BSM Higgs and Vector Boson Scattering at HL-LHC

S. Casasso
on behalf of the ATLAS and CMS collaborations

Higgs Hunting 2015
July 30-August 1 2015 Orsay (France)

Outline

- Beyond Standard Model (BSM) Higgs
  - Direct searches
  - Indirect limits
- Vector boson scattering (VBS)
  - SM electroweak di-boson production
  - Anomalous quartic gauge couplings (aQGC)

BSM Higgs

How to find BSM Higgs

- **Direct searches** for additional Higgs particles
  - production mechanism is similar to SM Higgs
    - gluon-fusion, VBF
    - b-associated production can be enhanced
- **Indirect limits** from the 125 GeV Higgs
  - couplings, rare decays
- Both involve low rates and accurate measurements
  - not necessarily higher energies ⇒ **excellent case for HL-LHC**

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2HDM in a nutshell

- Class of models predicting a second Higgs doublet (SUSY, Axion, Baryogenesis)
- Five physical particles: $h,H,A,H^{\pm}$
- Higgs sector described by 7 parameters:
    - m_h, m_H, m_A, $m_{H\pm}$, **$\tan\beta$**, **α**, m_{12}^2
- 4 options for fermion couplings
    - **Type I**: ϕ_1 couples to vector bosons, ϕ_2 couples to fermions ("Fermiophobic")
    - **Type II**: ϕ_1 couples up-type fermions, ϕ_2 couples to down-type fermions ("MSSM")
    - **Type III**: quarks as in Type I and charged leptons as in Type II ("lepton-specific")
    - **Type IV**: quarks as in Type II and charged leptons as in Type I ("flipped")
- Benchmarks identify the light CP-even *h* with the 125 GeV Higgs boson
    - SM-like ⇒ focus on **$\cos(\beta-\alpha)\rightarrow 0$ (SM limit)**

$A \to Zh \to llbb$

- The Zh decay mode is in general the dominant for $m_A < 2m_{top}$
- Better sensitivity at **low tanβ**
    - complementary to h coupling measurements and other searches
- 4 times better sensitivity with 3000 fb^{-1} wrt 300 fb^{-1}

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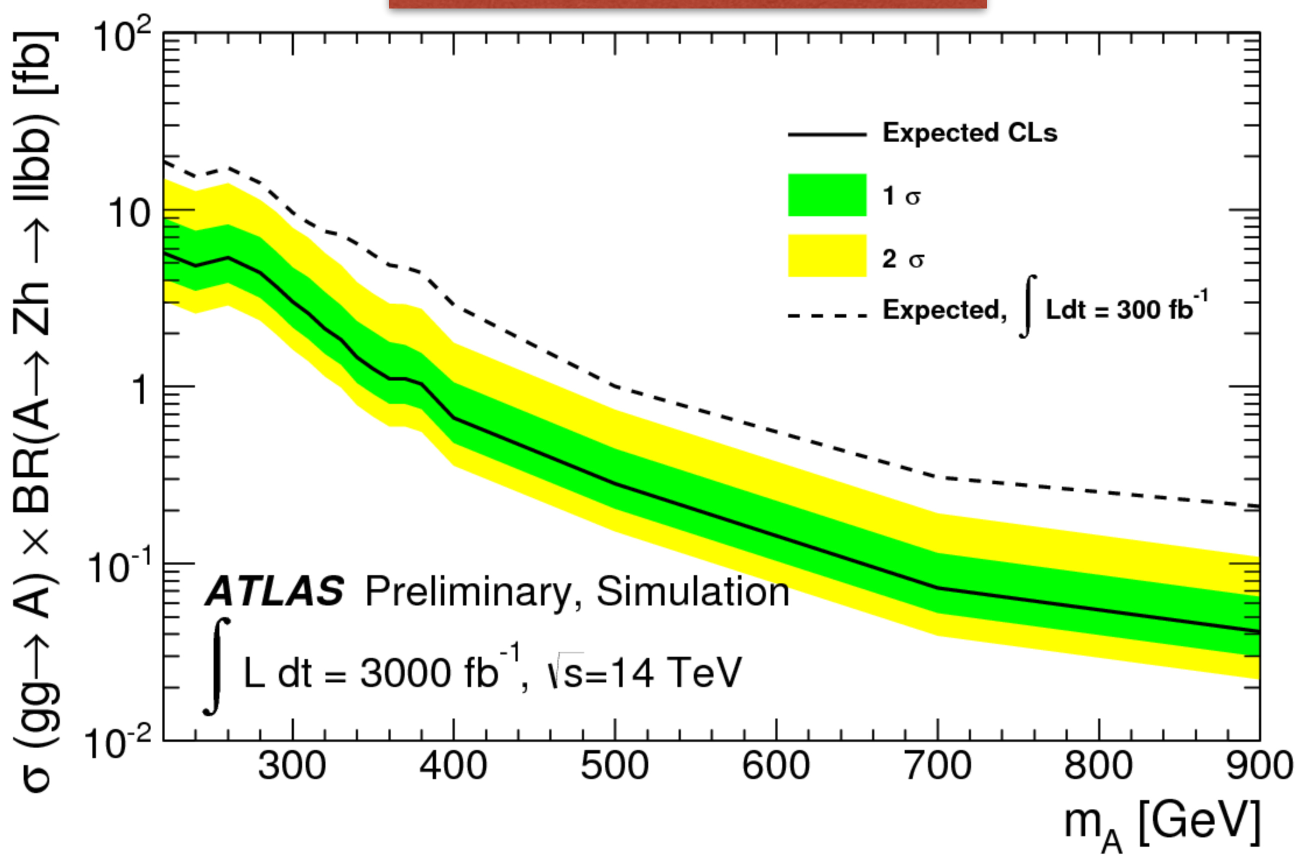
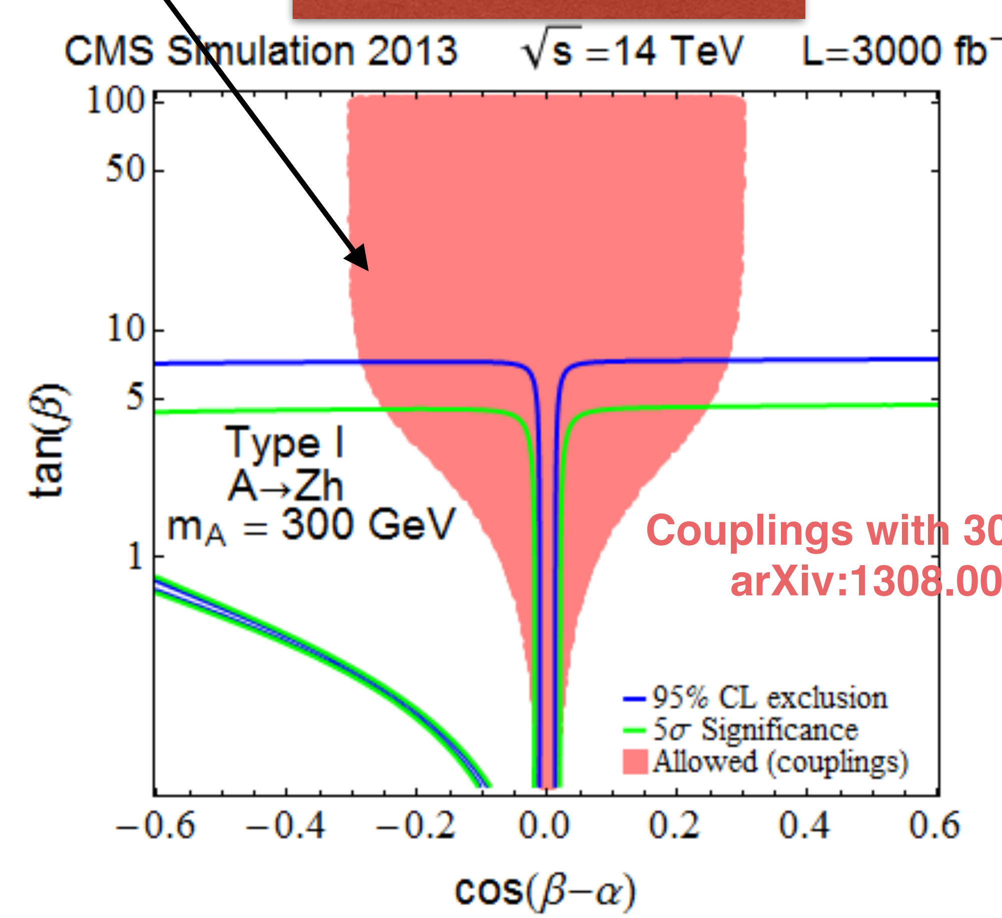


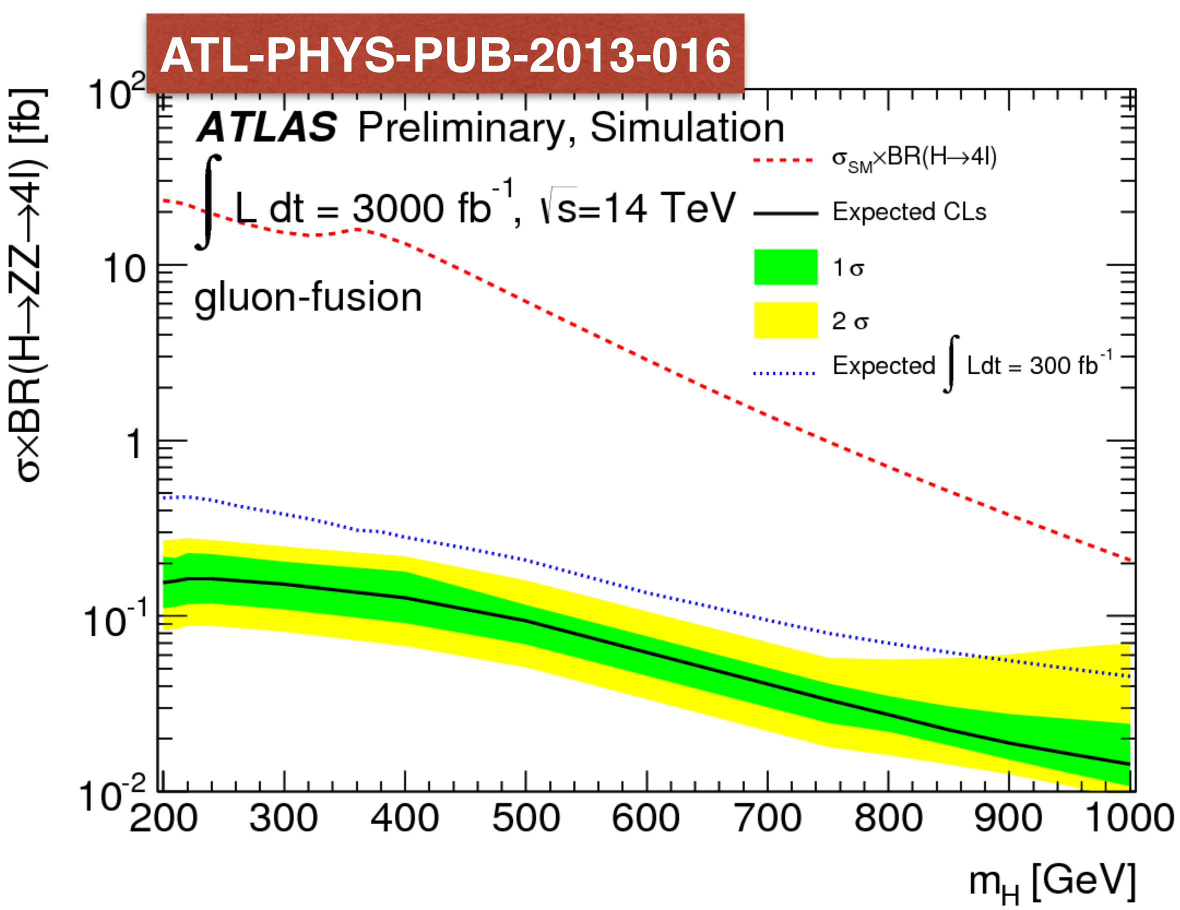
CMS PAS FTR-13-024

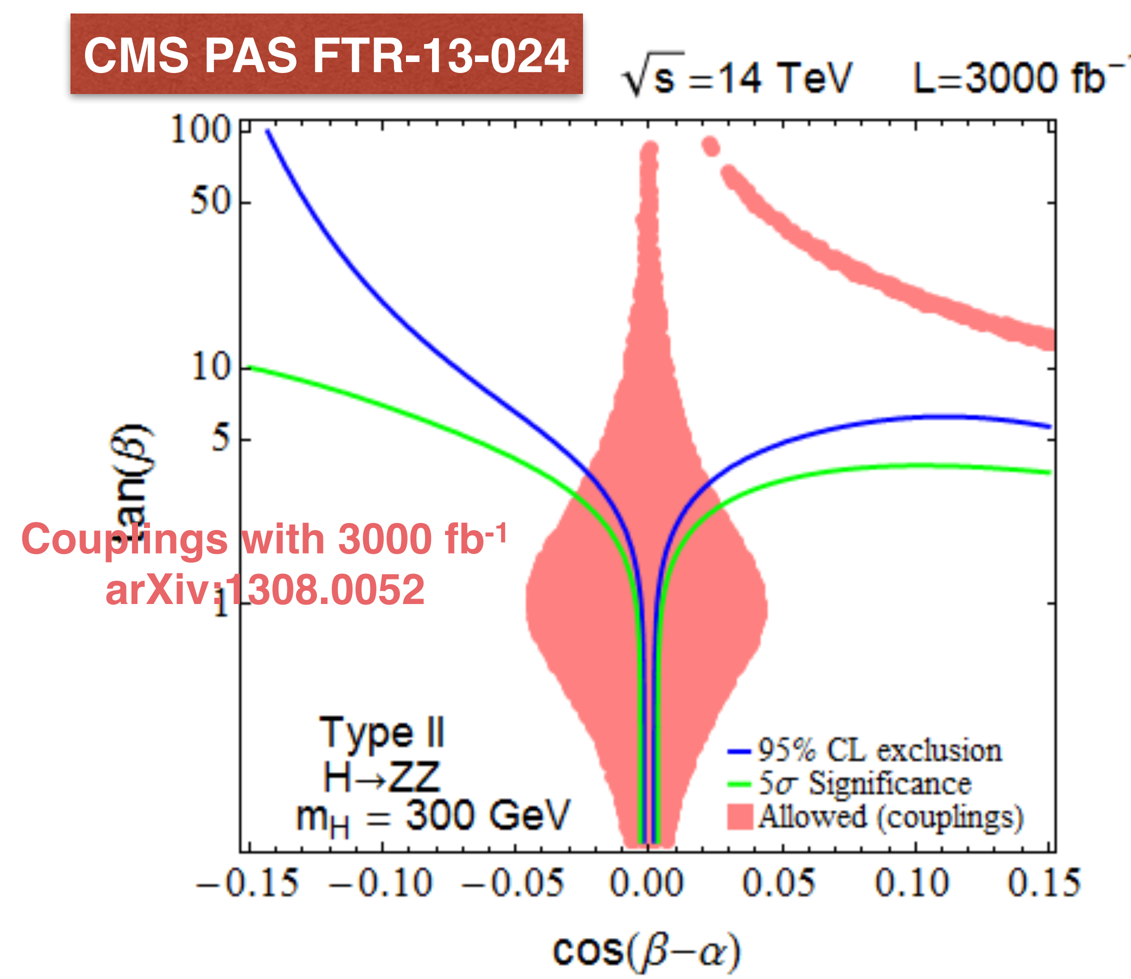


Couplings with 3000 fb^{-1}
arXiv:1308.0052

H→ZZ→4l

- The 4l final state has small cross section but is clean and well reconstructed
- A heavy SM-like Higgs boson decaying to 4l occurs in several extensions of the scalar sector (2HDM,EWK singlet)
- Limits improve by a factor ~3 with 3000 fb^{-1}
- Similar sensitivity for ATLAS and CMS (~0.01-0.1 fb)





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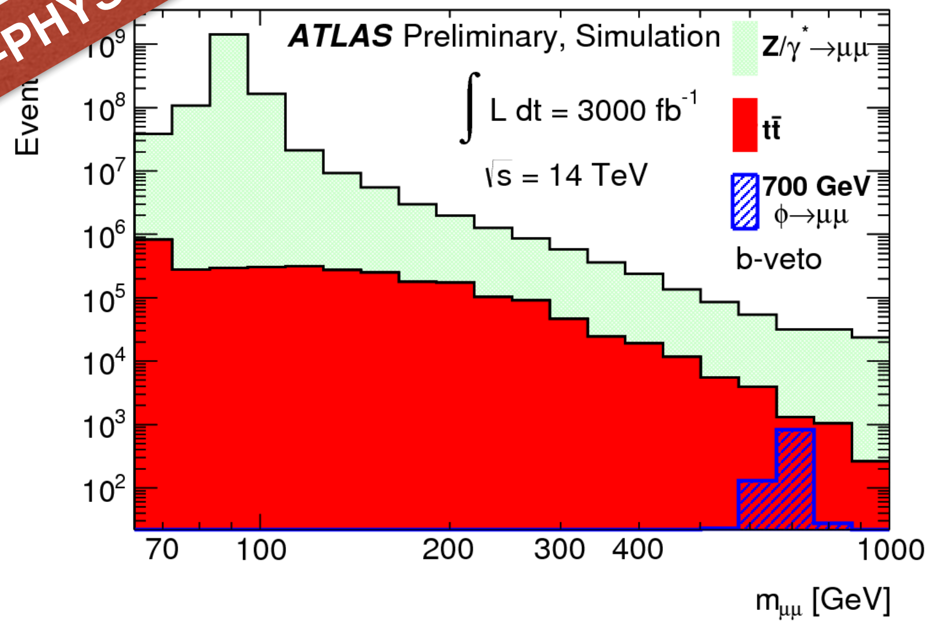
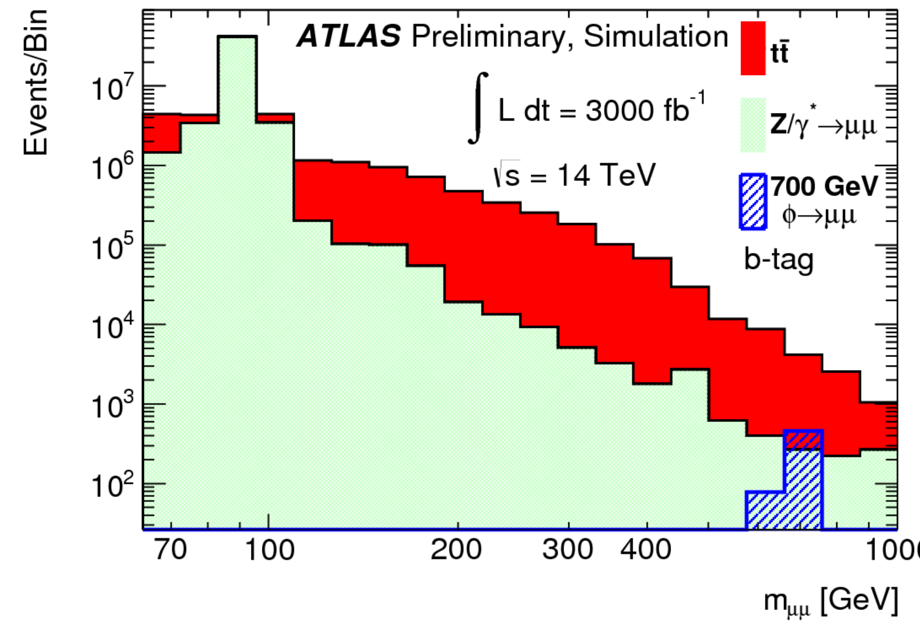
$\phi \to \mu\mu$

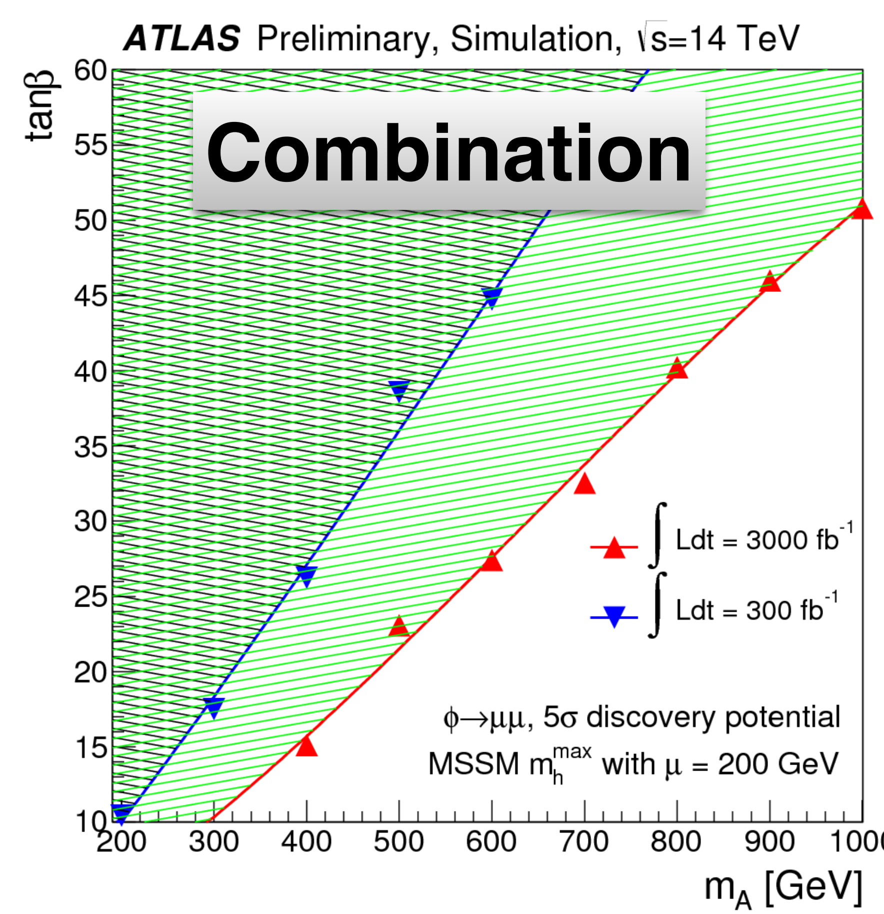


b-veto: target gluon-fusion



≥1 b-tag: target b-associated

- **MSSM**-inspired scenario with mass degenerate A/H Higgs bosons
- Clean final state, with excellent mass resolution
- Better sensitivity at **high tanβ**
- Significant improvement with 3000 fb^{-1} with respect to 300 fb^{-1}



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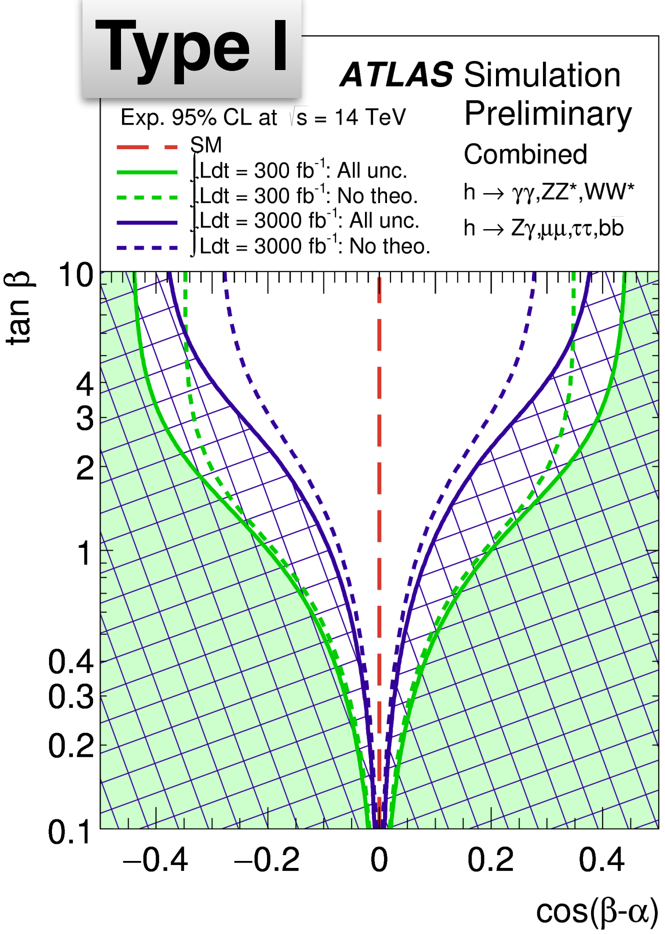
Indirect limits: 2HDM

- Use expected accuracy in the couplings k_i of the 125 GeV Higgs boson
  - functions of the parameters of the model
- Same decays as in the SM are assumed (b-associated production included as a correction)

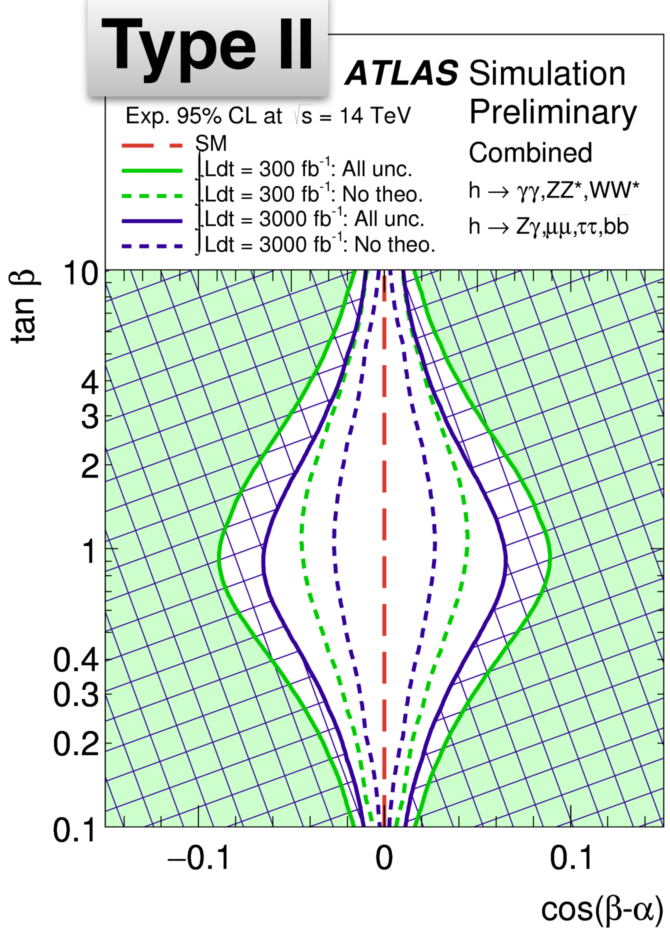
h(125) is the light scalar of the 2HDM

Coupling scale factor	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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

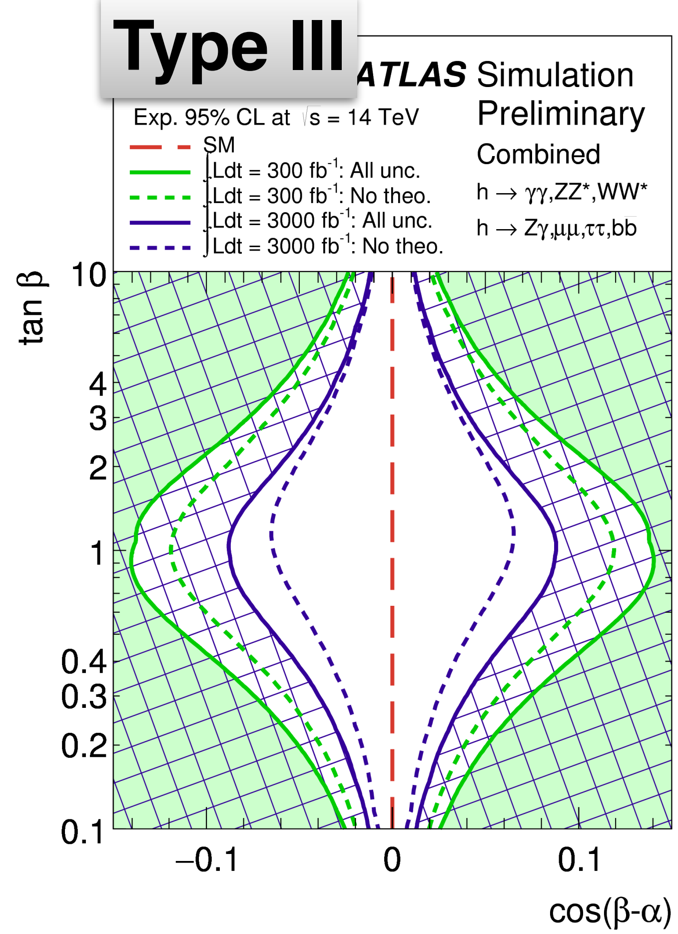
Type I



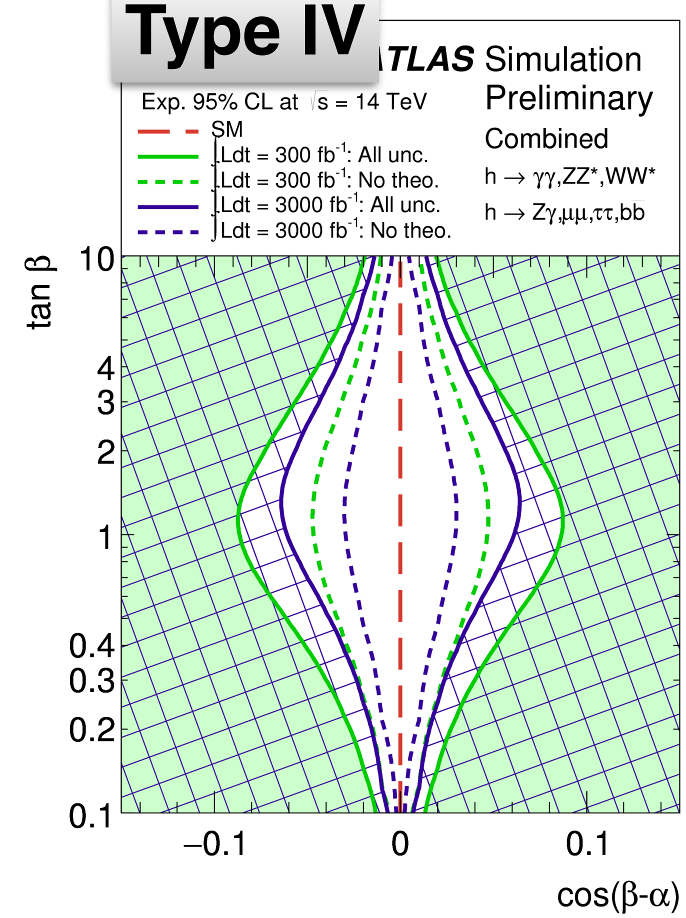
Type II



Type III



Type IV



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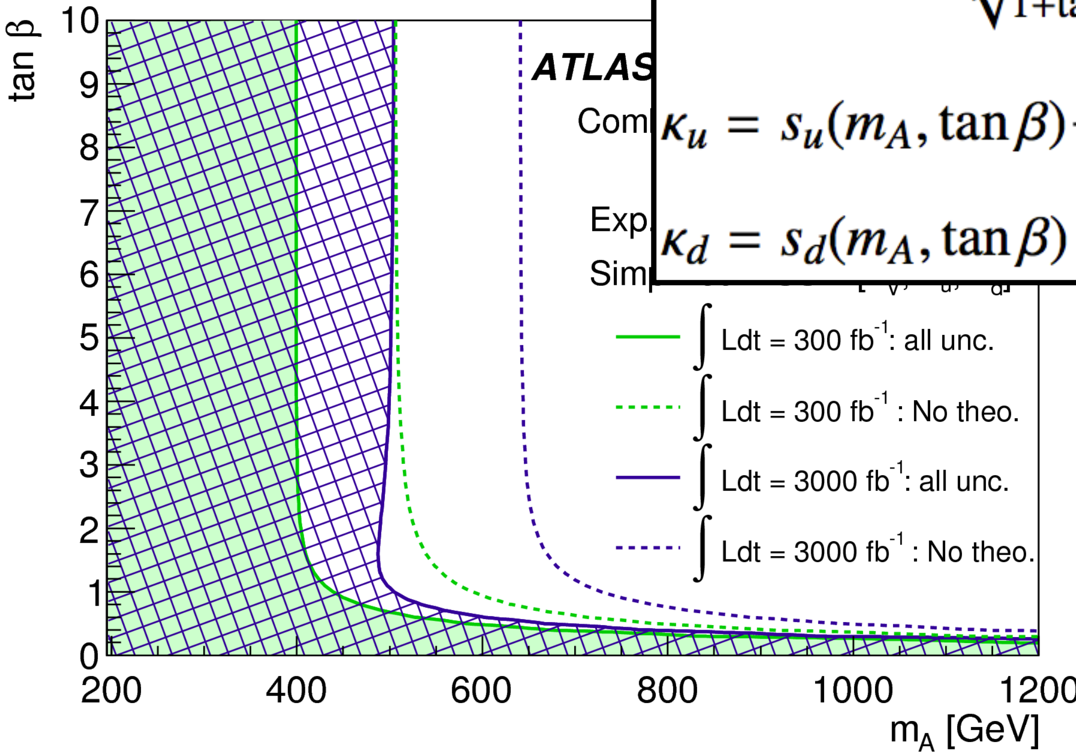
Indirect limits: other models

Simplified MSSM

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

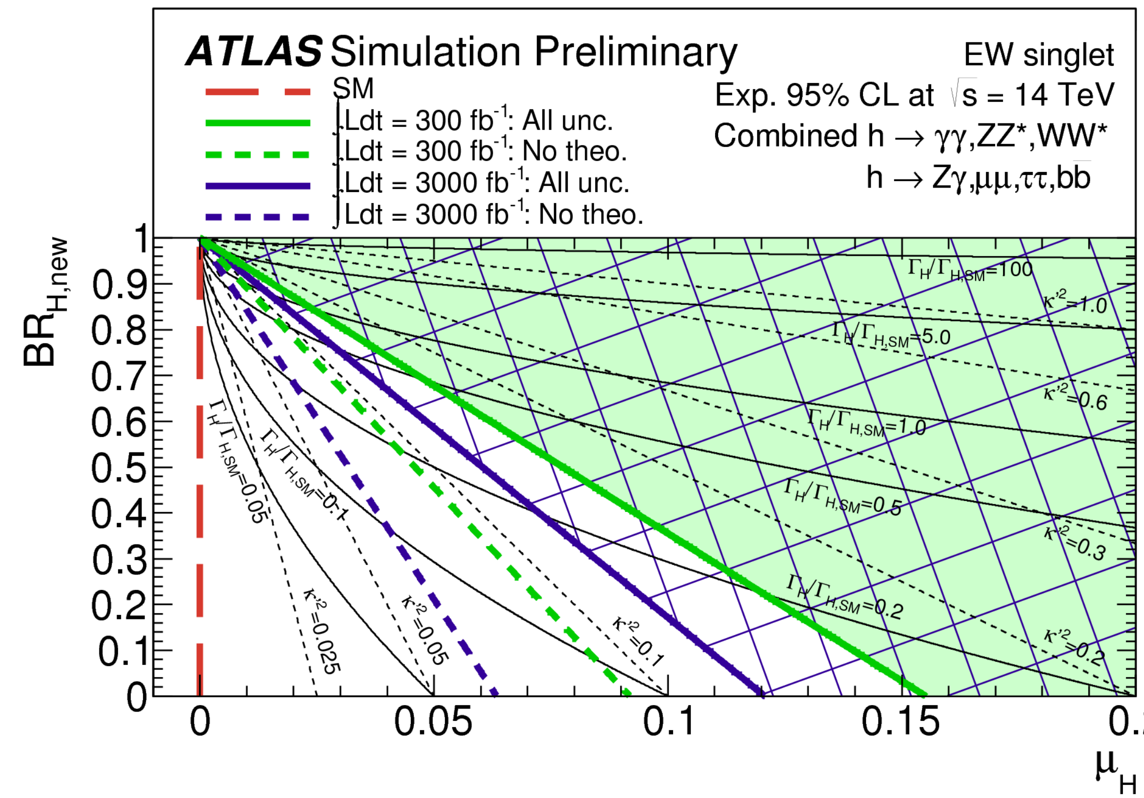
$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta},$$



EWK singlet

$$\kappa'^2 = 1 - \mu_h$$



Composite Higgs

$\xi = v^2/f^2$ **f is the compositeness scale**

Model	Couplings	95% CL low limit L=300/fb	95% CL low limit L=3000/fb
MCHM4	$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$	f > 620 GeV	f > 710 GeV
MCHM5	$\kappa_V = \sqrt{1-\xi}$ $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}.$	f > 780 GeV	f >1 TeV

H→invisible

- Direct search ZH (3000/fb):

  BR(H→inv.) < 8% (16%) at 95% CL

  for a realistic (conservative) scenario for systematics

- Indirect constraints from the measurement of the 125 GeV couplings (3000/fb):

  BR(H→inv.) < 13% at 95% CL

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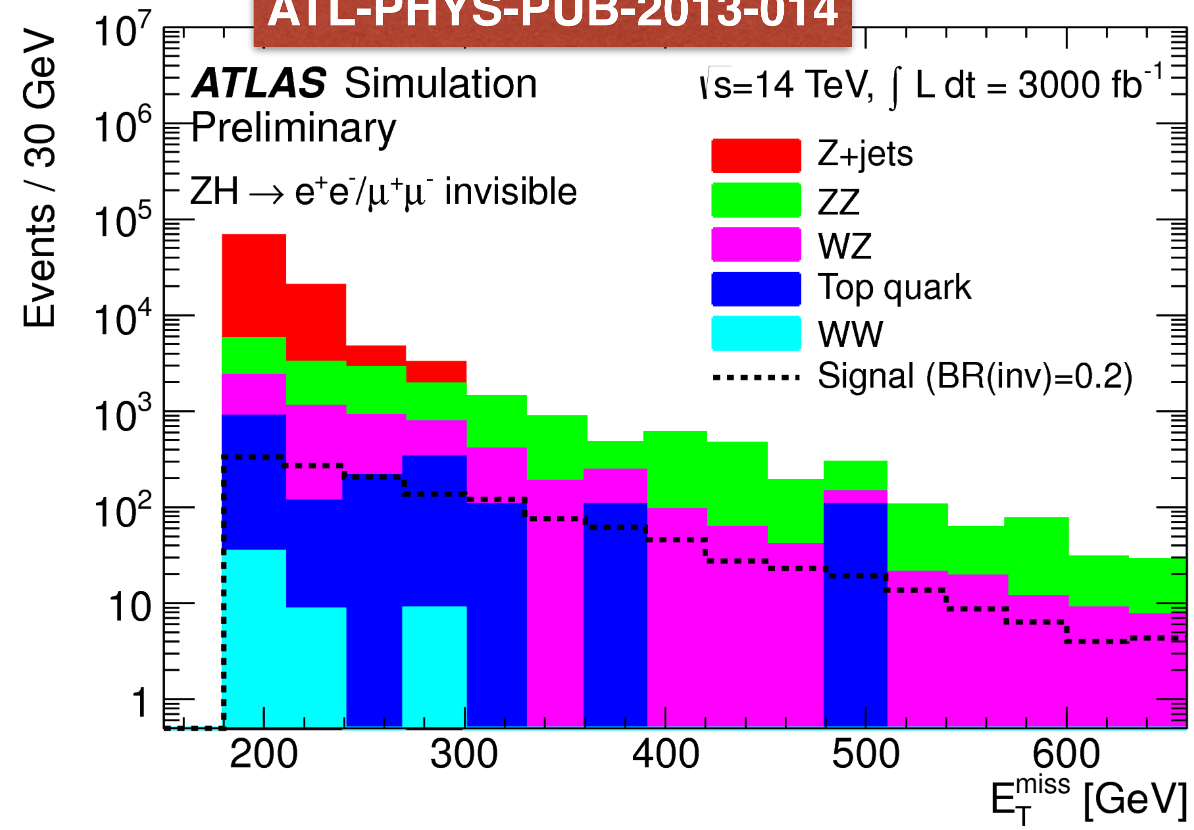

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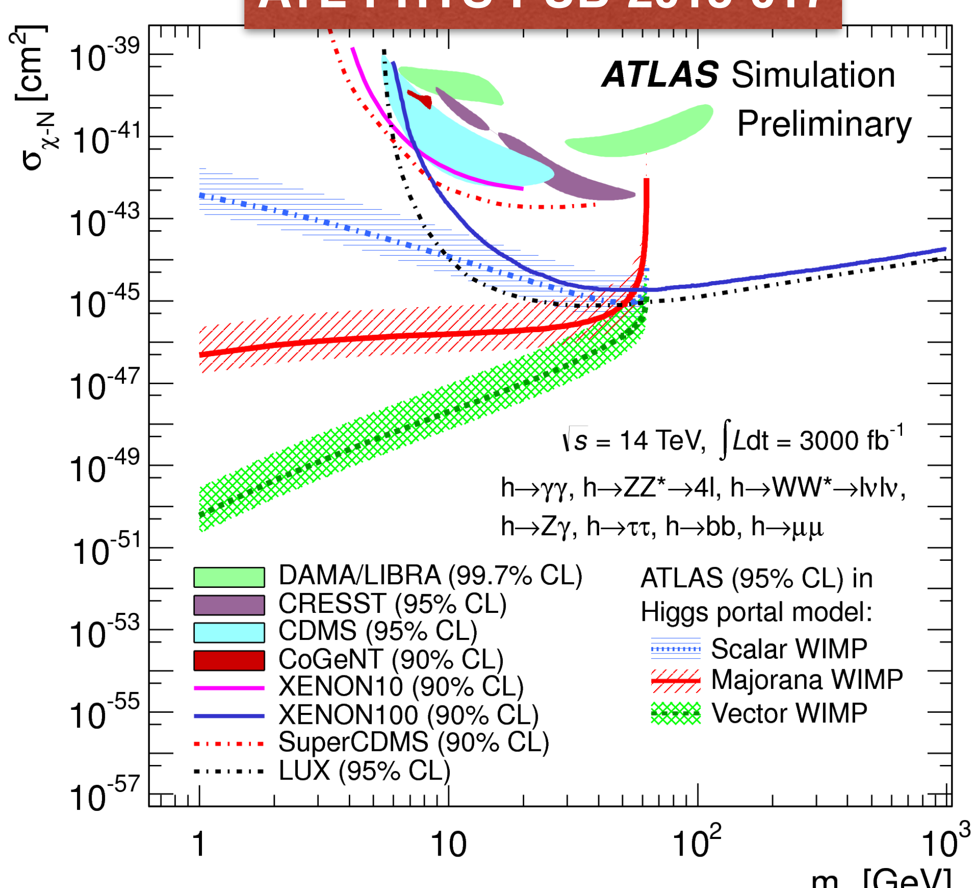
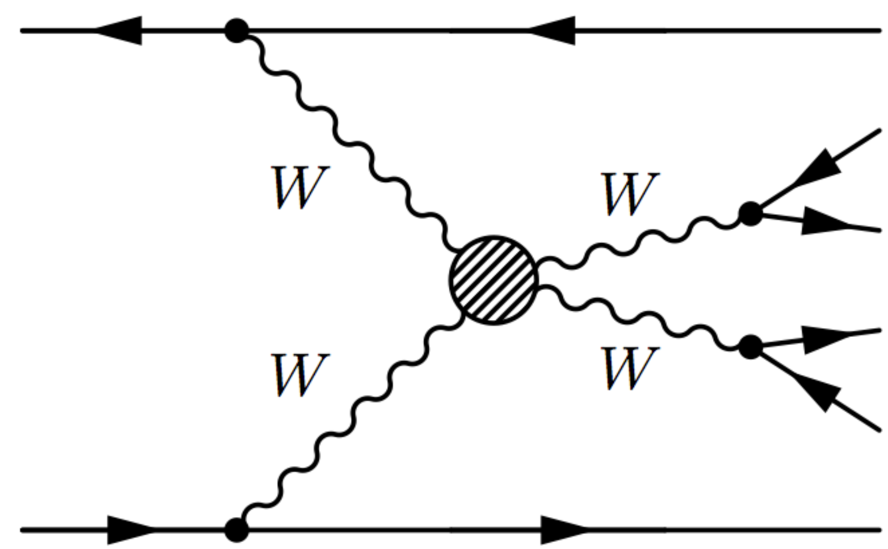


- If H→inv. is only due to decay to a pair of WIMPs, limits are set on the DM-nucleon cross section
- Large improvement (~factor 5) with respect to the 8 TeV results
- Collider results are competitive with other experiments (low DM masses)

Vector boson scattering

VBS in a nutshell

- **$W_L W_L$ scattering** violates unitarity at high energies
  - in the SM it is restored by the Higgs boson
  - need experimental confirmation



- **VBS** is sensitive to QGC and to the electroweak symmetry breaking
- New physics (aQCG) can alter the VBS cross section
  - exchange of heavy scalar particles
- **aQCGs** are parameterised through higher dimension operators in effective field theory
- Experimental signature: di-boson production in association with 2 jets with large rapidity gap and large invariant mass

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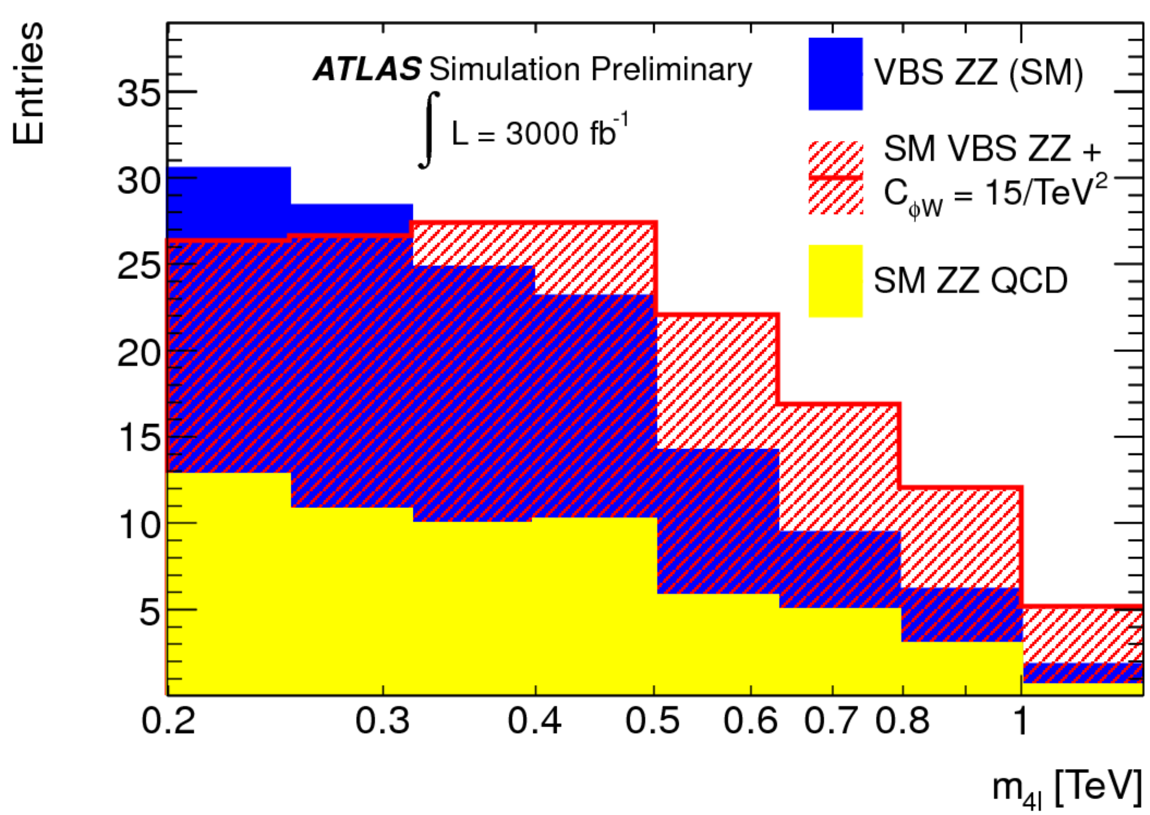
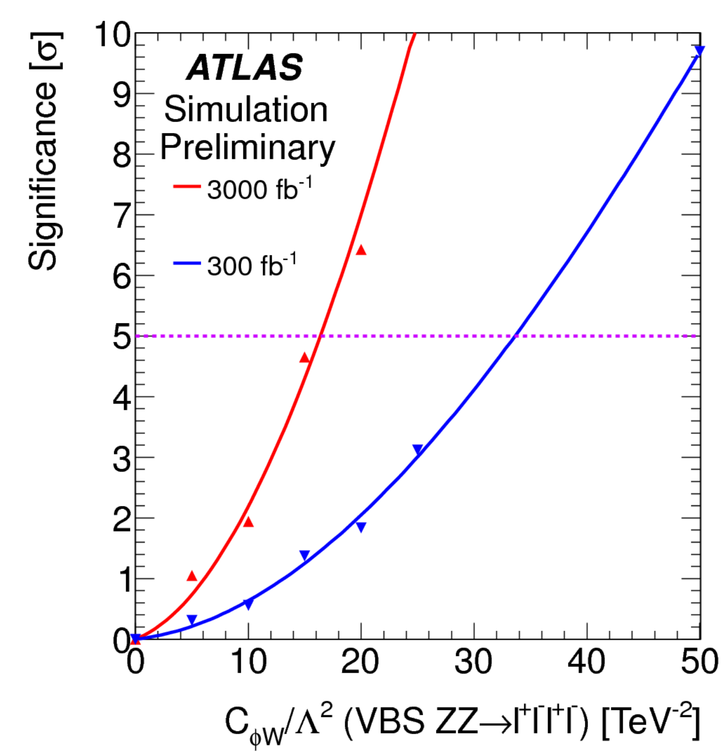
pp→ZZjj→4ljj

- Small cross section but clean final state
- Sensitivity extracted using the m_{4l} mass spectrum
- Results are interpreted for the coefficient of the dim-6 operator $\mathbf{O_{\phi W}}$ involving Higgs and gauge boson fields

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

	Coefficient	5σ (L=300/fb)	5σ (L=3000/fb)
ATLAS	$c_{\phi W}/\Lambda^2$	**34 TeV^{-2}**	**16 TeV^{-2}**

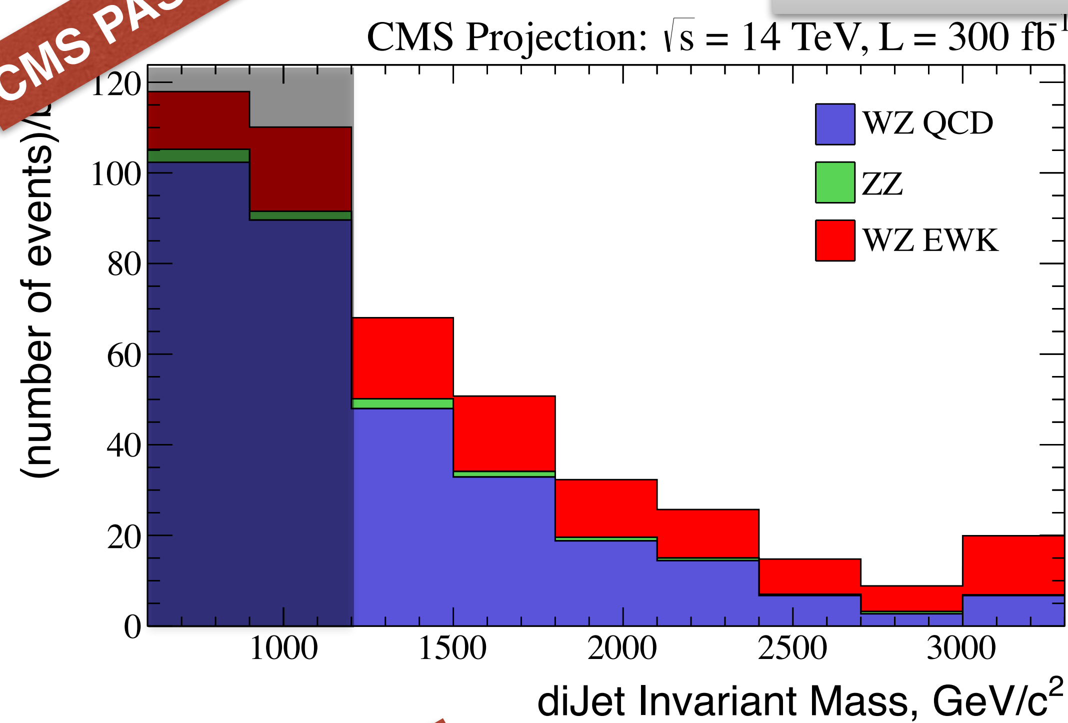




$pp \to WZjj \to l\nu lljj$

SM electroweak WZ production

CMS PAS FTR-13-006



- Counting experiment for $m_{jj} > 1.2$ TeV
- Evidence at **5σ with 185 fb^{-1}**

aQGC

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

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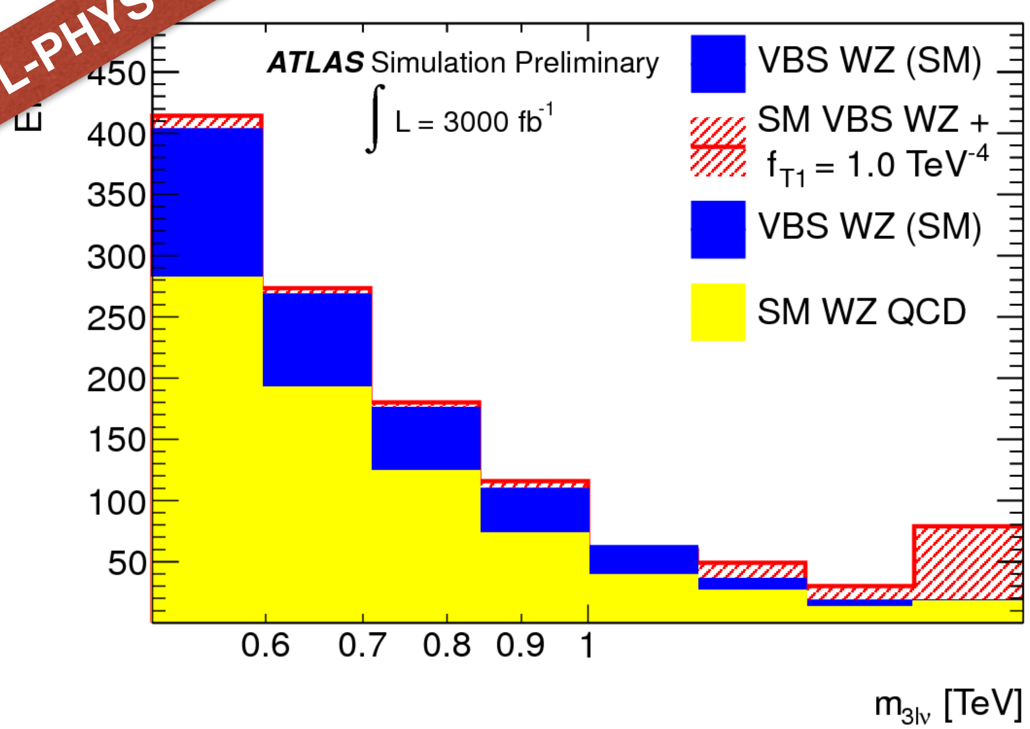

	Coefficient	5σ (L=300/fb)	5σ (L=3000/fb)
ATLAS	f_{T1}/Λ^4	**1.3 TeV^{-4}**	**0.6 TeV^{-4}**
CMS	f_{T1}/Λ^4	**1.00 TeV^{-4}**	**0.55 TeV^{-4}**

$pp \rightarrow W^\pm W^\pm jj \rightarrow l\nu l\nu jj$

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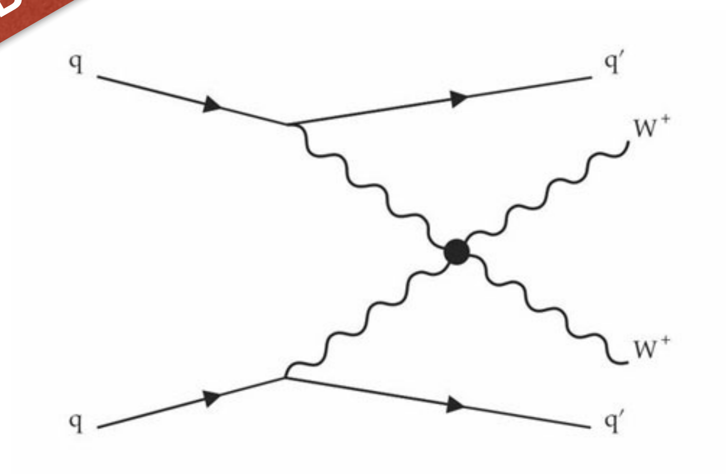

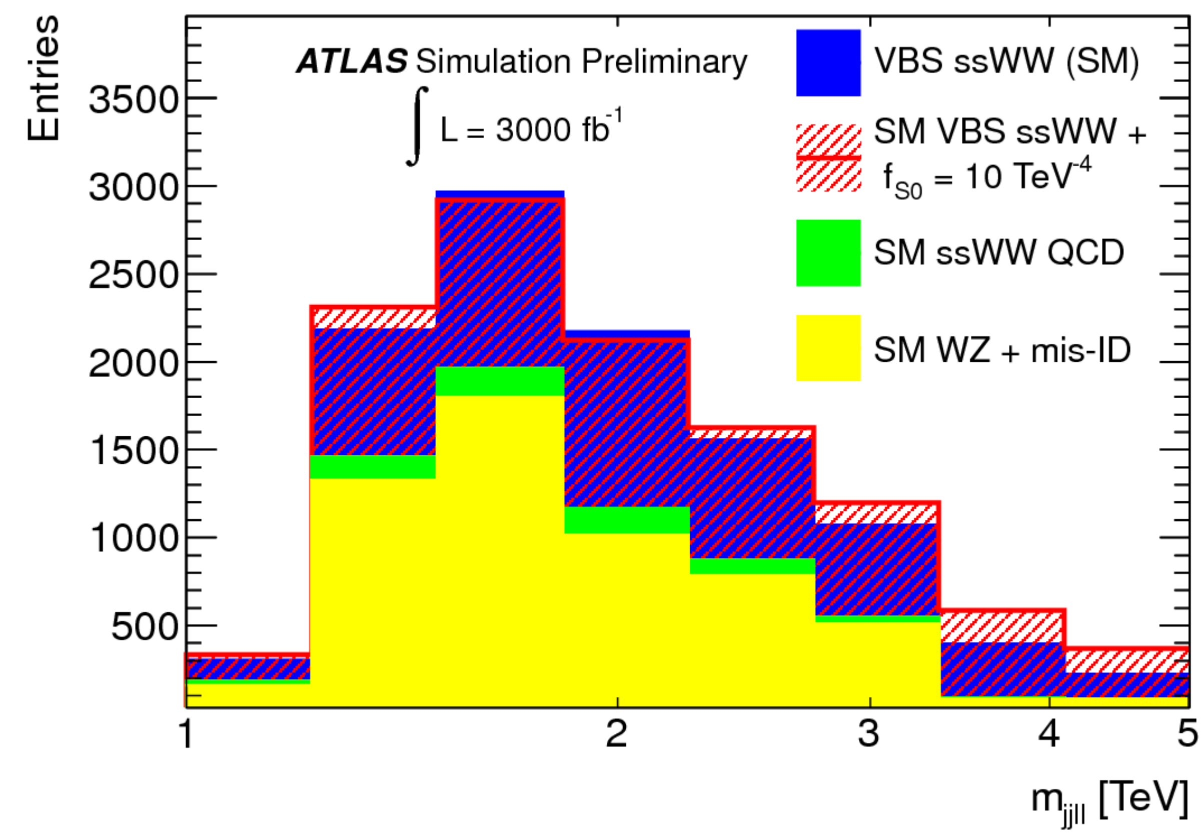

- The m_{lljj} variable is used to discriminate from the background
- Main background is WZ (lost lepton from Z decay)
- Sensitivity to dim-8 with only derivatives of Higgs field

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

	Coefficient	5σ (L=300/fb)	5σ (L=3000/fb)
ATLAS	f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

Summary

- The **HL-LHC** is a unique possibility to look for new physics in the Higgs sector
    - significant gain in studying processes with **small cross sections** and performing **precision measurements** of the couplings
- Phase II upgrade is crucial for most of these channels
    - improved Trigger, extended Tracking, forward Calorimetry
- Projections by **ATLAS** and **CMS** confirm the presence of a promising physics program with L_{int}=3000 fb^{-1}

Additional slides

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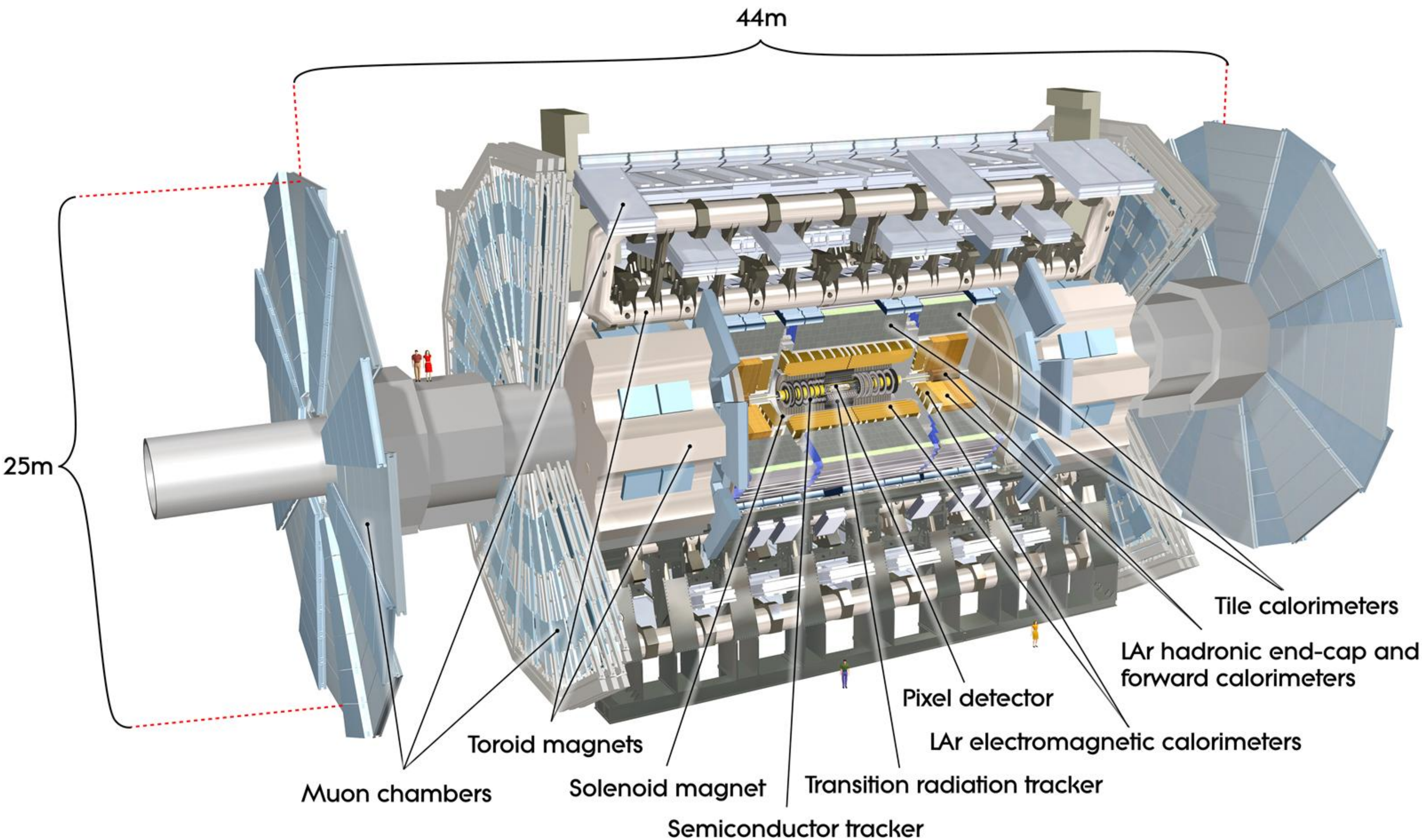
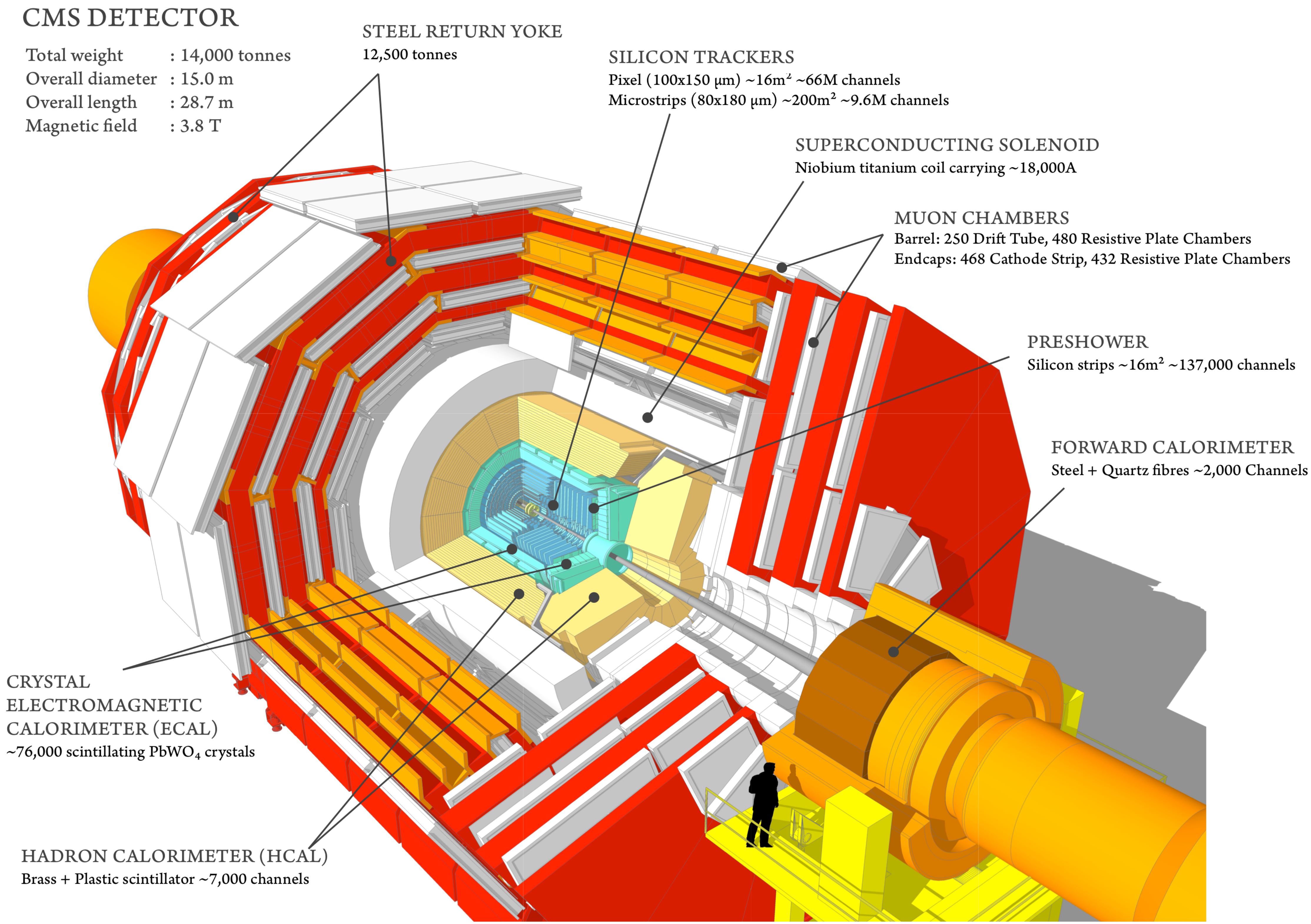
ATLAS detector



CMS detector



Phase I detector upgrades

- **ATLAS**
  - Muon detector: new small wheels
  - Calorimeter: improved granularity for L1 Trigger
  - Fast track trigger
  - Forward system installation
- **CMS**
  - Pixel detector: replacement
  - Hadron Calorimeter: new photodetectors and electronics
  - L1-Trigger: FPGAs and μTCA backplane technology, new architecture
  - Muon detector: CSC and RPC 4th station

Phase II detector upgrade

- **ATLAS**
  - Tracker detector: replacement (new layout)
  - LAr calorimeter: new electronics
  - Forward calorimeter: upgrade under study
  - Muon system: replacement of forward detectors
  - Muon Track Trigger
- **CMS**
  - Tracker detector: replacement (new layout)
  - Pixel detector: extended coverage
  - Track Trigger
  - Calorimeter: High Granularity Calorimeter (endcap), replacement of electronics
  - Muon System: new forward detector, replacement of electronics

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2HDM: couplings

Most general 2HDM Lagrangian

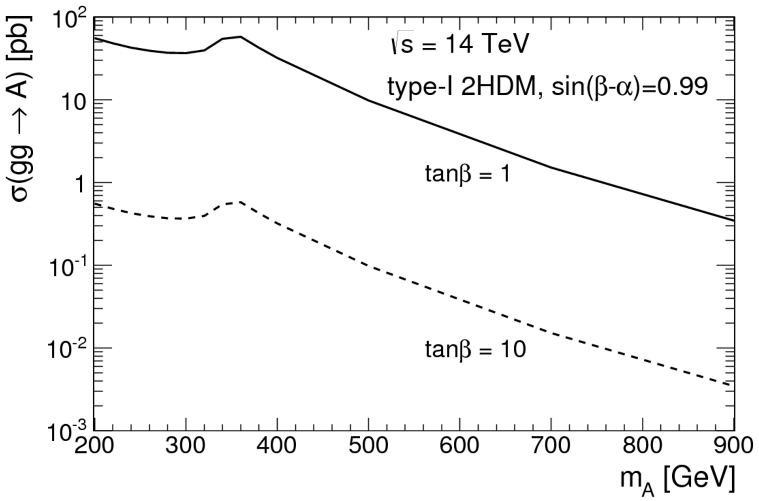
$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + \text{h.c}\right\} \quad (1)$$

- Parameters are real (CP-conservation)
- Only soft Z_2 symmetry breaking (no FCNC at tree-level) ⇒ $\lambda_6=\lambda_7=0$
  - additional freedom to choose the form of the Z_2 symmetry
- $\sin(\beta-\alpha)\to 1$ is the SM limit

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

2HDM cross sections and BR

σ(gg→A) x BR(A→Zh)



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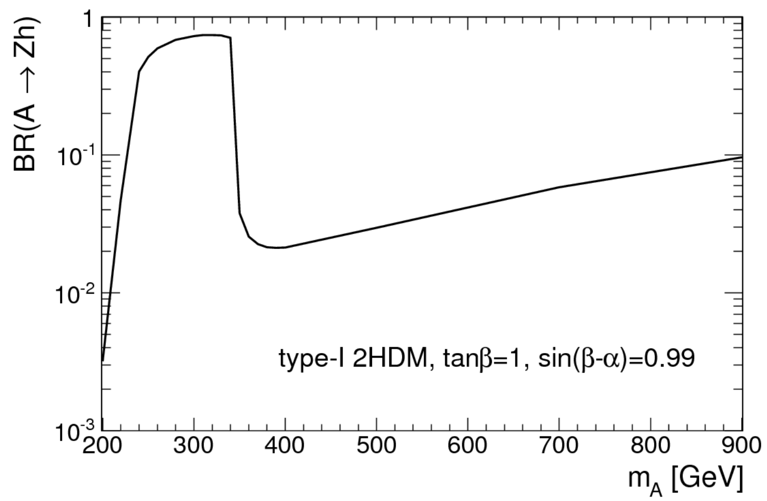


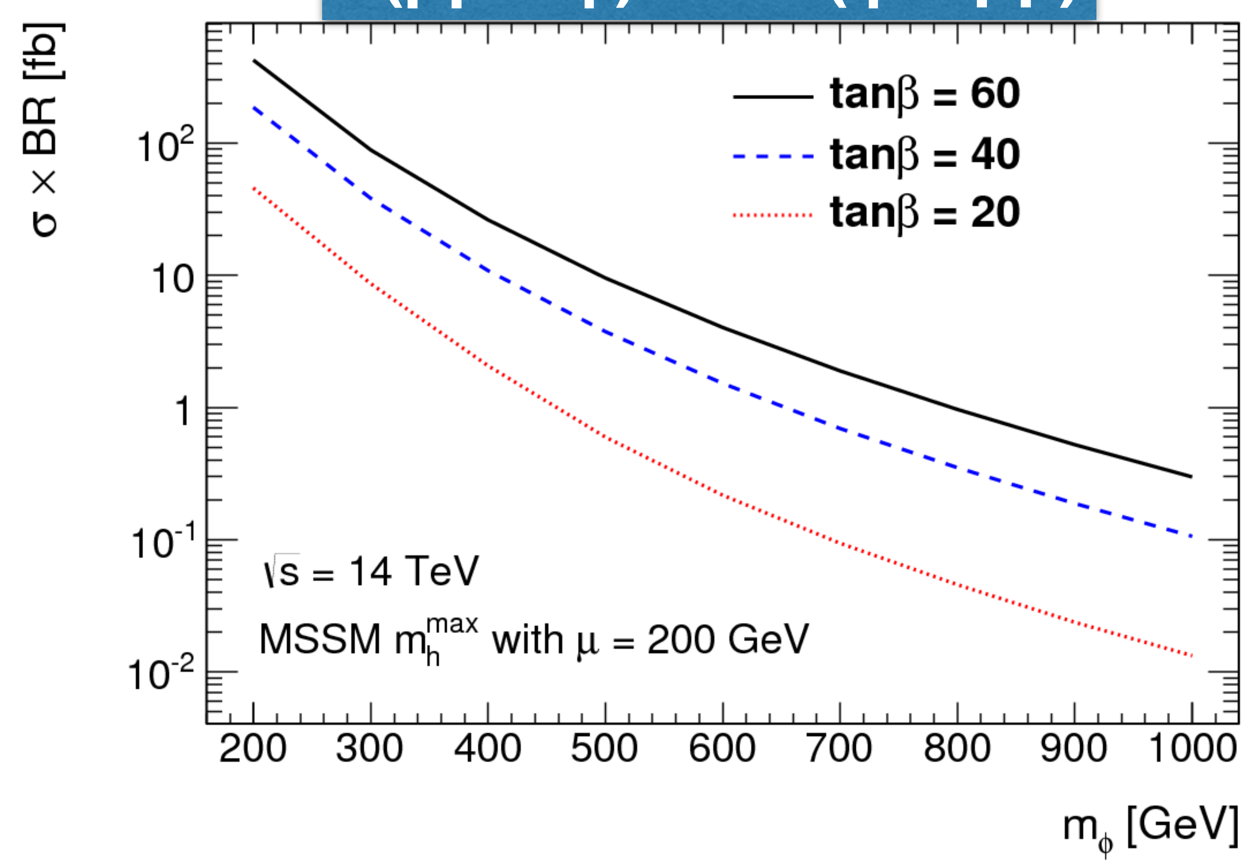
- m_h=125GeV
- $m_A = m_H = m_{H^\pm}$
- Narrow width
- gluon fusion cross section known to up to NNLO QCD accuracy
- b-associated production
  - Type I: negligible
  - TypeII: ~25% of gluon-fusion for tanβ=3
- $m_{12}^2 = m_A^2 \tan\beta/(1-\tan^2\beta)$

σ(pp→φ) x BR(φ→μμ)

- m_h^{max} scenario is used to derive conservative limits on (m_A,tanβ)
- gluon-fusion and b-associated cross section are added
- cross sections for CP-even H and CP-odd A are added (mass degeneracy assumed)

m_h^{max} scenario

$$m_t = 173.2 \text{ GeV},$$
$$M_{SUSY} = 1000 \text{ GeV},$$
$$\mu = 200 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{OS} = 2\, M_{SUSY} \text{ (FD calculation)},$$
$$X_t^{\overline{MS}} = \sqrt{6}\, M_{SUSY} \text{ (RG calculation)},$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV}.$$



A→Zh→llbb (ATLAS)

- GEN level quantity are smeared according to parameterised response studied on full-sim (GEANT)
  - <140> pile-up assumed
- $m_A^{rec} = m_{llbb} - m_{ll} - m_{bb} + m_Z^0 + m_h^0$ is used
- ΔR(bb) cut, m_A-dependent
- 30% systematic on backgrounds and signal yields (uncorrelated)
- Asymptotic CL_S is used
- Binned likelihood fit in bins of m_A

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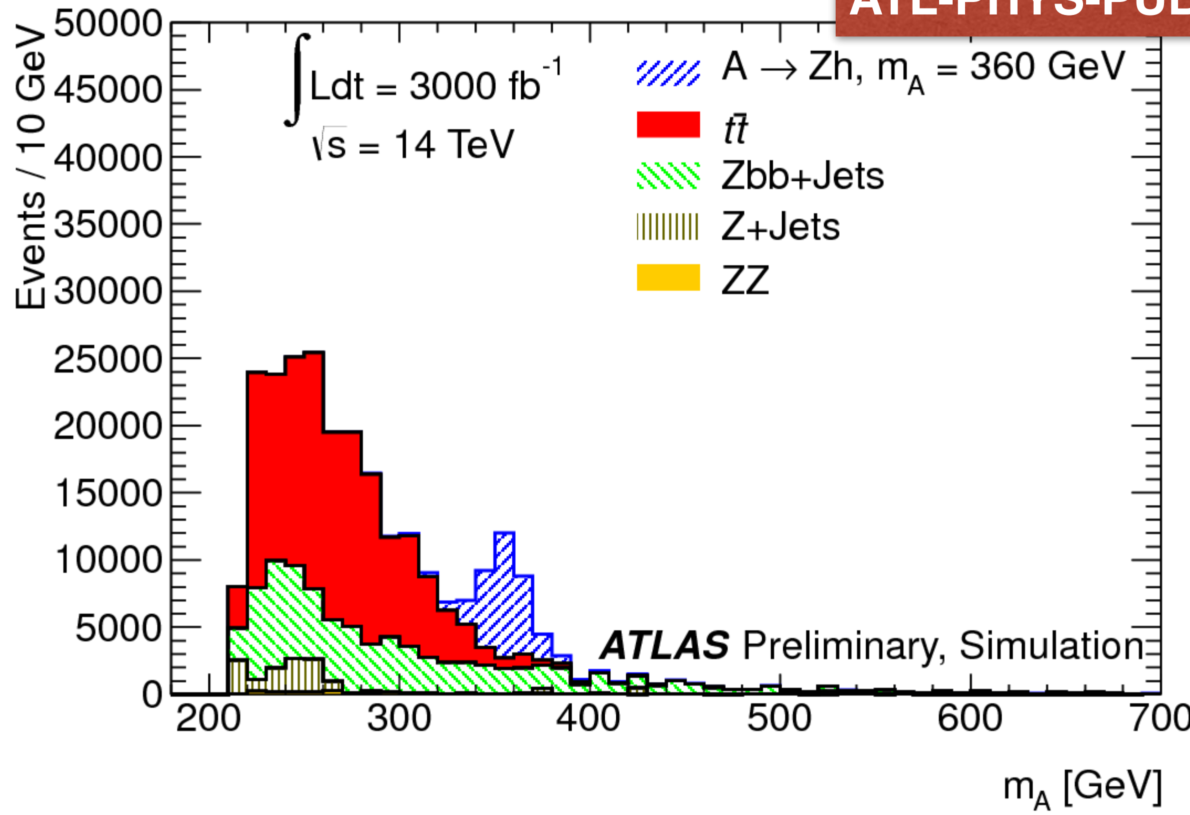

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$A \to Zh \to llbb$ (CMS)

CMS PAS FTR-13-024

- Delphes used for detector response simulation
  - <140> pile-up assumed
- Tau-veto to maintain orthogonality with $A \to Zh \to ll\tau\tau$
- $|\Delta\phi(l_1,l_2)|$, $p_T(Z)$, $p_T(Z)/p_T(h)$ cuts applied to further discriminate against background
- Binned likelihood fit in bins of m_A

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$\phi \rightarrow \mu\mu$ (ATLAS)

- GEN level quantity are smeared according to parameterised response studied on full-sim (GEANT)
  - <140> pile-up assumed
- No systematic uncertainty is considered
- Asymptotic CL_S is used

H→ZZ→4l (ATLAS)

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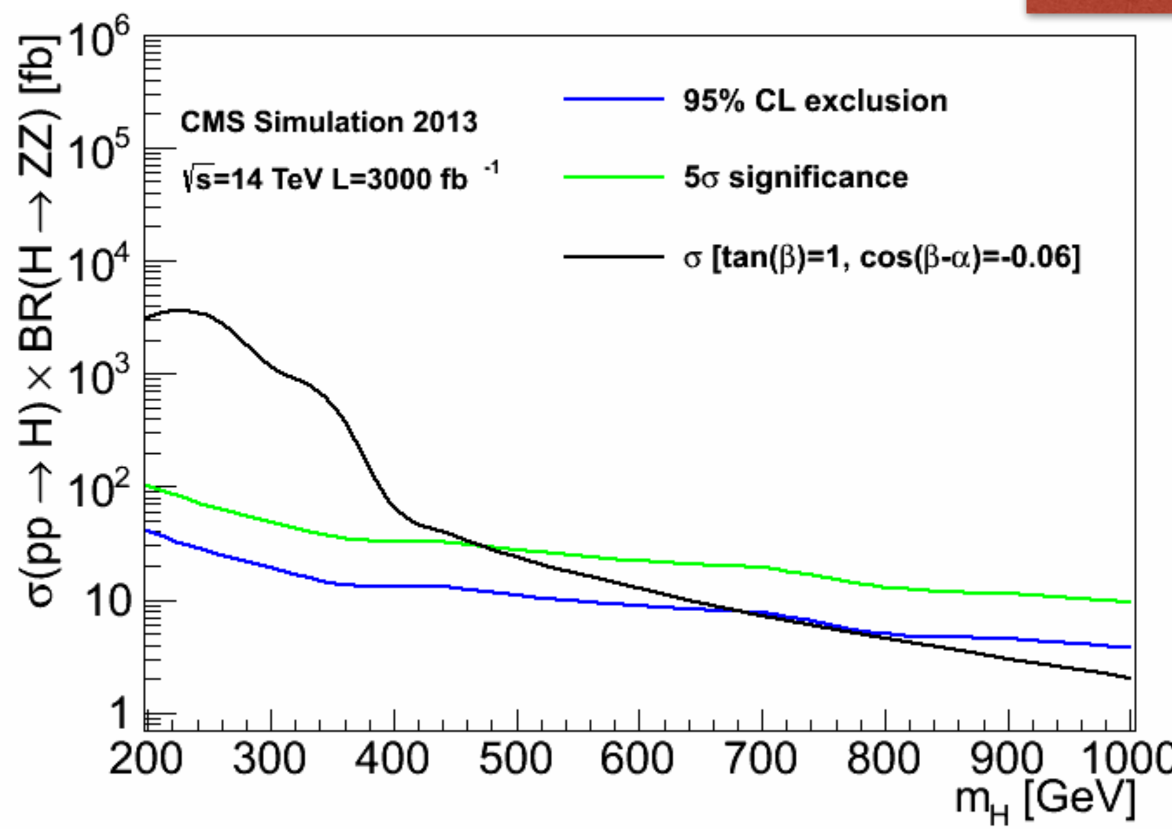
- GEN level quantity are smeared according to parameterised response studied on full-sim (GEANT)
  - <140> pile-up assumed
- Same systematic uncertainty as in Run1 is assumed
- The natural width is the same as for a SM Higgs
- The Higgs lineshape is calculated using the complex-pole-scheme
- Interference with the background is taken into account in the background systematics
- Asymptotic CL_S is used

H→ZZ→4l (CMS)

- Delphes used for detector response simulation
  - <140> pile-up assumed
- Narrow width is assumed
  - good approximation in the parameter space allowed by coupling fit
- MSSM-like scenario: $\lambda_{5,6,7}=0$
- 20% systematic on the background
- Binned likelihood fit in bins of m_H

CMS PAS FTR-13-024



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$A \to Zh \to llbb$: 2HDM Type I

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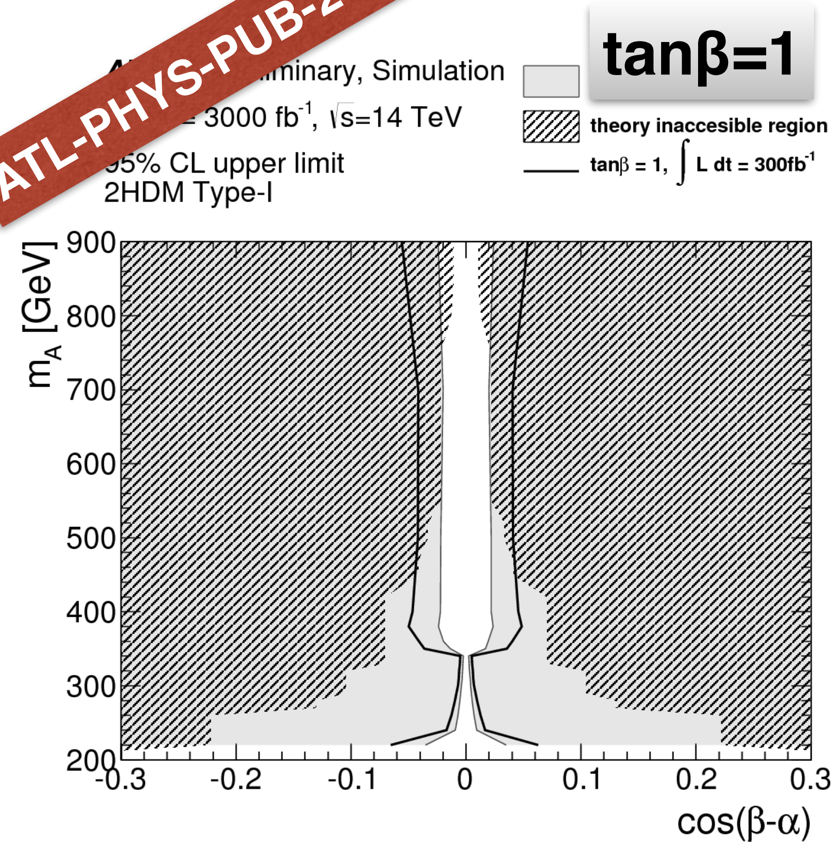
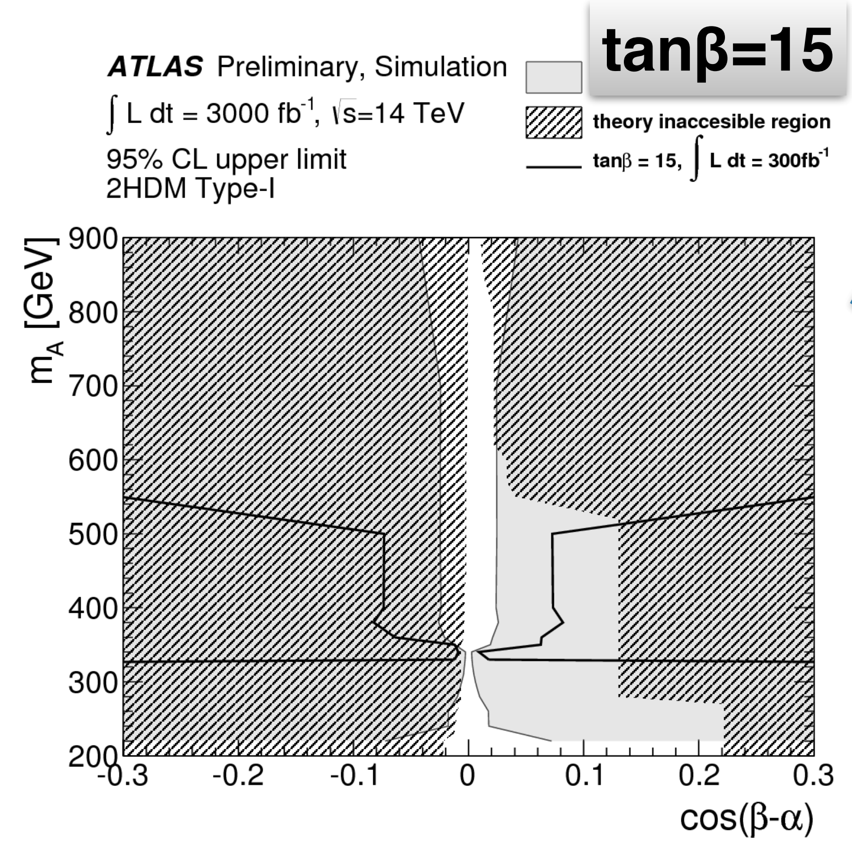
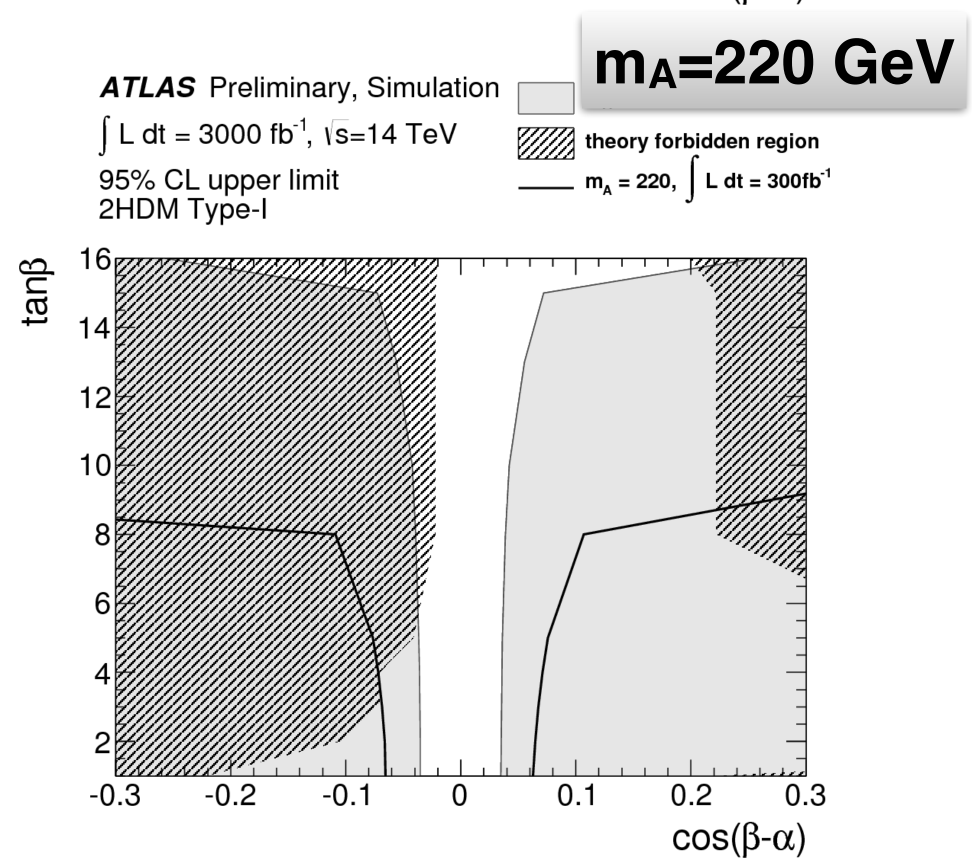
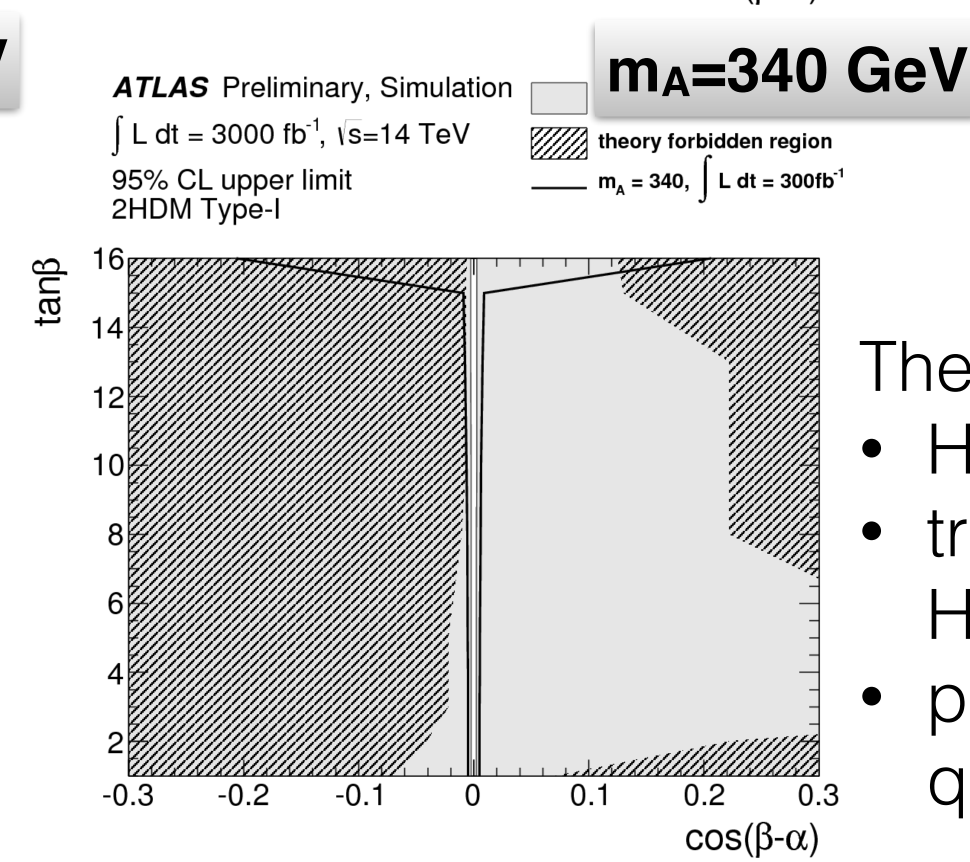




Exclusion limits





Best sensitivity at ~340 GeV (<~ $2m_{top}$)

Theoretical bounds include:

- Higgs potential stability
- tree-level unitarity of Higgs scattering
- perturbativity of the quartic

A→Zh→llbb: 2HDM Type I

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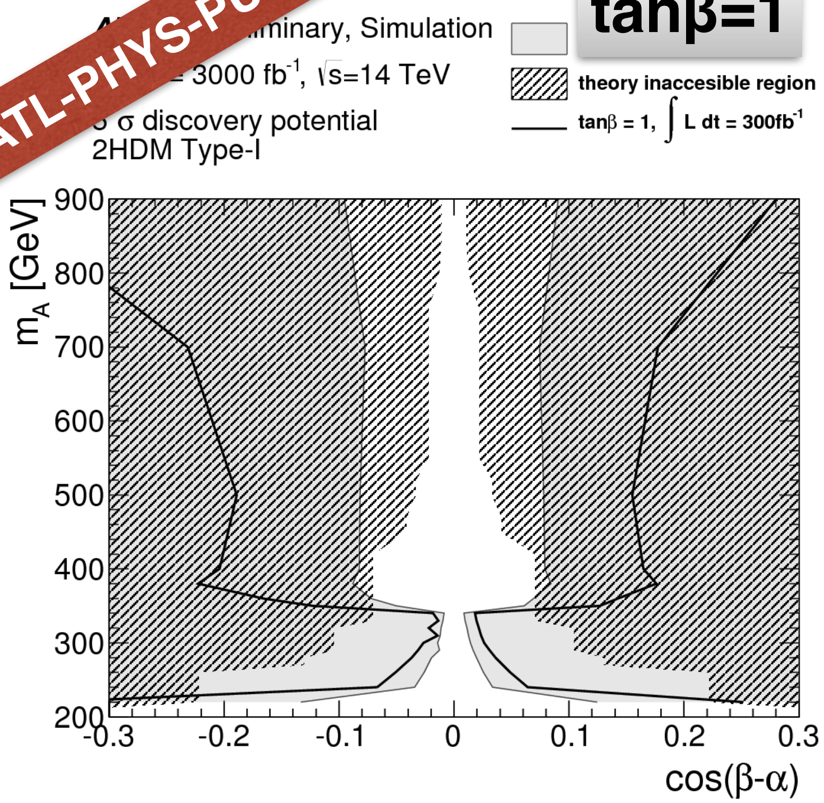
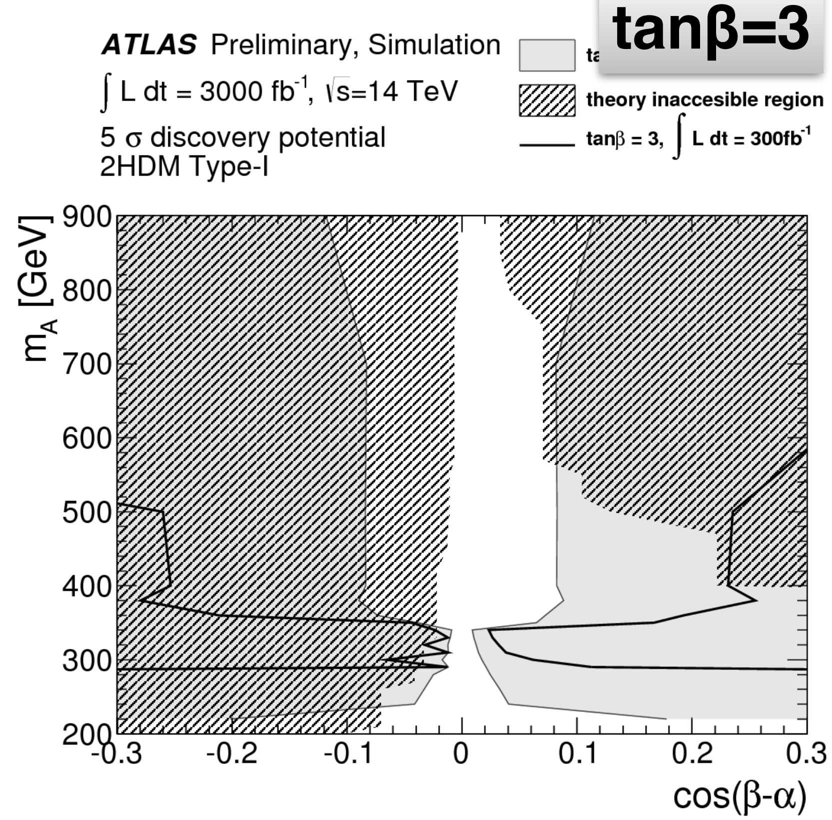
tanβ=1

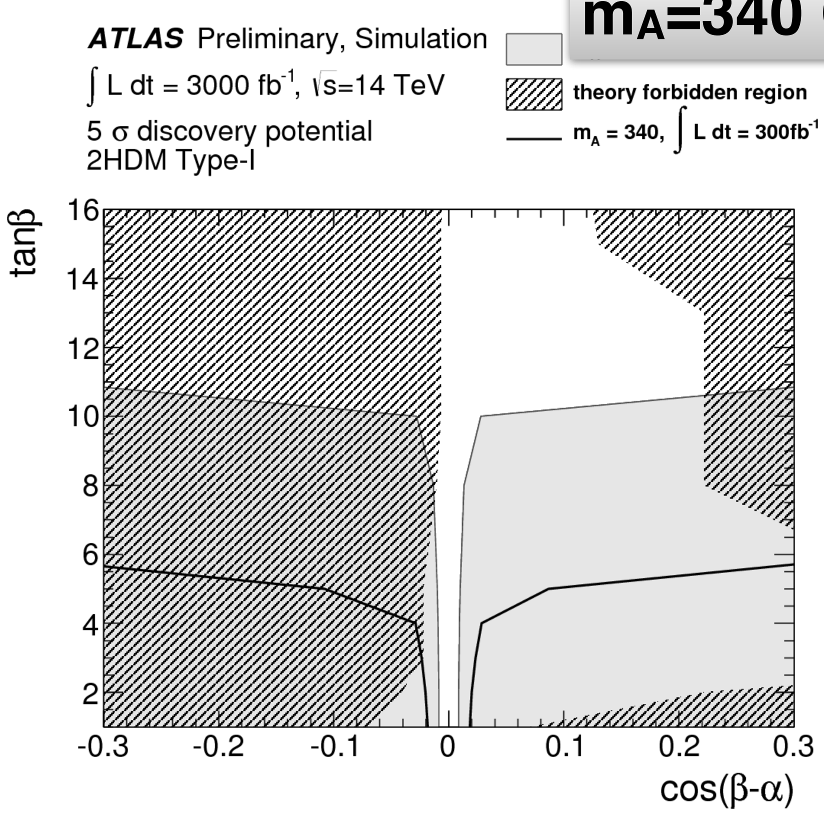


tanβ=3

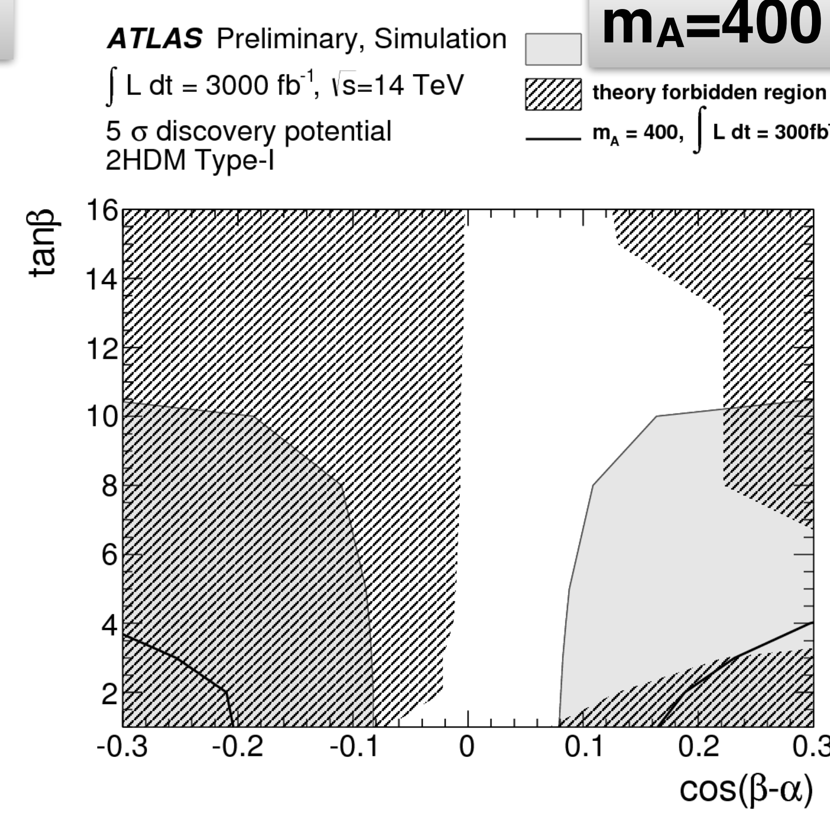


5σ discovery

m_A=340 GeV



m_A=400 GeV



Best sensitivity at ~340 GeV (<~ $2m_{top}$)

Theoretical bounds include:

- Higgs potential stability
- tree-level unitarity of Higgs scattering
- perturbativity of the quartic

A→Zh→llbb: 2HDM Type II

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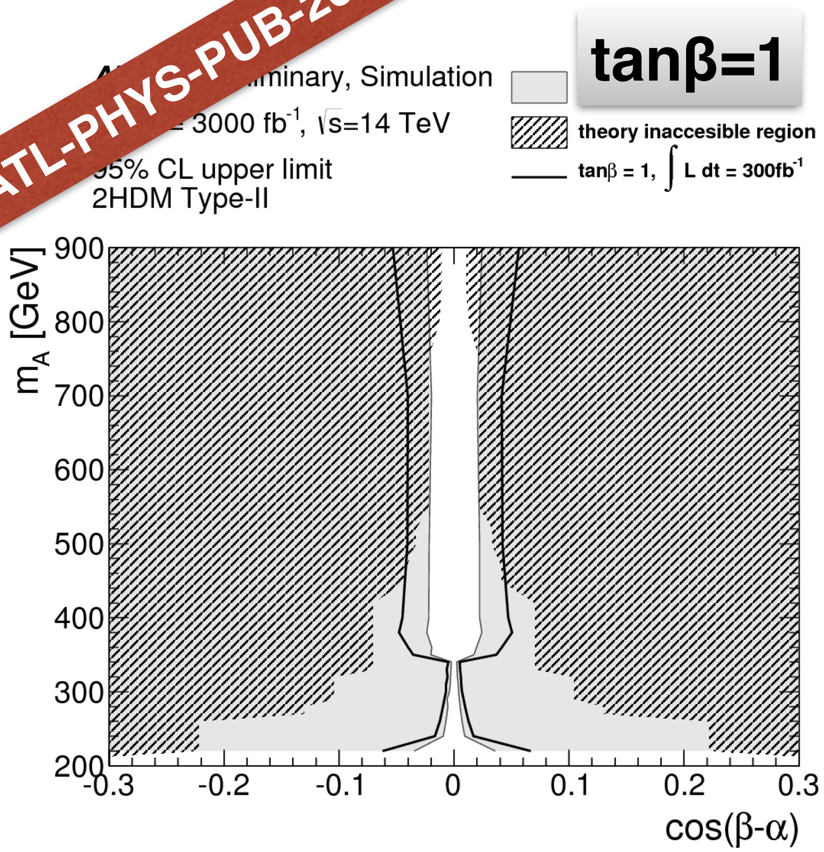
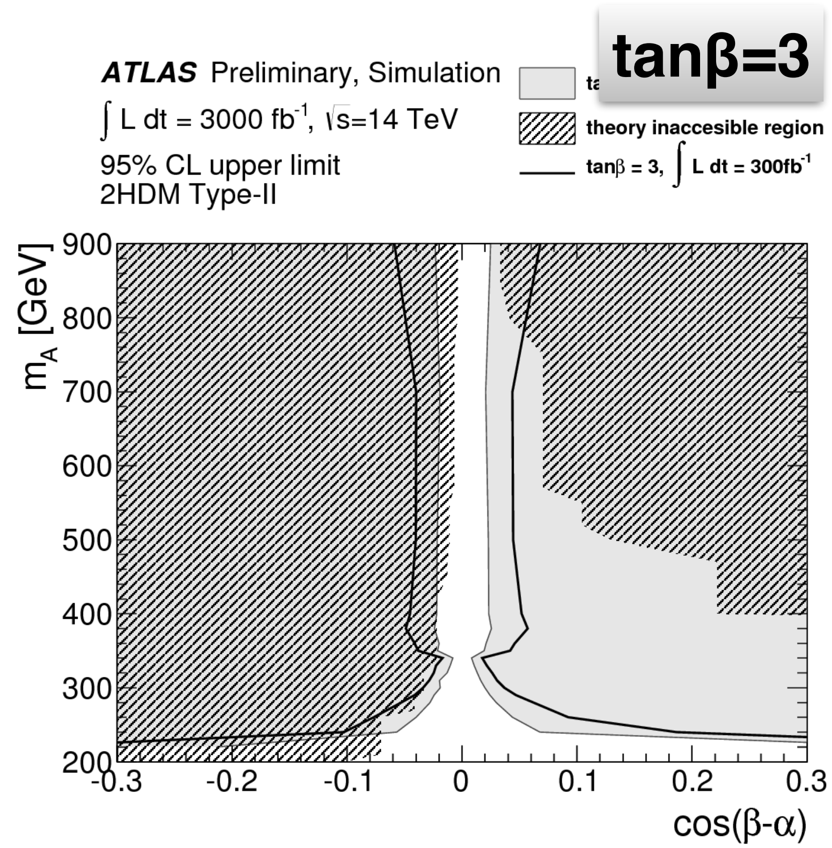
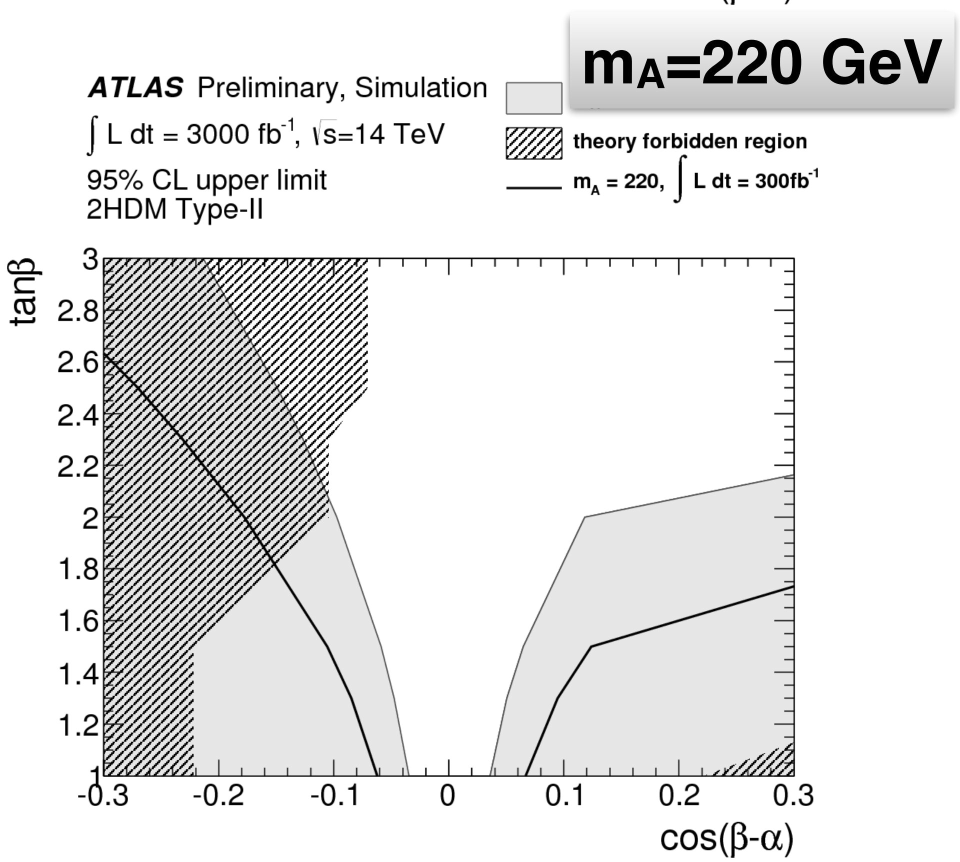
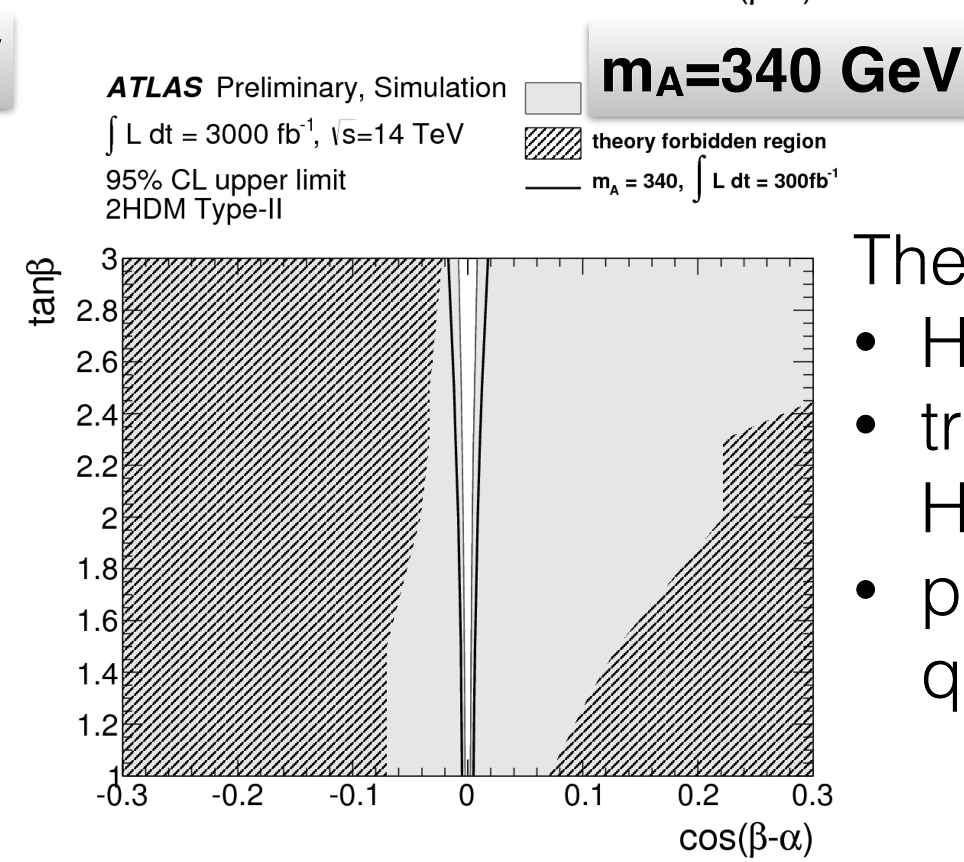




Exclusion limits

Best sensitivity at ~340 GeV (<~ $2m_{top}$)





Theoretical bounds include:

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- perturbativity of the quartic

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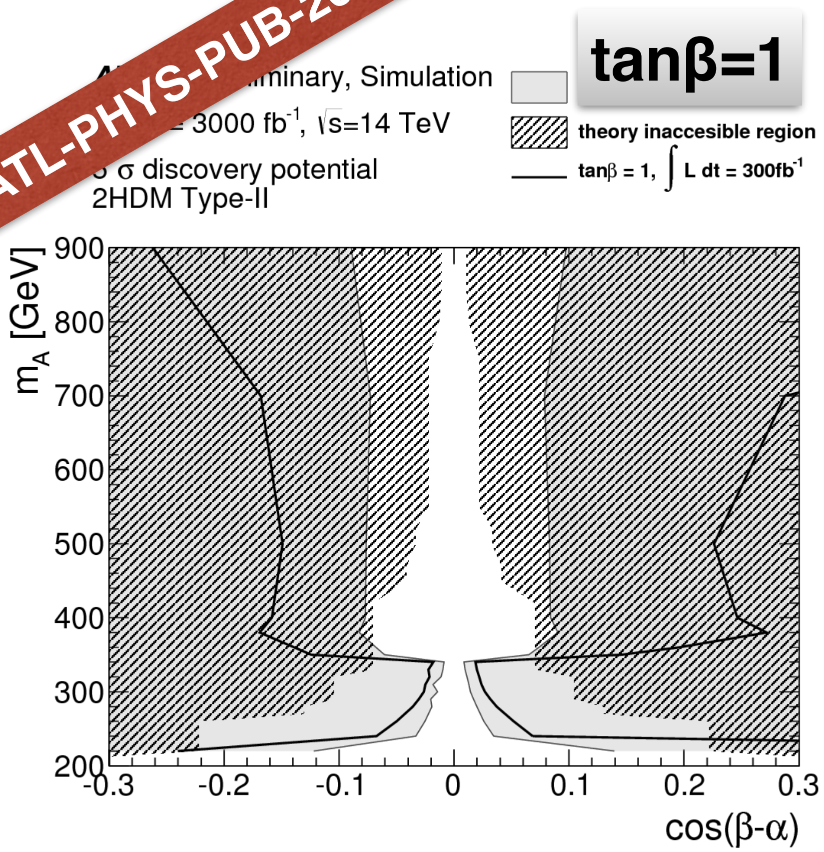
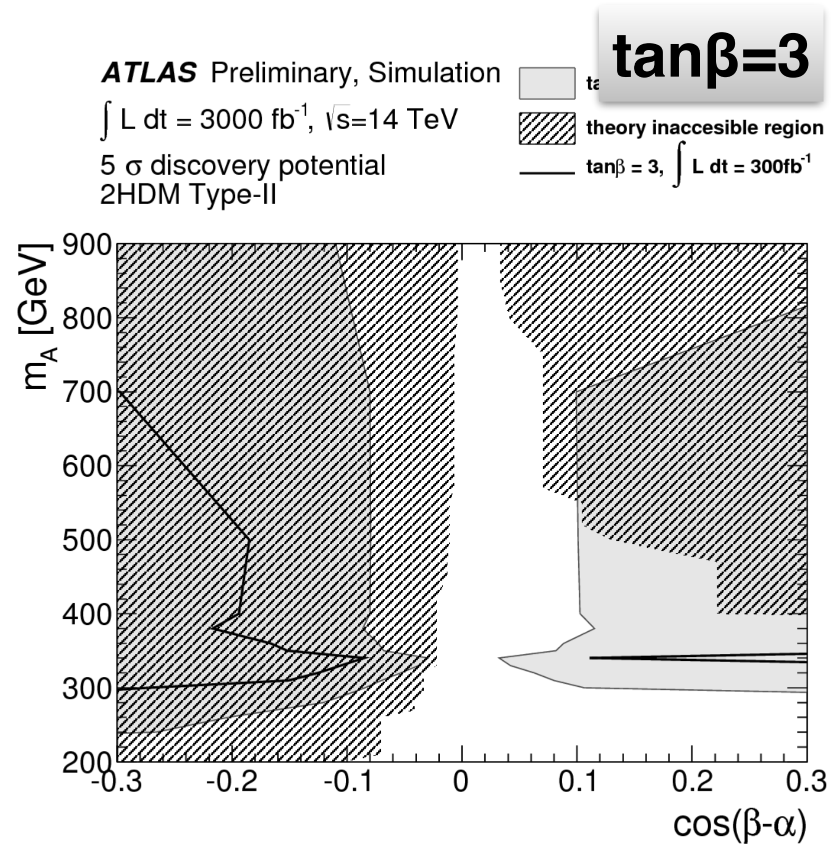
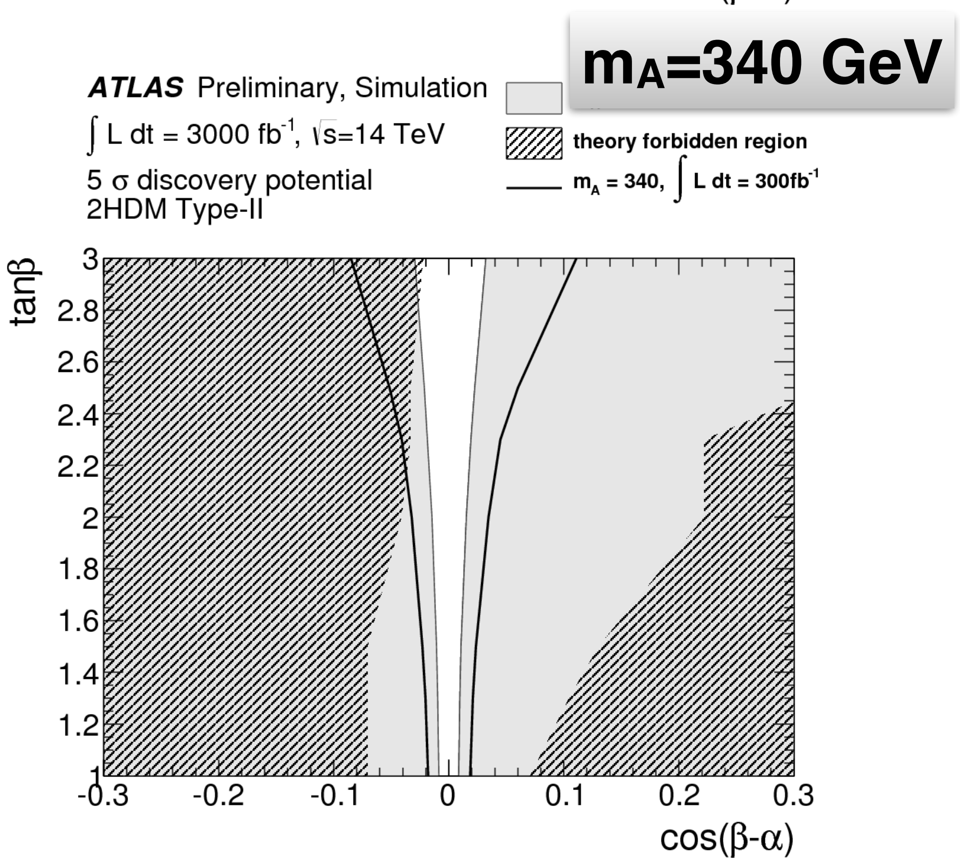
A→Zh→llbb: 2HDM Type II

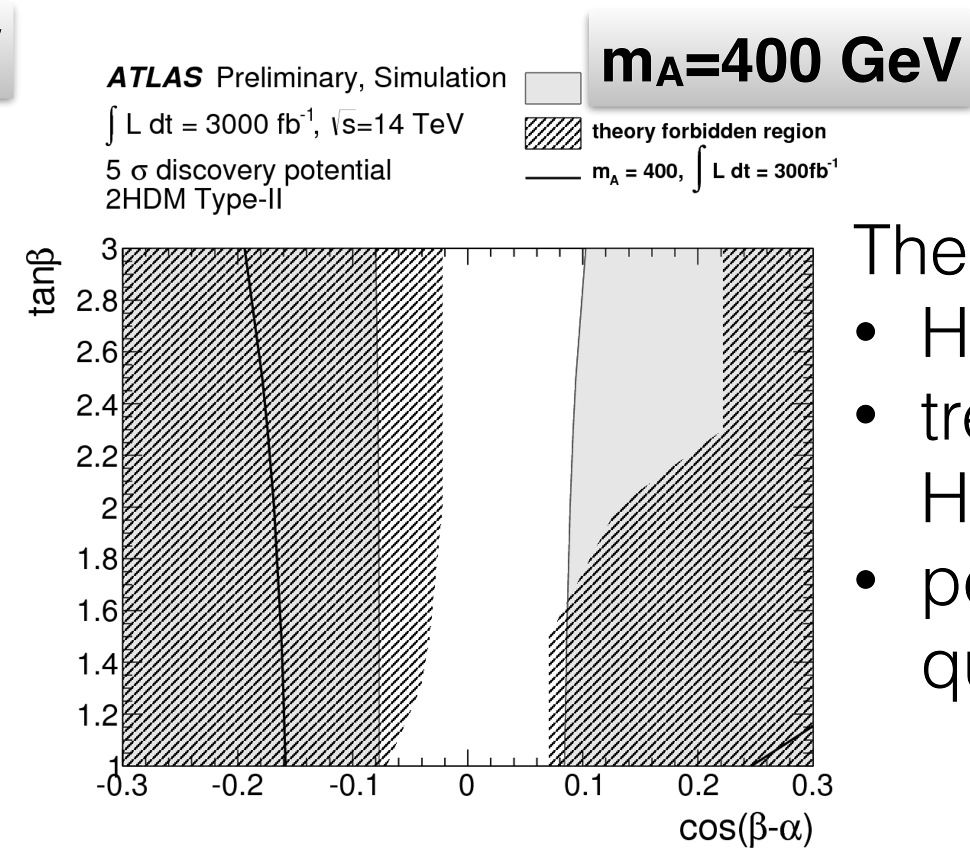




5σ discovery

Best sensitivity at ~340 GeV (<~ 2m$_{top}$)





Theoretical bounds include:

- Higgs potential stability
- tree-level unitarity of Higgs scattering
- perturbativity of the quartic

Imperial College London

ATL-PHYS-PUB-2014-017

Coupling accuracy

	Model	Coupling parameter	Description	Expected precision 300 fb^{-1} All syst.	300 fb^{-1} w/o theory	3000 fb^{-1} All syst.	3000 fb^{-1} w/o theory
1	MCHM4, EW singlet	μ_h	Overall signal strength	8.5%	4.8%	6.5%	3.4%
		$\kappa = \sqrt{\mu_h}$	Universal coupling	4.2%	2.4%	3.2%	1.7%
2	MCHM5, 2HDM Type I	κ_V	Vector boson (W, Z) coupling	4.3%	2.5%	3.3%	1.7%
		κ_F	Fermion ($t, b, \tau, \mu, \ldots$) coupling	8.8%	7.1%	5.1%	3.2%
3	2HDM Type II, MSSM	κ_V	Vector boson coupling	5.9%	5.3%	3.7%	3.0%
		κ_u	Up-type fermion (t, c, u) coupling	8.9%	7.2%	5.4%	3.4%
		κ_d	Down-type fermion ($b, \tau, \mu, \ldots$) coupling	12%	12%	6.7%	6.1%
4	2HDM Type III	κ_V	Vector boson coupling	4.3%	2.5%	3.3%	1.7%
		κ_q	Quark coupling	11%	7.8%	6.6%	3.6%
		κ_l	Lepton (τ, μ, e) coupling	10%	9.3%	6.0%	5.1%
5	2HDM Type IV	κ_V	Vector boson coupling	7.9%	7.6%	4.3%	3.7%
		$\kappa_{u',l}$	Up-type quark (t, c, u) & lepton coupling	11%	10%	5.6%	4.5%
		$\kappa_{d'}$	Down-type quark (b, s, d) coupling	21%	21%	11%	9.6%
6	Mass scaling parametrization	κ_Z	Z boson coupling	8.1%	7.8%	4.3%	3.8%
		κ_W	W boson coupling	8.5%	8.1%	4.8%	3.9%
		κ_t	t quark coupling	14%	11%	8.2%	5.3%
		κ_b	b quark coupling	23%	22%	12%	10%
		κ_τ	τ lepton coupling	14%	13%	9.8%	8.7%
		κ_μ	Muon coupling	21%	21%	7.3%	7.0%
7	Higgs portal	κ_g	Gluon effective coupling	8.9%	6.3%	6.7%	2.8%
		κ_γ	Photon effective coupling	4.9%	4.7%	2.1%	1.7%
		$\kappa_{Z\gamma}$	$Z\gamma$ effective coupling	23%	23%	14%	14%
		BR_i	Invisible branching ratio	<22%	<20%	<14%	<10%

Simplified MSSM

- Radiative corrections are extracted by evaluating the mass-mixing matrix of the neutral CP-even bosons at $m_h = 125$ GeV
- The components of the *h* eigenvector are used to rewrite the couplings as a function of m_A, tanβ
- Loop corrections due to stops are neglected (<5% for $m_{stop} > 500$ GeV)
- Universality of down type fermion is assumed ($k_b = k_\tau$, etc.)
- b-associated production is accounted for as a correction scaling with y_b^2
  - assuming same differential distribution as for gluon fusion

Higgs portal

- Invisible decay BR of the Higgs is all due to decay to a pair of WIMPs X
  - $m_X < 0.5 * m_h$
  - give conservative limits on the DM-Higgs couplings
- DM-nucleon cross sections are expressed as a function of the Higgs-DM couplings for different DM spin hypothesis

$$\text{scalar } S: \quad \sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

$$\text{fermion } f: \quad \sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

$$\text{vector } V: \quad \sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2},$$

f_N is the Higgs-nucleon form factor (lattice QCD)

Excluded cross section is proportional to the limit on BR(H→inv)