Vector boson scattering and anomalous quartic couplings from ATLAS and CMS

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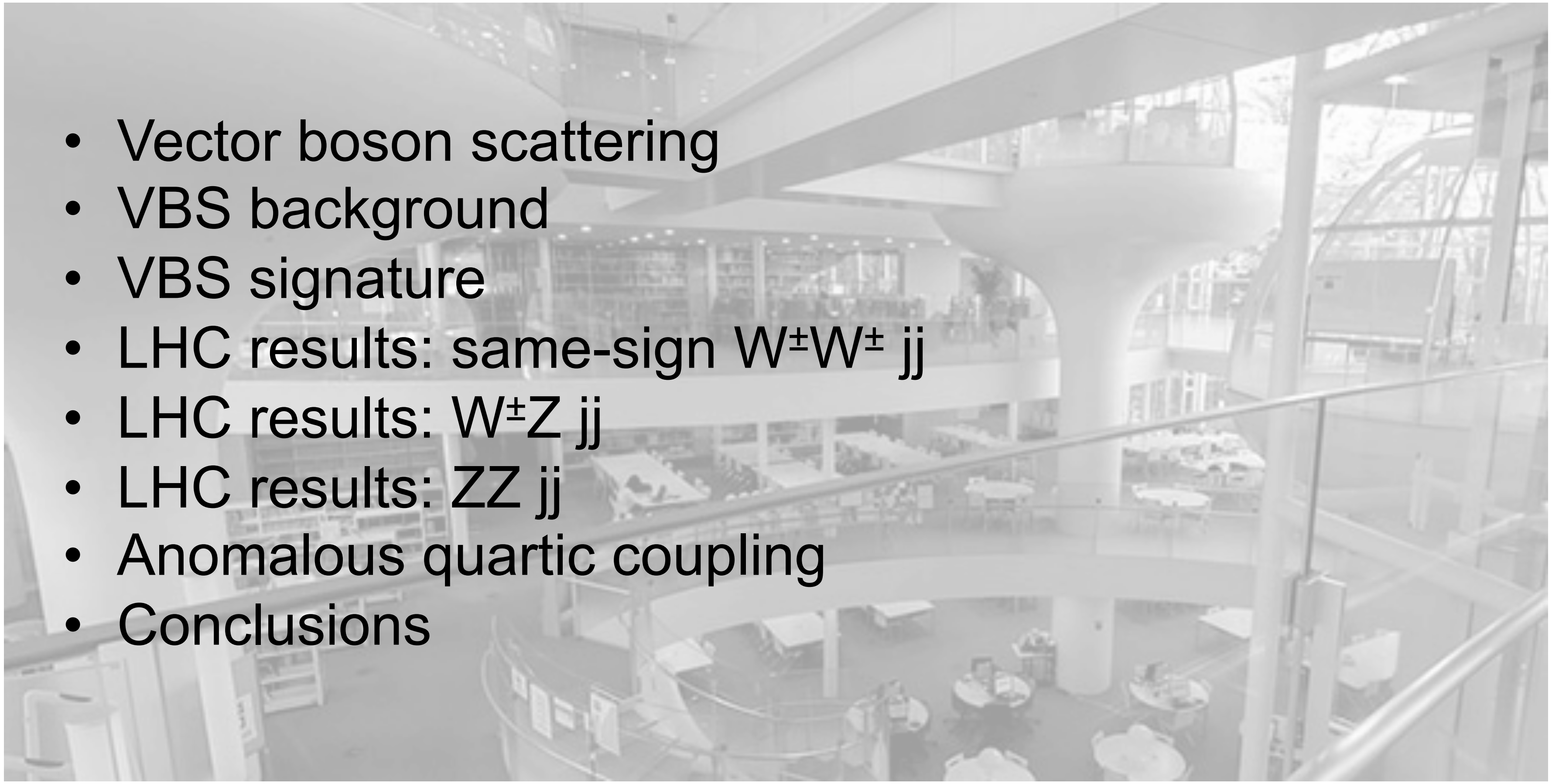
On behalf of CMS and ATLAS collaborations

November 26th-30th 2018 Higgs Couplings 2018 Ryogoku, Tokyo, Japan

Overview



- Vector boson scattering
- VBS background
- VBS signature
- LHC results: same-sign $W^{\pm}W^{\pm}$ jj
- LHC results: $W^{\pm}Z$ jj
- LHC results: ZZ jj
- Anomalous quartic coupling
- Conclusions

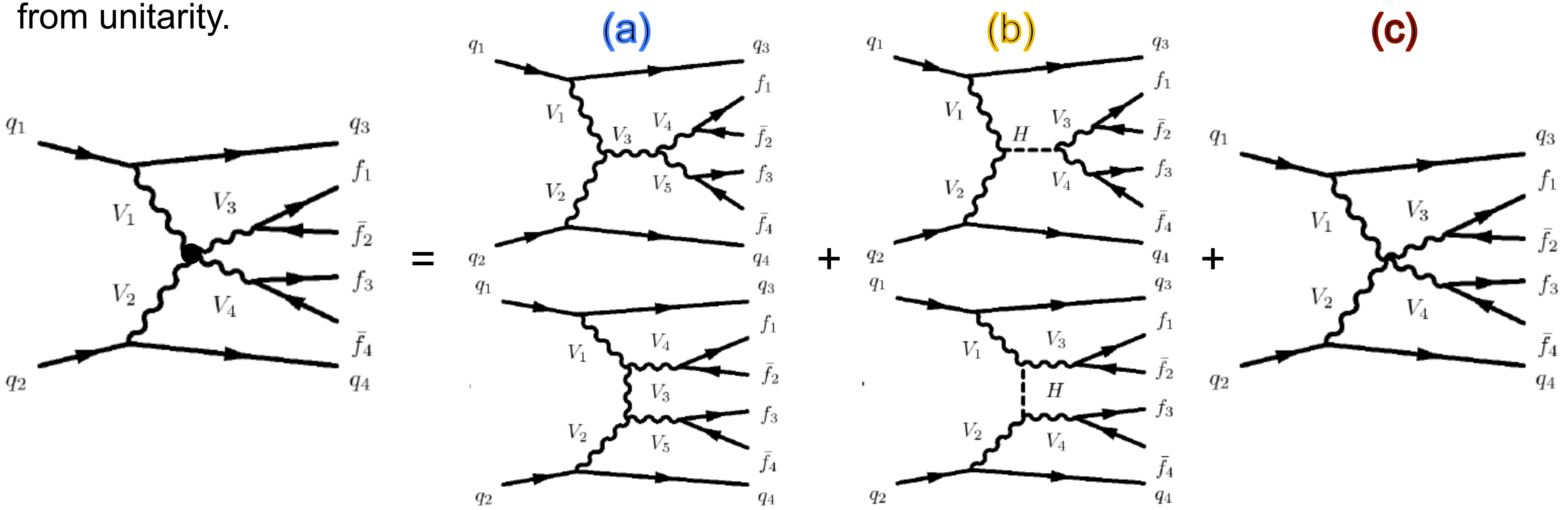
Vector boson scattering VV→ VV

Within the Standard Model (SM), cancellations between Feynman amplitudes involving

(a) trilinear gauge boson couplings,
(b) Higgs exchange,
(c) quartic gauge boson interactions,

EW contributions at $O(\alpha^6)$

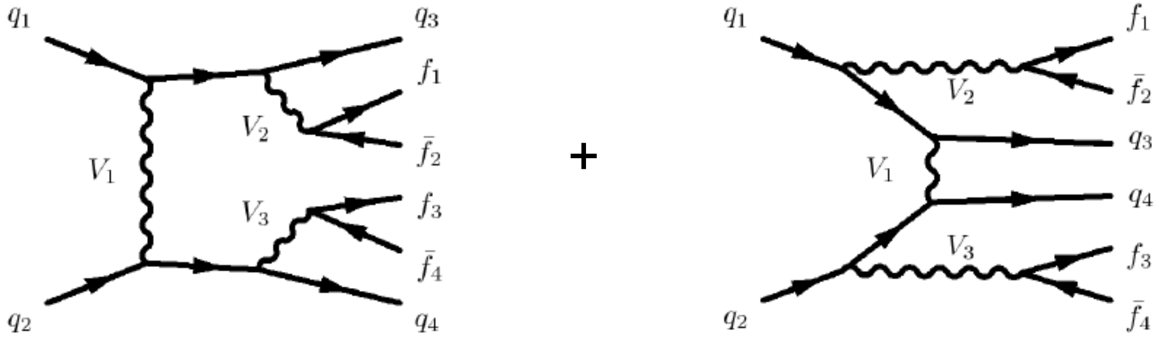
lead to scattering amplitudes which do not grow with energy and which respect bounds derived from unitarity.



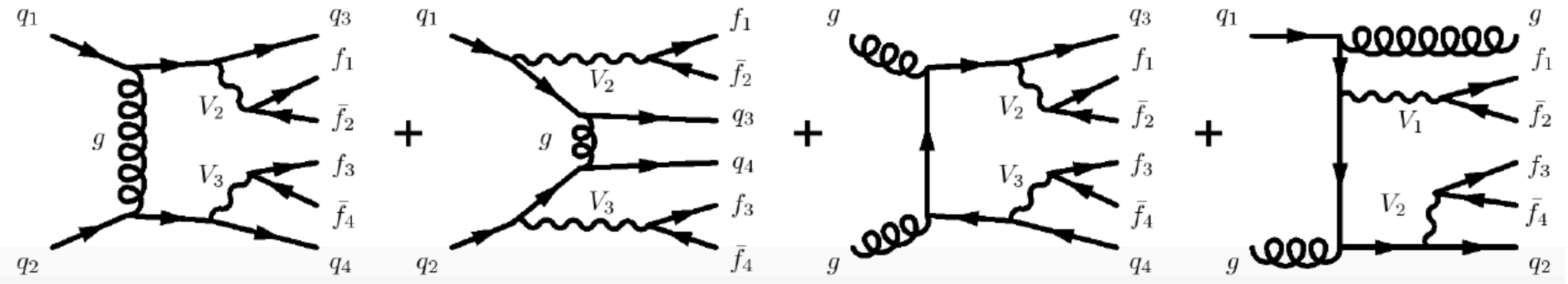
Trilinear couplings are well constrained by LEP, Tevatron and LHC measurements. Deviation in the SM coupling of the Higgs boson to the gauge bosons or anomalous quartic gauge couplings (QGC) break this delicate cancellation. These measurements can test the electroweak symmetry breaking mechanism and can provide limits for new physics.

VBS background

EW irreducible contributions at $O(\alpha^6)$ with 2V and 2 jets but not VBS



QCD induced contributions at $O(\alpha_s^2\alpha^4)$



Interference of the EW and QCD amplitudes contributes at $O(\alpha_s\alpha^5)$

VBS signature

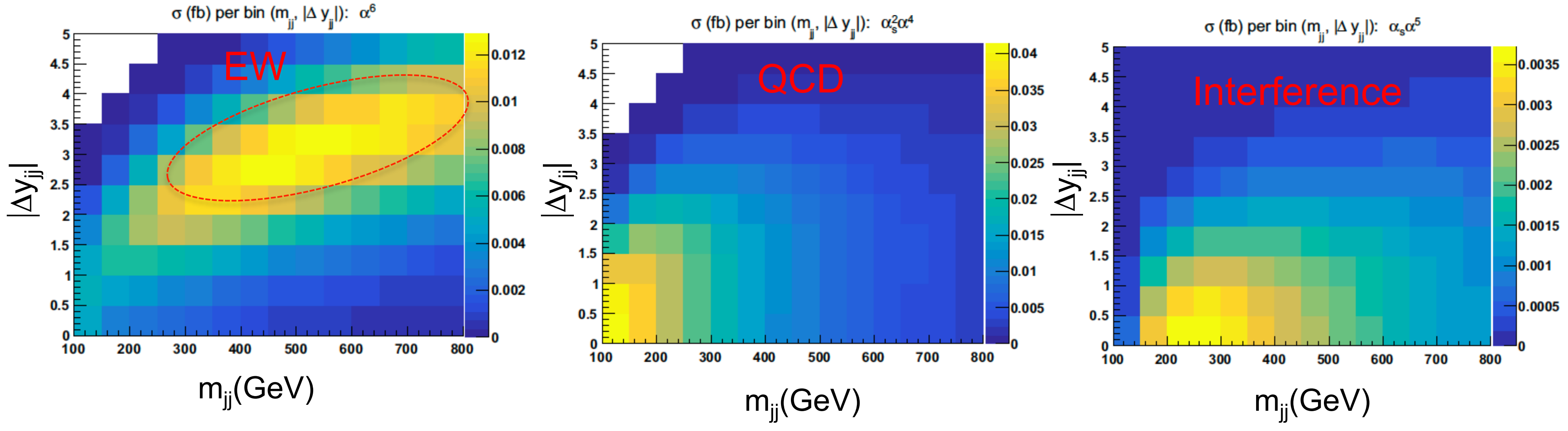
Signature of VBS events:

- 2 energetic jets (from q_3 and q_4) with
  - high di-jet invariant mass (m_{jj})
  - large rapidity Δy_{jj} (or $\Delta\eta_{jj}$) separation

- Central rapidity region with only VV decays
  - WW 2 leptons + MET
  - WZ 3 leptons + MET
  - ZZ 4 leptons

Cross sections differential distributions in the variables (m_{jj} , $|\Delta y_{jj}|$) for the three LO contributions $O(\alpha^6)$, $O(\alpha_s^2\alpha^4)$, $O(\alpha_s\alpha^5)$ to the process $pp \to \mu^+ \nu_\mu e^+ \nu_e jj$ at $\sqrt{s}$ = 13 TeV

(Ballestrero et al. Eur. Phys. J. C (2018) 78:671)



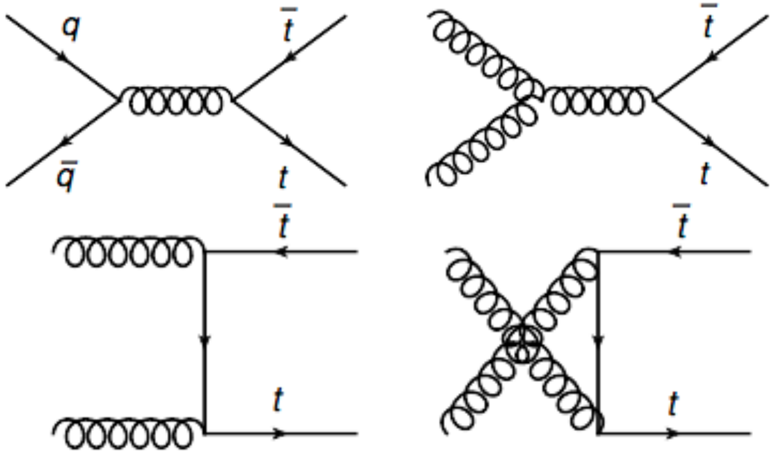
LHC results: same-sign $W^{\pm}W^{\pm}$ jj

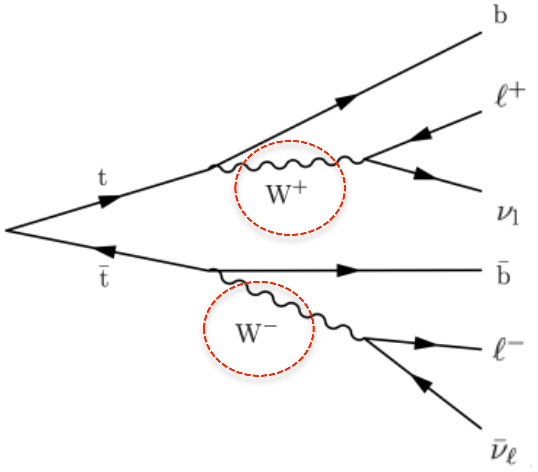
Measurements of EW production of same sign $W^{\pm}W^{\pm}$ jj by ATLAS and CMS:

	ATLAS: ATLAS-CONF-2018-030 (July 2018)	**CMS**: PRL 120, 081801 (Nov. 2017)
√s, Integr. Luminosity	13 TeV, 36.1 fb^{-1} (2015+2016)	13 TeV , 35.9 fb^{-1} (2016)

The selection of same-sign lepton events (from leptonic decays of same-sign WW):

- reduces the contribution form the strong production of WW bosons
- and suppresses background contributions with opposite-sign lepton final state ($t\bar{t}$).





VBS signal in the s-channel ($W^+W^- \rightarrow Z/H \rightarrow W^+W^-$) are absent processes.

LHC results: same sign $W^{\pm}W^{\pm}$ jj

Event selection:
2 same sign leptons (e, or μ)   and 2 jets

Signal selection: m_{jj} , $\Delta\eta_{jj}$, E_T^{miss}

Requirements	ATLAS	CMS
$p^l_T >$ (GeV)	27/27	25/20
$p^j_T >$ (GeV)	65/35	30/30
$\|\eta_j\| <$	4.5	5.0

Requirements	ATLAS	CMS
$m_{jj} >$ (GeV)	500	500
$\|\Delta y_{jj}\|$, $\|\Delta\eta_{jj}\| >$	2	2.5
E_T^{miss}, $p_T^{miss} >$ (GeV)	30	40
$m_{ll} >$ (GeV)	20	20

Measurement performed in ee, $\mu\mu$, and eμ final states

Major backgrounds (estimated from data):

- non-prompt leptons — control region: QCD enriched sample, ratio tight/loose lepton ID
- WWjj QCD induced — control region: low m_{jj}
- EW WZ — control region: 3 leptons

Other backgrounds (estimated from data):

- Electron charge mis-reconstruction — measured from Z -> ee events

Other backgrounds (estimated from MC):

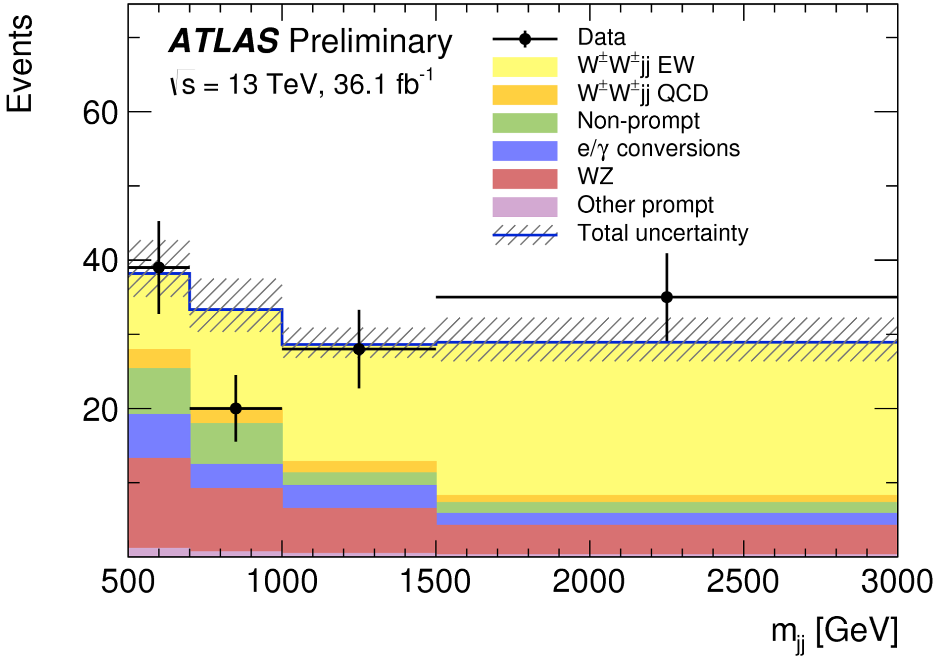
- ZZ, Vγ, VVV, ttV

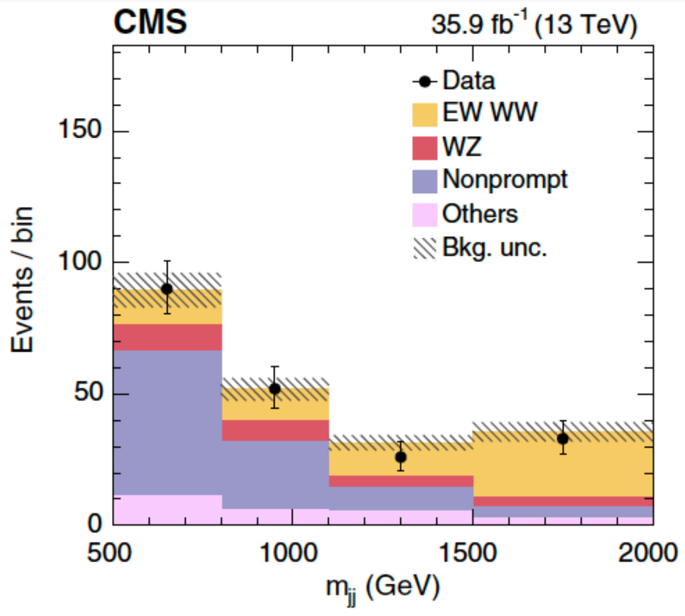
LHC results: same sign W±W± jj

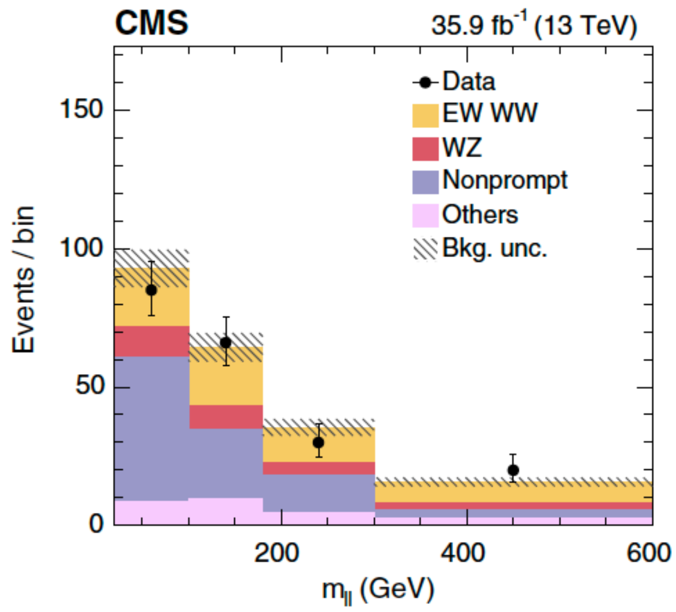
Data, W±W±jj EW signal and backgrounds after signal selection.

ATLAS: m_{jj} distribution

CMS: m_{jj} and m_{ll} distributions







e/γ conversion: Electron charge misreconstr. + Vγ

Others: QCD WW + e/γ conversion

LHC results: same sign $W^{\pm}W^{\pm}$ jj

$W^{\pm}W^{\pm}$jj EW signal significances:

Evidence

ATLAS: 6.9 σ observed (4.6 σ expected)

Evidence

CMS: 5.5 σ observed (5.7 σ expected)

Signal extraction:

	ATLAS	CMS
MC signal:	SHERPA (LO)	MADGRAPH5_aMC@NLO (LO)
Data:	Fit m_{jj} shape in 6 cathegories $(e^+e^+\ e^-e^-\ e^+\mu^+\ e^-\mu^-\ \mu^+\mu^+\ \mu^-\mu^-)$	2D fit m_{ll} - m_{jj} shape

Fiducial regions:

Defined by the selection criteria.
The main difference between ATLAS and CMS is the jet selection.
The measured cross section is corrected for the acceptance in this fiducial region using Monte Carlo generator.

LHC results: same sign W±W± jj

Fiducial cross sections:

ATLAS

$\sigma^{fid}(W^{\pm}W^{\pm}jj) = 2.91 \pm 0.51\ (\text{stat.}) \pm 0.27\ (\text{sys.})\ \text{fb}$

$\sigma^{th}(W^{\pm}W^{\pm}jj) = 2.01^{+0.33}_{-0.23}\ \text{fb @ LO (SHERPA)}$

$\sigma^{th}(W^{\pm}W^{\pm}jj) = 3.08^{+0.45}_{-0.46}\ \text{fb @ LO (POWHEG)}$

CMS

$\sigma^{fid}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\ (\text{stat.}) \pm 0.35\ (\text{sys.})\ \text{fb}$

$\sigma^{th}(W^{\pm}W^{\pm}jj) = 4.25 \pm 0.27\ \text{fb @ LO (MADGRAPH)}$

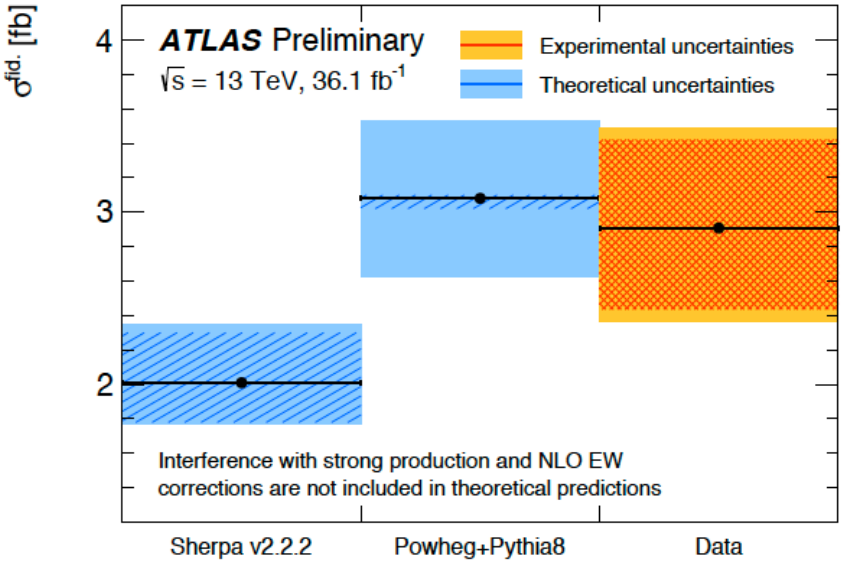
The MADGRAPH MC systematic uncertainty: $^{+6.3\%}_{-6.3\%}$

The SHERPA MC systematic uncertainty includes: $^{+16.4\%}_{-11.4\%}$

variation of renormalization and factorization scales: $^{+14\%}_{-11\%}$

PDF uncertainties: $^{+8\%}_{-1\%}$

parton shower modeling: $^{+2.5\%}_{-1.5\%}$



Fiducial cross sections are compatible with SM expectations.

LHC results: same sign $W^{\pm}W^{\pm}$ jj

Higher order corrections are not negligible.

Same sign WW is the only diboson process with full NLO computation (EW and QCD)
(B. Biedermann, A. Denner, and M. Pellen JHEP 1710 (2017) 124)

$$\begin{tikzcd}
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s^2\alpha^4) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & \\
\textbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}(\alpha_s^2\alpha^5) & & \mathcal{O}(\alpha_s^3\alpha^4)
\end{tikzcd}$$

NLO computation (EW and QCD) for pp -> $e^+\nu_e\, \mu^+\mu^-$jj

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

The expected NLO cross section is 17% lower than σ_{LO}
(the dominant contribution is -13% due to NLO EW corrections)

ATLAS

$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ = 2.91± 0.51 (stat.) ± 0.27 (sys.) fb

$\sigma^{th}(W^{\pm}W^{\pm}jj) = 1.67^{+0.27}_{-0.19}$ fb @ NLO (SHERPA)

CMS

$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ = 3.83± 0.66 (stat.) ± 0.35 (sys.) fb

$\sigma^{th}(W^{\pm}W^{\pm}jj)$ = 3.52± 0.22 fb @ NLO (MADGRAPH)

LHC results: same sign $W^\pm W^\pm$ jj

Limits in the Georgi-Machacek (GM) model:

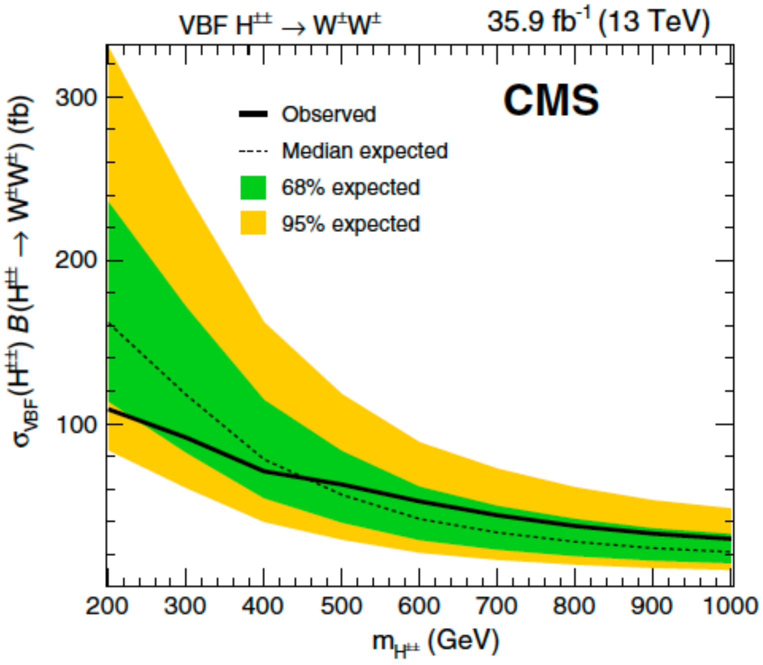
complex isospin doublet Y=1 (ϕ^+,ϕ^0)
real triplet with Y=0 $(\zeta^+,\zeta^0,\zeta^-)$
complex triplet with Y=2 $(\chi^{++},\chi^+,\chi^0)$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix} \qquad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

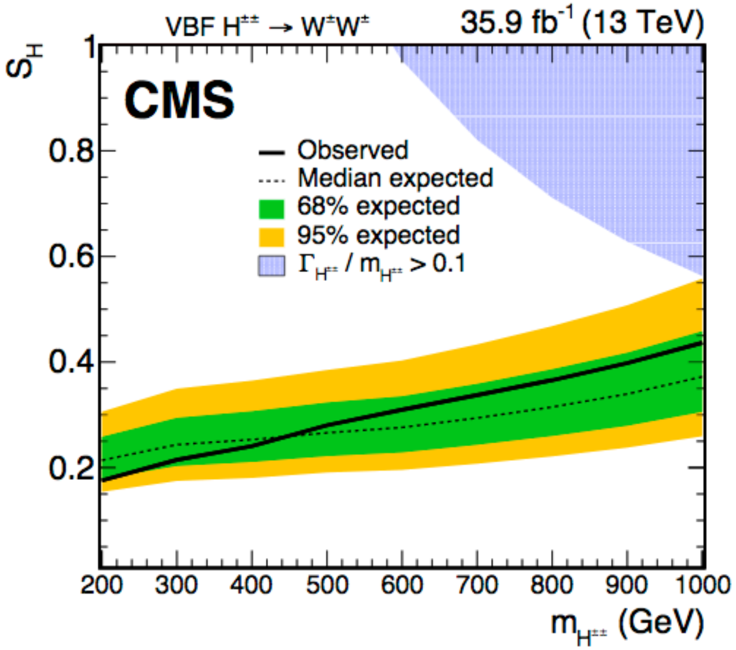
$s_H = \sin\theta_H$, mixing angle of vevs

$$s_H \equiv \sin\theta_H = \frac{2\sqrt{2}\,v_\chi}{v}, \qquad v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246\ \text{GeV})^2$$

Limits on $\sigma_{VBF}(H^{\pm\pm})\mathcal{B}(H^{\pm\pm}\to W^\pm W^\pm)$



Limits on s_H vs $m_{H^{\pm\pm}}$



$s_H < 0.18$ @ 200 GeV $s_H < 0.44$ @ 1000 GeV

LHC results: $W^{\pm}Z$ jj

Measurements of EW production of $W^{\pm}Z$ jj by ATLAS and CMS:

	ATLAS: ATLAS-CONF-2018-033 (July 2018)	**CMS**: CMS-PAS-SMP-18-001(July 2018)
$\sqrt{s}$, Integr. Luminosity	13 TeV, 36.1 fb^{-1} (2015+2016)	13 TeV , 35.9 fb^{-1} (2016)

Event selection:
3 leptons (e, or μ) and 2 jets

Signal selection: m_{jj} , $\Delta\eta_{jj}$, E_T^{miss}

Requirements	**ATLAS**	**CMS**
$p^l_T >$ (GeV)	27/20/20	$25_{(Zl1)}/15_{(Zl2)}/20_{(W)}$
2l from Z	✓	✓
$p^j_T >$ (GeV)	40/40	50/50
$\lvert\eta_j\rvert <$	4.5	4.7

Requirements	**ATLAS**	**CMS**
$m_{jj} >$ (GeV)	500	500
$-(\eta_{j1} * \eta_{j2})$, $\lvert\Delta\eta_{jj}\rvert >$	0	2.5
m_T^W, $p_T^{miss} >$ (GeV)	30	30
$m_{3l} >$ (GeV)		100

Measurement performed in $e^+e^-\mu^{\pm}$, $e^+e^-e^{\pm}$, $\mu^+\mu^-\mu^{\pm}$, and $\mu^+\mu^-e^{\pm}$ final states

Major backgrounds (estimated from data):

- WZjj QCD induced	control region: low m_{jj}

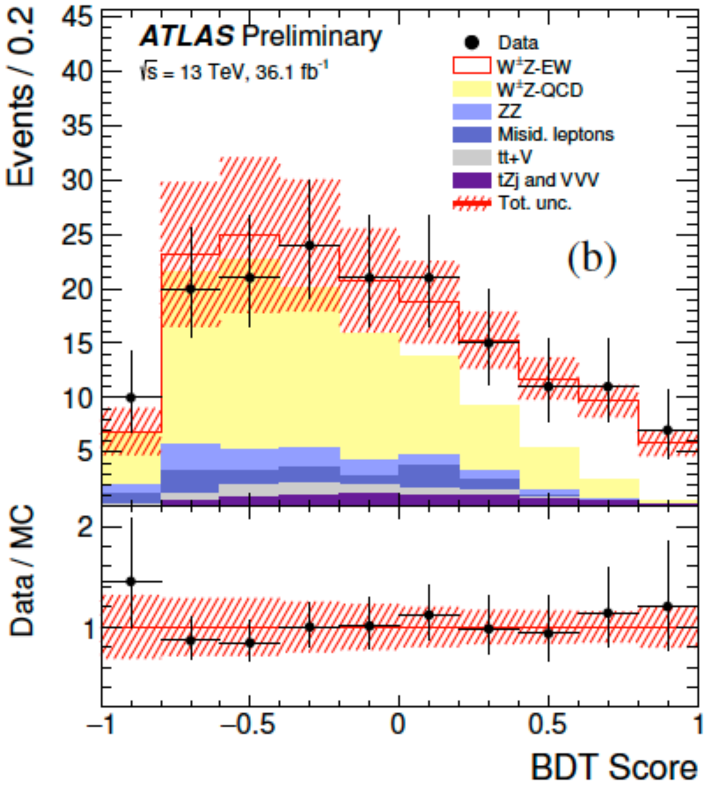
Other backgrounds (estimated from data):

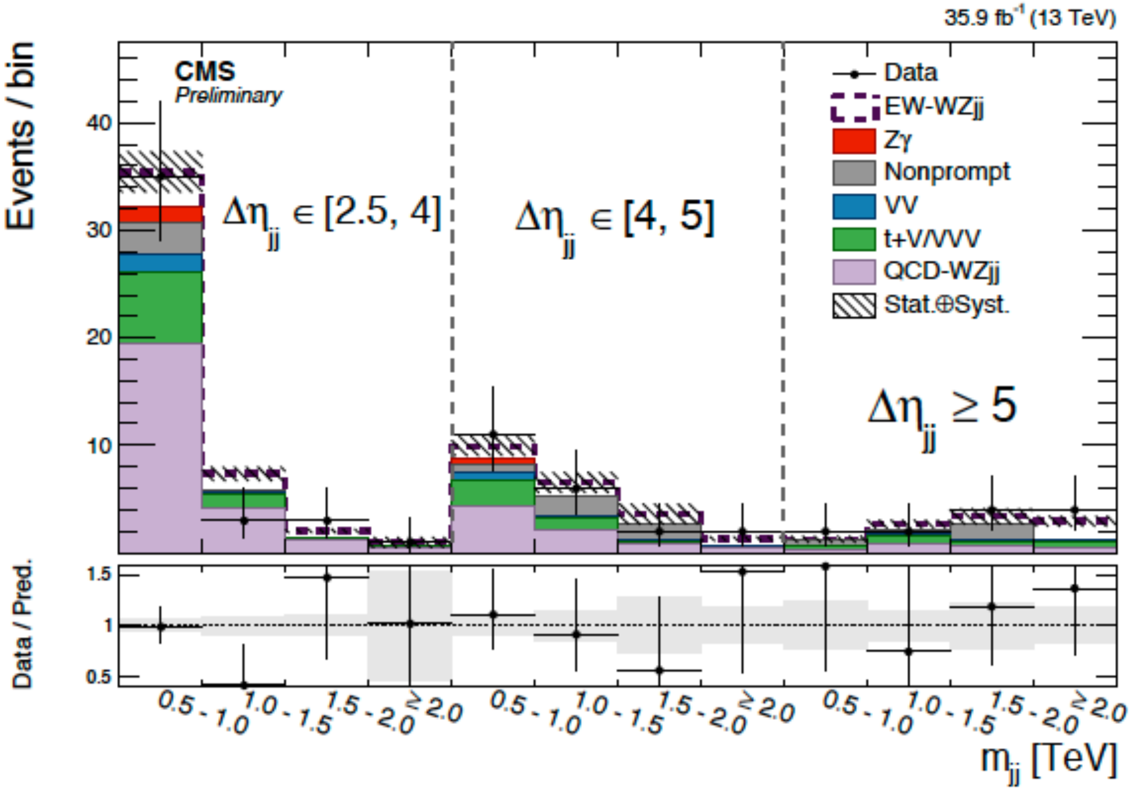
- ZZ	control region: 1 additional loose ID lepton
- $t\bar{t}$ + V	control region: b-tagged jets

Other backgrounds (estimated from MC):

- VVV, tZj

LHC results: W±Z jj





W±Zjj EW signal significances:

Evidence

ATLAS: 5.6 σ observed (3.3 σ expected)

CMS: 1.9 σ observed (2.7 σ expected)

LHC results: $W^{\pm}Zjj$

Signal extraction:

	ATLAS	**CMS**
MC signal:	SHERPA (LO)	MADGRAPH5_aMC@NLO (LO)
Data:	BDT trained to separate WZ EW signal from other processes	2D fit m_{jj} - $|\Delta\eta_{jj}|$ shape

Fiducial cross sections:

ATLAS

$\sigma^{\text{fid,EW}}(W^{\pm}Zjj) = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{sys.})\,^{+0.04}_{-0.03}\,(\text{th.})$ fb

$\sigma^{\text{th,EW}}(W^{\pm}Zjj) = 0.32 \pm 0.03$ fb @ LO
(SHERPA)

$\sigma^{\text{th,EW}}(W^{\pm}Zjj) = 0.366 \pm 0.004(\text{stat.})$ fb @ LO
(MADGRAPH)

CMS

$\sigma^{\text{fid}}(W^{\pm}Zjj) = 2.91\,^{+0.53}_{-0.49}\,(\text{stat.})\,^{+0.41}_{-0.34}\,(\text{sys.})$ fb

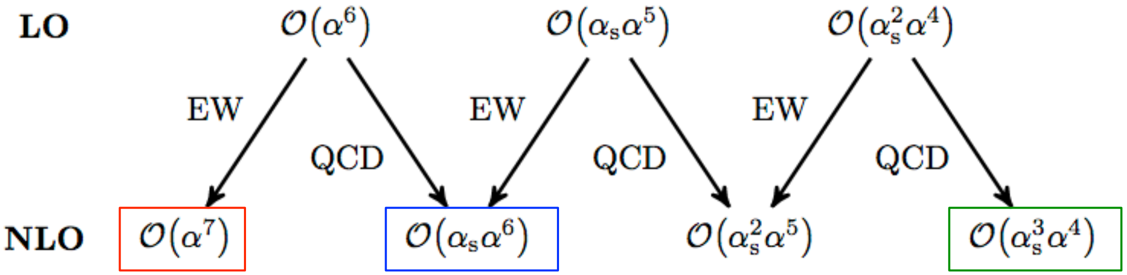
$\sigma^{\text{th}}(W^{\pm}Zjj) = 3.27\,^{+0.39}_{-0.32}\,(\text{scale}) \pm 0.15\,(\text{PDF})$ fb @ LO
(MADGR.)

ATLAS and CMS σ^{fid} are different because ATLAS measured the EW component, CMS the total

Fiducial cross sections are compatible with SM expectations, for ATLAS small discrepancy of 1.7σ

LHC results: $W^{\pm}Z\,jj$

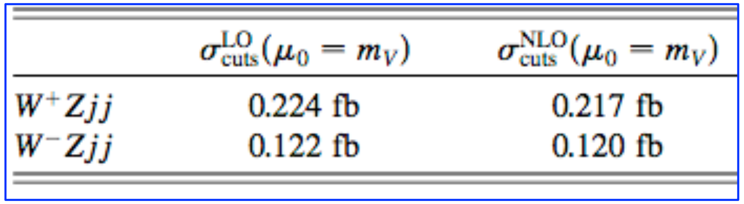
NLO computation (EW and QCD) for pp -> $e^+\nu_e\,\mu^+\mu^- jj$



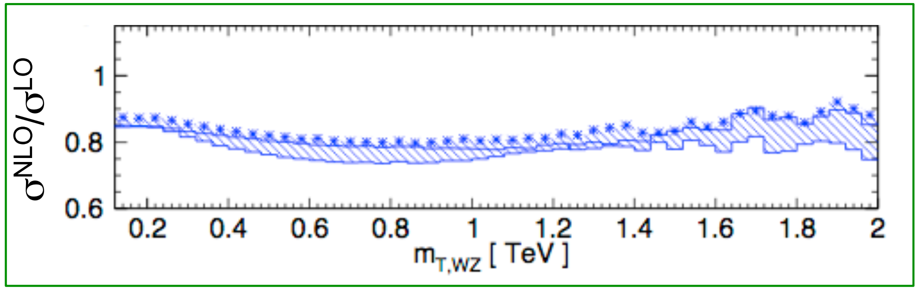
$$\begin{tikzcd}
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & & \mathcal{O}(\alpha_s^2\alpha^4) \arrow[dl, "\mathrm{EW}"'] \arrow[dr, "\mathrm{QCD}"] & \\
\textbf{NLO} & \boxed{\mathcal{O}(\alpha^7)} & & \boxed{\mathcal{O}(\alpha_s\alpha^6)} & & \mathcal{O}(\alpha_s^2\alpha^5) & & \boxed{\mathcal{O}(\alpha_s^3\alpha^4)}
\end{tikzcd}$$

Phys.Rev.Lett. 111 (2013) no.5, 052003

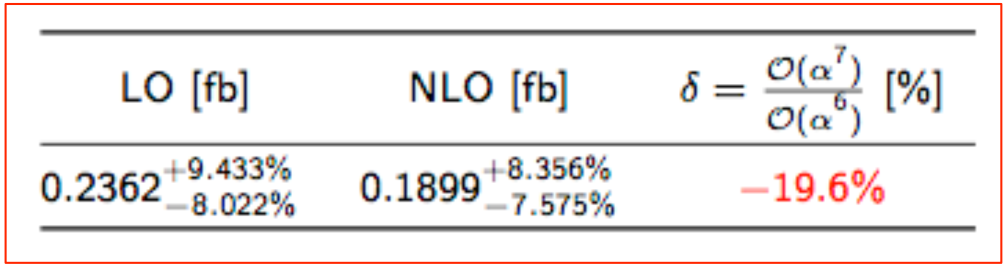
Phys. Rev. D 75, 073004 (2007)



	$\sigma^{\mathrm{LO}}_{\mathrm{cuts}}(\mu_0 = m_V)$	$\sigma^{\mathrm{NLO}}_{\mathrm{cuts}}(\mu_0 = m_V)$
W^+Zjj	0.224 fb	0.217 fb
W^-Zjj	0.122 fb	0.120 fb



Preliminary $\boxed{\mathcal{O}(\alpha^7)}$ from like sign WW expected to have large contribution
(Christopher Schwan, Ansgar Denner, Stefan Dittmaier, Philipp Maierhöfer, Mathieu Pellen)
(High Precision for Hard Processes 2018 *Freiburg* 1-3 October 2018)



LO [fb]	NLO [fb]	$\delta = \frac{\mathcal{O}(\alpha^7)}{\mathcal{O}(\alpha^6)}$ [%]
$0.2362^{+9.433\%}_{-8.022\%}$	$0.1899^{+8.356\%}_{-7.575\%}$	−19.6%

LHC results: ZZ jj

Measurements of EW production of ZZ jj by CMS:

CMS: Phys. Lett. B 774 (2017) 682 (August 2017)

√s, Integr. Luminosity 13 TeV , 35.9 fb^{-1} (2016)

Event selection: 4 leptons (e, or μ) and 2 jets

Signal selection: m_{jj} , $\Delta\eta_{jj}$, E_T^{miss}

Requirements	**CMS**
$p^{l}_T >$ (GeV)	$20_{(Zl1)}/12_{(Ze2)}, 10_{(Z\mu2)}$
4l from ZZ	✓
$p^{j}_T >$ (GeV)	30/30
$\lvert\eta_j\rvert <$	4.7

Requirements	**CMS**
$m_{jj} >$ (GeV)	400
$\lvert\Delta\eta_{jj}\rvert >$	2.4

Major backgrounds (estimated from data):

- ZZjj QCD induced control region: low m_{jj}

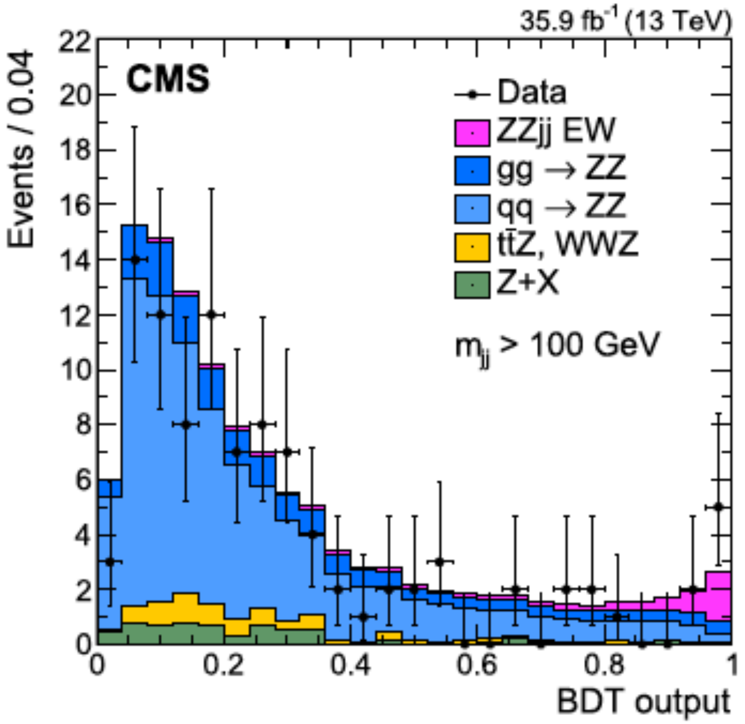
Other backgrounds (estimated from data):

- Z+jets control region: inverted lepton ID criteria

Other backgrounds (estimated from MC):

- ttZ + jets
- WWZ + jets

LHC results: ZZ jj



ZZjj EW signal significances:

CMS: 2.7 σ observed (1.6 σ expected)

Signal extraction:

MC signal: MADGRAPH5_aMC@NLO (LO)

Data: BDT trained to separate ZZ EW signal from other processes

Fiducial cross sections:

$$\sigma^{\text{fid,EW}}(\text{ZZjj}) = 0.40\ ^{+0.21}_{-0.16}\ (\text{stat.})\ ^{+0.13}_{-0.09}\ (\text{sys.})\ \text{fb}$$

$$\sigma^{\text{th}}(\text{ZZjj}) = 0.29\ ^{+0.02}_{-0.03}\ \text{fb @ LO (MADGRAPH)}$$

Fiducial cross section is compatible with SM expectation

Anomalous quartic coupling (aQGC)

Effective Field Theory

Add additional operators to the SM Lagrangian density with dimension larger than E^4:

$$L_{eff} = L_{SM} + \sum_n \frac{c_n}{\Lambda_n} O^{(n+4)}$$

Coupling constants c_n/Λ_n with dimensions E^{-n}
Operators are constructed by defining particle content
Operators are suppressed if the accessible energy is low compared to mass scale

All possible dimension 6 operators (*) :

Only 5 operators affect Vector Boson Self interactions:

3 with C and P conserved

2 with C and/or P violated

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D_\mu\Phi)$$

$$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{DW} = Tr([D_\mu,\hat{W}_{\nu\rho}][D^\mu,\hat{W}^{\nu\rho}])$$

$$\mathcal{O}_{DB} = -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3$$

$$\boxed{\mathcal{O}_{WWW} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho]}$$

$$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\boxed{\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D^\nu\Phi)}$$

$$\boxed{\mathcal{O}_{B} = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D^\nu\Phi)}$$

$$\mathcal{O}_{\tilde{W}W} = \Phi^\dagger\tilde{\hat{W}}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\boxed{\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger\tilde{\hat{W}}^{\mu\nu}(D^\nu\Phi)}$$

$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger\tilde{\hat{B}}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{\tilde{B}} = (D_\mu\Phi)^\dagger\tilde{\hat{B}}^{\mu\nu}(D^\nu\Phi)$$

$$\mathcal{O}_{B\tilde{W}} = \Phi^\dagger\hat{B}_{\mu\nu}\tilde{\hat{W}}^{\mu\nu}\Phi$$

$$\mathcal{O}_{D\tilde{W}} = Tr([D_\mu,\tilde{\hat{W}}_{\nu\rho}][D^\mu,\hat{W}^{\nu\rho}])$$

$$\boxed{\mathcal{O}_{\tilde{W}WW} = Tr[\tilde{\hat{W}}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho]}$$

(*) Only even-dimensional operators conserve both lepton and baryon number

Anomalous quartic coupling (aQGC)

All possible dimension 8 operators:

Only from dimension 8 there are operators contributing to QGC but not to trilinear gauge coupling (TGC)

$$L_{S0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi],$$

$$L_{S1} = \frac{f_{S1}}{\Lambda^4}[(D_\mu\Phi)^\dagger D_\mu\Phi] \times [(D^\nu\Phi)^\dagger D^\nu\Phi],$$

$$L_{M0} = \frac{f_{M0}}{\Lambda^4} Tr[W_{\mu\nu}W^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi],$$

$$L_{M1} = \frac{f_{M1}}{\Lambda^4} Tr[W_{\mu\nu}W^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi],$$

$$L_{M2} = \frac{f_{M2}}{\Lambda^4} [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi],$$

$$L_{M3} = \frac{f_{M3}}{\Lambda^4} [B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi],$$

$$L_{M4} = \frac{f_{M4}}{\Lambda^4} [(D_\mu\Phi)^\dagger W_{\beta\nu} D^\mu\Phi)] \times B^{\beta\nu},$$

$$L_{M5} = \frac{f_{M5}}{\Lambda^4} [(D_\mu\Phi)^\dagger W_{\beta\nu} D^\nu\Phi)] \times B^{\beta\mu},$$

$$L_{M6} = \frac{f_{M6}}{\Lambda^4} [(D_\mu\Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu\Phi)],$$

$$L_{M7} = \frac{f_{M7}}{\Lambda^4} [(D_\mu\Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu\Phi)],$$

$$L_{T0} = \frac{f_{T0}}{\Lambda^4} Tr[W_{\mu\nu}W^{\mu\nu}] \times Tr[W_{\alpha\beta}W^{\alpha\beta}],$$

$$L_{T1} = \frac{f_{T1}}{\Lambda^4} Tr[W_{\alpha\nu}W^{\mu\beta}] \times Tr[W_{\mu\beta}W^{\alpha\nu}],$$

$$L_{T2} = \frac{f_{T2}}{\Lambda^4} Tr[W_{\alpha\mu}W^{\mu\beta}] \times Tr[W_{\beta\nu}W^{\nu\alpha}],$$

$$L_{T5} = \frac{f_{T5}}{\Lambda^4} Tr[W_{\mu\nu}W^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta},$$

$$L_{T6} = \frac{f_{T6}}{\Lambda^4} Tr[W_{\alpha\nu}W^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu},$$

$$L_{T7} = \frac{f_{T7}}{\Lambda^4} Tr[W_{\alpha\mu}W^{\mu\beta}] \times [B_{\beta\nu}B^{\nu\alpha}],$$

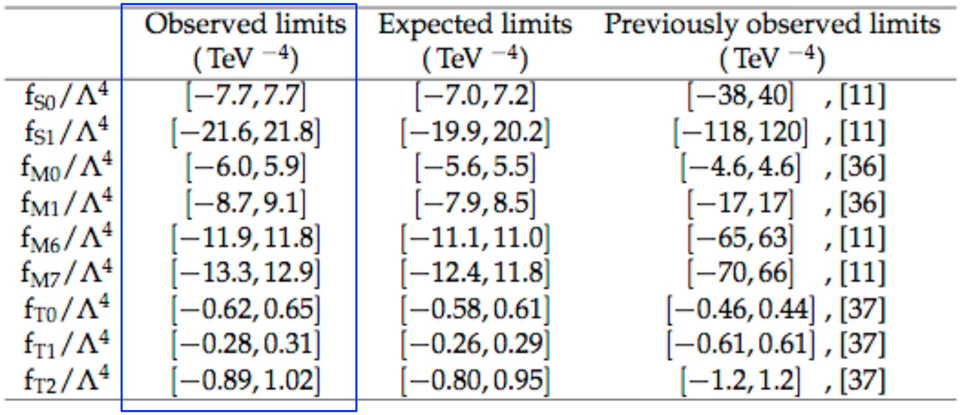
$$L_{T8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},$$

$$L_{T9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
L_{S0}, L_{S1}	X	X	X						
$L_{M0}, L_{M1}, L_{M6}, L_{M7}$	X	X	X	X	X	X	X		
$L_{M2}, L_{M3}, L_{M4}, L_{M5}$		X	X	X	X	X	X		
L_{T0}, L_{T1}, L_{T2}	X	X	X	X	X	X	X	X	X
L_{T5}, L_{T6}, L_{T7}		X	X	X	X	X	X	X	X
L_{T8}, L_{T9}			X			X	X	X	X

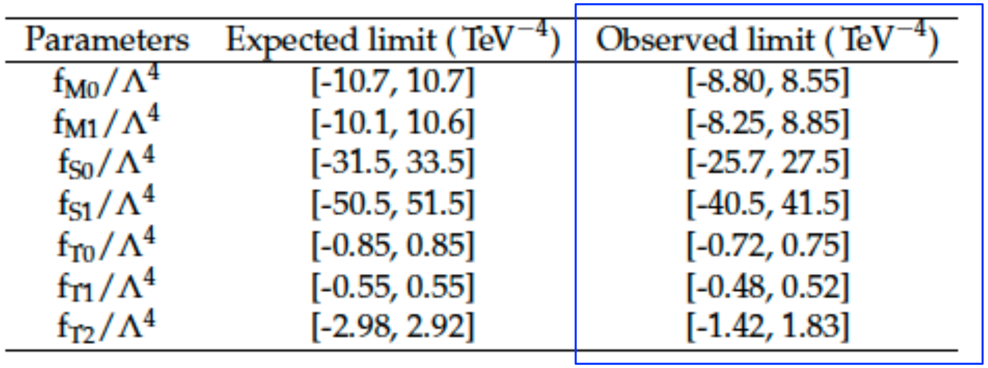
Anomalous quartic coupling (aQGC)

CMS WWjj PRL 120, 081801 (Nov. 2017)



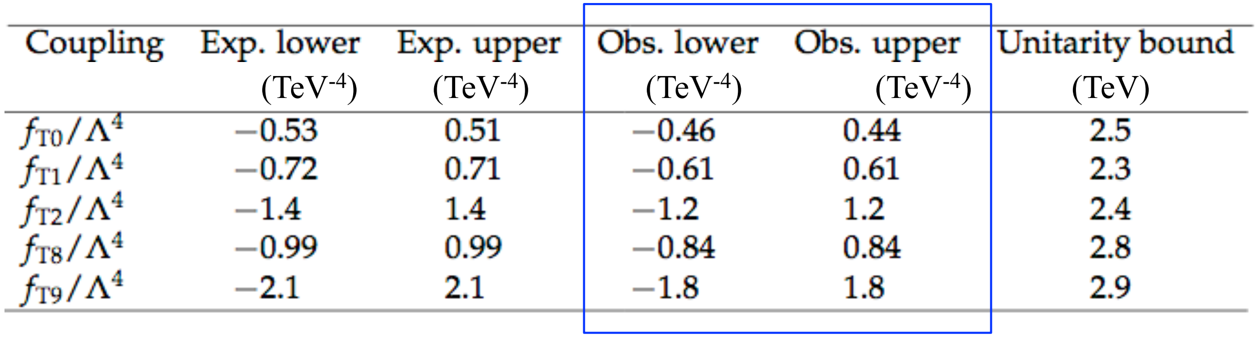
	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Previously observed limits (TeV^{-4})
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$	$[-38, 40]$, [11]
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$	$[-118, 120]$, [11]
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$	$[-4.6, 4.6]$, [36]
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$	$[-17, 17]$, [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]

CMS WZjj CMS-PAS-SMP-18-001(July 2018)



Parameters	Expected limit (TeV^{-4})	Observed limit (TeV^{-4})
f_{M0}/Λ^4	[-10.7, 10.7]	[-8.80, 8.55]
f_{M1}/Λ^4	[-10.1, 10.6]	[-8.25, 8.85]
f_{S0}/Λ^4	[-31.5, 33.5]	[-25.7, 27.5]
f_{S1}/Λ^4	[-50.5, 51.5]	[-40.5, 41.5]
f_{T0}/Λ^4	[-0.85, 0.85]	[-0.72, 0.75]
f_{T1}/Λ^4	[-0.55, 0.55]	[-0.48, 0.52]
f_{T2}/Λ^4	[-2.98, 2.92]	[-1.42, 1.83]

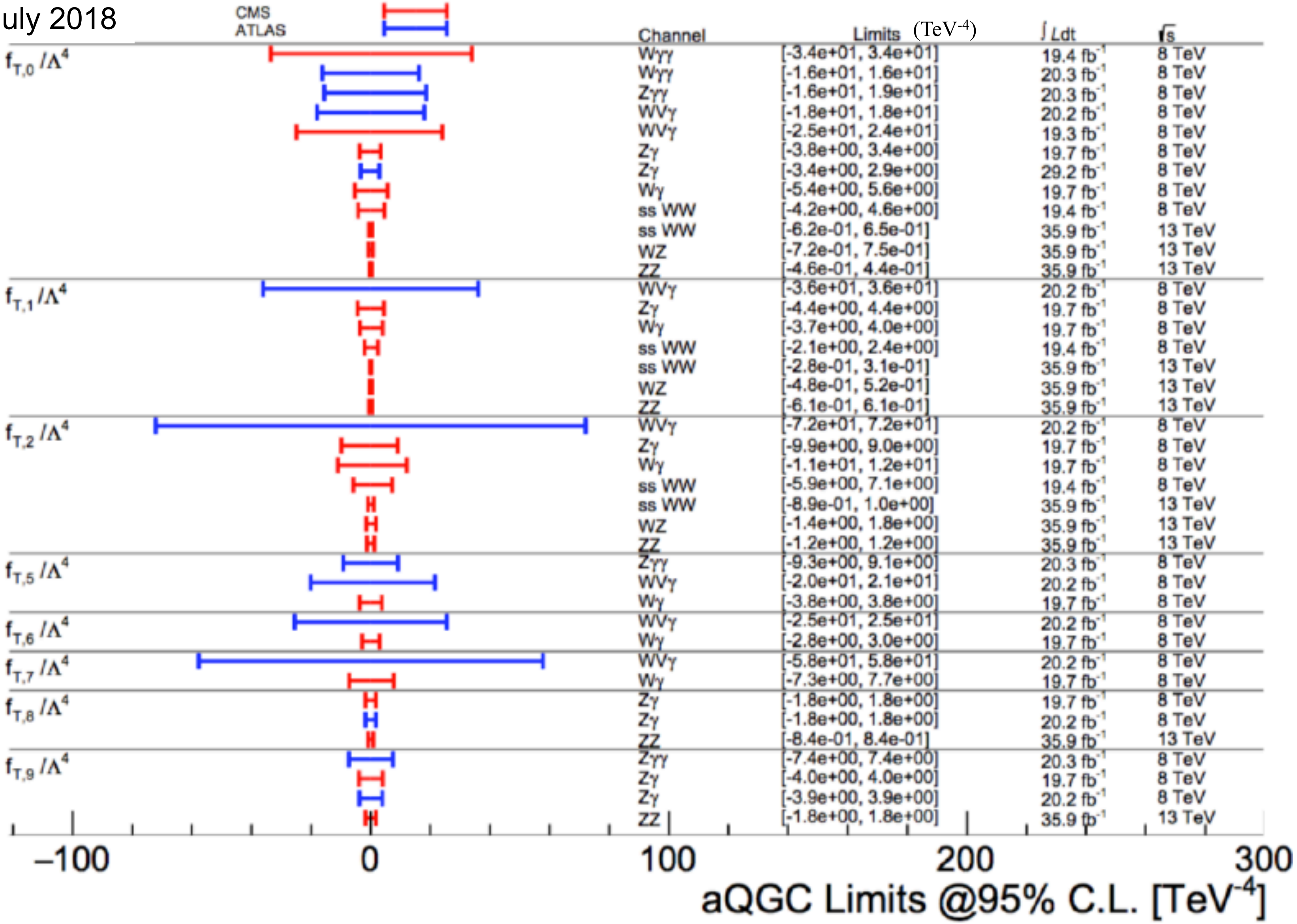
CMS ZZjj Phys. Lett. B 774 (2017) 682 (August 2017)



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

Anomalous quartic coupling (aQGC)

Strong improvement of aQGC limits with √s = 13 TeV data



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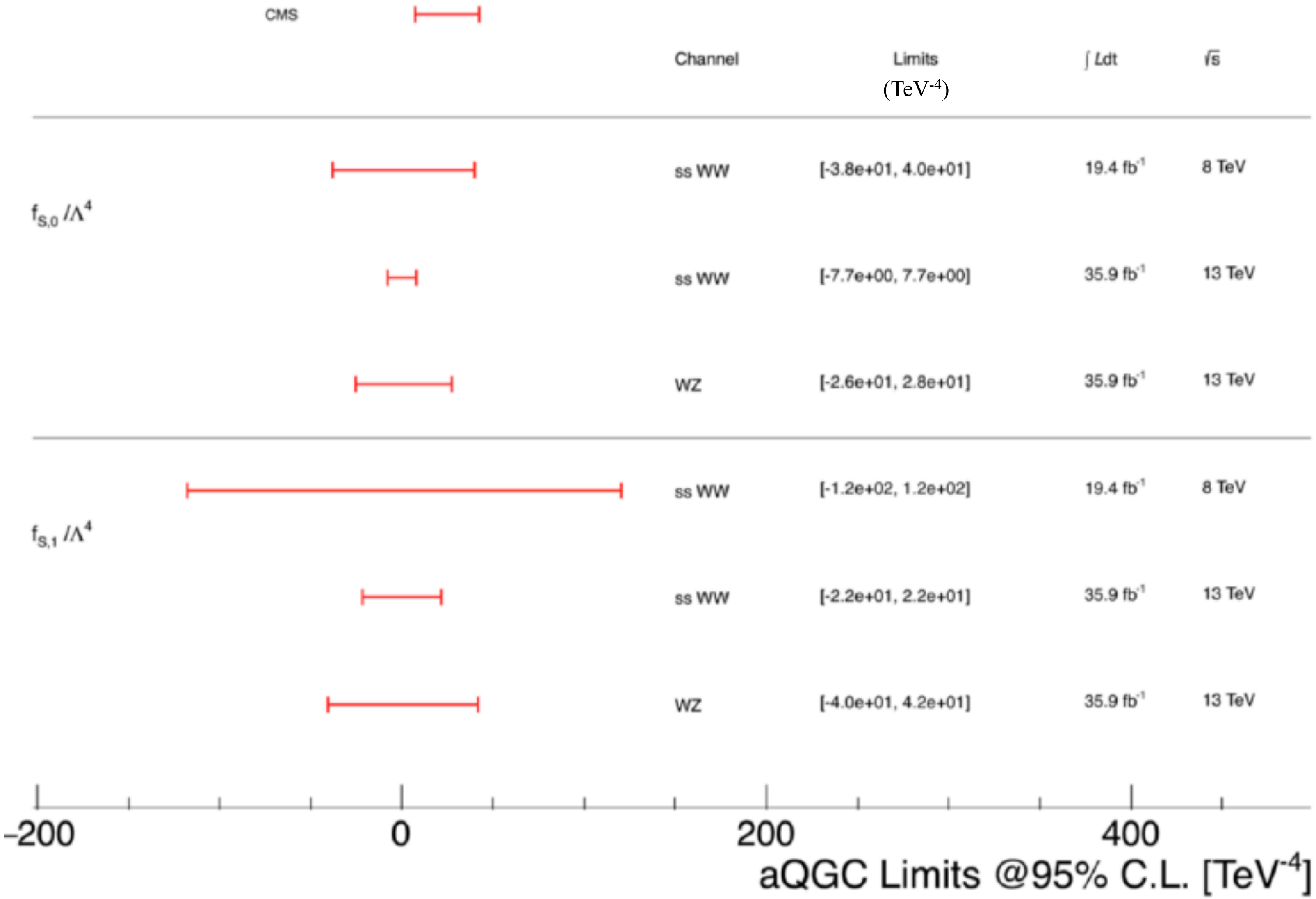
	Channel	Limits (TeV^{-4})	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Wγγ	[-3.4e+01, 3.4e+01]	19.4 fb^{-1}	8 TeV
	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	Zγγ	[-1.6e+01, 1.9e+01]	20.3 fb^{-1}	8 TeV
	WVγ	[-1.8e+01, 1.8e+01]	20.2 fb^{-1}	8 TeV
	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-7.2e-01, 7.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WVγ	[-3.6e+01, 3.6e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.8e-01, 5.2e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WVγ	[-7.2e+01, 7.2e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-1.4e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	WVγ	[-2.0e+01, 2.1e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	WVγ	[-2.5e+01, 2.5e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	WVγ	[-5.8e+01, 5.8e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

Anomalous quartic coupling (aQGC)



July 2018

	Channel	Limits (TeV^{-4})	$\int L dt$	$\sqrt{s}$
$f_{S,0}/\Lambda^4$	ss WW	[-3.8e+01, 4.0e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-7.7e+00, 7.7e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-2.6e+01, 2.8e+01]	35.9 fb^{-1}	13 TeV
$f_{S,1}/\Lambda^4$	ss WW	[-1.2e+02, 1.2e+02]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.2e+01, 2.2e+01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.0e+01, 4.2e+01]	35.9 fb^{-1}	13 TeV

Conclusions

- Non-abelian gauge structure of Standard Model:
  - evidence of of triple gauge coupling (TGC) by LEP
  - evidence of VBS (which includes QGC) by LHC

We have done it !

- Fiducial cross sections of $W^{\pm}W^{\pm}jj$, WZjj and ZZjj are compatible with standard model expectations
  Analyses have been performed with ~36 fb^{-1} collected in 2016.
  Statistical errors are larger than systematic errors (twice for $W^{\pm}W^{\pm}jj$)
  they will be reduced with the full Run2 data sample ~150 fb^{-1}
- Limits on anomalous QGC have been strongly improved with respect to previous limits obtained with $\sqrt{s}$=8 TeV Run 1 data sample.