Higgs Physics
- current status and future prospects

Higgs physics at the LHC
Higgs physics at the CEPC

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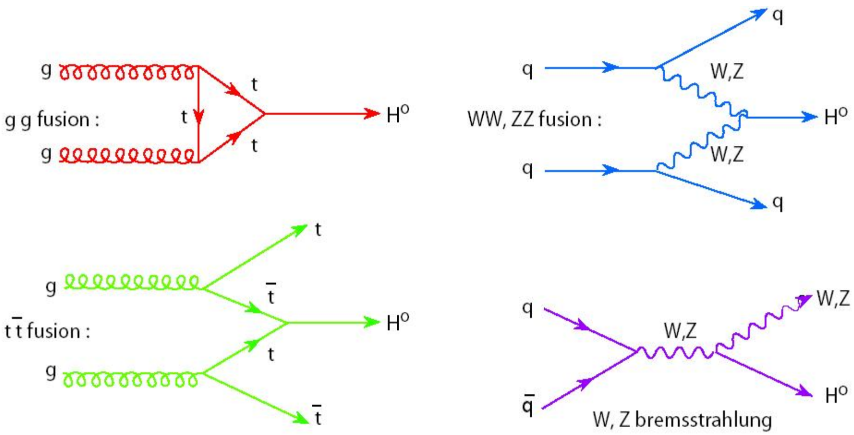
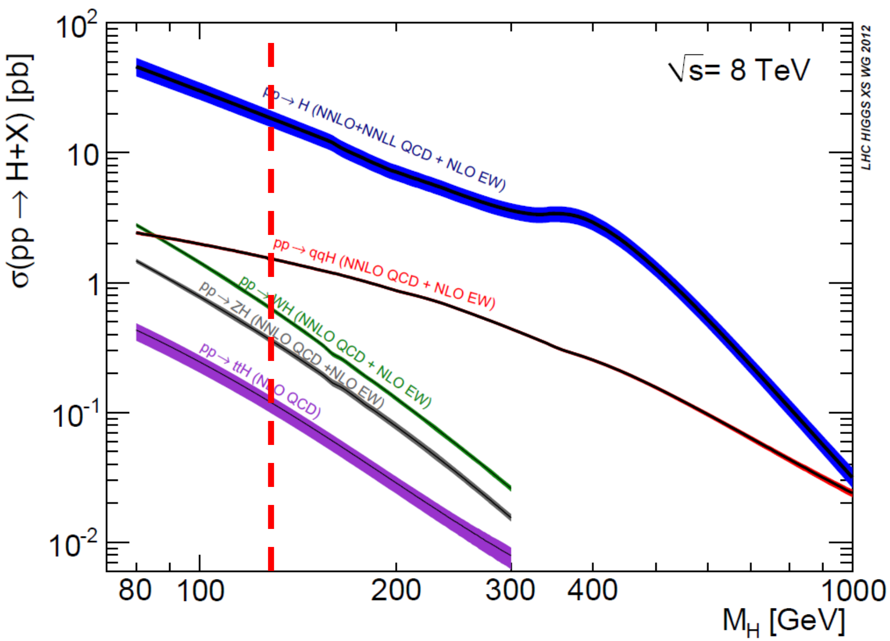
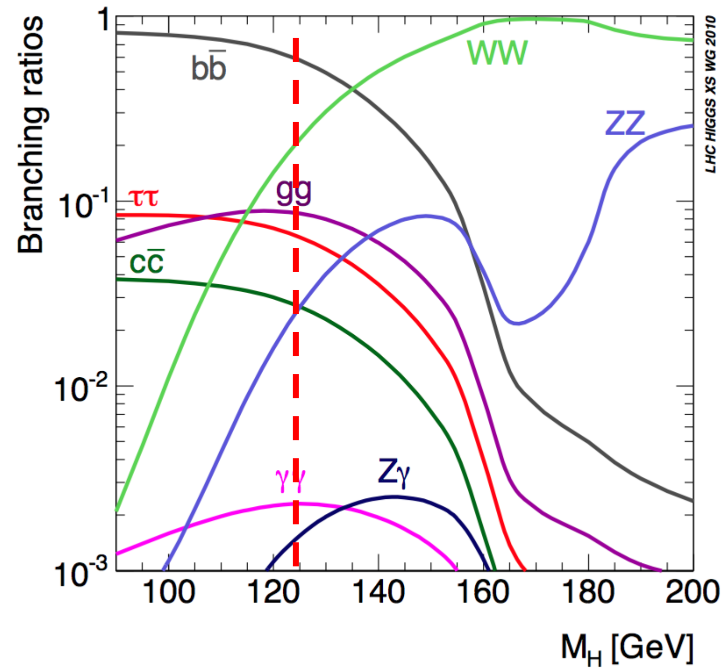
ACFI workshop, Amherst, September 17-19, 2015

Higgs Productions and Decays



$m_H = 125$ GeV	$\sigma_H = 22.3$ pb
Branching ratio	
$H \to b\bar{b}$	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%

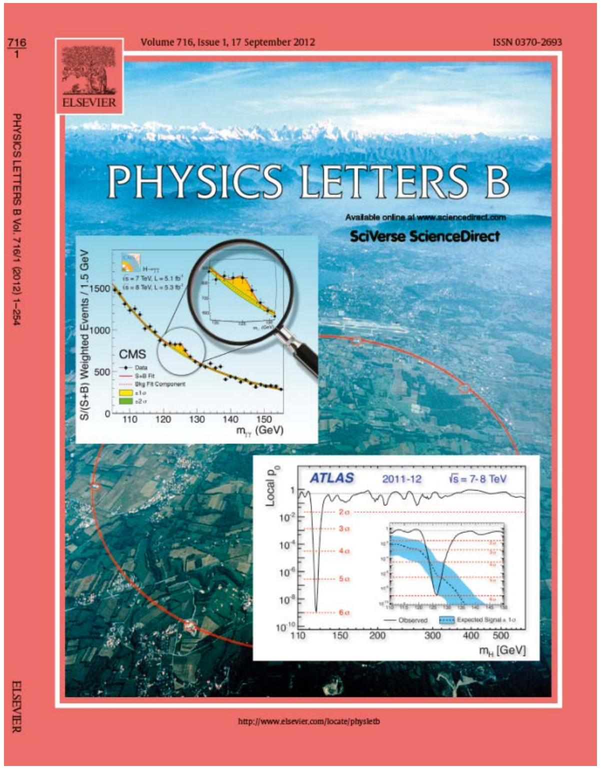




Over 1,000,000 Higgs bosons produced at LHC so far ⇒ Higgs factory !

Status at a Glance

A long way since the discovery. 88% of the Higgs boson decays have been studied…



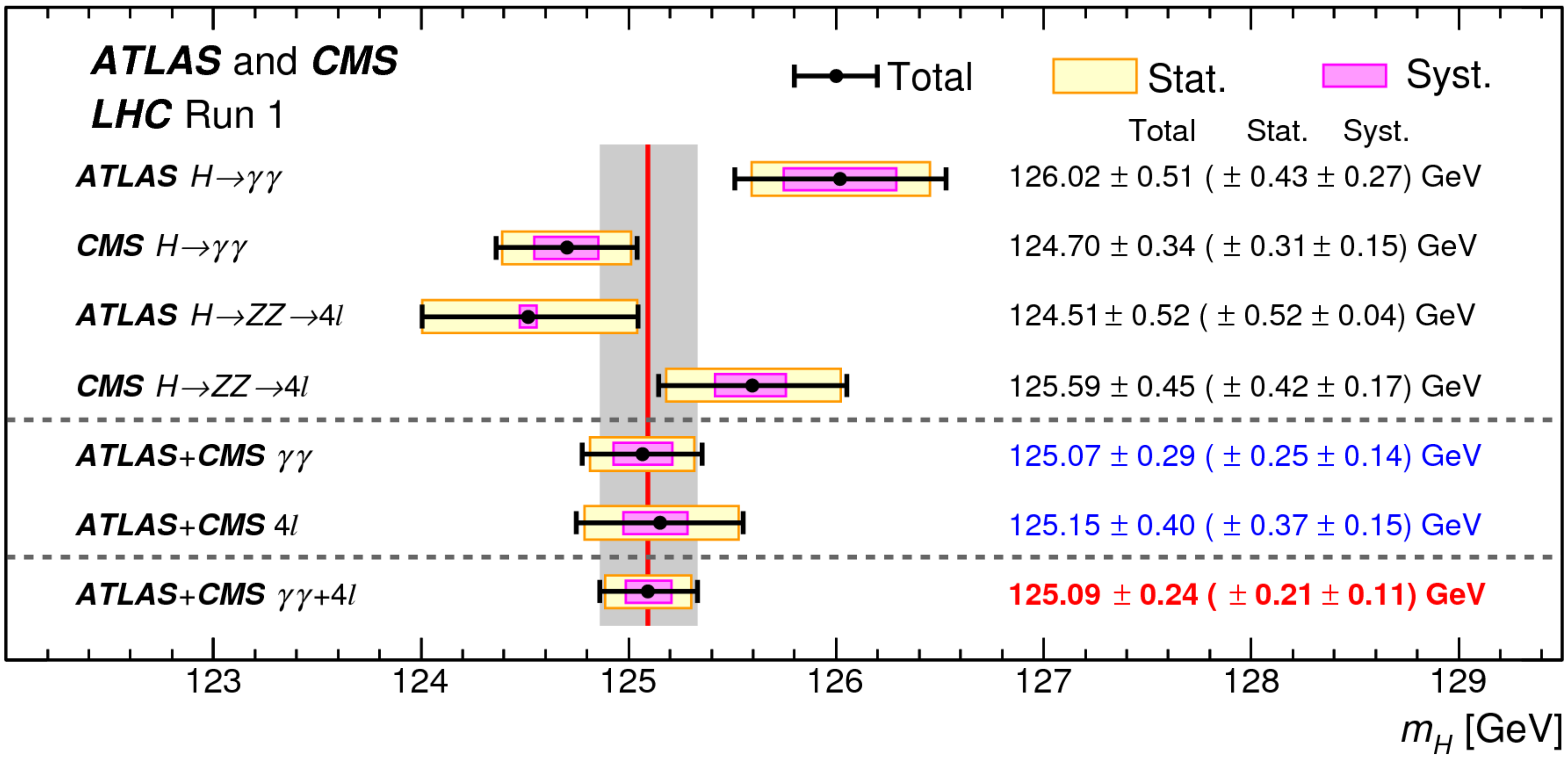
Observed (expected) significance

Decay Mode	$h \to \gamma\gamma$	$h \to ZZ^*$	$h \to WW^*$	$h \to \tau\tau$	$h \to bb$
ATLAS	5.0 (4.6)	6.6 (5.5)	6.8 (5.8)	4.4 (3.3)	1.7 (2.7)
CMS	5.7 (5.1)	7.0 (6.8)	4.8 (5.6)	3.4 (3.7)	2.0 (2.5)

Discovery-level significances in three bosonic decay modes;
Weakest signal in $H \to bb$, the decay mode with the largest BR !

ATLAS and CMS Combination

Combining measurements in H $\rightarrow \gamma\gamma$ and H $\rightarrow$ ZZ* $\rightarrow 4\ell$ taking into account correlations of uncertainties

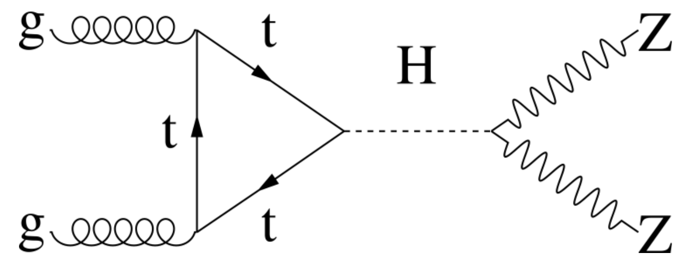


$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) = 125.09 \pm 0.24 \text{ GeV}$$

arXiv:1503.07589

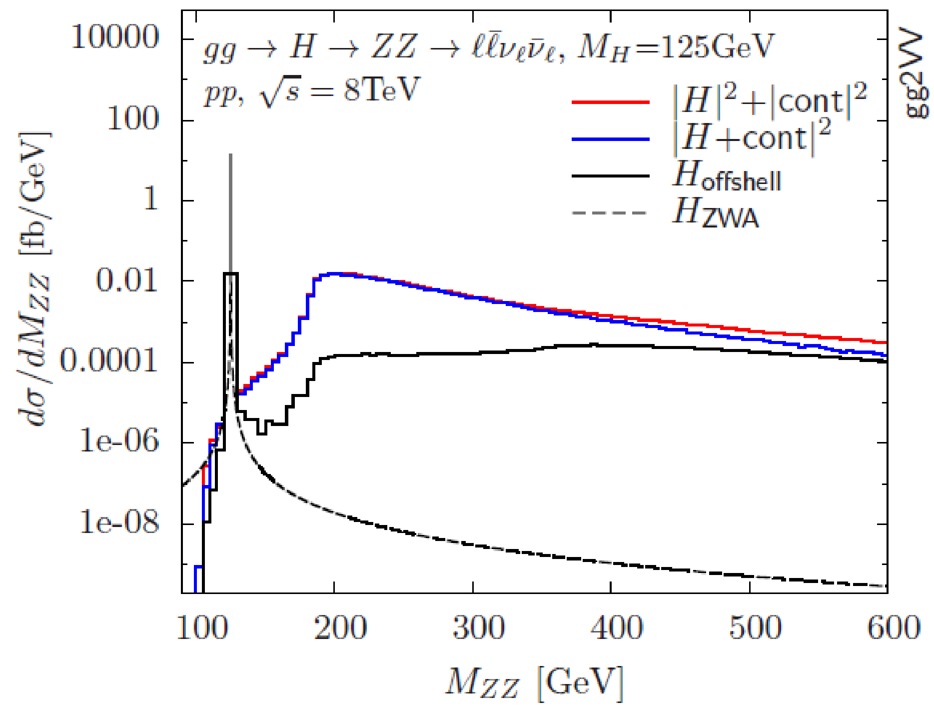
Indirect Width Measurement

Process $i \to H \to f$: $\dfrac{d\sigma}{dm^2} \sim \dfrac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$

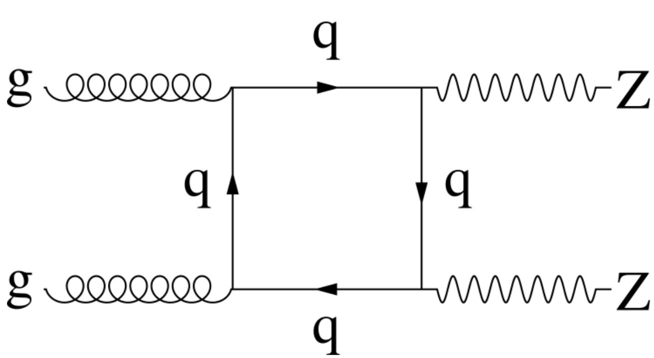


On-peak: $\dfrac{d\sigma}{dm^2} \sim \dfrac{\boxed{g_i^2 g_f^2}}{m_H^2 \boxed{\Gamma_H^2}}$

Off-peak: $\dfrac{d\sigma}{dm^2} \sim \dfrac{\boxed{g_i^2 g_f^2}}{\left(m^2 - m_H^2\right)^2}$



Extract Γ_H by comparing the on-shell and off-shell measurements, but complicated by backgrounds:

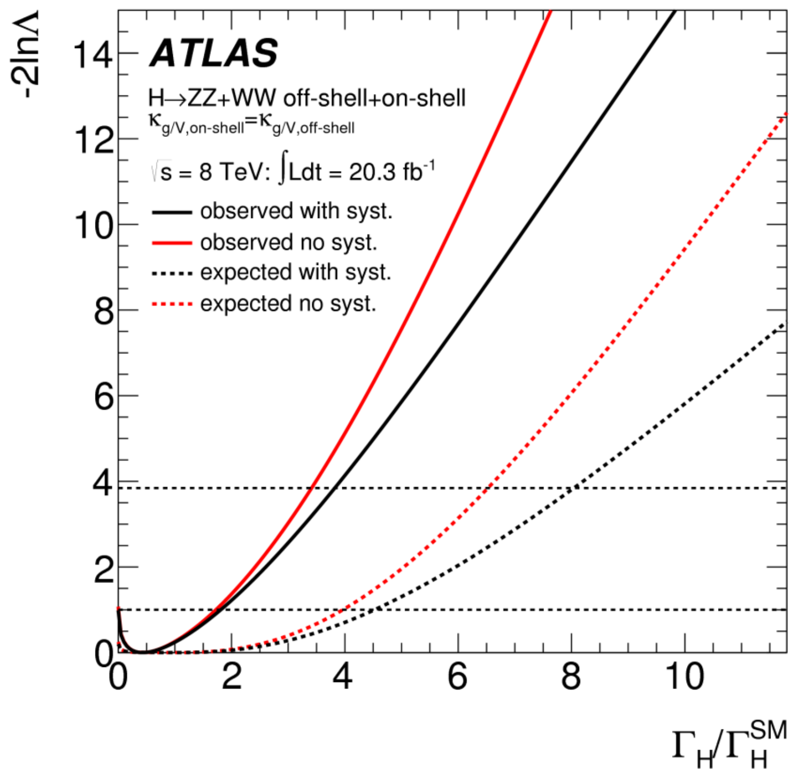


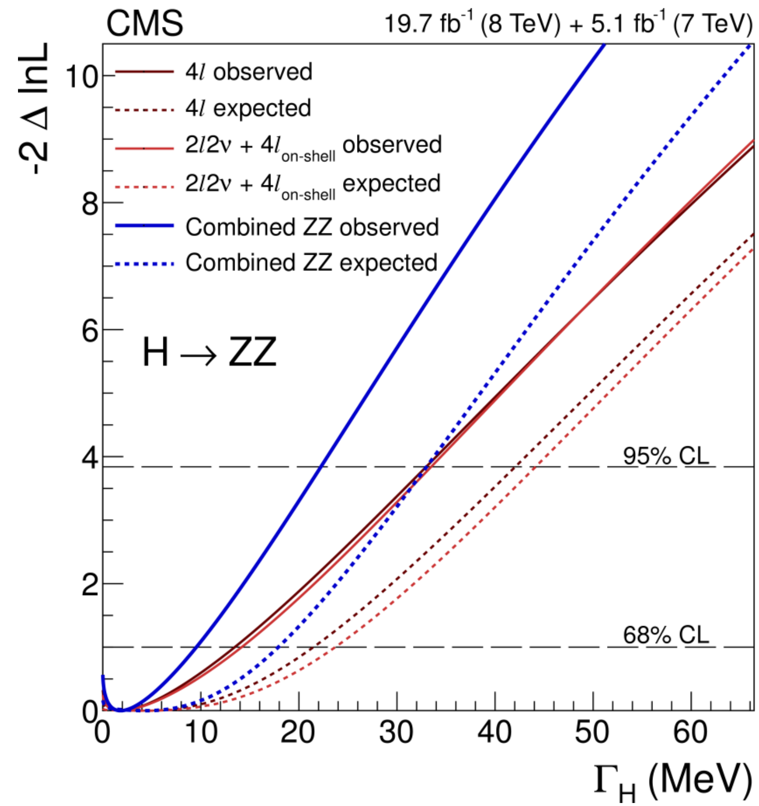
Kauer & Passarino, arXiv:1206.4803
Caola & Melnikov, arXiv:1307.4935
Campbell & Ellis, arXiv:1311.3589

Indirect Width Measurements

The key issue is to extract the $gg \to H^* \to VV$ signal from the $gg \to VV$ background. Assumptions are made about the $gg \to VV$ cross section.

arXiv:1503.01060 (ATLAS)





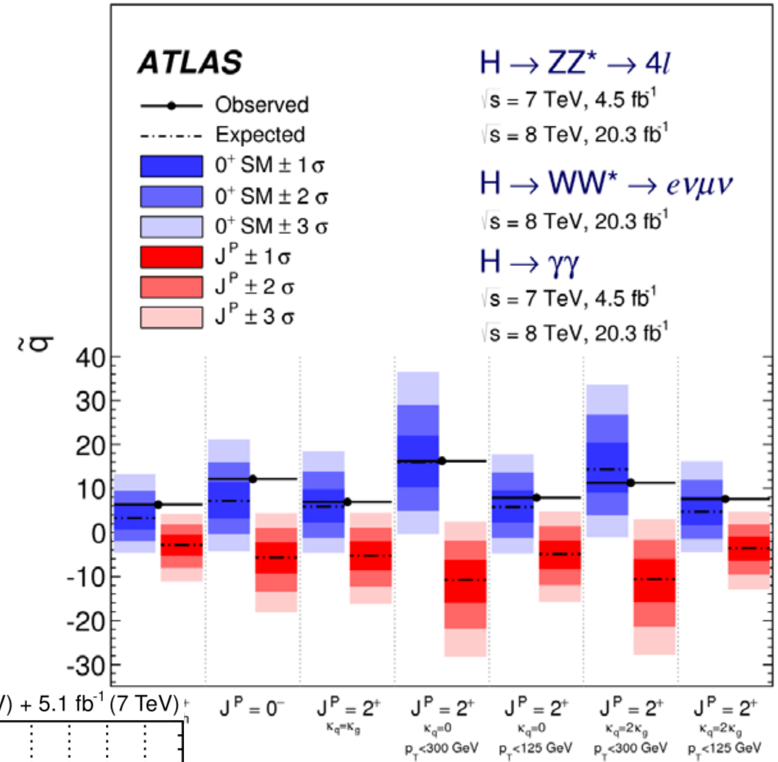
arXiv:1405.3455 (CMS)

Assuming $K(gg \to VV) = K(gg \to H^* \to VV)$, the observed (expected) 95% CL limits:

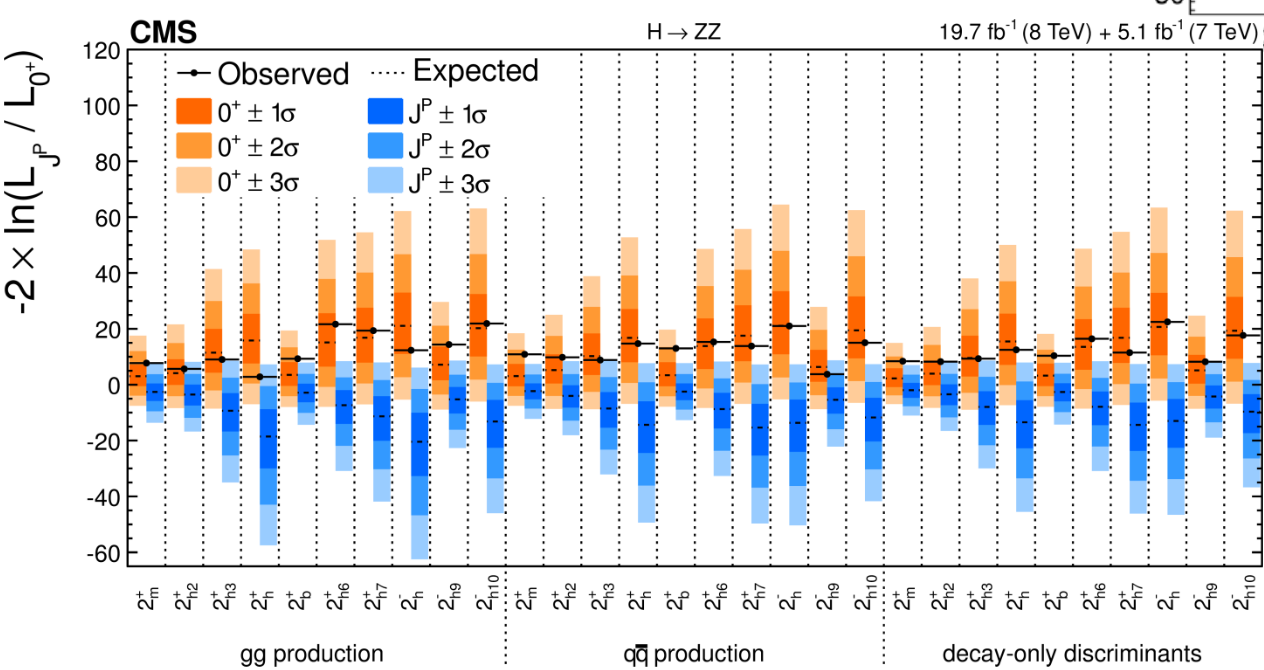
$$\Gamma_H < 22.7\ (33.0)\ \text{MeV [ATLAS]}; \quad \Gamma_H < 22\ (28.0)\ \text{MeV [CMS]}$$

Spin/CP Tests

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



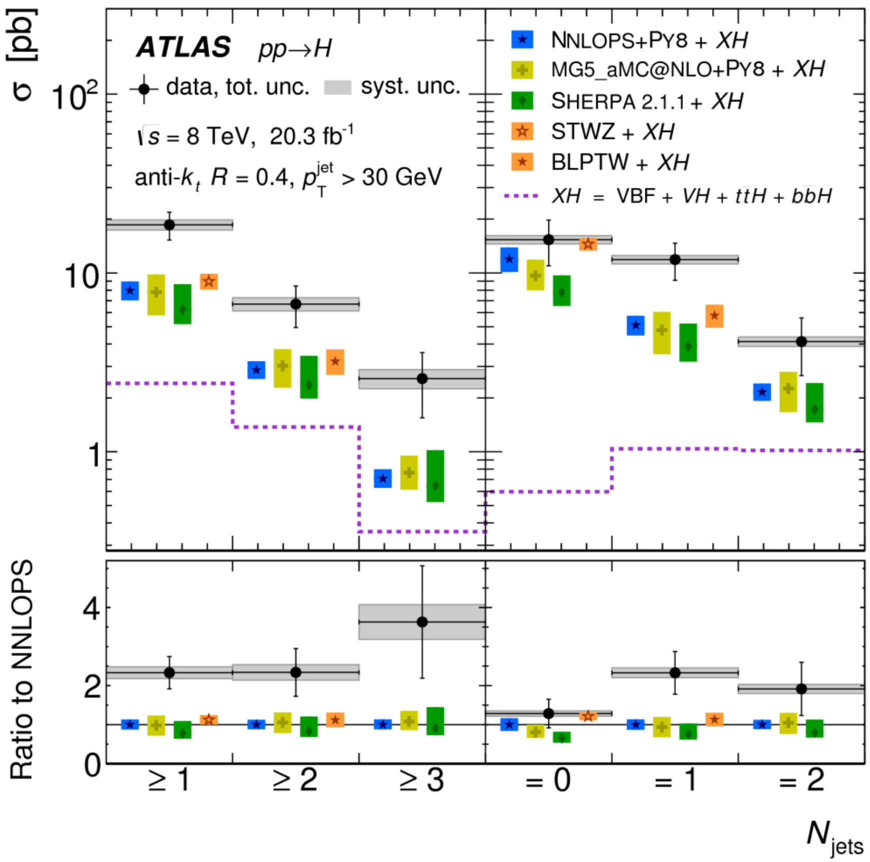
arXiv:1411.3441 (CMS)

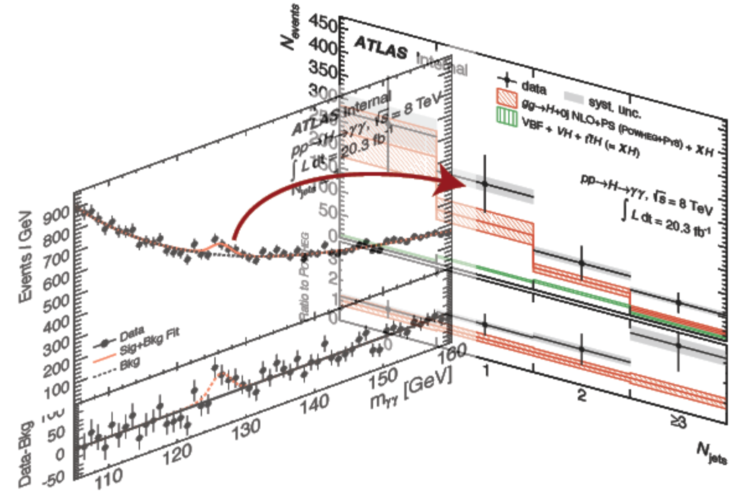


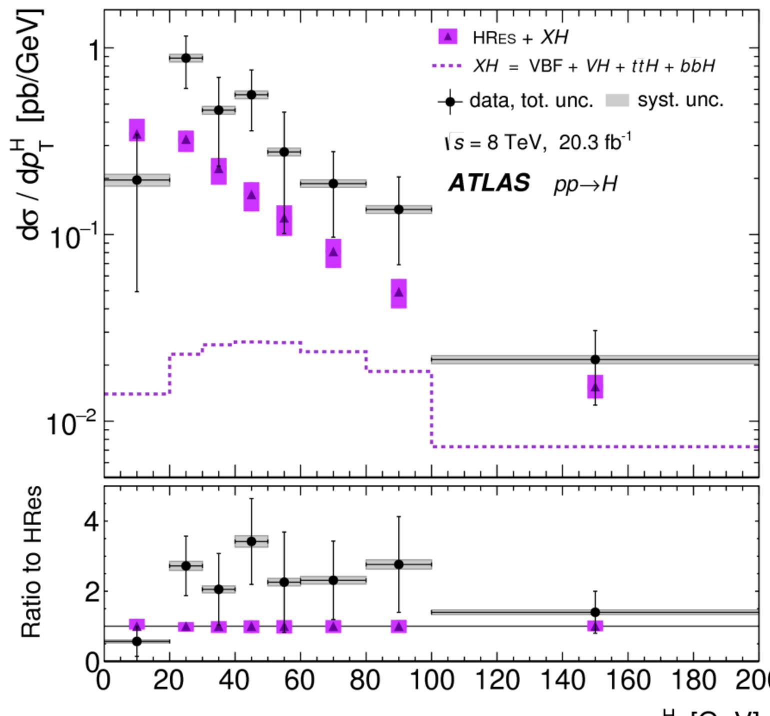
SM prediction of $J^p=0^+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher

Differential Distributions

Going beyond inclusive distributions, study kinematics of candidate events.



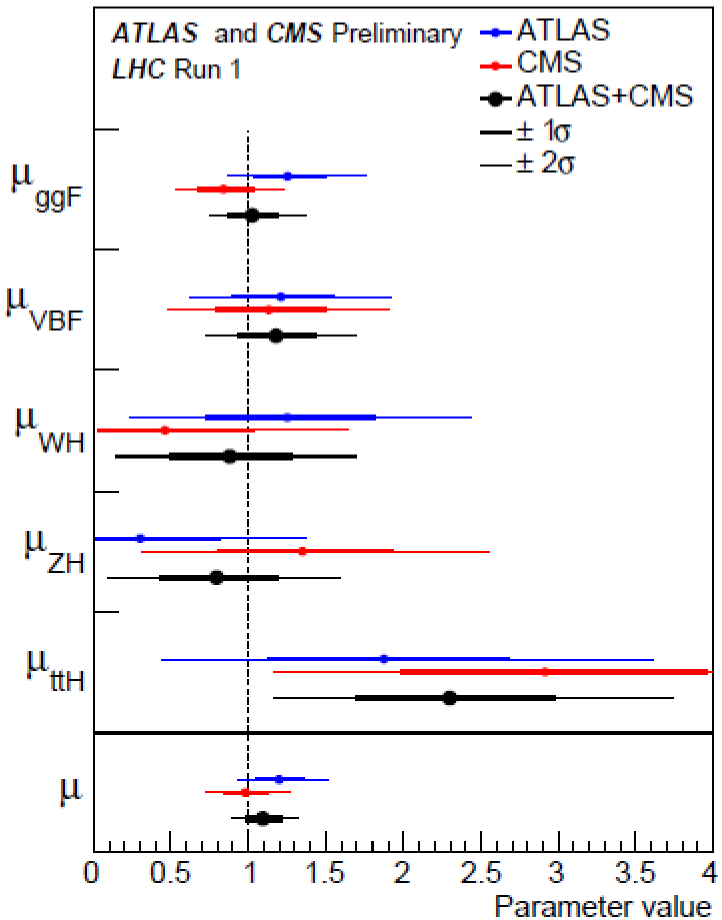


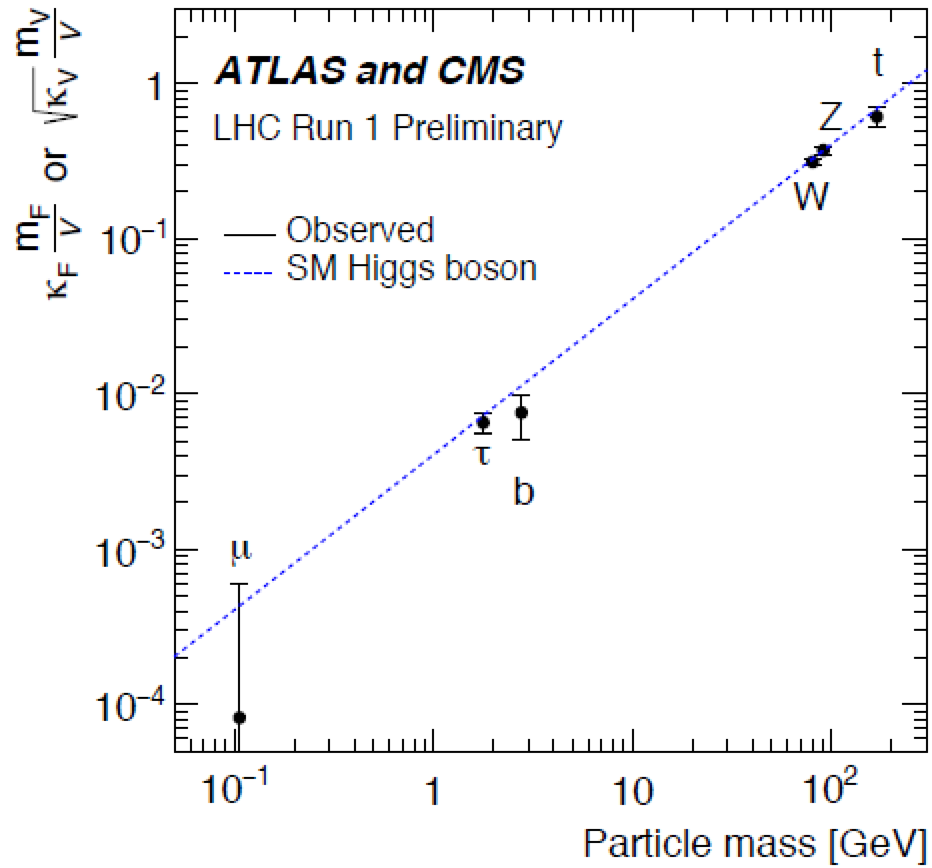


arXiv:1504.05833 (ATLAS)

Reasonable agreements between data and the SM expectations, need to watch out a few distributions with more statistics….

Signal Strengths and Couplings





With the current precision, the production rates agree with the SM prediction and the Higgs boson couples to fermions and vector bosons as expected.

Constraints on the Heavy Higgs Boson

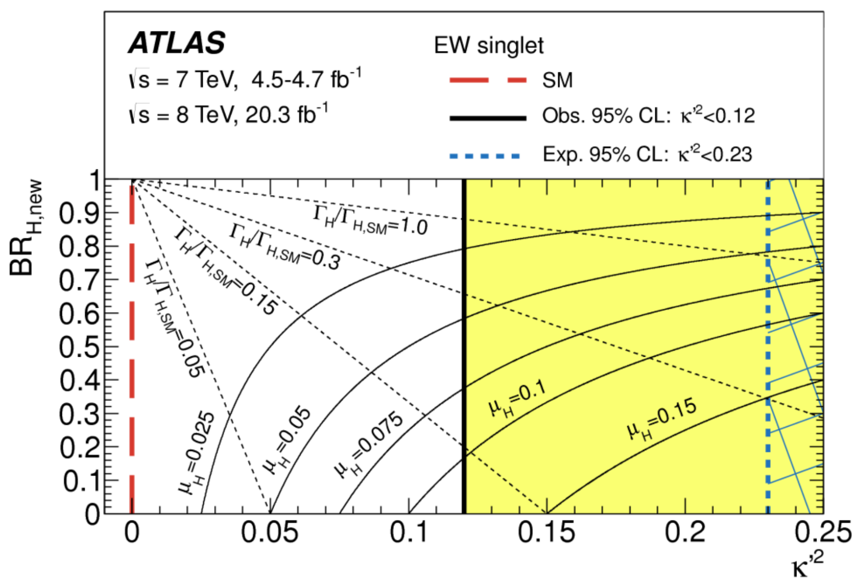
The mixing of H_{SM} and S leads to the modifications $\left(\kappa^2 = \cos^2\theta \text{ and } \kappa'^2 = \sin^2\theta\right)$

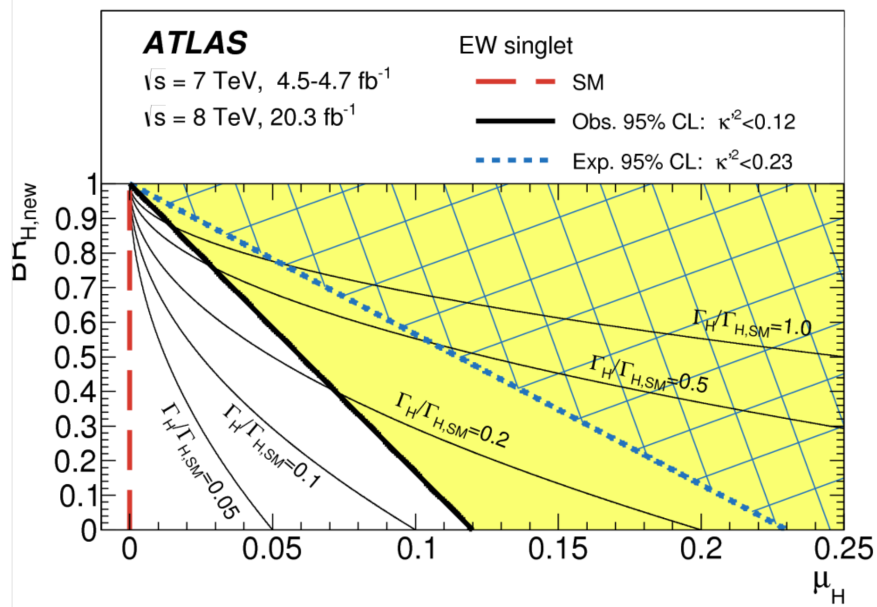
$$\sigma_h = \kappa^2 \times \sigma_h^{SM}, \qquad \Gamma_h = \kappa^2 \times \Gamma_h^{SM}, \qquad \mathrm{BR}_h = BR_h^{SM},$$

$$\sigma_H = \kappa'^2 \times \sigma_H^{SM}, \qquad \Gamma_H = \frac{\kappa'^2}{1 - BR_{new}} \times \Gamma_H^{SM}, \qquad \mathrm{BR}_H = \left(1 - BR_{new}\right) \times BR_H^{SM}$$

The measurement of the light Higgs boson can constrain the heavy Higgs boson:

$$\mu_h = \frac{(\sigma \times BR)_h}{(\sigma \times BR)_h^{SM}} = \kappa^2 \quad \Rightarrow \quad \mu_H = \frac{(\sigma \times BR)_H}{(\sigma \times BR)_H^{SM}} = \kappa'^2\left(1 - BR_{new}\right) = \left(1 - \mu_h\right)\left(1 - BR_{new}\right)$$





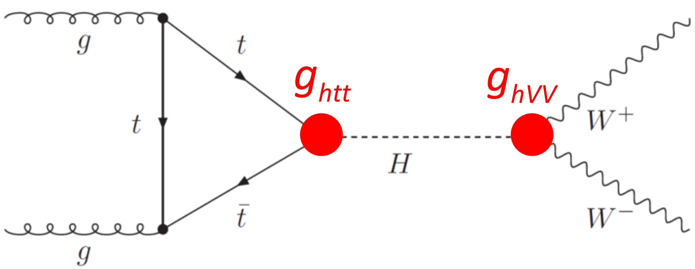
independent of the mass of the heavy Higgs boson m_H.

Constraints on 2HDM

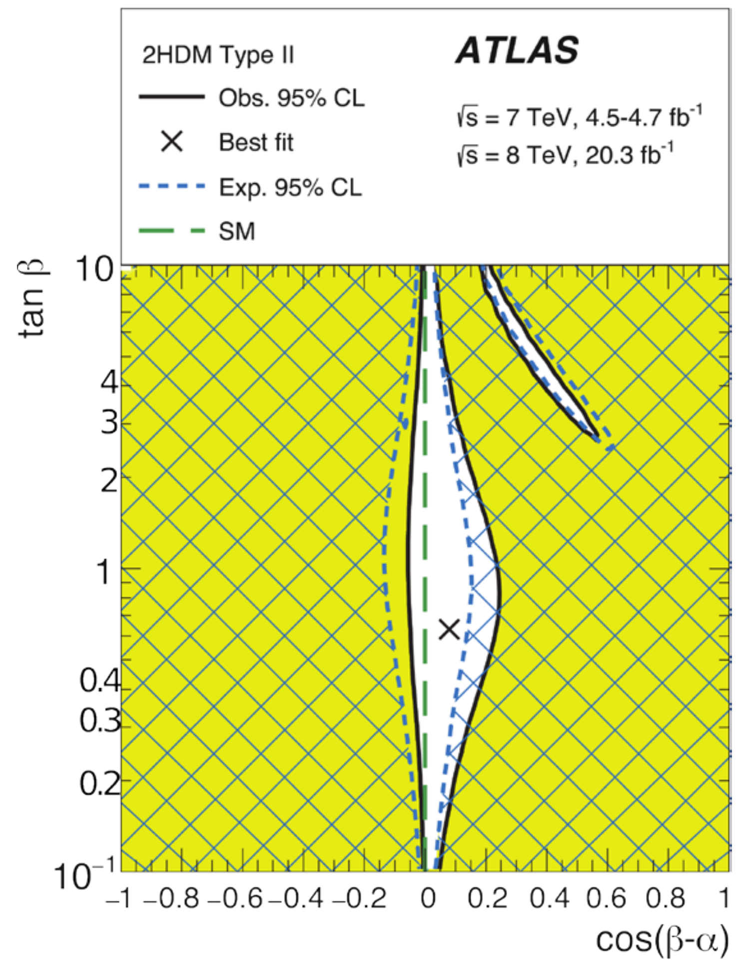
Assuming no change in Higgs decay kinematics and no new production process, the measured rates of $h(125)$ can be turned into constraints on the two 2HDM parameters: α and β

Parametrized using $\tan\beta$ and $\sin(\beta-\alpha)$

Vertex	Type II tree-level coupling factor
$h\,VV$	$\sin(\beta-\alpha)$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

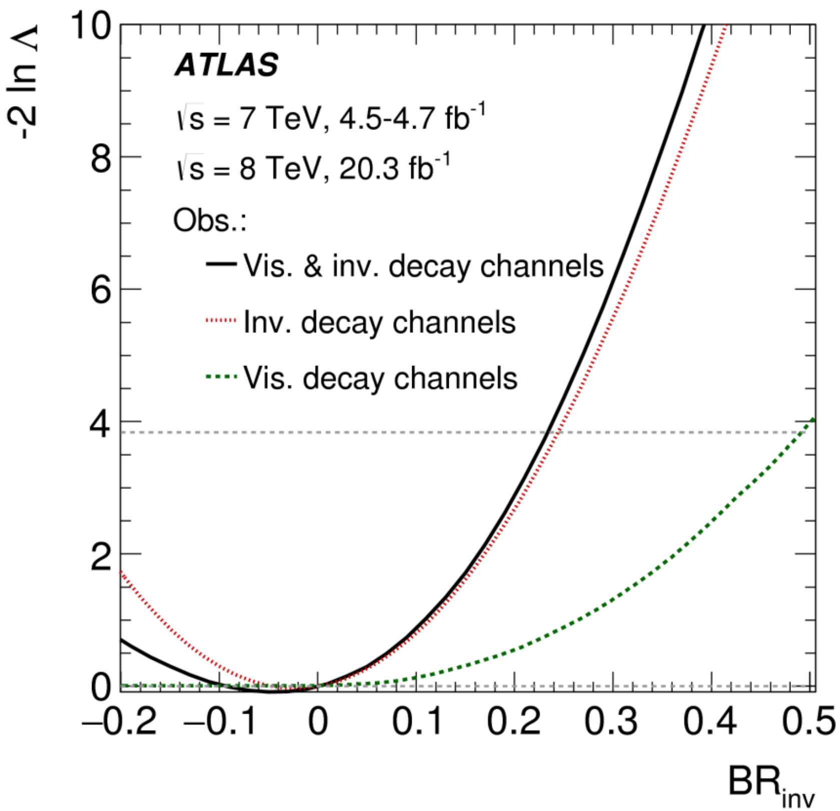


$$\frac{(\sigma\cdot BR)(gg\to h\to WW)}{\left[\sigma(gg\to h)\cdot BR(h\to WW)\right]_{SM}} \approx \left(\frac{g_{htt}}{g_{htt}^{SM}}\right)^2 \times \left(\frac{g_{hVV}}{g_{hVV}^{SM}}\right)^2$$



BR_{inv} from direct and indirect constraints

Assuming $\mathrm{BR}_{NEW} = BR_{inv}$, i.e., all new decays are invisible decays,
constraints from: - the rate measurements: $BR_{inv} < 0.49$ for $\kappa_V \leq 1$;
- the direct searches: $BR_{inv} < 0.25$



arXiv:1509.00672 (ATLAS)

Combining the direct searches with the indirect (rate measurements) in the most general model: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv} with

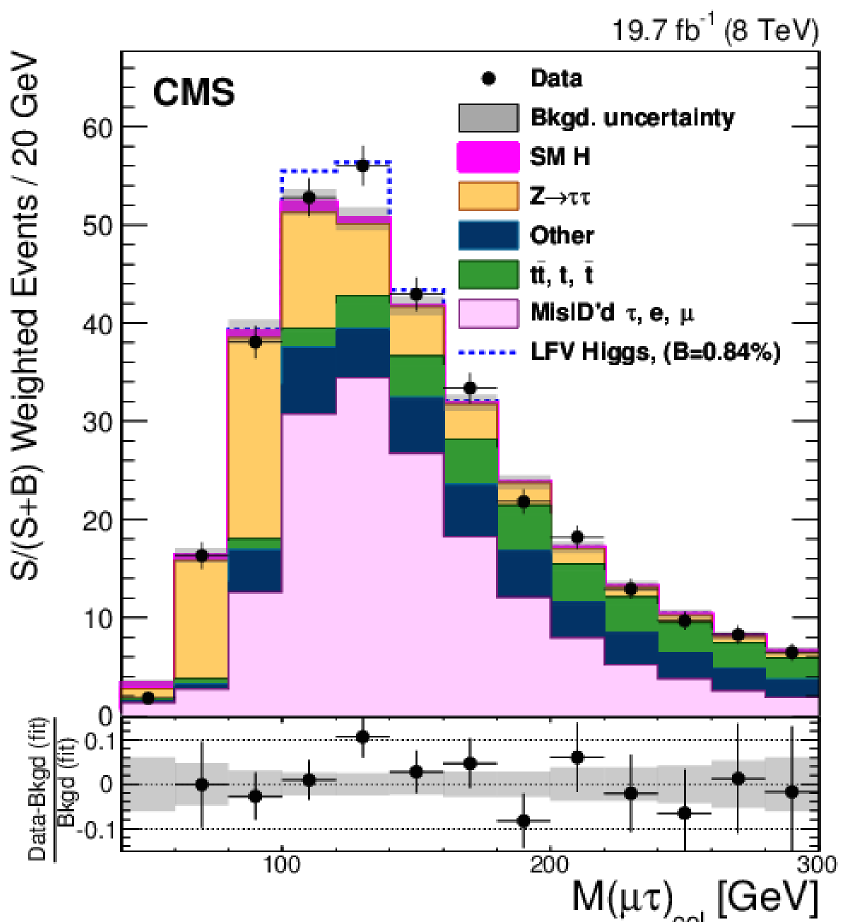
The total Higgs boson width

$$\Gamma_h = \frac{\kappa_h^2 \cdot \Gamma_h^{SM}}{1 - BR_{inv}}$$

$BR_{inv} < 23\% \; (24\%)$ at 95% CL

Searches for H→μτ Decay

CMS: τ decay final states considered: $\tau \to$ e, $\tau \to$ hadrons, categorization according to number of jets: 0, 1 and 2 jets



An excess with a significance of 2.4σ is observed, corresponding to $BR(H \to \mu\tau) = \left(0.84^{+0.39}_{-0.37}\right)\%$

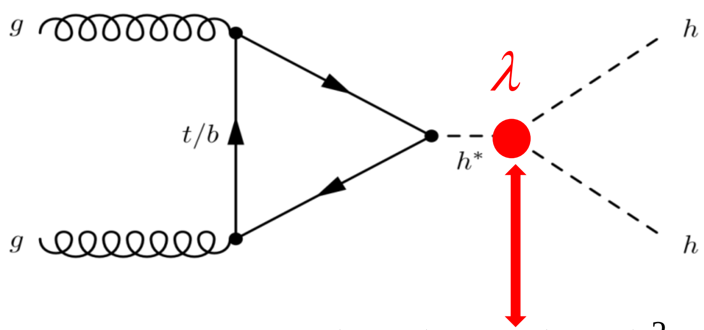
ATLAS result from H$\to \mu\tau \to \mu\tau_{\text{had}}$:
BR$(H \to \mu\tau) = (0.77 \pm 0.62)\%$.

Consistent with both null and the CMS result, more information is needed…

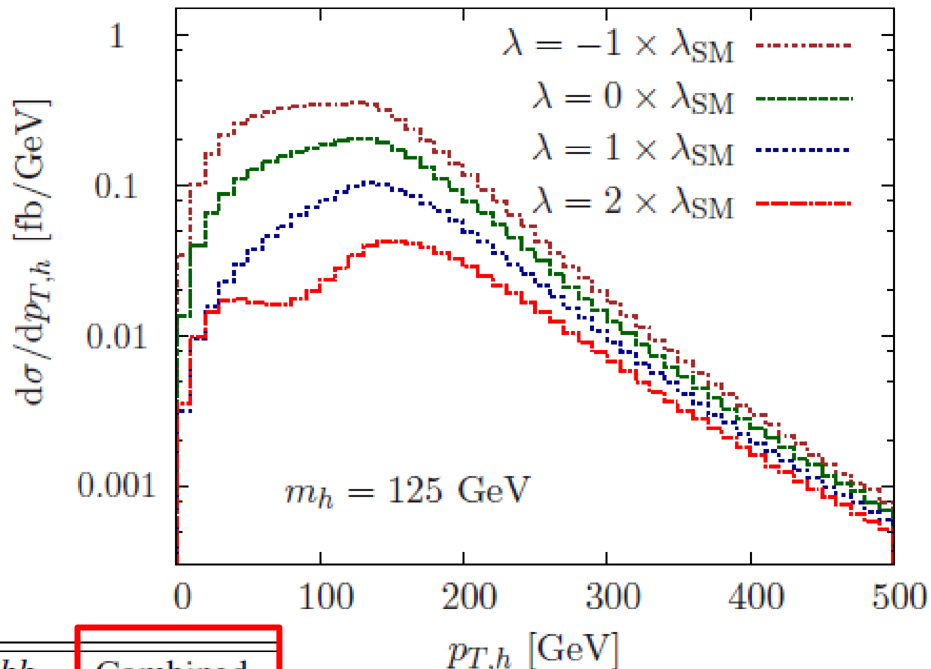
arXiv:1502.07400 (CMS)
arXiv:1508.03372 (ATLAS)

Higgs Boson Pair Production

Non-resonant production offers a direct probe of the Higgs boson self-coupling, but the rates are low and backgrounds are high



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



Dolan et al, arXiv: 1206.5001

$\sigma(gg \to hh) \approx 9.9$ pb in SM

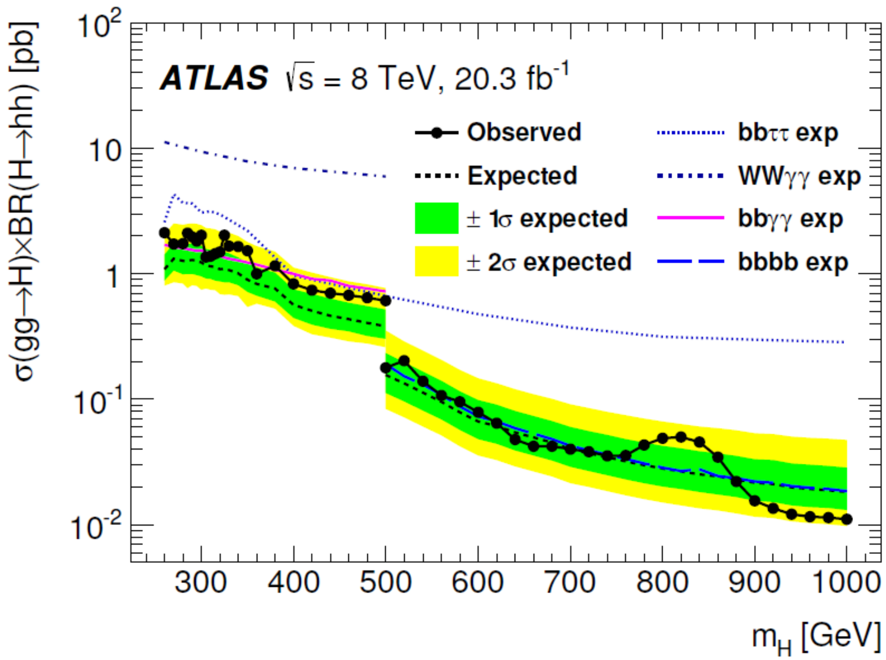
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

arXiv:1509.04670 (ATLAS)

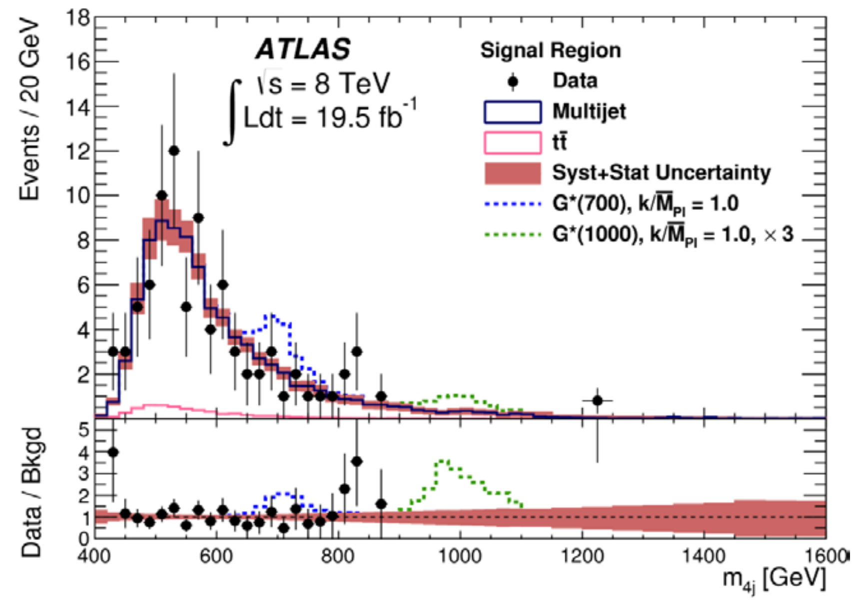
Higgs Boson Pair Production

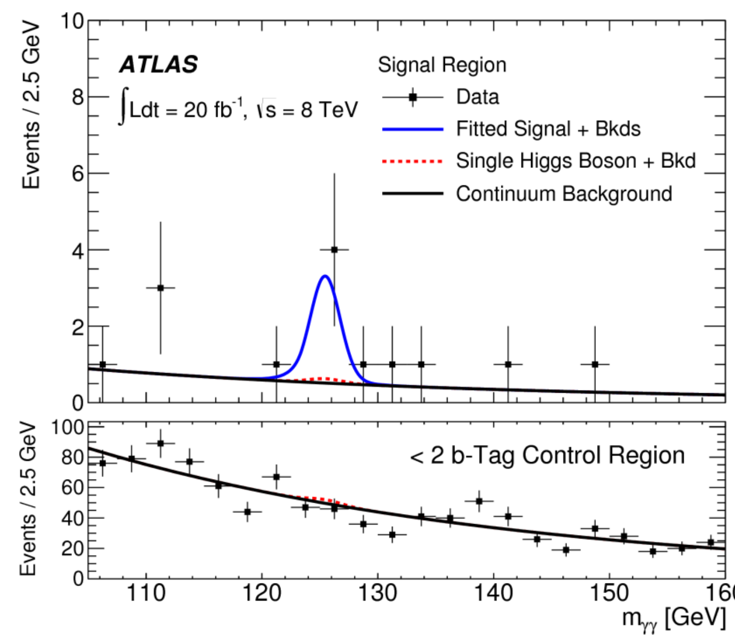
Resonant production: $H \rightarrow hh$

$bb\gamma\gamma$ and $bb\tau\tau$ have comparable sensitivities at low mass, bbbb dominates at high mass

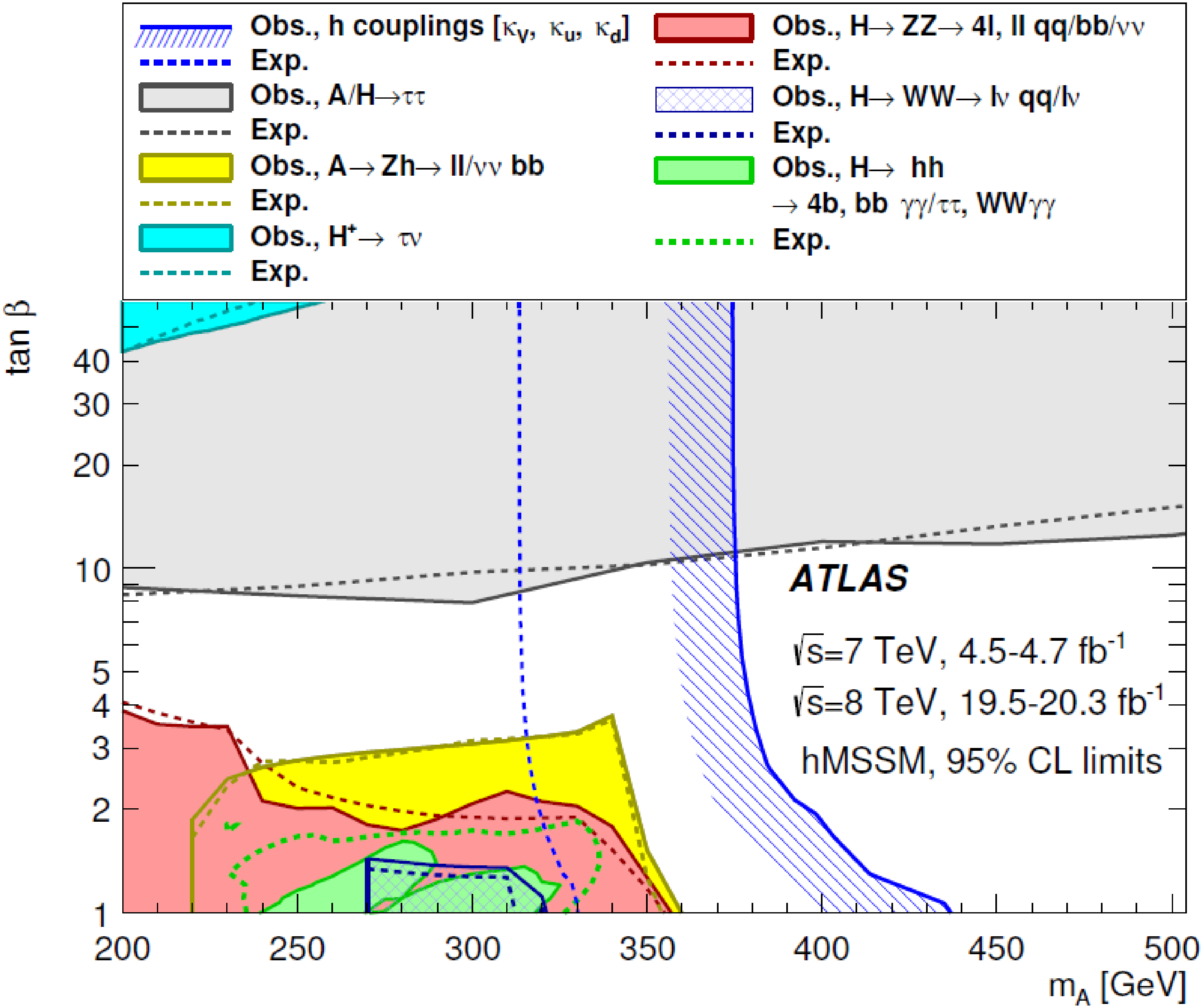


arXiv:1509.04670 (ATLAS)





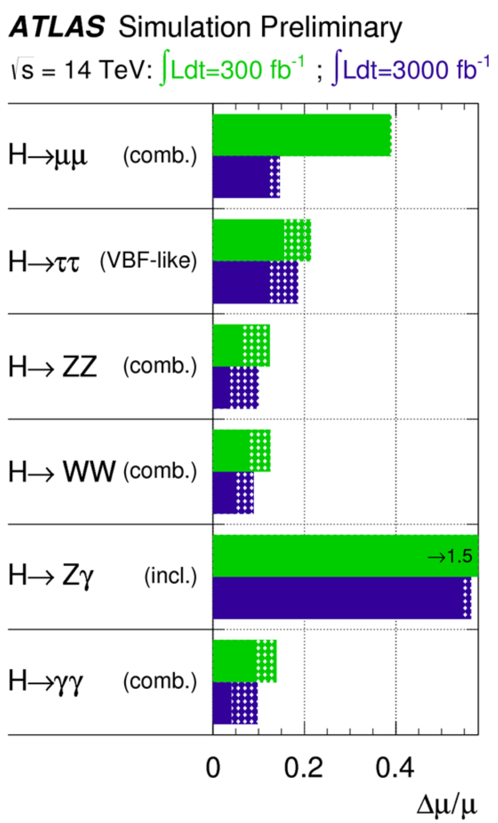
hMSSM Scenario



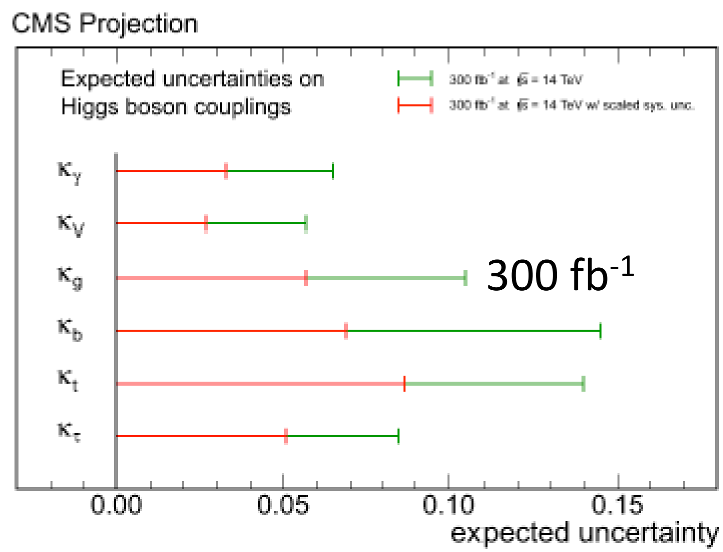
Coupling Projections

Many studies done for US Snowmass process, Europe ECFA studies.

Snowmass Higgs report, arXiv:1310.8361



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

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

Even with the projected precisions at HL-LHC, the couplings are not expected to be constrained better than ~ 5%.

Case for a Precision Higgs Program

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:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 6\% \text{ @ M} \sim 1 \text{ TeV}$$

(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.

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

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

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

(ILC DBDPhysics)

$\Rightarrow$ Need percent-level or better measurements!

e^+e^- Collider

Electroweak production

cross sections are predicted with (sub)percent level precisions in most cases

Relative low rate

can trigger on every event

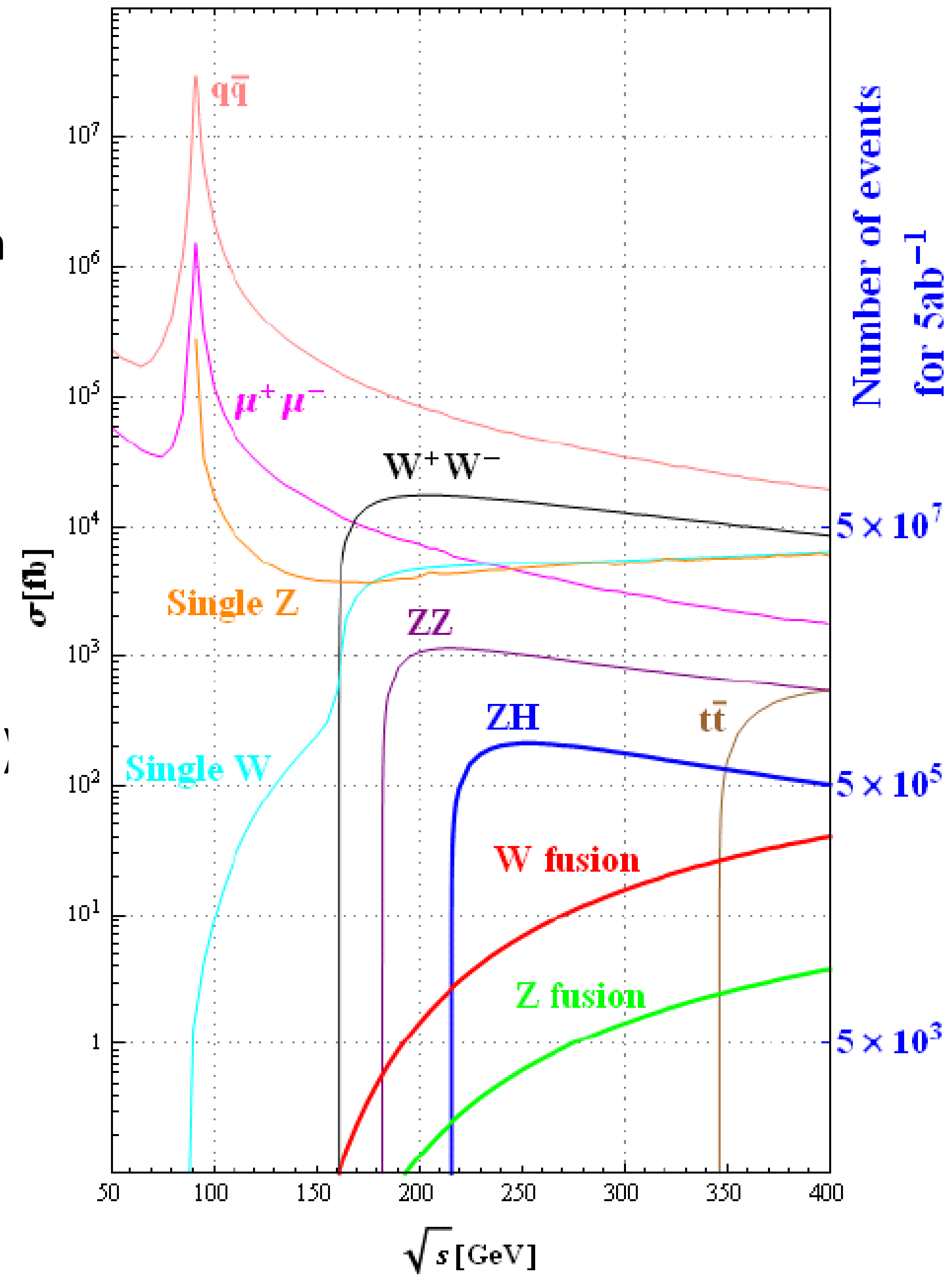
Well defined collision energy

allow for the “missing” mass reconstruction (*eg* recoiling mass)

Clean events, smaller background

small number of processes

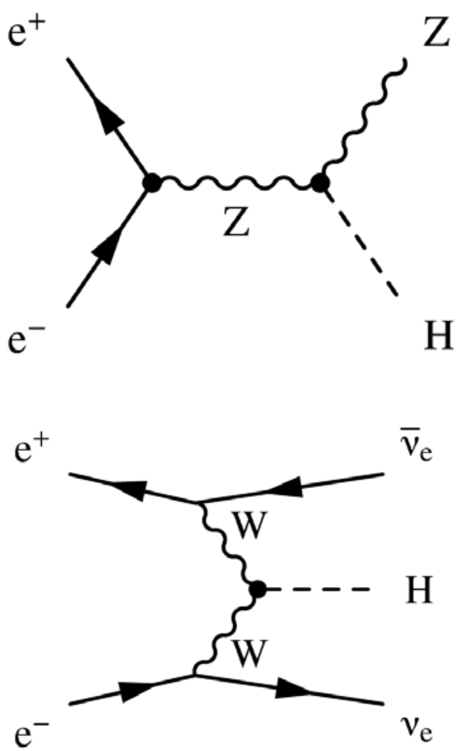
Ideal for precisions:
measurements or searches

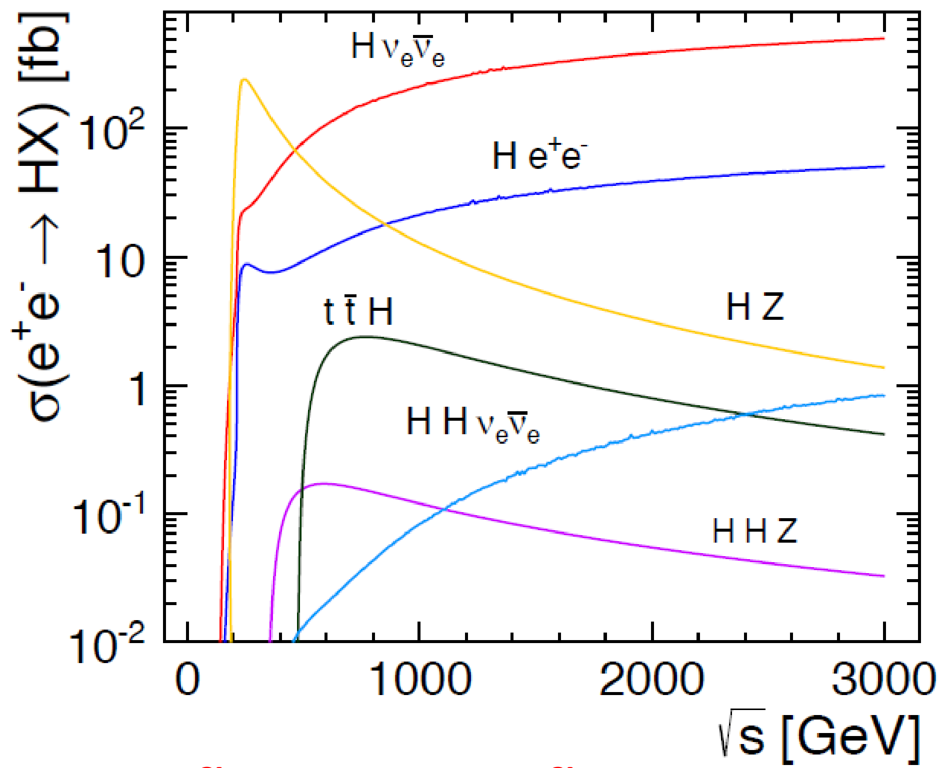


Higgs Boson Production

At $\sqrt{s} \sim 240-250$ GeV, $ee \to ZH$ production is maximum and dominates with a smaller contribution from $ee \to \nu\nu H$.

Beyond that, the cross section decreases asymptotically as $1/s$ for $ee \to ZH$ and increases logarithmically for $ee \to \nu\nu H$.





$$\sqrt{s} = 250 \text{ GeV: } \sigma_{ZH} \approx 200 \text{ fb}, \ \ \sigma_{\nu\nu H} \approx 10 \text{ fb}$$

Cross Sections and Event Rates

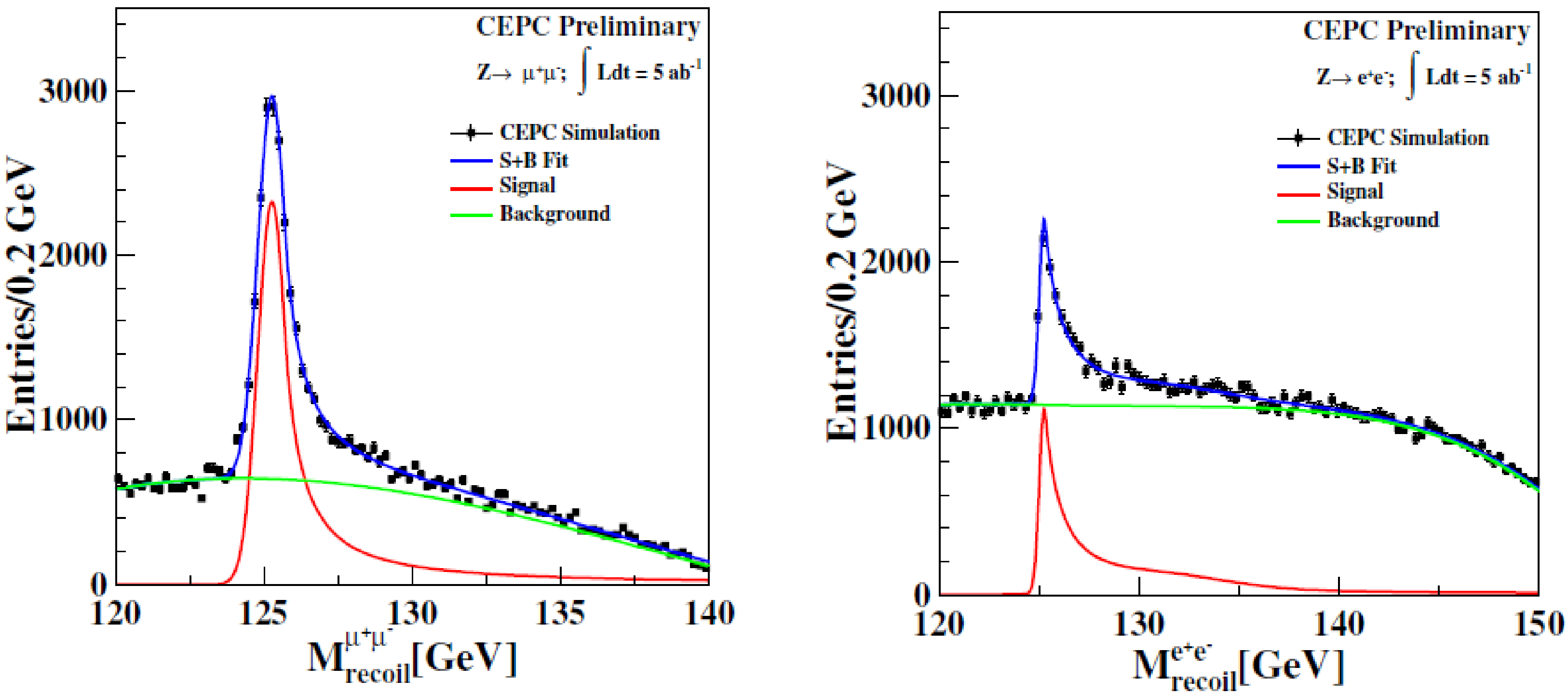
$5\ \mathrm{ab}^{-1}$ @ $\sqrt{s} = 250$ GeV

Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}\,(\gamma)$	50.2	2.5×10^8
$e^+e^- \to \mu^+\mu^-\,(\gamma)$ [or $\tau^+\tau^-\,(\gamma)$]	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to e^+e^-Z$	4.73	2.4×10^7
$e^+e^- \to e^+\nu W^- / e^-\bar{\nu}W^+$	5.14	2.6×10^7

>1,000,000 Higgs boson events

Recoil Mass Distributions

Unique to lepton colliders, the energy and momentum of the Higgs boson in $ee \to ZH$ can be measured by looking at the Z kinematics only.



Recoil mass reconstruction:

$$m_{\mathrm{recoil}}^2 = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

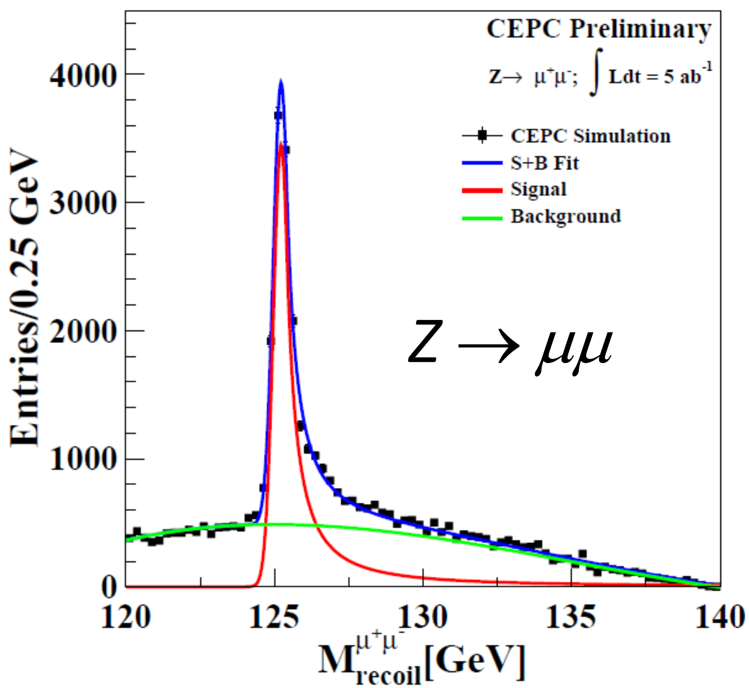
$\Rightarrow$ identify Higgs without looking at Higgs.

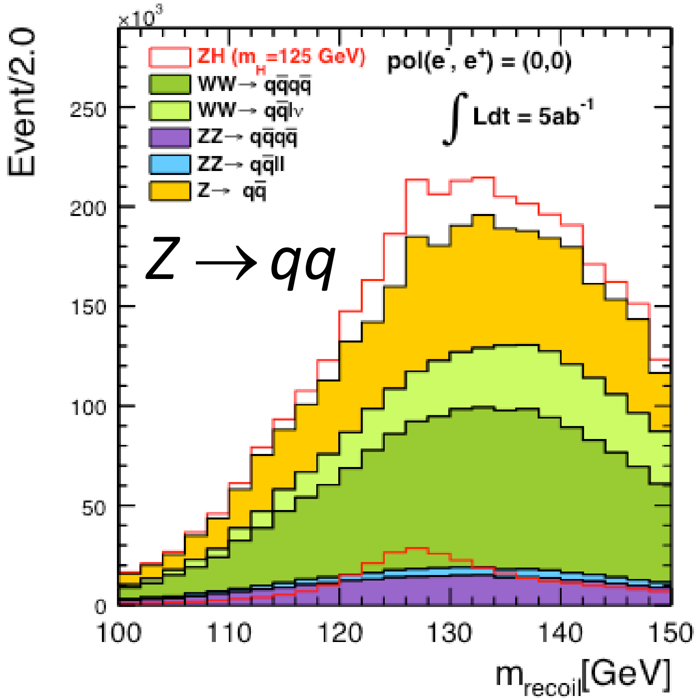
Measure $\sigma\left(ee \to ZH\right)$ independent of the Higgs boson decay !

Mass and Cross Section

The Higgs boson mass and the $ee \to ZH$ cross section can be extracted from the recoil mass spectra:

resonance peak $\approx M_H$, resonance height $\sim \sigma(ee \to ZH)$





$\Delta M_H \sim 5.5$ MeV

from leptonic decays $Z \to ee, \mu\mu$
(resolution important)

$\Delta\sigma_{ZH}/\sigma_{ZH} \sim 0.5\%$

from $Z \to ee, \mu\mu$ and qq decays
(statistics important)

Accessible Decay Modes

Higgs boson decays can be studied by examining the system recoiling against the Z boson decays

SM decay		Accessible?	
mode	branching ratio	(HL-)LHC	Higgs factories
$H \to bb$	57.7%	✓, × *	✓
$H \to gg$	8.57%	×	✓
$H \to cc$	2.91%	×	✓
$H \to ss$	2.46×10^{-4}	×	?
$H \to \tau\tau$	6.32%	✓	✓
$H \to \mu\mu$	2.19×10^{-4}	✓	✓
$H \to WW$	21.5%	✓	✓
$H \to ZZ$	2.64%	✓	✓
$H \to \gamma\gamma$	0.23%	✓	✓
$H \to Z\gamma$	0.15%	✓	✓

* Not all production mode.

Limitations: statistics even with 1 million events

At HL-LHC: trigger and systematics

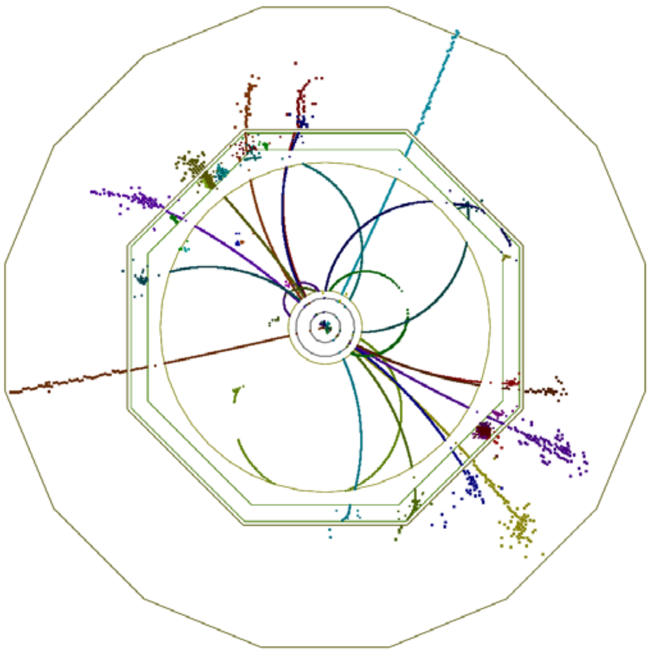
CEPC will be sensitive to *unknown* Higgs boson decays

Branching Ratios

Examining the rest of the events to study Higgs boson decays and measure

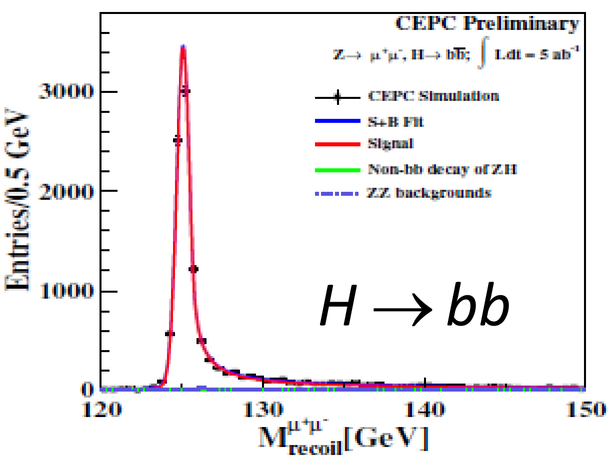
$$\sigma\left(ee \to ZH\right) \times BR\left(H \to XX\right)$$

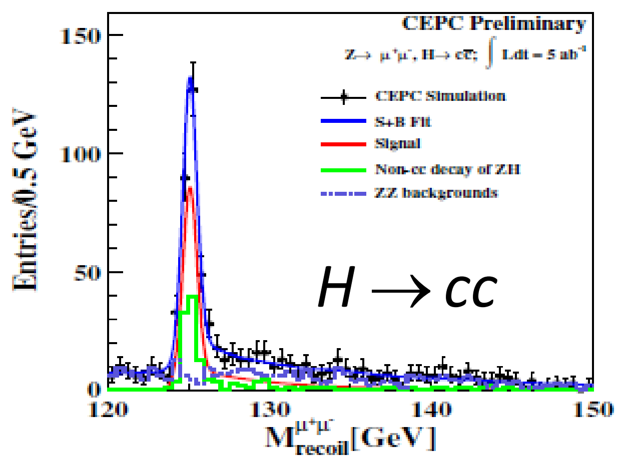
thus allowing the measurements of Higgs decay BR without assumptions.

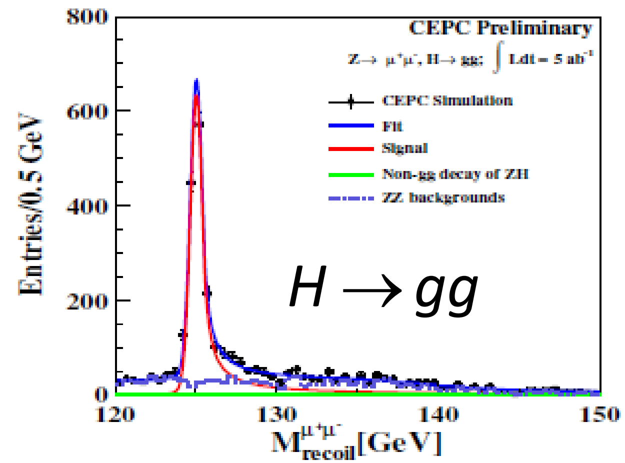


$H \to hadrons$

Apply flavor tagging to separate $H \to bb,\ cc,\ gg$







Total Decay Width

The SM predicted value of $\Gamma_H \sim 4$ MeV is much smaller than the experimental resolution $(\sim \text{GeV})$ of the recoil mass $\Rightarrow$ cannot measured directly with a reasonable precision.

The Higgs total width can be inferred from the cross section and branching ratio measurements in a model-independent way. Two independent measurements:

$$\sigma(ee \to ZH): \quad \Gamma_H = \frac{\Gamma(H \to ZZ^*)}{BR(H \to ZZ^*)} \propto \frac{\sigma(ee \to ZH)}{BR(H \to ZZ^*)}$$

(Limited by the $H \to ZZ^*$ statistics)

$$\sigma(ee \to \nu\nu H \to \nu\nu bb): \quad \Gamma_H = \frac{\Gamma(H \to bb)}{BR(H \to bb)} \propto \frac{\sigma(ee \to \nu\nu H \to \nu\nu bb)}{BR(H \to bb) \bullet BR(H \to WW^*)}$$

(Limited by the $ee \to \nu\nu H \to \nu\nu bb$ statistics)

Summary of Measurement Precision

Δm_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\bar{\nu}H) \times \mathrm{BR}(H \to b\bar{b})$
5.9 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau^+\tau^-$	1.2%	1.3%
$H \to WW^*$	1.5%	1.6%
$H \to ZZ^*$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu^+\mu^-$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

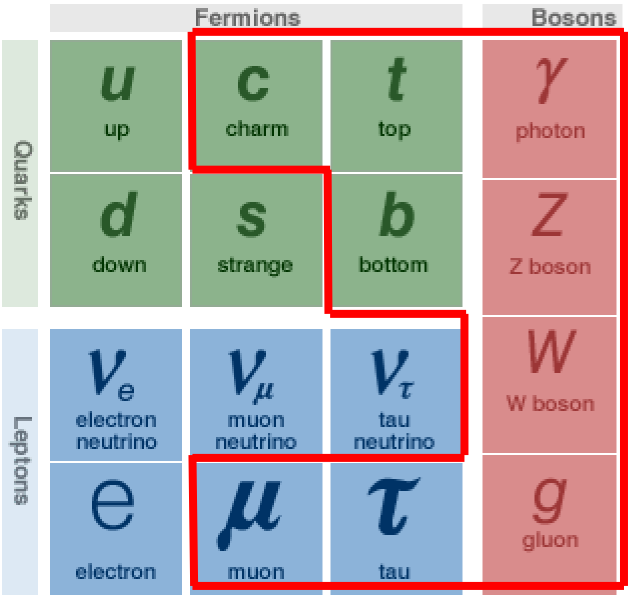
95% CL upper limit is quoted for $H \to$ inv decay

Coupling Fit Models

Most general model: one modifier per observable Higgs coupling

With $\sim 10^6$ events, the Higgs factories will be able to explore Higgs couplings to 9 fundamental particles in SM

- No direct access to Htt coupling at $\sqrt{s} \sim 240-250$ GeV, sensitivity through the $H \rightarrow gg$ loop



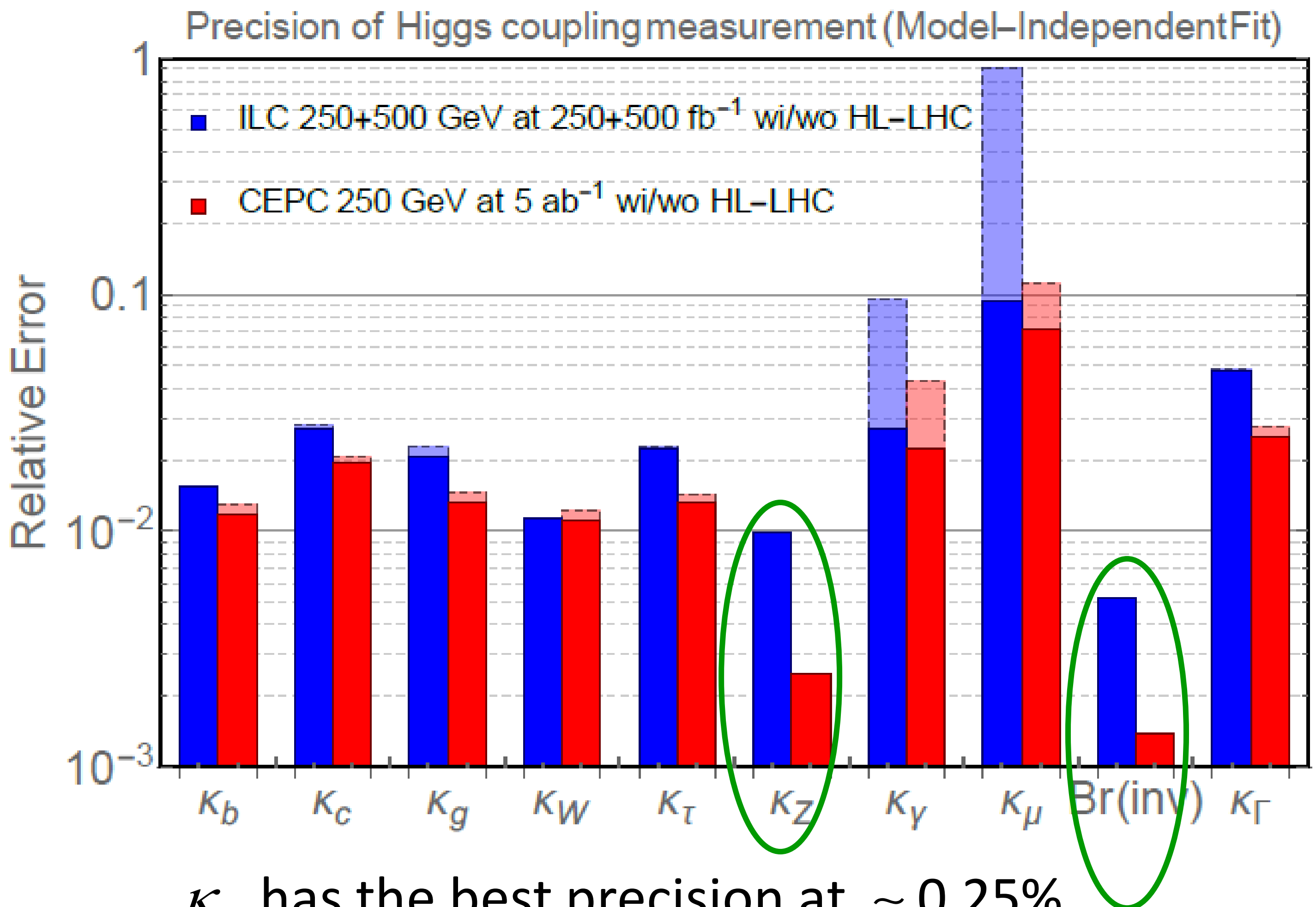
\+ sensitive BSM H $\rightarrow$ invisible decay

\+ sensitive to other exotic decays with unknown signature through the total width

Model-independent coupling fit: 10 parameter

$$\boxed{\kappa_b,\ \kappa_c,\ \kappa_\tau,\ \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR}_{\mathrm{inv}},\ \Gamma_h}$$

Results of the 10-Parameter Fit



κ_Z has the best precision at $\sim 0.25\%$

Stringent constraint on $\mathrm{BR}(H \to inv)$

(Compared with the ILC, most of the gains are from statistics)

Comparisons with LHC

Fully model-independent fit is not possible at the LHC

Assumptions:

no BSM decays

up-type quarks: $\kappa_u = \kappa_c = \kappa_t$

down-type quarks: $\kappa_d = \kappa_s = \kappa_b$

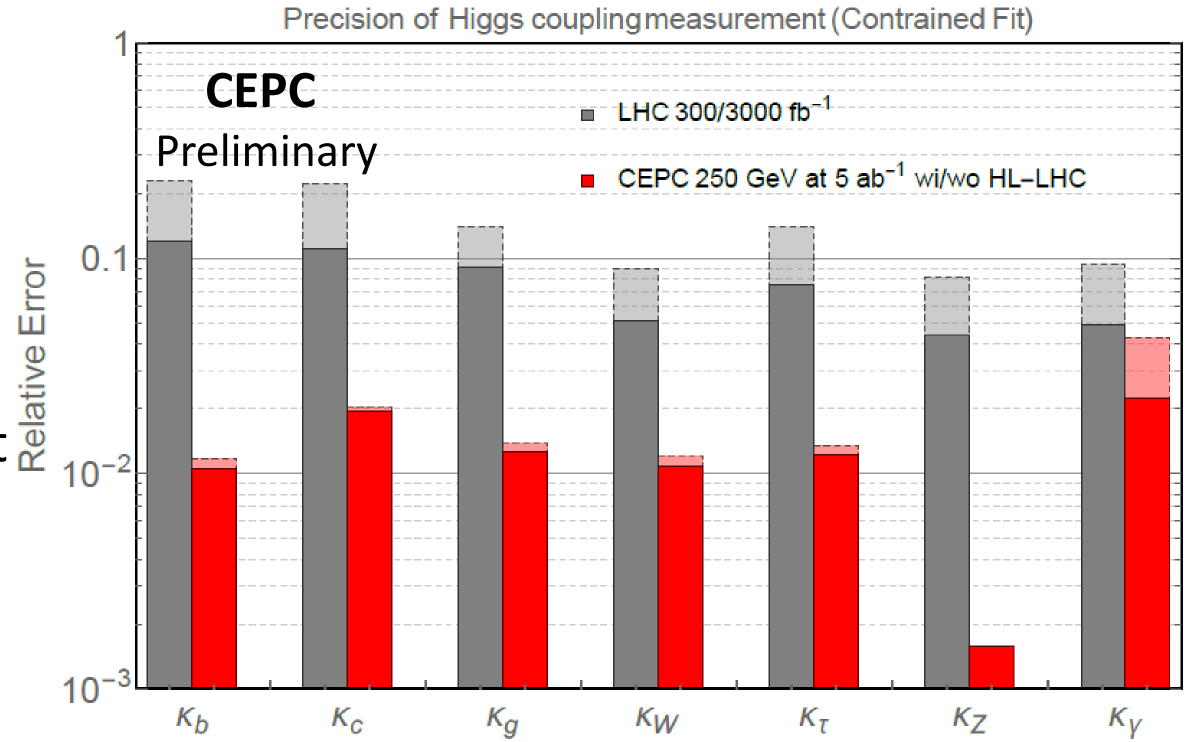
charged leptons: $\kappa_e = \kappa_\mu = \kappa_\tau$

7-parameter model:

$$\boxed{\kappa_c\,,\ \kappa_b\,,\ \kappa_\ell\,,\ \kappa_W\,,\ \kappa_Z\,,\ \kappa_g\,,\ \kappa_\gamma}$$

CEPC vs HL-LHC

Order of magnitude improvements expected over the HL-LHC for most of the couplings



HL-LHC: ATL-PHYS-PUB-2014-016

Results of Coupling Fits

Expected precisions of coupling fits

Proposed Facility	CEPC 250 [1]	TLEP 240 [2]	ILC 250 [2]	ILC 250+500 [2]
$\int \mathcal{L}dt$	5 ab^{-1}	10 ab^{-1}	0.25 ab^{-1}	0.25+0.5 ab^{-1}
Γ_H	2.8%	1.9%	12%	5.0%
κ_b	1.3%	0.88%	5.3%	1.7%
κ_c	1.7%	1.0%	6.8%	2.8%
κ_τ	1.4%	0.94%	5.7%	2.4%
κ_μ	8.6%	6.4%	91%	91%
κ_W	1.2%	0.85%	4.8%	1.2%
κ_Z	0.25%	0.16%	1.3%	1.0%
κ_g	1.5%	1.1%	6.4%	2.3%
κ_γ	4.7%	1.7%	18%	8.4%
95% CL upper limit				
BR($H \to$ inv)	0.28%	0.19%	0.9%	0.9%

[1] Very preliminary; [2] arXiv:1310.8361 (Snowmass report).

Percent-level or better precision for many couplings

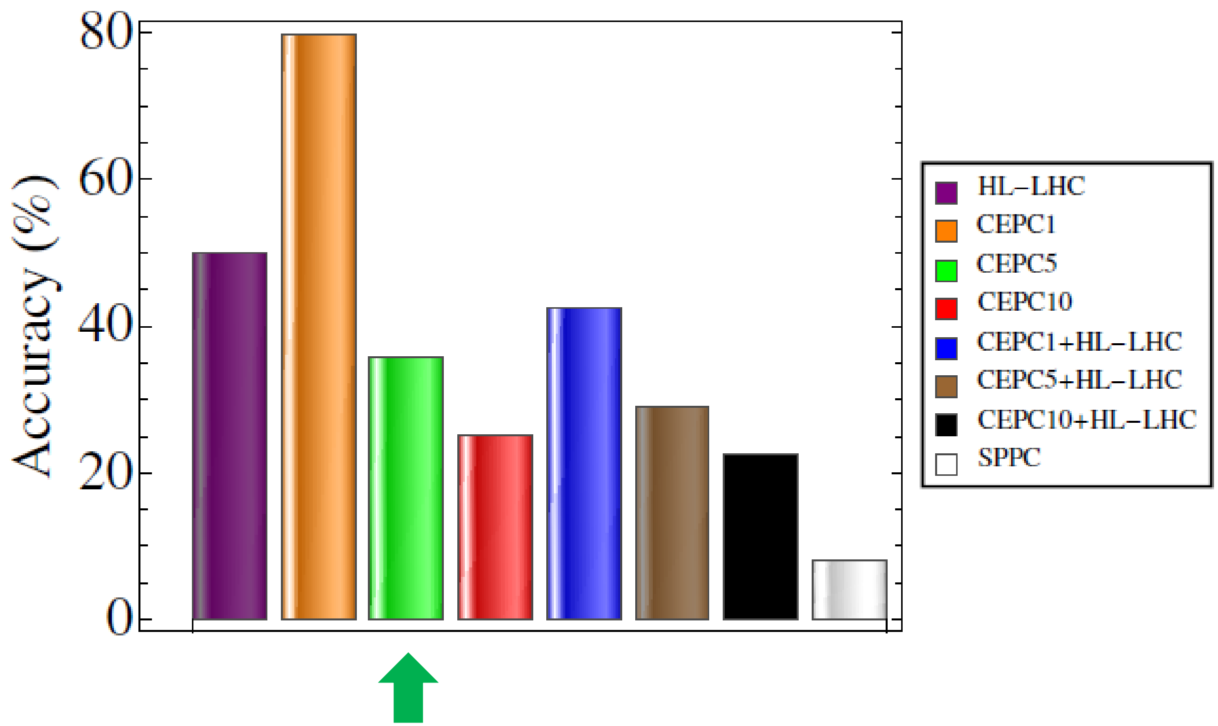
Higgs Boson Self-Coupling

No Higgs boson pair production at the CEPC

$\Rightarrow$ no direct probe of the self-coupling

However, $\lambda(hhh)$ coupling affects the *hZZ* coupling at 1-loop level $\Rightarrow$ indirect measurement

McCullough, arXiv:1312.3322

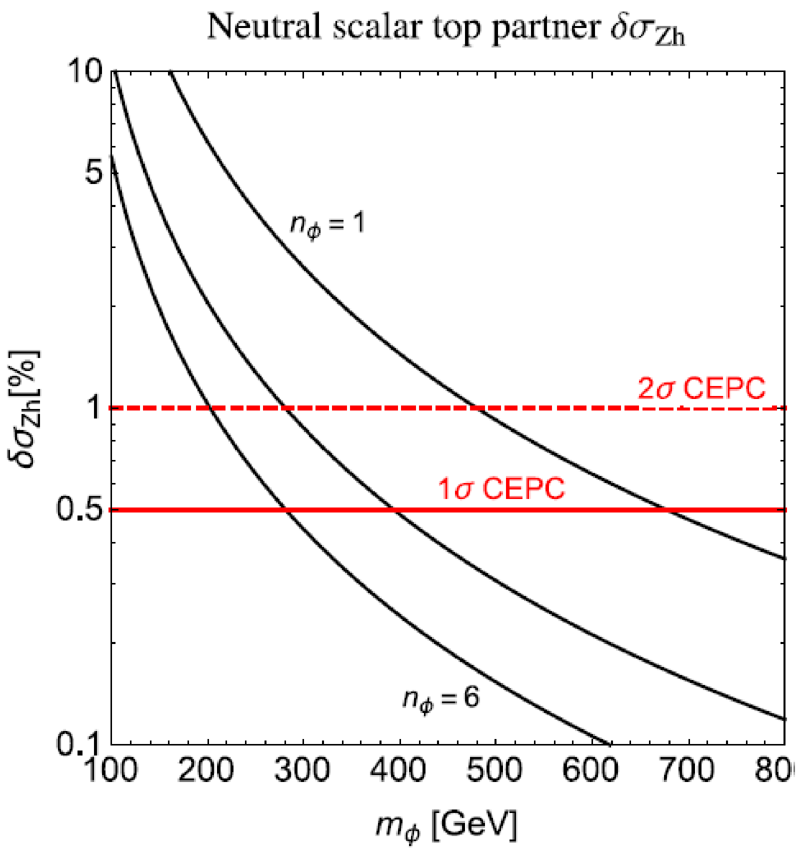


$$\frac{\Delta\lambda}{\lambda} \sim 35\%$$

Impacts on Example BSM Models

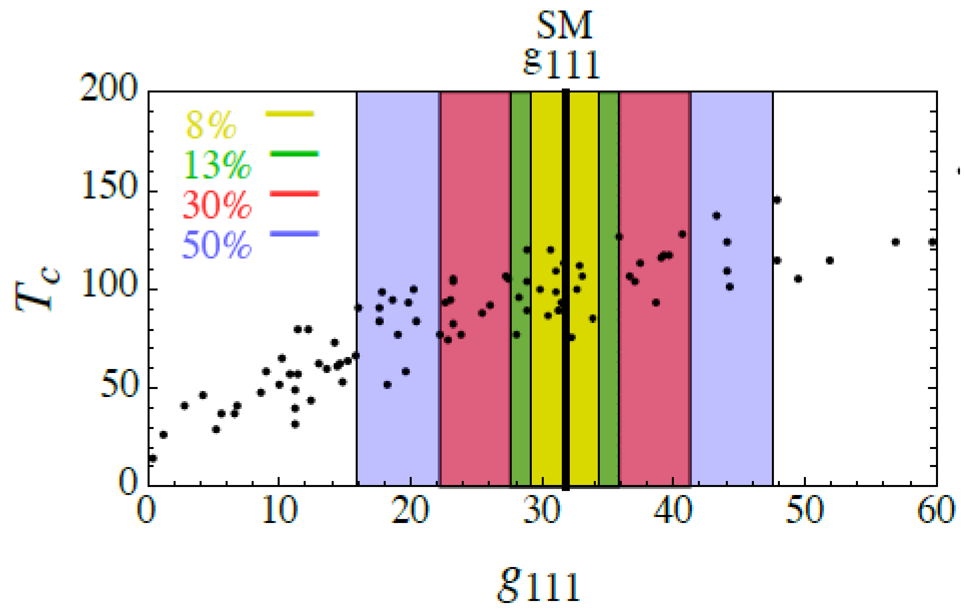
Scalar top partner model

Generic singlet model



Craig et al., arXiv:1305.5251

Can shift the *hZZ* coupling by $>0.5\%$



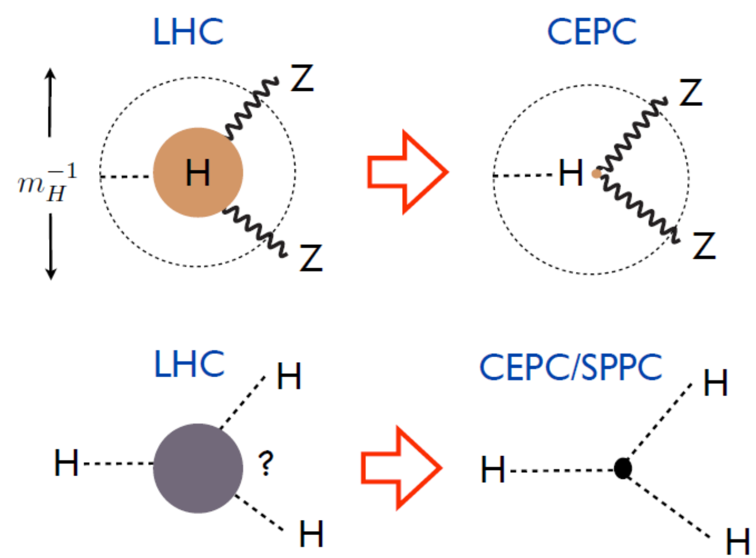
Profumo et al., arXiv:1407.5342

Summary

The current precision on the Higgs boson coupling measurements at the LHC is at 10-20% level, HL-LHC can improve the precision to ~5% for some couplings. Moreover, LHC has the potential to discover additional Higgs states.

A lepton collider Higgs factory is complement of the LHC. It allows for model-independent measurements of the Higgs boson properties and can significantly improve their precision.

The CEPC (FCC-ee) has the potential to "undress" the Higgs boson as what LEP has done to the Z boson, and possibly shed light on the direction of new physics. The SPPC complements the CEPC and will significantly extend the discovery reach.



Coupling Comparison (Snowmass)

ILC projections are from Tim Barklow. The rest is mostly taken from the presentation by Patrick Janot at the BNL workshop. The LHC numbers are *per experiment* (unless noted) of CMS projections of two scenarios of systematics assumptions.

Facility	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3 (4 IP)	TLEP (4 IP)
Energy (GeV)	14,000	14,000	250	250+500+1000	350+500+1500	240	240+350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250	250+500+1000	500+500+1500	2000	10000+1400
N_H produced	1.7×10^7	1.7×10^8	80,000	370,000	618,000	600,000	3,200,000
				Measurement precision			
m_H (MeV)	100	50	35	35	70	26	7
$\Delta\Gamma_H$	–	–	11%	6%	6%	4%	1.3%
$\mathrm{BR_{inv}}$	NA	NA	<0.8%	<0.8%	NA	<0.7%	<0.3%
$\Delta g_{H\gamma\gamma}$	5.1 – 6.5%	1.5 – 5.4%	18%	4.1%	NA	3.4%	1.4%
Δg_{Hgg}	5.7 – 11%	2.7 – 7.5%	6.4%	1.8%	NA	2.2%	0.7%
Δg_{HWW}	2.7 – 5.7%†	1.0 – 4.5%†	4.8%	1.4%	1%	1.5%	0.25%
Δg_{HZZ}	2.7 – 5.7%†	1.0 – 4.5%†	1.3%	1.3%	1%	0.25%	0.2%
$\Delta g_{H\mu\mu}$	< 30%	< 10%	–	16%	15%	14%	7%
$\Delta g_{H\tau\tau}$	5.1 – 8.5%	2.0 – 5.4%	5.7%	2.0%	3%	1.5%	0.4%
Δg_{Hcc}	–	–	6.8%	2.0%	4%	2.0%	0.25%
Δg_{Hbb}	6.9 – 15%	2.7 – 11%	5.3%	1.5%	2%	0.7%	0.22%
Δg_{Htt}	8.7 – 14%	3.9 – 8.0%	–	4.0%	3%	–	30%
Δg_{HHH}	–	30%‡	–	26%	16%	–	–

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ~ 2.
† assuming the same deviation for the HWW and HZZ couplings. ‡ two experiments.

Higgs Physics at e^+e^- Colliders

A precision Higgs physics program is a key component of all proposals, difference is in energy and luminosity. Physics should have little difference for the same energy and luminosity.

CEPC $\sqrt{s} \sim 240-250$ GeV, focusing on measurements with $ee \to ZH$ with some contributions from $ee \to \nu\nu H$.

FCC-ee (TLEP)

same as CEPC, but $\sqrt{s}$ up to 350 GeV, significantly increase $ee \to \nu\nu H$ cross section.

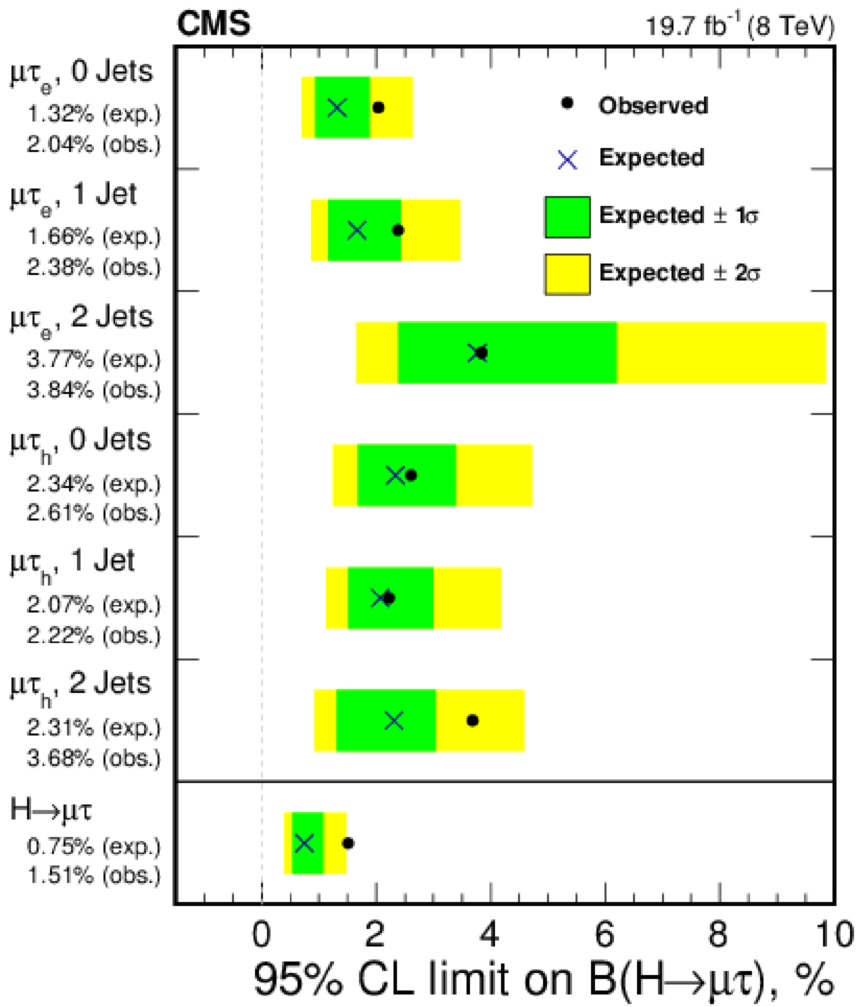
ILC

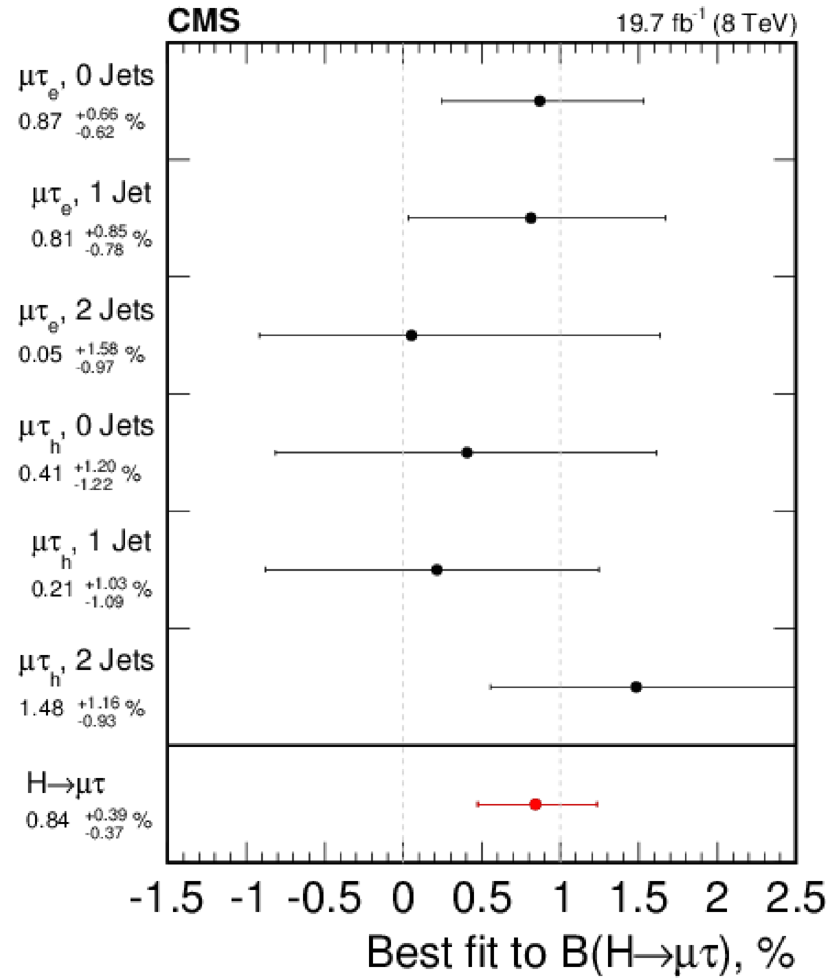
higher $\sqrt{s}$, looked at 250 GeV and 500 GeV for Higgs physics

Proposal	CEPC (2 IP)	TLEP (4 IP)		ILC*	
$\sqrt{s}$ (GeV)	250	240	350	250	500
$\int \mathcal{L}dt$ (ab^{-1})	5	10	2.6	0.25	0.5
# ZH events	1,000,000	2,000,000	340,000	75,000	50,000
# $\nu\nu H$ events	30,000	50,000	70,000	3,000	75,000

* Baseline design with polarization.

Search $H \rightarrow \mu\tau$





SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi,S)=\left\{\mu^2\phi^\dagger\phi+\lambda\left(\phi^\dagger\phi\right)^2\right\}+\left\{m_S^2S^2+\rho S^4\right\}+\kappa\left(\phi^\dagger\phi\right)S^2$$

Interesting phenomenology depends on whether $\langle S\rangle=0$.

If $\langle S\rangle\neq 0$, in general the singlet scalar and the "SM" Higgs boson can mix to form two mass eigenstates: $(h,\ H)$ assuming $h=h(125)$:

$$\begin{pmatrix} h \\ H \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}\begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

and new decay $H\to hh$ opens up if kinematically allowed.

If $\langle S\rangle=0$, there will be no mixing and the physical scalar $\boxed{s}$ can be stable and is therefore a dark matter candidate.

W Fusion Production

$ee \to \nu\nu H$ and $ee \to ZH \to \nu\nu H$ have the identical final states

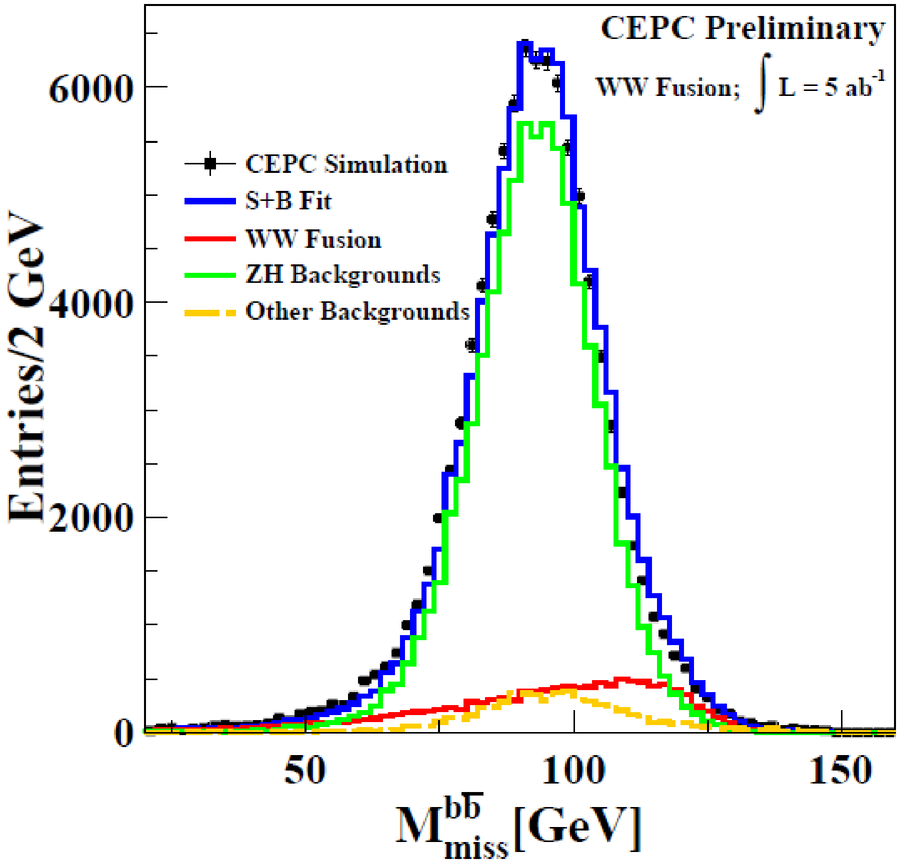
$$\text{At } \sqrt{s} = 250 \text{ GeV}, \ \frac{\sigma(ee \to \nu\nu H \to \nu\nu bb)}{\sigma(ee \to ZH \to \nu\nu bb)} \approx 0.16$$

Kinematically, the "missing mass" recoiling against the bb system provides the best discrimination

$$\frac{\Delta(\sigma_{ZH} \times BR_{bb})}{\sigma_{ZH} \times BR_{bb}} \approx 0.28\%$$

$$\Downarrow$$

$$\frac{\Delta(\sigma_{\nu\nu H} \times BR_{bb})}{\sigma_{\nu\nu H} \times BR_{bb}} \approx 3.2\%$$



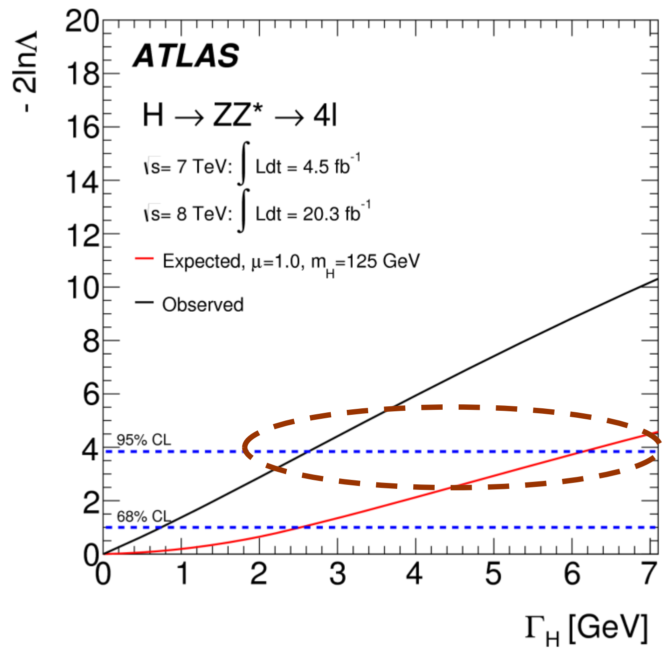
Direct Width Measurement

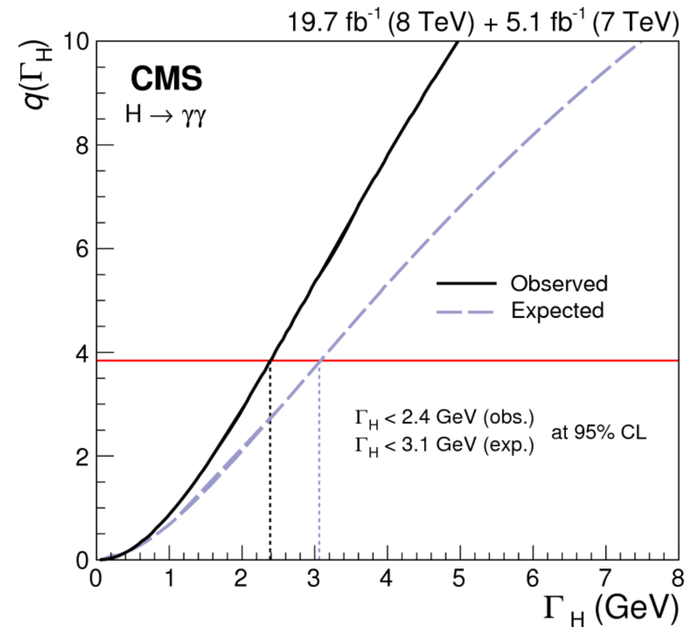
The Higgs width can be in principle extracted from the $m_{\gamma\gamma}$ or $m_{4\ell}$ distributions with the signal lineshape

$$\text{Breit-Wigner}(m, \Gamma_H) \otimes \text{Resulution}(\sigma)$$

Limited by detector mass resolution, statistics and backgrounds

arXiv:1406.3827 (ATLAS)





arXiv:1407.0558 (CMS)

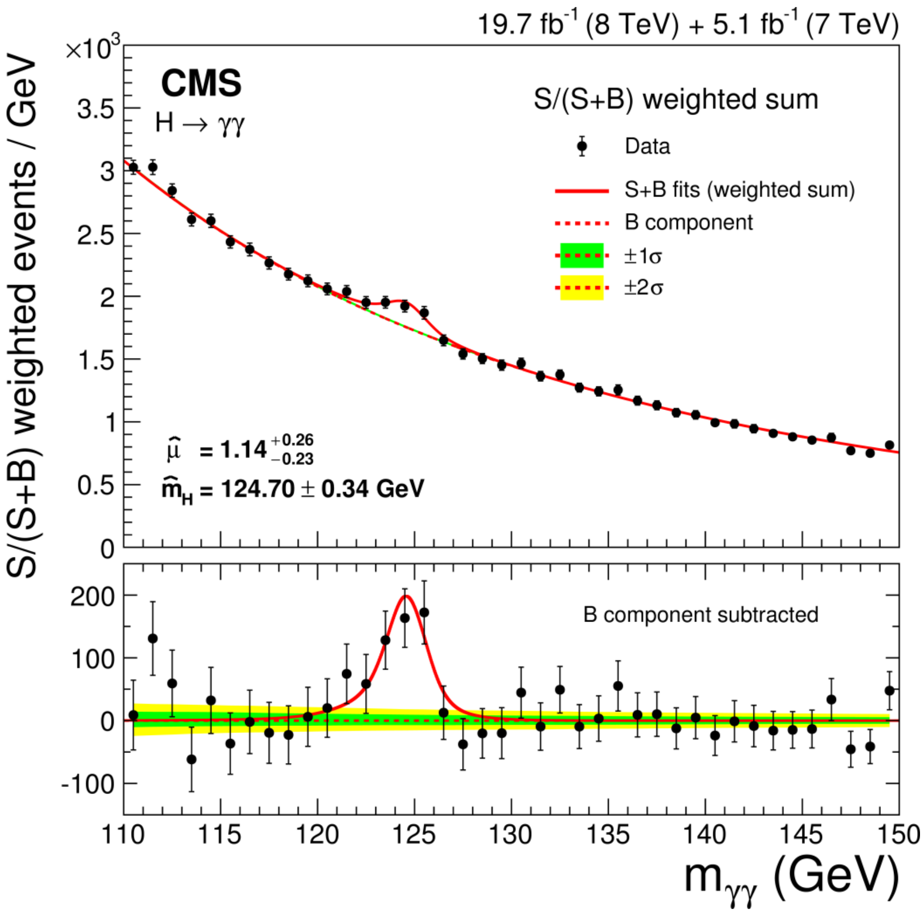
The observed high μ value plays an important role in the difference between the observation and the expectation.

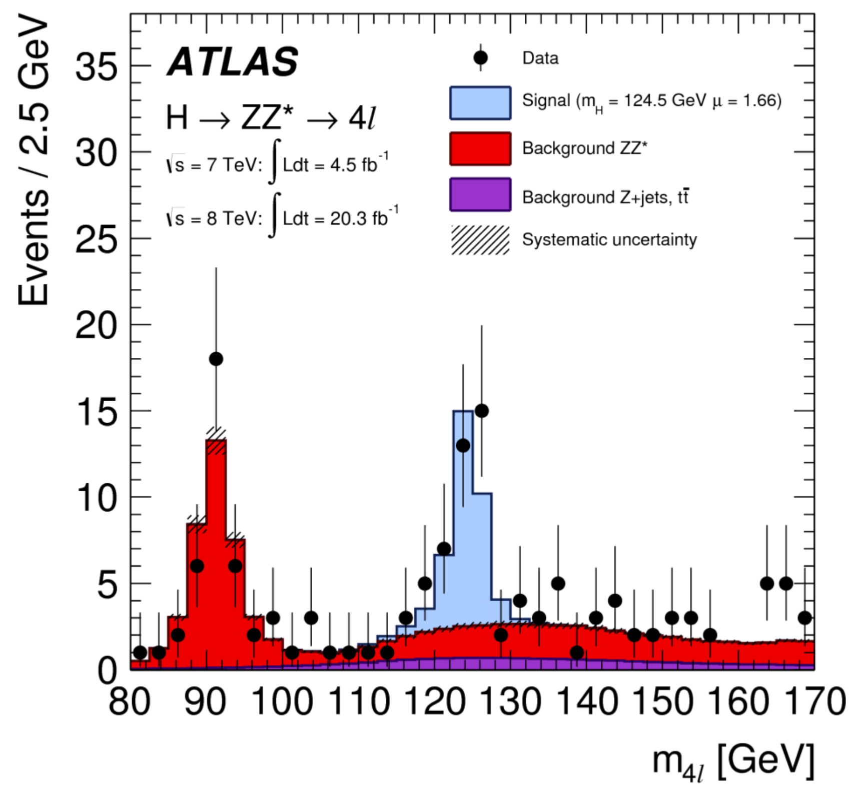
Observed (expected) upper limit on Γ_H in GeV

Final state	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
ATLAS	5.0 (6.2)	2.6 (6.2)
CMS	2.4 (3.1)	3.4 (2.8)

x2 difference in sensitivity between ATLAS and CMS?

Higgs Boson Mass Measurement





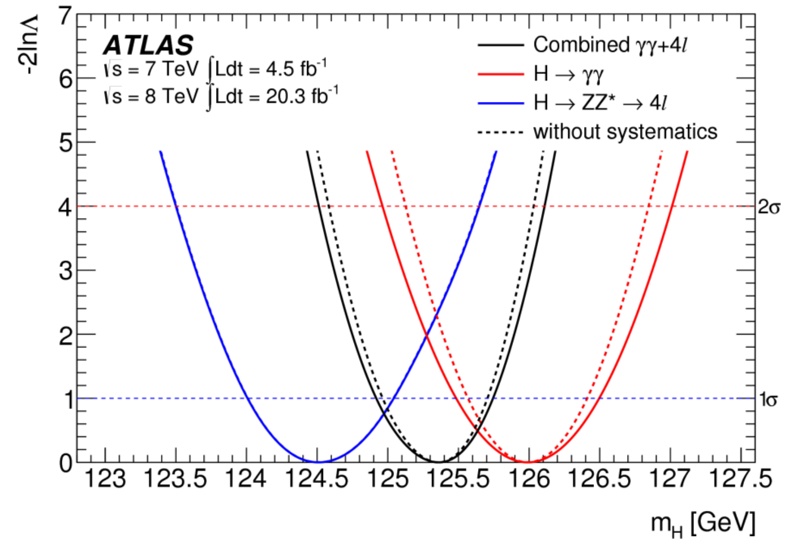
Individual Experiment Combination

ATLAS:

$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(stat) \pm 0.28(syst)\ \text{GeV}$$

$$m_H^{4\ell} = 124.51 \pm 0.52(stat) \pm 0.06(syst)\ \text{GeV}$$

a 2.0σ difference between $m_H^{\gamma\gamma}$ and $m_H^{4\ell}$



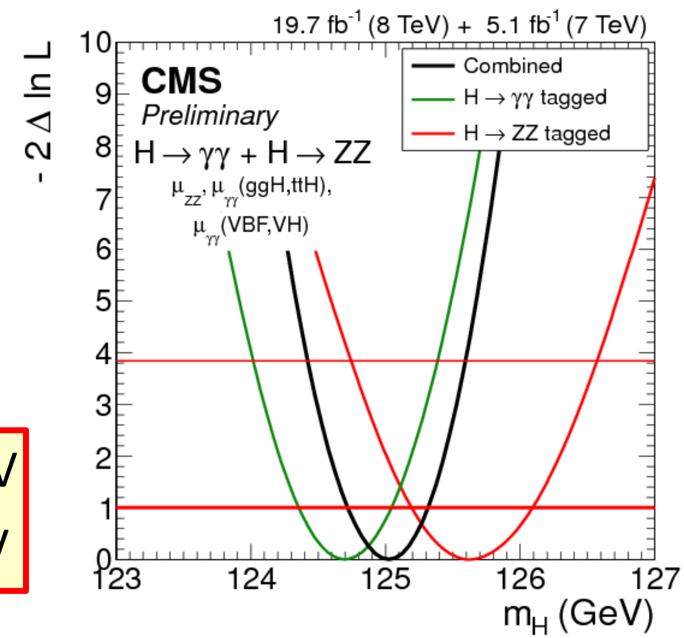
arXiv:1406.3827 (ATLAS)

CMS:

$$m_H^{\gamma\gamma} = 124.70 \pm 0.31(stat) \pm 0.15(syst)\ \text{GeV}$$

$$m_H^{4\ell} = 125.6 \pm 0.4(stat) \pm 0.2(syst)\ \text{GeV}$$

$\sim 1^{+}\sigma$ difference in the other direction



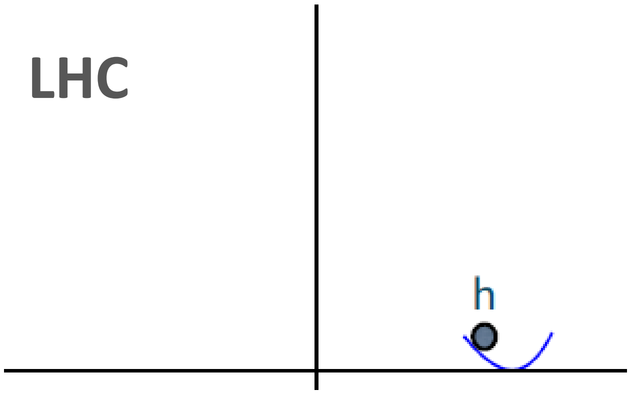
CMS-PAS-HIG-14-009

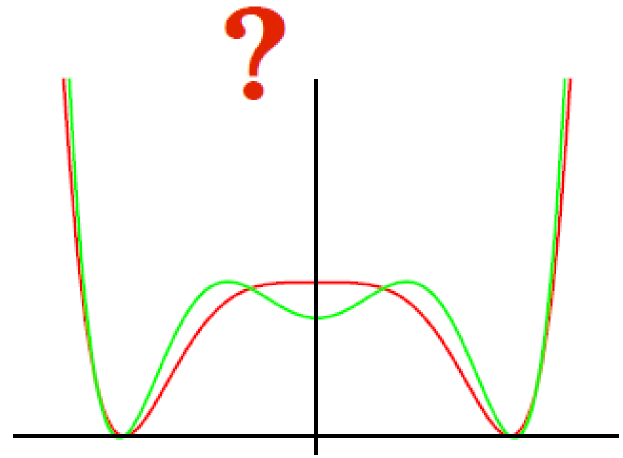
Combined:

$$\boxed{\begin{aligned} m_H^{ATLAS} &= 125.36 \pm 0.37(stat) \pm 0.18(syst)\ \text{GeV} \\ m_H^{CMS} &= 125.03 \pm 0.27(stat) \pm 0.14(syst)\ \text{GeV} \end{aligned}}$$

Electroweak Phase Transition

LHC





SPPC

Direct search of additional Higgs boson such as an electroweak singlet

Measurement of the Higgs boson self-coupling

$$\frac{\Delta\lambda}{\lambda} < 10\%?$$