"Physics at the High-Luminosity LHC" Workshop, 11 – 13 May 2015, CERN

Prospects for BSM Higgs bosons searches at HL-LHC with ATLAS and CMS

Nikolaos Rompotis
(University of Washington)
On behalf of the ATLAS and CMS Collaborations

How to find BSM Higgs

- Direct searches for additional Higgs bosons
  - Production mechanism is similar to SM Higgs in many cases, i.e., gluon-fusion, VBF (could be b-associated production as well)
    - Low cross sections
- Indirect searches
  - Through deviations in precision measurements of 125 GeV Higgs boson, top decays (t->cH), rare Higgs decays etc

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These features need high luminosity and not necessarily higher energies! An excellent case for HL-LHC

Bibliography (I)

- There are various BSM Higgs projections for HL-HLC
  - All of them are available here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

  - Relevant notes:

ATL-PHYS-PUB-2014-017

Prospects for New Physics in Higgs Couplings Studies with the ATLAS Detector at the HL-LHC

ATL-PHYS-PUB-2013-016

Beyond-the-Standard-Model Higgs boson searches at a High-Luminosity LHC with ATLAS

Bibliography (II)

- Relevant notes (cont.)

ATL-PHYS-PUB-2013-013

Prospects for measurements of the HZZ vertex tensor structure in $H \rightarrow ZZ^* \rightarrow 4l$ decay channel with ATLAS

ATL-PHYS-PUB-2013-012

Sensitivity of ATLAS at HL-LHC to flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$

ATL-PHYS-PUB-2013-014

Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters with the ATLAS detector at a HL-LHC
(contains ZH with H->inv decay)

CMS-PAS-FTR-13-024

2HDM Neutral Higgs Future Analysis Studies

CMS-NOTE-13-002 (arXiv:1307.7135)

Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process
(contains Higgs to invisible projections)

Bibliography (III)

- Detector performance for ATLAS studies shown here follows suggestions from:

ATL-PHYS-PUB-2013-009

Performance assumptions based on full simulation for an upgraded ATLAS detector at a High-Luminosity LHC

- Detector performance for CMS studies in **CMS-PAS-FTR-13-024** here uses a Delphes [arXiv:1307.6346] parametrization of the CMS detector and 140 average pile-up interactions per bunch crossing (see in Refs. for more details)

Direct searches

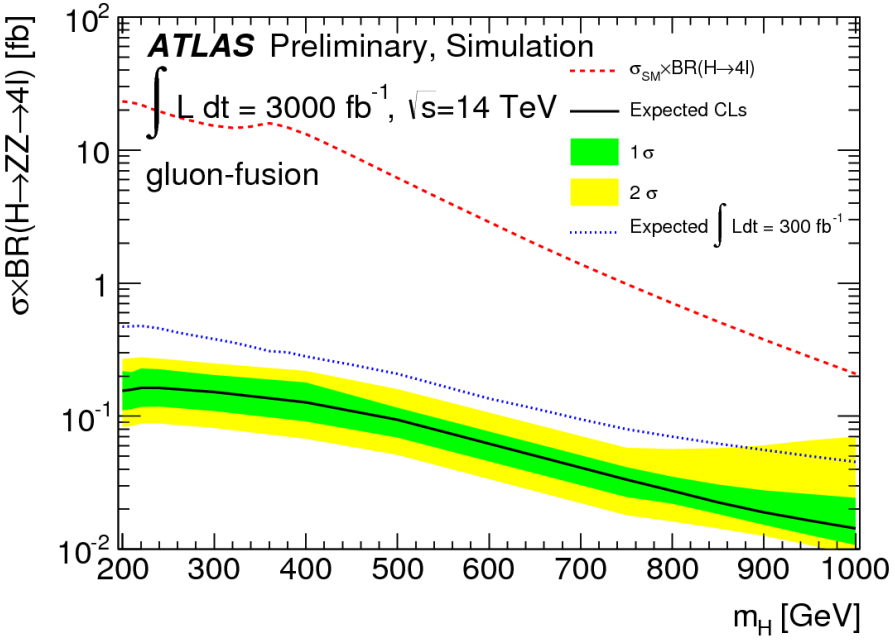
- Both ATLAS and CMS have studied various channels in the context of 2HDM
  - H->ZZ->4l (ATLAS, CMS)
  - A->Zh->llbb (ATLAS, CMS)
  - A/H->μμ (ATLAS)
- Both present results for 3000fb^{-1}. ATLAS shows numbers for 300 fb^{-1} as well.

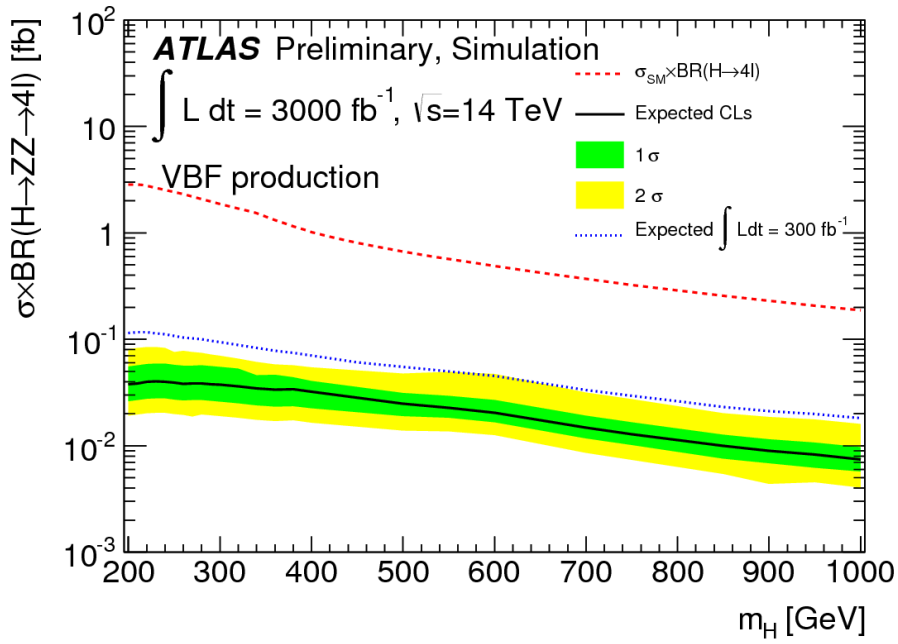
ATL-PHYS-PUB-2013-016

CMS-PAS-FTR-13-024

H->ZZ->4l

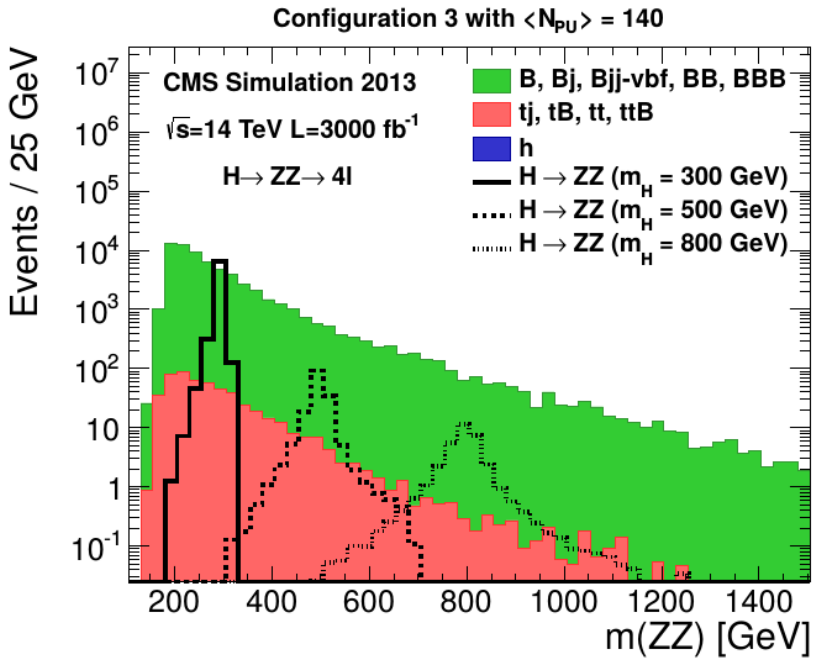
- ATLAS projected the analysis in arXiv:1307.1427 for a Higgs boson with SM-Higgs width and taking interference into account as in the SM
  - Projected limits assume that Higgs is produced either via gluon fusion or via vector-boson-fusion (VBF)

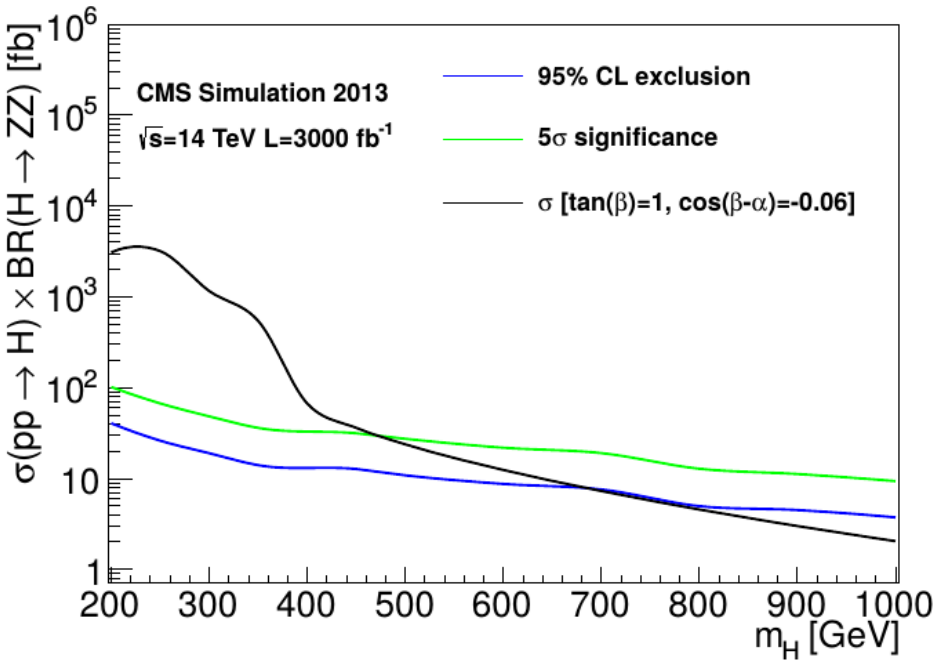




H->ZZ->4l

- CMS has assumed a narrow width Higgs produced via gluon fusion

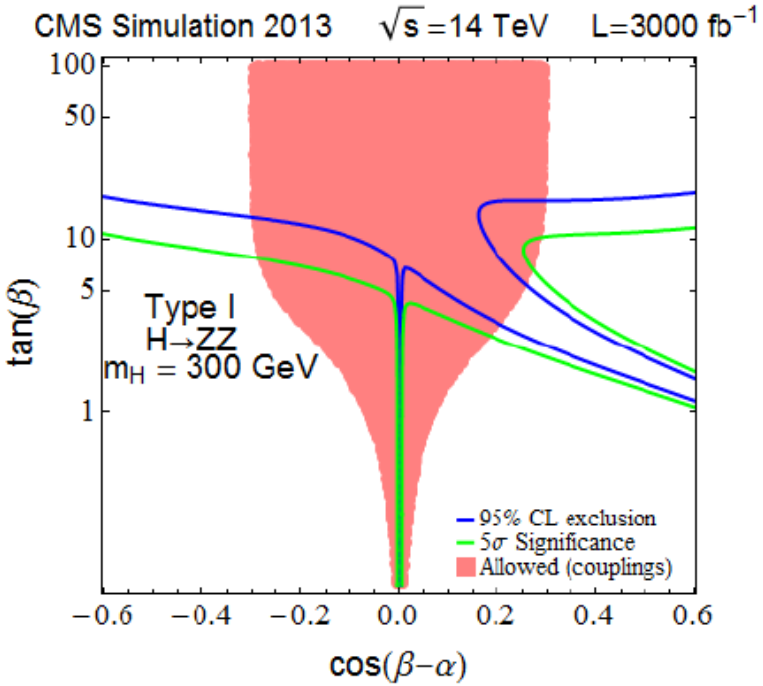


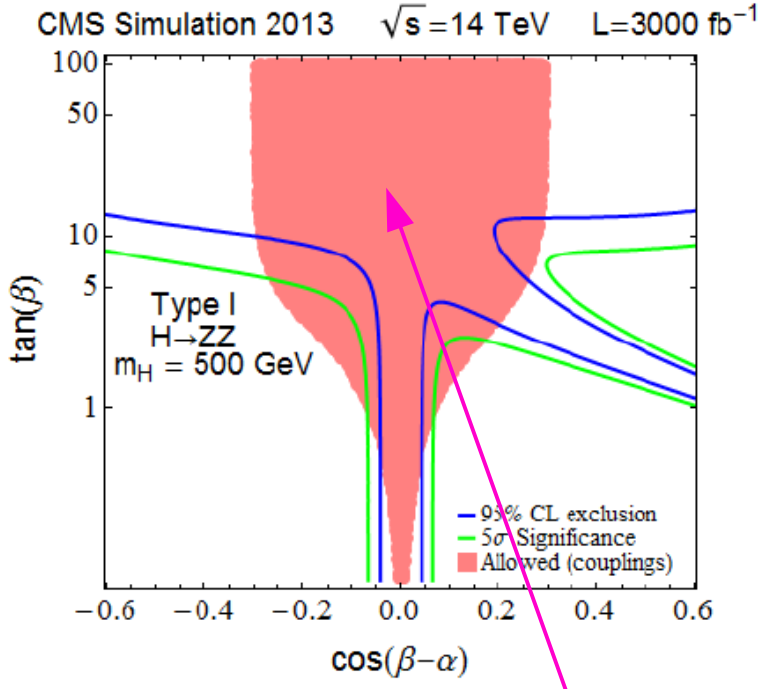


NB: for comparison with the ATLAS limit you need to multiply BR(ZZ->4l)~0.45%; very good agreement between the two results.

H->ZZ->4l

- CMS shows also the constraints from this cross section limit projection to the CP-conserving 2HDM parameter space



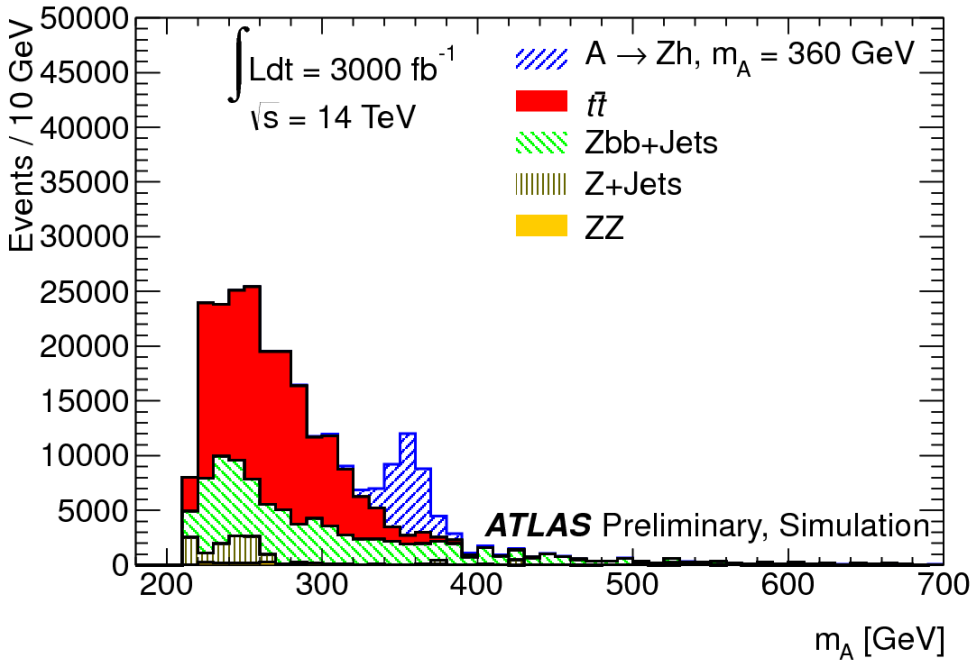


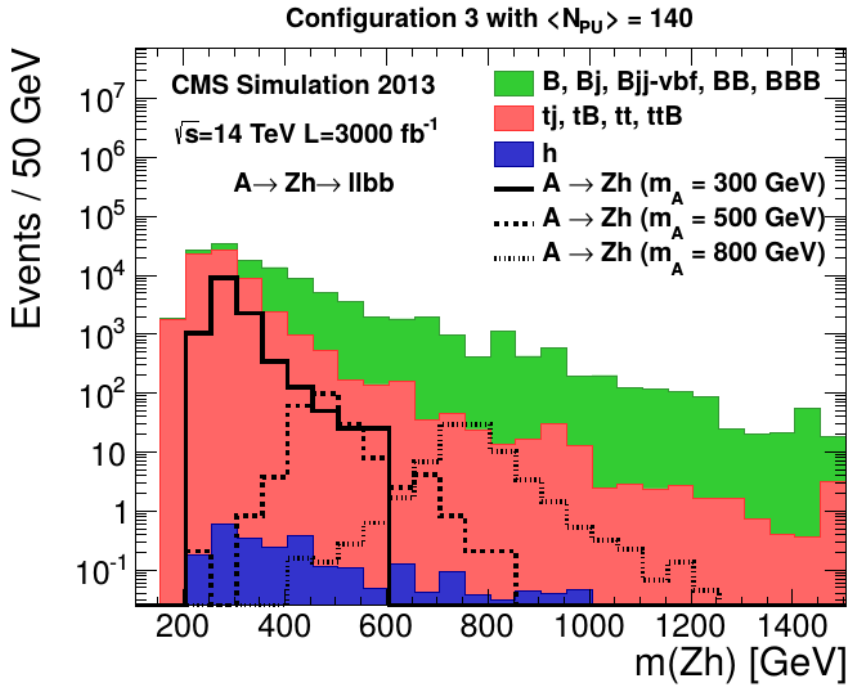
See **CMS-PAS-FTR-13-024** for 2HDM type-II plots

Pink area: constraints from HL-LHC @ 3000 fb^{-1}
Higgs couplings projections from arXiv:1308.0052

A->Zh->llbb

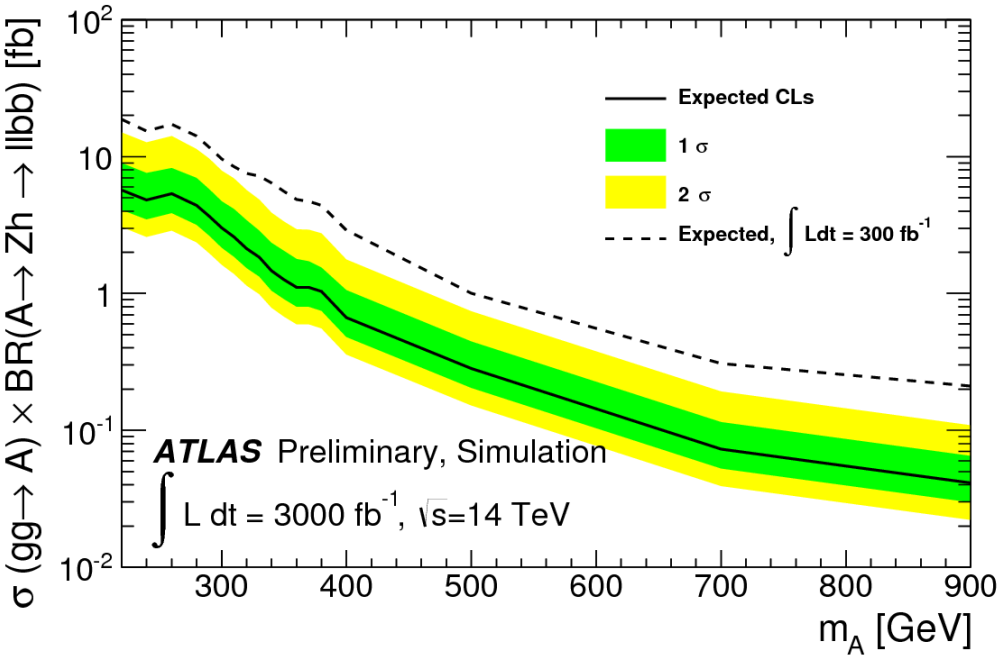
- Both ATLAS and CMS estimated sensitivities for a heavy CP-odd Higgs boson decaying to Zh->llbb

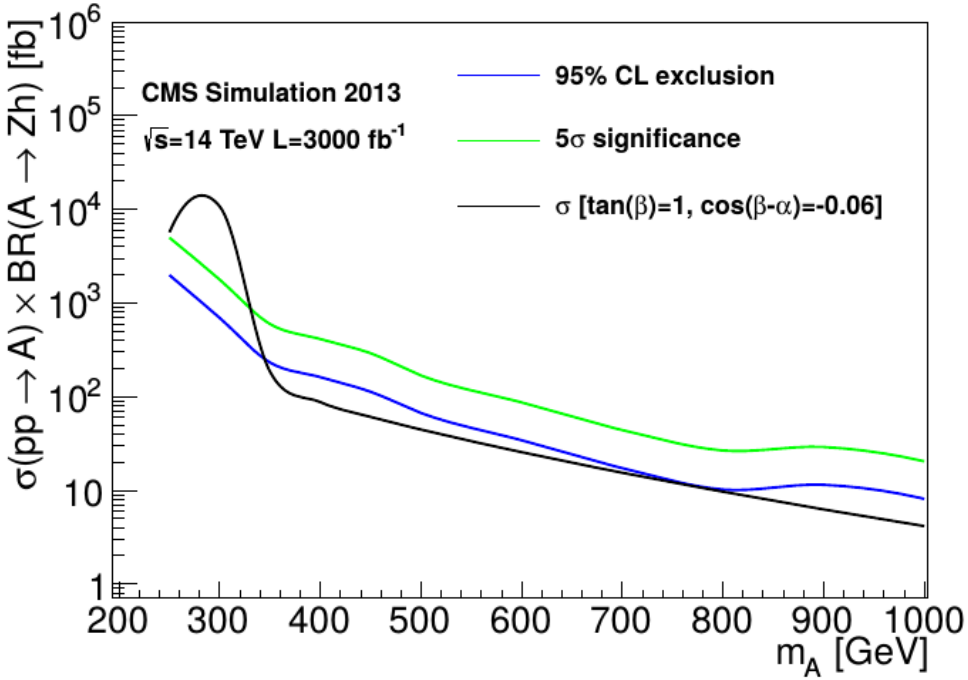




A->Zh->llbb

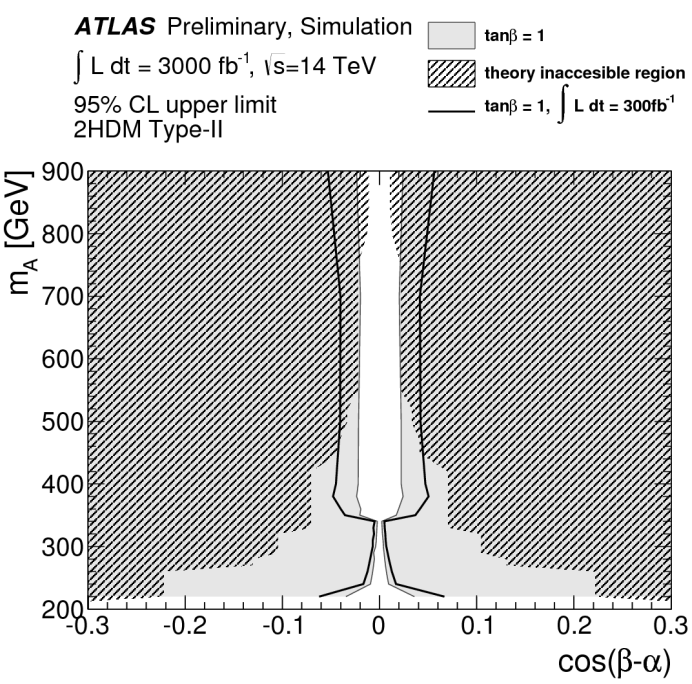
- Projected cross section limits

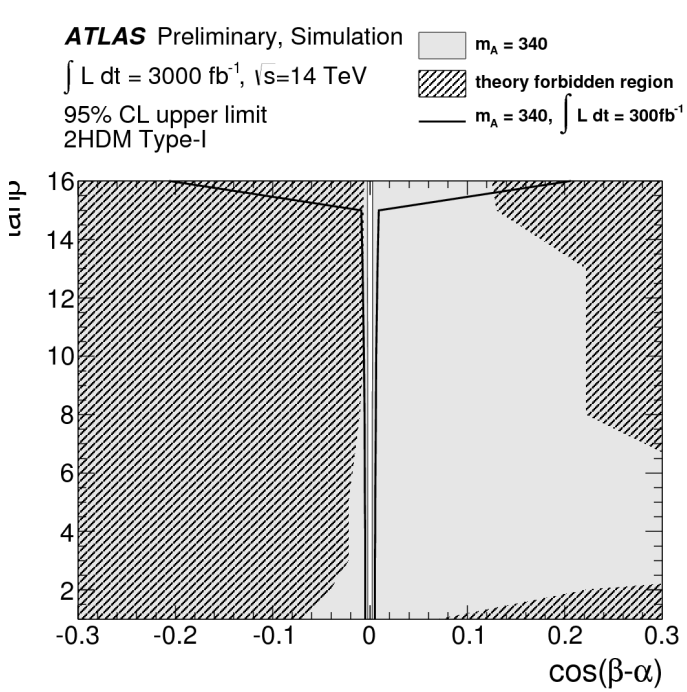


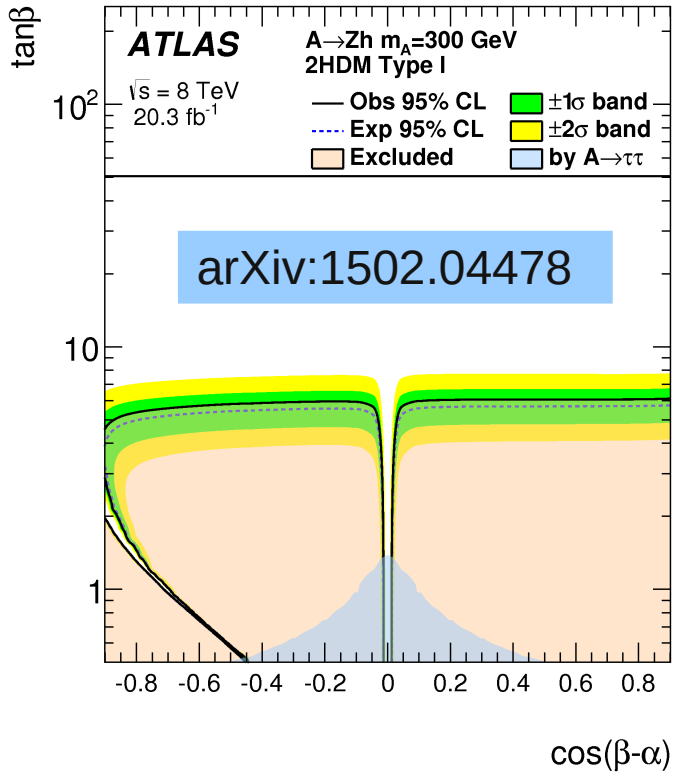


A->Zh->llbb

- Projected sensitivities from ATLAS
  (also: comparison with the Run-I ATLAS result)



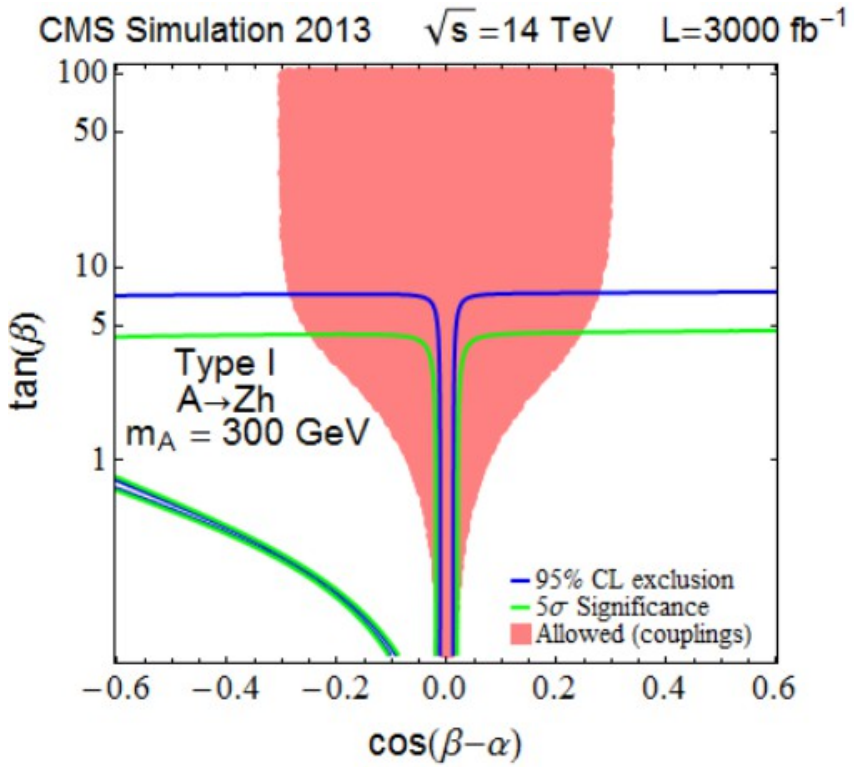


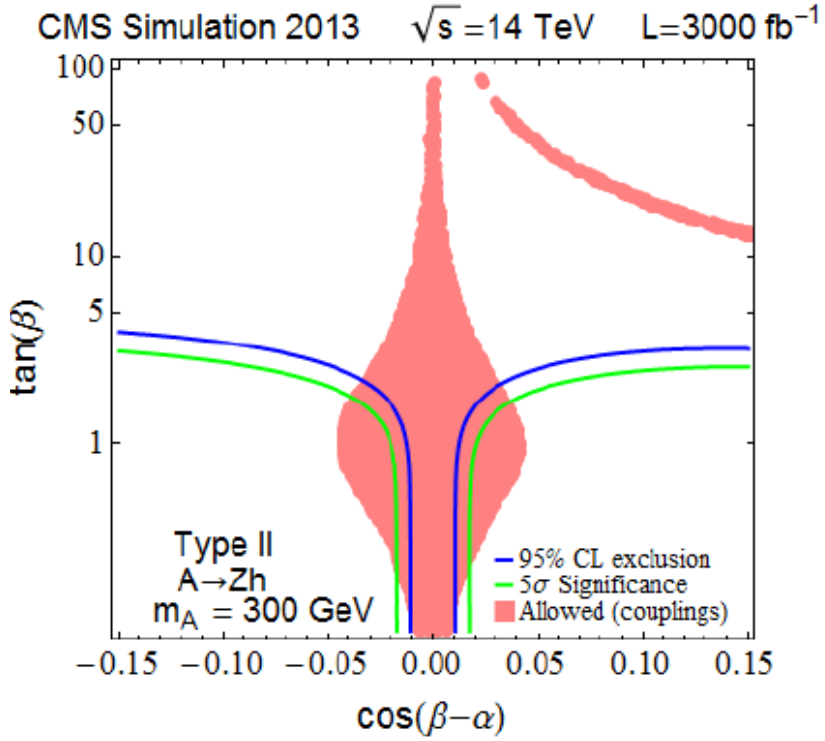


Example from 2HDM Type-I and Type-II; see note for many more plots, discovery potential, other mass points etc

A->Zh->llbb

- Projected sensitivities from CMS





Examples from 300 GeV mass point; see the note for 500 GeV mass point as well

Indirect searches

- Indirect searches for BSM Higgs
  - Precision measurements of 125-GeV Higgs couplings (ATLAS)
  - Search for the FCNC t->cH (ATLAS)
  - Constraining CP-odd component through H->ZZ->4l (ATLAS)
  - Higgs to invisible (ATLAS/CMS)

ATL-PHYS-PUB-2014-017

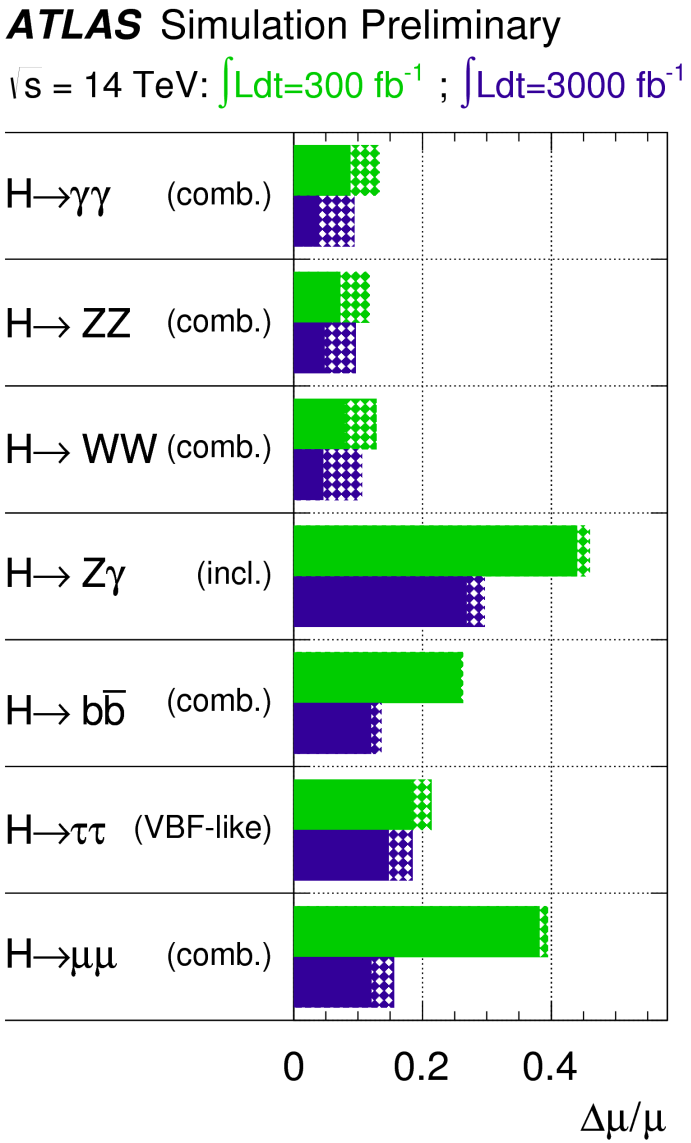
ATL-PHYS-PUB-2013-013

ATL-PHYS-PUB-2013-012

CMS-NOTE-13-002 (arXiv:1307.7135)

Higgs couplings

- The projected Higgs coupling measurements in ATLAS described in ATL-PHYS-PUB-2014-016 can be interpreted in various BSM Higgs models



Measurements from **ATL-PHYS-PUB-2014-016** used in **ATL-PHYS-PUB-2014-017**

No information from differential measurements is included.

Notation for the next slides

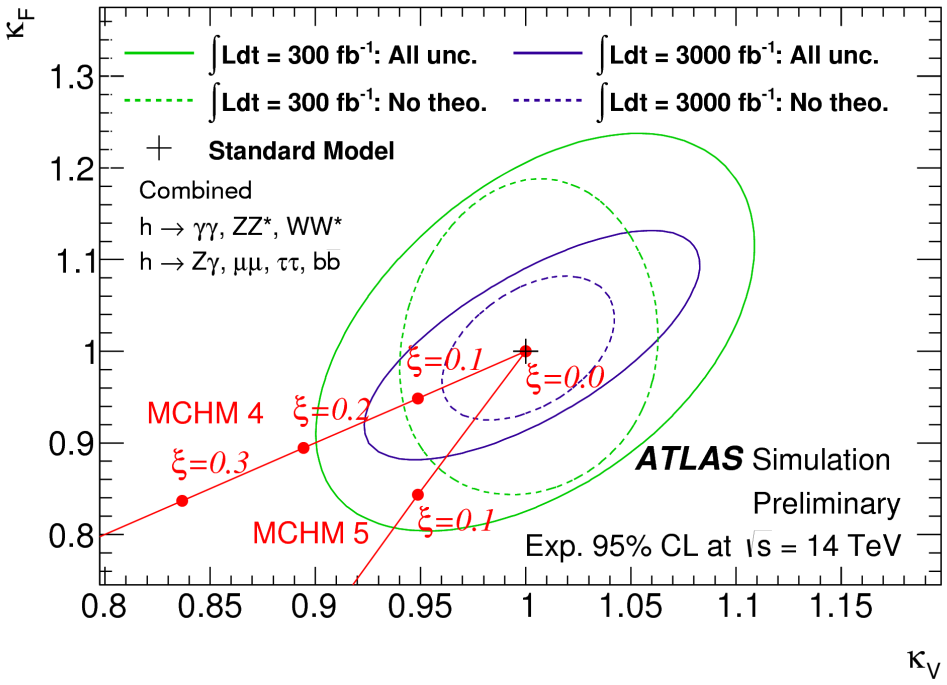
κ_i is a parametrisation of the Higgs coupling hii: ratio of its measured value to the SM value

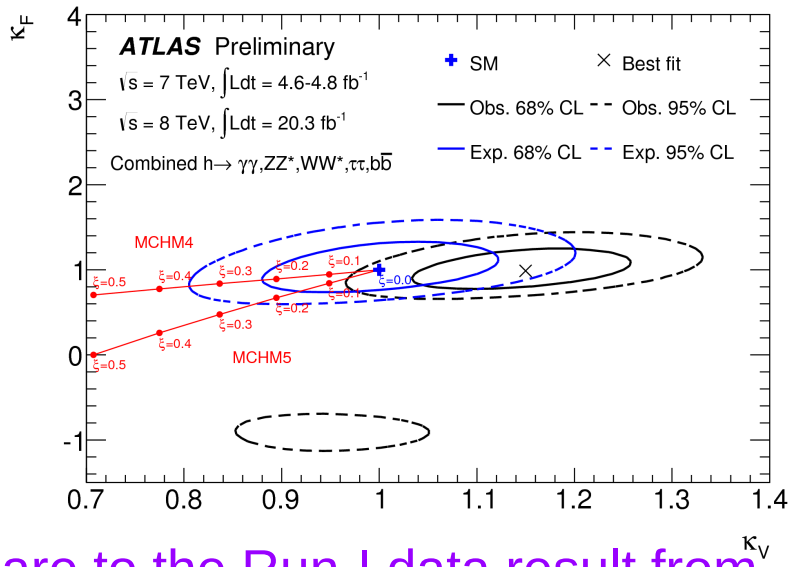
Higgs couplings: Composite Higgs

- Constraint on the compositeness scale f for various models ($\xi = \upsilon^2 / f^2$)

MCHM4: $\kappa = \kappa_V = \kappa_F = \sqrt{(1 - \xi)}$

MCHM5: $\kappa_F = \sqrt{(1 - \xi)}$, $\kappa_V = (1-2\xi)/\sqrt{(1 - \xi)}$

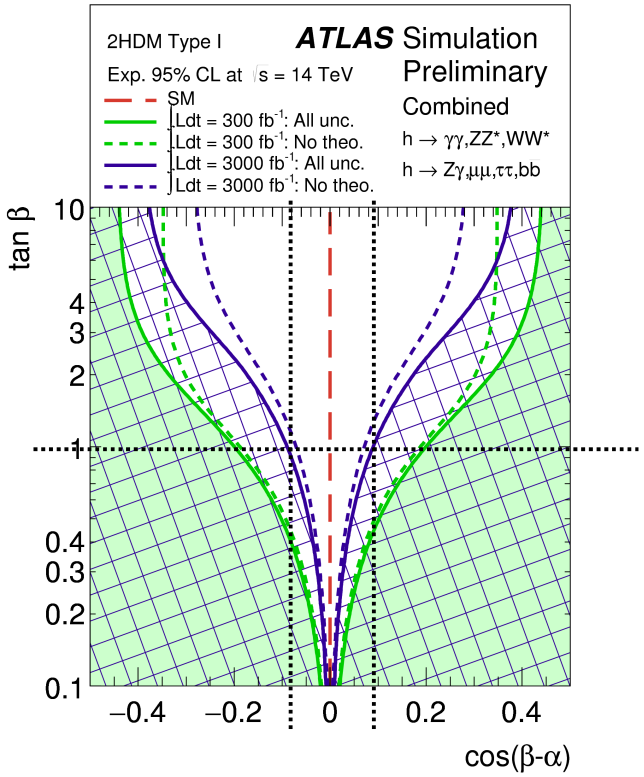


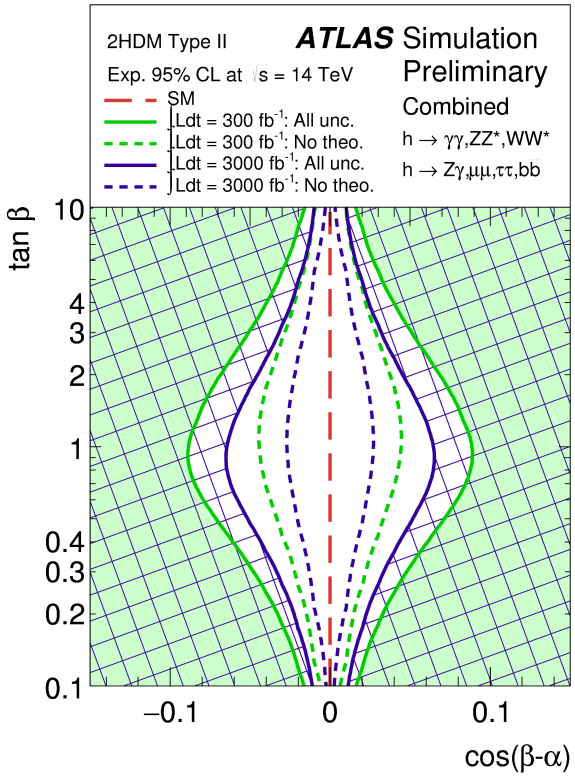


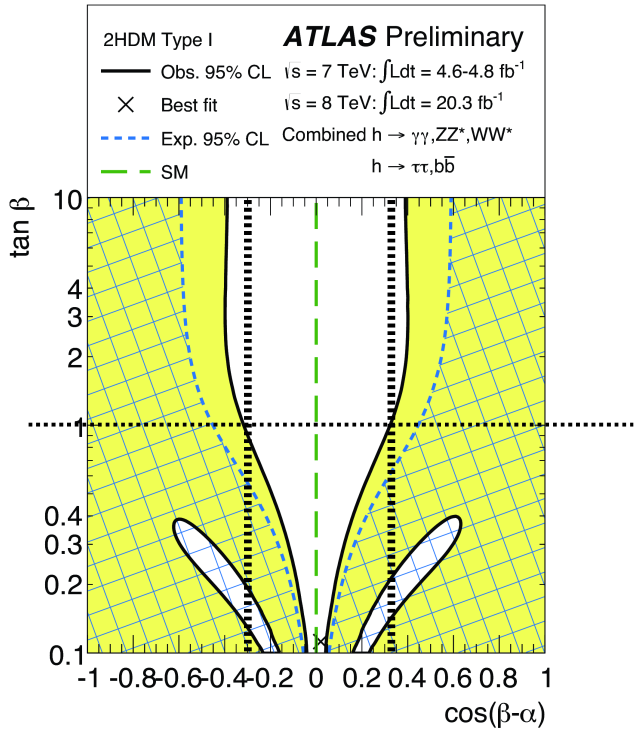
Compare to the Run-I data result from ATLAS (**ATLAS-CONF-2014-010**)

Higgs couplings: 2HDM

- Constraints on the 2HDM parameter space based on κ_V, κ_u, κ_d, κ_l precision and shown on the **tanβ** (ratio of the vevs of the two doublets) versus **cos(β-α)** (cos(β-α) → 1 is the SM-like limit)





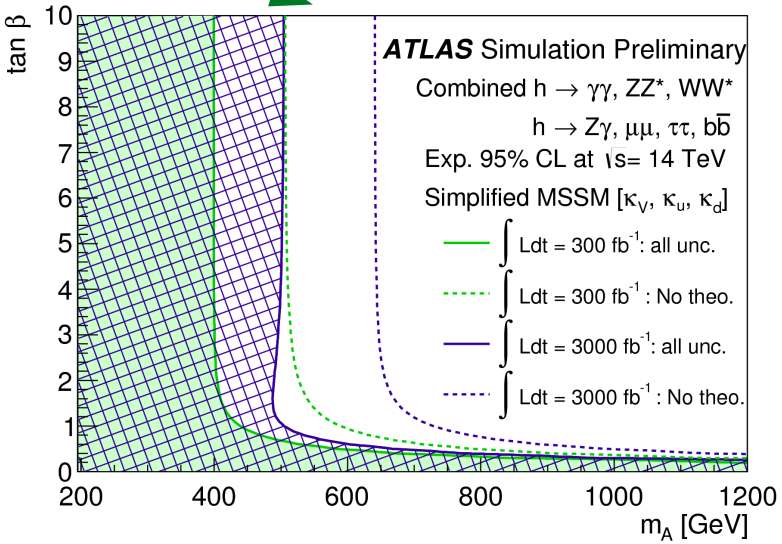


Compare to the Run-I data result from ATLAS (**ATLAS-CONF-2014-010**)

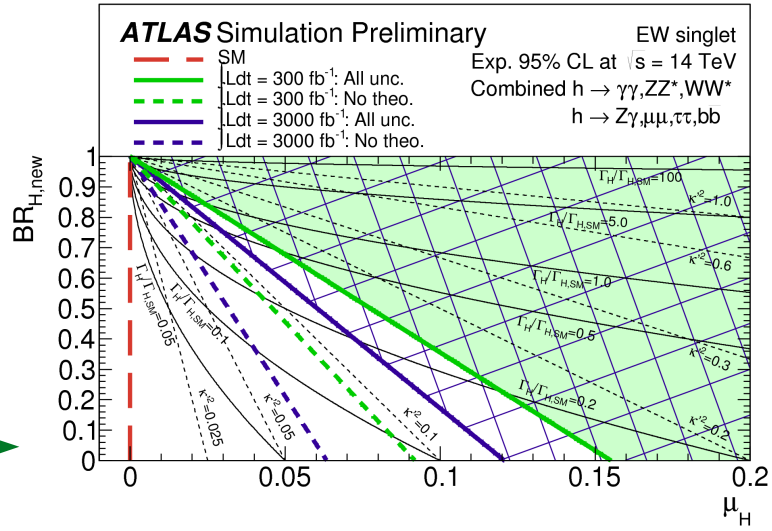
Higgs couplings: other models

- There are other models constrained as well: look them up in the note for details

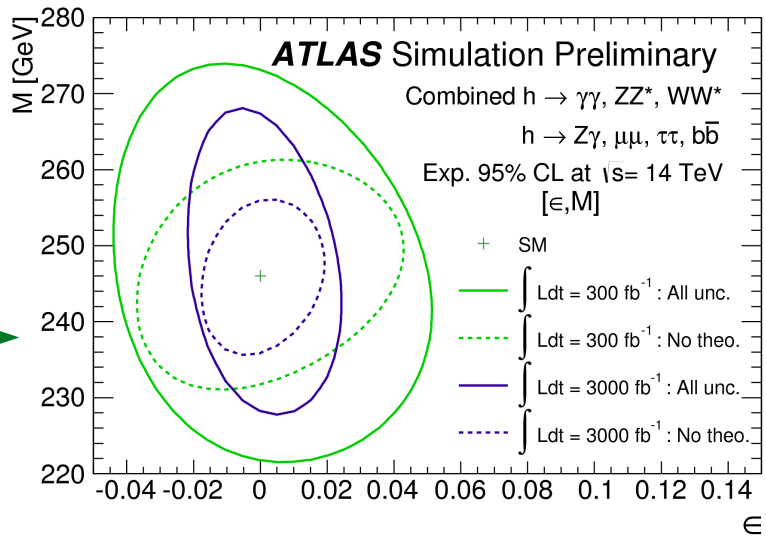
"hMSSM" by fitting κ_V, κ_u, κ_d as a function of m_A and tanβ



Electroweak singlet (fit a universal coupling κ)

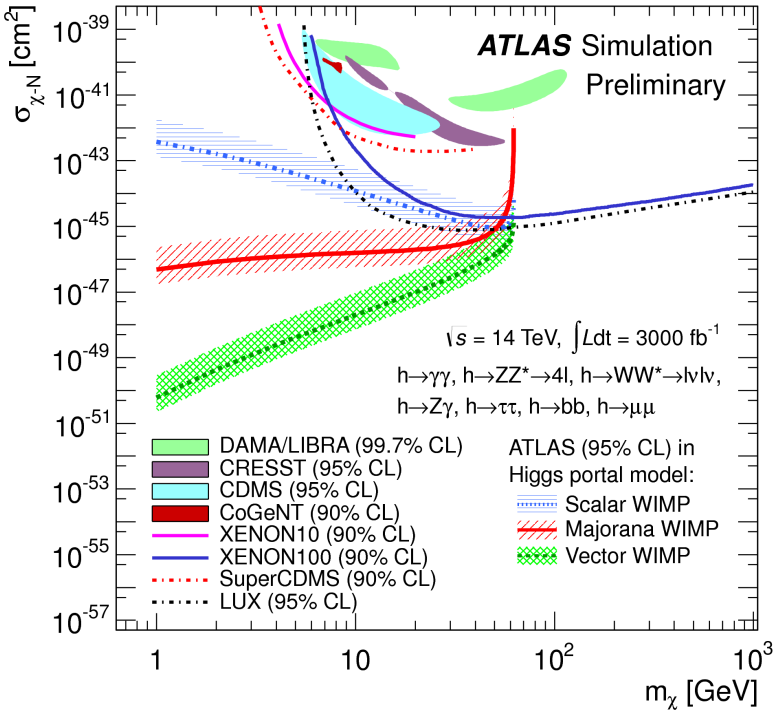


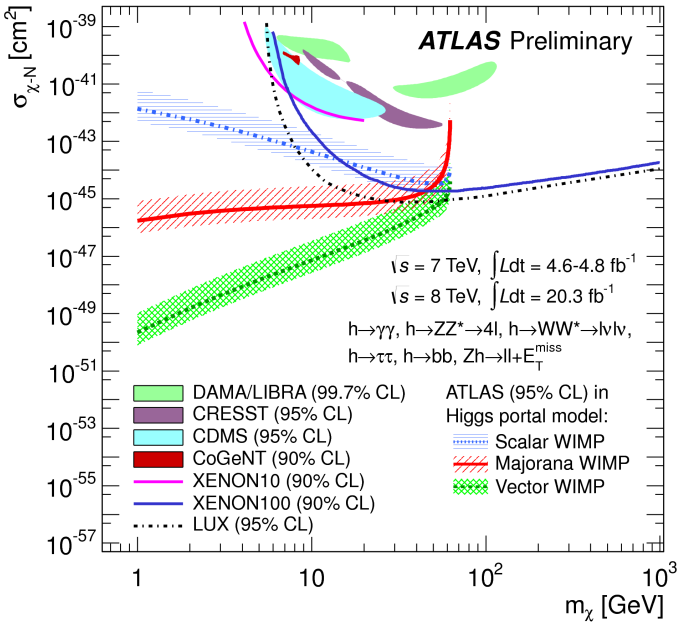
Mass scaling of couplings ($y_f \sim (m/M)^{\varepsilon}$ etc)



Higgs Couplings: Dark Matter

- The Higgs to invisible BR is interpreted to WIMP constraint assuming that H->invisible goes to WIMPs all the time





Compare to the Run-I data result from ATLAS (**ATLAS-CONF-2014-010**)

NB: log scale, so the difference, although large, is less prominent; the Run-I plot contains also ZH,H->inv

Higgs to invisible produced via ZH

- Projection for invisible Higgs decays

BR($H \rightarrow$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

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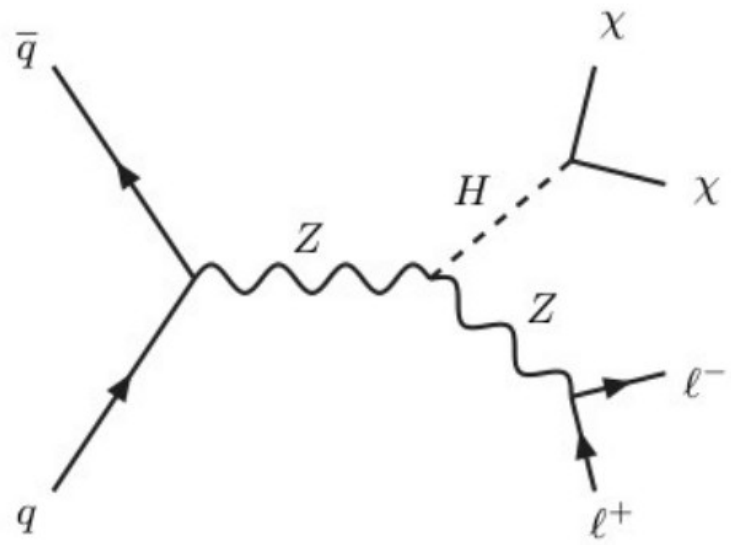
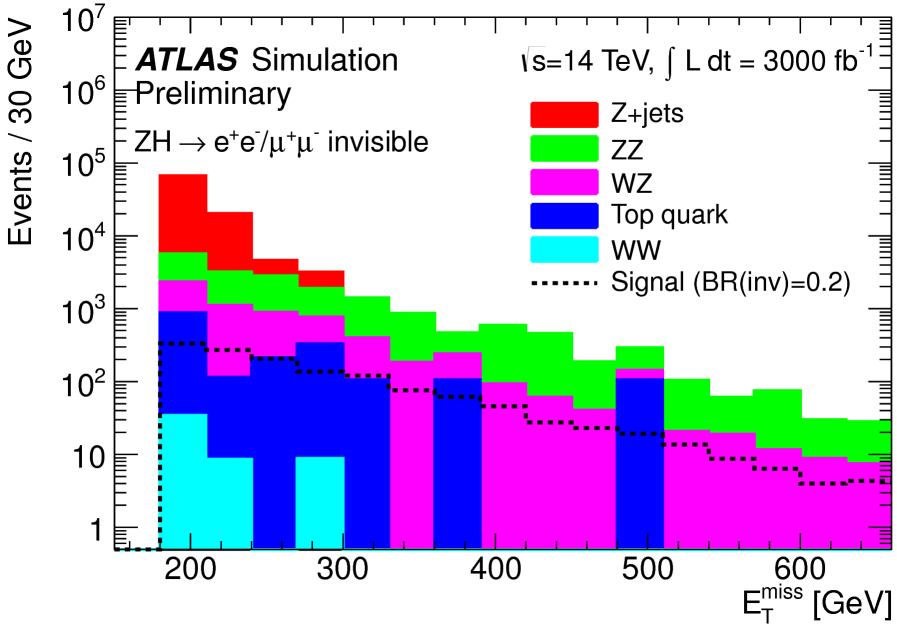
c.f. ATLAS Run-I result BR(H->inv) < 62% (exp.) (arXiv:1402.3244)



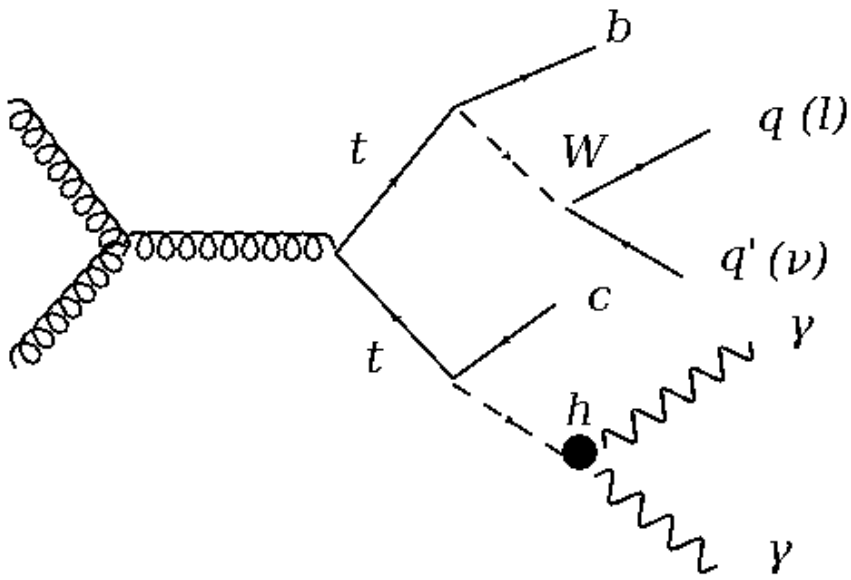


FCNC: t->cH

- Higgs-induced flavor changing neutral currents can be probed with rare top decays

ATLAS has published a search for t->qH in which the Higgs boson decays to a photon pair in **arXiv:1403.6293**

The projection study in **ATL-PHYS-PUB-2013-012** follows this analysis

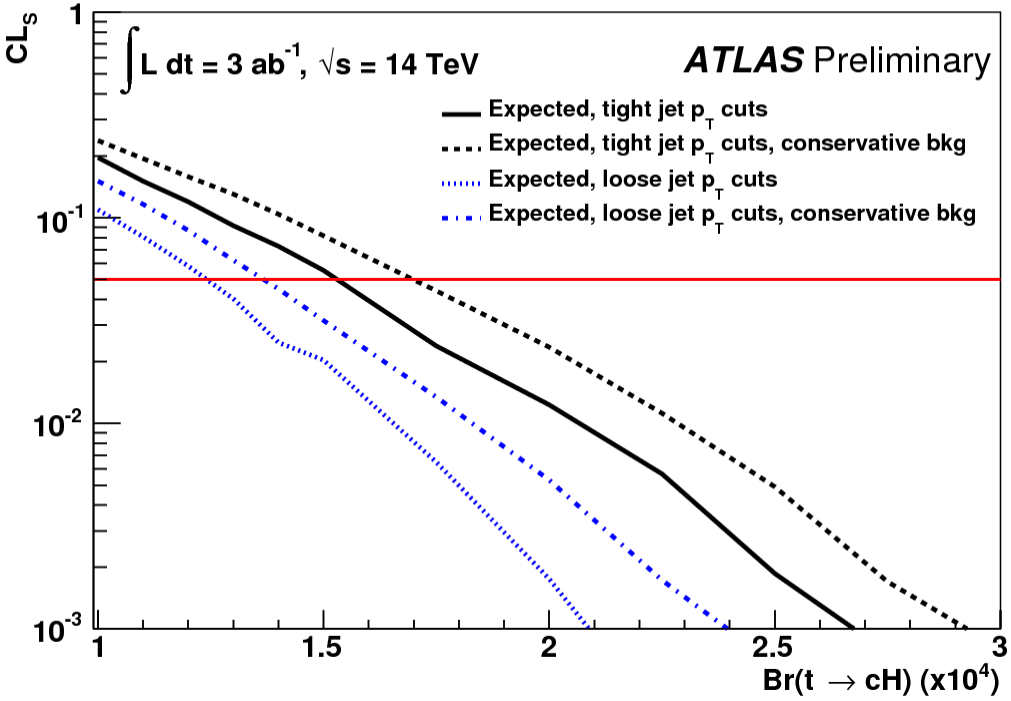


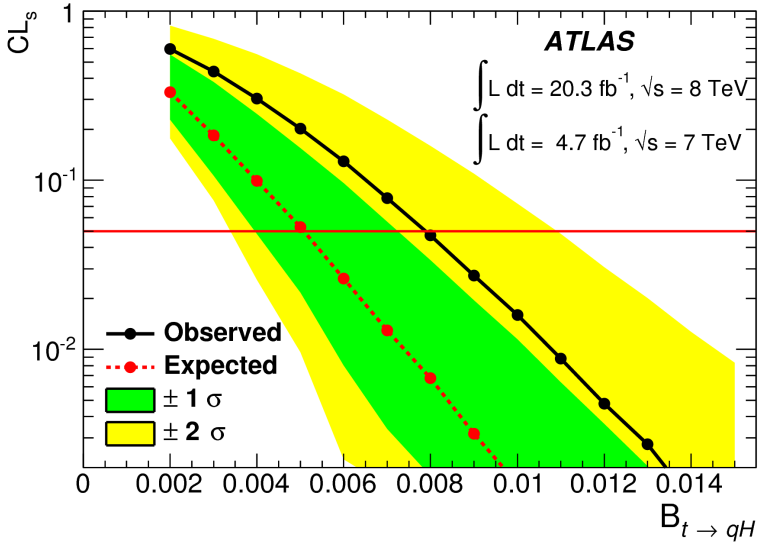
See detailed presentation of this search in the “rare decay” talk by Giovanni Marchiori

FCNC: t->cH

- Result for a conservative and a less conservative scenario

BR(t->cH) < 1.2 x 10^{-4} (1.4 x 10^{-4}) for nominal (conservative); compare the Run-1 result BR < 0.8 x 10^{-2} and the order of magnitude for type-III 2HDM BR ~ 10^{-3}





Compare to the Run-I data result from ATLAS arXiv:1403.6293

See detailed presentation of this search in the “rare decay” talk by Giovanni Marchiori

HZZ vertex tensor structure

- The observation of the H->WW/ZZ decays favor H to be CP-even
- However, one can still find models (see e.g. arXiv:1003.5585) where a CP-odd Higgs can still have considerable BRs to vector bosons
  - These can be constrained through an analysis of the H->ZZ->4l final state

The amplitude for a spin 0 particle to decay to vector bosons can be written as (See LHC HXSG YR3 for details):

Scalar terms

Pseudoscalar term

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

The idea is to perform an analysis using observables that are sensitive to:

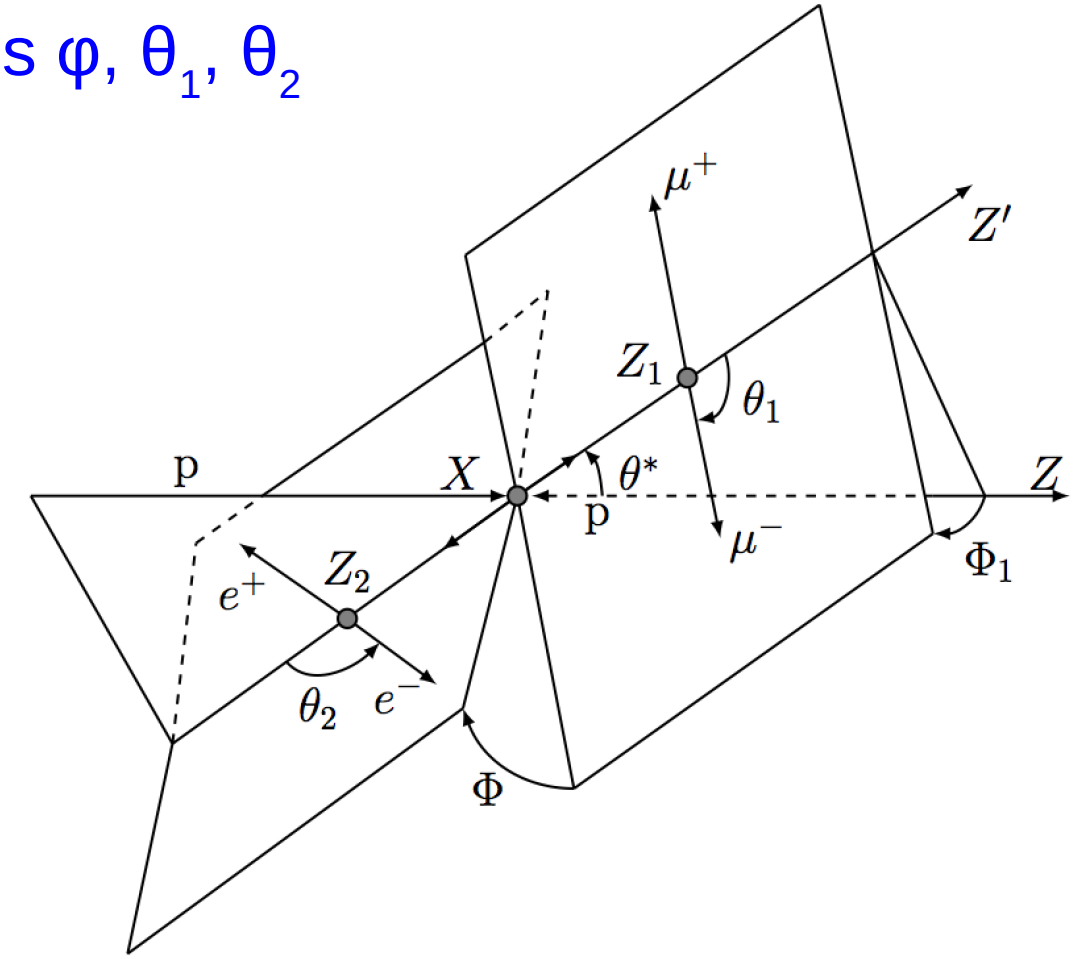
$$f_{gi} = \frac{|g_i|^2 \sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \qquad \phi_{gi} = \arg\left(\frac{g_i}{g_1}\right)$$

σ_i = effective cross section for $g_j = \delta_{ij}$

HZZ vertex tensor structure

- Variables with sensitivity to the HZZ tensor structure:
  - Masses of Z and Z*, angles φ, θ_1, θ_2

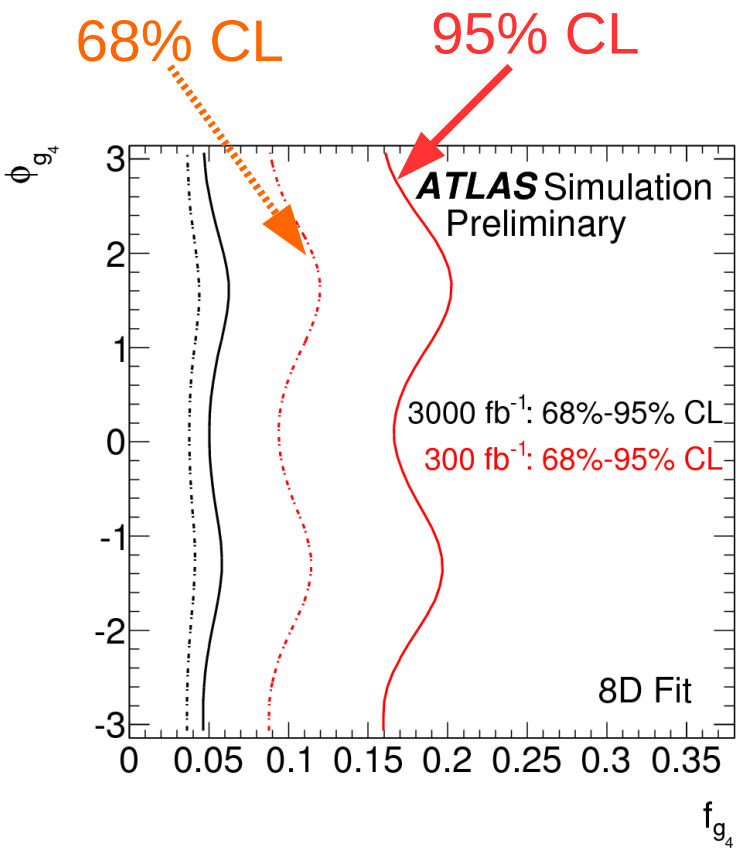
ATLAS study described in
ATL-PHYS-PUB-2013-013
uses these and other variables in two different methodologies: a Matrix-Element (ME) based fit and a 8D likelihood fit to derive constraints on f_{gi} and φ_{gi}

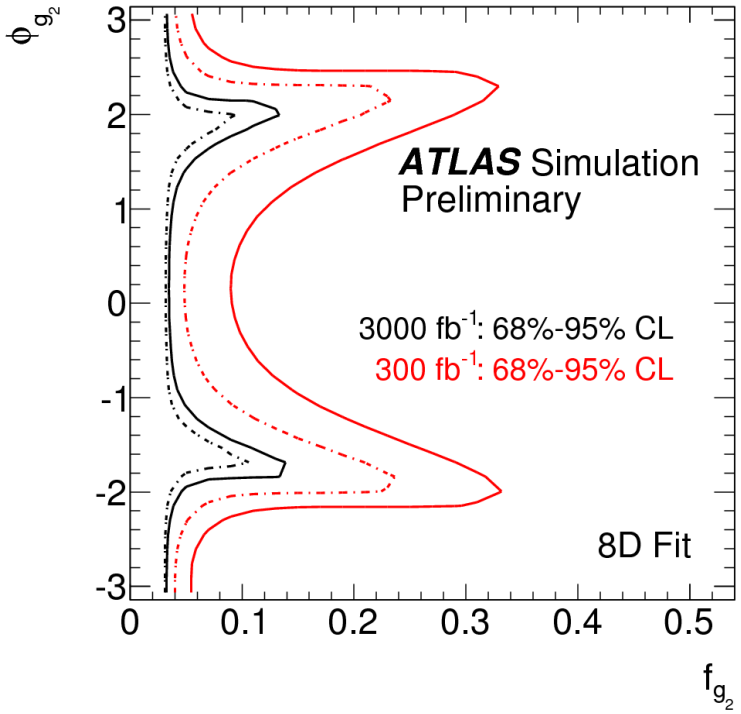


HZZ vertex tensor structure

- Results

Examples of constraints from the 8D likelihood fit; look at the note for more details.





ME based

Luminosity	f_{g_4}	f_{g_2}
300 fb^{-1}	0.15	0.43
3000 fb^{-1}	0.037	0.20

8-D LLH fit

Luminosity	f_{g_4}	f_{g_2}
300 fb^{-1}	0.20	0.29
3000 fb^{-1}	0.06	0.12

Compare the result with the sensitivity for the ATLAS Run-I result (ATLAS-CONF-2015-008)

$H \to ZZ^* \to 4\ell$		
$f_{g2} < 0.94$ for $\phi_{g2} = 0$	and	$f_{g2} < 0.16$ for $\phi_{g2} = \pi$
$f_{g4} < 0.56$ for $\phi_{g4} = 0$	and	$f_{g4} < 0.56$ for $\phi_{g4} = \pi$

Concluding Remarks

- HL-LHC is a good opportunity to look for BSM Higgses both directly and indirectly
  - High integrated luminosity samples at 14 TeV: potential to direct searches that are unique (i.e. cannot be done in a dedicated e^-e^+ or $\mu^-\mu^+$ Higgs factory)
  - Higher precision in 125-GeV Higgs measurements will improve the reach to indirect constraints
- Only a handful of analyses have been extrapolated by the experimental collaborations but they can already provide a glimpse into the physics reach

Additional Slides

Theory needs

- There is currently a very nice collaboration for Higgs physics with the theory community within the LHC Higgs Cross sections group:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3 ← **BSM Higgs specific**

- For BSM specific items we have the tools to calculate cross sections and BR
  - SusHi, HIGLU can calculate 2HDM and MSSM gluon-fusion and b-associated production
  - Branching ratios are available from HDECAY, FeynHiggs
  - LHC HXSG is open to more contributions! Please come and contribute!

Higgs Couplings

	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, τ, μ, ...) 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, τ, μ, ...) 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%