# New Vector Boson Scattering (VBS) "observations" at LHC

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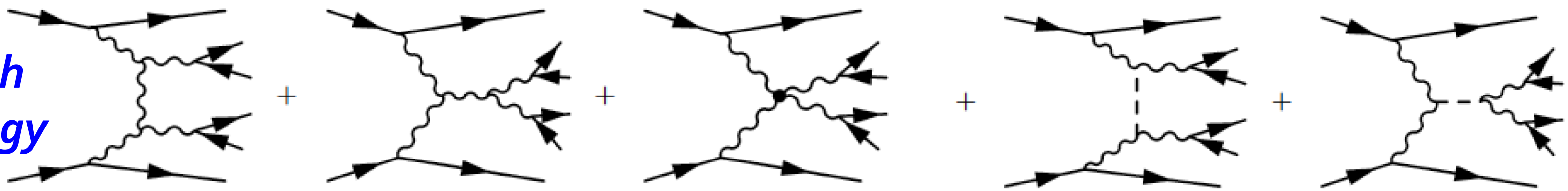
On behalf of ATLAS and CMS collaborations

# 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 ($\alpha^4$)*



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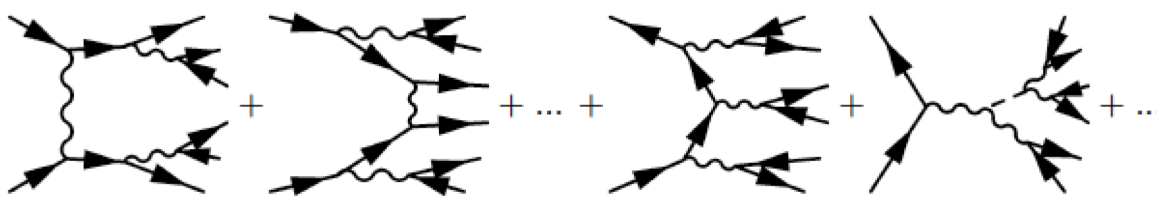
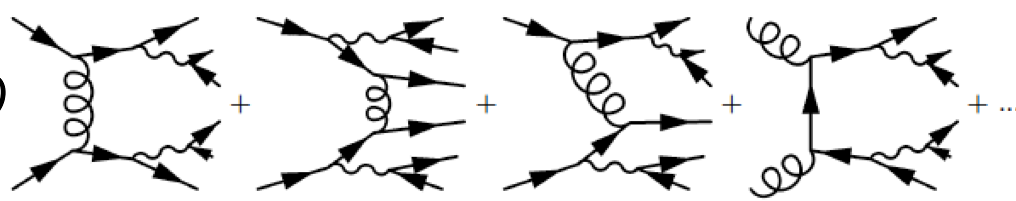


*QCD background ($\alpha_s^2\alpha^2$)*

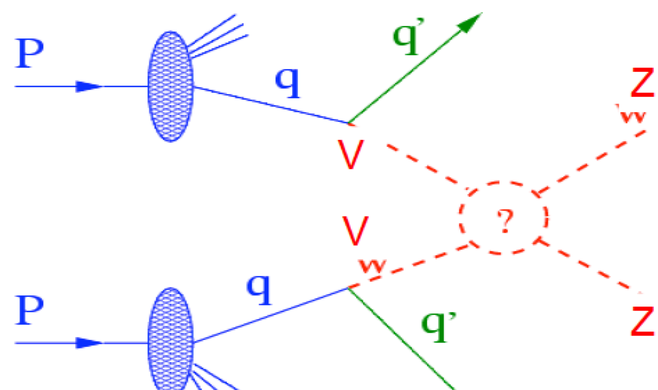


# Why VBS?

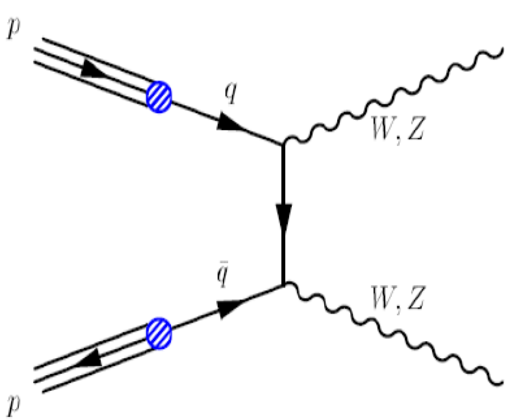
**Unitarity violation of Vector Boson Scattering**

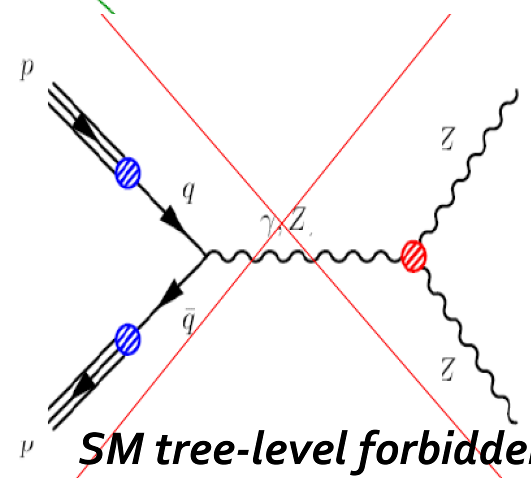
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$

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



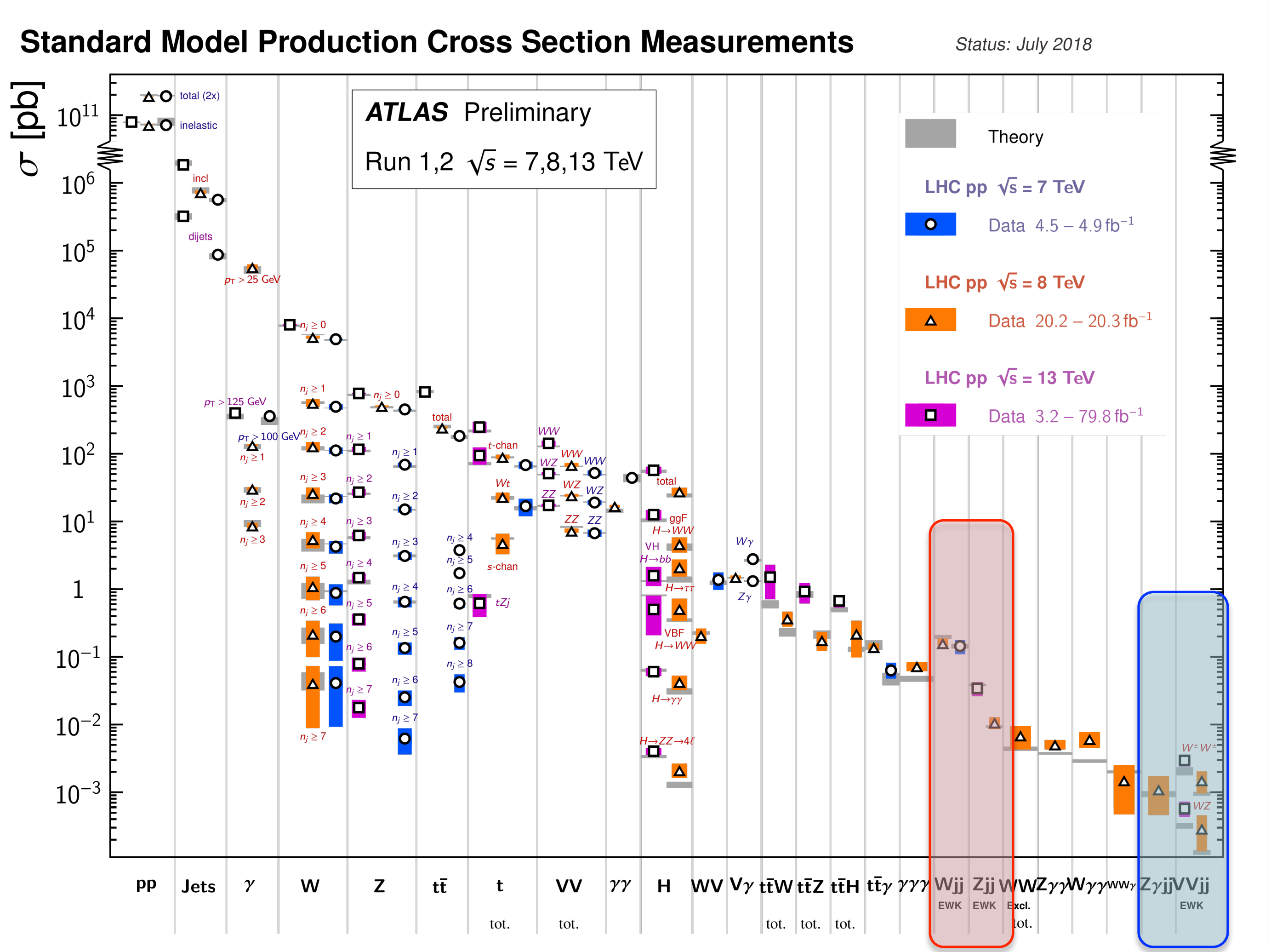

*New physics show up via SM boson self-interactions, parameterized by effective lagrangians and effective field theories*




***SM tree-level forbidden***

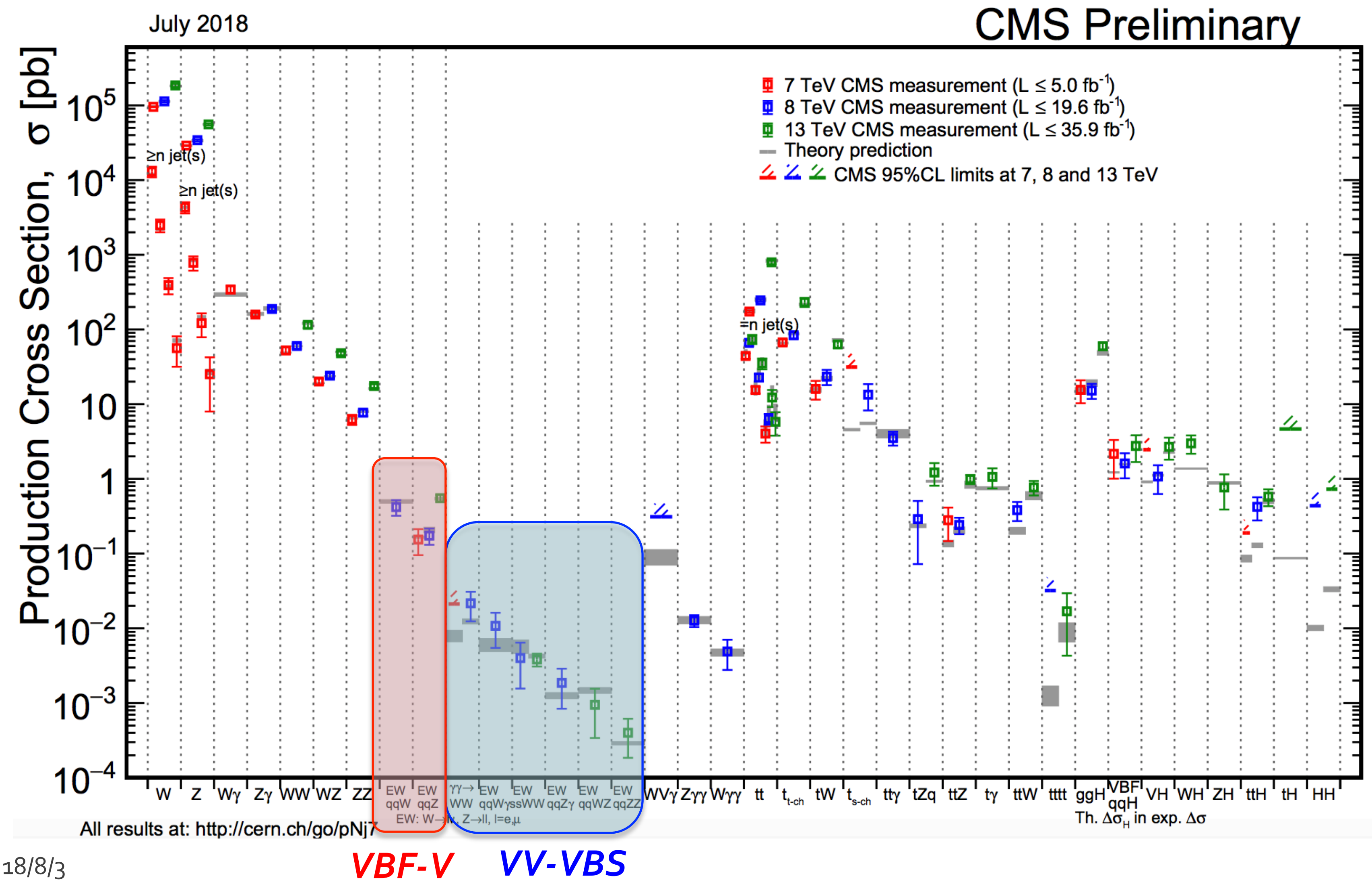
# VBS measurements in ATLAS



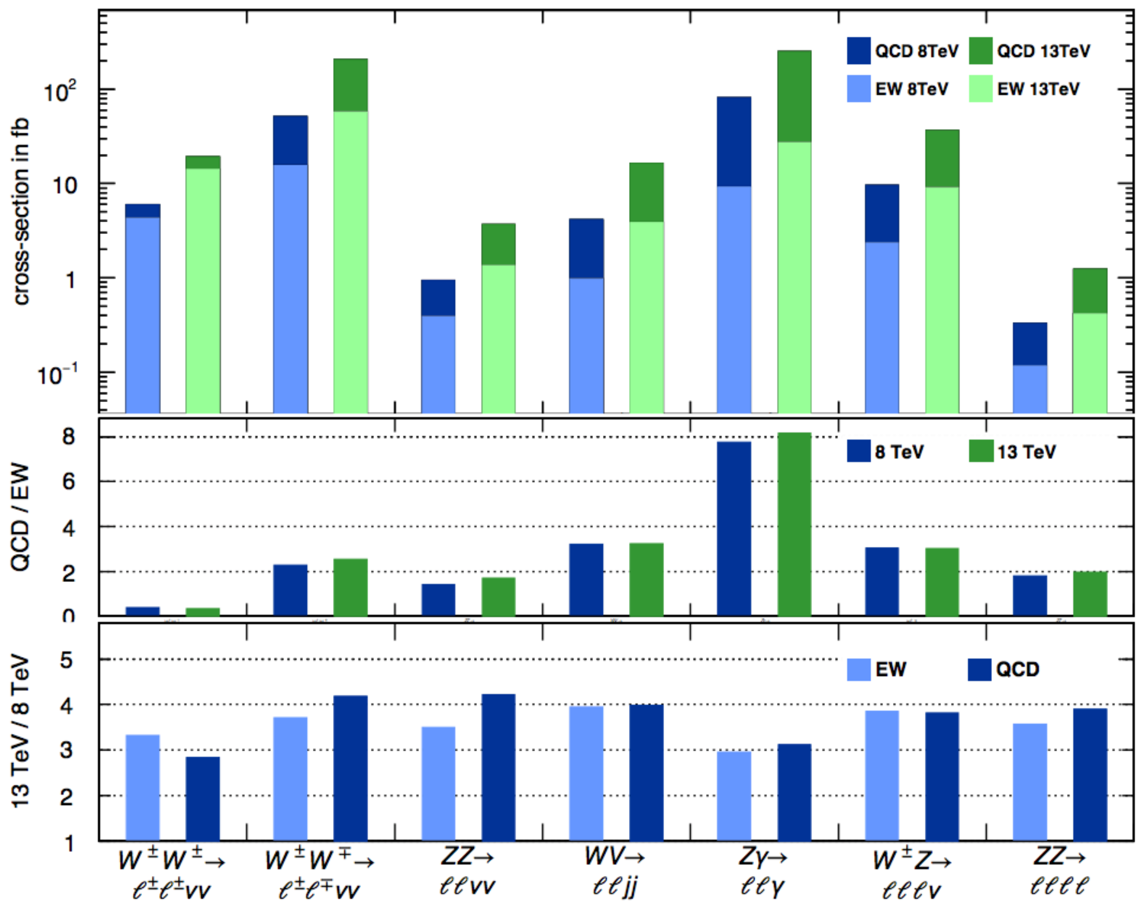

VBF-V

VV-VBS

# VBS measurements in CMS



# VBS measurement sensitivity prospect at 8TeV vs 13TeV



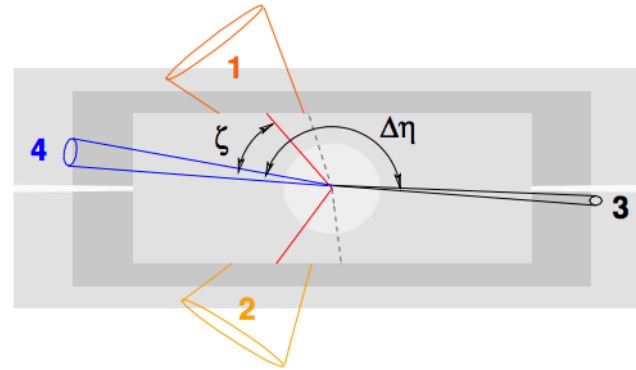

[CERN-THESIS-2014-105]

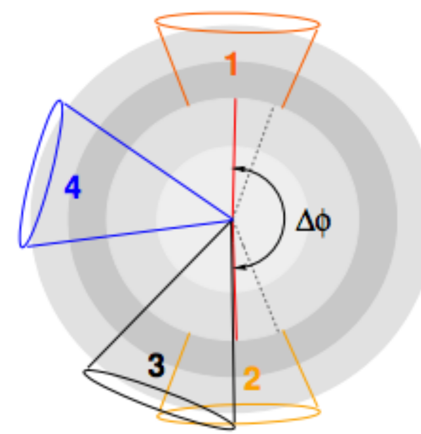
**How much the jump in energy buy us**

- 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 √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: $\frac{\sum_i \vec{p_{\mathrm{T}}}_i}{\sum_i |\vec{p_{\mathrm{T}}}_i|}$
    - All hard process decay products and jets



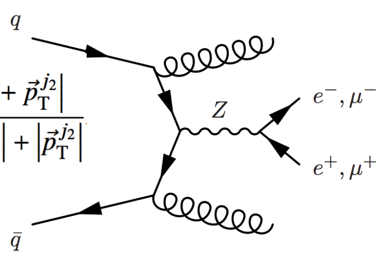



# Experimental challenges per final states

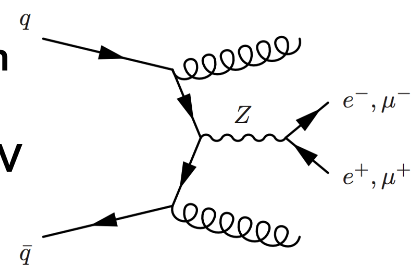
| channel | final state | comment * |
| --- | --- | --- |
| VBF W *Observed!* | ℓν jj | statistics is not a problem, good modelling of W+jets needed |
| VBF Z *Observed!* | ℓℓ jj | statistics is not a problem, good modelling of Z+jets needed |
| VBS $W^{\pm}W^{\pm}$ *New Observed!* | $\ell^{\pm}\nu\ell'^{\pm}\nu$ 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

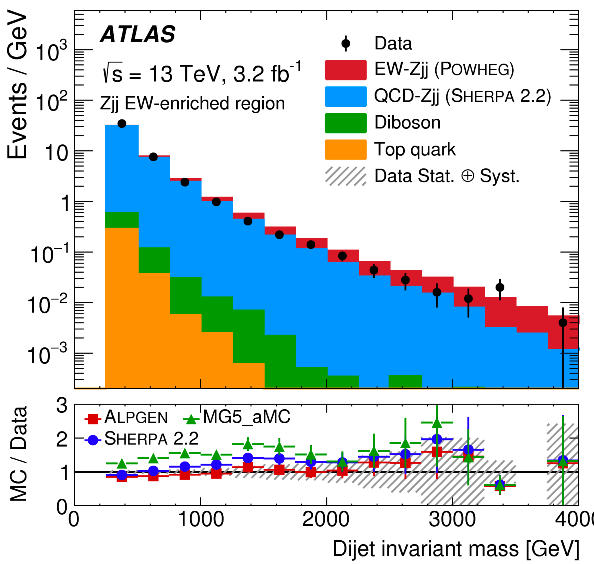
$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

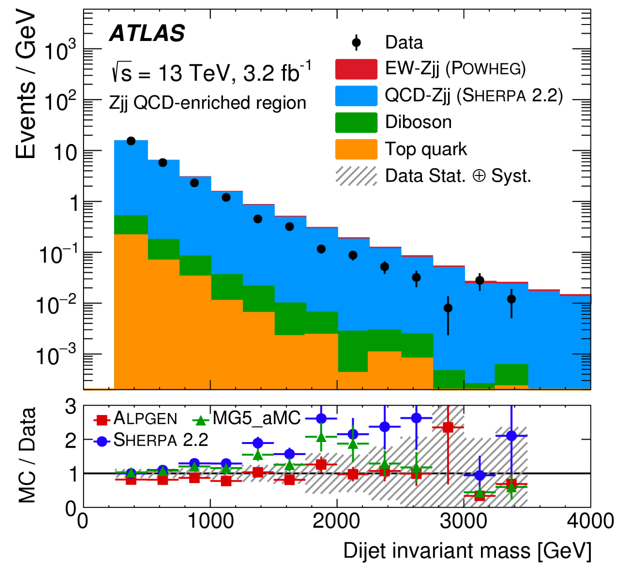



**EW enriched region**
$M_{jj}$>250GeV (1TeV)
pT_balance < 15GeV
# of central jet ==0




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

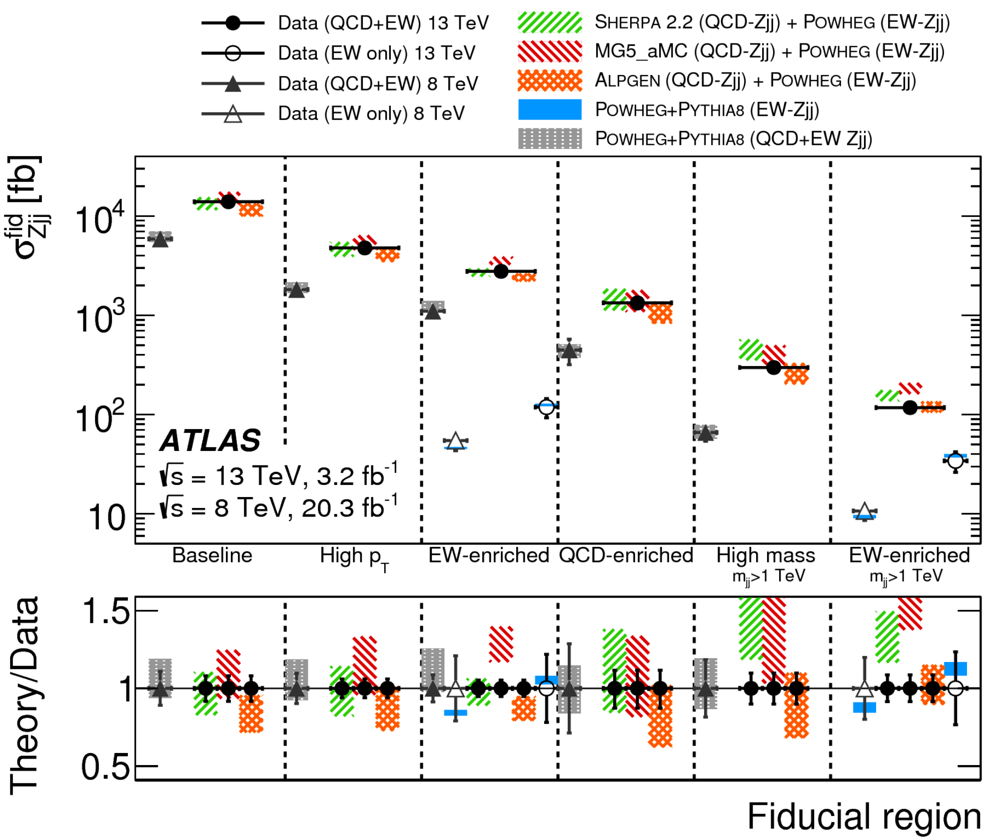



*Physics Letters B 775 (2017) 206*

***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.*

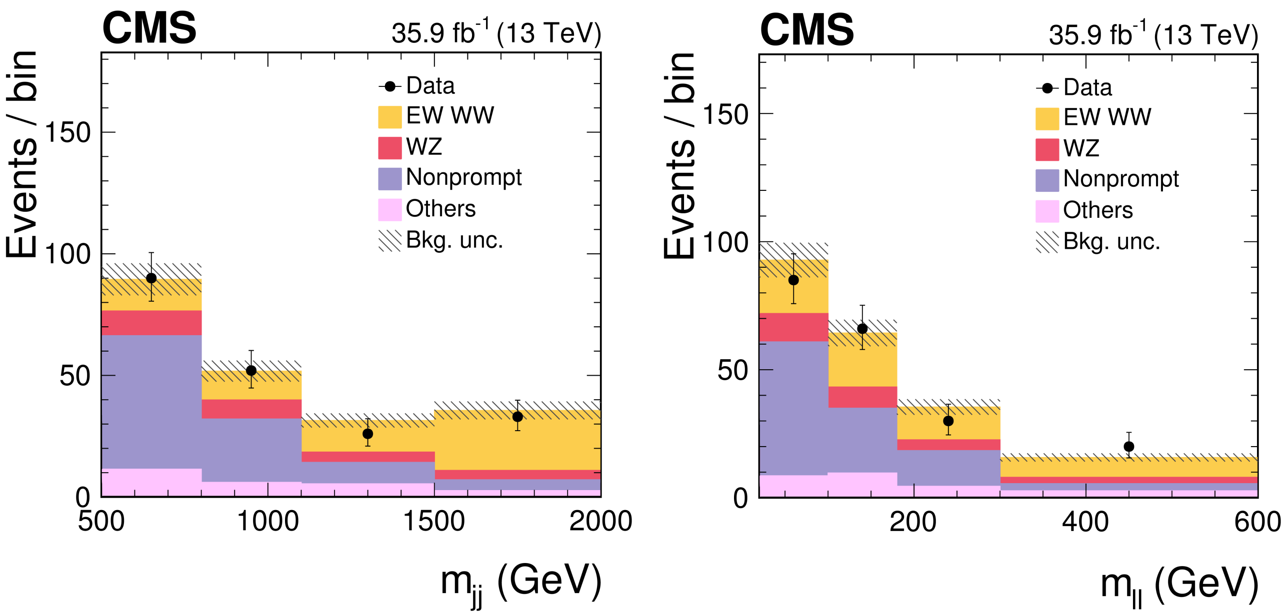
*EWK-ONLY cross section measured in two fiducial regions with EWK component enriched.*

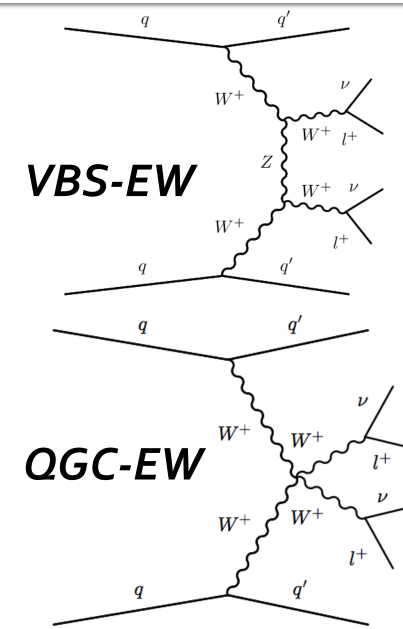
*Measurements in good agreement with theory.*

*Physics Letters B 775 (2017) 206*

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

[Phys. Rev. Lett. 120 (2018) 081801](https://doi.org/10.1103/PhysRevLett.120.081801)




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

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

**1st ever $5\sigma$ *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 $\sigma$***

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

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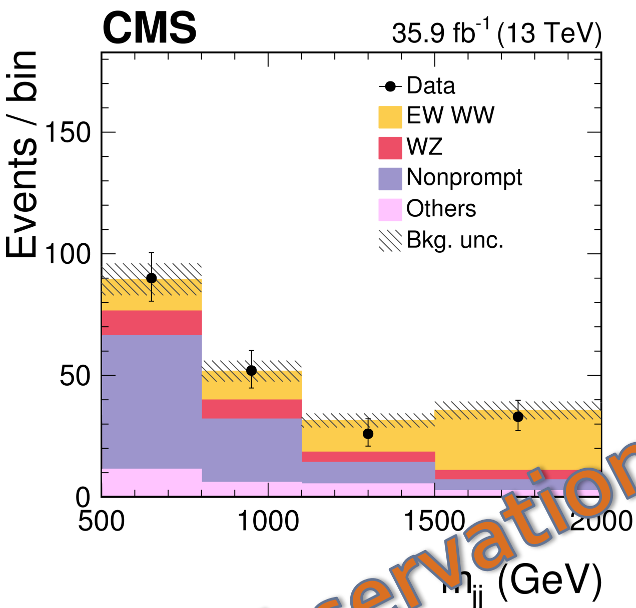
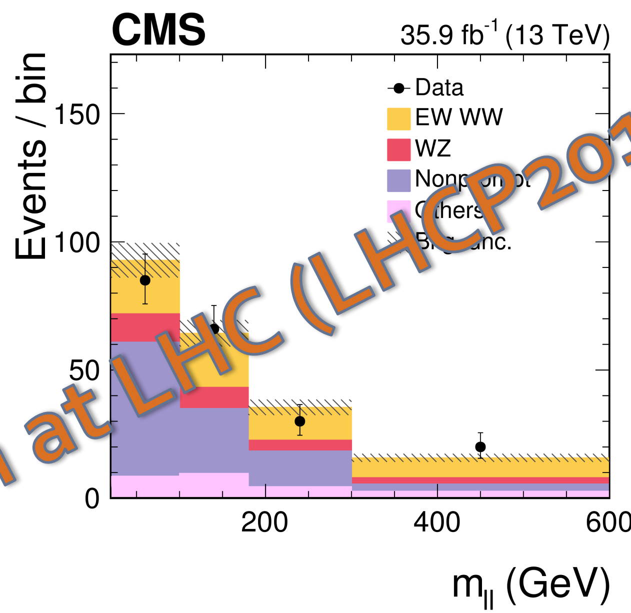
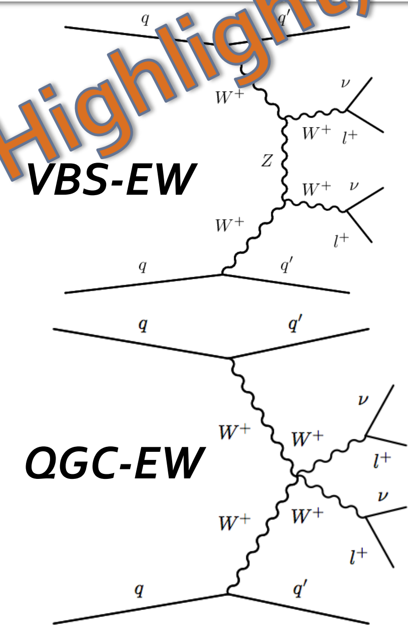
[Phys. Rev. Lett. 120 (2018) 081801]




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

- **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)***

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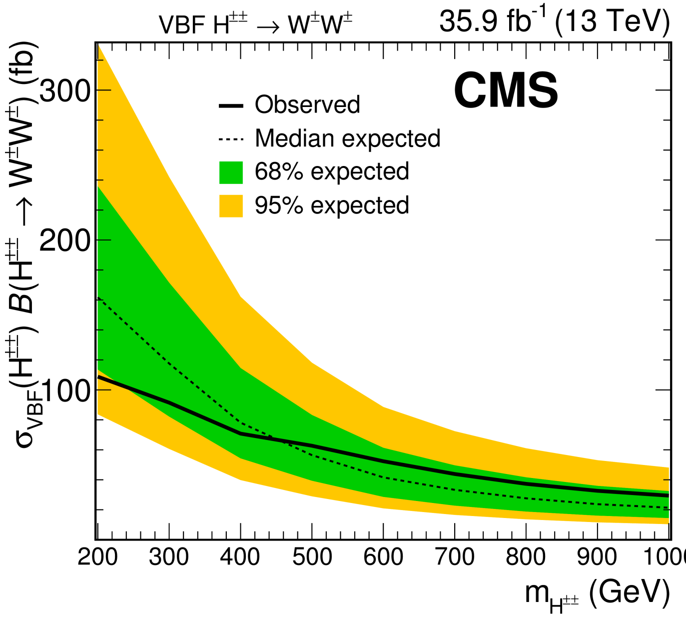
***In agreement with LO prediction $\sigma_{LO}(\ell\ell jj)$ = 4.25 ± 0.21 fb***

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

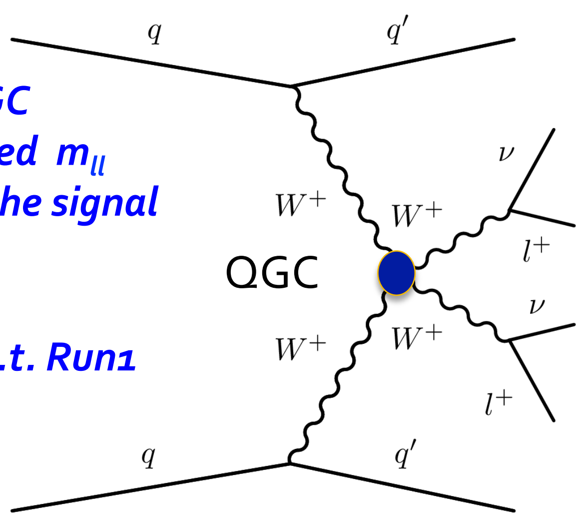
*Phys. Rev. Lett. 120 (2018) 081801*

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



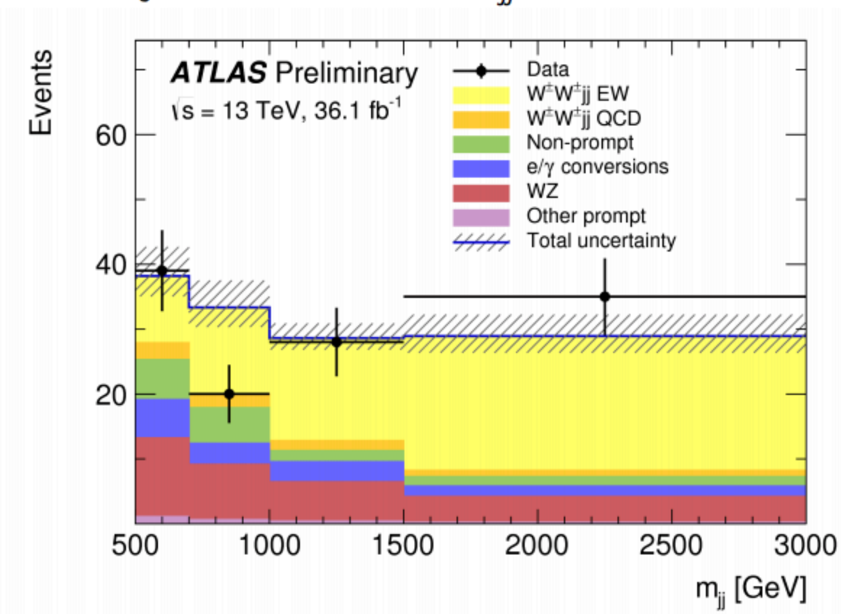

Doubly charged Higgs bosons are predicted in models containing a Higgs triplet field. (Georgi–Machacek model)

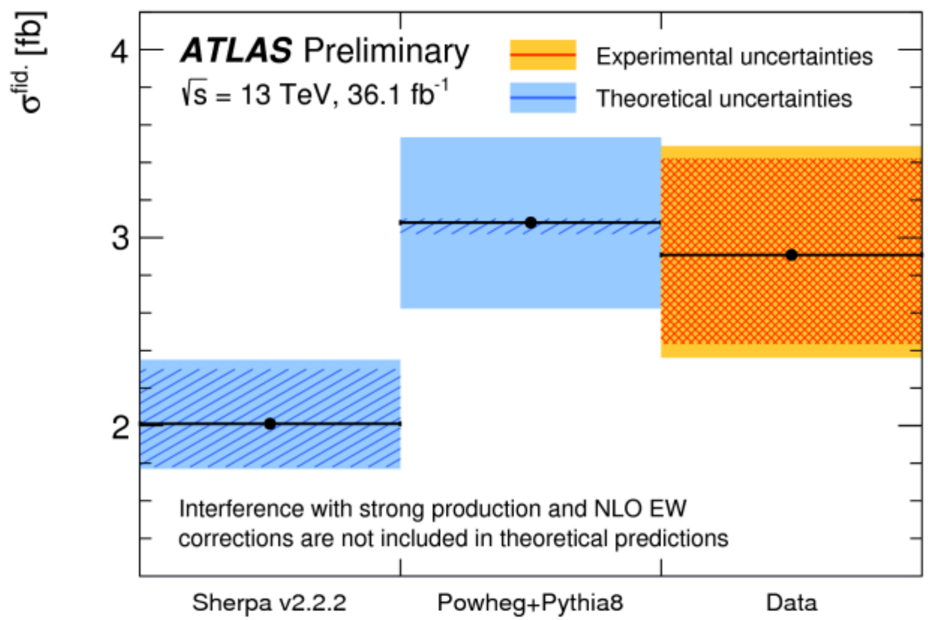
1[st] limits placed on $H^{\pm\pm} \rightarrow W^\pm W^\pm$ cross section using ($m_{jj}$, $m_{ll}$) two-dimensional distributions

# Observation of electroweak W±W±(→2l2ν)jj at 13TeV by ATLAS

ATLAS-CONF-2018-030

Dijet invariant mass for $m_{jj} > 500$ GeV



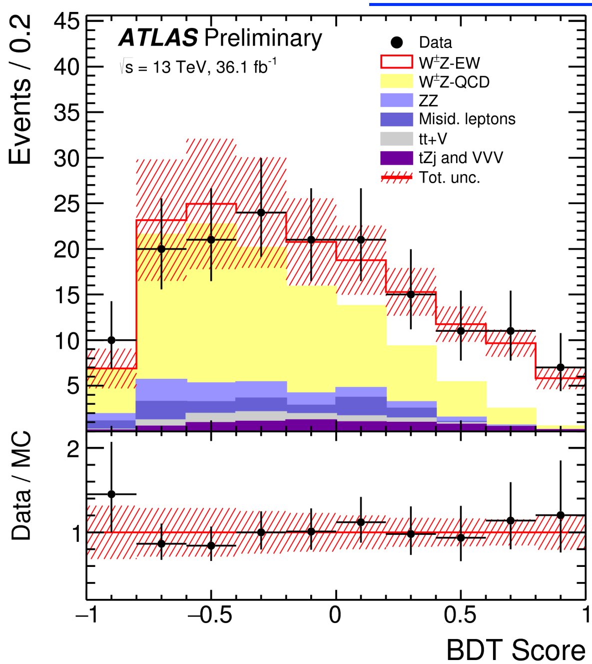

*Likelihood fit performed in:*

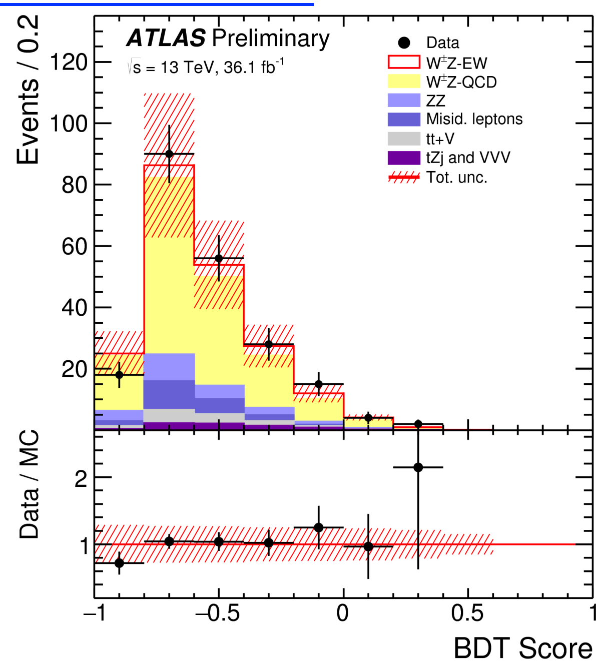
- *6 channels: ee, eμ, μμ*
- *Signal region: 4 $m_{jj}$ bins for $m_{jj} > 500$GeV*
- *Control region: $200 < m_{jj} < 500$GeV*

*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

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)

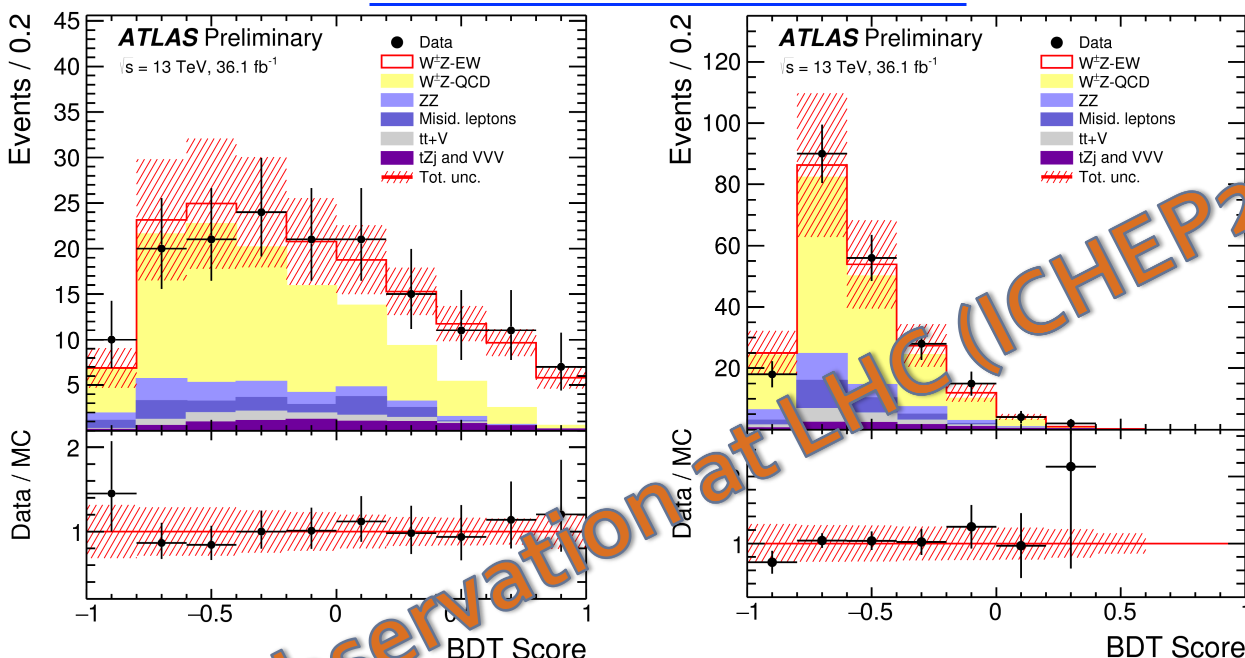
Corresponding fid. cross section:

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

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

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

[ATLAS-CONF-2018-033](ATLAS-CONF-2018-033)




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

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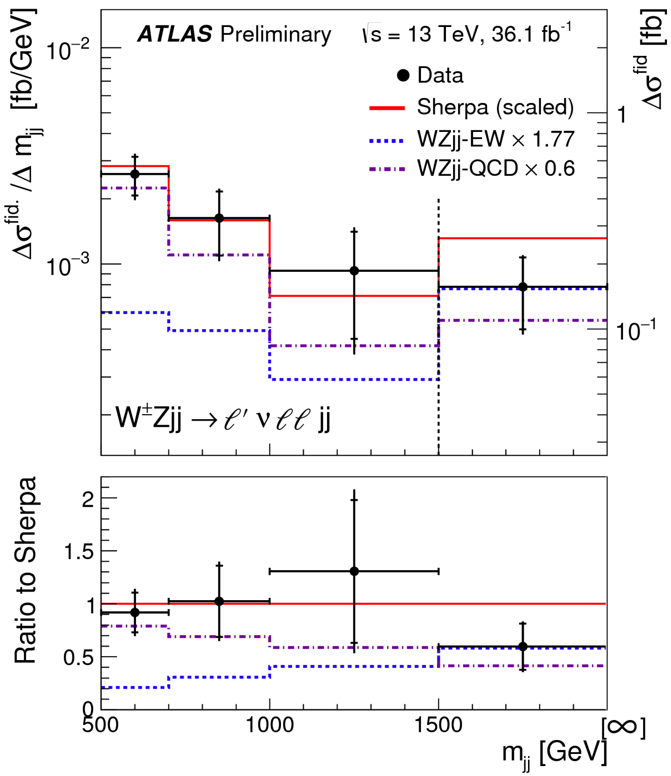
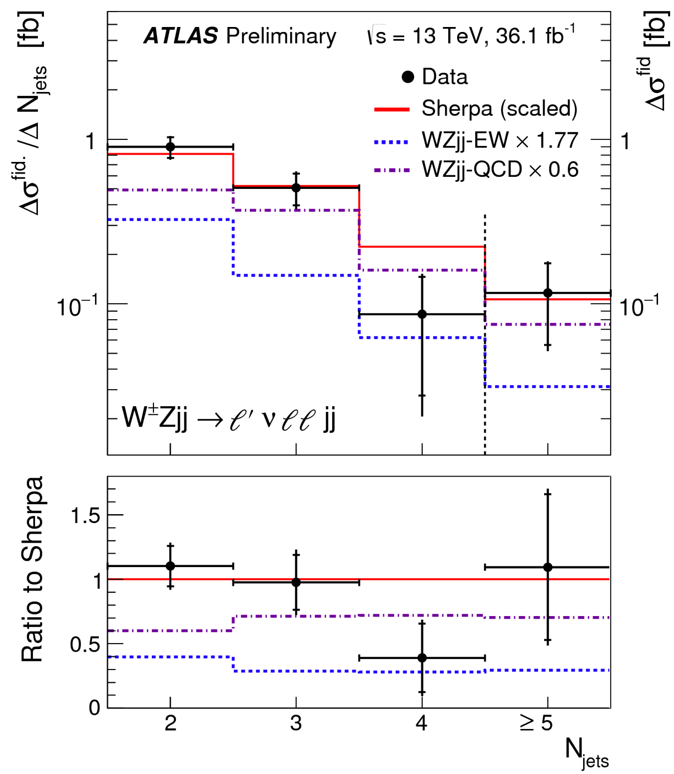
# 1st differential measurements of electroweak $W^{\pm}Z(\rightarrow l\nu ll)jj$ at 13TeV by ATLAS

[ATLAS-CONF-2018-033]

**1st 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)**

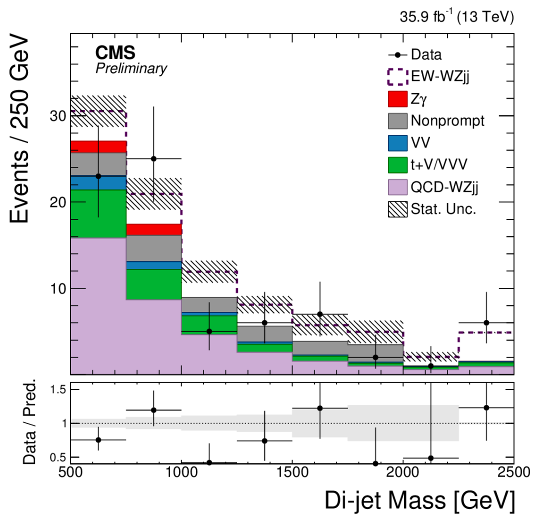


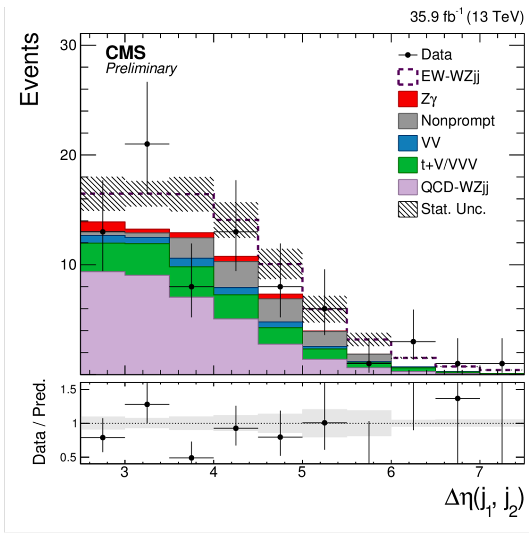

**Jet-multiplicities**

*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)

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

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

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

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

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

*Two fiducial region defined for theo. Vs exp. comparison*

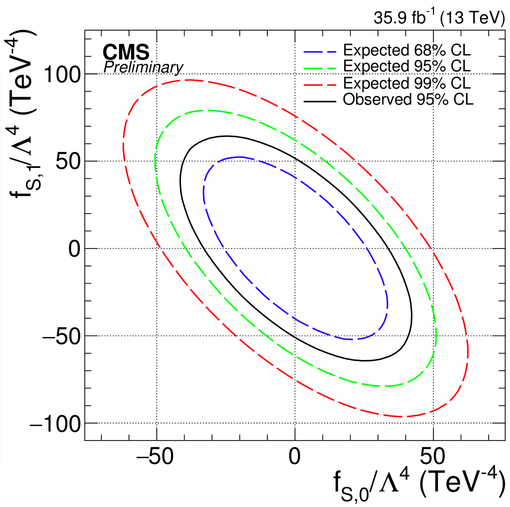
## Fiducial Regions

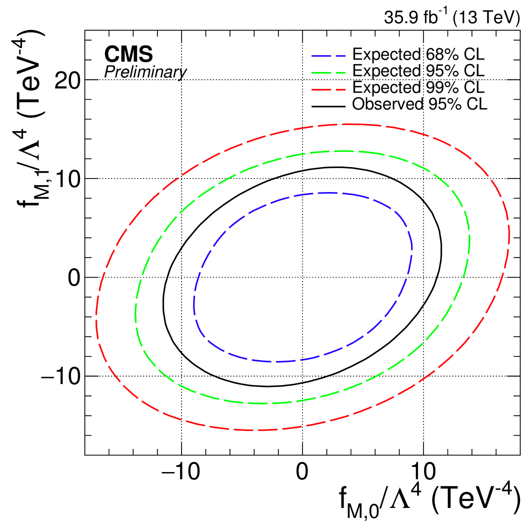
| | Tight Fiducial | Loose Fiducial |
|---|---|---|
| $p_T(\ell_{Z,1})$ [GeV] | $> 25$ | $> 20$ |
| $p_T(\ell_{Z,2})$ [GeV] | $> 15$ | $> 20$ |
| $p_T(\ell_W)$ [GeV] | $> 20$ | $> 20$ |
| $\lvert\eta(\mu)\rvert$ | $< 2.5$ | $< 2.5$ |
| $\lvert\eta(e)\rvert$ | $< 2.5$ | $< 2.5$ |
| $\lvert m_Z - m_Z^{PDG}\rvert$ [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] | $> 50$ | $> 30$ |
| $\lvert\Delta R(j,\ell)\rvert$ | $> 0.4$ | $> 0.4$ |
| $n_j$ | $\geq 2$ | $\geq 2$ |
| $p_T(b)$ [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*

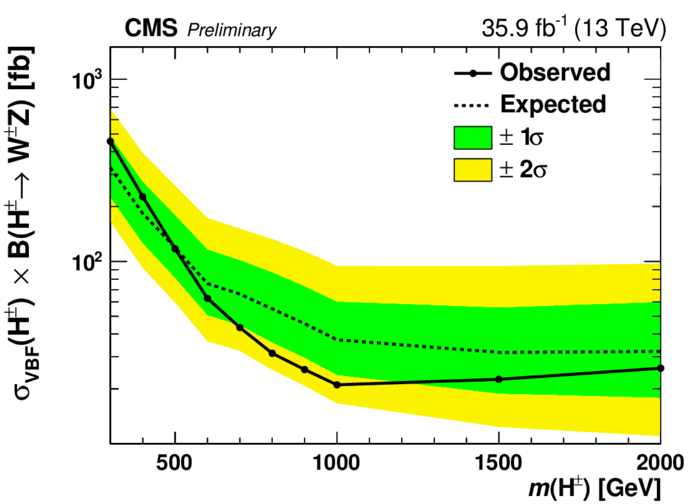
# Probing new physics using electroweak W±Z(→lνll)jj production at 13TeV by CMS

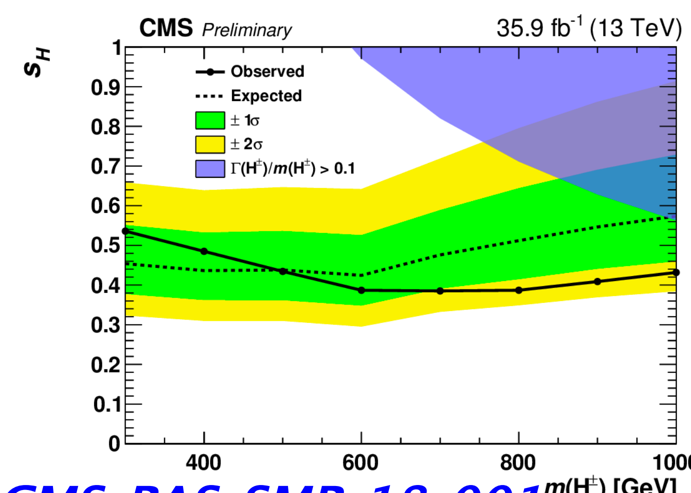
*Limits on aQGC parameterized with Eboli's dimension-8 EFT model (hep-ph/0606118) using $m_T(WZ)$*




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

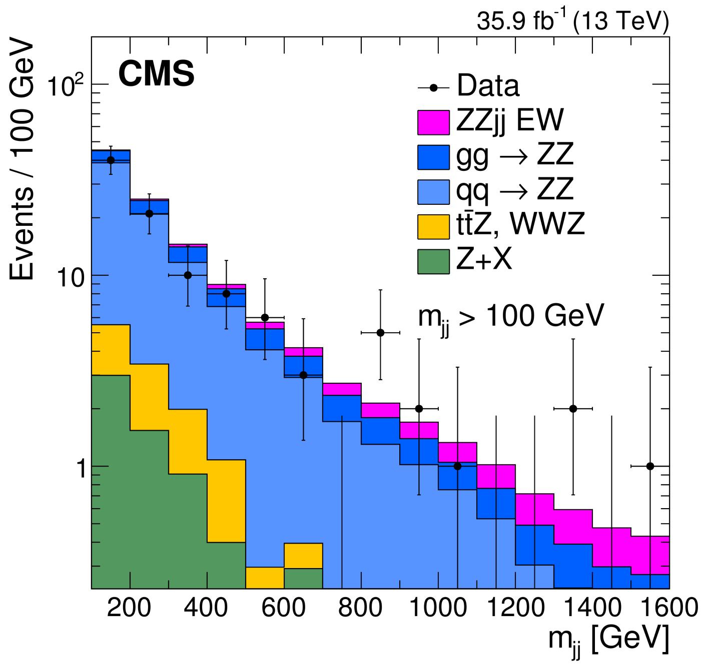



[CMS-PAS-SMP-18-001](CMS-PAS-SMP-18-001)

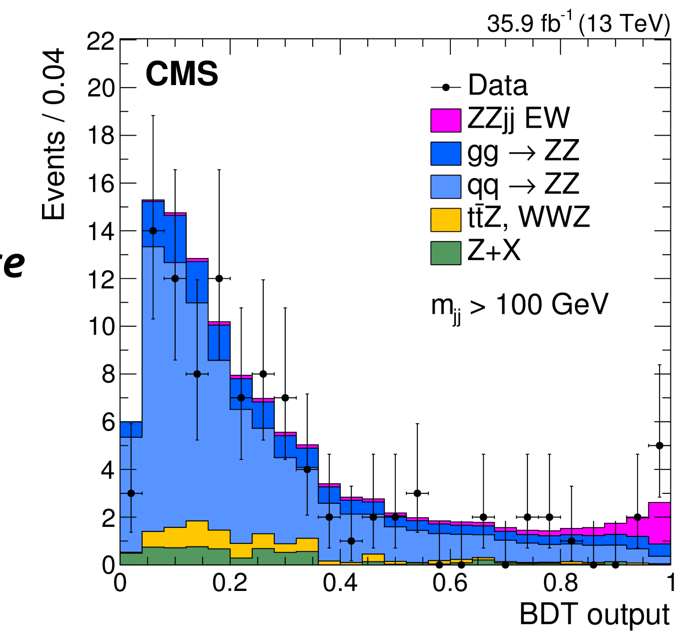
# Measurement of electroweak ZZ(→4l)jj production cross section at 13TeV by CMS

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




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

*BDT training*



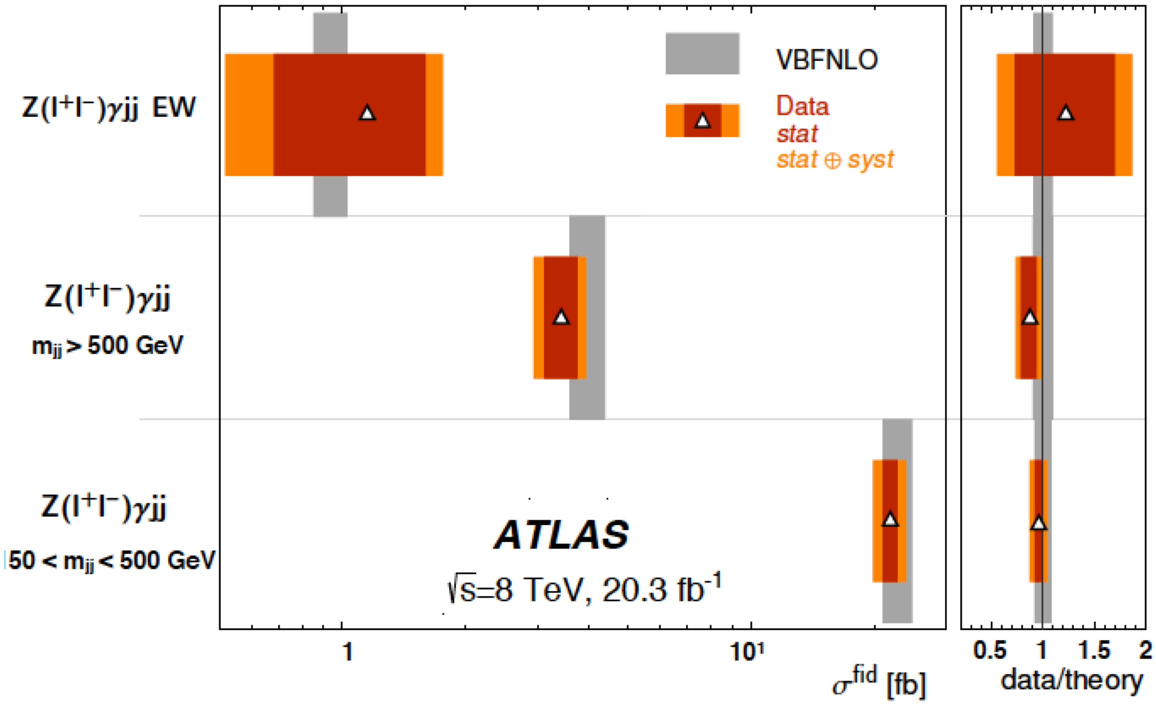

**Inclusive region:** $m_{jj}$>100GeV
**VBS region:** $|\Delta\eta_{jj}| > 2.4$ + $m_{jj} > 400$ GeV
**non-VBS region:** $|\Delta\eta_{jj}| < 2.4$ or $m_{jj} < 400$ GeV

***EWK signal significance 2.7σ (exp 1.6σ)***

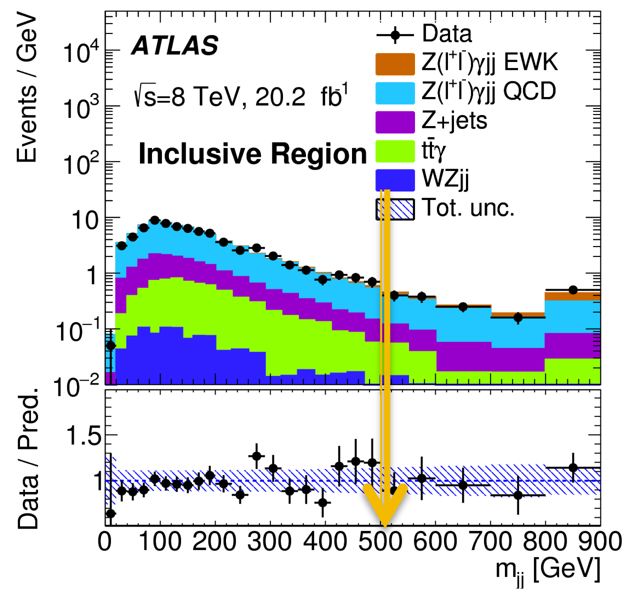
**Limits on aQGCs w/ EFT dim-8 operators and comparison with unitarity validity range**

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

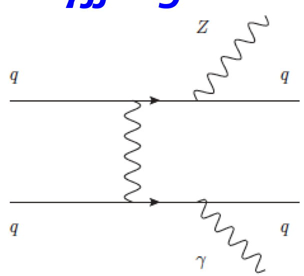
# First Measurement of Zγ+jj Electroweak production in ATLAS



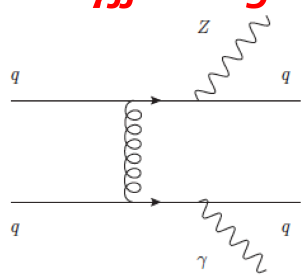

[JHEP07(2017)107]



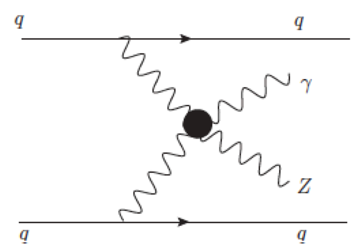

*EW Zγjj Signal*




*QCD Zγjj Background*



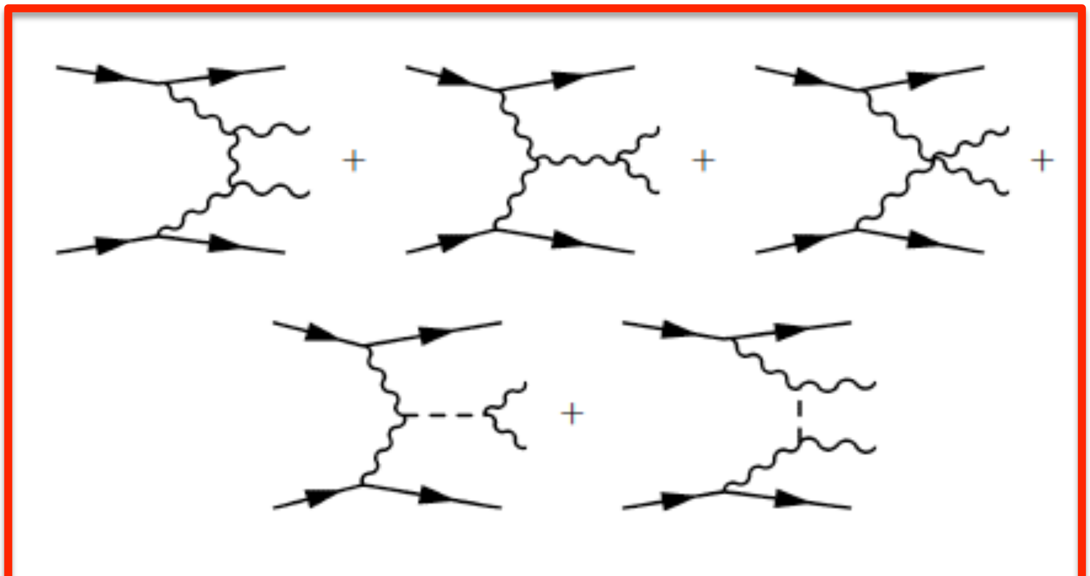

*New Physics Vertex (BSM signal)*



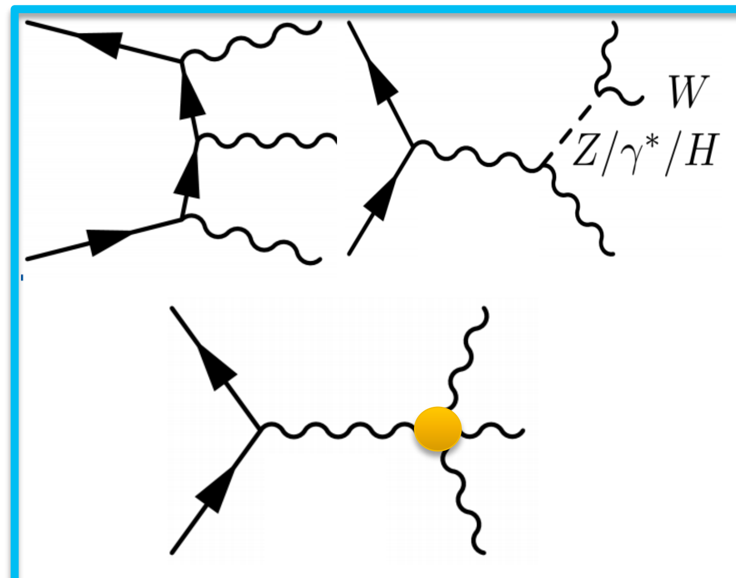
# Review of Anomalous Quartic Coupling in VBS (+ Triboson processes)

# 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

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

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

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

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

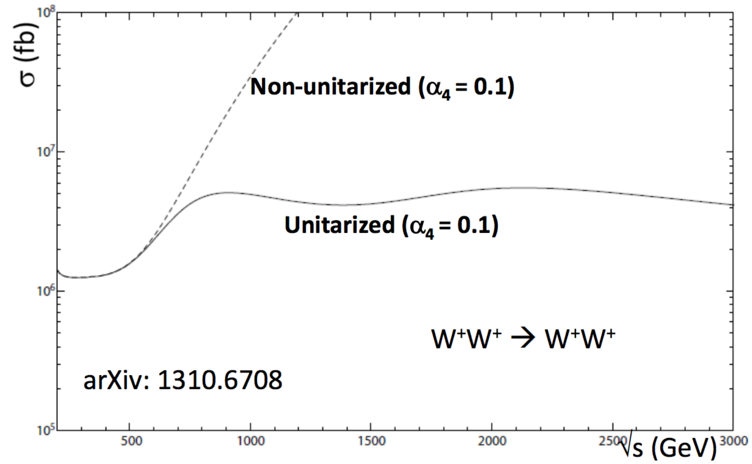
| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$ | X | X | X | | | | | | |
| $\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$ | X | X | X | X | X | X | X | | |
| $\mathcal{O}_{M,2}$,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

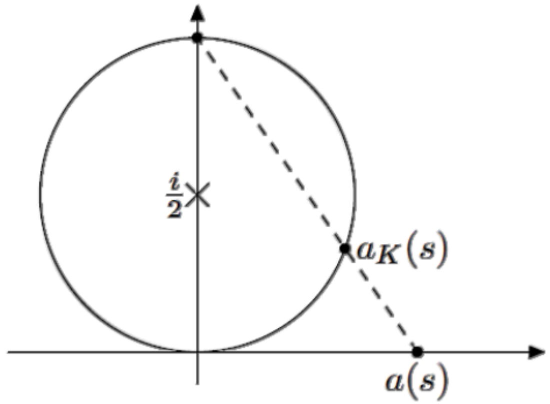


Phys. Rev. D 74, 073005 (2006)

# Unitarization treatment

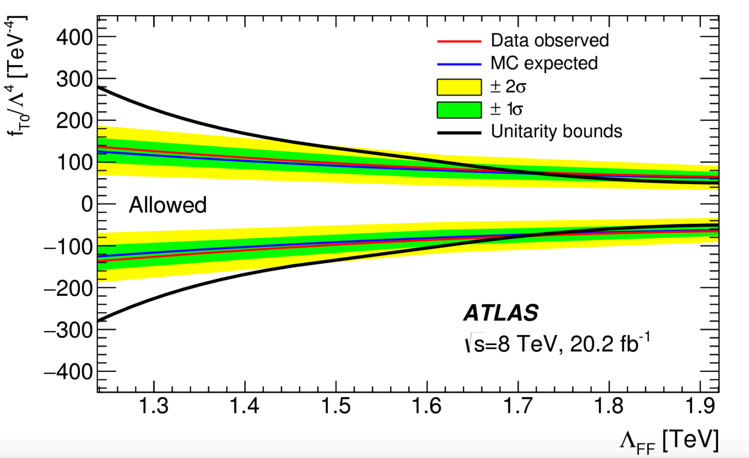
- Currently four schemes of unitarization treatments in ATLAS and CMS aQGC analysis
  - **No unitarity violation prevention (provided by both ATLAS and CMS)**
  - **DiPole Form-Factor unitarization (provided mostly by ATLAS)**
    - Introduce specific form-factor leads to actual model dependence, arbitrarity…
    - 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

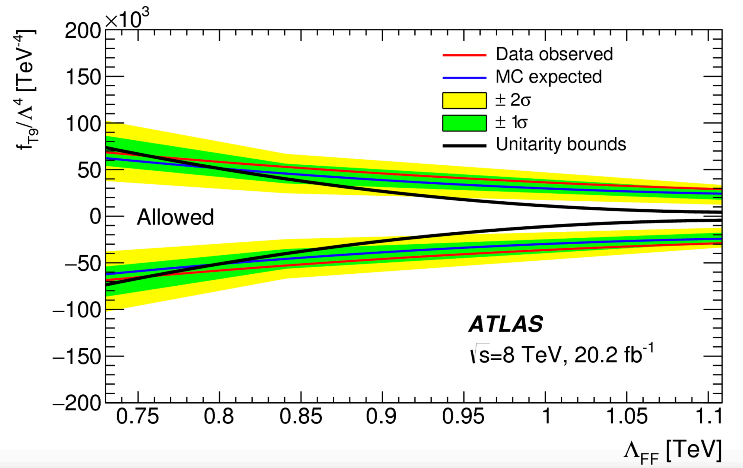


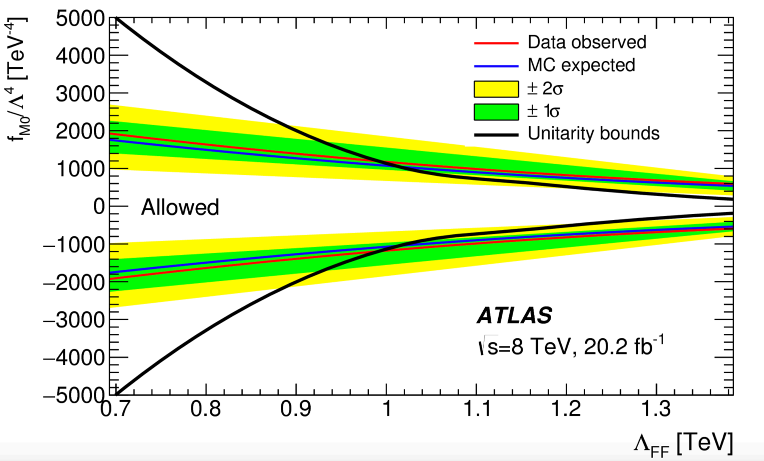



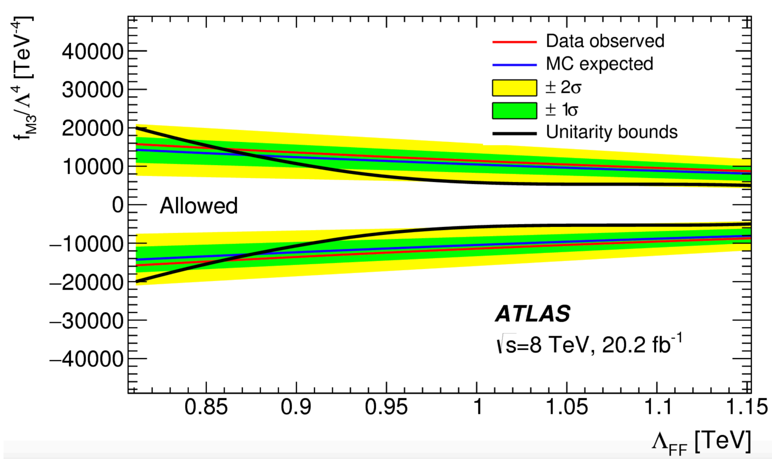

Argand circle

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



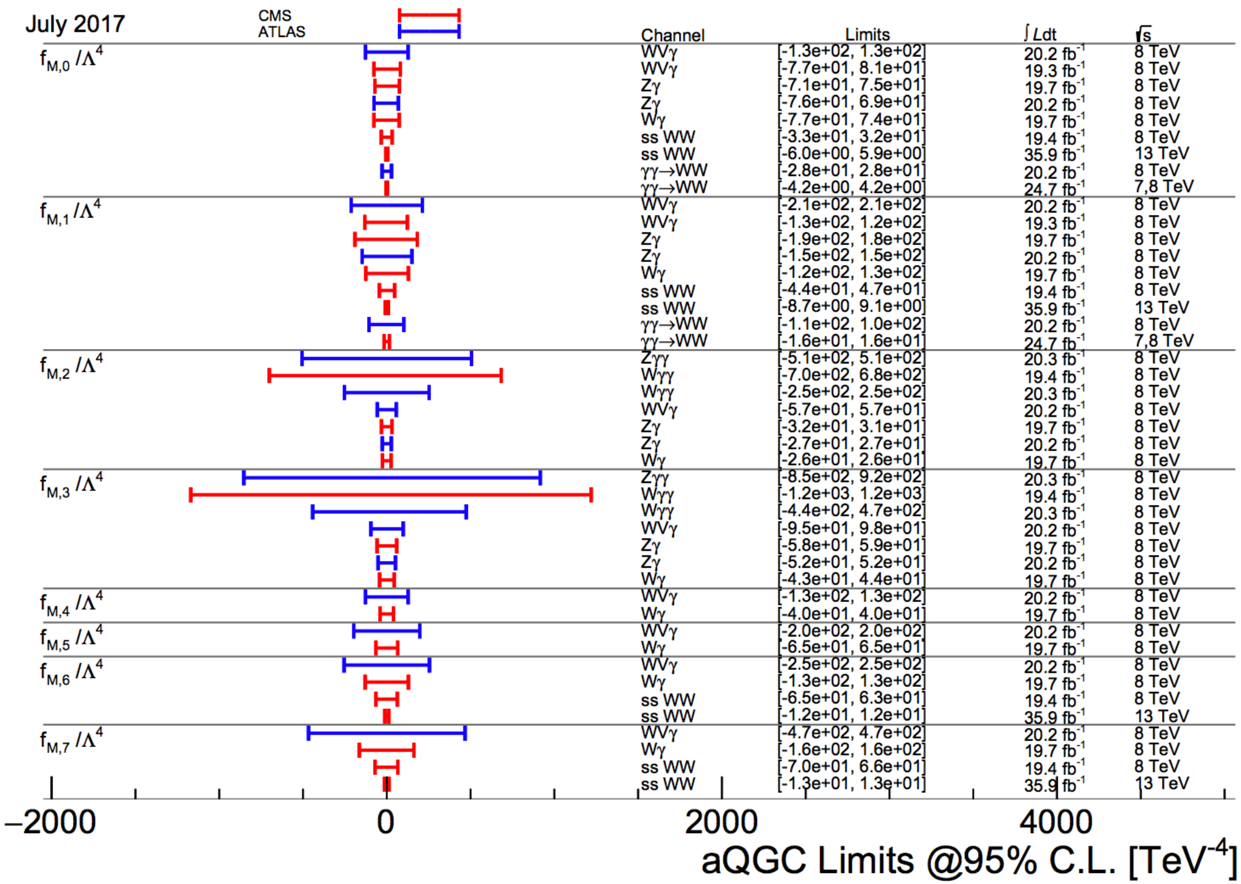






JHEP07(2017)107

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




$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

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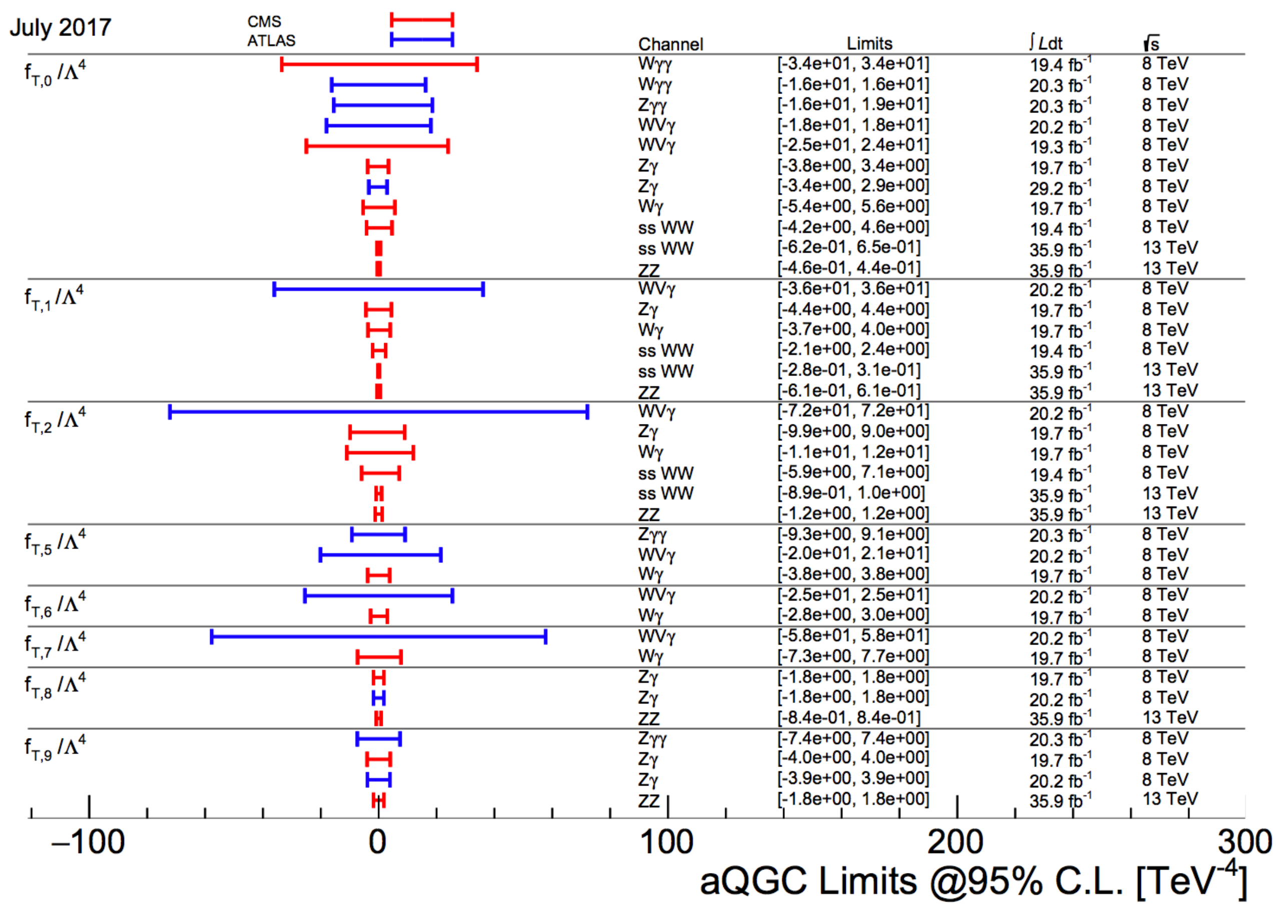
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

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

18/8/22 https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

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




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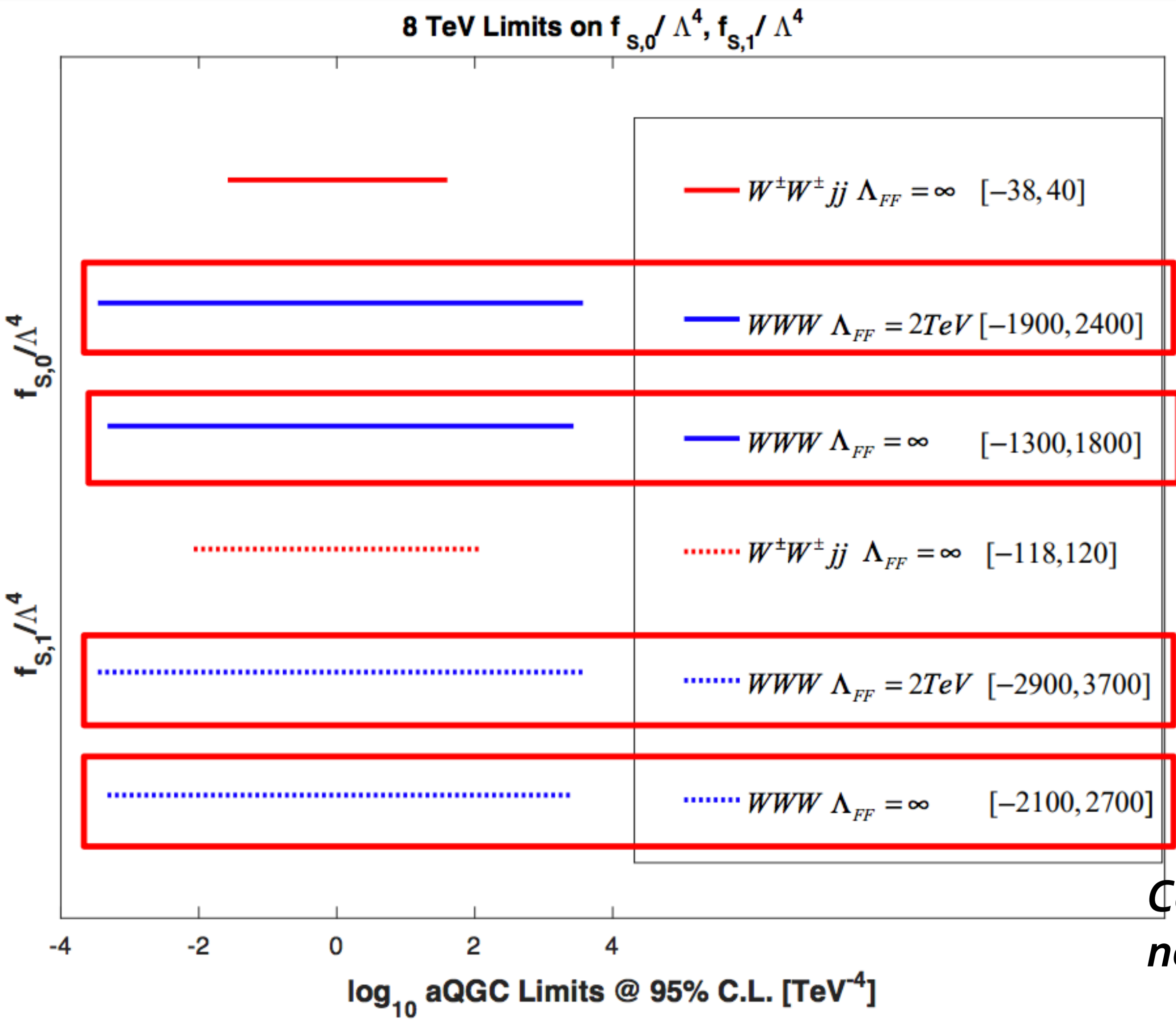
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

***Dim-8 Operators containing only the field strength tensors***

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

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




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

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

***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