New Vector Boson Scattering (VBS) “observations” at LHC

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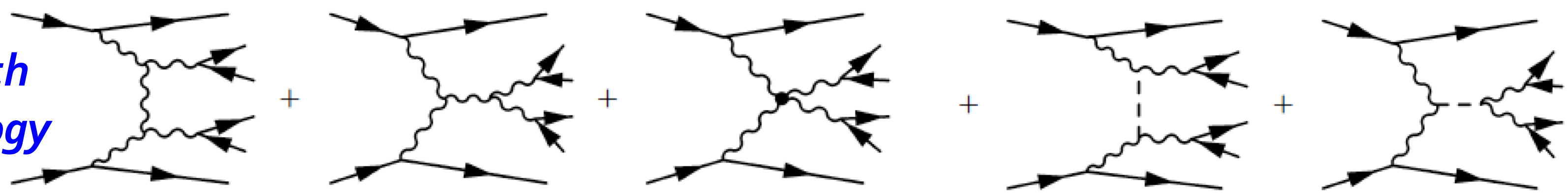
On behalf of ATLAS and CMS collaborations

Motivation

- Stringent test of EWSB mechanism and EW sector of SM predictions. Probe of Higgs Mechanism for scattering w/ longitudinal polarization
- Sensitive to beyond SM physics via anomalous gauge couplings and narrow resonances. Neutral coupling is forbidden at tree-level in SM.
- Irreducible backgrounds of many new physics searches in vector boson fusion mode.
- *Signature*: associated di-jet production with high inv. mass and large gap.

Signal with VBS topology (α^4)



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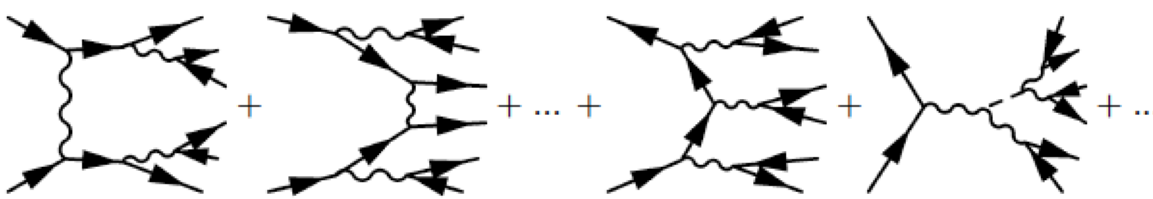
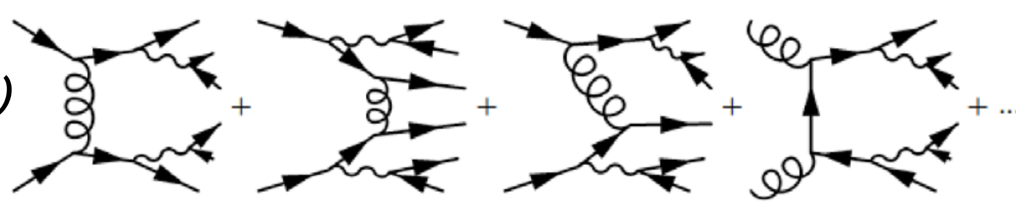


QCD background ($\alpha_s^2\alpha^2$)

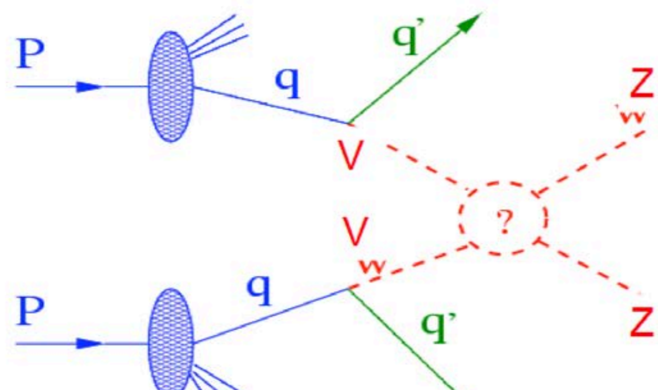


Why VBS?

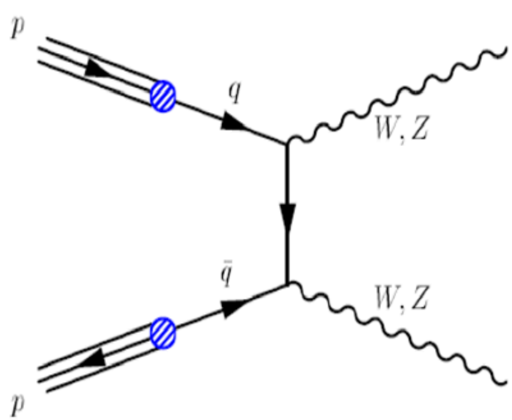
Unitarity violation of Vector Boson Scattering

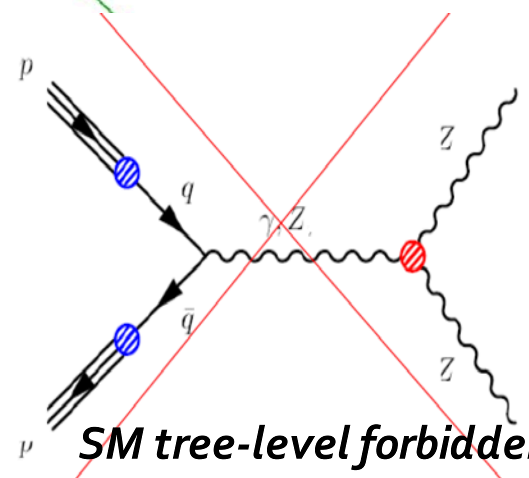
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$

"bulk" production mode incorporating SM processes and probing high precision QCD/EWK high order calculation via measuring the decay products of bosons



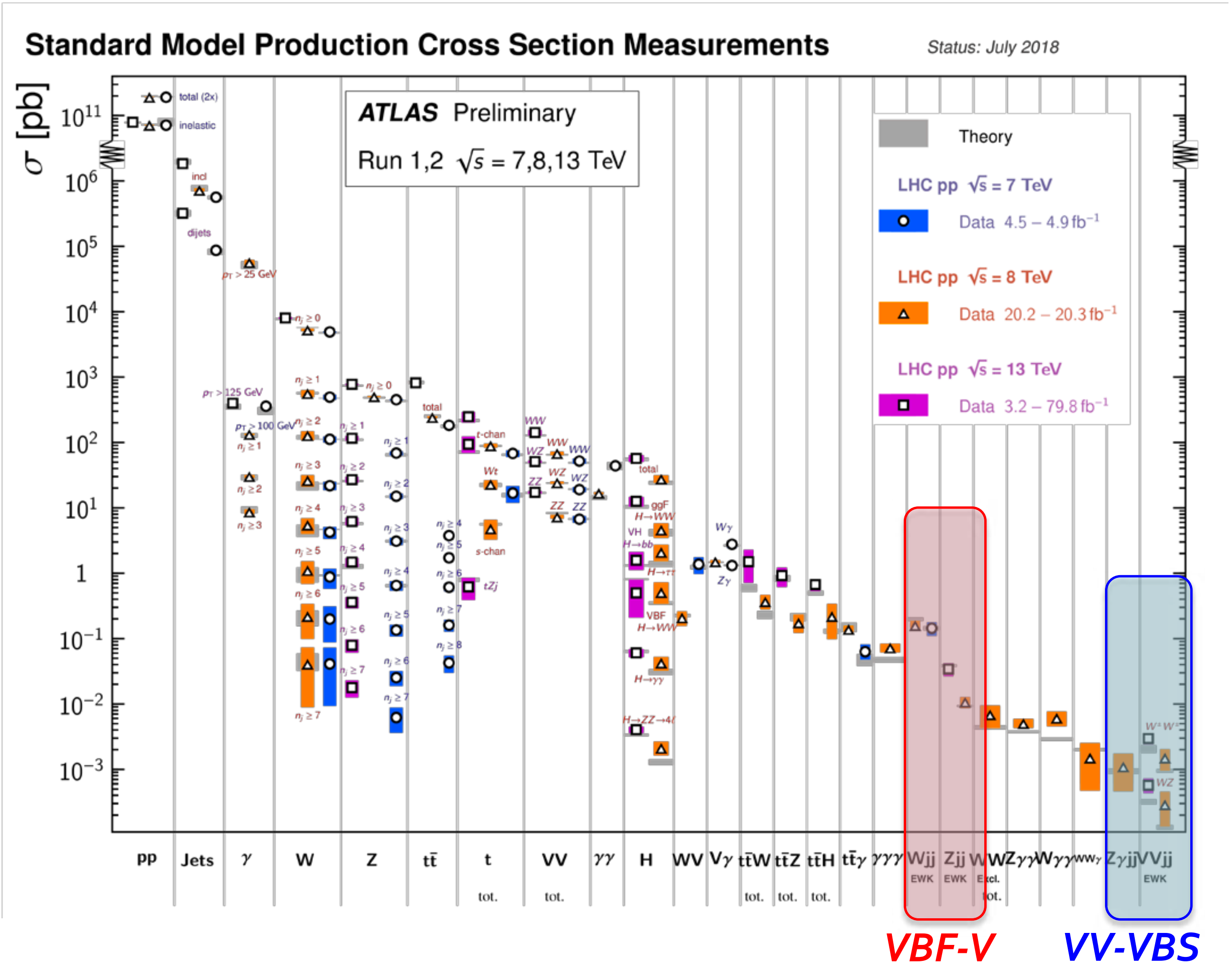
New physics show up via SM boson self-interactions, parameterized by effective lagrangians and effective field theories



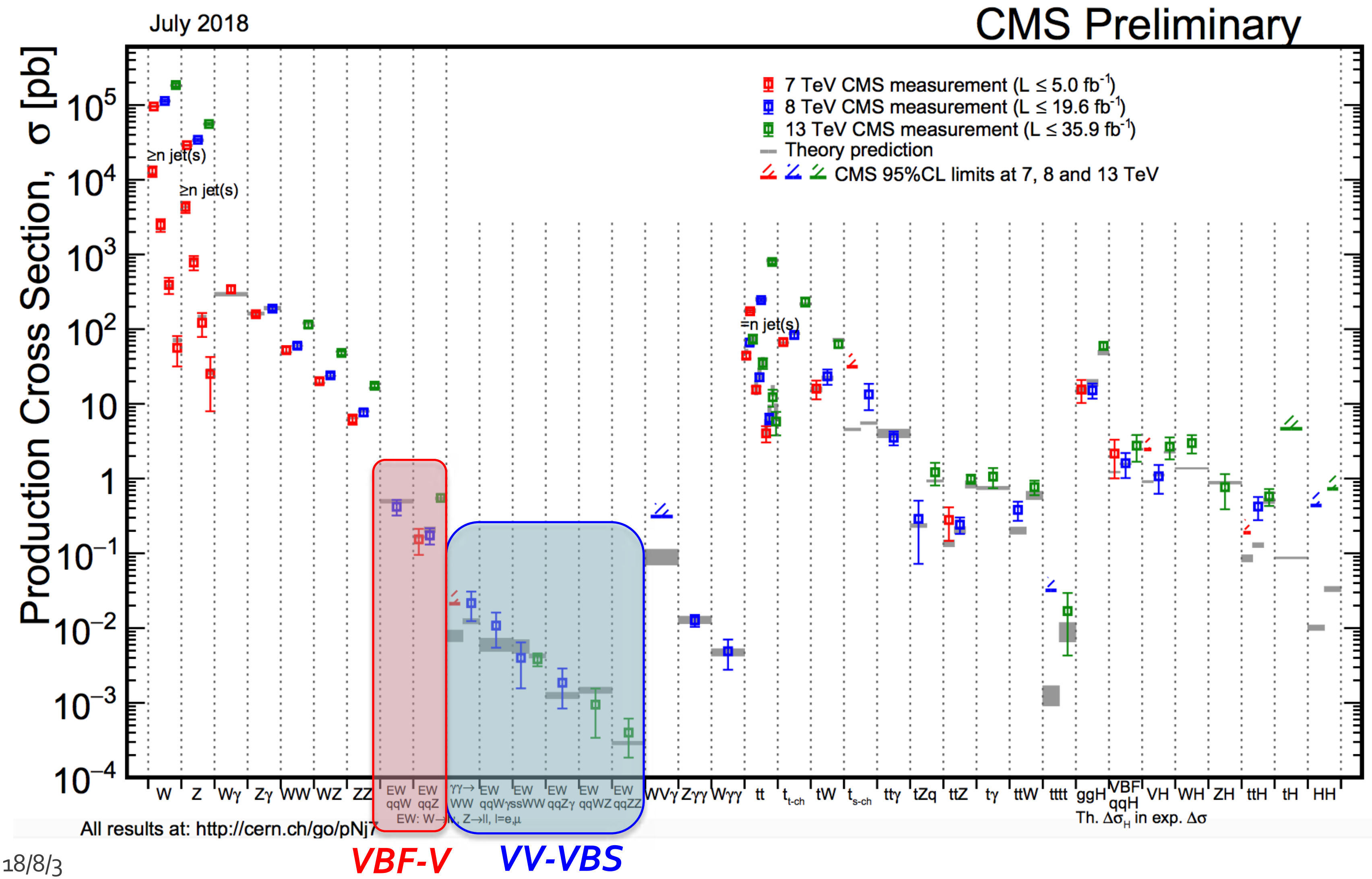


SM tree-level forbidden

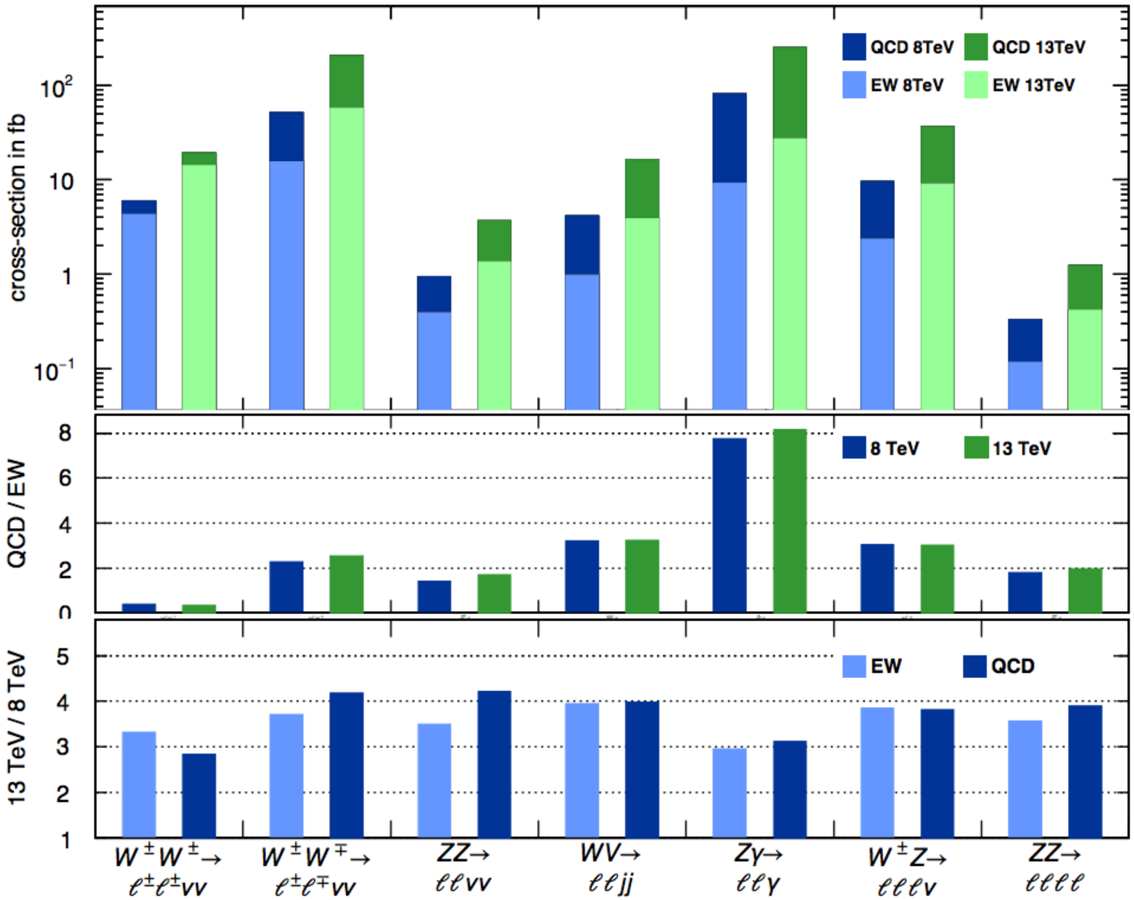
VBS measurements in ATLAS



VBS measurements in CMS



VBS measurement sensitivity prospect at 8TeV vs 13TeV



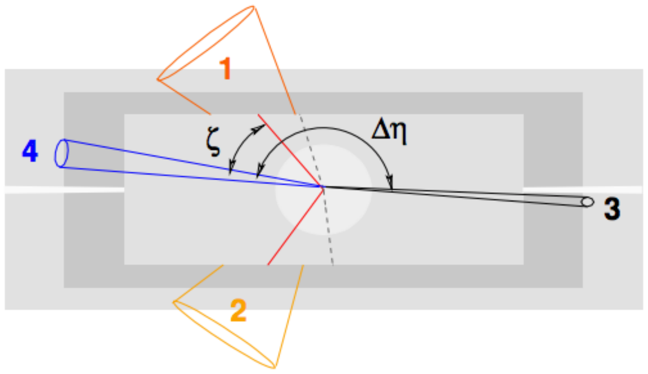
[CERN-THESIS-2014-105]

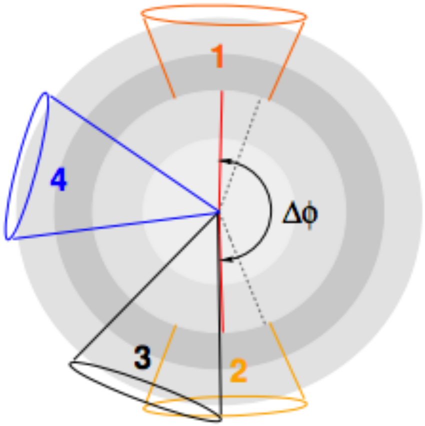
How much the jump in energy buy us

- Measurements mostly stat. limited
- Signals mostly qq initiated→no huge jumps in inclusive x-sec
- Still EWK production tends to raise slightly faster than QCD at high m(jj), being the most interesting part sensitive to high $\sqrt{s}$ of the bosons scattering

VBS signatures in short

- Typical VBS topology
  - tagging jets:
    - transverse momenta: pT(j1), pT(j2)
    - invariant mass: M(jj)
    - rapidity difference: ΔY(jj)
  - central jet veto
  - centrality: $\max\left(\left|\frac{y_i - 0.5(y(j_1)+y(j_2))}{y(j_1)-y(j_2)}\right|\right)$
  - pT balance: $\frac{\sum_i \vec{p_T}_i}{\sum_i |\vec{p_T}_i|}$
    - All hard process decay products and jets



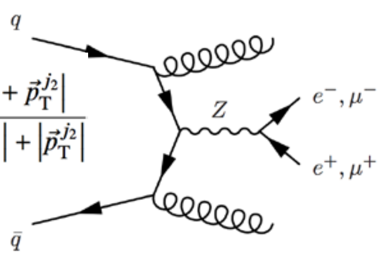


Experimental challenges per final states

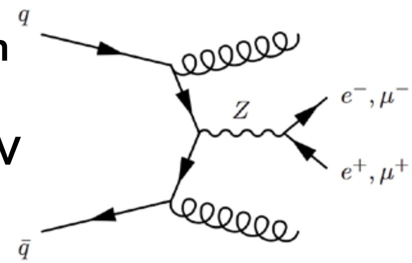
channel	final state	comment *
VBF W *Observed!*	ℓν jj	statistics is not a problem, good modelling of W+jets needed
VBF Z *Observed!*	ℓℓ jj	statistics is not a problem, good modelling of Z+jets needed
VBS $W^{\pm}W^{\pm}$ *New Observed!*	$\ell^{\pm}\nu\ell'^{\pm}\nu$ jj	"golden channel": very good EW/QCD ratio, mainly experimental (charge misID) background, good statistics
VBS $W^{\pm}W^{\mp}$	$\ell^{\pm}\nu\ell'^{\mp}\nu$ jj	hard to investigate due to dileptonic ttbar background, Higgs group does also use this final state
VBS WZ *New Observed!*	ℓℓℓ'ν jj	similar cross section as ssWW, but larger QCD background, fair reconstructibility of fs
VBS Wγ/Zγ	ℓνγ jj / ℓℓγ jj	photon brings higher stat. (and different experimental systematics), lacks sensitivity to BSM in Higgs sector
VBS WV	ℓνjj jj	large backgrounds (W+jets, ttbar), but promising boosted regime when looking for NP effects
VBS ZV	ℓℓjj jj	large backgrounds (Z+jets, ttbar), but promising boosted regime when looking for NP effects, no neutrinos in final state
VBS ZZ	ℓℓℓ'ℓ' jj	very clean channel, very good reconstructibility of final state and low background contamination, but small cross-section
VBS ZZ	ℓℓνν jj	challenging to measure invisible Z decay, combination with leptonic decay might help to suppress dileptonic ttbar background

Measurement of electroweak Z(→ll)jj production cross section at 13TeV by ATLAS

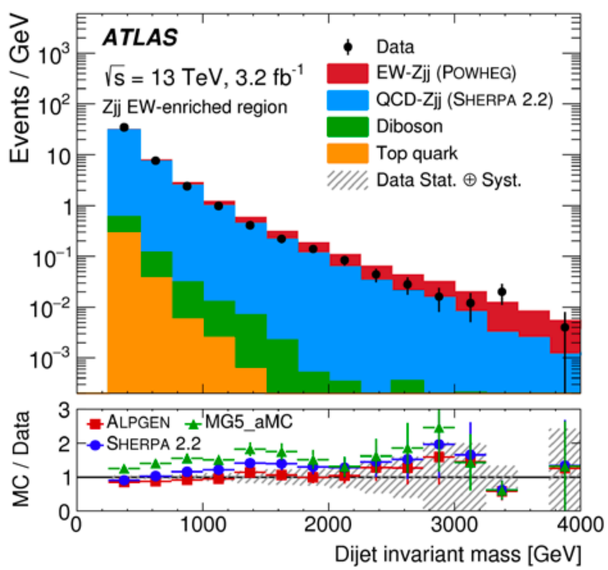
$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

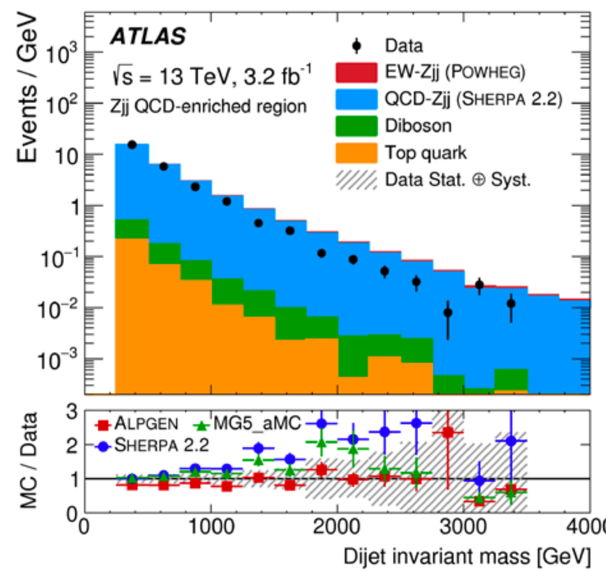


EW enriched region
- M_{jj}>250GeV (1TeV)
- pT_balance < 15GeV
- # of central jet ==0



QCD enriched region
- M_{jj}>250GeV
- pT_balance < 15GeV
- # of central jet >=1

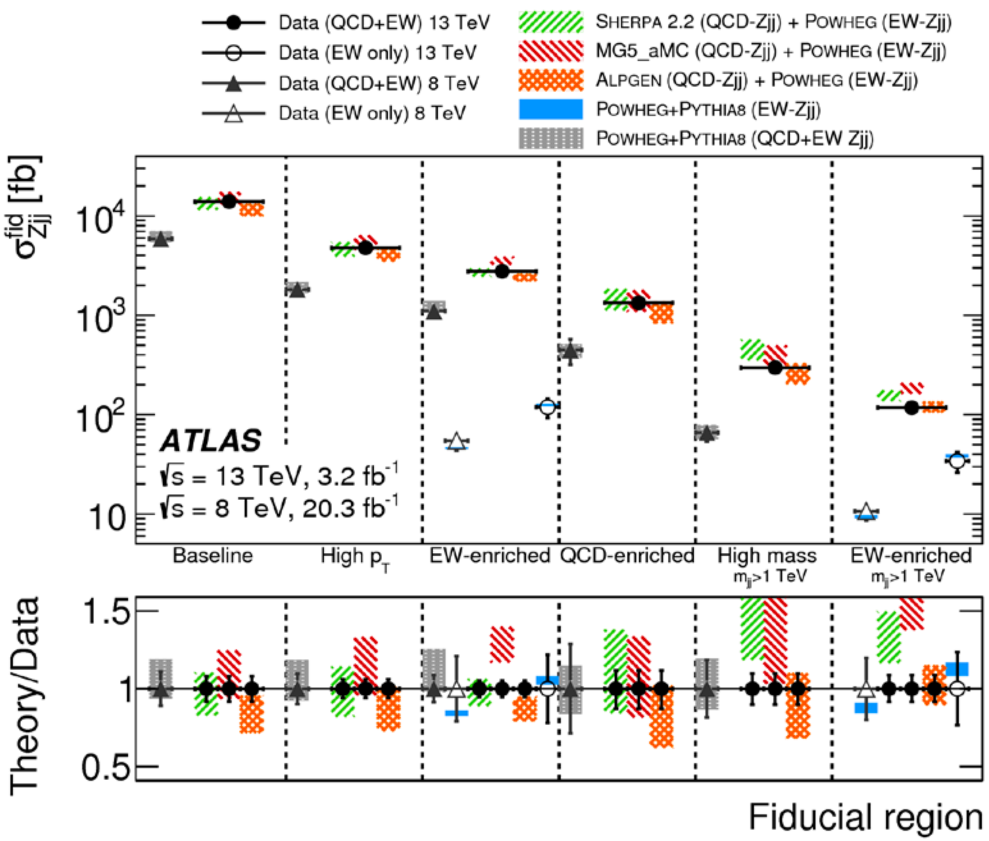




Physics Letters B 775 (2017) 206

Signal extraction via binned likelihood fit of QCD&EWK m_{jj} templates in EWK-enriched region after reweighting the m_{jj} shape of the QCD Zjj MC based on a fit to the data in the QCD-enriched region

Measurement of electroweak Z(→ll)jj production cross section at 13TeV by ATLAS



QCD+EWK cross section measured in six fiducial regions.

EWK-ONLY cross section measured in two fiducial regions with EWK component enriched.

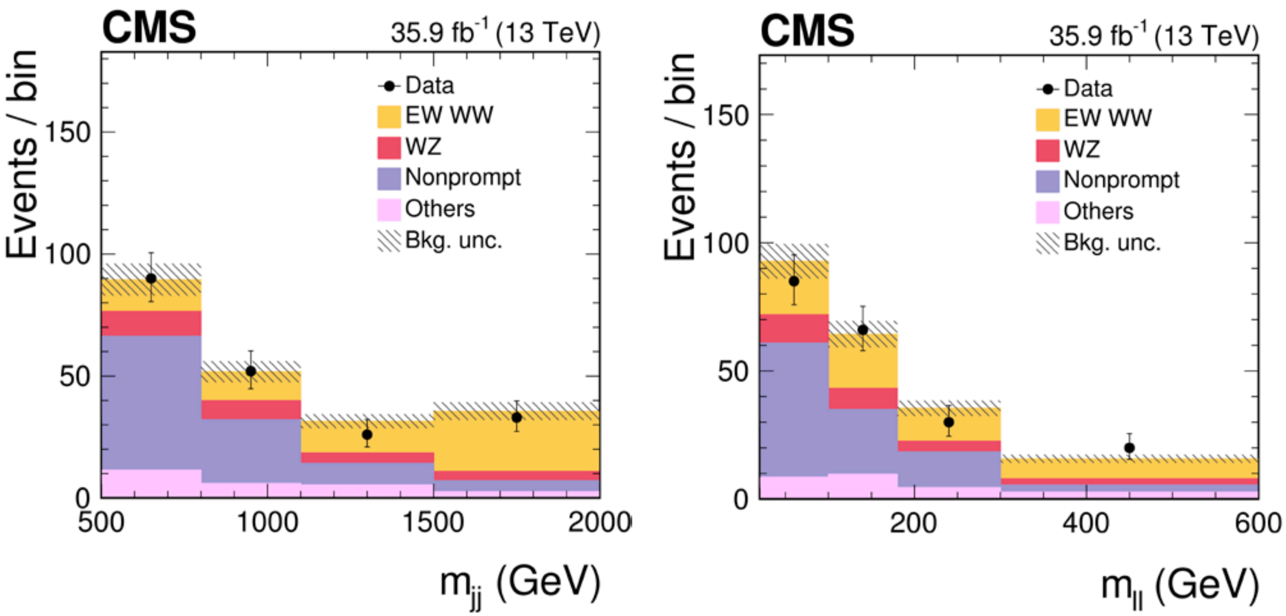
Measurements in good agreement with theory.

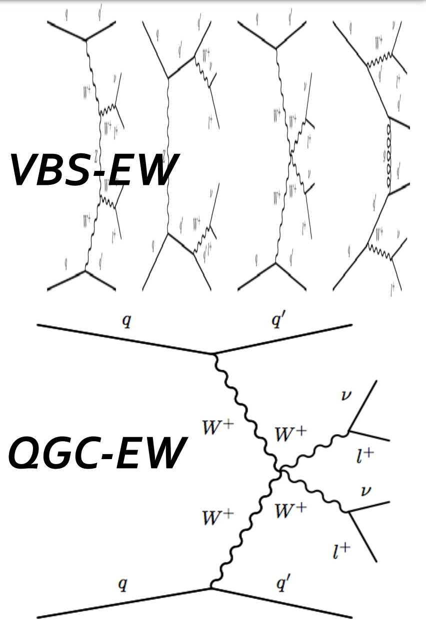
[*Physics Letters B 775 (2017) 206*]

Observation of electroweak $W^{\pm}W^{\pm}(\rightarrow 2l2\nu)jj$ at 13TeV by CMS

A. Levin, Q.Li, et. al. (PKU)

Phys. Rev. Lett. 120 (2018) 081801





Same-sign Highest EW/QCD ratio in all VVjj channels

Fid. Region: M_{jj}>500GeV and $\Delta\eta_{jj}$>2.5

1st ever 5σ *observation of VVjj-EWK (w/ VBS signature)*

Obs. $\sigma_{EW}(\ell\ell jj)$ *= 3.83 ± 0.66 (stat) ± 0.35 (syst) fb, obs./exp. Signif. = 5.5/5.7 σ*

In agreement with LO prediction $\sigma_{LO}(\ell\ell jj)$ *= 4.25 ± 0.21 fb*

Observation of electroweak $W^{\pm}W^{\pm}(\rightarrow 2l2\nu)jj$ at 13TeV by CMS

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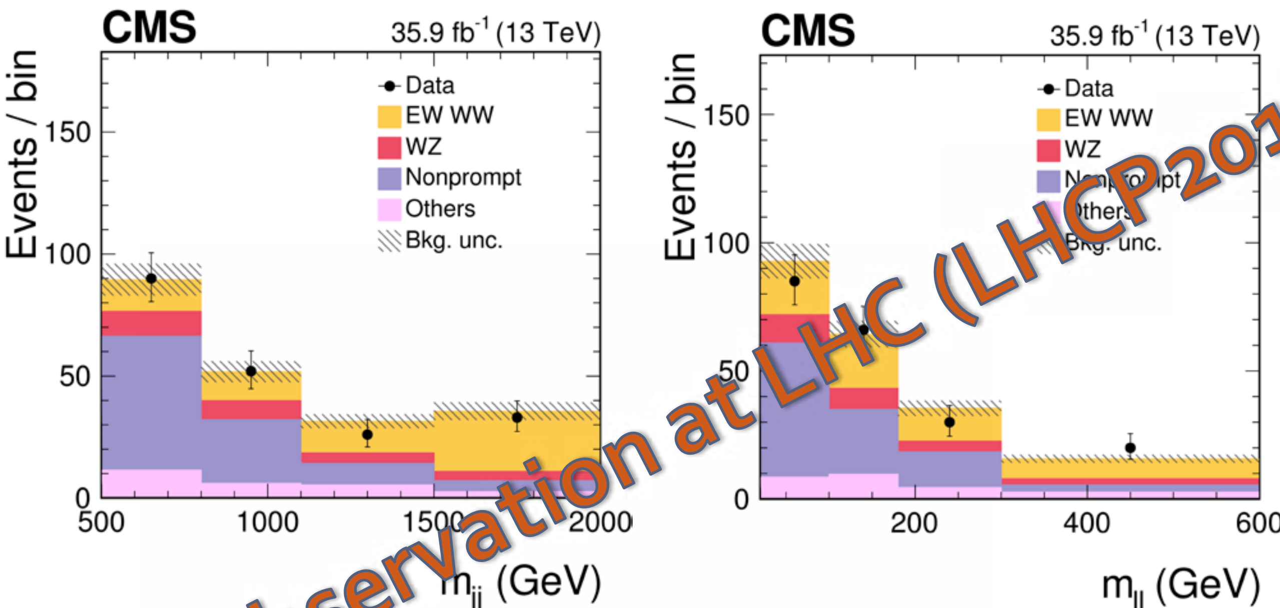
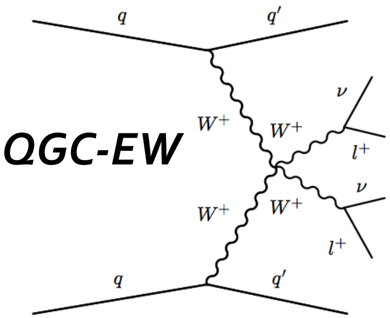
1st 5-σ observation at LHC (LHCP2017 Highlight)



VBS-EW



QGC-EW

Same-sign Highest EW/QCD ratio in all VVjj channels

Fid. Region: M_{jj}>500GeV and $\Delta\eta_{jj}$>2.5

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Obs. $\sigma_{EW}(\ell\ell jj)$ = 3.83 ± 0.66 (stat) ± 0.35 (syst) fb, obs./exp. Signif. = 5.5/5.7 σ

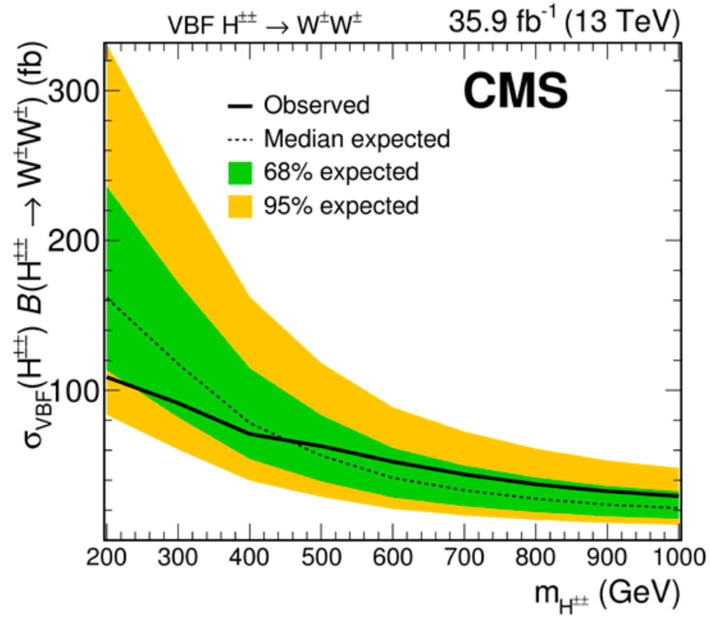
In agreement with LO prediction $\sigma_{LO}(\ell\ell jj)$ = 4.25 ± 0.21 fb

Constraint on aQGC using electroweak $W^{\pm}W^{\pm}(\rightarrow 2l2\nu)jj$ production at 13TeV by CMS

A. Levin, Q.Li, et. al. (PKU)

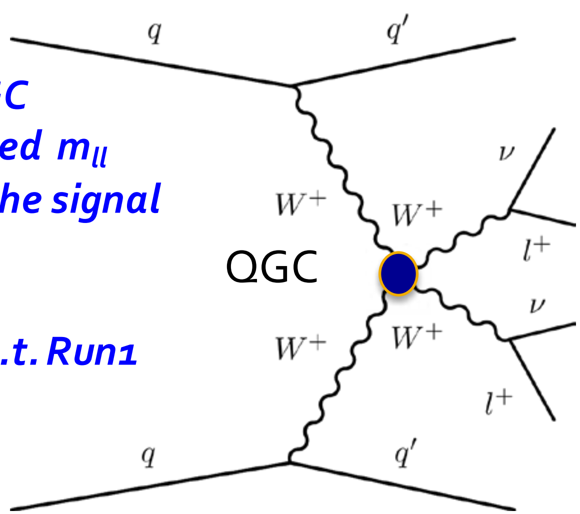
Phys. Rev. Lett. 120 (2018) 081801

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Run-I limits (TeV^{-4})
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [29]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [29]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [30]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]



95% CL limits on aQGC
Using the the measured m_{ll} distributions both in the signal and WZ regions.

Greatly improved w.r.t. Run1



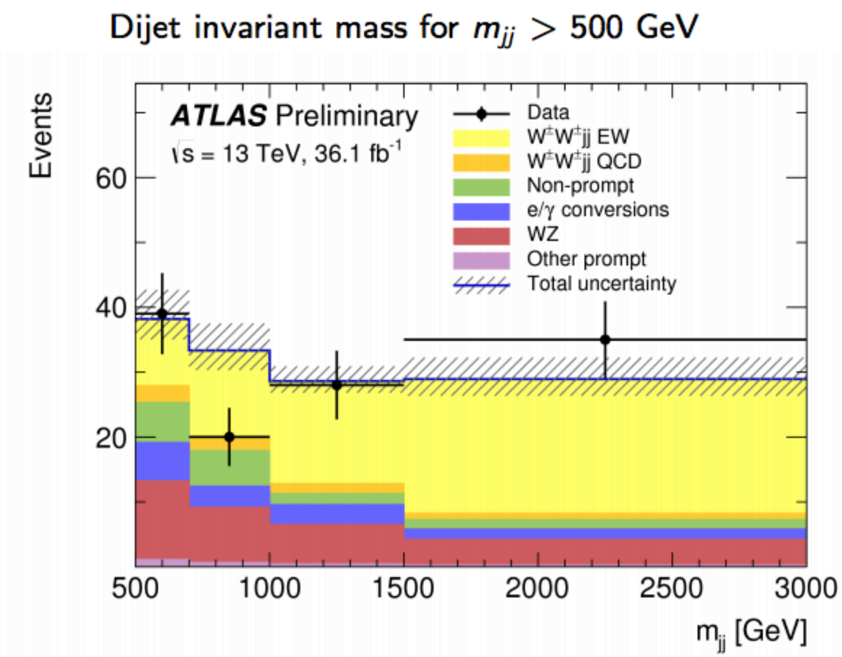
Doubly charged Higgs bosons are predicted in models containing a Higgs triplet field. (Georgi–Machacek model)

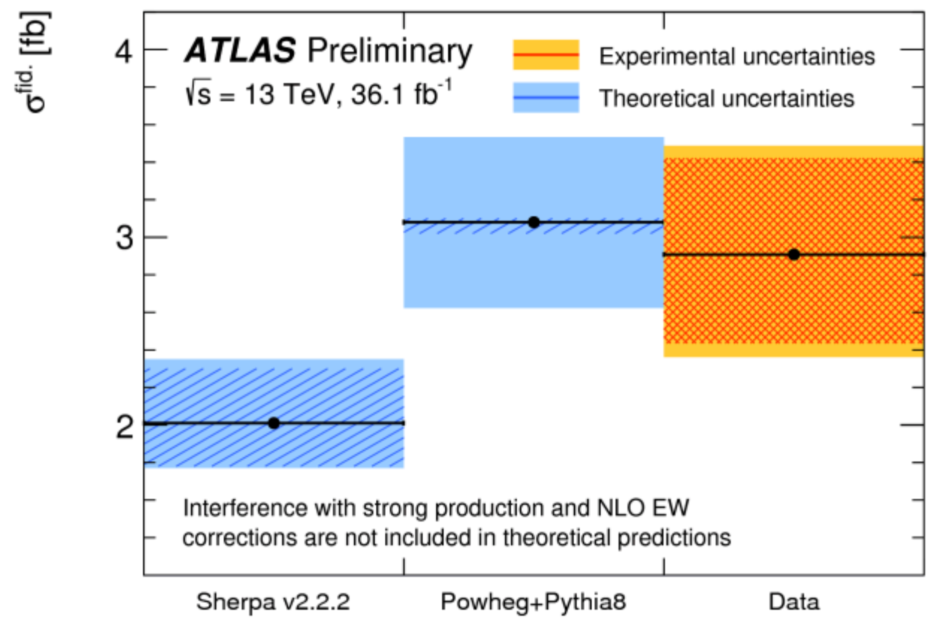
1st limits placed on $H^{\pm\pm}\rightarrow W^{\pm}W^{\pm}$ cross section using (m_{jj}, m_{ll}) two-dimensional distributions

Observation of electroweak $W^{\pm}W^{\pm}(\rightarrow 2l2\nu)jj$ at 13TeV by ATLAS

L. Zhang, R. Ospanov, J. Liu, Y. Liu, Y. Wu, et. al. (USTC)
E. Yatsenko, M. Mittal, S. Li, J. Guo, H. Yang, et. al. (TDLI/SJTU)

ATLAS-CONF-2018-030





Likelihood fit performed in:

- *6 channels: ee, eμ, μμ*
- *Signal region: 4 m_{jj} bins for m_{jj} > 500GeV*
- *Control region: 200 < m_{jj} < 500GeV*

SM prediction:
NLO electroweak corrections (–16% for Sherpa) and interference (+6%) are not Included
Obs.(Exp.) signif. = 6.9σ (4.6σ)

Observation of electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ at 13TeV by ATLAS

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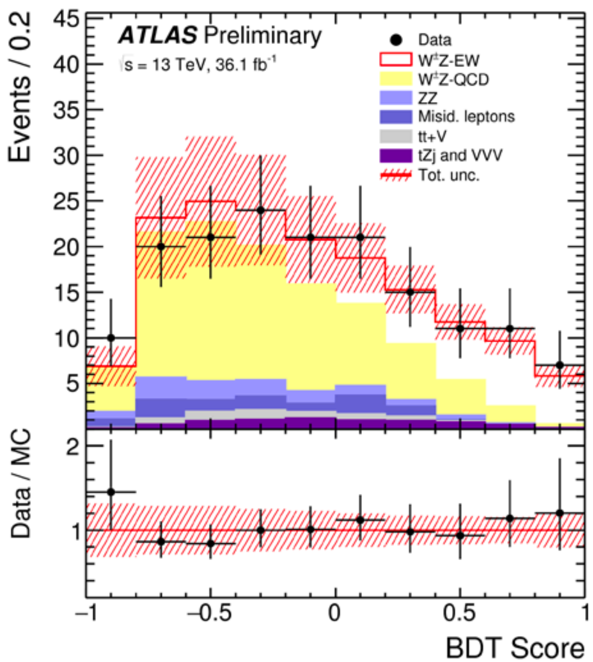
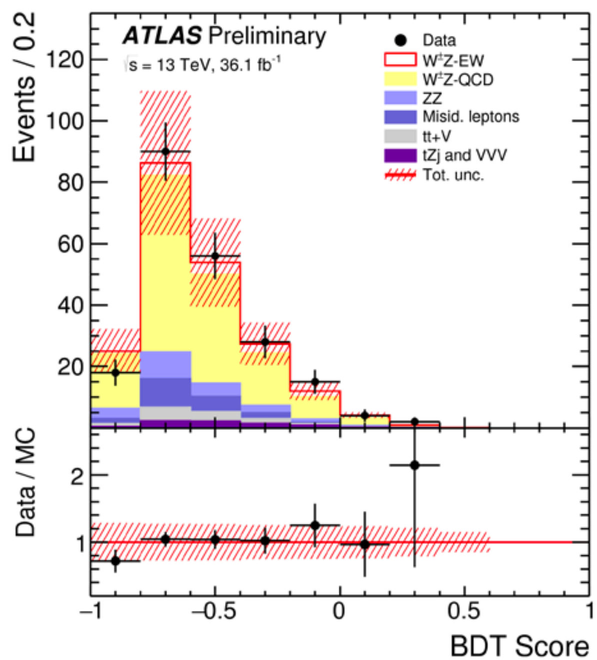
ATLAS-CONF-2018-033





- ***BDT discriminant trained with 15 input variables***
- ***Preselection:***
  - $p_T(j)>40GeV$
  - $M(jj)>500GeV$
  - ***B-jet veto***
- ***Background constrained via 3-CR and fitted w/ SR***

Post-fit background normalisations

$\mu_{WZ\text{-}QCD} = 0.60 \pm 0.25$

$\mu_{ttV} = 1.18 \pm 0.19$

$\mu_{ZZ} = 1.34 \pm 0.29$

WZjj-EW measured signal strength:

$$\mu_{EW} = 1.77 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.}) = 1.77 \pm 0.45$$

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

$$\sigma^{\text{fid., EW}}_{WZ^{\pm}jj\rightarrow\ell\nu\ell\ell jj} = 0.57\,^{+0.15}_{-0.14}\text{ fb} = 0.57\,^{+0.14}_{-0.13}(\text{stat.})\,^{+0.05}_{-0.04}(\text{sys.})\,^{+0.04}_{-0.03}(\text{th.})\text{ fb}$$

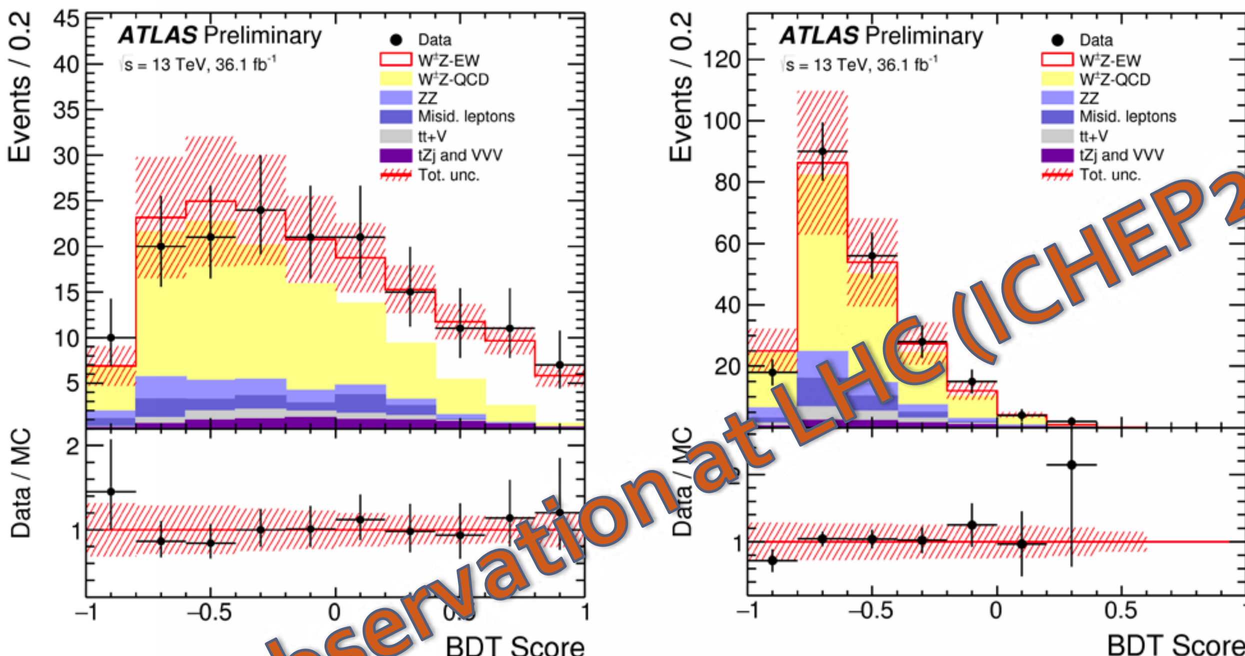
$$\sigma^{\text{fid., EW th.}}_{\text{Sherpa}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\text{ fb}$$

Observation of electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ at 13TeV by ATLAS

E. Yatsenko, S. Li, et. al. (TDLI/SJTU)

ATLAS-CONF-2018-033

1st 5-σ observation at LHC (ICHEP2018 Highlight)



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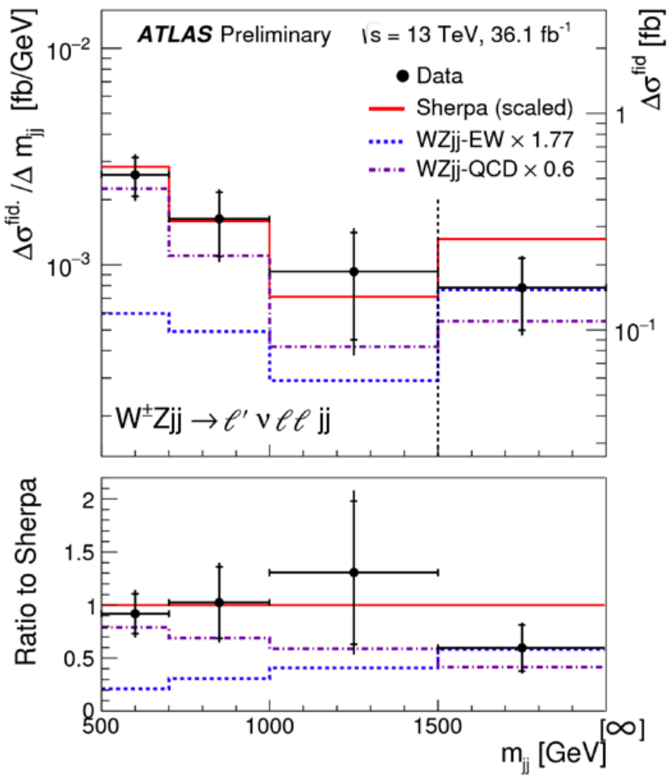
1^{st} differential measurements of electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ at 13TeV by ATLAS

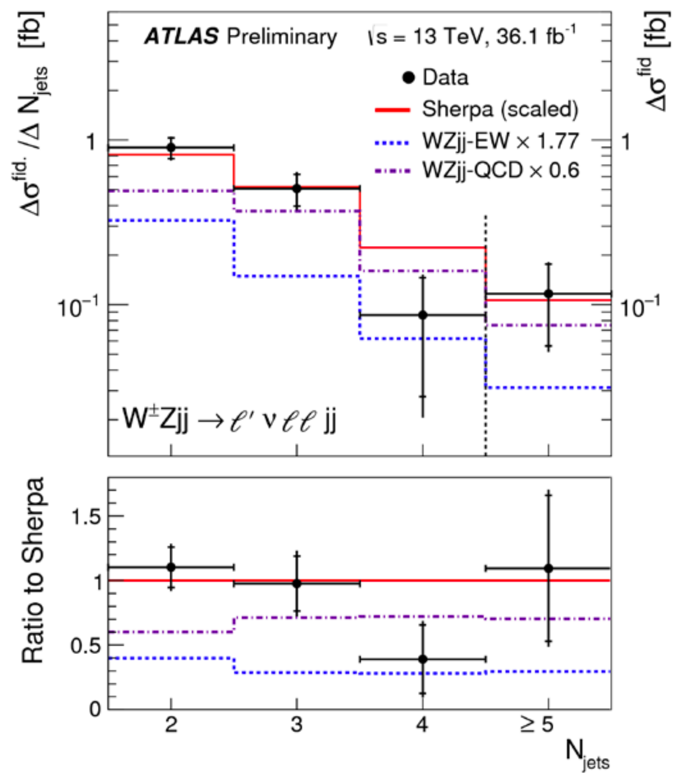
E. Yatsenko, S. Li, et. al. (TDLI/SJTU)

ATLAS-CONF-2018-033

1^{st} unfolded distribution measured in WZjj-EWK:
m(jj), N_{jet}, $\Sigma p_T(l)$, $m_T(WZ)$, $\Delta Y(jj)$, $\Delta\phi(jj)$, $\Delta\phi(W,Z)$, N_{jets}^{gap}



M(jj)

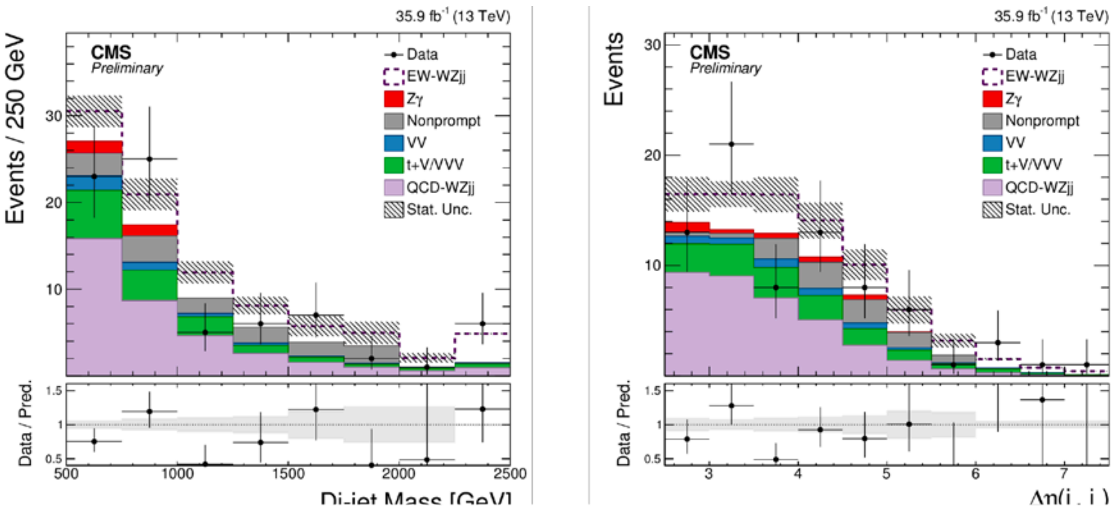


Jet-multiplicities

Sherpa2.2 LO prediction normalized in comparison to DATA

Neither QCD/EWK interference effects nor NLO EWK corrections are imployed

Measurements of electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ at 13TeV by CMS



Observed (expected) significance of EW WZ 1.9σ (2.7σ)

$$\mu_{EW} = \sigma_{EW,obs}/\sigma_{EW,\text{theo}} = 0.64^{+0.45}_{-0.37}$$

QCD: MG5_aMC@NLO (<=3j LO), EWK: MG5 LO

Tight $\sigma^{\text{fid}}_{\text{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\text{stat})\ ^{+0.41}_{-0.34}\,(\text{syst})$

Loose $\sigma^{\text{fid,loose}}_{\text{WZjj}} = 4.01^{+0.72}_{-0.68}\,(\text{stat})\ ^{+0.57}_{-0.47}\,(\text{syst})$

MG5 LO Tight $\sigma_{\text{fid,MG}} = 3.27\,^{+0.39}_{-0.32}(\text{scale}) \pm 0.15\,(\text{PDF})$

Two fiducial region defined for theo. Vs exp. comparison

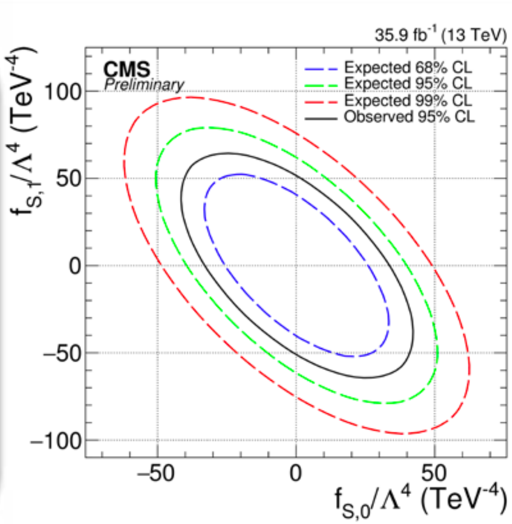
Fiducial Regions

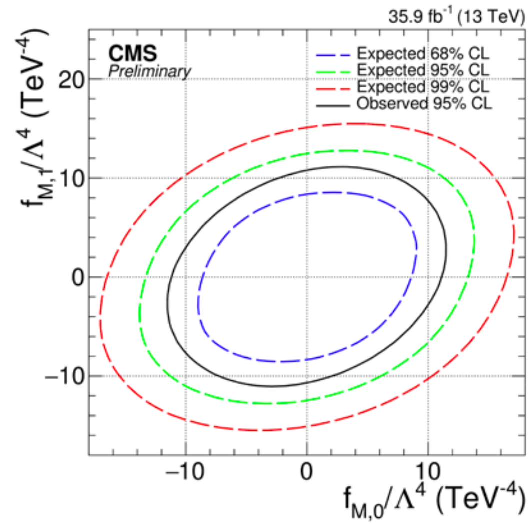
	Tight Fiducial	Loose Fiducial
$p_T(\ell_{Z,1})$ [GeV]	> 25	> 20
$p_T(\ell_{Z,2})$ [GeV]	> 15	> 20
$p_T(\ell_W)$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.5	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_Z - m_Z^{PDG}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_T^{miss} [GeV]	-	-
$\lvert\eta(j)\rvert$	< 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]	-	-
n_{b-jet}	-	-
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	-

CMS-PAS-SMP-18-001

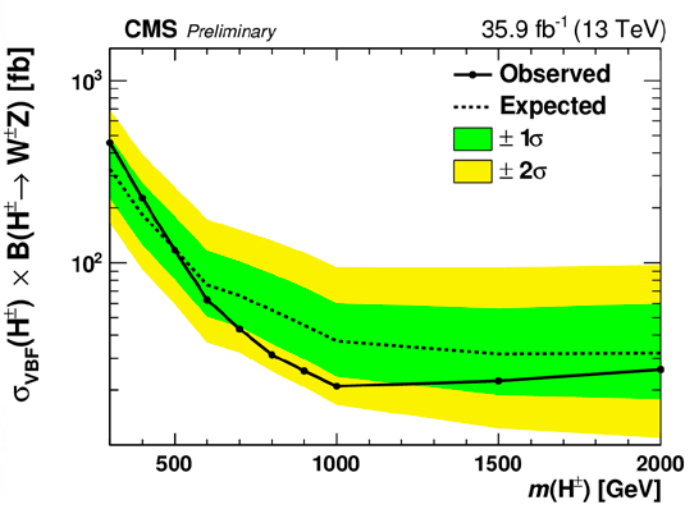
Probing new physics using electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ production at 13TeV by CMS

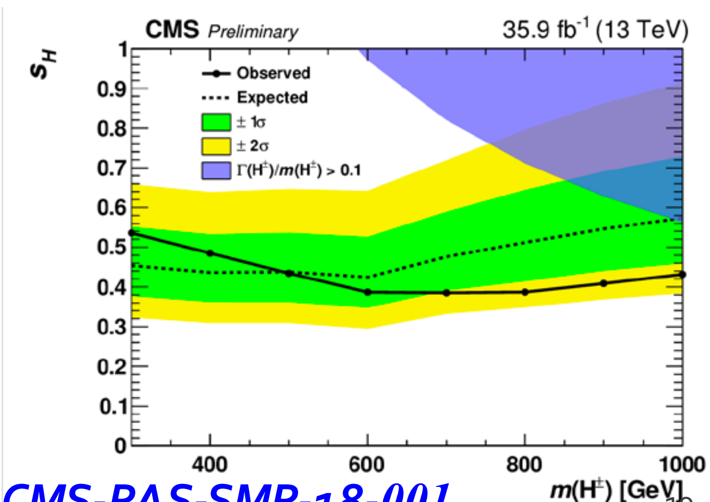
Limits on aQGC parameterized with Eboli's dimension-8 EFT model (hep-ph/0606118) using $m_T(WZ)$





Limits on Charged Higgs using Georgi–Machacek (GM) model (Nucl. Phys. B 262 (1985))

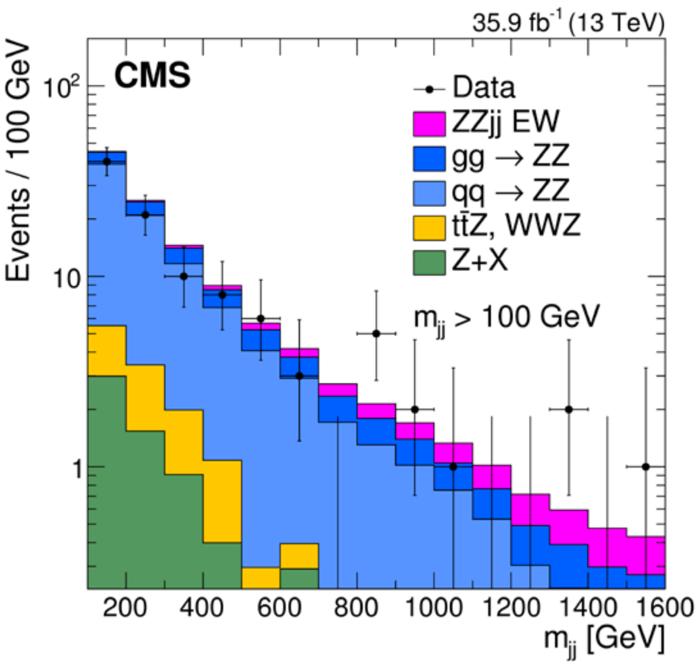




[CMS-PAS-SMP-18-001]

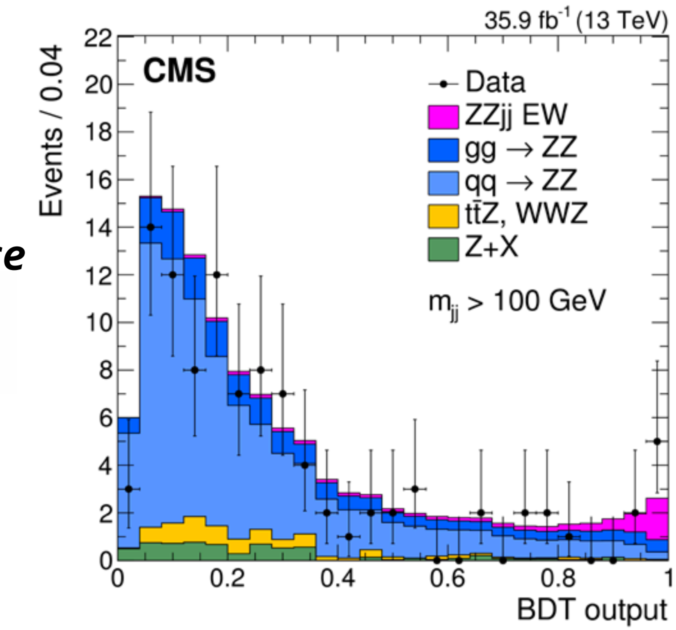
Measurement of electroweak ZZ(→4l)jj production cross section at 13TeV by CMS

[Phys. Lett. B 774 (2017) 682](#)



+ $\Delta\eta_{jj}$ + m_{ZZ} +
Centrality* + P_T *balance

BDT training



Inclusive region: m_{jj}>100GeV
VBS region: $|\Delta\eta_{jj}|$ > 2.4 + m_{jj} > 400 GeV
non-VBS region: $|\Delta\eta_{jj}|$ < 2.4 or m_{jj} < 400 GeV

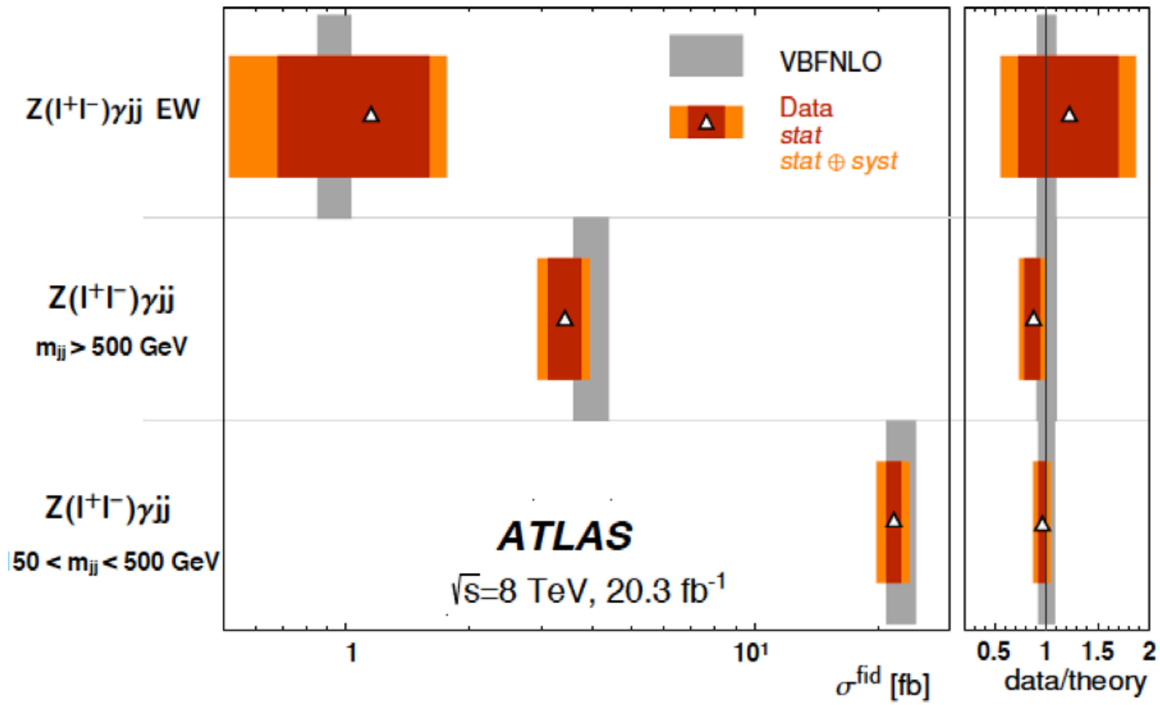
EWK signal significance 2.7σ (exp 1.6σ)

Limits on aQGCs w/ EFT dim-8 operators and comparison with unitarity validity range

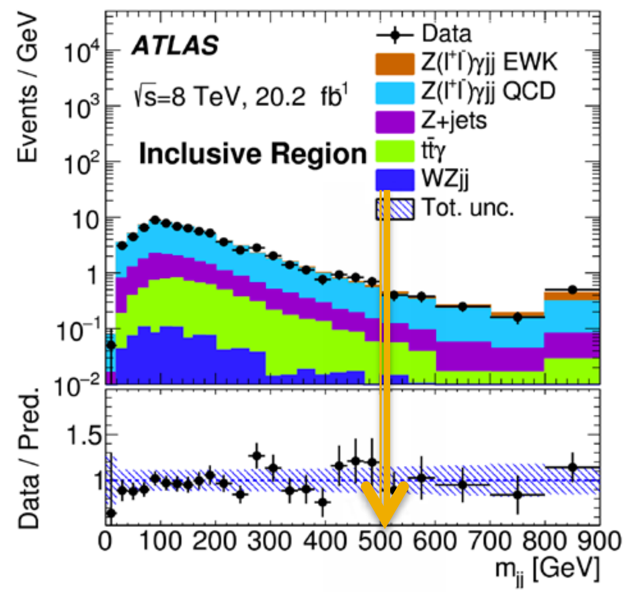
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T_0}/Λ^4	−0.53	0.51	−0.46	0.44	0.6
f_{T_1}/Λ^4	−0.72	0.71	−0.61	0.61	0.6
f_{T_2}/Λ^4	−1.4	1.4	−1.2	1.2	0.6
f_{T_8}/Λ^4	−0.99	0.99	−0.84	0.84	2.8
f_{T_9}/Λ^4	−2.1	2.1	−1.8	1.8	2.9

First Measurement of Zγ+jj Electroweak production in ATLAS

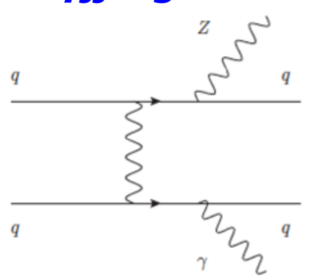
S. Li (TDLI/SJTU), Z. Liang (IHEP), et. al.



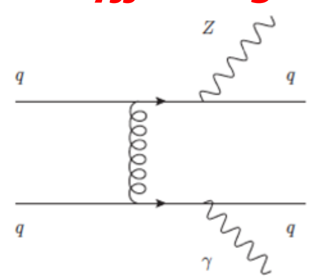
JHEP07(2017)107



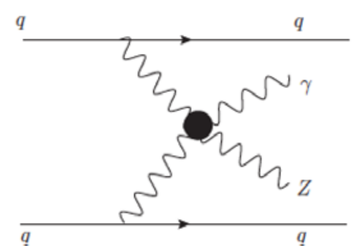
EW Zγjj Signal



QCD Zγjj Background



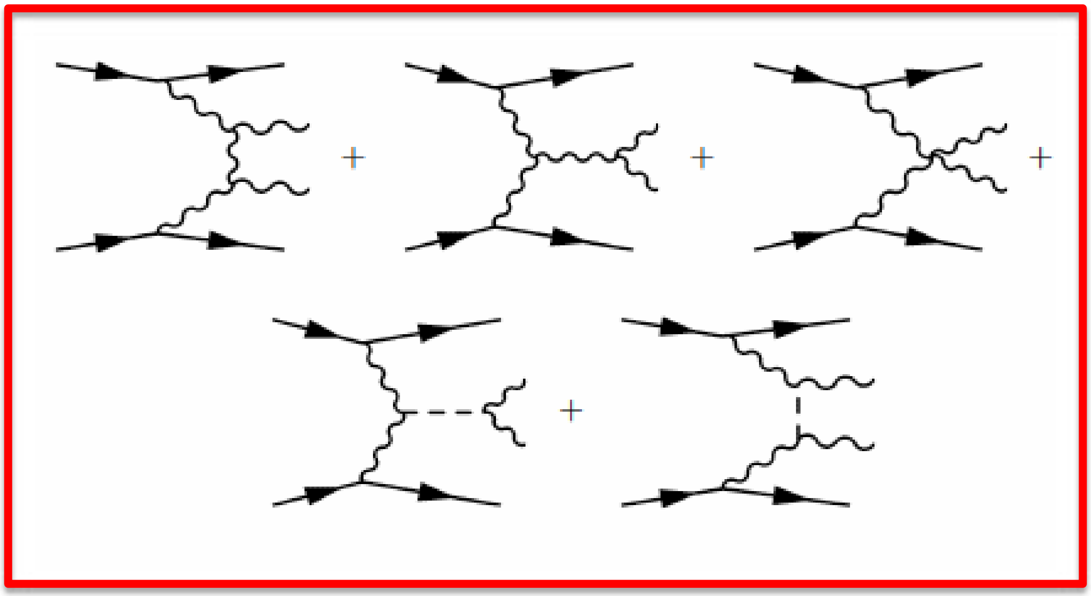
New Physics Vertex (BSM signal)



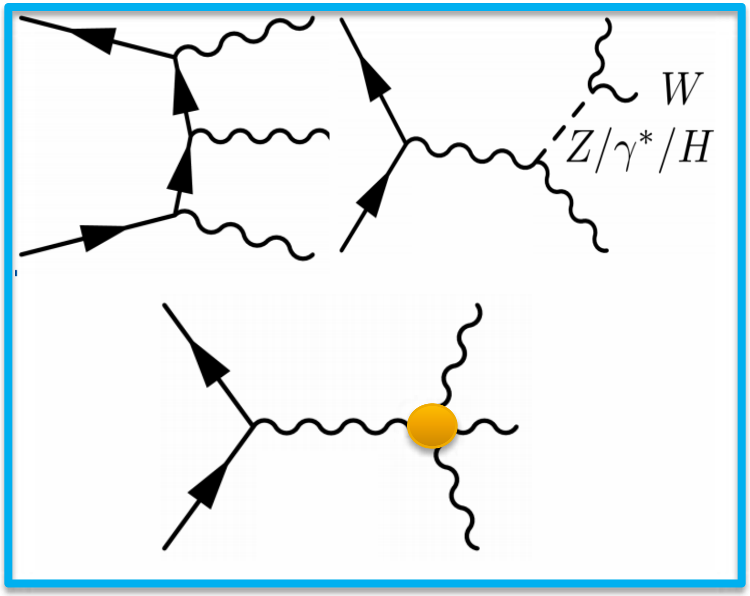
Review of Anomalous Quartic Coupling in VBS (+ Triboson processes)

EFT with dim8 operators for aQGC interpretation

- Assuming Higgs boson belongs to a $SU(2)_L$ doublet
- dimension 8: the ***lowest dimension operators*** exhibiting quartic couplings in VBS but NOT in two or three gauge boson vertices



Vector Boson Scattering



Triboson

EFT with dim8 operators II

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

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

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
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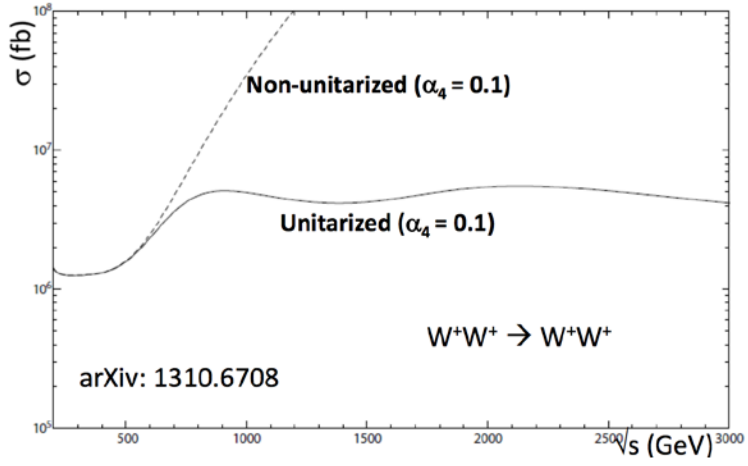
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

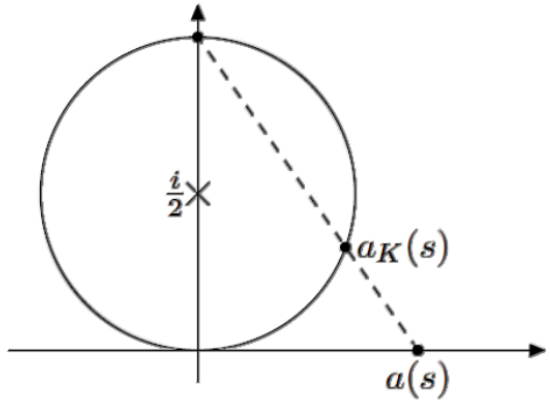
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,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

Phys. Rev. D 74, 073005 (2006)

Unitarization treatment

- Currently four schemes of unitarization treatments in ATLAS and CMS aQGC analysis
  - **No unitarity violation prevention (provided by both ATLAS and CMS)**
  - **DiPole Form-Factor unitarization (provided mostly by ATLAS)**
    - Introduce specific form-factor leads to actual model dependence, arbitrarity…
    - Scanning form-factor vs UV bound would be a useful study for theorist but very CPU intensive
  - **K-matrix unitarization (first deployed in WHIZARD and then VBFNLO)**
    - Projecting the scattering amplitude A(s) onto the Argand circle: Saturation of the amplitude to achieve unitarity
    - Amplitudes satisfying unitarity are invariant under K-matrix unitarization
    - Difficulty: very few operators are implemented with k-matrix, doesn't support in generators the triboson processes and those with photon presence
  - **Clipping the events according to the UV bound**
    - Run2 and long term recommendation in ATLAS, to be pursued along with other treatments

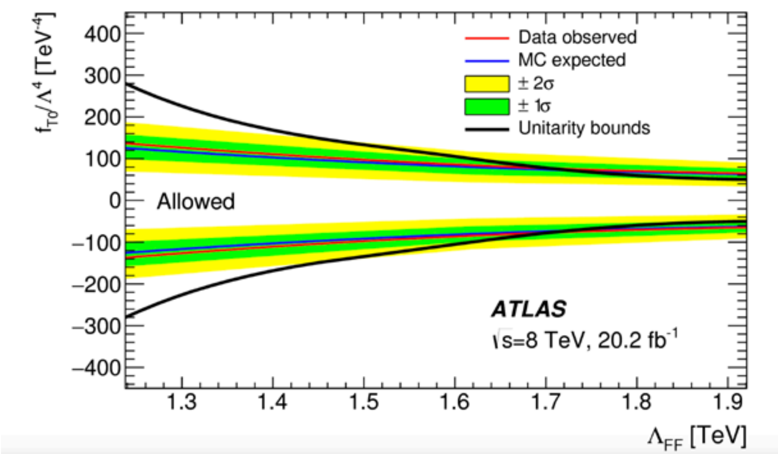


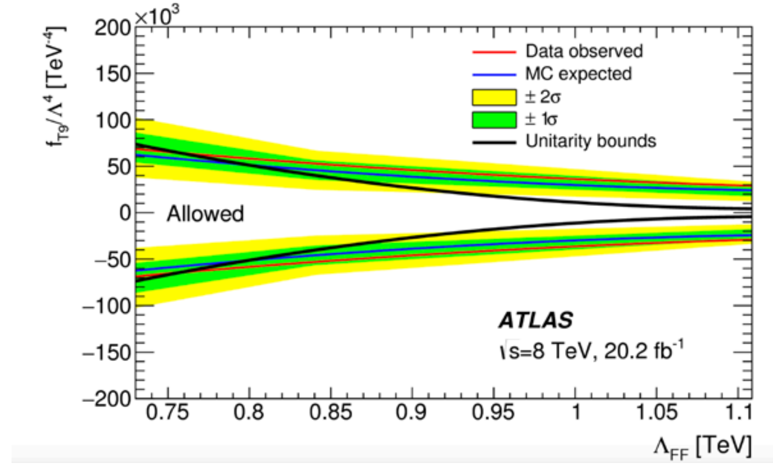


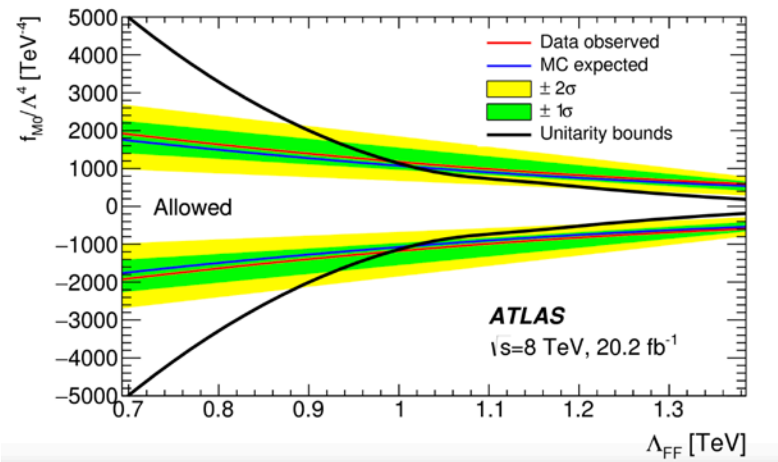
Argand circle

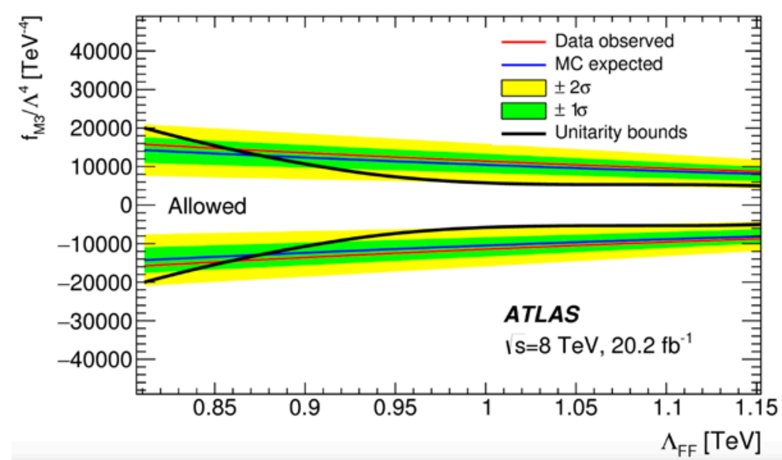
Currently searched limits vs unitarity violation bounds: VBS Zγ for example

S. Li (TDLI/SJTU), Z. Liang (IHEP), et. al.



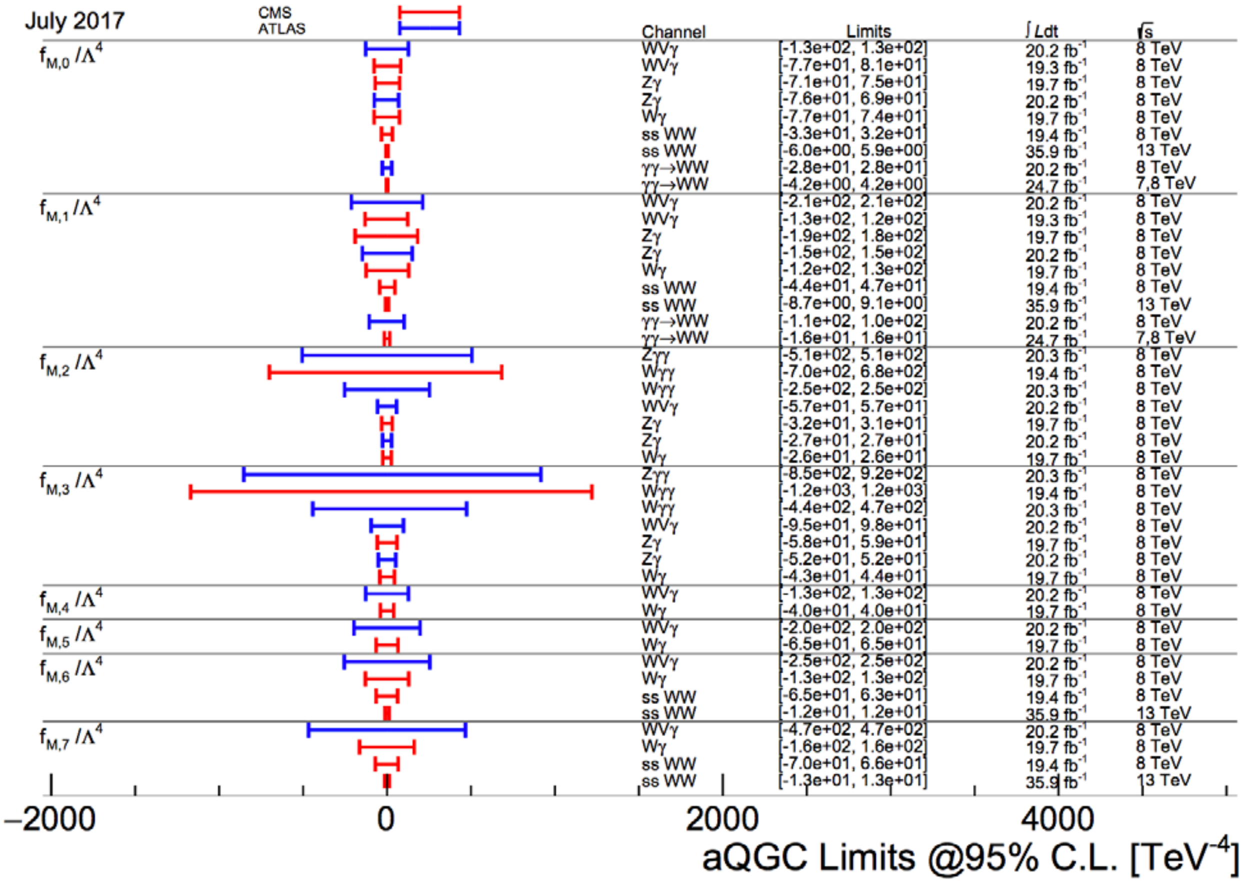






JHEP07(2017)107

Current triboson aQGC limits of $F_{M,x}$



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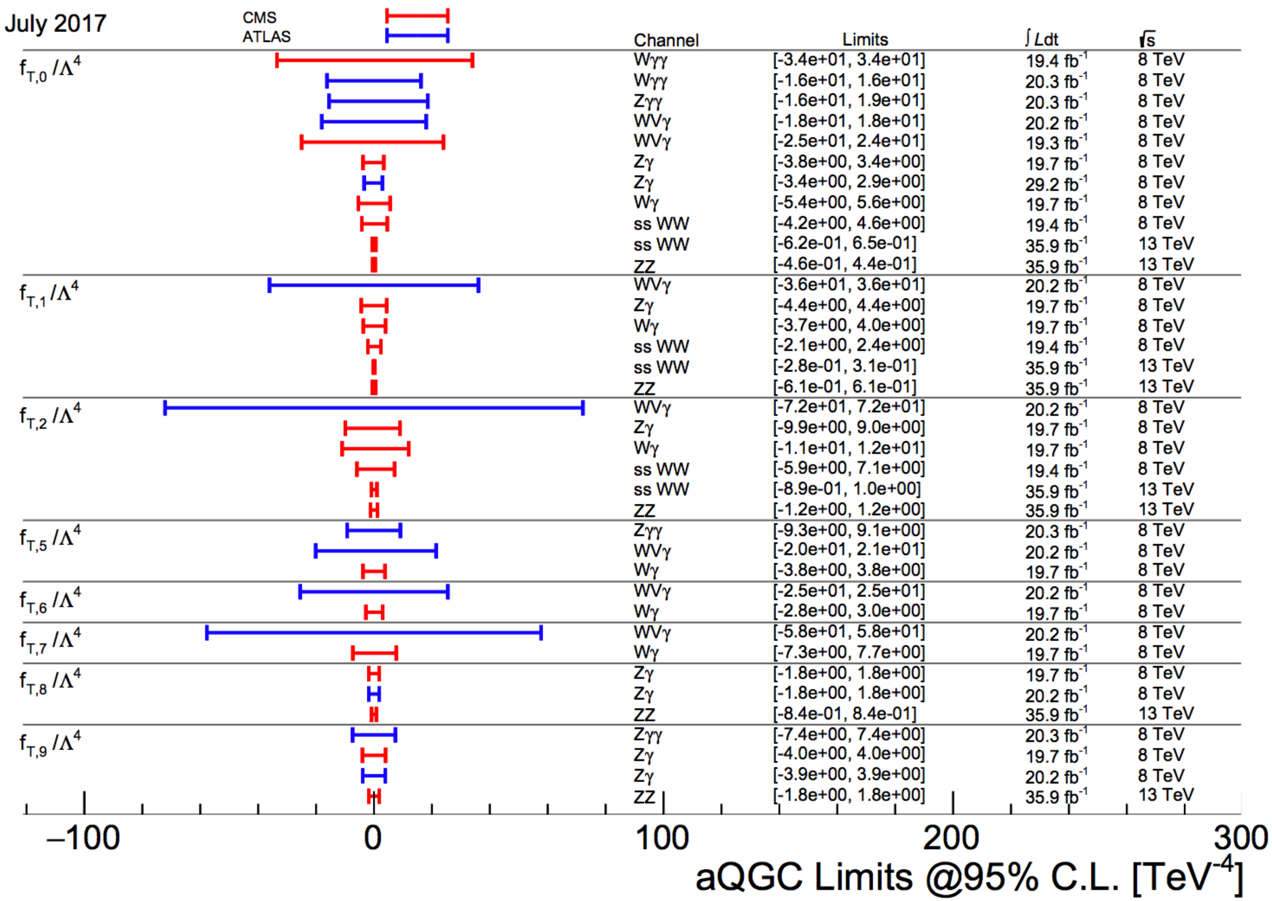
Dim-8 Operators containing both Higgs $SU(2)_L$ doublet covariant derivatives and field strength tensors

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Current triboson aQGC limits of $F_{T,x}$



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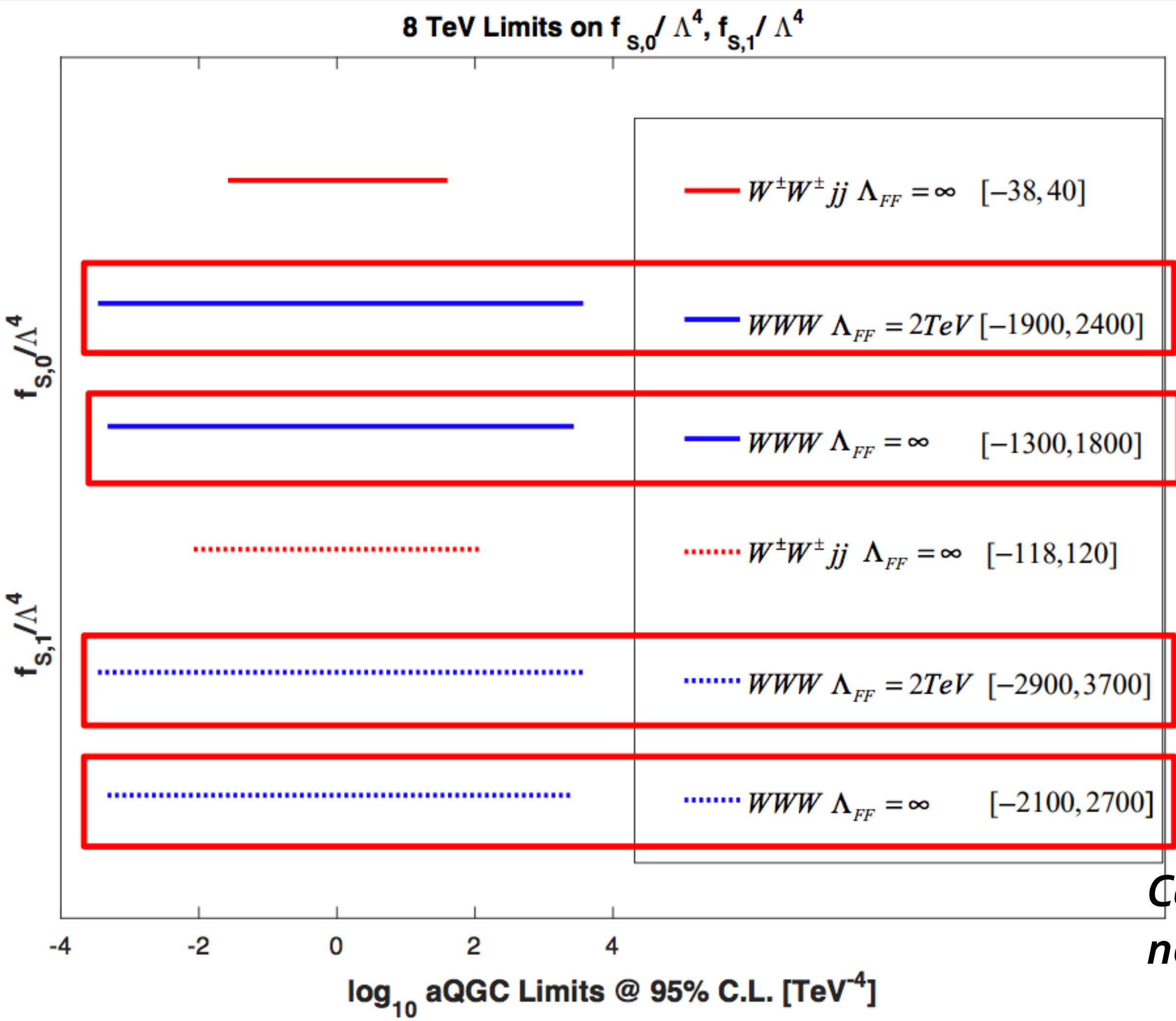
Dim-8 Operators containing only the field strength tensors

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Current triboson aQGC limits of $F_{S,x}$



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Dim-8 Operators containing only Higgs $SU(2)_L$ doublet covariant derivatives

Conversion to chiral lagrangrian non-linear operators

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8} \qquad \alpha_4 + 2\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

Eur. Phys. J. C 77 (2017) 141

Brief Notes: Openning issues and prospects

- LHC Run2 provides large amount of pp collision data at a higher center-of-mass energy, giving rish to VBS observation sensitivity
  - Observed VBS-VV channels: like-sign WW, WZ
  - Upcoming channels w.i.p.: ZZ, W/Z+γ, semileptonic WV(jj)/ZV(jj)
  - Important test of EWSB and higgs mechanism in the unitarization of VV→VV scattering
  - Next steps: differential measurements, 1st extraction of $V_L V_L$ polarization components

- Potential showstoppers and improvements
  - Quark/Gluon induced jet separation using jet substructure technique to distinguish “color-charge” (tracking info, multiplicities, track jet width, calo topo cluster width, etc.)
  - Forward tracking improvement in future LHC upgrade
  - Pileup jet suppression in forward region
  - Theoretical uncertainties: improvement of high order precision in QCD irreducible background modelings, high order EWK effect predictions, interference modeling
  - Experimental challenges: Charge flips, soft-leptons
  - New physics probing: (doubly-)charged higgs, MSSM, aQGCs challenged by unitarity violation

Backup