Studies of Higgs Boson Properties in Future LHC Runs (Snowmass & ECFA studies)

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On behalf of the
ATLAS & CMS collaborations

Blois 2014,
May 21st, 2014

Future LHC Goals

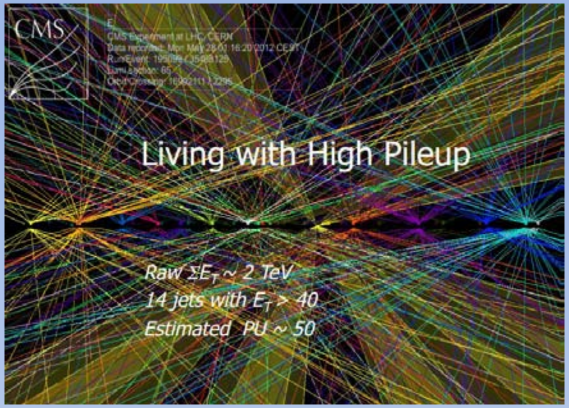
ESTIMATED LUMINOSITY and PILEUP (ATLAS & CMS)

LHC			HL-LHC	
Run I	Run II	Run III	Run IV	Run V+
2010-2012	2015-2017	2019-2021	2024-2026	2028-2030+
25 fb^{-1}	**100 fb^{-1}**	**300 fb^{-1}**	**------>**	**3000 fb^{-1}**
6×10^{33} $cm^{-2}s^{-1}$	10^{34} $cm^{-2}s^{-1}$	2×10^{34} $cm^{-2}s^{-1}$	**------>**	5×10^{34} $cm^{-2}s^{-1}$
$\langle\mu\rangle \leq 21$	**≈ 40**	**≤ 60**	**------>**	**≈ 140**

LHC Run II : Beam in January, Physics in April (13/14 TeV)

2015	2015	2015	2015	2016
Spring	July (EPS)	August (LP)	Fall (LHCP)	March (Moriond)
0-1 fb^{-1}	**1-2 fb^{-1}**	**2-5 fb^{-1}**	**3-10 fb^{-1}**	**15-30 fb^{-1}**

Detector Upgrades



High pileup will be compensated by detector upgrades.

Phase-0 upgrade (2013-2014)

- **ATLAS: Insertable B-layer (IBL), Level-1 topological trigger, complete muon coverage, repairs (TRT, LAr and Tile)**
- **CMS: 4th muon end-cap station, complete muon coverage, new detector consolidation, colder tracker**

Phase-1 upgrade (2018-2019)

- **ATLAS: Fast Track Trigger (FTK), High granularity Level-1 calorimeter trigger, new small wheel for Level-1 muon trigger**
- **CMS: New Level-1 trigger system, new Si pixel detector, new photo-detector & electronics for HCAL**

Phase-2 upgrade (2023-2025)

- **ATLAS: New silicon tracker & forward calorimeter & electronics, Level-1 track trigger**
- **CMS: New tracker with Level-1 capability, DAQ/HLT upgrade, replace end-cap & forward calo; possibly extension of muon coverage & EM pre-shower system**

Higgs Physics Goals of ATLAS and CMS

A wide Higgs physics program **(e.g. Snowmass 2013 arXiv:14016081)**

LHC:

- "Rediscovery" of the Higgs boson in ZZ and $\gamma\gamma$ channels (2015)
- Early cross section measurements with ZZ and $\gamma\gamma$ (2015)
- The 1st measurement of ttH coupling
- Searches for heavy BSM Higgs bosons
- Higgs boson couplings and mass at the 10% level
- Spin and CP at the 10% level

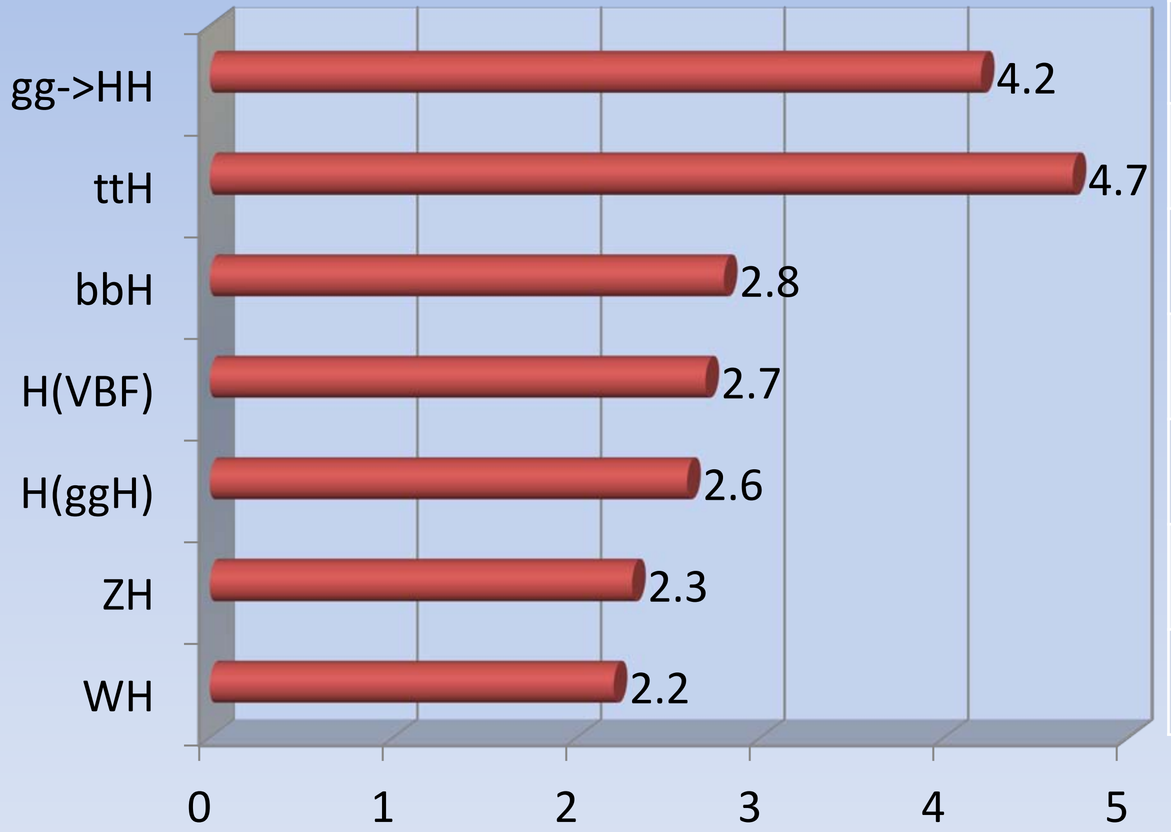
Higgs Physics Goals of ATLAS and CMS

HL-LHC:

- Precision measurements of Higgs boson couplings with sensitivity of 2-10%
- Precision measurement (1%) for the ratio of γγ and ZZ couplings
- Precision CP measurements
- Rare decays and couplings ($\mu^+\mu^-$ and Zγ with 100M Higgs bosons)
- Provide the 1st evidence of the Higgs boson pair production
- Extended search of BSM Higgs bosons

Cross Sections

Cross section ratios: σ(14 TeV) / σ(8 TeV)



Process	Cross section
gg->HH	33.86 fb
ttH	0.6043 pb
bbH	0.5739 pb
H(VBF)	4.22 pb
H(ggF)	49.13 pb
ZH	0.9574 pb
WH	1.502 pb

$\sqrt{s} = 14 TeV$ MH=125.5 GeV

(gg->HH MH=125 GeV)

Signal Strength Uncertainties Δμ/μ

L, fb^{-1}		γγ , %	WW	ZZ	bb	ττ	Zγ	μμ	Invis.
300	ATLAS	[9,14]	[8,13]	[6,12]	-	[16,22]	[145,147]	[38,39]	-
	CMS	[6,12]	[6,11]	[7,11]	[11,14]	[8,14]	[62,62]	[40,42]	[17,28]
3000	ATLAS	[4,10]	[5,9]	[4,10]	-	[12,19]	[54,57]	[12,15]	-
	CMS	[4,8]	[4,7]	[4,7]	[5,7]	[5,8]	[20,24]	[20,24]	[6,17]

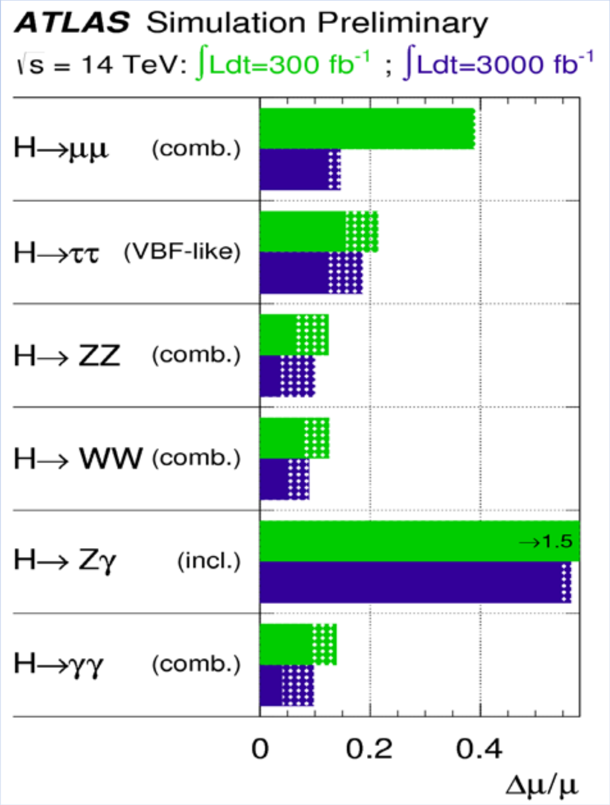
$$\mu = \sigma \times BR / (\sigma \times BR)_{SM}$$

ATLAS [1,2]:

1. Only current statistical and experimental systematic uncertainties
2. With theory systematic uncertainties

CMS [1,2]:

1. Theoretical uncertainties are scaled by a factor of 1/2, systematic uncertainties are scaled by $1/\sqrt{L}$
2. All current systematic uncertainties



Higgs Boson Couplings

Snowmass 2013
arXiv:1401.6081

Coupling scale factors

$$\frac{\sigma \cdot BR(gg->H->\gamma\gamma)}{\sigma_{SM}(gg->H)\cdot BR_{SM}(H->\gamma\gamma)} = \frac{k_g^2 k_\gamma^2}{k_H^2}$$

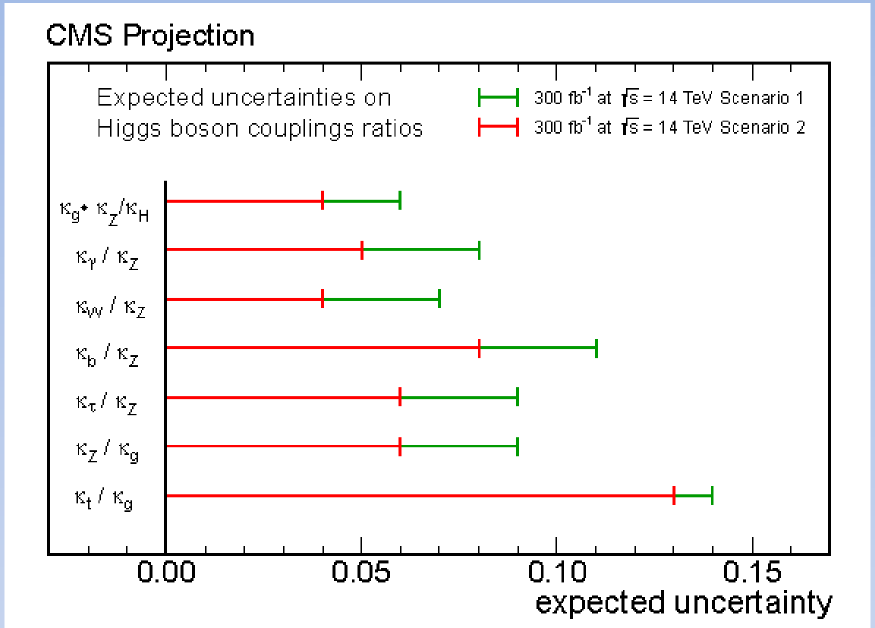
$$k_H^2 = \sum_X k_X^2 \cdot BR_{SM}(H->X)$$

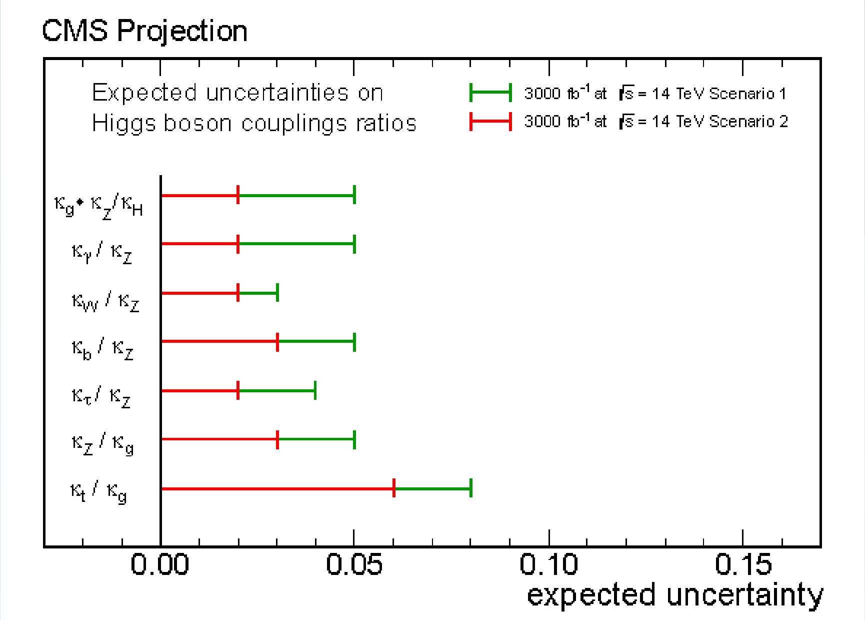
Assumptions:
Only one and narrow Higgs resonance.
Tensor structure of SM.

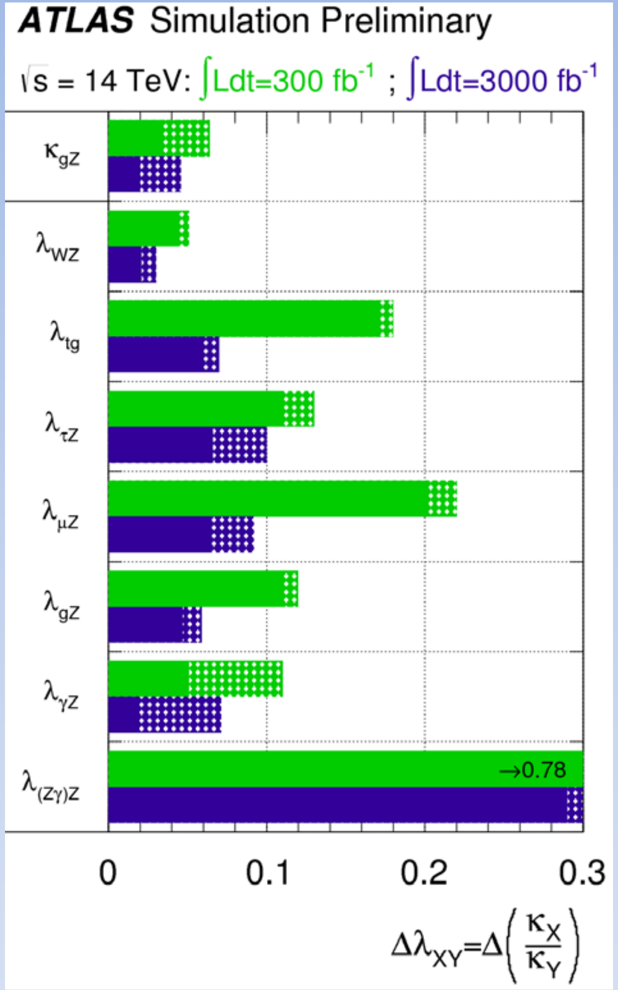
Model	k_V , %	k_b , %	k_γ , %
Singlet Mixing	6	6	6
2HDM	1	10	1
Decoupling MSSM	-0.001	1.6	<1.5
Composite	-3	-(3-9)	-9
Top Partner	-2	-2	1

L		K_γ , %	k_W	k_Z	k_g	k_b	k_t	k_τ	$k_{Z\gamma}$	k_μ
300 fb^{-1}	ATLAS	[8,13]	[7,8]	[7,8]	[9,11]	-	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000 fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	-	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Higgs Boson Coupling Ratios







Good agreement between ATLAS and CMS.

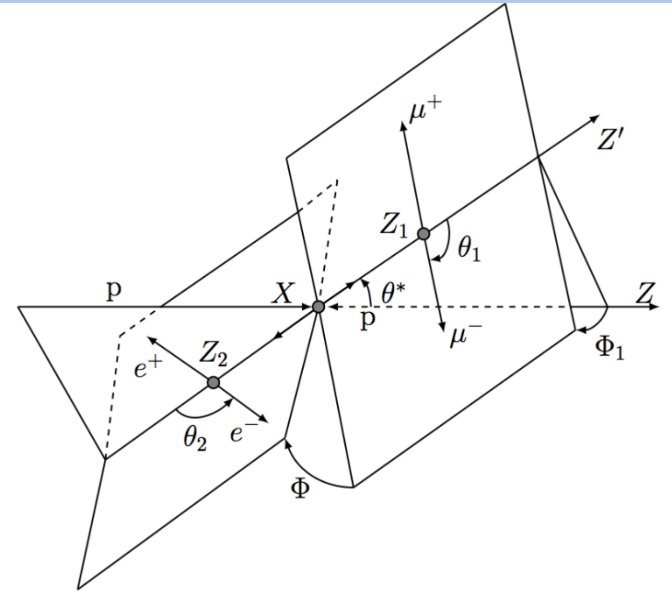
HZZ vertex tensor structure

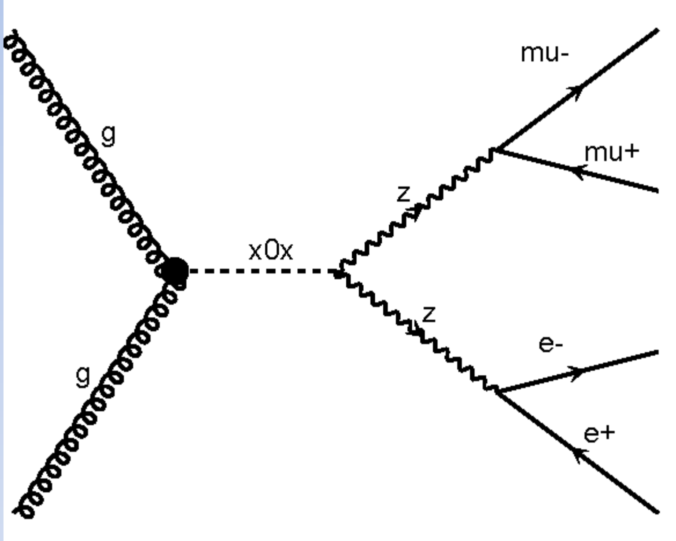
$$A(X->VV) = v^{-1}[g_1 M_V^2 \varepsilon_1^* \varepsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}]$$

SM, tree level

CP-even

CP-odd



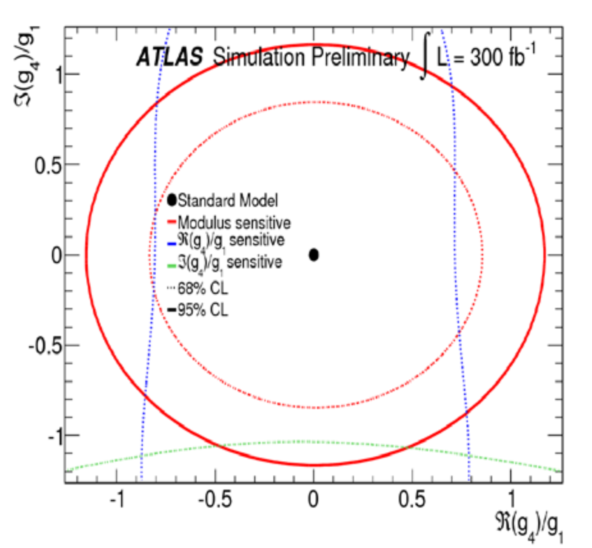


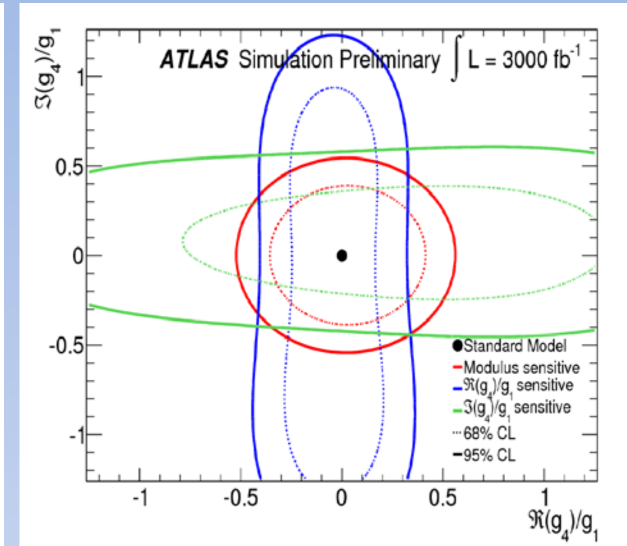
Analysis of mass and angular distributions in the process
gg -> X -> ZZ -> 4l

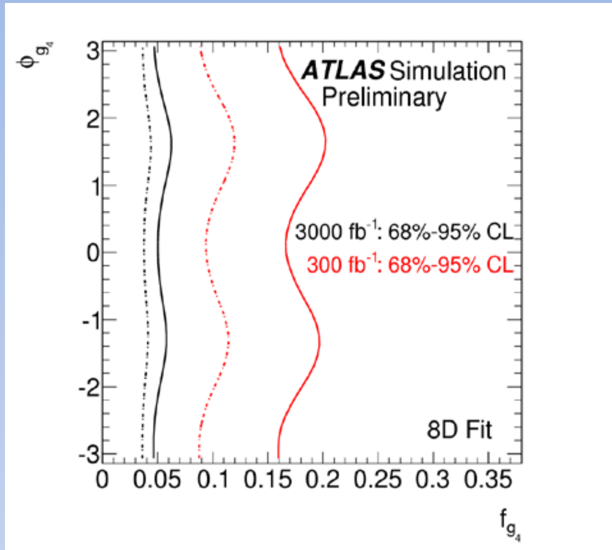
Measure of CP violation

$$f_{g_i} = \frac{|g_i|^2 \sigma_i}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4}$$

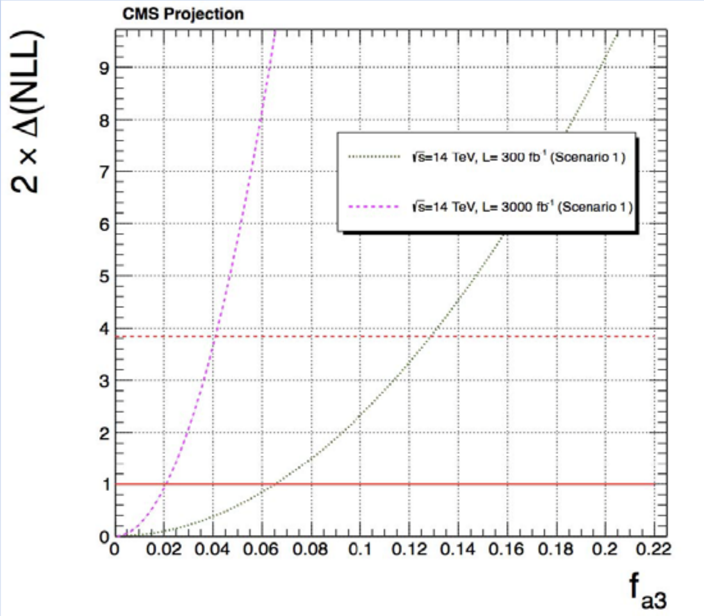
HZZ vertex tensor structure







At 95% CL : $\sqrt{s} = 14 TeV$



$f_{g4} < 0.58$ CMS (25 fb^{-1}, LHC Run I)

$f_{g4} < 0.15$ (0.05) for 300 fb^{-1}(3000 fb^{-1})
Snowmass projection

$f_{g2} < 0.29$ (0.12) for 300 fb^{-1}(3000 fb^{-1})
ECFA studies

CP from H->$\tau^+\tau^-$ decay channel

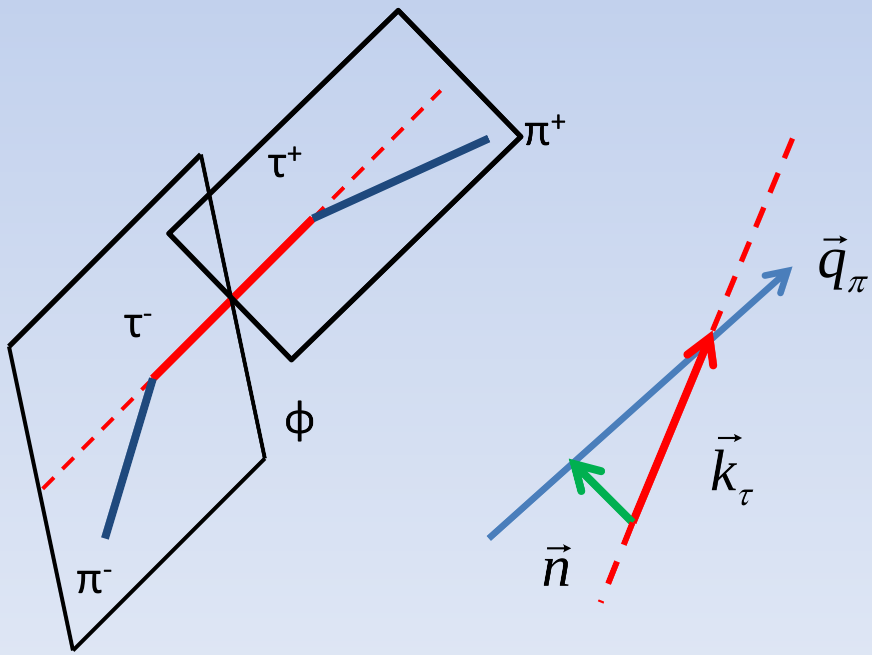
$$L = (a\bar{\tau}\tau + ib\bar{\tau}\gamma_5\tau)X$$

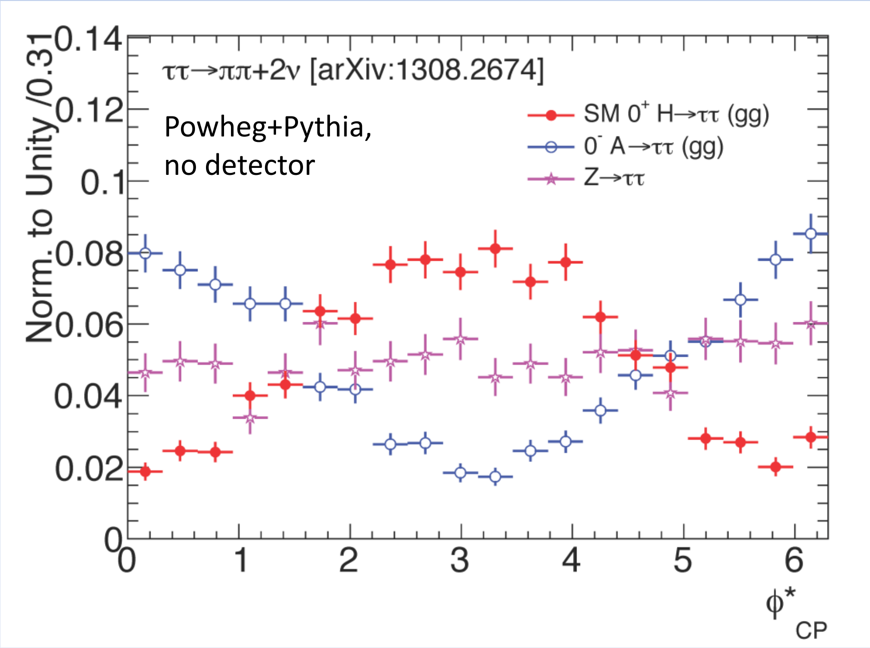
CP-even CP-odd

- Large branching ratio BR = 6.24%.
- Access to CP at tree level.
- Angular distributions of decay products are sensitive to spin correlations.
- CP-even, CP-odd, and mixed CP states can be distinguished.

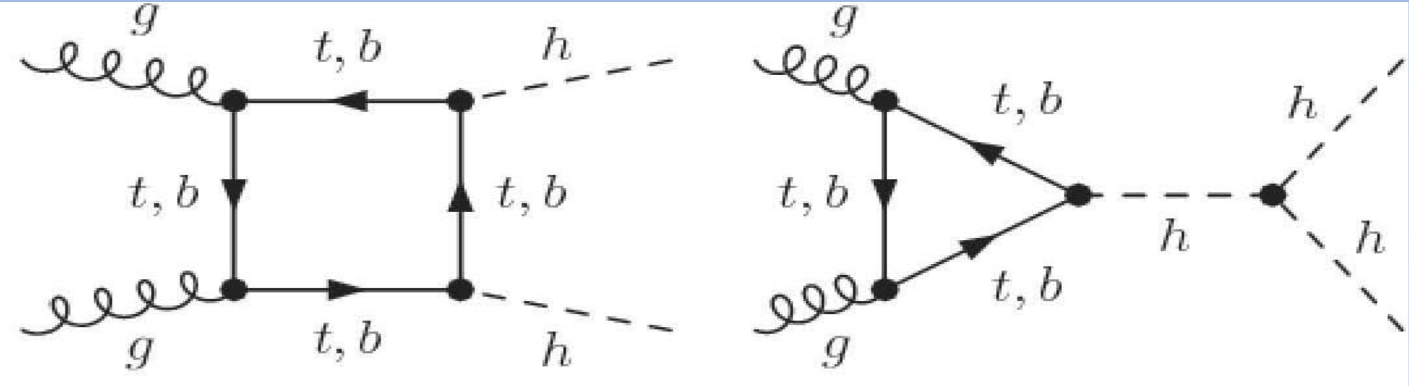
$$\tau \to l\nu_l\nu_\tau, \pi\nu_\tau, \pi\pi^0\nu_\tau, \pi 2\pi^0\nu_\tau, 2\pi^\pm\pi^\mp\nu_\tau$$

$$\Phi^*_{CP} = \arcsin(\vec{q}^{\,*}_- \cdot (\vec{n}^{*+}_T \times \vec{n}^{*-}_T))$$





Higgs Boson self-coupling



One of the top priorities of Higgs boson physics.
λ_{HHH} determines the shape of the Higgs potential.

Large background.
Destructive interference.

- It's extremely challenging.
- High demands on detectors.
- Analysis should involve many channels.
- Combined ATLAS/CMS data

λ_{HHH}	σ(14 TeV), fb^{-1}	σ(33 TeV), fb^{-1}
λ_{SM}	34	207
0	71	414
$2\lambda_{SM}$	16	101

Important decay modes: bbττ and bbγγ. Studies are ongoing.

The double Higgs production cross section increases rapidly with energy.

Higgs boson width

New CMS result [arXiv:1405.3455] based on the Higgs boson off-shell production and decays H->ZZ->4l, H->ZZ->2l2ν:

Γ_H < 22 MeV at the 95% CL .

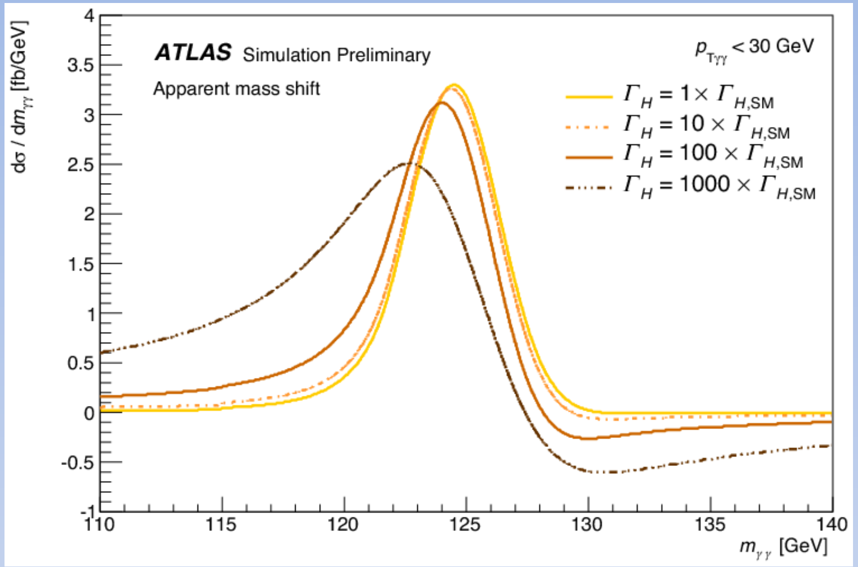
CMS direct width measurement from H->ZZ->4l [arXiv:1312.5353]: Γ_H < 3.4 GeV at the 95% CL.

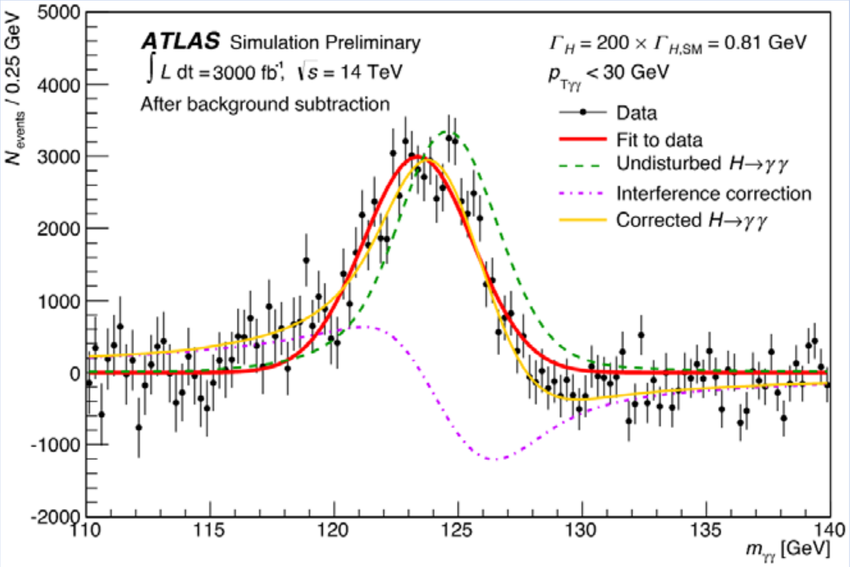
γγ channel: Γ_H < 6.9 GeV CMS

Interference between signal and background -> shift in peak position [arXiv:1305.3854]

Γ_H < 880 MeV for 300 fb^{-1}

Γ_H < 160 MeV for 3000 fb^{-1}



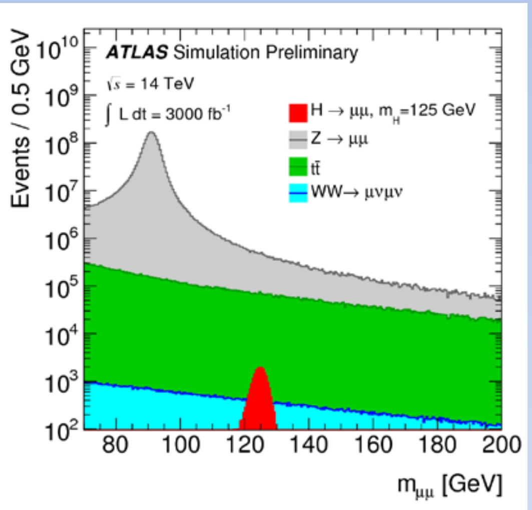


Rare decays H->μμ, H->Z γ and ttH coupling

(update will be available soon)

H->μ⁺μ⁻ : Direct probe of the H coupling to 2nd generation fermions.
Can contribute to mass measurements (high resolution 1-2% of $\mu^+ \mu^-$ invariant mass).
Test of the ratio of 2nd to 3rd generation lepton couplings (m_μ^2 / m_τ^2 in SM LO).
Low branching ratio BR=$2.2 \cdot 10^{-4}$. Very large background from Z/γ*.

H->μμ	L, fb^{-1}	Signal significance	Δμ/μ , %
ATLAS	300	2.3σ	46
ATLAS	3000	7σ	21
CMS	3000	~5σ	8



ttH coupling plays a special role in studies of electroweak symmetry breaking σ = 0.6 pb at 14 TeV.

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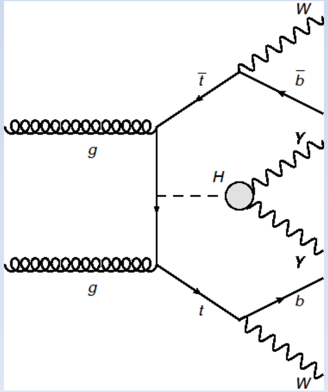
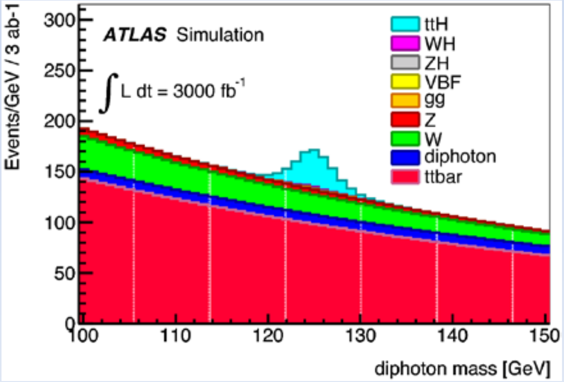




H->Z γ:
sensitive to new particles in loops
(only charged particles in SM)
2.1 σ with 3000 fb^{-1}

Flavor Changing Neutral Currents

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
t->cH	$3{\cdot}10^{-15}$	$4.1{\cdot}10^{-5}$	$1.5{\cdot}10^{-3}$	$\sim10^{-5}$	10^{-5}

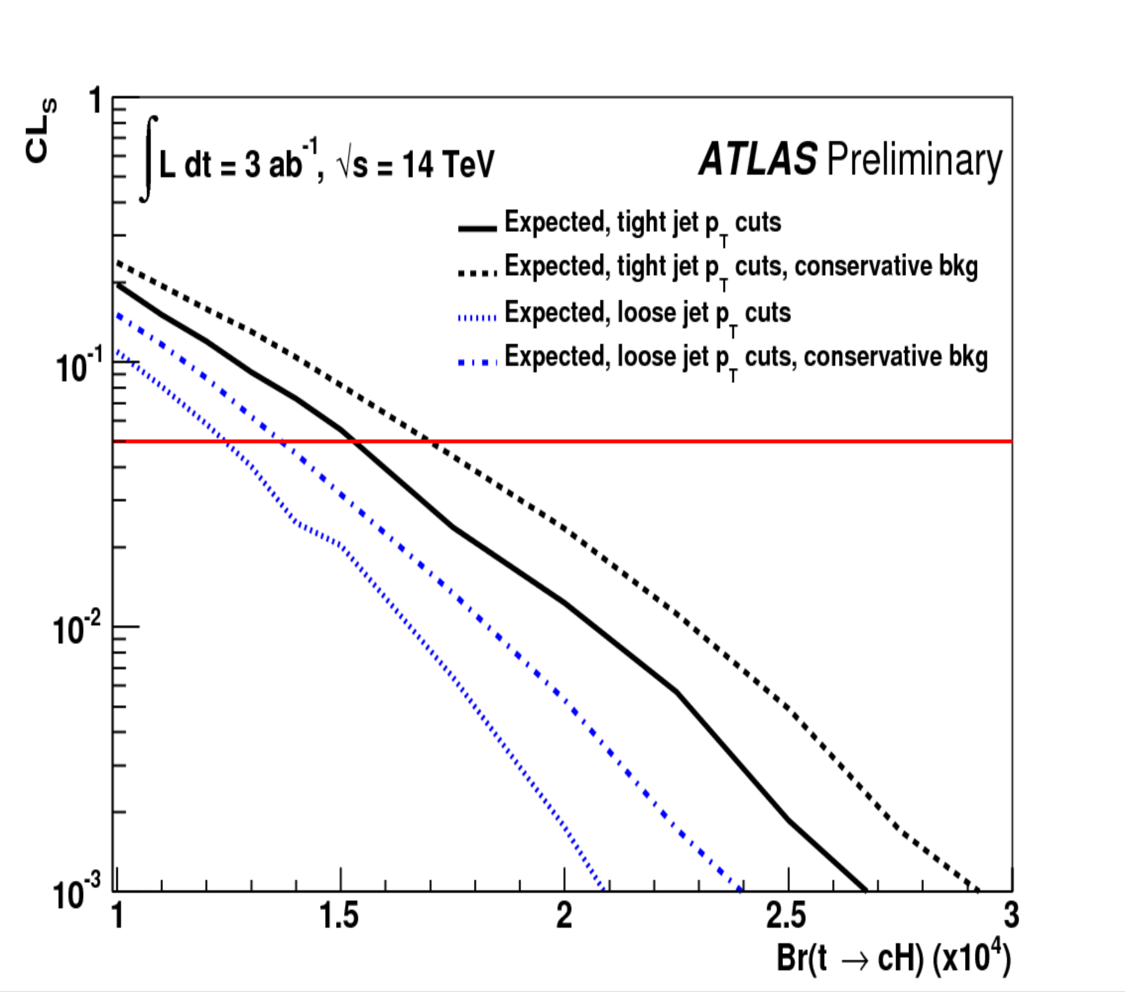
SM:
FCNC decays are negligible.

Models with the extended Higgs sector, R-parity violating SUSY models: BR ~ 10^{-5} - 10^{-4}

$$t\bar{t}->WbHc \quad H->\gamma\gamma$$

Peak in γγ + jet system

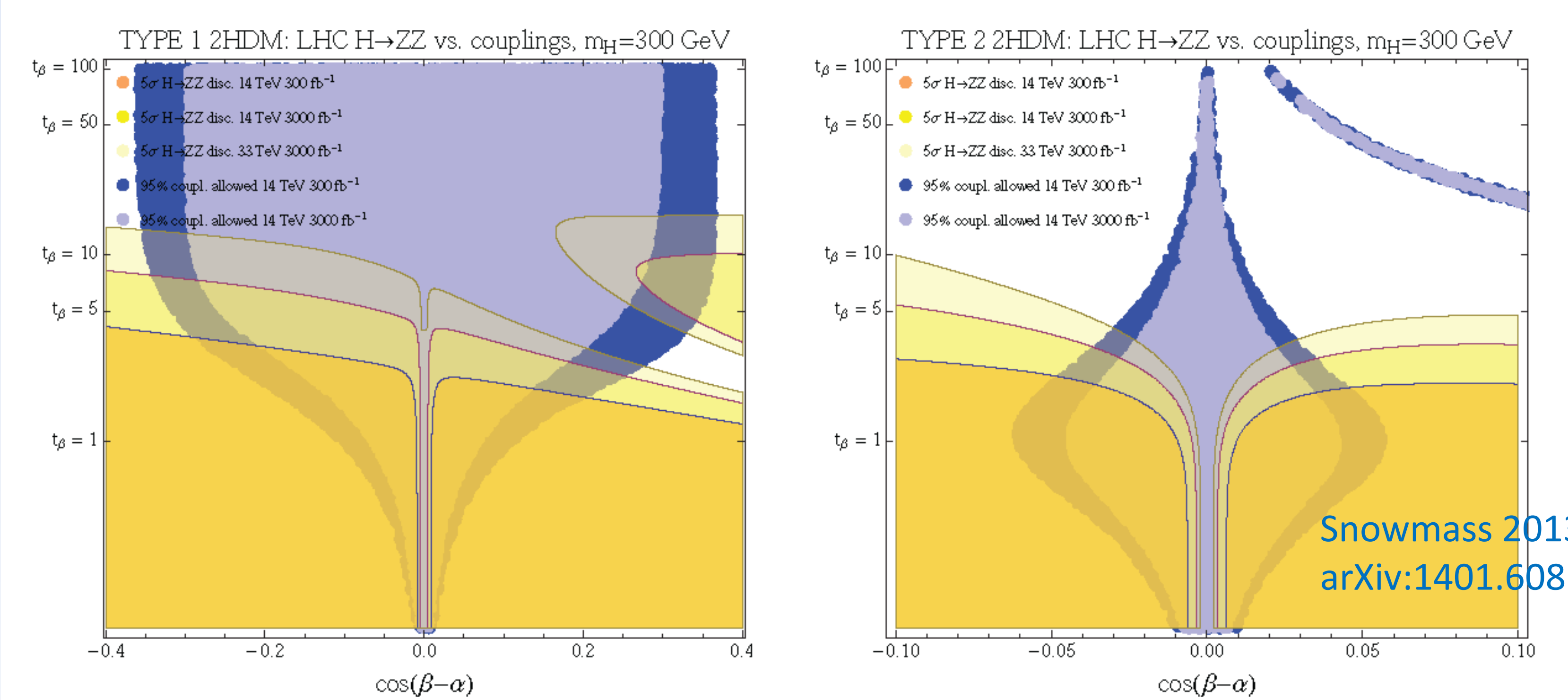
The expected upper limit at the 95% confidence level on BR, assuming a luminosity of 3000 fb^{-1} (HL-LHC) at 14 TeV is $1.5 \cdot 10^{-4}$.



BSM Higgs Bosons

Strong motivation for existence of BSM Higgs bosons.
Additional doublet -> H(CP even), A(CP odd), H^+ , and H^- .

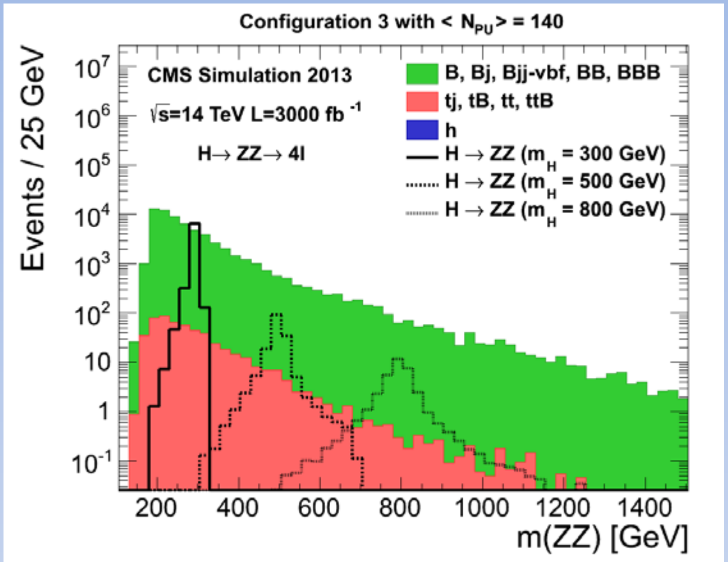
Region of parameters of 2HDM models expected to be excluded.
The yellow regions show the 5σ reach in direct searches.
The blue regions are allowed at 95% CL by coupling measurements.



Snowmass 2013
arXiv:1401.6081

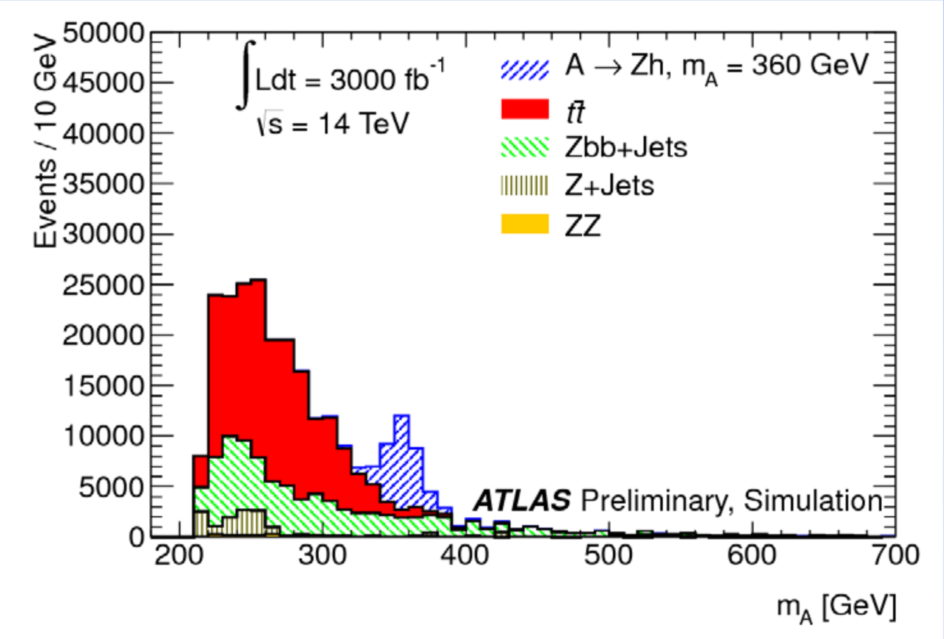
BSM Higgs Bosons

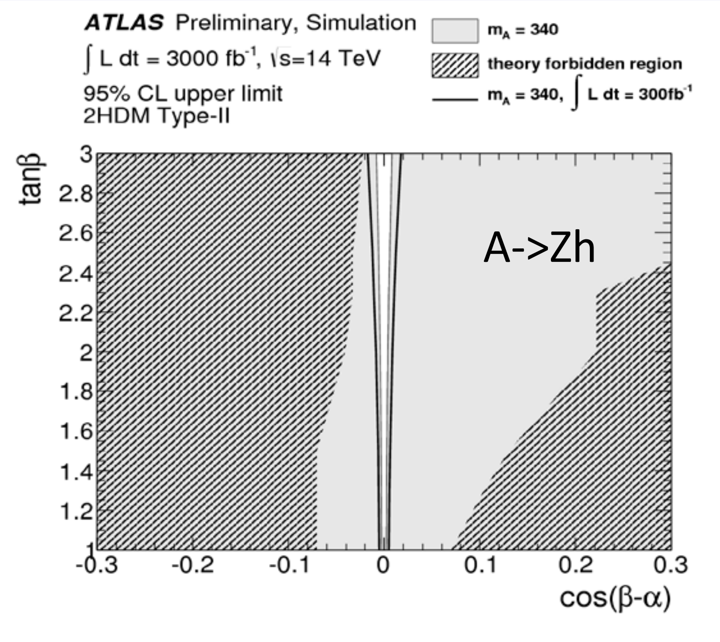
Coupling studies and direct searches are complimentary.



gg->A->Zh , gg-> H(A) -> $t\bar{t}$ **low tanβ**

$b\bar{b}$ -> H(A) -> $\tau^+\tau^-$ **large tanβ**

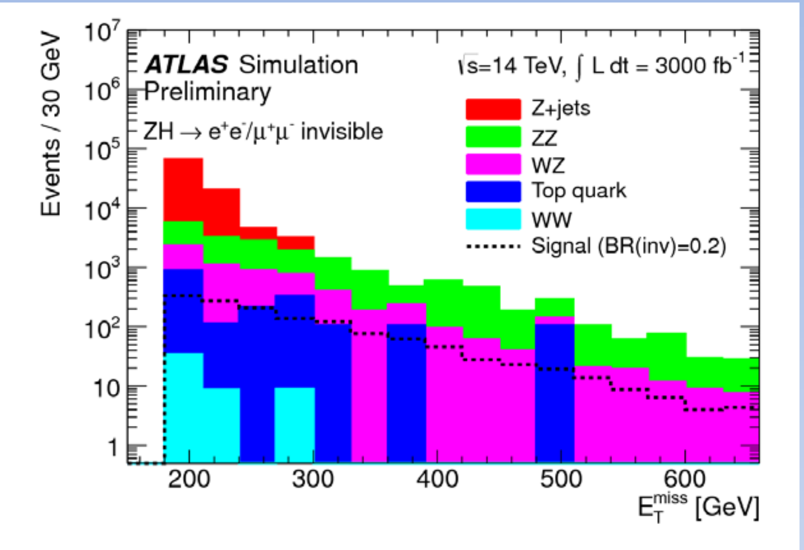




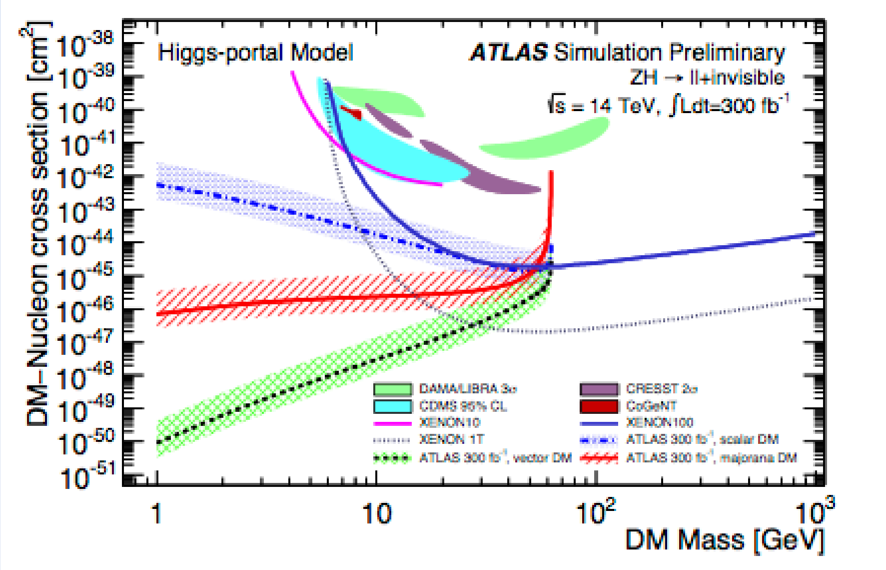
Invisible Decays of the Higgs Boson

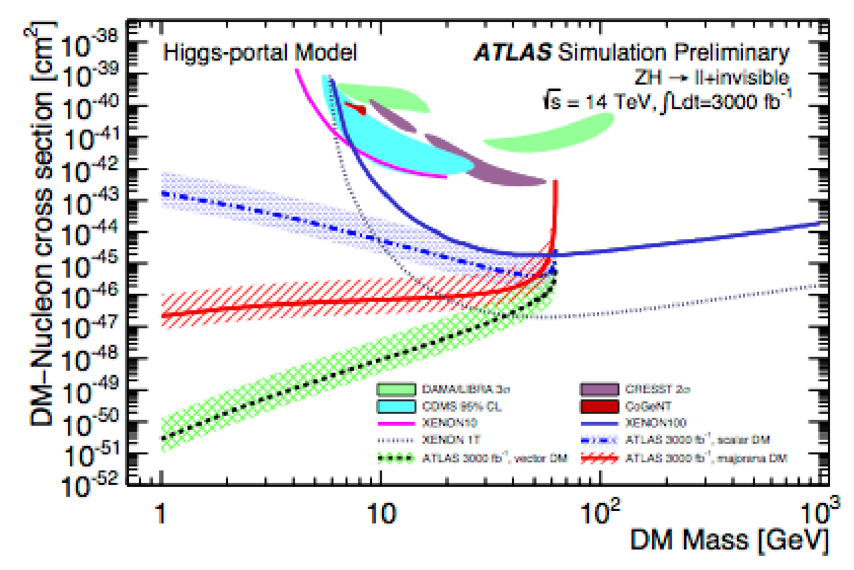
Direct search for the invisible decays of H in $ZH \to l^+l^-$ + invisible

L, fb^{-1}		BR(H->invis.)
300	ATLAS	[23,32]
	CMS	[17,18]
3000	ATLAS	[8,16]
	CMS	[6,17]



Strong constraints on Higgs-portal models





Conclusion

- So far all measurements are consistent with the SM expectations.
- The deviations up to 30% are possible in some models.
- The re-start of the LHC in 2015 is a beginning of a very rich program to clarify the nature of the Higgs boson.
- HL-LHC is crucial for the precision Higgs boson physics.

Mass/Width	Spin/Parity
Couplings	BSM Higgs Bosons
Rare decays	TeV Scale

Backup

References

1. ATL-PHYS-PUB-2013-007, “Physics at a High-Luminosity LHC with ATLAS”
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3. ATL-PHYS-PUB-2013-013, “Prospects for measurements of the HZZ vertex tensor structure in H → ZZ* → 4l decay channel with ATLAS”
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7. CMS-PAS-HIG-13-002, “Properties of the Higgs-like boson in the decay H->ZZ->4l in pp collisions at sqrt(S)=7 and 8 TeV”
8. CMS-PAS-HIG-13-005, “Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV”
9. CMS-PAS-HIG-13-015, “Search for ttH production in events where H decays to photons at 8 TeV collisions”
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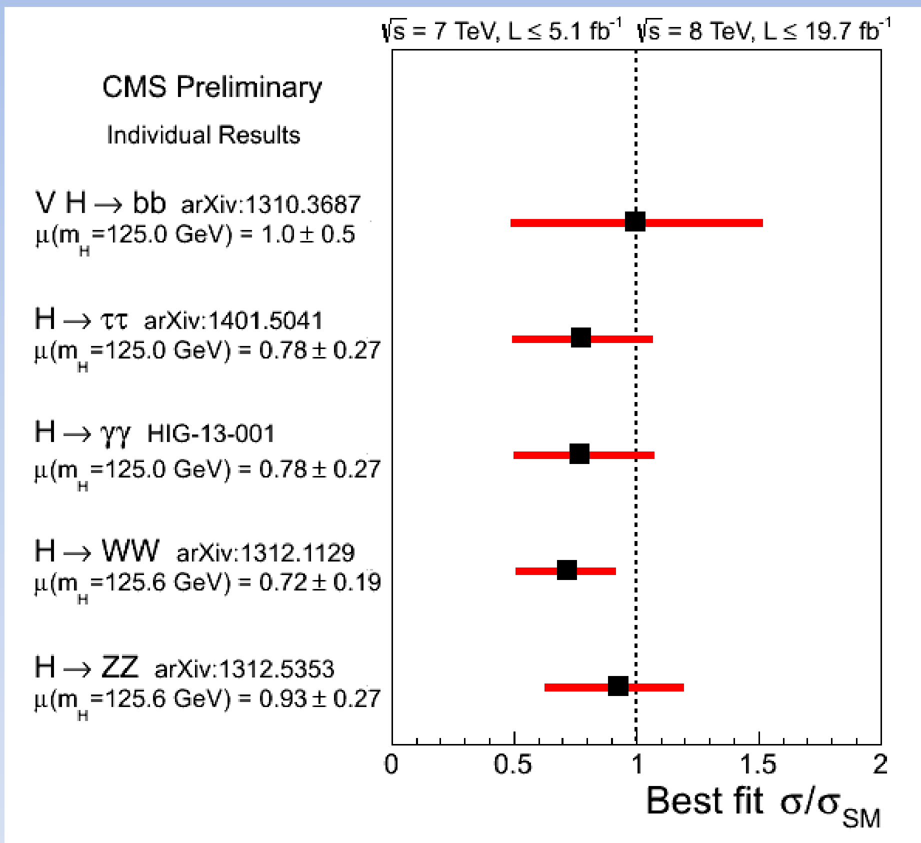
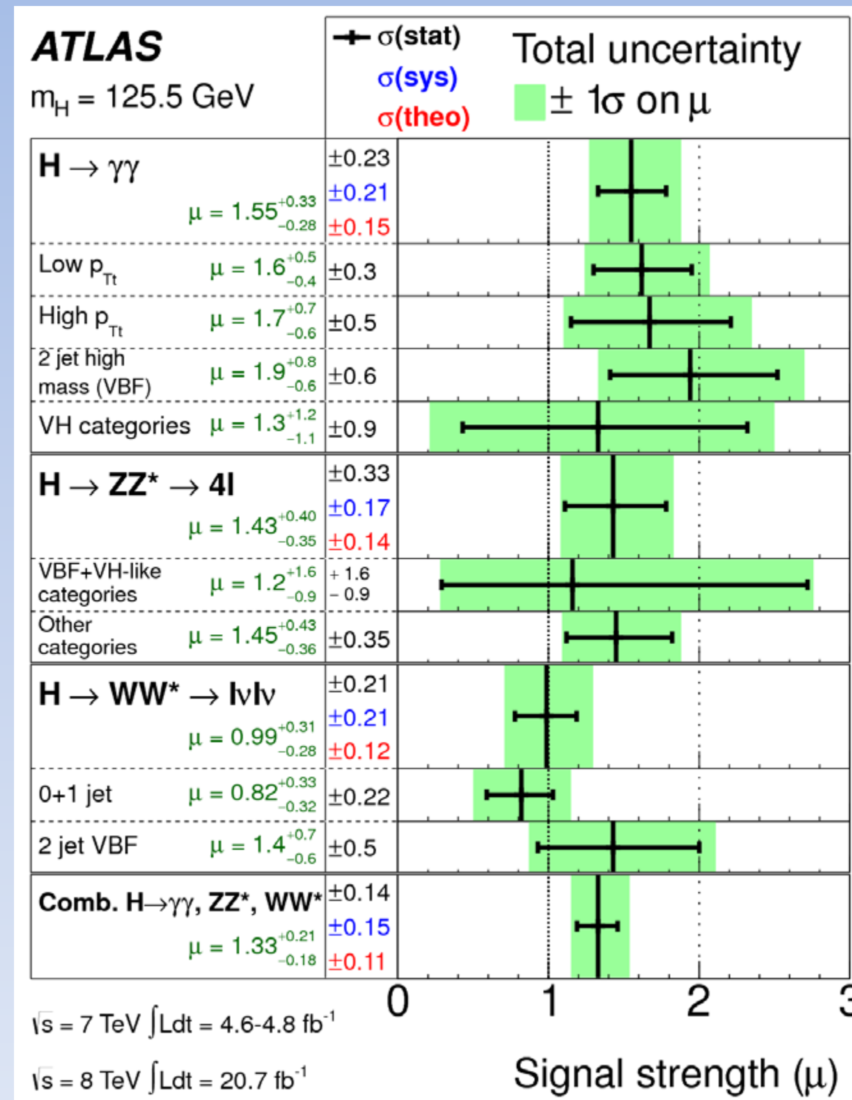
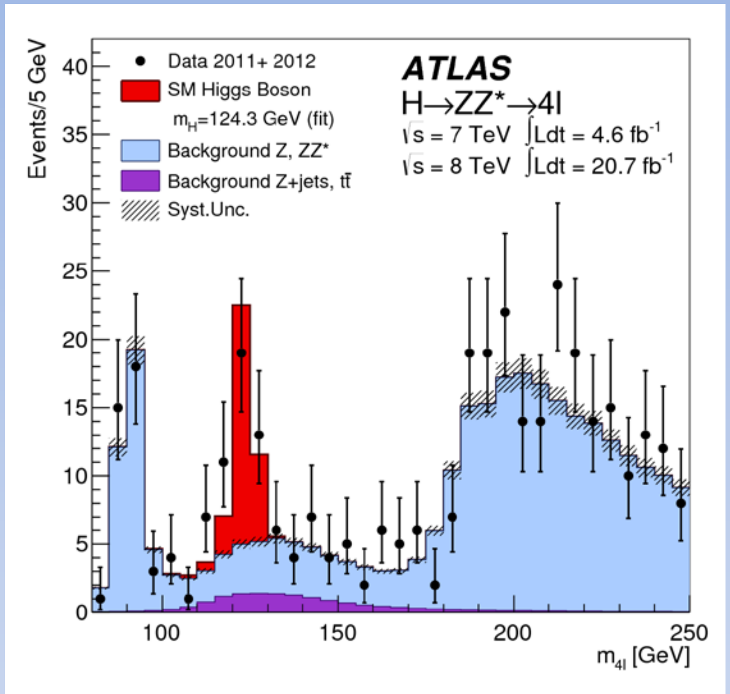
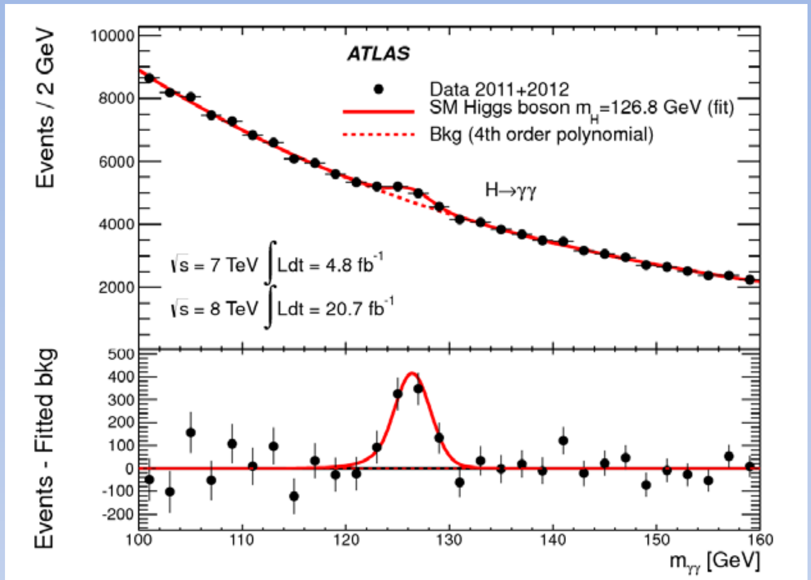
Higgs Boson Results





Mass Measurement



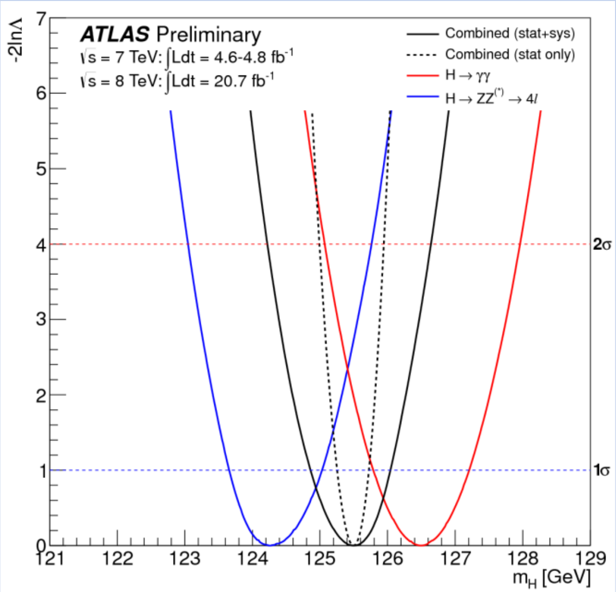


Combined mass (γγ , ZZ ATLAS):

$$M_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst) \text{ GeV}$$

Combined mass (γγ , ZZ, WW, bb, ττ CMS):

$$M_H = 125.7 \pm 0.3(stat) \pm 0.3(syst) \text{ GeV}$$



Higgs Boson J^P