Snowmass Study: Higgs Prospects

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

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International Symposium on Higgs Physics, Beijing, August 12-16, 2013

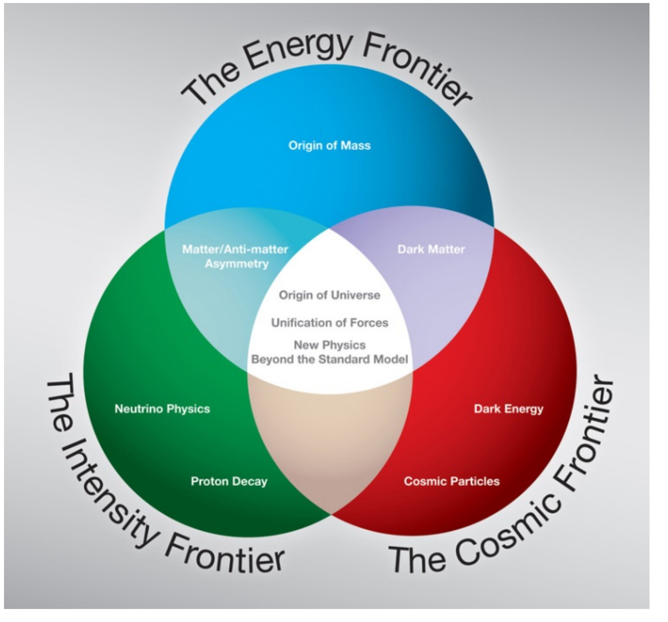
Community Summer Study 2013

Snowmass on the Mississippi, Minneapolis, July 29 – August 6, 2013

The American Physical Society's Division of Particles and Fields is pursuing *a long-term planning exercise for the high-energy physics community. Its goal is to develop the community's long-term physics aspirations*. Its narrative will communicate the opportunities for discovery in high-energy physics to the broader scientific community and to the government.

Seven frontiers

Sciences: Energy, Intensity, Cosmic
Enablers: Facility, Instrumentation,
Computing, Education & Outreach



Kick-off

Community Planning Meeting,
Fermilab, October 11-13, 2012

A 10-month long study with many topical meetings…

Energy Frontier

With the completion of the Tevatron program, the High Energy Frontier is now located at CERN, where the Large Hadron Collider offers a program of discovery that may continue for twenty years or longer.

The task of the High Energy Frontier study group is to *investigate the major areas of particle physics relevant to possible high energy accelerators, to review their current state, and to map the opportunities they provide for future discoveries*. In addition, these studies should explore the motivations for other possible energy frontier accelerators that may complement the LHC.

Six study groups:

The Higgs Boson
Precision study of electroweak interactions
Fully Understanding of the Top Quark
BSM – New Particles, Forces and Dimensions
QCD
Flavor Mixing and CP Violations

Two general meetings:

Brookhaven National Laboratory, April 3-6, 2013
University of Washington, Seattle, June 30 – July 3, 2013

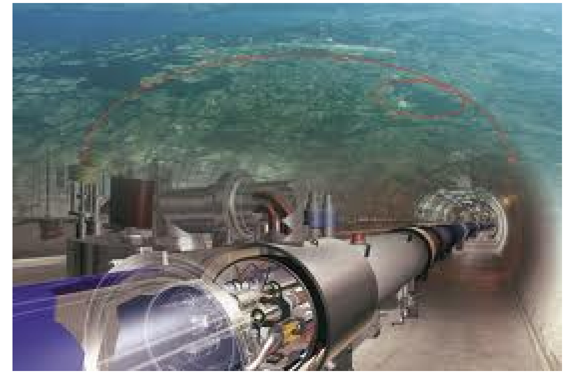
Facilities

pp colliders:

LHC at 14 TeV with 300 fb^{-1}

HL-LHC at 14 TeV with 3000 fb^{-1}

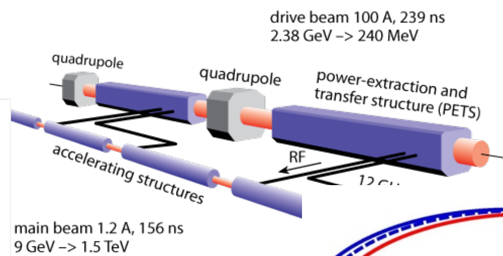
HE-LHC at 33 TeV and VLHC at 100 TeV

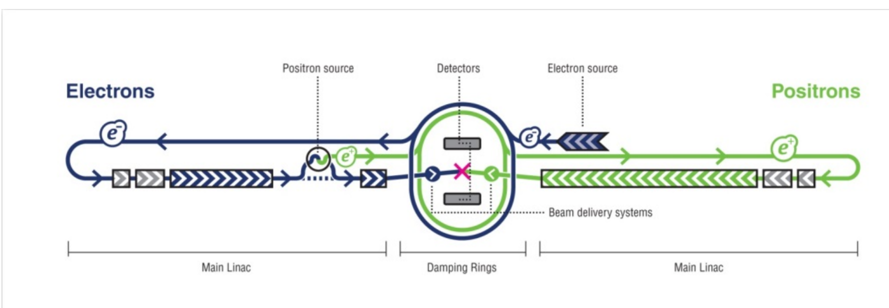


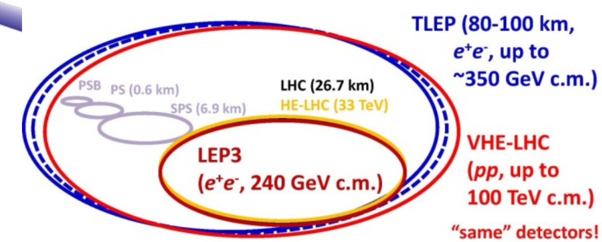
e^+e^- colliders:

Linear: ILC 250/500/1000 GeV, CLIC 350/1400/3000 GeV

Circular: TLEP @ 240 and 350 GeV





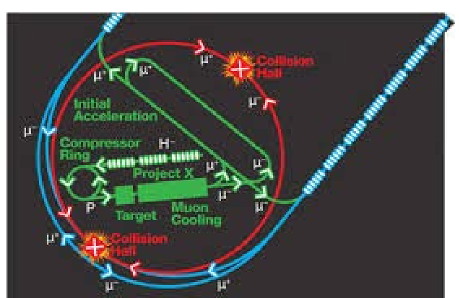


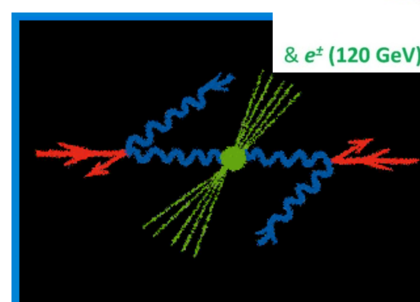
& $e^{\pm}$ (120 GeV) – *p* (7, 16 & 50 TeV) collisions ([(V)HE-]TLHeC)

Others:

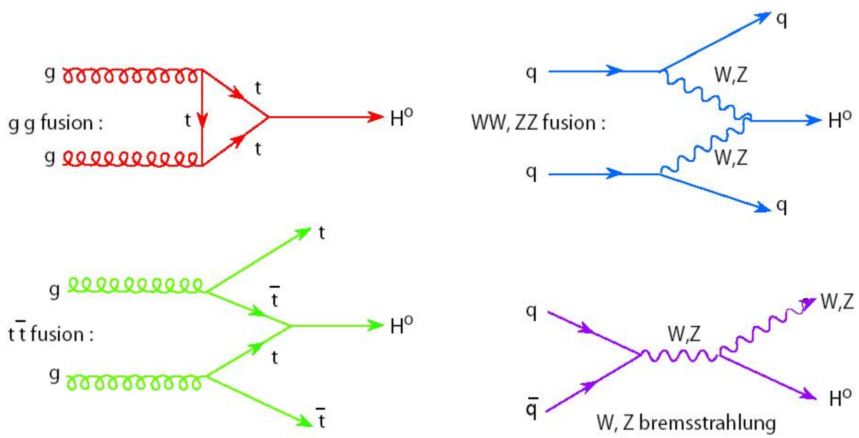
$\mu^+\mu^-$ collider

$\gamma\gamma$ collider





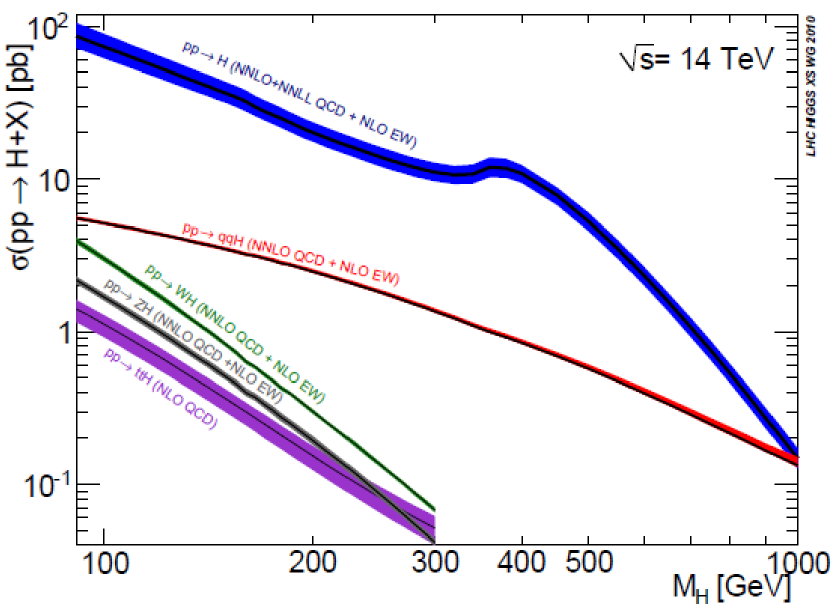
Higgs Production at LHC



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%

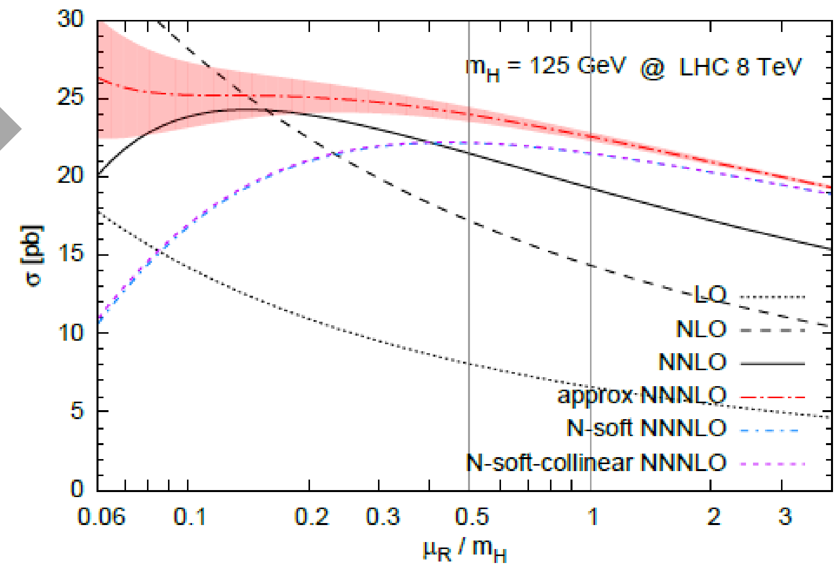
Already a major systematic to analysis in jet-bins.

Theory – Progress in σ Calculations

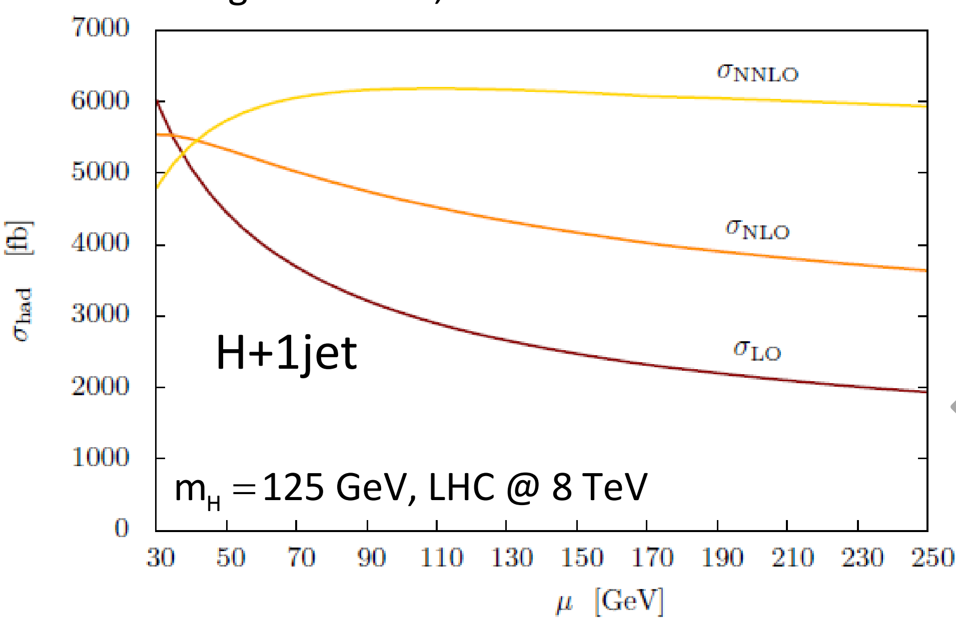
The gg→H cross section at LHC is calculated from NNLO+NNLL, but it still suffers from large QCD scale variations at ~8%.

Approximate NNNLO calculations are becoming available which can reduce the uncertainty to a few percent

Ball et al., arXiv:1303.3590



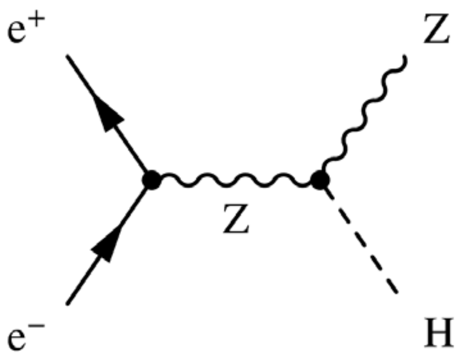
Boughezal et al., arXiv:1302.6216

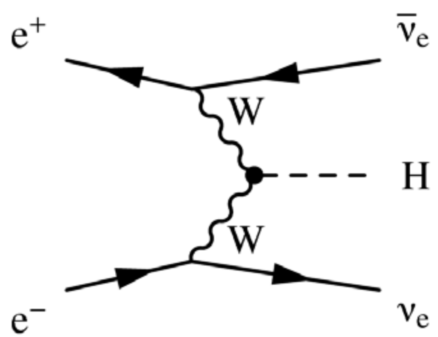


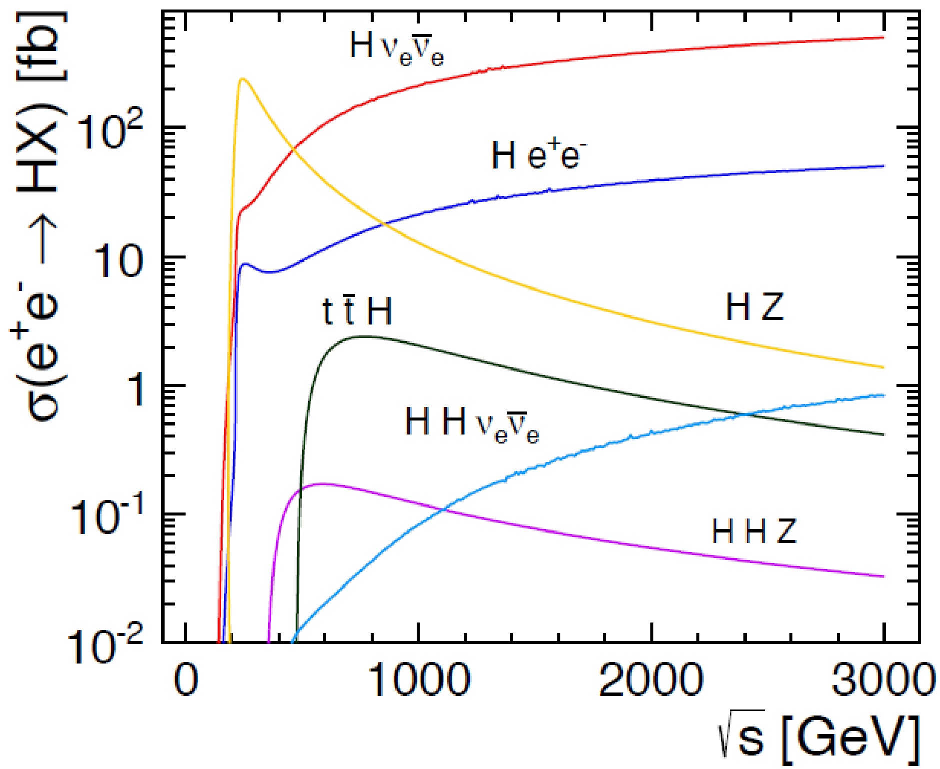
Not just the inclusive cross sections, analyses are often done in jet bins:

- better signal-background ratio;
- separate production processes

Higgs Production at Lepton Colliders





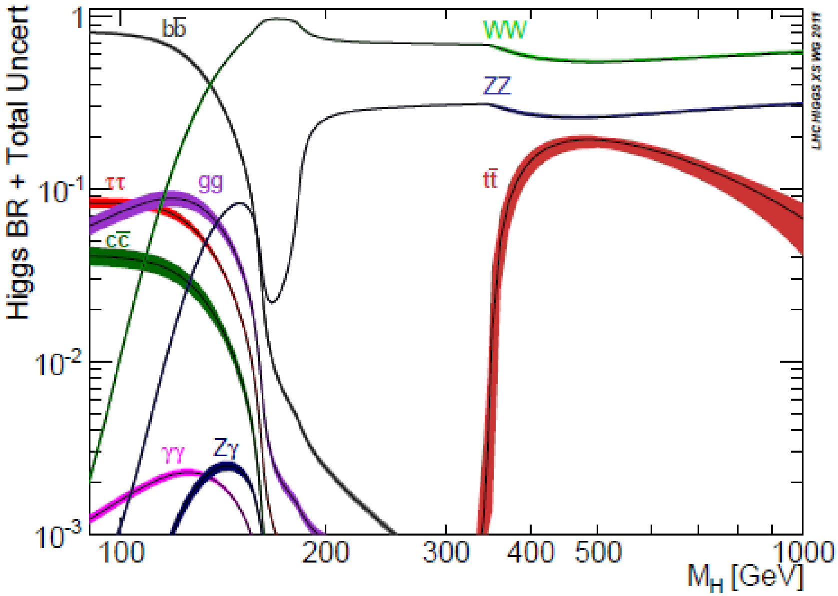


Cross sections for $m_H = 125$ GeV

$\sqrt{s}$	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$ (fb)	300	129	500	13	6	1
$\sigma(e^+e^-) \to \nu\nu H)$ (fb)	18	30	75	210	309	484

With polarized beams $\mathcal{P}(e^-, e^+) = (-0.8, 0.3)$

Higgs Decays



ΔBR/BR at $M_H = 125$ GeV

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

A. Denner et al., arXiv:1107.5909

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

$m_H = 125$ 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%

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

	Higgs X-section Working Group [5]	PDG [8]	non-lattice	Lattice (2013)	Lattice (2018)
$\Delta\alpha_s$	0.002	0.0007	0.0012 [8]	0.0006 [9]	0.0004
Δm_c (GeV)	0.03	0.025	0.013 [10]	0.006 [9]	0.004
Δm_b (GeV)	0.06	0.03	0.016 [10]	0.023 [9]	0.011

Difference in pp and e^+e^- Collisions

pp collisions:

Higgs candidates are selected from their decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell, \ldots \Rightarrow$ always measure $\sigma \times$BR, not possible to separate the two without assumptions

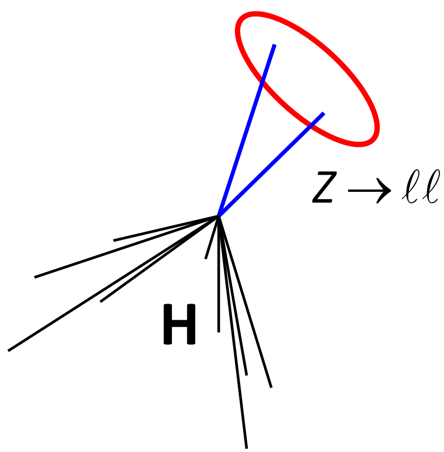
e^+e^- collisions:

ZH production provides a way to tag the Higgs without looking at it's decay $\Rightarrow$ allow to measure σ and BR separately

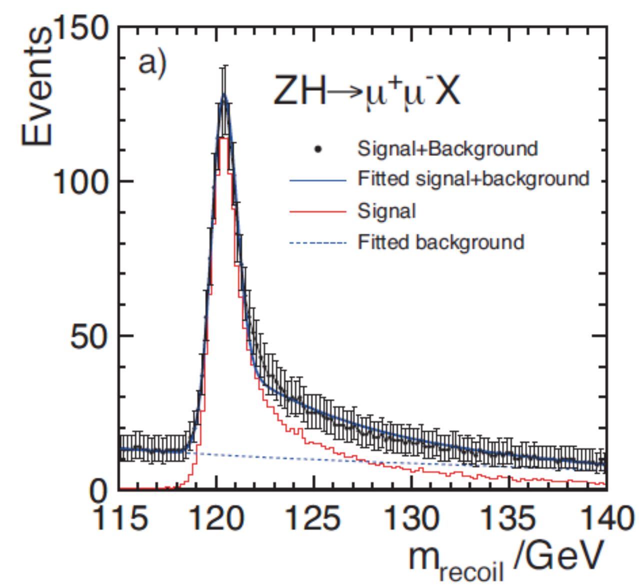
$e^+e^- \to ZH$ with

$Z \to \ell^+\ell^-$

$H \to X$

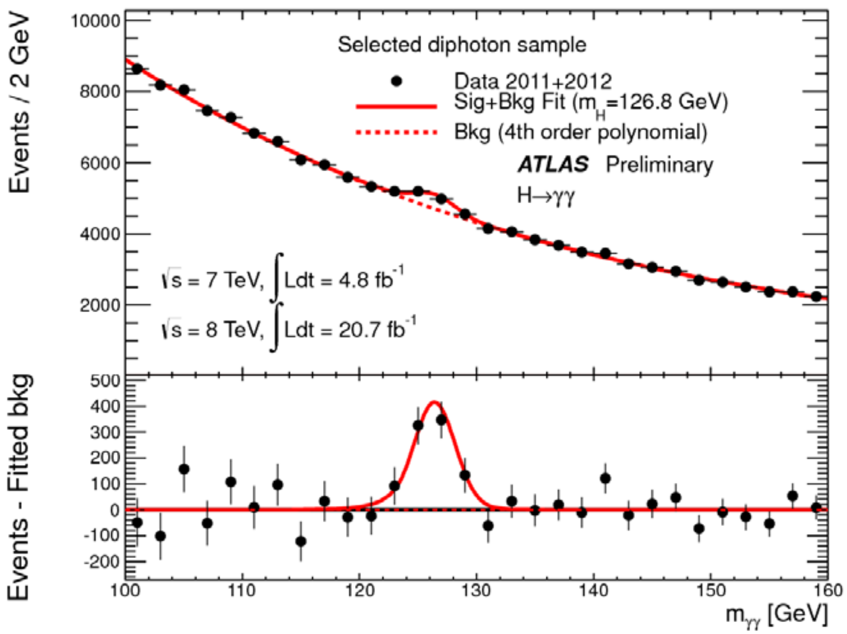


$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - \left|\vec{p}_{\ell\ell}\right|^2$$



Higgs Boson Mass at LHC

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

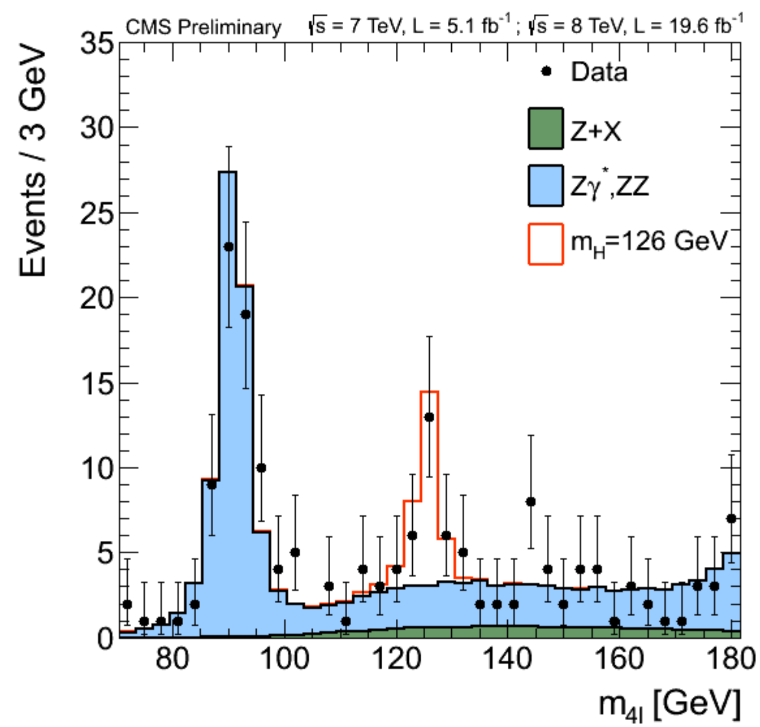


ATLAS:

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

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 at LHC

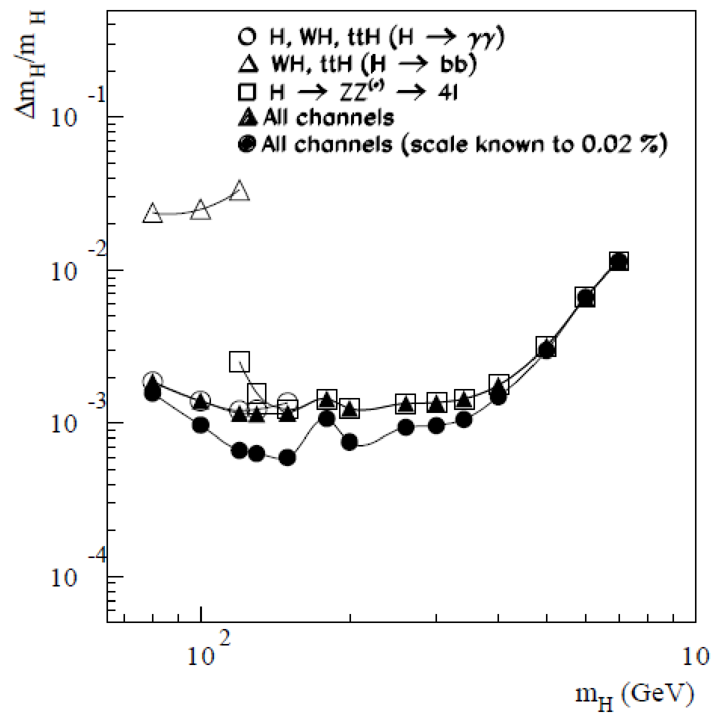
With 300 fb^{-1}, ATLAS estimates a precision of 0.07% @ 125 GeV $\Rightarrow \Delta m_H \approx 90$ MeV.

Precision in MeV on m_H

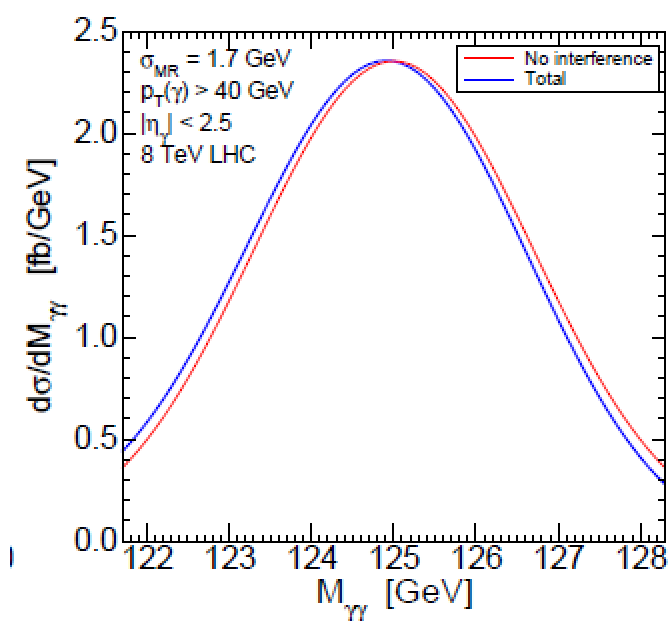
	Δ(stat)	Δ(syst)	Δ(total)
Present	250	450	520
300 fb^{-1}	50	80	100
3000 fb^{-1}	15	25	30

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

ATLAS TDR: CERN-LHCC-1999-15



Martin, arXiv:1303.3342



For $H \rightarrow \gamma\gamma$, 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 at LHC

Diffcult to extract from the rate measurements without some assumptions

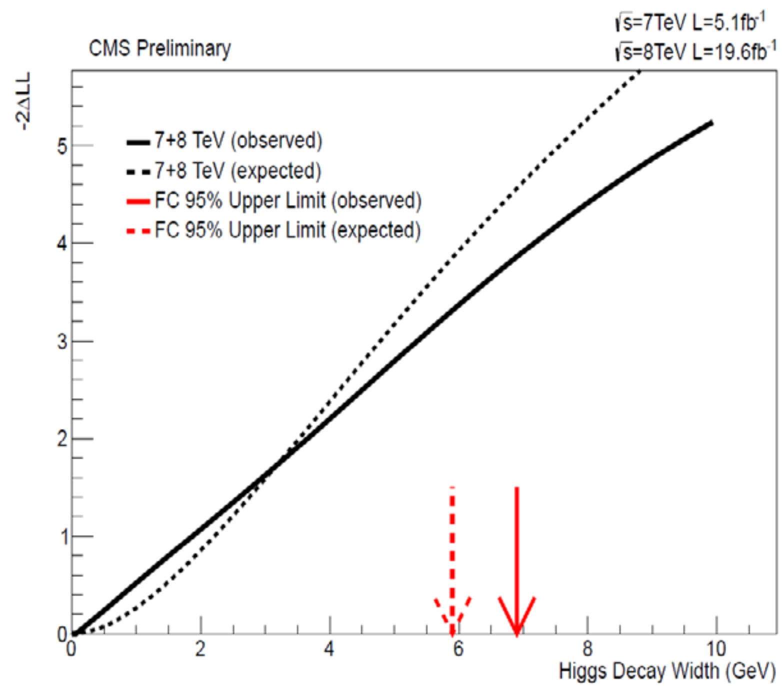
on couplings: $\sigma \cdot \mathrm{BR}\left(i \to H \to f\right) \propto \dfrac{g_i^2 \cdot g_f^2}{\Gamma_H}$

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

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 ~ 200 MeV or $\sim 50 \times \Gamma_H^{SM}$ with 3000 fb^{-1}.

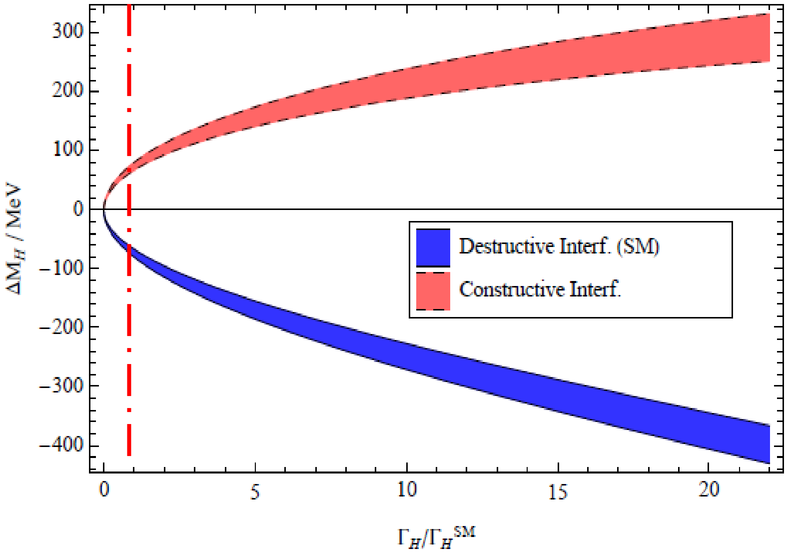
Higgs Total Width at LHC

$\gamma\gamma$ 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: $\Gamma_H <\sim 10\Gamma_H^{SM}$

Lepton Colliders

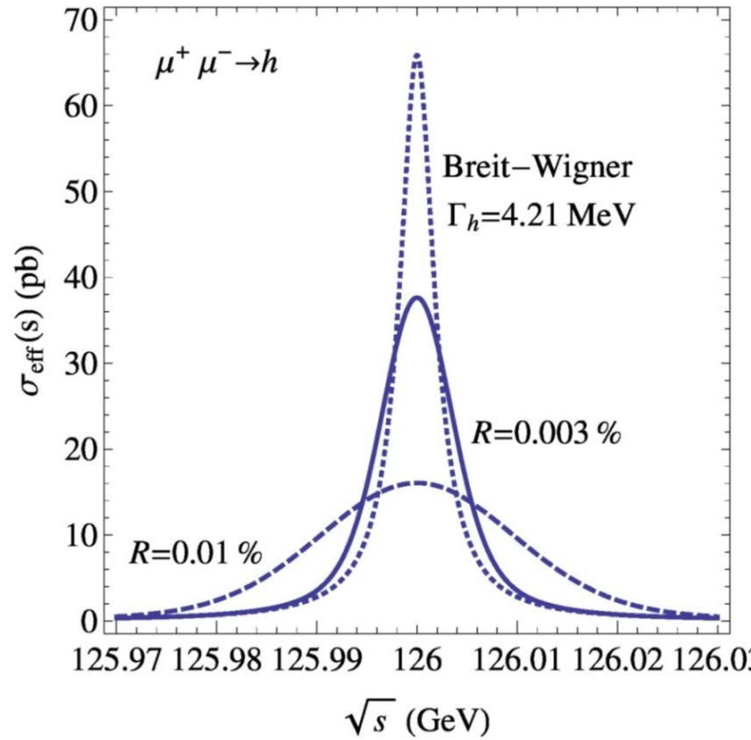
e+e- collider:

ZH recoil mass ⇒ Higgs mass

$$m_H^2 \equiv m_{\text{recoil}}^2 = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - \left|\vec{p}_{\ell\ell}\right|^2$$

Rates ⇒ Higgs width

$$\Gamma_H = \frac{\Gamma\left(H \to ZZ^*\right)}{BR\left(H \to ZZ^*\right)} \propto \frac{\sigma\left(ZH\right)}{BR\left(H \to ZZ^*\right)}$$



Facility	Δm_H (MeV)	$\Delta\Gamma_H/\Gamma_H$
LHC	100	–
HL-LHC	50	–
ILC500	35	5.9%
ILC1000	35	5.6%
ILC1000-up		2.7%
CLIC	33	8.4%
TLEP (4 IP)	7	0.6%
μC	0.06	4.3%

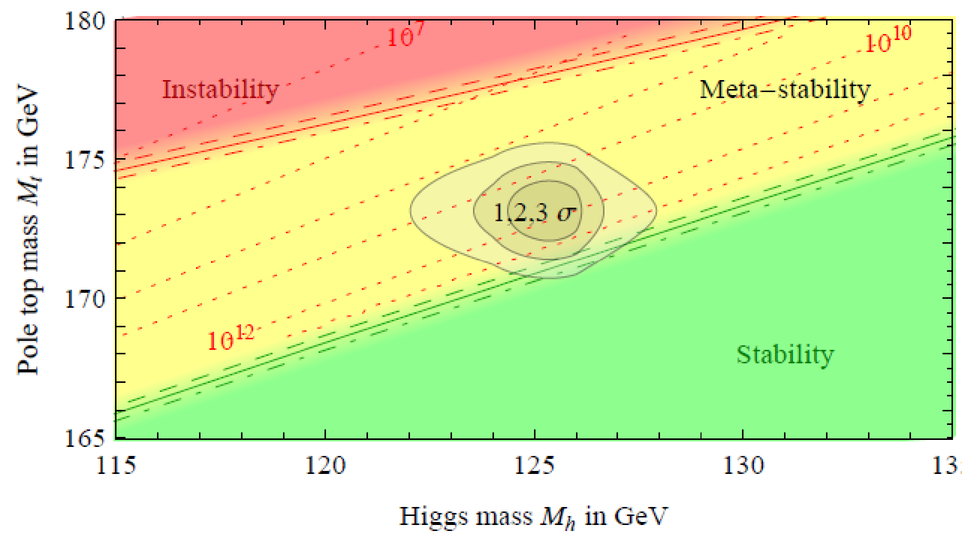
μμ collider:

resonance scan for both the mass and the width

$$\sigma\left(\sqrt{s}\right) \sim \frac{1}{\left(s - m_H^2\right)^2 + \Gamma_H^2 m_H^2}$$

How well do we need to know…

Mass is important to understand the stability of the vacuum, see for example arXiv:1205.6497 by Degrassi et al.



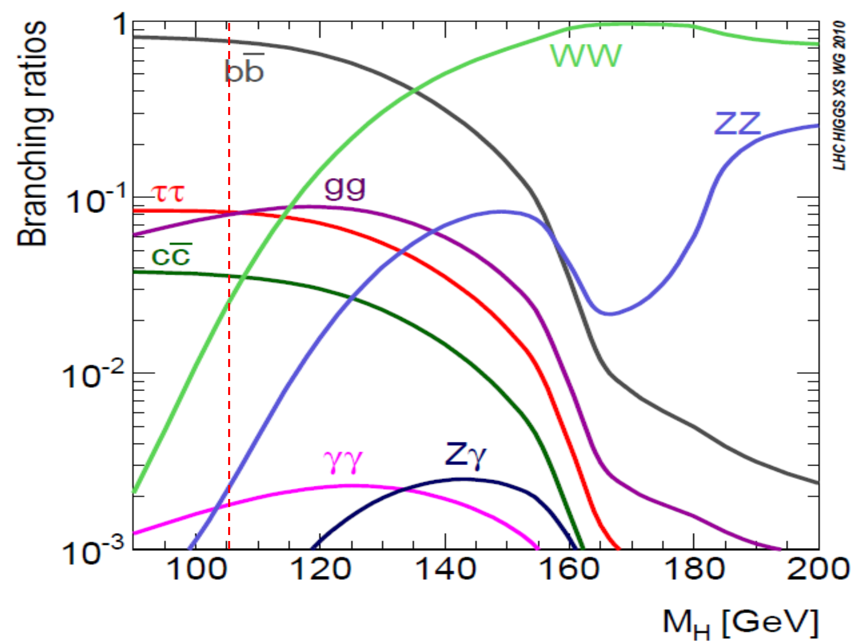
But also important for precision Higgs measurement:

At $m_H \approx 125.5$ GeV

$H \to WW^*$: $(\Delta BR/BR)/\Delta m_H \approx 7\%/\text{GeV}$

$H \to ZZ^*$: $(\Delta BR/BR)/\Delta m_H \approx 9\%/\text{GeV}$

A ΔBR ~ 0.5% measurement will require $\Delta m_H \sim 50$ MeV or better.



The total width can reveal new physics,

⇒ The more precise, the better!

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:

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

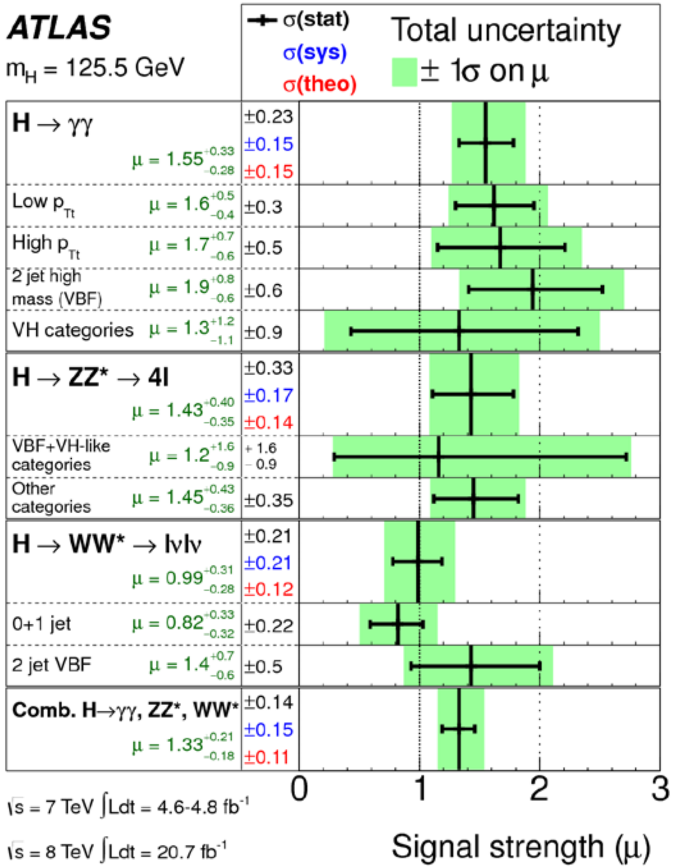
(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

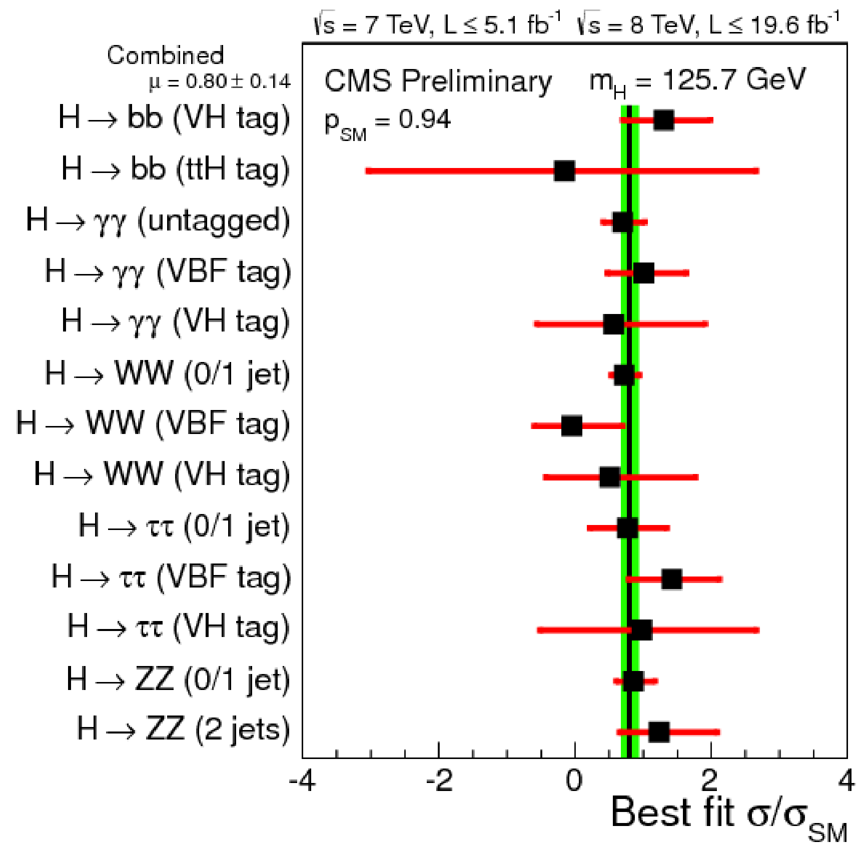
Typical sizes of coupling modification from some selected BSM models

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

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.

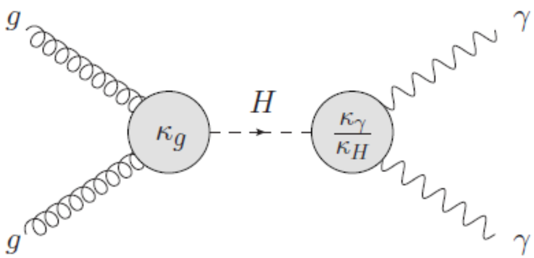
There is no model-independent way to separate σ and BR.

Coupling Scale Parameters

Parametrizing deviations from SM using scale parameters: κ (SM: $\kappa = 1$)

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

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



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

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

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

Benchmark models with different assumptions. Most models assume no BSM decays $(BR_{BSM} = 0)$.

Five-Parameter Model

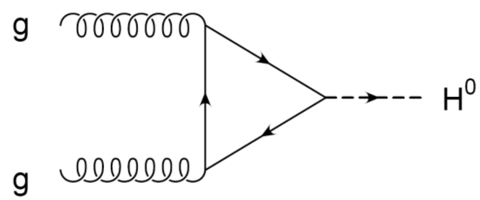
$\kappa_W,\ \kappa_Z,\ \kappa_t,\ \kappa_b,\ \kappa_\tau$

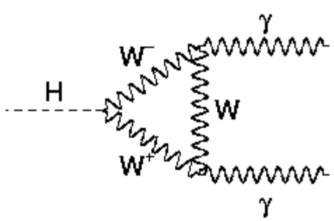
$$\kappa_H^2 = 0.577\kappa_b^2 + 0.215\kappa_W^2 + 0.086\kappa_g^2 + 0.063\kappa_\tau^2 + 0.029\kappa_c^2 + 2.63\times10^{-2}\kappa_Z^2 + 2.28\times10^{-3}\kappa_\gamma^2 + \ldots$$

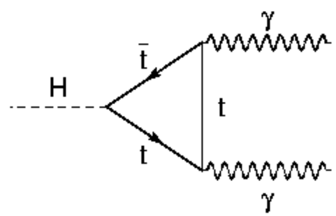
up-quarks: $\kappa_c^2 = \kappa_t^2$;   down-quarks: $\kappa_s^2 = \kappa_b^2$

Decompose loop diagrams:

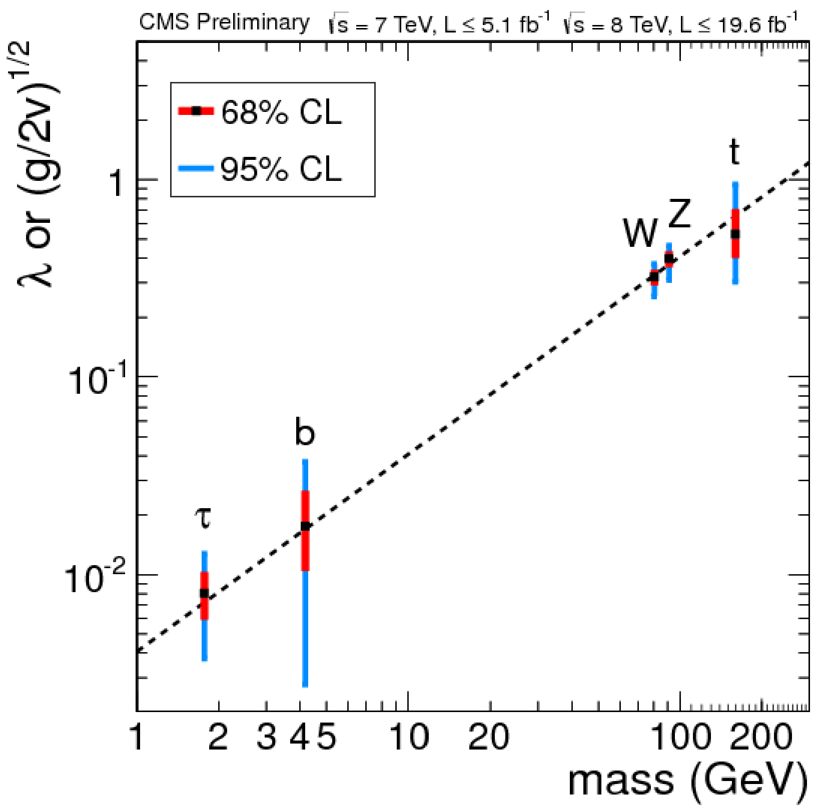
$\kappa_g^2 \approx \kappa_t^2$







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



Good agreement with SM expectation ⇒ SM-like Higgs boson

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;

κ_W, κ_Z : for vector bosons;

κ_u, κ_d : for up- and down-type quarks;

κ_ℓ : for charged leptons.

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$
	additional parameters	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$34-35\%$	$9-11\%$
$\mathrm{BR}_{\mathrm{BSM}}$	$<14-18\%$	$<7-11\%$

Two assumptions on systematics:

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

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.

Precision at e^+e^- Colliders

- *ZH* cross section measurements:

$$\frac{\Delta\sigma}{\sigma} \sim 2.5\%(\text{ILC}),\ 1.2\%(\text{ILC LumiUp}),\ 0.4\%(\text{TLEP})$$

- Classify the rest of the events to measure $\text{BR}(H \to XX)$

Results from model-independent fits

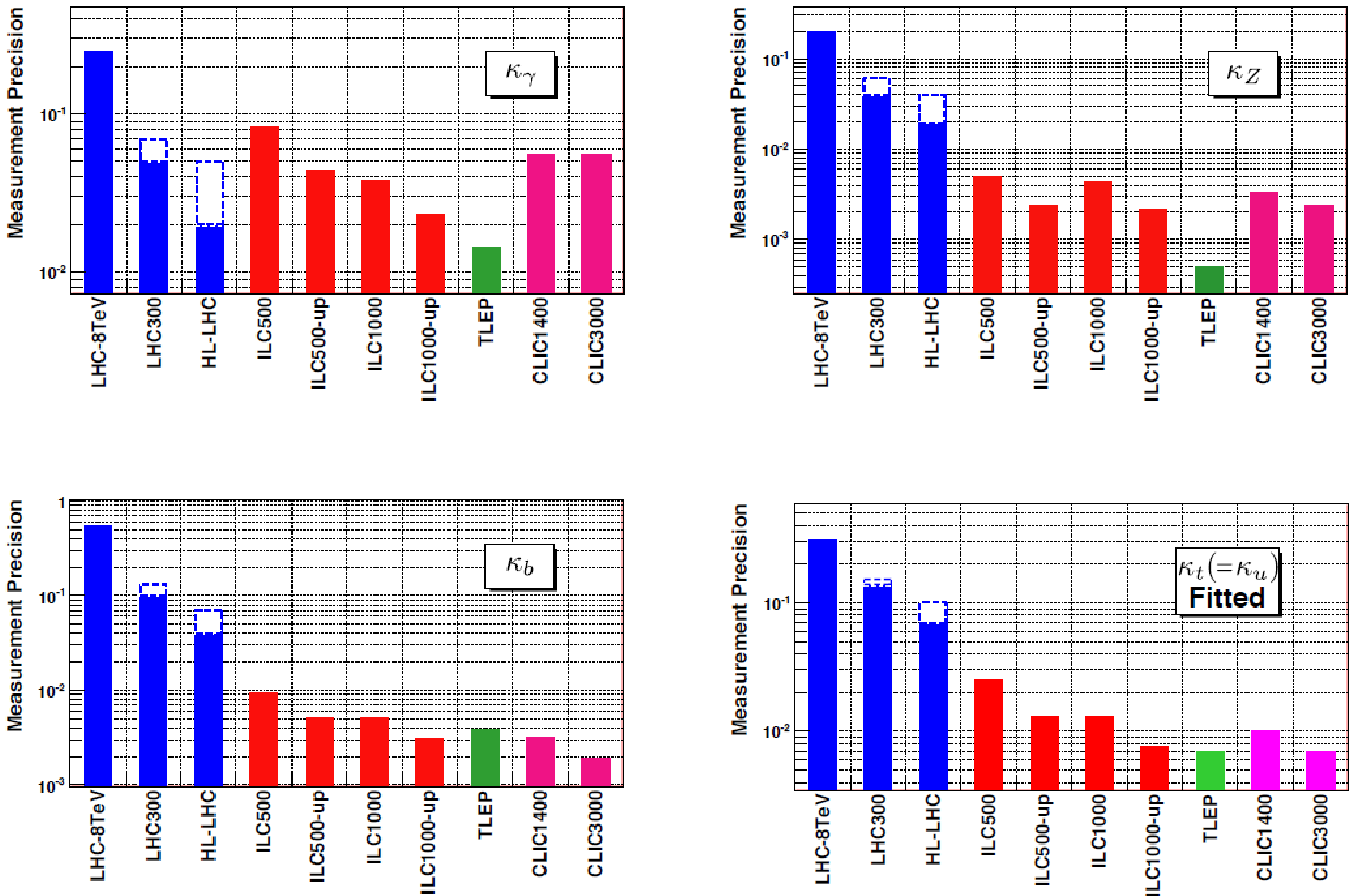
Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	11%	5.9%	5.6%	2.7%	1.9%	1.0%	9.2%	8.5%	8.4%
BR_{inv}	$< 0.69\%$	$< 0.69\%$	$< 0.69\%$	$< 0.32\%$	0.19%	$< 0.19\%$			
κ_γ	18%	8.4%	4.1%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.4%	1.8%	0.93%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.8%	1.4%	1.4%	0.65%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.3%	1.3%	0.61%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.7%	2.4%	1.9%	0.99%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.9%	2.0%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.8%	1.5%	0.74%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%

Fits to 7-parameter model

κ_g, κ_γ, κ_W, κ_Z, κ_t, κ_b, κ_τ

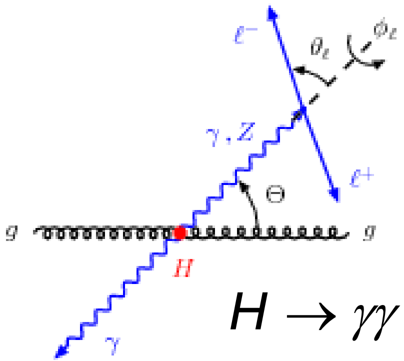
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

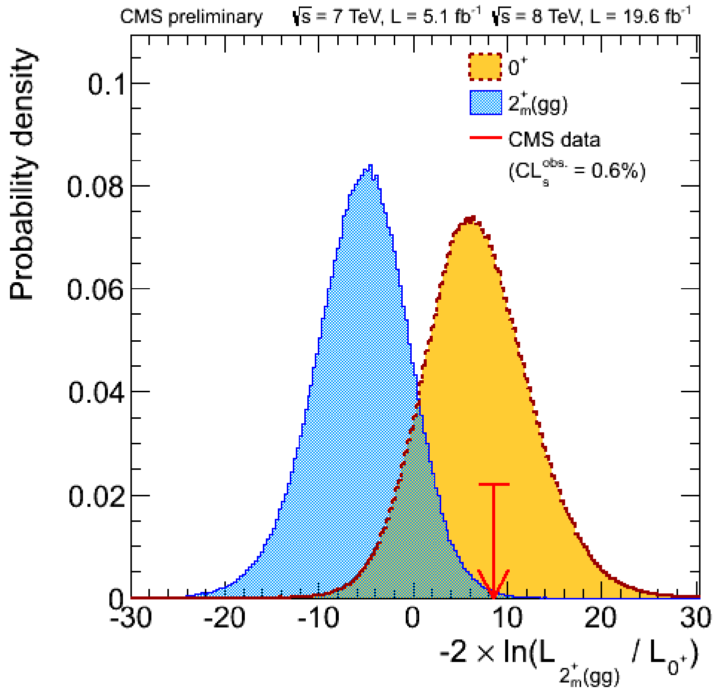
Precision at Different Facilities



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:

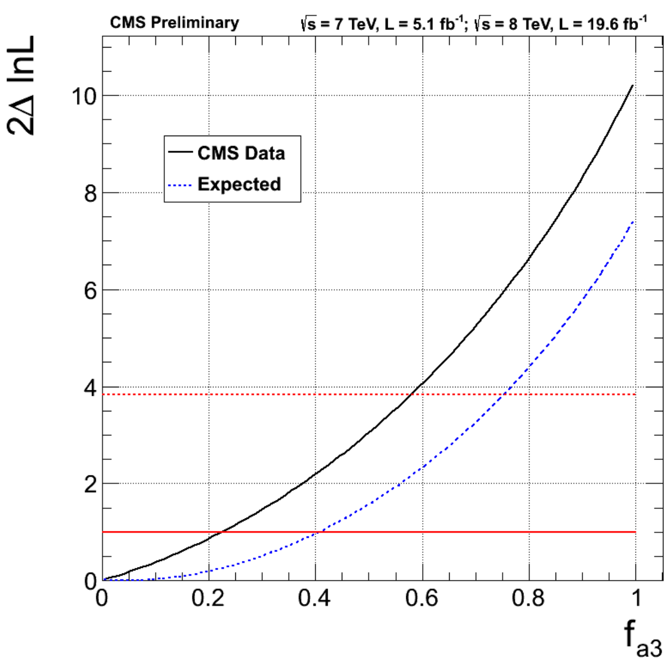
$$A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$$

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 $f_{CP} < 10^{-5}$.

Projected Sensitivities

Collider E (GeV) $\mathcal{L}$ (fb^{-1})	pp 14,000 300	pp 14,000 3,000	e^+e^- 250 250	e^+e^- 350 350	e^+e^- 500 500	e^+e^- 1,000 1,000	$\gamma\gamma$ 126 250	$\mu^+\mu^-$ 126	target (theory)
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
ZZH	$0.07^\dagger$	$0.02^\dagger$	$7\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$7\cdot10^{-6}$	✓	✓	$< 10^{-5}$
WWH	$3\cdot10^{-3\ddagger}$	$5\cdot10^{-4\ddagger}$	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
ggH	✓	✓	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	–	–	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

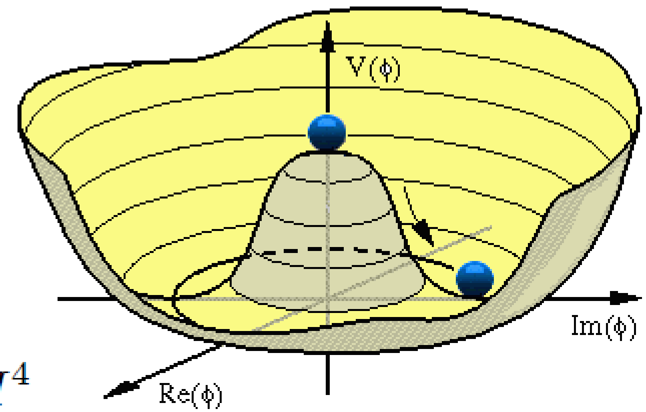
† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^*V^* \to H$ (VBF) production mode

Higgs Potential and Self-Coupling

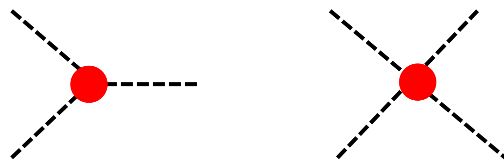
At the heart of the theory is the Higgs potential

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



Spontaneous symmetry breaking leads to

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



with

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

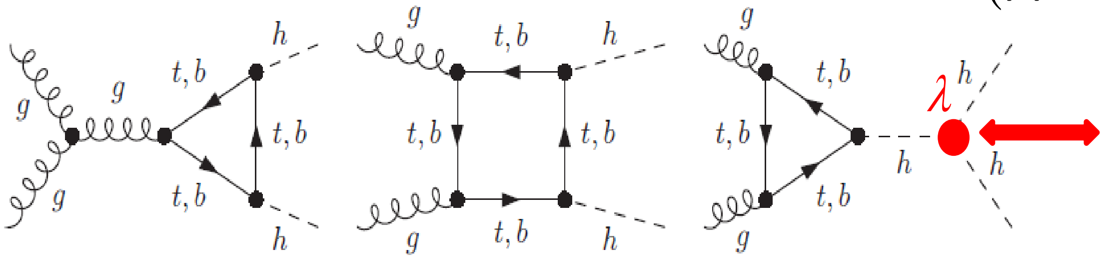
Once the Higgs mass is known, the two parameters are fixed:

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

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

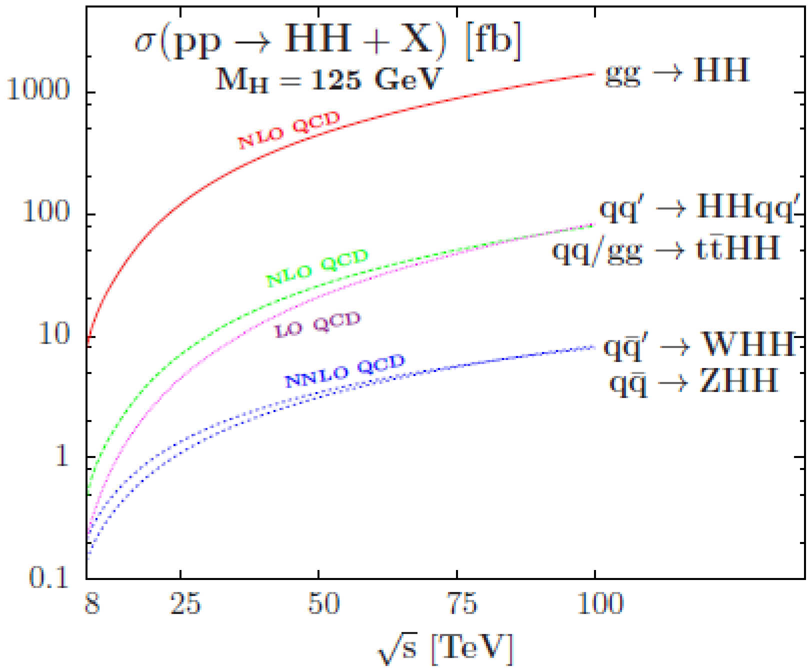
Higgs Pair Production at LHC

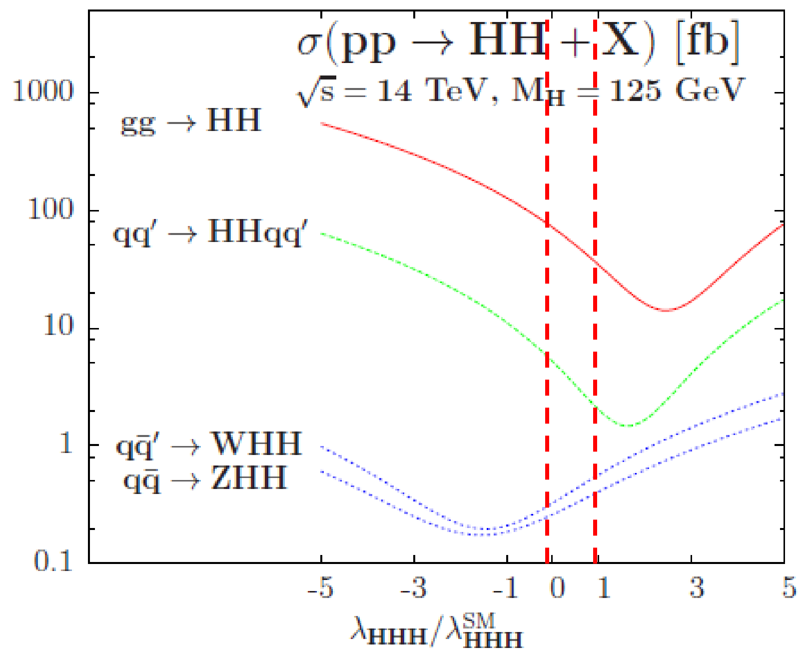
$\sigma(pp \to HH + X) \approx 34$ fb @ 14 TeV



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

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 at LHC

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

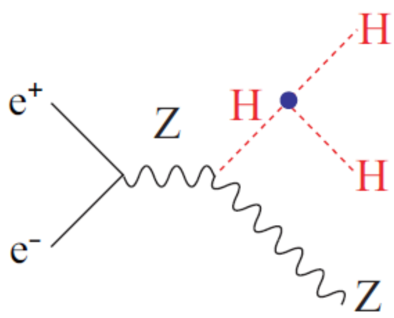
Several studies by theorists, some very preliminary studies by ATLAS.

$\sigma(pp \to HH)$@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

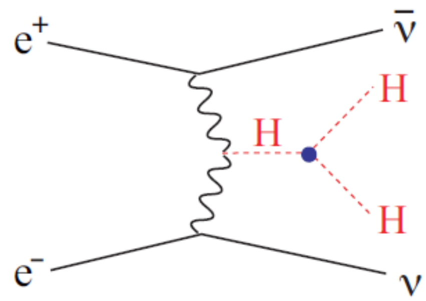
$HH \to bb\gamma\gamma$ is likely the most sensitive channel with major backgrounds from $t\bar{t}H \to bb\gamma\gamma + X$ and $ZH \to bb\gamma\gamma$, a signal-background ratio better than 1:3 can be achieved. $HH \to bb\tau\tau$ should help too. Will likely need to combine many final states to maximize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

e^+e^- Colliders – Self-coupling



$$\frac{\Delta\lambda}{\lambda} \approx 1.8 \frac{\Delta\sigma}{\sigma}$$

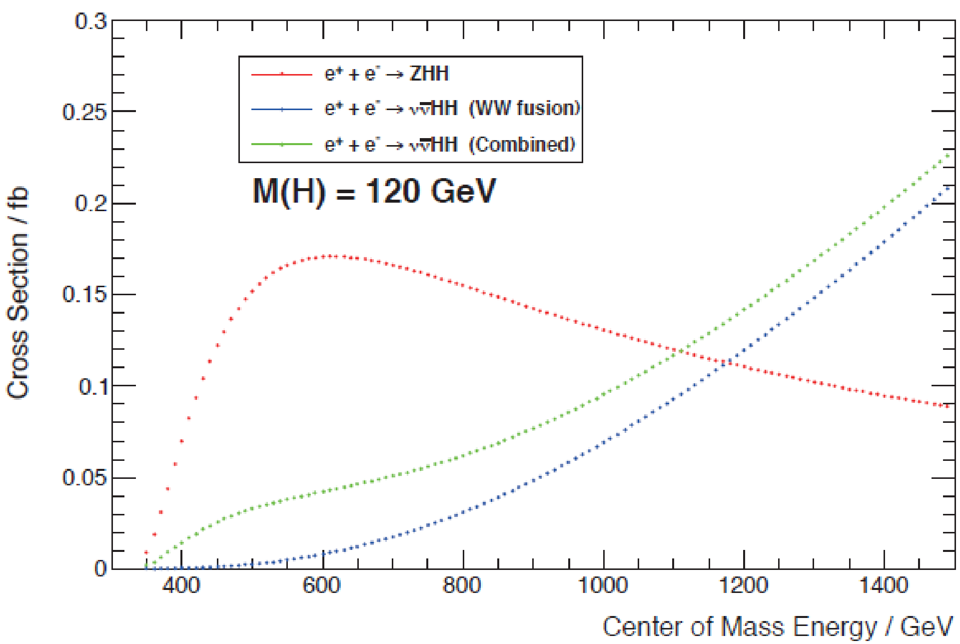


$$\frac{\Delta\lambda}{\lambda} \approx 0.85 \frac{\Delta\sigma}{\sigma}$$

$$\sqrt{s} \geq\sim 500 \text{ GeV}$$

$$(\text{ILC} + \text{CLIC})$$

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



Low rates:

- ~400 events total at ILC
- ~1000 events at CLIC

and there is a significant contamination from continuum HH production

$$\Rightarrow \frac{\Delta\lambda}{\lambda} \sim 21\% \text{ (ILC)}, 16\% \text{ (CLIC)}$$

Higgs Self-coupling Precisions

pp colliders

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

e^+e^- colliders

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

Facility Summary

LHC at 14 TeV with 300 fb^{-1} of data is essential to firmly establish the five major production mechanisms of a Higgs boson (ggH, VBF, WH, ZH, $t\bar{t}H$) and the main bosonic and fermionic decay modes $\left(\gamma\gamma, ZZ^{*}, WW^{*}, \tau\tau, b\bar{b}\right)$. This will lead to about a factor of $3-5$ improvements in the most precise measurements compared to the 8 TeV run of LHC. It will also lead to about 100 MeV precision on the Higgs boson mass and the measurement of the boson spin.

HL-LHC provides unique capabilities to measure rare statistically limited SM decay modes such as $\mu\mu$ and Zγ and make the first measurement of the Higgs self-coupling. The high luminosity program increases the precision on the couplings compared to the LHC with 300 fb^{-1} by roughly a factor of $2-3$ and has a high discovery potential for heavy Higgs bosons.

TeV-scale *ee* linear colliders (ILC and CLIC) offer the full menu of measurements of the 126 GeV Higgs Higgs boson with better precision than the LHC, though their mass reach for heavy Higgs bosons are generally weaker than the high-energy *pp* colliders, except for CLIC running at 3 TeV. The two linear colliders have different capabilities $-$ the ILC can run on the Z peak while CLIC has a higher mass reach and better precision in Higgs self-coupling measurement when operating at 3 TeV.

Facility Summary

TLEP offers the best precisions for most of the Higgs coupling measurements because of its projected integrated luminosity and multiple detectors. This program also includes high luminosity operation at the Z peak and top threshold. There is no sensitivity to *ttH* and Higgs self-coupling at these center-of-mass energies.

A higher energy *pp* collider such as a 33 TeV (HE-LHC) or 100 TeV (VLHC) hadron collider provides high sensitivity to the Higgs self-coupling as well as the highest discovery potential for heavy Higgs bosons.

A TeV-scale muon collider should have similiar physics capabilities as the ILC and CLIC with potentially higher energy reach, but this needs to be demonstrated with more complete studies. The muon collider also has the potential for resonant production of heavy Higgs bosons. CP measurements are possible if a beam polarization option is included.

A $\gamma\gamma$ collider is able to study CP mixture and violation in the Higgs sector with polarized photon beams. It can improve the precision of the effective $\gamma\gamma H$ coupling measurement through s-channel production.

There is a physics case
for a Higgs factory (facility?),

the question is when, how and where.

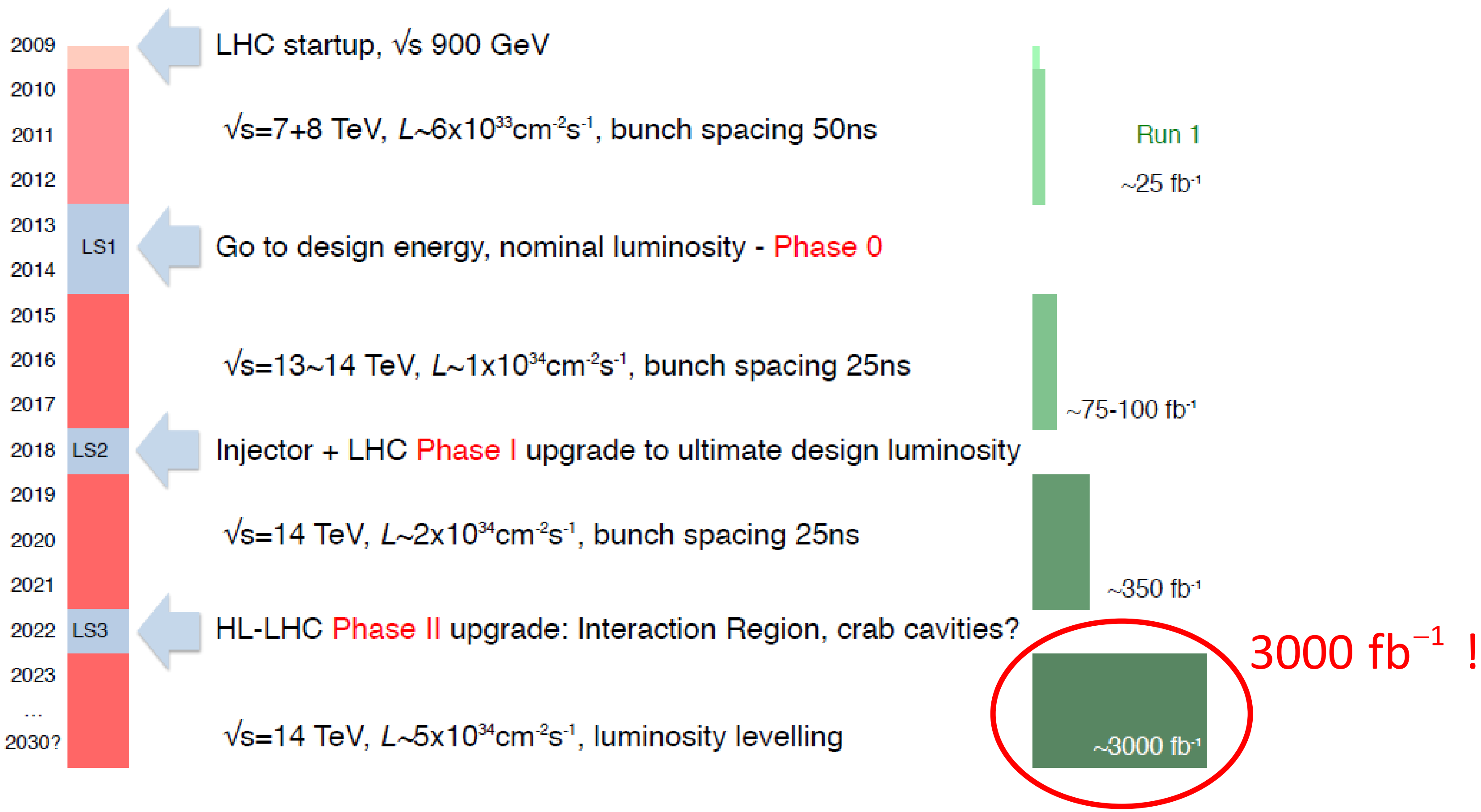
For details, see the draft report of the Snowmass Higgs working group:
http://www.snowmass2013.org/tiki-index.php?page=The+Higgs+Boson

Additional Slides

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."



Higgs Event Rates

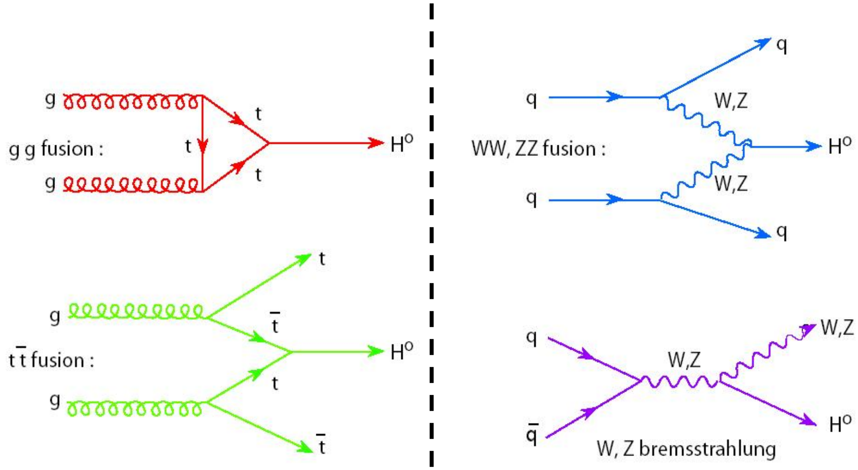
$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

	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}			
$H \to \gamma\gamma$	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.

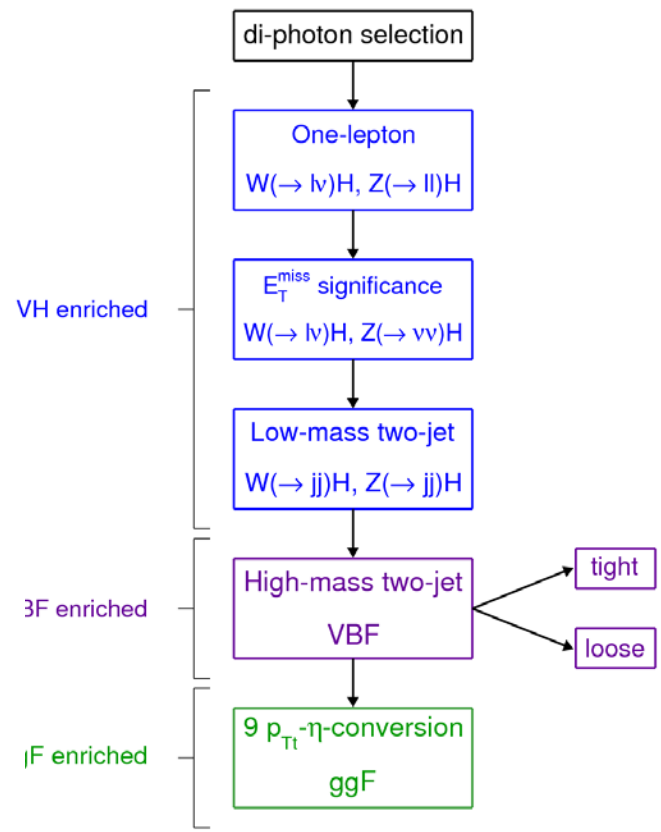
Production Processes

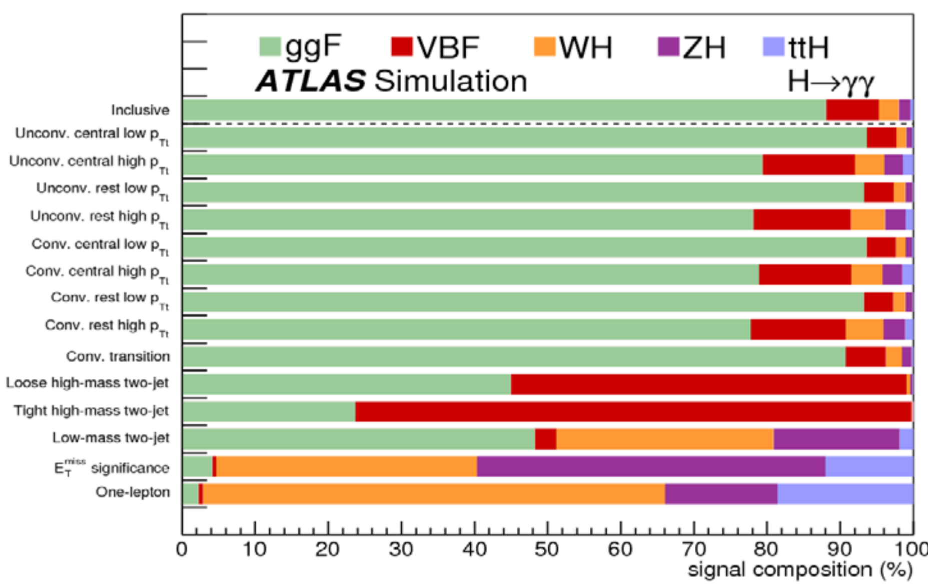


Htt coupling

HVV coupling

Production inspired categorization





VBF enriched

VH enriched

H→μμ Decay

Small $BR(H \to \mu\mu) = 2.2\times10^{-4}$ @ 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%

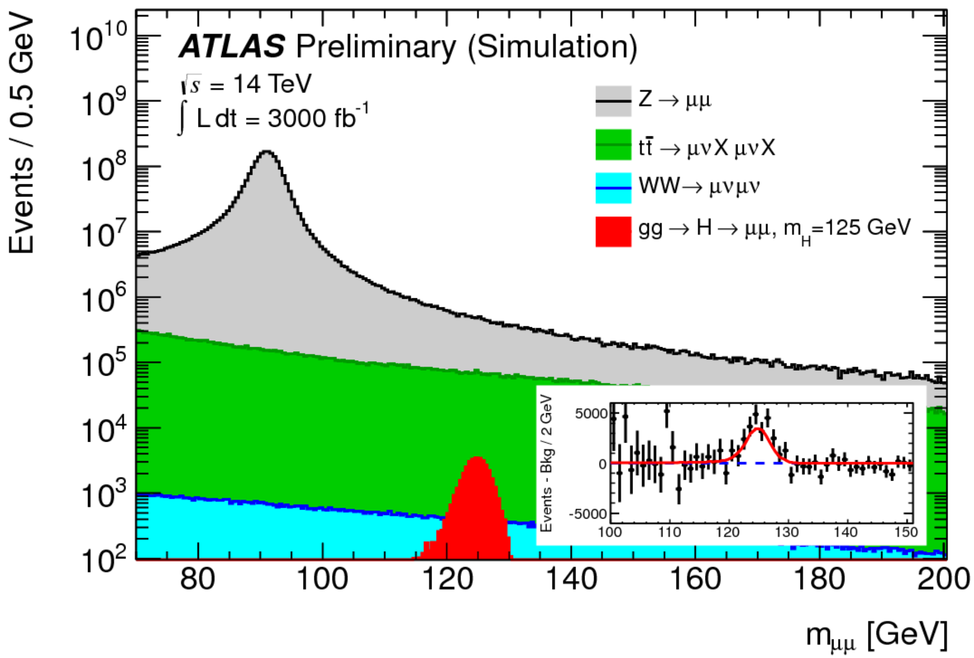
$|m_{\mu\mu} - m_H| \leq 5$ GeV

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

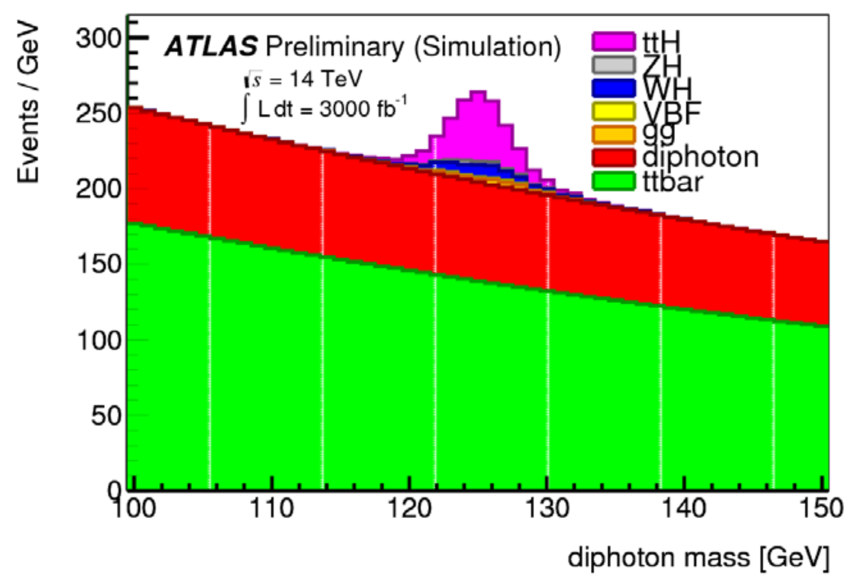
S/B ~ 1:4

Two analysis categories:

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

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)

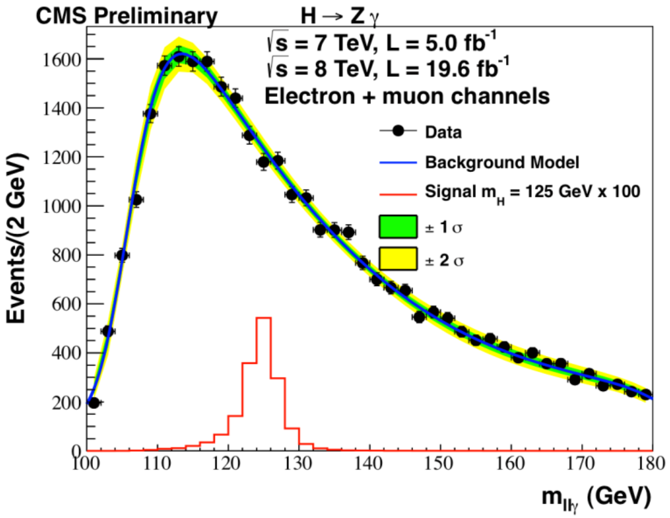


Other Rare Decays

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

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:

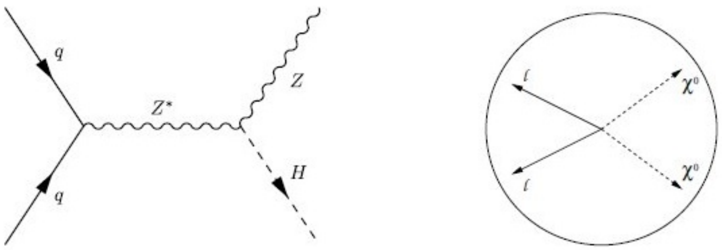
$$BR(H \rightarrow J/\psi\,\gamma) = 2.5\times10^{-6} \text{ and } BR(J/\psi \rightarrow \ell\ell) = 5.9\%$$

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

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

Invisible Decay

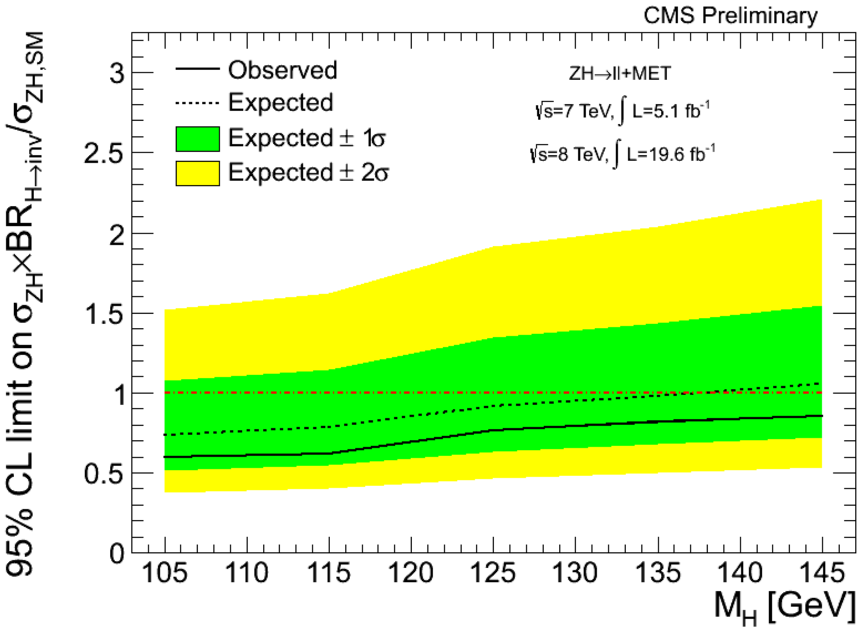
One non-SM Higgs decay that has garnered interests is the decay to "invisible". VBF and ZH productions are expected to have the best sensitivity.



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.

HL-LHC sensitivity

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

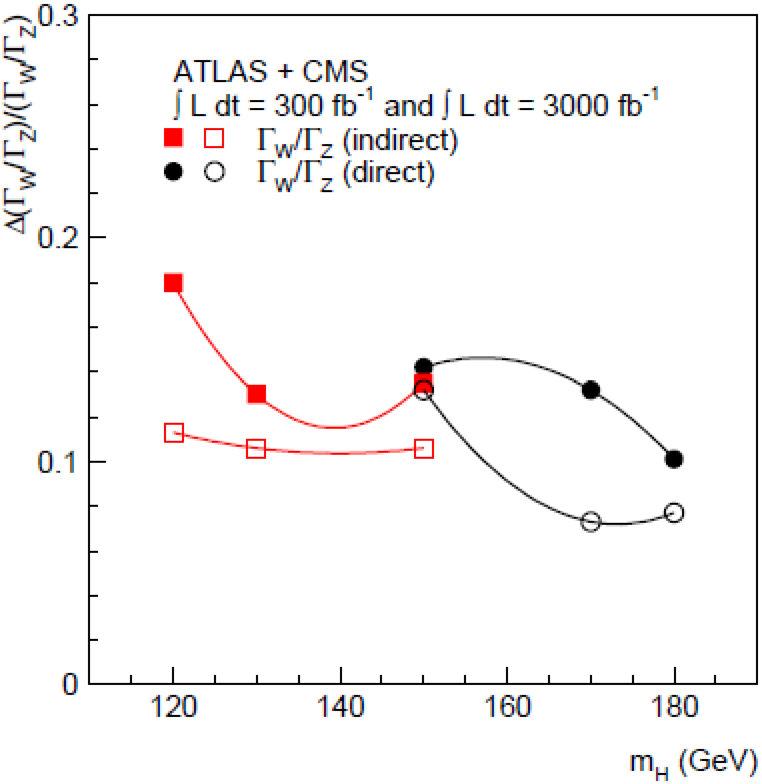
A word of optimism...

Projections/predictions are often subject to pleasant surprises as we learn and do better than expected.

A case in point:

$H \to WW^* \to \ell\nu\ell\nu$ was thought not possible 10 years ago at low mass...

Gianotti et al., hep-ph/0204087



"At smaller masses the process $H \to WW^* \to \ell\nu\ell\nu$ has too low a rate but one can use the measured rate of $H \to \gamma\gamma$ to extract Γ_W"

Not only the $H \to WW^* \to \ell\nu\ell\nu$ has been directly observed, the projected precision on Γ_W/Γ_Z is far better.

We have done far better than predicted...