Measurements of the Higgs Boson Couplings and Other Properties at the LHC

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(on behalf of the ATLAS and CMS collaborations)

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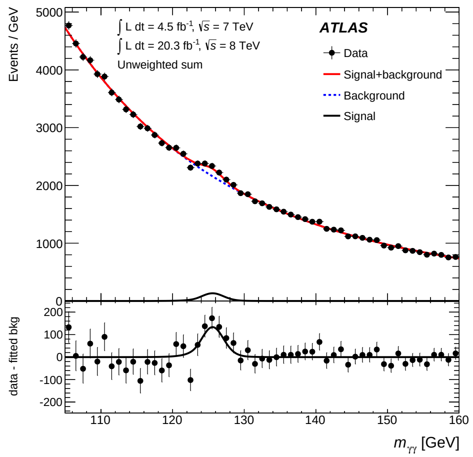
Observation of a new particle — July 4th, 2012

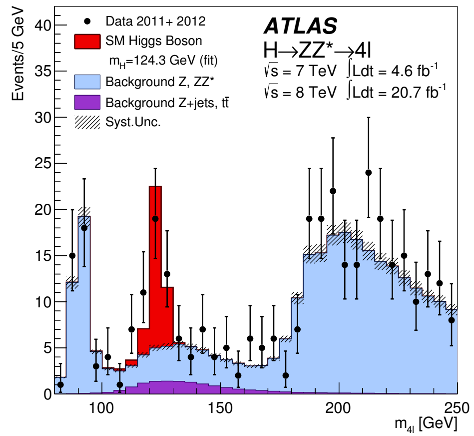
After the end of LHC run-I

2 independent observations:
ATLAS: combination of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$
CMS: combination of several decay channels

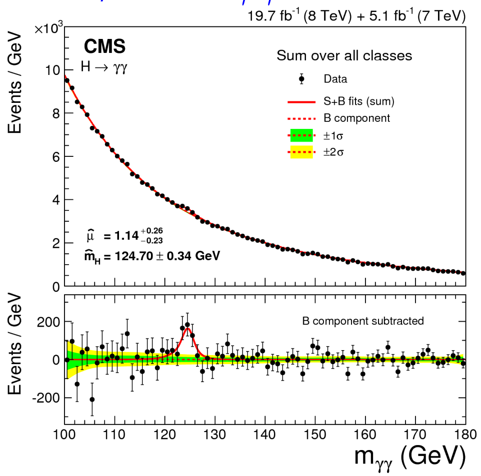
ATLAS, $H \to \gamma\gamma$



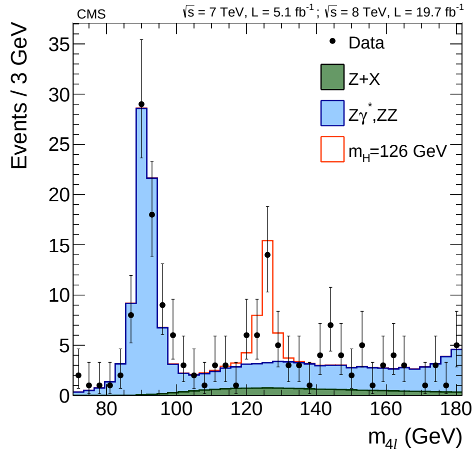
ATLAS, $H \to ZZ^* \to 4\ell$



CMS, $H \to \gamma\gamma$



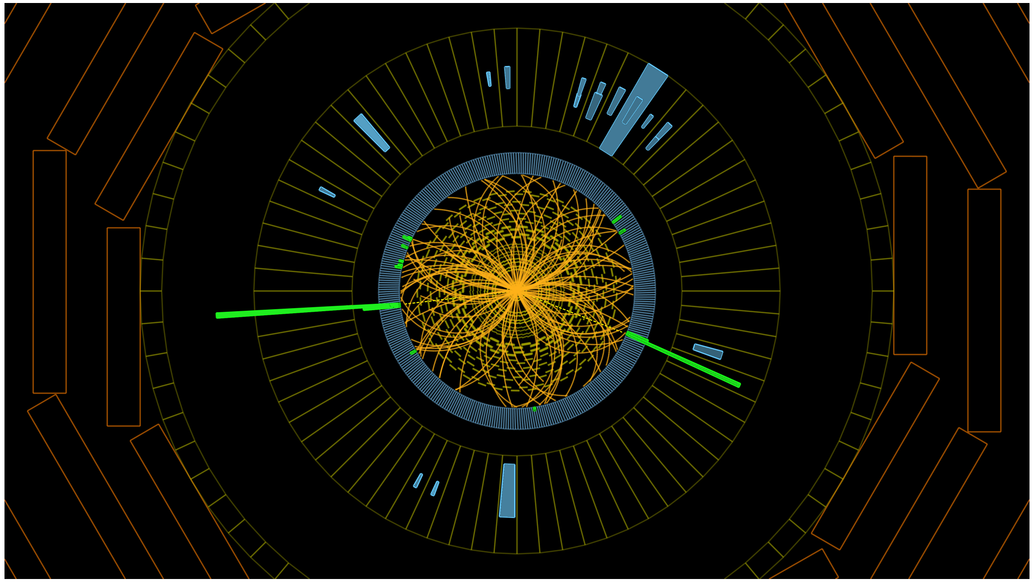
CMS, $H \to ZZ^* \to 4\ell$



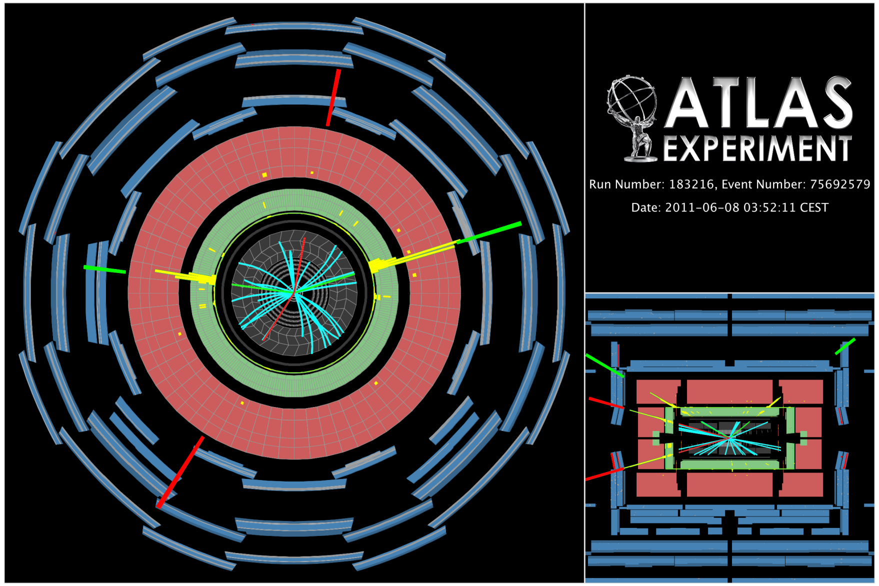
$\Rightarrow$ **mass of the new particle $\simeq$ 125 GeV**

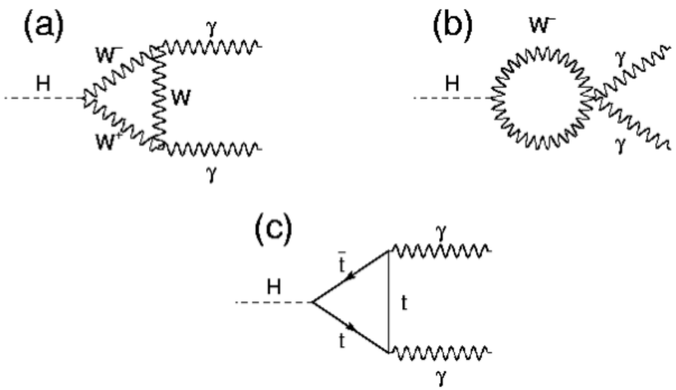
Higgs candidates : H $\rightarrow \gamma\gamma$ and H $\rightarrow ZZ^* \rightarrow 4\ell$

$H \rightarrow \gamma\gamma$ candidate at CMS

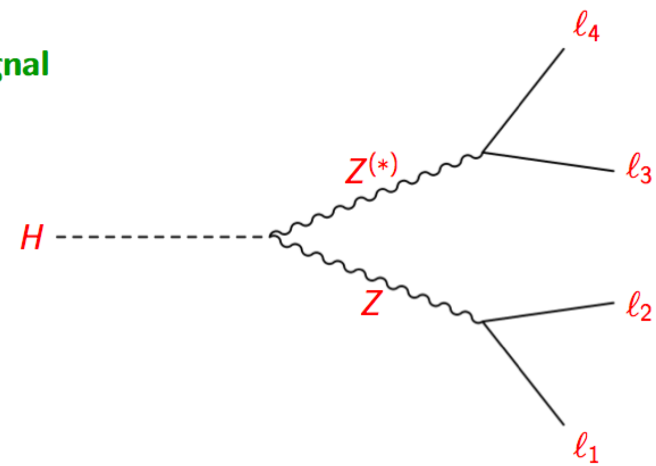


$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$ candidate at ATLAS

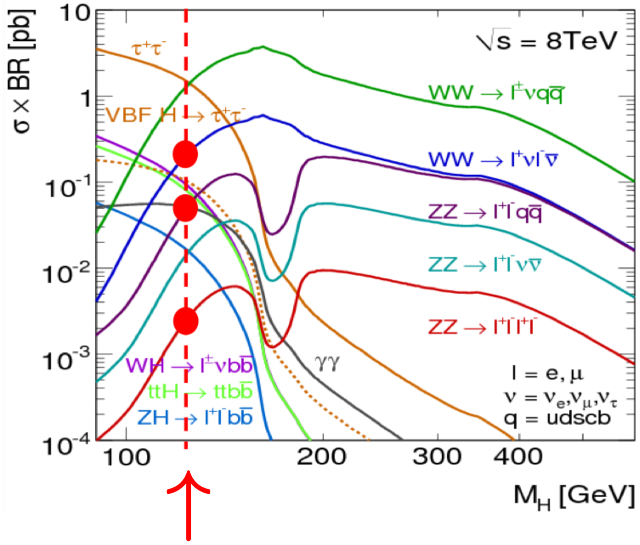




Signal



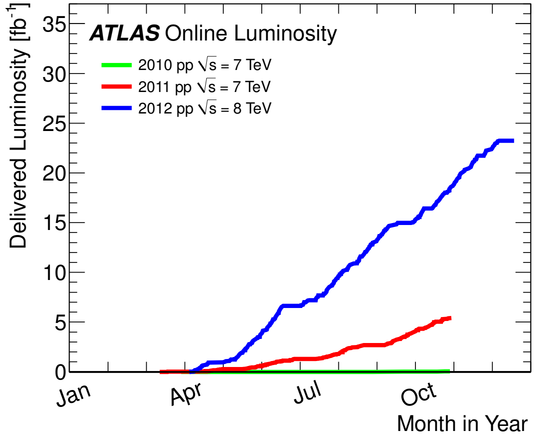
Is it the Standard Model Higgs boson, indeed?



If it is the Standard Model Higgs boson, its properties are:

- spin-parity : $J^{CP} = 0^{++}$
- couplings to vector bosons : $g_V = 2\,\frac{m_V^2}{v}$
- couplings to fermions : $g_f = \frac{m_f}{v}$

For a mass $m_H \simeq 125\ \mathrm{GeV}$, several decay modes are kinematically accessible
$\Rightarrow$ a thorough study of its properties is possible



The "LHC run-1" ended in December 2012
Overall integrated luminosity :
$\int L\,dt \sim 5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7\ \mathrm{TeV}$
$\int L\,dt \sim 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$

ATLAS and CMS observed decays into $\gamma\gamma$, ZZ^* , WW^* , $\tau^+\tau^-$

$\Rightarrow$ can probe several couplings and J^{CP} states

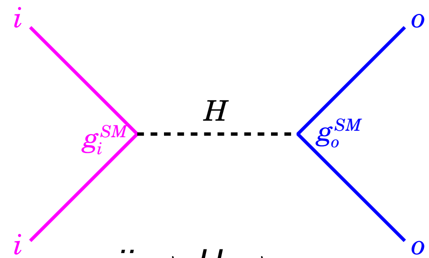
Observation of $H \to \gamma\gamma \Rightarrow C = +1$ and $J \neq 1$ (Landau-Yang theorem)

Anatomy of the new particle

Measurements: general strategy

If it is the Higgs boson, its mass m_H is the only free parameter of the model.
$\Rightarrow$ needs precise measurement.

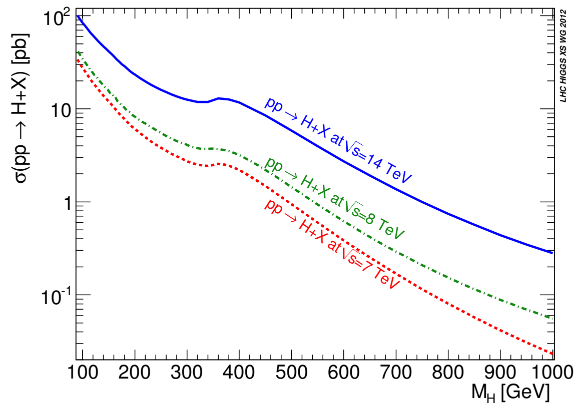
Once m_H is known, all the other properties are predicted by the Standard Model

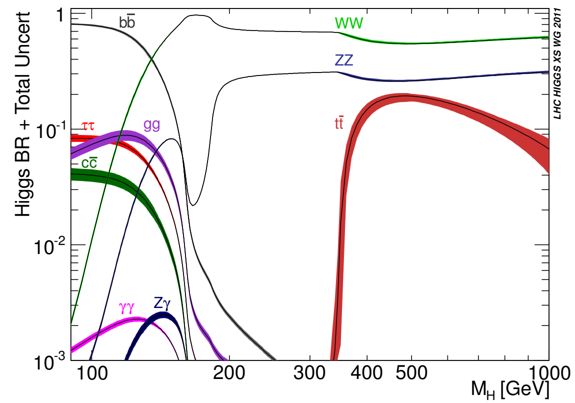


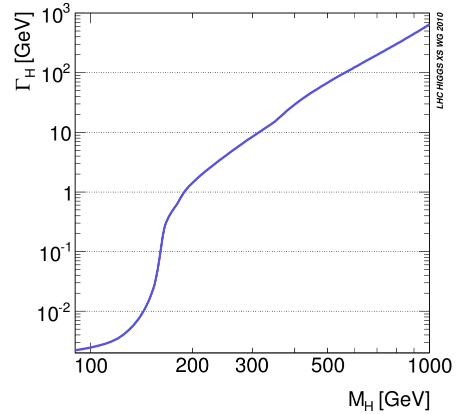
$ii \rightarrow H \rightarrow oo$

- couplings to gauge bosons : $g_V^{SM} = 2\dfrac{m_V^2}{v}$
- couplings to fermions : $g_f^{SM} = \dfrac{m_f}{v}$
- production cross-sections $\sigma_{ii\rightarrow H}^{SM}$
- branching ratios $BR_{H\rightarrow oo}^{SM}$
- total decay width Γ_H
- differential cross-sections $\dfrac{d\sigma^{SM}}{dp_T}$, $\dfrac{d\sigma^{SM}}{dY}$, . . .

$\Rightarrow$ we can test the Standard Model predictions on observed data







Statistical models used in measurements

Extended likelihood function: $\mathcal{L}(\vec{\alpha};\vec{\nu})$:

$$-\ln\mathcal{L}(\vec{\alpha};\vec{\nu}) = (n_s+n_b) - \sum_e \Bigg[\overbrace{n_s\cdot f_s\left(\vec{x}_e|\vec{\alpha},\vec{\nu}_s\right)}^{\text{signal pdf}} + \overbrace{n_b\cdot f_b\left(\vec{x}_e|\vec{\nu}_b\right)}^{\text{background pdf}}\Bigg] - \overbrace{\sum_k \ln\pi_k(\nu_k)}^{\text{ancillary pdfs}}$$

n_s, n_b: signal / background yields
$\vec{x}$: observables
f_s, f_b: signal / background pdfs
$\vec{\alpha}$: parameters of interest
(mass, cross-section, couplings, ...)
$\vec{\nu}$: "nuisance parameters"
(shape parameters, systematics, ...)
π_k: pdfs obtained from auxiliary measurements

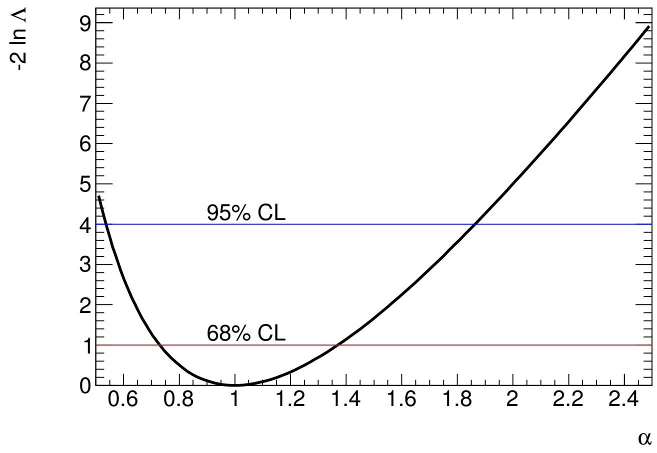
Test statistic: "Profiled Likelihood Ratio" (PLR)

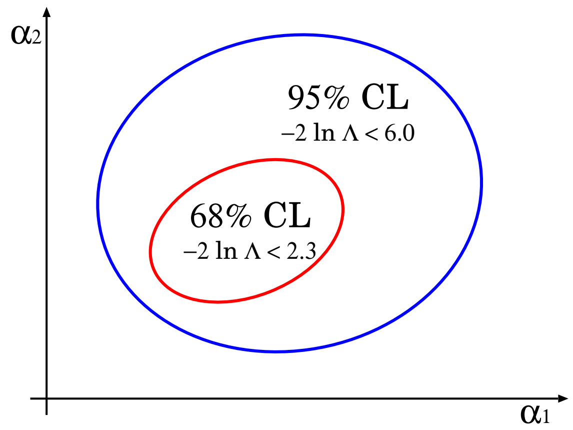
$$q_{\vec{\alpha}} = -2\ln\Lambda(\vec{\alpha}) = -2\ln\frac{\mathcal{L}(\vec{\alpha};\hat{\hat{\vec{\nu}}}(\vec{\alpha}))}{\mathcal{L}(\hat{\vec{\alpha}};\hat{\vec{\nu}})}$$

$\leftarrow \mathcal{L}(\vec{\alpha};\hat{\hat{\vec{\nu}}}(\vec{\alpha}))$: likelihood for fixed $\vec{\alpha}$ and "profiled" $\vec{\nu}$
$\leftarrow \mathcal{L}(\hat{\vec{\alpha}};\hat{\vec{\nu}})$: maximum likelihood for free $\vec{\alpha},\vec{\nu}$

Wilks' theorem : *if $\vec{\alpha} = \vec{\alpha}^{true}$, then $q_{\vec{\alpha}}$ follows a χ^2_D distribution, with D being the number of parameters of interest $\vec{\alpha}$*

$\Rightarrow$ compute confidence intervals for $\vec{\alpha}$

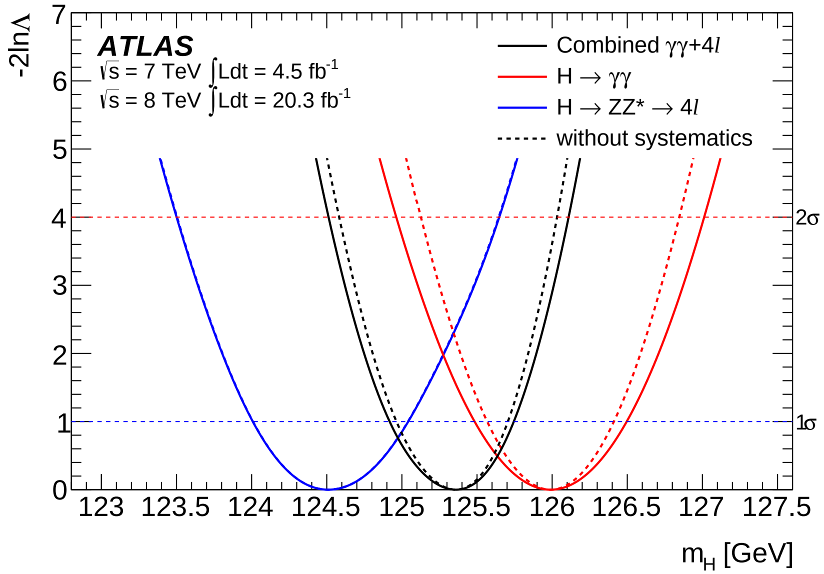




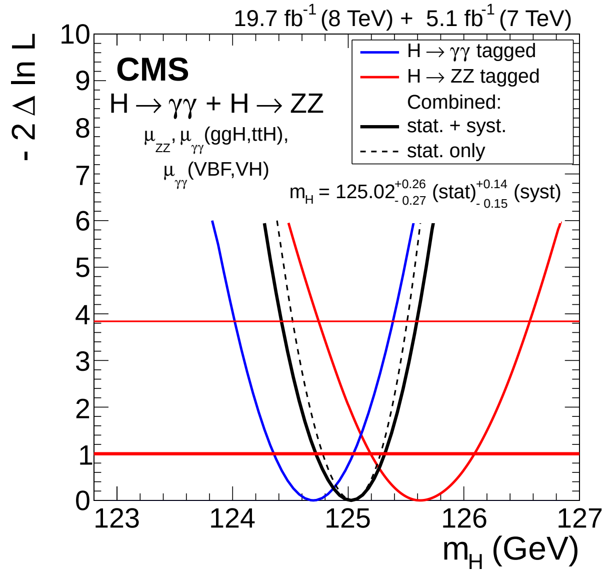
Mass measurement

Use the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels
that allow a full kinematics reconstruction with good invariant mass resolution ($\mathcal{O}(1\ \mathrm{GeV})$)

ATLAS



CMS

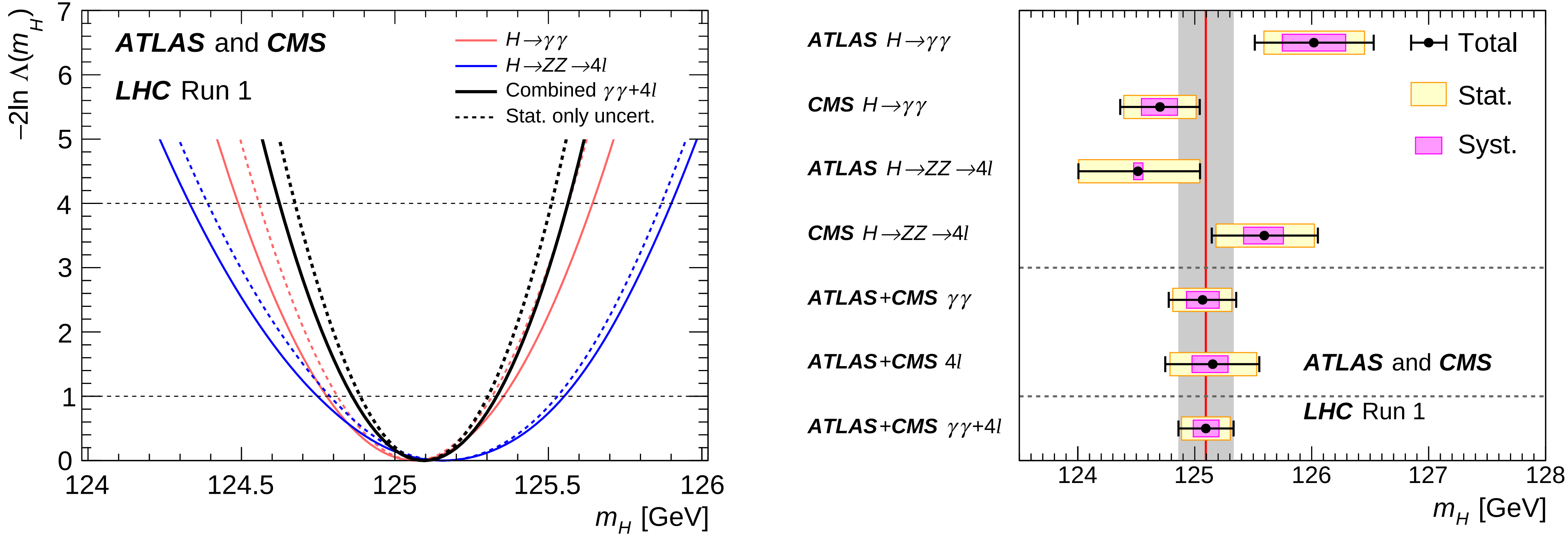


$\hat{m}_H = 125.36 \pm 0.37(stat) \pm 0.18(syst)\ \mathrm{GeV}$

$\hat{m}_H = 125.02 \pm 0.27(stat) \pm 0.15(syst)\ \mathrm{GeV}$

(e, μ energy scales from $J/\psi, \Upsilon, Z \to \ell\ell$; γ energy scale from $Z \to e^+e^-$ and $e \to \gamma$ extrapolation)

Mass measurement: ATLAS+CMS combination



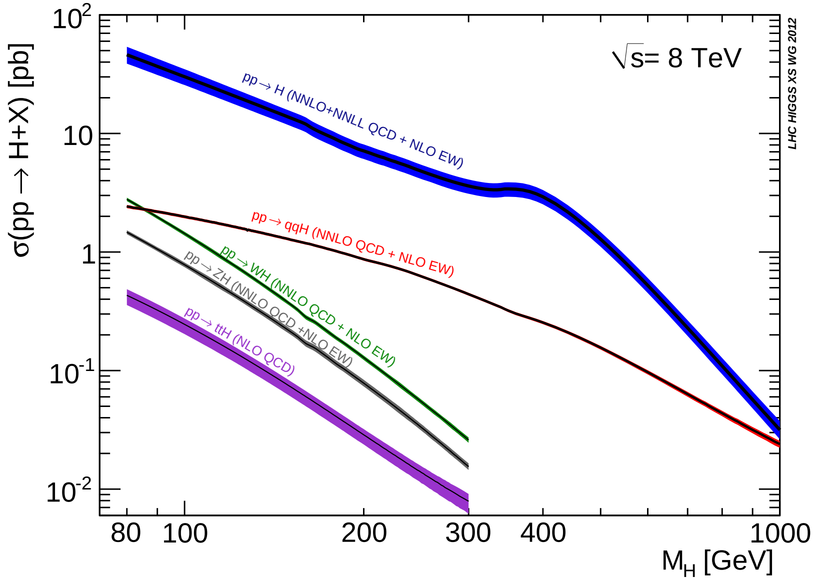
$$\hat{m}_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ \mathrm{GeV}$$

BUT : in the following, each experiment uses its own best $\hat{m}_H$

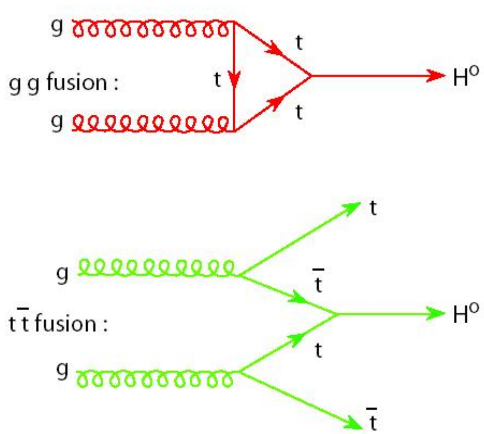
Measurements of the couplings

Higgs boson production at LHC

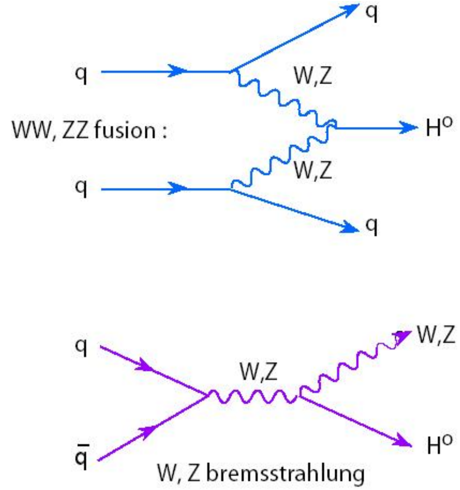
Production mechanisms at LHC



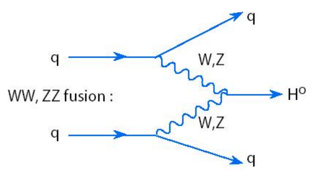
QCD production

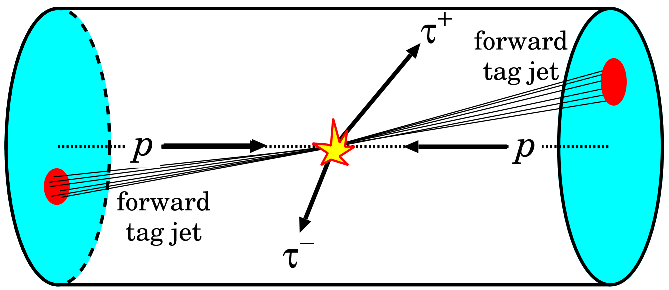


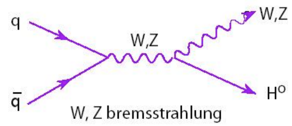
EW production

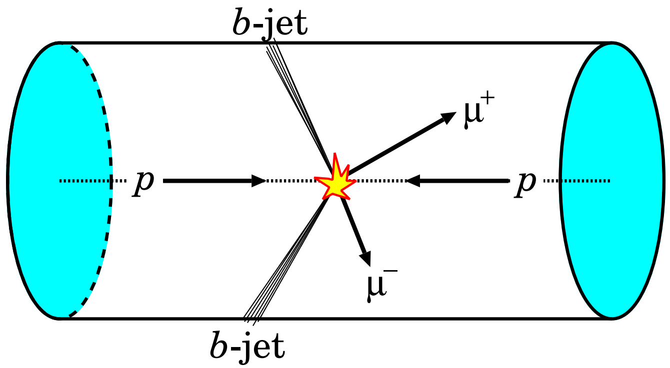


Experimental identification of VBF and VH productions (“tagging”):









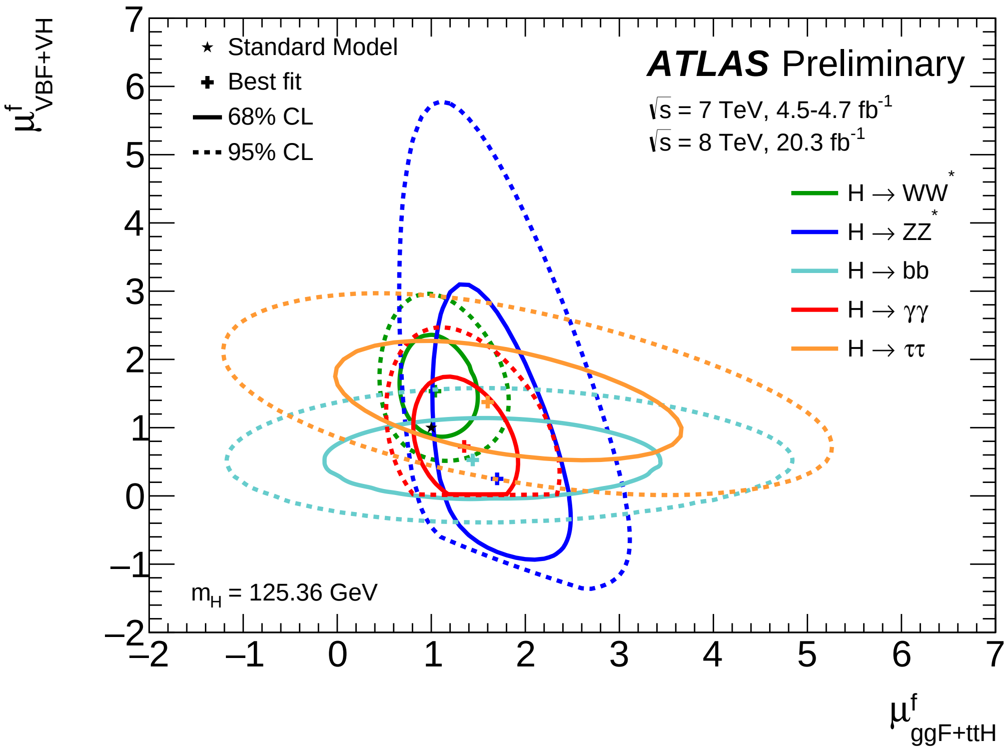
Production via gg-fusion and via weak boson(s)

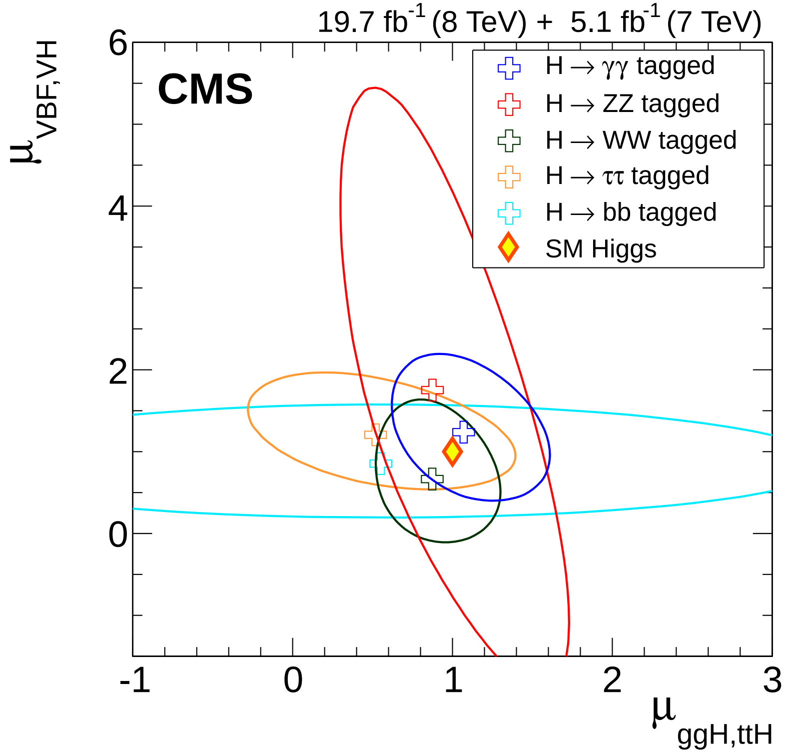
Introduce cross-section modifiers: $\mu = \dfrac{\sigma \cdot BR}{\sigma^{SM} \cdot BR^{SM}}$ (aka "signal strengths")

$\Rightarrow$ split by QCD production (ggF+$t\bar{t}$H) and EW production (VBF+VH):

$\Rightarrow$ $\mu_{\mathrm{VBF+VH}}$ probes HWW, HZZ vertices (EWSB)

$\Rightarrow$ $\mu_{\mathrm{ggF+ttH}}$ probes ttH vertex (Yukawa coupling)

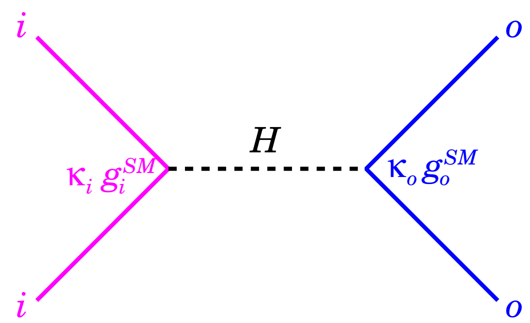




(CAVEAT: need to account for contaminations across "tagged" categories)

Couplings

Reminder: in SM Higgs couplings are $g_f^{SM} = \frac{m_f}{v}$ and $g_V^{SM} = 2\frac{m_V^2}{v}$



Couplings are accessible through production ($ii \to H$) and decay ($H \to oo$)

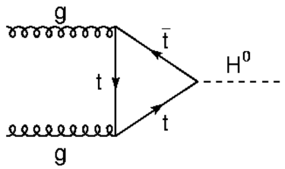
Define "couplings modifiers" $\kappa_x = \frac{g_x}{g_x^{SM}}$

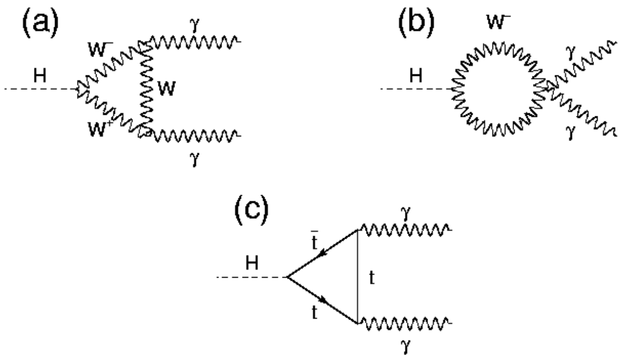
$$\Rightarrow \sigma_{ii \to H \to oo} = \sigma^{SM}_{ii \to H \to oo} \times \frac{\kappa_i^2 \, \kappa_o^2}{\kappa_H^2}$$

$$\left(\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}} = \sum_o \kappa_o^2 BR^{SM}_{H \to oo}\right)$$

$\Rightarrow$ Several couplings: $\kappa_W, \ \kappa_Z, \ \kappa_t, \ \kappa_b, \ \kappa_\tau \ \ldots$

Assume weak gauge boson universality: $\kappa_W = \kappa_Z = \kappa_V$ and fermion universality: $\kappa_t = \kappa_b = \kappa_\tau = \kappa_f$





Loop-mediated interactions described as in SM:

$gg \to H$ (mainly) through top quark virtual loop

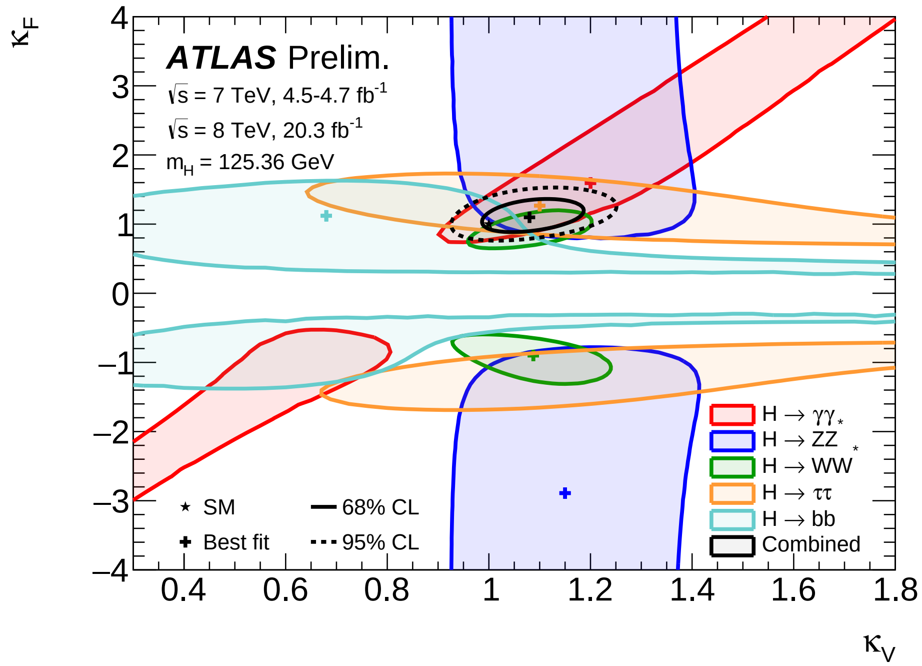
$\Rightarrow \kappa_g = \kappa_t = \kappa_f$

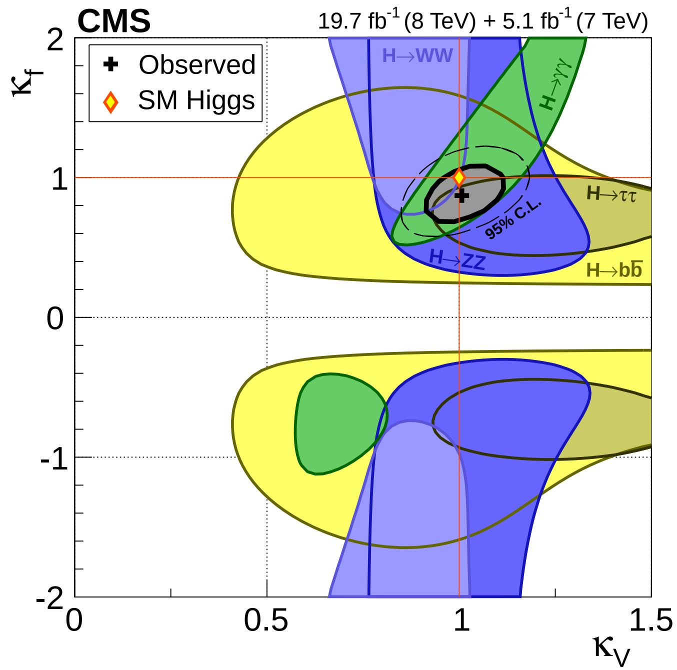
$H \to \gamma\gamma$ through top and W virtual loops

$\Rightarrow \kappa_\gamma^2 = (1.26\,\kappa_W - 0.26\,\kappa_t)^2 = (1.26\,\kappa_V - 0.26\,\kappa_f)^2$

(Universal) couplings to fermions and weak bosons

⇒ measure κ_V, κ_f for each decay channel $H \to \gamma\gamma$, $H \to WW^*$, $H \to ZZ^*$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$
⇒ then combine decay channels

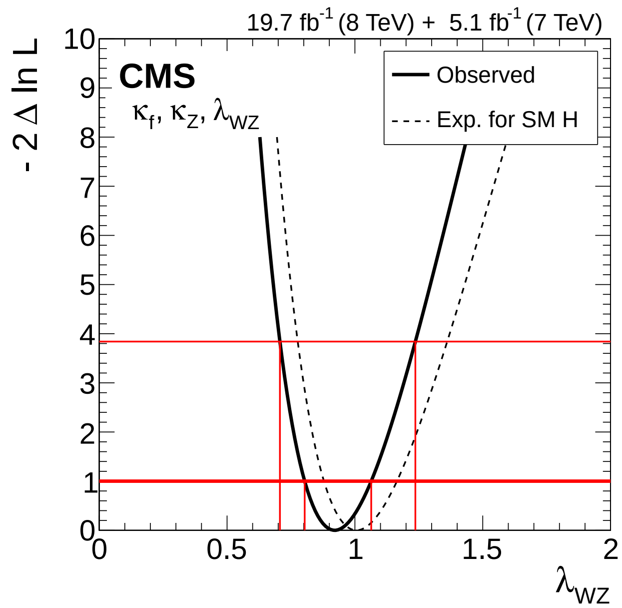




⇒ all measurements compatible with SM prediction $(\kappa_V = 1,\ \kappa_f = 1)$

Relaxing some assumptions on couplings . . .

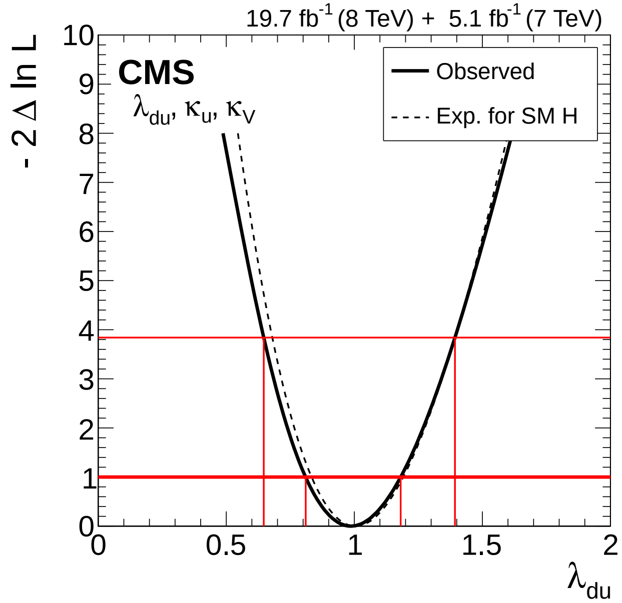
Test the weak gauge boson universality: $\lambda_{WZ} = \dfrac{\kappa_W}{\kappa_Z}$

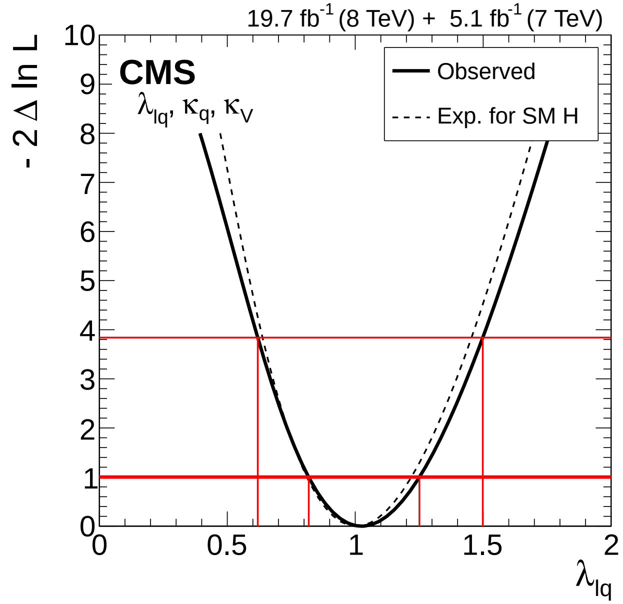


Test the isospin universality for fermions: $\lambda_{du} = \dfrac{\kappa_d}{\kappa_u}$

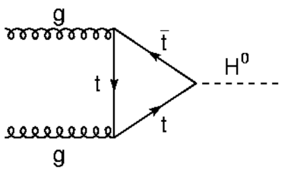
(“u”/“d” refers to fermions isospin $+/-\ \frac{1}{2}$)

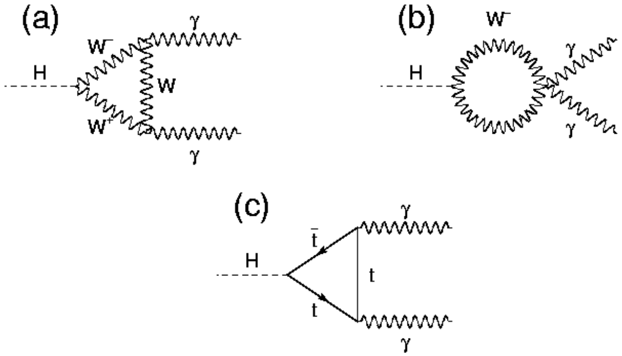
and lepton/quark universality: $\lambda_{\ell q} = \dfrac{\kappa_\ell}{\kappa_q}$





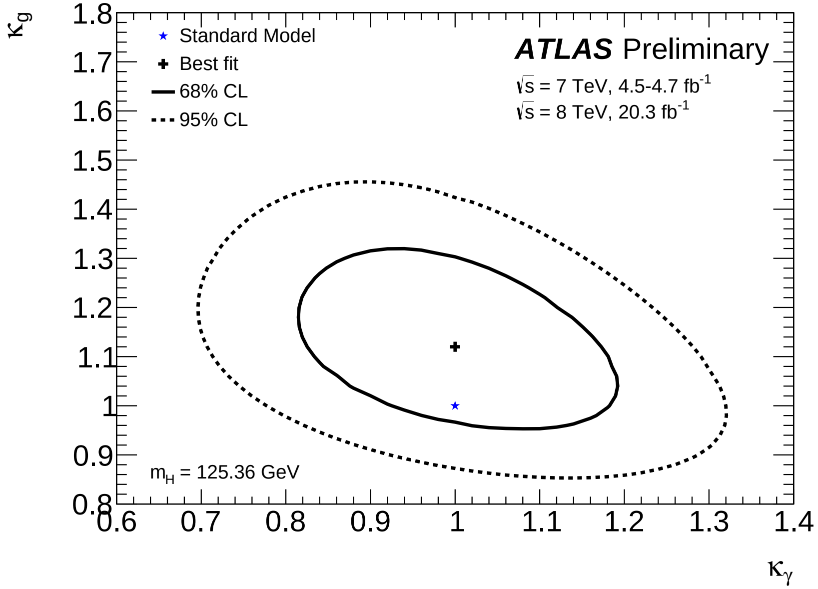
Tests on ggH and $H\gamma\gamma$ interactions

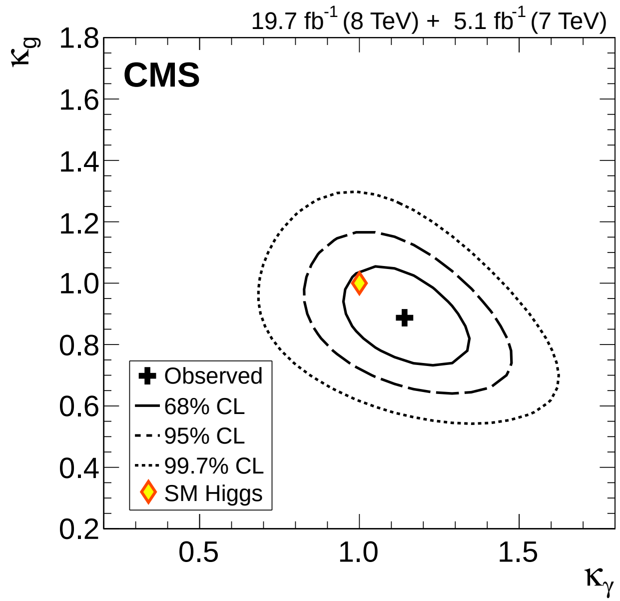




ggH and $H\gamma\gamma$ interactions in SM are mediated by loops
$\Rightarrow$ particularly sensitive to new particles in the loops

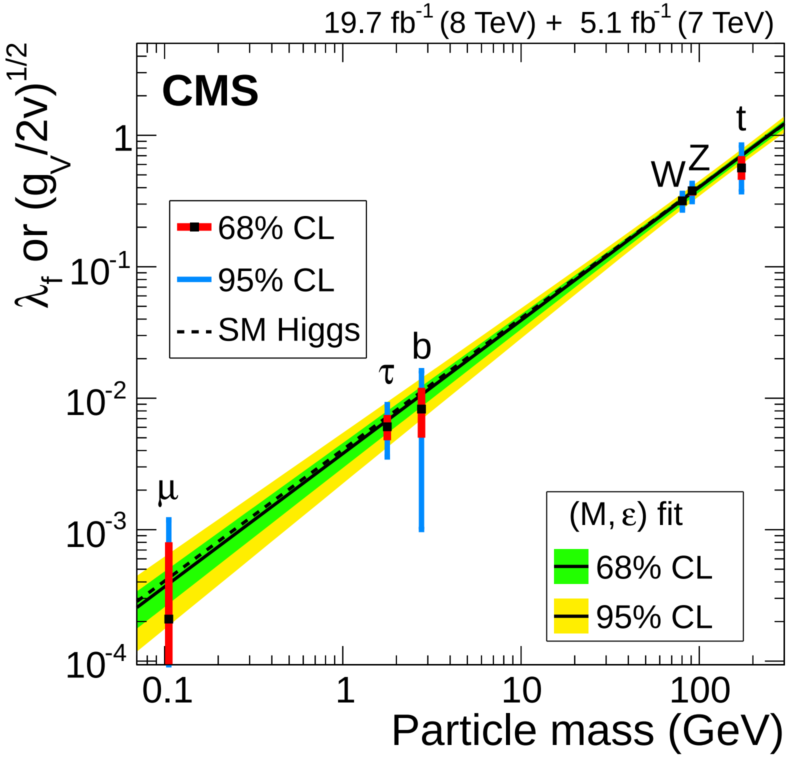
$\Rightarrow$ consider κ_g, κ_γ as free and profile others

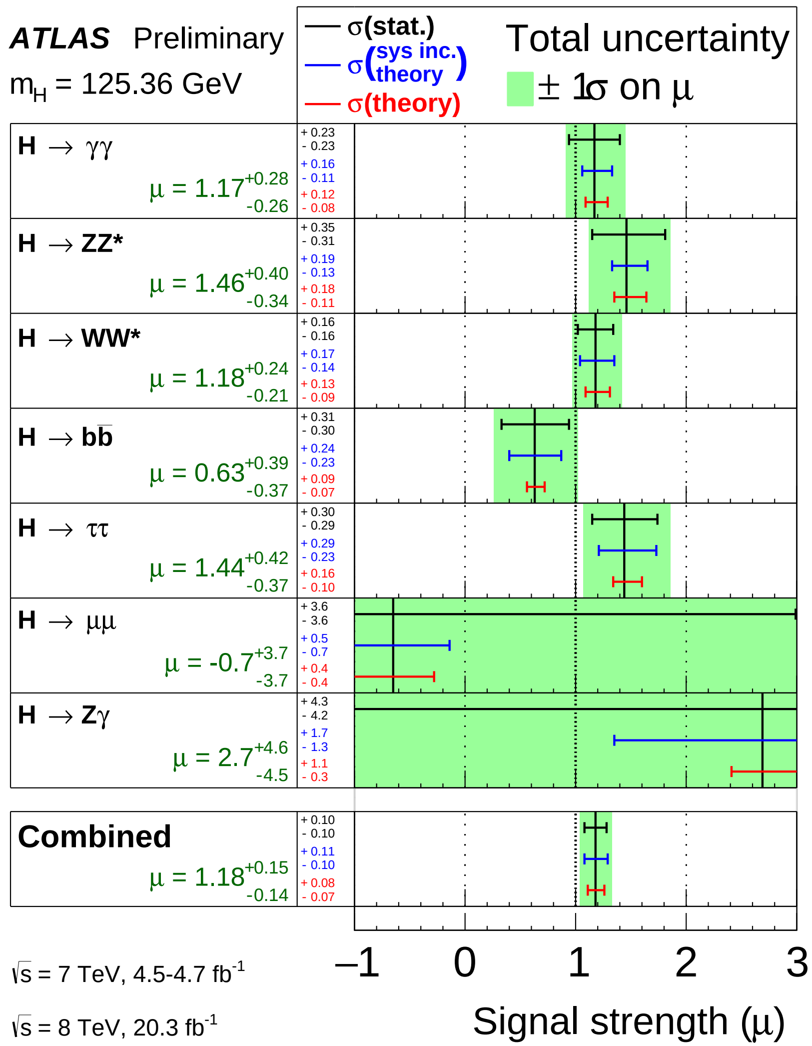




Summary of the couplings and signal strengths

So far, none of the measurements shows discrepancies wrt Standard Model predictions





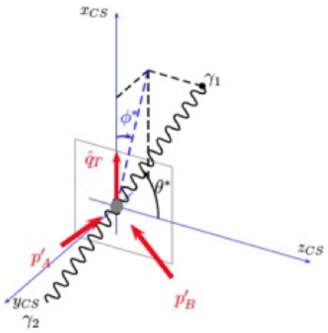
g_f and $\sqrt{\frac{g_V}{2v}}$ scale with m_f, m_V as expected!

BUT : uncertainties are sizable! (stat, experimental syst, and theory)

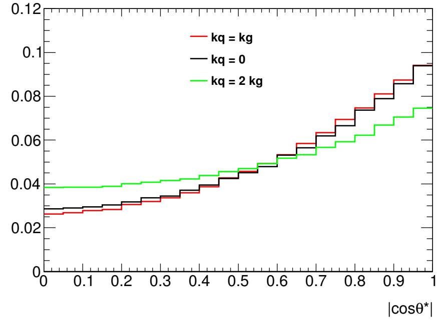
Spin hypothesis test and parity measurements

Spin/parity measurement

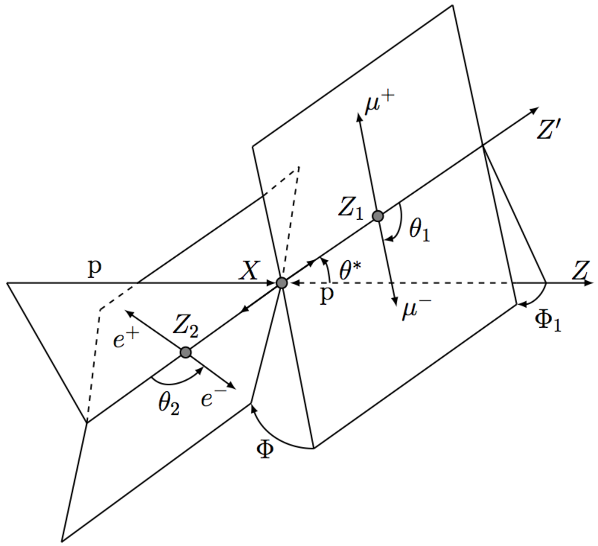
$H \to \gamma\gamma$: flat $|\cos\theta^*|$ for spin-0, sensitive to spin-2



spin 2



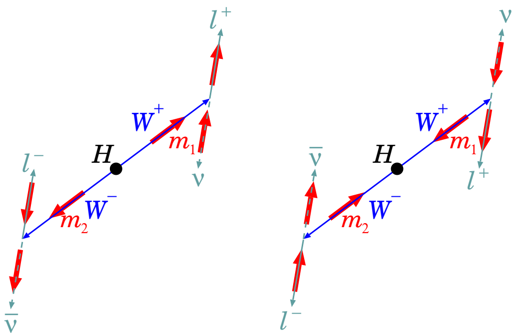
$H \to ZZ^* \to 4\ell$:

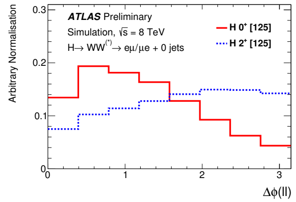


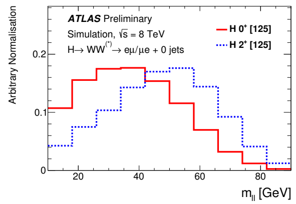
several angular observables + m_{12}, m_{34} sensitive to spin and parity

$H \to WW^* \to \ell\nu\ell\nu$: W^+/W^- spin correlation

spin 0





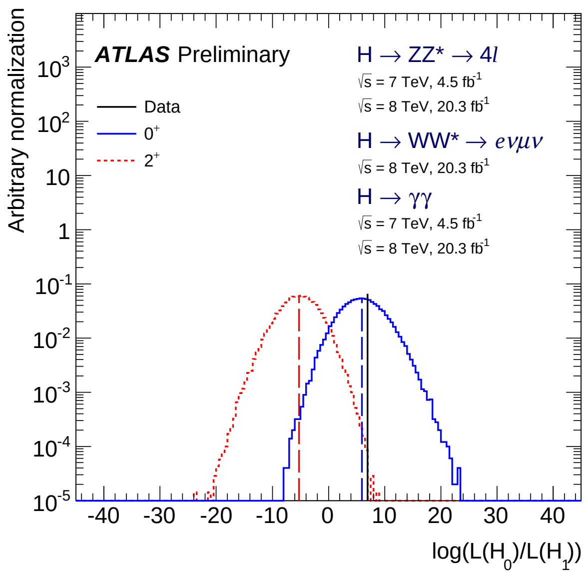


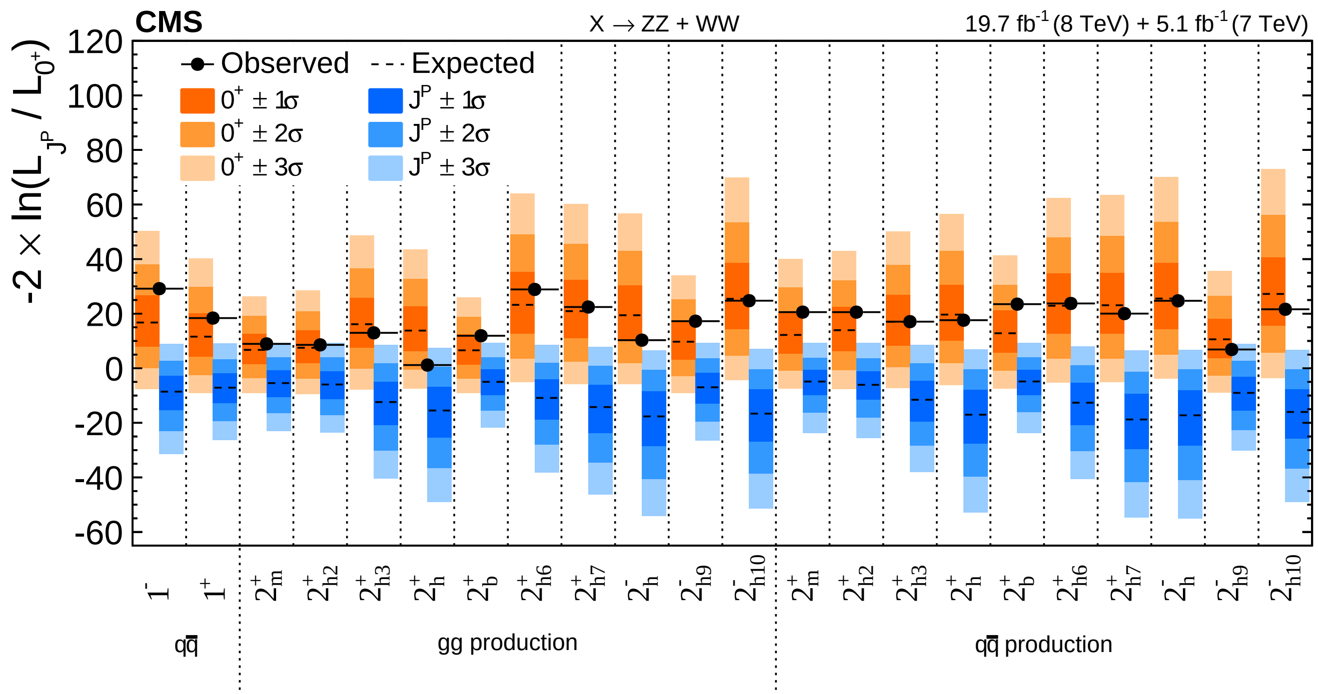
sensitive to spin and parity

Spin-2 tests

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

$$\begin{aligned}
A(X_{J=2}VV) \sim \Lambda^{-1}\Big[& 2c_1^{VV} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2^{VV} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\
&+ c_3^{VV} t_{\beta\nu}\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2}\left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}\right) + c_4^{VV} t_{\mu\nu}\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} f^{*1,\alpha\beta} f^{*2}_{\alpha\beta} \\
&+ m_V^2\left(2c_5^{VV} t_{\mu\nu}\epsilon^{*\mu}_{V1}\epsilon^{*\nu}_{V2} + 2c_6^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}\left(\epsilon^{*\nu}_{V1}\epsilon^{*\alpha}_{V2} - \epsilon^{*\alpha}_{V1}\epsilon^{*\nu}_{V2}\right) + c_7^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2}\epsilon^*_{V1}\epsilon^*_{V2}\right) \\
&+ c_8^{VV} t_{\mu\nu}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} f^{*1,\alpha\beta}\tilde{f}^{*2}_{\alpha\beta} \\
&+ m_V^2\left(c_9^{VV} t^{\mu\alpha}\frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}_{V1}\epsilon^{*\rho}_{V2} q^\sigma}{\Lambda^2} + c_{10}^{VV} t^{\mu\alpha}\frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma\left(\epsilon^{*\nu}_{V1}(q\epsilon^*_{V2}) + \epsilon^{*\nu}_{V2}(q\epsilon^*_{V1})\right)}{\Lambda^4}\right)\Big]
\end{aligned}$$

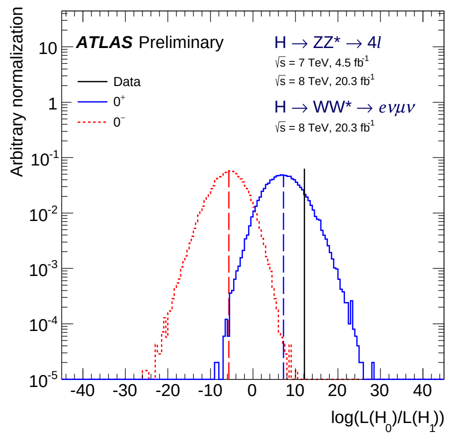




⇒ **data favour spin-0**

Parity and CP-mixing

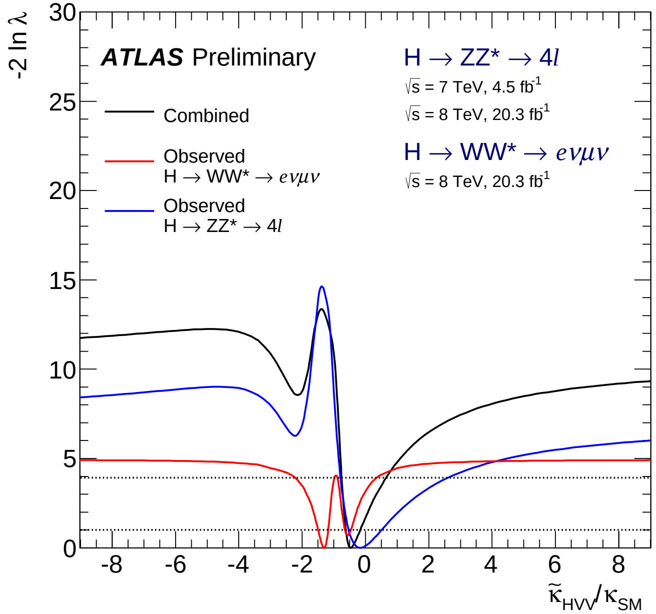
$$
\begin{aligned}
\mathcal{L}_0^V \;=\; X_0 \cdot \Big\{ & \cos\alpha\ \kappa_{\rm SM}\left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right] \\
& -\frac{1}{4\Lambda}\left[\cos\alpha\ \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin\alpha\ \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\
& -\frac{1}{2\Lambda}\left[\cos\alpha\ \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \sin\alpha\ \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\}
\end{aligned}
$$

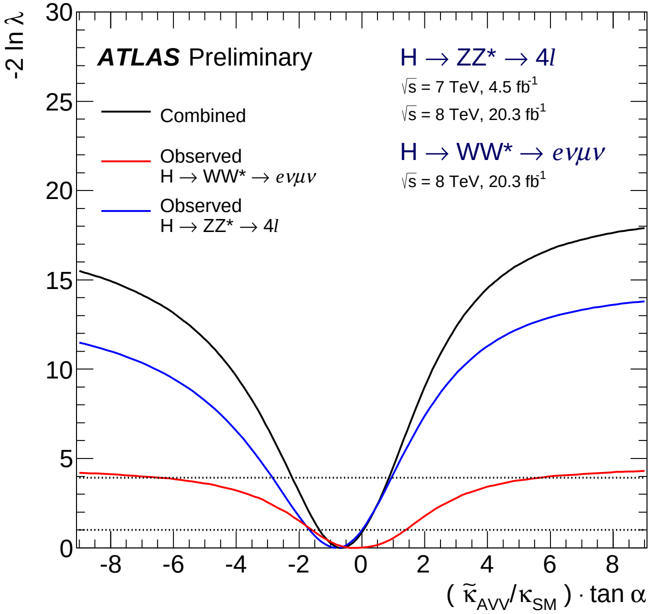


Standard Model : $\alpha = 0\ ,\ \kappa_{HVV} = 0\ ,\ \kappa_{AVV} = 0$

Beyond SM : $\kappa_{HVV} \Rightarrow CP$-even , $\kappa_{AVV} \Rightarrow CP$-odd

CP-mixing for $\alpha \neq 0$ and $\alpha \neq \frac{\pi}{2}$





$$\tilde{\kappa}_{HVV} = \frac{v}{4\Lambda}\kappa_{HVV}$$
$$\tilde{\kappa}_{AVV} = \frac{v}{4\Lambda}\kappa_{AVV}$$

$\Rightarrow \tilde{\kappa}_{HVV},\ \tilde{\kappa}_{AVV}$ compatible with 0

Width measurement

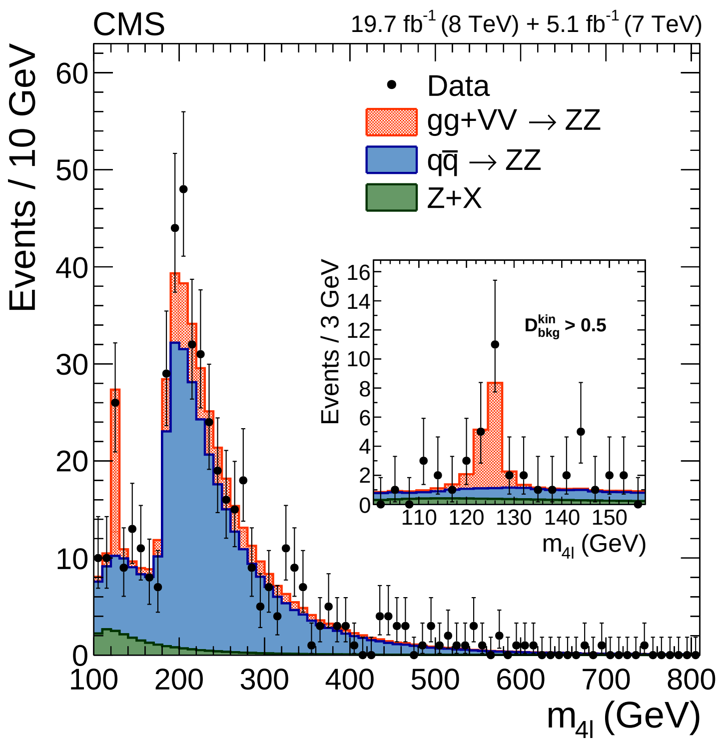
Width measurement

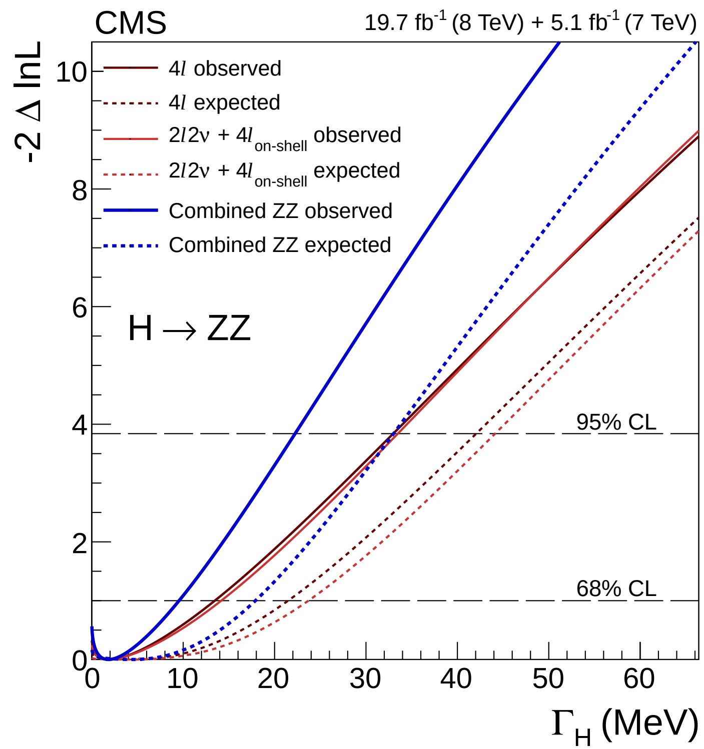
In Standard Model, the Higgs decay width is expected to be $\Gamma_H \simeq 4\ \mathrm{MeV}$
$\Rightarrow$ cannot measure it from the observed resonance width (experimental uncertainty $\mathcal{O}(\mathrm{GeV})$)

Use $H \to ZZ^{(*)} \to 4\ell$ decays.
Compare Higgs on-shell ($gg \to H \to ZZ^*$) and off-shell ($gg \to H^* \to ZZ$) production cross-sections:

$$\sigma_{gg\to H\to ZZ^*} \propto \frac{g_{Hgg}^{(\sqrt{\hat{s}}=m_H)} \cdot g_{HZZ}}{\Gamma_H m_H} \quad ; \quad \sigma_{gg\to H^*\to ZZ} \propto \frac{g_{Hgg}^{(\sqrt{\hat{s}}=2m_Z)} \cdot g_{HZZ}}{(2m_Z)^2}$$

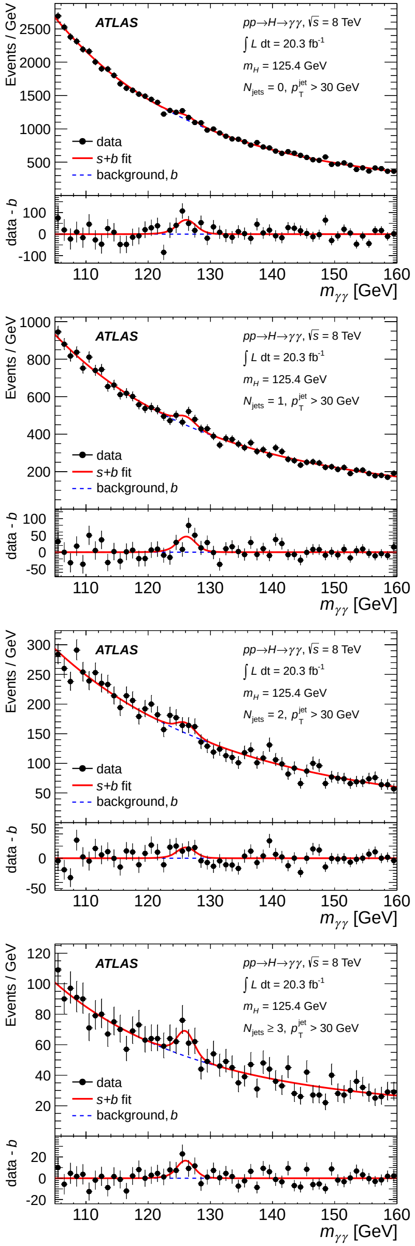
$\Rightarrow$ under specific assumptions on g_{Hgg}, g_{HZZ}, their ratio gives a measurement of Γ_H
(e.g. need to assume that g_{Hgg} be completely described by SM loops and scale accordingly with partonic $\sqrt{\hat{s}}$)



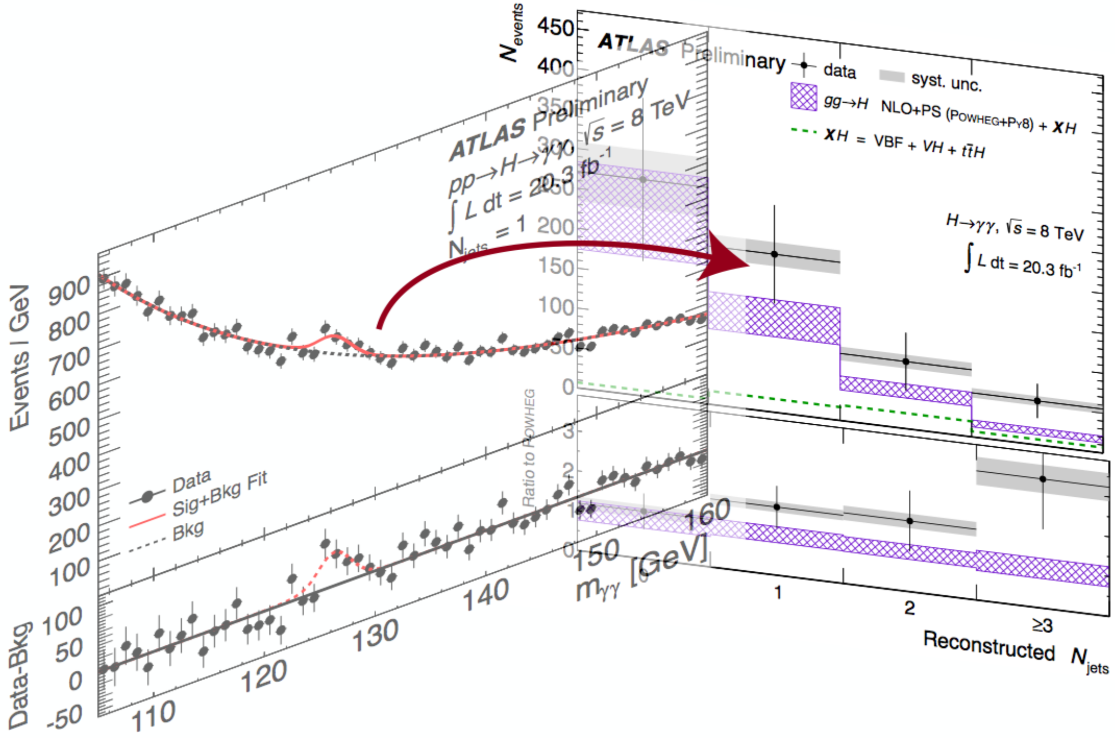


Differential cross-sections

Extraction of signal yield per category . . .



- divide events in categories (e.g. number of jets, bins of $p_T^{\gamma\gamma}$, bins of $Y_{\gamma\gamma}$, etc . . .)
- from the invariant mass spectrum, extract the signal yield in each category / bin

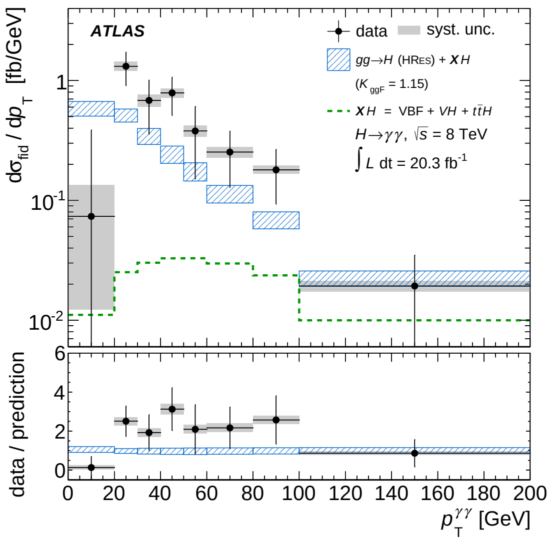


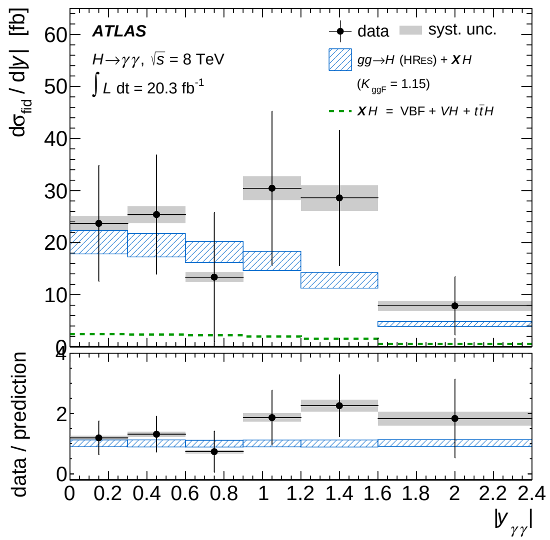
- then unfold the experimental effects (efficiencies, migrations, . . .)

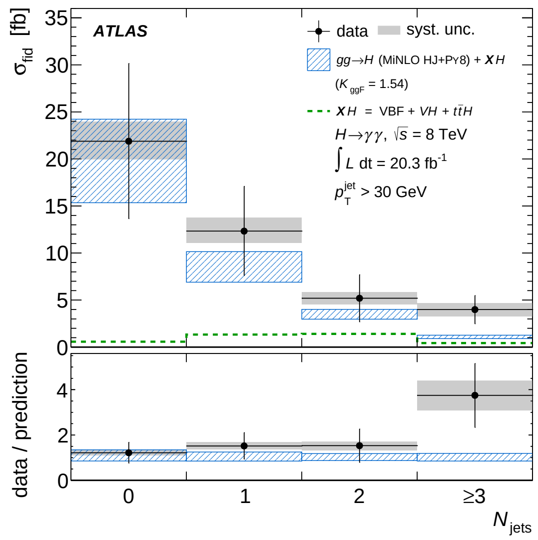
$\Rightarrow$ get the cross-section per category / bin

Differential cross-sections

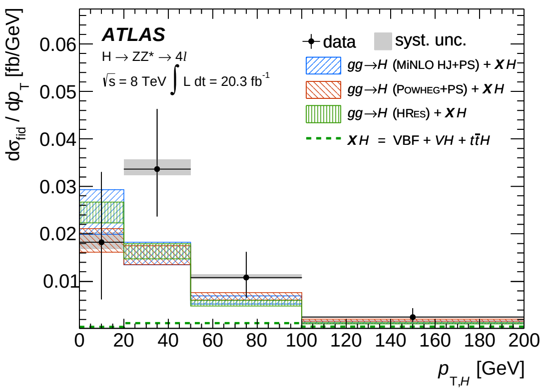
H $\to \gamma\gamma$

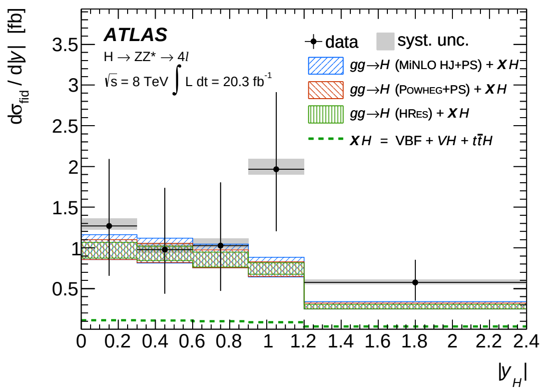


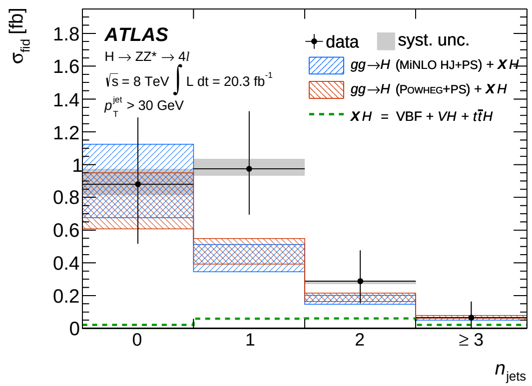




H $\to$ ZZ* $\to 4\ell$







Summary

The state of the art

ATLAS and CMS have analysed all LHC run-1 data.
Strong evidence for $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\nu\ell\nu$, $H \to \tau^+\tau^-$

The new particle is compatible with a state $J^{CP} = 0^{++}$ — several alternative states disfavoured to $> 99\%$ CL.

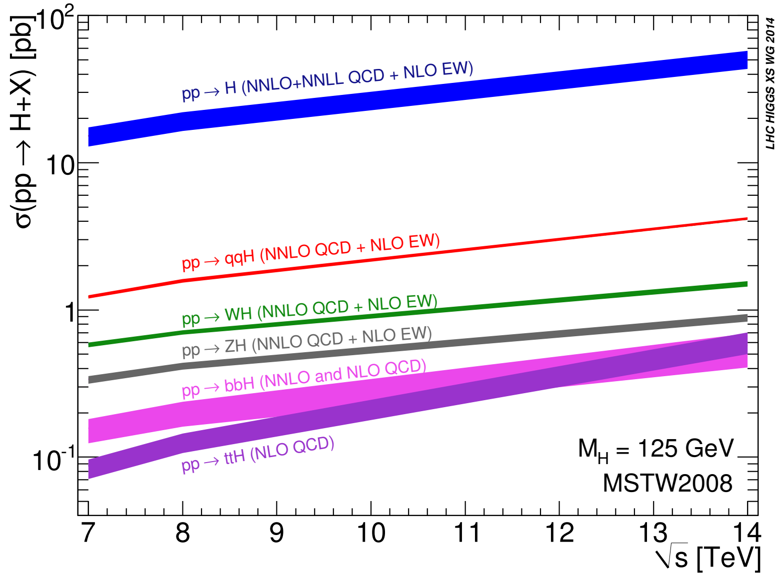
All couplings' measurements do not show any significant deviation from the Standard Model predictions
— but measurements of individual κ's are precise to $\approx 10\% - 30\%$
— affected by statistics, experimental effects, and theory uncertainties

"New results indicate that particle discovered at CERN is a Higgs boson" — CERN press release

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. [...] The new particle is looking more and more like a Higgs boson [...] It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. [...] To characterize all of the decay modes will require much more data from the LHC.

Perspectives at LHC run-II

LHC recently delivered 1st p-p collisions at 13 TeV— we are back into the game!



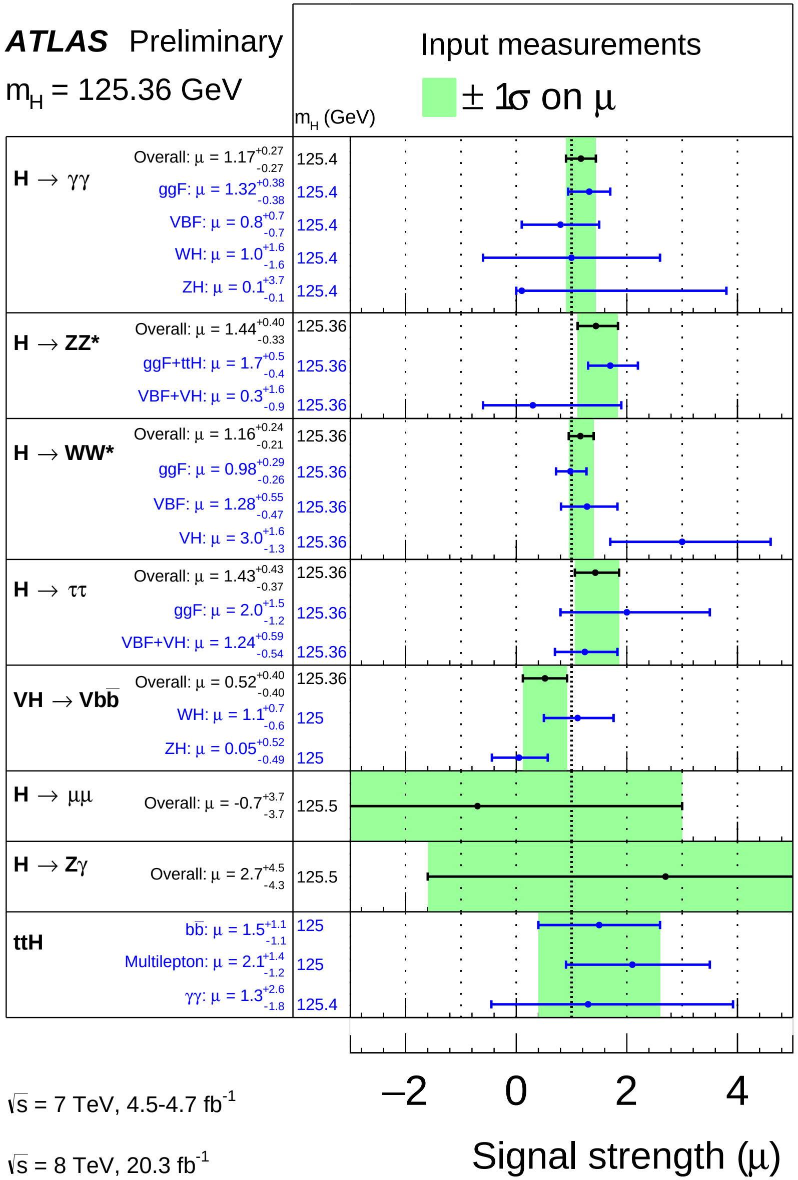
Run-II program (2015–2018)
p-p collisions at $\sqrt{s} = 13$ (14?) TeV
$\Rightarrow$ σ_H increases by a factor 2.3 (2.6 at 14 TeV)
Foreseen integrated lumi 100 fb^{-1} per experiment (10 fb^{-1} in 2015 ?)
$\Rightarrow$ with 100 fb^{-1}, $\approx$ 10 $\times$ more Higgs events than in run-I
(and similar increase in backgrounds. . .)

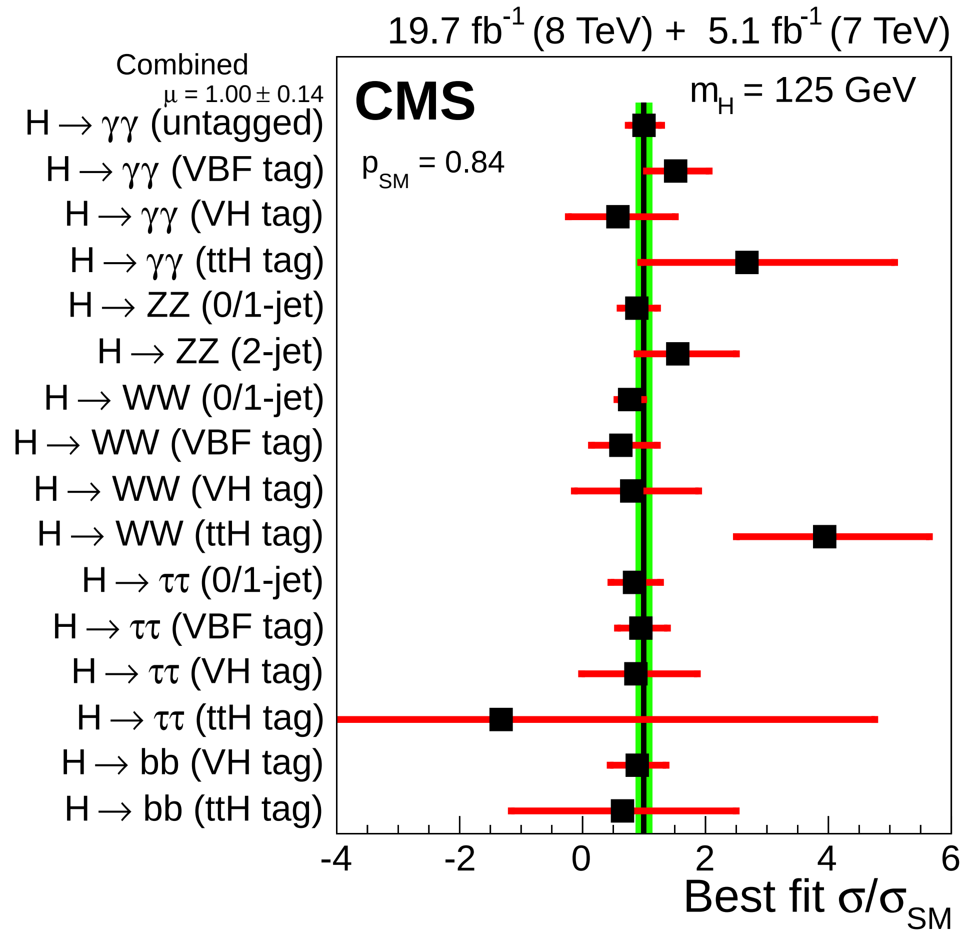
Presently, theory prediction are dominated by PDF and α_S uncertainties, and QCD scales ($\approx 7\% \oplus 7\%$ overall)
Hard work ongoing from theorists on PDFs: more NNLO computations, more LHC processes introduced in the fits, better methodology. Also, Higgs partonic cross-section evaluated at N^3LO.
$\Rightarrow$ expect theory uncertainties to reduce sizably (down to $\sim 3\%$?)

Some "educated guesses"
— With 100 fb^{-1}at 13–14 TeV:
Precise measurements of $H \to \tau^+\tau^-$, observation of $H \to b\bar{b}$, evidence of $t\bar{t}H$ production
— With 300 fb^{-1}at 14 TeV(2020–2022):
Evidence of $H \to \mu^+\mu^-$, precision measurements of all individual κ's to $\lesssim 10\%$ accuracy

More material

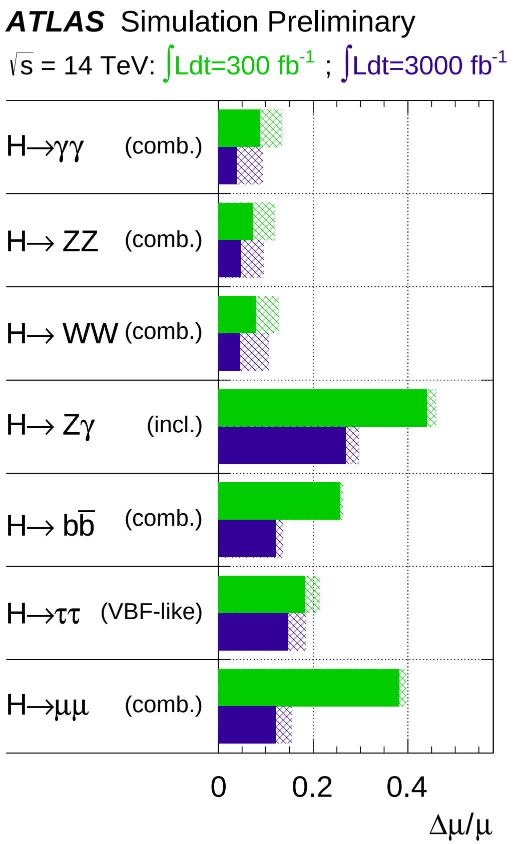
Summary of the signal strengths

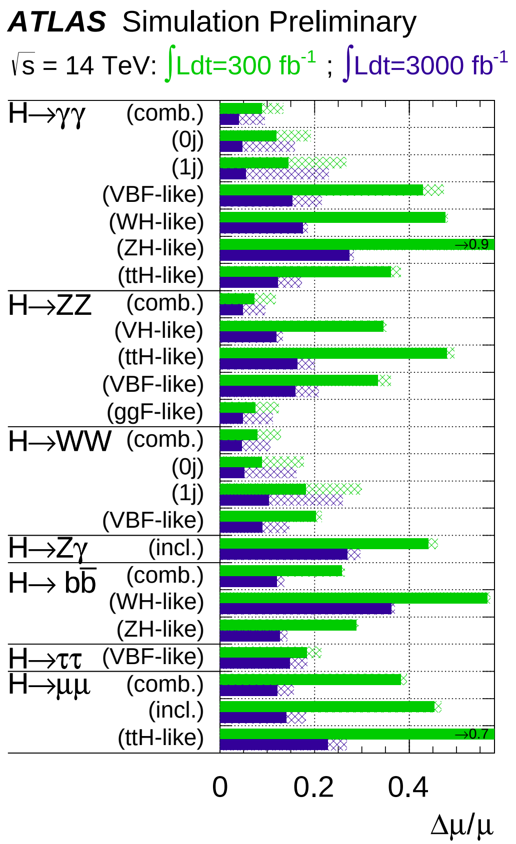


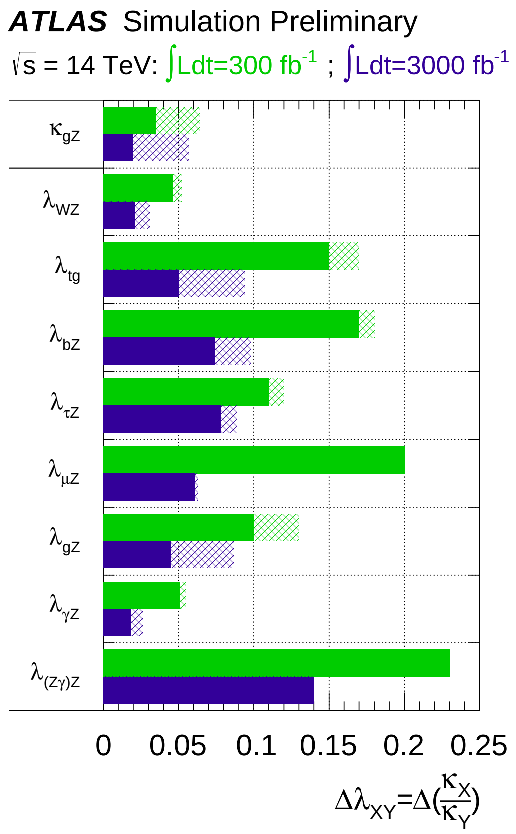


So far, none of the measurements shows discrepancies wrt Standard Model predictions

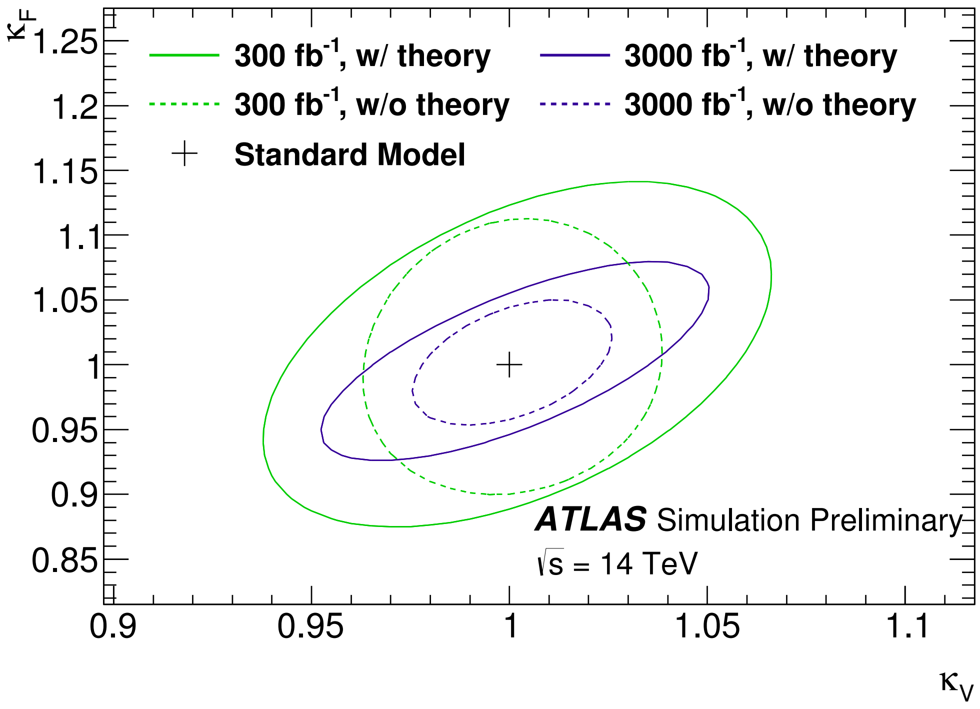
Expectations for 300 and 3000 fb^{-1}

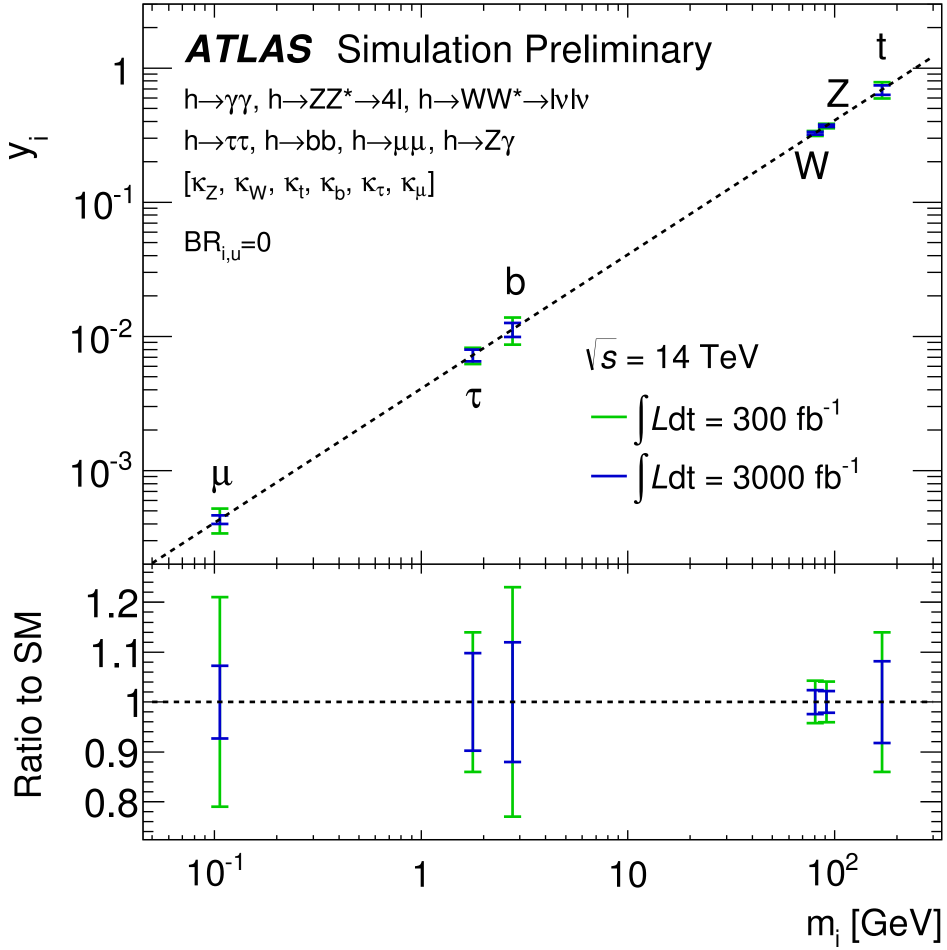






Expectations for 300 and 3000 fb^{-1}



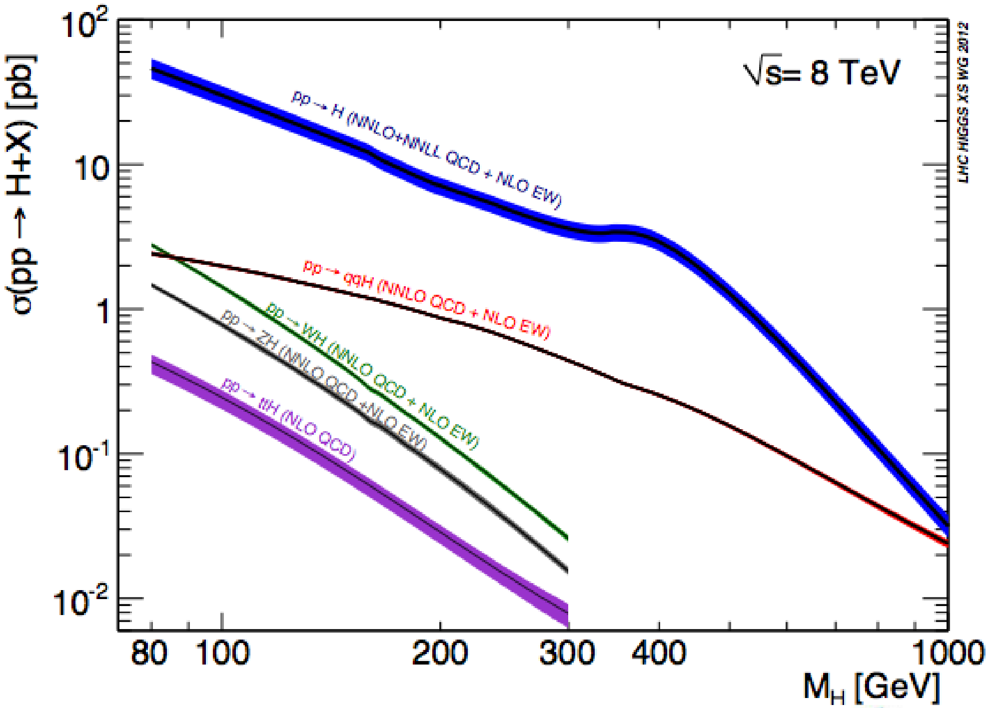


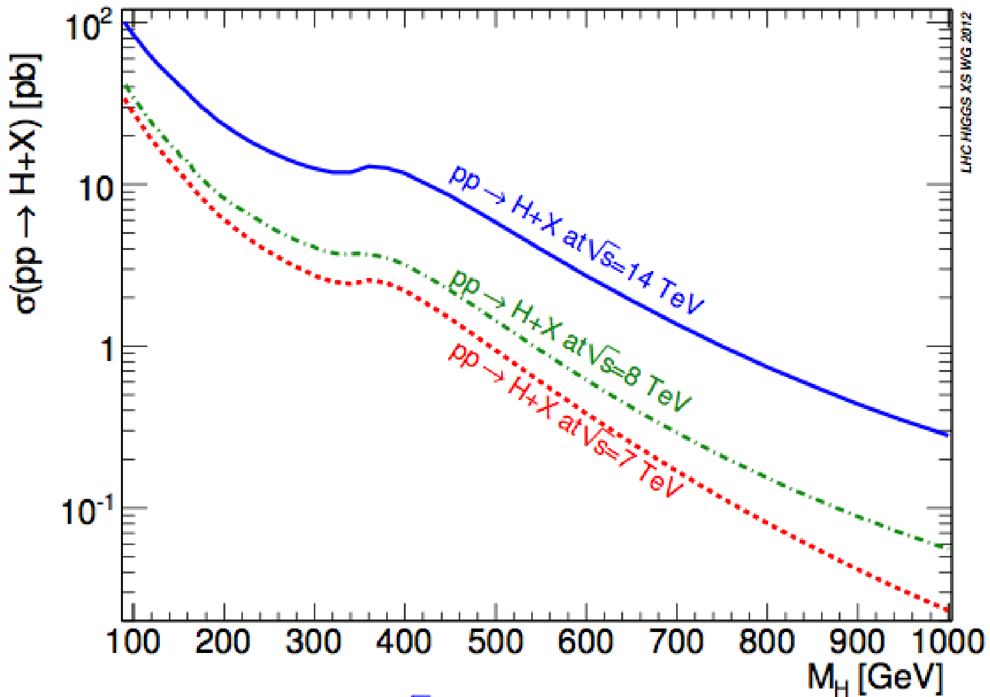
Expectations for 300 and 3000 fb^{-1}

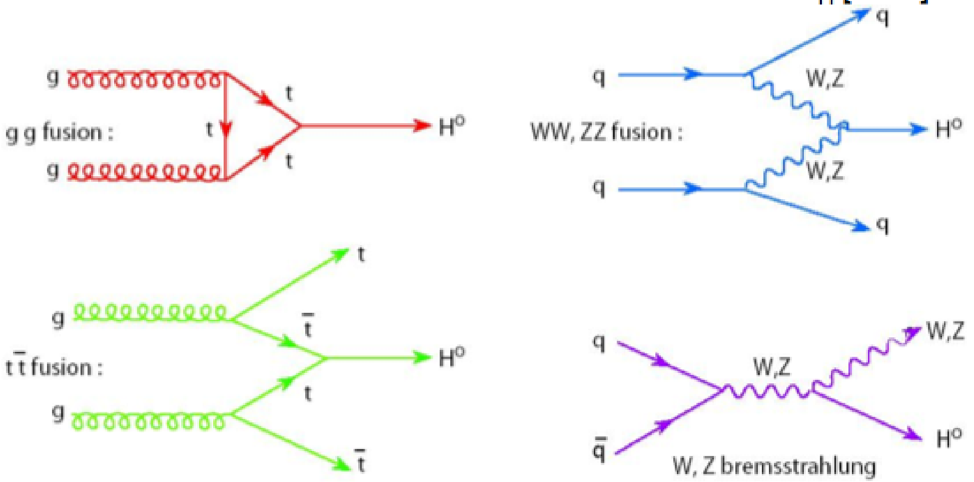
Expected uncertainties on $\kappa \equiv \frac{g}{g^{SM}}$ at 300 fb^{-1} and 3000 fb^{-1}.

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	4.2%	3.0%	2.4%	3.2%	2.2%	1.7%
2	$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%
3	κ_Z	4.7%	3.7%	3.3%	3.3%	2.3%	1.9%
	κ_W	4.9%	3.6%	3.1%	3.6%	2.4%	1.8%
	κ_F	9.3%	7.9%	7.3%	5.4%	4.0%	3.4%
4	κ_V	5.9%	5.4%	5.3%	3.7%	3.2%	3.0%
	κ_u	8.9%	7.7%	7.2%	5.4%	4.0%	3.4%
	κ_d	12%	12%	12%	6.7%	6.2%	6.1%
5	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	8.7%	7.8%	6.6%	4.5%	3.6%
	κ_l	10%	9.6%	9.3%	6.0%	5.3%	5.1%
6	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	9.0%	8.1%	6.7%	4.7%	3.8%
	κ_τ	12%	11%	11%	9.2%	8.4%	8.1%
	κ_μ	20%	20%	19%	6.9%	6.3%	6.1%
7	κ_Z	8.1%	7.9%	7.8%	4.3%	3.9%	3.8%
	κ_W	8.5%	8.2%	8.1%	4.8%	4.1%	3.9%
	κ_t	14%	12%	11%	8.2%	6.1%	5.3%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	13%	13%	9.8%	9.0%	8.7%
	κ_μ	21%	21%	21%	7.3%	7.1%	7.0%
8	κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
	κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
	κ_t	22%	21%	20%	11%	8.5%	7.6%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
	κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
	κ_g	14%	12%	11%	9.1%	6.5%	5.3%
	κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
	$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Higgs production at LHC





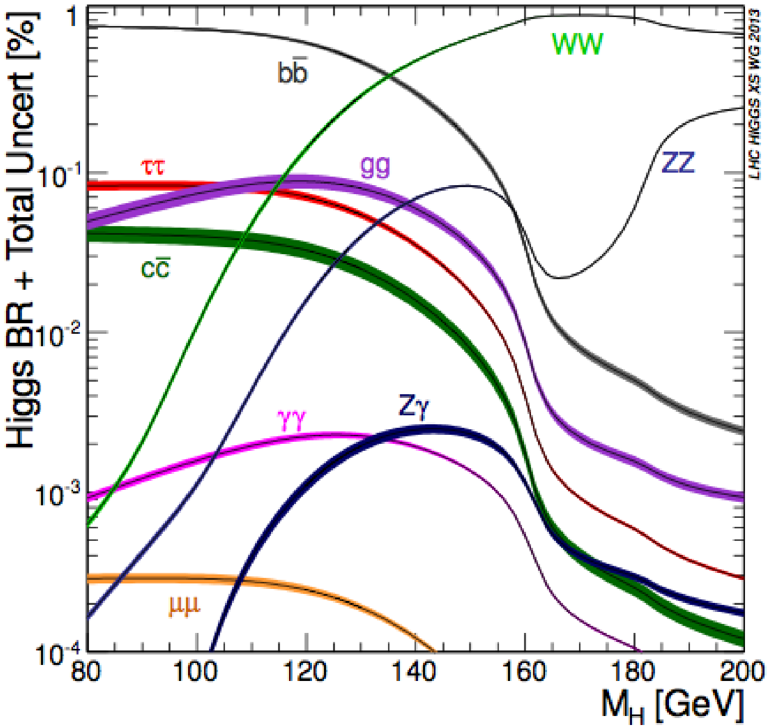


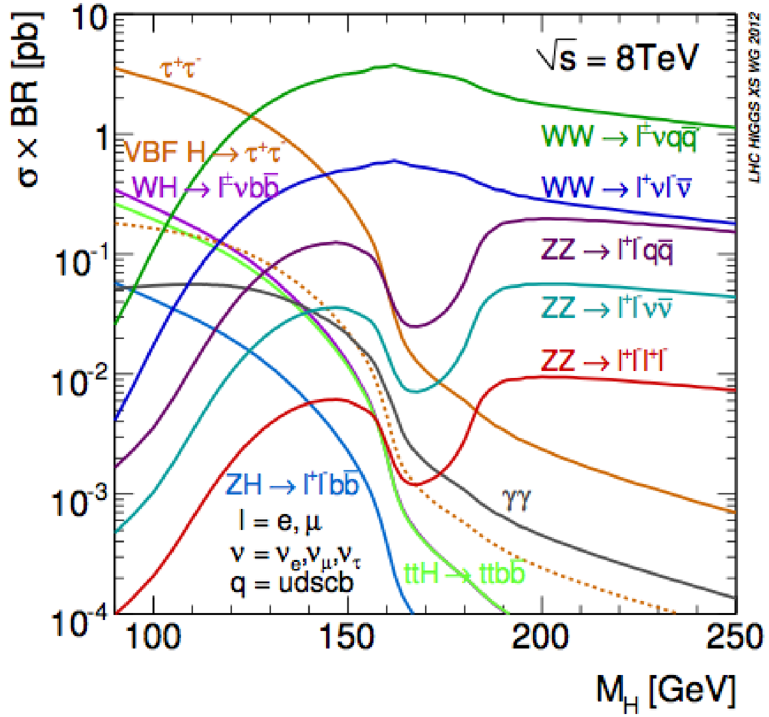
cross-sections at $\sqrt{s} = 8$ TeV for $m_H = 125$ GeV

production	σ_H (pb)	(%)	uncertainty (%) (QCD scale)	(PDF $\oplus\ \alpha_S$)
ggF	19.27	87.2%	+7.2% −7.8%	+7.5% −6.9%
VBF	1.578	7.1%	+0.2% −0.2%	+2.6% −2.8%
WH	0.7046	3.2%	±1.0%	±2.3%
ZH	0.4153	1.9%	±3.1%	±2.5%
$t\bar{t}H$	0.1293	0.6%	+3.8% −9.3%	+8.1% −8.1%

Higgs decay modes

All hadronic decay modes ($H \to b\bar{b}$ and $H \to ZZ, W^+W^- \to q\bar{q}q\bar{q}$) are dominant, but overwhelmed by the QCD backgrounds! $\Rightarrow$ final states with isolated leptons, photons, missing transverse energy are the only viable





$H \to$	BR (@ $m_H = 125$ GeV)	$\sigma \cdot BR$ (fb)	events produced with 25 fb^{-1}	mass resolution	m_H range	background
$\gamma\gamma$	$2.28 \cdot 10^{-3}$	50	1250	☺☺	$\lesssim 150$ GeV	☹
$ZZ^* \to 4\ell$	$1.25 \cdot 10^{-4}$	2.7	67	☺☺	$\gtrsim 130$ GeV	☺
$WW^* \to \ell\nu\ell\nu$	$1.06 \cdot 10^{-2}$	230	5700	☹☹☹	anywhere	☹
$\tau^+\tau^-$ (VBF)	$6.32 \cdot 10^{-2}$	100	2500	☹	$\lesssim 150$ GeV	☹☹
$b\bar{b}$ (VH, $Z \to \ell^+\ell^- + W \to \ell\nu$)	$5.77 \cdot 10^{-1}$	106	2600	☹	$\lesssim 150$ GeV	☹☹

Cross-sections at LHC

Main reactions, in order of decreasing cross-section:

process	cross-section (pb) at $\sqrt{s} = 8$ TeV	events/s at $L = 10^{33}$ cm^{-2}s^{-1}
low-Q^2 QCD ("minimum bias")	$\approx 10^{11}$	$\approx 10^{8}$
high-Q^2 QCD	$\approx 10^{9}$	$\approx 10^{6}$
W production	$\approx 10^{5}$	≈ 100
Z production	$\approx 5 \cdot 10^{4}$	≈ 50
$t\bar{t}$ production	≈ 240	≈ 0.24
SM Higgs ($m_H = 125$ GeV)	≈ 22	≈ 0.022

The "interesting processes" are overwhelmed by QCD interactions: typically events with two or more hadronic jets, balanced in transverse momentum $\vec{P}_T$.

$\Rightarrow$ We need to apply several filters, starting from the trigger and then in the off-line analysis

- an isolated lepton ($\ell^\pm \equiv e^\pm, \mu^\pm$) or photon with high transverse momentum p_T
- a large missing transverse momentum $\not{\vec{P}}_T$
- combinations of more $\ell^\pm$ and/or γ and/or $\not{\vec{P}}_T$, possibly with lower thresholds