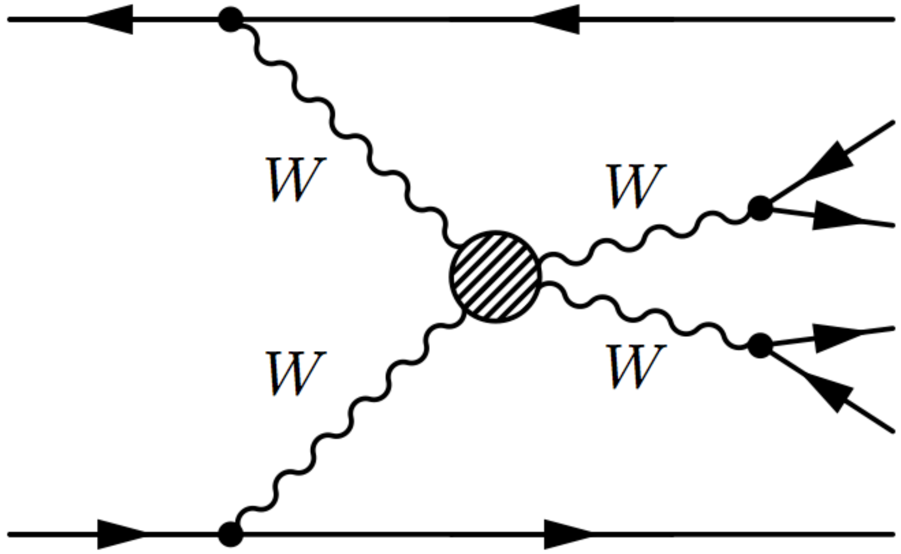
Electroweak Physics In Multiboson Final States

Jakob Salfeld-Nebgen on behalf of the CMS Collaboration

CERN LHC Seminar, Oct. 23rd, 2018



Outline

- **Introduction:**
  - **Non-abelian gauge structure, Experimental test for TGC**
  - **EW Gauge Structure and the Higgs, Lee-Quigg-Thacker**
  - **Effective Field Theory, aQGC and aTGC**

- **Experimental Status**
- **Triple Gauge Couplings:**
  - **Inclusive WZ production**
  - **Inclusive ZZ production**
- **Quartic Gauge Couplings:**
  - **EW dijet associated WZ production**
  - **EW dijet associated $W^{\pm}W^{\pm}$ production**
  - **EW dijet associated ZZ production**

SM Non-Abelian Structure

- **Standard Model of particle physics is a Gauge Theory**

$$\mathcal{L} = \boxed{-\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu}}$$

- Gauge Interactions

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - igf^a_{bc}A^b_\mu A^c_\nu$$

$$\boxed{+\, i\bar{\psi}D\psi + h.c.}$$

- Fermion Interactions

$$\boxed{+\, \bar{\psi}_i y_{ij}\psi_j\phi + h.c.}$$

- Yukawa Interactions

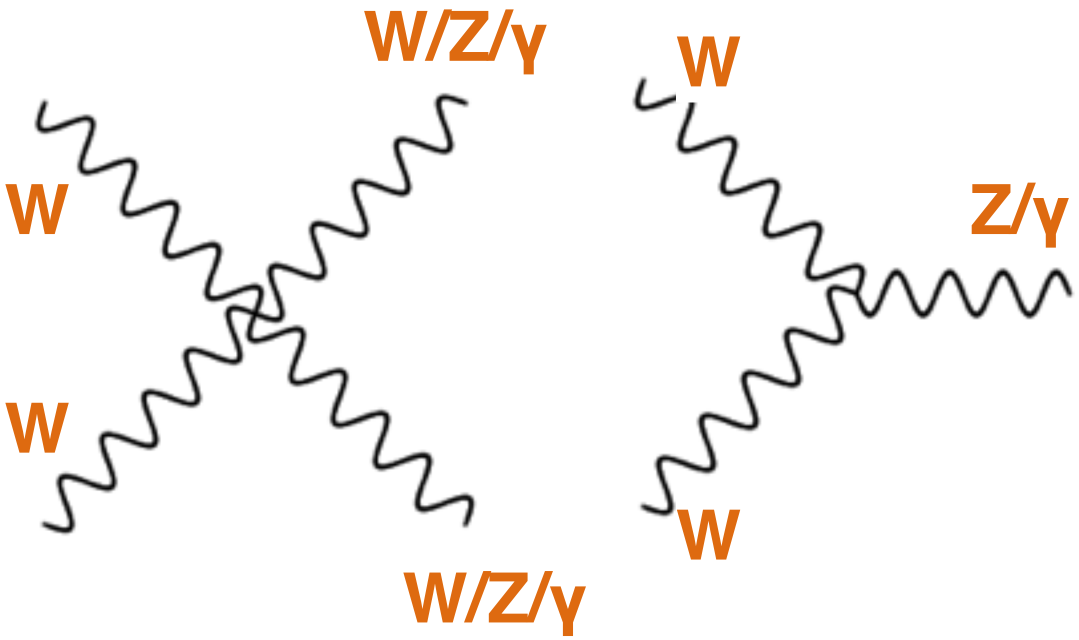
$$\boxed{+\, |D_\mu\phi|^2 - V(\phi)}$$

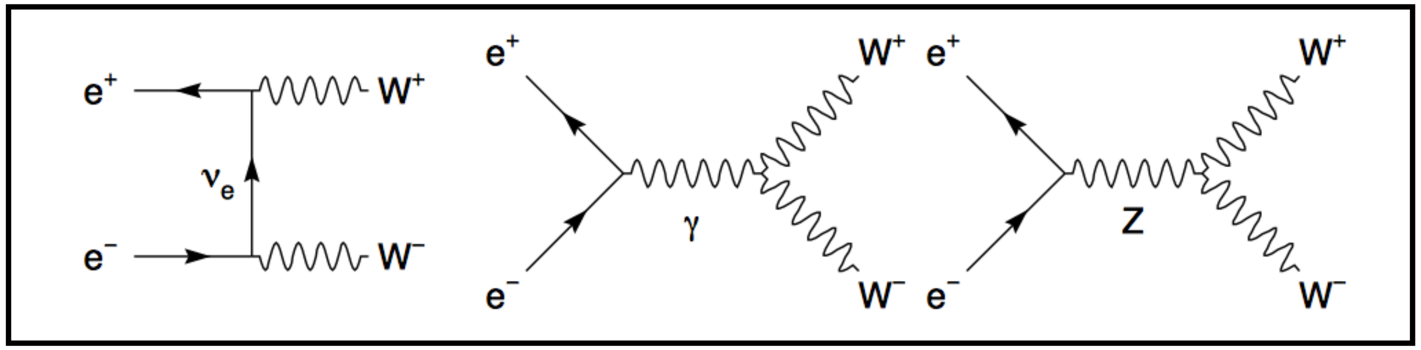
- Higgs Potential

- **Boson self-couplings predicted by non-abelian U(1)xSU(2)xSU(3) Standard Model gauge group**

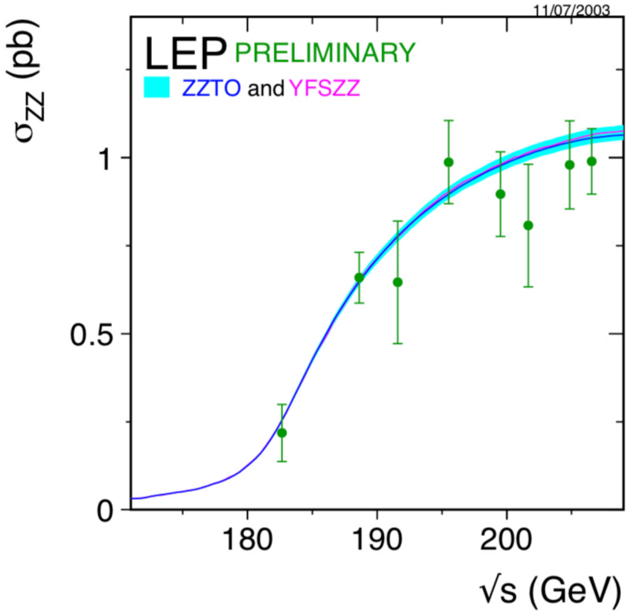
Triple Gauge Couplings at LEP

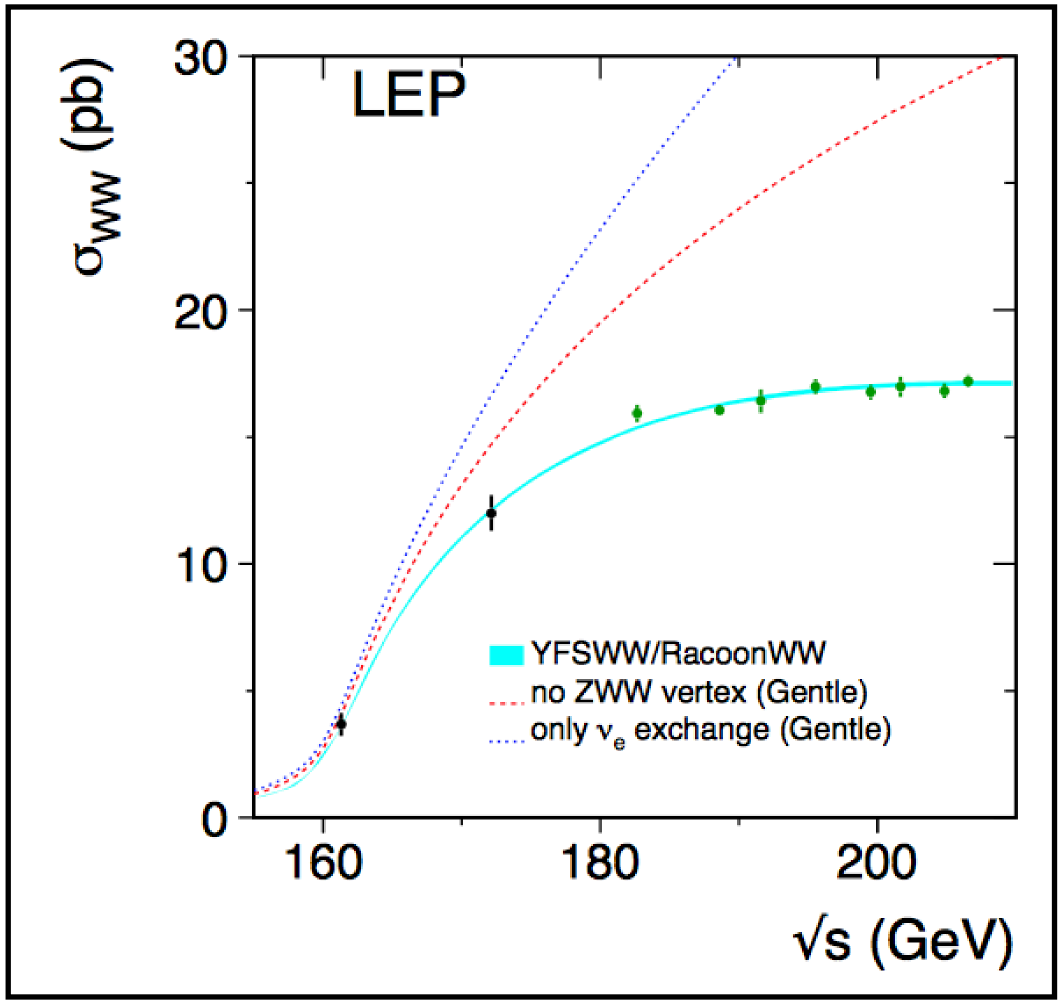
- **Electroweak gauge group predicts:**
  - **QGC: WWZZ, WWWW, WWZγ, WWγγ**
  - **TGC: WWZ, WWγ**
- **Neutral couplings absent in SM:**
  - **ZZZZ, ZZγγ, ZZγ, ZZZ, …..**
- **First experimental evidence at LEP2**





- **Z, γ and ν_e exchange restore unitarity**
  - **In ZZ production gauge interactions absent, induced via t-channel *e* exchange**





EW Triple/Quartic Gauge Couplings

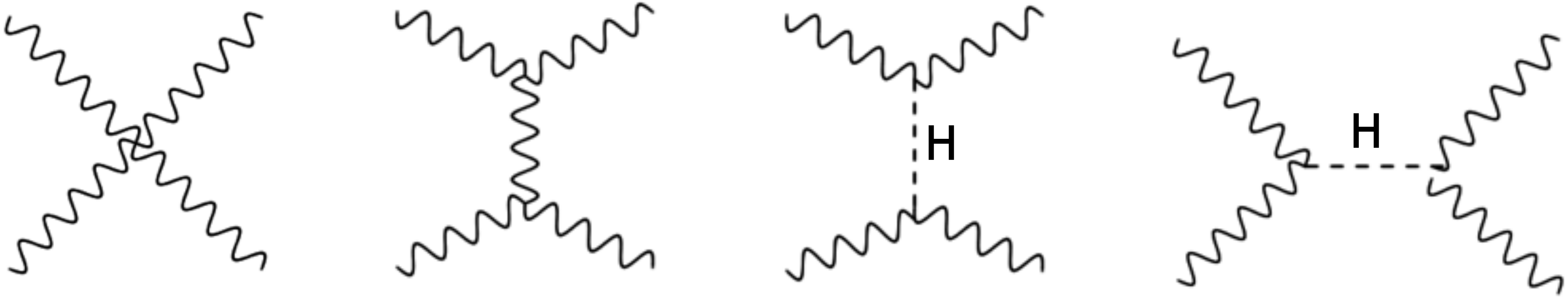
- **SM parameters entering TGC and QGC terms precisely known**

$$\boxed{\begin{aligned}\mathcal{L}_3 = ie\cot\theta_W &\left\{(\partial^\mu W^\nu - \partial^\nu W^\mu)\, W^\dagger_\mu Z_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right) W_\mu Z_\nu + W_\mu W^\dagger_\nu\,(\partial^\mu Z^\nu - \partial^\nu Z^\mu)\right\}\\ &+ ie\left\{(\partial^\mu W^\nu - \partial^\nu W^\mu)\, W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right) W_\mu A_\nu + W_\mu W^\dagger_\nu\,(\partial^\mu A^\nu - \partial^\nu A^\mu)\right\};\end{aligned}}$$

$$\boxed{\begin{aligned}\mathcal{L}_4 = &-\frac{e^2}{2\sin^2\theta_W}\left\{\left(W^\dagger_\mu W^\mu\right)^2 - W^\dagger_\mu W^{\mu\dagger} W_\nu W^\nu\right\} - e^2\cot^2\theta_W\left\{W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right\}\\ &- e^2\cot\theta_W\left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\}\\ &- e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\}.\end{aligned}}$$

- **However, W/Z bosons are massive:**
  - **longitudinal polarization ≠ 0:** $\epsilon^\mu_{T_1,T_2} = \frac{1}{\sqrt{2}}(0,1,\pm i,0)$ $\boxed{\epsilon^\mu_L = \frac{1}{m}(k_3,0,0,E)}$
  - **Electroweak symmetry breaking mechanism strongly related to restoring unitarity in vector boson scattering**

$$\mathcal{A}(W_L W_L \rightarrow W_L W_L) \propto (-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2})$$

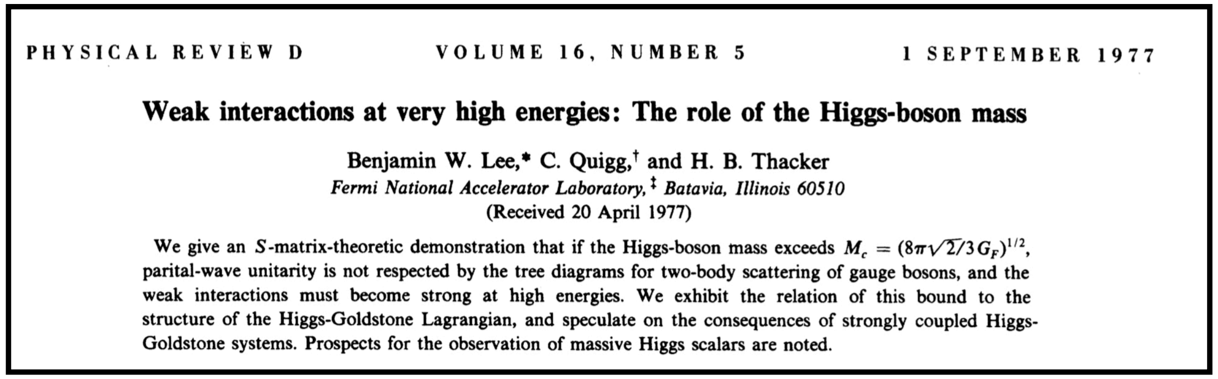


Lee-Quigg-Thacker

ECFA Lausanne 1984, ECFA-CERN Workshop on Large Hadron Collider in the LEP tunnel

- **No-Loose case for LHC**
  - **Lee-Quigg-Thacker unitarity bound:**

$$M_H{}^2 \le \frac{8\pi\sqrt{2}}{3G_F} \equiv M_c{}^2 \simeq (1\ \mathrm{TeV}/c^2)^2$$



PHYSICAL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMBER 1977

Weak interactions at very high energies: The role of the Higgs-boson mass

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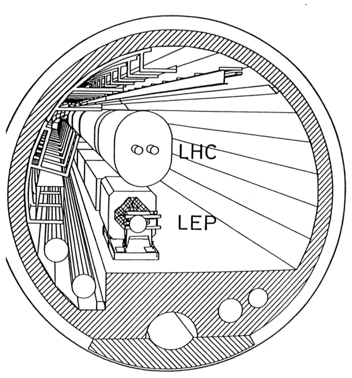
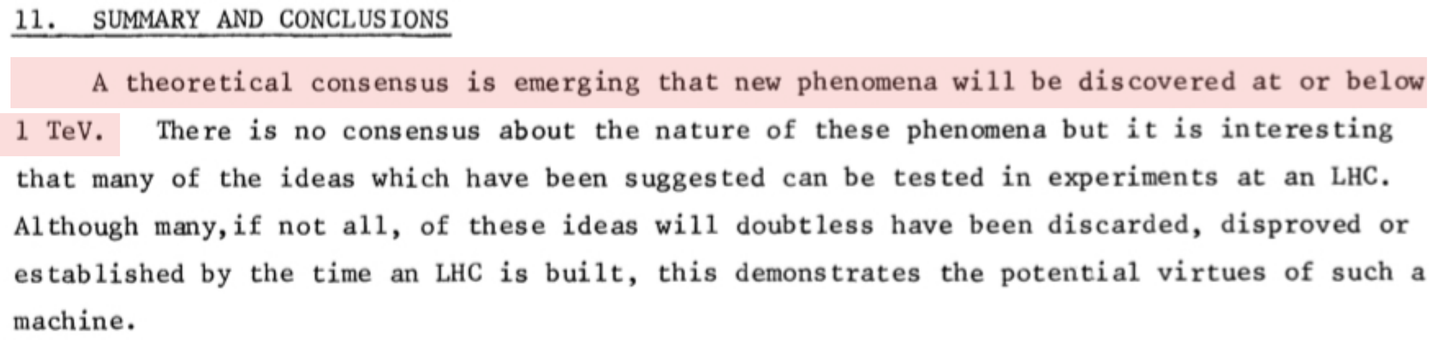
(Received 20 April 1977)

We give an S-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.



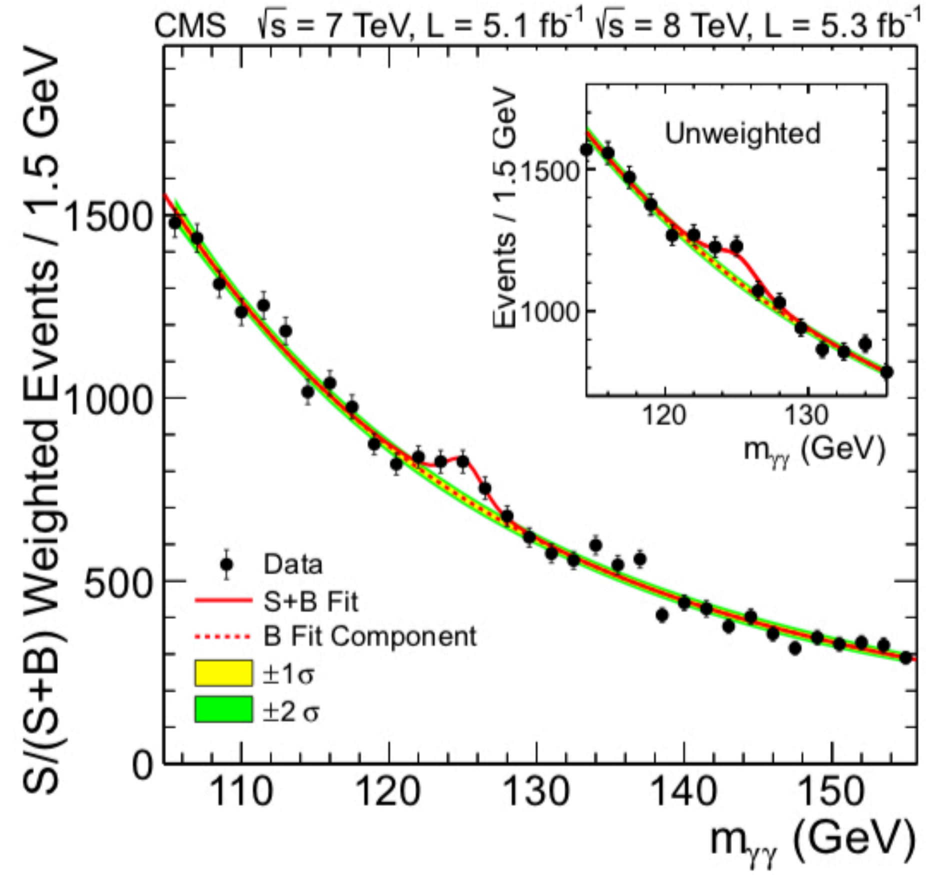
LARGE HADRON COLLIDER
IN THE LEP TUNNEL
Vol. I



11. SUMMARY AND CONCLUSIONS

A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

- **Higgs Discovery July 4th 2012**



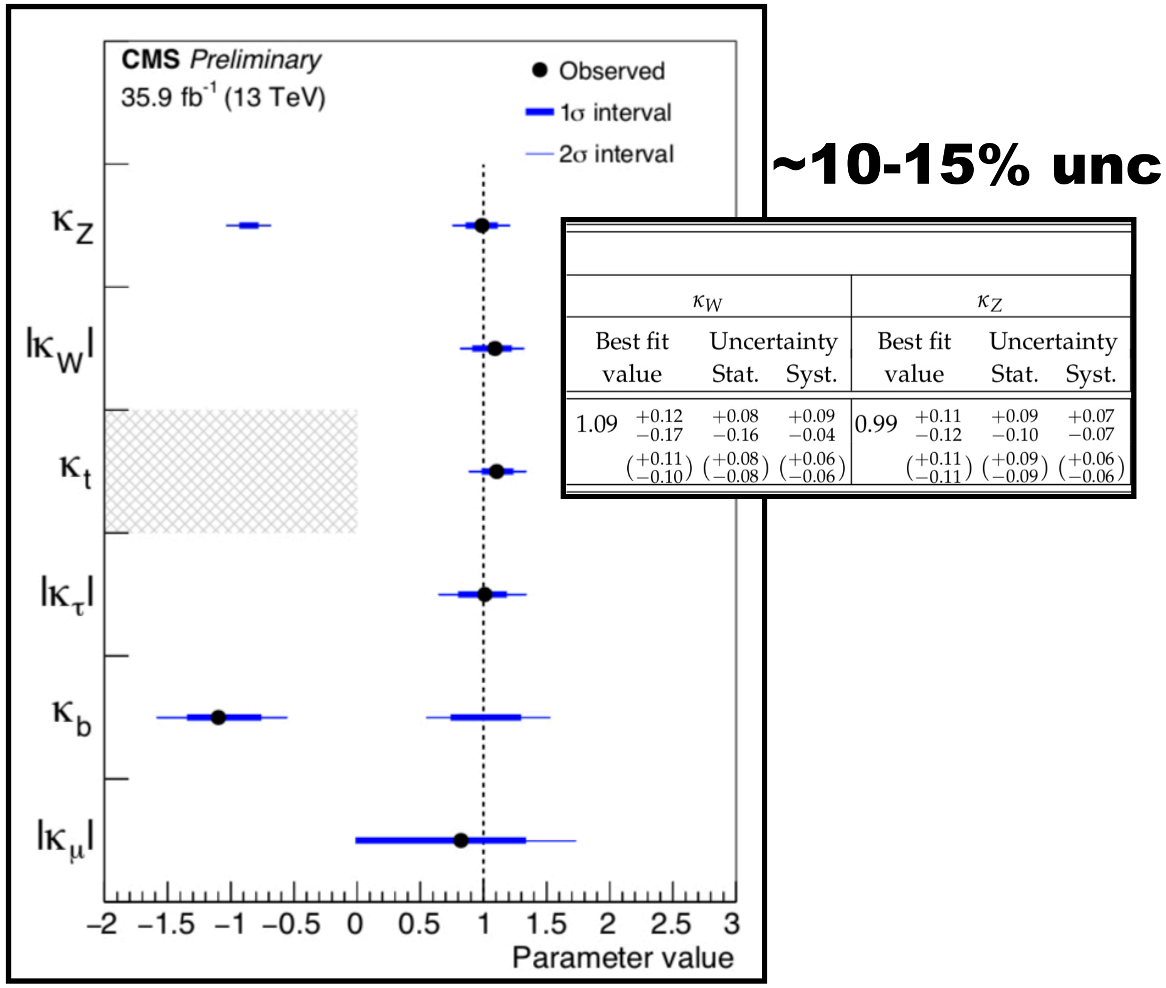
ATLAS CMS Run-1 combination:

$$\boxed{m_{\mathrm{H}} = 125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\ \mathrm{GeV}}$$

Higgs Couplings and VBS

- **Unitarity in VBS restored if and only if parameters have exact SM values** $\mathcal{A}(W_L W_L \to W_L W_L) \propto f(\alpha, M_Z, G_F, M_H, c_W^H \ldots)$

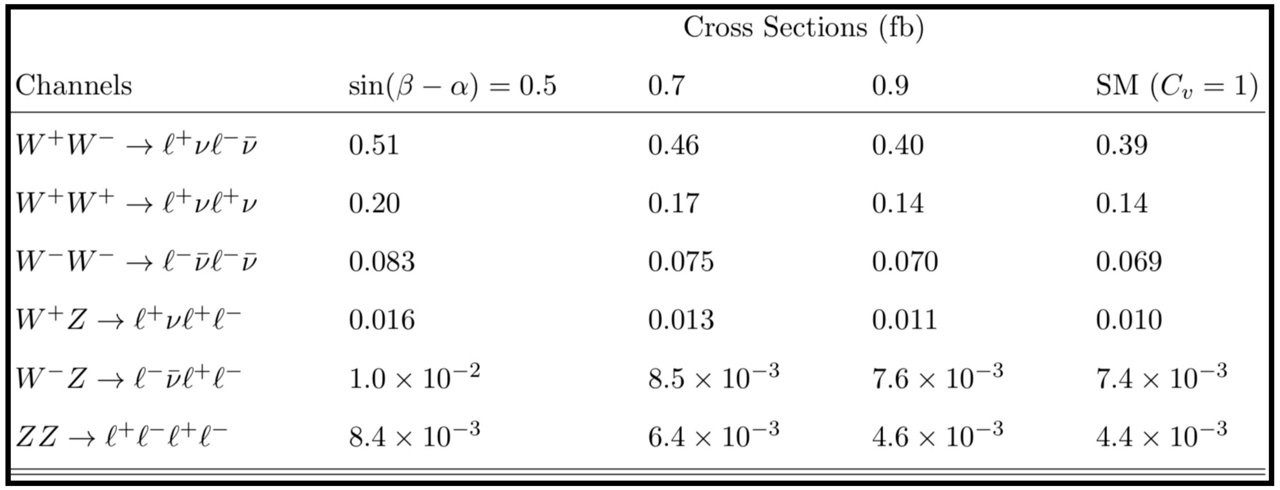
- **Deviations from SM Higgs couplings, e.g. via extended Higgs Sectors result in large cross section changes**
  - **In 2HDM: $g_{hWW} = \sin(\beta-\alpha) g_{hWW}^{\mathrm{SM}}$, heavy Higgs mass chosen to restore unitarity at high energies**



~10-15% unc.

κ_W			κ_Z		
Best fit value	Uncertainty Stat.	Syst.	Best fit value	Uncertainty Stat.	Syst.
$1.09 \,^{+0.12}_{-0.17}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.08}_{-0.16}$ $\left(^{+0.08}_{-0.08}\right)$	$^{+0.09}_{-0.04}$ $\left(^{+0.06}_{-0.06}\right)$	$0.99 \,^{+0.11}_{-0.12}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.10}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.06}_{-0.06}\right)$

2σ (30%) deviation
=> 15-30% cross section change



	Cross Sections (fb)			
Channels	$\sin(\beta-\alpha) = 0.5$	0.7	0.9	SM ($C_v = 1$)
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	0.51	0.46	0.40	0.39
$W^+W^+ \to \ell^+\nu\ell^+\nu$	0.20	0.17	0.14	0.14
$W^-W^- \to \ell^-\bar{\nu}\ell^-\bar{\nu}$	0.083	0.075	0.070	0.069
$W^+Z \to \ell^+\nu\ell^+\ell^-$	0.016	0.013	0.011	0.010
$W^-Z \to \ell^-\bar{\nu}\ell^+\ell^-$	1.0×10^{-2}	8.5×10^{-3}	7.6×10^{-3}	7.4×10^{-3}
$ZZ \to \ell^+\ell^-\ell^+\ell^-$	8.4×10^{-3}	6.4×10^{-3}	4.6×10^{-3}	4.4×10^{-3}

arxiv:1303.6335

Effective Field Theory aTGC/aQGC

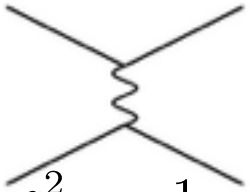
- **Effective Field Theory (EFT) approach used to probe for new physics in TGC and QGC**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\mathrm{dim-6}} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}^j_{\mathrm{dim-8}} + \ldots$$

  - **$O_{i,j}$ gauge invariant operators, build from SM fields**

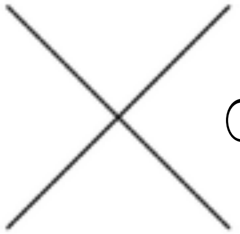
- **Historic example: 4-fermion vertex (dim-6), Weak Interactions**

$$\Lambda = M_W$$



$$\propto \frac{g^2}{8}\frac{1}{q^2 - M_W^2}$$

$$\xrightarrow{q^2 << M_W^2}$$



$$\propto \frac{g^2}{8}\frac{1}{M_W^2} = \frac{G_F}{\sqrt{2}}$$

- **Anomalous Triple Gauge Coupling parametrization used at LEP**
  - **example WWZ vertex, mapping to dim-6 operators possible** arXiv:hep-ph/9601233
  - **3 CP-even dim-6 operators**

$$\begin{aligned} \mathcal{O}^{(6)}_{\mathrm{WWW}} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho{}^\mu], \\ \mathcal{O}^{(6)}_{\mathrm{W}} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi), \\ \mathcal{O}^{(6)}_{\mathrm{B}} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi). \end{aligned}$$

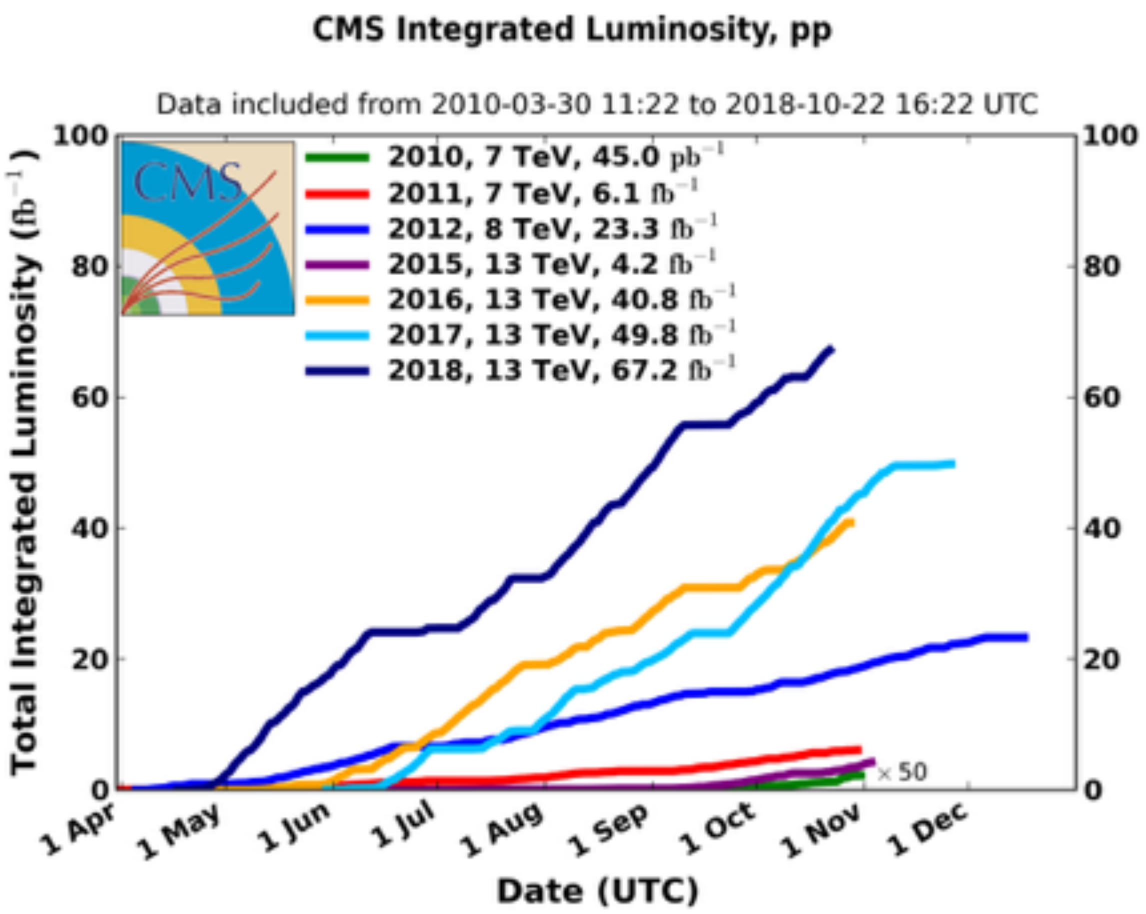
$$\begin{aligned} \mathcal{L} = -ie\Big[&g_1^\gamma(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})A^\nu + \kappa_\gamma W^+_\mu W^-_\nu A^{\mu\nu} \\ &+ \frac{\lambda_\gamma}{M_{\mathrm{W}}^2}W^{+\nu}_\mu W^{-\rho}_\nu A_\rho{}^\mu\Big] - igc\Big[g_1^Z(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})Z^\nu \\ &+ \kappa_Z W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{M_{\mathrm{W}}^2}W^{+\nu}_\mu W^{-\rho}_\nu Z_\rho{}^\mu\Big], \end{aligned} \qquad (2)$$

  - **relation from LEP parameters to wilson coefficients**

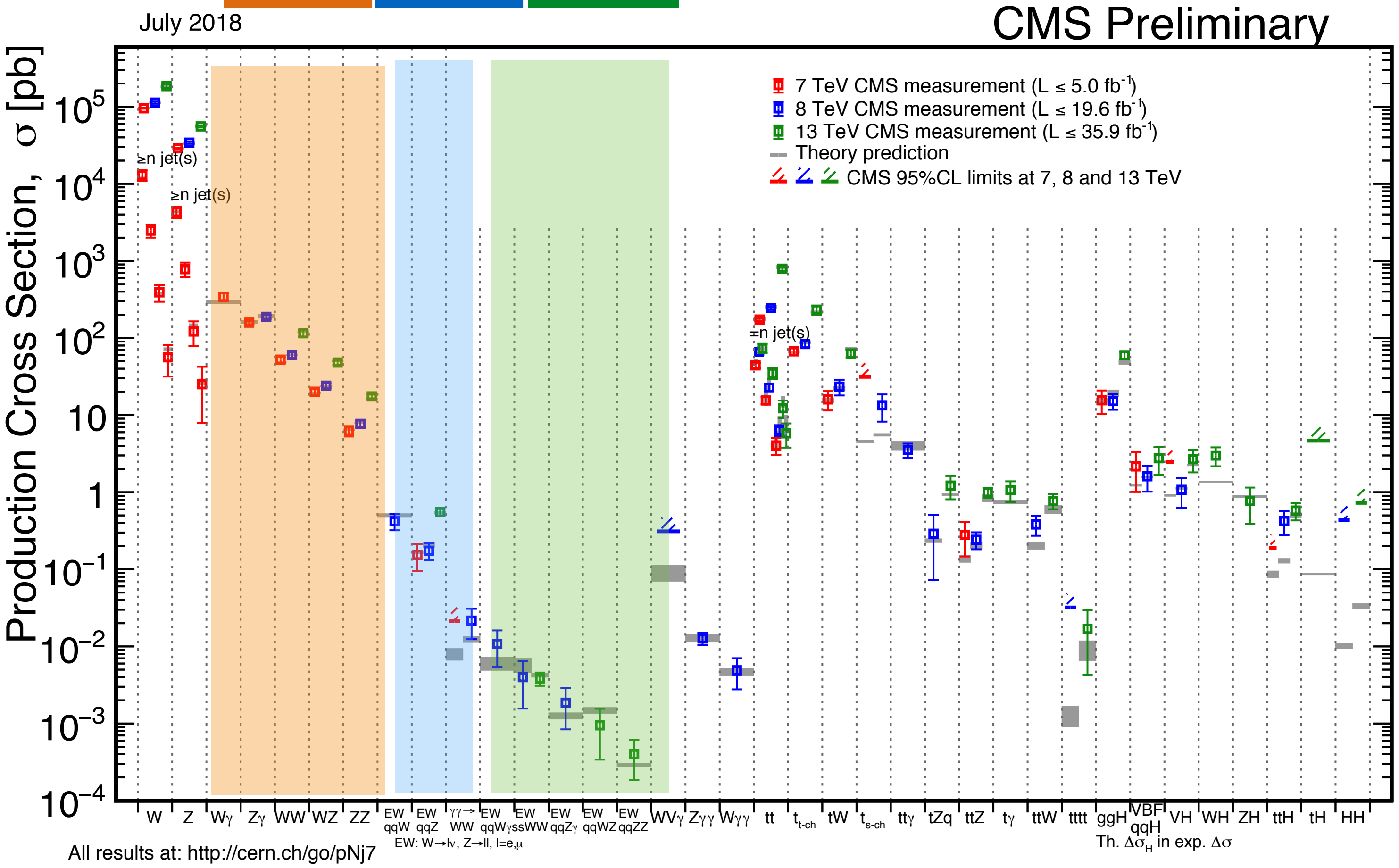
$$\Delta g_1^Z = \frac{c_W m_Z^2}{2\Lambda^2} \quad \Delta\kappa_Z = (c_W - c_B \tan^2\theta_{\mathrm{W}})\frac{\mathrm{m}_{\mathrm{W}}^2}{2\Lambda^2} \quad \lambda_Z = \frac{3c_{WWW}g^2 m_W^2}{2\Lambda^2}$$

LHC Experimental Status

- **Experiments have accumulated ~25 fb^{-1} at 7/8 TeV and >150 fb^{-1} at 13 TeV (Run-2 is coming to an end, start of Run-3 in 2021)**
- **To study TGC/QGC, measure cross sections over 5 orders of magnitude VBS: *O*(1fb), VBF:*O*(100fb) and VV-Inclusive: *O*(10pb)**
  - **Current CMS multiboson results based on Run-1 dataset and 36 fb^{-1} of Run-2 collected in 2016**



VV VBF VBS



CMS published more than 20 analyses targeting QGC/TGC specifically

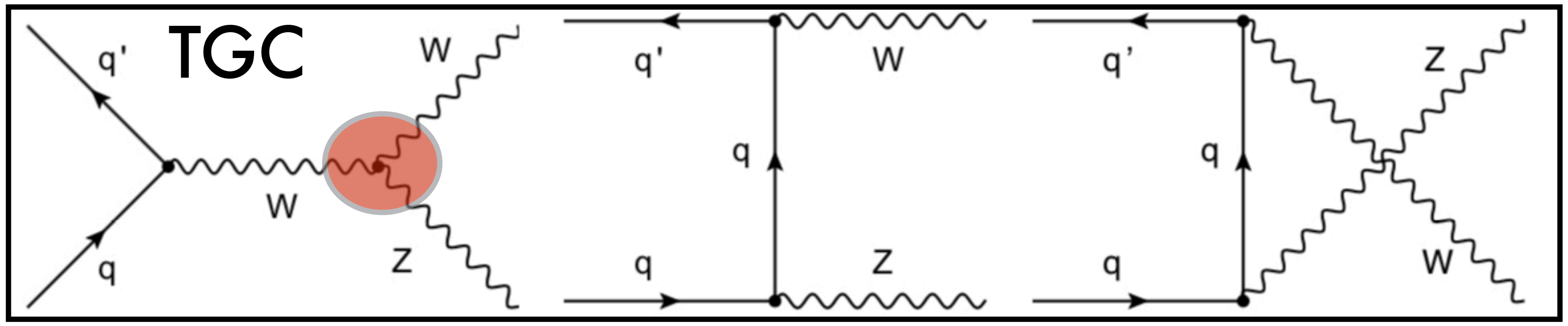
CMS Run-2 Diboson Analyses

- **CMS analyses studying triple and quartic gauge boson couplings at 13 TeV, and being presented here**

sqrt(s)	VBS process	CMS	Luminosity [fb^{-1}]
13 TeV	Inclusive W+W-	SMP-16-006	2.3
	Inclusive WV	SMP-16-012	2.3
	VBF Z	SMP-16-018	35.9
	Inclusive ZZ	SMP-16-017	35.9
	Inclusive WZ	SMP-18-002	35.9
	EW W±W± (2l2v)	PRL 120, 081801	35.9
	EW ZZ (4l)	Phys. Lett. B 774 (2017) 682	35.9
	EW WZ (3lv)	SMP-18-001	35.9

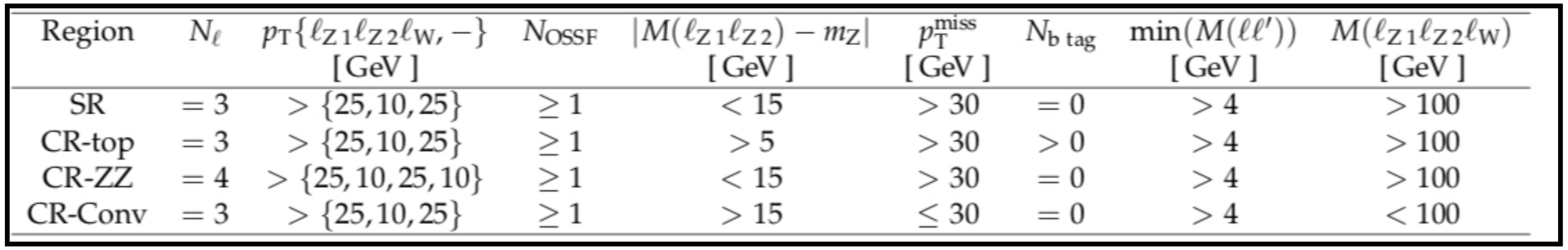
CMS WZ Inclusive Production

- **SMP-18-002: Inclusive WZ production cross secton measurement with CMS**

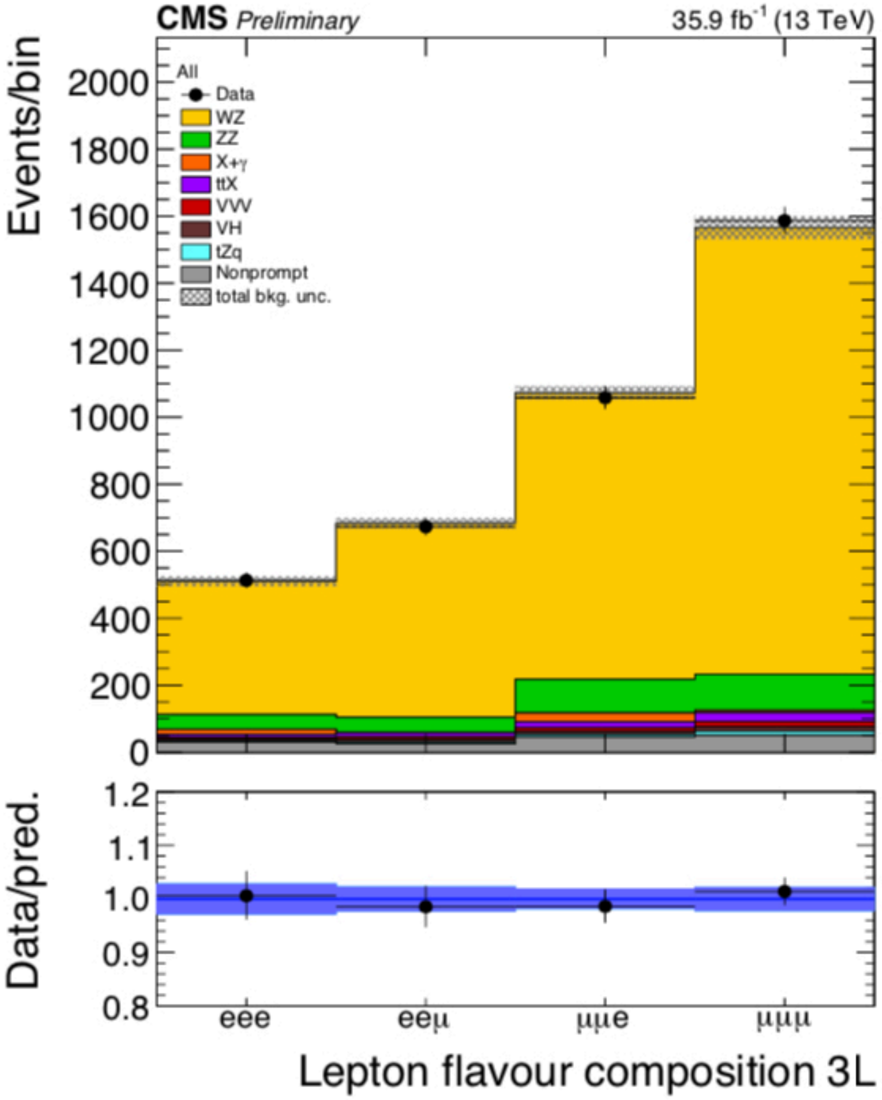


eeeν,μμμν,
eμμν,eeμν

- **Event selection criteria exploit distinct 3-lepton signature, major backgrounds controlled in the data**



Region	N_ℓ	$p_T\{\ell_{Z1}\ell_{Z2}\ell_W,-\}$ [GeV]	N_{OSSF}	$\lvert M(\ell_{Z1}\ell_{Z2})-m_Z\rvert$ [GeV]	p_T^{miss} [GeV]	$N_{b\ tag}$	$\min(M(\ell\ell'))$ [GeV]	$M(\ell_{Z1}\ell_{Z2}\ell_W)$ [GeV]
SR	$=3$	$>\{25,10,25\}$	≥ 1	<15	>30	$=0$	>4	>100
CR-top	$=3$	$>\{25,10,25\}$	≥ 1	>5	>30	>0	>4	>100
CR-ZZ	$=4$	$>\{25,10,25,10\}$	≥ 1	<15	>30	$=0$	>4	>100
CR-Conv	$=3$	$>\{25,10,25\}$	≥ 1	>15	≤ 30	$=0$	>4	<100

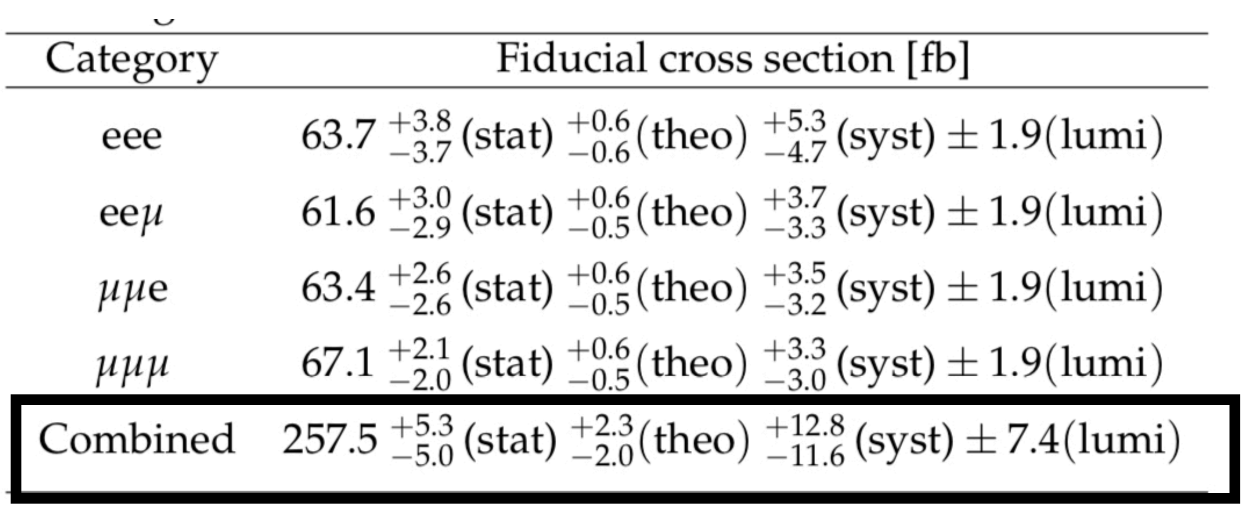


- **85% purity after event selection**
- **Largest background contributions:**
  - **ZZ (4-lepton), Nonprompt leptons (using the fake rate method)**

WZ Inclusive 13 TeV 36 fb^{-1}

- **Fiducial cross section measured (similar to signal selection):**
  - POWHEG (NLO) ~12% difference,
    2 standard deviations

$$\boxed{\sigma_{\text{fid}}^{\text{POWHEG}} = 227.6\,^{+8.8}_{-7.3}(\text{scale}) \pm 3.2(\text{PDF})\ \text{fb}}$$



Category	Fiducial cross section [fb]
eee	$63.7\,^{+3.8}_{-3.7}(\text{stat})\,^{+0.6}_{-0.6}(\text{theo})\,^{+5.3}_{-4.7}(\text{syst}) \pm 1.9(\text{lumi})$
eeμ	$61.6\,^{+3.0}_{-2.9}(\text{stat})\,^{+0.6}_{-0.5}(\text{theo})\,^{+3.7}_{-3.3}(\text{syst}) \pm 1.9(\text{lumi})$
$\mu\mu$e	$63.4\,^{+2.6}_{-2.6}(\text{stat})\,^{+0.6}_{-0.5}(\text{theo})\,^{+3.5}_{-3.2}(\text{syst}) \pm 1.9(\text{lumi})$
$\mu\mu\mu$	$67.1\,^{+2.1}_{-2.0}(\text{stat})\,^{+0.6}_{-0.5}(\text{theo})\,^{+3.3}_{-3.0}(\text{syst}) \pm 1.9(\text{lumi})$
Combined	$257.5\,^{+5.3}_{-5.0}(\text{stat})\,^{+2.3}_{-2.0}(\text{theo})\,^{+12.8}_{-11.6}(\text{syst}) \pm 7.4(\text{lumi})$

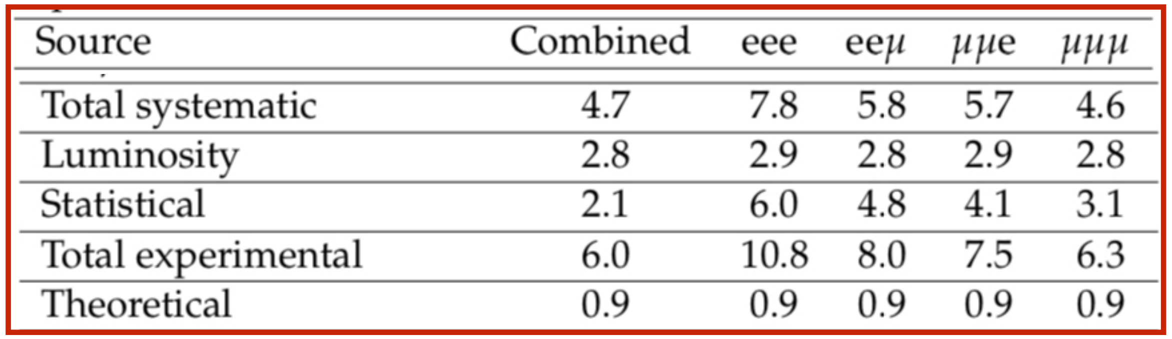
- **Total inclusive cross section measurement:**
  - $$\boxed{\sigma_{\text{Tot}}(pp \to WZ) = 48.09^{+2.98}_{-2.78}\ \text{pb} = 48.09\,^{+1.00}_{-0.96}\ (\text{stat})\,^{+0.44}_{-0.37}\ (\text{theo})\,^{+2.39}_{-2.17}\ (\text{syst}) \pm 1.39\ (\text{lumi})\ \text{pb}}$$
  - NLO (NNLO) MATRIX prediction:

    NLO->NNLO: >10% !

$$\boxed{\sigma_{\text{NNLO}}(pp \to WZ) = 49.98^{+2.2\%}_{-2.0\%}}$$

$$\boxed{\sigma_{\text{NLO}}(pp \to WZ) = 45.09^{+4.9\%}_{-3.9\%}}$$

- **Leading experimental systematic uncertainties:**



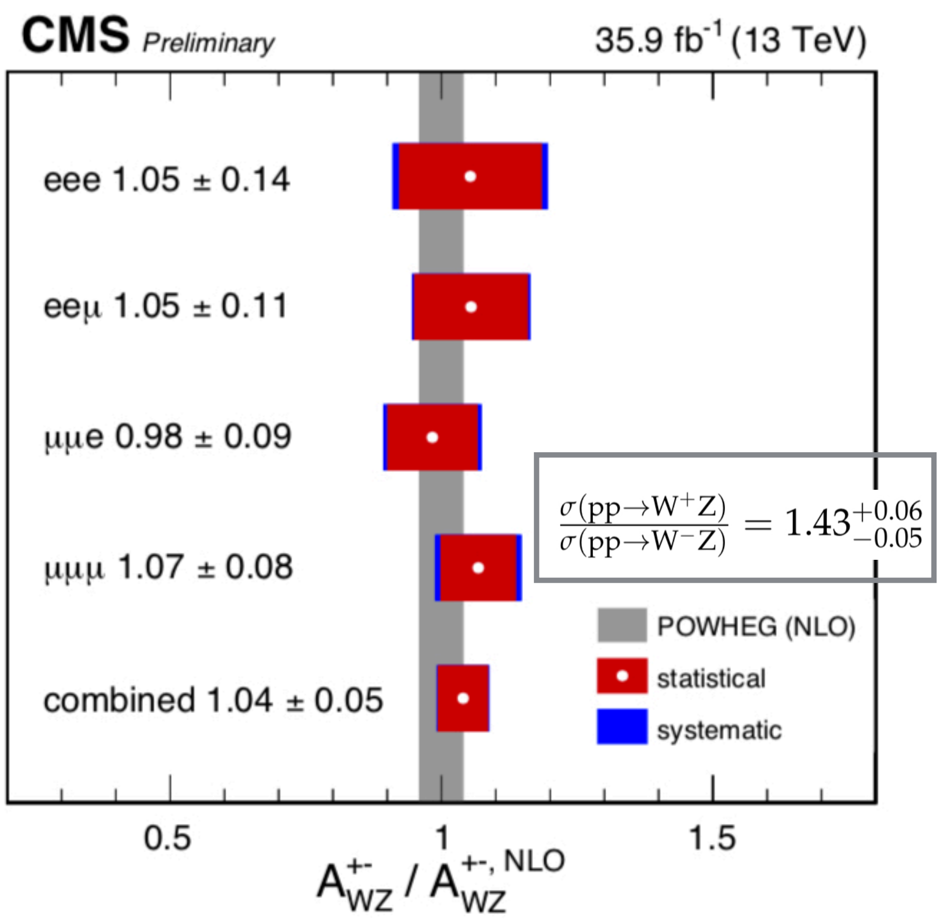
Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Total systematic	4.7	7.8	5.8	5.7	4.6
Luminosity	2.8	2.9	2.8	2.9	2.8
Statistical	2.1	6.0	4.8	4.1	3.1
Total experimental	6.0	10.8	8.0	7.5	6.3
Theoretical	0.9	0.9	0.9	0.9	0.9

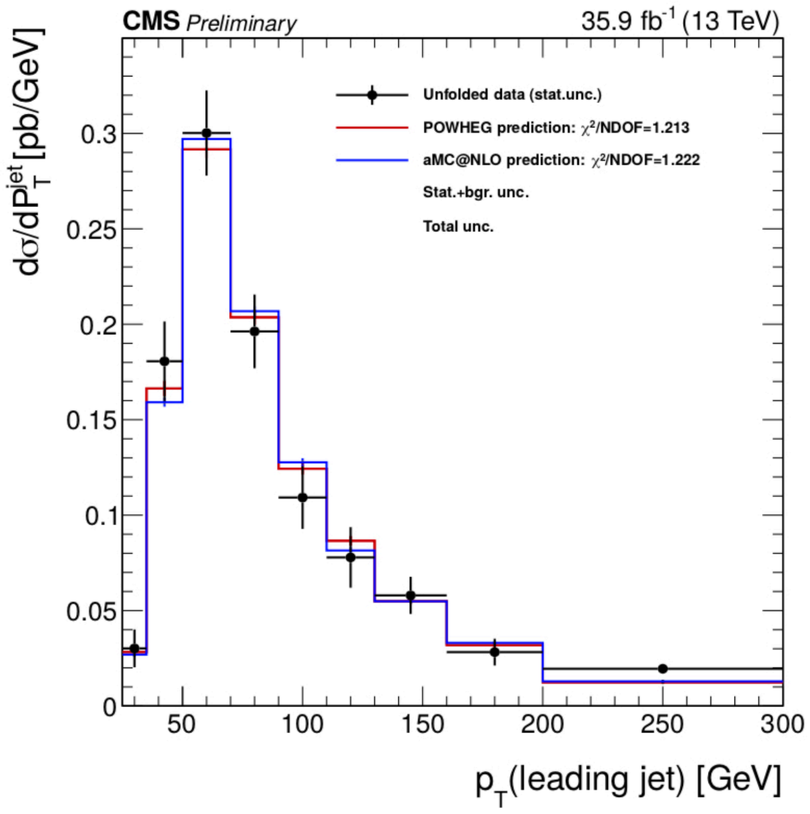
in percent

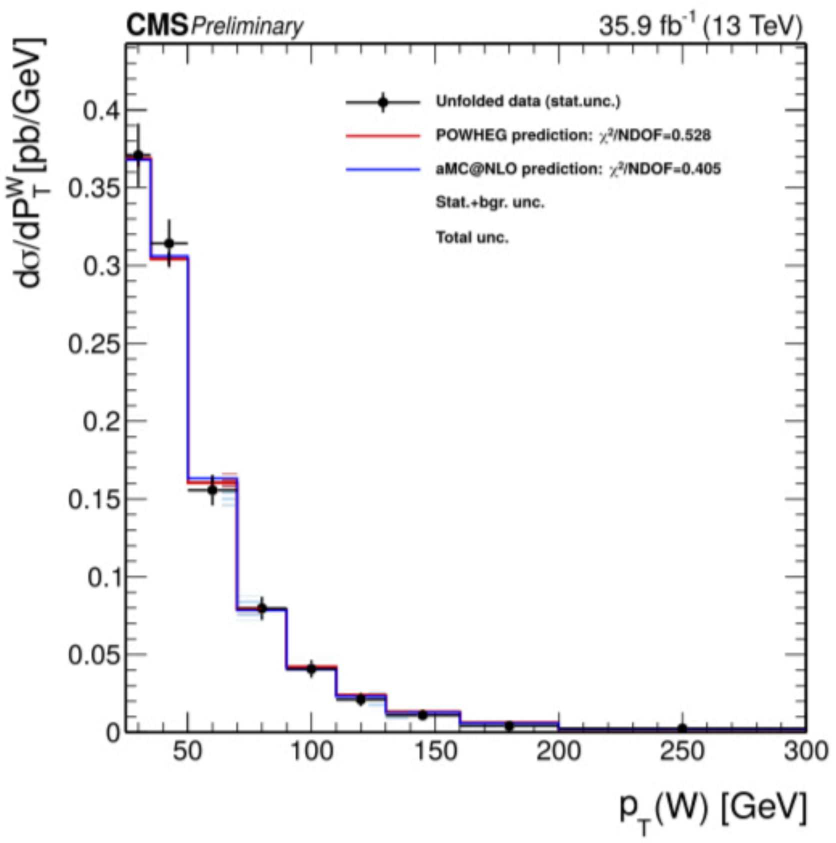
WZ Inclusive 13 TeV 36 fb^{-1}

- **Differential cross section measurements performed, (pTj, pT(Z), pT(W), M(WZ))**
  - **generally well described by NLO+PS prediction, when normalized to inclusive MATRIX NNLO prediction**

- **Measurement of charge asymmetry of production cross section performed, measurement**

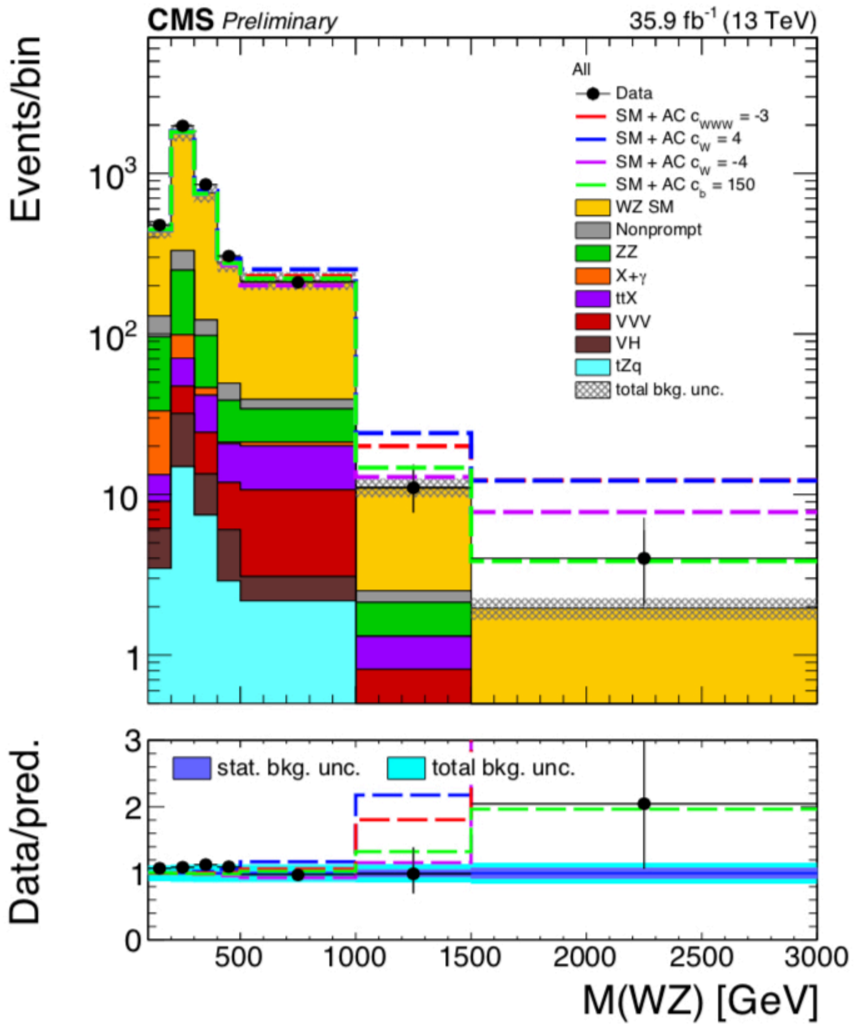




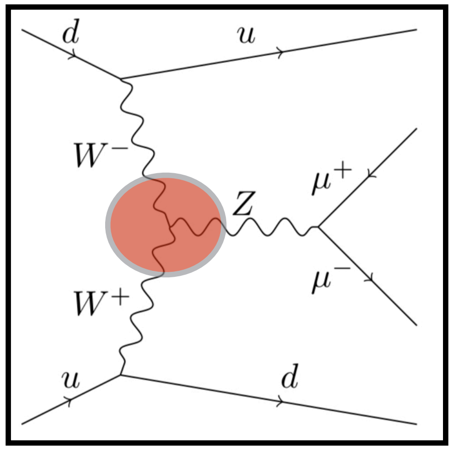


WZ EFT Interpretation

- **Exclusion limits for contributions from dim-6 operators are derived**
  - **M(WZ) used to derive exclusion limits**
- **Experimentally independent approach to study WWZ triple gauge coupling with Z boson production via Vector Boson Fusion (arxiv:1712.09814)**



$$m_X^2 = (p_T(\ell_1) + p_T(\ell_2) + p_T(\ell_3) + p_T(\nu))^2$$



Incl. WZ

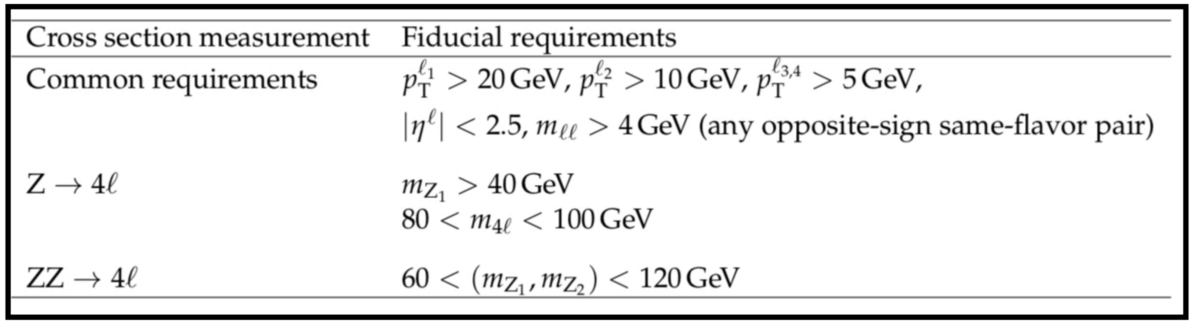
Parameter	95% CI (expected)	95% CI (observed)
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

VBF Z

Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-3.7, 3.6]$	$[-2.6, 2.6]$
c_W/Λ^2	$[-12.6, 14.7]$	$[-8.4, 10.1]$

ZZ Inclusive Production

- **SMP-16-017: Inclusive ZZ production cross section measurment in 4-lepton final state (4e,4μ,2e2μ)**



Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\mathrm{GeV}$, $p_T^{\ell_2} > 10\,\mathrm{GeV}$, $p_T^{\ell_{3,4}} > 5\,\mathrm{GeV}$, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell\ell} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair)
$Z \to 4\ell$	$m_{Z_1} > 40\,\mathrm{GeV}$ $80 < m_{4\ell} < 100\,\mathrm{GeV}$
$ZZ \to 4\ell$	$60 < (m_{Z_1}, m_{Z_2}) < 120\,\mathrm{GeV}$

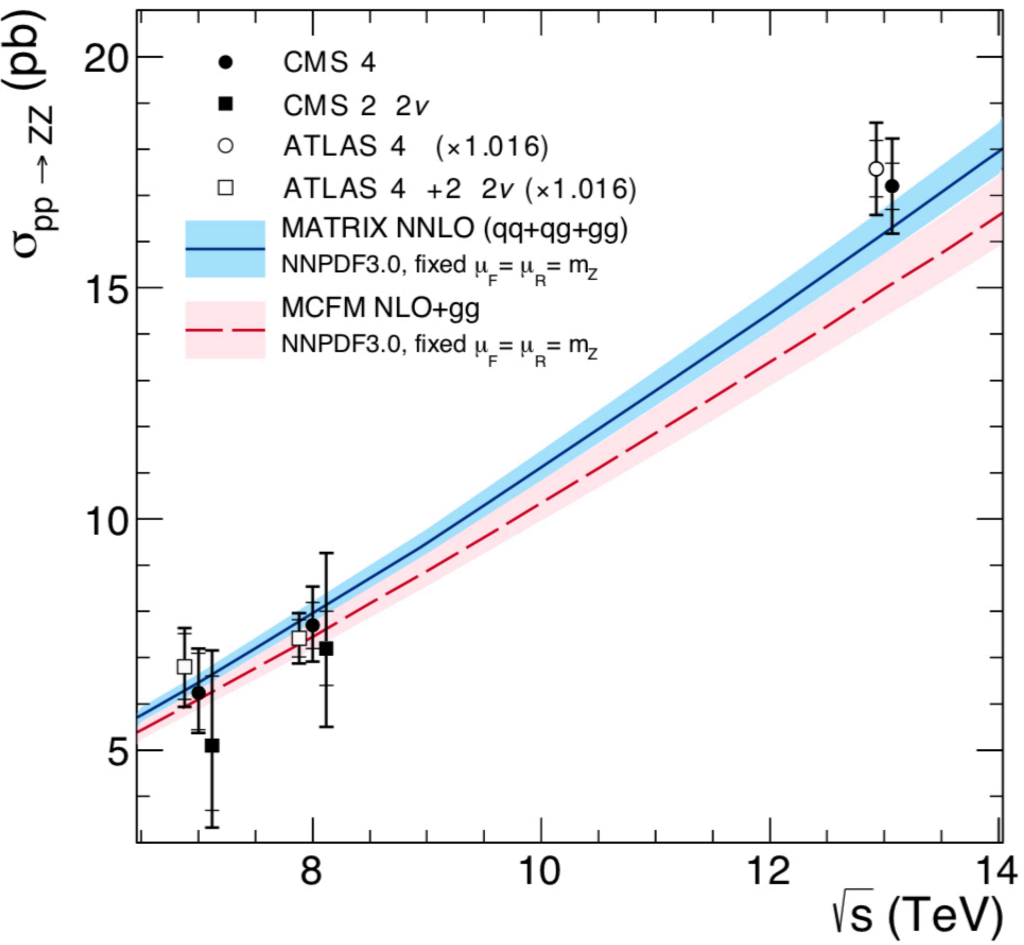
- **measured total inclusive:** 6.5% uncertainty

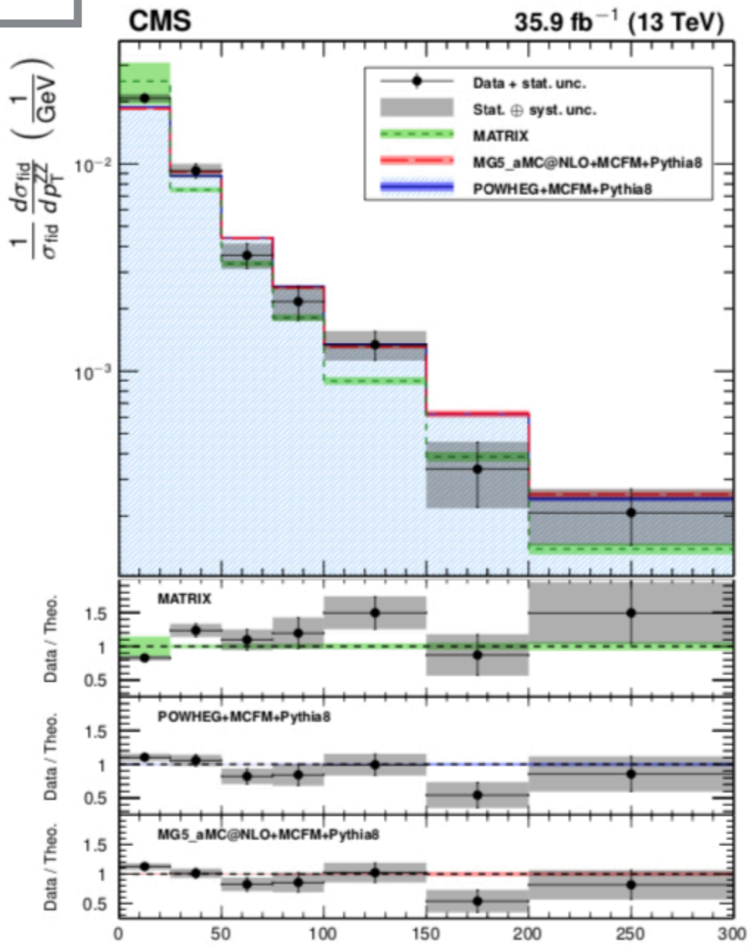
$$\boxed{\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 17.5^{+0.6}_{-0.5}\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\,\mathrm{pb}}$$

Note: no TGC ZZZ predicted in SM

- **MATRIX (NNLO QCD, NLO -> NNLO ~ 10%):**

$$\boxed{\sigma^{NNLO}(pp \to ZZ) = 16.2^{+0.6}_{-0.4}\mathrm{pb}}$$





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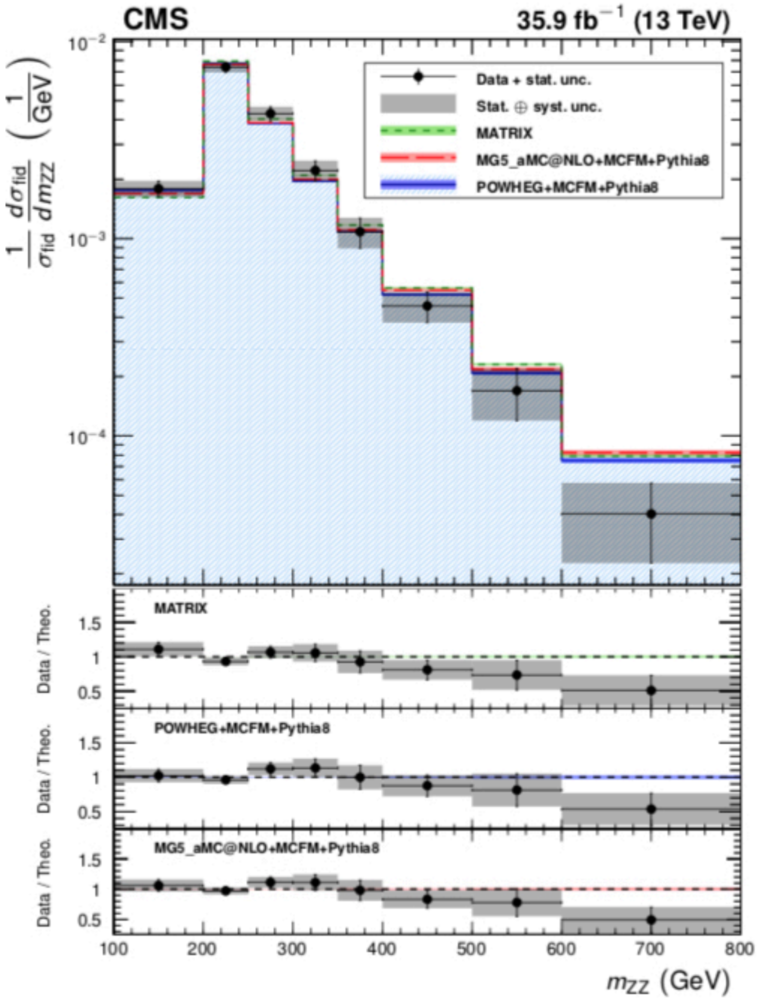
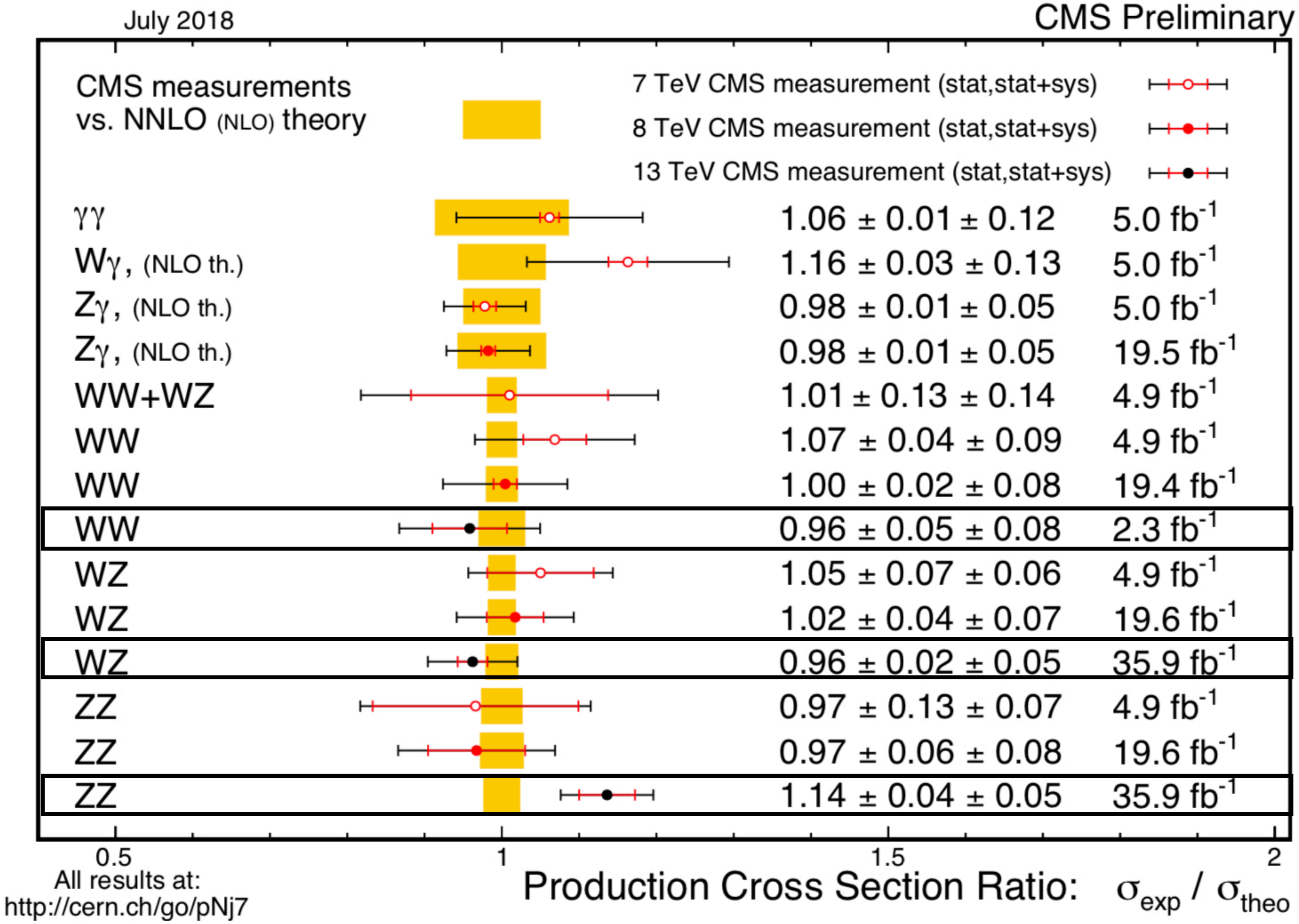


Summary on Diboson Production

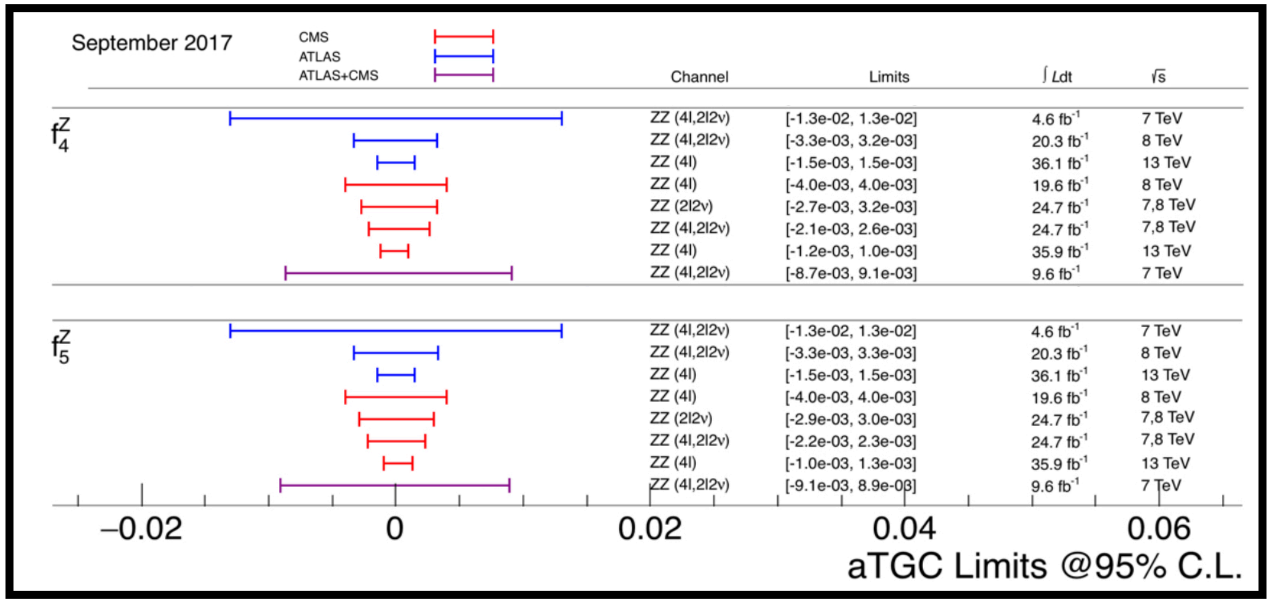
- **CMS measured total inclusive diboson production cross sections with statistical unc. of ~2% and systematic unc. ~5%**
  - **Differential cross sections: more data -> higher precision in the tails of distributions (sensitivity to perturbative higher order corrections)**

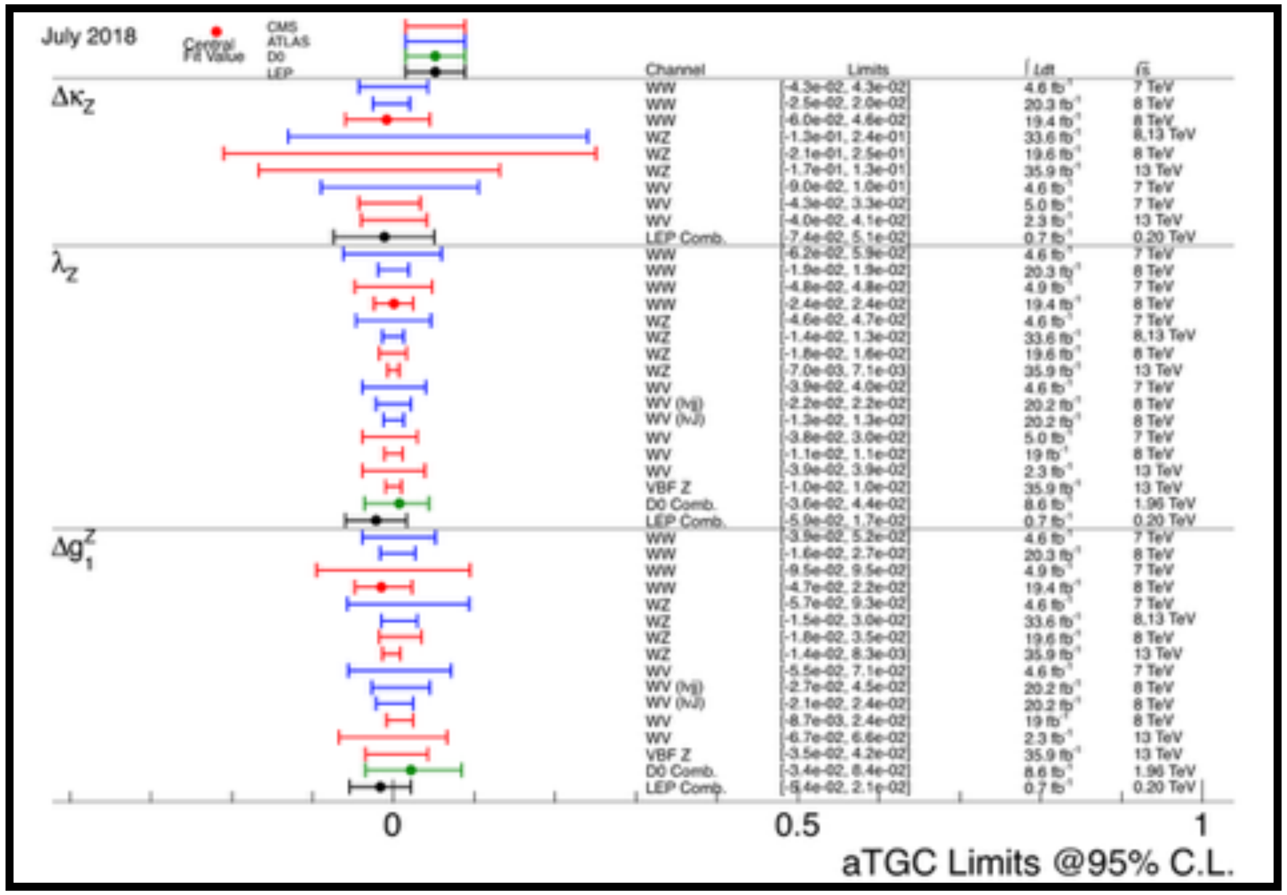


$\gamma\gamma$	1.06 ± 0.01 ± 0.12	5.0 fb^{-1}
$W\gamma$, (NLO th.)	1.16 ± 0.03 ± 0.13	5.0 fb^{-1}
$Z\gamma$, (NLO th.)	0.98 ± 0.01 ± 0.05	5.0 fb^{-1}
$Z\gamma$, (NLO th.)	0.98 ± 0.01 ± 0.05	19.5 fb^{-1}
WW+WZ	1.01 ± 0.13 ± 0.14	4.9 fb^{-1}
WW	1.07 ± 0.04 ± 0.09	4.9 fb^{-1}
WW	1.00 ± 0.02 ± 0.08	19.4 fb^{-1}
WW	0.96 ± 0.05 ± 0.08	2.3 fb^{-1}
WZ	1.05 ± 0.07 ± 0.06	4.9 fb^{-1}
WZ	1.02 ± 0.04 ± 0.07	19.6 fb^{-1}
WZ	0.96 ± 0.02 ± 0.05	35.9 fb^{-1}
ZZ	0.97 ± 0.13 ± 0.07	4.9 fb^{-1}
ZZ	0.97 ± 0.06 ± 0.08	19.6 fb^{-1}
ZZ	1.14 ± 0.04 ± 0.05	35.9 fb^{-1}

Summary on Diboson Production

- **Results on aTGC superseeds results from previous experiments**
  - **Sensitivity improves with √L, signal appears in tails of mass or pT distritbutions**





- **So far no indication for effective ZZZ coupling observed**

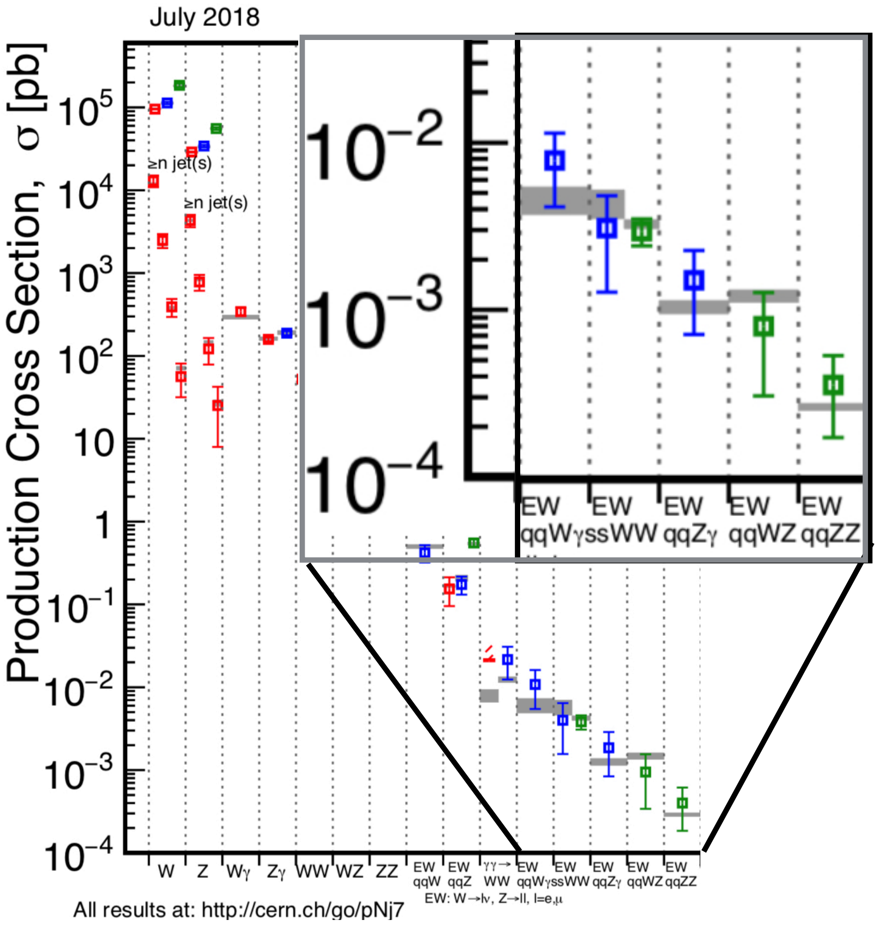
- **Indirectly probing BSM mass scales with c_{WWW} operator of about 700 GeV**
  - **Improved sensitivity expected from semi-leptonic analysis (ZV/WV)**

$$\lambda_Z = \frac{3c_{WWW}g^2m_W^2}{2\Lambda^2}$$

CMS VBS Studies

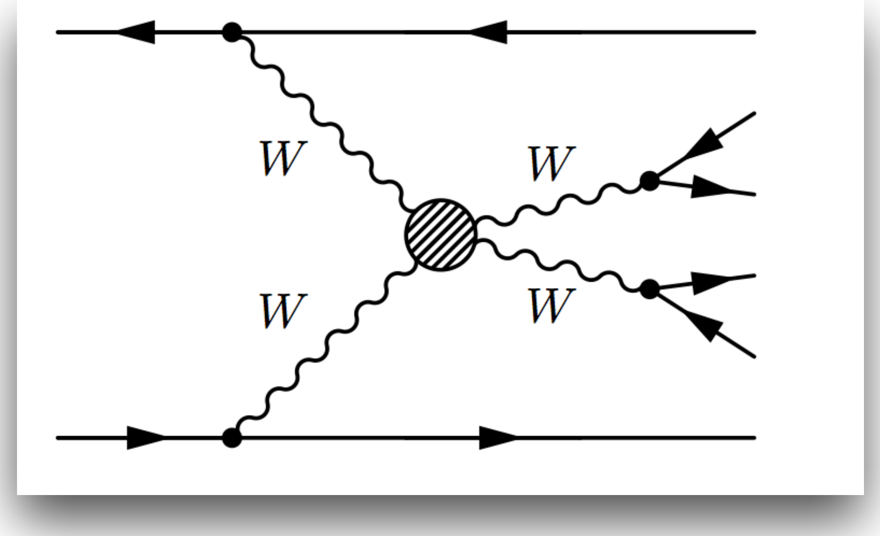
- **LHC enables W/Z quartic coupling studies measurements for the first time**
- **$W^{\pm}W^{\pm}$ largest EW cross section and signal to background ratio**
- **WZ and ZZ processes become feasible with the full Run-2 dataset**
  - **low cross section larger QCD induced diboson background**
- **CMS performed all these measurements with 35.9 fb^{-1} at 13 TeV**
  - **In principle, quartic couplings also accessible via triboson production**

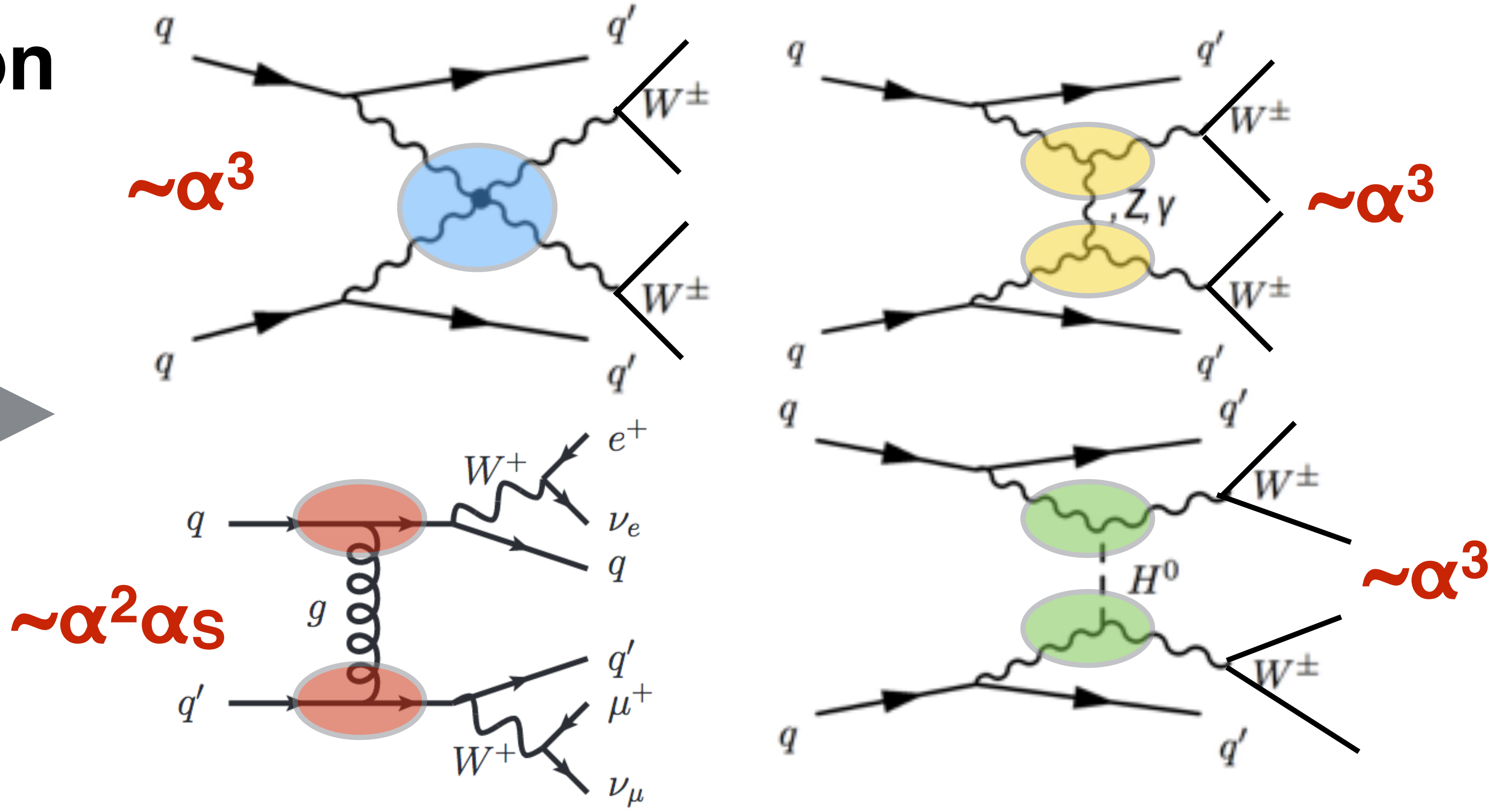
sqrt(s)	VBS process	CMS	Comment
8 TeV	EW W±W± (lvlv)	PRL 114 (2015) 051801	CMS finds 2.0 σ
	EW Zγ (νν/llγ)	Phys.Lett. B770 (2017) 380-402	CMS finds evidence
	EW Wγ (lνγ)	JHEP 1706 (2017) 106	CMS finds 2.7 σ
	EW WZ (3lν)	PRL 114 (2015) 051801	CMS meas. QCD+EW xsec
13 TeV	EW W±W± (2l2ν)	PRL 120, 081801	CMS first observation
	EW ZZ (4l)	Phys. Lett. B 774 (2017) 682	CMS finds 2.7 σ
	EW WZ (3lν)	SMP-18-001	CMS finds 1.9 σ, aQGC studies and limits on H+



Electroweak Diboson Production

- **EW 2-jet associated (VBS) signal definition based on order of α and α_S entering the cross section at LO**





- **At LO production cross section is sum of terms also involving strong coupling constant**

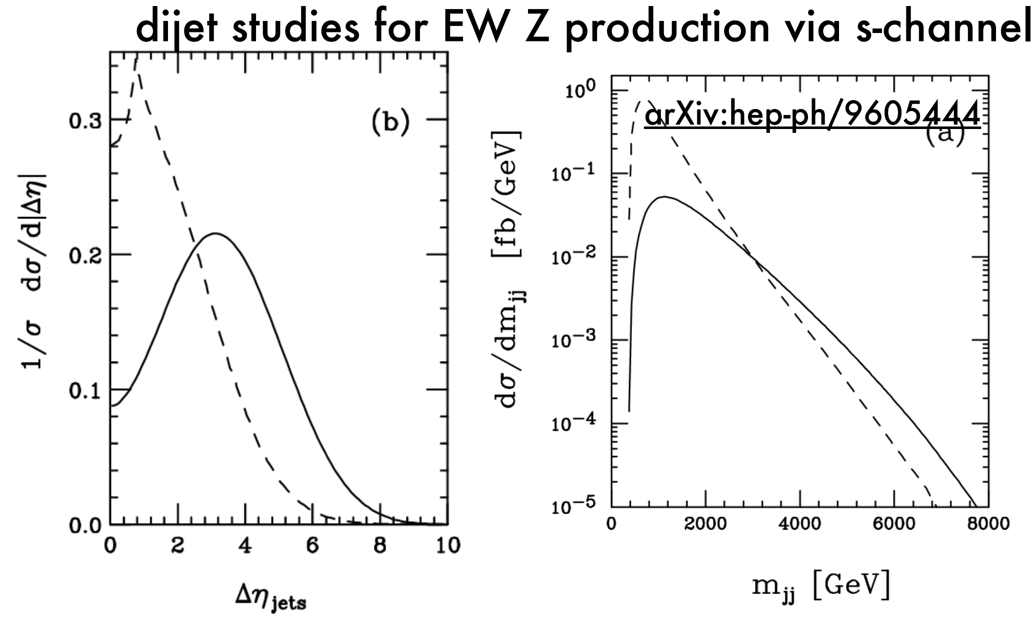
$\sigma_{EW} \propto \mathcal{O}(\alpha^6)$	$\sigma_{EW\times QCD} \propto \mathcal{O}(\alpha^5\alpha_S)$	$\sigma_{QCD} \propto \mathcal{O}(\alpha^4\alpha_S^2)$
EW Signal	**Interference, uncertainty or added to background, usually O(1%)**	**Background (QCD induced)**

- $\dfrac{\sigma_{EW}(VV+jj)}{\sigma_{QCD}(VV+jj)}$ **largest for W±W± production**
  - **most sensitive to probe quartic gauge coupling**

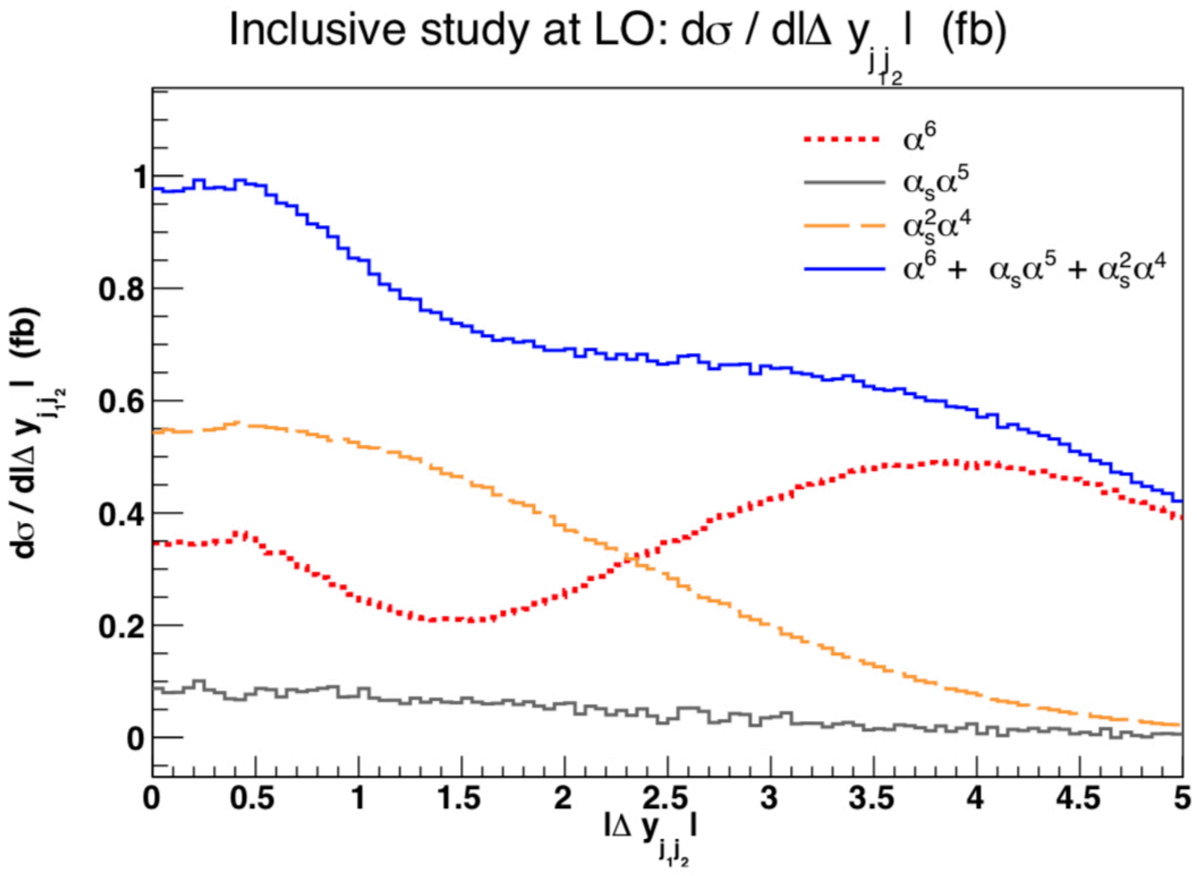
VBS Signature in the Detector

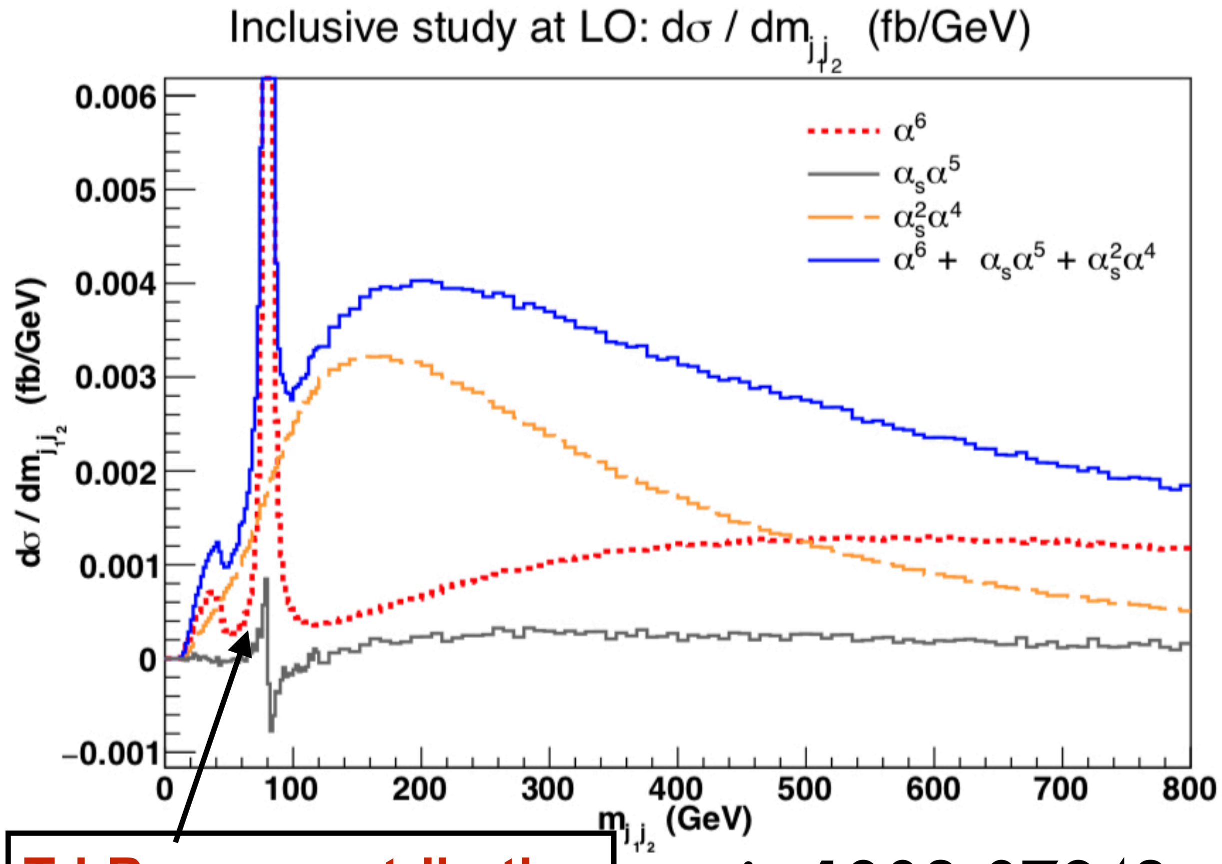
- **Distinct 2-jet topology**
  - **large dijet invariant mass ($m_{JJ} > 500$ GeV)**
  - **large pseudorapidity separation ($|\Delta\eta_{JJ}|>2.5$)**
  - **diboson system centralilty wrt dijets ($|\eta_{VV} - <\eta_{JJ}>| <2.5$),"zeppenfeld variable"**

$$\boxed{\eta* = \eta_{3l} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})}$$


dijet studies for EW Z production via s-channel

arXiv:hep-ph/9605444


Inclusive study at LO: $d\sigma / d|\Delta y_{j_1j_2}|$ (fb)


Inclusive study at LO: $d\sigma / dm_{j_1j_2}$ (fb/GeV)

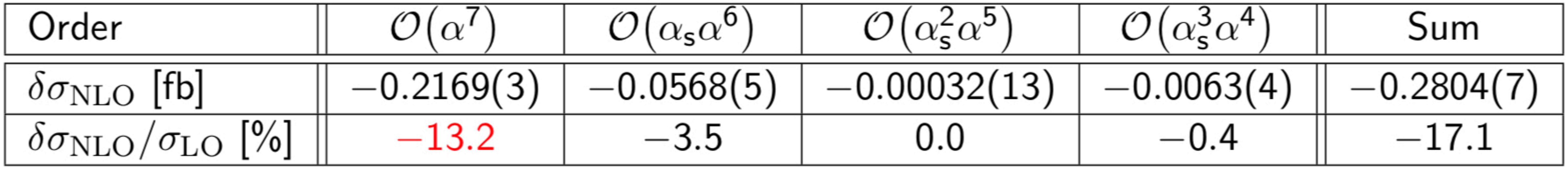
Tri-Boson contribution

arxiv:1803.07943

Progress On Theoretical Pred.

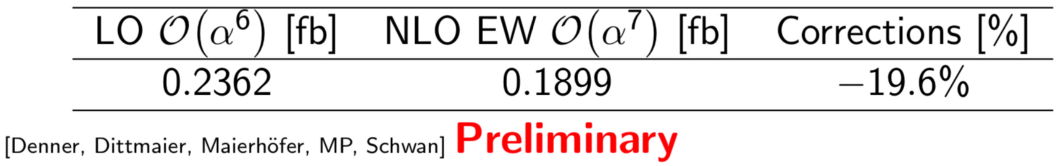
- **Diboson production cross section predictions recently improved**
  - **Full QCD+EW NLO computation for VBS W±W± (Biedermann, Denner, Pellen arXiv:1708.00268)**
  - **Full QCD+EW NLO computation for VBS W±Z (work in progress Pellen, Schwan et. al.)**
- **For W±W± -13% effect on cross section, ~ -19% for WZ**

W±W±



Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

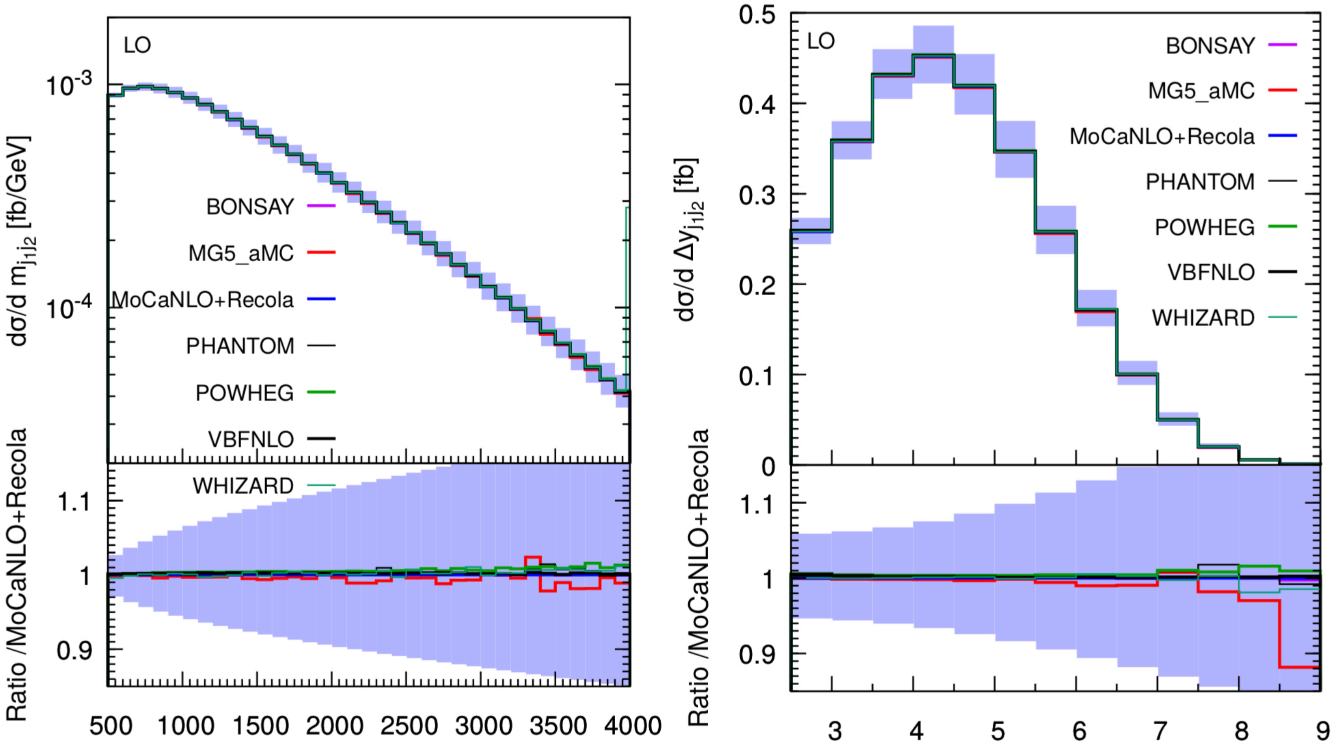
WZ



LO $\mathcal{O}(\alpha^6)$ [fb]	NLO EW $\mathcal{O}(\alpha^7)$ [fb]	Corrections [%]
0.2362	0.1899	-19.6%

[Denner, Dittmaier, Maierhöfer, MP, Schwan] Preliminary

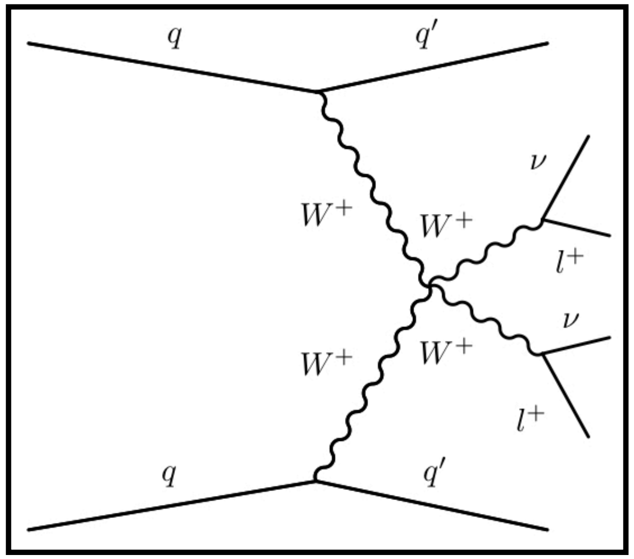
- **At LO, various generators show good agreement**
  - **Additional comparisons being performed also for the QCD-Induced background**



arxiv:1803.07943

$W^{\pm}W^{\pm}$ VBS (Observation 13 TeV)

- **SMP-17-004: VBS EW $W^{\pm}W^{\pm}$ measurement performed inclusively in ee, eμ, μμ channel, with 35.9 fb^{-1}**
  - **Probing the WWWW quartic coupling**

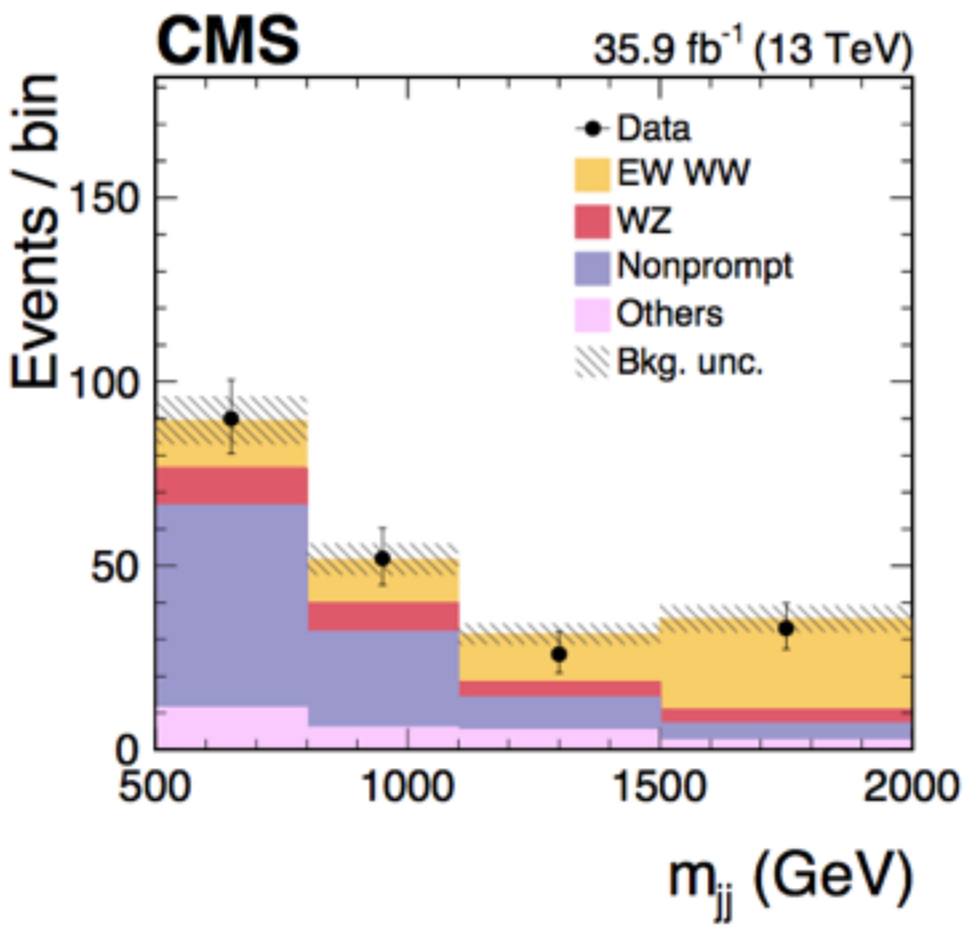


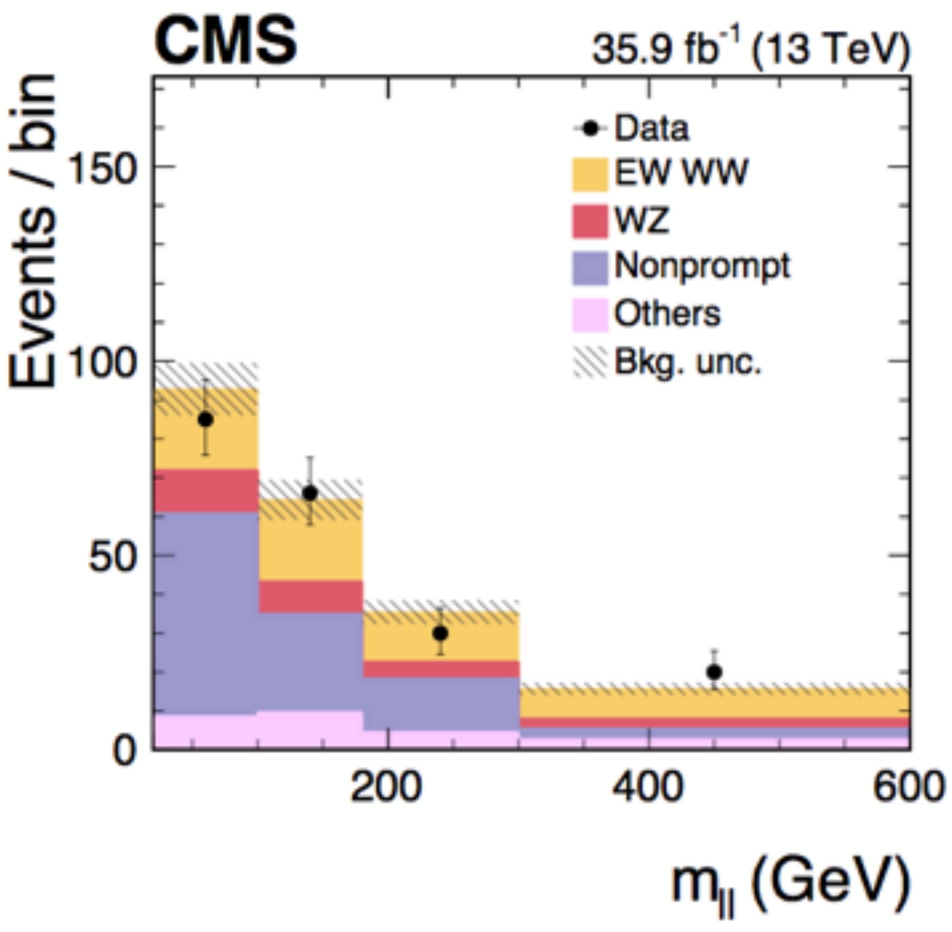
- **Event Selection:**
  - **Two same-sign isolated leptons p_T>25,20 GeV and $|\eta|$<2.5**
  - **VBS selection: 2 jets with p_T > 30 GeV m_{jj} > 500 GeV $|\Delta\eta_{JJ}|$> 2.5**
  - **Additional kinematic cuts to remove tt+jets and WZ contributions (b-jet veto and 3rd lepton veto)**
- **Largest background from non-prompt lepton and WZ processes, both controlled in the data**

Data	201
Signal + total bkg.	205 ± 13
Signal	66.9 ± 2.4
Total bkg.	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD WW	4.8 ± 0.4
Wγ	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

$W^{\pm}W^{\pm}$ VBS (Observation 13 TeV)

- **2d m_{ll} vs m_{jj} distribution used to measure best-fit signal strength modifier, enhances sensitivity**
  - **Major syst. unc.: jet energy scale, non-prompt background**
- **Significance with respect to background only hypothesis:**
  - **Observed (expected): 5.5σ (5.7σ)** $\sigma^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\text{fb}$
  - **Madgraph LO prediction:** $\sigma_{LO}^{EW} = 4.25 \pm 0.27\text{fb}$

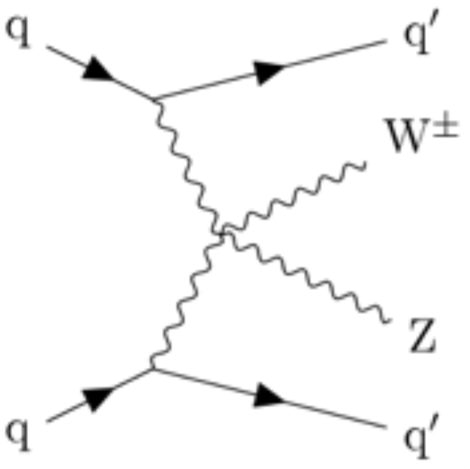


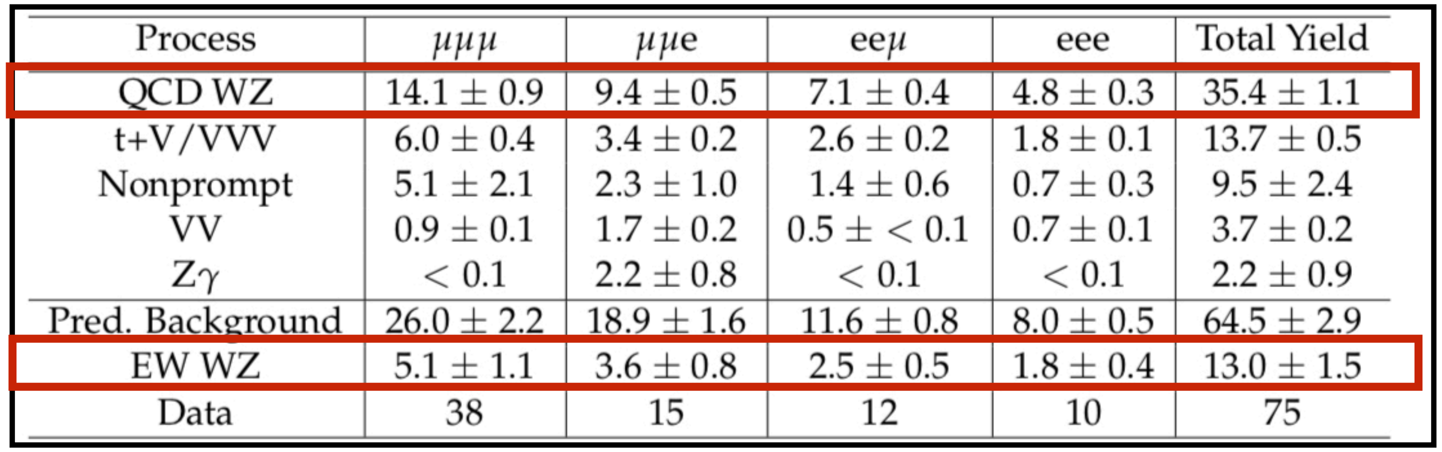


WZ VBS at 13 TeV

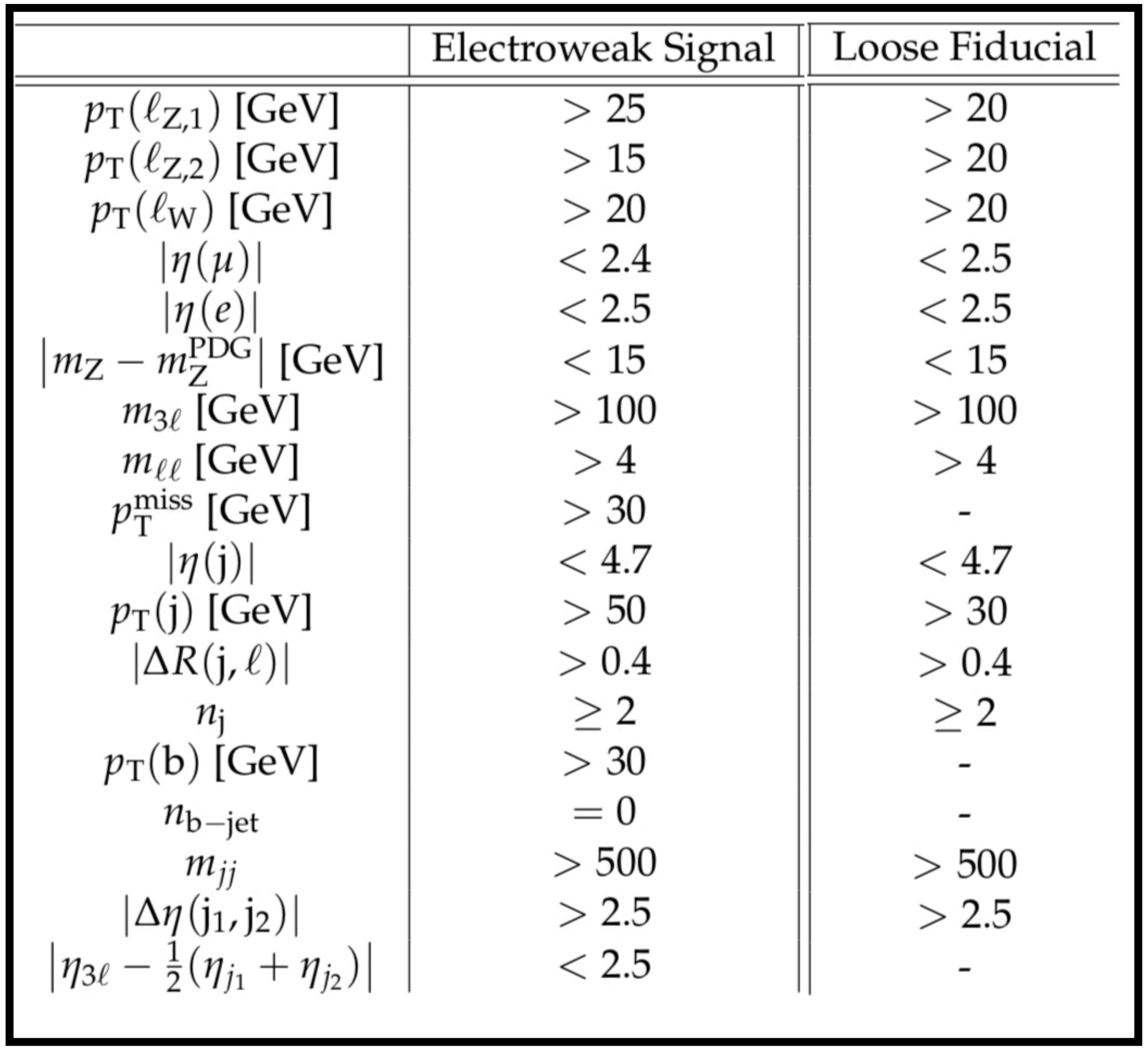
- **SMP-18-001: Most recent CMS VBS analysis, EW WZ cross section measurement performed with 35.9 fb^{-1}, in 3-lepton final-state (electron/muon)**

- **Probing the WWZZ quartic coupling**





Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total Yield
QCD WZ	14.1 ± 0.9	9.4 ± 0.5	7.1 ± 0.4	4.8 ± 0.3	35.4 ± 1.1
t+V/VVV	6.0 ± 0.4	3.4 ± 0.2	2.6 ± 0.2	1.8 ± 0.1	13.7 ± 0.5
Nonprompt	5.1 ± 2.1	2.3 ± 1.0	1.4 ± 0.6	0.7 ± 0.3	9.5 ± 2.4
VV	0.9 ± 0.1	1.7 ± 0.2	$0.5 \pm < 0.1$	0.7 ± 0.1	3.7 ± 0.2
$Z\gamma$	< 0.1	2.2 ± 0.8	< 0.1	< 0.1	2.2 ± 0.9
Pred. Background	26.0 ± 2.2	18.9 ± 1.6	11.6 ± 0.8	8.0 ± 0.5	64.5 ± 2.9
EW WZ	5.1 ± 1.1	3.6 ± 0.8	2.5 ± 0.5	1.8 ± 0.4	13.0 ± 1.5
Data	38	15	12	10	75

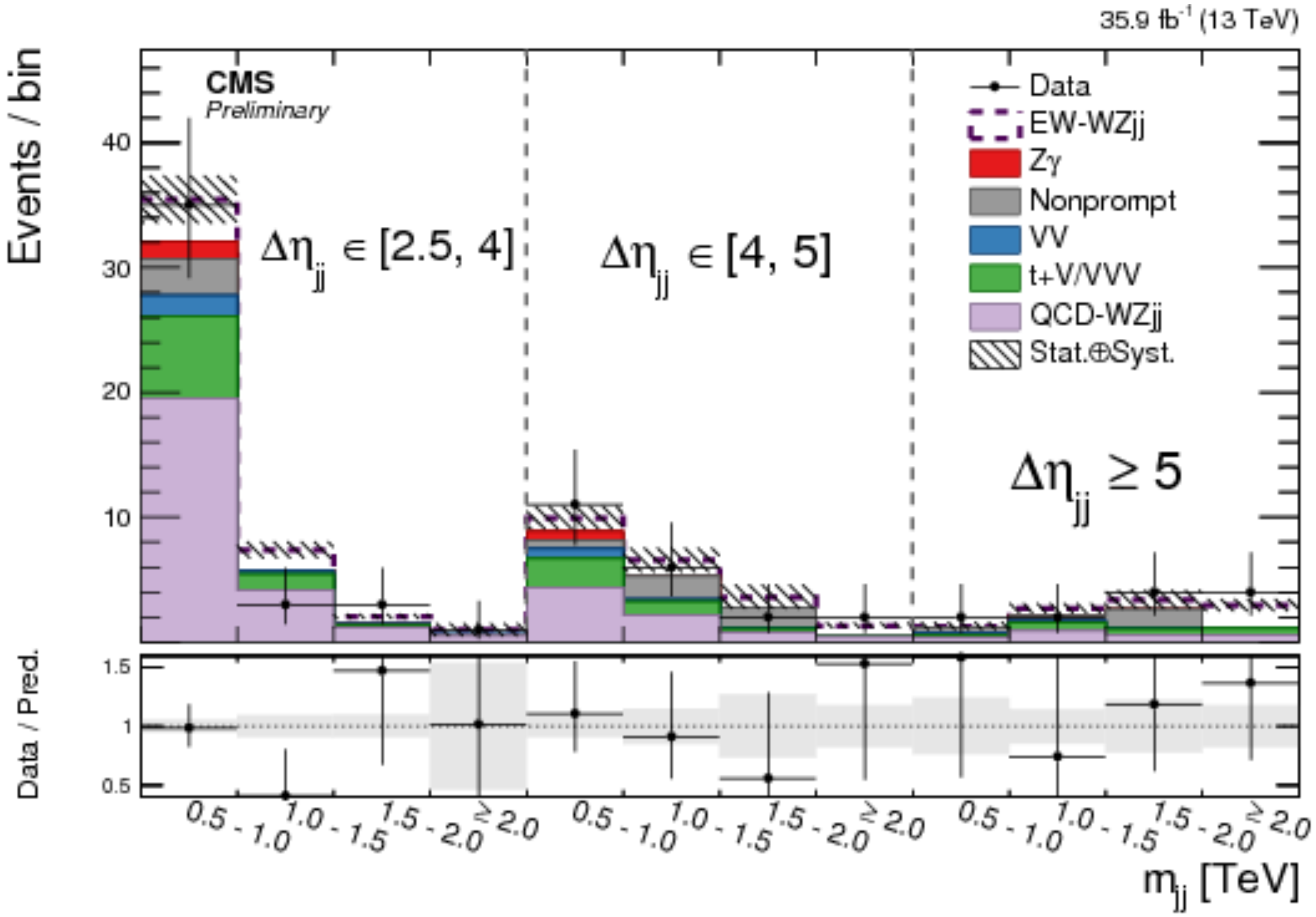


	Electroweak Signal	Loose Fiducial
$p_T(\ell_{Z,1})$ [GeV]	> 25	> 20
$p_T(\ell_{Z,2})$ [GeV]	> 15	> 20
$p_T(\ell_W)$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.4	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_Z - m_Z^{PDG}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_T^{miss} [GeV]	> 30	-
$\lvert\eta(j)\rvert$	< 4.7	< 4.7
$p_T(j)$ [GeV]	> 50	> 30
$\lvert\Delta R(j,\ell)\rvert$	> 0.4	> 0.4
n_j	≥ 2	≥ 2
$p_T(b)$ [GeV]	> 30	-
n_{b-jet}	$= 0$	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta(j_1, j_2)\rvert$	> 2.5	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5	-

- **WZ QCD induced largest background contribution, followed by VVV,ttV,tV and non-prompt**

WZ VBS at 13 TeV

- **QCD WZ process controlled in background enriched side-band**
  - **Signal region: events pass the VBS cuts m_{JJ} > 500 GeV, $|\Delta\eta_{JJ}|$>2.5, $|\eta^*|$<2.5**
  - **Control region: events pass m_{JJ} > 100 GeV and fail either of the VBS cuts**
- **Additional control regions: non-prompt (ttbar and Z+jets) enriched**
- **EW Signal extraction using 2d m_{JJ} vs $|\Delta\eta_{JJ}|$ distribution, combined fit performed with QCD WZ background control region**



WZ VBS at 13 TeV

- **Full 2-jet associated (QCD+EW) WZ production measured in VBS fiducial volume**
  - **measured:** $\sigma^{\text{fid,loose}}_{\text{WZjj}} = 4.01^{+0.72}_{-0.68}\,(\text{stat})\ ^{+0.57}_{-0.47}\,(\text{syst})$ fb
  - **MadGraph (LO) predicted:**

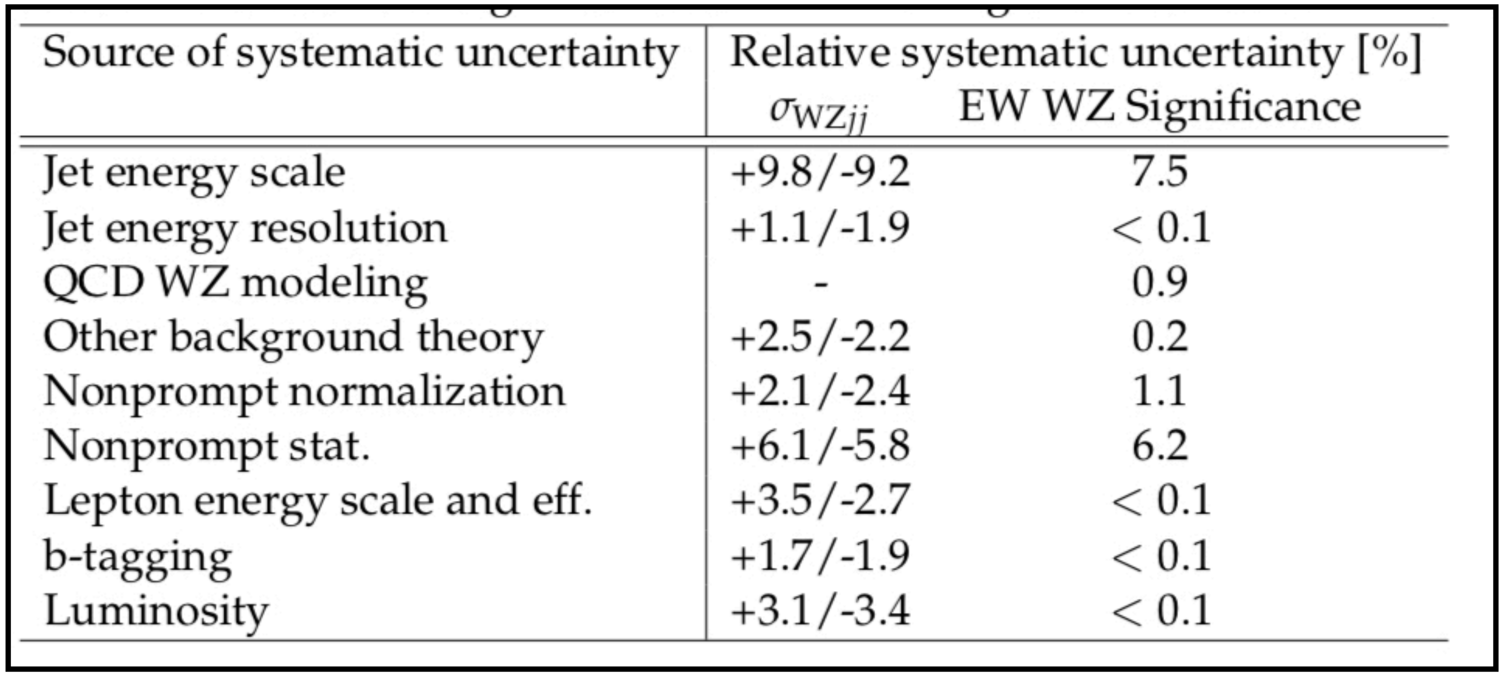
$$\sigma_{LO} = 4.51^{+0.59}_{-0.45}(\text{scale}) \pm 0.18(\text{PDF})\ \text{fb}$$

Ideal for comparisons to full QCD+EW NLO predictions

- **Significance with respect to background only hypothesis**
  - **Observed (expected) significance: 1.9σ (2.7σ)**
- **Best fit signal strength modifyer value for EW VBS WZ production**

$$\sigma^{pred.}_{EW} = 1.48^{+0.12}_{-0.11}(\text{scale}) \pm 0.07(\text{PDF})\text{fb}$$

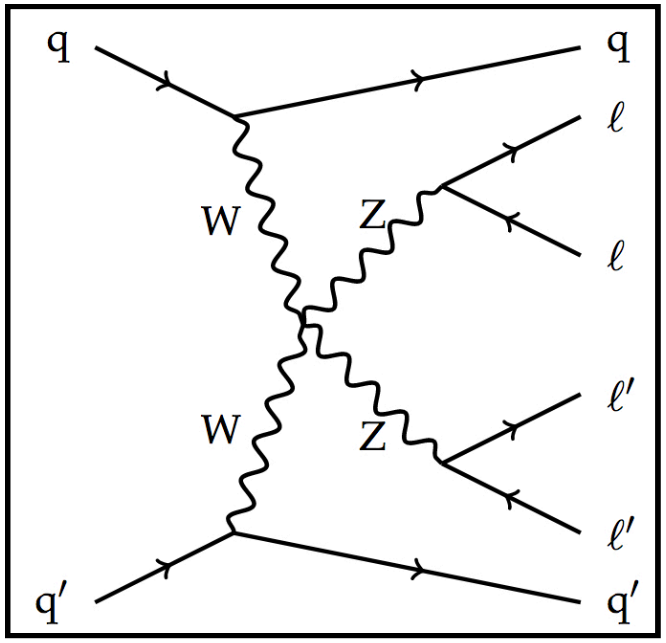
$$\boxed{\mu_{EW} = 0.64^{+0.45}_{-0.37}}$$



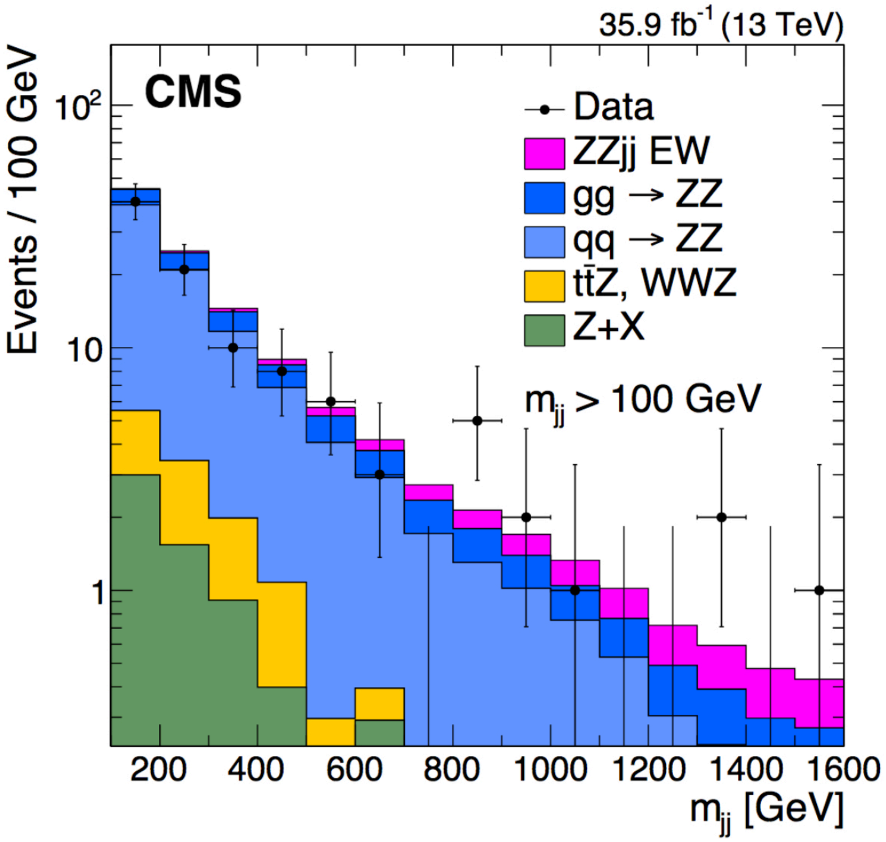
Source of systematic uncertainty	Relative systematic uncertainty [%]	
	$\sigma_{\text{WZ}jj}$	EW WZ Significance
Jet energy scale	+9.8/-9.2	7.5
Jet energy resolution	+1.1/-1.9	< 0.1
QCD WZ modeling	-	0.9
Other background theory	+2.5/-2.2	0.2
Nonprompt normalization	+2.1/-2.4	1.1
Nonprompt stat.	+6.1/-5.8	6.2
Lepton energy scale and eff.	+3.5/-2.7	< 0.1
b-tagging	+1.7/-1.9	< 0.1
Luminosity	+3.1/-3.4	< 0.1

ZZ VBS at 13 TeV

- **SMP-17-006**: EW VBS ZZ production cross section measurement performed in fully leptonic final state with 35.9 fb^{-1}
    - Probing the **WWZZ** quartic coupling, but also “effective” **ZZZZ** coupling!



- Event selection requires:
    - 4 leptons: $p_T > 20,12,7,7$ $(20,10,5,5)$ GeV, $|\eta|<2.5$ (2.4) for electrons (muons)
    - 2 OSSF dilepton pairs with $60 < m_{ll} < 120$ GeV
    - 2 jets with $p_T > 30$ GeV and $m_{jj} > 100$ GeV



Selection	tt̄Z 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

$m_{jj} > 400\,\mathrm{GeV}$ and $|\Delta\eta_{jj}| > 2.4$

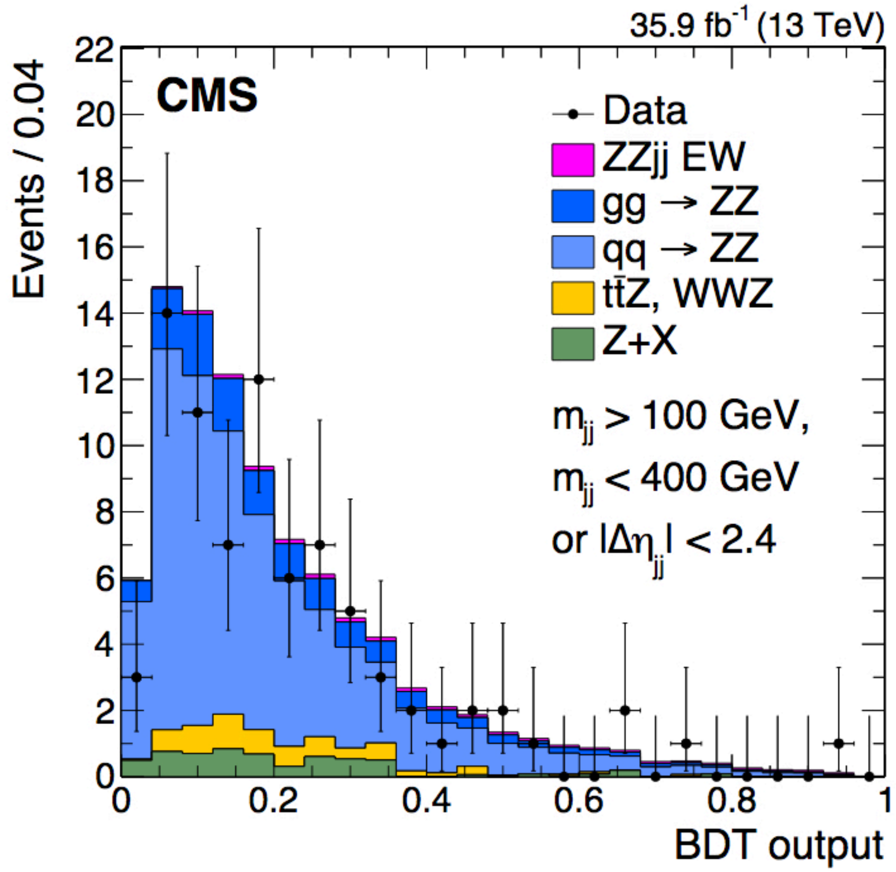
ZZ VBS at 13 TeV

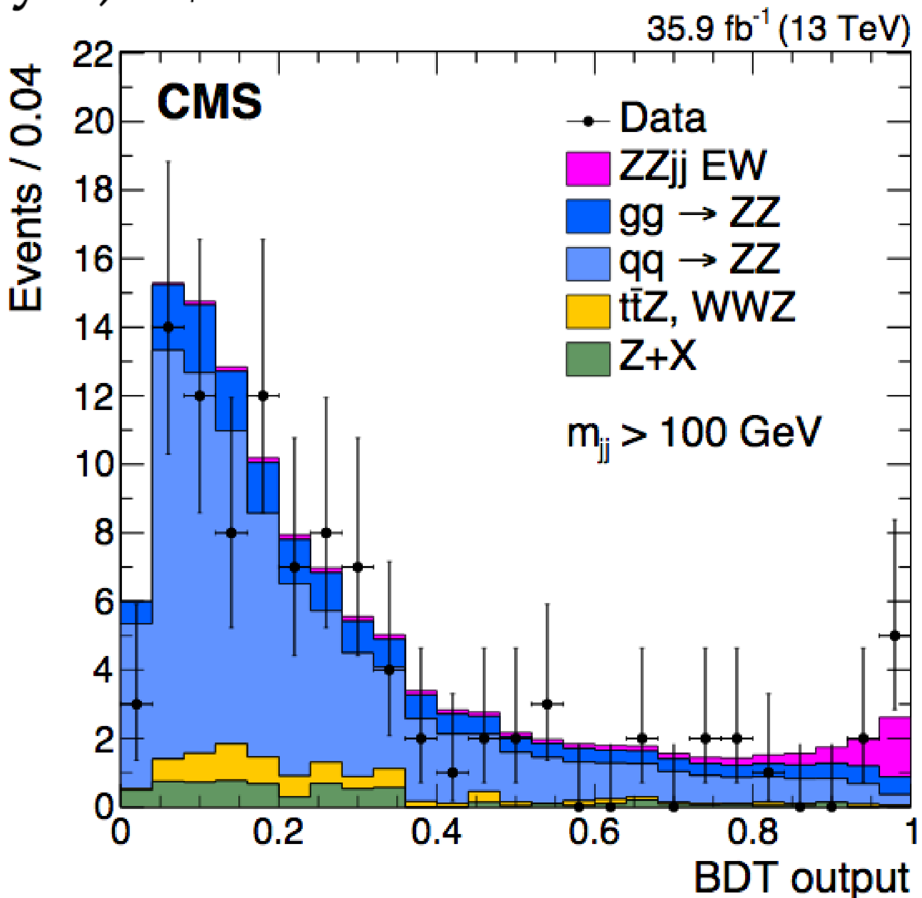
- **Signal extraction performed exploiting boosted decision tree to enhance sensitivity (7 most performant variables used)**
  - **m_{JJ}, $\Delta\eta_{JJ}$, m_{ZZ}, $Z_{1,2}$-centrality, vector/scalar sum of VBS-jets and of ZZ+jets**
- **Significance with respect to background only hypothesis**
  - **2.7σ (1.6σ) observed (expected)**
- **Best fit signal strength modifier for EW VBS ZZ production:**

$$\sigma^{LO}_{EW} = 0.29^{+0.02}_{-0.03}\,\mathrm{fb}$$

$$\mu = 1.39^{+0.86}_{-0.65}$$

$$\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{ZZjj} \to \ell\ell\ell'\ell'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,{}^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$$





Summary of EW Diboson Production

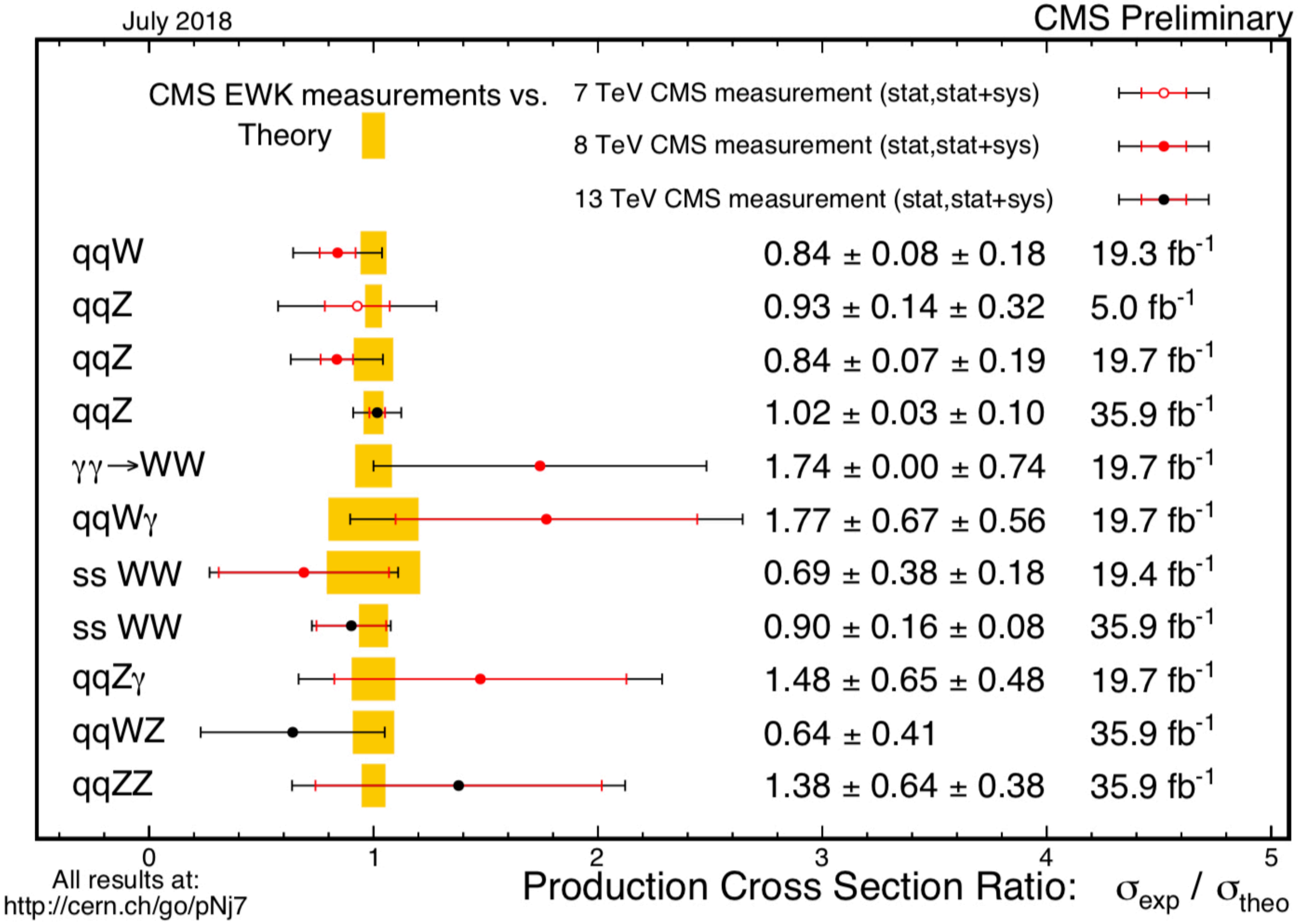
- **General experimental features of the different analysis shown in table below (for 2016 dataset):**
  - **EW cross section largest for $W^{\pm}W^{\pm}$, smallest for ZZ**
  - **Relative QCD contribution largest for ZZ, smallest for $W^{\pm}W^{\pm}$**
  - **Non-prompt background largest for $W^{\pm}W^{\pm}$, smallest for ZZ**
  - **WZ is in between $W^{\pm}W^{\pm}$ and ZZ**

	W±W±	**WZ**	**ZZ**
exp. EW yield in VBS region	**67**	**13**	**4**
exp. QCD yield in VBS region	**5**	**35**	**19**
#leptons	**2+2v**	**3+v**	**4**
major backgrounds	**non-prompt**	**non-prompt/VVV/ QCD**	**QCD**

- **Jet energy scale uncertainty has largest impact on the measurements, similar to EW W/Z production via VBF**

Summary of EW Diboson Production

- **First EW 2-jet associated diboson production process observed**
- **EW NLO corrections are 10-20% for VBS processes**
  - **Statistical unc. for W±W± will decrease to ~10% on full Run-2 dataset**
- **With full Run-2 dataset aim for observation of VBS WZ and ZZ production**



Dim-8 Operators and EFT

- **Anomalous Quartic Gauge Couplings (aQGC), basis from Eboli et al (hep-ph/0606118)**
  - Note 1.: dim-6 operators can also change QGC
  - Note 2.: New Physics models exist for which dim-8 effects are larger than effects introduced on TGC from dim-6
- **Unitarity generally not preserved**
  - Unitarity constraints on EFT introduce model dependence
  - By default, no unitarization scheme applied
    - **comparisons made using clipping method**

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}\,,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}\,,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}\,,$$
$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}\,,$$
$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}\,,$$
$$\mathcal{O}_{T,3} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\widehat{W}^{\nu\alpha}\right] \times \widehat{B}_{\beta\nu}$$
$$\mathcal{O}_{T,4} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\alpha\mu}\widehat{W}^{\beta\nu}\right] \times \widehat{B}_{\beta\nu}$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]\,,$$
$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]\,,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\mu\Phi\right] \times \widehat{B}^{\beta\nu}\,,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\nu\Phi\right] \times \widehat{B}^{\beta\mu}\,,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right]\,.$$

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

Will we see effective ZZZZ couplings at the LHC?

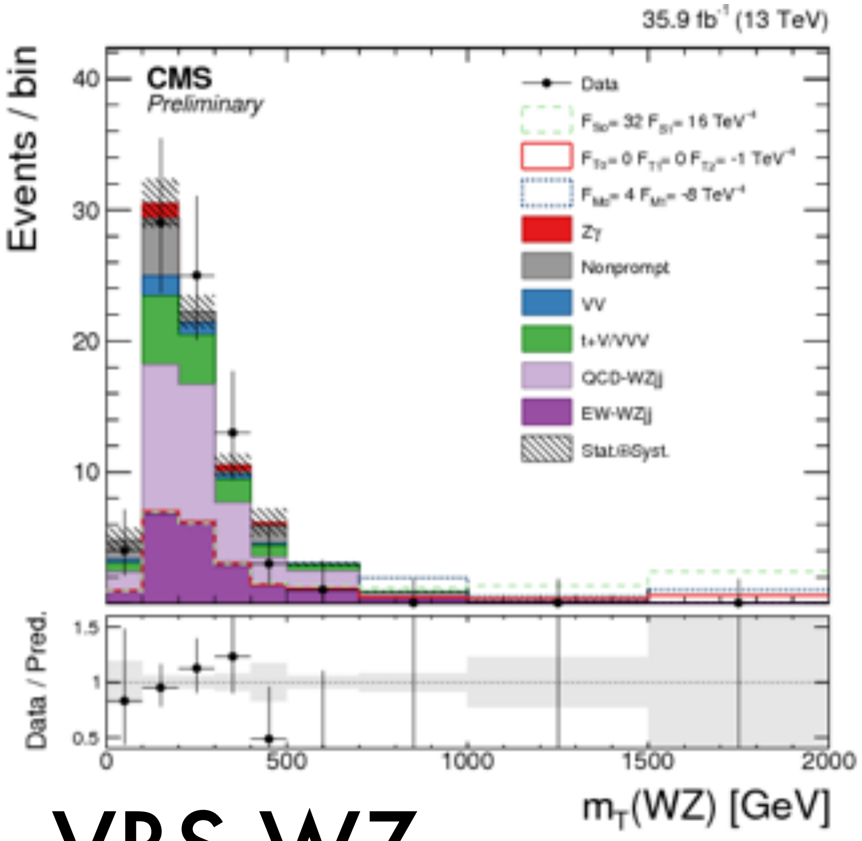
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

Work ongoing for specific model applications and dim-6 dim-8 aQGC disentanglement

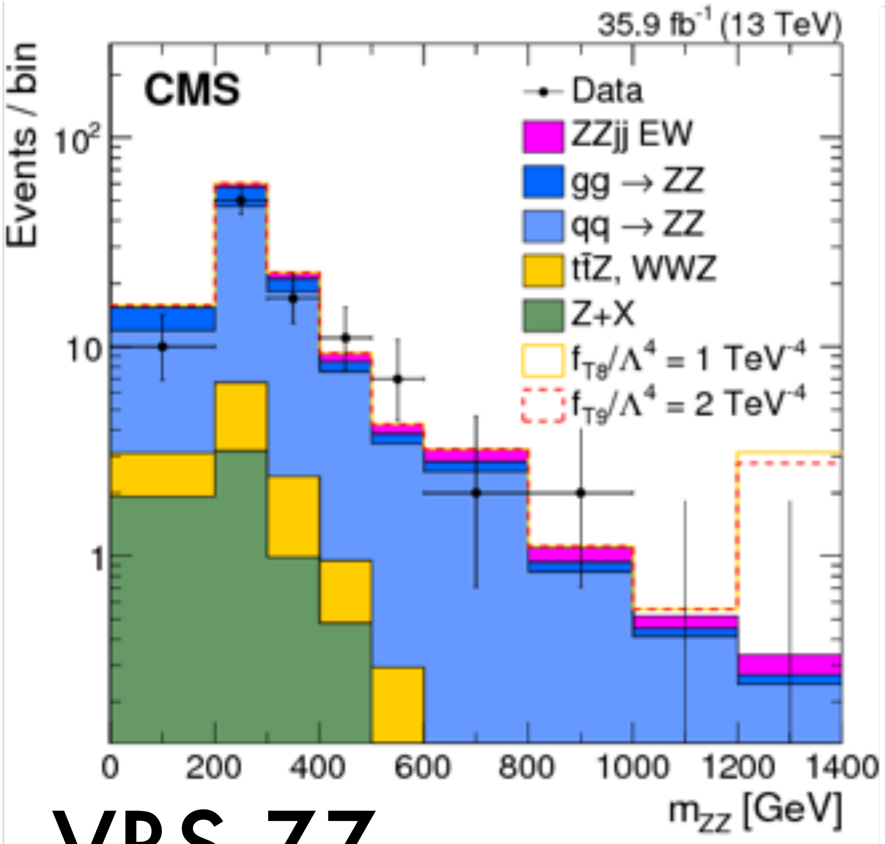
arxiv.1307.8170

EFT Interpretation

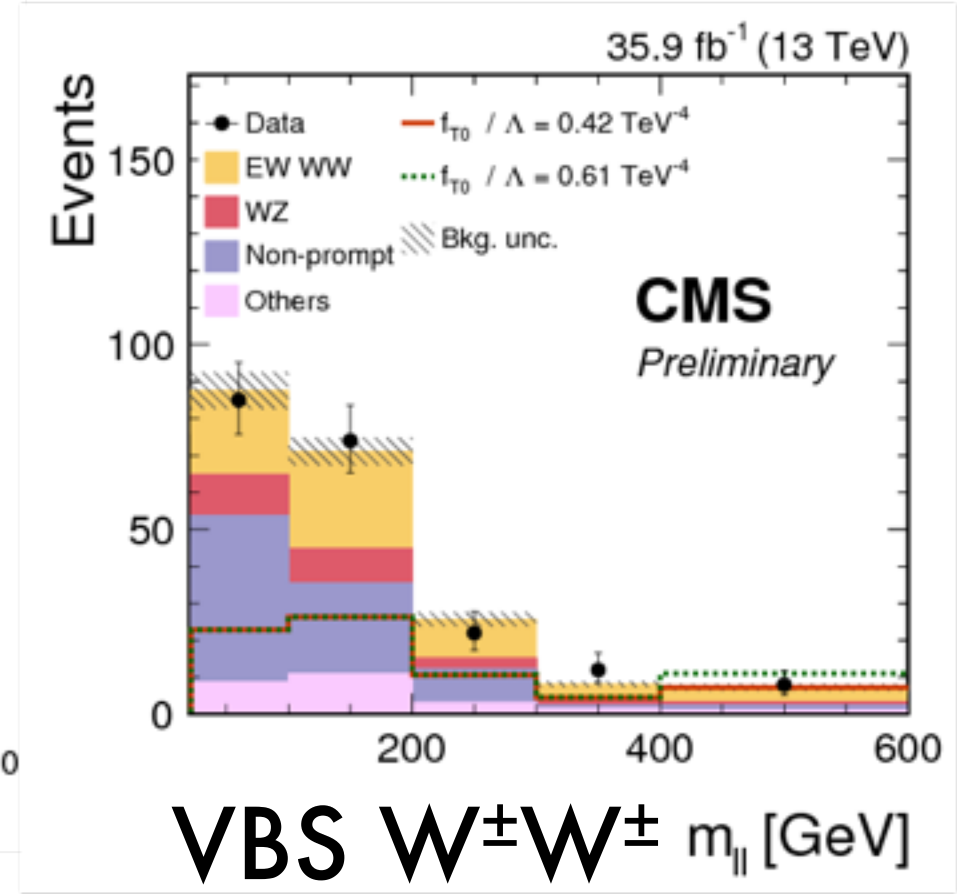
- **Contributions from EFT dimension-8 operators would be signaled by an excess of events at high diboson invariant masses**
  - **transverse mass used for VBS WZ**
  - **m(4l) used for VBS ZZ**
  - **m(2l) used for VBS W±W±**



VBS WZ



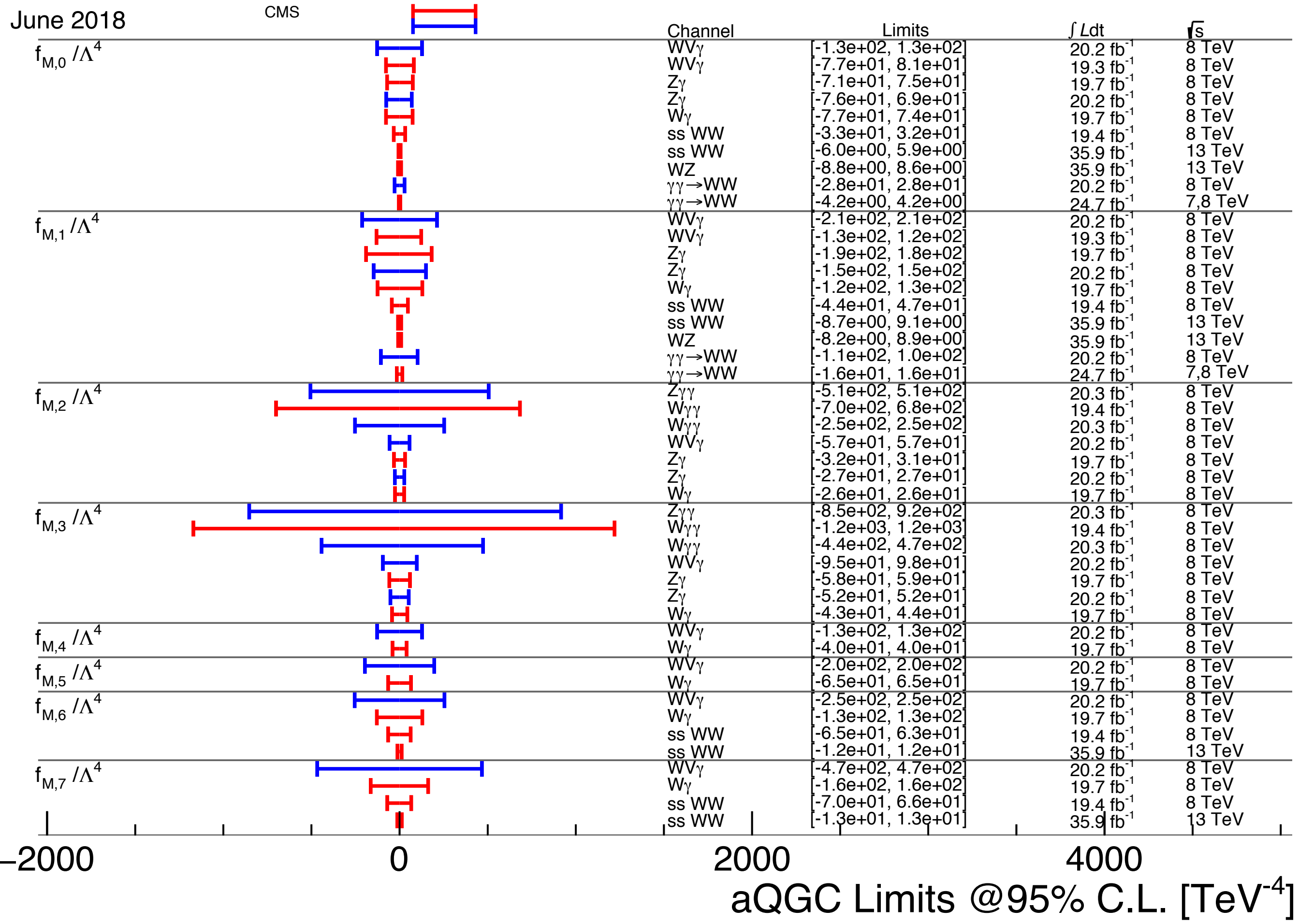
VBS ZZ

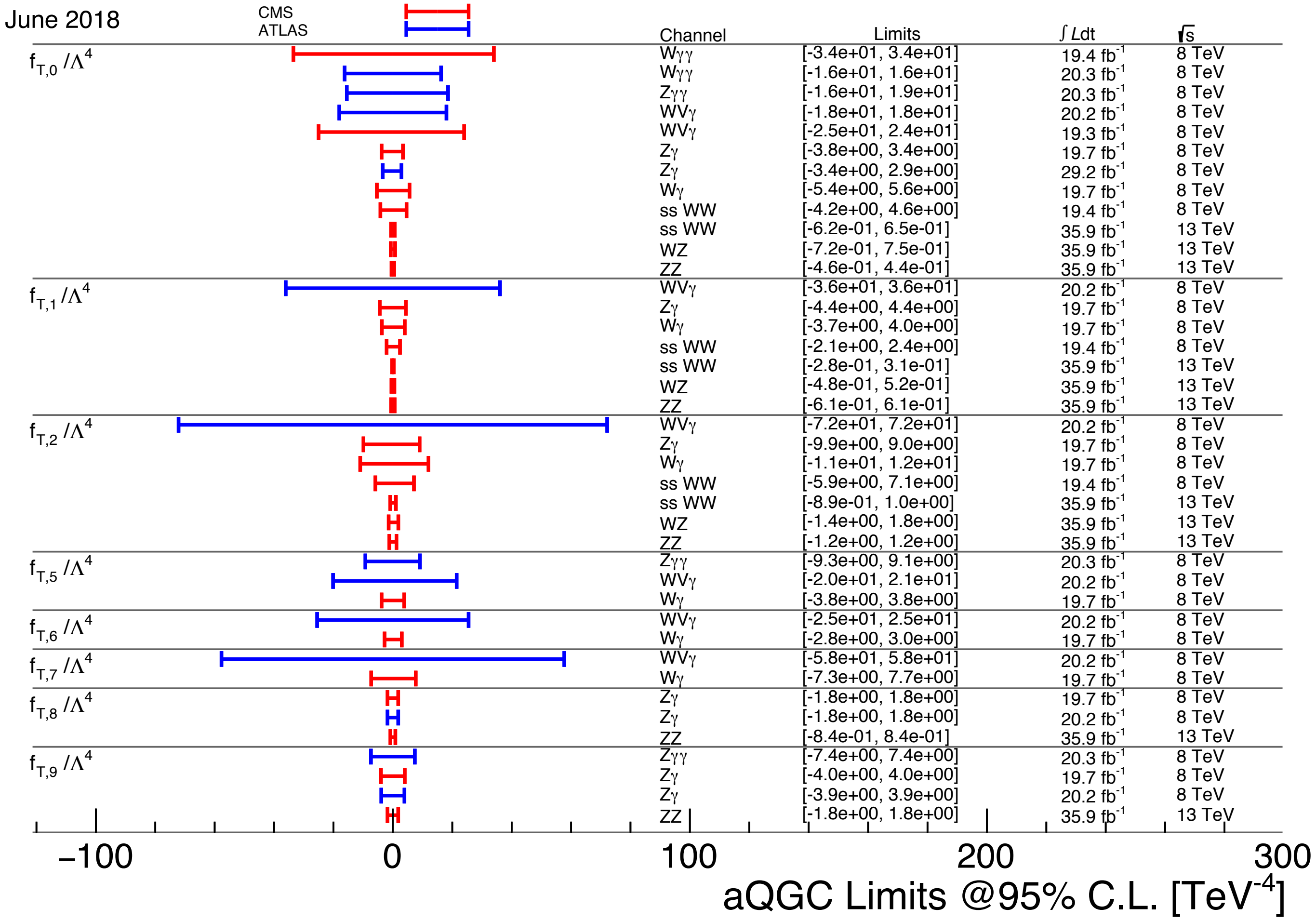


VBS W±W±

- **Madgraph used for simulation of dim-8 operator contributions**

Constraints on dim-8 Operators

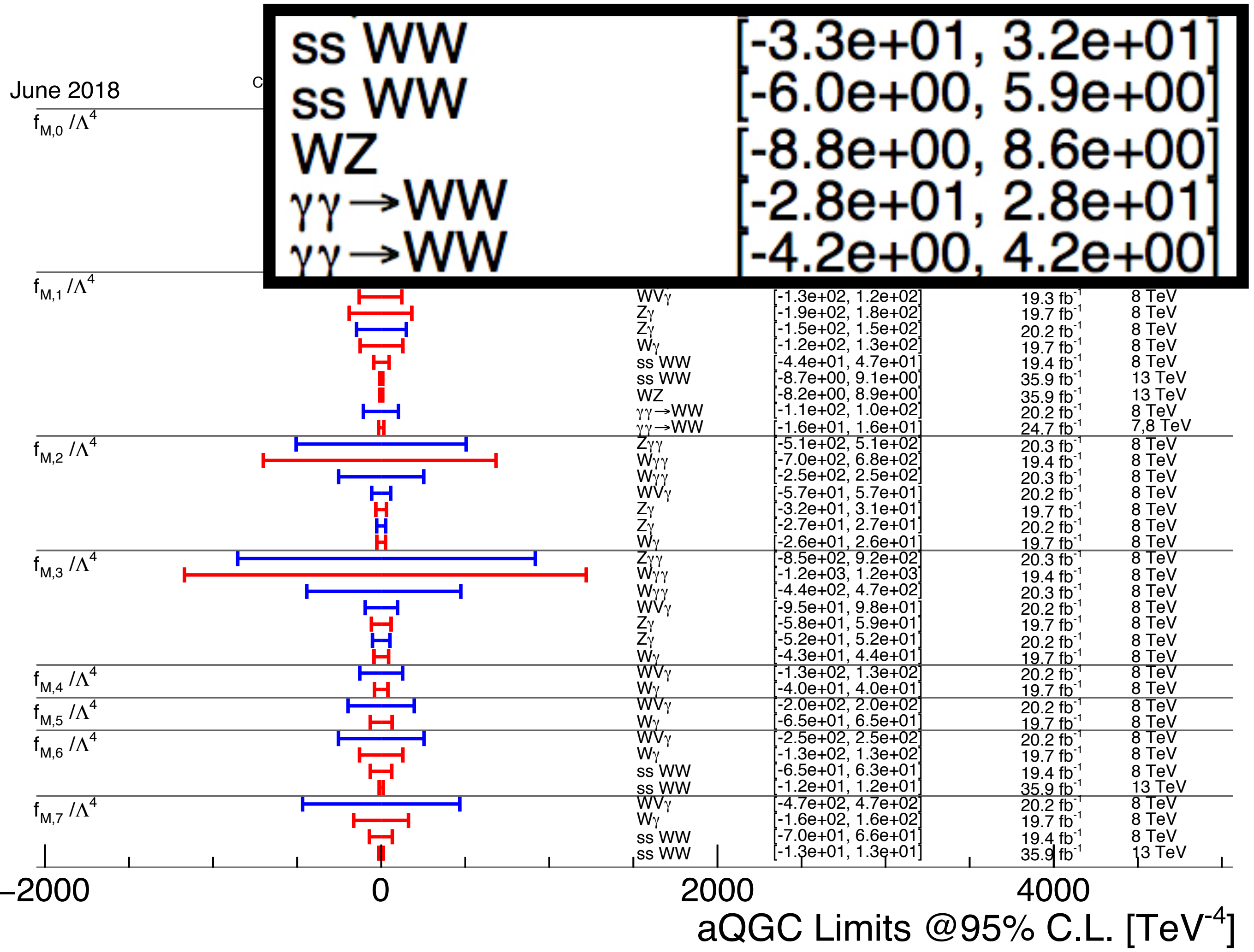




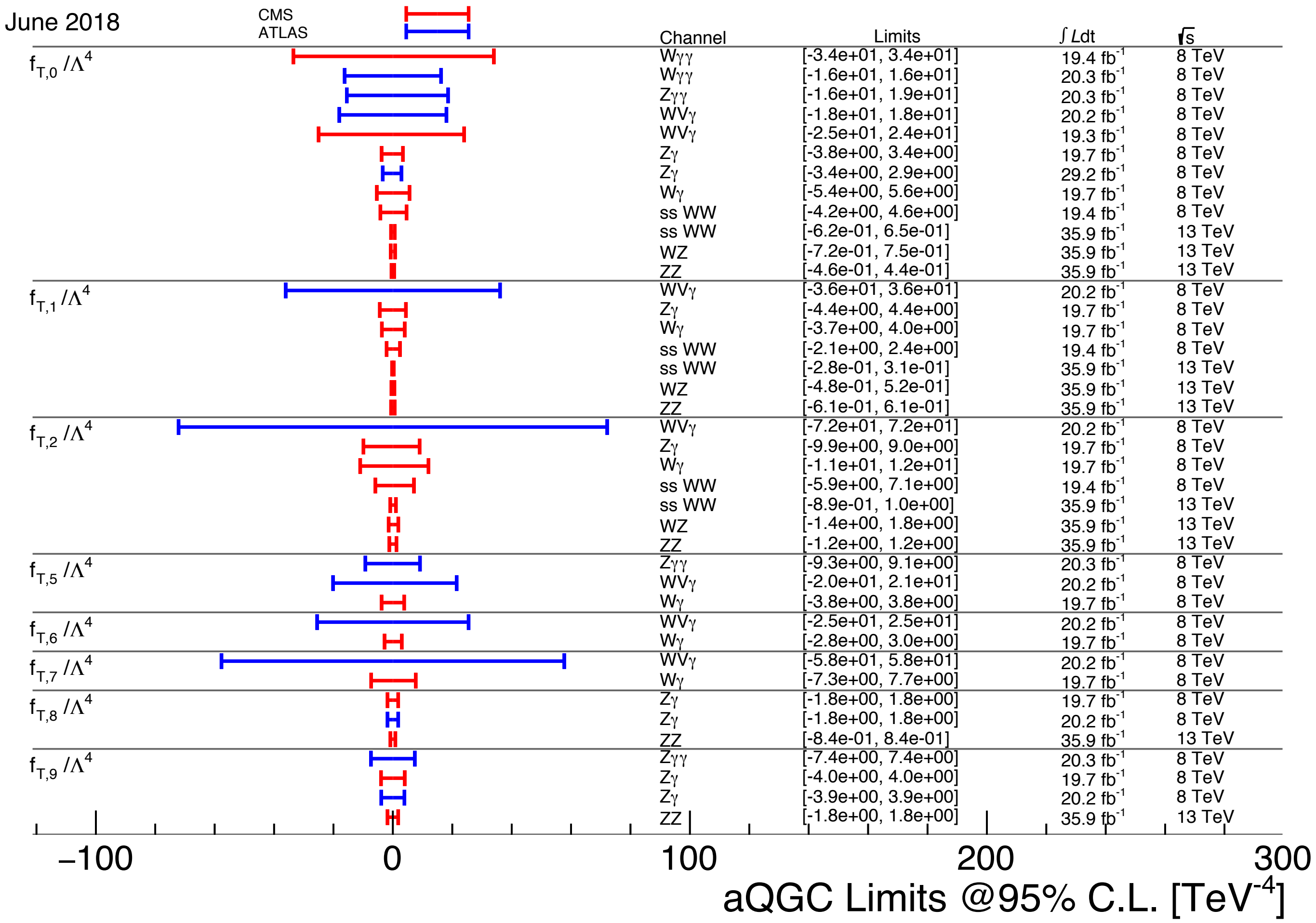
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

- **Important to probe all diboson processes to cover full range of contributions dim-8 operators**

Constraints on dim-8 Operators



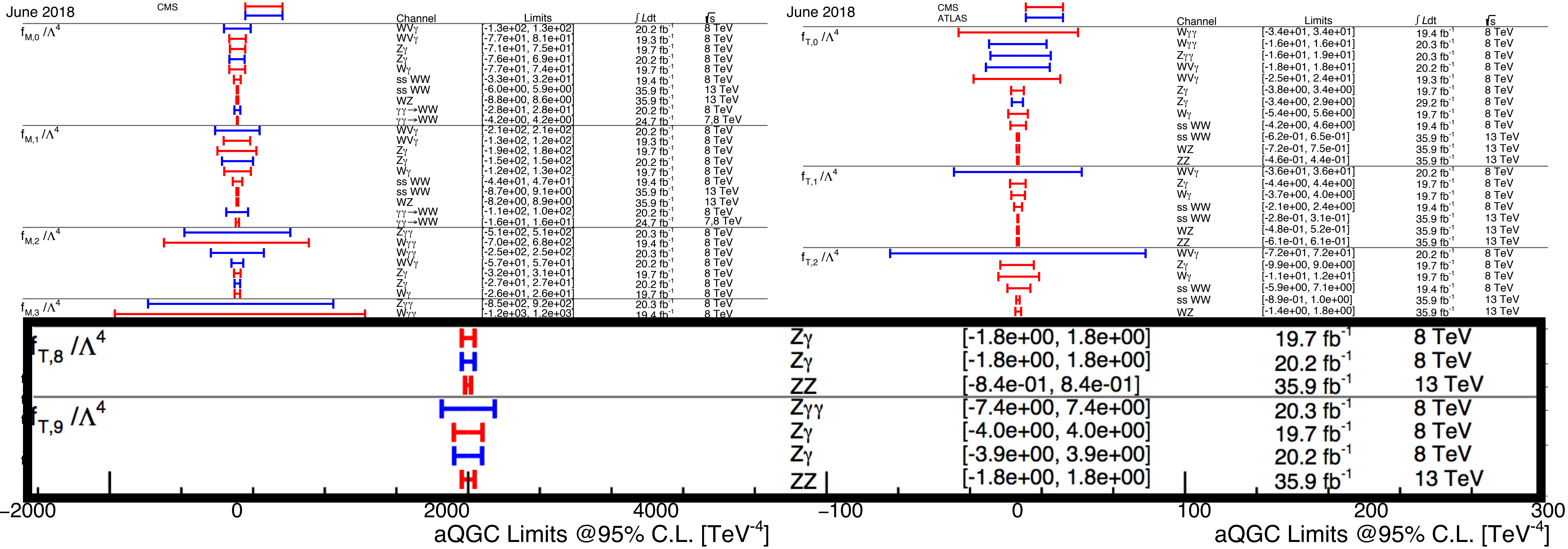
ss WW	[-3.3e+01, 3.2e+01]
ss WW	[-6.0e+00, 5.9e+00]
WZ	[-8.8e+00, 8.6e+00]
γγ→WW	[-2.8e+01, 2.8e+01]
γγ→WW	[-4.2e+00, 4.2e+00]



	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

- **Generally, VBS W±W± places most stringent limits**
  - **with few exceptions, $f_{M,0}$ exclusive γγ→WW analysis at 8 TeV places more stringent limits than W±W± results**

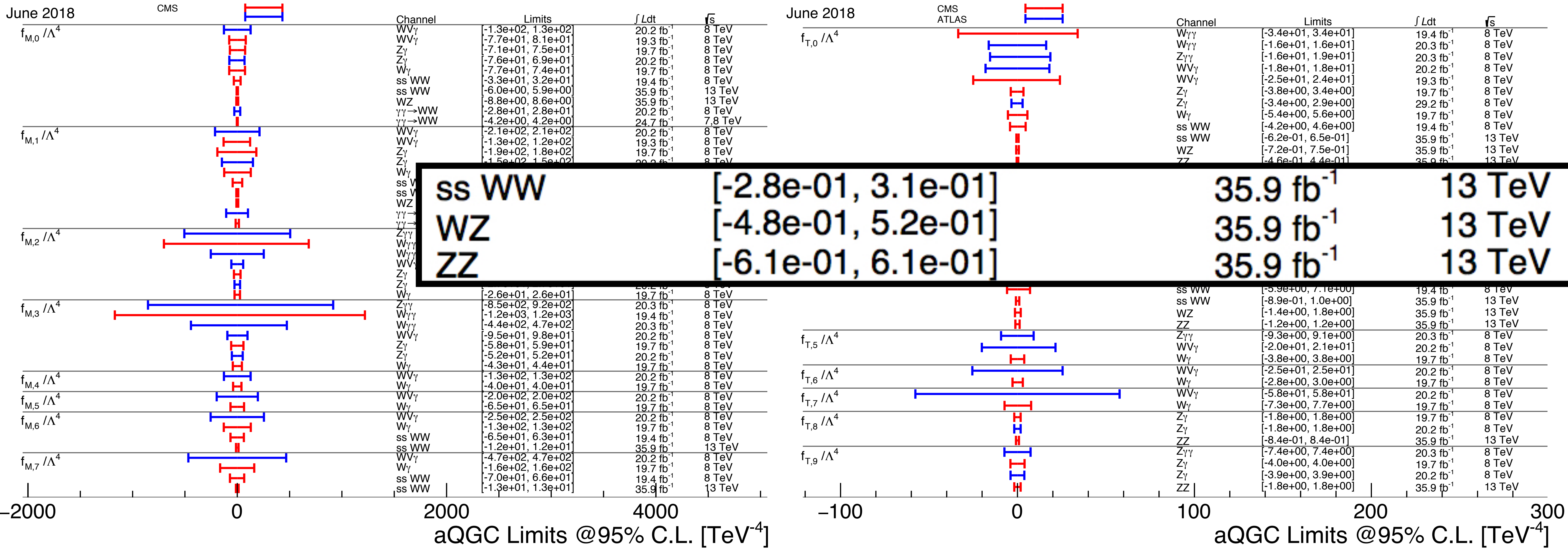
Constraints on dim-8 Operators

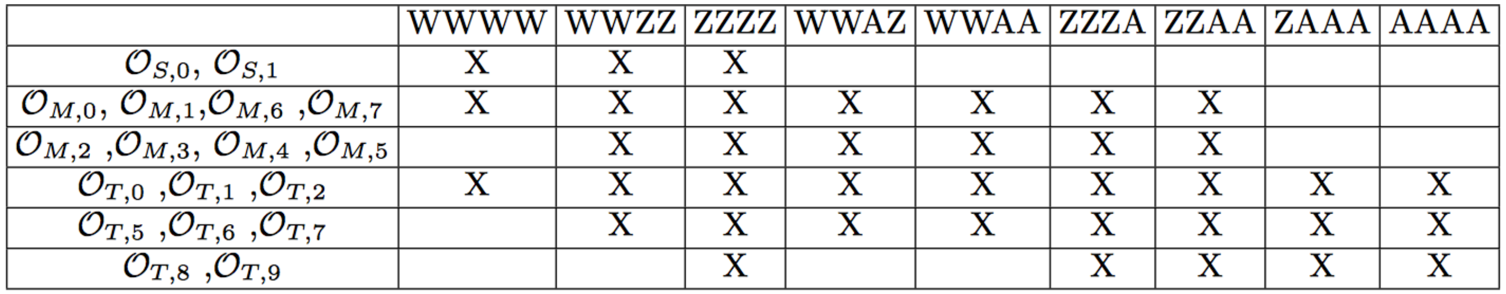


	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

- **Generally, VBS W±W± places most stringent limits**
- **W±W± not sensitive to neutral $f_{T,8}$,$f_{T,9}$ operators, VBS ZZ search needed**

Constraints on dim-8 Operators



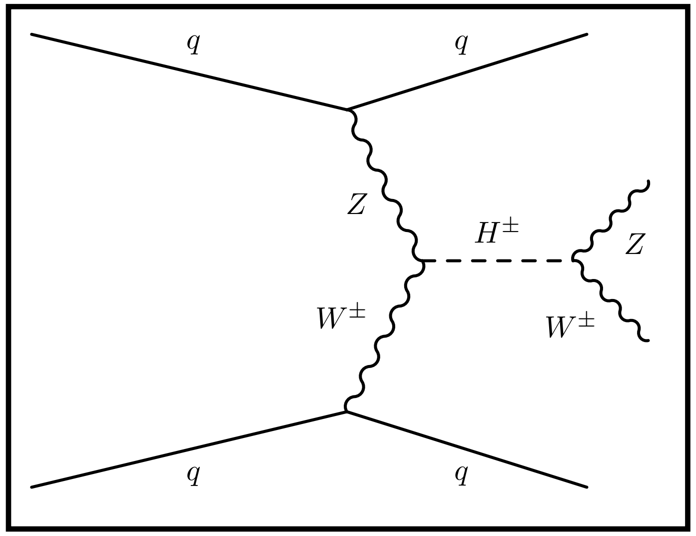


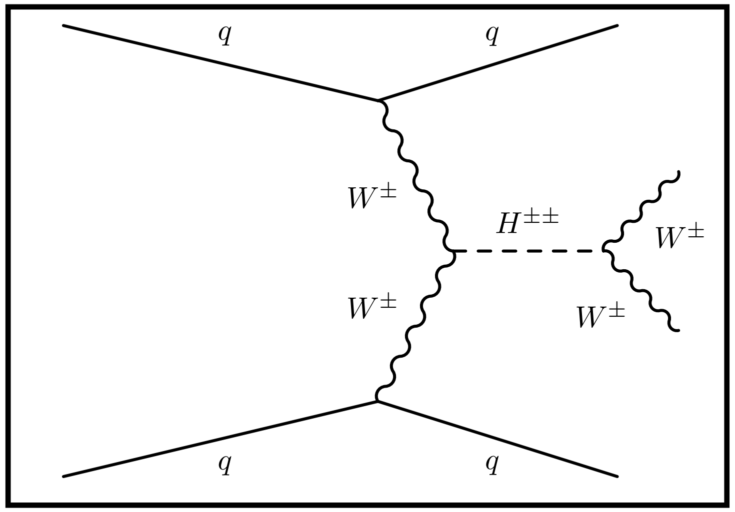
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

- **Indirectly probing mass scales of >1 TeV with $f_{T,1}$ operator (assuming coupling coefficient of O(1)) with ZZ, WZ and $W^\pm W^\pm$**

Extended Higgs Sectors in VBF

- **Experiments usually search charged Higgs bosons in lepton decays, inspired by models with additional Higgs doublets (nHDM)**
  - **Higgs sectors are largely constrained by custodial symmetry**
  - **Simple triplet extensions are constrained to have very small vacuum expectation value**
- **H. Georgi, M. Machacek 1985 found trick to cancel violating effects for SU(2) triplets at tree-level (next-to-minimal Higgs extensions)**



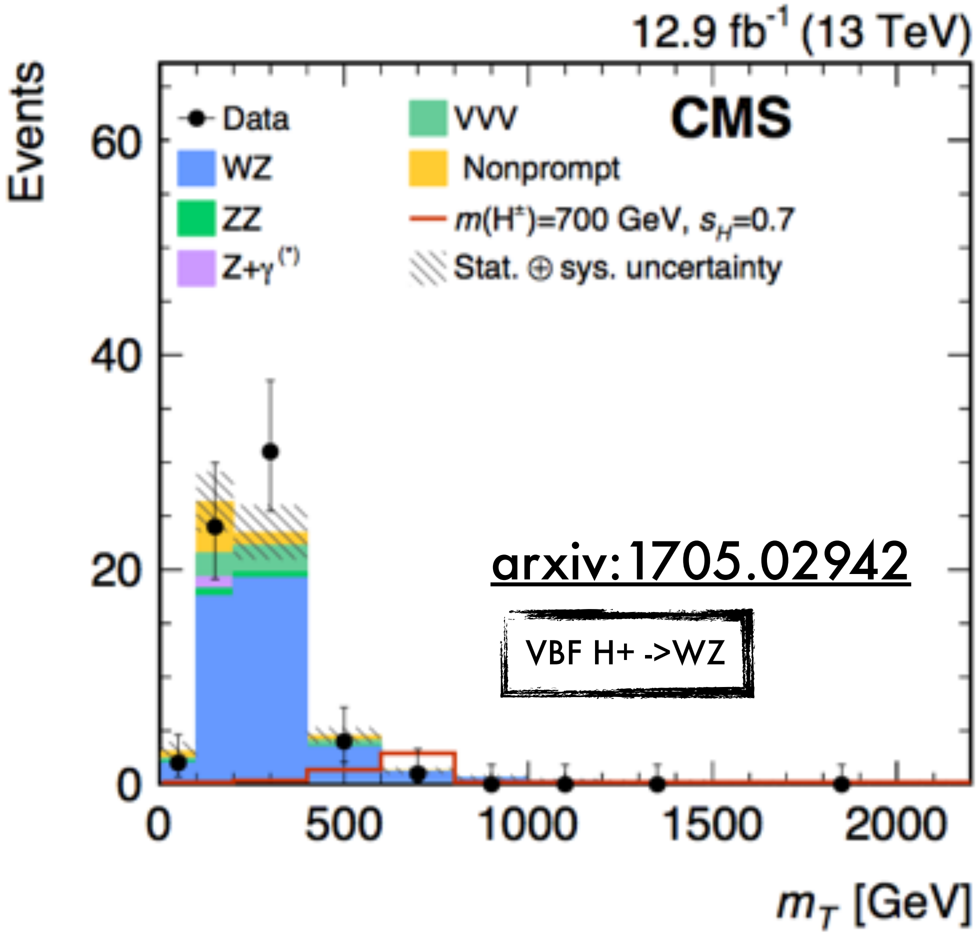


- **Distinct phenomenological features: VBF production of charged Higgs bosons**
  - **doubly-charged Higgs bosons**
  - **large couplings to vector bosons, small couplings to fermions**
- **Model parameters consist of additional Higgs masses and s_H, fraction of W mass generated by Higgs triplets**

VBF Diboson Resonances (13 TeV)

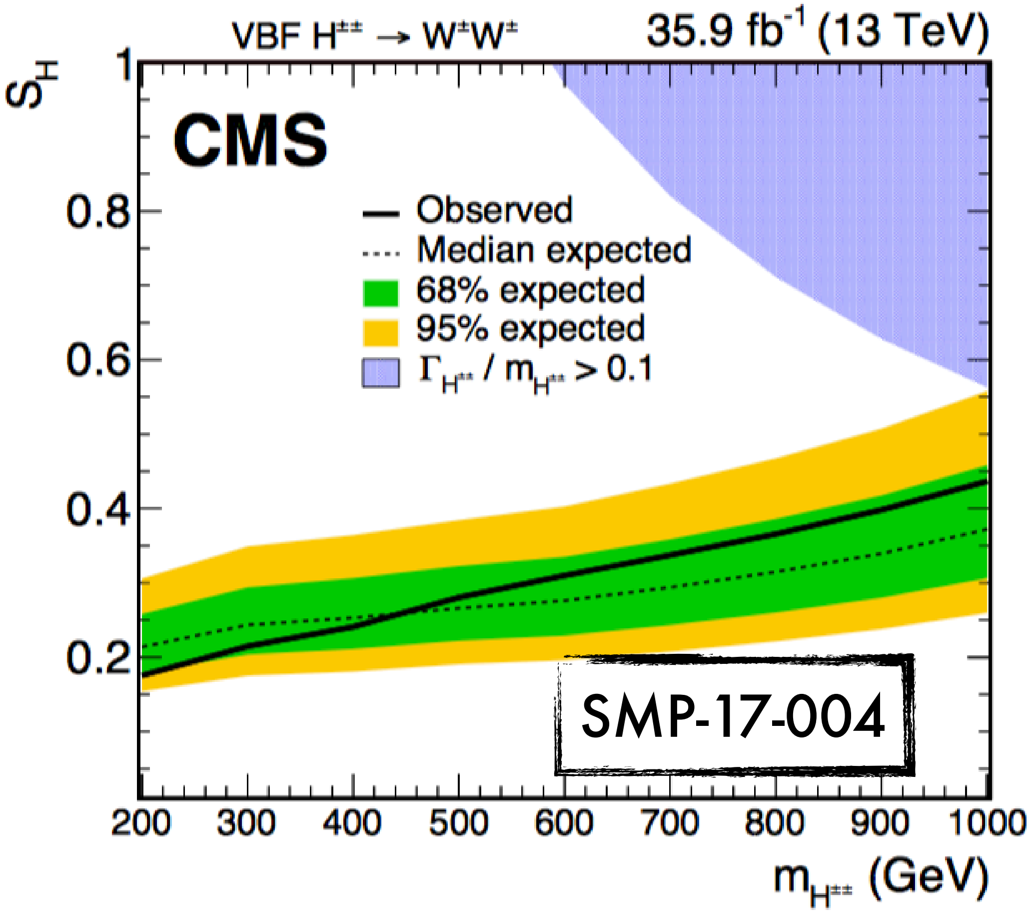
- **CMS performed searches for VBF H^{++} and H^{+} production at 13 TeV**

- **VBF/VBS dijet selection applied exploiting**
- **$W^{\pm}W^{\pm}$ analysis most performant when interpreted in Georgi-Machacek Model**

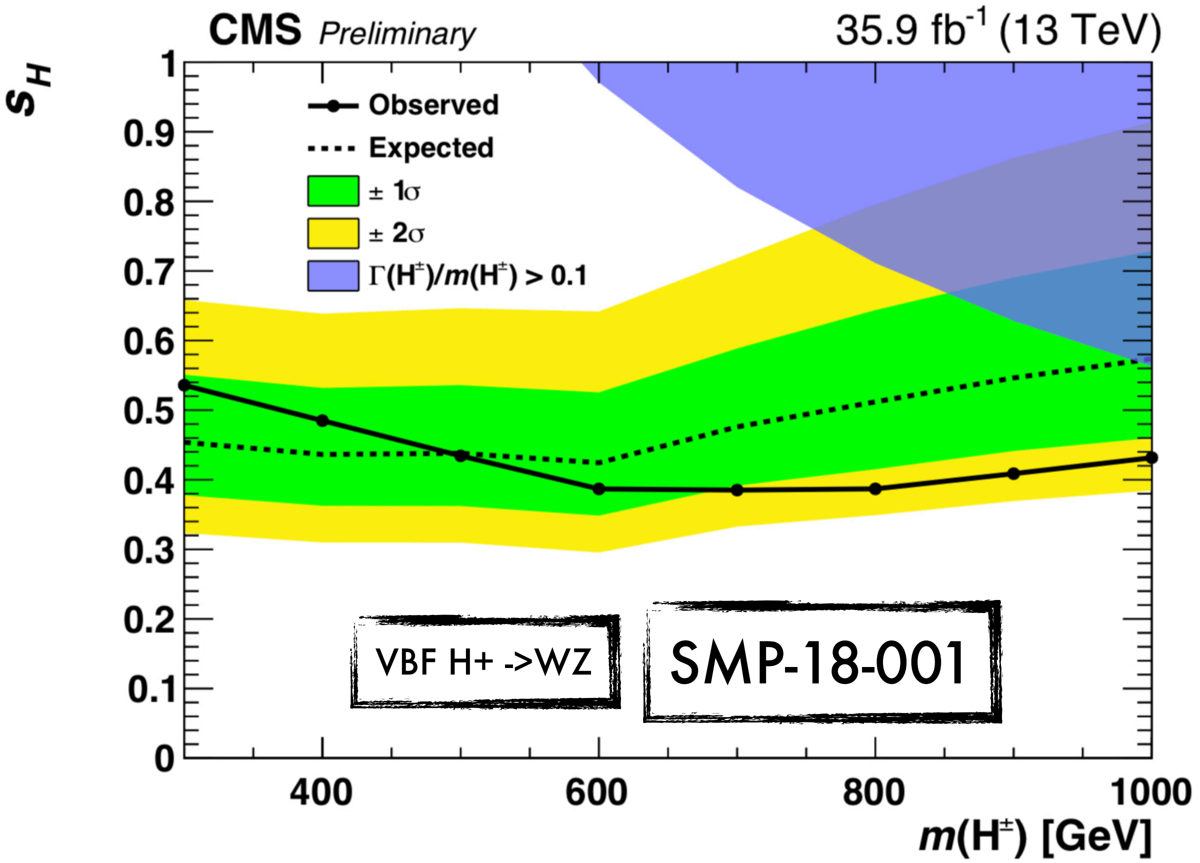


arxiv:1705.02942

VBF H+ ->WZ



SMP-17-004

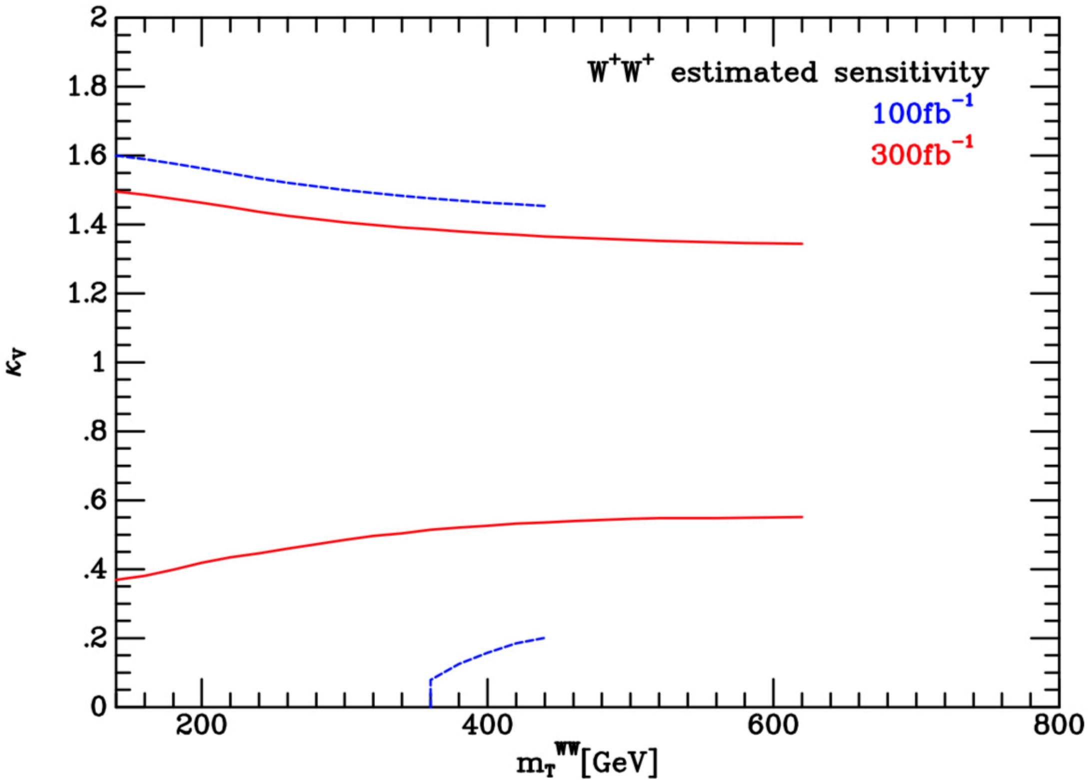


VBF H+ ->WZ

SMP-18-001

Future Of VBS Measurements

- **Disentangle longitudinal from transverse amplitudes in the scattering process**
  - **Particular sensitivity to BSM contributions to EWSB mechanism**
  - **Recent dedicated workshop in VBScan project (link)**
  - **Interesting new approaches being developed (arxiv.org:1510.01691)**



- **Related to the above: investigate and derive constraints on Higgs sector from VBS measurements (e.g. Ellis, Campbell: arxiv.org:1502.02990)**

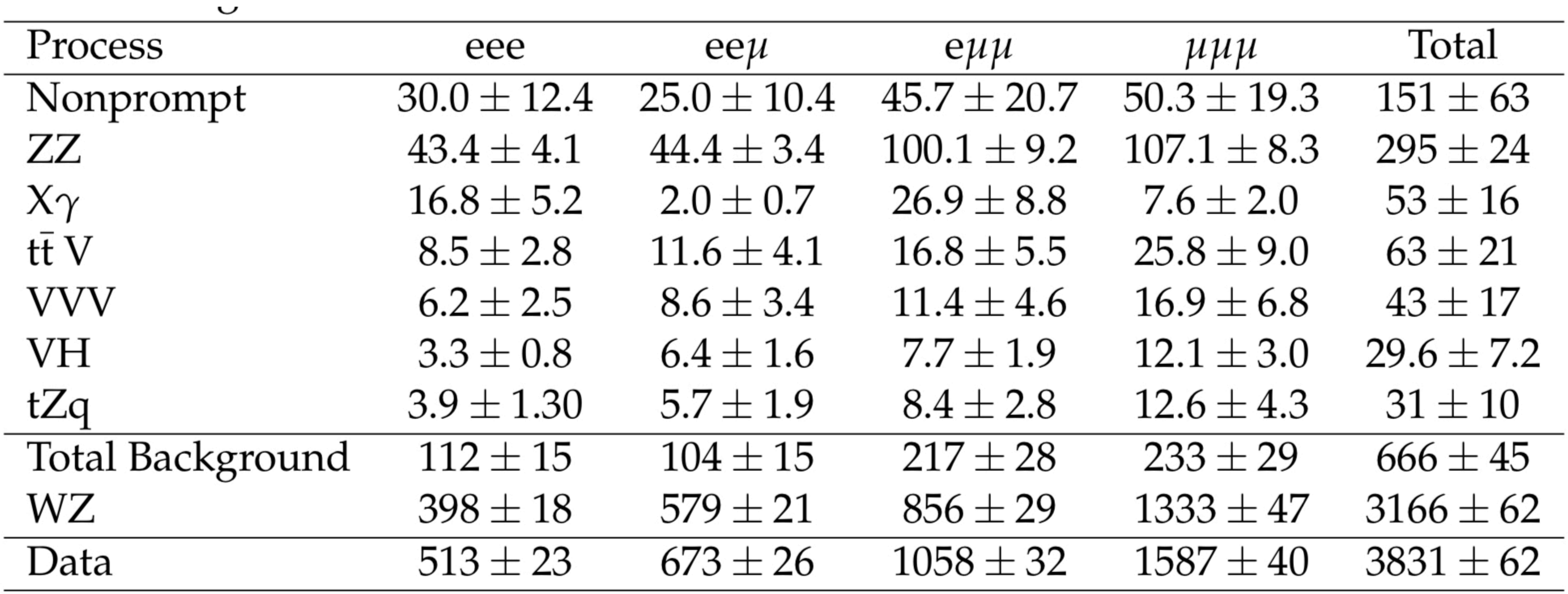
- **Improve meaning of constraints on EFT operators, derive concise bounds and strategy to apply for possible New Physics guidelines**

Conclusions

- The SM EW quartic and triple gauge couplings are under intense scrutiny at the LHC, full suite of measurments performed:
  - Higgs coupling measurements
  - Triple gauge couplings with VV inclusive, VBF W/Z
  - Quartic gauge couplings with VBS processes
- First observation of VBS $W^{\pm}W^{\pm}$ with 35.9 fb^{-1} at 13 TeV initiates an independent test for full closure of the Standard Model predictions
  - Unitarity in VBS only restored iff Standard Model predictions are exact
- Inclusive diboson production cross section measurements probe ~10% NNLO QCD corrections, VBS probe EW NLO corrections of 10-20%
  - High gain with more data for differential cross section measurements of inclusive diboson production
- CMS results probing TGC/QGC involving all EW gauge bosons (γ,Z,$W^{\pm}$) are in the pipeline, including triboson production

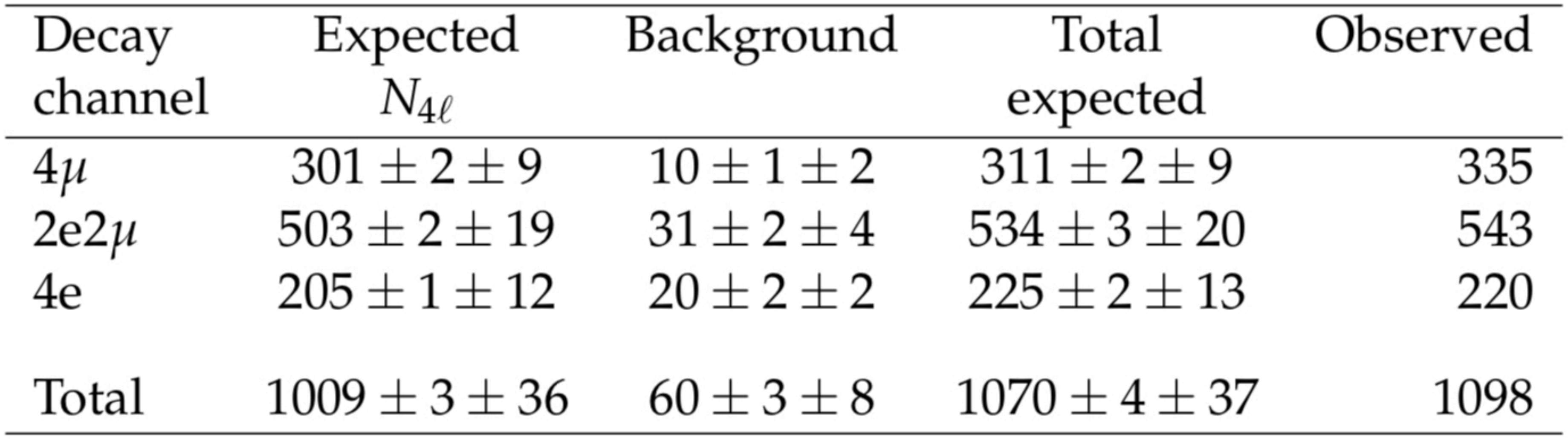
Additional Material

WZ Inclusive Event Yields



Process	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$	Total
Nonprompt	30.0 ± 12.4	25.0 ± 10.4	45.7 ± 20.7	50.3 ± 19.3	151 ± 63
ZZ	43.4 ± 4.1	44.4 ± 3.4	100.1 ± 9.2	107.1 ± 8.3	295 ± 24
Xγ	16.8 ± 5.2	2.0 ± 0.7	26.9 ± 8.8	7.6 ± 2.0	53 ± 16
$t\bar{t}$ V	8.5 ± 2.8	11.6 ± 4.1	16.8 ± 5.5	25.8 ± 9.0	63 ± 21
VVV	6.2 ± 2.5	8.6 ± 3.4	11.4 ± 4.6	16.9 ± 6.8	43 ± 17
VH	3.3 ± 0.8	6.4 ± 1.6	7.7 ± 1.9	12.1 ± 3.0	29.6 ± 7.2
tZq	3.9 ± 1.30	5.7 ± 1.9	8.4 ± 2.8	12.6 ± 4.3	31 ± 10
Total Background	112 ± 15	104 ± 15	217 ± 28	233 ± 29	666 ± 45
WZ	398 ± 18	579 ± 21	856 ± 29	1333 ± 47	3166 ± 62
Data	513 ± 23	673 ± 26	1058 ± 32	1587 ± 40	3831 ± 62

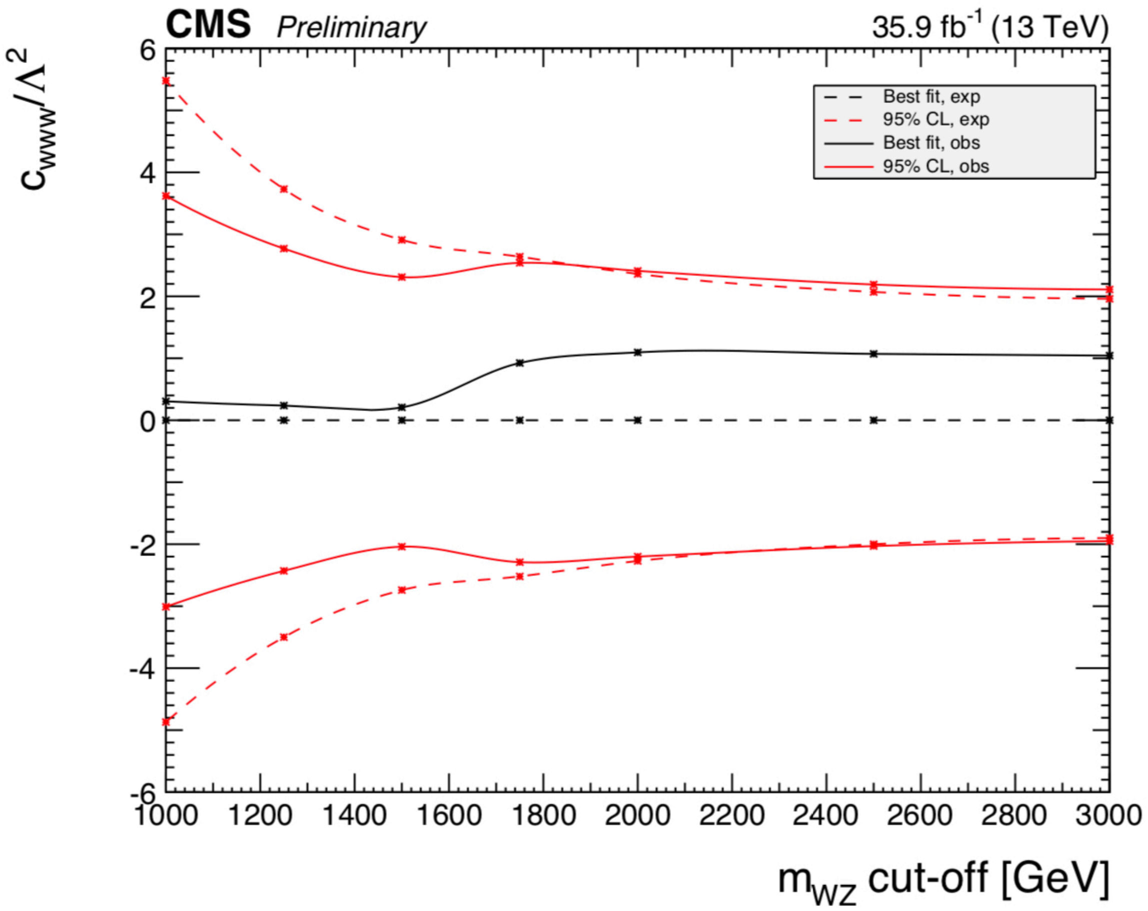
ZZ Inclusive Event Yields

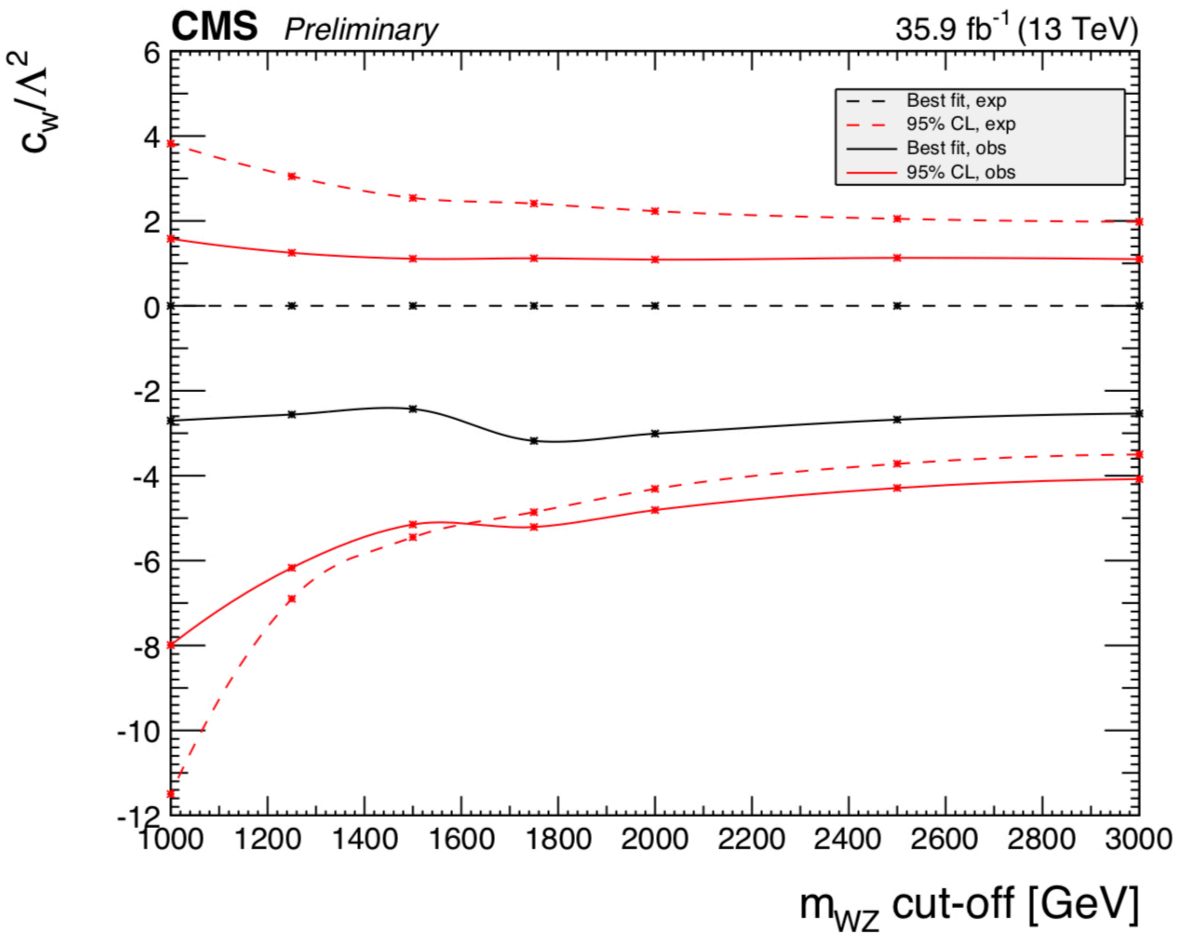


Decay channel	Expected $N_{4\ell}$	Background	Total expected	Observed
4μ	$301 \pm 2 \pm 9$	$10 \pm 1 \pm 2$	$311 \pm 2 \pm 9$	335
$2e2\mu$	$503 \pm 2 \pm 19$	$31 \pm 2 \pm 4$	$534 \pm 3 \pm 20$	543
4e	$205 \pm 1 \pm 12$	$20 \pm 2 \pm 2$	$225 \pm 2 \pm 13$	220
Total	$1009 \pm 3 \pm 36$	$60 \pm 3 \pm 8$	$1070 \pm 4 \pm 37$	1098

WZ Dim-6 Unitarity Check

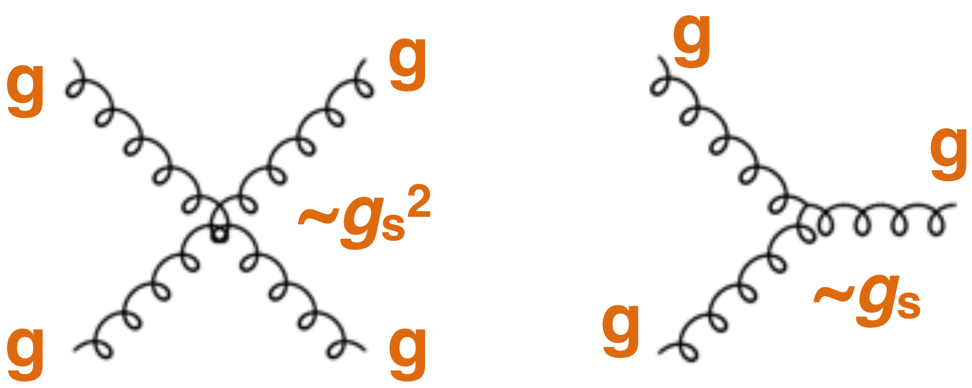
- “Clipping” method used, scan limits on EFT operators as function of cut-off on the invariant mass variable



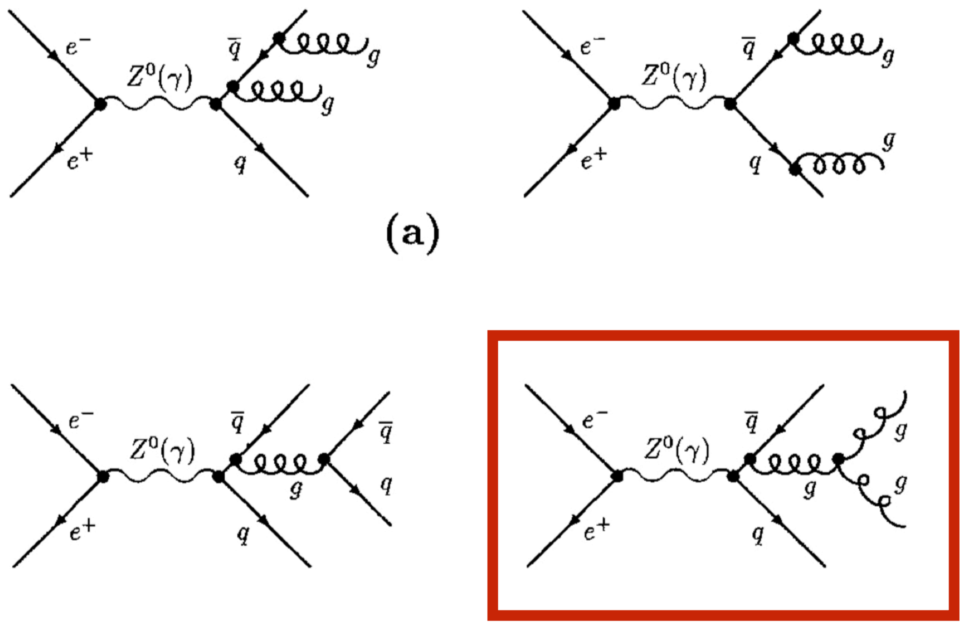


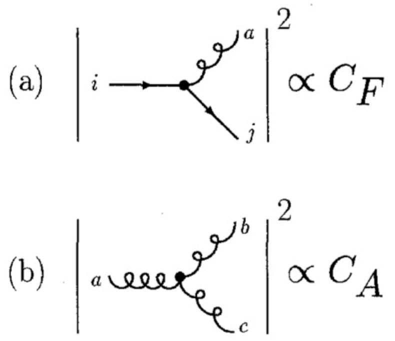
Non-Abelian Structure at Colliders

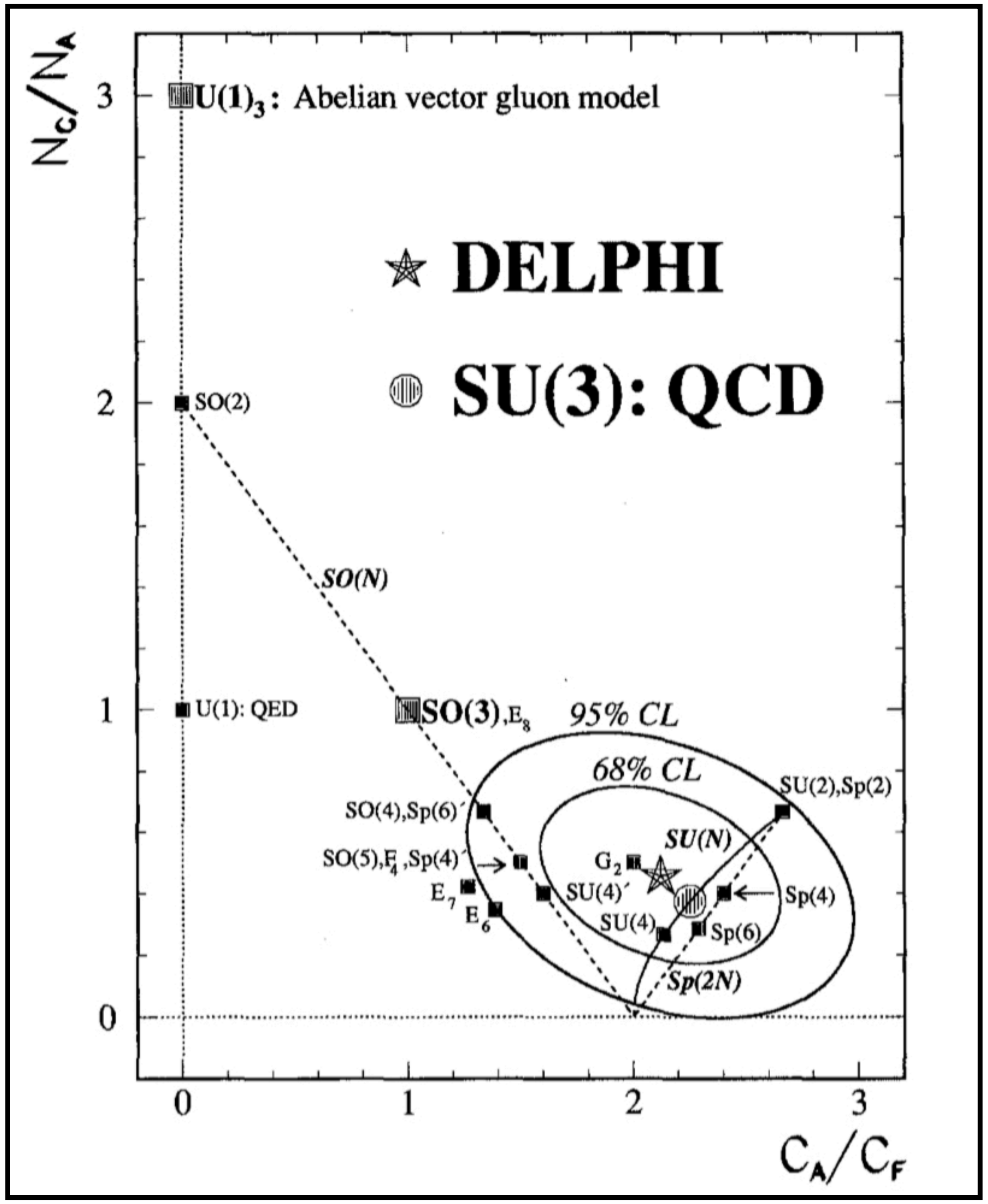
- **Quartic- and triple-gluon interaction vertices predicted through SU(3) gauge group**



- **Experimental studies performed e+e- at LEP2 early 1990s**
  - **4-jet events**
  - **discrimination of gluon/quark jets**



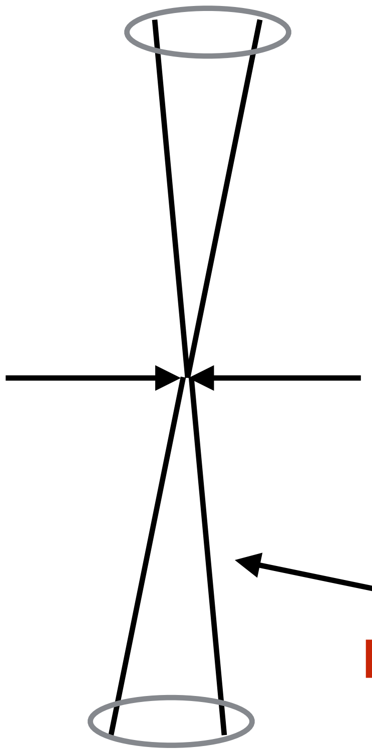




N_A: #gluons, N_C: #colors

Interlude: Fake Rate Method

- <u>**Fake Rate method applied in almost all CMS multi-lepton analyses**</u>
  - **Measure contributions for processes with leptons not coming from W, Z or tau decays in signal region**
- **Select clean “nonprompt”-lepton enriched samples, compute “loose” to “tight” transfer-factor, prompt-lepton contributions subtracted using simulated samples**
  - **Option 1: Z+jets, same as WZ selection, but invert MET cut, third lepton is a jet**
  - **Option 2: di-jet events, jet firing single lepton trigger**
- **Loose-to-tight transfer factors usually around ~30%**
- **Uncertainty of 30%, based on flavour composition and closure on simulated samples**



Firing prescaled single lepton trigger