Beyond Standard Model Higgs physics: prospects for HL-LHC

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Outline

- Overview of High-Luminosity ATLAS and CMS detector upgrades
- Sensitivity to $VV \rightarrow VV$ scattering and anomalous Higgs couplings
  - $ZZjj \rightarrow lllljj$
  - $WZjj \rightarrow lll\nu jj$
  - same sign $WWjj \rightarrow l\nu l\nu jj$
- Two Higgs Doublet Model sensitivity
  - $H \rightarrow ZZ \rightarrow 4l$
  - $A \rightarrow hZ \rightarrow 2b2l$
  - $A \rightarrow \mu\mu$
- Sensitivity to flavour changing neutral current top decays to Higgs bosons
  - top $\rightarrow$ h + (u/c)
- Summary / Outlook

Phase II detector upgrades

Subsystem	ATLAS	CMS
Pixel	4 barrel layers, 6 discs/endcap 100…150µm thickness 25 x 150µm^2 size	4 barrel layers, 5 discs/endcap extend to |η|=4 thin (100µm) sensors, smaller (30x100µm^2)
Inner tracker	Full silicon, low material $\leqq 0.5X_0$ for $\|\eta\| \leqq 1.5$	Full silicon, low material $\leqq 0.6X_0$ for $\|\eta\| \leqq 1.5$
ECAL barrel	replace frontend electronics	
ECAL endcap	-	Shashlik (W or Pb absorber + scintillator) Silicon High Granularity Calorimeter
HCAL barrel	replace frontend electronics	-
HCAL endcap/forward	-	Use radiation hard scintillator, potentially increase transverse segmentation / HGC

Phase II detector upgrades

Subsystem	ATLAS	CMS
Muon systems	replace frontend electronics	Adding GEMs in first two stations in $\|\eta\|=1.6..2.4$, glass RPCs in last two stations, Considering muon tagging up to $\|\eta\|=4$
Hardware trigger	500 L0 / 200 kHz readout track trigger (500 kHz input)	Track trigger, crystal granularity for ECAL Barrel Up to 1 MHz readout track trigger (40 MHz input)
HLT output	10 kHz	

Vector Boson Scattering

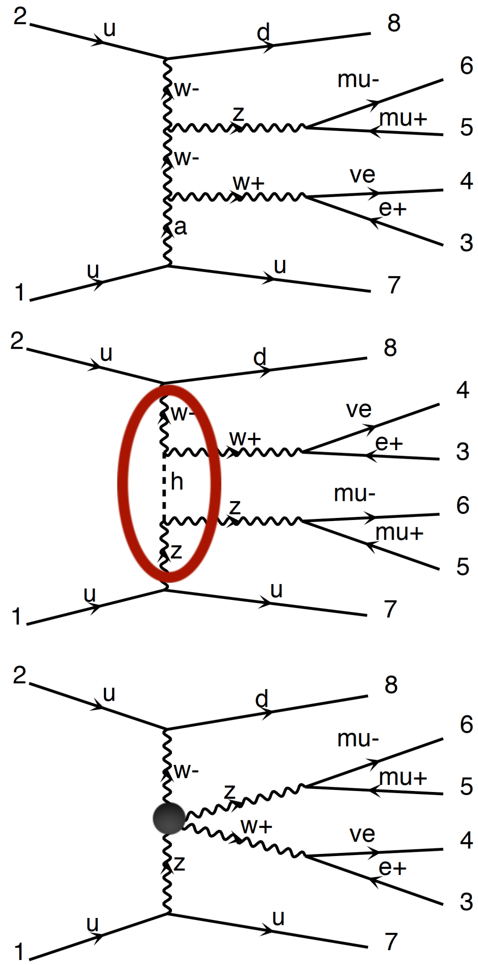
Vector Boson Scattering

- WW→WW scattering **violates unitarity** at high energies
- A **scalar**, such as the Higgs boson, fixes this (partially)
- Probing characteristics of VV scattering is an **important test** of the nature of **electroweak symmetry breaking**

- **Strong destructive interference** between the diagrams → new physics would modify the interference
  - Affect vector boson $\mathbf{p_T}$ and **di-boson mass** distribution

- Additional heavy bosons will affect **quartic** couplings at tree level (triple couplings only at loop level)

- Experimental signature: two jets with **large pseudorapidity difference** plus **leptons** (from W and Z decays)



Anomalous quartic couplings

dim 8 op with derivatives of Higgs and gauge boson field strengths

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

dim 8 op with only gauge boson field strengths

ATLAS, CMS lvlljj → $\mathcal{L}_{T,1}$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W} \ldots\right]$$ [hidden]
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

ATLAS Zγγ ($\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$)

dim 6 op with Higgs and gauge boson fields

ATLAS llllljj → $\mathcal{O}_{\Phi W}$

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi)G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud}d)$

dim 8 op with only derivatives of Higgs field

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

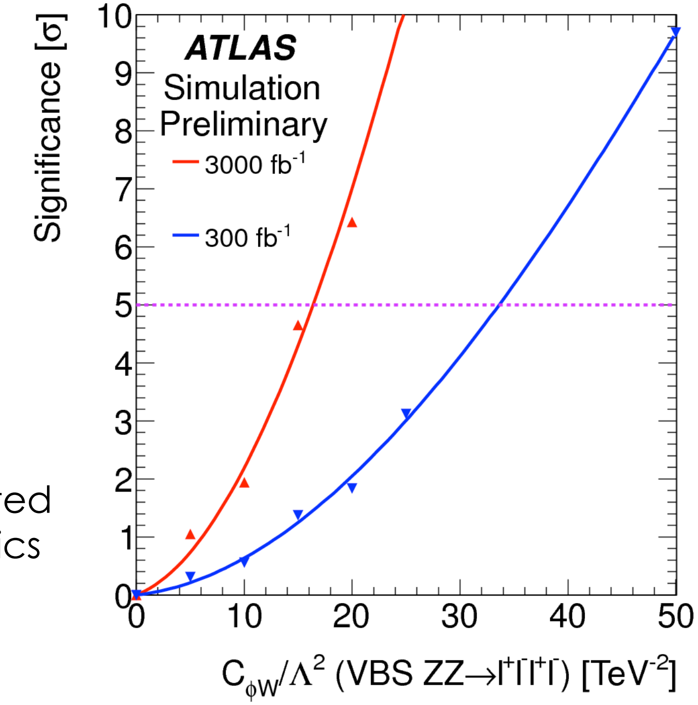
ATLAS (lvlvjj) → $\mathcal{L}_{S,0}$

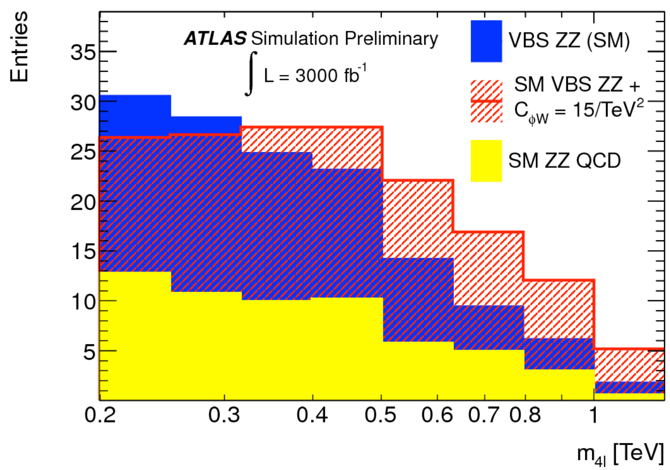
ATLAS ZZjj→lllljj

ATL-PHYS-PUB-2013-006

$$\mathcal{O}_{\Phi W} = (\Phi^\dagger \Phi) W^I_{\mu\nu} W^{I\mu\nu}$$

- small cross section × branching ratio but very pure
- Selection
  - leptons:
    - **= 4 leptons**, p_T > 25 GeV, one above the trigger threshold
    - **two** opposite sign, same flavour pairs (**Z candidates**)
  - jets:
    - **at least two jets** with p_T > 50 GeV
    - m(two highest p_T jets) > **1 TeV**





full kinematics
can be reconstructed
→ probe new physics
as function of $\sqrt{\hat{s}}$

5σ reach

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

CMS WZjj→lvlljj selection

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

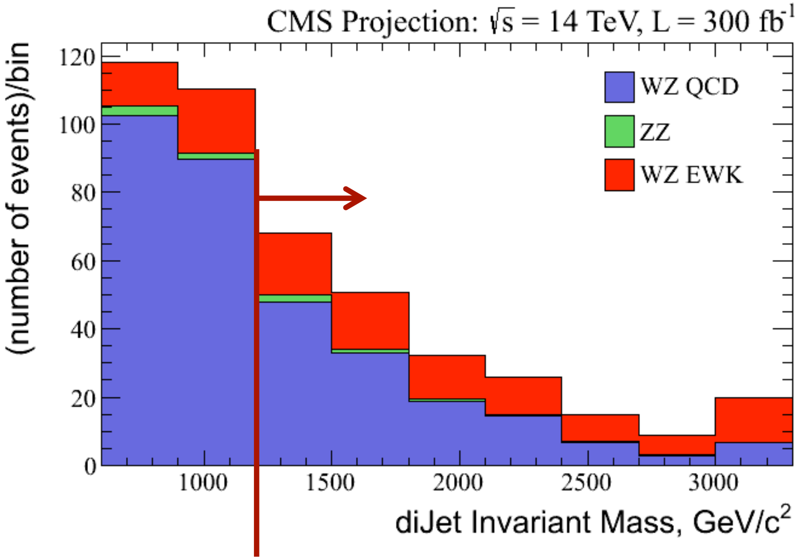
- Cross sections [fb]

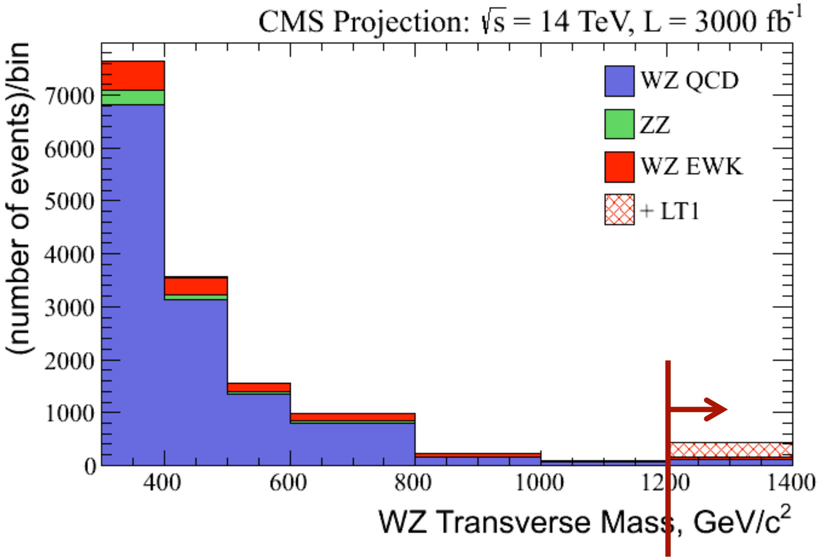
	WZ EWK	WZ QCD	ZZ	L_{T1}
Total	7.7	270	16	3.1
Fiducial	0.69	0.96	0.038	0.57

- Selection:
  - **3 electrons/muons** with p_T > 20 GeV, |η| < 2.4
    - two with same flavour, opposite charge (**Z candidate**)
    - at least one Z candidate with mass within 20 GeV of m_Z
    - all Z candidates must have mass **> 20 GeV**
    - **no additional leptons** with p_T > 10 GeV
    - **isolation**: scalar sum of p_T a in cone (ΔR = 0.4) < 20% of lepton p_T
  - **two jets** with **large pseudorapidity separation**
    - p_T > 50 GeV, |η| < 5.7
    - |Δη| > 4.0
    - m_{jj} > 600 GeV
  - **no overlap**: ΔR(between leptons) > 0.04, ΔR (jets, leptons) > 0.4
- Backgrounds:
  - QCD WZjj and electroweak WZjj production
- Systematic uncertainties:
  - Diboson background: ~10% normalization uncertainty

CMS-PAS-FTR-13-006

CMS WZjj→lνlljj sensitivity





Variable with highest Discrimination power of WZ scattering signal from other SM processes

Anomalous coupling signal for f_{T1} / λ^4 = 1.0 TeV^{-4}

not assuming extended |η| acceptance

Expected sensitivity to beyond Standard Model quartic coupling:

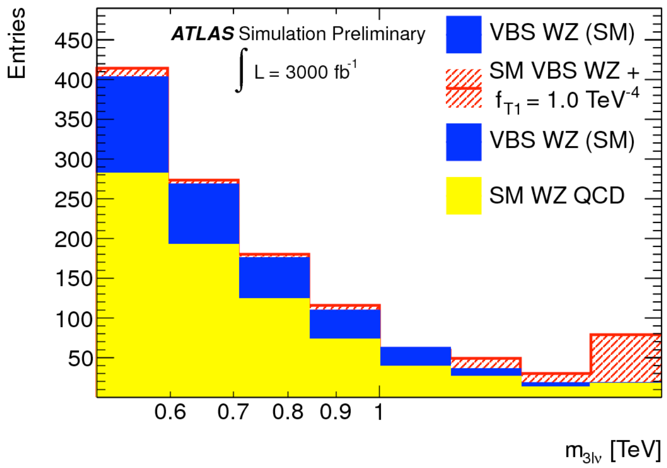
Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

ATLAS WZjj→lνlljj

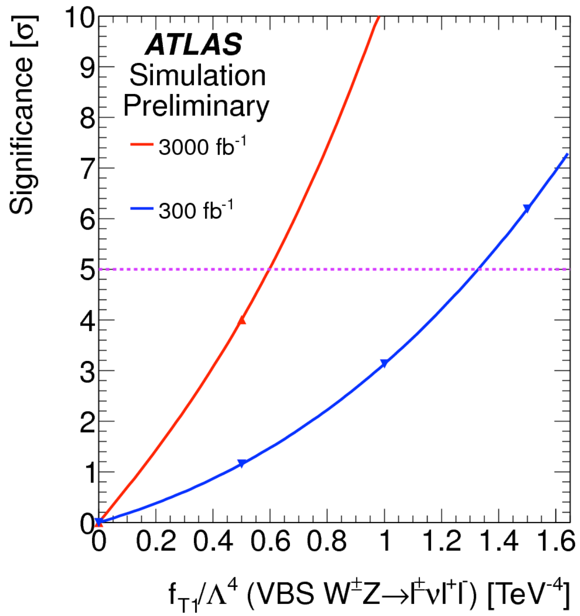
ATL-PHYS-PUB-2013-006

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

- larger cross section · BR, only one neutrino
- Selection:
  - leptons:
    - **= 3 identified leptons**, p_T > 25 GeV, one above trigger threshold
    - a **Z candidate**: one opposite sign, same flavour pair
    - use **W mass constraint**
  - jets:
    - **at least two jets** with p_T > 50 GeV
    - m(two highest p_T jets) > **1 TeV**



full kinematics
can be reconstructed
→ probe new physics
as function of √ŝ



5σ reach

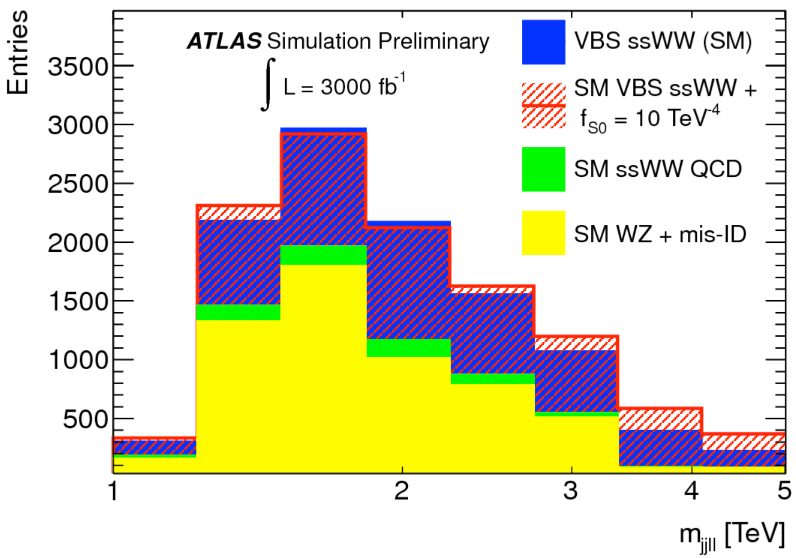
	$300\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
f_{T1}/Λ^4	$1.3\,\mathrm{TeV}^{-4}$	$0.6\,\mathrm{TeV}^{-4}$

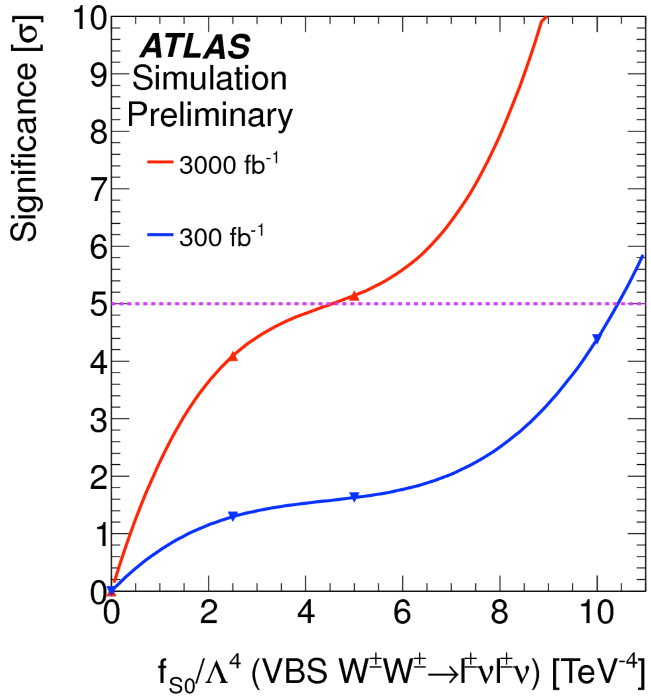
ATLAS $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$

ATL-PHYS-PUB-2013-006

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

- Selection:
  - leptons:
    - **= 2 identified leptons**, p_T > 25 GeV, one above trigger threshold
    - **same sign**
  - jets:
    - **at least two jets** with p_T > 50 GeV
    - m(two highest p_T jets) > **1 TeV**





5σ reach

model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

Two Higgs Doublet Models

Two Higgs Doublet Models

- Motivation: Supersymmetry, Axion models, Baryon/Anti-baryon asymmetry
- Five physical Higgs bosons: **h, H, A, $H^{\pm}$**
- Parameters if no CP violation at tree level:
  - 4 masses $\mathbf{m_h, m_H, m_A, m_{H\pm}}$
  - **tan β**, mixing angle **α**(mixing between CP even bosons h and H)
  - Three scalar couplings: $\boldsymbol{\lambda_5, \lambda_6, \lambda_7}$ (zero in the MSSM)
- Distinguish the following 2HDM classes:

Type	description	Doublet Φ_1	Doublet Φ_2
I	Fermiophobic		u d ℓ
II	MSSM like	d ℓ	u
	Lepton-specific	ℓ	u d
	flipped	d	u ℓ
III	FCNC	u d ℓ	u d ℓ

Alignment limit (h ~ SM)

Second Higgs Doublet Decay Topology	Alignment Limit
$H \to WW, ZZ$	–
$H, A \to \gamma\gamma$	✓
$H, A \to \tau\tau, \mu\mu$	✓
$H, A \to tt$	✓
$A \to Zh$	–
$H \to hh$	–
$t \to H^{\pm}b$	✓

arXiv:1305.2424

CMS 2HDM pp→H→ZZ→4l

- **Lepton selection**:
  - $p_T(e) > 10$ GeV / $p_T(\mu) > 5$ GeV
  - within **tracker acceptance**: $|\eta| < 2.5$
  - **isolation**: Scalar p_T sum (all objects) in cone $\Delta R = 0.3 < 10\%$ of lepton p_T
  - per event average energy density **ρ subtracted**
  - Ensure **trigger efficiency**: p_T(lead) > 30 GeV or p_T(lead) > 20 GeV and p_T(sublead) > 10 GeV

- **Z candidates**:
  - Require same flavour, opposite sign lepton pairs
  - $60 < m_{ll} < 100$ GeV/c
  - Require **exactly two Z** candidates
  - At least one **on-shell Z** with $80 < m_{ll} < 100$ GeV
- $m_{ZZ} > 150$ GeV

- Assume **20% background** normalization uncertainty

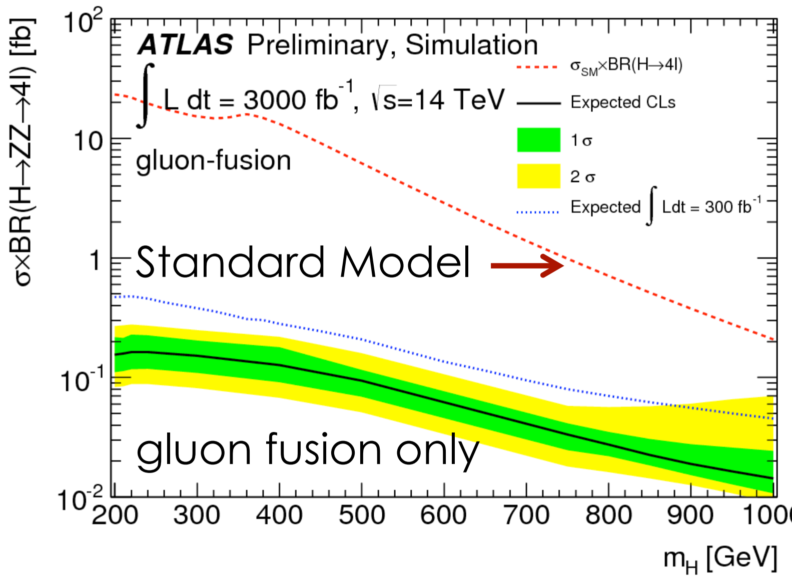
Source	Selected Events
B, Bj, Bjj-vbf, BB, BBB	6.4×10^4
tj, tt, tB, ttB	$< 1\%$
h (m_h=125 GeV)	$< 1\%$
Total Background	6.4×10^4
$H \to ZZ$ ($m_H = 300$ GeV)	6.9×10^3
$H \to ZZ$ ($m_H = 500$ GeV)	170
$H \to ZZ$ ($m_H = 800$ GeV)	35

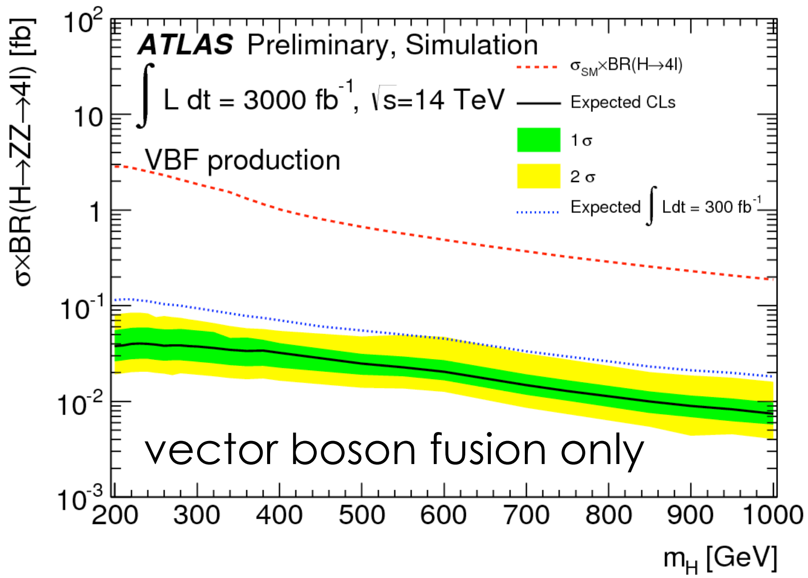
Expected events for 3000 fb^{-1}

pp→H→4l expected sensitivity

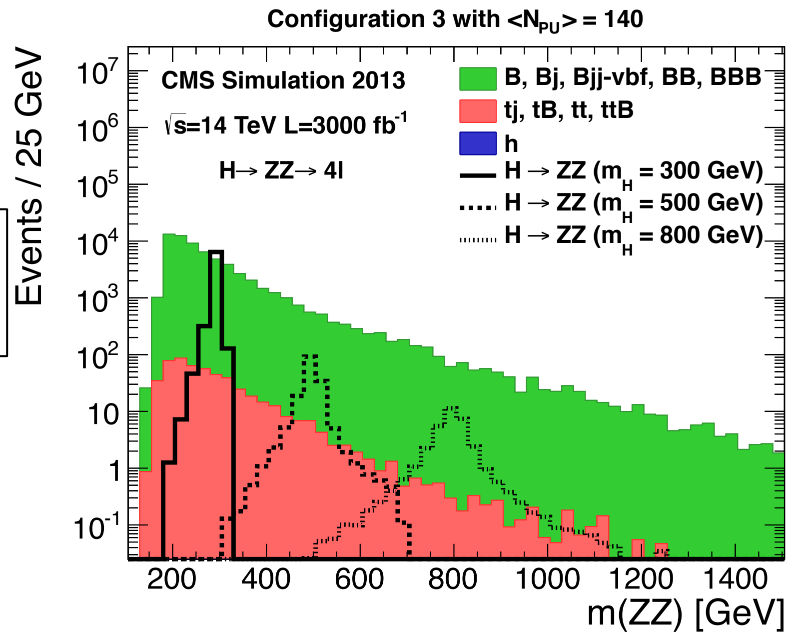
ATL-PHYS-PUB-2013-016
CMS PAS FTR-13-024

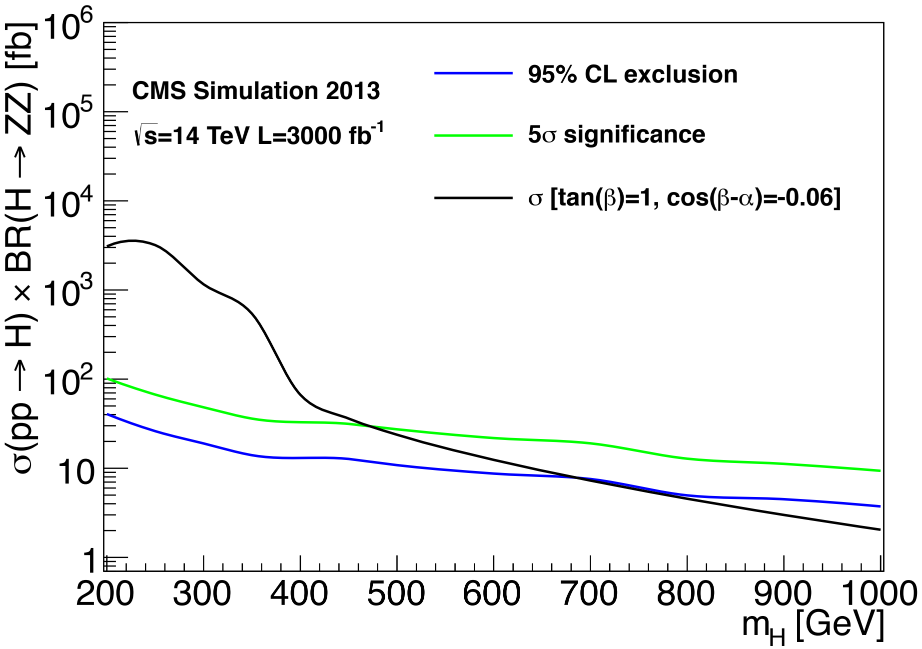
ATLAS





CMS



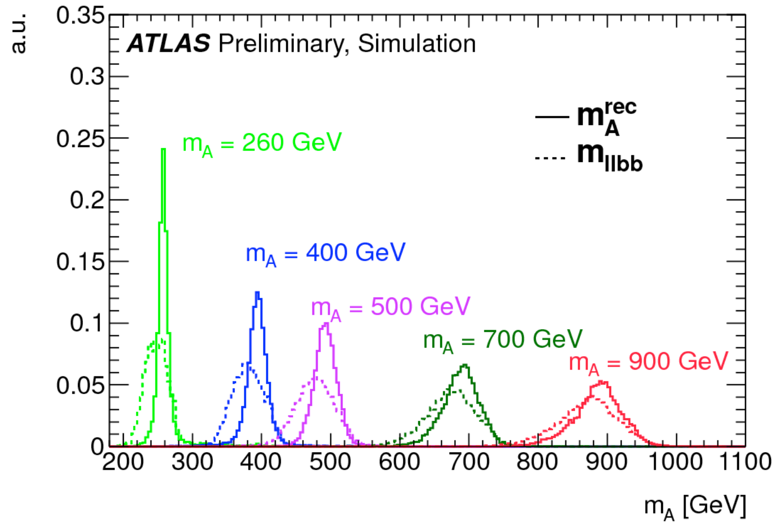


ATLAS pp→A→hZ→2l2b selection

- Leptons:
  - Electrons: E_T > 25 GeV, |η| < 2.47 excluding transition region
  - Muons: p_T > 25 GeV, |η| < 2.5
  - **at least two** with same-flavour, opposite sign
  - **M_{ll} = 80 ... 110 GeV**,
- Jets: |η| < 2.5, p_T > 41 GeV (|η|<2.1),
  > 77 GeV (|η|=2.1 … 2.5)
  - **at least two** b-jets
  - B-identification **efficiency: 70%**
  - m_{bb} = 90 ... 140 GeV
- ΔR between jets: m_A dependent (1.4 ... 1.8)
- **mass reconstruction**:

$$m_A^{\rm rec} \equiv m_{llbb} - m_{ll} - m_{bb} + m_Z^0 + m_h^0,$$

Sample	m_A = 360 GeV	m_A = 700 GeV
$A \to Zh \to llbb$	2.7×10^2	5.4×10^2
$t\bar{t}$	1.4×10^5	2.2×10^3
Zbb	8.0×10^4	2.9×10^3
Z+jets	1.3×10^4	4.9×10^2
ZZ	3.0×10^3	3.1×10^2



CMS pp→A→hZ→2l2b selection

- **Lepton selection** like for pp→H→ZZ→4l
  - Z→ll candidate selection like for pp→H→ZZ (but m_{ll} = 60 … 100 GeV)
- **b jets**:
  - p_T > 20 GeV, |η| < 2.5
  - Tight working point
    - **~ 70% efficiency** for |eta|<1.2 / 60% for |eta|≧1.2
    - Light jet **mistag rate ~ 0.01%**
  - m_{bb} = 90 … 150 GeV
- Require exactly one Z candidate and one h candidate
- **m_{hZ} > 150 GeV**
- |Δφ(leptons)|< 1.9 rad
- $p_T(Z)$ > 40 GeV
- **$p_T(Z)/p_T(h)$ = 0.4..2.75**

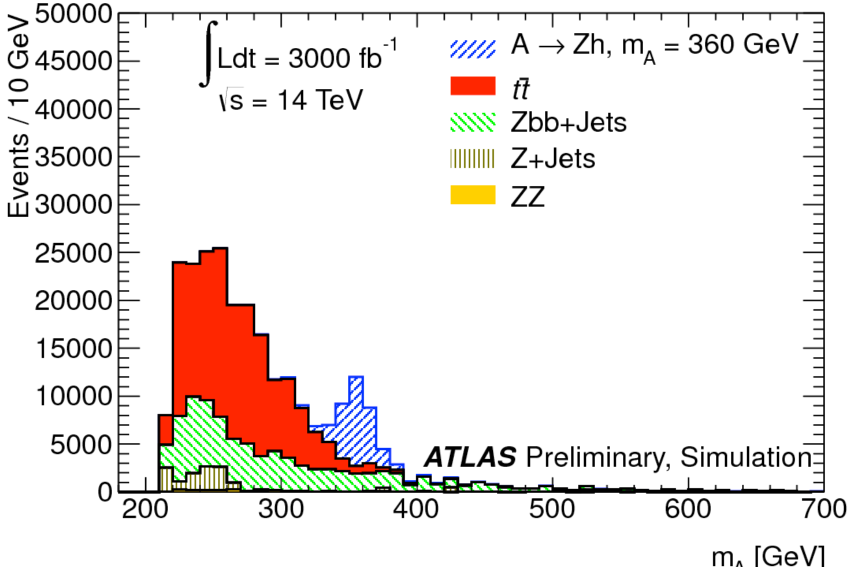
- Assume 20% background normalization uncertainty

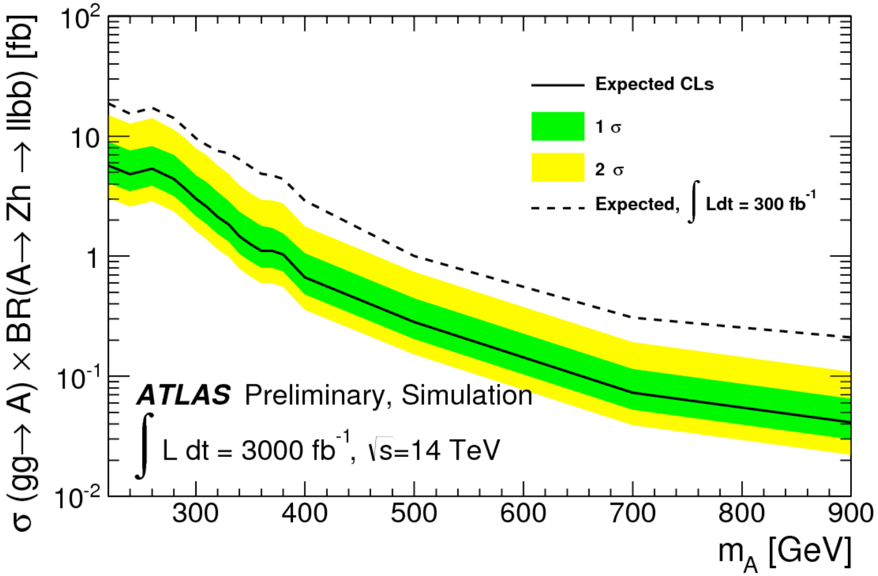
Source	Selected Events
B, Bj, Bjj-vbf, BB, BBB	5.8×10^4
tj, tt, tB, ttB	6.6×10^4
h (m_h=125 GeV)	$< 1\%$
Total Background	1.2×10^5
$\mathcal{A} \to Zh$ ($m_{\mathcal{A}}$ = 300 GeV)	1.3×10^4
$\mathcal{A} \to Zh$ ($m_{\mathcal{A}}$ = 500 GeV)	210
$\mathcal{A} \to Zh$ ($m_{\mathcal{A}}$ = 800 GeV)	85

Expected events for 3000 fb^{-1}

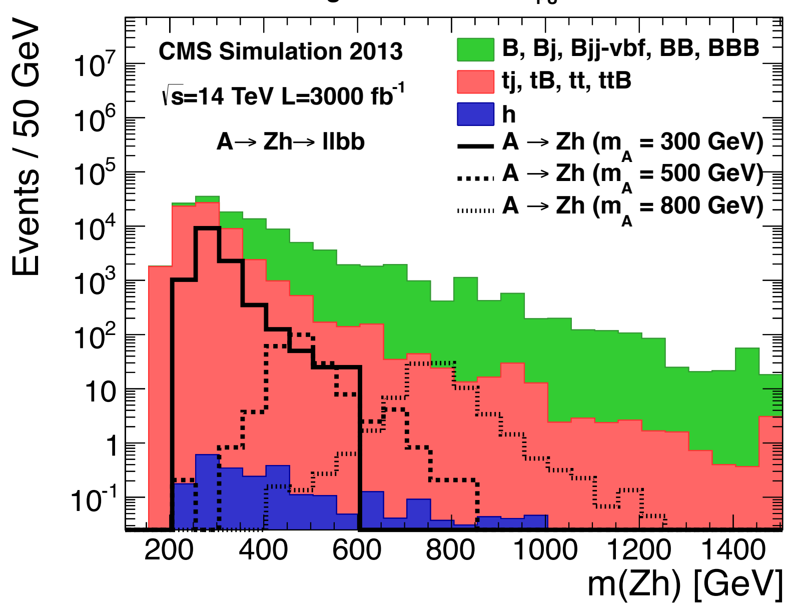
pp→A→Zh→2l2b expected sensitivity

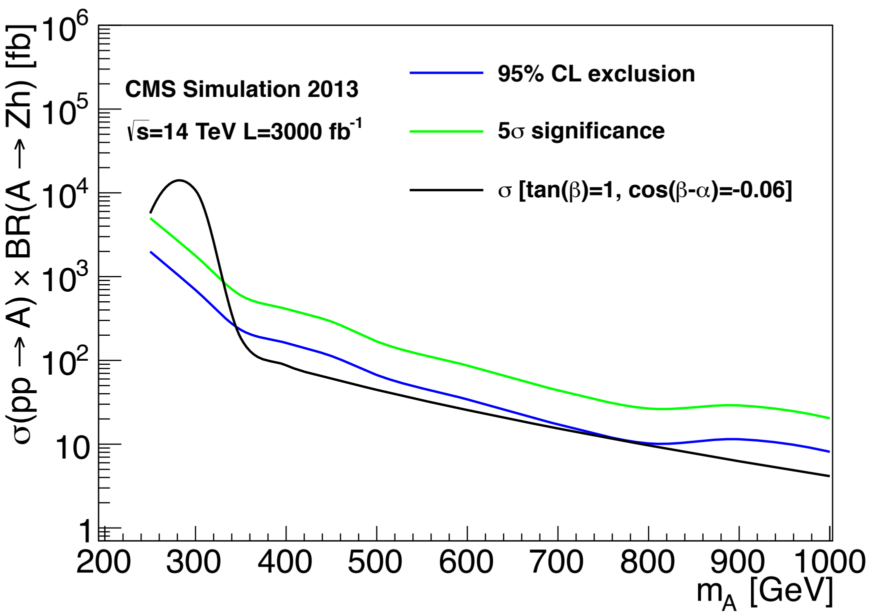
ATLAS





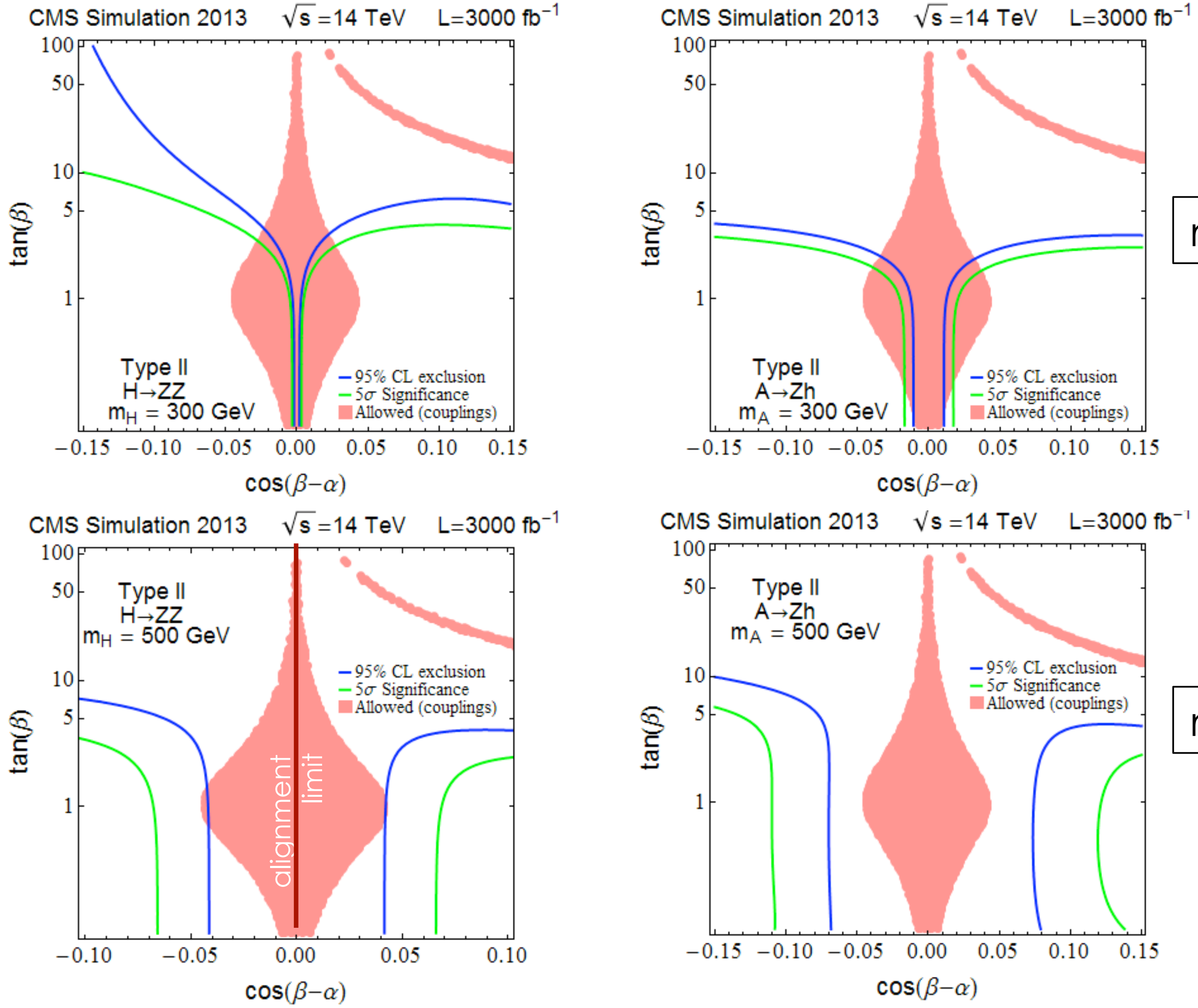
CMS





CMS PAS FTR-13-024

CMS Type II 2HDM expected sensitivity



$m_{A/H}$ = 300 GeV

Type I 2HDM

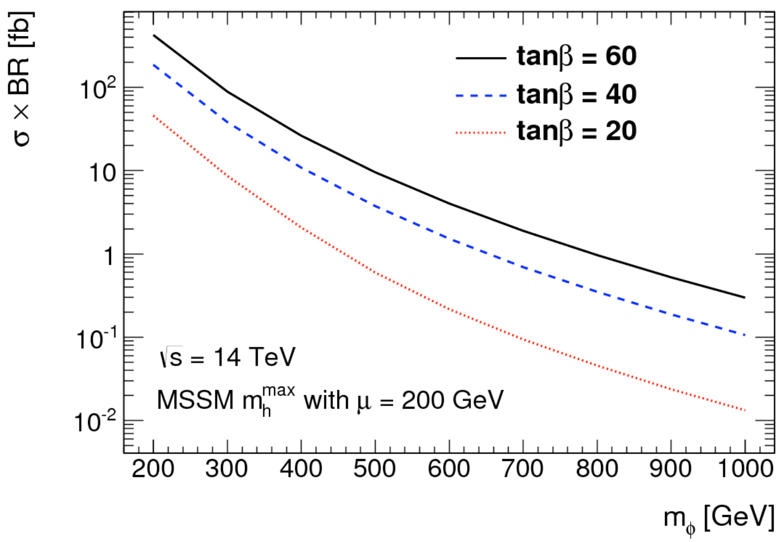
$m_{A/H}$ = 500 GeV

H→ZZ→4l

A→Zh→2l2b

H/A→μ⁺μ⁻

- Relevant in the **high tan β region**: complementary to A → Zh search
- High mass resolution
- **Gluon fusion** and **b associated production**
- Main backgrounds: Z/γ* → μ⁺μ⁻, top pairs
- Selection:
  - **= 2 muons** with opposite charge
  - **Two categories** (to separate production mechanisms):
    - no b-tagged jet
    - ≧1 b-tagged jet

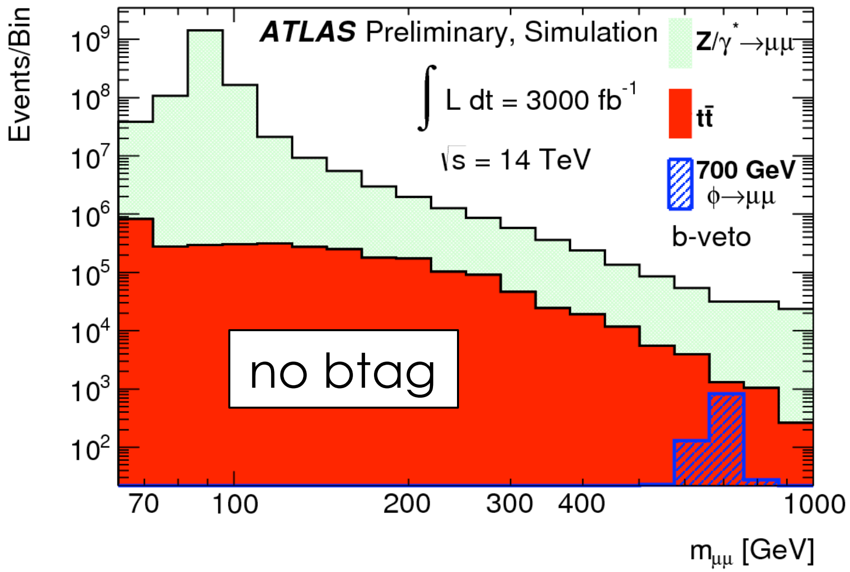


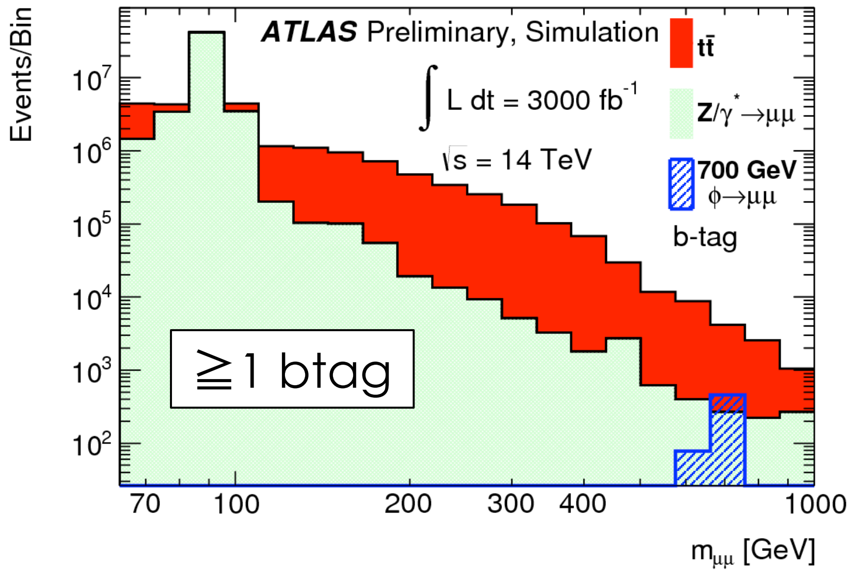
tan β=40

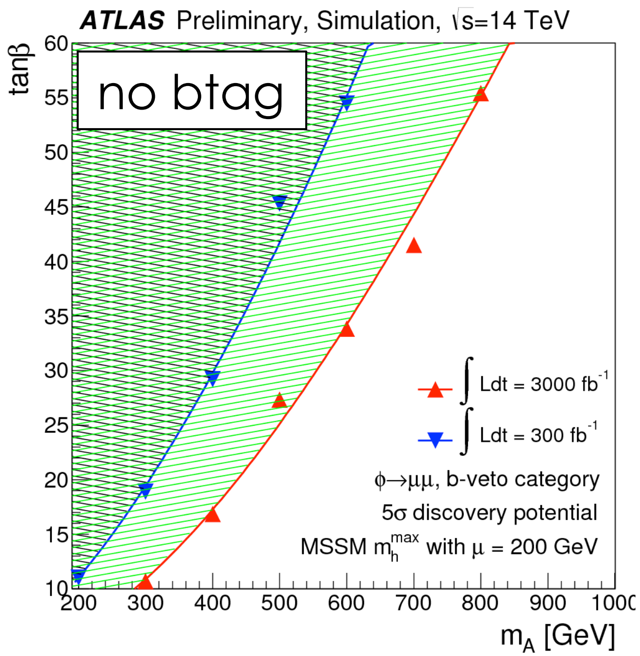
Sample	two muons with opposite charge	*b*-veto category	*b*-tag category
m_ϕ =700 GeV $gg\phi$	54	52	2.0
m_ϕ =700 GeV $bb\phi$	1.6×10^3	1.0×10^3	5.9×10^2
Z/γ^*+jets	1.8×10^9	1.7×10^9	4.3×10^7
Z/γ^*+bb	3.2×10^7	2.6×10^7	6.5×10^6
$t\bar{t}$	1.2×10^7	2.8×10^6	9.3×10^6

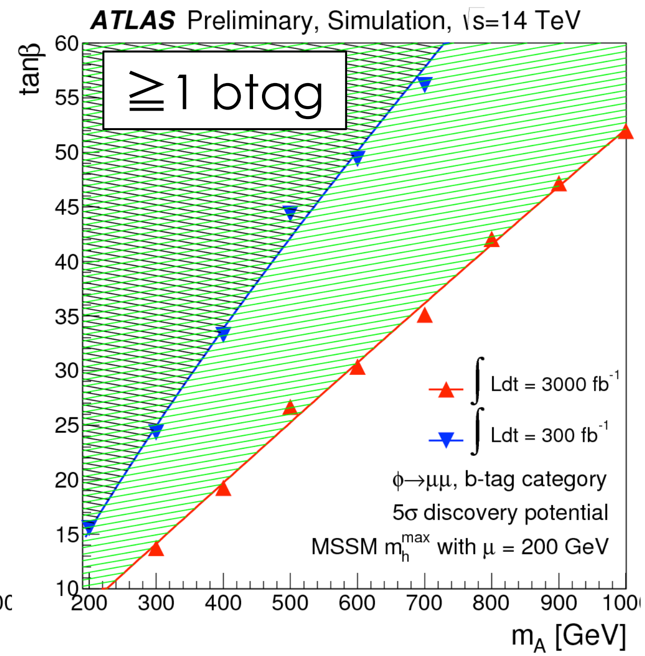
number of expected events for 3000 fb^{-1}

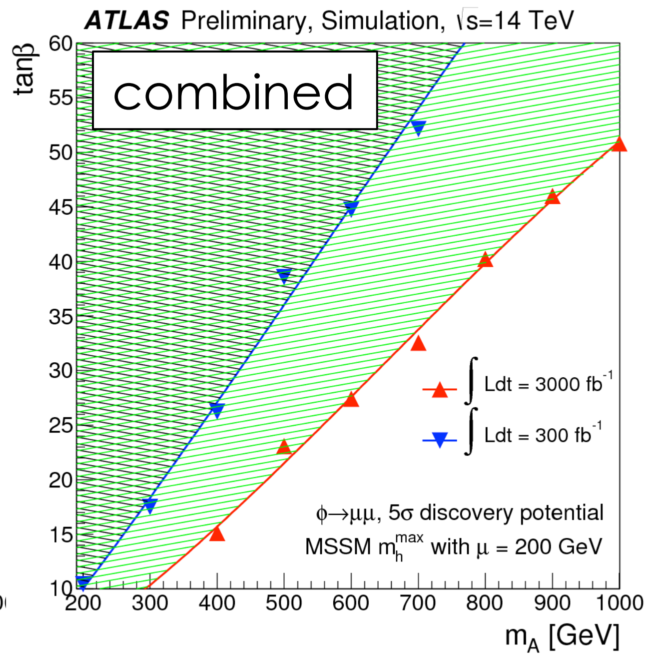
ATLAS H/A→$\mu^+\mu^-$ expected sensitivity











FCNC top decays to Higgs

ATLAS FCNC t→hc, h→γγ

- **top pair** events, one decaying to Wb, the other to γγ + charm
- similar to t→Zc searches
- **small branching ratio** for h→γγ but **very clean signature**
- current limit: BR(t→h + u/c) < 0.56%) @ 95% CL

- expected sensitivity for HL-LHC by **scaling published analysis**
- event selection
  - require **two photons**
  - consistency with **top pair decay**
  - requirement on **diphoton mass**, background from sidebands
- two topologies, depending on the other top (W) decay:
  - t_2→Wb→lν + b-jet
  - t_2→Wb→2 jets + b-jet

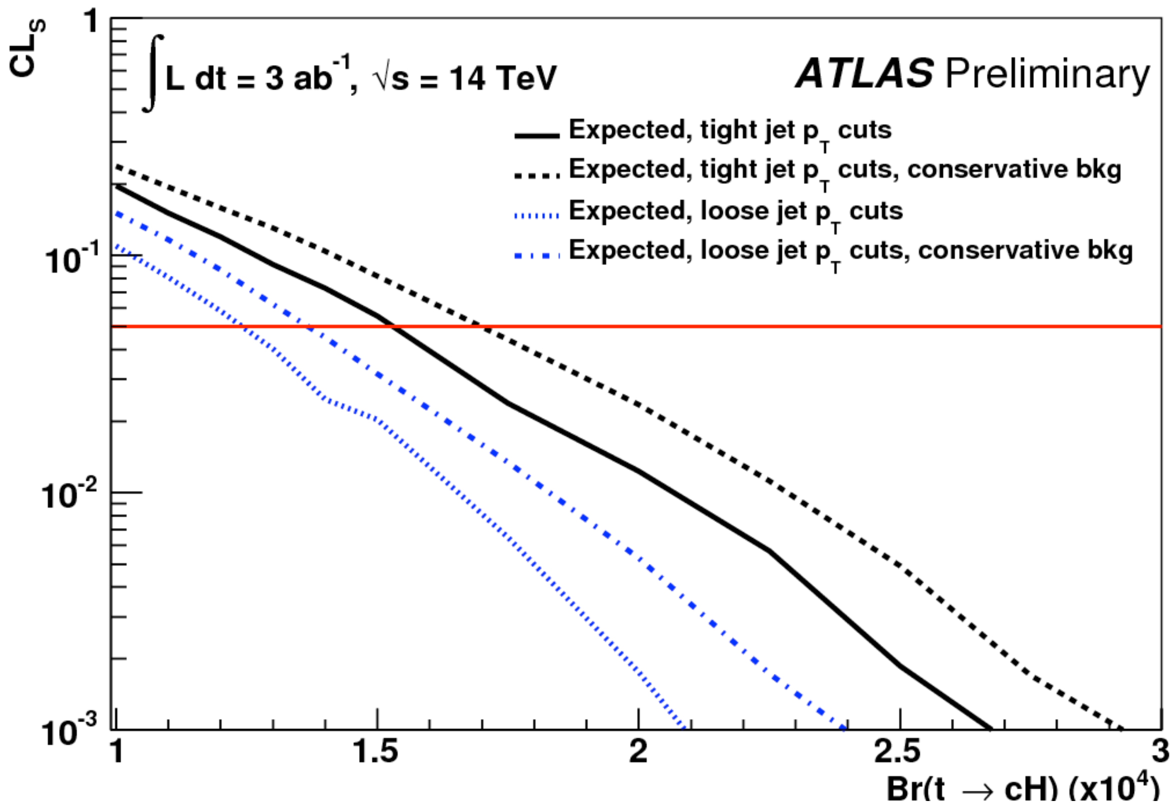
Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

upper limits on branching ratios in various BSM scenarios

ATLAS FCNC t→hc, h→γγ

expected signal for BR(t→hq)=0.01% for 3000 fb^{-1}

		Expected FCNC signal	SM sources	Background
std cuts	Hadronic events	34	61	1750
	Leptonic events	11	21	37
tight cuts	Hadronic events	13	24	350
	Leptonic events	7	14	25



expeceted upper limit on BR(t→hq) **1.5 · 10^{-4}** @ 95% CL

Summary / Outlook

- Prospects for High-Luminosity LHC (Phase II upgrade) for beyond the Standard Model Higgs physics:
  - sensitivity to anomalous VV scattering
  - sensitivity to 2HDM models
  - FCNC top decays to Higgs

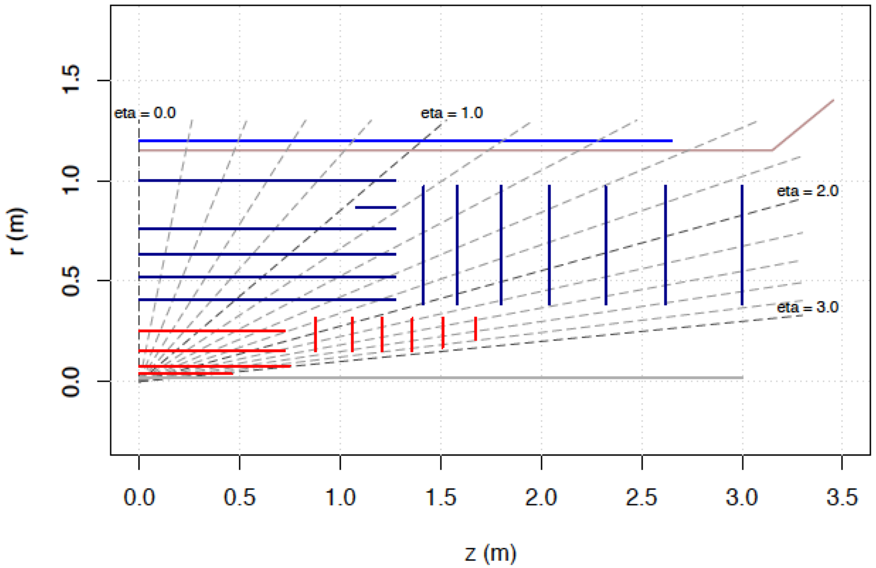
- LHC Phase II (High Luminosity LHC) documents:
  - ATLAS Letter of Intent published December 2012
  - CMS Phase II upgrade Technical Proposal expected to come out soon

- Studies to be repeated with **full detector simulation**
  - After optimizing event reconstruction and isolation criteria for average pileup of 140

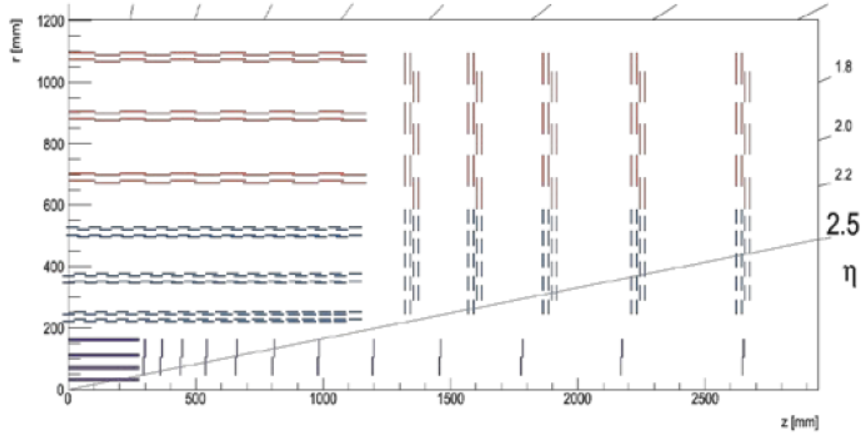
- **More** physics **channels** to be added
  - in particular Higgs self coupling channels $bb\tau\tau$ and $bb\gamma\gamma$

BACKUP

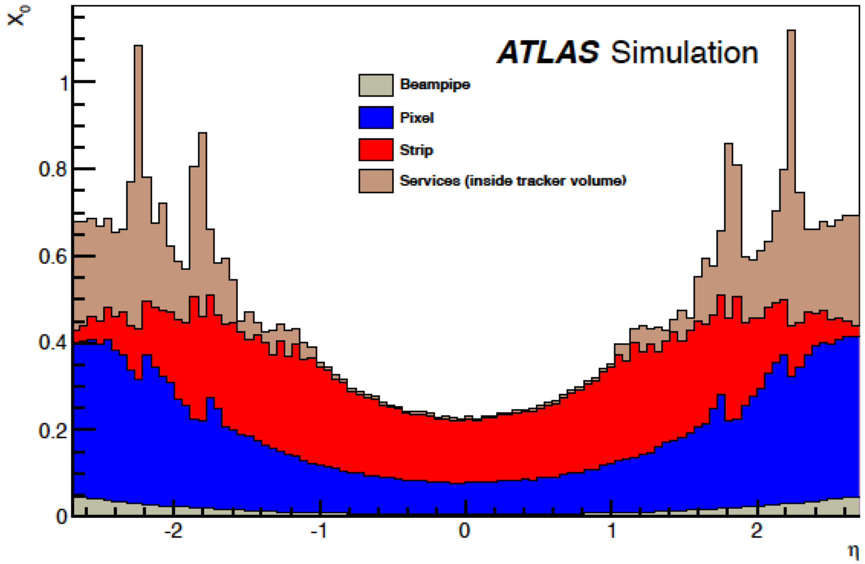
Phase II inner tracker upgrades



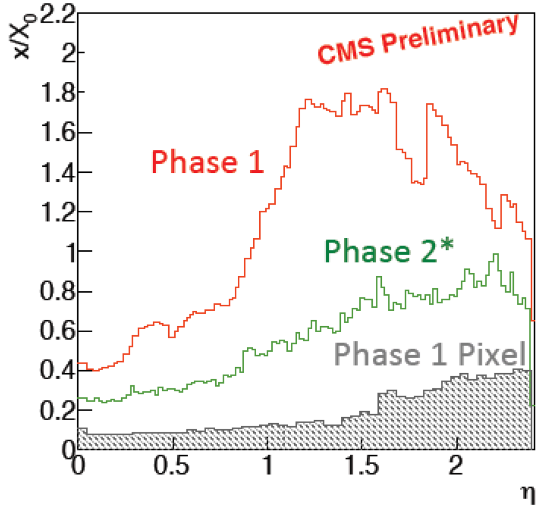
ATLAS baseline



CMS



Radiation length in tracker



CMS same sign WW at 8 TeV

Table 3: Observed and expected upper and lower limits at 95% CL on the nine dimension 8 operators that affect quartic couplings between the weak gauge bosons. Some operators for anomalous quartic gauge boson couplings may lead to tree-level unitarity violation. We report the values of the operator coefficient for which unitarity is restored at the scale of the 8 TeV, the unitarity limit. The units are TeV^{-4}.

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

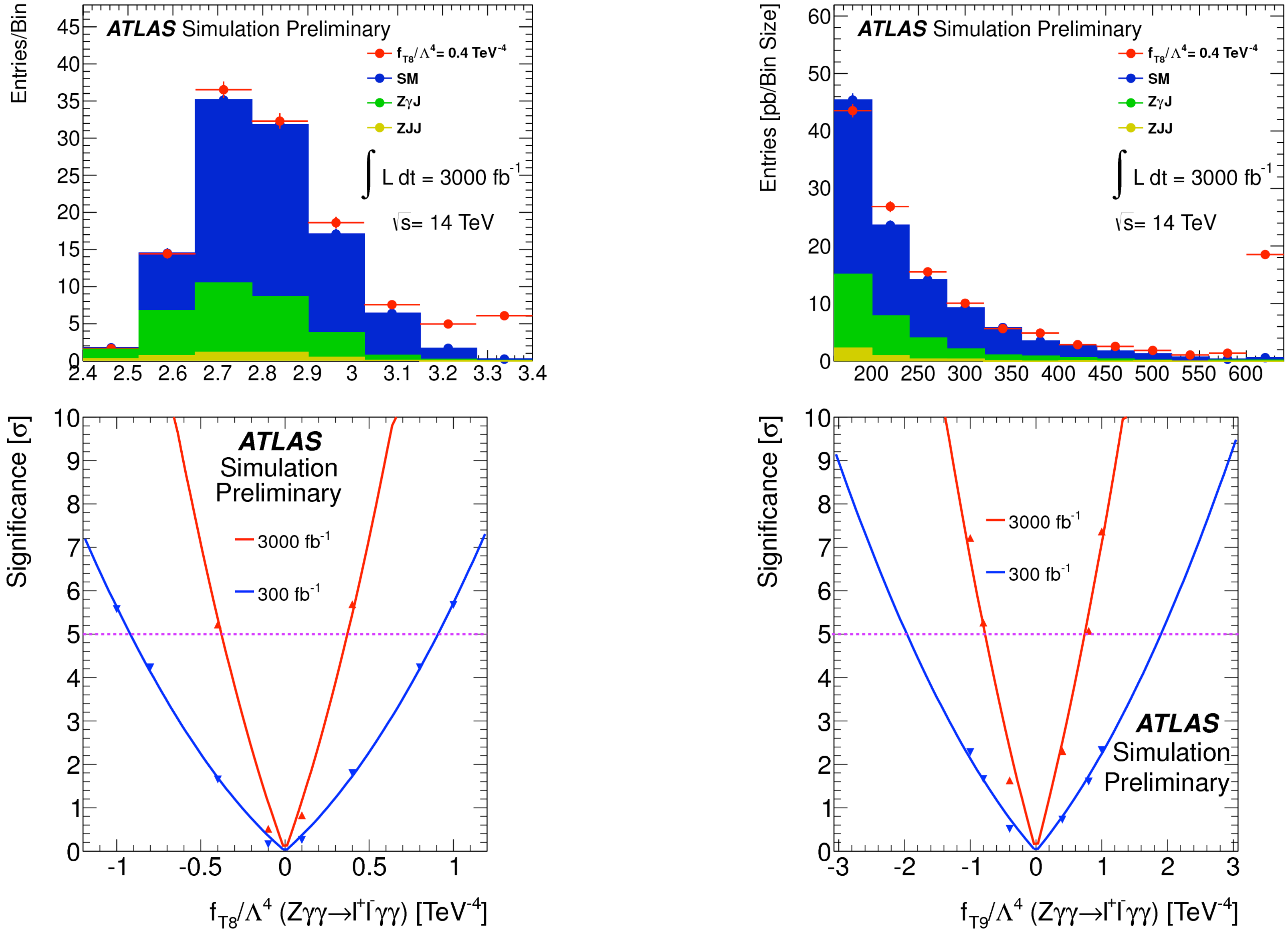
ATLAS Zγγ→llγγ

- sensitive to f_{T8} and f_{T9}
- Selection:
  - photons and leptons:
    - 2 identified leptons, $p_T > 25$ GeV, $|\eta| < 2.0$, one with $p_T > 160$ GeV
    - 2 identified photons, $p_T > 25$ GeV, $|\eta| < 2.0$, one with $p_T > 160$ GeV
    - $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(l,\gamma) > 0.4$, $\Delta R(l,l) > 0.4$

5σ reach

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

ATLAS Zγγ→llγγ



5σ reach

ATLAS Vector Boson Scattering searches

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Table 5: 5σ-significance discovery values and 95% CL limits for coefficients of higher-dimension operators. Λ_{UV} is the unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1} of integrated luminosity.

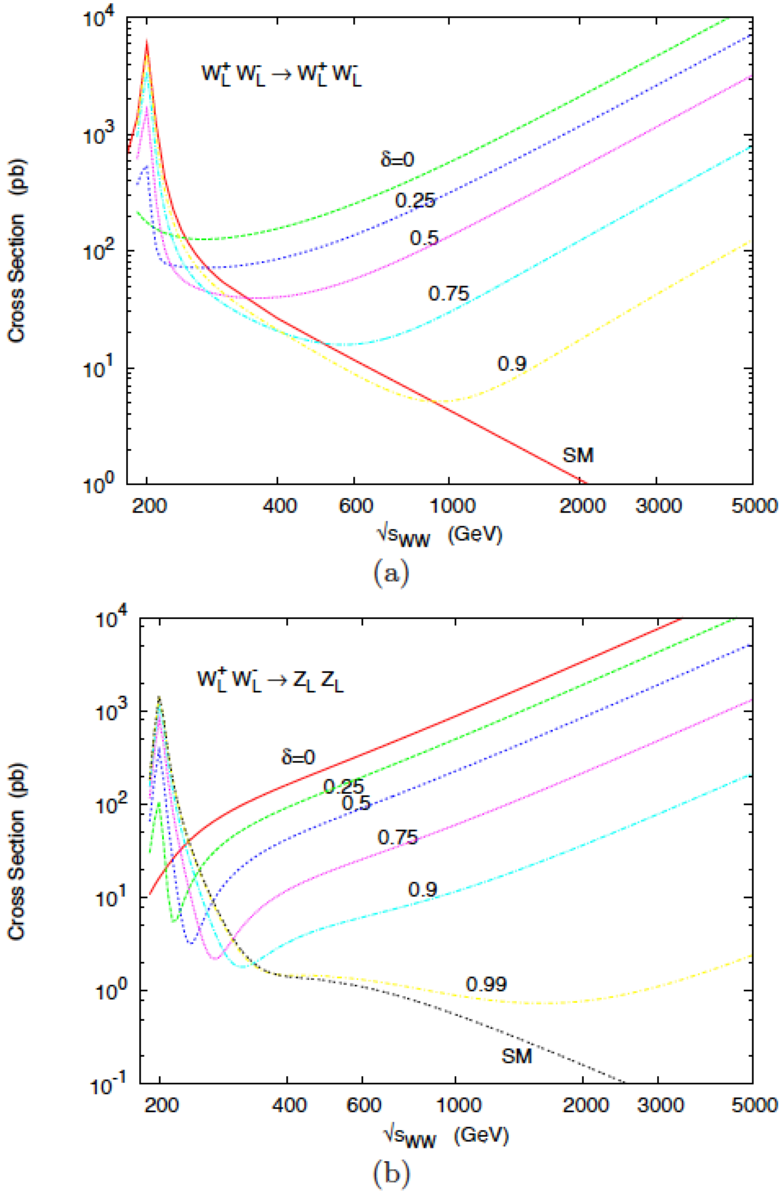


FIG. 1: Scattering cross sections for (a) $W_L^+ W_L^- \to W_L^+ W_L^-$ and (b) $W_L^+ W_L^- \to Z_L Z_L$ versus $\sqrt{s_{WW}}$. Various values of δ are shown, where δ denotes the size of the Higgs amplitude relative to the SM one. An angular cut of $|\cos\theta_{WW}| < 0.8$ is applied and the light Higgs boson mass $m_h = 200$ GeV is assumed.

arXiv:0803.2661

Anomalous quartic couplings containing just derivatives of the Higgs field

ATLAS (lvlvjj) →

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

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

Anomalous quartic couplings involving derivatives of the Higgs field and the boson field strengths

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

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

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

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

Anomalous quartic couplings operator only involving field strength

See also hep-ph/0606118

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

ATLAS, CMS lvlljj →

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

ATLAS Zγγ →

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

ATLAS Zγγ →

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

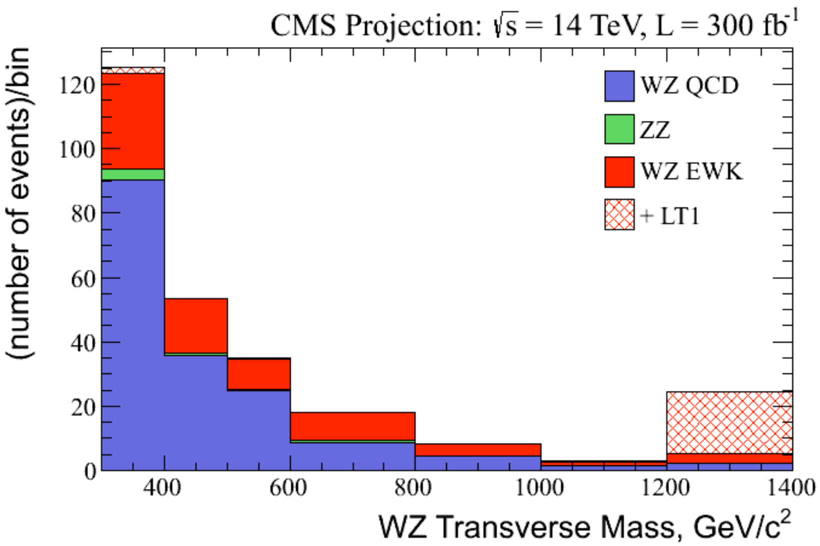
Anomalous Higgs couplings

Handbook of LHC Higgs cross sections, part 3 (arXiv:1307.1347)

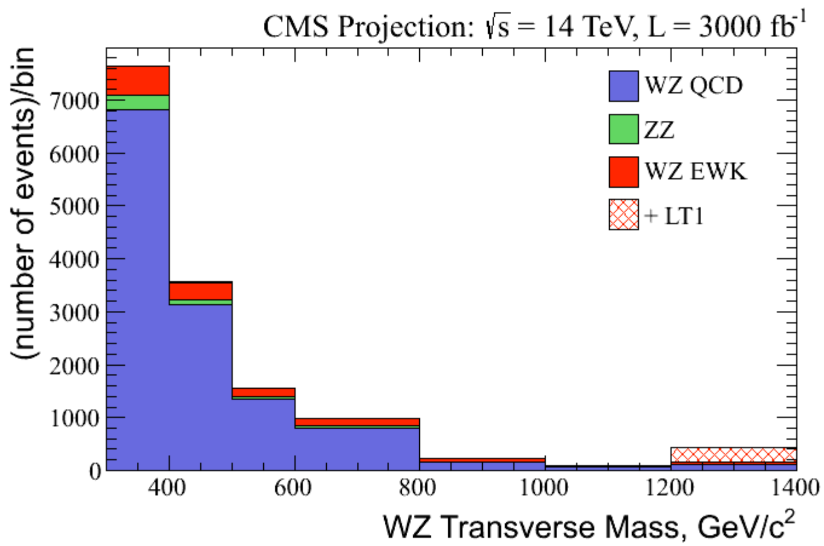
Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2 X\Phi$ operators and for $\mathcal{O}_{\Phi\mathrm{ud}}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\tilde{\Phi})$	$\mathcal{O}_{\tilde{G}} = f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\tilde{W}} = \varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\tilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\tilde{G}} = (\Phi^\dagger\Phi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
ATLAS llllj → $\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\tilde{W}} = (\Phi^\dagger\Phi) \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\tilde{\Phi}) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\tilde{B}} = (\Phi^\dagger\Phi) \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\tilde{W}B} = (\Phi^\dagger\tau^I\Phi) \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\tilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

CMS results



300 fb^{-1}

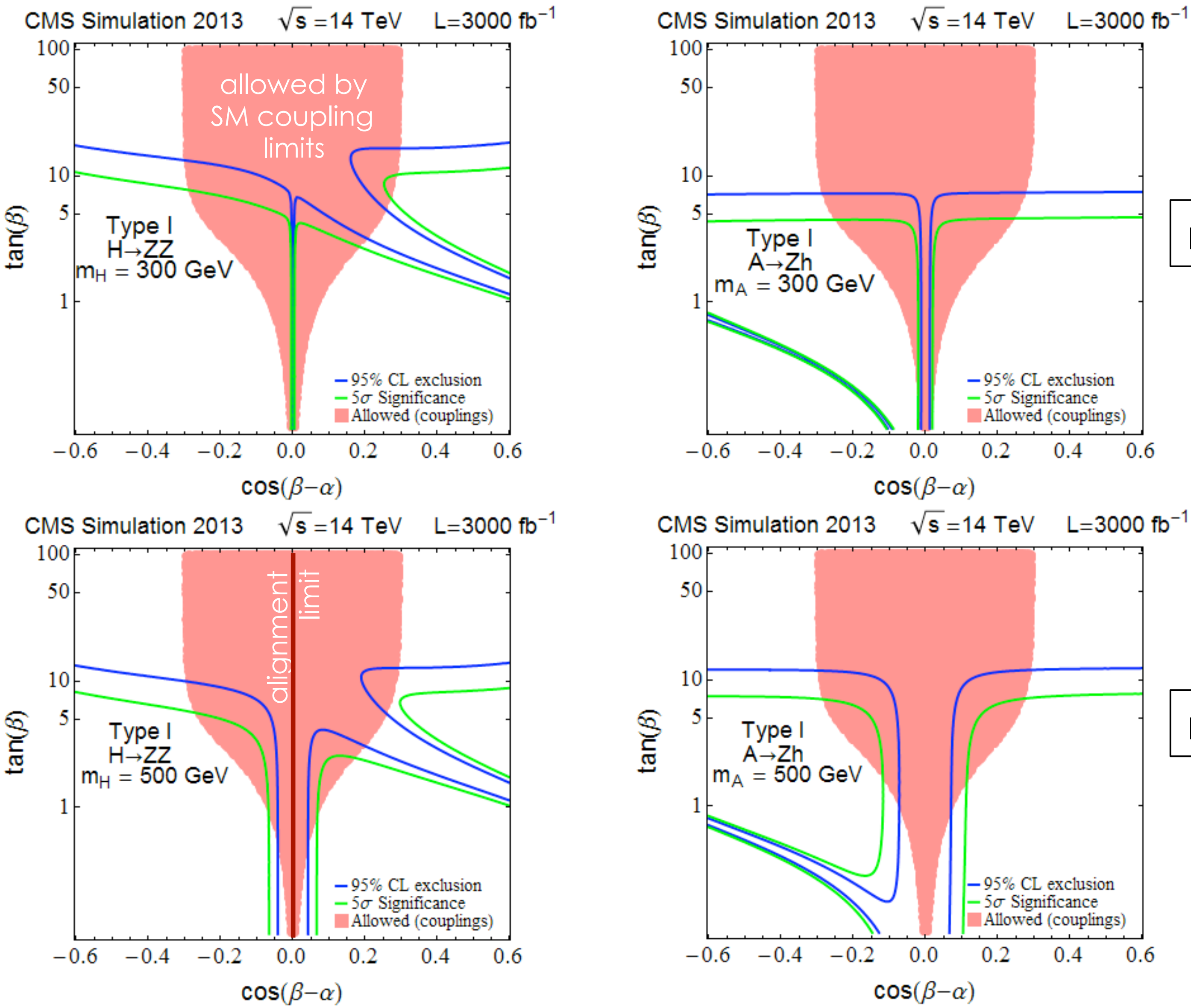


3000 fb^{-1}
(no MET selection applied)

Anomalous coupling signal
for $f_{T1} / \lambda^4 = 1.0\ TeV^{-4}$

CMS PAS FTR-13-024

CMS Type I 2HDM expected sensitivity



$m_{A/H}$ = 300 GeV

Type I 2HDM

$m_{A/H}$ = 500 GeV

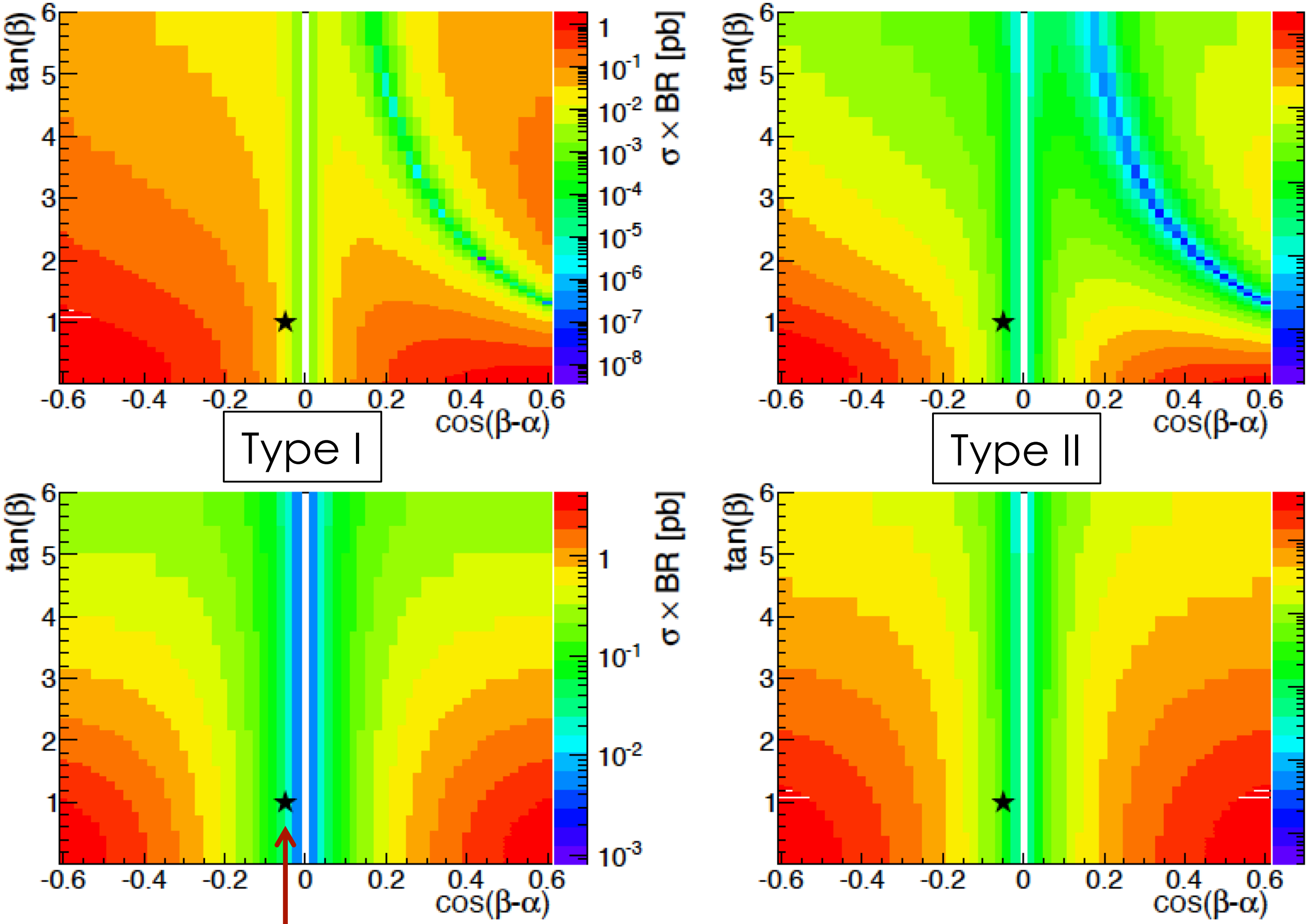
H→ZZ→4l

A→Zh→2l2b

2HDM cross sections times BR

pp→H→ZZ

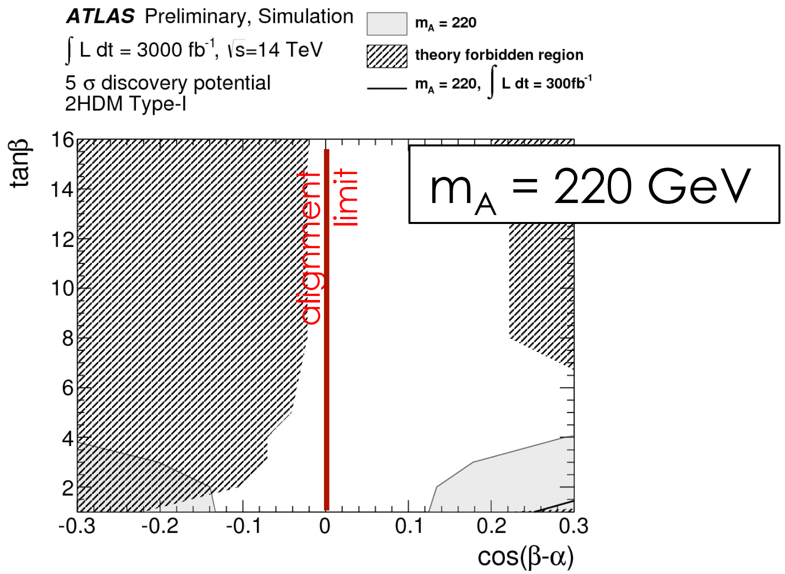
pp→A→Zh

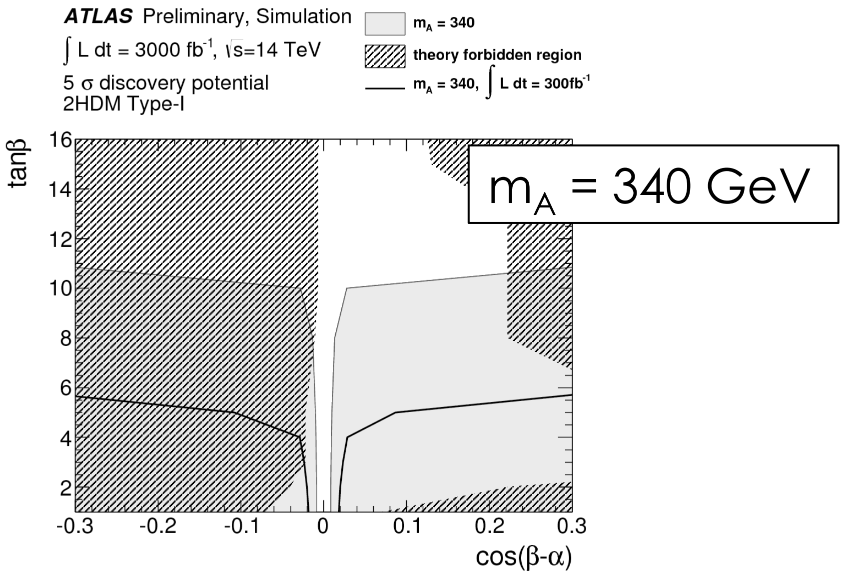


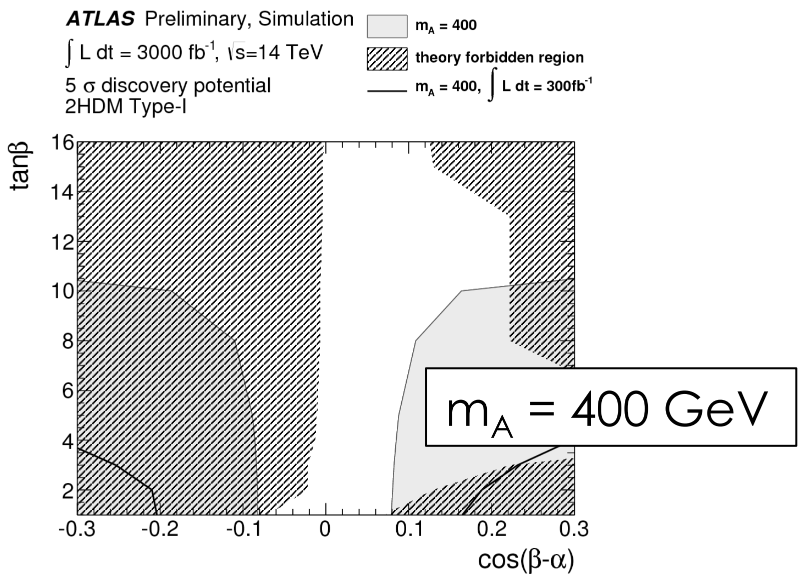
√s=14 TeV

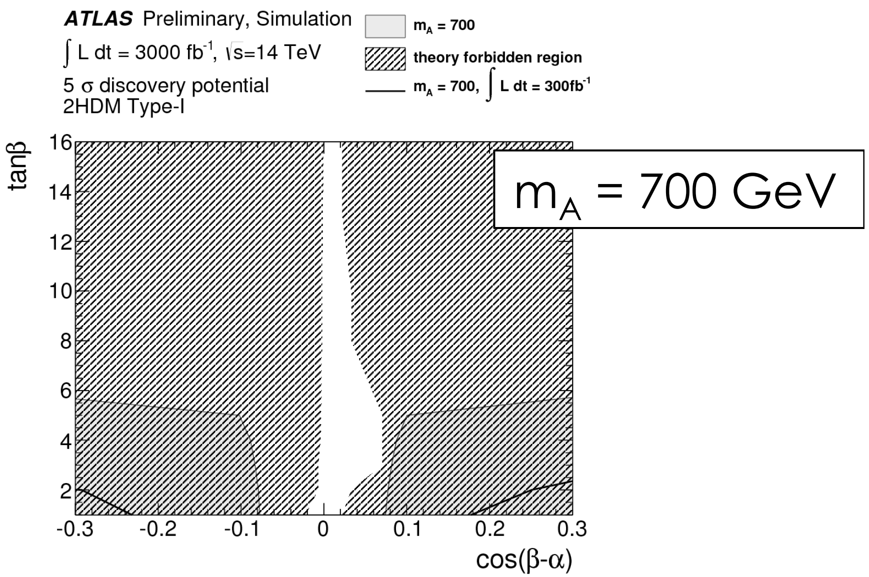
cos(β-α) = -0.06 / tan(β) = 0.7854

ATLAS 2HDM Type I discovery potential

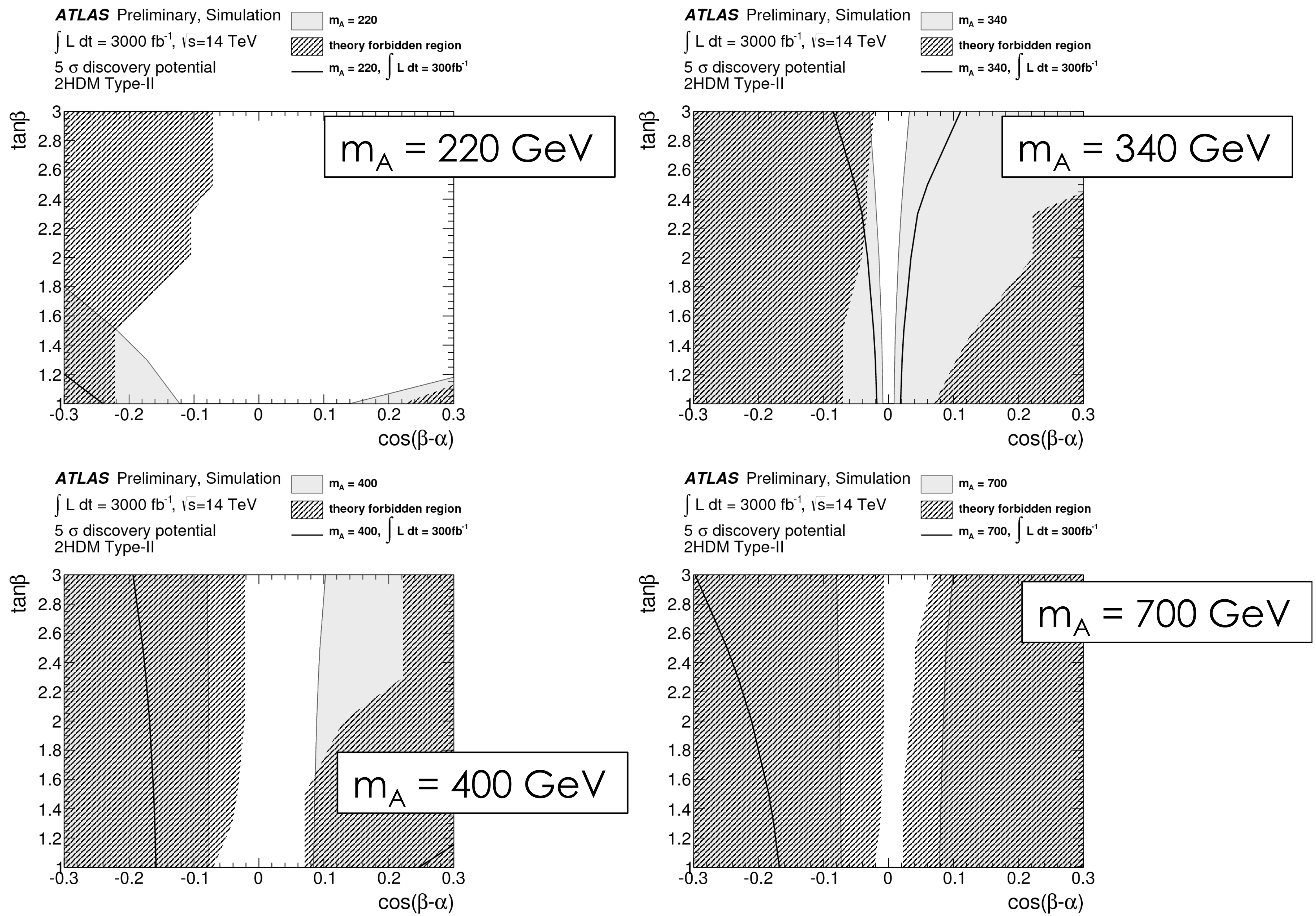




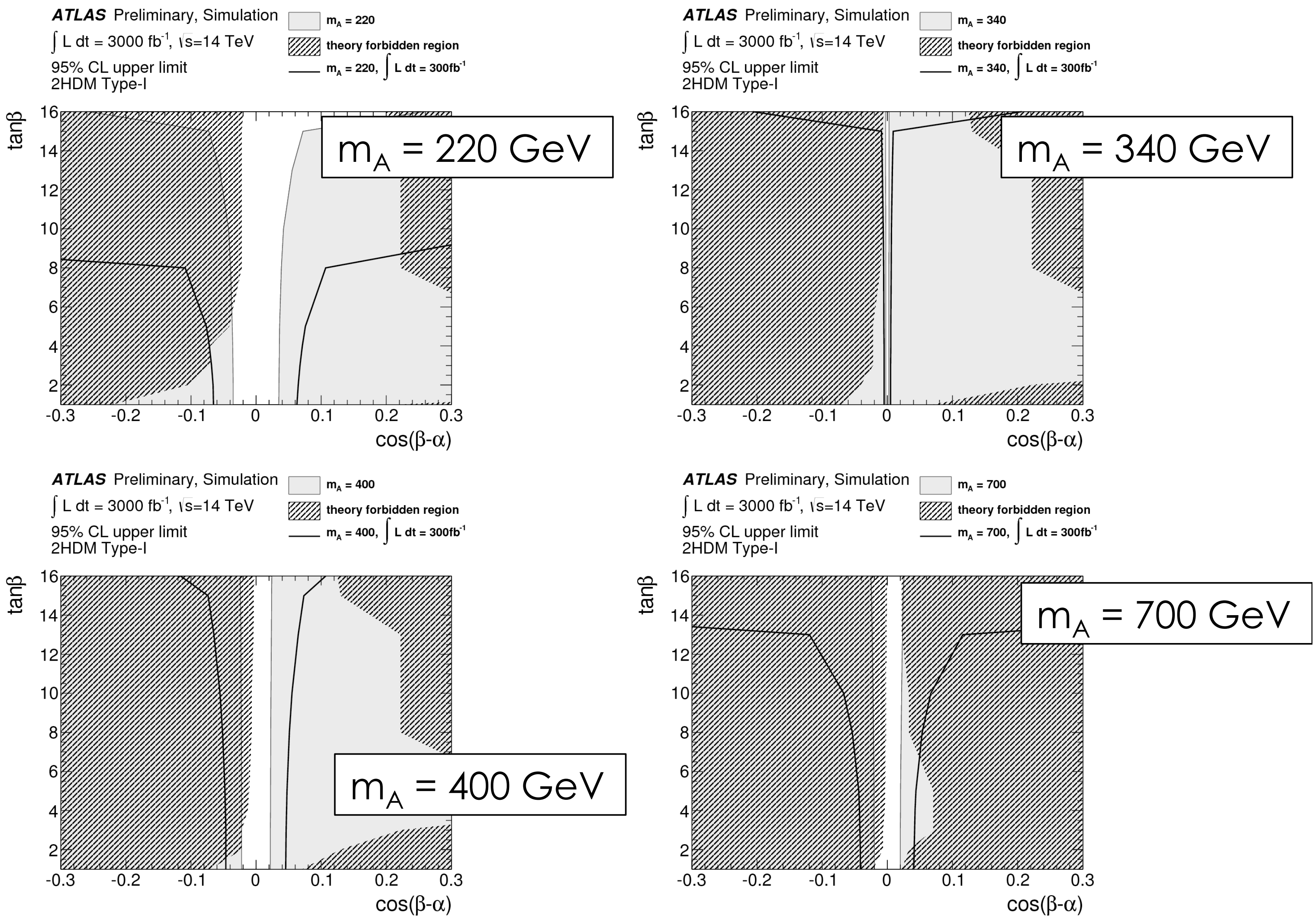




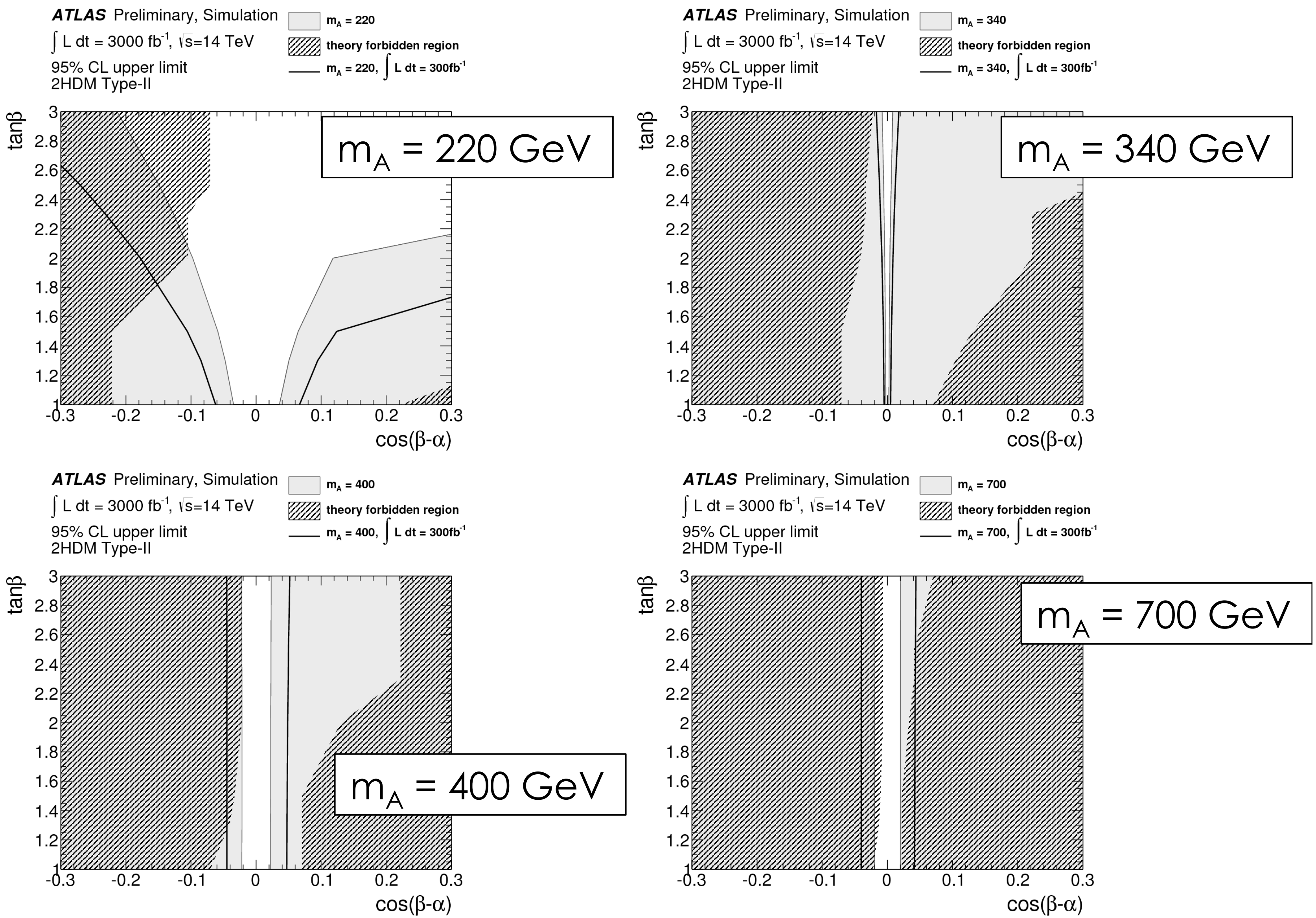
ATLAS 2HDM Type II discovery potential



ATLAS 2HDM Type I expected exclusion

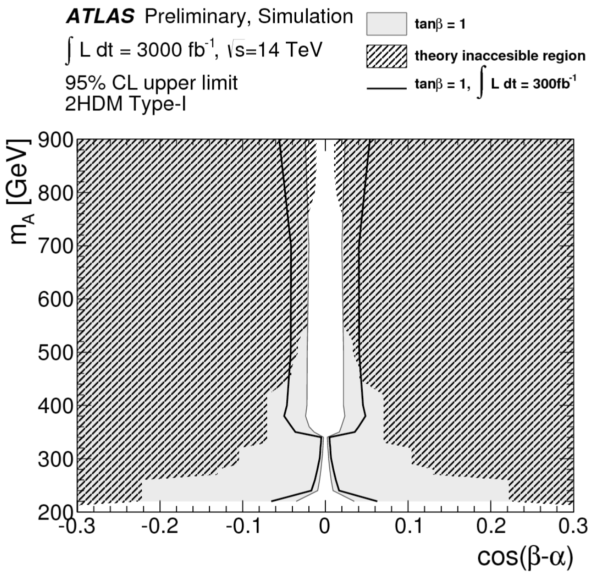


ATLAS 2HDM Type II expected exclusion

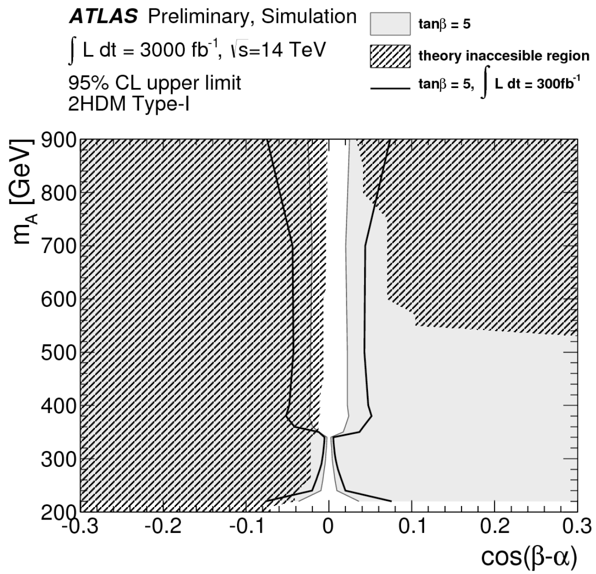


ATLAS 2HDM expected exclusion (type I)

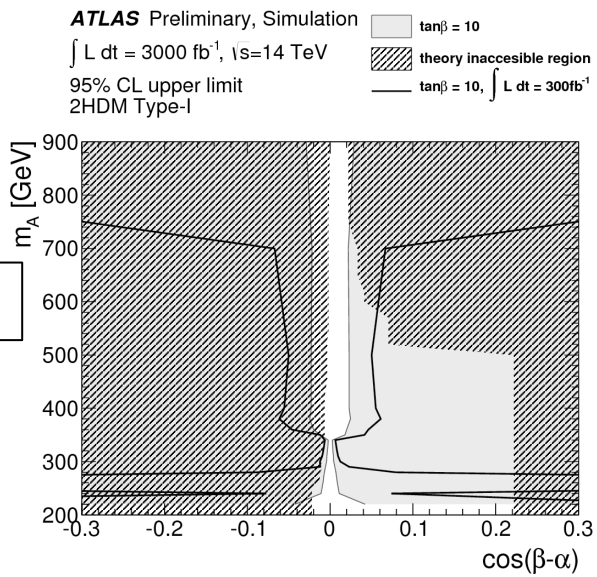
tan β = 1



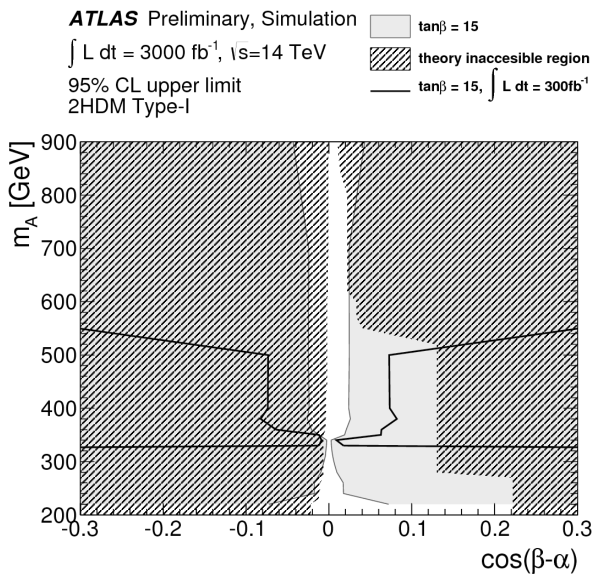
tan β = 5



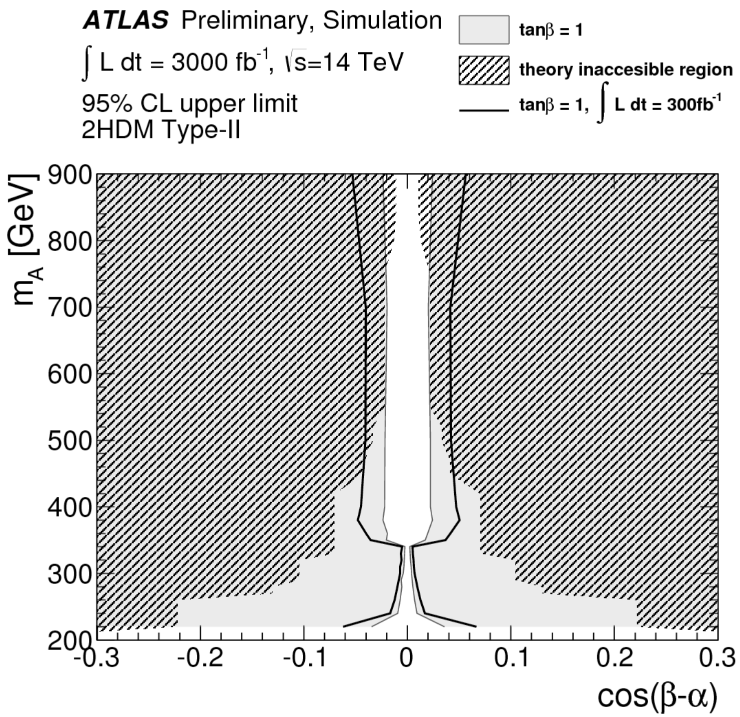
tan β = 10



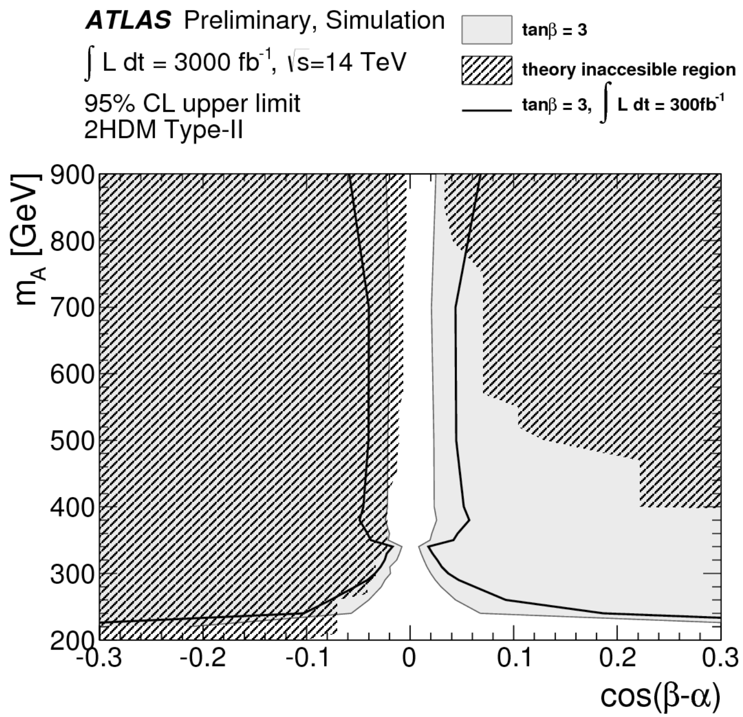
tan β = 15



ATLAS 2HDM expected exclusion (type II)

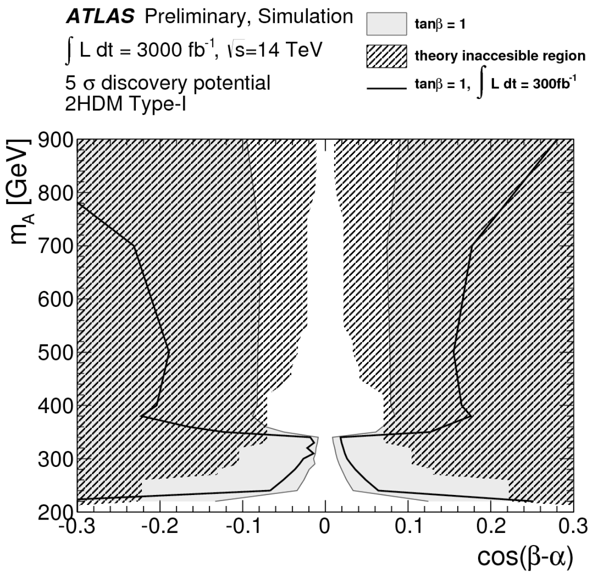


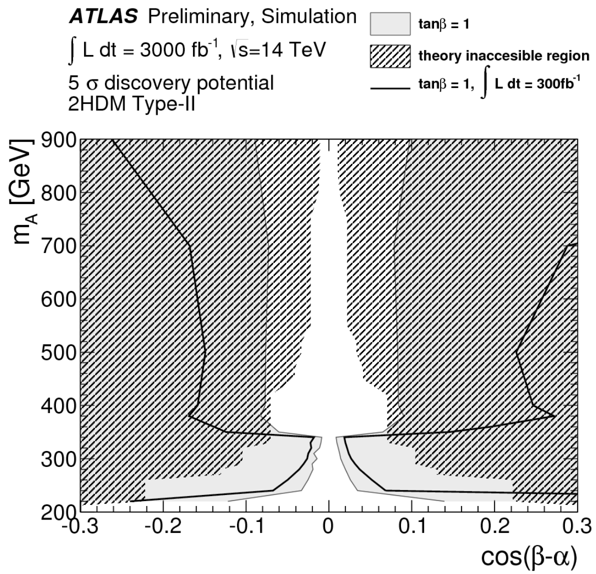
tan β = 1



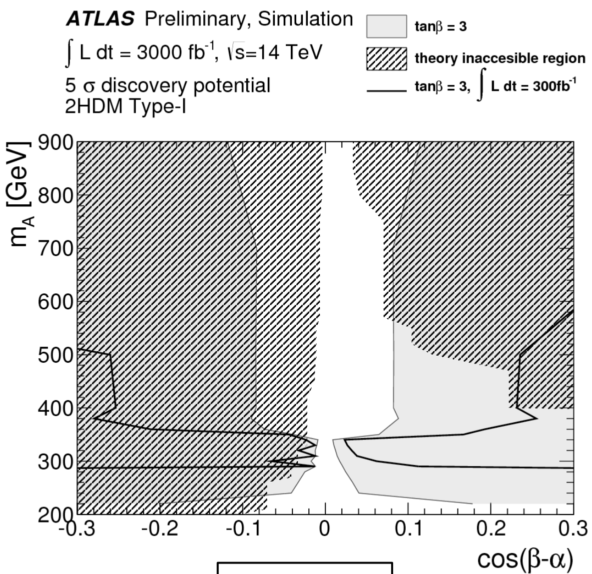
tan β = 3

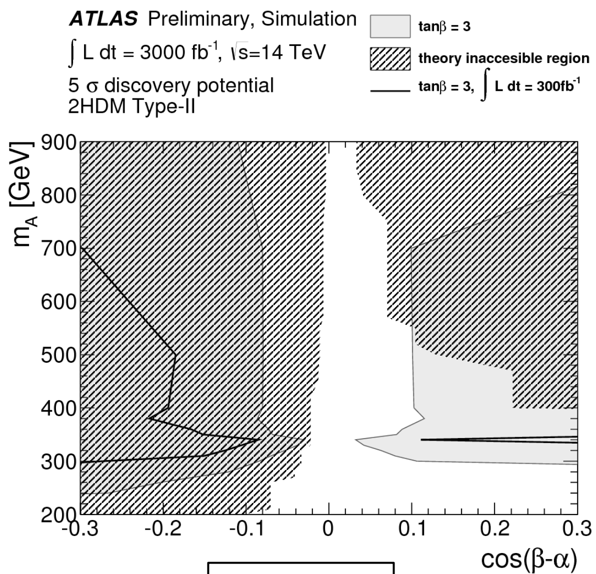
ATLAS 2HDM discovery potential





tan β = 1





tan β = 3

Type I

Type II

ATLAS H/A→$\mu^+\mu^-$ expected significance

m_ϕ [GeV]	b-veto		b-tag		combined	
	300 fb^{-1}	3000 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$\tan\beta = 20$						
300	5.2	16.5	3.1	9.9	6.2	19.3
400	1.9	6.0	1.4	4.5	2.4	7.6
500	0.6	2.0	0.6	2.0	0.9	2.8
$\tan\beta = 40$						
500	3.8	12.1	4.0	12.8	5.6	17.6
600	2.4	7.6	3.1	9.8	3.9	12.4
700	1.5	4.7	2.2	7.0	2.7	8.5
$\tan\beta = 60$						
800	1.9	6.1	3.9	12.3	4.3	13.7
900	1.1	3.4	2.9	9.3	3.1	9.9
1000	0.8	2.6	2.3	7.6	2.4	7.7

number of Gaussian sigmas

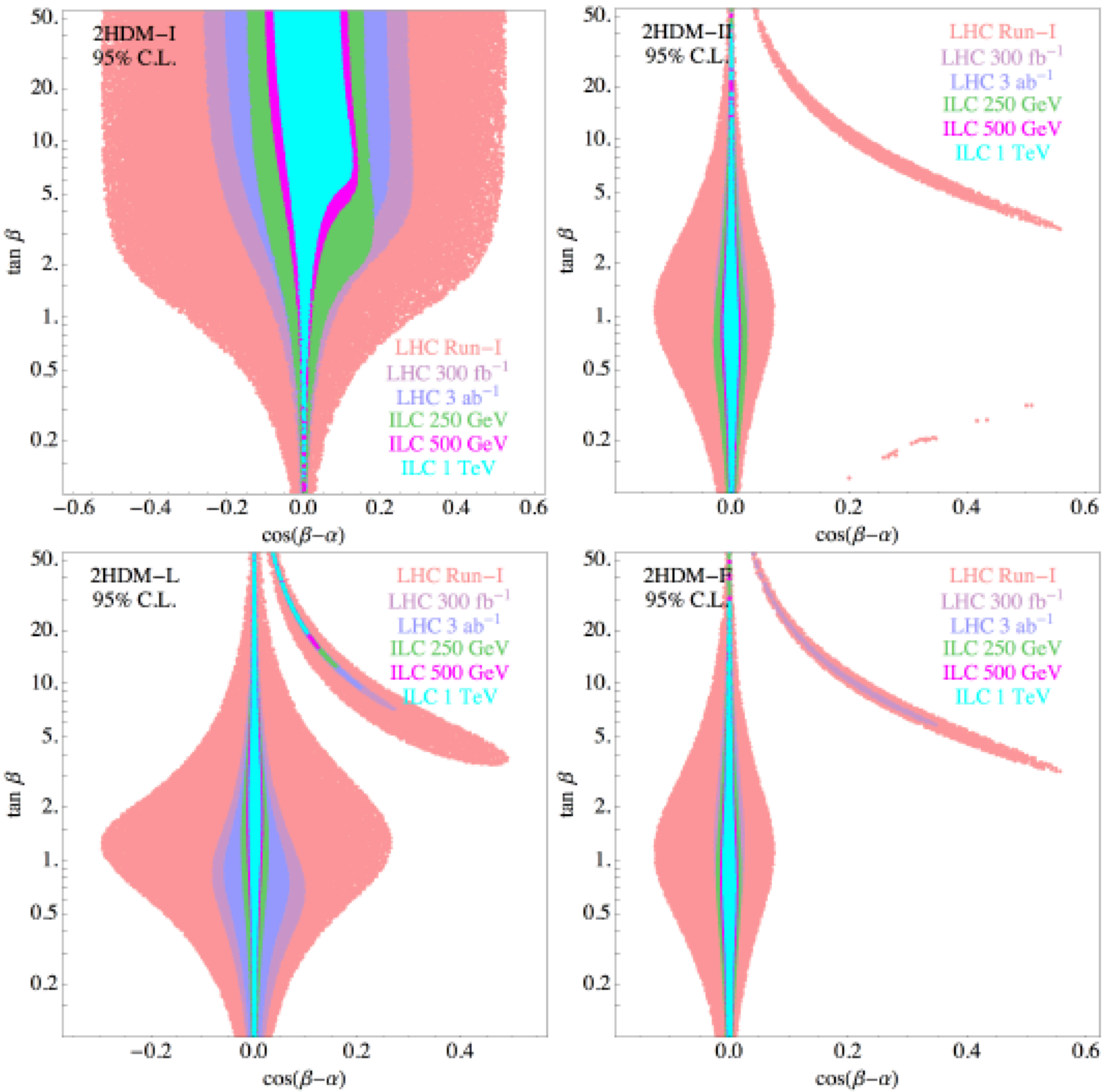
Statistical uncertainty only

2HDMs and SM Higgs coupling limits

Table 5: Yukawa couplings of the fermions to the lightest Higgs with respect to the SM for traditional 2HDMs.

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

Barger et. al.
arxiv:1308.0052



Note: y scale linear,
x scale different

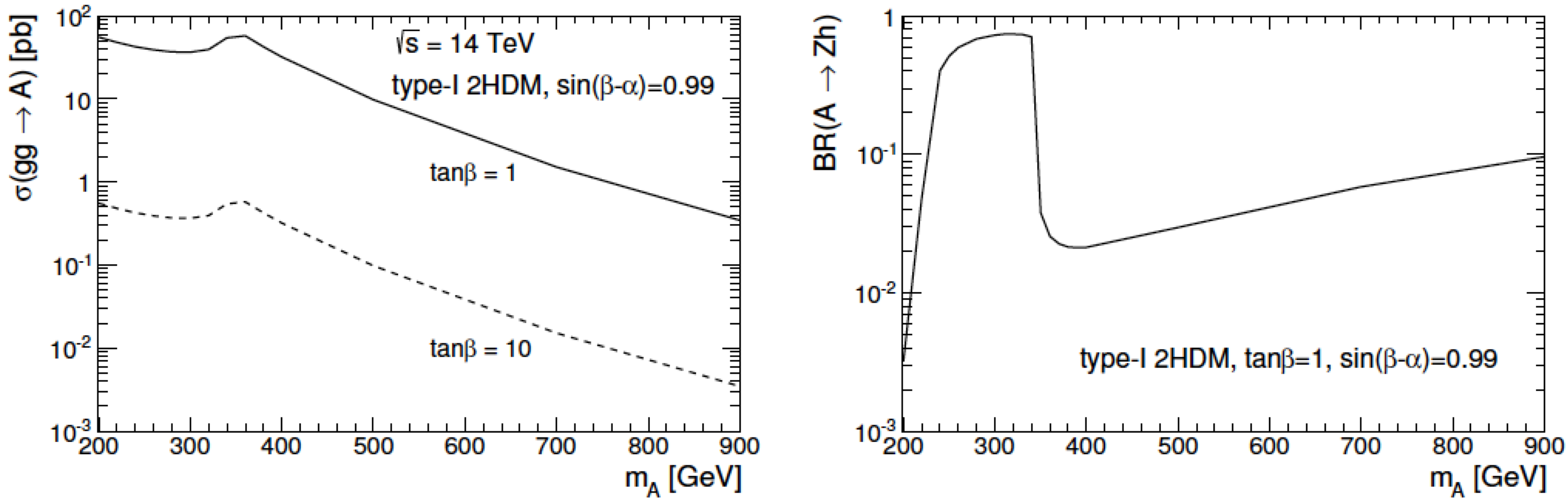
Most general gauge invariant 2HDM potential:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \text{h.c}\right\} \quad (1)$$

	type-I	type-II
ξ_h^u	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
ξ_h^d	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_h^l	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_H^u	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
ξ_H^d	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_H^l	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_A^u	$1/\tan\beta$	$1/\tan\beta$
ξ_A^d	$-1/\tan\beta$	$\tan\beta$
ξ_A^l	$-1/\tan\beta$	$\tan\beta$

Table 1: Yukawa coupling coefficients of the neutral bosons of the type-I and type-II 2HDMs for up-type quarks (u), down-type quarks (d) and charged leptons (l). These coefficients are defined such that the Yukawa Lagrangian terms are $-(m_f/v)\bar{f}f\phi$ and $i(m_f/v)\bar{f}\gamma_5 fA$ where $f = u, d, l$ and $\phi = h, H$.



(a) (b)

Figure 1: The gluon-fusion production cross section (a) and the branching ratio BR($A \to Zh$) (b) for a CP-odd Higgs boson A as a function of its mass, m_A, for $\sin(\beta - \alpha) = 0.99$ and type-I 2HDMs. More details on the assumptions and the calculation are given in the text.

In the MSSM (Type II)

- Summary of the Higgs couplings to gauge bosons

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
$H^0W^+W^-$	$h^0W^+W^-$
H^0ZZ	h^0ZZ
ZA^0h^0	ZA^0H^0
$W^{\pm}H^{\mp}h^0$	$W^{\pm}H^{\mp}H^0$
$ZW^{\pm}H^{\mp}h^0$	$ZW^{\pm}H^{\mp}H^0$
$\gamma W^{\pm}H^{\mp}h$	$\gamma W^{\pm}H^{\mp}H^0$

In the MSSM (Type II)

$$-\mathscr{L} = h_t(\bar{t}P_L t H_u^0 - \bar{t}P_L b H_u^+) + h_b(\bar{b}P_L b H_d^0 - \bar{b}P_L t H_u^-) + \text{h.c.}$$

$$h_b = \frac{\sqrt{2}m_b}{v_d} = \frac{\sqrt{2}m_b}{v\cos\beta} \qquad h_t = \frac{\sqrt{2}m_t}{v_u} = \frac{\sqrt{2}m_t}{v\sin\beta}$$

Couplings relative to SM values

decoupling limit

$h^0\bar{b}b$:	$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\to 1$
$h^0\bar{t}t$:	$\frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\to 1$
$H^0\bar{b}b$:	$\frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)$	$\to \tan\beta$
$H^0\bar{t}t$:	$\frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)$	$\to -(\tan\beta)^{-1}$
$A^0\bar{b}b$:	$\gamma_5\tan\beta$	
$A^0\bar{t}t$:	$\gamma_5\cot\beta$	

ATLAS FCNC t→hc, h→γγ

Centre of mass energy	8 TeV	14 TeV
$t\bar{t}$ (pb)	246 (+9,-11)	954 (+27,-38)
$t\bar{t}H$ (fb)	130 (+16,-22)	610 (+15,-18)
Sherpa $\gamma\gamma j$ (pb)	61.6	135

ATLAS FCNC t→hc, h→γγ

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