Future Prospects for Higgs Measurements at LHC Run 2+3

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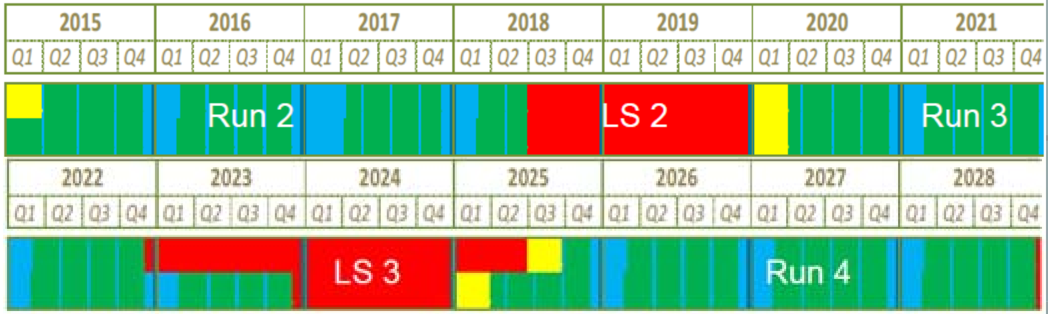
for the ATLAS & CMS collaborations

The LHC program

LHC run 2 + 3 data taking at 13-14 TeV cms energy until end of 2022

LHC Injectors

LHC Injectors

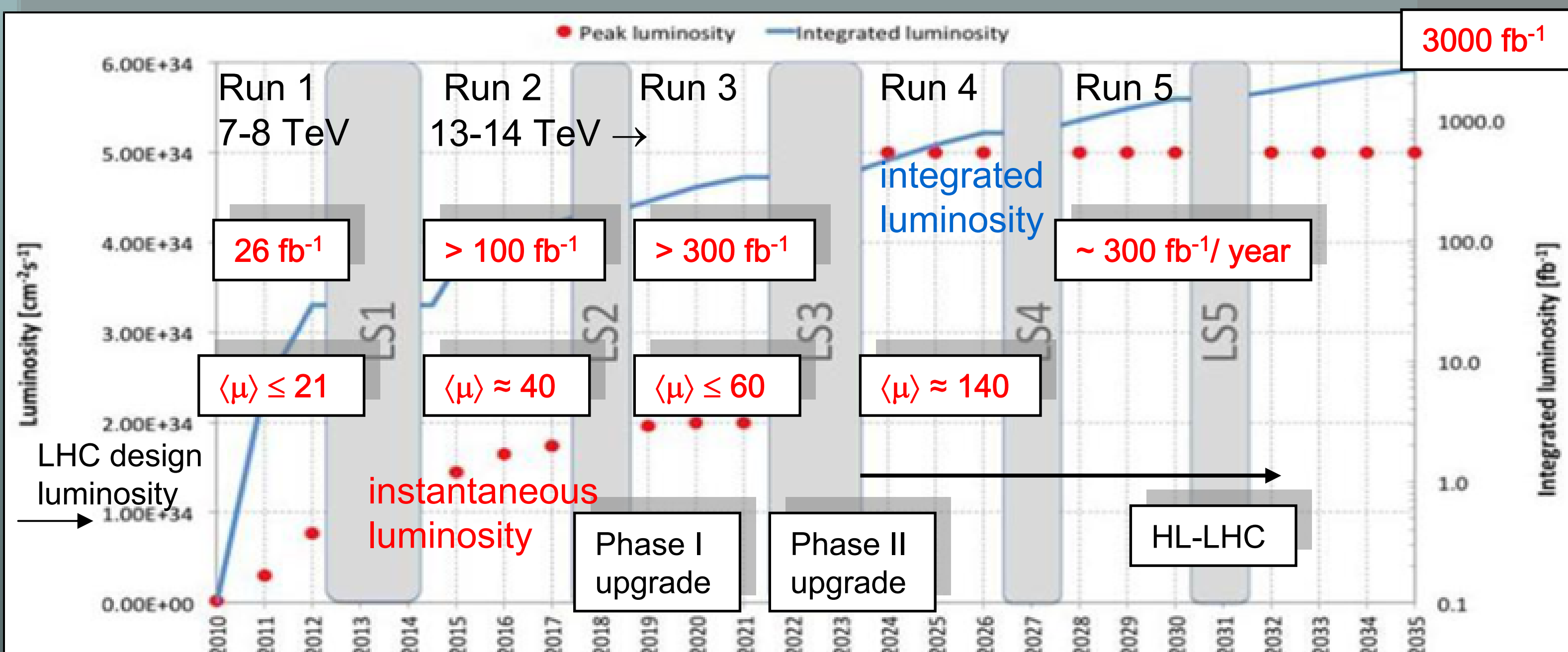


LHC schedule of 02/12/2013, (F.Bordry to LHCC, 04/12/2013),

runs 2 and 3 approved

Start of run 2 parameters defined:
13 TeV, $\beta^* \leq 0.5$ m

	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	2508	1.15×10^{11}	1.9 μm	1.6×10^{34} $cm^{-2}s^{-1}$	~43	~42 fb^{-1}



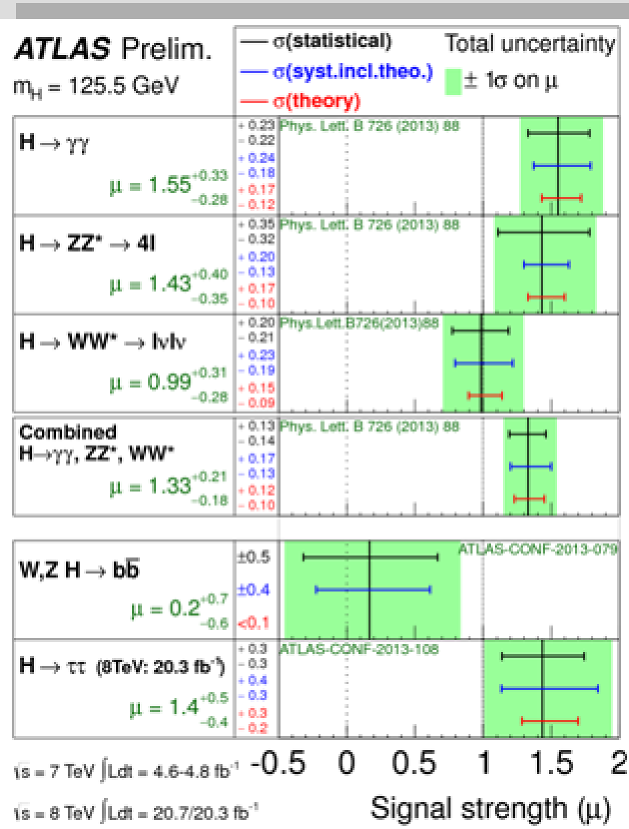
$\langle\mu\rangle$ = average number of pile-up pp interactions per BC.

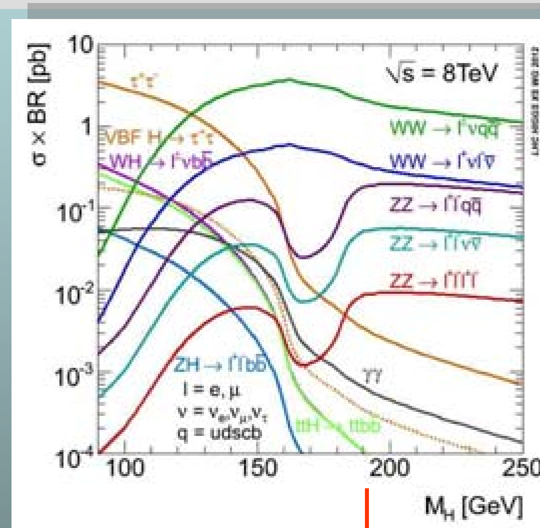
$\mu = \sigma_{inel} L/n_b f_r$

Higgs status

With 26 fb^{-1} at 7-8 TeV (run 1, 2010-2012):

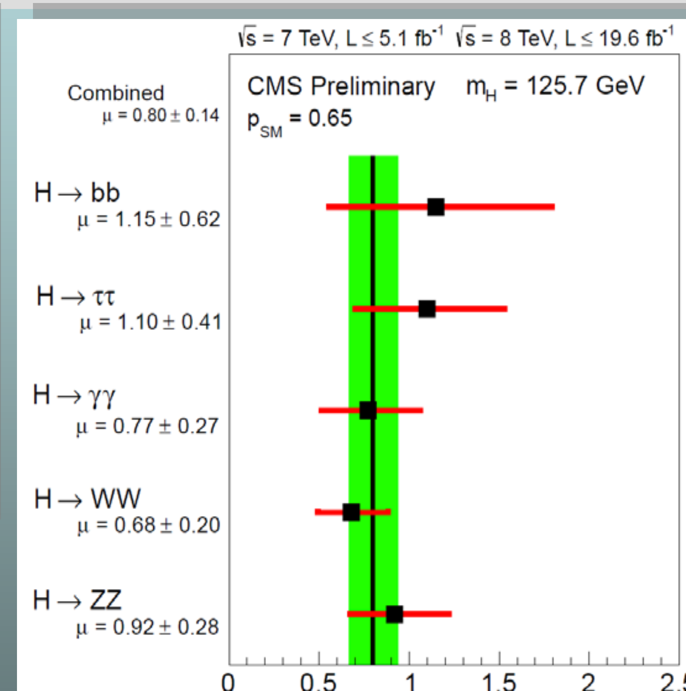
- **2012/13:** Discovery of a scalar (~3σ) Higgs boson in decays into gauge boson pairs γγ, ZZ, WW with mass of 125.6 GeV (ATLAS-CONF-2013-014, CMS-PAS-HIG-13-005).
- **2013:** Evidence for decays into fermions: $H \to \tau\tau$: ATLAS 4.1 σ (ATLAS-CONF-2013-108), CMS 3.4 σ (CMS-HIG-13-004, M.Vazquez Acosta, CERN-LHC seminar 03/12/2013)





ATL-CONF-2013-108

$\mu = \sigma\, BR / (\sigma\, BR)_{SM}$



CMS-HIG-13-005

Δμ/μ [%] (26 fb^{-1})	γγ	WW	ZZ	ττ	bb
ATLAS	20	30	26	32	325
CMS	35	26	29	33	54

ATL-CONF-2013-108

CMS-HIG-13-005, 002, 023, arXiv 1312:5353, arXiv 1312:1129

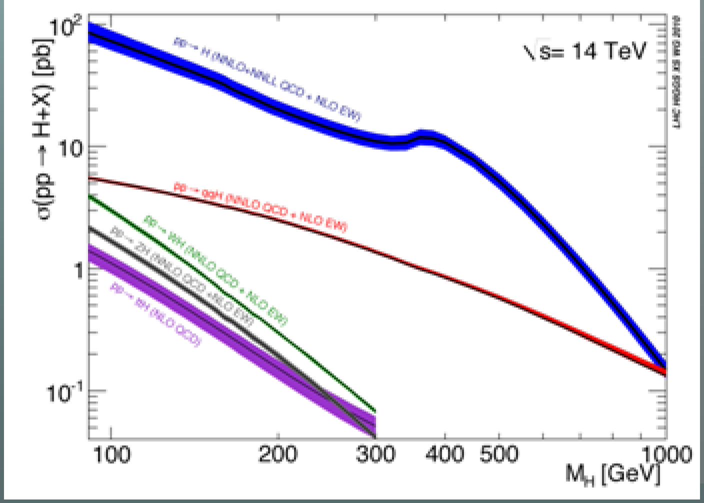
Higgs physics with 300 fb^{-1} at 13-14 TeV

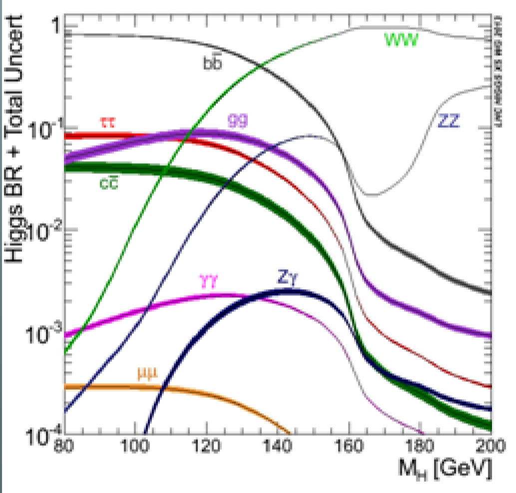
With > 10 x existing data set, 2.5 x inclusive Higgs production cross section:

- Precise measurements of Higgs production and decay rates, couplings and mass.

  ⇒ Test of the Standard Model in the Higgs sector and probe for new physics (order of few percent effects on Higgs couplings in most models).
- Search for rare/ new/ invisible decay modes.
- Measurements of tensor structure of Higgs couplings and possible CP violating contributions.
- Search for additional Higgs bosons beyond the Standard Model.
- Measurement of Higgs self-coupling only realistic for HL-LHC; not discussed here.

Theory: NNLO/NNLL QCD + NLO EWK calculations of Higgs ggF (VBF) production cross sections with 8% (0.6%) scale and 7% (1.7%) PDF+α_s uncertainties.
Branching ratios with typically 3-5% uncertainty.





Projections for future LHC runs

- Projections for run 2 + 3 together with HL-LHC projections have been prepared for European Strategy Update 2012, Snowmass Summer Study 2013 and the ECFA HL-LHC workshop October 2013 (most recent update).
- Goal to keep the current performance in run 2 and 3 for maximum double pile-up level with the planned detector and software upgrades, mainly in pixel detectors and trigger system (run 2 & 3).
- Encouraged by successful mitigation of effects of early large pile-up in run 1.
- Full simulation of signal and background processes for run 2 not yet available.

ATLAS:

Parametrisation of the detector response derived from

- full run 1 detector simulation with pile-up up to $\langle\mu\rangle$ = 69 and
- full Phase I detector simulation for $\langle\mu\rangle$ up to 80 and 14 =TeV cms energy.
- Also simulation of Phase II detector options for $\langle\mu\rangle$ = 80, 140, 200 for HL-LHC.

CMS:

Rescaling of run 1 signal and background yields for 14 TeV cms energy with the assumption that current detector performance kept after upgrades.
Complemented by parametrized detector simulation (e.g. for 2HDM studies).

Higgs coupling measurements

Measurement of $\sigma(XX \rightarrow H) \cdot BR(H \rightarrow YY) \sim \Gamma_X \, \Gamma_Y / \Gamma_H$ (in "small width approx.")
with total Higgs width $\Gamma_H = \Sigma_{SM} \, \Gamma_Y$ (+ Γ_{BSM}), dominated by Γ_b .

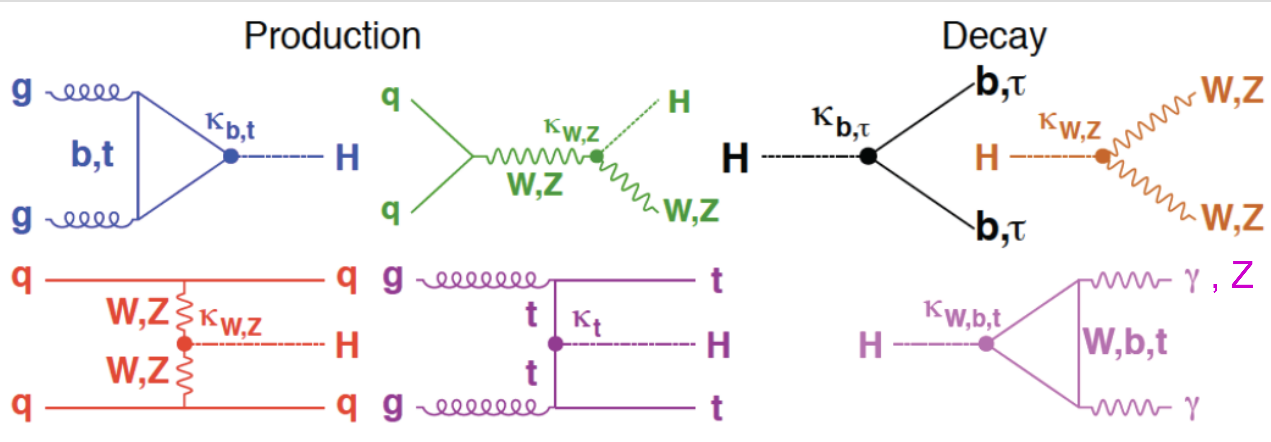
$\Gamma_{H,SM}$ = 4.2 MeV not directly measurable at LHC, but expected limits Γ_H < 920 (200) MeV at 300 fb^{-1} (3000 fb^{-1}) from mass shift due to finite width effects in $H \rightarrow \gamma\gamma$ signal and $\gamma\gamma$ background interference (ATLAS-PHYS-PUB-2013-014).

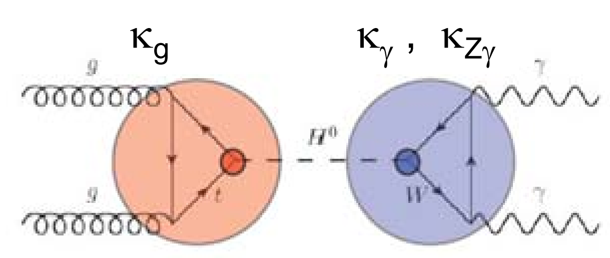
1) **Signal strengths** $\mu = \sigma \, BR / (\sigma \, BR)_{SM}$ determined directly for each production & decay channel.

2) **Higgs coupling scale factors** $\kappa_Y = g_{YY} / g_{YY\,SM}$ from fit to $\sigma \cdot$BR meas. test deviations from SM.

- Universal couplings κ_V and κ_F to weak gauge bosons (V= W,Z) and fermions (F= b, t, τ) in SM.
- $\Gamma_Y \sim \kappa_Y^2$, except Γ_γ and $\Gamma_{Z\gamma}$ which depend on W and fermion loops in SM, global coupling scale factor $\kappa_H^2 = \Gamma_H / \Gamma_{H,\,SM}$.
- Contributions from new physics through Γ_{BSM} and loop processes.

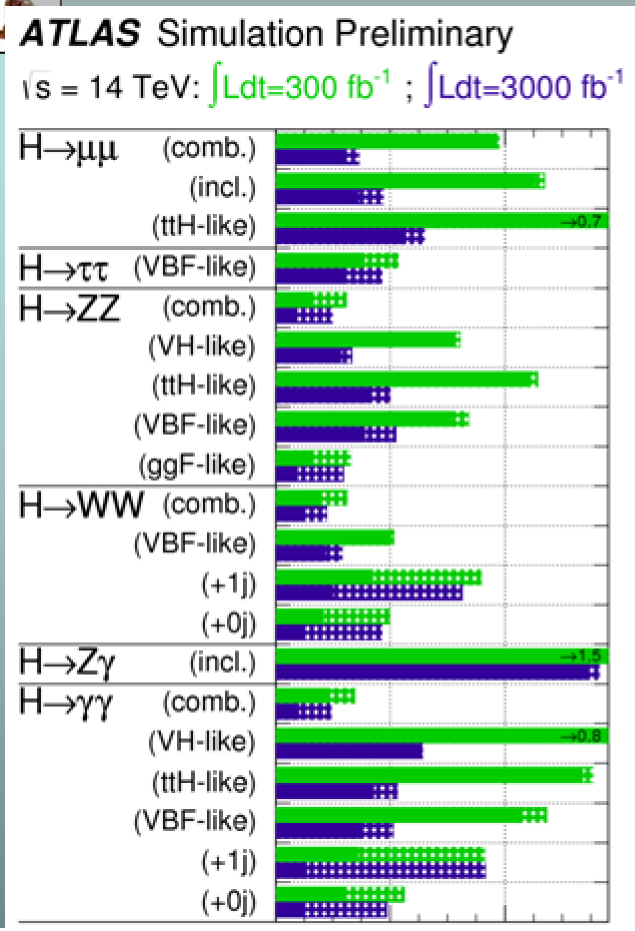
3) **Coupling scale factor ratios** $\lambda_{XY} = \kappa_X / \kappa_Y$ independent of assumptions on Higgs total width.





ATLAS: Syst. errors as run 1, with (without) theory errors

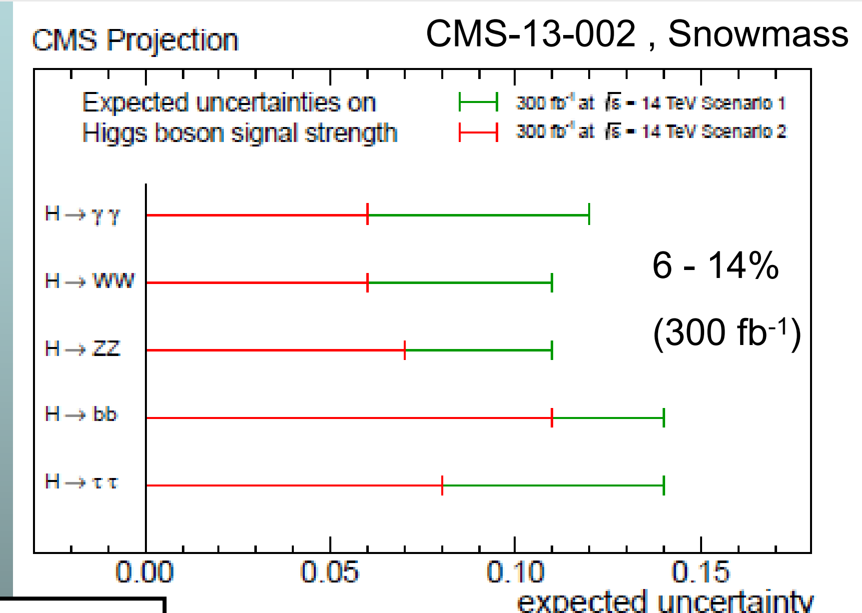
CMS: Scenario 1: all systematic errors as run 1.
(Scenario 2: exp. syst. errors ~ 1/√ L, theory errors x ½).



ECFA Workshop
ATL-PHYS-PUB-2013-014

6 - 20%

(300 fb^{-1})



6 - 14%

(300 fb^{-1})

Not yet updated for much improved MVA analysis

Very conservative systematic errors

Not included in projections since new, much improved analysis in progress

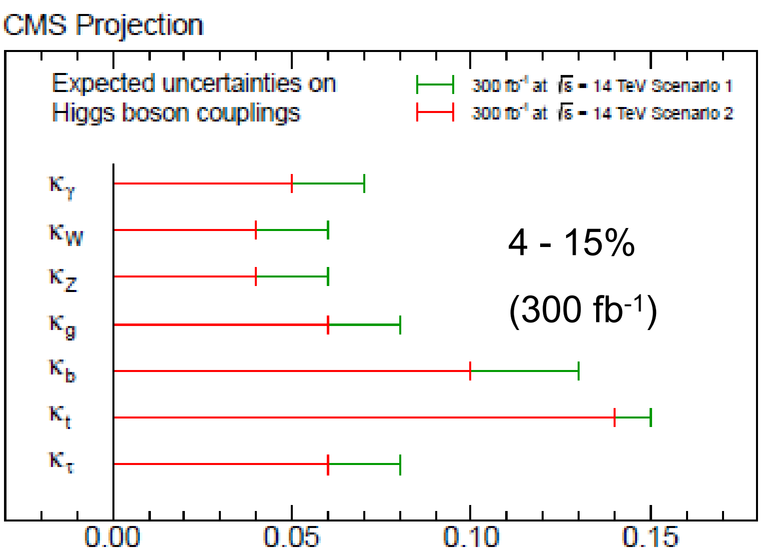
Δμ/μ [%] (300 fb $^{-1}$)	γγ	WW	ZZ	ττ	bb	μμ	Zγ
ATLAS	14 (9)	13 (8)	12 (6)	22 (16)	not incl.	39 (38)	147 (145)
CMS	12 (6)	11 (6)	11 (7)	14 (8)	14 (11)	42 (40)	62 (62)

Higgs couplings

Combined fits of selected coupling scale factors κ_Y assuming the Standard Model.
Largest fit version:

$\Delta\kappa/\kappa$ [%] (300 fb^{-1})	$\gamma\gamma$	WW	ZZ	gg	$\tau\tau$	bb	tt	$\mu\mu$	$Z\gamma$
ATLAS	13 (8)	8 (7)	8 (7)	11 (9)	18 (13)	$\kappa_b = \kappa_\tau$	22 (20)	23 (21)	79 (78)
CMS	7 (5)	6 (4)	6 (4)	8 (6)	8 (6)	13 (10)	15 (14)	23 (23)	41 (41)

Rare decay modes



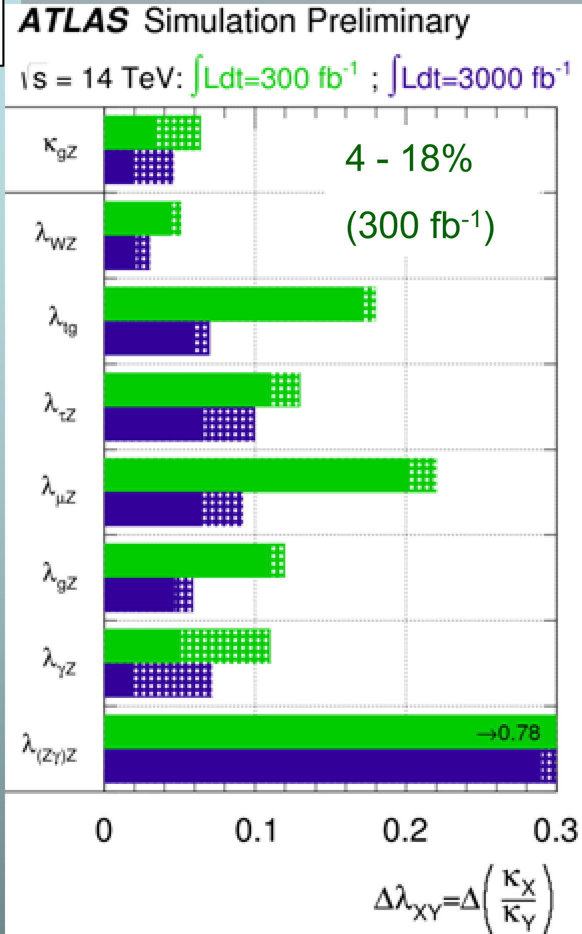
CMS-13-002, Snowmass

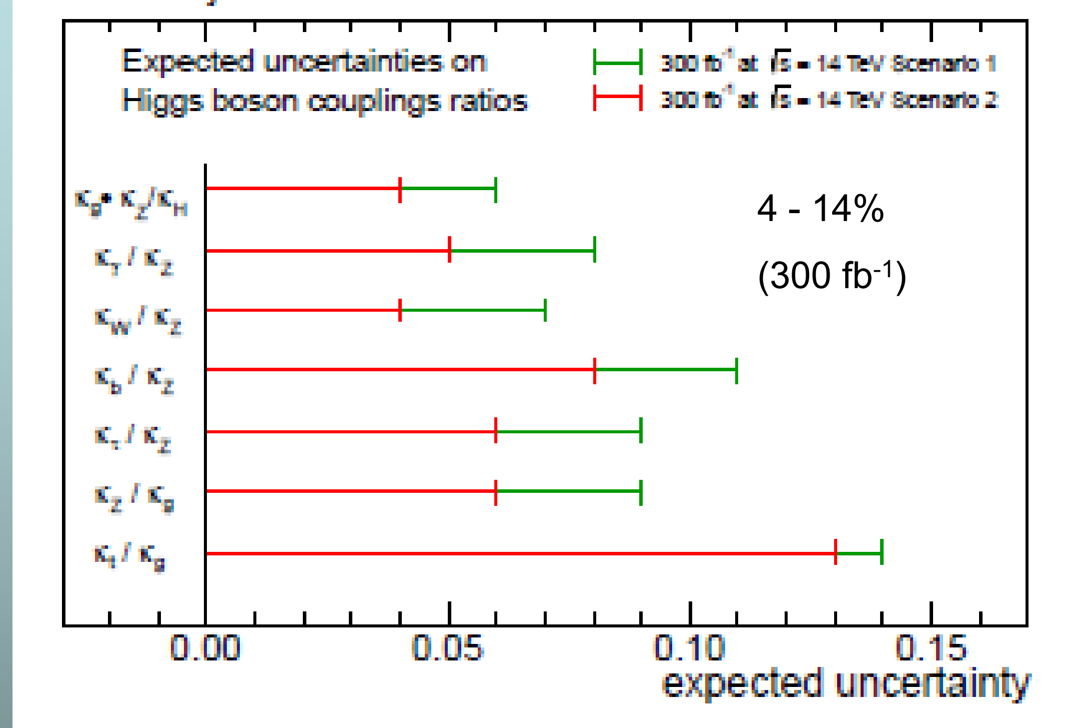
Other benchmark tests:

1) Universal couplings to fermions (F) and weak vector bosons (V) as in the Standard Model
2) Overall coupling scale factor κ_H (sensitive to new physics).
3) Branching fraction BR_{inv} to invisible, undetected final states (sensitive to new physics).

$\Delta\kappa/\kappa$ [%] (300 fb^{-1})	κ_H	κ_V	κ_F	BR_{inv} limit [%]
ATLAS	3.2 (2.5)	3.3 (2.7)	8.6 (7.1)	< 28 (<25)
CMS		6 (3)	9 (7)	< 28 (<17)

Higgs coupling ratios





CMS-13-002, Snowmass

ATLAS-PHYS-PUB-2013-014, ECFA WS

Generic combined fit of coupling scale factor ratios $\lambda_{XY} = \kappa_X / \kappa_Y$ w/o assumptions on total width:

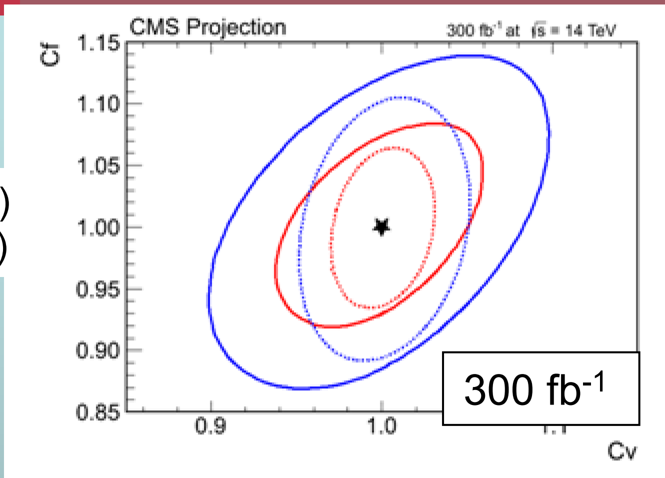
$\Delta\lambda / \lambda$ [%] (300 fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	W/Z	γ/ Z	g/Z	τ/Z	b/Z	t/g	μ/Z	Zγ/Z
ATLAS	6 (3)	5 (4)	11 (5)	12 (11)	13 (11)	$\kappa_b = \kappa_\tau$	18 (17)	22 (20)	78 (78)
CMS	6 (4)	7 (4)	8 (5)	9 (6)	9 (6)	11 (8)	14 (13)	23 (22)	42 (40)

Higgs couplings summary

CMS, Europ. Strategy

Test of universal couplings to fermions (F) vs. weak vector bosons (V)

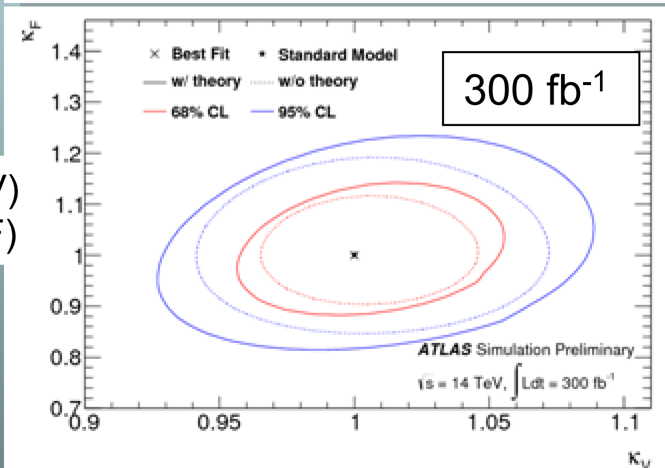
3 - 6% (V)
7 - 9% (F)



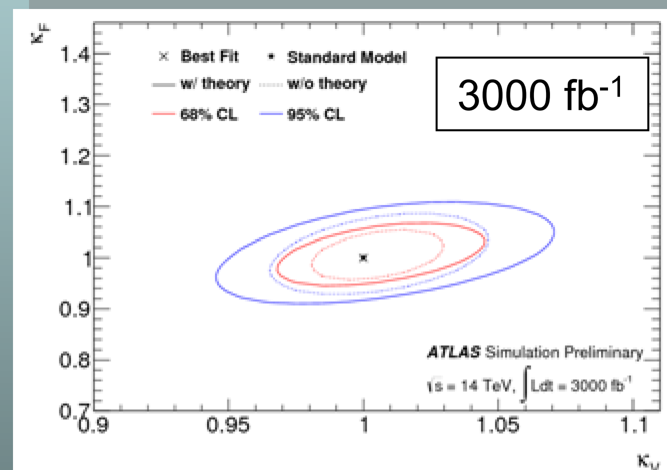
Red: 1σ errors   Blue: 2σ errors

Full lines: with current theory errors
Dashed lines: without theory errors

2.7 - 3.3% (V)
7.1 - 8.6% (F)



ATLAS
ECFA WS



1.7 - 2.6% (V)
3.2 - 4.1% (F)

- About 5% (10%) precision in Higgs couplings to vector bosons (fermions) reachable with run 2&3.
- BSM effects on Higgs couplings expected well below 10% level.
- Improvements with 3000 fb^{-1} by ~20-30% for vector bosons (depending on reduction of theory uncertainties) and by ~ 50% for fermions.
  Sensitivity to rare decay modes to μμ (second fermion generation!) and Zγ only at HL-LHC.

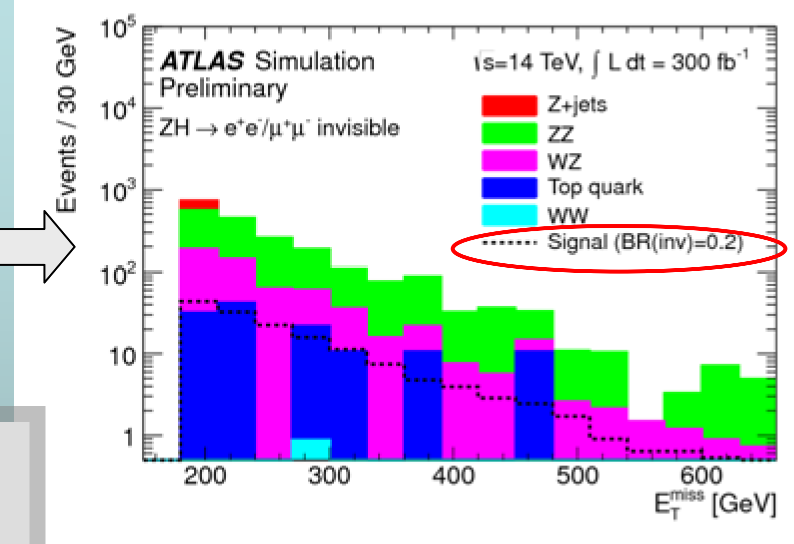
Invisible Higgs decays: Higgs as portal to Dark Matter

Comparable 95% CL limits (ATLAS)
on invisible branching ratio BR_{inv} for 300 fb^{-1}

1) indirectly from Higgs coupling fit: < 28% (25%)

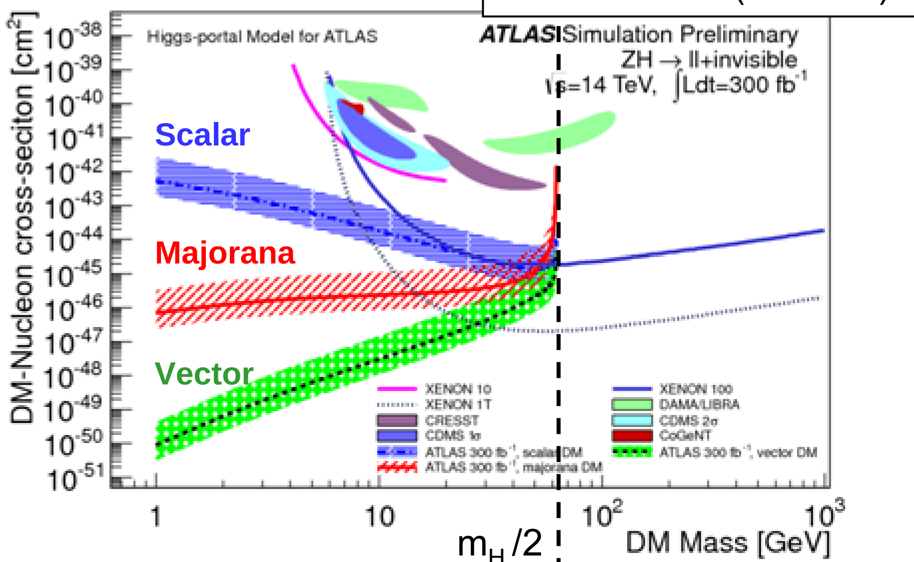
2) and from direct search for ZH → (ee $\mu\mu$) + E_T^{miss}: < 32% (23%)

Improvement by factor of 2 for 3000 fb^{-1}.



Interpretation in terms of dark matter particles coupling mainly to Higgs ("Higgs-portal" models):
expected direct upper limits DM-nucleon cross section depending on WIMP spin:

Direct search (90% CL)



Sensitivity to low WIMP mass range < m_H /2, exceeding sensitivity of generic astrophysical Dark Matter searches.

Comparable sensitivity of direct and indirect searches.

ATLAS-PHYS-PUB-2013-014/15/16, ECFA WS

Sensitivity to new physics from Higgs couplings

ATLAS-PHYS-PUB-2013-015, ECFA Workshop

1) **Extra Higgs electroweak singlet H** mixing with 126 GeV Higgs h with the same couplings.

Effects on Higgs couplings can be rather large of order 6%.

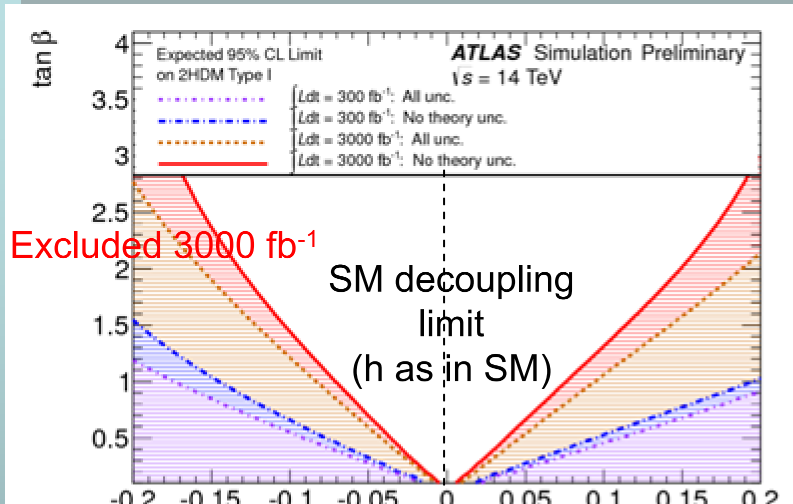
Sensitivity via constraint $\kappa_h^2 + \kappa_H^2 = 1$ on Higgs width scale factors independent of m_H, $BR_{H,new}$.

From coupling fit of κ_h: $\boxed{\kappa_H < 0.35\ (0.31)}$ (95 % CL) for 300 fb^{-1} (< 0.31 (0.25) for 3000 fb^{-1}).

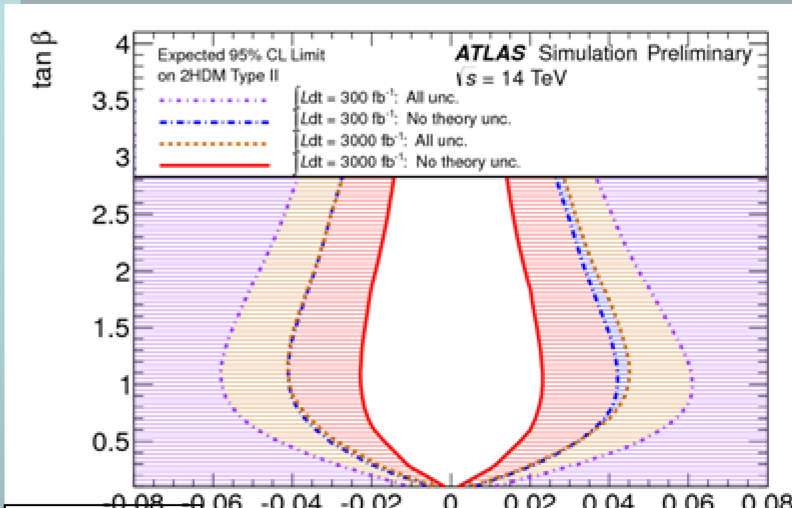
2) **"Two Higgs Doublet Models" 2HDM** (more general than MSSM Higgs sector), modify the couplings of the light neutral scalar Higgs h to weak vector bosons and fermions depending on $\tan\beta = v_2 / v_1$ and the mixing angle α of the two neutral scalars h and H (up to 6% effects on κ_b):

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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$
Couplings doublet 1 to doublet 2 to	 W/Z fermions	 up fermions down fermions	to quarks as I to leptons as II (lepton specific)	to quarks as II to leptons as I ("flipped")

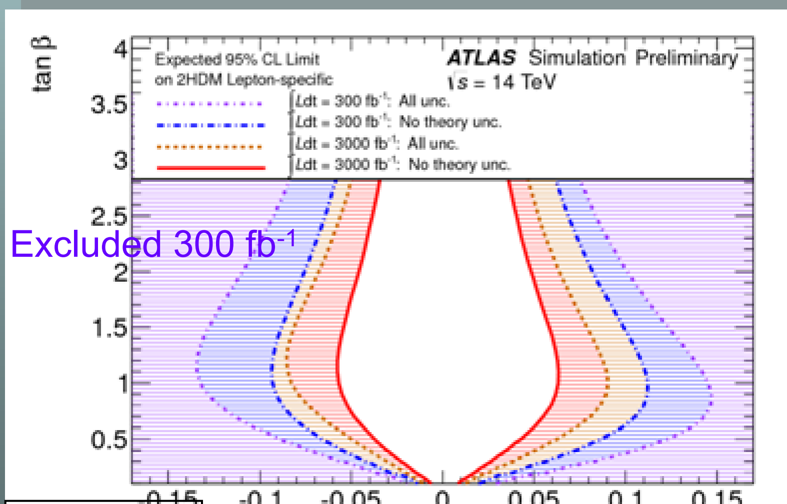
includes MSSM



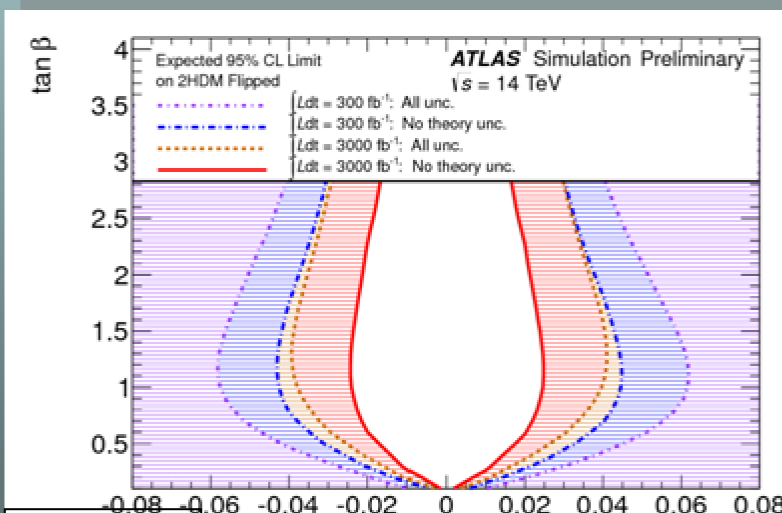
Type I



Type II



Type III



Type IV

Indirect limits from couplings independent of m_A

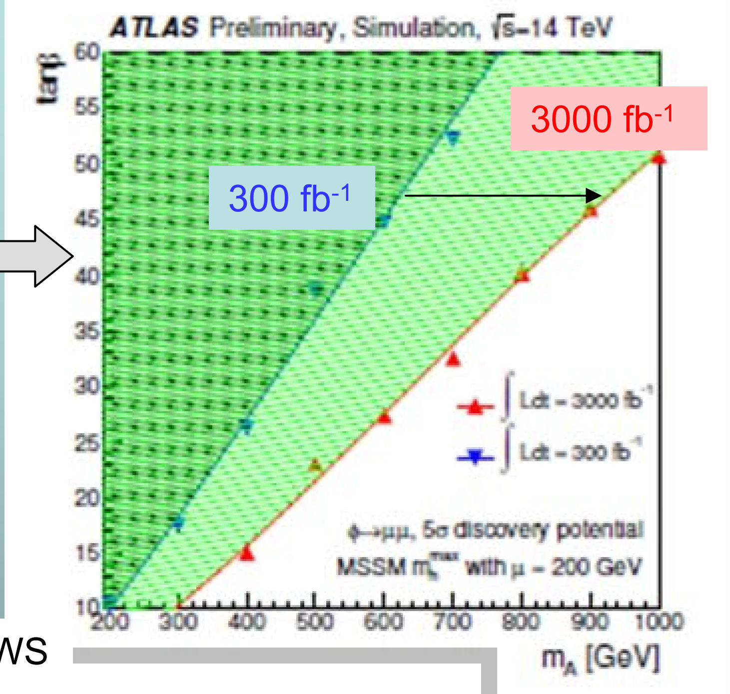
ATLAS-PHYS-PUB-2013-015, ECFA WS

Direct search for BSM Higgs bosons in 2HDMs

Clean decay channels with full mass reconstruction (ATLAS & CMS for HL-LHC, ATLAS also for run 2&3) :

1) Heavy neutral Higgs decays H/A → μμ,

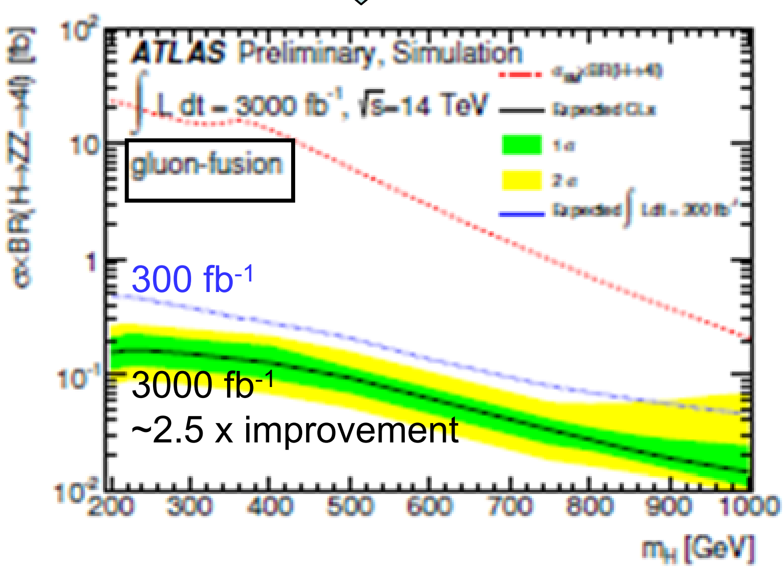
   5σ discovery potential in MSSM framework:

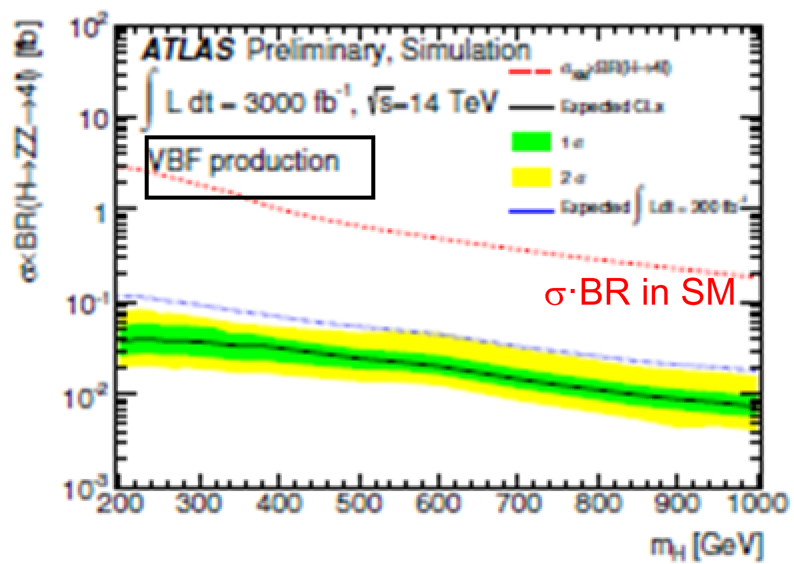


2) Heavy CP even Higgs decays H → ZZ → 4l,

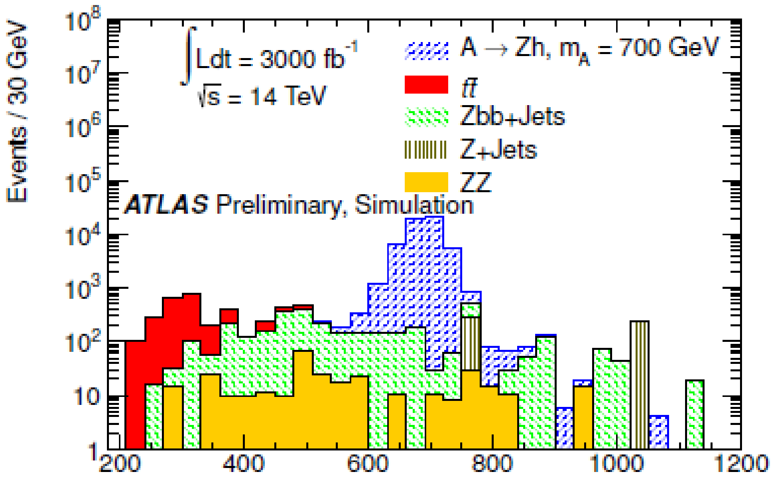
   expected 95% CL upper limits on σ·BR, projection of current results:

ATLAS-PHYS-PUB-2013-016, ECFA WS



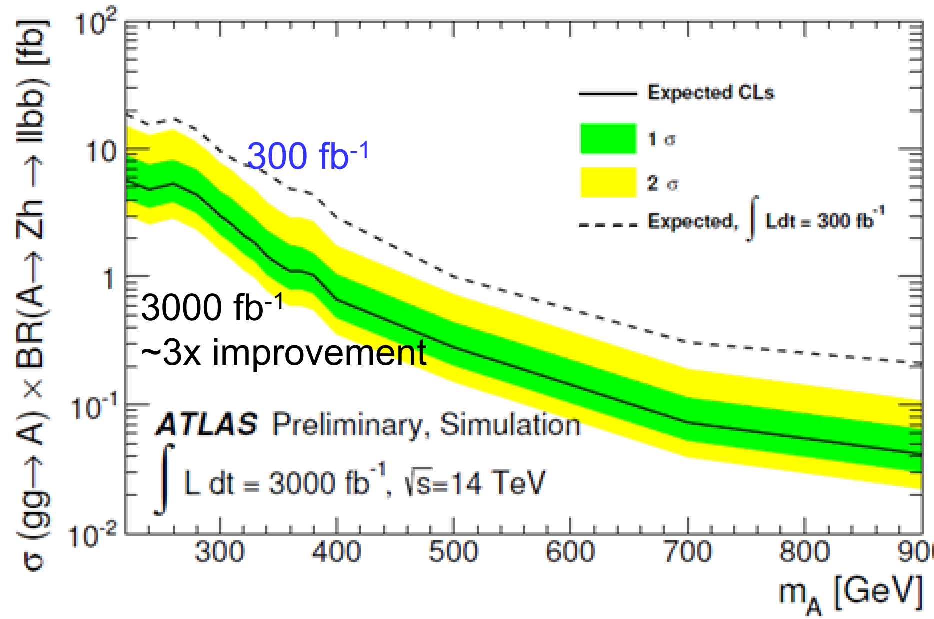


3) CP odd Higgs decays $A \to Z\,h$ with $Z \to ll$, $h \to bb$

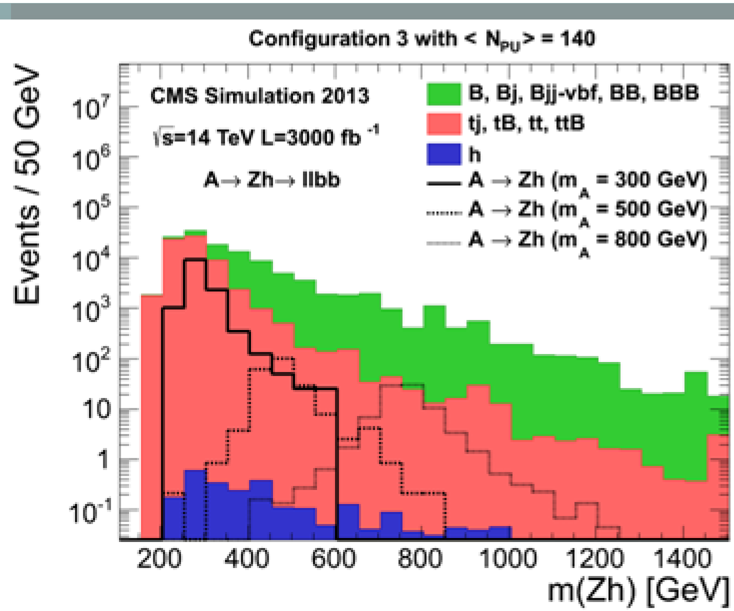


for $\sigma \cdot BR(A \to Zh)$ = 100 fb

Expected upper limit on $\sigma \cdot$ BR:

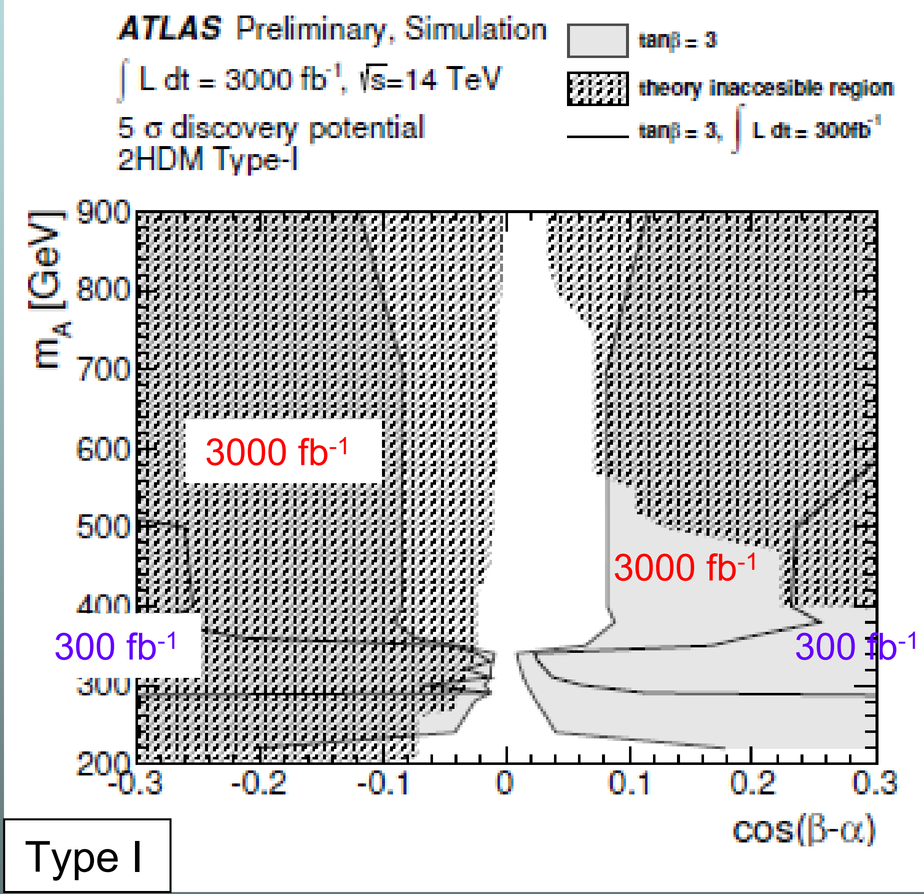


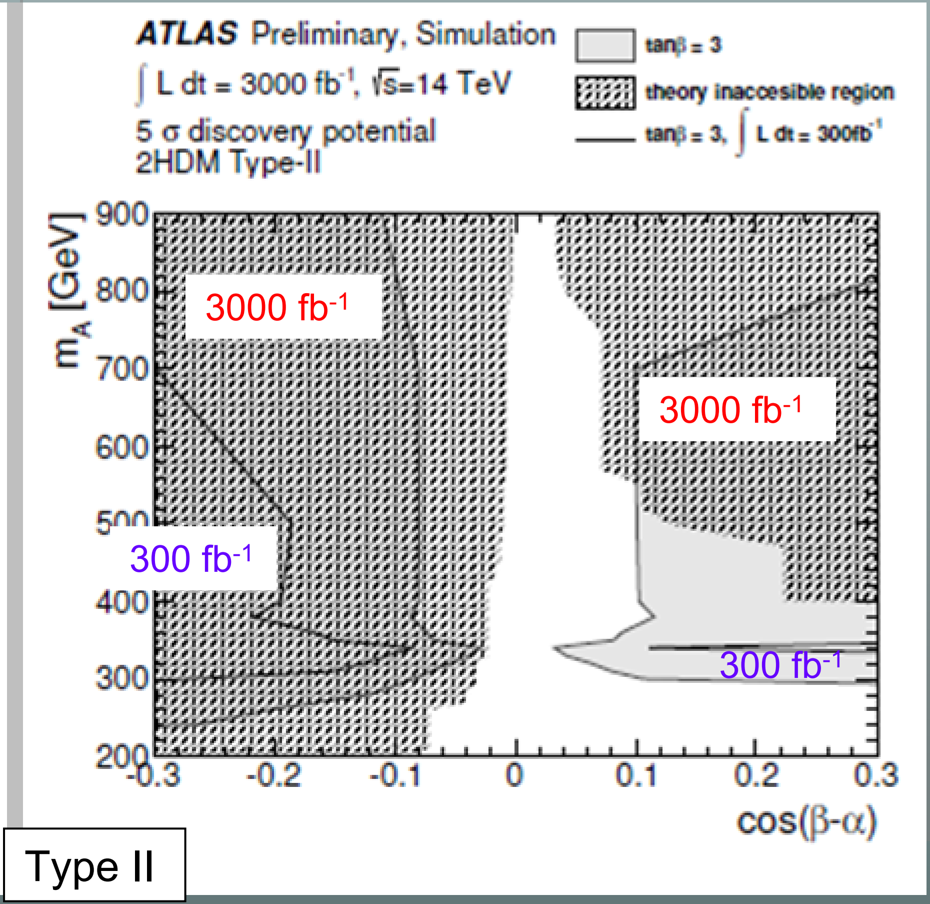
ATLAS-PHYS-PUB-2013-016, ECFA Workshop



CMS PAS FTR-13-024, ECFA WS

⇒ 5σ discovery regions for $A \to Z\,h$ for m_A depending on $\cos(\beta - \alpha)$ for $\tan\beta = 3$:





Hatched: theoretically forbidden due to vacuum stability and unitarity

Higgs coupling tensor structure

General mixing of CP states of a spin-0 Higgs boson decaying into ZZ (V=Z) in effective field theory:

$$A(X_{J=0} \rightarrow VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f^{*(2)}_{\mu\alpha} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$

CP even Higgs
SM tree process

anomalous CP even Higgs contributions
loop induced: small, neglected
SM rad. corr. $O(10^{-2})$, BSM?

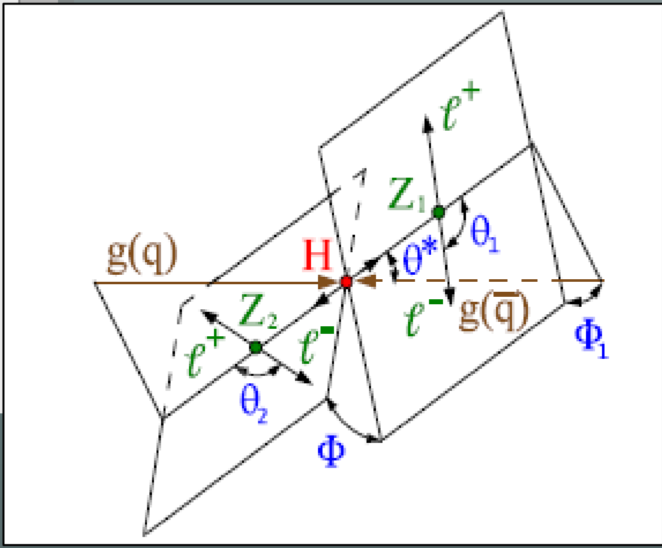
CP odd Higgs contribution:
BSM

Test for admixtures with couplings g_2 or g_4 (CP violating) to SM g_1=1 tree level term.

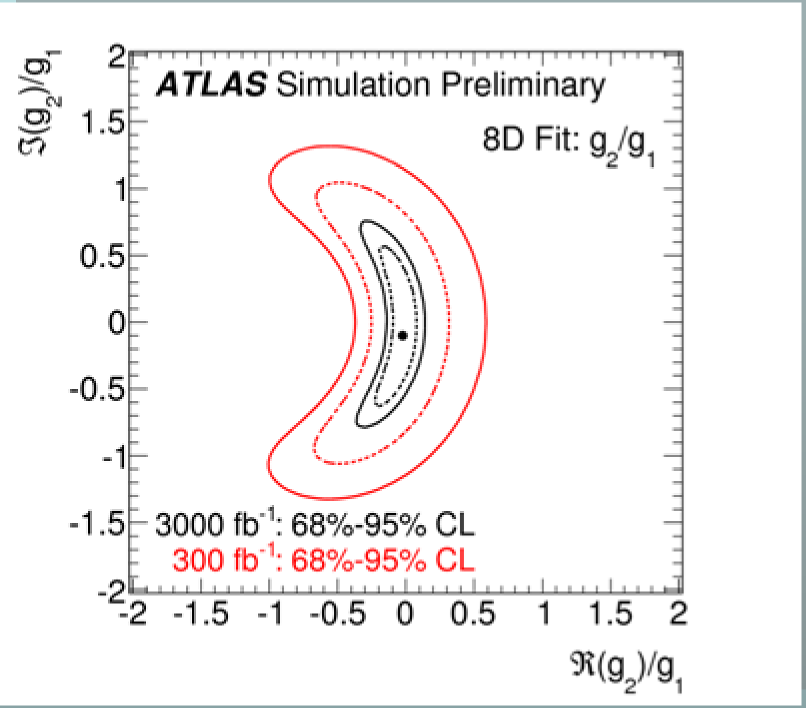
ATLAS:
8D fit to distributions of kinematic variables (m_{4l}, $m_{Z_{1,2}}$, $\theta_{1,2}$, φ, φ_1, θ^*) generated depending on g_2 and g_4

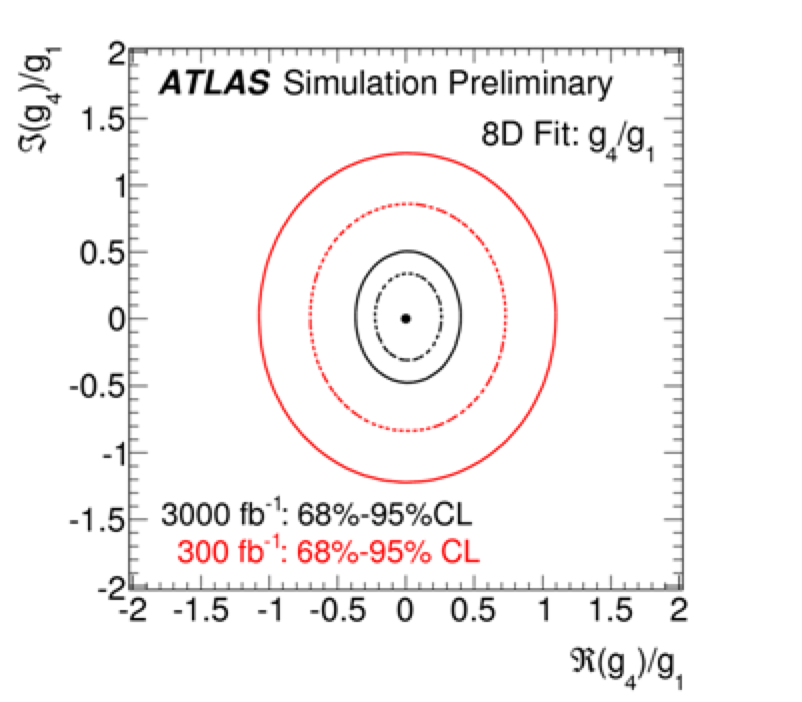
Free parameters:
Real and imaginary part of couplings g_2 and g_4 rel. to g_1.

Alternatively: fit of collection of matrix element ratios for SM and alternative hypotheses.



CMS: Matrix element likelihood approach as for run 1.





ATLAS-PHYS-PUB-2013-013, ECFA Workshop

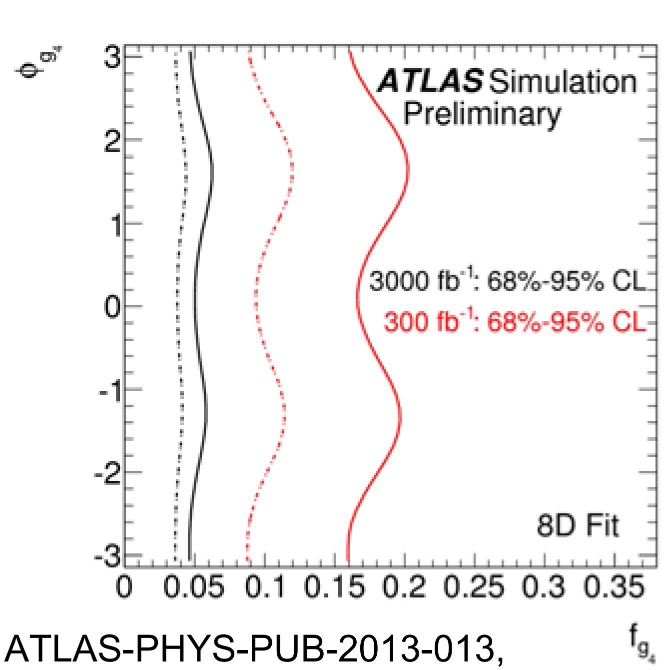
Luminosity	$\lvert g_4\rvert/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\lvert g_2\rvert/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300 fb^{-1}	1.20	(-0.88, 0.91)	(-1.02, 1.05)	1.02	(-0.84,0.44)	(-1.19, 1.18)
3000 fb^{-1}	0.60	(-0.30, 0.33)	(-0.39, 0.42)	0.60	(-0.30,0.11)	(-0.71, 0.68)

Expected 95% CL regions

Factor 2-3 improvement with HL-LHC

Higgs to ZZ tensor structure and CP mixing

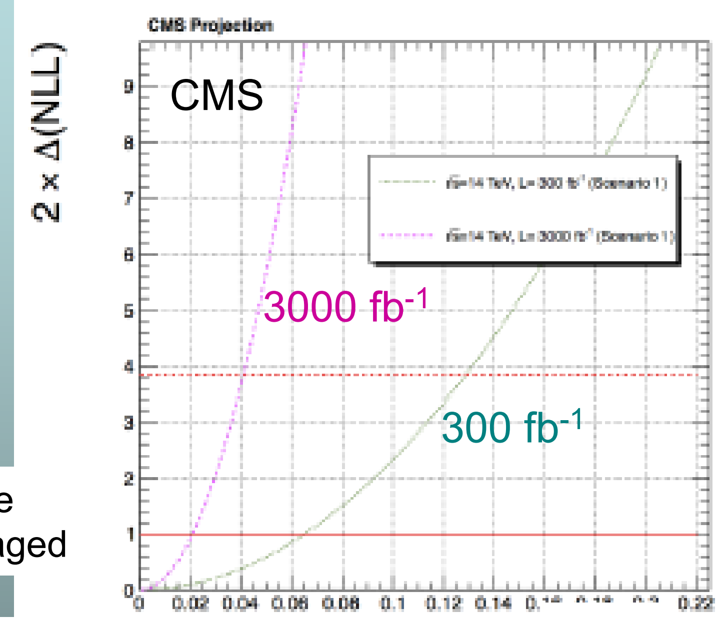
Alternative description in terms of cross section fractions $f_{g_{2,4}} = |g_{2,4}|^2 \sigma_{2,4} / (\sigma_1 + |g_{2,4}|^2 \sigma_{2,4})$ and relative phases $\phi_{g_{2,4}} = \arg(g_{2,4}/g_1)$:



g_4

phase dependent

ATLAS-PHYS-PUB-2013-013, ECFA Workshop



phase averaged

CMS-13-002, Snowmass

$f_{g4} = f_{a3}$

Sensitivity for 10-20% CP violating admixture with run 2&3.
Factor 2-3 improvement with HL-LHC.

95% CL limit $f_{g_4} < 0.51$ from CMS run 1 data.

95% CL upper limits		ATLAS 8D fit		ATLAS ME fit	
	Luminosity	f_{g4}	f_{g2}	f_{g4}	f_{g2}
ATLAS	300 fb^{-1}	0.20	0.29	0.15	0.43
	3000 fb^{-1}	0.06	0.12	0.037	0.20
CMS	300 fb^{-1}	0.13		0.13	
	3000 fb^{-1}	0.04		0.04	

Conclusions

- One of the main goals of LHC run 2 & 3 (14 TeV, 300 fb^{-1}):

  Precise measurement of Higgs properties, in particular:

  - Higgs couplings to gauge bosons at 5%, to fermions (b, τ) at 10% level.
  - Sensitivity for CP-odd admixtures to scalar Higgs at 10-20% level.

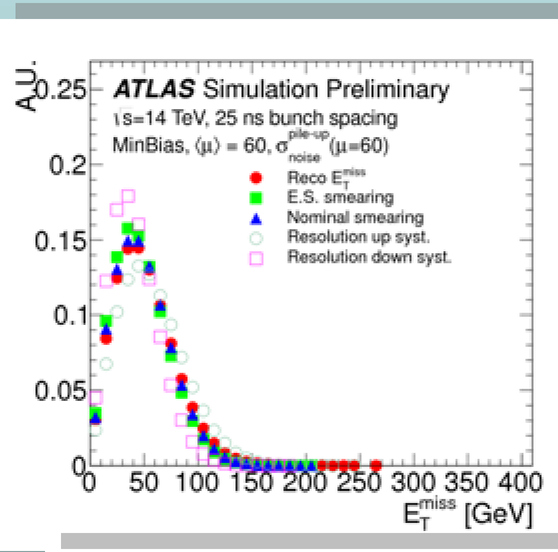
- Similar conclusions from ATLAS and CMS projections taking into account in spite of differences in the assumptions.
- Similar sensitivity of direct searches and indirectly from Higgs coupling measurements to
  - extensions of the Higgs sector
  - Dark Matter coupling to Higgs.
- Typically factor of 2-3 improvement with 3000 fb^{-1} at HL-LHC.
  Improvement of theory precision needed, too.
- Sensitivity to rare Higgs decay modes (including coupling to second fermion generation, $H \rightarrow \mu\mu$) and Higgs self-coupling only at HL-LHC.

Backup

Detector upgrades performance for runs 2 & 3

Detector upgrades for high-luminosity, high pile-up conditions in run 2 & 3 mainly in pixel detectors and trigger.

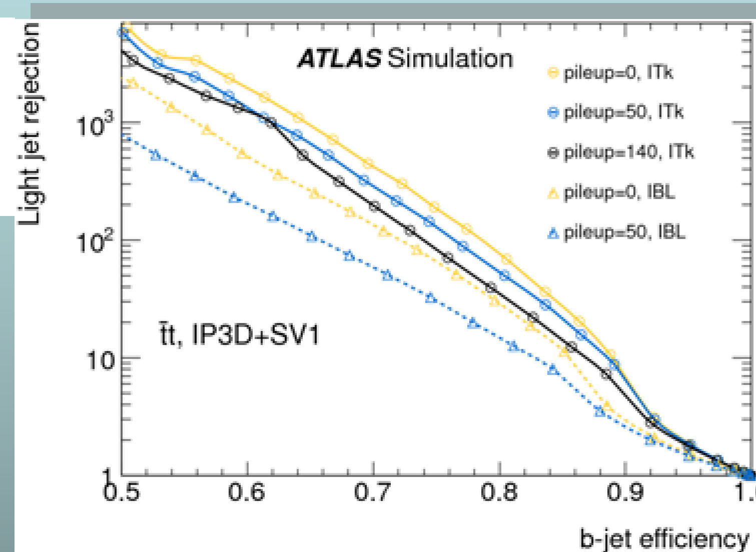
Main improvements in missing energy resolution, b tagging performance and trigger efficiency



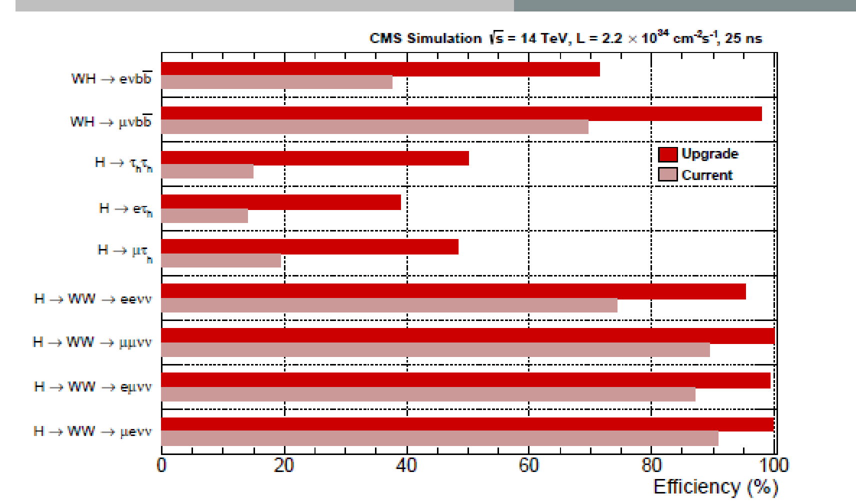
ATLAS E_T^{miss} distribution for <μ> = 60 in run 3

ATLAS-PHYS-PUB-2013-009, ECFA WS

ATLAS b-tagging performance dep. on pile-up level <μ> and silicon tracker upgrades



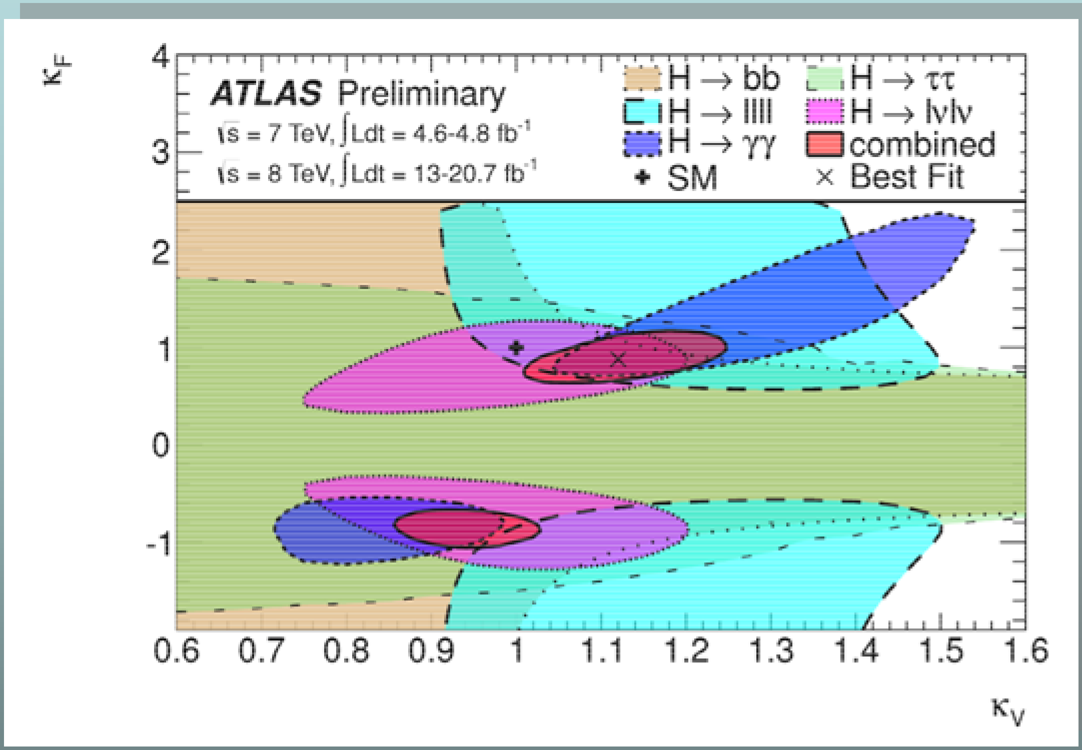
ATLAS-PHYS-PUB-2013-007, arXiv 1307:7292, Snowmass

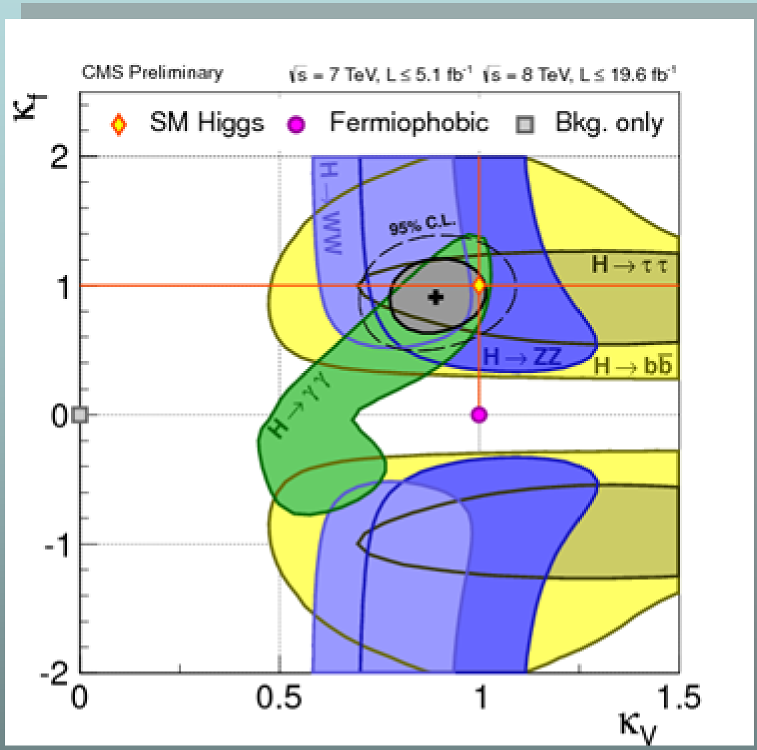


Improvement of the CMS trigger efficiency for Higgs channels due to upgrades in run 2 at L = $2.2 \cdot 10^{34}$ cm $^{-2}$ s $^{-1}$

CMS-13-002, Snowmass

Backup: Higgs status





Typical magnitudes of BSM Higgs coupling modifications

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

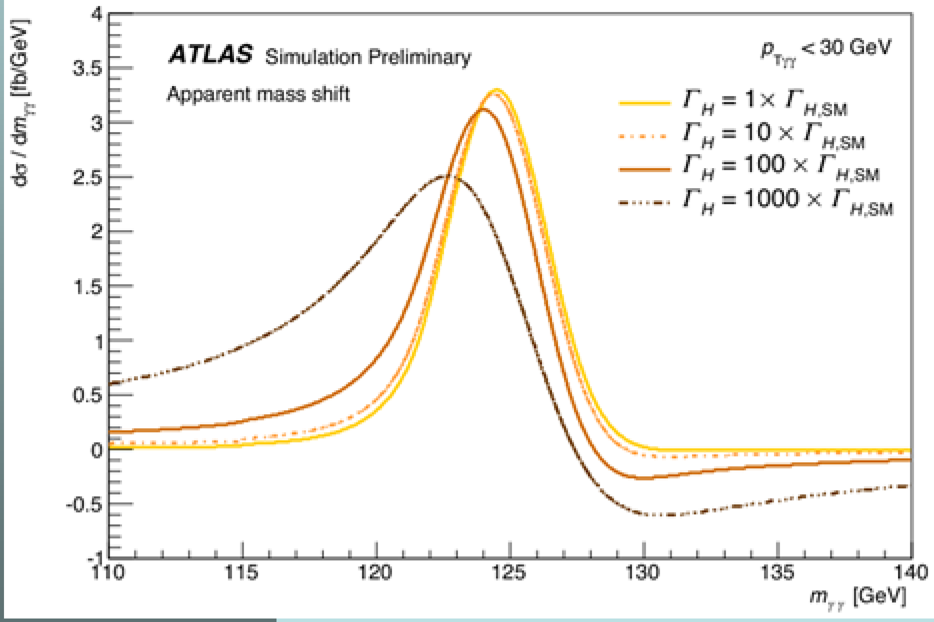
SM width of 4.2 MeV for m_H = 126 GeV not measurable at LHC.

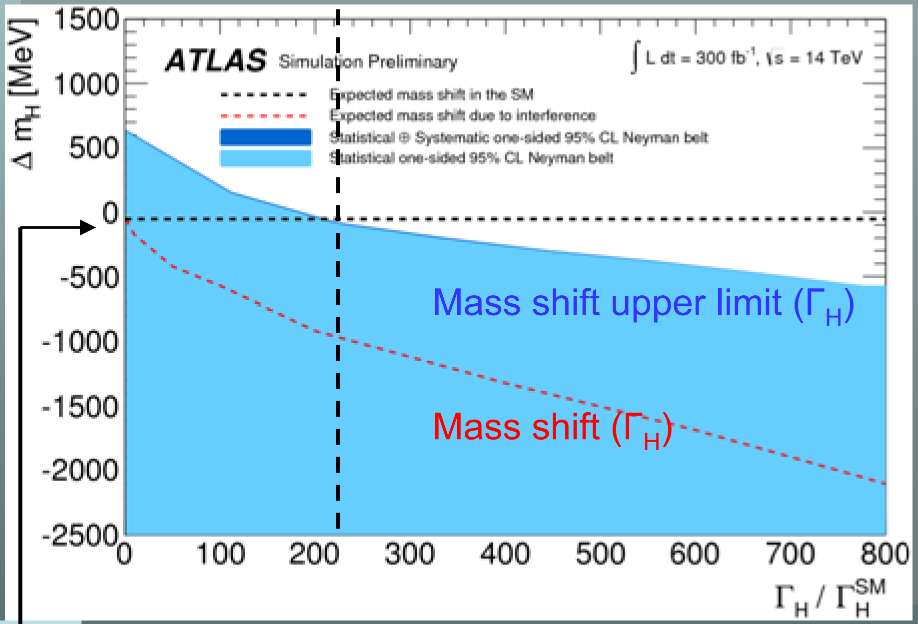
Finite width effects: apparent Higgs mass shift due to interference between $H \to \gamma\gamma$ signal and continuum diphoton production background (L.J. Dixon and Y.Li, arXiv:1305:3854, Sep. 2013, S.P. Martin, arXiv:1303:3342, March 2013).

CMS limit from run1 data: Γ_H < 6.9 GeV (95% CL).

ATLAS expected limits for 300 fb^{-1} (3000 fb^{-1}): Γ_H < 920 MeV (200 MeV) (95% CL).

ATLAS-PHYS-PUB-2013-014, ECFA Workshop



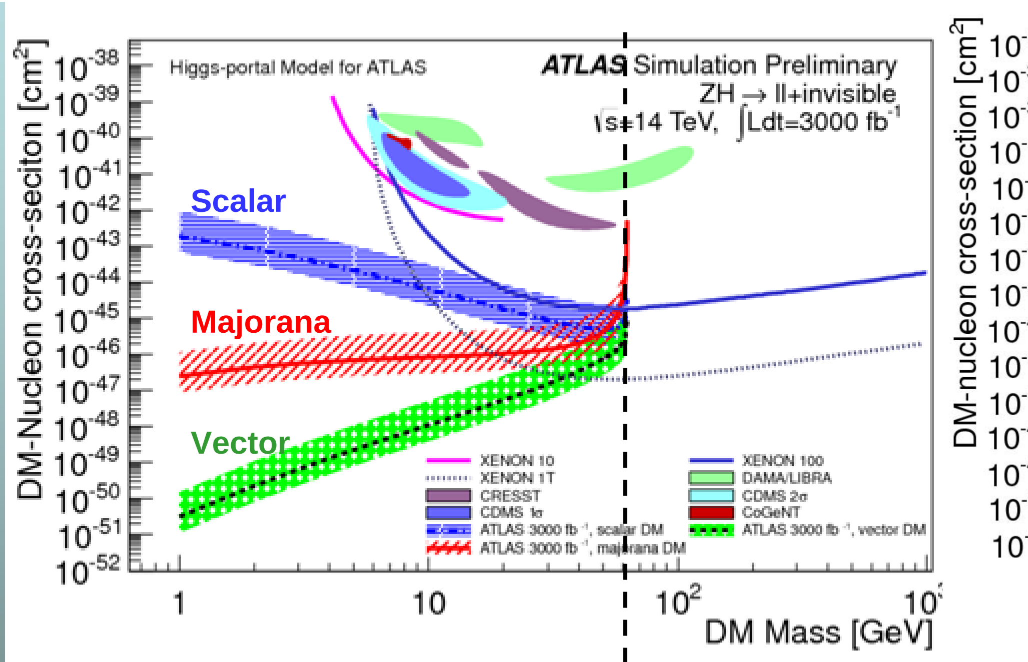


Expected SM mass shift = -54.4 MeV

Higgs Portal to Dark Matter

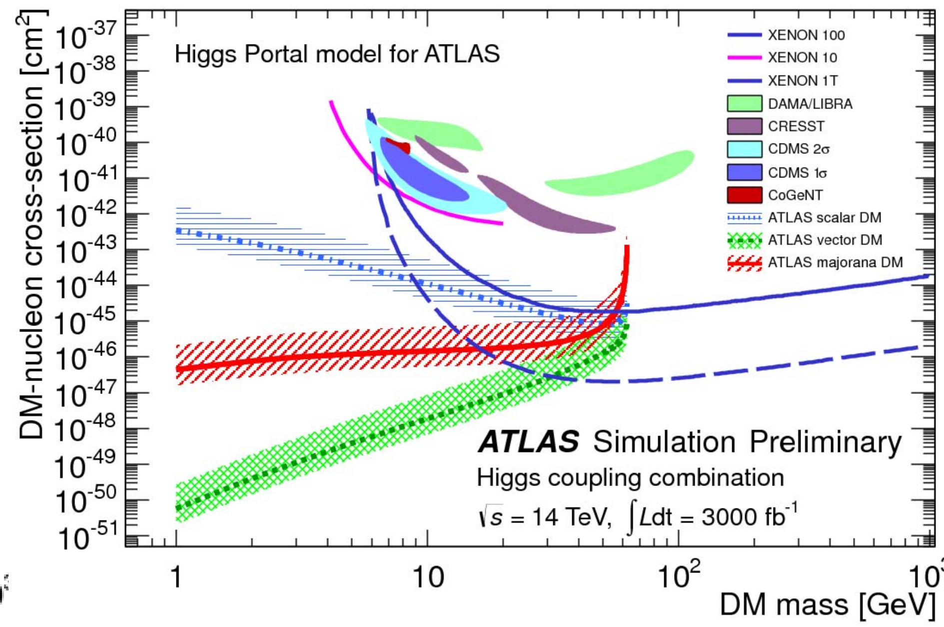
ATLAS-PHYS-PUB-2013-014

Direct limits: 90% CL



ATLAS-PHYS-PUB-2013-015

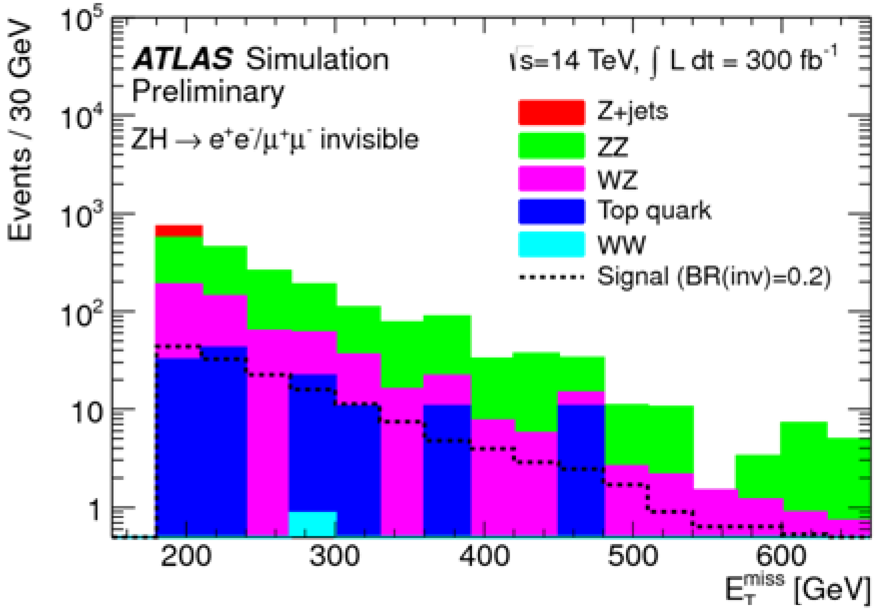
Indirect limits: 95% CL

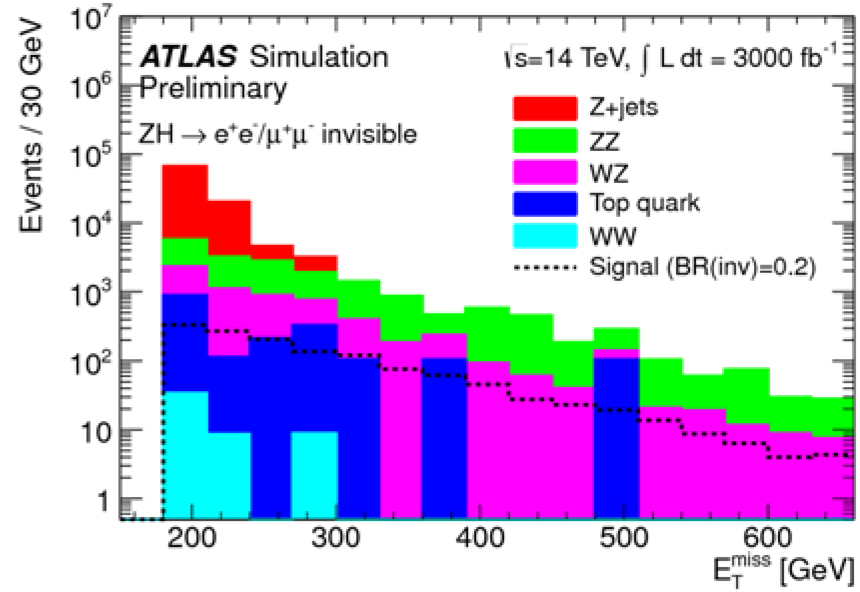


Sensitivity to low WIMP mass range < m_H /2,
exceeding sensitivity of generic astrophysical DM searches.

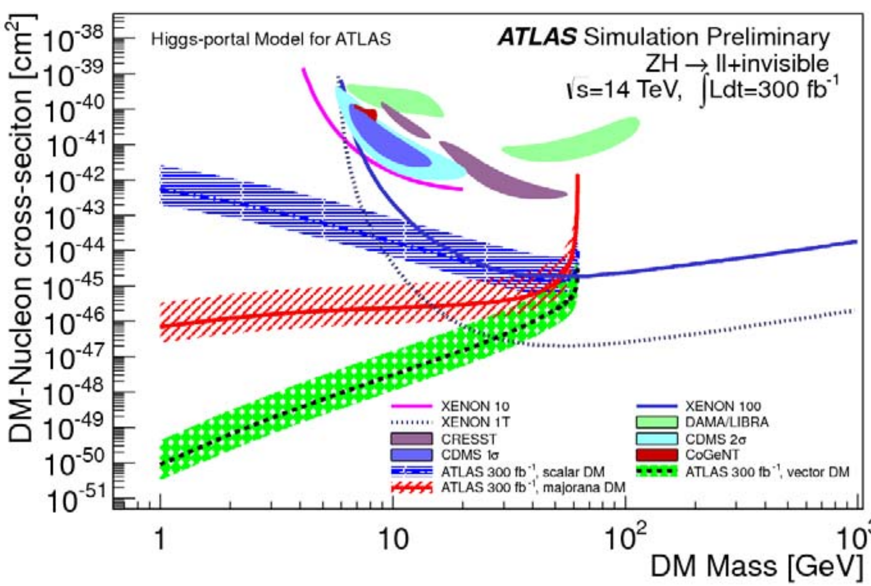
Sensitivity of Higgs coupling measurements comparable to the one of direct searches for invisible Higgs decays at LHC.

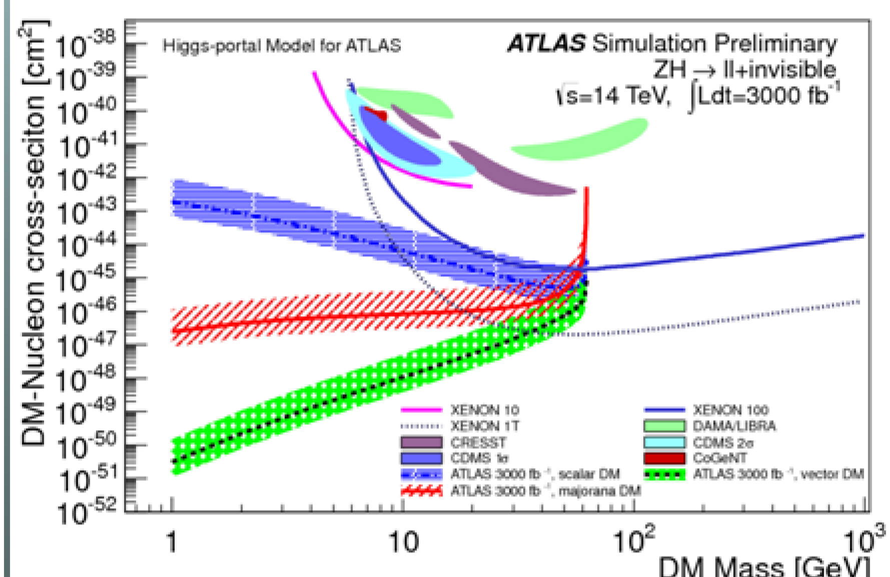
Backup: Higgs Portal Models for DM



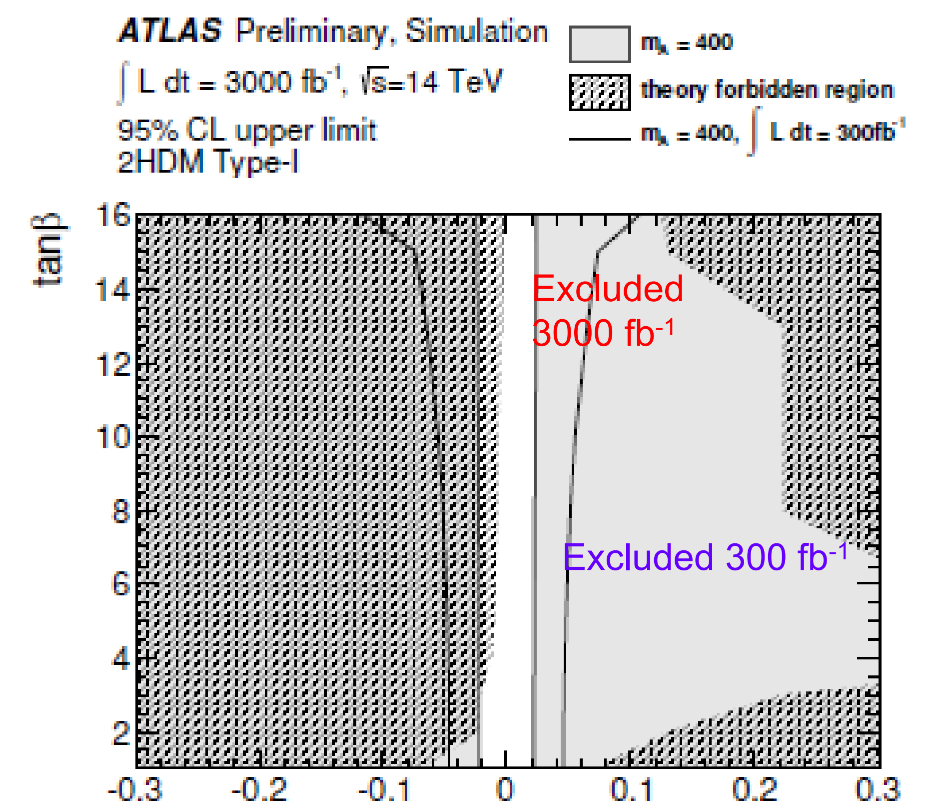


ATLAS-PHYS-PUB-2013-014, ECFA Workshop

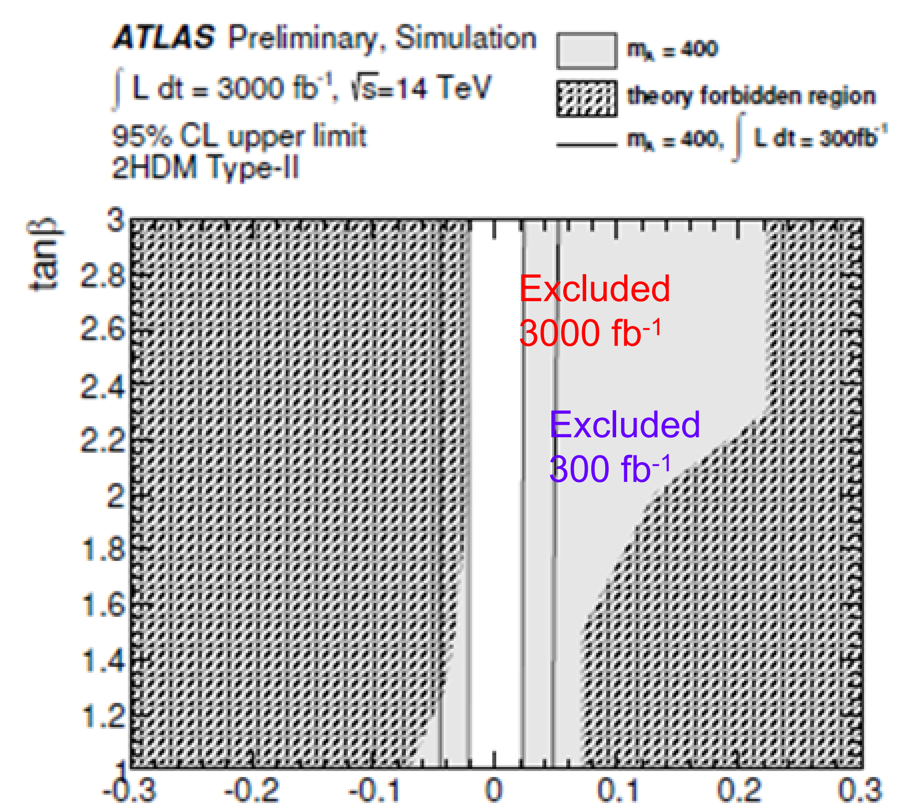




⇒ 95% CL A → Z h exclusion regions in $\tan\beta$ depending on $\cos(\beta - \alpha)$ for m_A = 400 GeV:



Type I



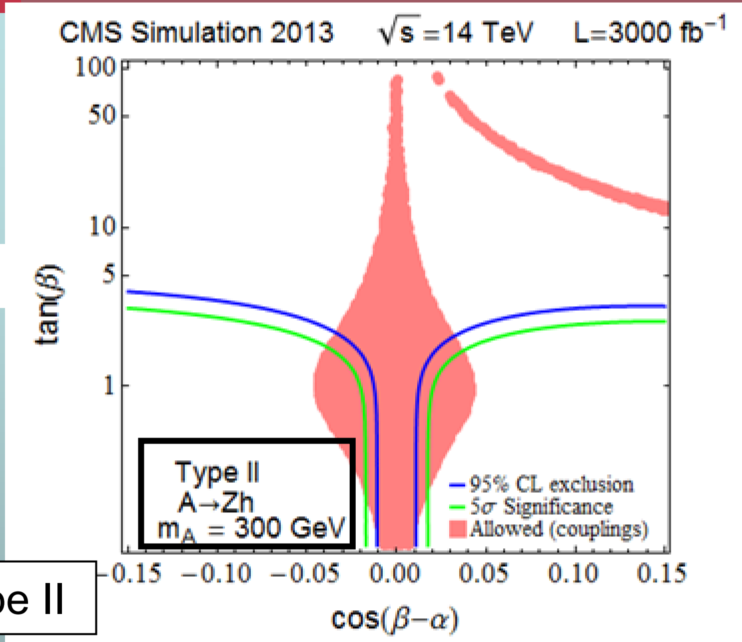
Type II

Hatched: theoretically forbidden due to vacuum stability and unitarity

Search for BSM Higgs bosons in 2HDMs

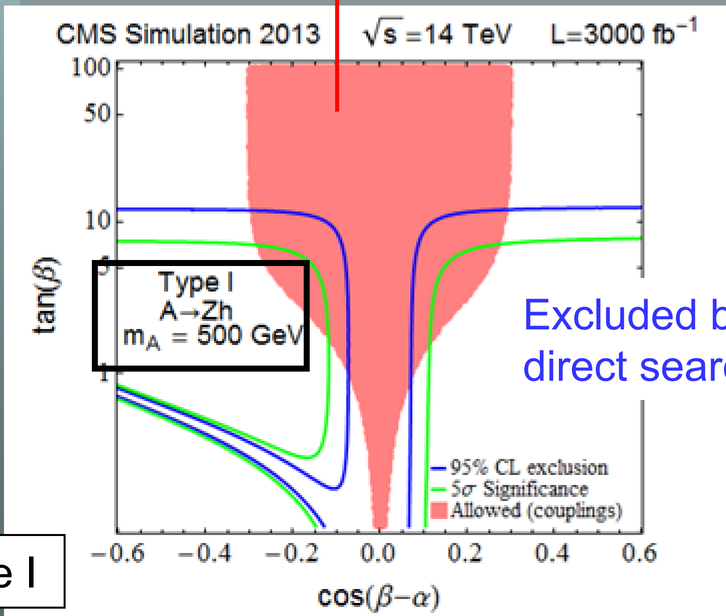
Direct vs. m_A –independent indirect limits on $A \to Z\,h$: complementary information

CMS PAS FTR-13-024, ECFA WS, 3000 fb^{-1}



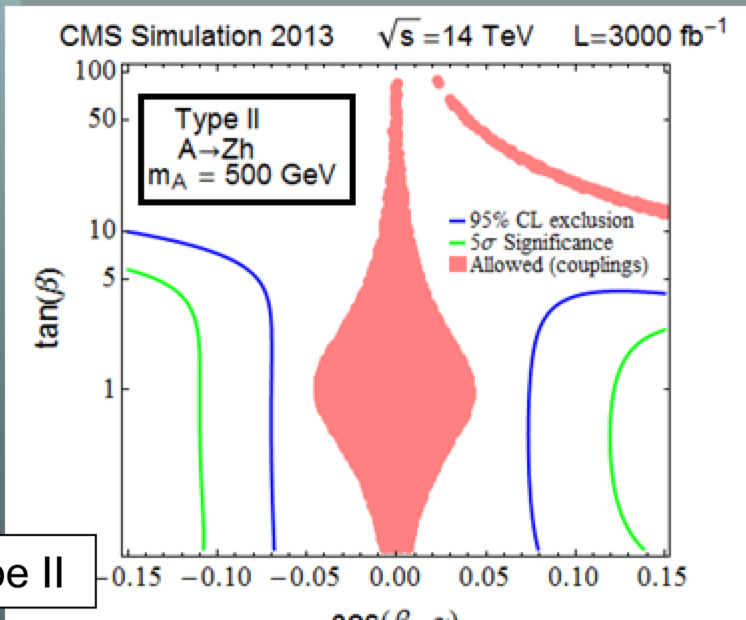
Type II

Allowed by indirect search



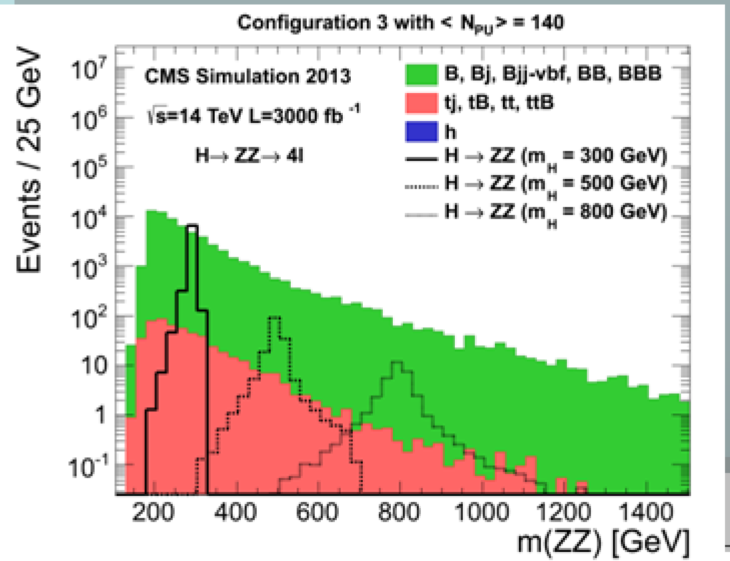
Excluded by direct search

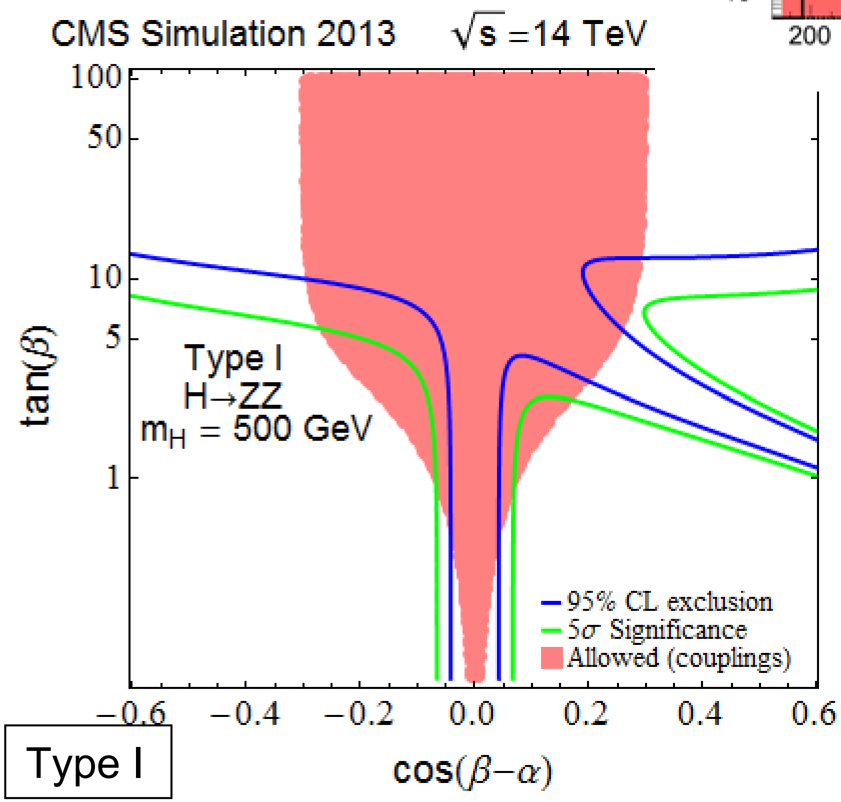
Type I



Type II

CMS PAS FTR-13-024, ECFA WS





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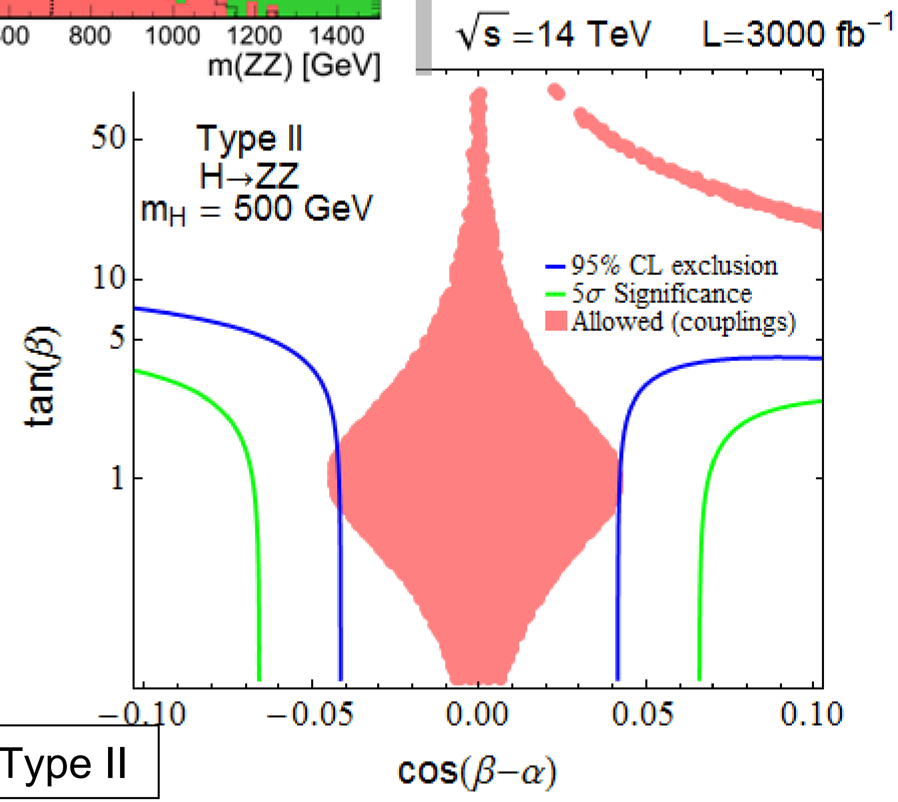

Type II