Higgs Prospects at HL-LHC

Mass and Width
Rates and Couplings
Spin/CP Properties
Self-Coupling

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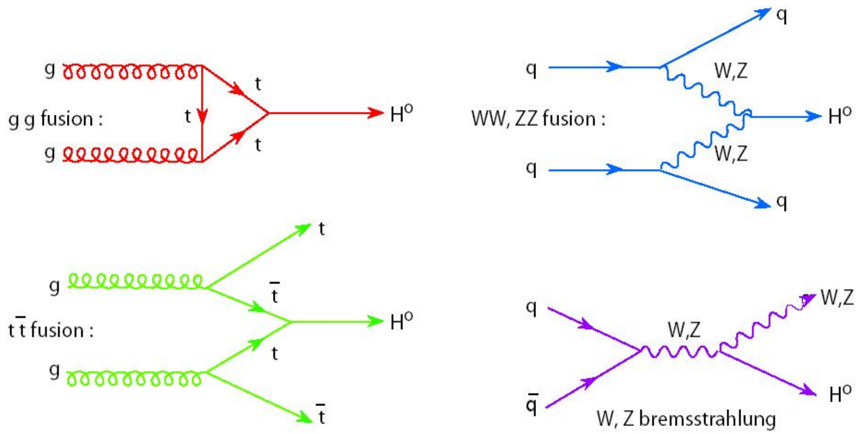
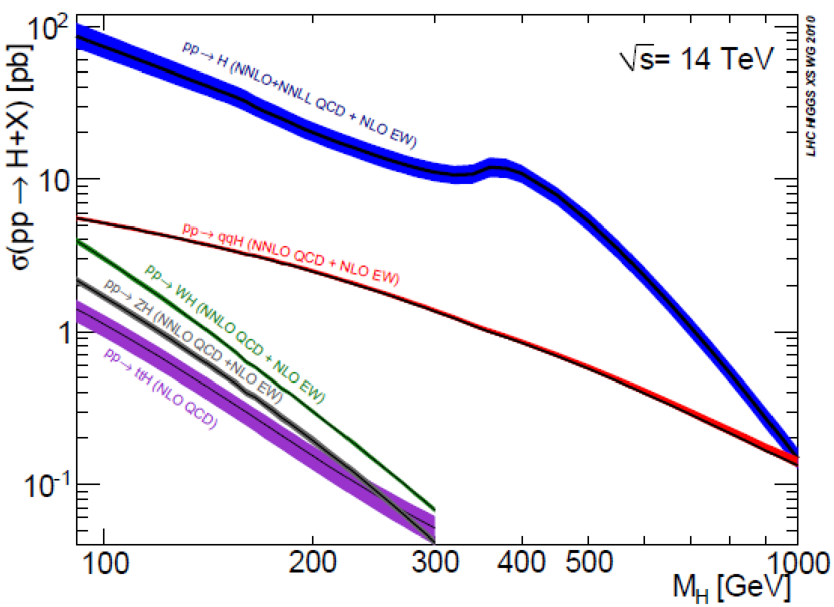
Higgs Production



Cross section increases by a factor of 2.6 or more from 8 to 14 TeV

Cross sections in pb for $m_H = 125$ GeV

$\sqrt{s}$ (TeV)	ggF	VBF	VH	$t\bar{t}H$
7	15.1	1.22	0.914	0.086
8	19.5	1.58	1.09	0.130
14	49.9	4.18	2.38	0.611

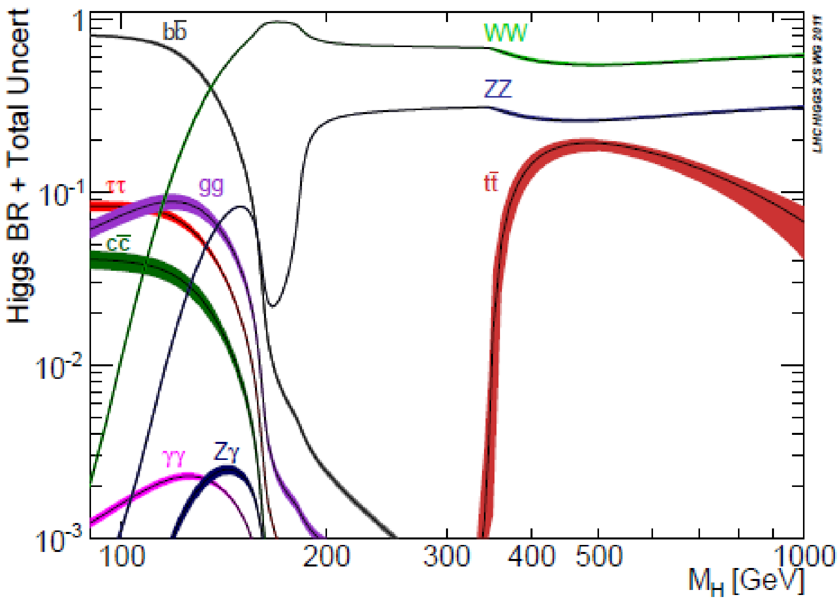


$\Delta\sigma/\sigma$ for pp at 14 TeV

Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	±10%	±7%	±17%
$t\bar{t}$H	±8%	±9%	±17%
VBF	±0.5%	±2.5%	±3.0%
VH	±0.5%	±3.5%	±4.0%

Already a major systematic to analysis in jet-bins.

Higgs Decays



$m_H = 125$ GeV	
$\sqrt{s} = 14$ TeV	$\sigma_H = 57.1$ pb

Branching ratio	
$H \to bb$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to \mu\mu$	0.02%

$\Gamma_{b\bar{b}} \approx 0.57\Gamma_H \Rightarrow \Delta m_b$ has a large impact

ΔBR/BR at $M_H = 125$ GeV

decay	theory	parameters	total (linear sum)
$H \to bb$	±1.3%	±1.5%	±2.8%
$H \to \tau\tau$	±3.6%	±2.5%	±6.1%
$H \to \mu\mu$	±3.9%	±2.5%	±6.4%
$H \to WW^*$	±2.2%	±2.5%	±4.8%
$H \to ZZ^*$	±2.2%	±2.5%	±4.8%
$H \to \gamma\gamma$	±2.9%	±2.5%	±5.4%

A. Denner et al., arXiv:1107.5909

Need to improve SM calculations and their inputs as we enter a new era of precision Higgs physics!

Higgs Event Rates

$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

	ggF	VBF	VH	$t\bar{t}H$	Total
Cross section (pb)	49.9	4.18	2.38	0.611	57.1

Numbers of events in 3000 fb^{-1}

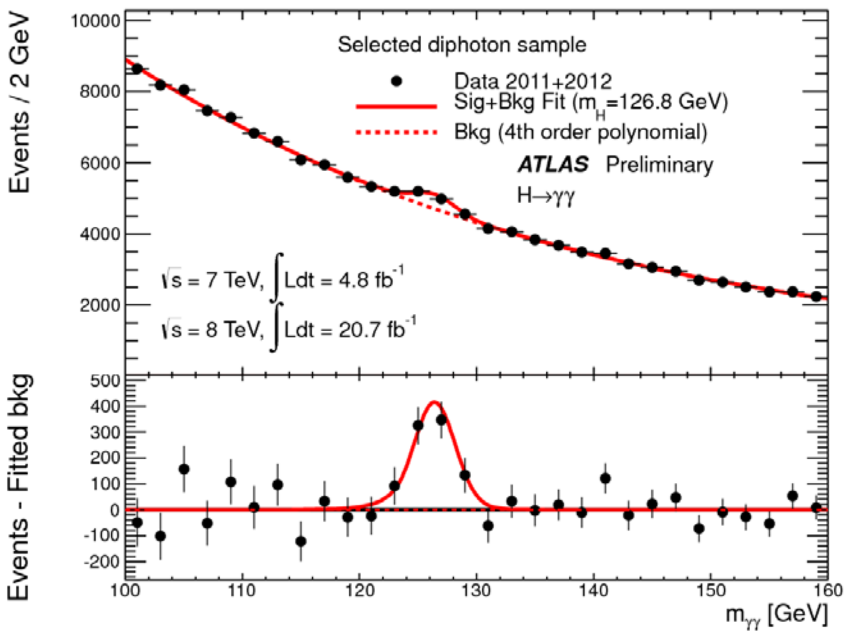
	ggF	VBF	VH	$t\bar{t}H$	Total
$H \to \gamma\gamma$	344,310	28,842	16,422	4,216	393,790
$H \to ZZ^* \to 4\ell$	17,847	1,495	851	219	20,412
$H \to WW^* \to \ell\nu\ell\nu$	1,501,647	125,789	71,622	18,387	1,717,445
$H \to \tau\tau$	9,461,040	792,528	451,248	115,846	10,820,662
$H \to b\bar{b}$	86,376,900	7,235,580	4,119,780	1,057,641	98,789,901
$H \to \mu\mu$	32,934	2,759	1,570	403	37,667
$H \to Z\gamma \to \ell\ell\gamma$	15,090	1,264	720	185	17,258
$H \to$ all	149,700,000	12,540,000	7,140,000	1,833,000	171,213,000

An ultimate Higgs factory!

Granted, only a small fraction of all events will be recorded.

Higgs Boson Mass

High resolution channels: $H \to \gamma\gamma$ and $H \to ZZ^{*} \to 4\ell$

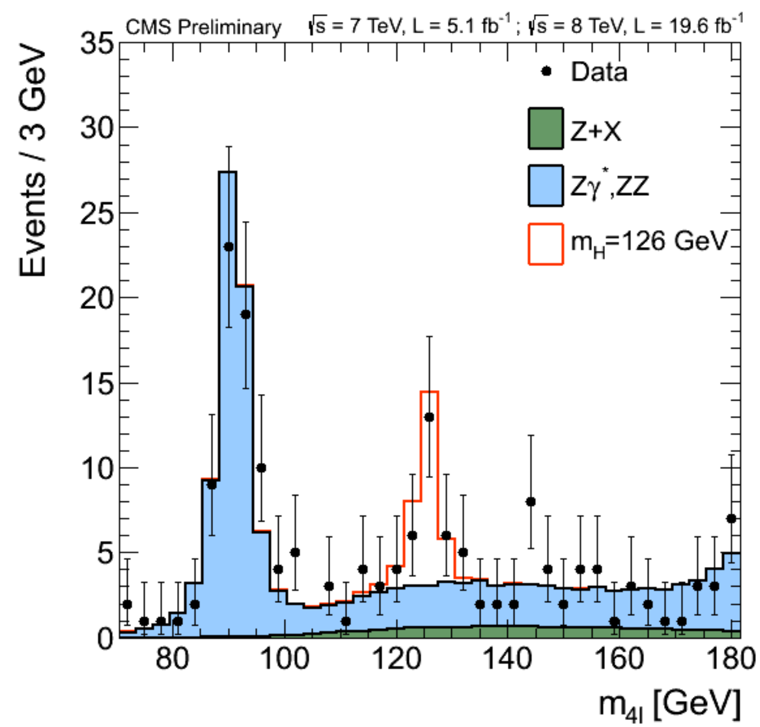


ATLAS:

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

CMS:

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



Poor man's average for extrapolation:

$$\Delta m_H = \pm 0.25\ (stat) \pm 0.45\ (syst)\ \text{GeV}$$

Uncertainty of energy/momentum scale is the dominant systematic uncertainty

$\Rightarrow$ should largely scale with $1/\sqrt{L}$.

Higgs Boson Mass

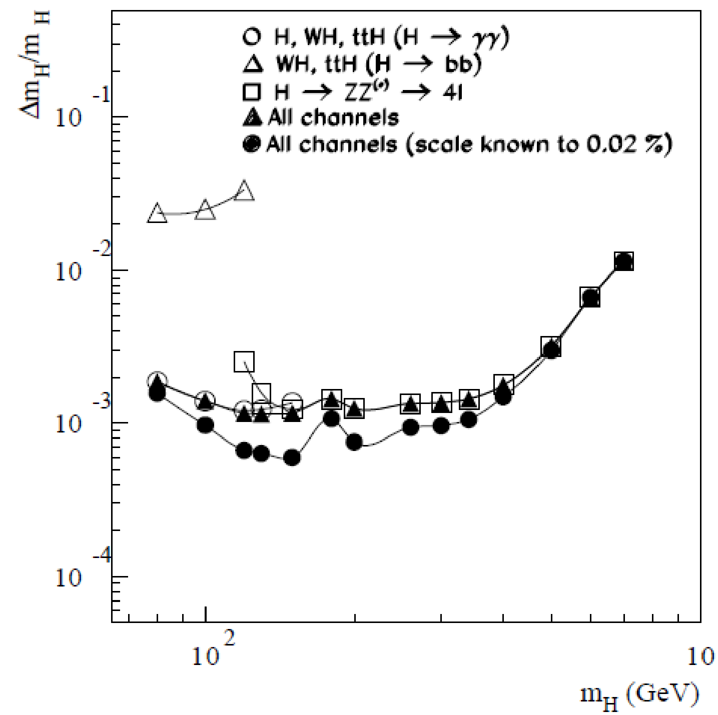
With 300 fb^{-1}, ATLAS estimates a precision of 0.07% @ 125 GeV $\Rightarrow \Delta m_H \approx 90$ MeV.

Precision in MeV on m_H

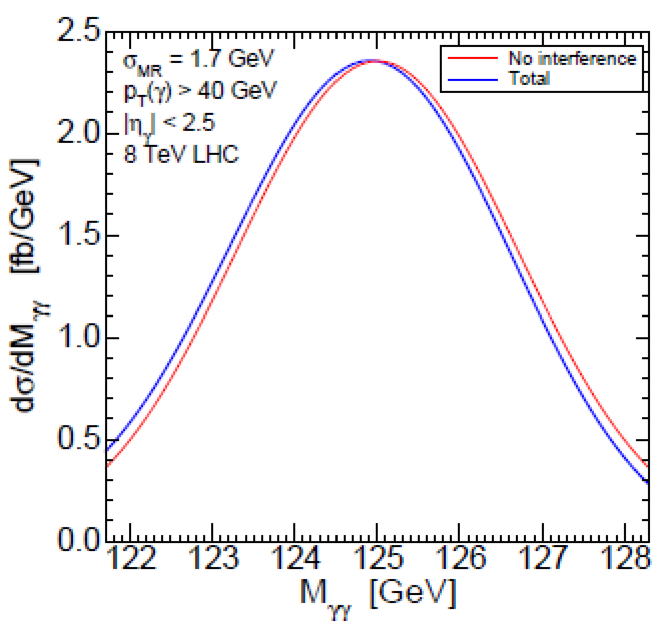
	Δ(stat)	Δ(syst)	Δ(total)
Present	250	450	520
300 fb^{-1}	50	80	100
3000 fb^{-1}	15	25	30

Assuming $\Delta \propto 1/\sqrt{\mathcal{L}}$.

ATLAS TDR: CERN-LHCC-1999-15



Martin, arXiv:1303.3342



For $H \to \gamma\gamma$, precision measurement will need to take into account the interference with the continuum.

$\Delta m_H \sim 100\ (50)$ MeV for 300 (3000) fb^{-1} should be achievable at the LHC.

Higgs Total Width

Diffcult to extract from the rate measurements without some assumptions

on couplings: $\sigma \cdot \mathrm{BR}(i \to H \to f) \propto \frac{g_i^2 \cdot g_f^2}{\Gamma_H}$

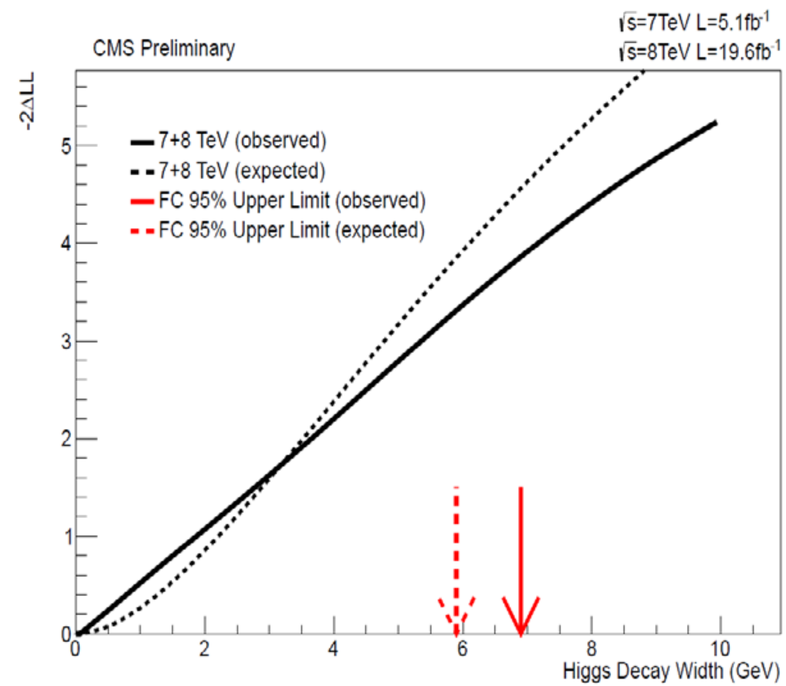
Examples: only SM decays or weaker assumptions $g_{HVV} \le g_{HVV}^{SM}$...

In these scenarios, the sensitivity $\sim \Gamma_H^{SM}$.

Γ_H can be determined model-independently through the fits to $m_{\gamma\gamma}$ and $m_{4\ell}$ distributions. The problem is that $\Gamma_H^{SM} = 4.1$ MeV $\ll \sigma_m$.

From the $m_{\gamma\gamma}$ distribution of the 7+8 TeV dataset, CMS observed (expected) an upper limit $\Gamma_H < 6.9\ (5.9)$ GeV @ 95% CL.

Assuming it scales with luminosity, an upper limit of ~ 300 MeV or $\sim 80 \times \Gamma_H^{SM}$ with 3000 fb^{-1}.



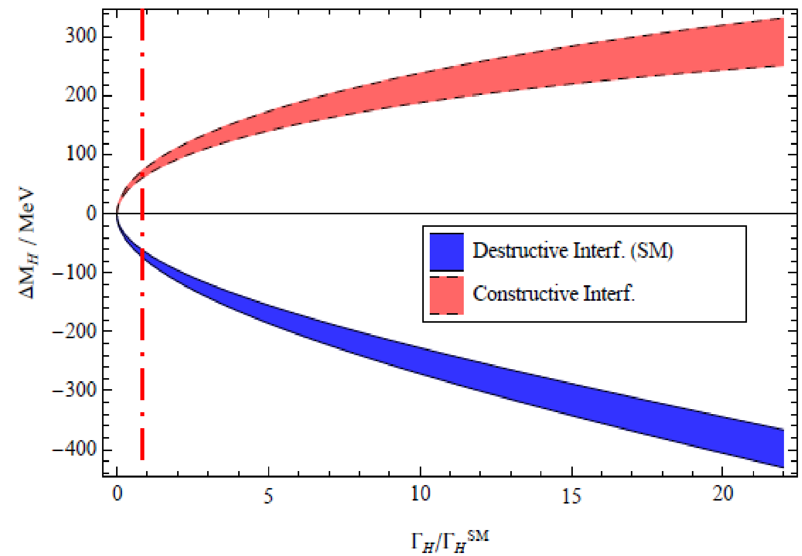
Higgs Total Width

$\gamma\gamma$ Interferometry: Dixon & Li, arXiv:1305.3854

$H \to \gamma\gamma$ interference with the continuum leads to shift in $m_H^{\gamma\gamma}$

$$\Delta m_H \equiv m_H^{\gamma\gamma} - m_H^{4\ell} \propto \sqrt{\Gamma_H}$$

Potentially sensitive to $\Gamma_H <\sim 2 \times \Gamma_H^{SM}$ with 3000 fb^{-1}.



Off-shell $gg \to H^* \to ZZ$ production: Caola & Melnikov, arXiv:1307.4935

$$\frac{d\sigma}{dm_{4\ell}^2} \sim \frac{g_g^2 \cdot g_Z^2}{\left(m_{4\ell}^2 - m_H^2\right)^2 + m_H^2\Gamma_H^2} \approx \frac{g_g^2 \cdot g_Z^2}{\left(m_{4\ell}^2 - m_H^2\right)^2}$$

Off-shell: determine $g_g^2 \cdot g_Z^2$

On-shell: extract Γ_H

Expected sensitivity: $\Gamma_H <\sim 10\Gamma_H^{SM}$

Coupling Deviations

How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

To be sensitive to a deviation Δ, the measurement precision needs to be much better than Δ, at least $\Delta/3$ and preferably $\Delta/5$!

Since the couplings of the 125 GeV Higgs boson are found to be very close to SM $\Rightarrow$ deviations from BSM physics must be small.

Typical effect on coupling from heavy state M or new physics at scale M:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 5\% \text{ @ } M \sim 1 \text{ TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

MSSM decoupling limit

Δ at sub-percent to a few percent, will be challenging to distinguish the MSSM decoupling limit from the SM in the case of no direct discovery.

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200 \text{ GeV}}{m_A}\right)^4$$

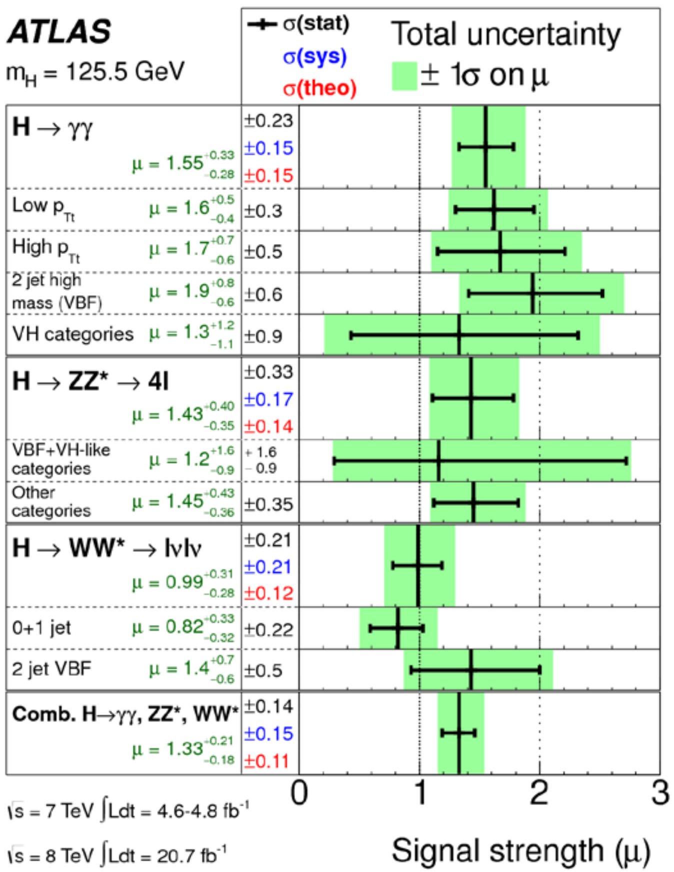
$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200 \text{ GeV}}{m_A}\right)^2$$

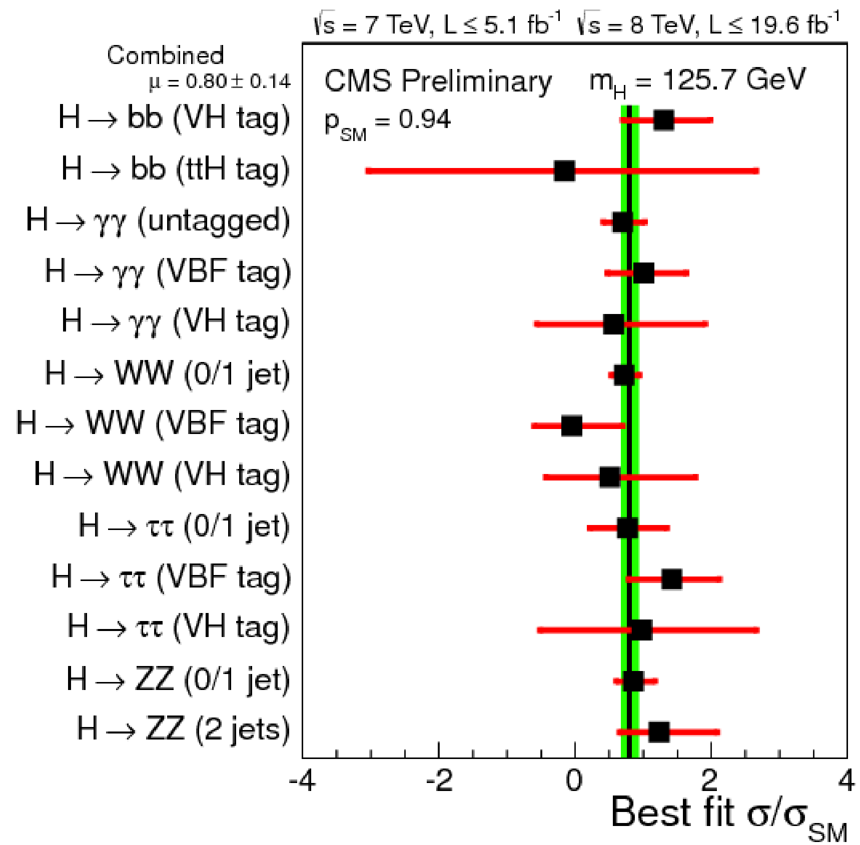
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200 \text{ GeV}}{m_A}\right)^2 .$$

(ILC DBDPhysics)

Inputs to Coupling Fits

Measured rates of different production and decay combinations





At the LHC, only the products of $\sigma \cdot$BR's are measured.

There is no model-independent way to separate σ and BR.

H→μμ Decay

Small $BR(H \to \mu\mu) = 2.2 \times 10^{-4}$ @ 125 GeV, good mass resolution ~2 GeV, 10 times smaller than $BR(H \to \gamma\gamma)$ with a larger background

ATLAS-CONF-2013-010

ATLAS has searched this decay in the 8 TeV dataset, the background is dominated by Z+jets: S/B~0.2%

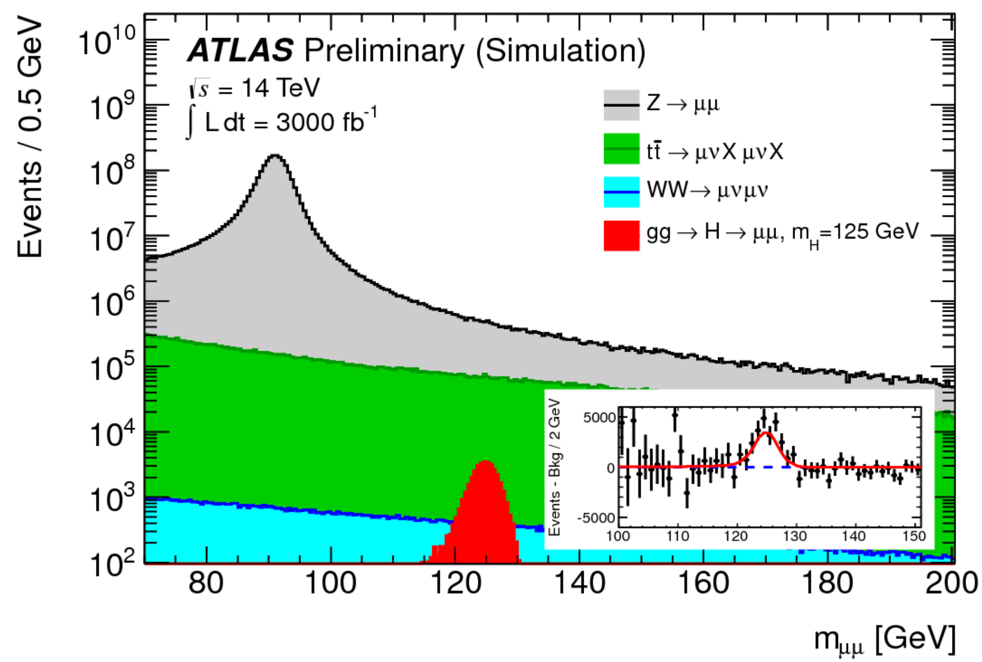
$|m_{\mu\mu} - m_H| \leq 5$ GeV

Background	Signal (125 GeV)	Data
$17,700 \pm 130$	37.7 ± 0.2	17,442

The 95% CL limit on σxBR relative to the SM: 9.8 (8.2) observed (expected). the analysis will clearly benefit from high luminosity

For 3000 fb^{-1}, the H→μμ decay is expected to be observed with a significance more than 6σ.

Moreover, 30 events are expected from ttH and H→μμ with a S/B better than 1 $\Rightarrow \Delta\mu/\mu \approx 25\%$ (assuming current theory uncertainty)



ttH with H→γγ

ATLAS has searched for ttH with H→γγ Decay in the current dataset

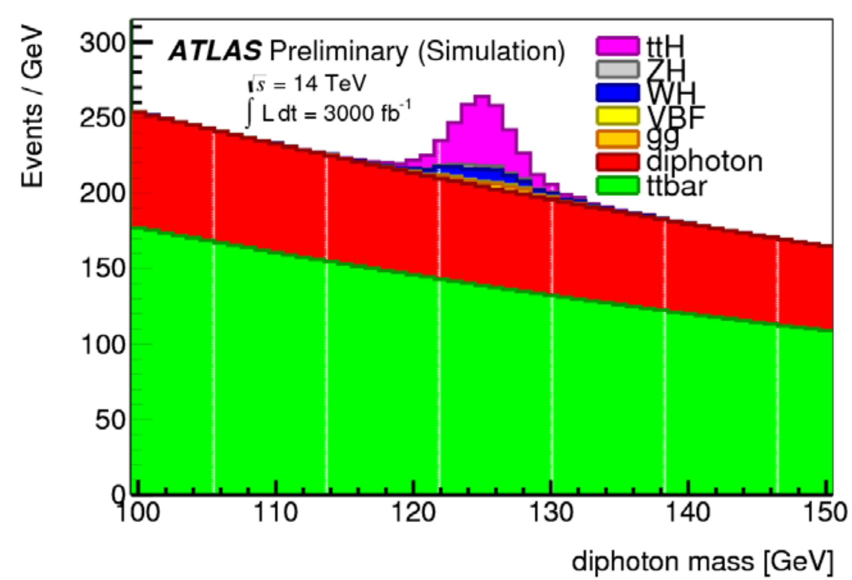
$120 < m_{\gamma\gamma} < 130$ GeV			
Analysis category	N_B	N_H ($m_H = 125$ GeV) ttH	H+other
Leptonic	1.2 (+0.6, −0.5)	0.46	0.10
Hadronic	1.9 (+0.7, −0.5)	0.32	0.03

Two analysis categories:

- Leptonic: $N_\ell \geq 1$, $N_{bjet} \geq 1$ and $\not{E}_T > 20$ GeV
- Hadronic: $N_{jet} \geq 6$, $N_{bjet} \geq 2$

S/B ~ 1:4

At $m_H = 126.8$ GeV, the 95% CL limit on $\sigma \times$BR relative to the SM: 5.3 observed (6.4 expected).



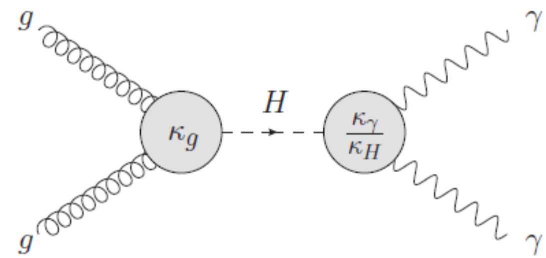
With 3000 fb^{-1}, expect to observe several hundred ttH→ttγγ candidates and achieve $\Delta\mu/\mu \approx 20\%$ (assuming current theory uncertainty)

Coupling Scale Parameters

Parametrizing deviations from SM using scale parameters: κ $\left(\text{SM: } \kappa = 1\right)$

$$g_{Hff} = \frac{m_f}{\upsilon}, \quad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{Hff} = \kappa_f \cdot \frac{m_f}{\upsilon}, \quad g_{HVV} = \kappa_V \cdot \frac{2m_V^2}{\upsilon}$$



For example: $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \left[\sigma(gg \to H) \cdot BR(H \to \gamma\gamma)\right]_{SM} \times \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

κ_H^2 is the scale factor to the total Higgs decay width

$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \to xx) \xrightarrow{\text{No non-SM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \to xx)$$

$$\xrightarrow{\text{With non-SM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \to xx)}{1 - BR_{non-SM}}$$

Benchmark models with different assumptions. Most models assume no non-SM decays $\left(BR_{non-SM} = 0\right)$.

Five-Parameter Model

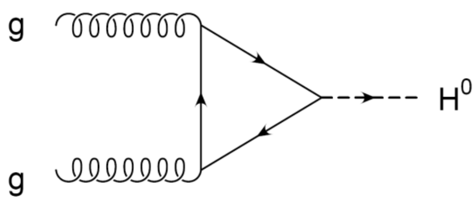
$\kappa_W, \ \kappa_Z, \ \kappa_t, \ \kappa_b, \ \kappa_\tau$

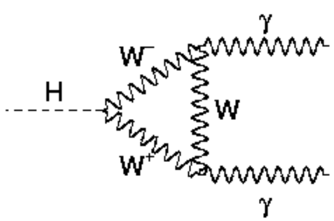
$$\kappa_H^2 = 0.577\kappa_b^2 + 0.215\kappa_W^2 + 0.086\kappa_g^2 + 0.063\kappa_\tau^2 + 0.029\kappa_c^2 + 2.63\times10^{-2}\kappa_Z^2 + 2.28\times10^{-3}\kappa_\gamma^2 + \ldots$$

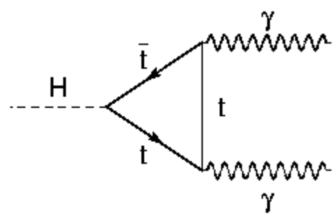
up-quarks: $\kappa_c^2 = \kappa_t^2$; down-quarks: $\kappa_s^2 = \kappa_b^2$

Decompose loop diagrams:

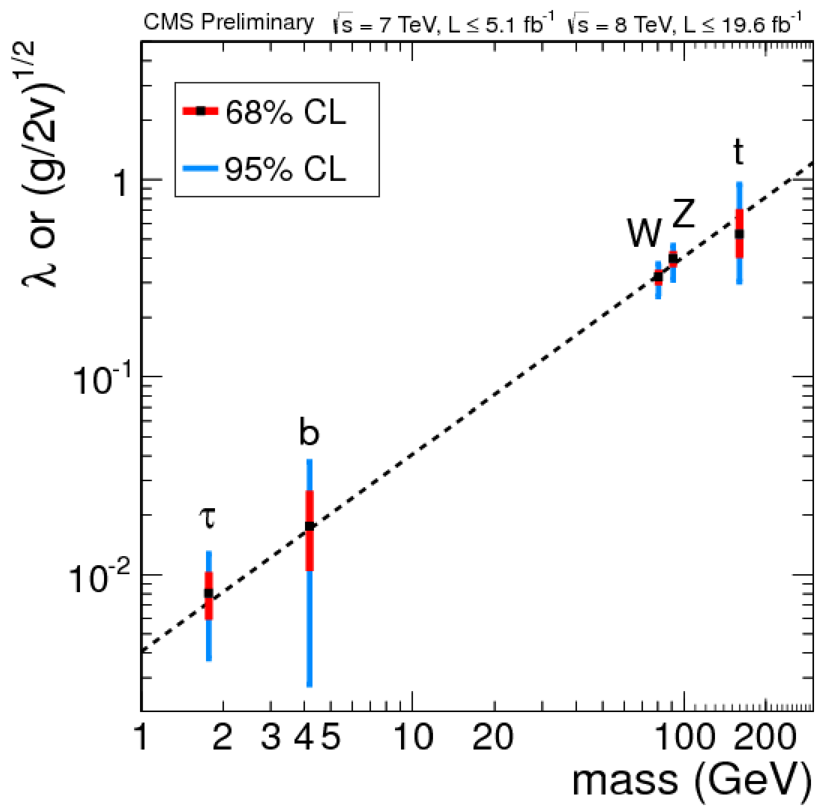
$\kappa_g^2 \approx \kappa_t^2$







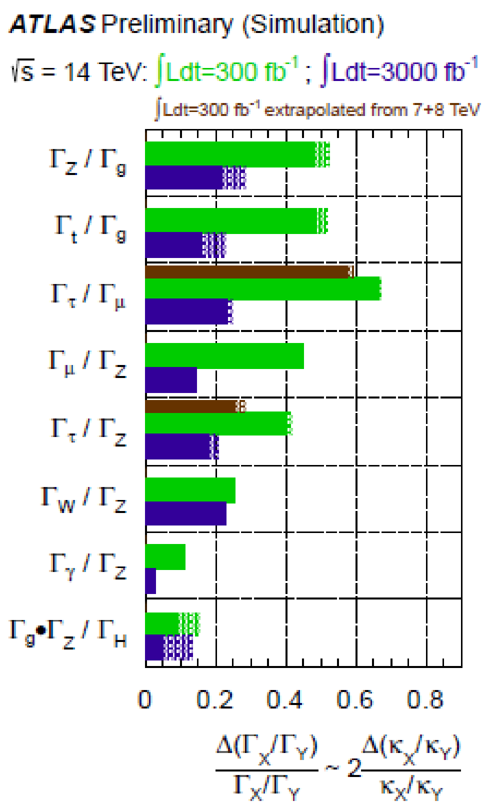
$\kappa_\gamma^2 \approx |1.26\kappa_W - 0.26\kappa_t|^2$



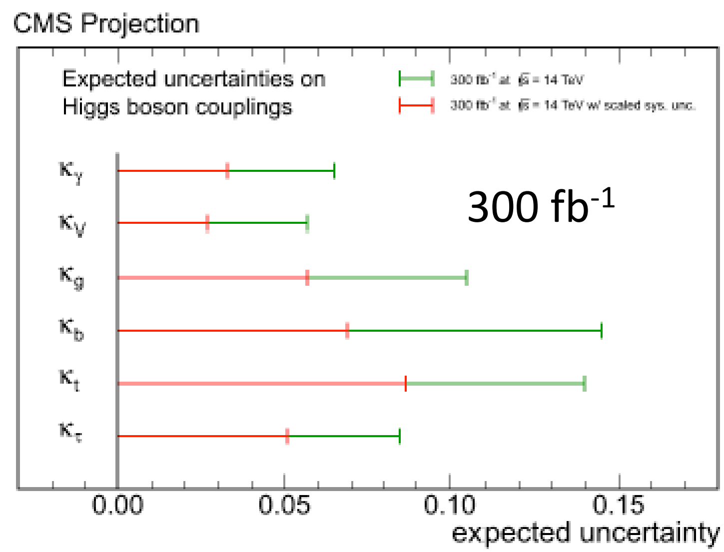
Good agreement with SM expectation ⇒ SM-like Higgs boson

Coupling Projections

Many studies done for European Strategy planning summarized in the Physics Briefing Book. Studies are being revisited and expanded.



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Ratios can be measured with better precisions, some can be measured at percent level.

Projection for 7-Parameter Model

$\kappa_g,\ \kappa_\gamma,\ \kappa_W,\ \kappa_Z,\ \kappa_t,\ \kappa_b,\ \kappa_\tau$

κ_g, κ_γ : for loop diagrams $\Rightarrow$ allow potential new physics;

κ_W, κ_Z : for vector bosons;

κ_t, κ_b : for up- and down-type quarks;

κ_ℓ : for charged leptons.

Coupling parameter	300 fb^{-1}	3000 fb^{-1}
κ_γ	$(5-7)\%$	$(2-5)\%$
κ_g	$(6-8)\%$	$(3-5)\%$
κ_W	$(4-5)\%$	$(2-3)\%$
κ_Z	$(4-5)\%$	$(2-3)\%$
κ_t	$(14-15)\%$	$(7-10)\%$
κ_b	$(10-13)\%$	$(4-7)\%$
κ_τ	$(6-8)\%$	$(2-5)\%$

(*assumed custodial symmetry, will be updated without it)

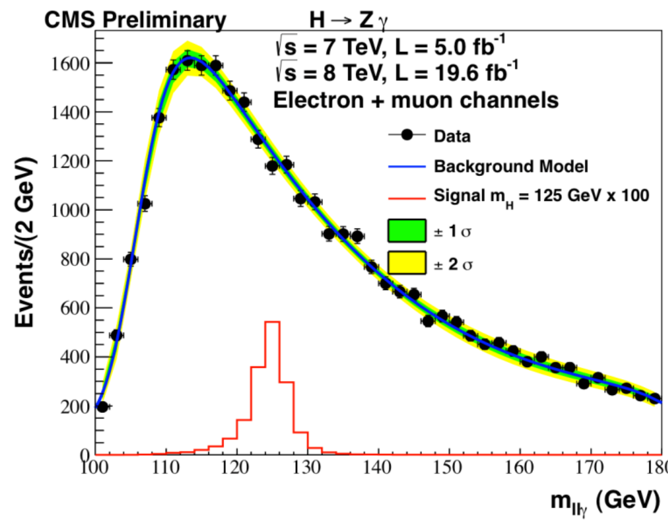
Most of the couplings can be measured with a precision of ~5% or better.
HL-LHC will improve the precision roughly by a factor of 2.

Other Rare Decays

$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$

is another high resolution channel, similar to $H \rightarrow \gamma\gamma$, but with a smaller $BR(H \rightarrow Z\gamma)$=0.15% and further suppressed by $BR(Z \rightarrow \ell\ell)$.

Current sensitivity is $\sim 13 \times$SM, statistics limited analysis, should largely scale with luminosity $\Rightarrow$ sensitivity @ $\sim 0.7 \times$SM with 3000 fb^{-1}.



$H \rightarrow J/\psi\,\gamma \rightarrow \ell\ell\gamma$

A recent suggestion (Bodwin et al., arXiv:1306.5770) to use this decay to get a handle on Hcc coupling:

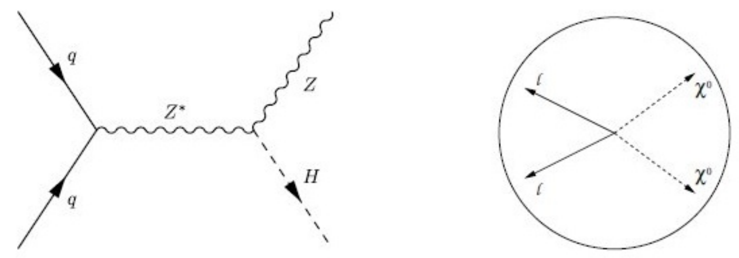
$$BR(H \rightarrow J/\psi\,\gamma) = 2.5 \times 10^{-6} \text{ and } BR(J/\psi \rightarrow \ell\ell) = 5.9\%$$

$\Rightarrow$ ~50 events in 3000 fb^{-1}

A tough one, but it is important to explore. New physics could enhance the rate.

Invisible Decay

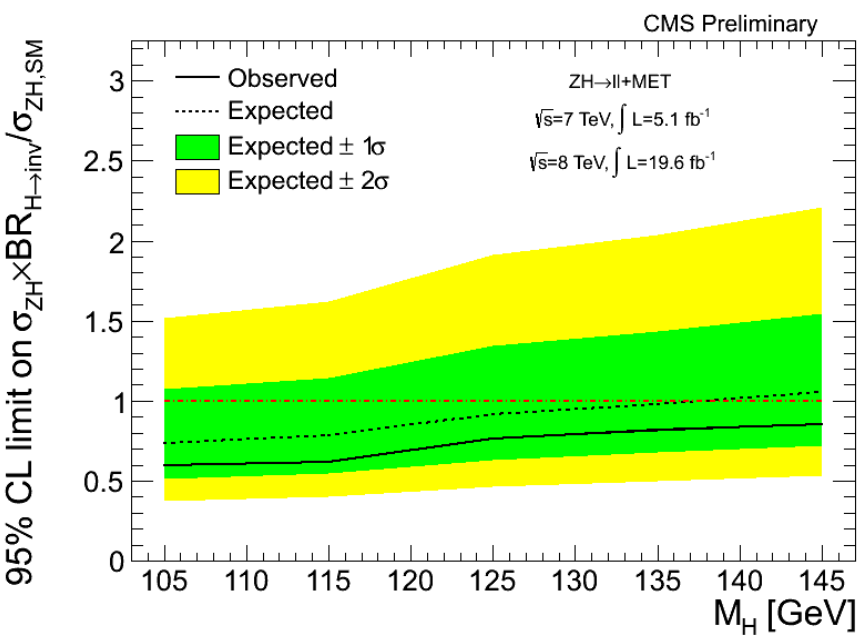
One non-SM Higgs decay that has garnered interests is the decay to "invisible". VBF and ZH productions are expected to have the best sensitivity.



Both ATLAS and CMS have results on ZH. Assuming SM production, the observed (expected) limits are

ATLAS: $BR_{inv} < 65\% \ (84\%)$

CMS: $BR_{inv} < 75\% \ (91\%)$



No estimate of sensitivity at HL-LHC is available. Cannot be easily scaled from luminosity. MET performance is the key.

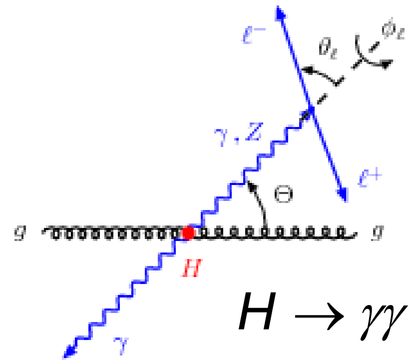
Back-of-envelope estimate:

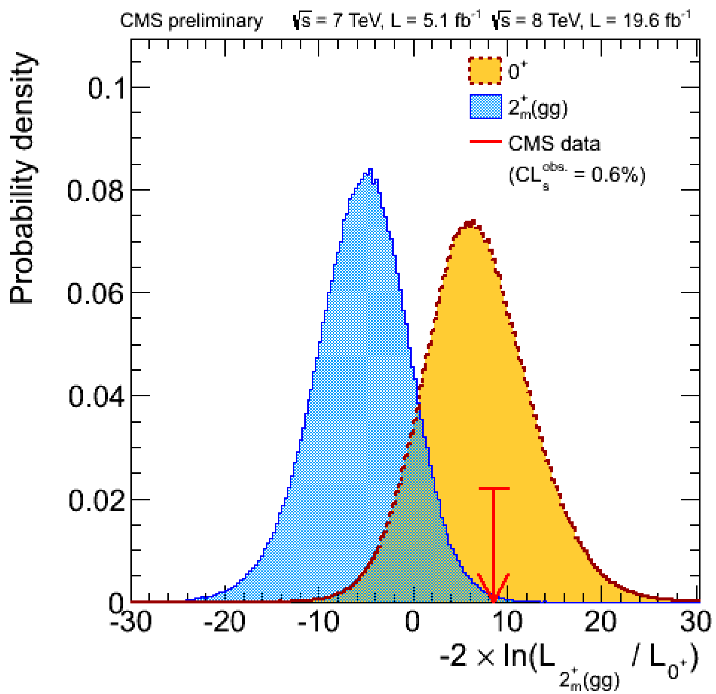
$$BR_{inv} <\sim (10-20)\%$$

is possible.

Spin Determination

Higgs decay kinematics depends on its properties of spin and parity. $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ final states have been analyzed to determine these properties.





SM prediction of $J^p=0^+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher.

The spin of the 125 GeV boson is already tightly constrained. Limited parameter space of spin-2 hypothesis remains.

CP Admixture

H→VV coupling:

$$A_{VV} \propto a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

a1: tree-level coupling to WW and ZZ
a2: loop-induced processes such as Zγ, γγ and gg
a3: pseudoscalar coupling

Scalar couples to VV at tree-level, pseudoscalar couples to VV at loop-level
⇒ strong suppression of CP admixture effect.

H→ff coupling:

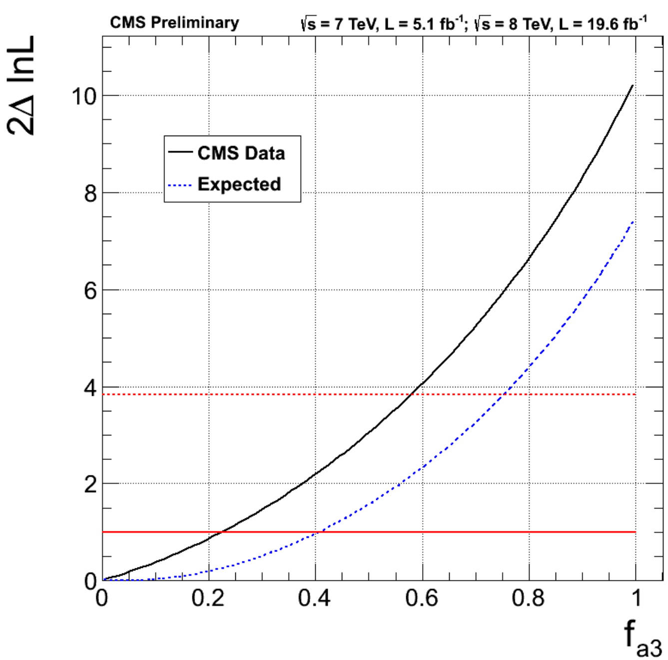
$$A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$$

No loop-suppression for pseudoscalar coupling to fermions. Can be studied in Higgs decays such as H→ττ as well as in the Higgs production of the ttH process.

CP Admixture

Parametrizing CP admixture using the CP-odd fraction: $f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$

CMS has measured f_{CP} by analyzing kinematics of $H \to ZZ^* \to 4\ell$ candidates of the current dataset: $f_{CP} = 0.00^{+0.23}_{-0.00}$ or $f_{CP} < 0.58$ @ 95% CL



The expected uncertainty is 0.4 which projects to

$\Delta f_{CP} = \pm 0.07$ at 300 fb^{-1}

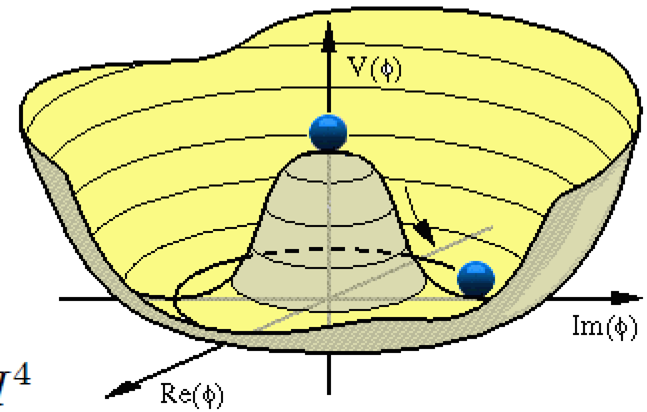
$\Delta f_{CP} = \pm 0.02$ at 3000 fb^{-1}

However, f_{CP} in $H \to VV$ decay is expected to be small due loop-suppression. A ~10% CP admixture will lead to $f_{CP} < 10^{-5}$.

Higgs Potential and Self-Coupling

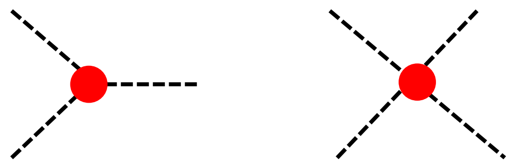
At the heart of the theory is the Higgs potential

$$V = -\mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$



Spontaneous symmetry breaking leads to

$$\Delta\mathcal{L} = -\frac{1}{2}m_H^2H^2 - \frac{1}{3!}g_{HHH}H^3 - \frac{1}{4!}g_{HHHH}H^4$$



with

$$m_H = \sqrt{2\lambda}v, \quad g_{HHH} = 6\lambda v = \frac{3m_H^2}{v}, \quad g_{HHHH} = 6\lambda = \frac{3m_H^2}{v^2}$$

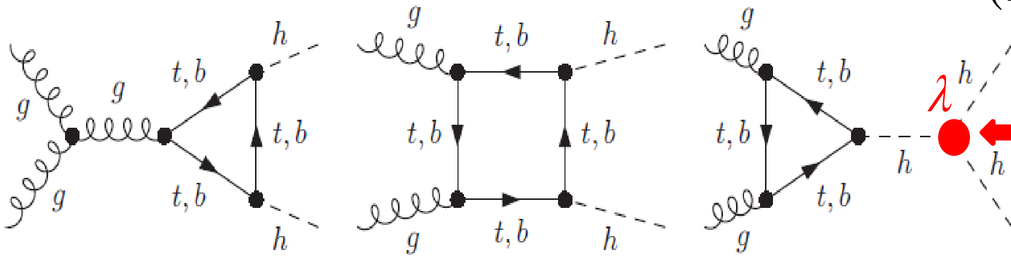
Once the Higgs mass is known, the two parameters are fixed:

$$\mu^2 = \frac{1}{2}m_H^2 \approx (89\ \mathrm{GeV})^2 \quad \text{and} \quad \lambda = \frac{m_H^2}{2v^2} \approx 0.13$$

Any new measurement will over constrain the system and therefore test the validity of the Higgs potential.

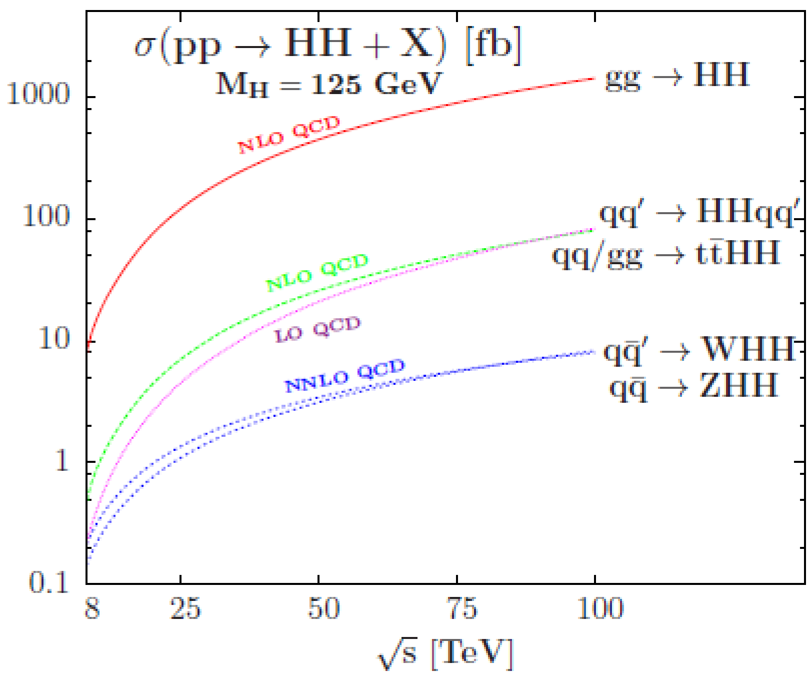
Higgs Pair Production

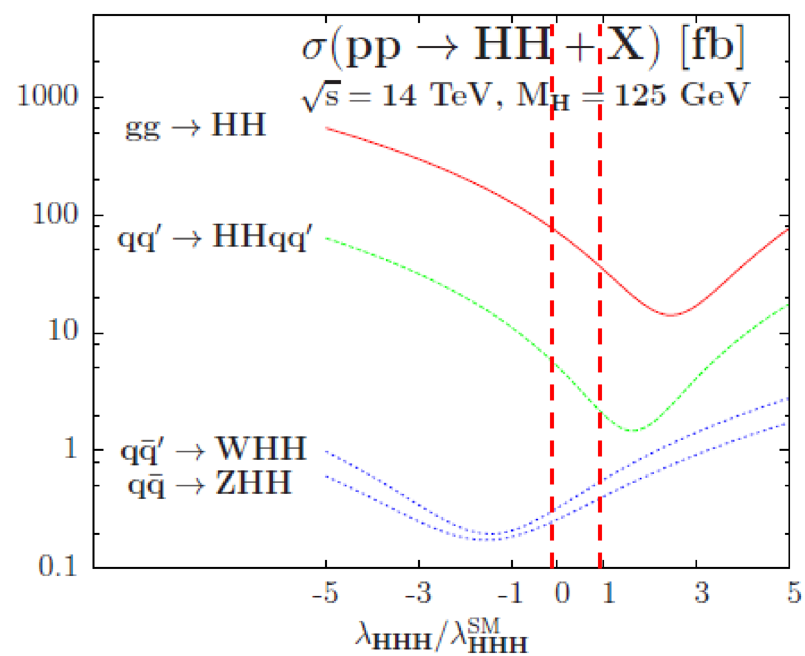
$\sigma(pp \to HH + X) \approx 34$ fb @ 14 TeV



$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$

Small cross sections, destructive interference between self-coupling and non-self-coupling diagrams. Cross section reduced by x2 with the self-coupling.





Baglio et al., arXiv:1212.5581

Higgs Self-coupling Studies

Many final states to explore, small number of events for clean channels.

Several studies by theorists, some very preliminary studies by ATLAS.

$\sigma(pp \to HH)$@14 TeV	34 fb
Events in 3000 fb^{-1}	
$HH \to bb\gamma\gamma$	270
$HH \to bb\tau\tau$	7,400
$HH \to bbWW$	25,000

$HH \to bb\gamma\gamma$ is likely the most sensitive channel with major backgrounds from $t\bar{t}H \to bb\gamma\gamma + X$ and $ZH \to bb\gamma\gamma$, a signal-background ratio better than 1:3 can be achieved. $HH \to bb\tau\tau$ should help too. Will likely need to combine many final states to maximize the sensitivity.

More studies are clearly needed from ATLAS and CMS experiments. But a ~30% measurement on the self-coupling is possible with 3000 fb^{-1} combining two experiments.

Higher energy will help. At 33 TeV, cross section increases by ~x7 for both the signal and main backgrounds

Summary

With 3000 fb^{-1} at 14 TeV, HL-LHC has the highest statistics than any future Higgs factory ⇒ unique opportunity for precision Higgs physics.

- The Higgs boson mass can be measured with a precision of ~100 MeV for 300 fb^{-1} and ~50 MeV for 3000 fb^{-1}.
- LHC is the place to study Higgs boson in the next decade. The expected precision of Higgs couplings to fermions and vector bosons are estimated to be 4-15% for 300 fb^{-1} and 2-10% for 3000 fb^{-1}. Better precisions can be achieved for some ratios.
- A ~30% ultimate measurement on the Higgs self-coupling is expected from HL-LHC, but this needs to be confirmed with more studies.

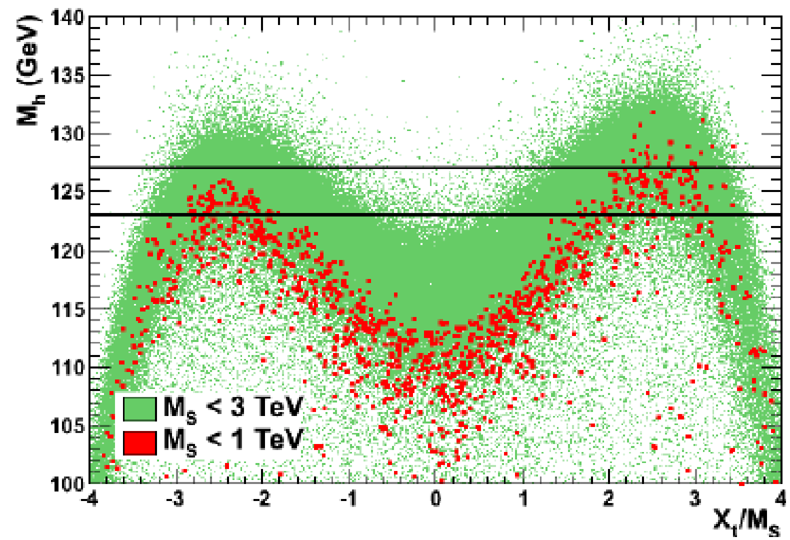
The full potential of the Higgs physics at the HL-LHC is yet to be studied!

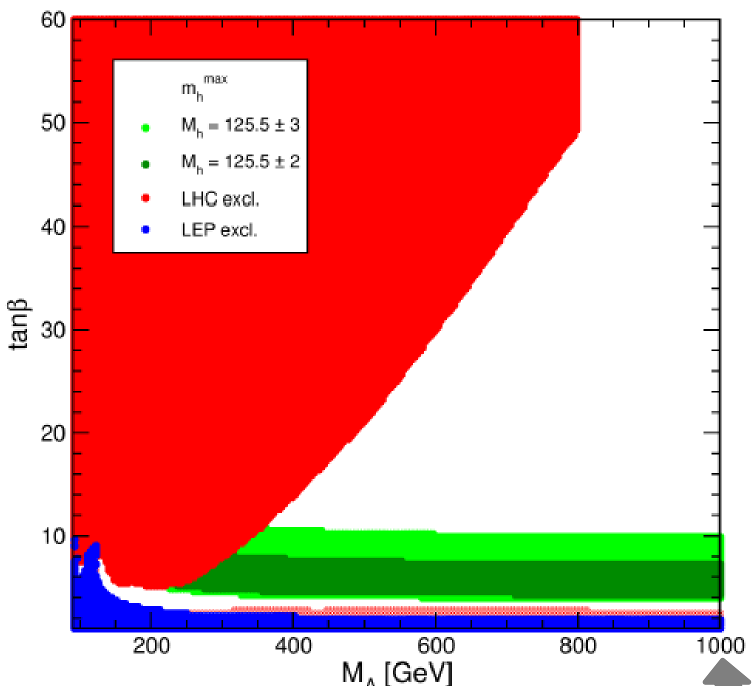
Beyond Standard Model

Understand the implication of a 125 GeV Higgs boson, whatever it is, it's SM-like…

For pMSSM, favoring large Ms
$\Rightarrow$ opens up small tanβ regions

Arbey et al., arXiv: 1112.3028





Carena et al., arXiv:1302.7033

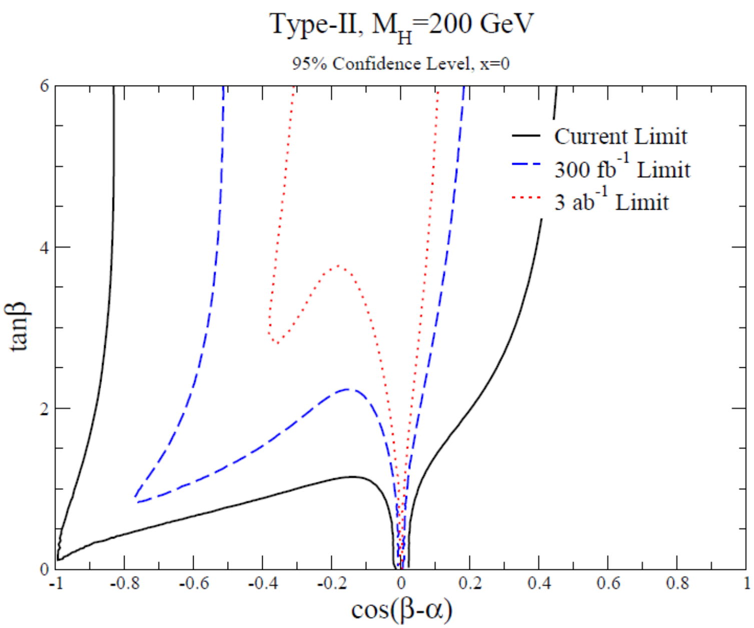
Develop new benchmark models

- Electroweak singlet
- Composite model
- 2 Higgs doublet model
- MSSM
- …

2 Higgs Doublet Model

5 Higgs bosons, the neutral scalars h and H share the role of electroweak symmetry breaking. Four types of general models:

Type I: one doublet couples to bosons, the other to fermions;
Type II: one to up-quarks, the other to down-quarks or leptons
Two other types:
Lepton-specific and flipped



Chen et al., arXiv:1305.1624

Couplings relative to SM

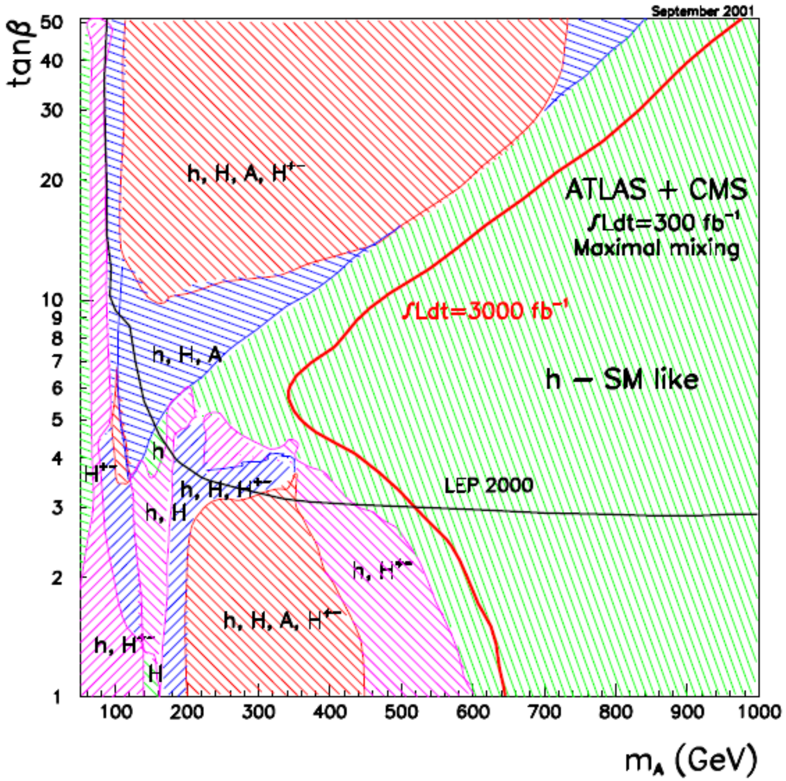
Coupling	Type I	Type II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Heavy Higgs will primarily decay to WW and ZZ bosons

HL-LHC will significantly increase the discovery potential or tighten the limit.

Beyond Standard Model

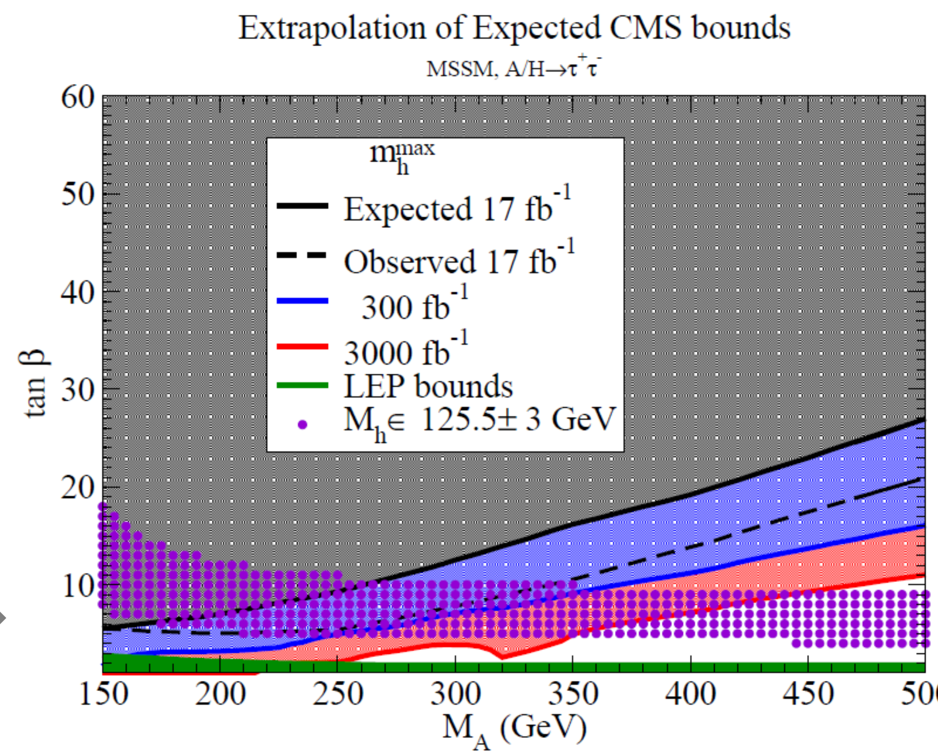
Gianotti et al., hep-ph/0204087



Most projections haven't been updated for 10 years ⇐ having too much fun with data

Nevertheless, the sensitivities are not expected to change much.

We know more than we did before

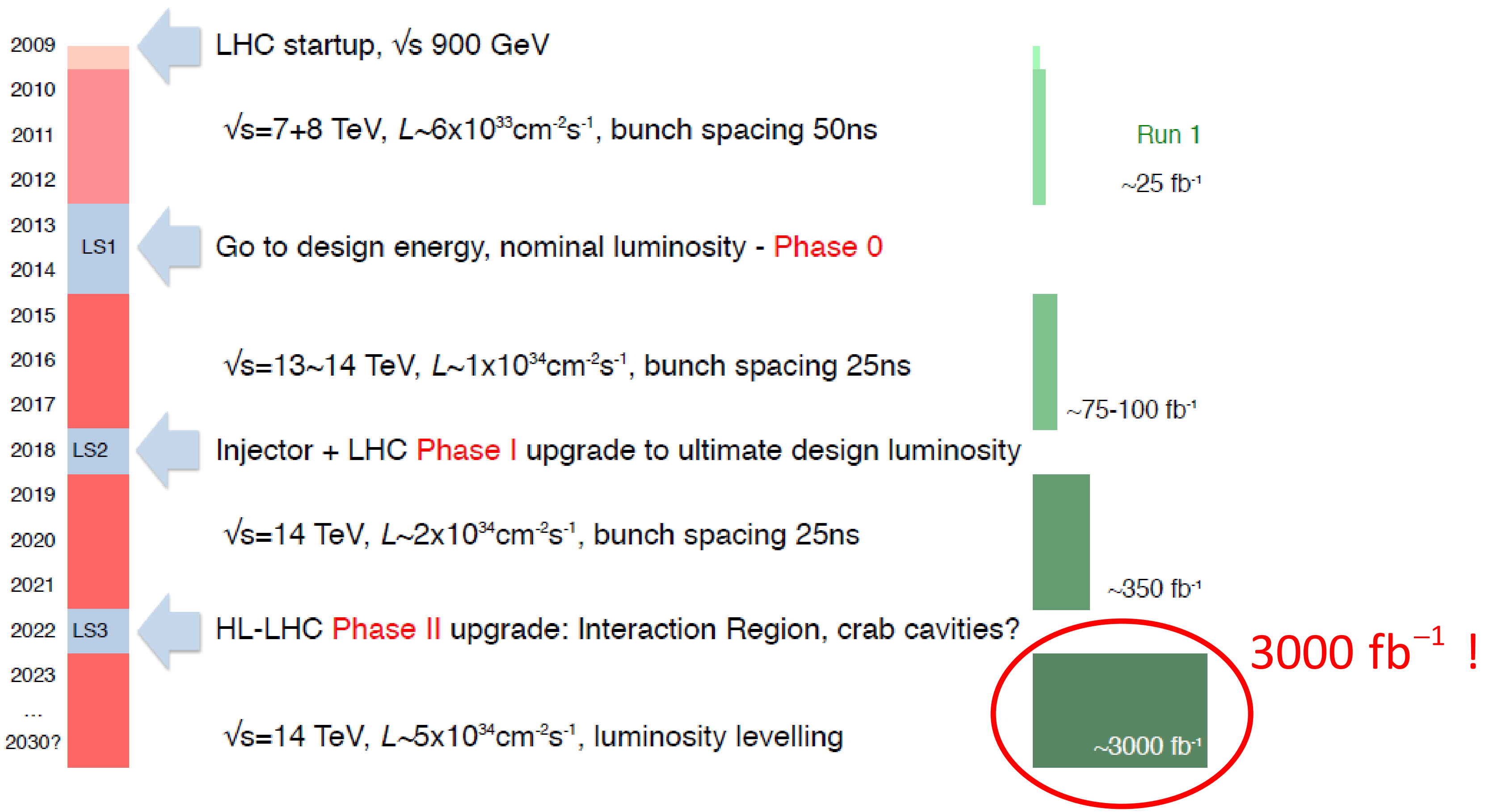


From the talk by Ian Lewis at the Seattle workshop

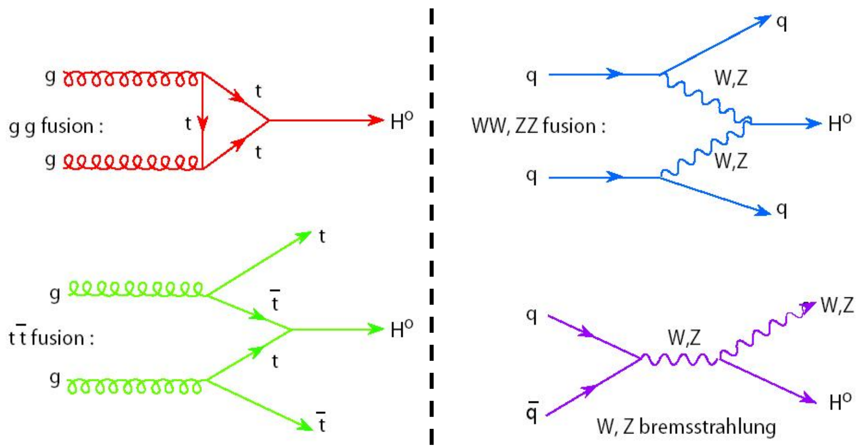
LHC – High Luminosity Upgrade

Update of European Strategy for Particle Physics:

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."



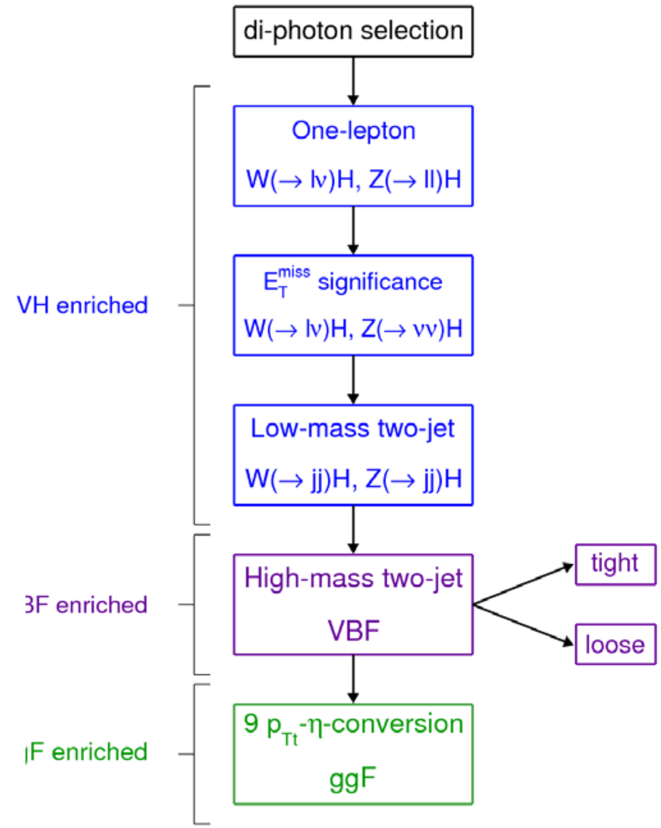
Production Processes

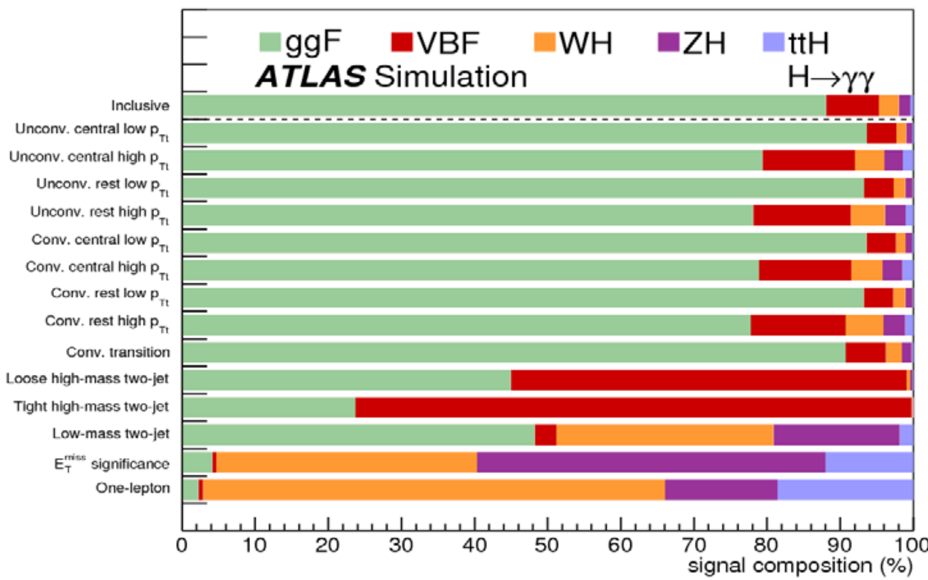


Htt coupling

HVV coupling

Production inspired categorization





VBF enriched

VH enriched