Prospects for Higgs boson physics beyond the Standard Model at the Large Hadron Collider (LHC)

Seminar: Physics at the Large Hadron Collider

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Contents

Introduction

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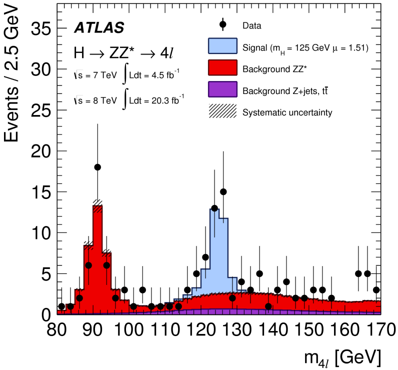
- In the Standard model:
  - Higgs sector is minimal
  - Include only one complex doublet: one CP-even Higgs boson
- 2012: Discovery of a Higgs-like boson with m_A =125.5 GeV and $J^P = 0^+$
- Combined coupling fits of the measured production and decay rates: no significant deviation from SM



Introduction

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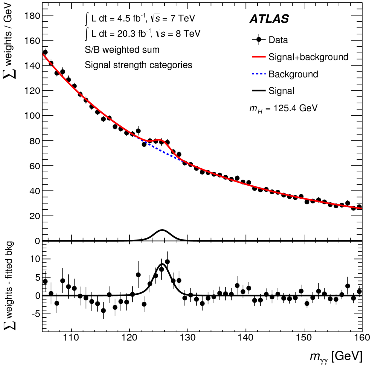
- Important question: Higgs sector minimal or extended, as predict in many beyond-SM theories
- Upgrade of LHC: better study of the higgs sector and search for new physics
- 2011/12: 25 fb^{-1} at $\sqrt{s} = 7\text{-}8$ TeV
- till 2022: 300 fb^{-1} at $\sqrt{s} = 13\text{-}14$ TeV
- till 2030: 3000 fb^{-1}
- Current studies:
  - What can be done with this Data ?
  - Which new physics can be observed ?



Introduction

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- Indirect search:
  - Measuring the signal strength in different channels
  - Combined coupling fits: determine couplings of higgs to fermions and vector bosons
  - Search for deviation from SM
  - Channels:
    - $H \to \gamma\gamma$
    - $H \to Z\gamma$, $Z \to ll$
    - $H \to \tau^+\tau^-$
    - $H \to ZZ^* \to 4l$
    - $H \to WW^* \to l\nu l\nu$
    - $H \to \mu\mu$
- Direct search:
  - Search for new particles in different decay channels:
    - $H, A \to \mu\mu$
    - $A \to Zh \to llb\bar{b}$
    - $H \to ZZ \to 4l$

Additional electroweak singlet

- Simplest extension of the SM Higgs sector: Addition of an electroweak singlet
- Both: Non-zero vacuum expectation values
- Spontaneous symmetry breaking ⇒ two CP-even Higgs bosons: h, H
  - Non-degenerate
  - Coupling to fermions and vector bosons similar to the SM Higgs boson
  - Strength reduced by a scale factor: κ_h, κ_H, with $\kappa_h^2 + \kappa_H^2 = 1$
- For the lighter Higgs boson h (identical decay modes SM Higgs):

$$\sigma_h = \kappa_h^2 \cdot \sigma_{h,SM} \ , \qquad \Gamma_h = \kappa_h^2 \cdot \Gamma_{h,SM} \ ,$$

$$\mathrm{BR}_{h,i} = \mathrm{BR}_{SM,i}$$

Additional electroweak singlet

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- For H: new decay modes possible ($H \to hh$):

$$\sigma_H = \kappa_H^2 \cdot \sigma_{H,SM} \ , \qquad \Gamma_H = \frac{\kappa_H^2}{1 - \mathrm{BR}_{H,new}} \cdot \Gamma_{H,SM} \ ,$$

$$\mathrm{BR}_{H,i} = \left(1 - \mathrm{BR}_{H,new}\right) \cdot \mathrm{BR}_{H,SM,i}$$

- Indirect searches for deviations in the fit of the Higgs boson couplings

- Expected 95 % CL upper limit on κ_H at $\sqrt{s} = 14$ TeV:

Coupling	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	All unc.	No theory unc.	All unc.	No theory unc.
κ_H	0.35	0.31	0.31	0.25

$H \to ZZ \to 4l$ (CMS)

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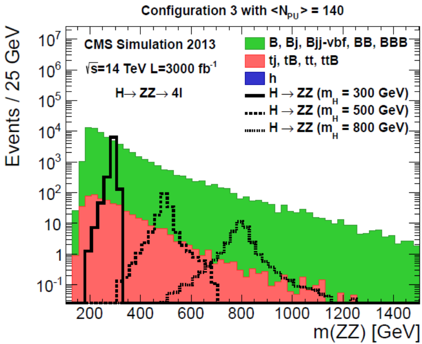
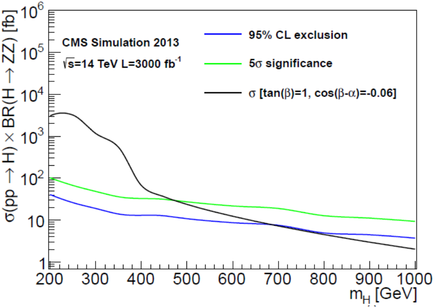
CMS PAS FTR-13-024

- Selection:
  - Electron $p_T >$10 GeV and muon $p_T >$5 GeV, $|\eta| < 2.5$
  - Lepton isolation
  - Ensure trigger efficiency: Leading lepton with $p_T >$30 GeV or leading with $p_T >$20 GeV and sub-leading with $p_T >$10 GeV
- Z candidates:
  - Same flavor, opposite sign
  - $60 < m_{ll} < 100$GeV
  - Require two candidates
  - One with $80 < m_{ll} < 100$GeV
- One $H \to ZZ$ candidate with $m_{ZZ} >$150 GeV

$H \to ZZ \to 4l$ (CMS)

CMS PAS FTR-13-024





Background: B, Bj, Bjj-vbf, BB, BBB
tj, tt, tB, ttB

The 2HDM

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- SM Higgs sector is extended by an additional doublet
- Vacuum expectation values: $v_1 = \langle\phi_1\rangle$ and $v_2 = \langle\phi_2\rangle$:
  $v_1^2 + v_2^2 = v^2 = (246\mathrm{GeV})^2$
- Predict five Higgs bosons: two neutral CP-even bosons h and H, two charges bosons $H^\pm$ and one CP-odd boson A
- Parameters (no CP violation):
  - m_h, m_H, m_A and $m_{H^\pm}$
  - $\tan\beta = v_2/v_1$
  - mixing angle α of the two neutral CP-even Higgs states
  - Scalar coupling: λ_5, λ_6 und λ_7
    (Minimal Supersymmetric Standard Model (MSSM) $\lambda_5 = \lambda_6 = \lambda_7 = 0$)

The 2HDM - Types

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- Couplings to the light Higgs boson h:

Coupling strength	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\cos(\alpha)/\sin(\beta)$

The 2HDM - Types

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Type	Name	Doublet ϕ_1	Doublet ϕ_2
I	fermiophobic		u d l
II	MSSM-like	d l	u
III	lepton-specific	l	u d
IV	flipped	d	u l

$\phi \to \mu\mu$ (ATLAS)

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- Higgs bosons (A, H) produced by gluon fusion and/or association with b-quark pair
- Selection: Event contains exactly two muons (opposite charge)
- Two categories:
  - b-tag: At least one b-tagged jet
  - b-veto: No b-tagged jet
- Background:
  - Z/γ^*+ jets
  - $Z/\gamma^* + bb$
  - $t\bar{t}$

$\phi \to \mu\mu$ (ATLAS)

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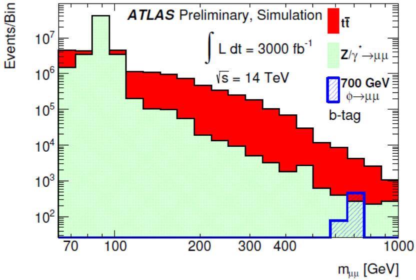
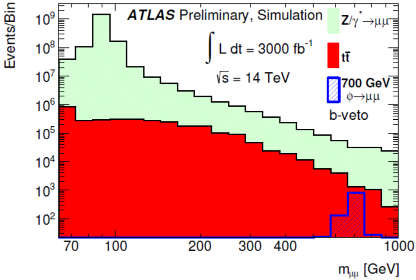
- Di-muon invariant mass distribution:





$\phi \to \mu\mu$ (ATLAS)

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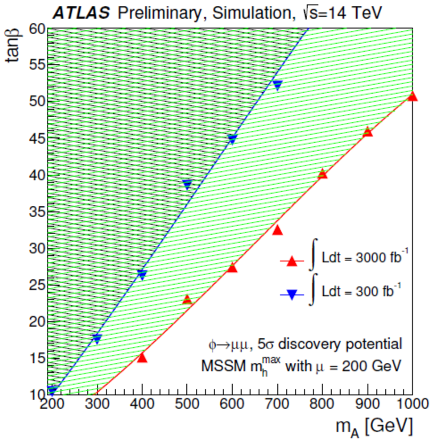
- Expected significance:



$A \to Zh \to llb\bar{b}$ (ATLAS)

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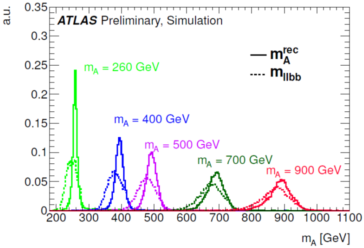
- Selection:
  - Electrons: $E_T > 25$ GeV and $|\eta| < 2.57$ (without $1.37 < |\eta| < 1.52$)
  - Muons: $p_T > 25$ GeV and $|\eta| < 2.5$
  - At least two with same flavor and opposite sign ($80 < m_{ll} < 100$ GeV)
  - At least 2 b-jets ($90 < m_{bb} < 140$ GeV)
  - $1.4 - 0.001 m_A < \Delta R(bb) < 1.8 - 0.001 m_A$



- Clean signature and fully reconstructible m_A

$$m_A^{rec} = m_{llbb} - m_{ll} - m_{bb} + m_Z^0 + m_h^0$$

$A \to Zh \to llb\bar{b}$ (ATLAS)

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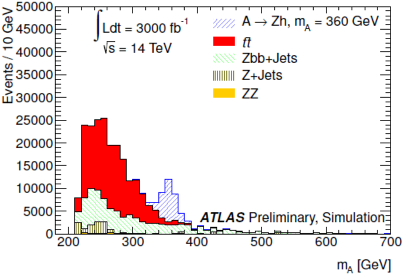

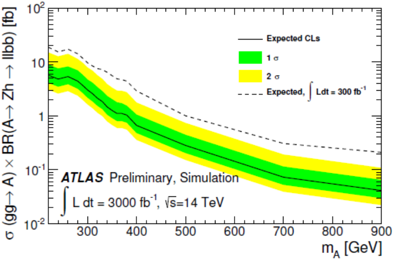

Background: $t\bar{t}$
$Z+$ jets
Zbb
ZZ

$A \to Zh \to llb\bar{b}$ (ATLAS)

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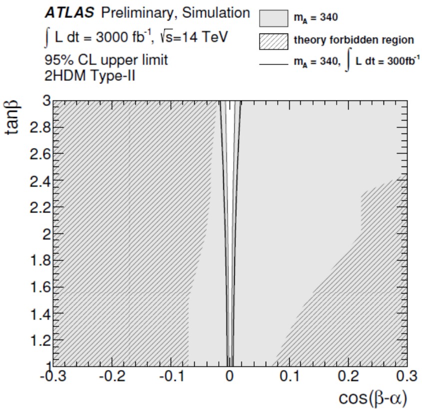
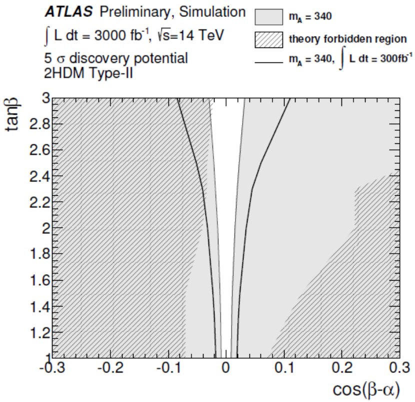
- Limits on the 2HDM parameter space:

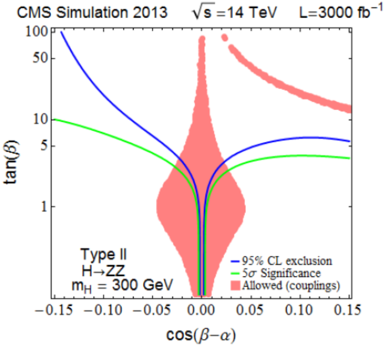




$H \rightarrow ZZ \rightarrow 4l$ (CMS)

CMS PAS FTR-13-024

- This decay channel also possible in the 2HDM
- Limits on the 2HDM parameter space:



Indirect search (ATLAS)

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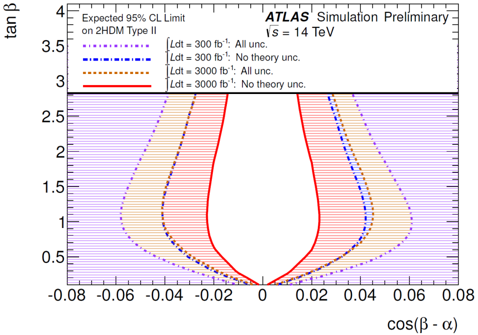
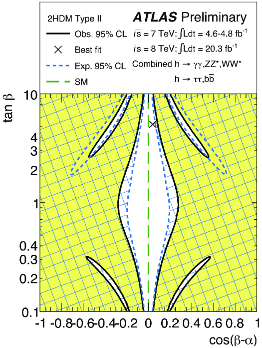
- Indirect measurement possible by setting constrains on the parameter:





Summery

- Discovery of the Higgs boson in 2012
- Question: Higgs sector minimal?
- New physics is observable in direct and indirect measurements
- Studies of expected limits on an additional electroweak singlet and electroweak doublet has been done
- New data at 13-14 TeV allow for the exploration of a wide range of Higgs sectors beyond the Standard Model, both via direct searches for new Higgs bosons and indirectly via fit of the Higgs boson couplings to the measured data

$H \to ZZ \to 4l$ (ATLAS)

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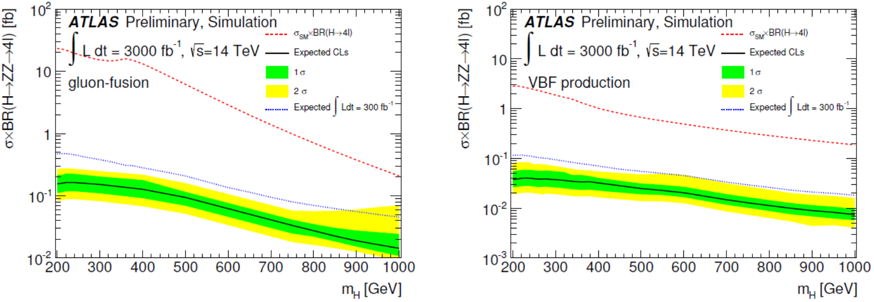

- Expected upper limits ($200 < m_H < 1000\,\text{GeV}$):

	ggF	VBF
$3000\ \text{fb}^{-1}$	$\sim 0.01 - 0.1$ fb	$\sim 0.008 - 0.04$ fb

$A \to Zh \to ll b\bar{b}$ (CMS)

CMS PAS FTR-13-024

- Same selections for Leptons as for $H \to ZZ$
  - One Z candidate (opposite sign and same flavor lepton pair with $60 < m_{ll} < 100$GeV)
- Selections for jets:
  - $p_T >$10 GeV and $|\eta| > 2.5$
  - One h candidate with $90 < m_{bb} <$150 GeV
- $|\Delta\phi(l_1 l_2)| < 1.9$ rad
- $p_T(Z) >$40 GeV
- $0.4 < p_T(Z)/p_T(h) < 2.75$

$A \to Zh \to ll b\bar{b}$ (CMS)

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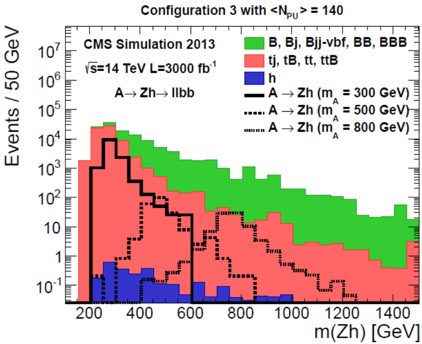
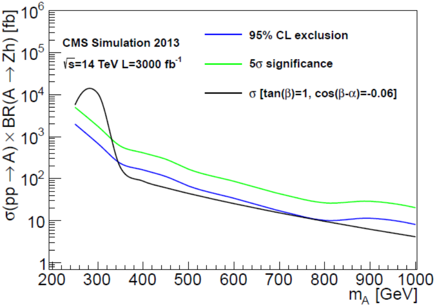


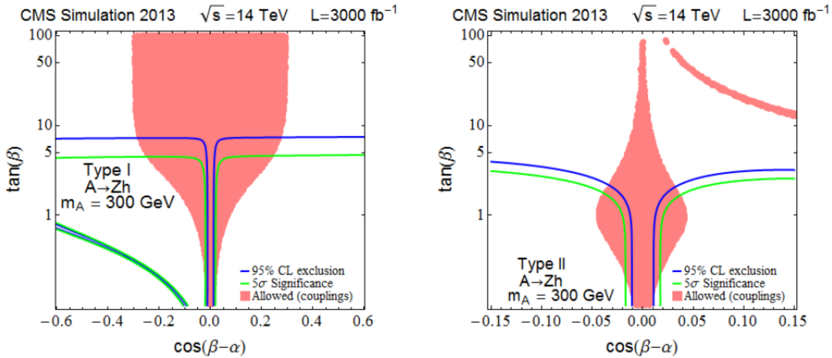


Source	Sel. events	Source	Sel. events
B, Bj, Bjj-vbf, BB, BBB	$5.8 \cdot 10^4$	$H \to Zh$ ($m_A = 300$GeV)	$1.2 \cdot 10^4$
tj, tt, tB, ttB	$6.6 \cdot 10^4$	$H \to Zh$ ($m_A = 500$GeV)	210
h	$< 1\%$	$H \to Zh$ ($m_A = 800$GeV)	85
Total Background	$1.2 \cdot 10^5$		

$A \to Zh \to llb\bar{b}$ (CMS)

CMS PAS FTR-13-024

- Limits on the 2HDM parameter space:



$A \to Zh \to llb\bar{b}$ (ATLAS)

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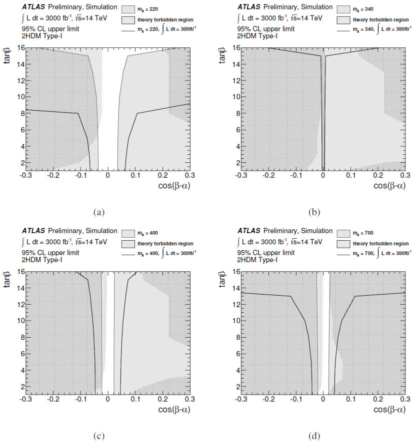

$A \to Zh \to llb\bar{b}$ (ATLAS)

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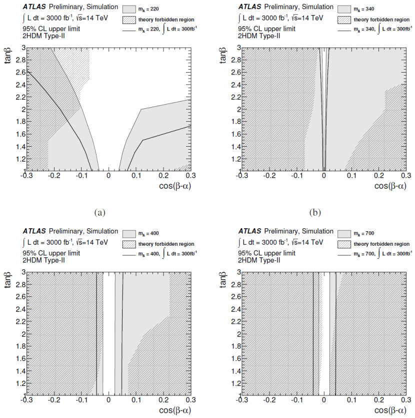

(a) (b) (c) (d)

$A \to Zh \to llb\bar{b}$ (ATLAS)

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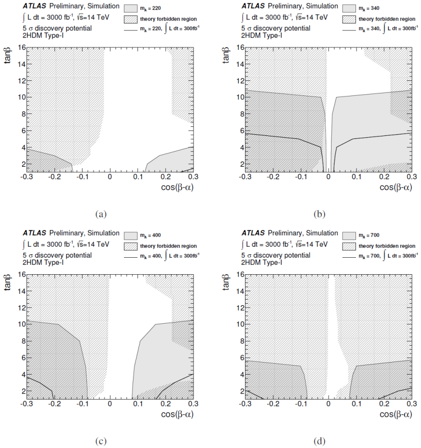

$A \to Zh \to llb\bar{b}$ (ATLAS)

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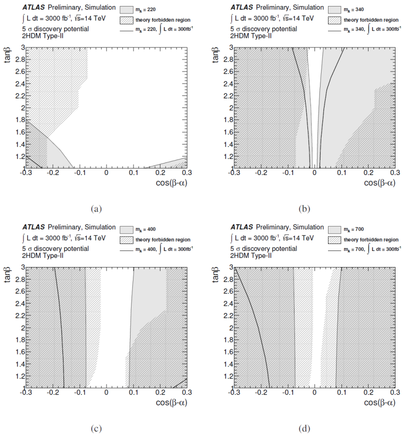
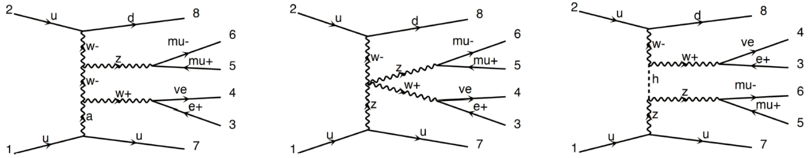


Vector-Boson-Scattering

CMS PAS FTR-13-006 and ATLAS-PHYS-PUB-2013-006

- Electroweak (EW) theory is non-abelian → self-interaction of gauge bosons
- Scattering of vector bosons: Triple and quartic boson couplings (TGC and QGC)



- Each of these processes violates unitarity at high energies
- In Standard Model (SM): Higgs maintain unitarity → probe SM nature of EWSB
- Scattering topology: Sensitive to new physics in EWSB sector (anomalous QGC)
- Addition to the scattering process → change the cross section

Vector-Boson-Scattering

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CMS PAS FTR-13-006 and ATLAS-PHYS-PUB-2013-006

- In *pp*-collisions: VBS in $pp \rightarrow VVjj$
- Experimental signature: two jets with large pseudorapidity difference plus leptons (from W and Z decays)
- SM Lagrangian: dimension-4 operators
- New physics: higher dimension operators in an effective field theory
- Multi-boson production: dimension-6 and dimension-8 operators (contain Higgs and/or gauge boson fields)
- New physics which is $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge invariant and CP-even operators

$ZZjj \rightarrow lllljj$ (ATLAS)

ATLAS-PHYS-PUP-2013-006

- Small cross section
- Final state: Fully reconstructible
- Operator (6-dimensional):

$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$$

where Λ: mass-dimensioned parameter

- Selection:
  - 4 Leptons with $p_T > 25\,\mathrm{GeV}$, two with opposite sign
  - 1 Lepton over detector threshold
  - 2 jets with $p_T > 50\,\mathrm{GeV}$
  - $m_{jj} > 1\,\mathrm{TeV}$

$ZZjj \to lllljj$ (ATLAS)

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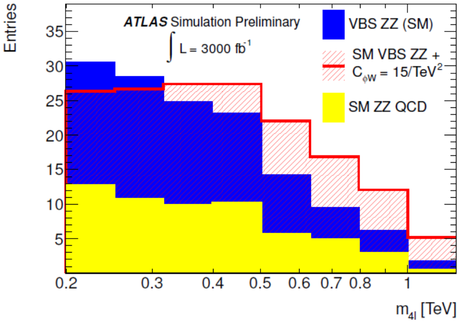

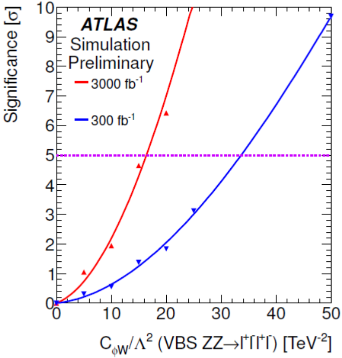

- 5σ discovery potential:

	300 fb^{-1}	3000 fb^{-1}
$c_{\phi W}/\Lambda^2$	34 TeV^{-2}	16 TeV^{-2}

$WZjj \to l\nu lljj$ (ATLAS)

ATLAS-PHYS-PUP-2013-006

- Larger cross section
- Final state: Reconstruction with neutrino p_z
- Operator (8-dimensional):

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

- Selection:
  - 3 Leptons with $p_T > 25$ GeV: opposite sign, same flavor pair + additional single lepton
  - 1 Lepton over detector threshold
  - 2 jets with $p_T > 50$ GeV
  - $m_{jj} > 1$ TeV

$WZjj \to l\nu lljj$ (ATLAS)

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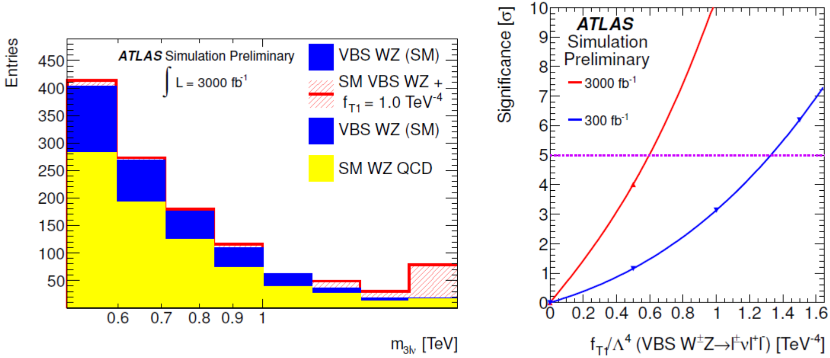

- 5σ discovery potential:

	300 fb^{-1}	3000 fb^{-1}
f_{T1}/Λ^4	1.3 TeV^{-4}	0.6 TeV^{-4}

$WZjj \rightarrow l\nu lljj$ (CMS)

CMS PAS FTR-13-006

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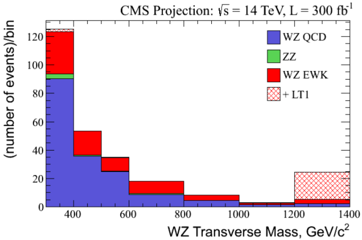
- Calculated cross sections [fb] (14 TeV pp-collision):

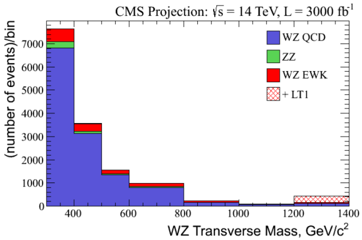
	WZ EWK	WZ QCD	ZZ	L_{T_1}
Total	7.7	210	16	3.1
Fiducial	0.69	0.96	0.038	0.57

- Selection:
  - 3 Electrons/muons with p_T >20 GeV and $|\eta| < 2.4$:
    same flavor pair and opposite charge
    one Z candidate with $m_{ll} > 20$ GeV
    no additional lepton with p_T >10 GeV
  - 2 jets with p_T >50 GeV and $|\eta| < 4.7$
    $\Delta\eta_{jj} > 4.0$
    m_{jj} >600 GeV
  - no overlap: $\Delta R(ll') > 0.04$ and $\Delta R(lj') > 0.4$

$WZjj \to l\nu lljj$ (CMS)

CMS PAS FTR-13-006





- Anomalous coupling signal for $f_{t_1}/\Lambda^4 = 1.0\,\text{TeV}^{-4}$
- Expected sensitivity to aGQC:

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

$W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$ (ATLAS)

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ATLAS-PHYS-PUP-2013-006

- Operator (8-dimensional):

$$\mathcal{L}_{T,0} = \frac{f_{S0}}{\Lambda^4} \left[(D_\mu \phi)^\dagger D_\nu \phi \right] \times \left[(D^\mu \phi)^\dagger D^n \nu \phi \right]$$

- Selection:
  - 2 Leptons with $p_T > 25$ GeV: same charge
  - 1 Lepton over detector threshold
  - 2 jets with $p_T > 50$ GeV
  - $m_{jj} > 1$ TeV

$W^{\pm}W^{\pm}jj \to l^{\pm}\nu l^{\pm}\nu jj$ (ATLAS)

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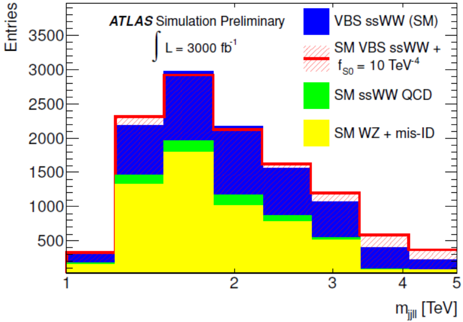

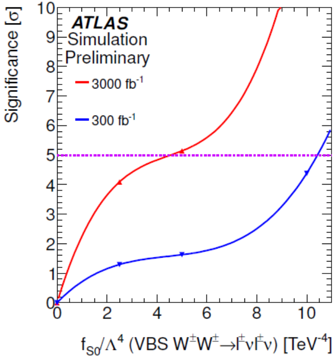

- 5σ discovery potential:

	300 fb^{-1}	3000 fb^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

$Z\gamma\gamma$ in dilepton + diphoton channel (ATLAS)

ATLAS-PHYS-PUP-2013-006

- Sensitive to BSM triboson contributions
- Operators (8-dimensional):

$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

- Selection:
  - Lepton and γ: $p_T >$25 GeV, $|\eta| < 2.0$
  - At least one lepton and γ: $p_T >$160 GeV
  - $|m_{ll} - 91\text{GeV}| < 10\text{GeV}$
  - $\Delta(\gamma,\gamma) > 0.4$; $\Delta(l,\gamma) > 0.4$; $\Delta(l,l) > 0.4$;

$Z\gamma\gamma$ in dilepton plus diphoton channel(ATLAS)

Technische Universität München

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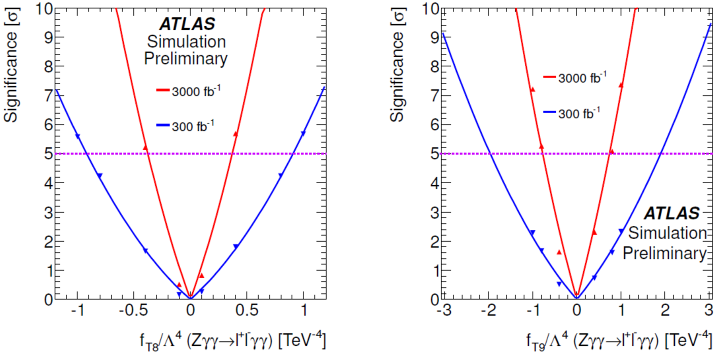

- 5σ discovery potential:

	300 fb^{-1}	3000 fb^{-1}
f_{T8}/Λ^4	0.9 TeV^{-4}	0.4 TeV^{-4}
f_{T9}/Λ^4	2.0 TeV^{-4}	0.7 TeV^{-4}