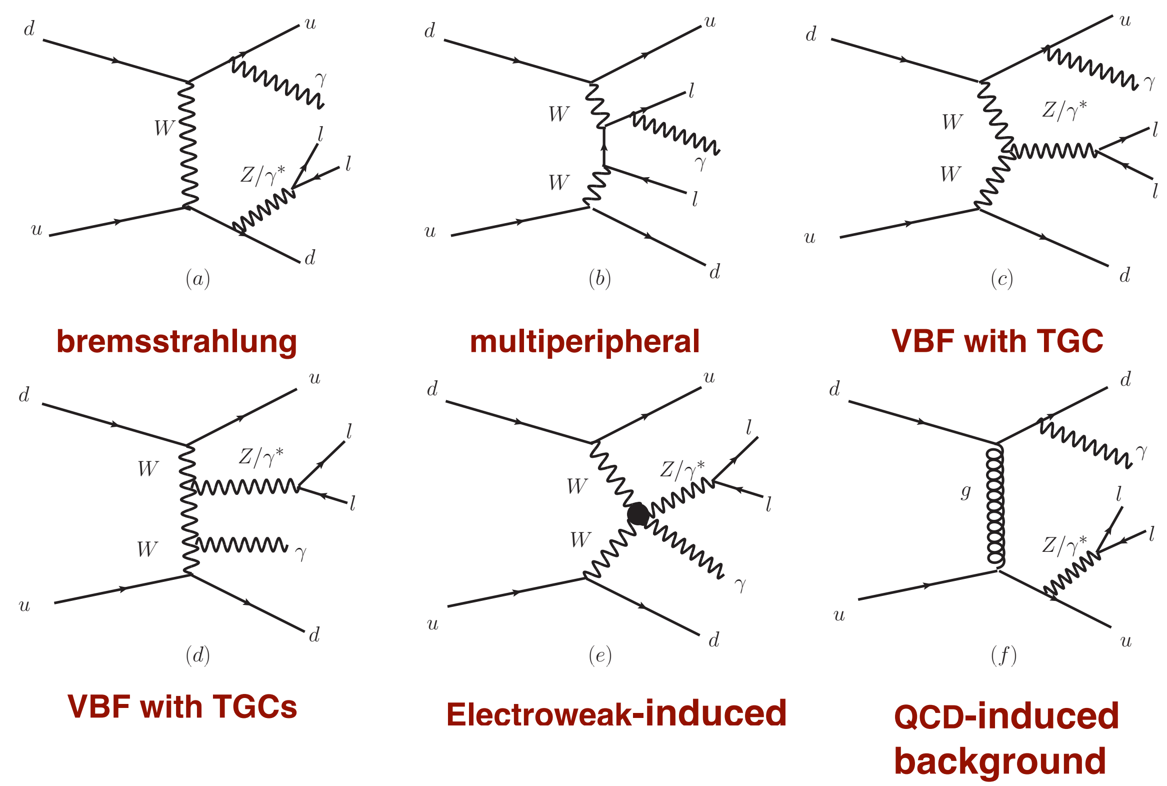


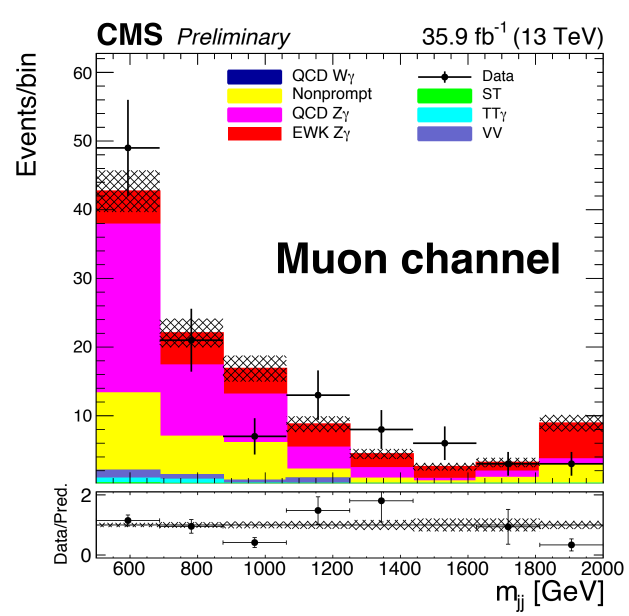
Zγ VBS

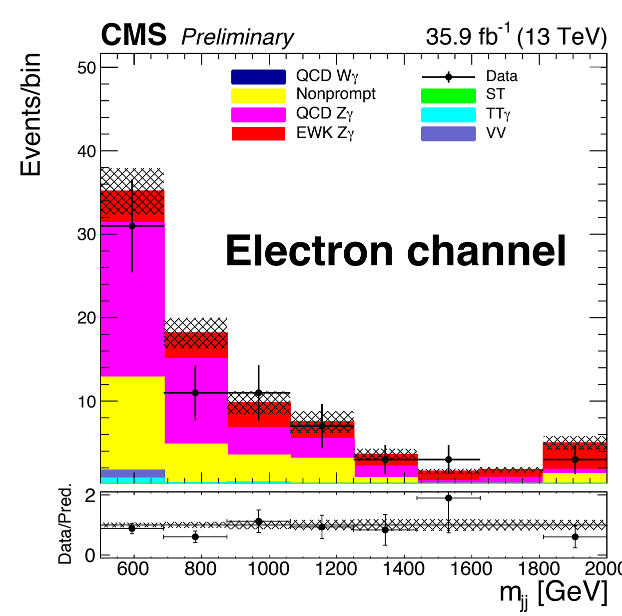
- Zγ→llγ (l=e,μ), p_T^{γ} > 20 GeV
- major backgrounds：QCD Zγjj and Z+jets (fake photon) events

Run-I	ATLAS	CMS
obs.	2.0σ	3.0σ
exp.	1.8σ	2.1σ

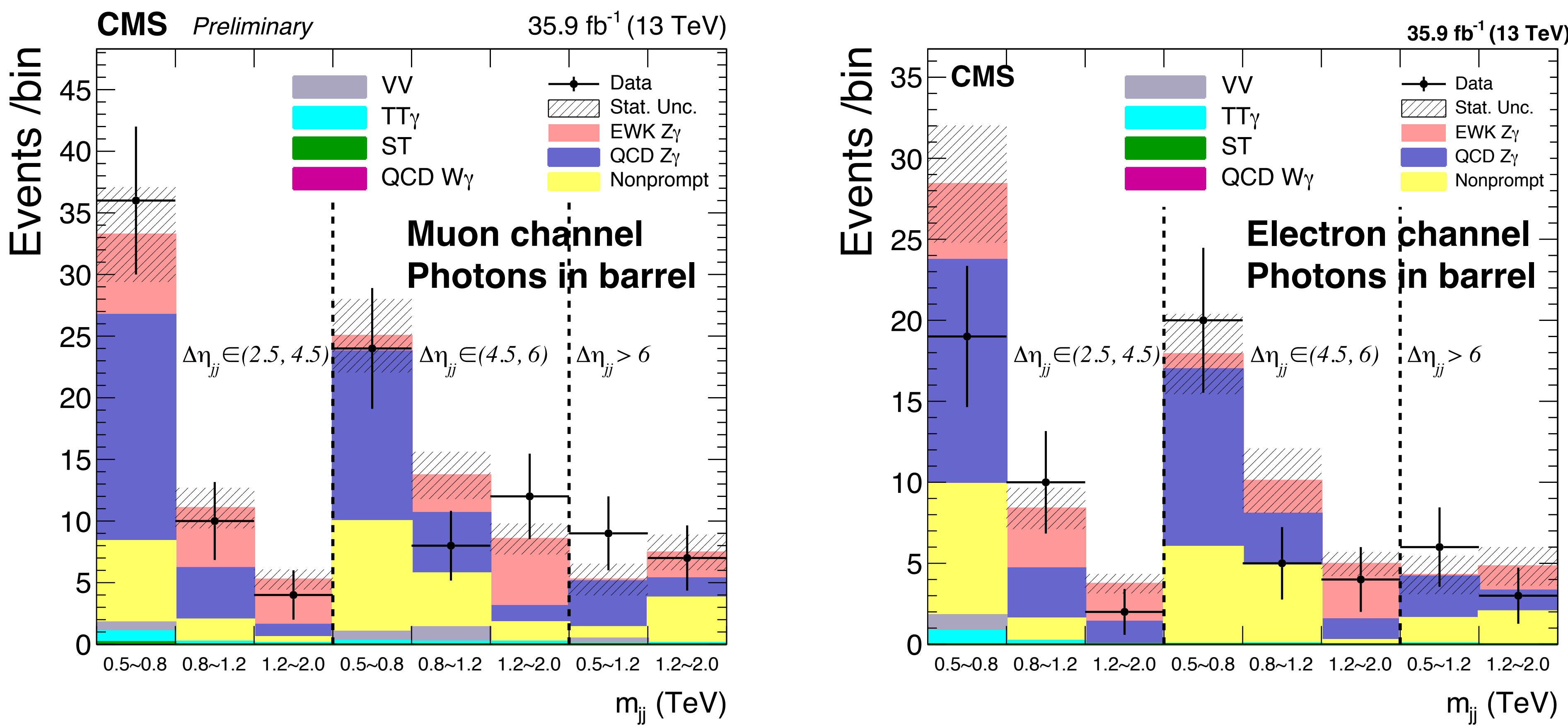
	muon channel	electron channel
Nonprompt photon	47.6 ± 4.5	39.3 ± 4.0
Other background	7.4 ± 1.4	2.7 ± 0.8
QCD $Z\gamma$jj	62.9 ± 3.1	49.6 ± 2.7
EW $Z\gamma$jj	36.5 ± 0.7	25.4 ± 0.6
Total background	117.9 ± 5.6	91.6 ± 4.8
Data	172 ± 13	113 ± 11







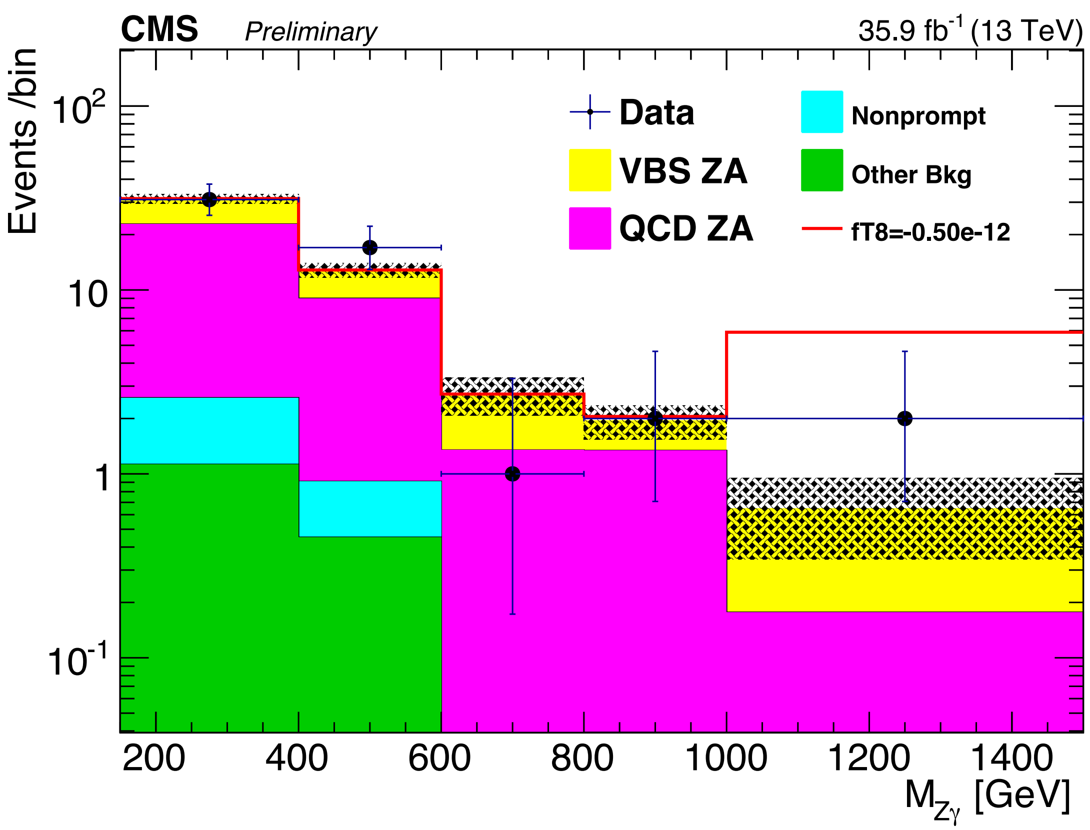
Zγ VBS: inclusive cross sections



- $\sigma^{fid}_{EW} = 3.20 \pm 1.00(stat) \pm 0.57(syst) \pm 0.07(lumi)\ fb\ (\mu^{EW} = 0.64^{+0.23}_{-0.21})$
- significance：3.9σ (obs.) 5.2σ (exp.) [2016]
- significance：4.7σ (obs.) 5.5σ (exp.) [Run1+2016]
- $\sigma^{fid}_{EW+QCD} = 15.07 \pm 1.15(stat) \pm 2.06(syst) \pm 0.44(lumi)\ fb\ (\mu_{EW+QCD} = 0.96^{+0.15}_{-0.13})$

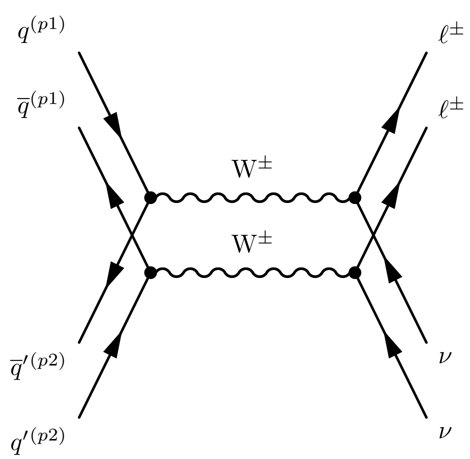
Zγ VBS: aQGC

- limits on aQGCs are extracted with $M_{Z\gamma}$
- the results are competitive or more stringent than previous constraints

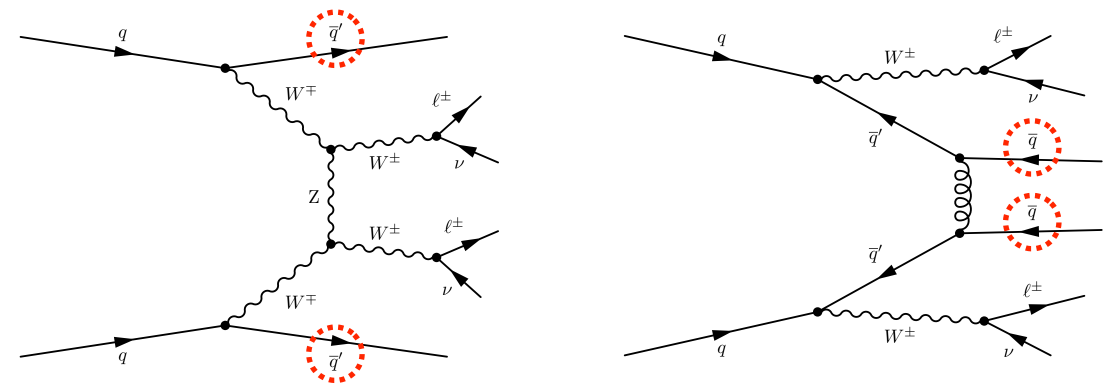


Observed Limits (TeV^{-4})	Expected Limits (TeV^{-4})
$-19.3 < F_{M,0}/\Lambda^4 < 20.2$	$-15.0 < F_{M,0}/\Lambda^4 < 15.1$
$-47.8 < F_{M,1}/\Lambda^4 < 46.9$	$-30.1 < F_{M,1}/\Lambda^4 < 30.0$
$-8.16 < F_{M,2}/\Lambda^4 < 8.04$	$-6.09 < F_{M,2}/\Lambda^4 < 6.06$
$-20.9 < F_{M,3}/\Lambda^4 < 21.1$	$-13.2 < F_{M,3}/\Lambda^4 < 13.3$
$-15.2 < F_{M,4}/\Lambda^4 < 15.8$	$-11.7 < F_{M,4}/\Lambda^4 < 11.7$
$-24.9 < F_{M,5}/\Lambda^4 < 24.4$	$-19.1 < F_{M,5}/\Lambda^4 < 18.2$
$-38.6 < F_{M,6}/\Lambda^4 < 40.5$	$-30.0 < F_{M,6}/\Lambda^4 < 30.1$
$-60.8 < F_{M,7}/\Lambda^4 < 62.6$	$-46.1 < F_{M,7}/\Lambda^4 < 46.3$
$-0.74 < F_{T,0}/\Lambda^4 < 0.69$	$-0.56 < F_{T,0}/\Lambda^4 < 0.51$
$-1.16 < F_{T,1}/\Lambda^4 < 1.15$	$-0.73 < F_{T,1}/\Lambda^4 < 0.72$
$-1.96 < F_{T,2}/\Lambda^4 < 1.85$	$-1.48 < F_{T,2}/\Lambda^4 < 1.37$
$-0.70 < F_{T,5}/\Lambda^4 < 0.74$	$-0.51 < F_{T,5}/\Lambda^4 < 0.57$
$-1.64 < F_{T,6}/\Lambda^4 < 1.67$	$-1.23 < F_{T,6}/\Lambda^4 < 1.26$
$-2.59 < F_{T,7}/\Lambda^4 < 2.80$	$-1.91 < F_{T,7}/\Lambda^4 < 2.12$
$-0.47 < F_{T,8}/\Lambda^4 < 0.47$	$-0.36 < F_{T,8}/\Lambda^4 < 0.36$
$-1.26 < F_{T,9}/\Lambda^4 < 1.27$	$-0.95 < F_{T,9}/\Lambda^4 < 0.95$

WW from double parton scattering (1/2)



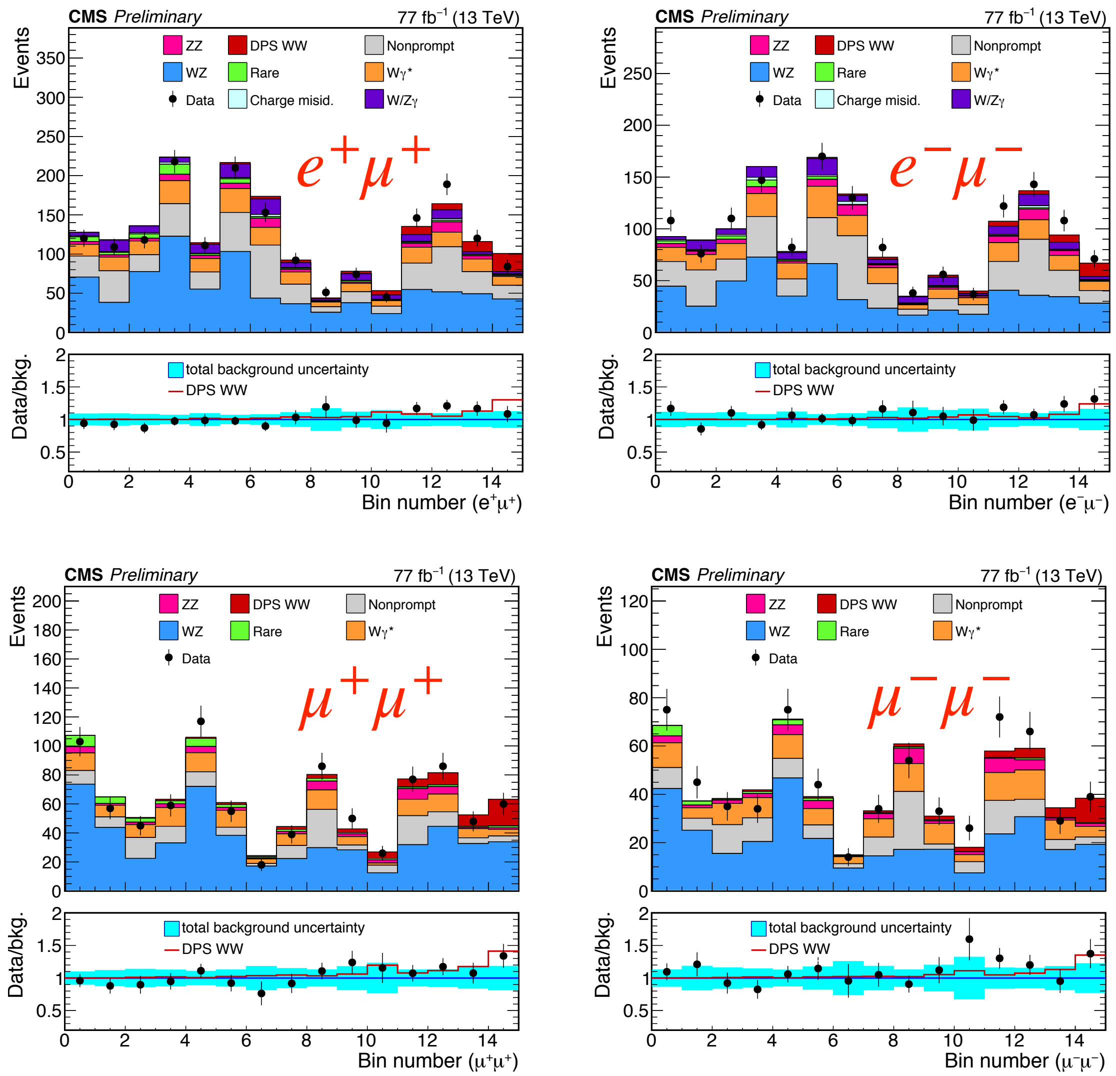
DPS

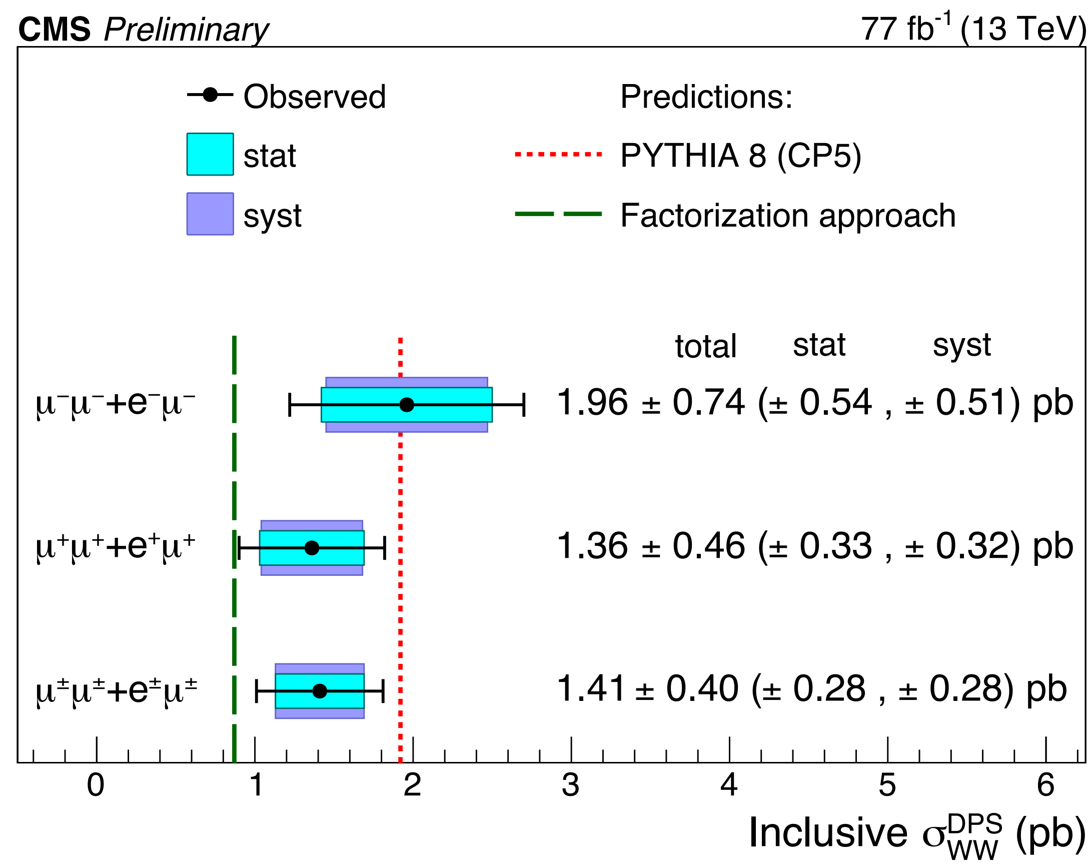


background: Single hard scattering (SHS)

- useful information on the parton distribution inside the proton in the transverse direction and on the correlations between them
- $W^{\pm}W^{\pm}$ in $\mu^{+}\mu^{+}, \mu^{-}\mu^{-}, e^{+}\mu^{+}, e^{-}\mu^{-}$ final states → allow for an accurate study
- background：SS WW with SHS with additional jets suppressed by the requirement on number of jets
- very wide range of predictions ($\sigma^{PYTHIA8} = 1.92\ pb$, $\sigma^{factorized} = 0.87\ pb$) → measurements are crucial for improving the theoretical understanding

WW from double parton scattering (2/2)





- major backgrounds from WZ, non-prompt lepton (W+jets, QCD), and Wγ*
- observed significance: 3.9σ → first evidence of DPS WW process
- $\sigma^{measured} = 1.41 \pm 0.28\ (stat) \pm 0.28\ (syst)\ pb$

Summary

- the cross sections of multiboson processes are measured over 5 orders of magnitude
  - the measurements of inclusive and differential cross section are pushing for more precise theoretical calculations
- first observation of the electroweak diboson production (SS WW) with 2016 data
- new results on Zγ VBS with 2016 data
- significant improvement on the sensitivity of indirect search for new physics
- also set limits on BSM physics
- future prospects: more differential cross sections and observations to come, more unexplored productions to probe, anomalous couplings to combine