Particle Physics II

(LPHY2133)

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Section 6.a

Putting things together

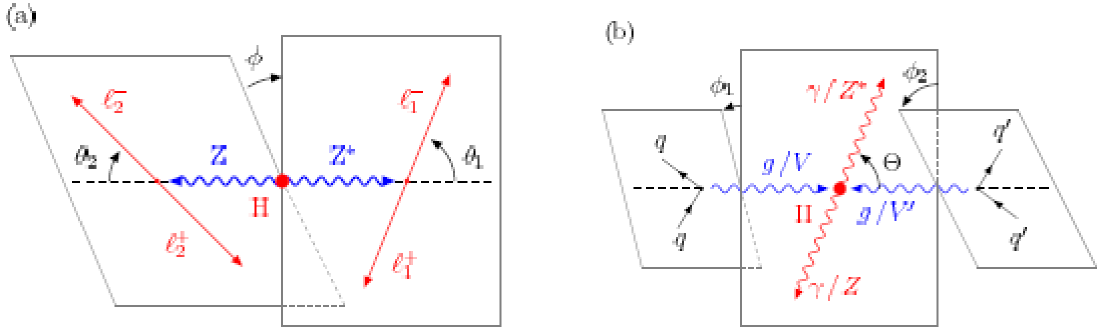
Complementary information

- The point about studying several final states is not only about getting more significance in the combination
  - Although this was an important consideration until 2012
- Different final states give complementary information
- Once you discover a new particle you also want to know which particle you have discovered
  - Those analyses were designed for the Higgs boson, but a different new particle may have passed the same selection
- Next slides are about how our understanding of this new particle has formed, based on the available data
- (For another historical case, you can compare to how the J/ψ's identity was understood in 1974: link)

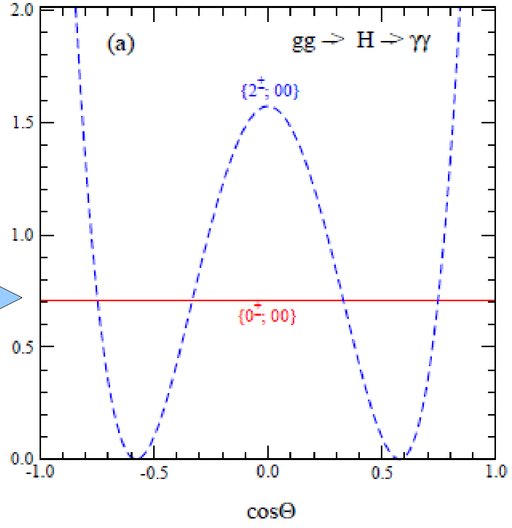
Spin of the new particle

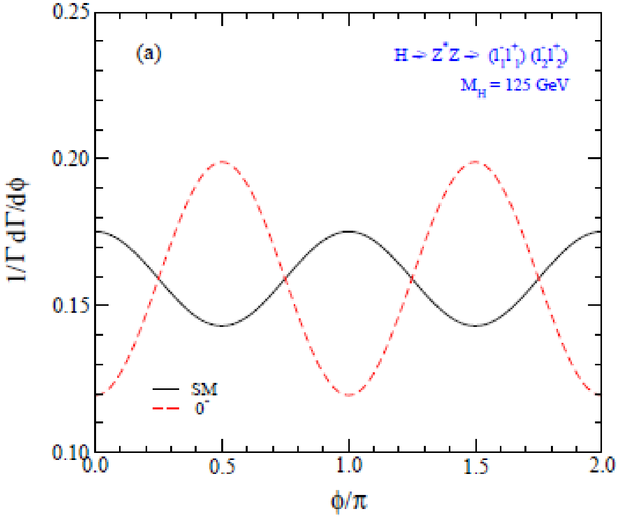
- From the fact that it decays into 2 γ, 2 Z, 2 W (all spin=1 particles), we know:
  - Spin cannot be fractional ($\Rightarrow$ it's a boson)
  - Decay into two spin-1 particles limits the spin to 0, 1, 2
  - (spin >2 only if large orbital angular momentum of decay products; not impossible but strongly disfavoured)
- The decay into two real γ's also excludes spin = 1
  - Because the photon is massless, hence it has only two polarization states (Landau-Yang theorem, ref.: link)
- Angular distributions of the decay products are affected by the spin and parity of the intermediate resonance

Spin and parity



Spin = 0 ⇒ no preferred direction ⇒ flat in cosθ (*Q: why?*)



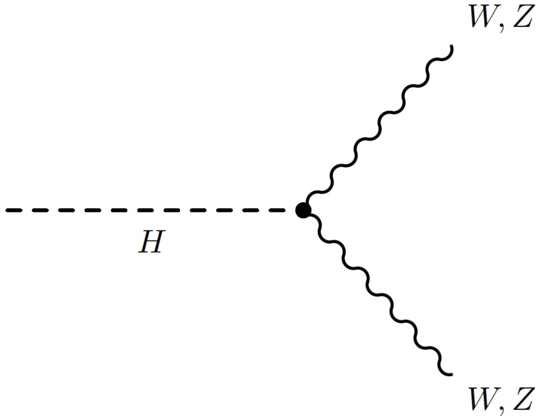


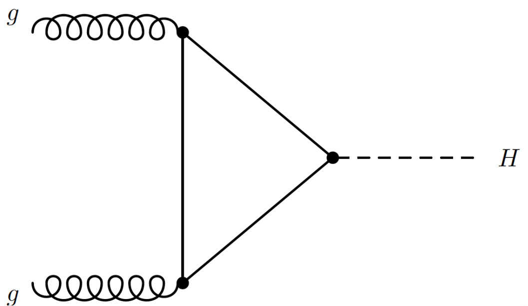
Modulation comes from spin of the Z; opposite parity (scalar vs pseudo-scalar) gives π difference in phase

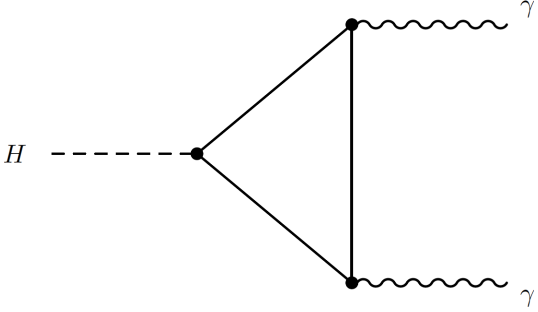
- Figures taken from a nice ref.: link; another good theory source: link
- Scalar hypothesis ($J^P=0^+$) confirmed by ATLAS and CMS in Run-1, combining several angles in MVA discriminants in ZZ, γγ, WW
- Most precise results from H→ZZ→4l (*Q: say at least two reasons*)

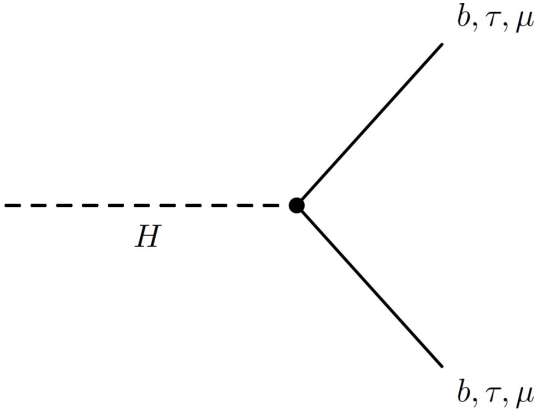
Couplings

- It decays to WW and ZZ ⇒ it couples to W and Z, as expected by the Higgs mechanism to explain their mass
- It is produced by gg→H and decays to γγ ⇒ *indirect* proof that it couples also to fermions (or at least the top quark)
- It decays to ττ and $b\bar{b}$ ⇒ *direct* proof that it couples also to fermions (or at least 3rd generation ones)



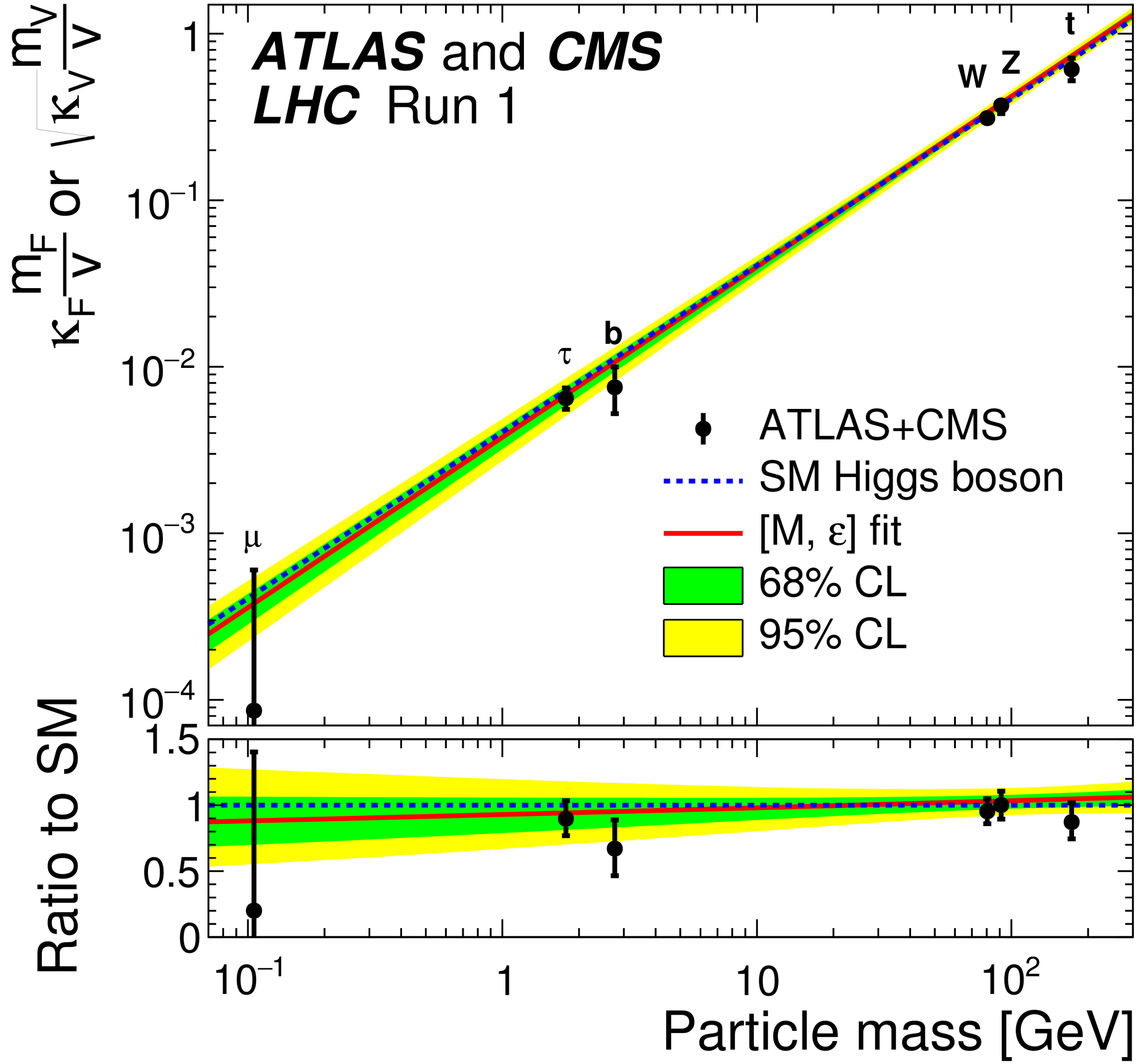






Couplings: quantitative tests of the SM's Higgs mechanism

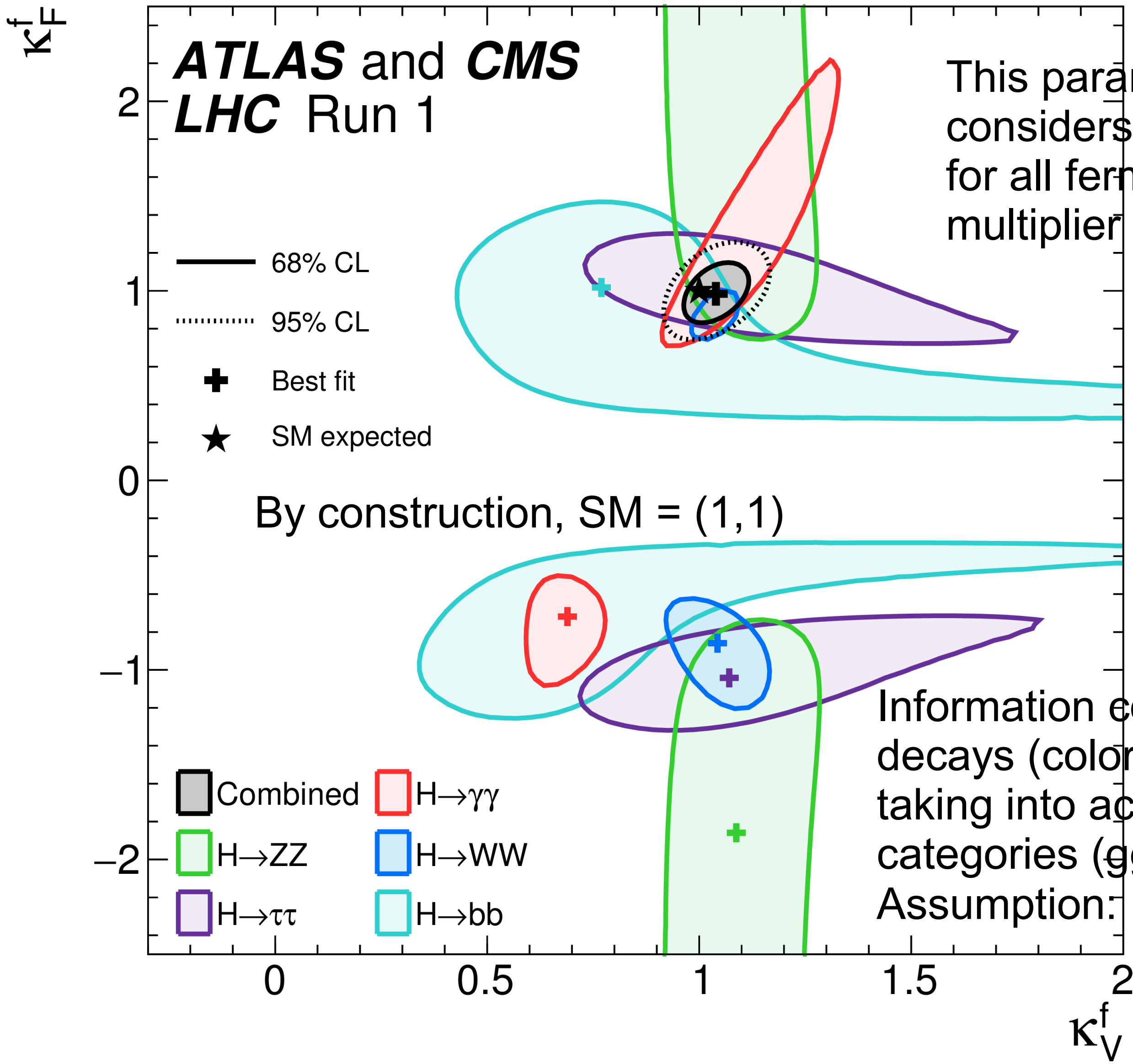
Reference: ATLAS & CMS, JHEP 08 (2016) 045



Fermion (k_F) and boson (k_V) coupling multipliers

Quiz:

- Explain ZZ
- Explain ττ
- Explain γγ



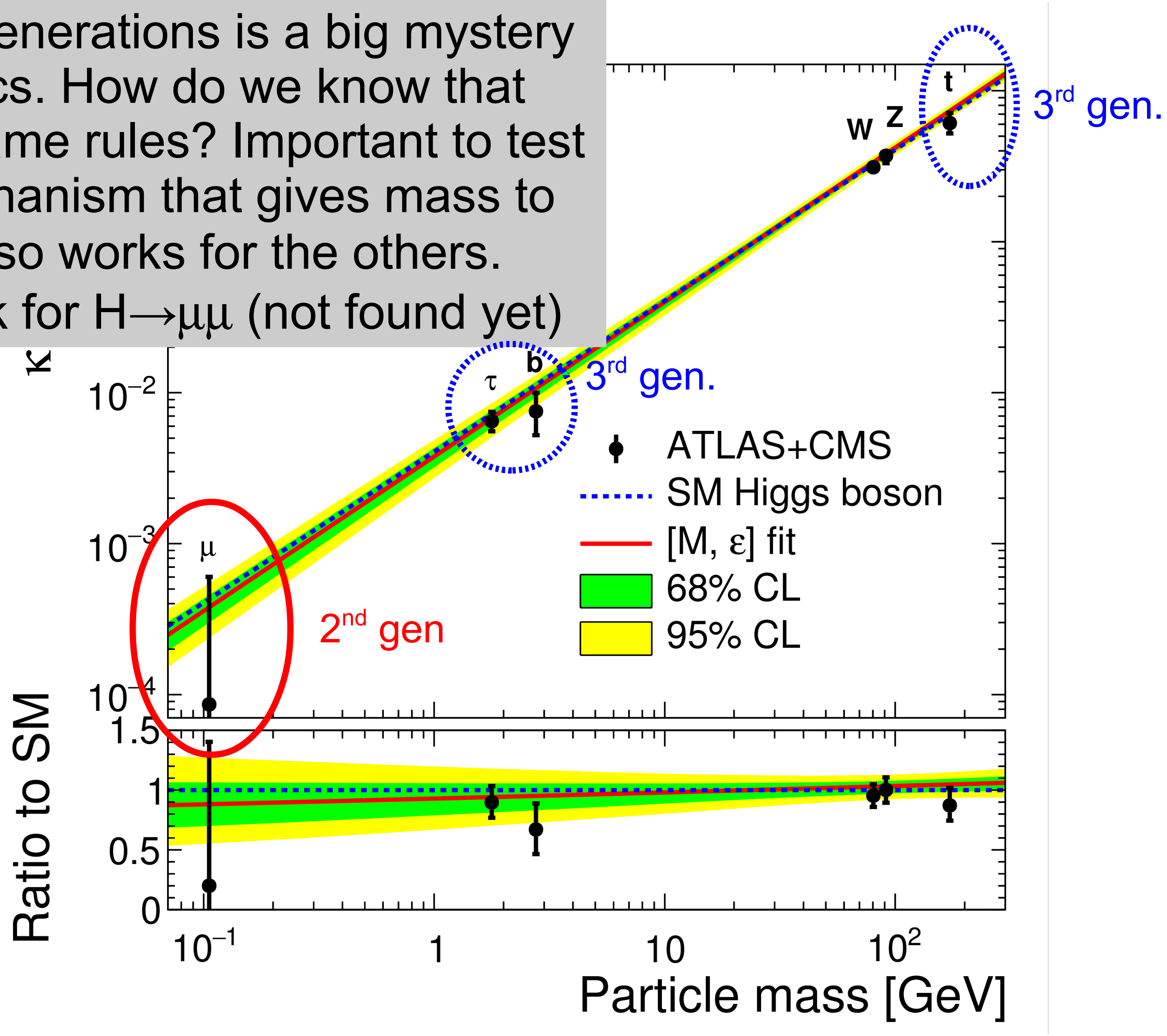
By construction, SM = (1,1)

This parameterization considers a single multiplier for all fermions, and a single multiplier for W & Z

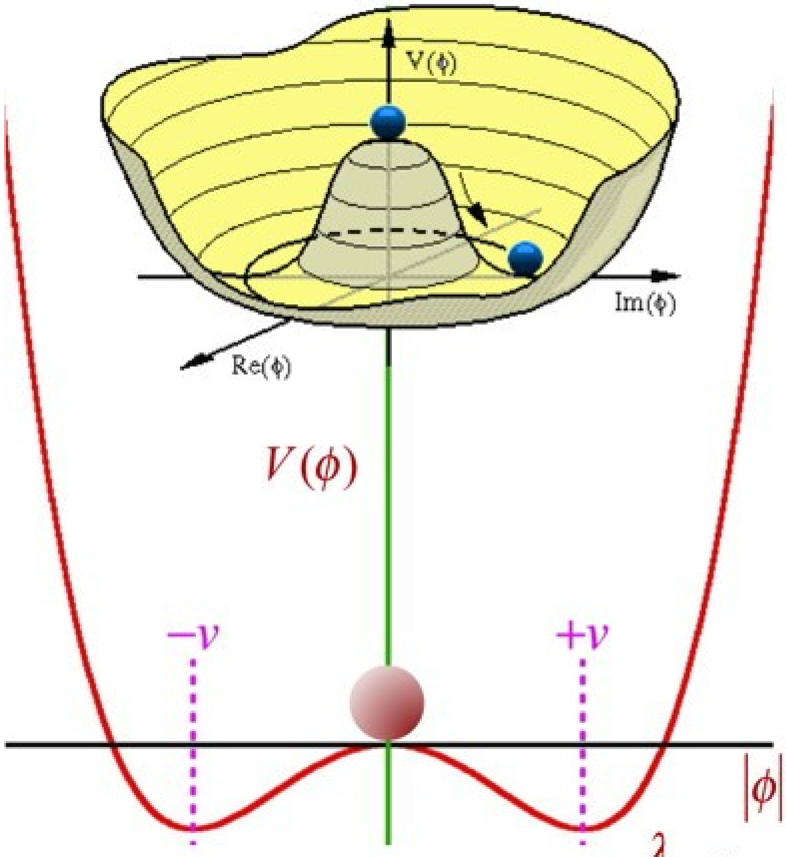
Information comes from the decays (colored areas) also taking into account the production categories (ggF, VBF, VH). Assumption: **no BSM in loops**

What's next:
are all generations the same?

Existence of 3 generations is a big mystery of particle physics. How do we know that they obey the same rules? Important to test if the same mechanism that gives mass to 3^{rd} generation also works for the others. Important to look for H→μμ (not found yet)



What's next:
testing the V(ϕ) slope



$$V(\phi) = \overbrace{\tfrac{1}{2}\mu^2\phi^\dagger\phi}^{\text{Mass term: proven}} + \overbrace{\tfrac{1}{4}\lambda(\phi^\dagger\phi)^2}^{\text{Postulated}}$$

Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$ ⇦ Well known

$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$$

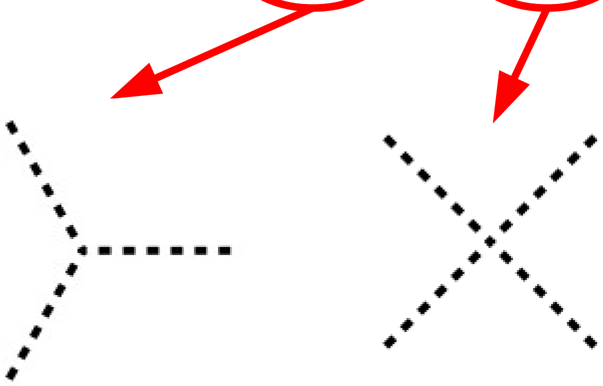
$$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$$

Picture from https://web2.ph.utexas.edu/~coker2/index.files/gaugef.htm

The Higgs self-interactions

From mass measurement   From H-H interactions

$$L=\frac{1}{2}(\partial_\mu h)^2-\lambda v^2 h^2-(\lambda v h^3+\frac{1}{4}\lambda h^4)+const.$$



Parameter λ is *indirectly* known from our knowledge of v and m_H.

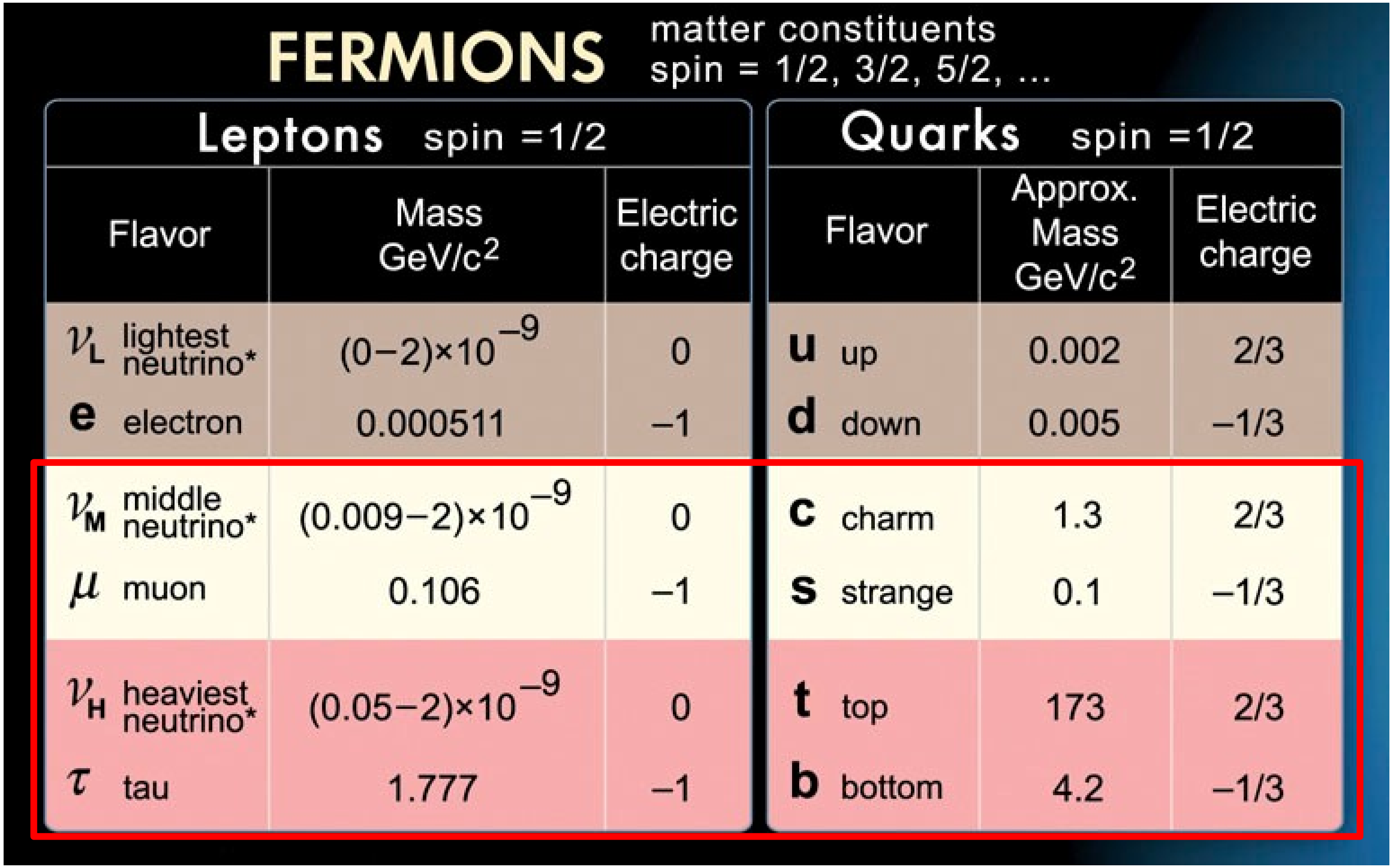
Reactions of the kind HH→H, H→HH and HH→HH would allow a model-independent knowledge of the Higgs potential, to be compared to the shape dictated by the SM.

This is one of the research directions at CP3.

Section 6.b

The top-Higgs connection

The flavour problem



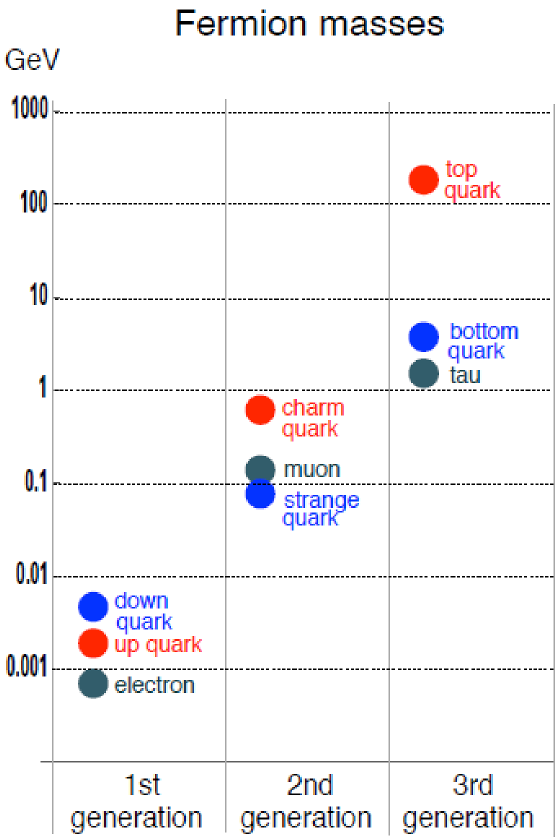
FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

	Leptons spin =1/2				Quarks spin =1/2		
	Flavor		Mass GeV/c^2	Electric charge	Flavor		Approx. Mass GeV/c^2	Electric charge
	ν_L	lightest neutrino*	$(0-2)\times10^{-9}$	0	**u**	up	0.002	2/3
	e	electron	0.000511	–1	**d**	down	0.005	–1/3
?	ν_M	middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c**	charm	1.3	2/3
	μ	muon	0.106	–1	**s**	strange	0.1	–1/3
?	ν_H	heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t**	top	173	2/3
	τ	tau	1.777	–1	**b**	bottom	4.2	–1/3

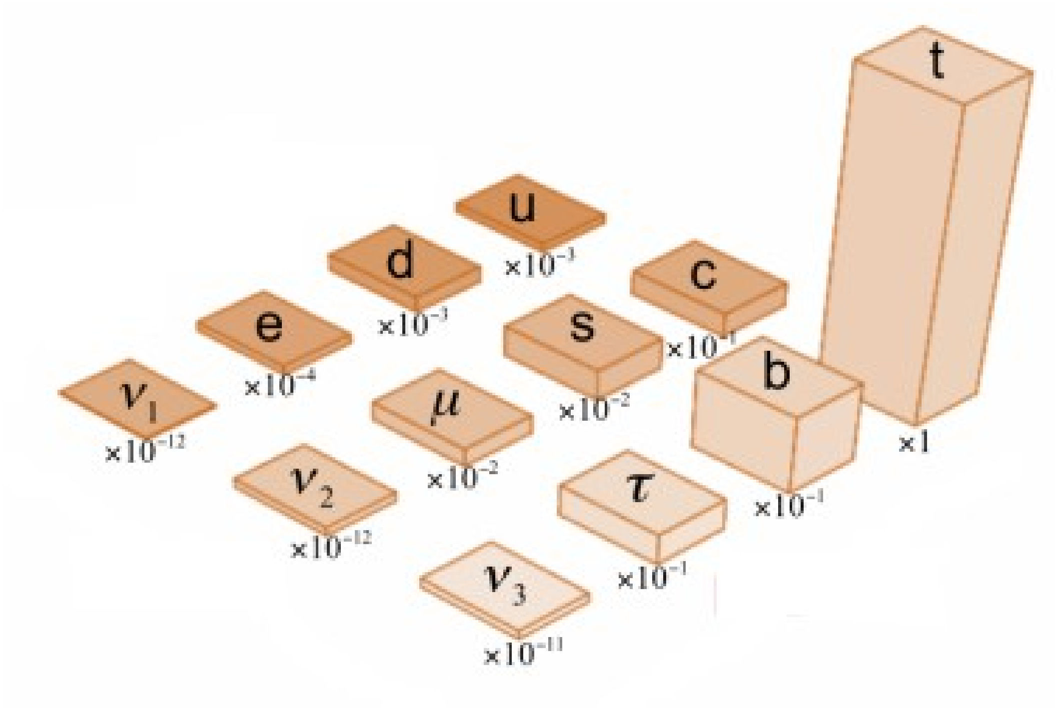
Image source: CPEP

Nicely arranged in three generations.
But we don't know why.

No clear pattern



From Gilad Perez



Picture stolen from here

Where is the top mass coming from?

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + h.c. \\ & + \boxed{\bar{\psi}_i y_{ij} \psi_j \phi} + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Where is the top mass coming from?

$$\phi = v + h \qquad\qquad L \supset \frac{y_t}{\sqrt{2}}\left(\boxed{v\bar{\psi}_t\psi_t} + \bar{\psi}_t\psi_t h\right)$$

In the SM, all fermion mass terms come from the Electro-Weak Symmetry Breaking.

The Vacuum Expectation Value, v, is well known from other fundamental parameters of the SM.

We have made some progress: we now know that the fermion mass hierarchy is a mere reflection of the hierarchy in Yukawa coupling strengths.
But no explanation for that hierarchy of Yukawa couplings

An example of a deeper explanation

- Randall-Sundrum mechanism (string-inspired):

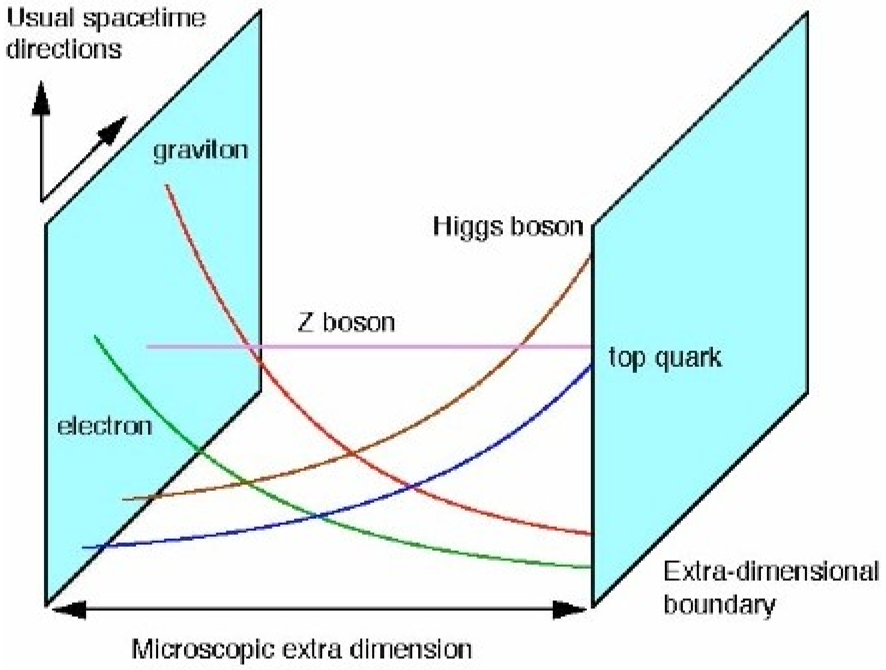


Image from here

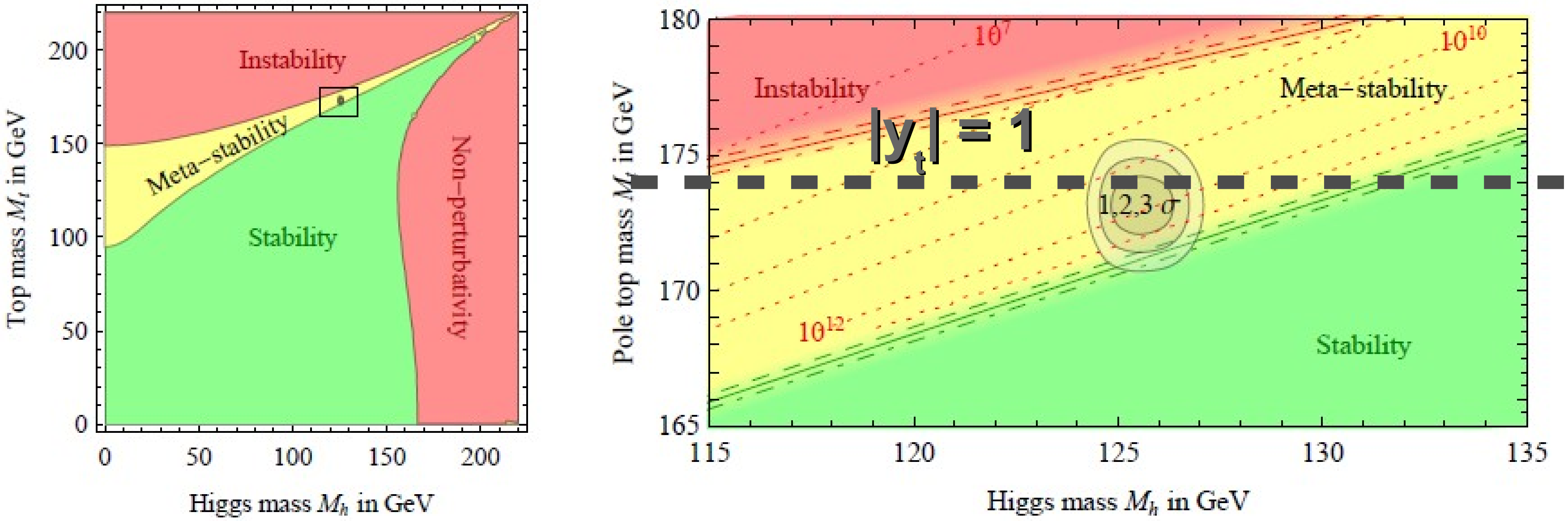
Coupling strengths come from the wavefunction shapes and their overlaps in the warped dimension.
Other models assume a special role of the top quark.

Yukawa coupling of the top

$$L \supset \frac{y_t v}{\sqrt{2}} \bar{\psi}_t \psi_t \equiv M_t \bar{\psi}_t \psi_t$$

- Fill actual numbers in:
  - $v = (\sqrt{2}G_F)^{-1/2}$ = 246.2196(1) GeV (G_F = 1.166 378 7(6)x10^{-5} GeV^{-2})
  - M_t^{CMS} = 172.44±0.49 GeV (CMS coll., Phys. Rev. D 93 (2016) 072004)
  - $M_t^{Tevatron}$ = 174.30±0.65 GeV (CDF&D0 coll., FERMILAB-CONF-16-298-E)
- We get y_t^{CMS} = 0.990±0.003, y_t^{Tev} = 1.001±0.004
  - Closeness to 1 is interesting, for an adimensional parameter
  - Pure chance, or does it reflect something deep?
  - The SM offers no explanation (apart from pure chance)

Stability of the Universe



Degrassi et al., JHEP 08 (2012) 098
(stimulated a prolific literature: link)

To understand the red areas, see also Sec.2.5 of *„The Higgs Hunter's Guide“*

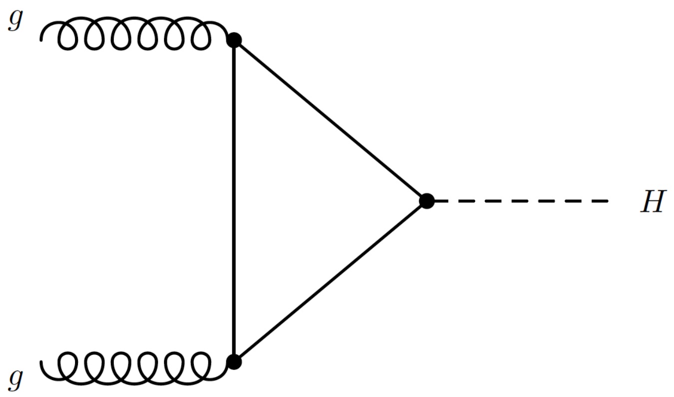
- This study assumes SM validity up to the Planck scale; and, in the SM, m_t and m_H are free parameters
- Under these assumptions, conspiracy of top and Higgs makes our Universe sit on the thin line between stability and instability
- We don't know if there is a deep reason for that

$y_t = \sqrt{2}\, M_t/v$?

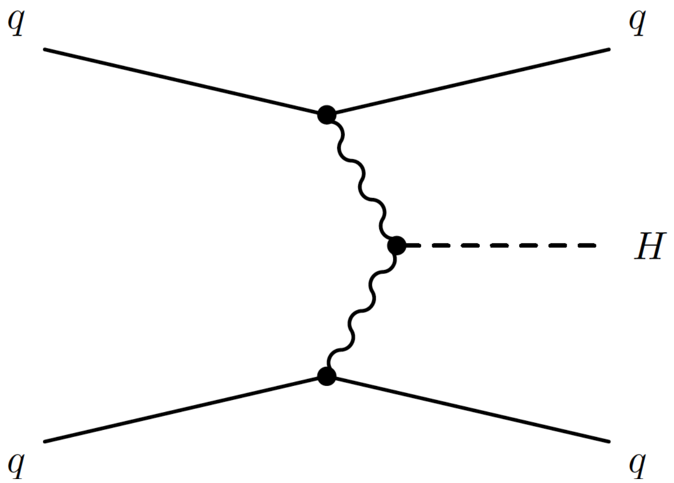
- Crucial test of the SM
  - If the equality is not exact, we prove that fermion masses are not (only) due to the Higgs mechanism
- To answer this question, we need to:
  - Measure the mass of the top quark precisely
    - (Not in the scope of this lecture; see my slides here)
  - Measure the Yukawa coupling through observables independent from the top mass
    - The most direct is the $t\bar{t}H$ cross section
    - Note: $t\bar{t}H$ has not even been observed (*) yet

(*) HEP convention: *evidence* at 3σ, *observation* at 5σ

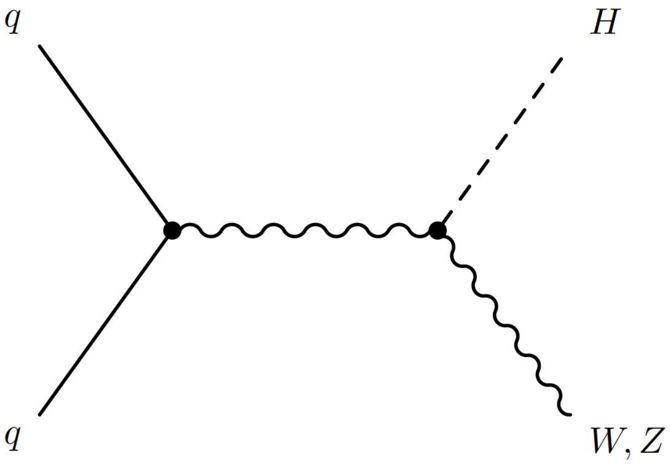
How to produce a Higgs boson



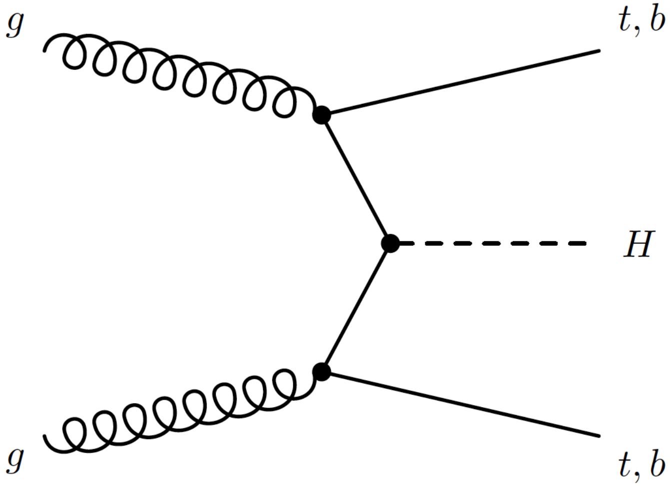
Gluon-gluon fusion



Vector-boson fusion

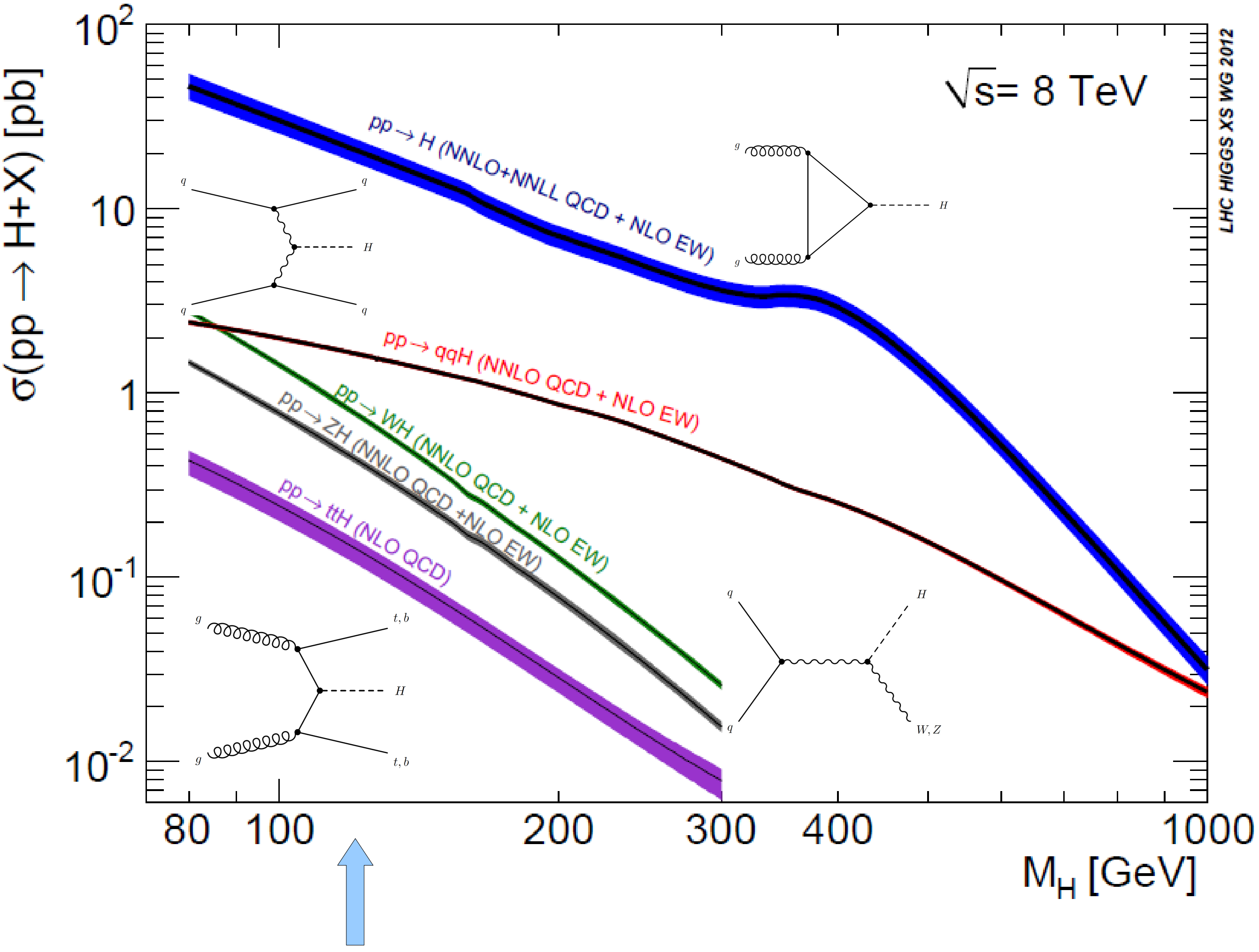


Higgs-strahlung



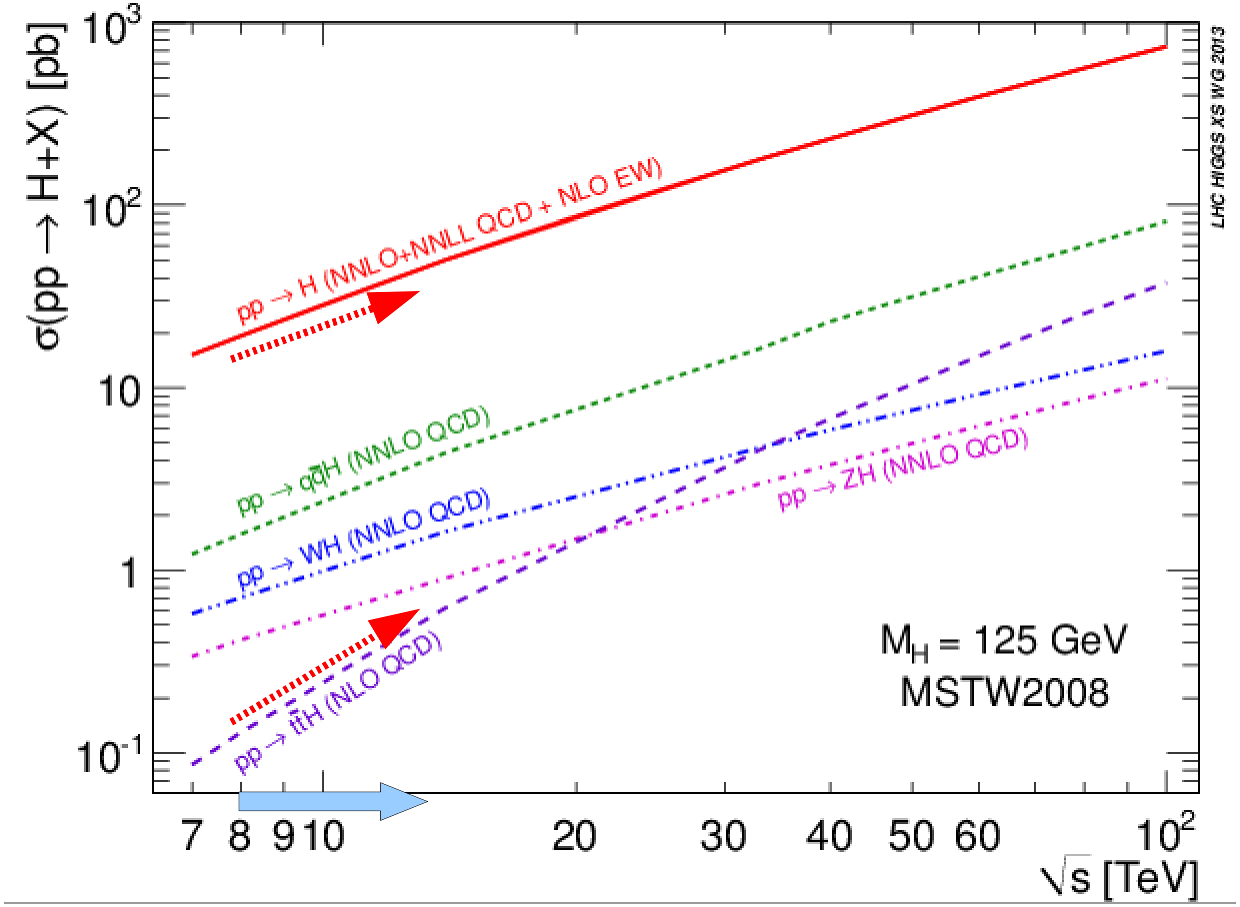
Top(bottom)-associated

Cross sections



125 GeV

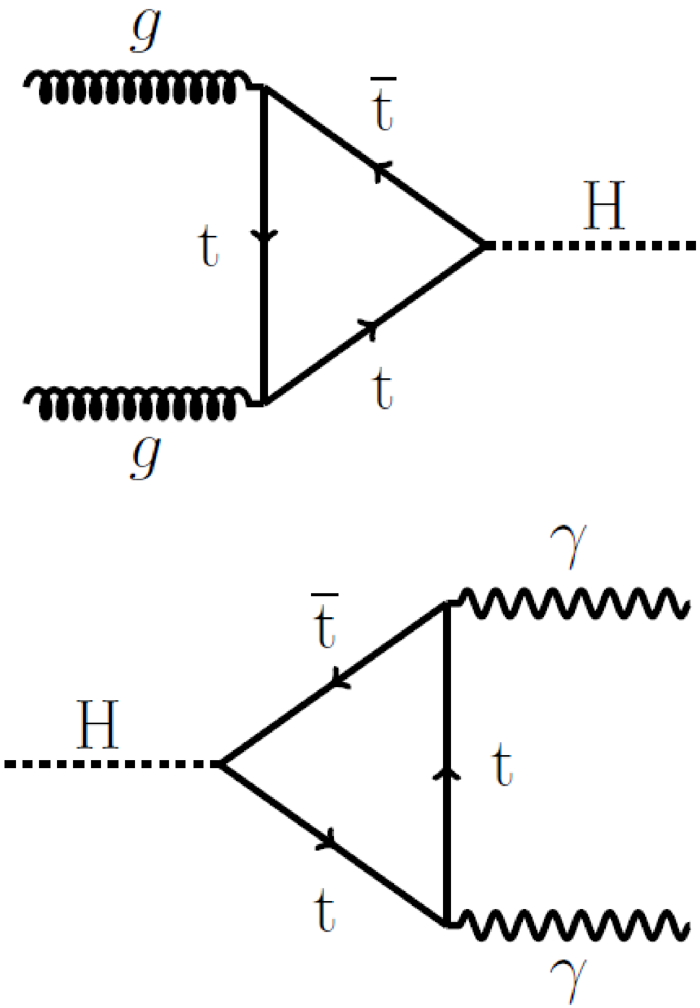
As function of collision energy



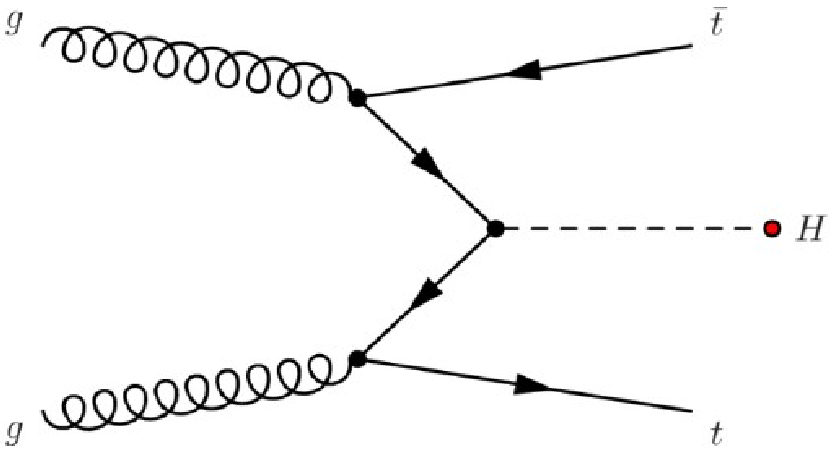
The larger the energy, the easier is ttH

From 8 to 13 TeV, 4x increase in cross section

Measuring $|y_t|$



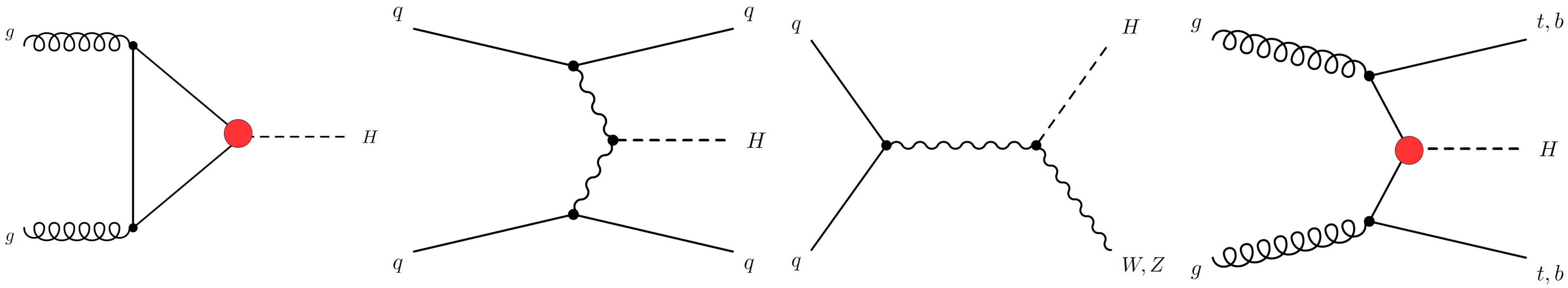
Indirect: through loops



Direct: at tree level

General consideration:
when sensitivity is induced by loops, one needs to rely more on some model assumptions (e.g., what particles run in the loop)

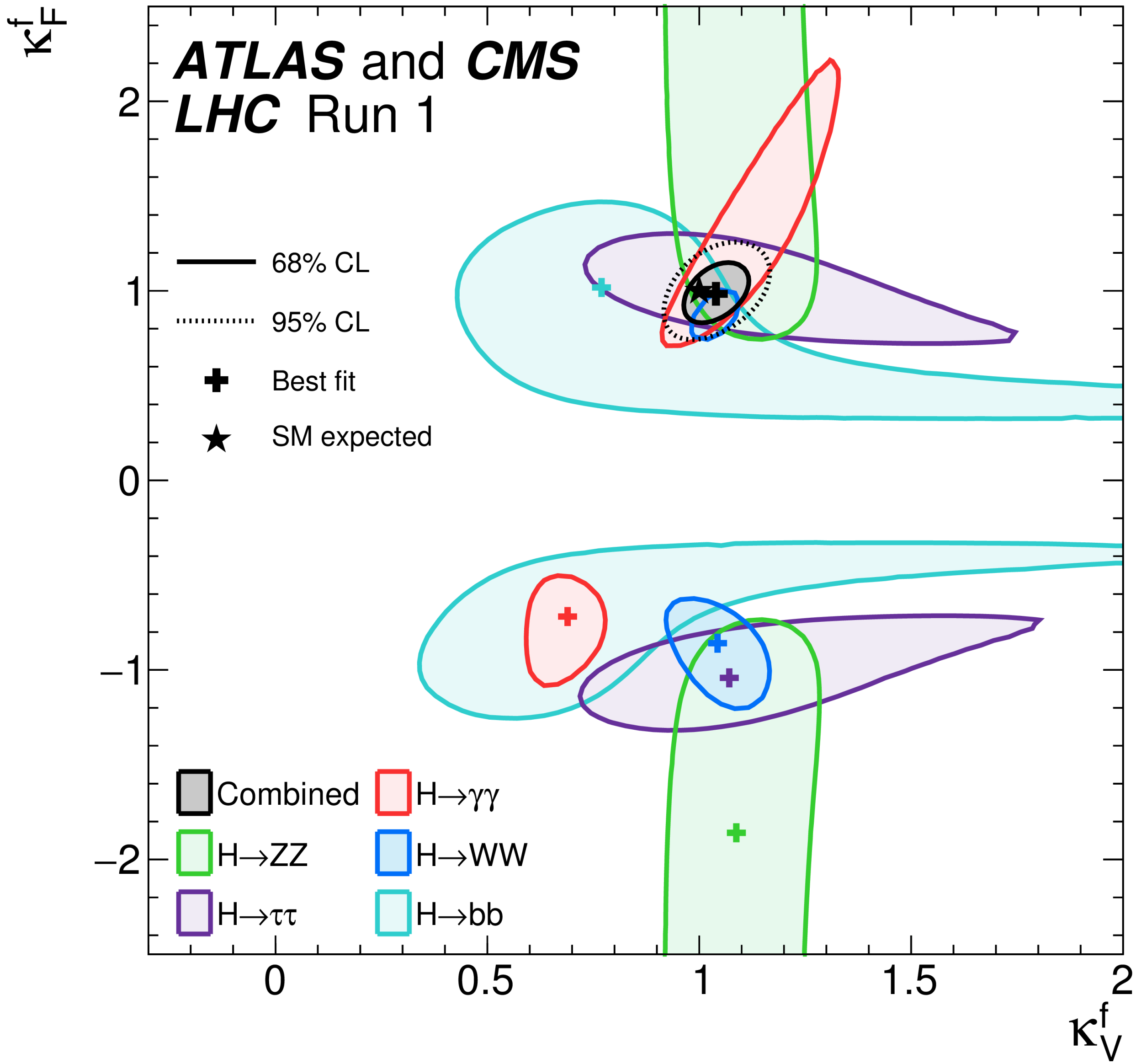
Measuring $|y_t|$: indirectly

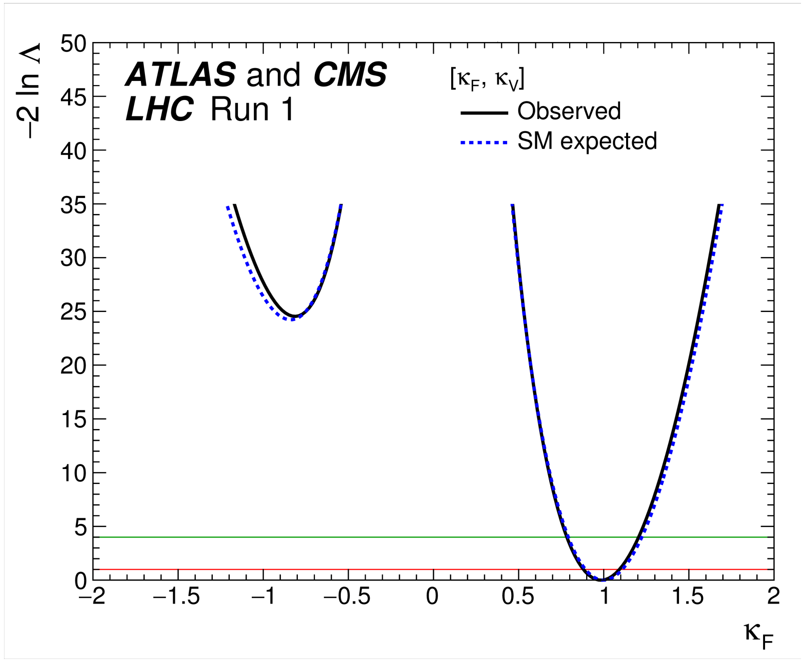


- Joint ATLAS+CMS run-1 Higgs properties paper (*) combines many final states to extract constraints on several couplings, with several alternative parameterizations and assumptions
- Diagrams with indirect (loop) and direct (tree) sensitivity to the top-Higgs coupling are both considered but, at the current state, precision on this parameter is driven by the loops
  - (For sake of clarity, I will not elaborate on the role of $t\bar{t}H$ and tH in this global combination; explicit $t\bar{t}H$ search presented later)

(*) ATLAS & CMS, JHEP 08 (2016) 045

Fermion (k_F) and boson (k_V) coupling multipliers

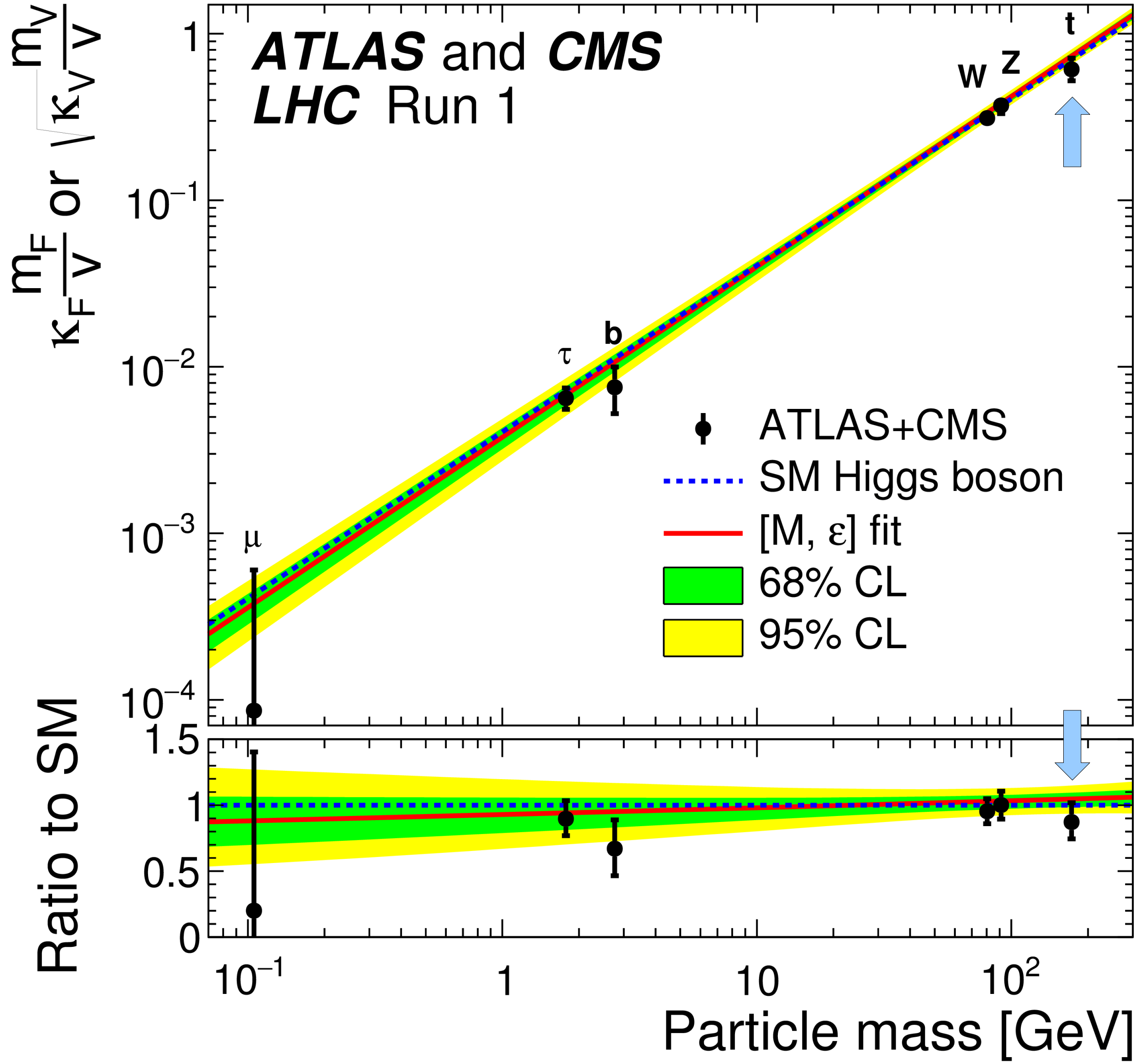




This parameterization considers a single multiplier for all fermions.
k_F ~ 1 ⇒ y_t ~ 1 (within ~25%)

Assumption: no BSM in loops

A test of the coupling-mass relationships

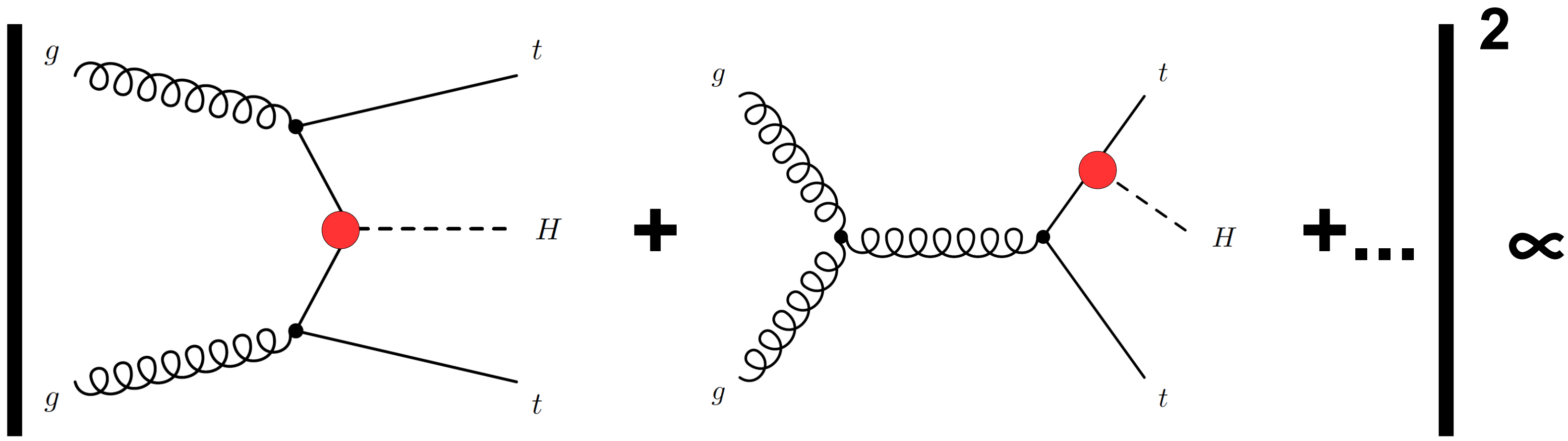


$\Rightarrow |y_t| \sim 1$

(within ~25%)

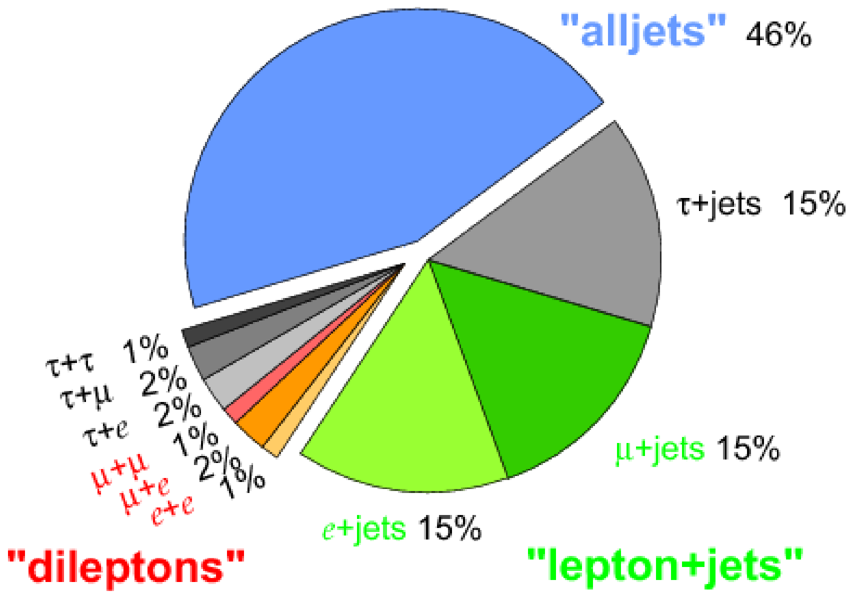
Measuring $|y_t|$: directly

$\sigma(t\bar{t}H)\propto$

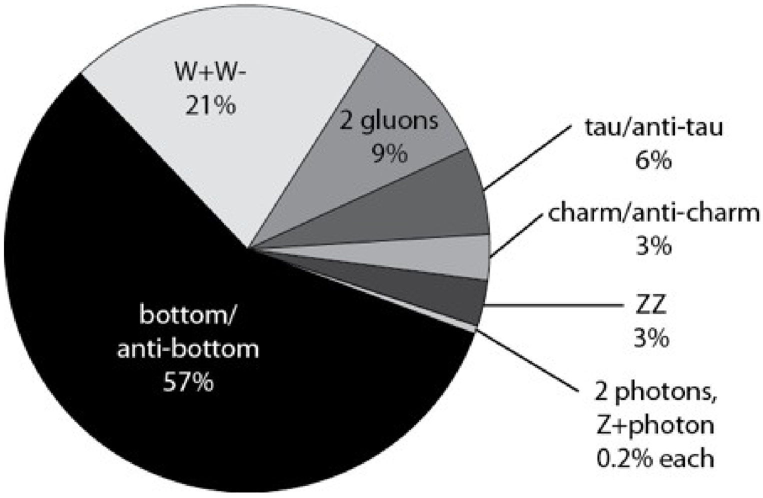


$\propto |y_t|^2$

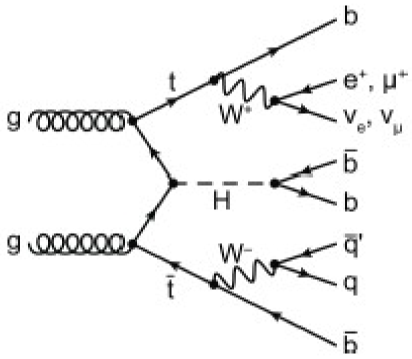
Top Pair Branching Fractions



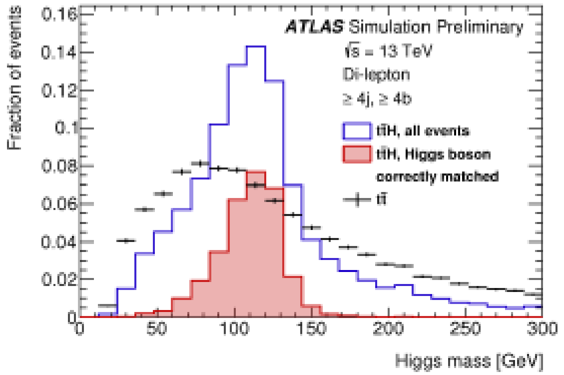
Decays of a 125 GeV Standard-Model Higgs boson



Searches for $t\bar{t}H$: $b\bar{b}$ channel



- Pros:
  - Largest BR (~60%)
  - Large multiplicity of jets and b-tags
- Cons:
  - Overwhelming $t\bar{t}$+jets background
  - Heavy flavour component of bkg ($t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$) is poorly constrained
  - Very large combinatorics of jet-parton associations
- Approaches:
  - Use several combinations of lepton / jet / b-tag multiplicities in simultaneous fit; it helps a lot in constraining bkg fractions
  - (MVA for jet-parton association, followed by) MVA for classification



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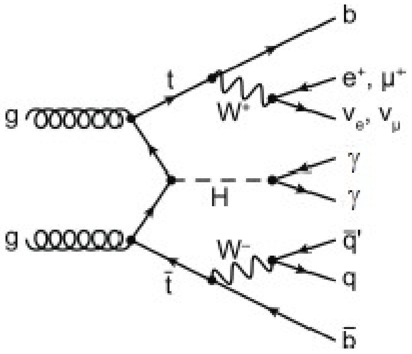
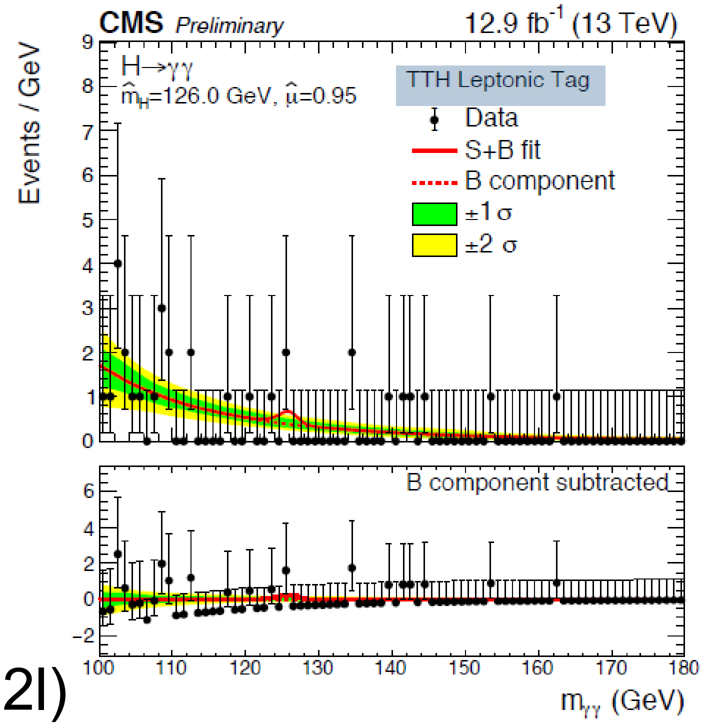
Searches for $t\bar{t}H$: γγ channel

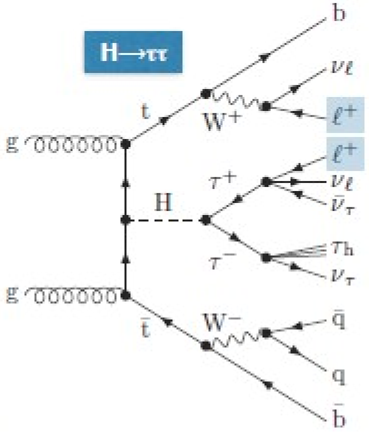


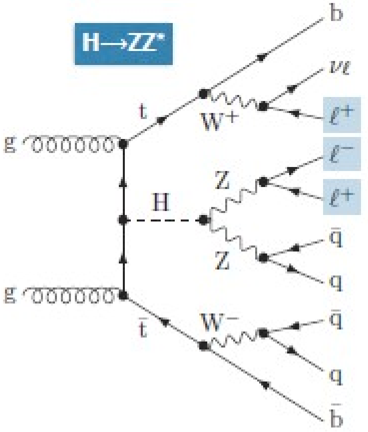
- Pros:
  - High-resolution mass peak
  - Background: smoothly falling mass spectrum
- Cons:
  - Small branching ratio (~0.2%)
- Approach:
  - Similar to standard γγ analysis
  - All possible $t\bar{t}$ final states are considered (0l,1l,2l)
  - Request two b-tagged jets

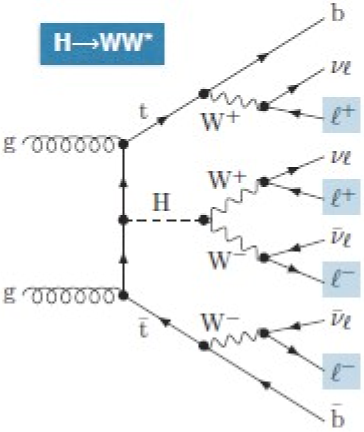


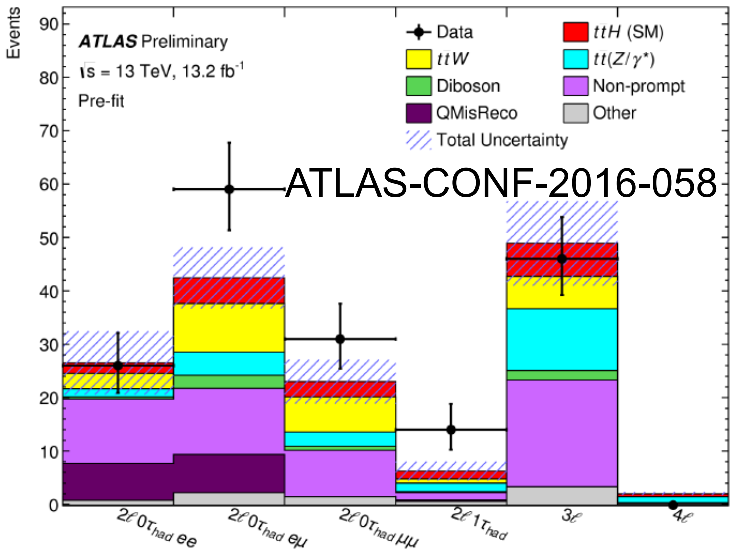
CMS-PAS-HIG-16-020

Searches for $t\bar{t}H$: multi-lepton









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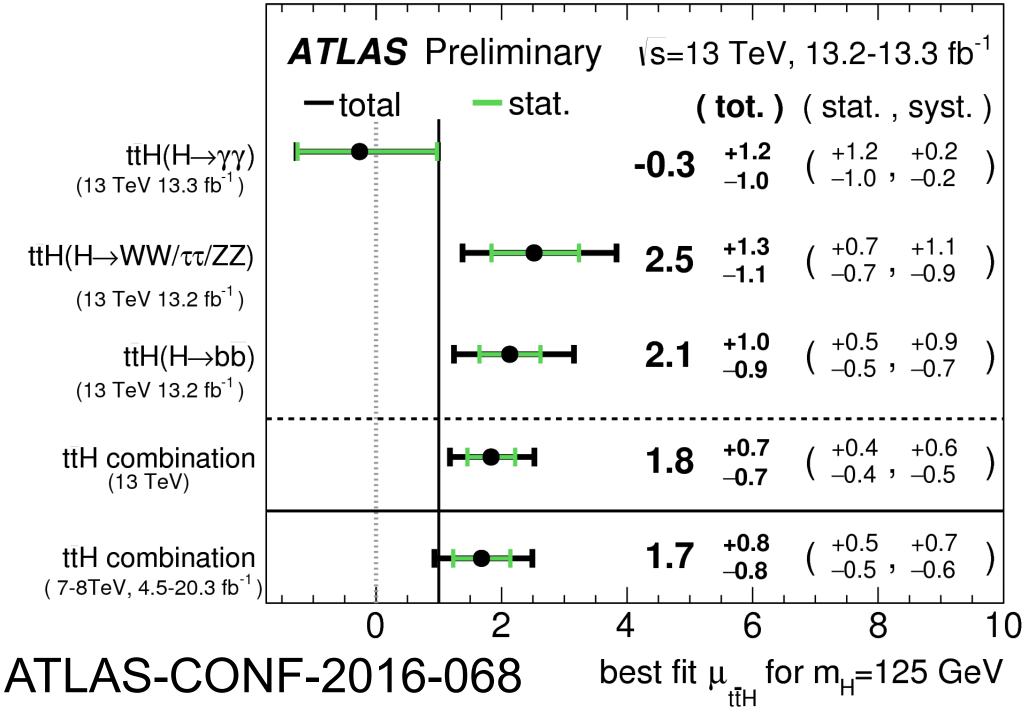
- Very clean selections: 2 same-sign leptons, or ≥3 leptons
  - Target final states with at least one leptonic top decay and more leptons from H→ττ (6.3%), H→ZZ (2.6%), H→WW (21.5%)
- Most challenging background is $t\bar{t}$ (1l,2l) plus non-prompt leptons (b/c→l, π/K→l, $\gamma \to e^+e^-$) or lepton charge confusion
  - Control regions are used to estimate fake rate from data
  - To estimate charge confusion: use $Z \to l^+l^+$ and $Z \to l^-l^-$ (*Q: how?*)

Searches for $t\bar{t}H$:
latest results (to be updated next Monday!)



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CMS (13-15/fb)**:**

- $H\to\gamma\gamma$: $\mu = 1.9^{+1.5}_{-1.2}$
  CMS-PAS-HIG-16-020
- Multilepton: $\mu = 2.0^{+0.8}_{-0.7}$
  CMS-PAS-HIG-16-022
- $H\to b\bar{b}$: $\mu = -0.2\pm0.8$
  CMS-PAS-HIG-16-038

LHC Run-1 combination:

- $\mu = 2.3^{+0.7}_{-0.6}$

~40% uncertainty on signal strength (μ) $\Rightarrow$ ~20% on y_t

$$(\mu \equiv \sigma_{obs}/\sigma_{exp} \propto y_t^2 \Rightarrow \Delta\mu/\mu = 2\Delta y_t/y_t)$$

Exam

- It will be on 23/06 (not 20/06) starting at 14:00
- Format:
  - Written "review" report of <10 pages in pdf format including pictures, references, etc., by 16/06
  - Oral exam (not a presentation!) on 23/06
  - Bonus if you do well at the mid-term evaluation next week
  - Bonus (up to 2 points in total) for the problem-solving evaluations during K.P.'s lectures

The written report

- Topics:
  - Muon collider: physics motivations
  - Muon collider: experimental challenges
  - New acceleration techniques
  - Dark matter searches (choose one type)
  - Free subject (but very well motivated)
- Purpose:
  - A short overview of the subject (in English or French)
- Structure:
  - Introduction: motivation + stating a "problem" + wider context
  - Present status of their studies and their relevance
  - Outlook: next steps and longer-term perspectives

Questions?