Standard Model Higgs basics (2nd class)

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Overview

Chapter 1: Introduction and electroweak symmetry breaking

Chapter 2: Interactions of the Higgs boson with
- gauge bosons
- fermions
- another Higgs boson

YESTERDAY

Phenomenology of the SM Higgs boson

Chapter 3: Precision determination of the Higgs couplings

Chapter 4: Higgs properties to understand better

TODAY

Goal: Introduce the basics of the Standard Model Higgs boson (theory + pheno)

Please interrupt to ask questions! We do not have to go through all slides! :)

You can also contact me per email: sgori@ucsc.edu

Yesterday we left with…

- Higgs couples to <u>fermion</u> mass:

$$\mathcal{L} \supset -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}(\bar{f}_L f_R + \bar{f}_R f_L)h$$

Largest coupling is to heaviest fermion
Is the top quark special?

We do not know if
the Higgs couples to neutrinos:

$$\bar{L}_L^i Y_N^{ij} N_R^j \tilde{\Phi}$$

do they exist?

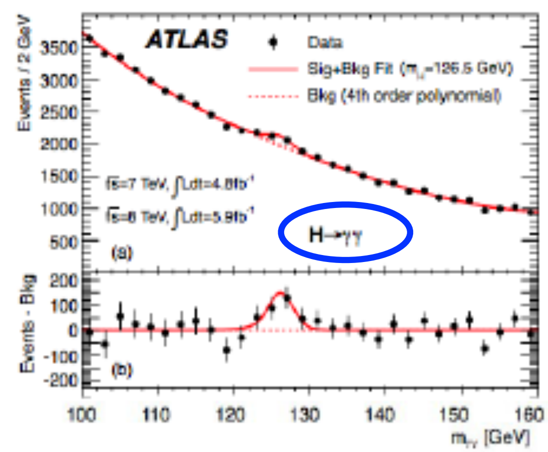
- Higgs couples to <u>gauge boson</u> mass:

$$\mathcal{L} \supset 2\frac{m_w^2}{v}W^{\mu+}W_\mu^-h + \frac{m_z^2}{v}Z^\mu Z_\mu h + \cdots$$

2 Higgs - 2 gauge boson interactions

Only free parameter is Higgs mass!

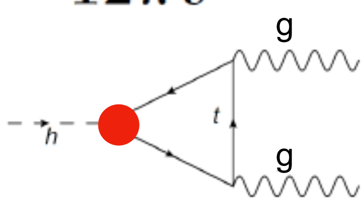
This is only for tree-level couplings…
<u>tomorrow</u> we will discuss
loop-induced couplings &
Higgs phenomenology

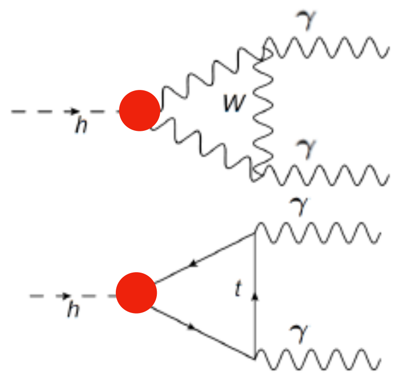


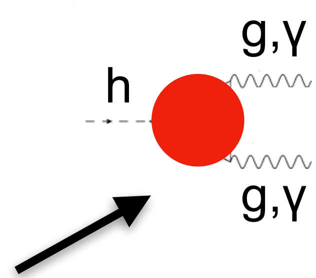
More Higgs couplings: 1 loop

The Higgs couples also to the massless SM photons and gluons

$$c_G \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{\mu\nu a} + c_\gamma \frac{\alpha_{em}}{8\pi v} h F_{\mu\nu} F^{\mu\nu}$$







we can write the couplings in terms of dimension 5 operators

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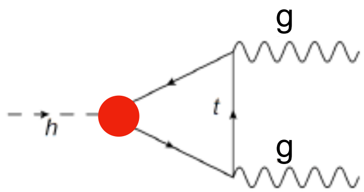
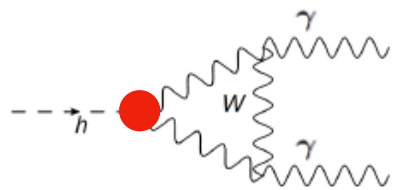
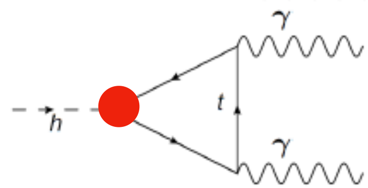
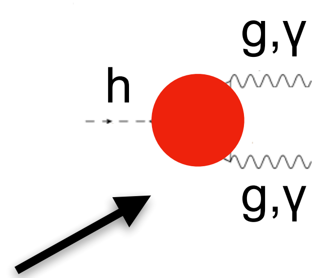








we can write the couplings in terms of dimension 5 operators

At the leading order (LO)

$$c_g^{(\rm SM)} = \frac{3}{4}\left(A_{1/2}(\tau_t) + A_{1/2}(\tau_b)\right)$$

$$c_\gamma^{(\rm SM)} = A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)$$

$$\tau_i \equiv 4m_i^2/m_h^2$$

Smaller NLO corrections to hγγ coupling

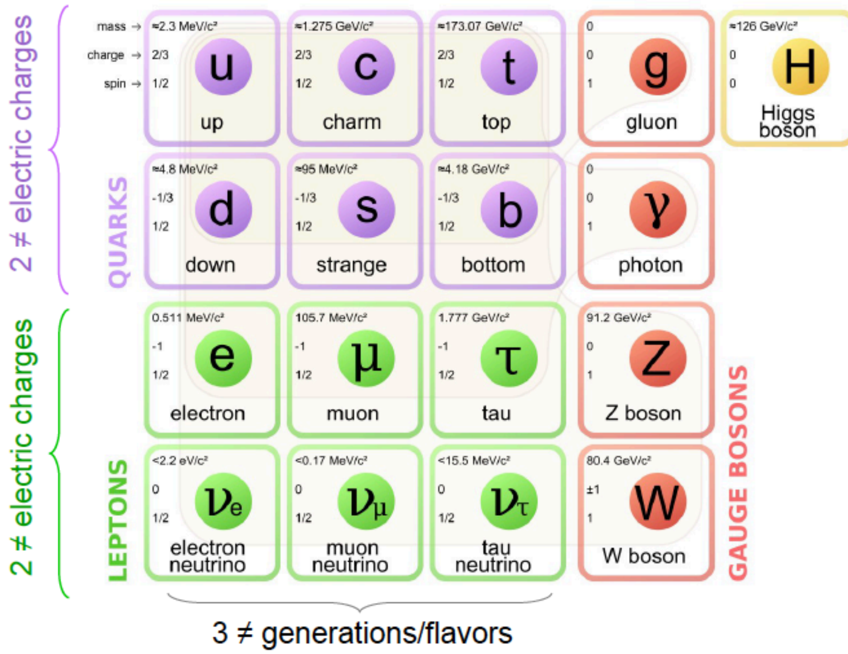
Sizable higher order corrections (computed at N^3LO)

$$c_{g,\rm NLO}^{(\rm SM)} = 1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \left[\frac{2777}{288} - N_f\frac{67}{96} + \left(\frac{19}{16} + \frac{N_f}{3}\right)\log\frac{\mu^2}{m_t^2}\right]\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots$$

$$= 1 + 0.09891 + 0.00796 + \cdots$$

- Djouadi, Spira, Zerwas, 1991
- Dawson, 1991
- Spira, Dawson, Graudenz, Zerwas, 1995

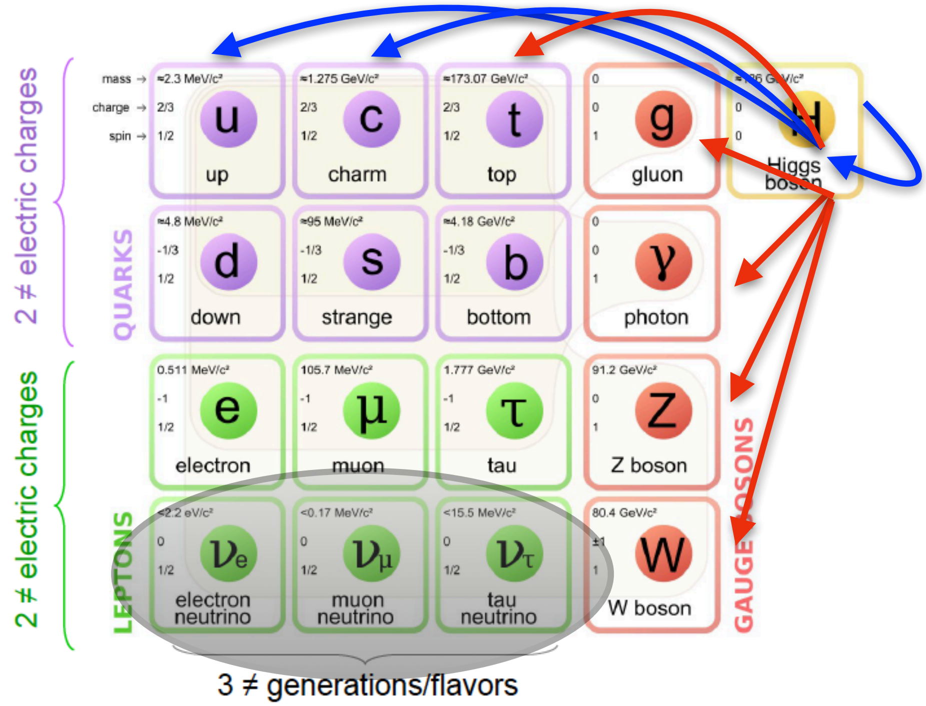
Questions for the remaining of today



Questions for the remaining of today

(1)
Precision determination of the Higgs coupling

couplings proportional to the mass?



coupling to all particles except neutrinos

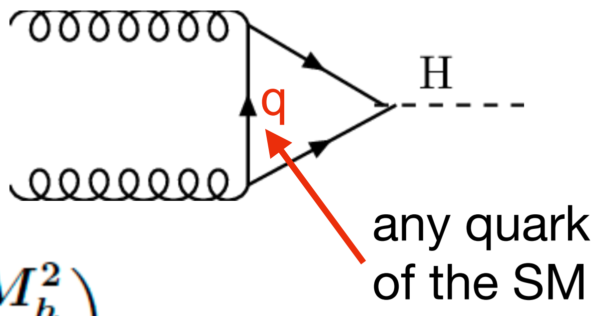
(2)
Higgs properties to understand better

Chapter I

(1) Precision determination of the Higgs couplings

(the ones we have already discovered)

How to make a Higgs boson @ the LHC: gluon fusion



The largest production rate for the Higgs at the LHC is from gluon fusion

$$\sigma(gg \to h)(s) = \frac{\alpha_s^2}{1024\pi v^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta\left(1 - \frac{M_h^2}{s}\right)$$

Largest contribution is from top quarks

Not a direct measurement of tth coupling since there could be new particles in loop

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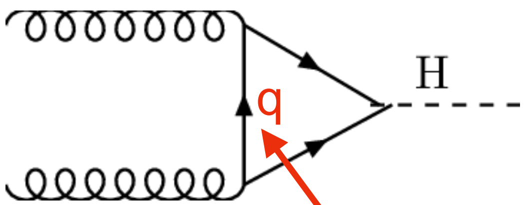

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At the leading order:

- For light quarks: $F_{1/2} \to \left(\frac{m_q}{M_h}\right)^2 \log^2\left(\frac{m_q}{M_h}\right)$
- For heavy quarks: $F_{1/2} \to -\frac{4}{3}$

* No dependence on m_t
* Heavy quarks don't decouple

(since Higgs coupling proportional to mass)

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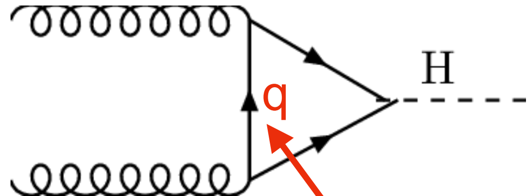

any quark of the SM

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LO → NLO → NNLO → NNNLO

100% increase, 20% increase, 2% increase

1977, 1995, 2002, 2015

From S. Dawson

Ruling out 4^{th} generation quarks

If there was a fourth generation of (heavy) quarks, they would contribute to the Higgs gluon fusion process.

For example, if I add the heavy (T, B) New Physics pair:

$$\sigma(gg \to h) = \sigma(gg \to h)_{\rm SM}(\underset{t}{1} + \underset{T}{1} + \underset{B}{1})^2 = 9\sigma(gg \to h)_{\rm SM}$$

!

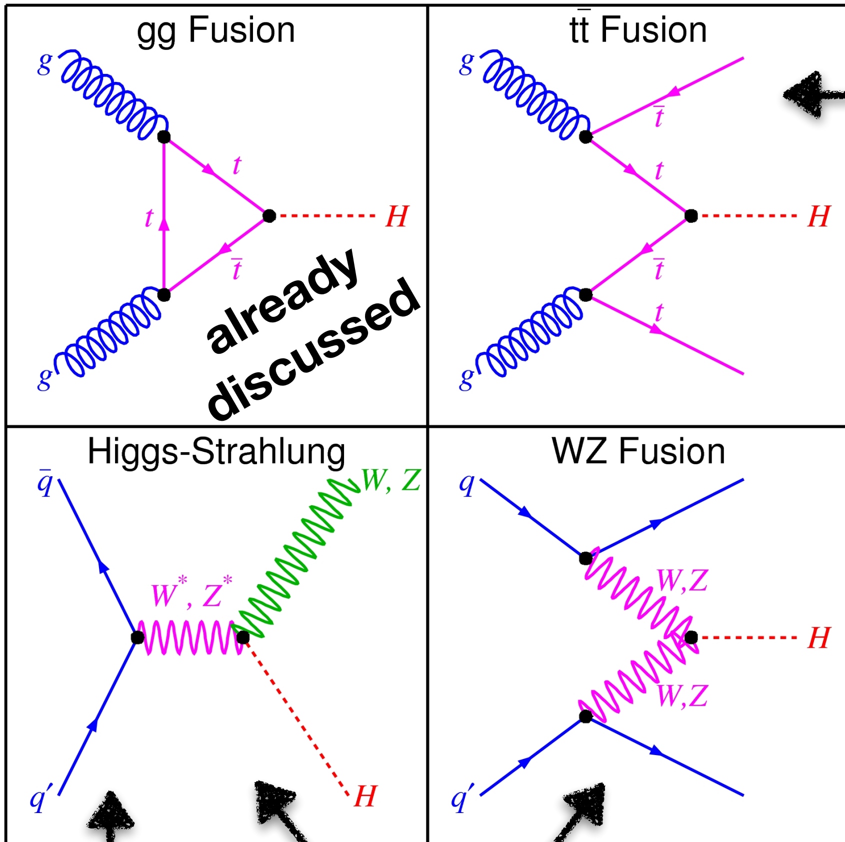
Note: The contribution from chiral fermions is roughly independent of fermion mass

As we will discuss, it is very hard to make this consistent with the experimental measurements

4th generation quarks are strongly disfavored

This argument doesn't hold for vector-like fermions (they are still allowed!)

How to make a Higgs boson @ the LHC subleading production modes



Testing the largest coupling of the Higgs (to top quarks)

Testing directly EWSB

Particularly useful for searches of background limited Higgs decay modes

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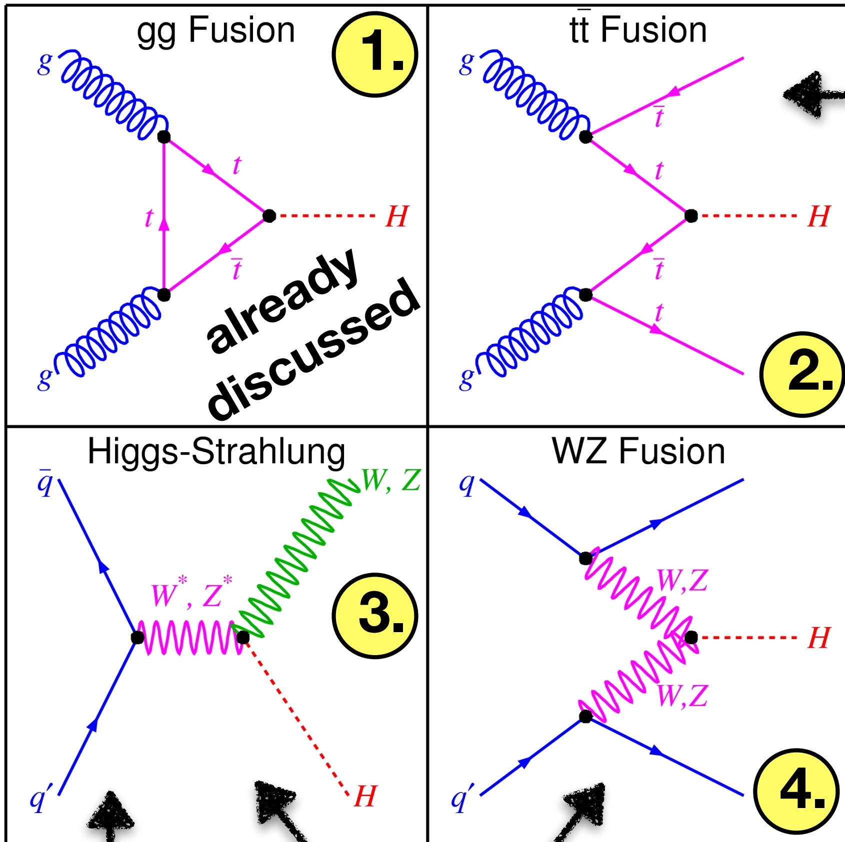

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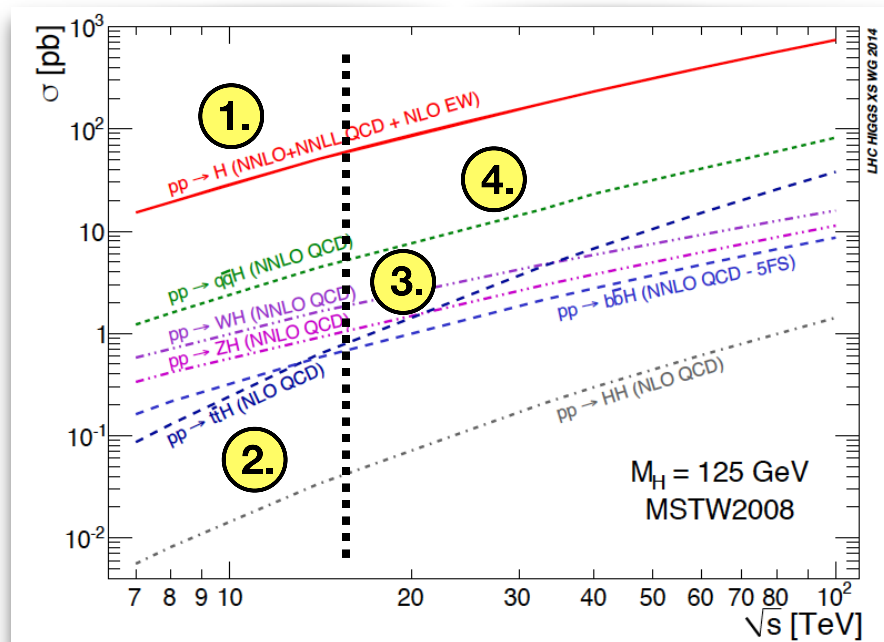
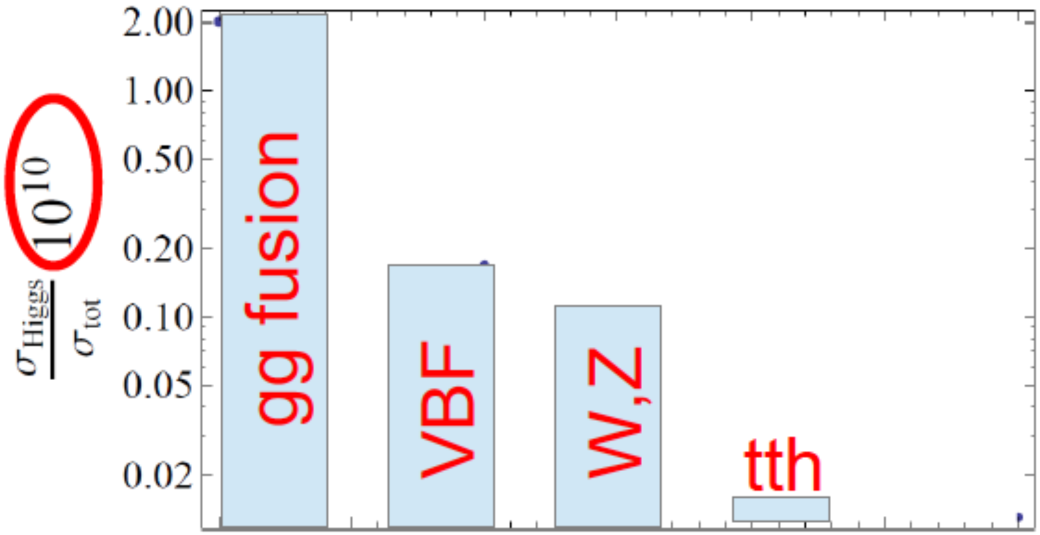
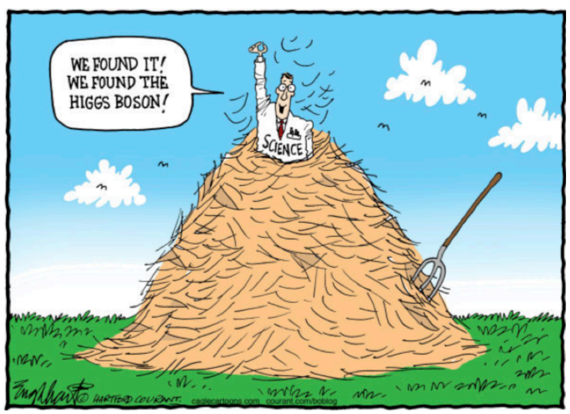


For comparison, $\sigma(W) \sim 10^5$ pb

Many events for a needle in the haystack



Many many LHC collisions are needed to produce a Higgs



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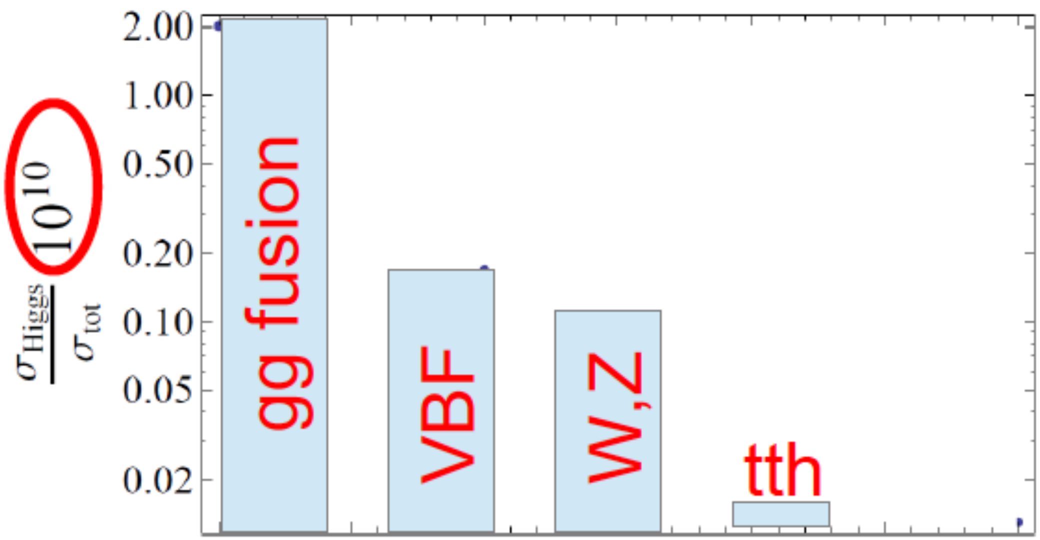

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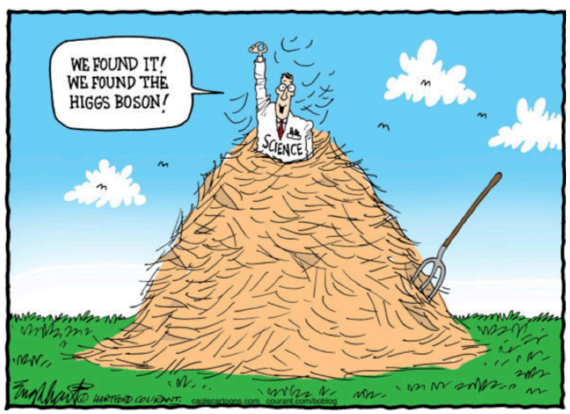

Nevertheless we have produced and we will be producing a lot of Higgs bosons:

By now:

Production	N. of events
ggF	6.8×10^6
VBF	5.9×10^5
$hW^\pm$	2.2×10^5
hZ	1.4×10^5
$t\bar{t}h$	7.3×10^4

HL-LHC:

Production	N. of events
ggF	1.4×10^8
VBF	1.2×10^7
$hW^\pm$	4.4×10^6
hZ	2.7×10^6
$t\bar{t}h$	1.5×10^6

Higgs decays

Once produced, the Higgs decays very quickly (life time ~ 10^{-22}s)

Knowing the several Higgs couplings (see yesterday's class), we can compute the several branching ratios of the Higgs boson.

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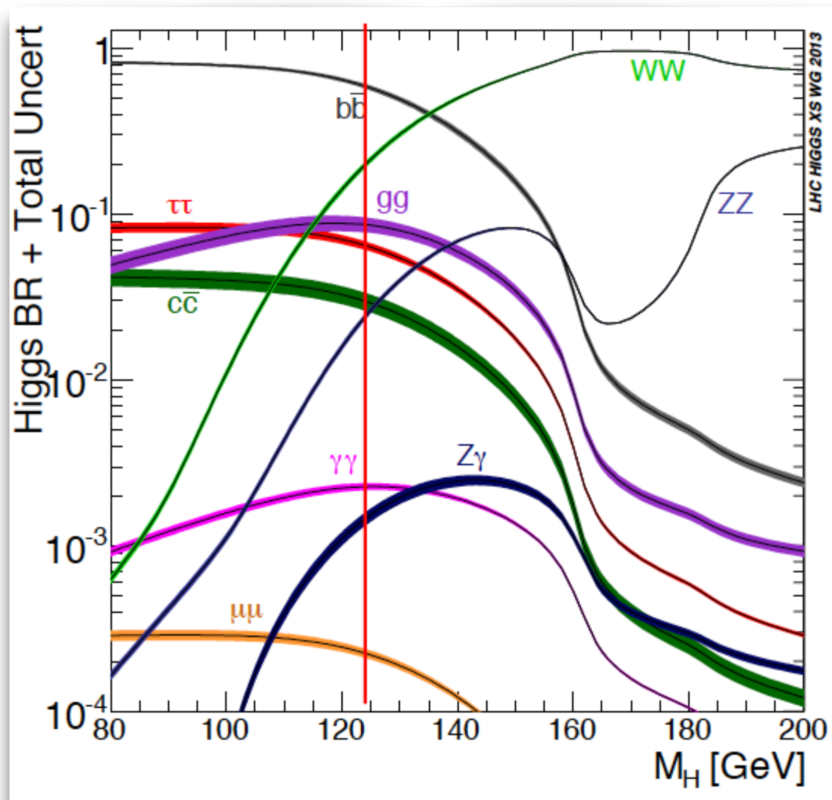
Knowing the several Higgs couplings (see yesterday's class), we can compute the several branching ratios of the Higgs boson.

125 GeV is a "good mass" for experimentalists, since several decay modes can be measured:

$$\begin{aligned} BR(h \to b\bar{b}) &= 58\%, \\ BR(h \to WW^*) &= 21.6\%, \\ BR(h \to \gamma\gamma) &= 0.22\%, \\ BR(h \to ZZ^*) &= 2.7\%, \\ BR(h \to \tau\bar{\tau}) &= 6.4\%, \\ BR(h \to \gamma Z) &= 0.16\% \end{aligned}$$



<u>Note</u>: SM precision predictions as soon as we specify the (measured) Higgs boson mass

Summary of searches

We can search for many different Higgs signatures at the LHC!

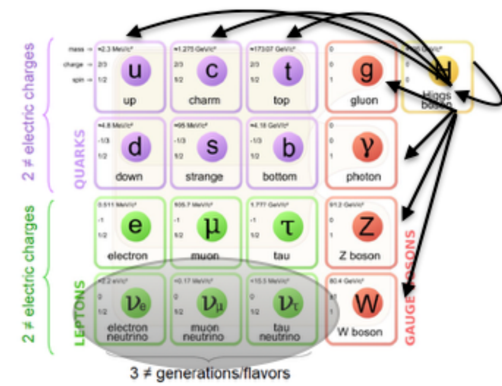
Summary of rate measurements at ATLAS (<= 80/fb), 1909.02845.

Process ($\lvert y_H \rvert < 2.5$)	Value [fb]	Uncertainty [fb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [fb]
ggF, $H \to \gamma\gamma$	97	± 14	± 11	± 8	± 2	$^{+2}_{-1}$	101.5 ± 5.3
ggF, $H \to ZZ^*$	1230	$^{+190}_{-180}$	± 170	± 60	± 20	± 20	1181 ± 61
ggF, $H \to WW^*$	10400	± 1800	± 1100	± 1100	± 400	$^{+1000}_{-900}$	9600 ± 500
ggF, $H \to \tau\tau$	2700	$^{+1700}_{-1500}$	± 1000	± 900	$^{+800}_{-300}$	± 400	2800 ± 140
VBF, $H \to \gamma\gamma$	11.1	$^{+3.2}_{-2.8}$	$^{+2.5}_{-2.4}$	$^{+1.4}_{-1.0}$	$^{+1.5}_{-1.1}$	$^{+0.3}_{-0.2}$	7.98 ± 0.21
VBF, $H \to ZZ^*$	249	$^{+91}_{-77}$	$^{+87}_{-75}$	$^{+16}_{-11}$	$^{+17}_{-12}$	$^{+9}_{-7}$	92.8 ± 2.3
VBF, $H \to WW^*$	450	$^{+270}_{-260}$	$^{+220}_{-200}$	$^{+120}_{-130}$	$^{+80}_{-70}$	$^{+70}_{-80}$	756 ± 19
VBF, $H \to \tau\tau$	260	$^{+130}_{-120}$	± 90	$^{+80}_{-70}$	$^{+30}_{-10}$	$^{+30}_{-20}$	220 ± 6
VBF, $H \to b\bar{b}$	6100	$^{+3400}_{-3300}$	$^{+3300}_{-3200}$	$^{+700}_{-600}$	± 300	± 300	2040 ± 50
VH, $H \to \gamma\gamma$	5.0	$^{+2.6}_{-2.5}$	$^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	± 0.5	± 0.1	$4.54\ ^{+0.13}_{-0.12}$
VH, $H \to ZZ^*$	36	$^{+63}_{-41}$	$^{+62}_{-41}$	$^{+5}_{-4}$	$^{+6}_{-4}$	$^{+4}_{-2}$	52.8 ± 1.4
VH, $H \to b\bar{b}$	1380	$^{+310}_{-290}$	$^{+210}_{-200}$	± 150	$^{+120}_{-80}$	± 140	$1162\ ^{+31}_{-29}$
$t\bar{t}H$+tH, $H \to \gamma\gamma$	1.46	$^{+0.55}_{-0.47}$	$^{+0.48}_{-0.44}$	$^{+0.19}_{-0.15}$	$^{+0.17}_{-0.11}$	± 0.03	$1.33\ ^{+0.08}_{-0.11}$
$t\bar{t}H$+tH, $H \to VV^*$	212	$^{+84}_{-81}$	$^{+61}_{-59}$	$^{+47}_{-44}$	$^{+17}_{-10}$	$^{+31}_{-30}$	$142\ ^{+8}_{-12}$
$t\bar{t}H$+tH, $H \to \tau\tau$	51	$^{+41}_{-35}$	$^{+31}_{-28}$	$^{+26}_{-21}$	$^{+6}_{-4}$	$^{+8}_{-6}$	$36.7\ ^{+2.2}_{-3.1}$
$t\bar{t}H$+tH, $H \to b\bar{b}$	270	± 200	± 100	± 80	$^{+40}_{-10}$	$^{+150}_{-160}$	$341\ ^{+20}_{-29}$

theory and experimental precision must go hand in hand!

Higgs rates and Higgs couplings

We would like to extract the Higgs couplings to the several SM particles. How can we do it?



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We introduce the **"reduced couplings", κ**

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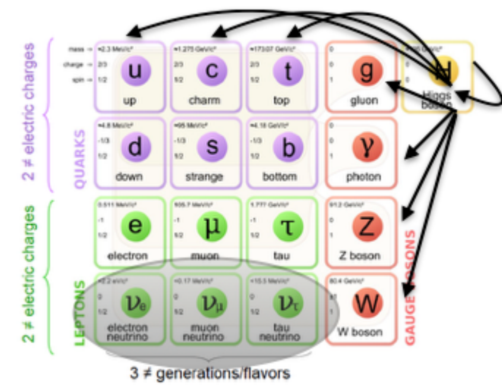

Example, let's look at the Higgs decaying into two photons

$$\sigma(pp \to h \to \gamma\gamma)_{\rm exp} = \sigma(pp \to h)_{\rm theory} \times {\rm BR}(h \to \gamma\gamma)_{\rm theory}$$

$$= \sigma(pp \to h \to \gamma\gamma)_{\rm SM} \times \frac{\sigma(pp \to h)_{\rm theory}}{\sigma(pp \to h)_{\rm SM}} \times \frac{{\rm BR}(h \to \gamma\gamma)_{\rm theory}}{{\rm BR}(h \to \gamma\gamma)_{\rm SM}}$$

—— computed to high precision

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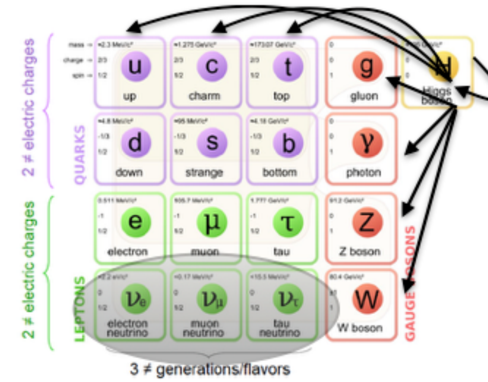

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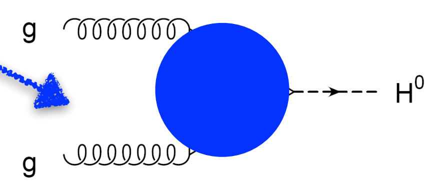
$$= \sigma(pp \to h \to \gamma\gamma)_{\text{SM}} \times \frac{\sigma(pp \to h)_{\text{theory}}}{\sigma(pp \to h)_{\text{SM}}} \times \frac{\text{BR}(h \to \gamma\gamma)_{\text{theory}}}{\text{BR}(h \to \gamma\gamma)_{\text{SM}}}$$

$$= \sigma_{\text{SM}} \times \kappa_g^2 \times \frac{\Gamma(h \to \gamma\gamma)_{\text{theory}}}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} \times \frac{\Gamma^{\text{tot}}_{\text{SM}}}{\Gamma^{\text{tot}}_{\text{theory}}} = \sigma_{\text{SM}} \times \kappa_g^2 \times \kappa_\gamma^2 \times \frac{\Gamma^{\text{tot}}_{\text{SM}}}{\Gamma^{\text{tot}}_{\text{theory}}} \quad (*)$$



computed to high precision
reduced couplings to be extracted

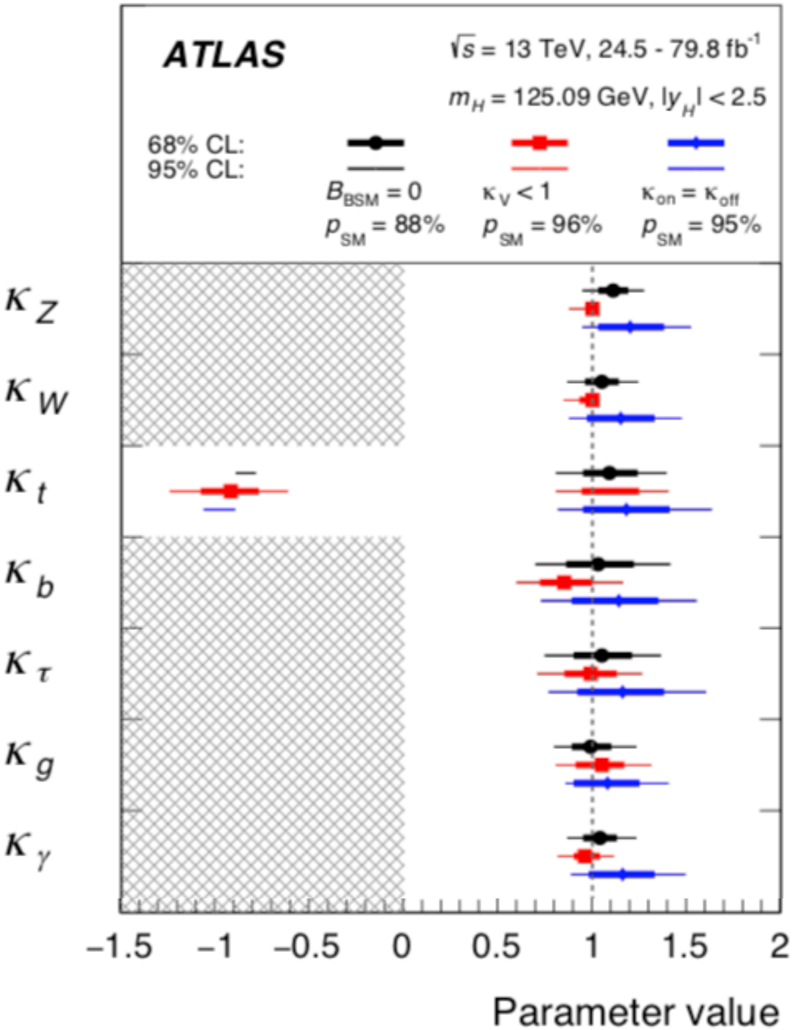
reduced coupling to
* gluons
* photons

(*) <u>Note</u>: dependence on the Higgs width!

Extracting Higgs couplings

We can now compare the rates measured at the LHC to the predictions of the SM to extract information on the reduced couplings

adapted from ATLAS, 1909.02845



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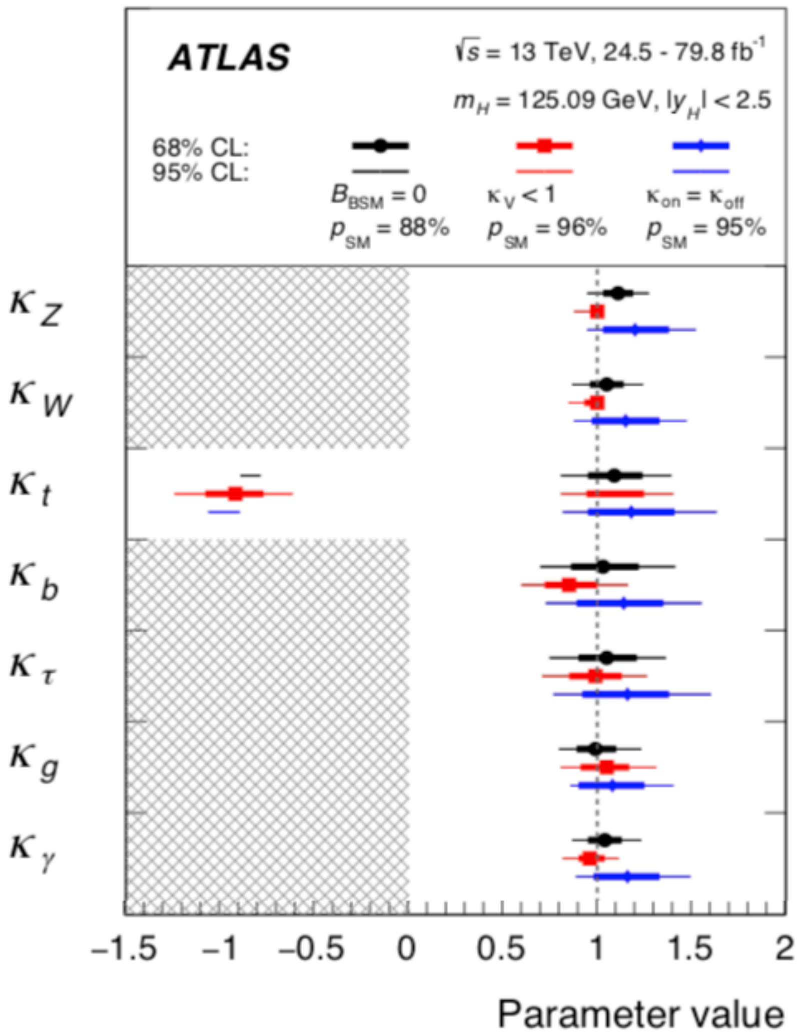

Assumptions:

- The Higgs phenomenology is only modified through the modification of the reduced couplings.

(e.g. no new production mechanisms of the Higgs through the decay of a New Physics resonance)

In principle, one can rescale the width and the couplings, such to obtain the SM rates (flat directions!).

$$\left(\sigma_{\rm SM} \times \kappa_g^2 \times \kappa_\gamma^2 \times \frac{\Gamma^{\rm tot}_{\rm SM}}{\Gamma^{\rm tot}_{\rm theory}} \right)$$

➡ Additional assumptions are needed!

Extracting Higgs couplings

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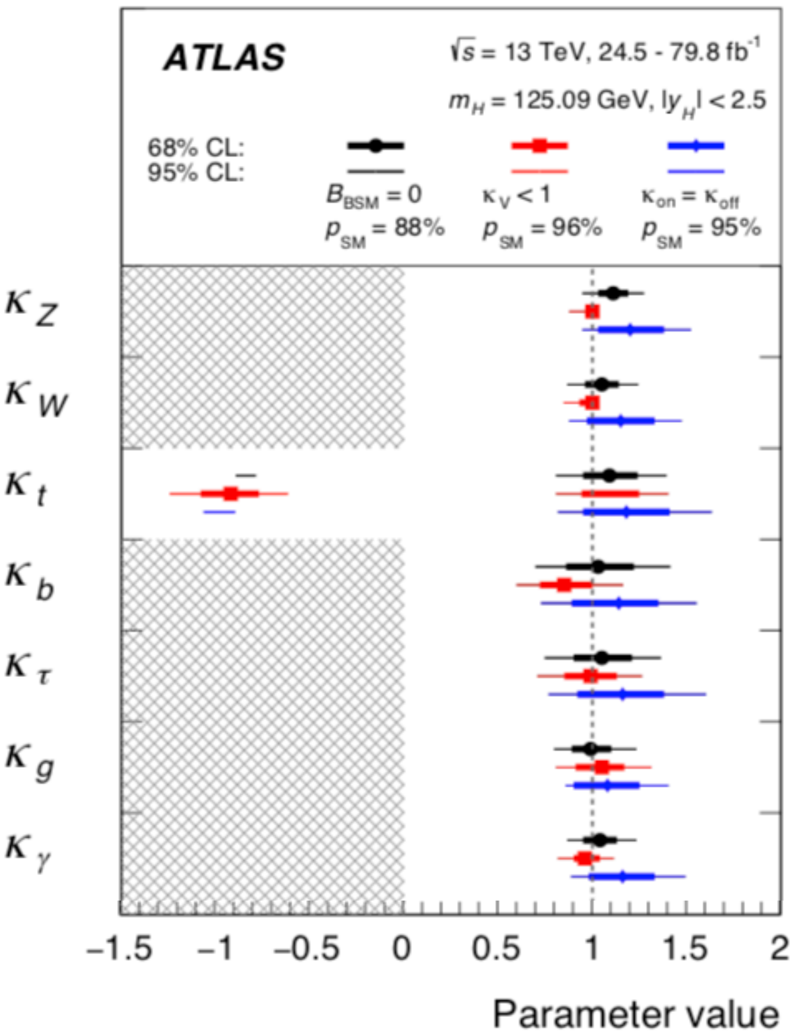

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For example:

* k_V<=1 (this is guaranteed in models with no extra Higgs fields in larger representations of the gauge group. i.e. triplets etc) **OR**
* **BR_{BSM}=0** (no Higgs exotic decays)

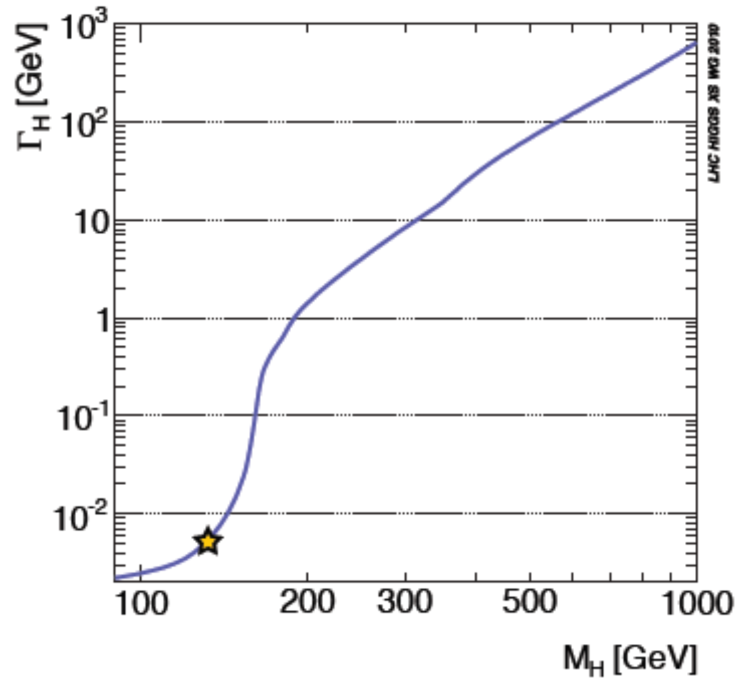
The Higgs width & its determination (1)

What do we know about the Higgs width?

The SM predicts a very small width: ~ 4MeV
What about the measurement?

It is very hard to determine the Higgs width at the LHC (or, in general, at hadron colliders)

 or  ?



Straightforward to affect the width in New Physics models:
Higgs exotic decays!

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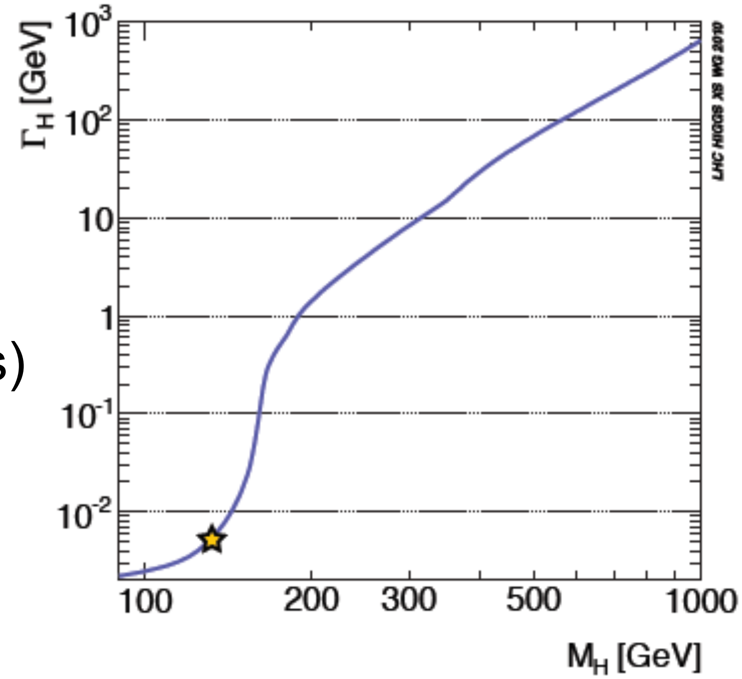
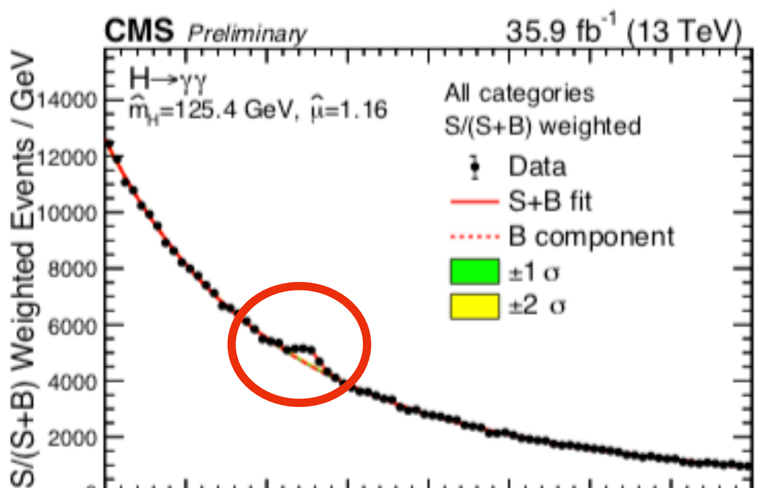


Model independently, we could look at the width of the distributions of Higgs events (γγ, ZZ final states)



However, the experimental resolution is not good enough to reach the SM value for the Higgs width: **Γ_{exp}< O(1GeV)**

The Higgs width & its determination (2)

What do we know about the Higgs width?

 or  ?

The SM predicts a very small width: ~ 4MeV
What about the measurement?

It is very hard to determine the Higgs width at the LHC (or, in general, at hadron colliders)

We can extract the width in a <u>more model dependent way</u>:
study of Higgs off-shell production: pp → H → ZZ →4l vs. pp → H* → ZZ →4l

on-peak off-peak

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot\text{BR})_{\text{SM}}$$

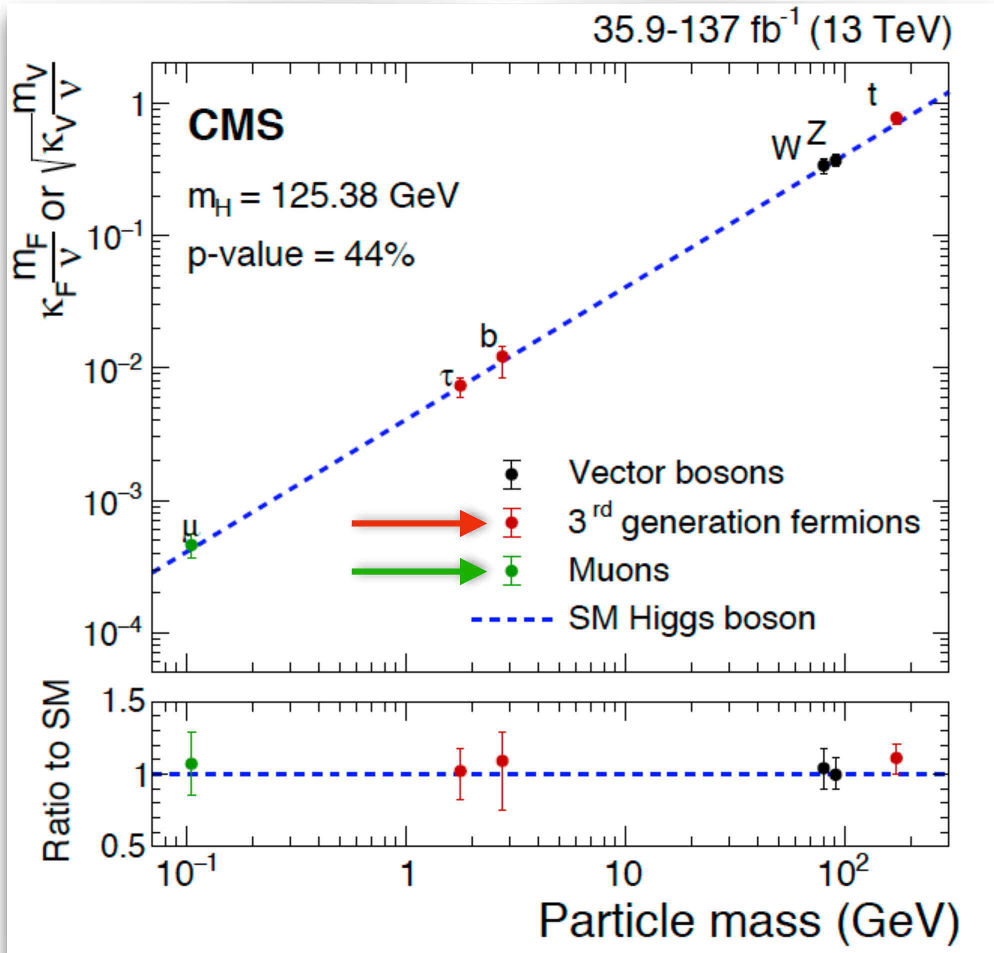
$$\frac{d\sigma(gg\to h^{(*)}\to ZZ)}{dm^2_{4\ell}} \sim \frac{\kappa_g^2\kappa_Z^2}{(m^2_{4\ell}-m_h^2)^2+m_h^2\Gamma_h^2}$$

$$r = \Gamma_H/\Gamma_H^{\text{SM}}$$

Γ_{exp}< 9.2 MeV
CMS PAS HIG-18-002

Other methods:
Study of the interference between gg →h→ γγ and gg → γγ
Dixon, Li, 1305.3854

Higgs couplings proportional to the mass!



CMS, 2009.04363

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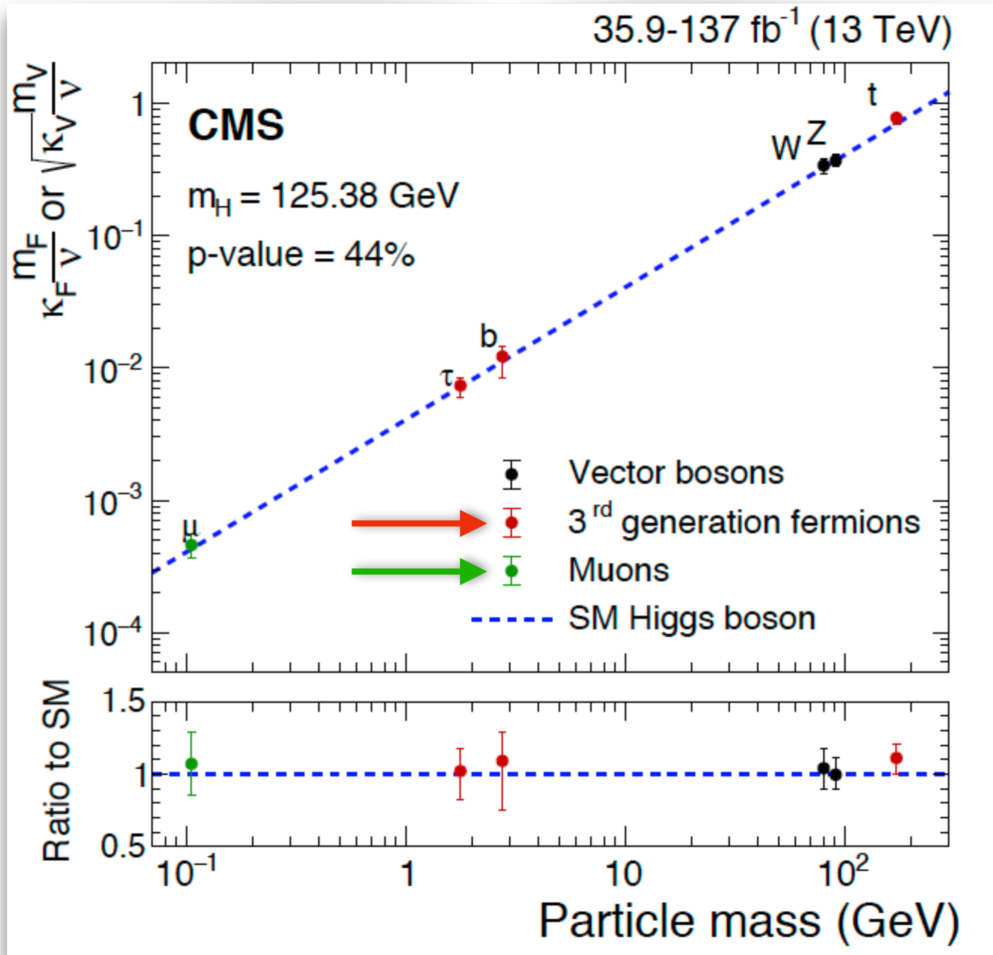

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Yesterday, we saw that in the SM the Higgs couplings to

- fermions are proportional to the fermion mass
- gauge bosons are proportional to the gauge boson mass square

This plot confirms the expectation!

Manifestation of the SM flavor puzzle

Relatively recent evidence for the Higgs decay into muons:

$$\mu = 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$ (CMS, 2009.04363)

$$\mu = \frac{\sigma(pp \to h \to \mu\mu)}{\sigma(pp \to h \to \mu\mu)_{\text{SM}}}$$

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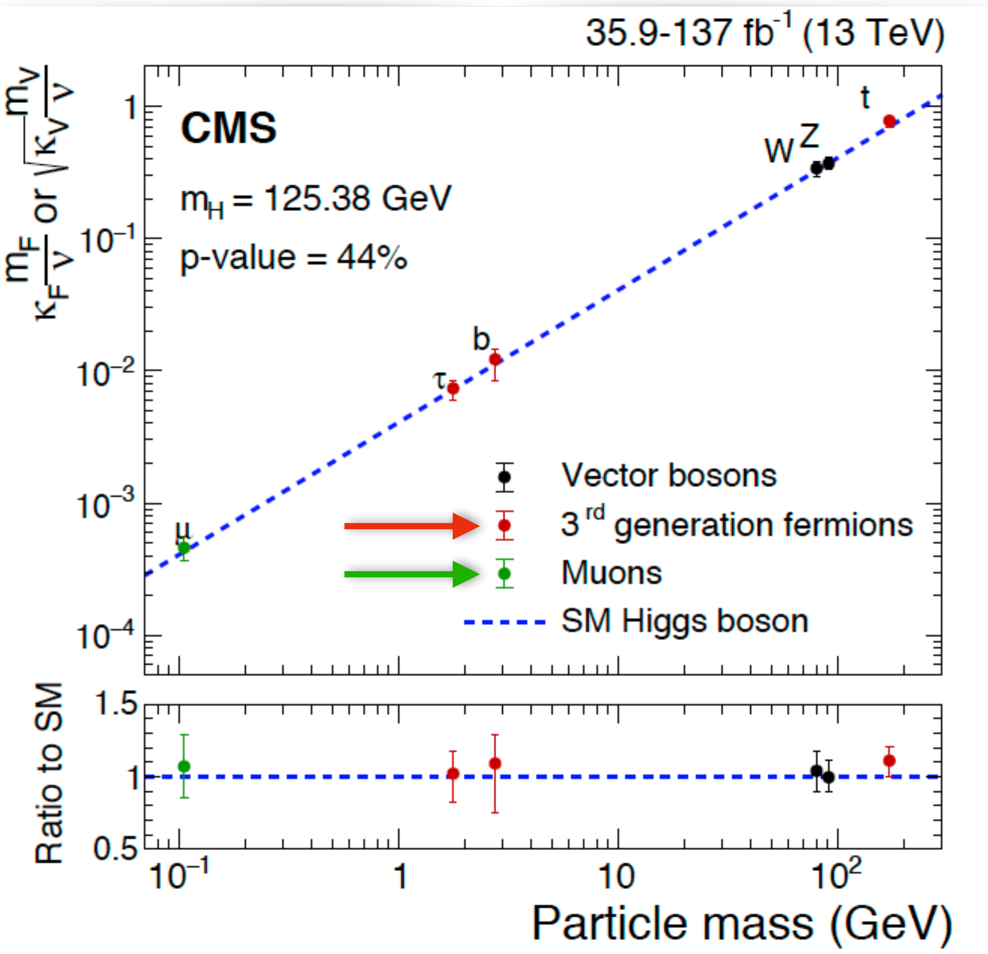

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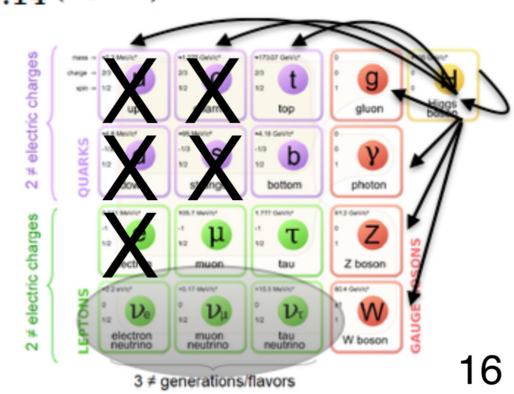

Chapter II

Higgs properties to understand better

- coupling to light quarks/leptons
- self-couplings
- CP violation
- …

Higgs coupling to light quarks

It is hard to probe the Higgs couplings to light quarks (charm, strange, up, down)

In fact:

- the couplings are relatively small (well, BR($h \to cc$)~3% to be compared to BR($h \to \gamma\gamma$)~0.2%)
- the corresponding Higgs decay is background limited

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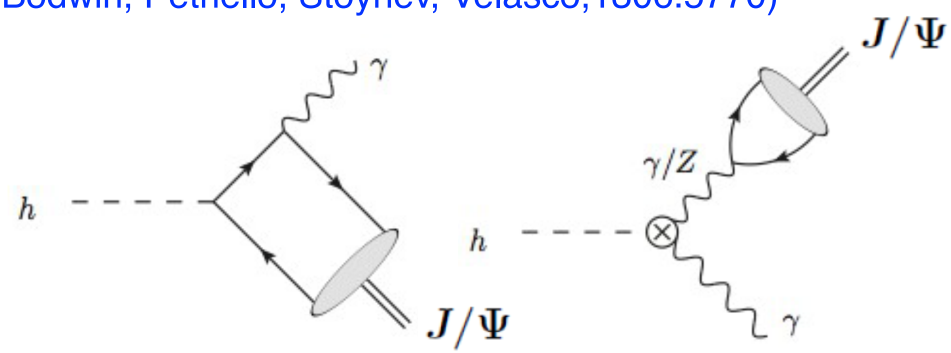
Strategies to probe light quark Yukawas
(warning: not exhaustive)

- Zh, $h \to cc$ (ATLAS-CONF-2021-021)
  $|\kappa_c| < 8.5$
- Rare Higgs decays
(Bodwin, Petriello, Stoynev, Velasco,1306.5770)



$$\mathrm{BR}(h \to J/\Psi + \gamma) = 3.4 \times 10^{-6}(\kappa_\gamma - 8.7 \cdot 10^{-2}\kappa_c)^2$$

- Higgs + charm production
  (Brivio, Isidori, Goertz 1507.02916)
- Higgs + jet production
  (Bishara, Haisch, Monni, Re, 1606.09253)
- Higgs η & p_T distributions
  (Soreq, Zhu, Zupan, 1606.09621)
- Charge asymmetry in $W^\pm h$ production (Yu,1609.06592)

Higgs coupling to light leptons

Soon we will be able to discover the Higgs coupling to **muons**!

We have already seen that:

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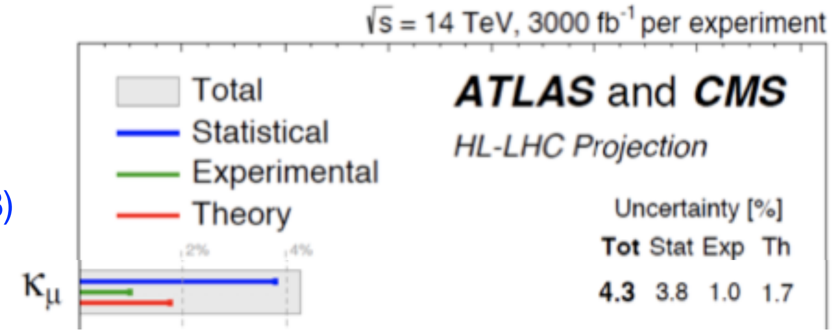
(using the full Run II data)

~30% uncertainty on the coupling



adapted from Physics Briefing Book 1910.11775

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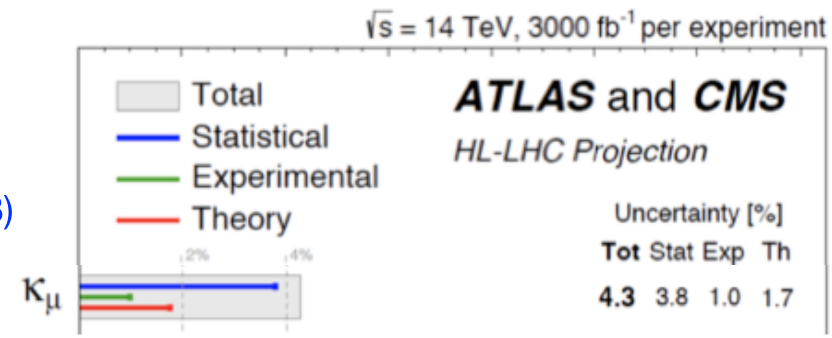


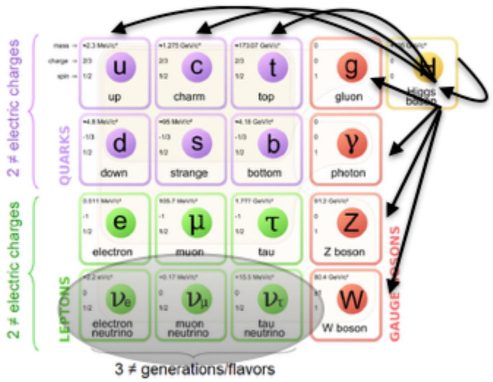
adapted from Physics Briefing Book 1910.11775

For **electrons**, the extraction of the Higgs coupling is much more complicated (the coupling is tiny!)

$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$
	TLEP (1/fb)	$\lvert\kappa_e\rvert \sim 50$
	TLEP (100/fb)	$\lvert\kappa_e\rvert \sim 10$
d_e	current	$\text{Im}\,\kappa_e \lesssim 0.017$
	future	$\text{Im}\,\kappa_e \sim 0.0001$
$(g-2)_e$	current	$\text{Re}\,\kappa_e \lesssim 3000$
	future	$\text{Re}\,\kappa_e \sim 300$

Altmannshofer, Brod, Schmaltz, 1503.04830

Higgs self-coupling & di-Higgs



this coupling is still missing!

How to probe the **Higgs self-interactions**?
and therefore the **shape of the Higgs potential**?

Yesterday we saw that $$V(h,\omega_i) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

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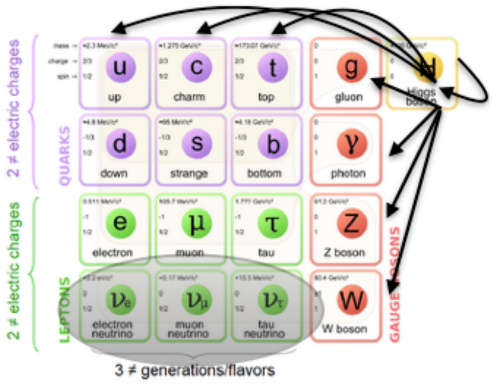

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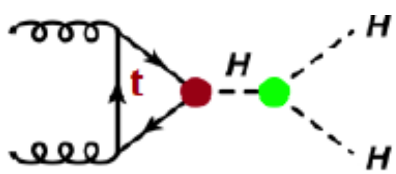
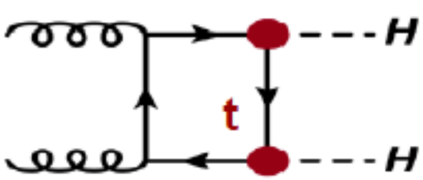
Di-Higgs production

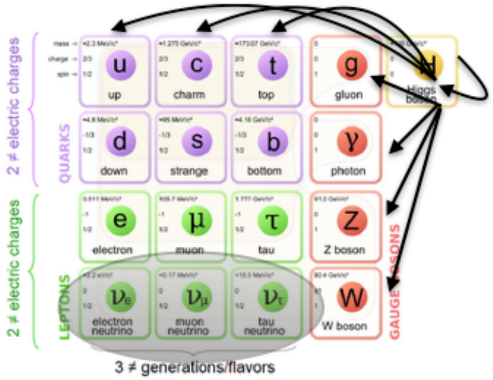




The cross section is small.
(the two diagrams interfere destructively)

$$\sigma(pp \to hh) \sim 31\text{fb} \quad (13\ \text{TeV})$$

Higgs self-coupling & di-Higgs



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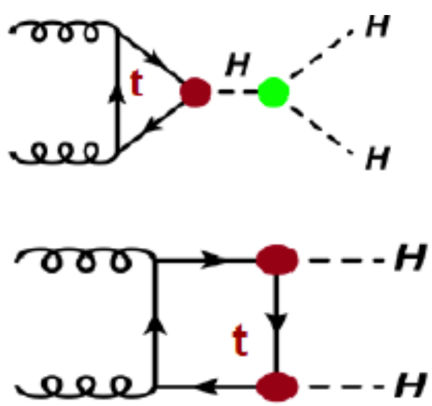

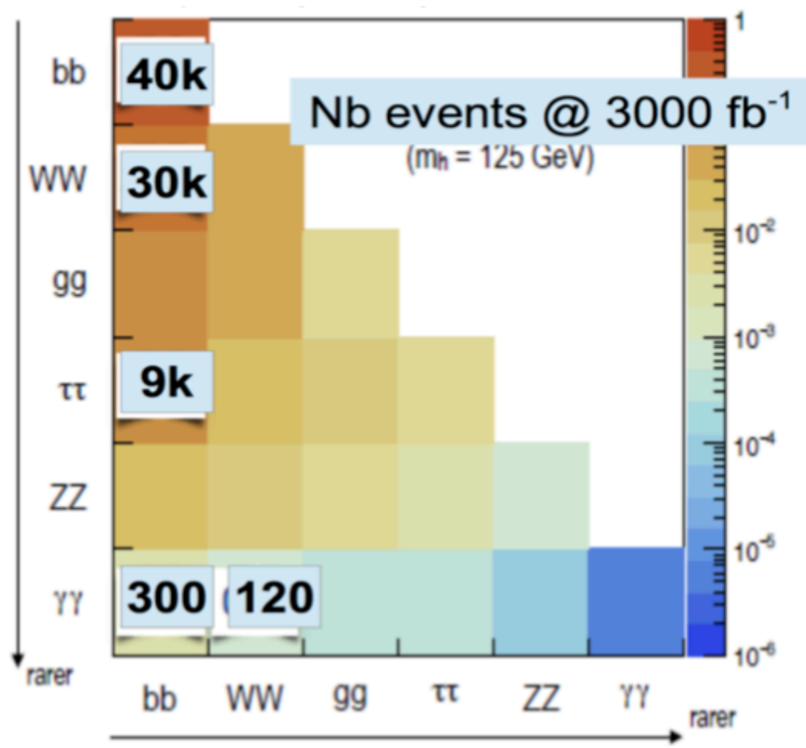

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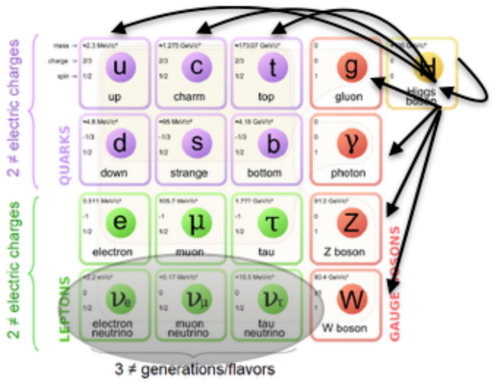

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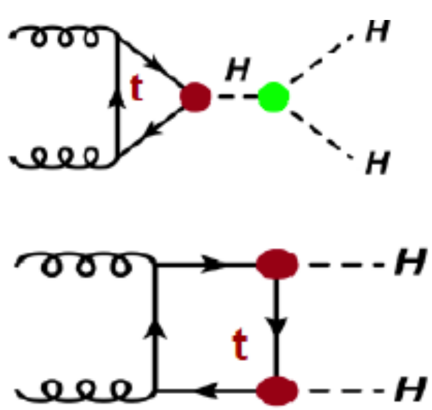

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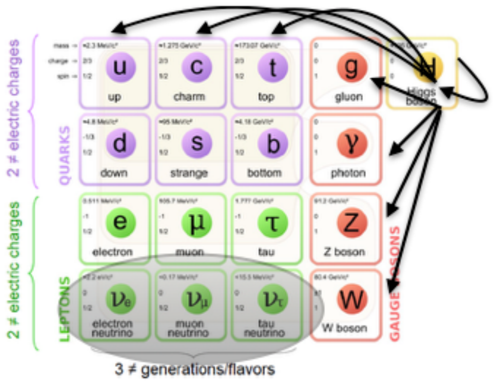
Searches at Run II:

Search channel	Collaboration	95% CL Upper Limit observed	expected
$b\bar{b}b\bar{b}$	ATLAS	13	21
	CMS	75	37
$b\bar{b}\gamma\gamma$	ATLAS	20	26
	CMS	24	19
$b\bar{b}\tau^+\tau^-$	ATLAS	12	15
	CMS	32	25
$b\bar{b}VV^*\ (\ell\nu\ell\nu)^*$	ATLAS	40	29
	CMS	79	89
$b\bar{b}WW^*\ (\ell\nu qq)$	ATLAS	305	305
	CMS	–	–
$WW^*\gamma\gamma$	ATLAS	230	160
	CMS	–	–
WW^*WW^*	ATLAS	160	120
	CMS	–	–
Combined	ATLAS	6.9	10
	CMS	22	13

x SM

Di Micco et al.,1910.00012

Higgs self-coupling & di-Higgs



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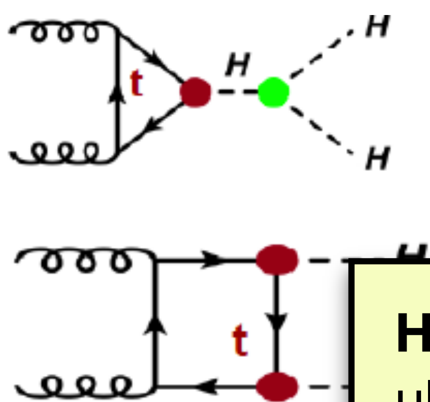

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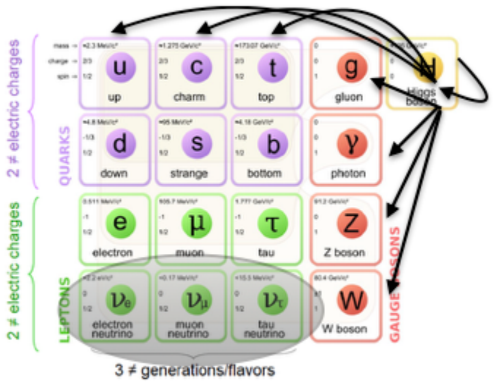
x SM

Di Micco et al.,1910.00012

HL-LHC: bbττ, bbγγ (and bbbb) will ultimately provide the best sensitivity (combined sensitivity of ~4-4.5σ)

Higgs self-coupling & single Higgs



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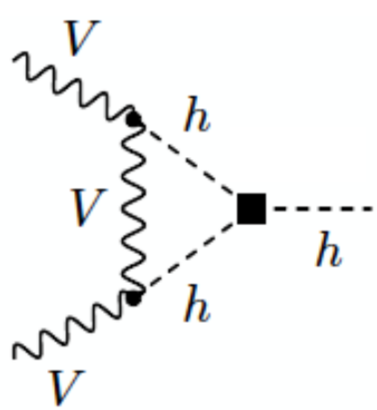
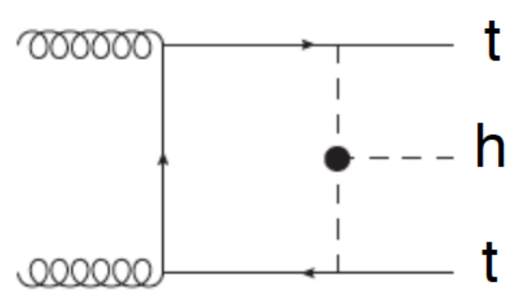
We can probe the Higgs self-interaction studying the **single Higgs production** at the LHC. In fact, for example:

- A value of h^3 different from the SM one will modify the Higgs couplings to W and Z



Bizon et al., 1610.05771

- tth production will be affected



Di Vita et al., 1704.01953

Once more, importance of precision Higgs measurements!

Higgs and CP

In the SM, the Higgs boson is a scalar and is 100% CP even.
Can we test the CP nature of the Higgs at the LHC?

Let's suppose the Higgs is a CP admixture:

$$h_{125} = \cos\alpha \; h_{\rm even} + \sin\alpha \; h_{\rm odd}$$

How to constrain the value of α?

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$h_{\rm odd}$ will couple to the SM particles in a different way, if compared to a CP even scalar:

$$\mathcal{L}_{\rm gauge} = -\frac{\tilde{g}_{hZZ}}{2} h_{\rm odd} Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \tilde{g}_{hWW} h_{\rm odd} W_{\mu\nu}\tilde{W}^{\mu\nu} - \frac{\tilde{g}_{h\gamma\gamma}}{2} h_{\rm odd} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{\rm yuk} = -\frac{m_f}{v}(i\tilde{\kappa}_f \bar{f}\gamma_5 f) h_{\rm odd}$$

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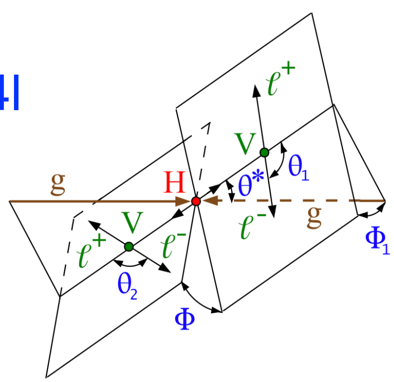
$$\mathcal{L}_{\text{yuk}} = -\frac{m_f}{v}(i\tilde{\kappa}_f \bar{f}\gamma_5 f) h_{\text{odd}}$$

Several measurements have been done to test these couplings:

$h\to ZZ^*\to 4l$

CMS, 1901.00174



tth, $h\to\gamma\gamma$
ATLAS, 2004.04545
α<43°

$h\to\tau\tau$
CMS PAS HIG-20-006
α<36°

Additional CPV Higgs coupling probes

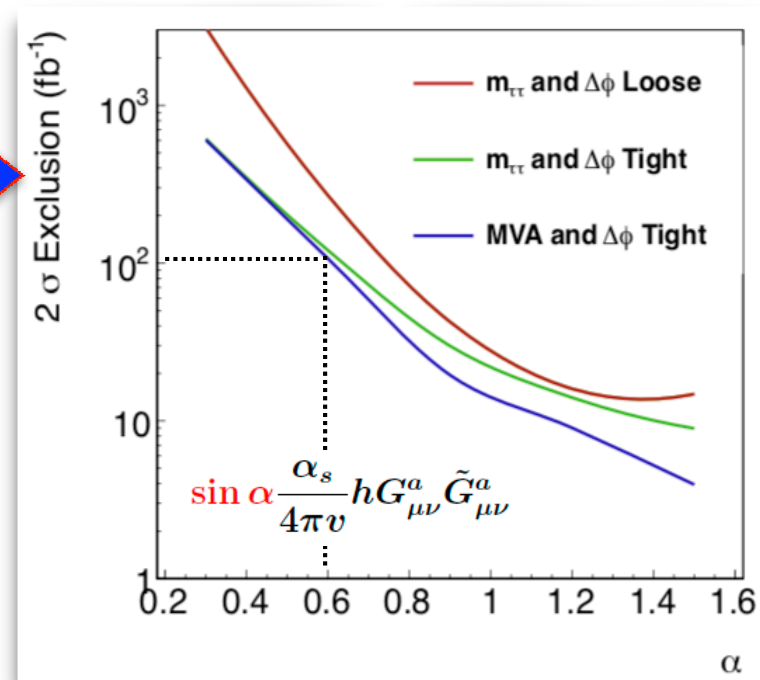
An (incomplete) list…

Zγ Farina, Grossman, Robinson [1503.06470]

Takes advantage of interference between continuum background and signal from gluon initiated events

gg Dolan, Harris, Jankowiak, Spannowsky [1406.3322]

gg → hjj, h → τ τ. Uses associated jets for angular analysis



tt Buckley, Golcalves [1507.07926]

pp → htt, h → b b. Azimuthal angle between the leptons from top decays

γγ Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]

Requires converted photons and angular resolution on leptonic opening angles

Conclusions and outlook

The (SM-like) Higgs boson discovery has been a milestone for particle physics

The Higgs is not only a new particle.
It is THE particle responsible for electroweak symmetry breaking (generating the mass of the W and Z bosons, as well as of the fermions of the SM).

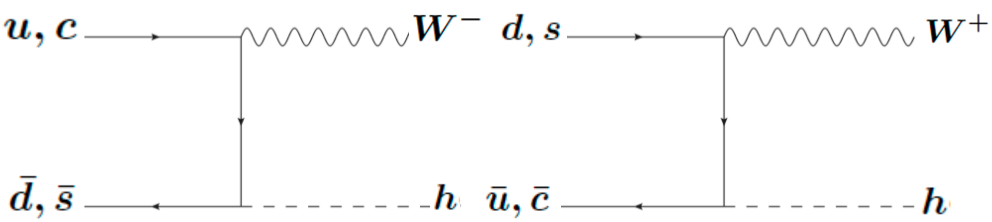
The SM theory for electroweak interactions is highly predictive.
We need Higgs precision measurements & precision predictions!

Many properties of the Higgs boson are only poorly known (self-interactions, light quarks and leptons, CP violation, …).
Need for more measurements!

Light quarks: Exploiting the Higgs production

Yu,1609.06592

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$



$$pp \to W^\pm h,$$
$$W^\pm \to \ell^\pm \nu,\ h \to WW \to \ell^\pm \nu jj$$

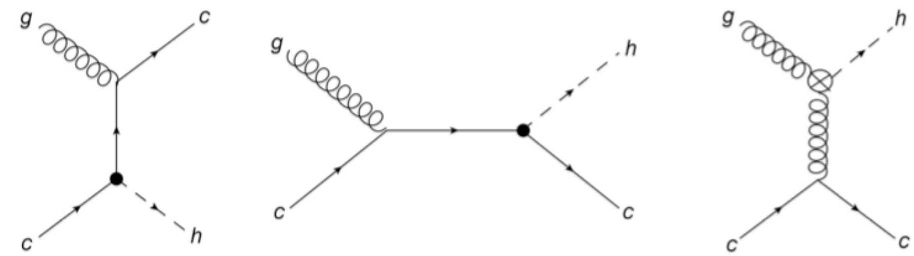
* 300 fb^{-1} of 14 TeV LHC: 8.6σ

* HL-LHC: statistical precision on the charge asymmetry of 0.4%

→ k_c determined at the O(1) level

Systematics?

Brivio, Isidori, Goertz 1507.02916



$$pp \to ch,\ h \to \gamma\gamma$$

HL-LHC:

κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

→ $|\kappa_c| < 2.5\ (3.9)$ (1σ, 2σ)

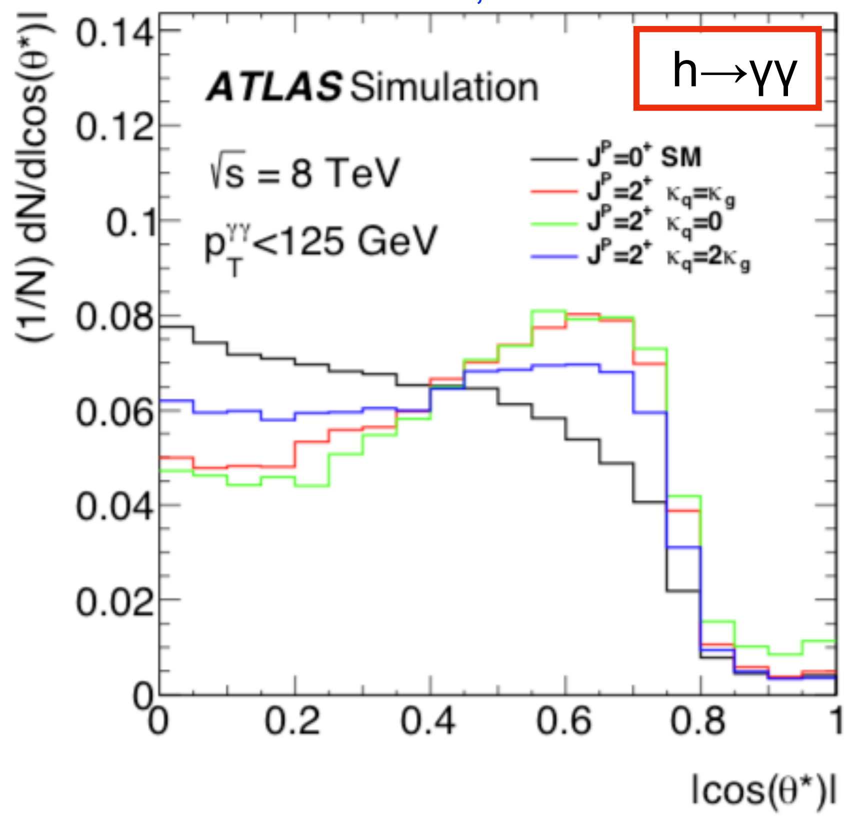
Spin-0 hypothesis

- The Landau–Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of photons

- spin-2:

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

ATLAS, 1506.05669



"Exclusion of all considered non-SM spin hypotheses at a more than 99.9% CL in favor of the SM spin-0 hypothesis"