Prospects for precision Higgs physics with ATLAS and CMS at High Luminosity LHC

HEFT2013, CERN, 15 Oct 2013

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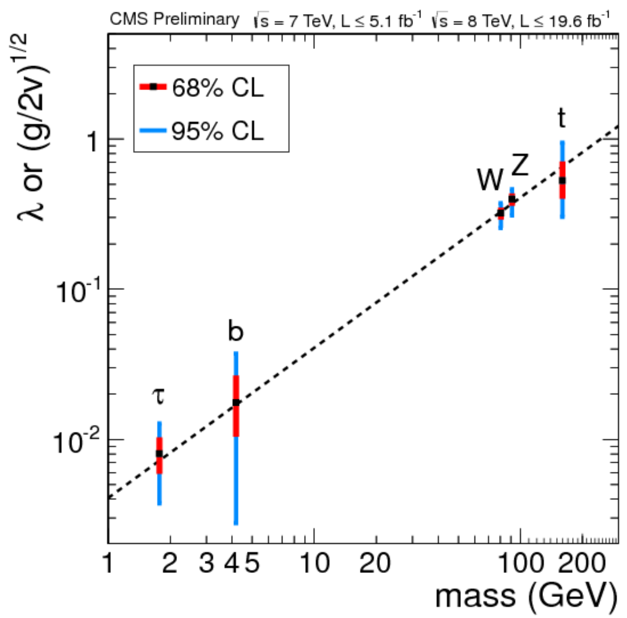
Higgs Physics goals

- It is "a Higgs boson", said CERN DG and Nobel committee confirmed
- Its properties must be compared with SM expectations:
  - Coupling constants and quantum numbers
  - Details of the EWSB and shape of the potential
  - Connections to BSM
- Does it fit in the SM?



Key questions in front of us

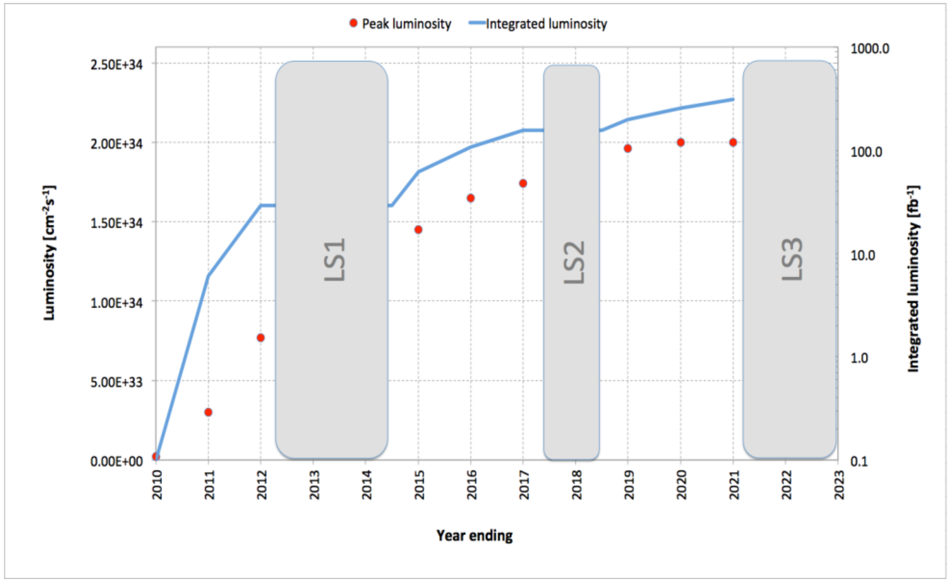
- How will the LHC perform till its end?
- Will the experiments be capable of facing the challenges set by high luminosity/radiation and age?
- To which level will we be able to fulfill the Higgs physics program?

- Answers elaborated in the last year in the context of ESG, Snowmass and ECFA

LHC up to 2021

- LHC is resuming (properly fixed) in 2015, with √s unlikely exceeding 13 TeV
  - Projections done assuming 14 TeV, little difference for analysis performance
- 25 ns bunch spacing instrumental for future physics reach
- Aim at 300 fb^{-1} by 2021

	n_B	Peak Lumi [$cm^{-2}s^{-1}$]	Pileup	Lumi [fb^{-1}]
25 ns	2760	9.2e33	21	24
25 ns low ε	***2508***	***1.6e34***	***43***	***42***
50 ns	1380	1.7e34 levelling 0.9e34	76 levelling 40	~45



Beyond 2021

- Instantaneous luminosity is limited by beam burn-off lifetime ➔ level luminosity, $\langle L \rangle \sim 5\times10^{34}$ $cm^{-2}s^{-1}$.
- Taking 2012 as reference:
  - $T=6.5\times10^{6}$ sec, $L=23fb^{-1}$ ➔ $\langle L \rangle = 3.7\ nb^{-1}s^{-1}$
- 10 years at $\langle L \rangle = 50nb^{-1}s^{-1}$ would give **$L=3000\ fb^{-1}$**
- Pileup (ATL-UPGRADE-PUB-2013-014)
  - $\sigma_{Inel}=81mb$, $n_b=2808$ (25 ns bunch spacing) ➔ **$\mu>130$**

- Major upgrades required on the LHC (replace more than 1.2 km):
  - New IR-quads Nb3Sn (inner triplets), new 11 T Nb3Sn (short) dipoles
  - Collimation upgrade
  - Cryogenics upgrade
  - Crab Cavities
  - …

Higgs factory

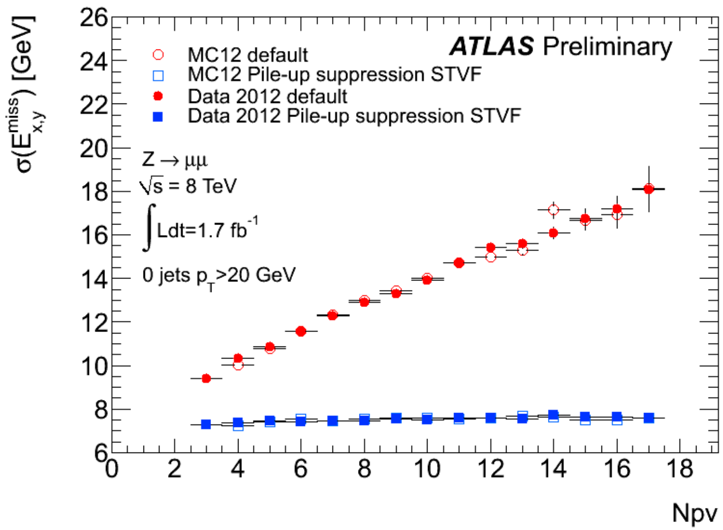
- A real Higgs factory, a couple of Higgs events produced per sec
  - Compare to e^+e^- colliders ($L=10^{34}\ cm^{-2}s^{-1}$): <10 events per hour

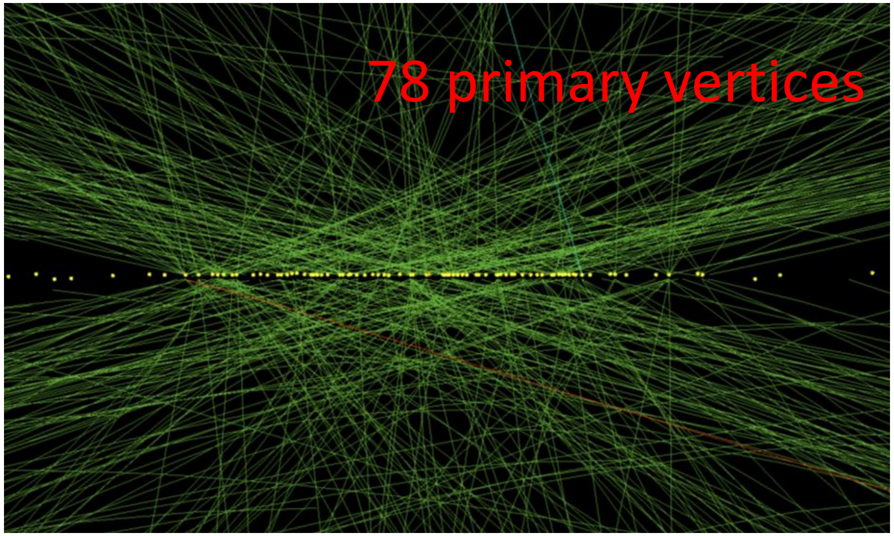
	σ(14 TeV) [pb]	Rate [Hz], $L=50\ pb^{-1}s^{-1}$	Events, $L=3ab^{-1}$	Events, $L=30fb^{-1}$
ggH	50.4	2.52	150M	570K
VBF	4.2	0.21	13M	48K
WH	1.5	0.08	4.5M	21K
ZH	0.9	0.04	2.6M	12K
ttH	0.6	0.03	1.8M	4K

- Most of the exclusive final states accessible, including very rare ones
  - 20K H->ZZ->4l, 30K H->$\mu\mu$, 50 H->J/ψ γ
- Possible to probe redundantly most of the coupling factors

Experimental issues: Pileup

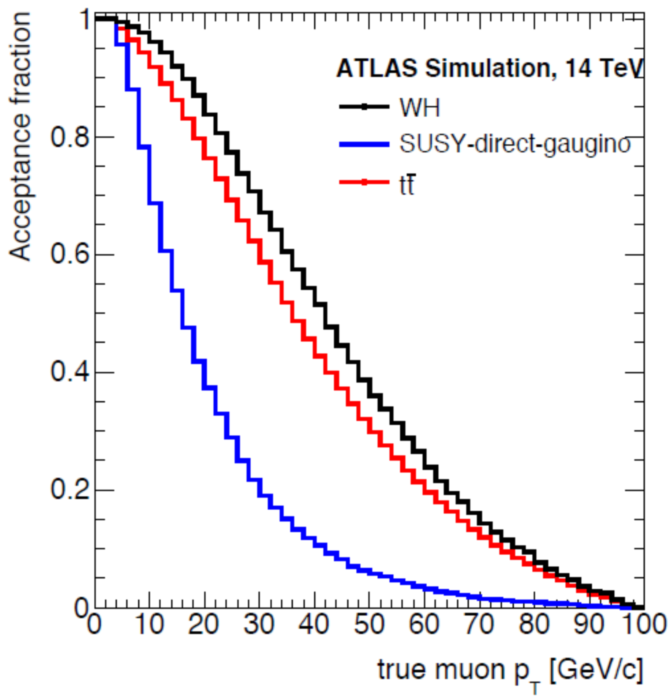
- CMS and ATLAS designed for relatively low pileup, μ~24:
  - Excellent performance in 2012 with μ up to 35!
- Is precision Physics possible with μ~140?
  - Primary Vertex identification (e.g. for H->γγ)
  - Secondary vertex and b-tagging
  - Tracking needs to cope with much higher occupancy
  - Huge energy flow (ΣE_T~60 GeV per pileup event), MET resolution and tails
  - Forward jets association to signal vertex (pivotal for VBS)





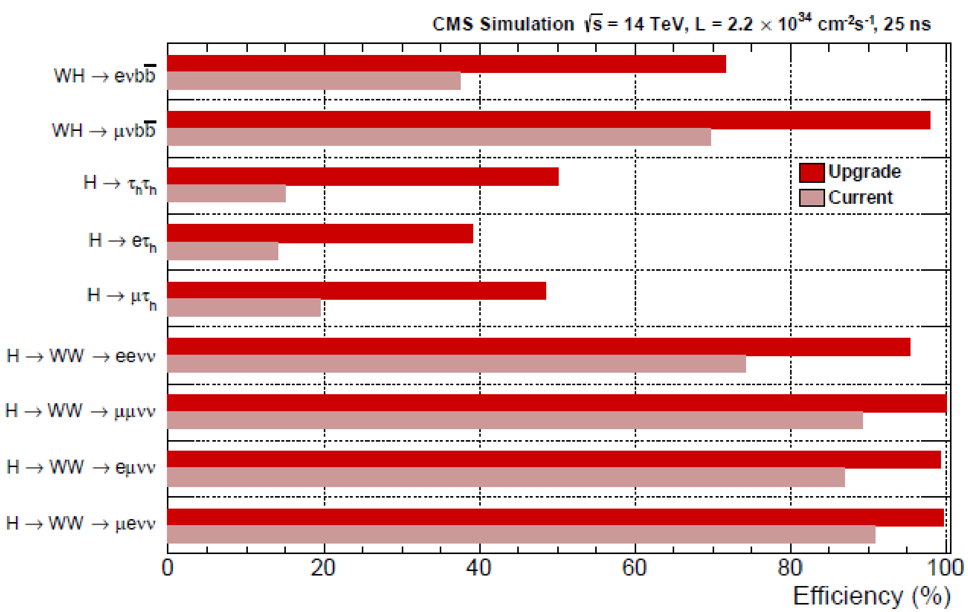
Experimental issues: Trigger

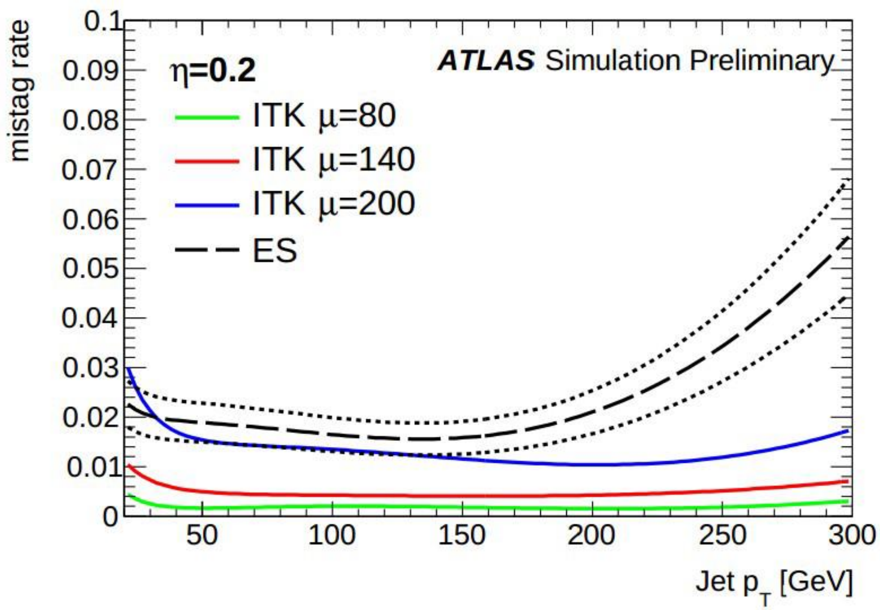
- Goal is to maintain the current sensitivity to EWK and Higgs physics, can't allow trigger thresholds to exceed that energy scale
- L1 trigger most problematic, 2012 output (100kHz) saturated
  - Same trigger system cannot fit same physics in the same bandwidth
- High pileup challenges triggering on rare decays
- Gain in increasing the instantaneous luminosity only if high signal efficiency is maintained



Detector upgrades

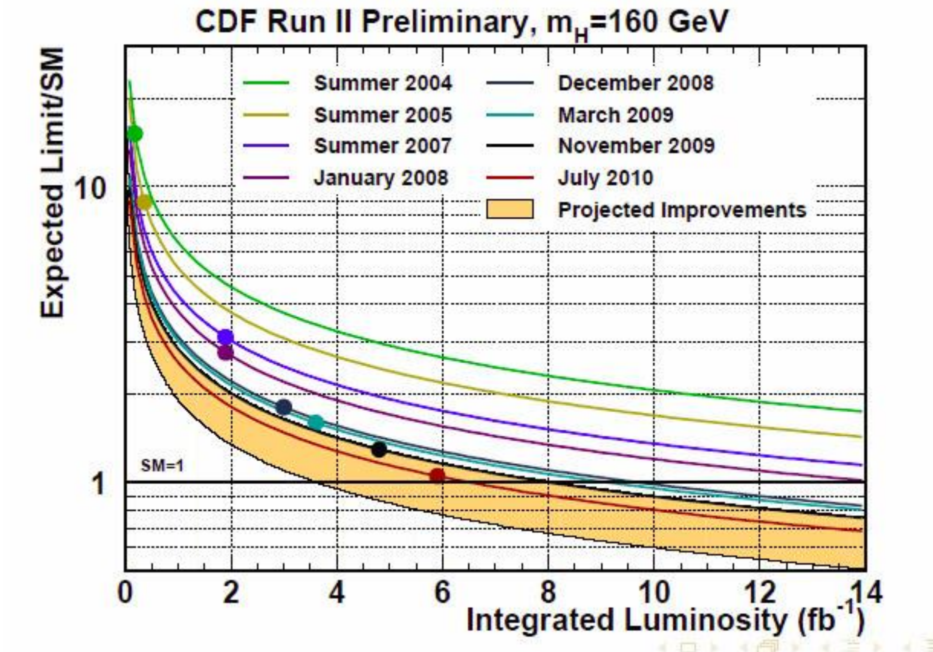
- Both ATLAS and CMS will undergo a series of detector and trigger upgrades during the next LHC shut-downs
- Several subdetectors will be improved (some completely replaced) and strengthened against high radiation environment
- **Goal is to maintain or enhance the current performances**





Aim of the projections

- Current Higgs results still limited by statistical uncertainty
- However, a lot of experience has been gathered on Higgs analyses
- Sensitivity for each channel will scale differently with integrated luminosity:
  - What are the most relevant systematic uncertainties?
  - What role do the theoretical uncertainties play?
  - Will the CDF scaling rule apply?



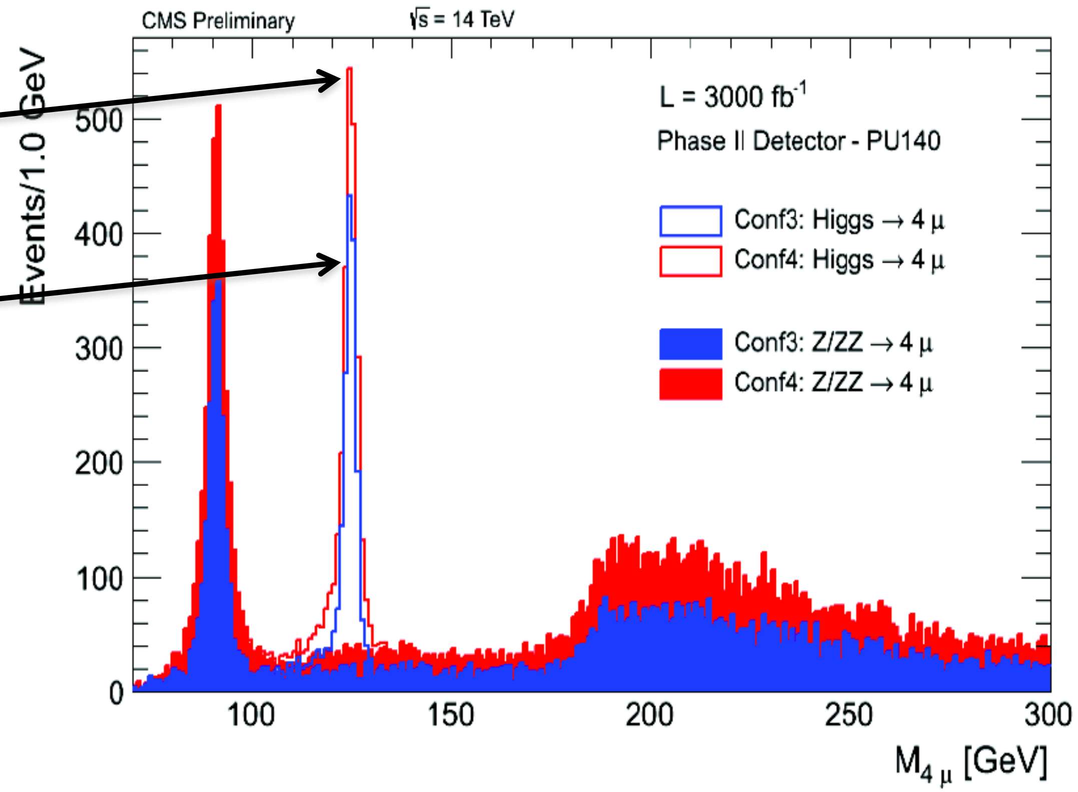
Tools for projections

- CMS:
  - Scale results of current analyses
    - Including those currently with little sensitivity, e.g. H->$\mu\mu$, ttH->$\gamma\gamma$, etc.
  - Two scenarios assumed reasonably covering the range of future performances:
    - Same systematic uncertainties as today (Scenario 1, conservative)
    - Experimental syst. scaled by 1/√L, theory syst. halved (Scenario 2, ambitious)
  - Results supported by dedicated full simulation studies
    - Fast simulation (DELPHES) validated against full symulation too
- ATLAS:
  - Detector response functions derived using full simulation
  - 300 fb-1 scenario assumes 50 PU events on average
    - Includes IBL and LAr trigger upgrades
  - 3000 fb-1 scenario assumes 140 PU events
    - Includes ITK

Example of full analyses

Muons up to |η|=4

Muons up to |η|=2.4

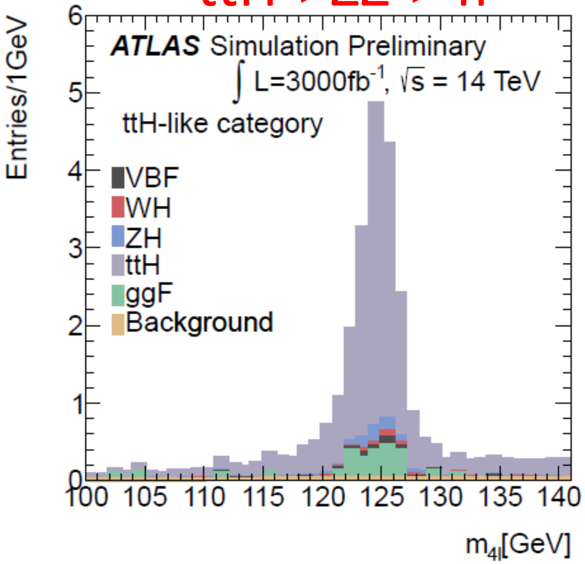


- Tracking and muon system coverage extension from |η|=2.4 to |η|=4 under study
- Sizable impact on the H->ZZ->4μ acceptance: +45%!

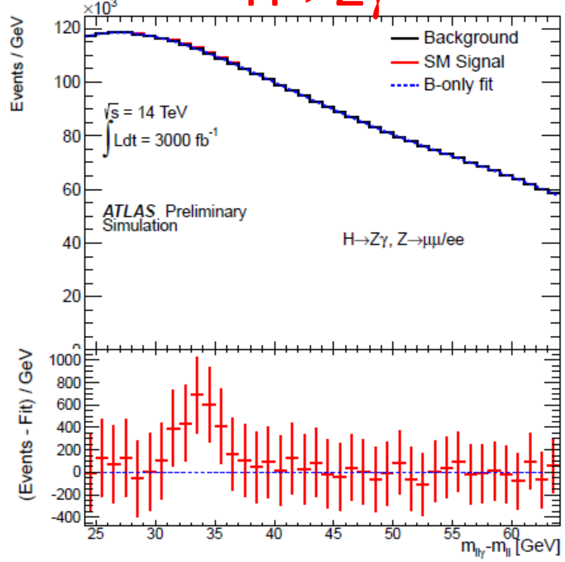
Example of full analyses

- High event rate will allow measuring exclusive channels with good precision:
  - Every production mode will be assessed in several channels
  - Rare decays as H->Zγ, H->μμ
- Example: ttH->ZZ only available at HL-LHC:
  - 35 events expected at 3ab^{-1} from ATLAS full simulation analysis

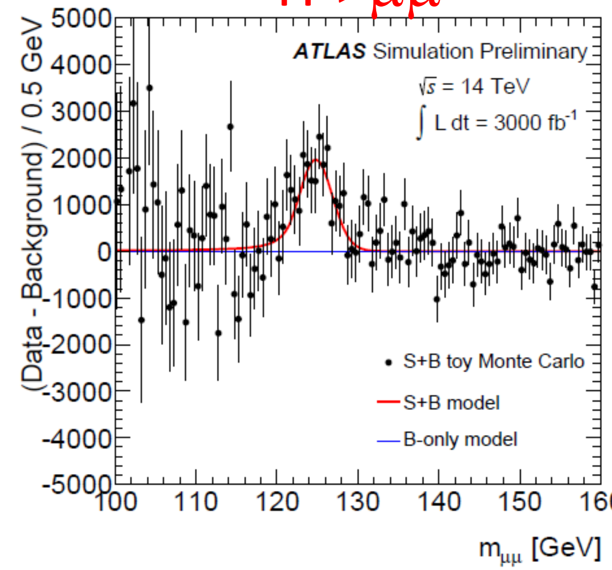
ttH->ZZ->4l



H->Zγ

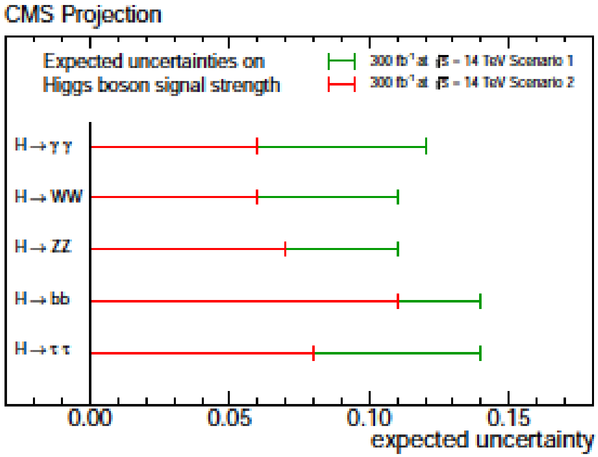


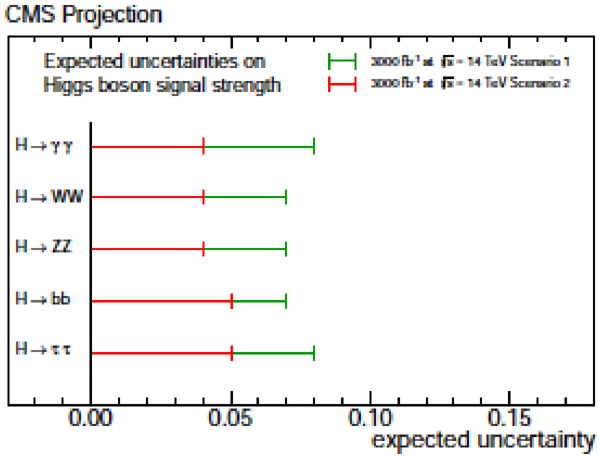
H->μμ

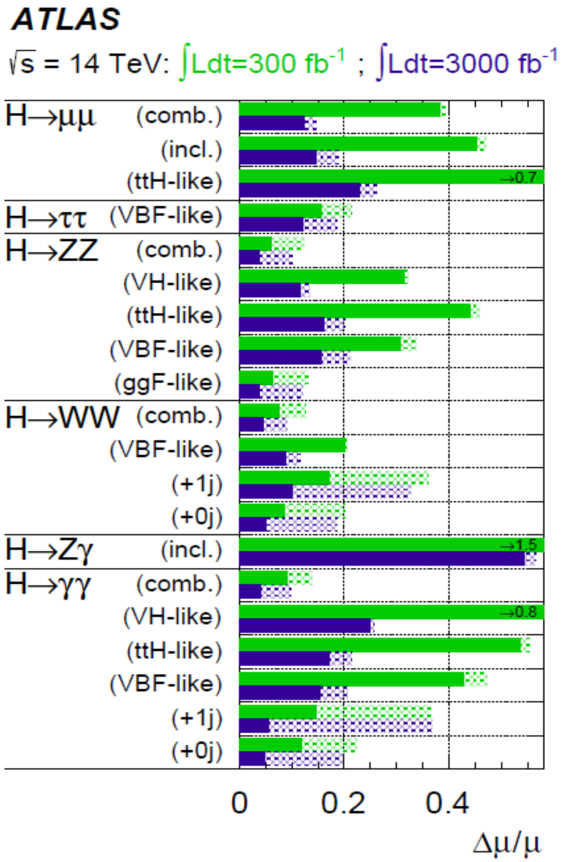


Signal strengths (I)

- Single parameter fit, signal strength $\mu=\sigma/\sigma_{SM}$
- Group channels together, typically by decay mode and express results as σ_μ/μ
- First step to assess compatibility to SM
  - Not always straightforward to interpret though







Signal strengths (II)

- Different scenarios assumed by the two experiments
  - ATLAS: with and without theory error (same exp. syst. as today)
  - CMS: Scenario 1 and Scenario 2
- EWK production modes (small theory error) allow overcome large theory uncertainty on gluon fusion production
- Aim at ~5% for the main five analyses

ATLAS

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H \to \tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H \to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H \to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H \to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H \to \gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05

CMS: [Scenario2, Scenario1]

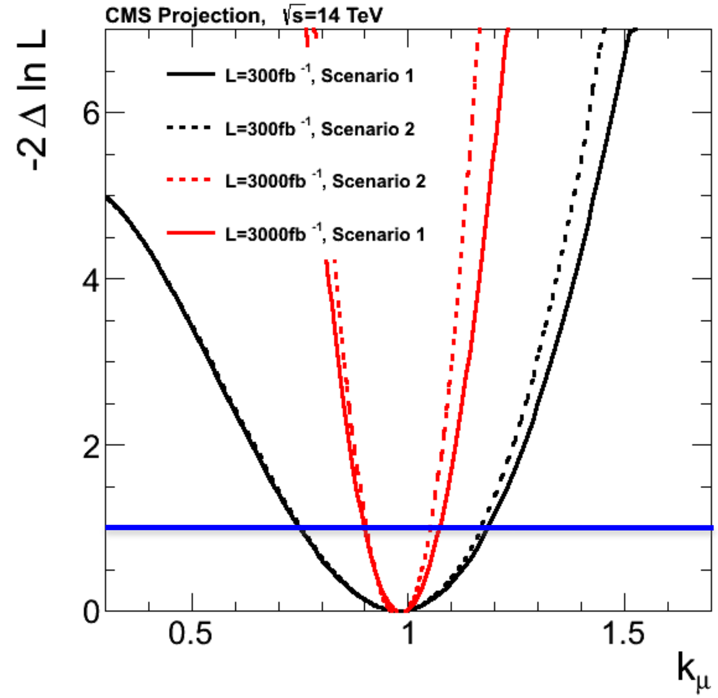
L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

Coupling fit framework (I)

- Follow recommendations and fit models described in Yellow Report 3 (arXiv:1307.1347)
- Signal cross section scaled w.r.t to SM predictions:

$$\sigma \cdot BR(ii \to H \to ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- Not targeted to any BSM model, goal is to quantify possible (small) deviations w.r.t SM
- Global fits targeting the κ factors
  - Assign a modifier to each coupling constant
    - Do not resolve loops, effective coupling instead (κ_g, κ_γ and $\kappa_{Z\gamma}$)
  - Results reported in terms of 68% uncertainties (-2ΔLnL=1) on k



Coupling fit framework (II)

- Total width not trivial to assess at the LHC
  - E.g. not possible to measure directly a production cross section as at a e+e- collider
- It can be expressed as the sum of other SM couplings:
  - Assuming SM BRs for inaccessible decays (H->cc) and not other contribution from BSM
    - In this case H->bb is pivotal!
  - Allow extra BSM contributions (e.g. BRInv) and set an upper bound on κ_V (κ_V<1)
    - Eventually use bounds from direct search for invisible Higgs decay
- Alternatively use a given process as reference for the other coupling modifiers
  - Use ggH->ZZ signal strength, κ_{gZ}==κ_g*κ_Z/κ_T

Coupling fits (I)

- Fits performed assuming $\kappa_H = \Sigma \kappa_i BR_i$, only for *i* in SM
- ATLAS doesn't use H->bb channel, κ_b linked to κ_τ in the fit → all other couplings penalized
  - CMS up to a factor 2 better in several cases
- In an ambitious scenario, ultimate precision ~2% for couplings involved in the main decay modes

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
$300 fb^{-1}$	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[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]	N/a	[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]

ATLAS: [no Th. syst., full Th. syst.] (same exp. syst.

CMS: [Scenario2, Scenario1]

Coupling fits (II)

- Results are more directly comparable if total width absorbed by a reference scale factor
  - Performances of the two experiments very similar
- HL-LHC can lead to an accuracy of ~2% for many coupling constants

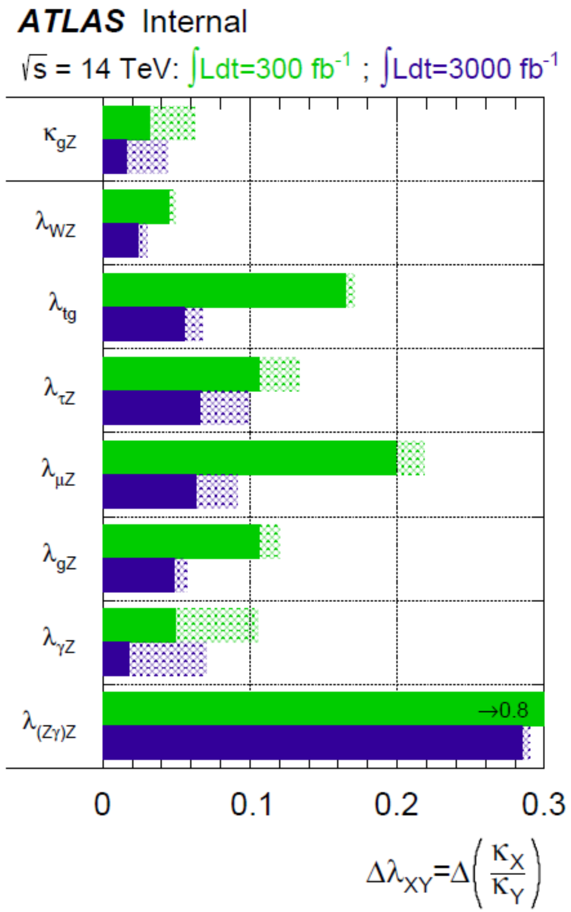
		$\kappa_g\kappa_{Z}/\kappa_H$	κ_W/κ_Z	κ_γ/κ_Z	κ_g/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_μ/κ_Z	$\kappa_{Z\gamma}\kappa_Z$	κ_t/κ_g
300fb^{-1}	ATLAS	[3,6]	[4,5]	[5,11]	[11,12]	N/a	[11,13]	[20,22]	[78,78]	[17,18]
	CMS	[4,6]	[4,7]	[5,8]	[6,9]	[8,11]	[6,9]	[22,23]	[40,42]	[13,14]
3000fb^{-1}	ATLAS	[2,5]	[2,3]	[2,7]	[5,6]	N/a	[7,10]	[6,9]	[29,30]	[6,7]
	CMS	[2,5]	[2,3]	[2,5]	[3,5]	[3,5]	[2,4]	[7,8]	[12,12]	[6,8]

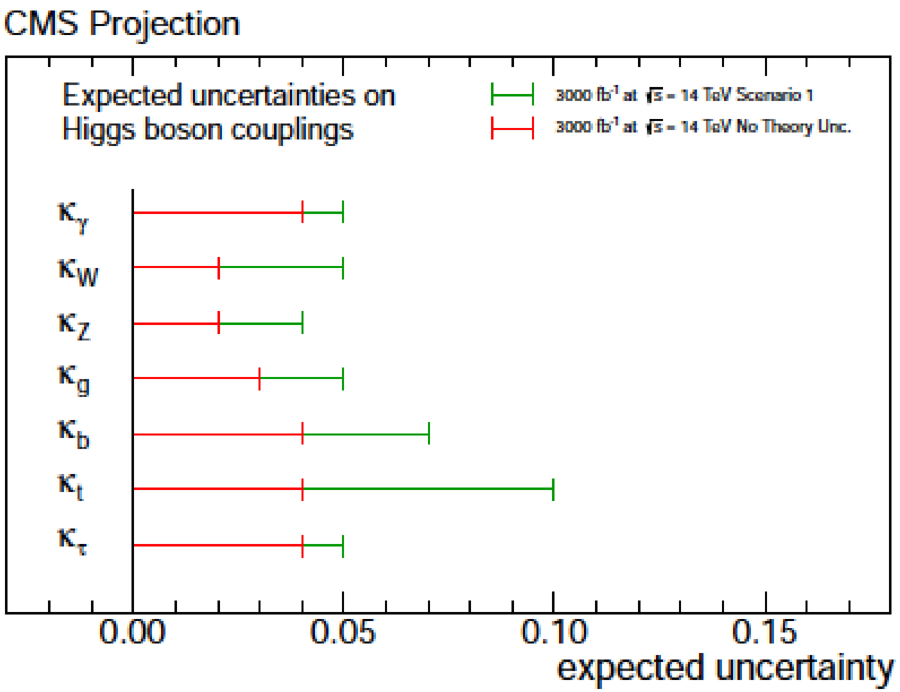
ATLAS: [no Th. syst., full Th. syst.] (same exp. syst.

CMS: [Scenario2, Scenario1]

Theoretical uncertainty effects

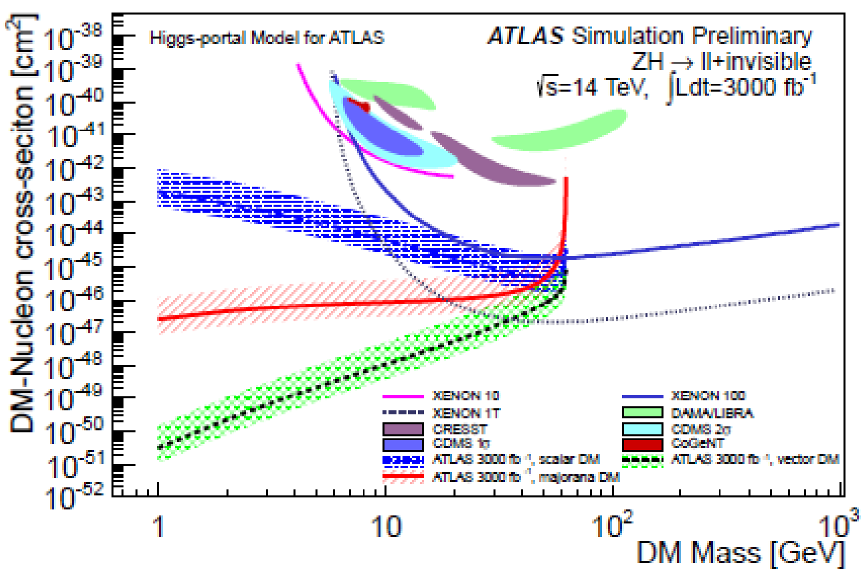
- Theoretical uncertainties affects the ultimate precision achievable by ATLAS and CMS
- **Reducing them it is for sure worth the effort!**





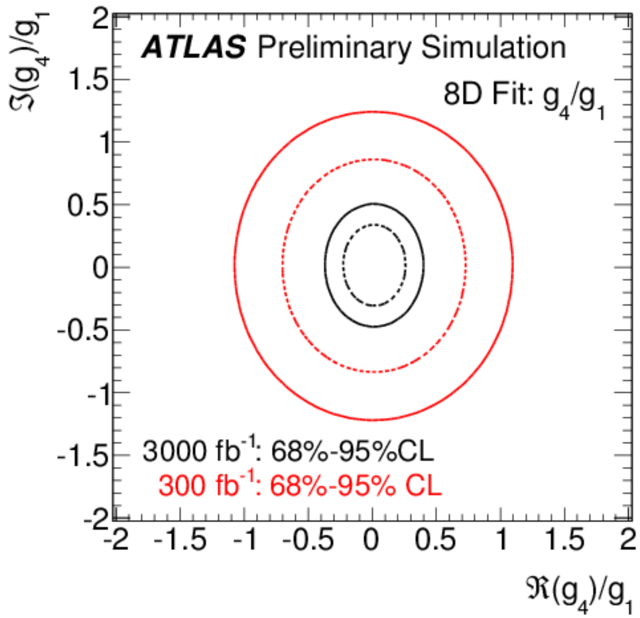
BR(H-> Inv)

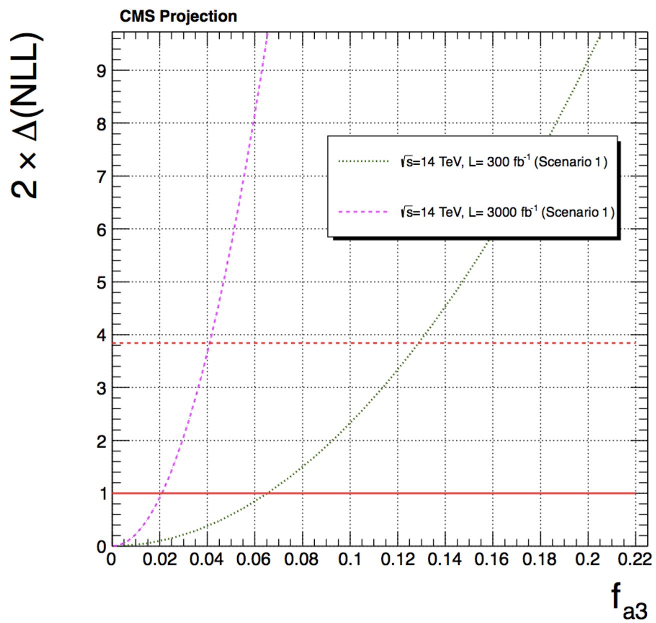
- Both experiments estimated their sensitivity to invisible decays by means of ZH, Z->ll
  - CMS: [0.09,0.17] at 95% CL (3ab^{-1})
  - ATLAS: [0.08,0.17] at 95% CL (3ab^{-1})
- Results greatly improved if VBF channel is considered
  - Very much dependent on experimental conditions, not reliably projectable
- If direct searches are combined with the other SM channels, precision could go down to ~5% level



J^{CP} properties

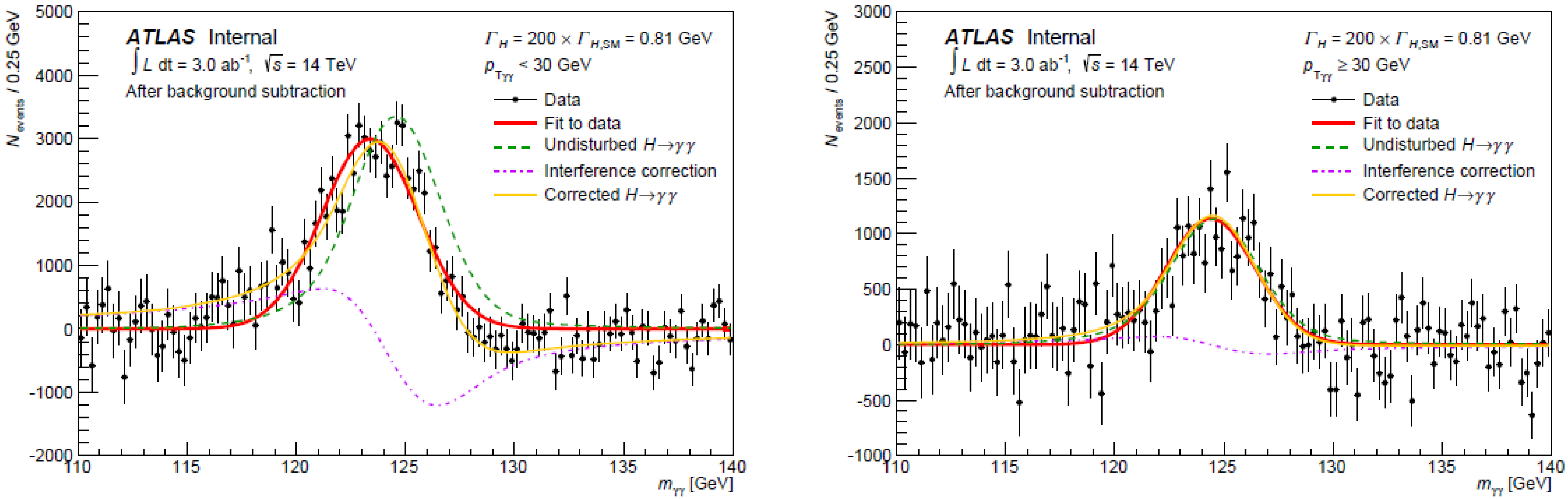
- Tensor structure of the Higgs sector (J^{CP} numbers) can be best probed by angular analysis
- Large event sample at $3ab^{-1}$ will allow assessing the individual terms in a generic parameterization of the Lagrangian
- Mixing between CP-even and CP-odd state can in particular being studied





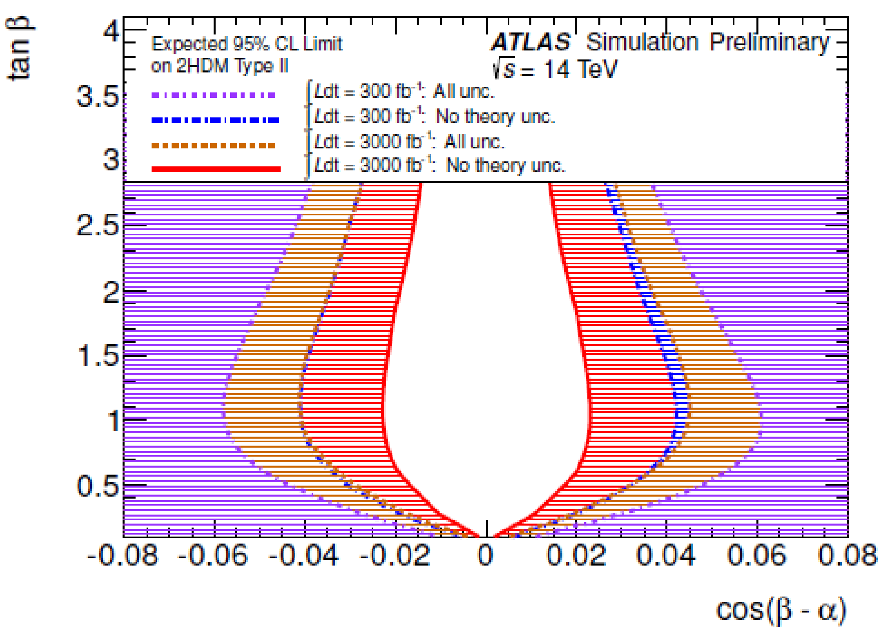
Total Width

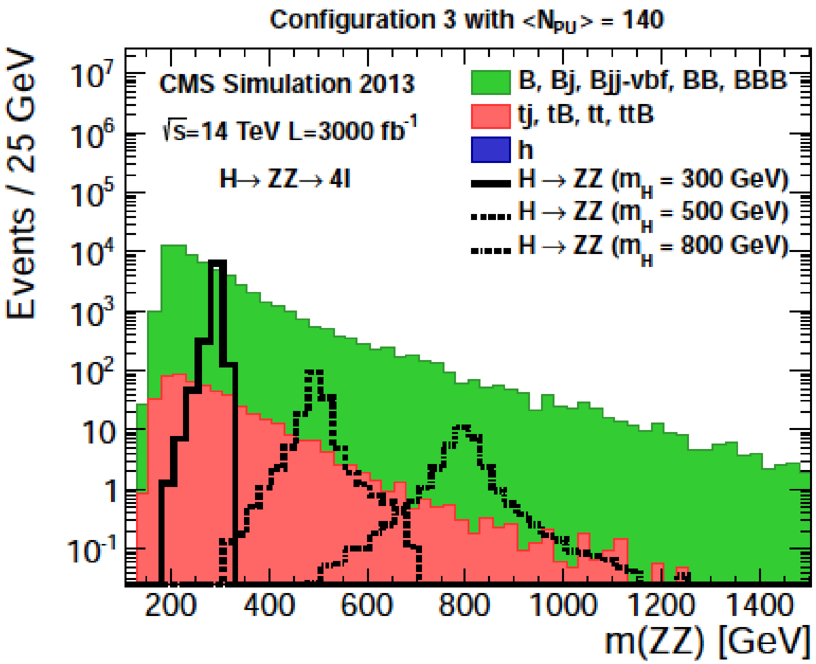
- Direct constraint on the natural width several order of magnitudes away from the SM value:
  - Γ_T<6.9 GeV from H->$\gamma\gamma$ currently in CMS
- Interference between signal and background shifts the peak → compare peak position in regions with different S/B
  - Split signal region in two Higgs pT ranges ([0-30] and [30-inf])
- Expect to set an upper bound at ~160 MeV at 3ab^{-1}



BSM (2HDM)

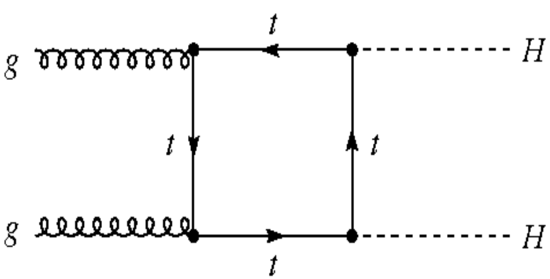
- A second Higgs double is present in many BSM models
- Additional Higgs fields can be searched for at high masses
- Both experiments performed full simulation analysis of ZZ and Zh resonances in Type I and II modes
  - Indirect constrains from SM coupling fits

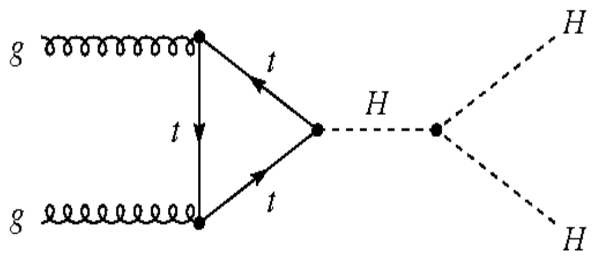




Higgs Self Coupling

- Double Higgs production among the main objectives of HL-LHC
- Tiny cross section, need very high integrated lumi
  - Problematic also at high energy e+e- machines
- Self coupling diagrams interferes destructively with double Higgs processes
  - Look for a deficiency in a small signal, rather tough indeed
- Experiments didn't release their projections yet





Yields at $3ab^{-1}$

bbWW	30K
$bb\tau\tau$	9K
WWWW	6K
$\gamma\gamma bb$	320
$\gamma\gamma\gamma\gamma$	1

Summary

- The approved LHC plan is to deliver 300fb^{-1} by 2021. The upgrade of the machine is designed to integrated up to 3ab^{-1} in the 10 years
- Experiments will have to face harsh conditions, major upgrades are planned to maintain or improve current performances
- Vast Higgs physics program ahead that will profit from a real Higgs factory
- Higgs properties are expected to be pinned down to the level of a few percent

BACKUP

Lepton machines

Table 8: Relative statistical uncertainty on the Higgs boson couplings, as expected from the physics programme at $\sqrt{s} = 240$ and 350 GeV at TLEP. The numbers between brackets indicates the uncertainties expected with two detectors instead of four. For illustration, the uncertainties expected from the ILC baseline programme at 250 and 350 GeV are also given. The first three columns give the results of a truly model-independent fit, while the last two include the two assumptions made in Ref. [39] on the W/Z couplings and on the exotic decays, for completeness and easier comparison. The column labelled "TLEP-240" holds for the sole period at 240 GeV for TLEP. The last line gives the *absolute* uncertainty on the Higgs boson branching fraction to exotic particles (invisible or not).

	Model-independent fit			Constrained fit	
Coupling	TLEP-240	TLEP	ILC	TLEP	ILC
g_{HZZ}	0.16%	**0.15%** (0.18%)	0.9%	0.05% (0.06%)	0.31%
g_{HWW}	0.85%	**0.19%** (0.23%)	0.5%	0.09% (0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%** (0.52%)	2.4%	0.19% (0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%** (0.87%)	3.8%	0.68% (0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%** (0.98%)	4.4%	0.79% (0.97%)	4.4%
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%** (0.66%)	2.9%	0.49% (0.60%)	2.6%
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%** (7.6%)	45%	6.2% (7.6%)	45%
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%** (1.8%)	14.5%	1.4% (1.7%)	14.5%
$\mathrm{BR}_{\mathrm{exo}}$	0.48%	**0.45%** (0.55%)	2.9%	0.16% (0.20%)	0.9%

Coupling Ratios

- Adopting model summarized in Table 50 of YR3 (pag 151)
  - Multi parameter model preferred by ATLAS
- Refer everything to ggHZZ signal strength ($\kappa_{gZ}==\kappa_g*\kappa_Z/\kappa_T$)
- 9 parameters in total
  - Including $\lambda_{\mu Z}$ and $\lambda_{Z\gamma Z}$

General parameterization allowing all gauge and third generation fermion couplings to float allowing for invisible or undetectable widths

Free parameters: $\kappa_{gZ}(=\kappa_g\cdot\kappa_Z/\kappa_H)$, $\lambda_{\gamma Z}(=\kappa_\gamma/\kappa_Z)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{bZ}(=\kappa_b/\kappa_Z)$, $\lambda_{\tau Z}(=\kappa_\tau/\kappa_Z)$, $\lambda_{Zg}(=\kappa_Z/\kappa_g)$, $\lambda_{tg}(=\kappa_t/\kappa_g)$.

ggH	$\kappa_{gZ}^2\cdot\lambda_{\gamma Z}^2$	κ_{gZ}^2	$\kappa_{gZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{gZ}^2\cdot\lambda_{bZ}^2$	$\kappa_{gZ}^2\cdot\lambda_{\tau Z}^2$
$t\bar{t}$H	$\kappa_{gZ}^2\lambda_{tg}^2\cdot\lambda_{\gamma Z}^2$	$\kappa_{gZ}^2\lambda_{tg}^2$	$\kappa_{gZ}^2\lambda_{tg}^2\cdot\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{tg}^2\cdot\lambda_{bZ}^2$	$\kappa_{gZ}^2\lambda_{tg}^2\cdot\lambda_{\tau Z}^2$
VBF	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\cdot\lambda_{\gamma Z}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\cdot\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\cdot\lambda_{bZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\cdot\lambda_{\tau Z}^2$
WH	$\kappa_{gZ}^2\lambda_{Zg}^2\lambda_{WZ}^2\cdot\lambda_{\gamma Z}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\lambda_{WZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\lambda_{WZ}^2\cdot\lambda_{bZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\lambda_{WZ}^2\cdot\lambda_{\tau Z}^2$
ZH	$\kappa_{gZ}^2\lambda_{Zg}^2\cdot\lambda_{\gamma Z}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\cdot\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\cdot\lambda_{bZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\cdot\lambda_{\tau Z}^2$

$\kappa_i^2=\Gamma_{ii}/\Gamma_{ii}^{SM}$

CMS Scenarios

- Scenario 1 (“conservative”):
  - Scale only the yields, same systematic uncertainties as for Moriond13
- Scenario 1.5 (some reasoned assumptions on the scaling):
  - hWW, hZZ, tthbb, tthgg as scenario 1
  - Htt
    - nuisance = (nuisance > 5%) ? 5% : nuisance
  - $H\gamma\gamma$
    - 1/sqrt(L/20) scaling for: CMS_hgg_n_id, CMS_hgg_n_sigmae, CMS_hgg_eff_trig, vtxEff,
    - Scale by factor 2: CMS_hgg_nuissancedeltamcatX, CMS_hgg_nuissancedeltasmearcatX
  - Hbb
    - See backup
- Scenario 2 (“ambitious”):
  - All experimental systs scaled by 1/sqrt(L/20)
  - Theoretical uncertainties divided by 2