Vector Boson Scattering

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Higgs Couplings 2013

Outline

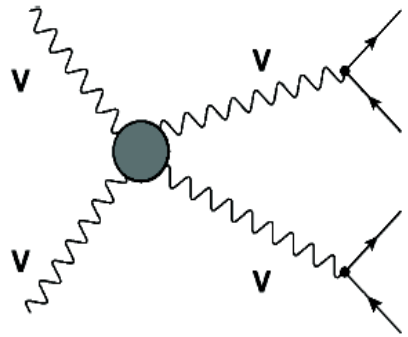
- Introduction
- Vector boson cross sections & anomalous triple gauge couplings
- Anomalous quartic gauge couplings
- Vector boson scattering & projections

Introduction

- Electroweak di(tri)boson measurements:
  - test of the electroweak sector of the Standard Model (SM) at the TeV scale
  - sensitive to Anomalous Triple (Quartic) Gauge Couplings (aTGC/aQGC)
  - background to Higgs analyses
  - $\mathrm{WW/WZ/ZZ}$ (VV) scattering $\rightarrow$ (massive, weak) Vector Boson Scattering (VBS):
    - measurable key process linked with Electro-Weak Symmetry Breaking (EWSB)
    - general final state: diboson plus at least two jets
- VBS at the LHC is the key process to experimentally probe the SM nature of EWSB:
  - complementary to direct Higgs boson measurements

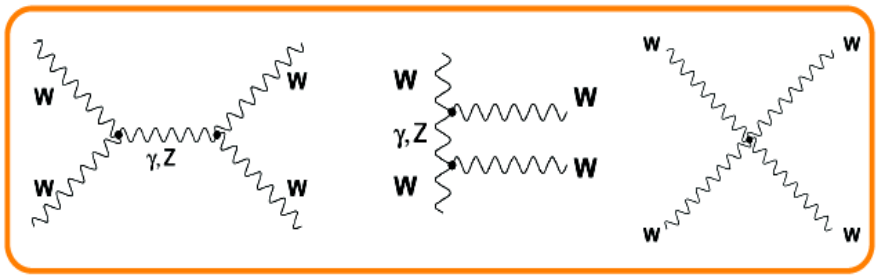
Unitarity Violation (I)

VV→VV

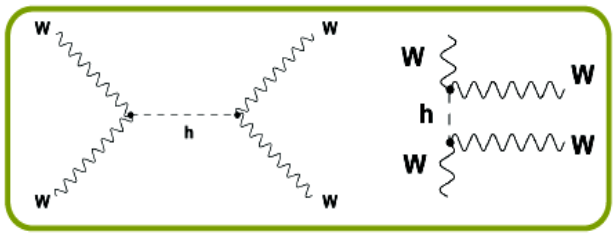


W, Z masses (→ longitudinal degrees of freedom) arise from the Higgs mechanism:

without the Higgs, $W^+_L W^-_L \to W^+_L W^-_L$ violates unitarity at $\sqrt{s} \geq 1.2$ TeV



S channel T channel QGC

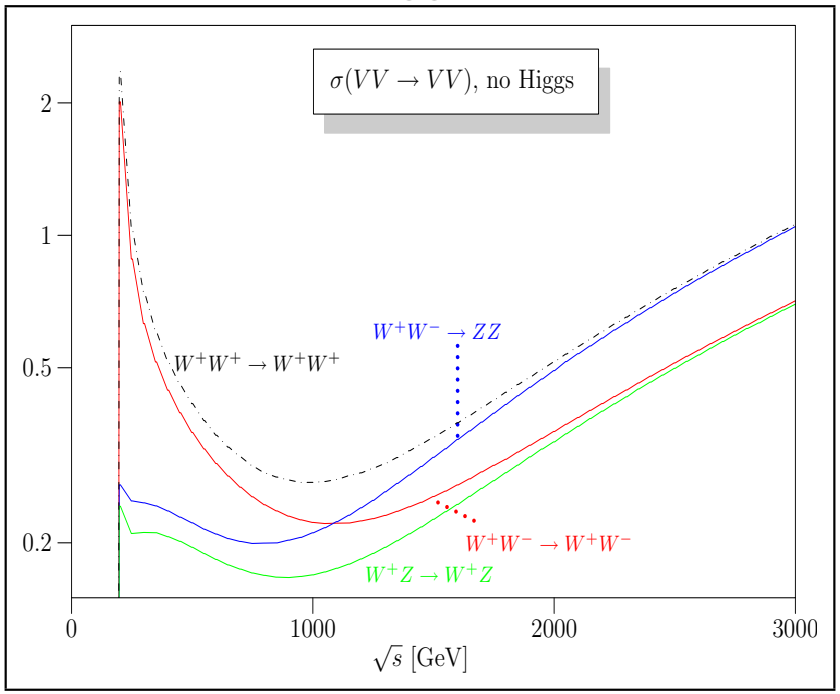


$$\sigma_{V_L V_L \to V_L V_L} \propto \left[-s - t - \frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2} \right]$$

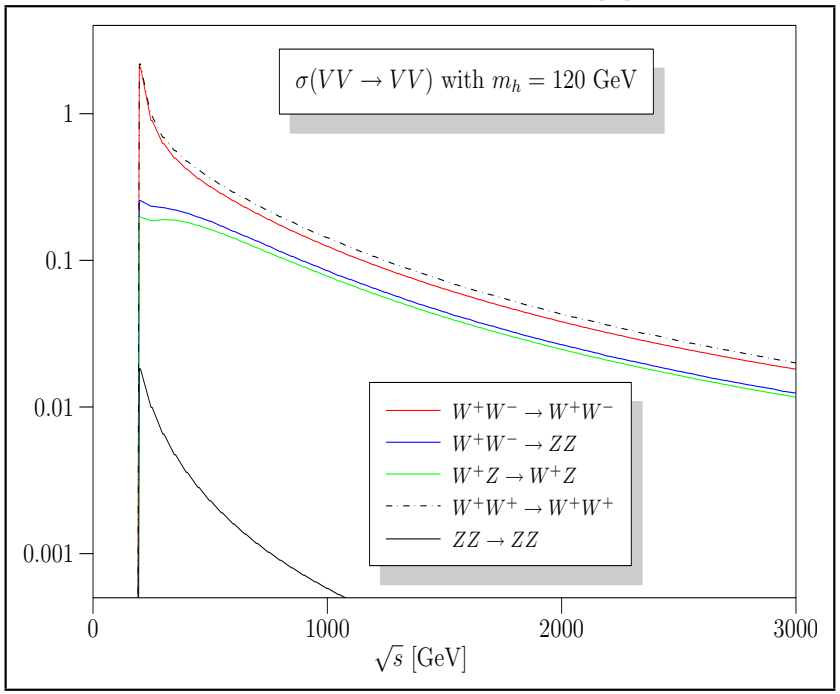
VV scattering a key component

Unitarity Violation (II)

SM without a Higgs boson



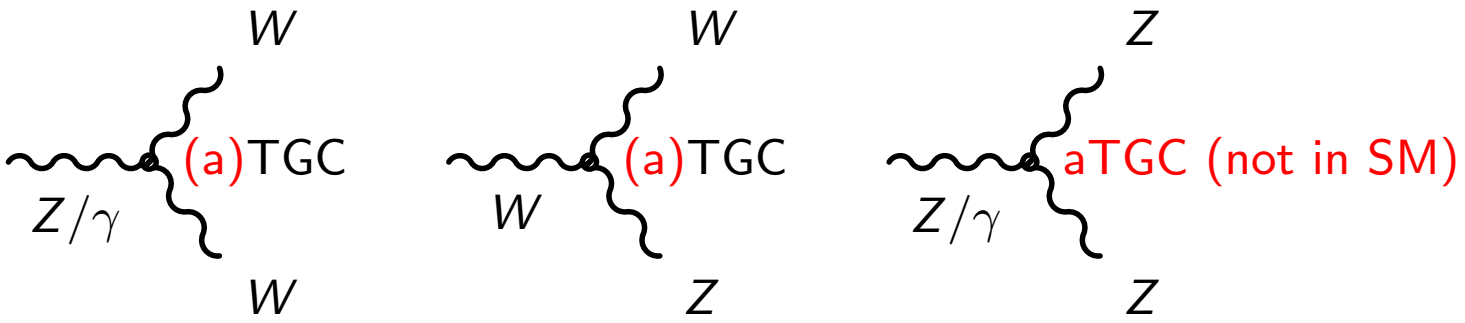
SM with a 120 GeV Higgs boson



from arXiv:0806.4145

- Without a "light" SM Higgs boson ($m_{\mathrm{H}} \leq 1$ TeV) VBS would violate unitarity
- Higgs boson contribution cancels increase for large $\sqrt{s}$ for SM-HWW coupling

Anomalous Triple Gauge Couplings (aTGCs)



- WWV ($V = Z/\gamma$) couplings $\longleftrightarrow$ WW and WZ (also $W\gamma$)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^+_{\mu\nu}W^\mu V^\nu - W^+_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^+_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

5 parameters: Δg_1^Z $(= g_1^Z - 1)$, $\Delta\kappa_Z$ $(= \kappa_Z - 1)$, $\Delta\kappa_\gamma$ $(= \kappa_\gamma - 1)$, λ_Z, λ_γ

- ZZV ($V = Z/\gamma$) couplings $\longleftrightarrow$ ZZ (also $Z\gamma$)

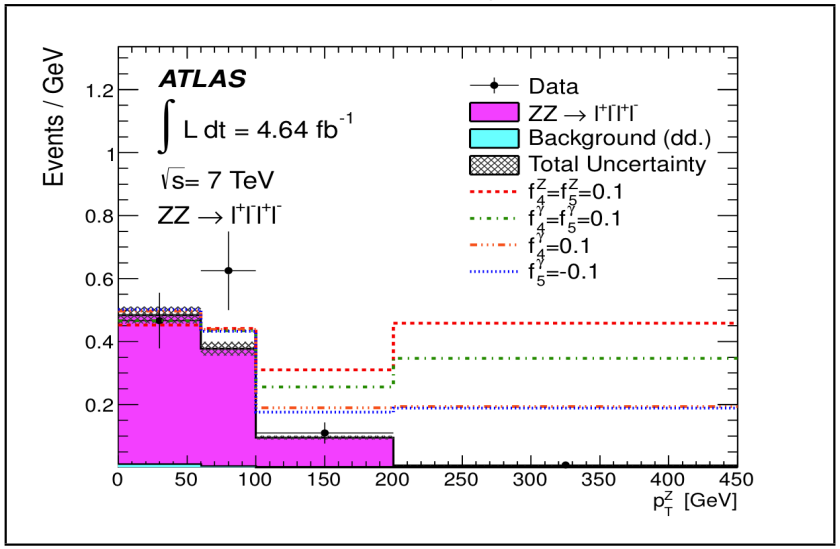
$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

4 parameters: f_4^Z, f_4^γ, f_5^Z, f_5^γ

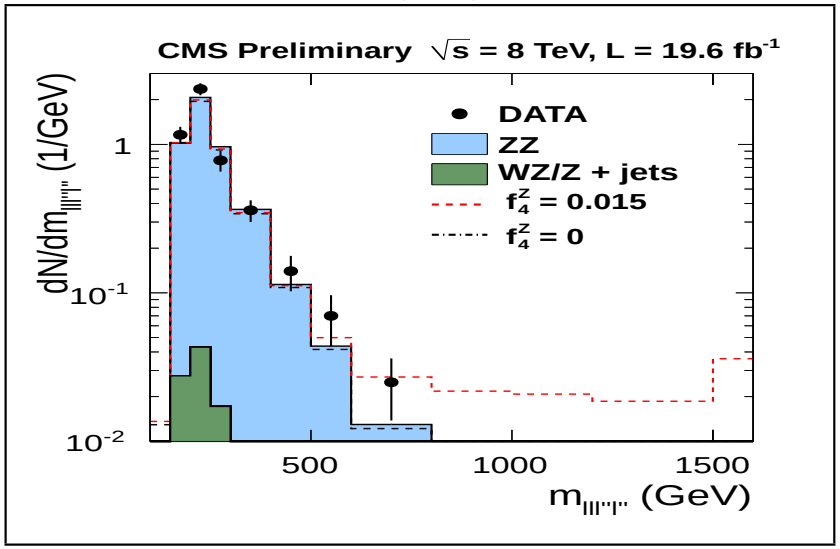
- Also 4 parameters for $Z\gamma Z$ and $Z\gamma\gamma$ vertices: h_3^γ, h_3^Z, h_4^γ, h_4^Z
- Parameters in red (aTGCs) are zero in the SM

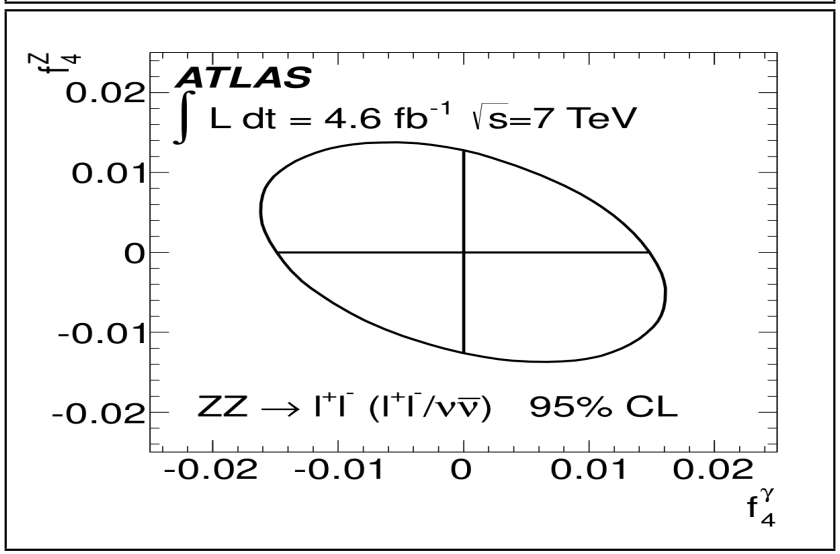
ZZ Cross Section & aTGCs

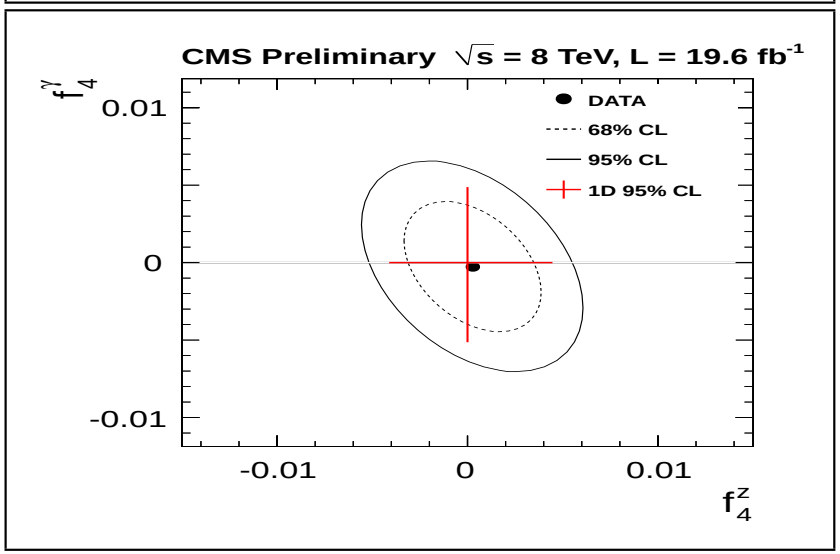
ATLAS



CMS



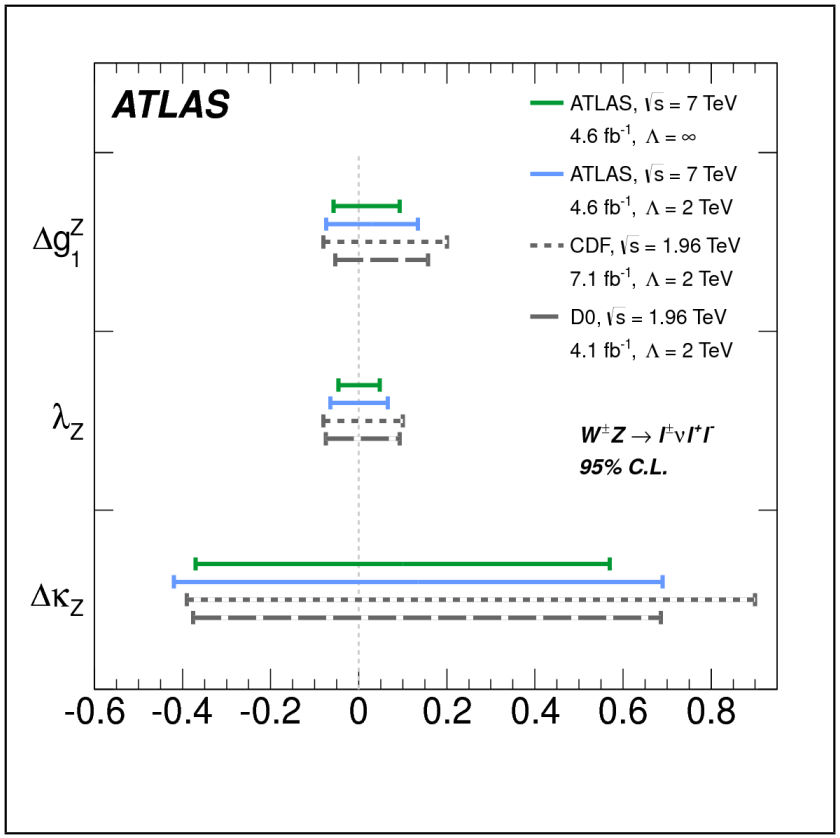




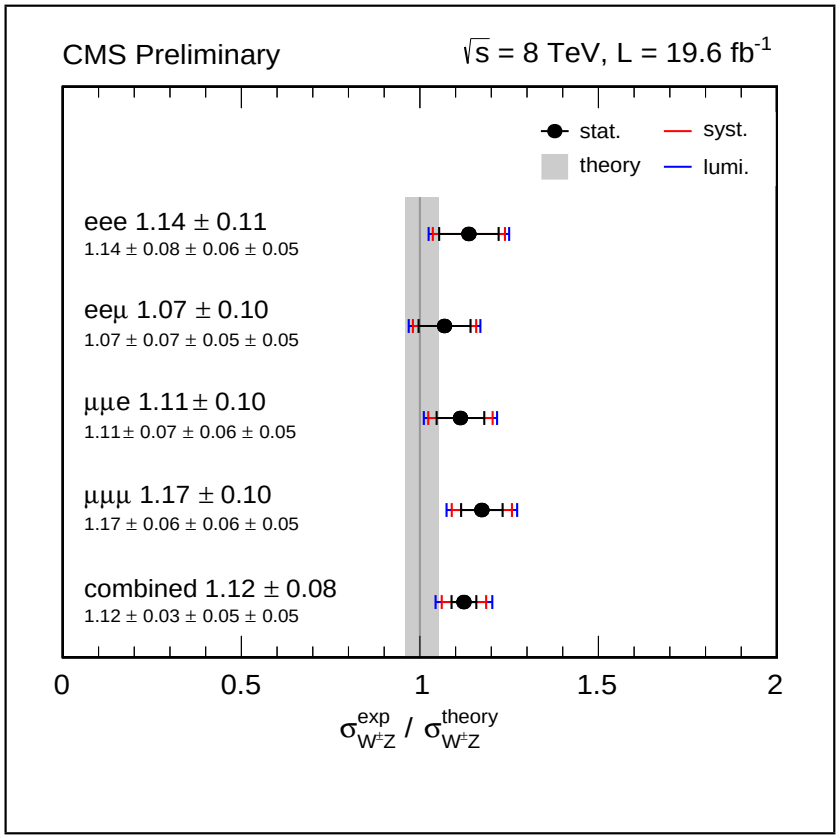
- Good agreement with SM expectation
- 7 TeV (~ 5 fb^{-1}) in ATLAS, 8 TeV (~ 20 fb^{-1}) in CMS
- Limits on aTGCs

WZ Cross Section & aTGCs

ATLAS (aTGCs)



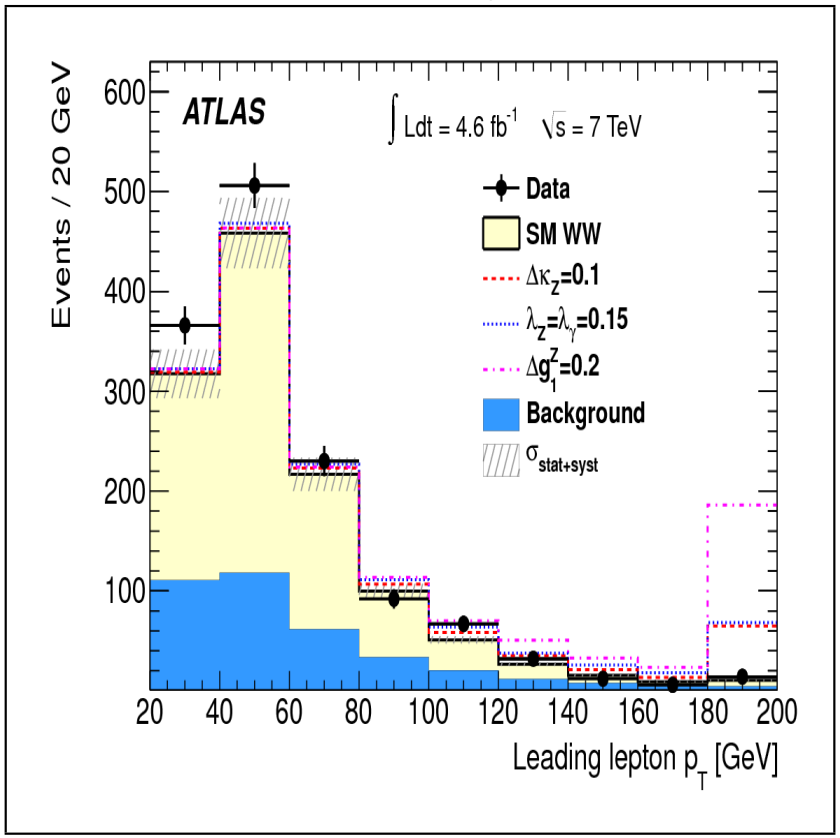
CMS (σ_{WZ})



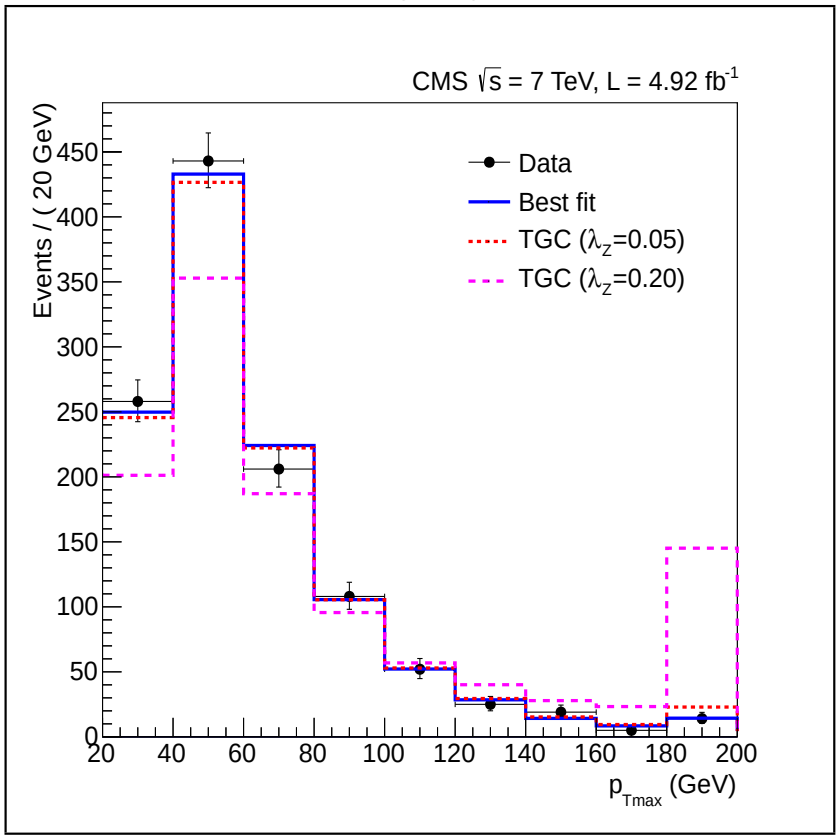
- Stringent aTGCs limits, analyses at $\sqrt{s} = 8$ TeV in progress
- Agreement at level of 2 standard deviations on σ_{WZ} in CMS

WW Cross Section & aTGCs

ATLAS

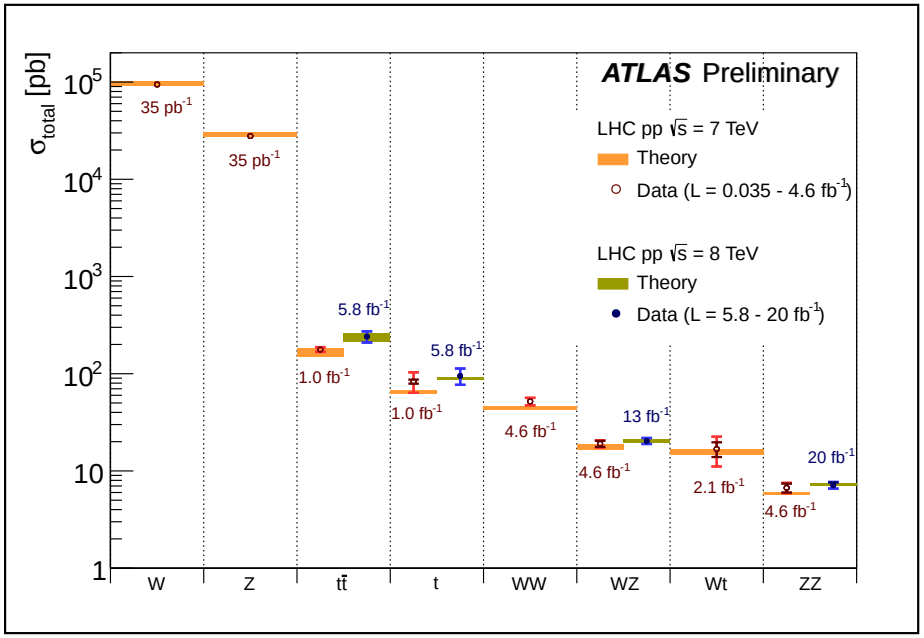


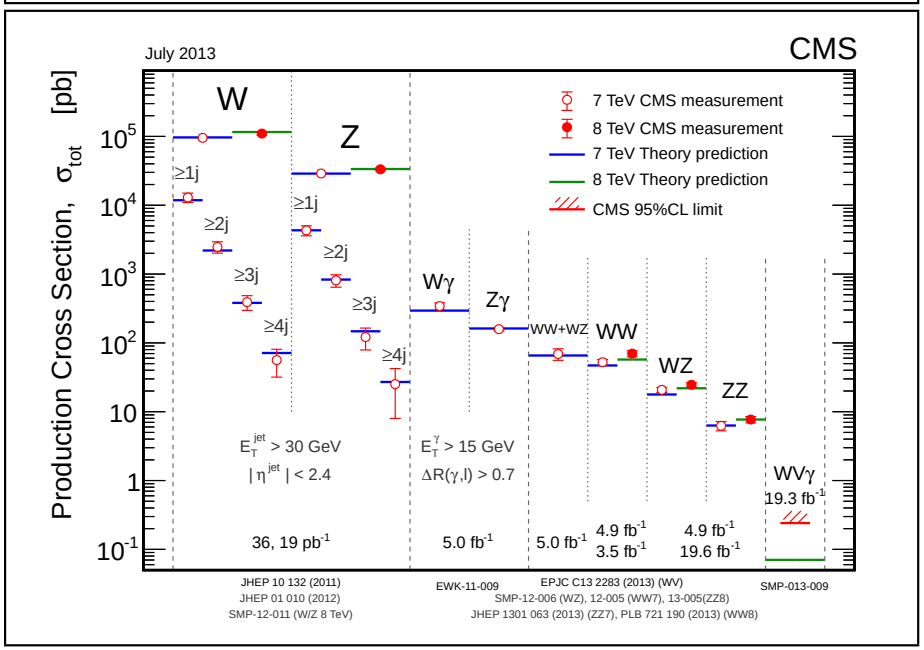
CMS



- $\sigma_{WW}/\sigma_{WW}^{SM} \sim 1.1$, consistent ratios among ATLAS & CMS, but within 1.0-1.5σ level to SM expectation
- Not consistent with aTGCs

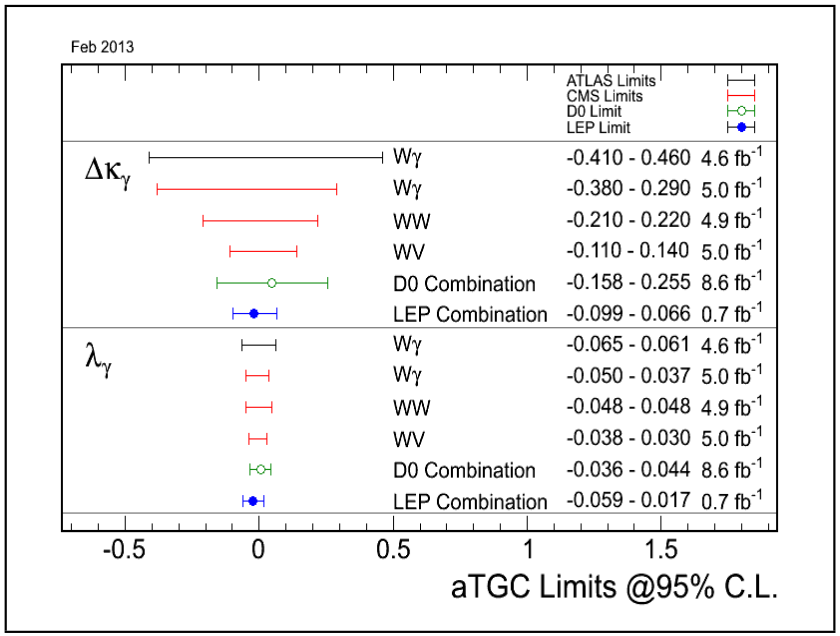
Summary of Inclusive Cross Section Measurements at LHC

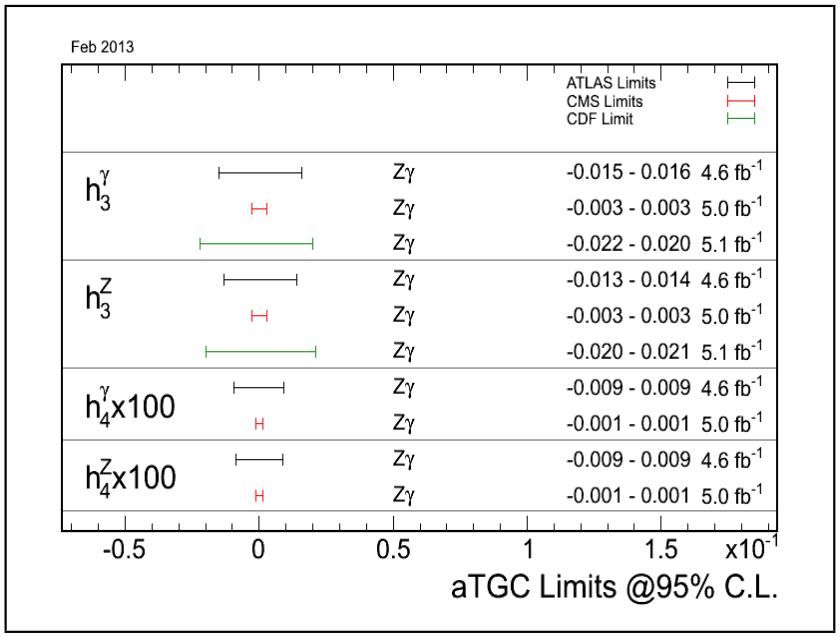


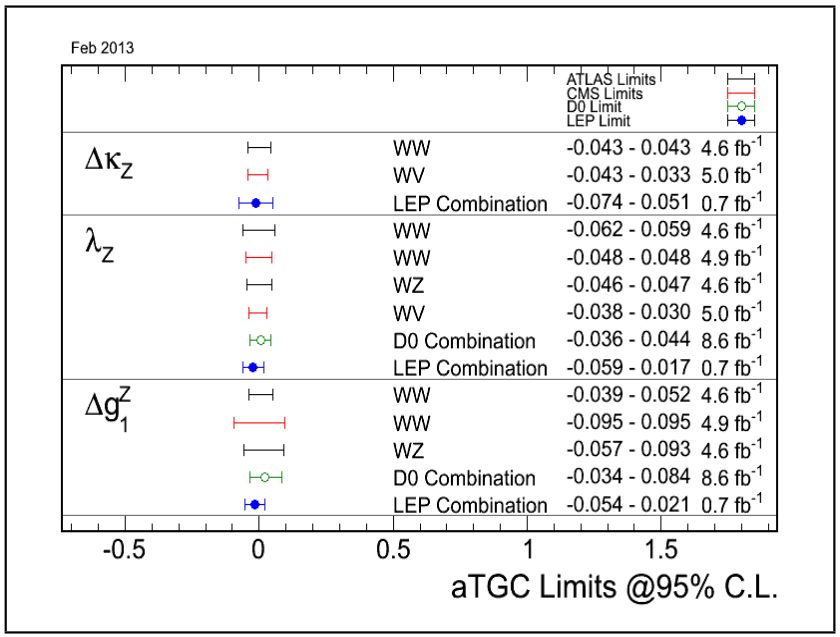


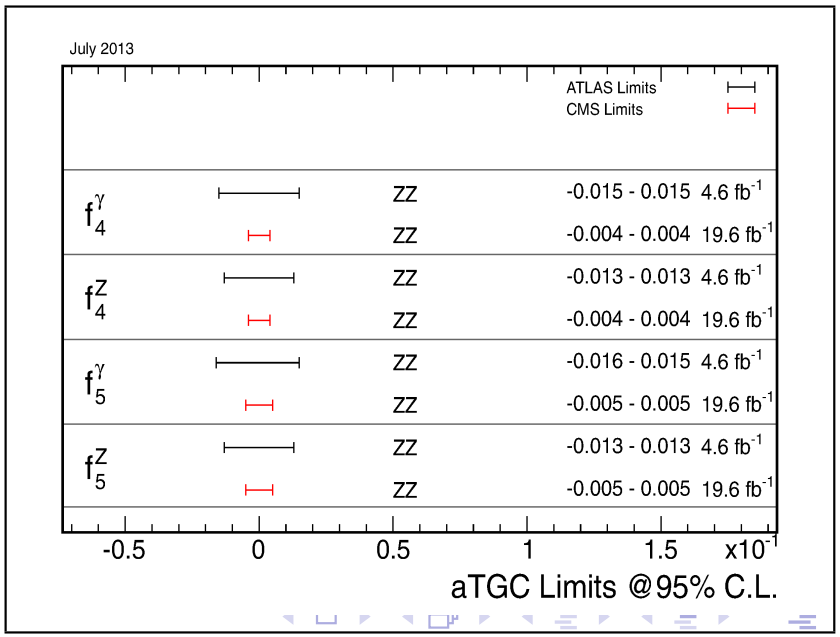
- No significant deviation from the SM expectation observed so far
- Diboson measurements in jet multiplicity bins not performed yet
- ATLAS/CMS combinations not performed yet
- Several analyses still to be done at $\sqrt{s} = 8$ TeV

aTGCs Limits





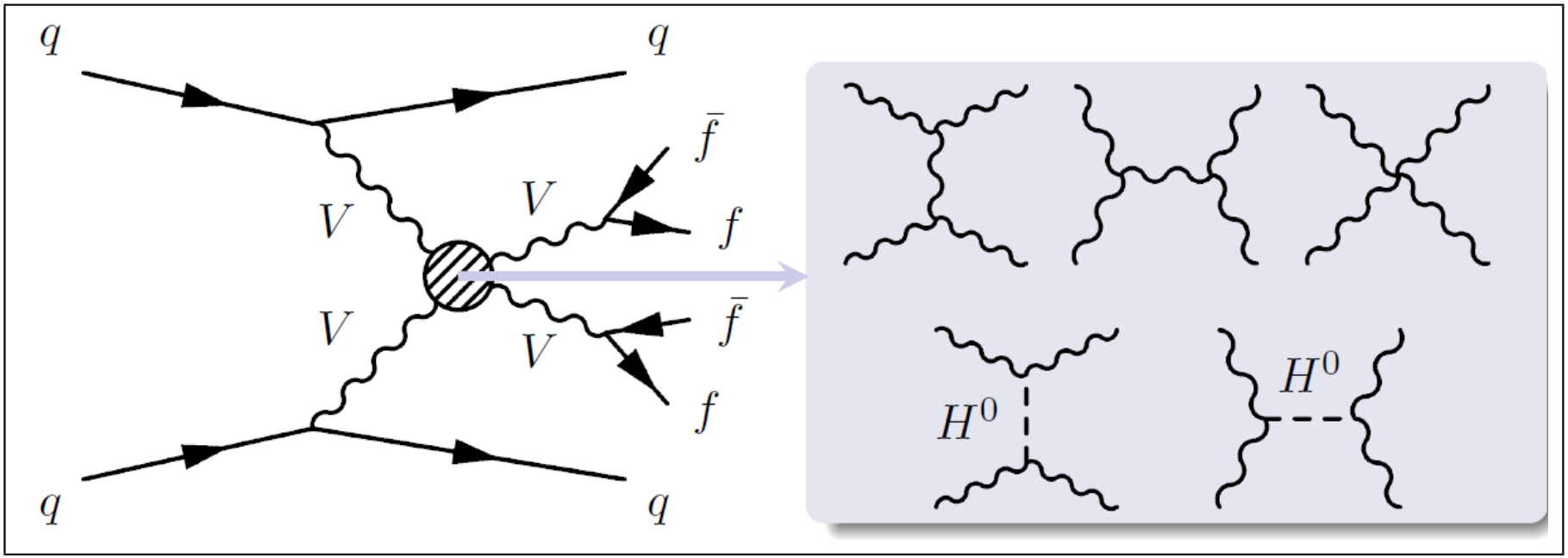




VV Scattering at the LHC

Characterized by *VVjj* final state:

triple and quartic gauge couplings (QGCs)



Higgs exchange and Higgs production via VBF

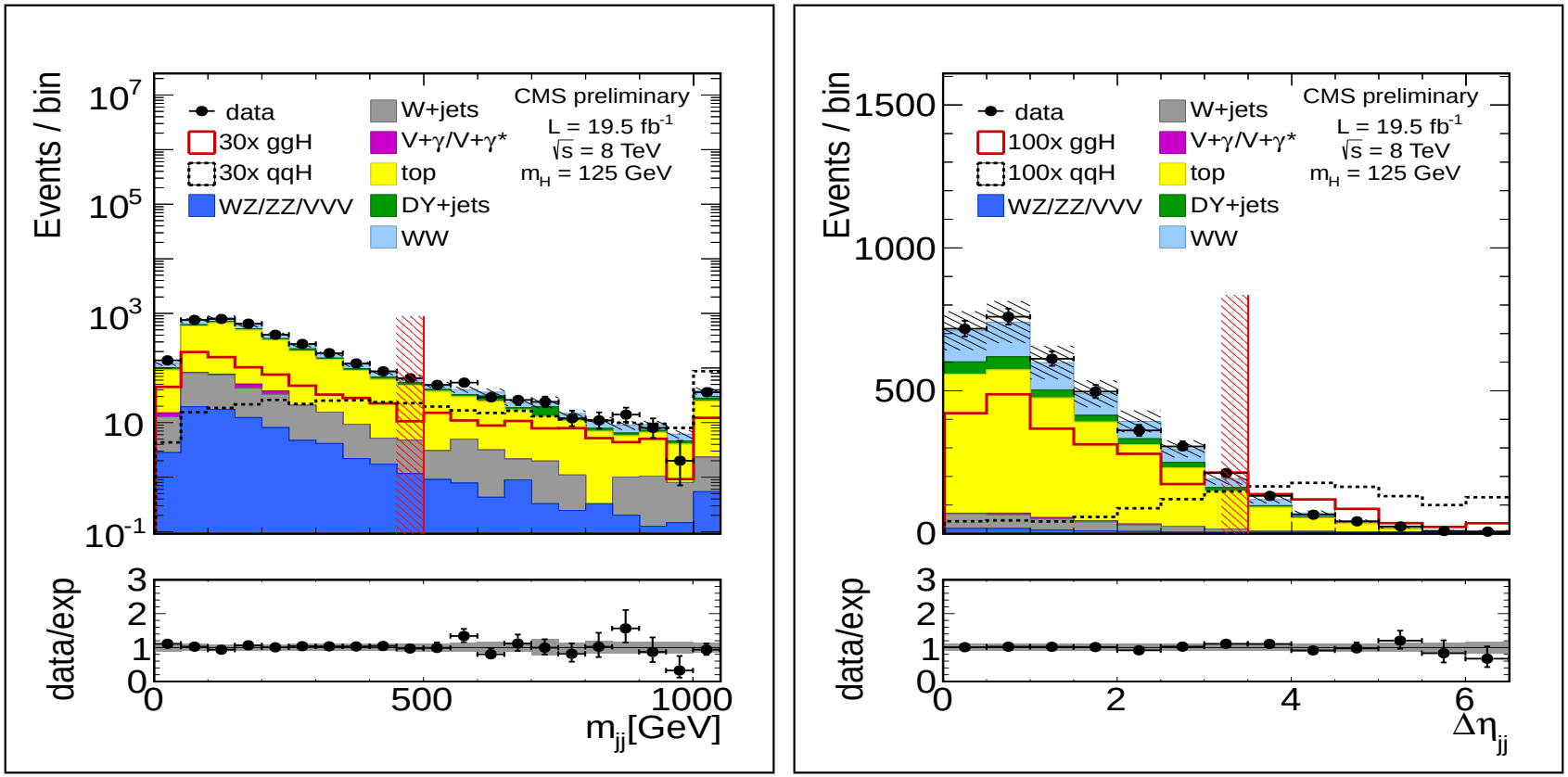
- Sensitivity to QGC $\longrightarrow$ setting exclusion limits on aQGCs
- Additional non-VV scattering contributions to the final state:
  - QCD = $O(\alpha_{EW}^4 \alpha_S^2)$
  - EW = $O(\alpha_{EW}^6)$: not gauge & gauge invariantly separable

VV Scattering Event Topology

- Diboson final states:
  - fully leptonic:
    - $\mathrm{W}^{\pm}\mathrm{W}^{\pm} \to \ell^{\pm}\nu\ell^{\pm}\nu$: best σ_{EW}/σ_{QCD} ratio
    - $\mathrm{W}^{\pm}\mathrm{W}^{\mp} \to \ell^{\pm}\nu\ell^{\mp}\nu$: relatively large top background
    - $\mathrm{W}^{\pm}\mathrm{Z} \to 3\ell\nu$: clean channel with three leptons
    - $\mathrm{ZZ} \to 4\ell$: very clean, limited number of events
    - $\mathrm{ZZ} \to 2\ell 2\nu$: more difficult analysis to perform, but relatively large branching ratio
  - semi-leptonic: $\mathrm{ZW/Z} \to \ell\ell jj$ & $\mathrm{WW/Z} \to \ell\nu jj$
    - more difficult due to larger backgrounds
    - high m_{VV} generates boosted jets which can be merged
- VBS topology:
  - two very energetic forward-backward tagging jets
  - large m_{jj} and $\Delta\eta_{jj}$
  - little hadronic activity between the two tagging jets in fully leptonic final states

VBF $\mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu$ as An Example

m_{jj} and $\Delta\eta_{jj}$ after WW $(e\mu)$ + 2 jets selection



- Clear separation between VBF $\mathrm{H} \to \mathrm{WW}$ and backgrounds
- Helps discriminating VBF Higgs against $gg \to \mathrm{H} + \mathrm{jets}$
  - equivalent to discrimination case between the VVjj EWK component and the VVjj QCD component

Anomalous Quartic Gauge Couplings (aQGCs)

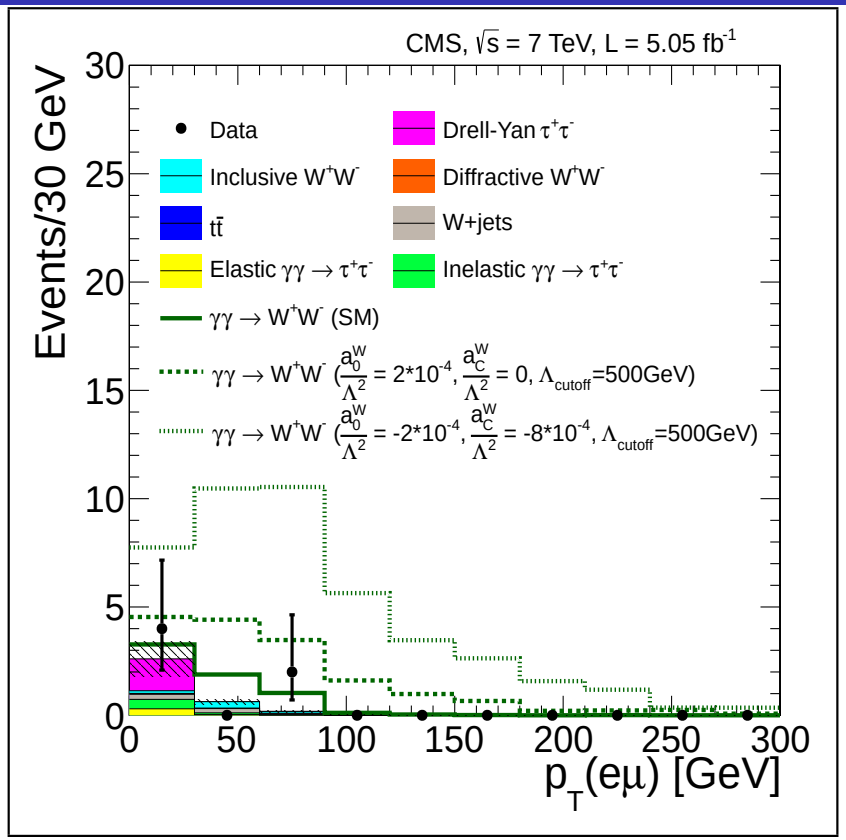
Extension of the SM Lagrangian by introduction additional dimension-8 operators for QGCs (with no effect on TGCs)

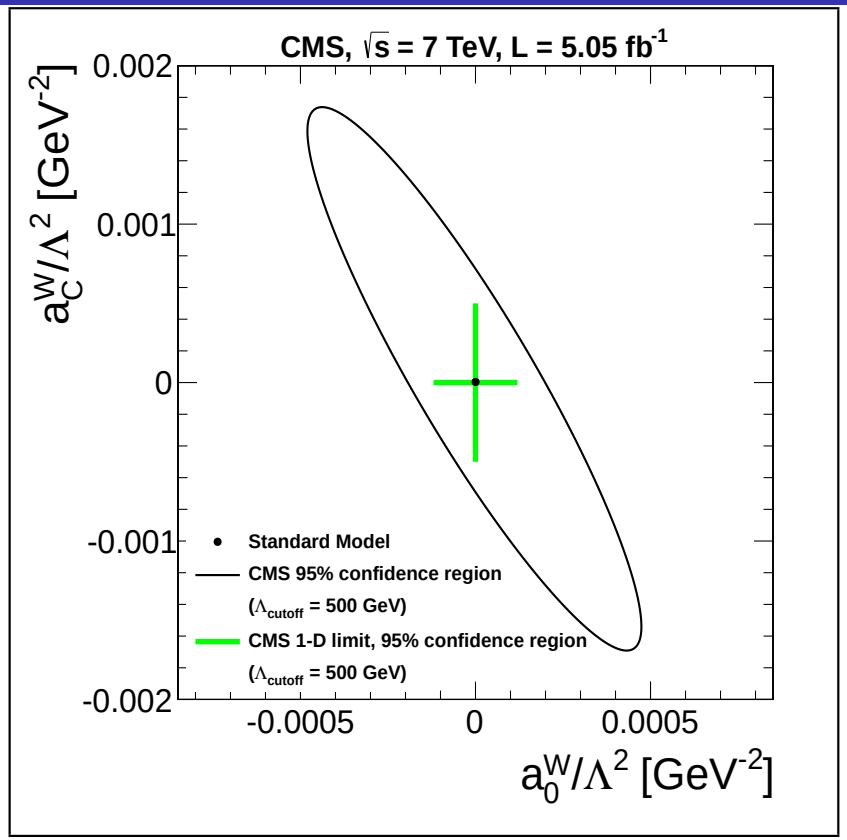
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + ... \text{ with } c_i^{VV} = c_{i,SM}^{VV} + g^2 \Delta c_i^{VV}$$

Model implemented in VBFNLO, similar implementations in WHIZARD and CALCHEP

- contains light SM Higgs boson
- operators:
  - coefficients in dimention-6 (see, e.g. hep-ph/9908254): $C_{\phi W}/\Lambda^2$ (VBFNLO), a_0^W/Λ^2, a_C^W/Λ^2 (CALCHEP)...
  - coefficients in dimension-8 (see, e.g. hep-ph/0606118): $f_{S,0}/\Lambda^4$, $f_{T,1}/\Lambda^4$...
- Λ is the scale of new physics, e.g. 1-2 TeV

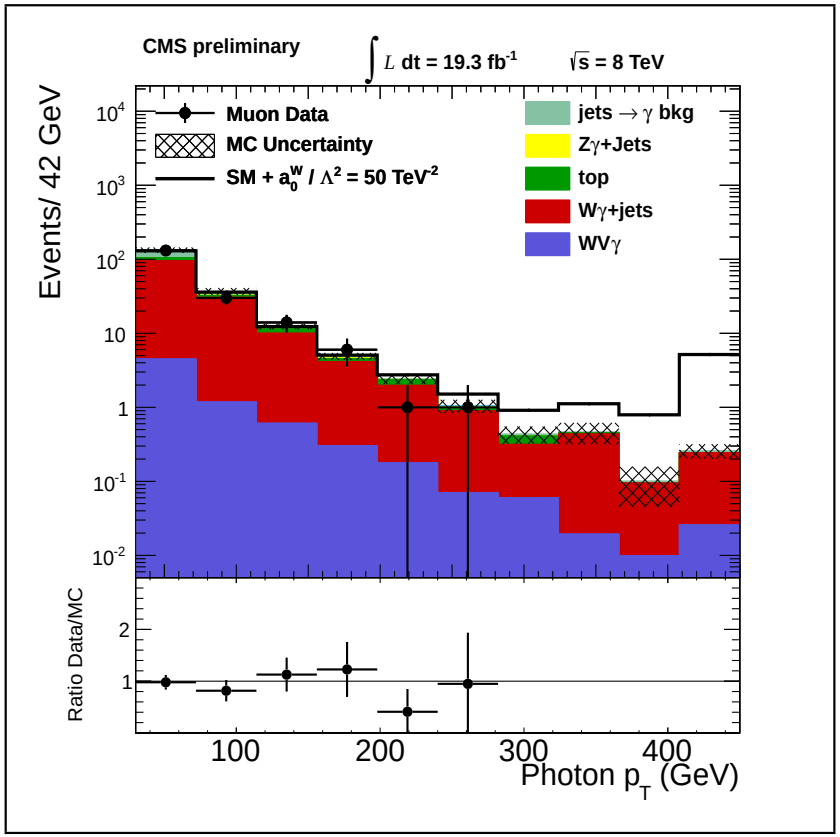
Limits on aQGCs with $\gamma\gamma \to \mathrm{WW}$

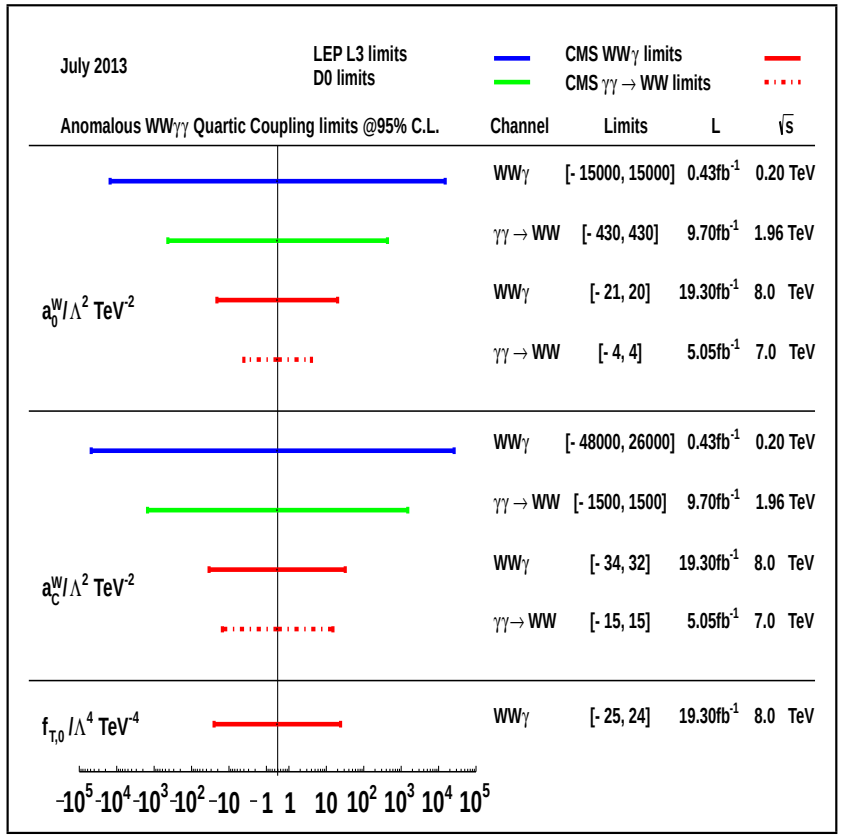




- Study of exclusive $pp \to p\mathrm{WW}p \to pp e\mu 2\nu$ events
- One $e\mu$ pair with no other tracks associated to their primary vertex, with large $p_{\mathrm{T}}^{e\mu}$ and $m_{e\mu}$
- Limits are set from number of events with $p_{\mathrm{T}}^{e\mu} > 100\ \mathrm{GeV}$

Limits on aQGCs with $\mathrm{WW}\gamma$ & $\mathrm{WZ}\gamma$

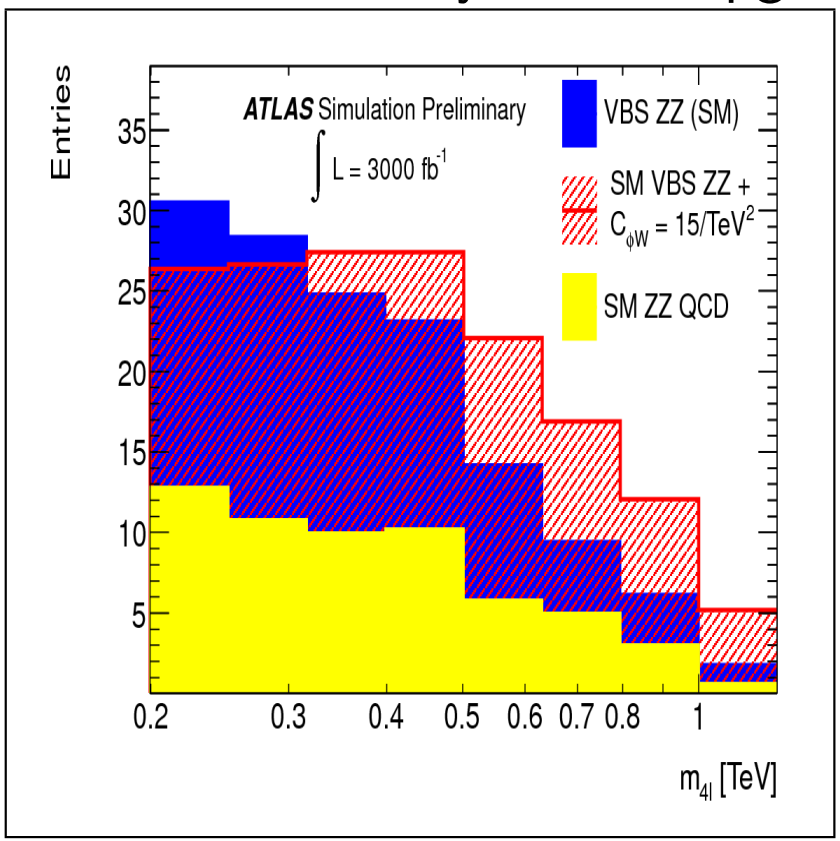


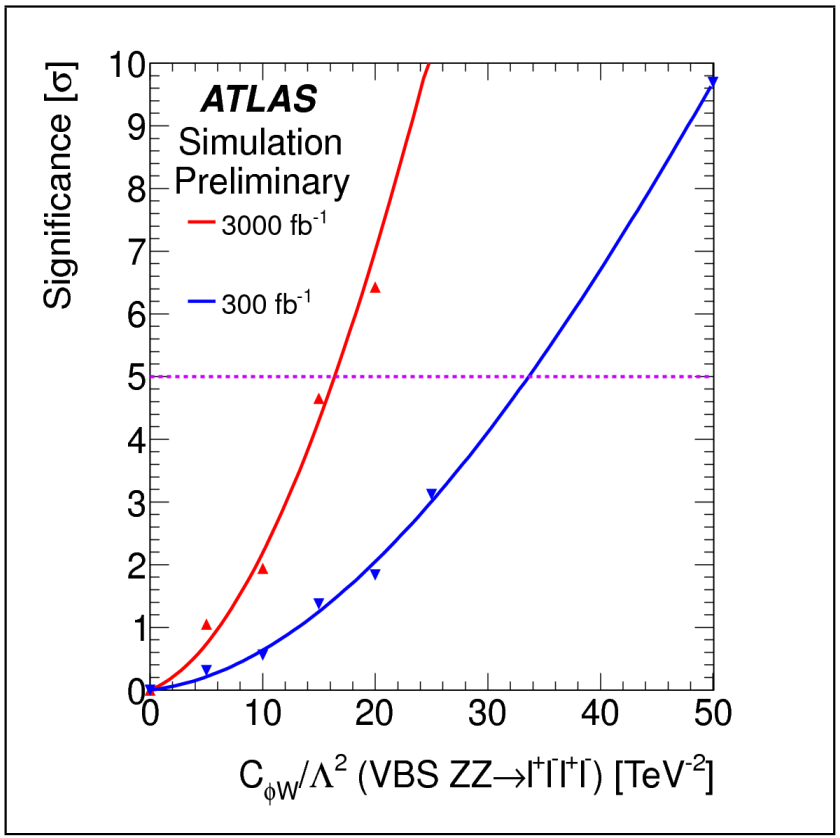


- Select events with one muon or electron, two jets from a W/Z boson, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and a high p_{T} photon
- Setting limits using p_{T}^{γ} as discriminant variable
- Comparable limits with respect to $\gamma\gamma \rightarrow \mathrm{WW}$ analysis

VBS with ZZ Events at $\sqrt{s} = 14$ TeV

Analysis with upgraded ATLAS detector

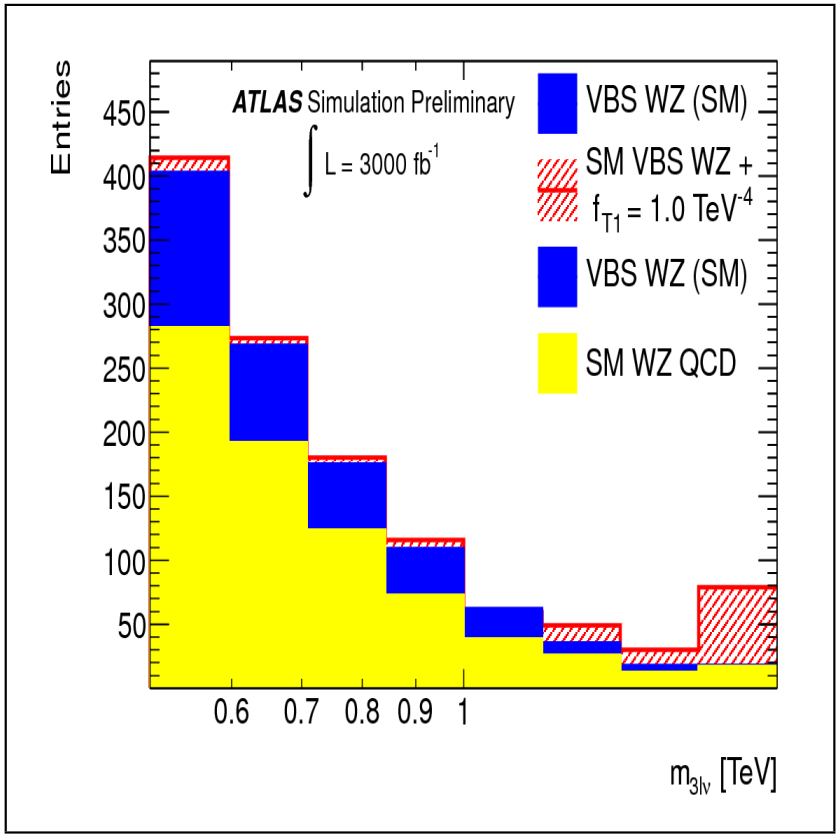




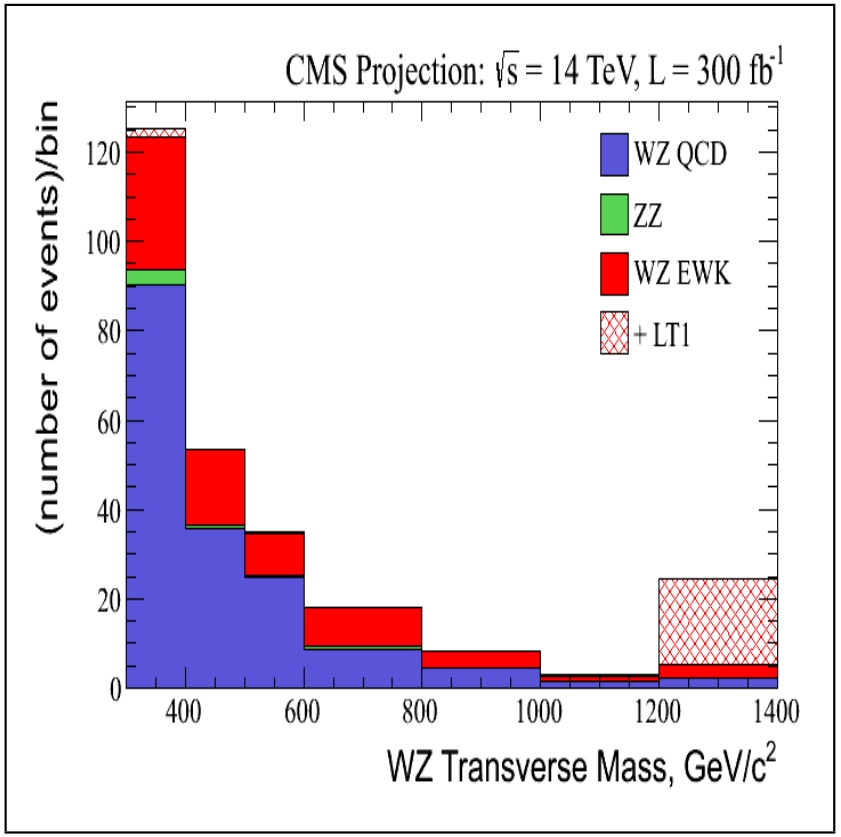
- Select events with four high p_{T} leptons and $m_{jj} > 1$ TeV
- Expected significance on $C_{\phi W}/\Lambda^2$ for different luminosity scenarios

VBS with WZ Events at $\sqrt{s} = 14$ TeV (I)

$\mathcal{L} = 3000\ \mathrm{fb}^{-1}$ (ATLAS)



$\mathcal{L} = 300\ \mathrm{fb}^{-1}$ (CMS)

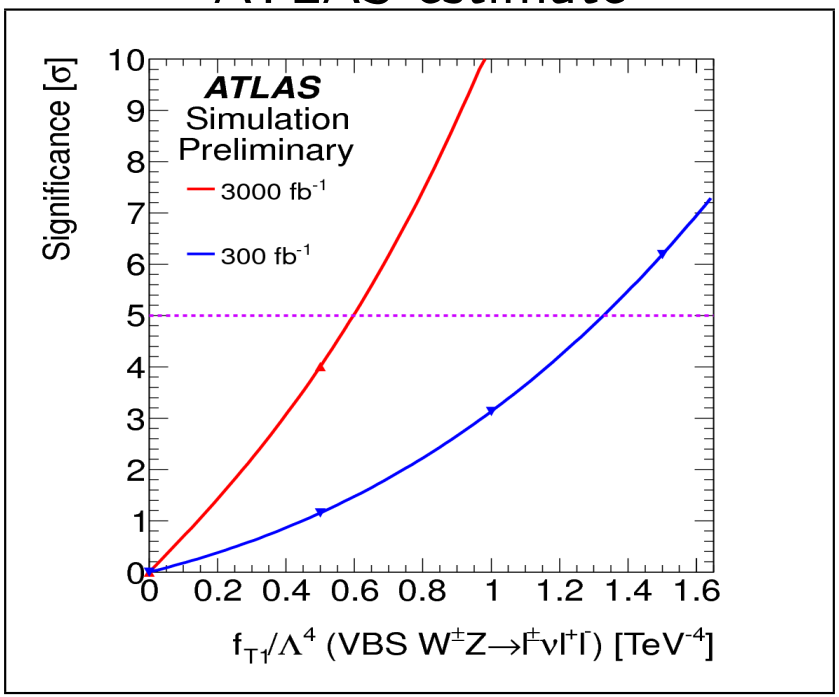


- Select events with three high p_{T} leptons, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{jj}
- Search for new Physics using $m_T^{3\ell\nu}$

VBS with WZ Events at $\sqrt{s} = 14$ TeV (II)

Expected significance on f_{T1}/Λ^4 for different luminosity scenarios

ATLAS estimate

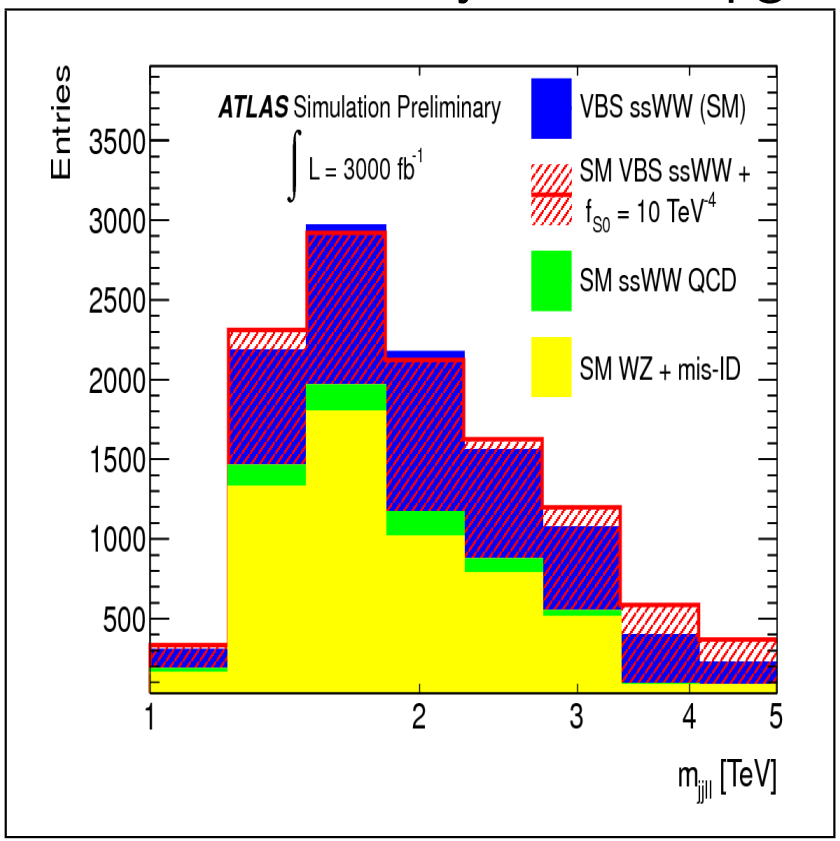


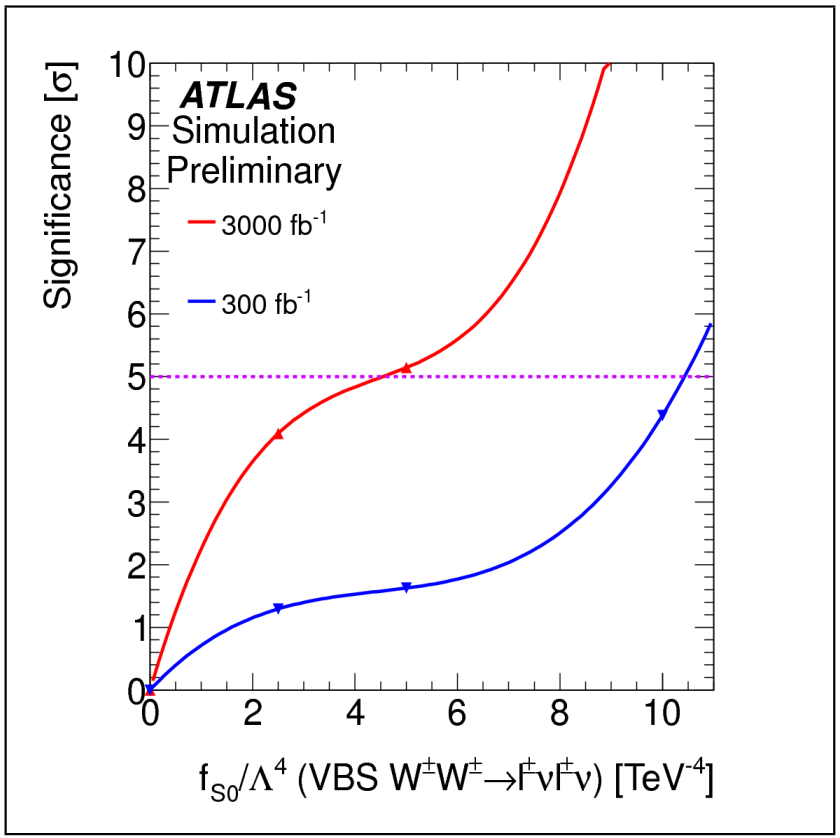
CMS estimate

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
$\frac{f_{T1}}{\Lambda^4}$ at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
$\frac{f_{T1}}{\Lambda^4}$ at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

VBS with $W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell^{\pm}\nu$ Events at $\sqrt{s} = 14$ TeV

Analysis with upgraded ATLAS detector





- Select same-sign lepton pairs events with $m_{jj} > 1$ TeV
- Expected significance on f_{S0}/Λ^4 for different luminosity scenarios

Summary

- Improvements on VV measurements:
  - no significant deviations from the SM
    - should keep an eye on WW and WZ cross section measurements
  - limits set on aTGCs and aQGCs
- VV scattering at LHC at high energy looks promising:
  - will be possible to experimentally probe the SM nature of EWSB
  - improved performance for VBS anomalous resonances with high luminosity
- Common future effort on the subject among ATLAS, CMS and theorists within the "High mass and BSM LHC HXSWG"
  - SM-like high mass Higgs in the WW and ZZ channels
  - see https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSM

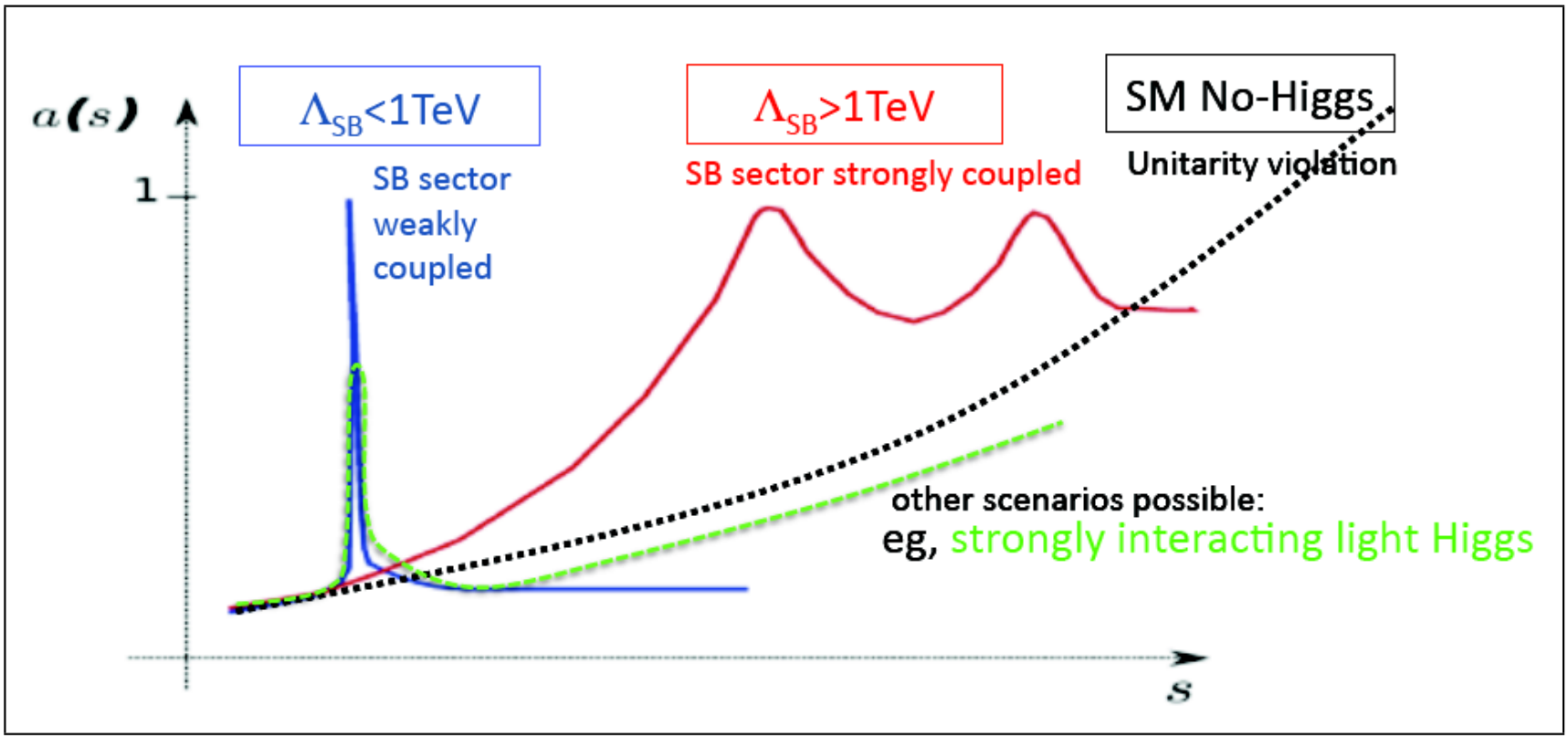
Back-Up

References

- ATLAS JHEP03(2013)128: ZZ cross section at $\sqrt{s} = 7\ \mathrm{TeV}$
- CMS-PAS-SMP-13-005: ZZ cross section at $\sqrt{s} = 8\ \mathrm{TeV}$
- ATLAS Eur. Phys. J. C (2012) 72:2173: WZ cross section at $\sqrt{s} = 7\ \mathrm{TeV}$
- CMS-PAS-SMP-12-006: ZZ cross sections at $\sqrt{s} = 7\ \mathrm{TeV}$ & $\sqrt{s} = 8\ \mathrm{TeV}$
- ATLAS Physics Letters B 712 (2012) 289-308: WW cross section at $\sqrt{s} = 7\ \mathrm{TeV}$
- CMS-PAS-SMP-12-005: WW cross section at $\sqrt{s} = 7\ \mathrm{TeV}$
- CMS-FSQ-12-010: exclusive two-photon production of WW at $\sqrt{s} = 7\ \mathrm{TeV}$
- CMS-PAS-SMP-13-009: $\mathrm{WW}\gamma$ and $\mathrm{WZ}\gamma$ study at $\sqrt{s} = 8\ \mathrm{TeV}$
- CMS-HIG-13-022: VBF $\mathrm{H} \rightarrow \mathrm{WW}$ search at $\sqrt{s} = 7\ \mathrm{TeV}$ & $\sqrt{s} = 8\ \mathrm{TeV}$
- ATL-PHYS-PUB-2013-006: VBS and triboson production projections at $\sqrt{s} = 14\ \mathrm{TeV}$
- CMS-FTR-13-006: VBS projections at $\sqrt{s} = 14\ \mathrm{TeV}$

VBS as probe for EWSB

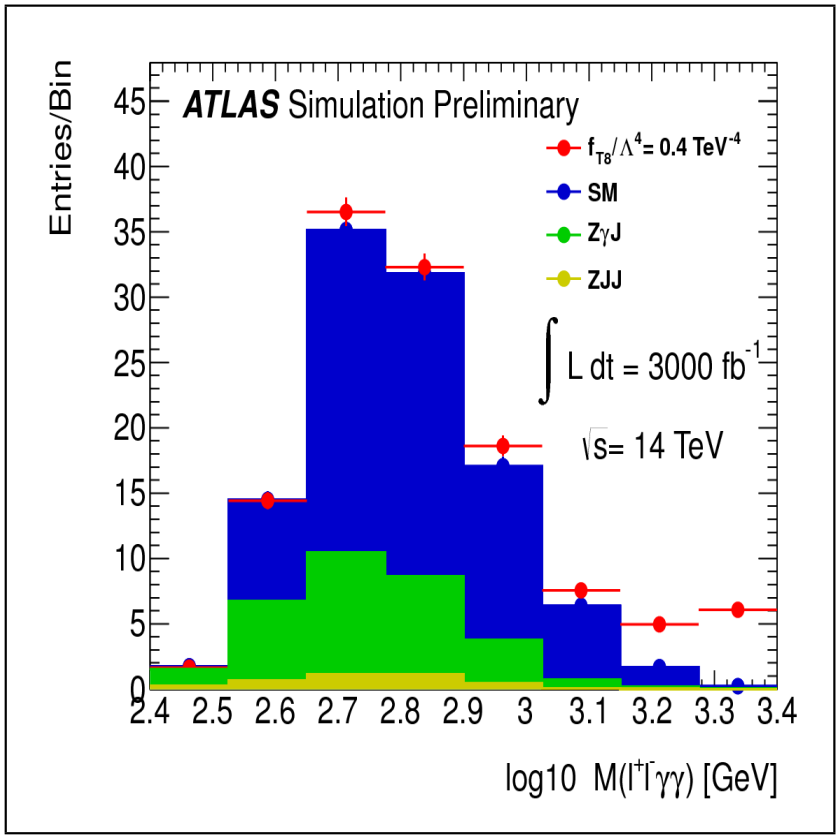
VBS spectrum $\sigma_{VV\to V}$ vs. m_{VV} is a fundamental probe to test the nature of the Higgs boson

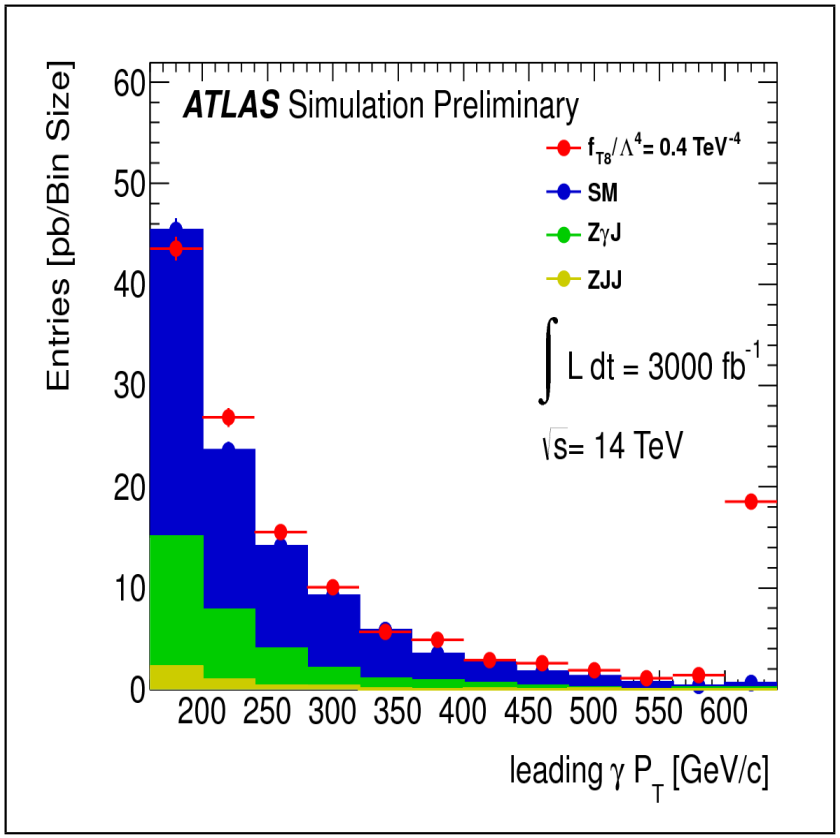


Search for possible discrepancies in m_{VV} spectrum

$ZZ\gamma\gamma$ Events at High Energy

Analysis with upgraded ATLAS detector





- Select $Z \to \ell\ell$ events with two high energetic photons
- Expected significance on higher dimension operators for different luminosity scenarios