Higgs

Judith Katzy, DESY

10 years of Higgs discovery
4.7.2012

Happy birthday!

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HELMHOLTZ
ASSOCIATION

Higgs

- Higgs mechanism predicted by Englert, Higgs and Brout in the 1960s
- Nobel prize in 2013 to Francois Englert and Peter Higgs

Higgs discovery seminar at CERN on 4.7.2012

The Higgs boson turns ten

Wise Old Owl • a day ago

I'm not a particle physicist but I believe the headline is fundamentally flawed as the Higgs Boson has, I suspect, been around for rather longer than 10 years..

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Observed particles of the Standard Model of Particle physics in 2011

- mass
- charge
- spin

QUARKS

mass / charge / spin			
	≃2.2 MeV/c² · ⅔ · ½ · u **up**	≃1.28 GeV/c² · ⅔ · ½ · c **charm**	≃173.1 GeV/c² · ⅔ · ½ · t **top**
	≃4.7 MeV/c² · −⅓ · ½ · d **down**	≃96 MeV/c² · −⅓ · ½ · s **strange**	≃4.18 GeV/c² · −⅓ · ½ · b **bottom**

LEPTONS

≃0.511 MeV/c² · −1 · ½ · e **electron**	≃105.66 MeV/c² · −1 · ½ · μ **muon**	≃1.7768 GeV/c² · −1 · ½ · τ **tau**
<1.0 eV/c² · 0 · ½ · ν_e **electron neutrino**	<0.17 MeV/c² · 0 · ½ · ν_μ **muon neutrino**	<18.2 MeV/c² · 0 · ½ · ν_τ **tau neutrino**

0 · 0 · 1 · g **gluon**	≃91.19 GeV/c² · 0 · 1 · Z **Z boson**
0 · 0 · 1 · γ **photon**	≃80.433 GeV/c² · ±1 · 1 · W **W boson**

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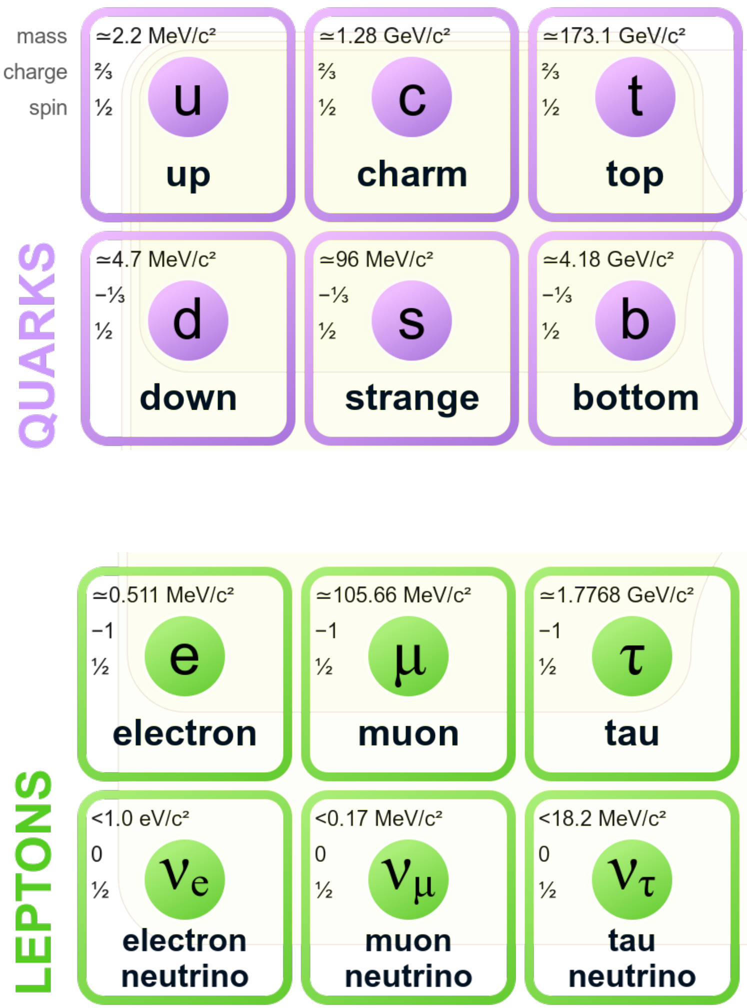
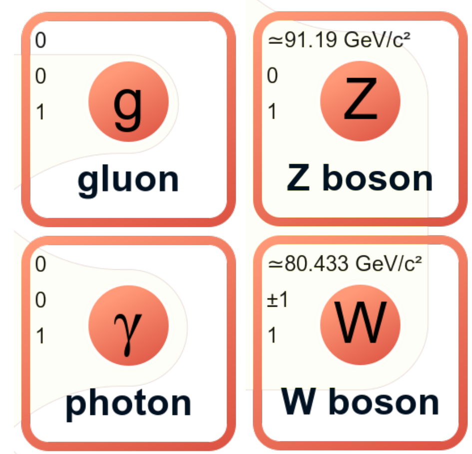
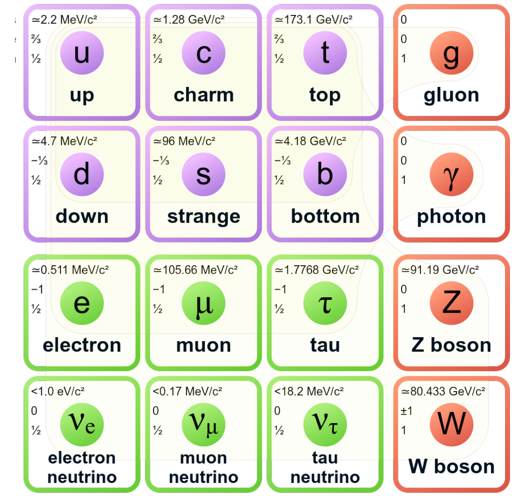




Fundamental particles well structured in terms of charge, spin and interactions

mass



gγ e ud sμ cτ b W,Z t

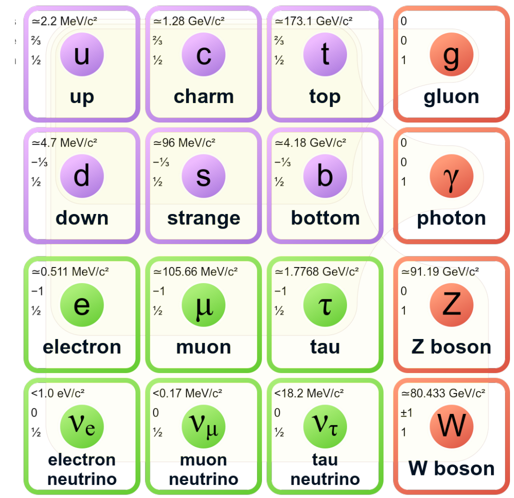
m 0 | 0,5 MeV | 1 GeV | 100 GeV | 175 GeV

But mass is a mess…..

Mass of gauge bosons: W, Z

- Observation: weak force is much weaker than em force
- Description: interactions are mediated by gauge bosons:
  - EM interaction:
    - long range - transmitted by massless gauge bosons (photons)
    - No exchange of charge - gauge boson is neutral (photons)
  - Weak interaction:
    - Short range - transmitted by massive gauge bosons (W,Z)
    - With and without exchange of charge - neutral (Z) and charged (W) gauge bosons

mass



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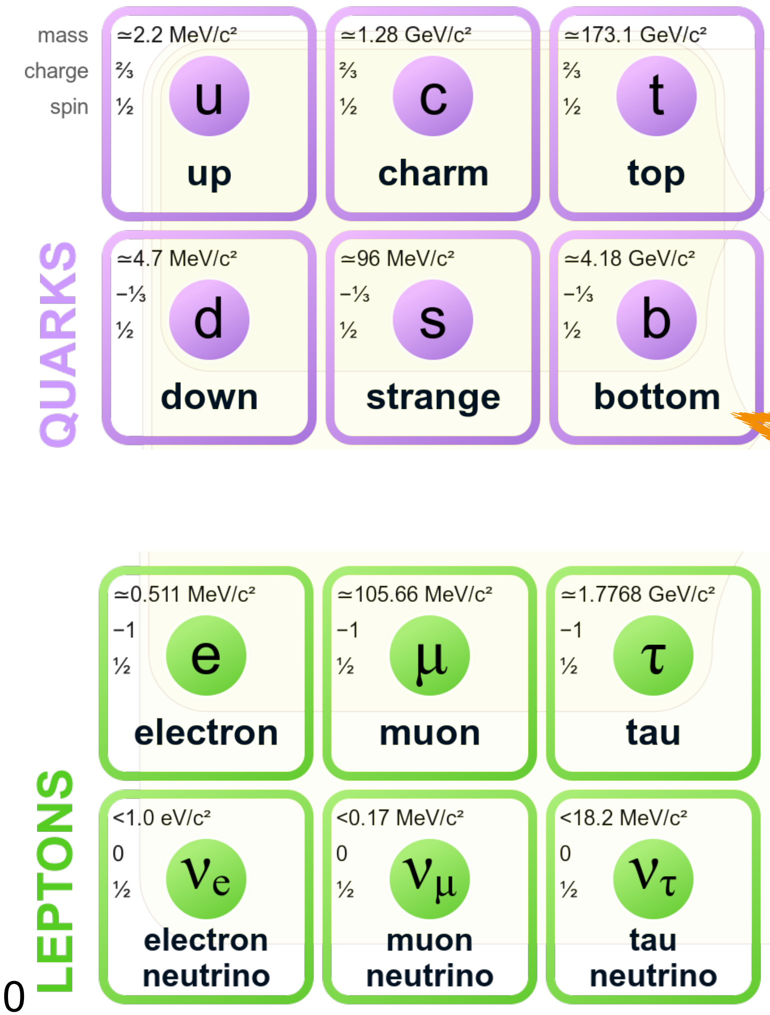
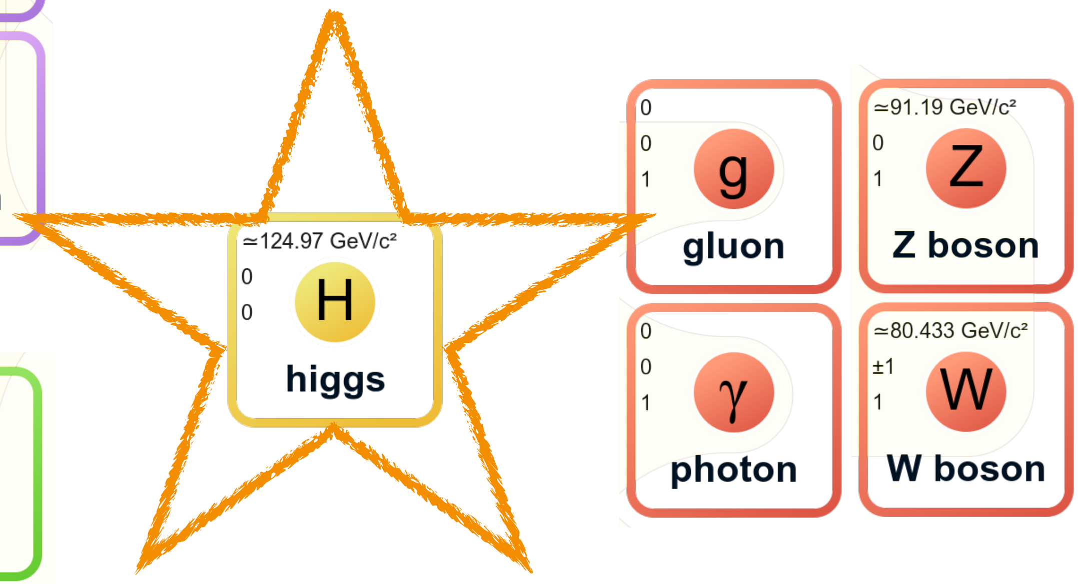
How do get particles mass?

Complete Standard Model of Particle physics in 2012





Responsible for the mass of fundamental particles

Higgs field & Higgs boson

- Higgs field
  - New type of fundamental field (“5th force”)
  - Higgs field is non-zero everywhere all the time
    - Independent of a source being present in the Universe
    - Reminiscent of Aether concept, but now consistent with special relativity
  - Strength of interaction between particles and the Higgs field causes their mass
- Higgs boson detected = proof of Higgs field exist

How do we notice the Higgs field?

Phys. Rev. D 79, 096002 (2009)

Indirect:

- Predict size of atoms:
  - Atomic radius proportional to $1/m_e$
  - A different radius would modify energy levels and chemical reactions of all elements

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    - Protons are stable

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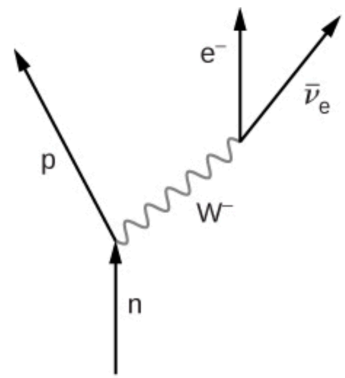
    - Protons are stable
- Sets timescale of radioactive β decays
  - Many radioactive decays involve the W boson
  - examples: fusion reaction in the Sun; life time of stars
  - Mass of W influences the rate of these reactions



How do we notice the Higgs field?

Phys. Rev. D 79, 096002 (2009)

Direct:

- Perturb the Higgs field a bit so that it jumps by a quantum and decays by emitting its field quant: the Higgs Boson
- Measure interaction of the Higgs Boson with the SM particles in proton proton collisions at the LHC

The Higgs Boson

- Powerful tool to study how the underlying Higgs field affects fundamental particles of the Standard Model. Measure
  - Higgs production
  - Higgs decay
  - Higgs mass
  - Higgs spin

- Since Higgs is everywhere use it to search for signatures of particles or effects hithero unkown and outside the Standard Model
  - Portal to dark matter
  - Explanation for Baryon asymmetry
  - …

The Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

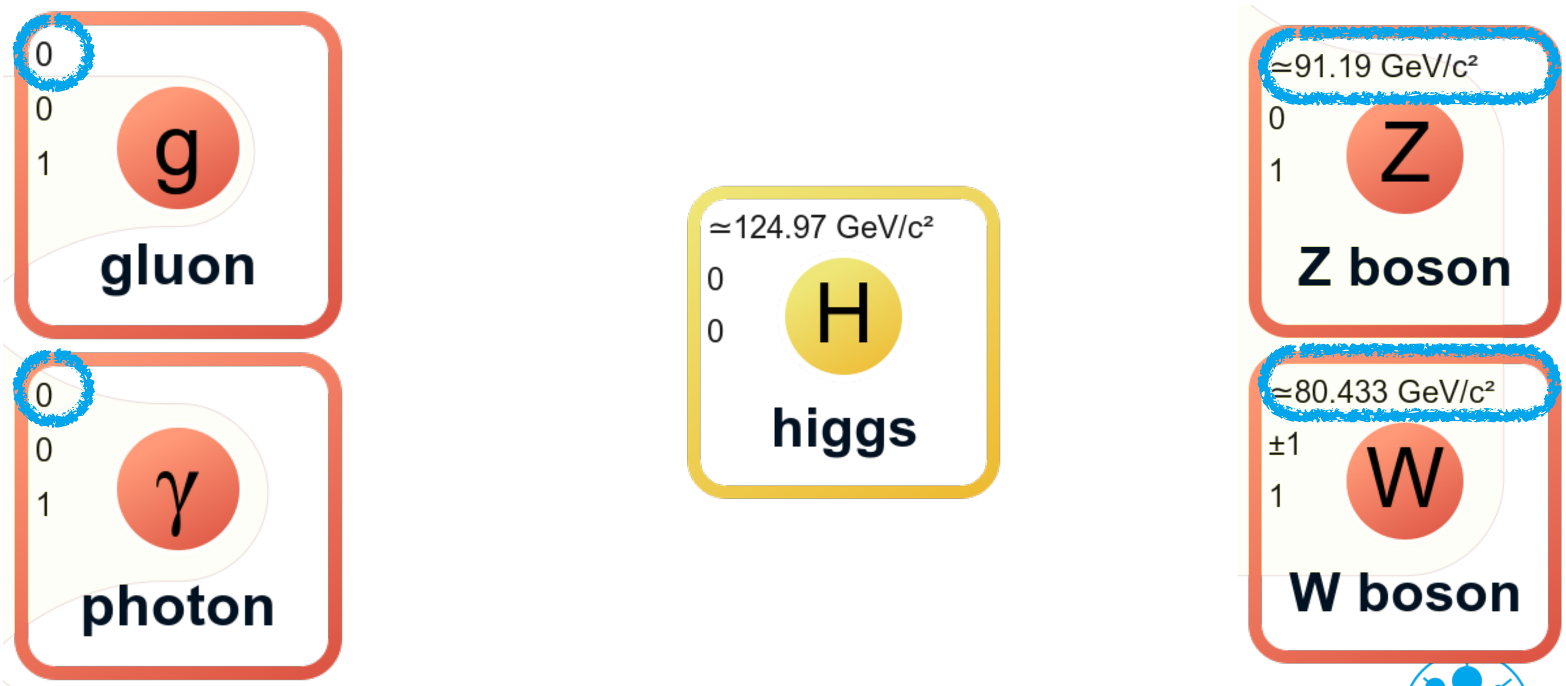
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

- Kinematic term of the gauge bosons
- Kinematic term of the fermions, and interaction between fermions and gauge bosons
- Higgs-fermions interaction
- Kinematic term of the Higgs boson, and interaction with the gauge bosons
- Higgs potential and self interaction

Higgs mechanism for gauge bosons

- Modify electroweak part of the Lagrangian to give mass to W and Z but leaving photons and gluons massless



Higgs mechanism for gauge bosons

- Goal: modify electroweak part of the Lagrangian to give mass to W and Z but leaving photons and gluons massless
  - Introduce a (complex) doublet scalar field ϕ (= 4 real scalar fields related to gauge bosons)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

Higgs mechanism for gauge bosons

- Goal: modify electroweak part of the Lagrangian to give mass to W and Z but leaving photons and gluons massless
  - Introduce a (complex) doublet scalar field ϕ (= 4 real scalar fields related to $W^{+/-}$, Z, photon)
  - Generate a mass term from kinetic energy term of ϕ (by breaking its symmetry)
- Add a Potential for the scalar field ϕ

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V\left(\Phi^\dagger \Phi\right)$$

Kinetic energy term — Potential

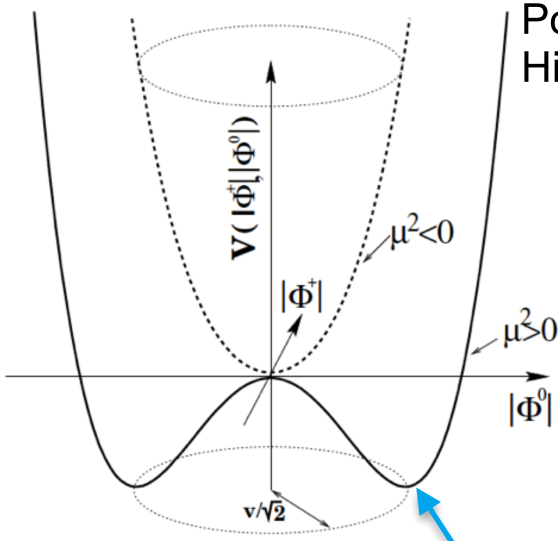
The Higgs Potential

$$V\left(\Phi^\dagger\Phi\right) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2, \qquad\qquad \mu^2, \lambda > 0$$

Notice the "wrong" mass sign.

$V\left(\Phi^\dagger\Phi\right)$ is $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$ symmetric.

- Higgs field at ϕ=0 is not the minimum
  - instable configuration!
- Higgs field has a constant value in vacuum corresponding to the minimum of the potential
  - "vacuum expectation value" v or vev
  - Higgs field at minimum of potential is non-zero
    - Higgs must be spin 0 to avoid violation of space-time symmetry
    - Higgs is the only fundamental particle with spin 0



Potential of Higgs field

Higgs field value In our Universe

Higgs field is a scalar field

- Assign a number (scalar) to each point in space
  - Example: temperature map
- Here: value of Higgs field at minimum of Higgs potential (in vacuum)
- We can derive this value:

$$m_W^2 = \frac{g^2 v^2}{4}$$

and

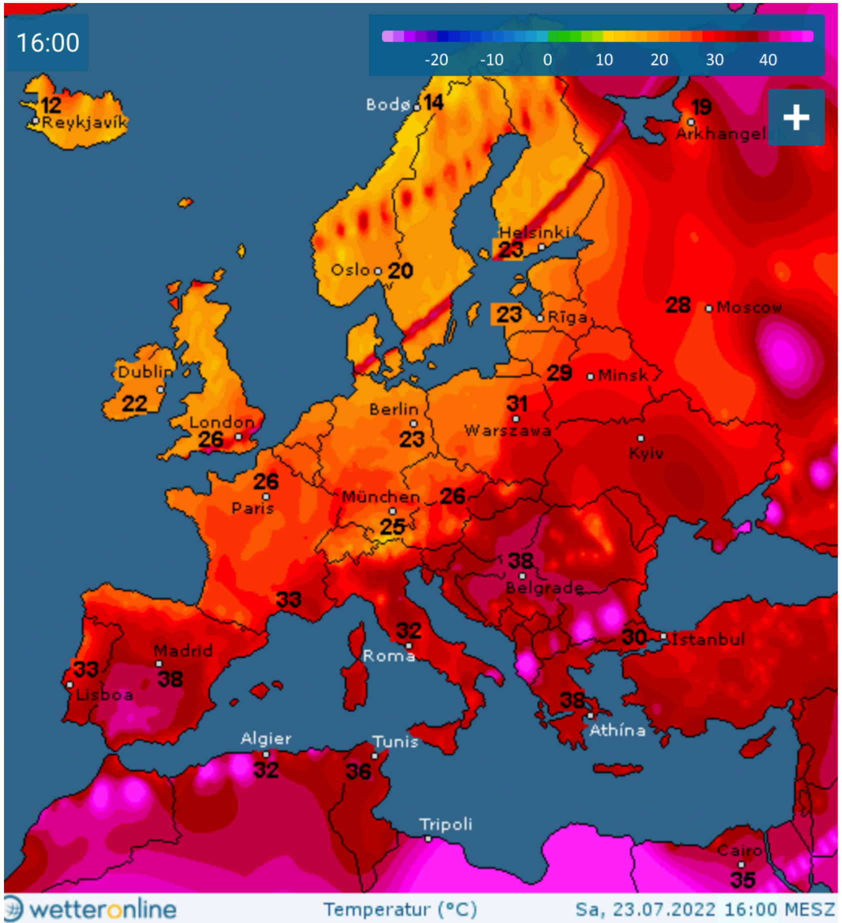
$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{m_W^2}$$

Charged currents

$$v = \sqrt{\frac{1}{\sqrt{2}G_F}}$$

Fermi G_F measured precisely from muon lifetime (with muon beam@PSI)

$$v = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246.22 \text{ GeV}$$



Consequences for the scalar field H

The scalar potential

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

expanded around the vacuum state

$$\Phi(x) = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v + H(x) \end{array}\right)$$

becomes

$$V \;=\; \frac{1}{2}\left(2\lambda v^2\right) H^2 \;+\; \lambda v H^3 \;+\; \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$

- the scalar field H gets a mass

$$m_H^2 = 2\lambda v^2$$

- there is a term of cubic and quartic self-coupling.
- a constant term: the cosmological constant (irrelevant in the Standard Model)

$$\rho_H \equiv \frac{\lambda}{4} v^4 = \frac{v^2 m_H^2}{8}$$

Consequences: the masses of the bosons

g: weak isospin
g':weak hypercharge

- Two massive charged vector bosons

$$m_W^2 = \frac{g^2 v^2}{4}$$

- One massless vector boson

$$m_\gamma = 0$$

- One massive neutral vector boson Z

$$m_Z^2 = (g^2 + g'^2) v^2 / 4$$

- One massive scalar particle: The Higgs Boson

$$m_H^2 = \frac{4\lambda(v) m_W^2}{g^2} = \lambda v^2$$

Whose mass is an unknown parameter of the theory as the quartic coupling λ

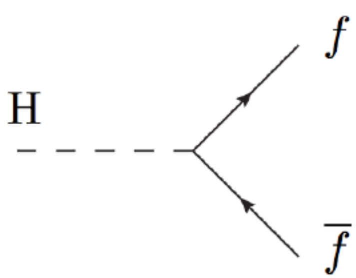
-> Higgs mass is not predicted by the model!

Fermion mass - Yukawa interaction

- Direct mass term not invariant under $SU(2)_L$ or $U(1)_Y$ gauge transformation
- Generate masses through Yukawa-type interaction terms
  - Lorentz invariant, gauge invariant and renormalizable

- $L_{Yukawa} = \bar{\psi}_i \, y_{ij} \, \psi_j \phi + h.c.$

- Coupling directly proportional to mass



$$\frac{m_f}{v}$$

Higgs as a "fifth force" - how does it act?

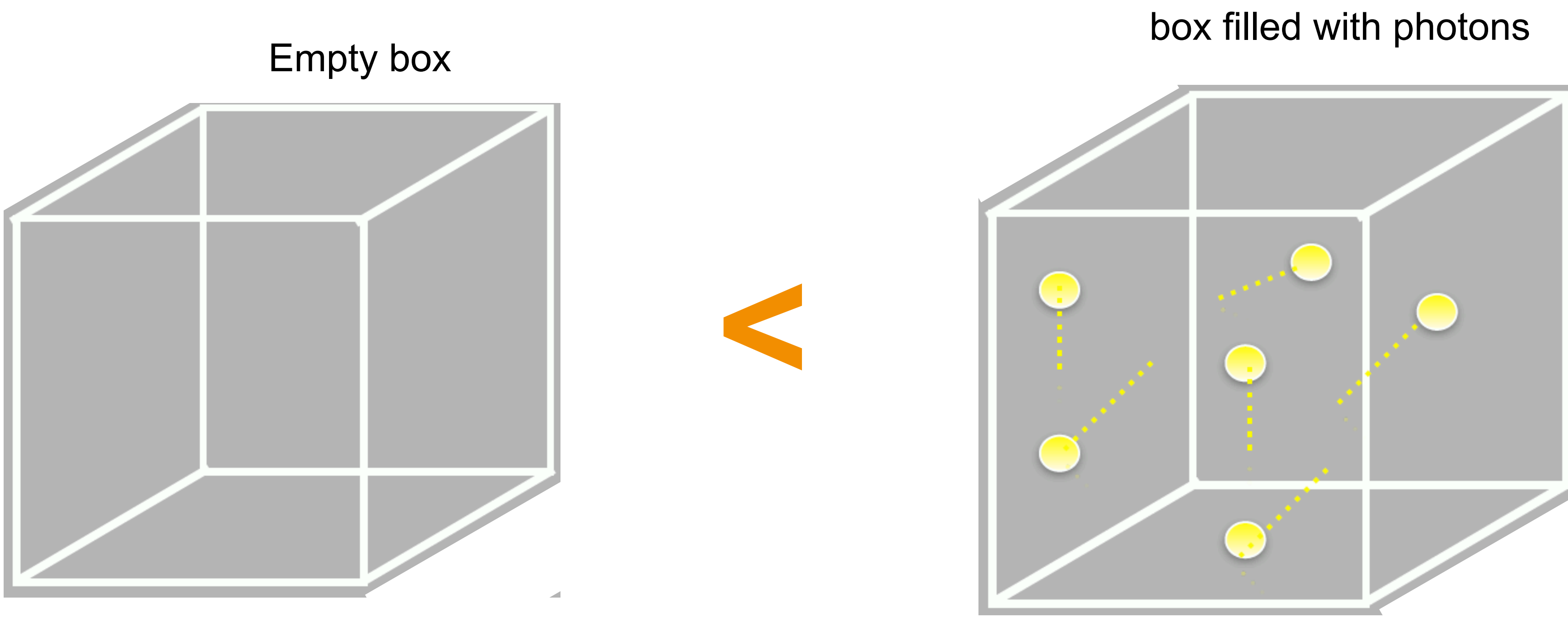
- Particles acquire mass by exchanging Higgs boson
  - Force is stronger for heavier particles
  - reminiscent of gravity

- Other forces in SM: interaction strength comes in multiples of some basic unit of charge
  - Electron charge for electric force

- Isn’t Gravity the force that acts on mass?
- Does Higgs explain the mass of matter?

Going back: what is mass?

- Einstein: $E = m / c^2$. <=> $m = E / c^2$



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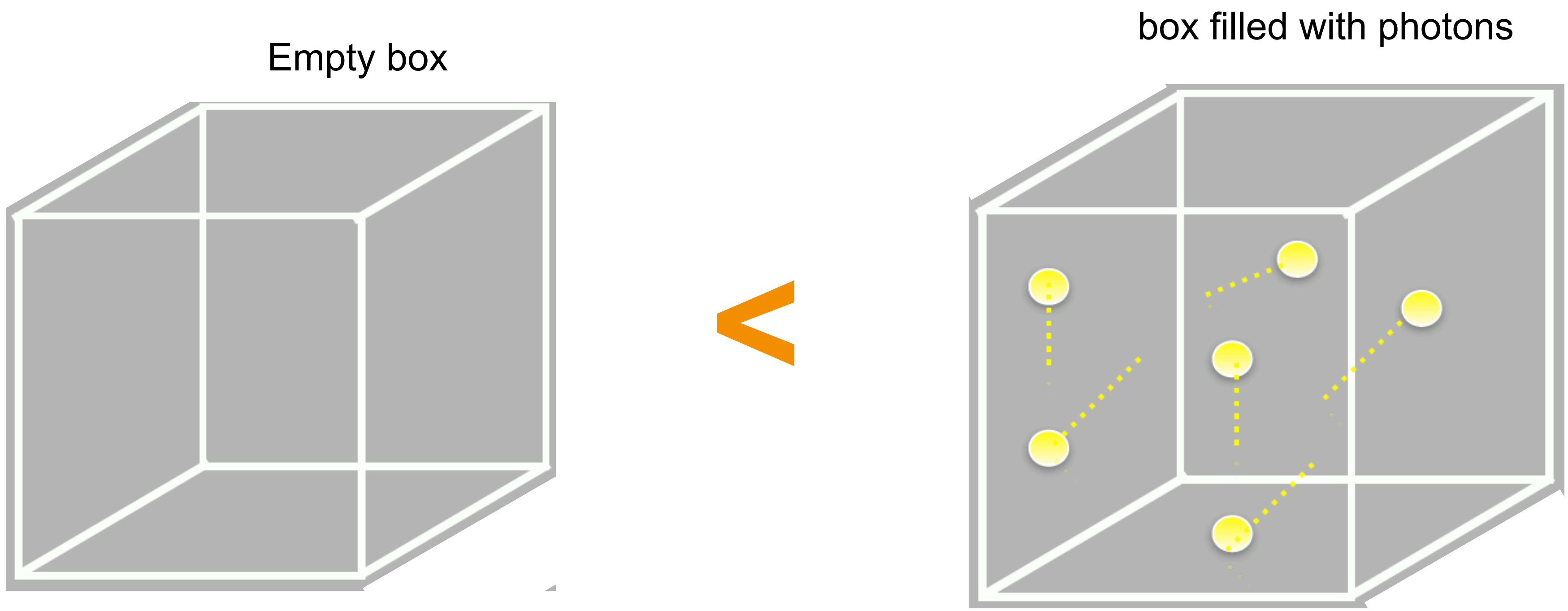
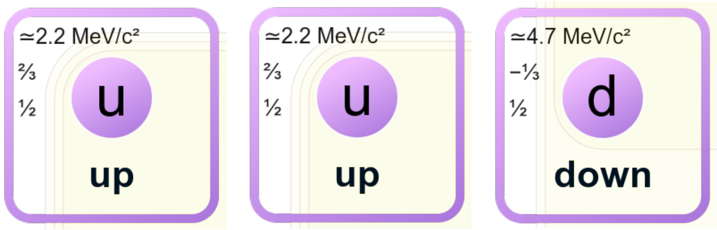
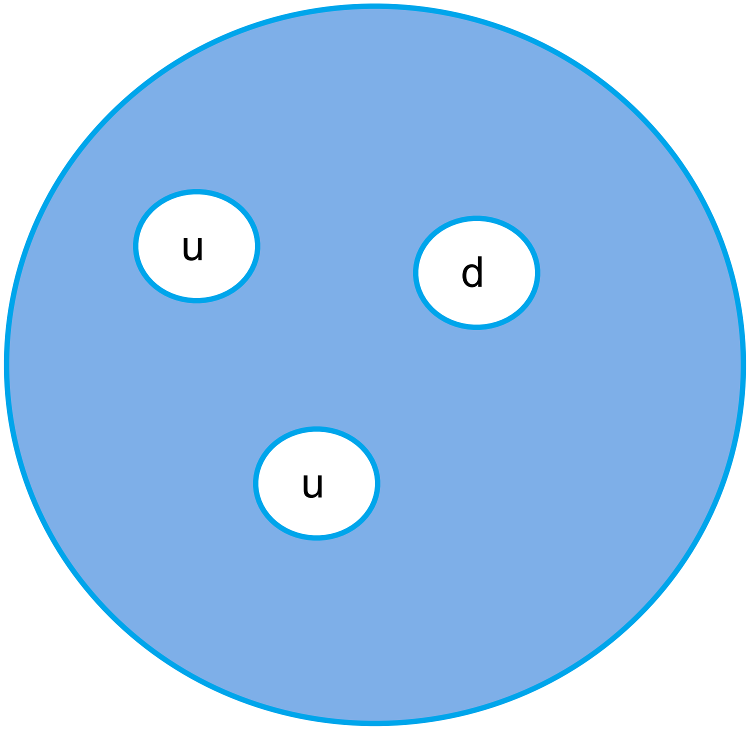


- A system of massless constituents can have a mass

In the real world

- Mass of valence quarks is 9.1 MeV / 1 GeV ~ 1% of the mass of the proton





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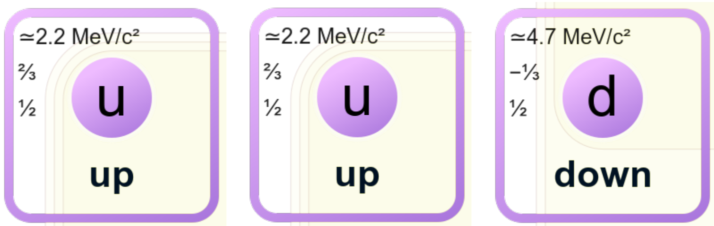
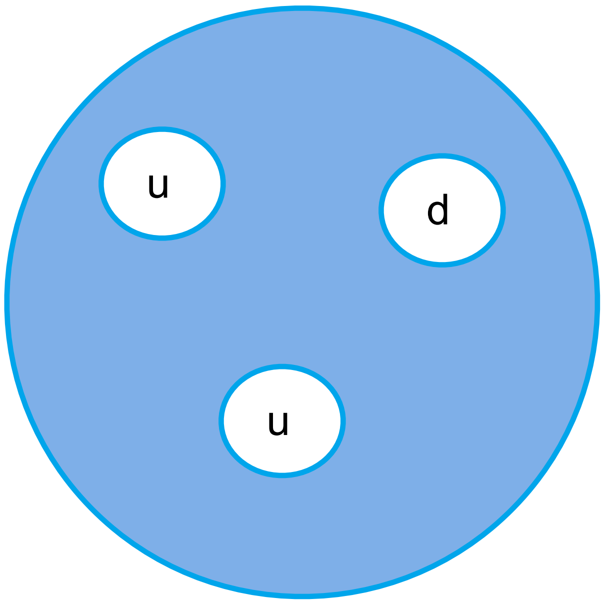
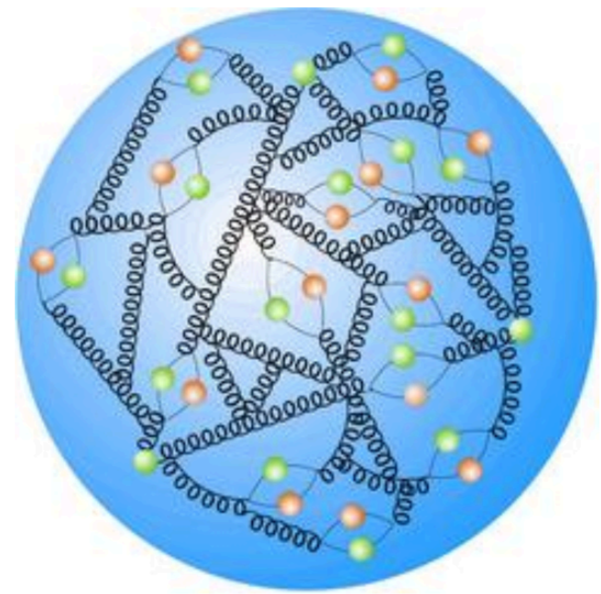




Picture of proton taken by the HERA accelerator

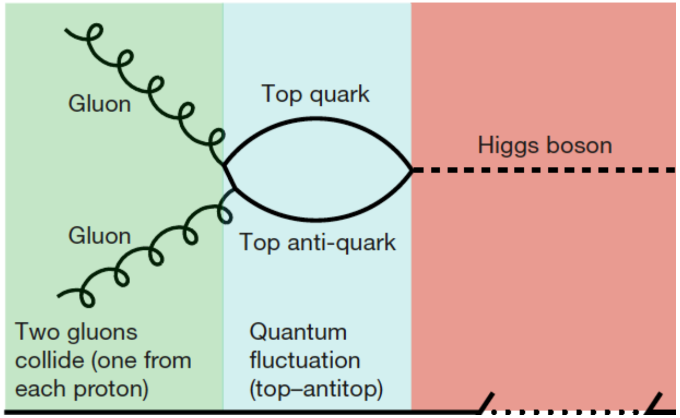


99% of the total mass is dynamically emerging from strong interactions!
Gravity couples to the total mass
Higgs only couples to mass of fundamental particles.

- What we know so far
  - Measurements of (with) the Higgs boson

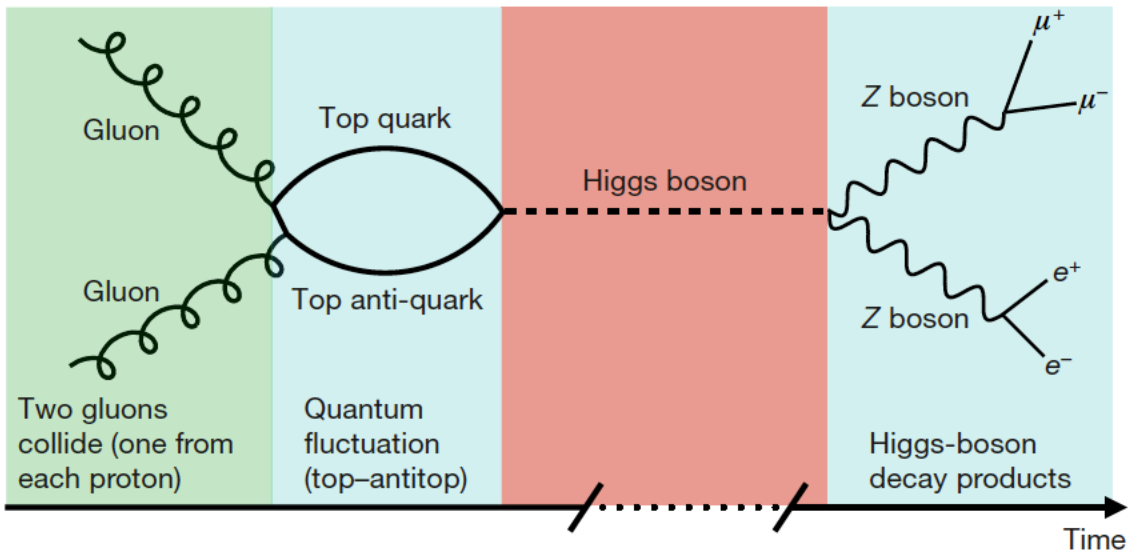
Higgs boson production at the LHC

- Higgs boson coupling increases with mass -> use heavy particles to study Higgs-particle interaction
- LHC: proton-proton collider
- Colliding (up and down) quarks and gluons are light
  - Only weak coupling to Higgs field
  - First produce heavy particles which than interact with the Higgs field
    - Quantum fluctuation into a top-antitop pair
      - mass of top: 172 GeV



Measurement of Higgs - example

- ~2.6% of Higgs decay to a pair of Z-bosons
  - Z-bosons decay into pairs of electron and muons which can be detected by the experiments



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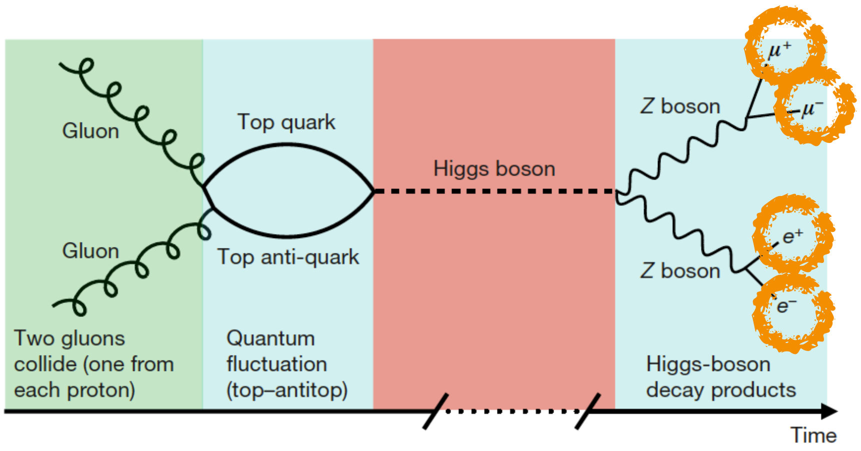

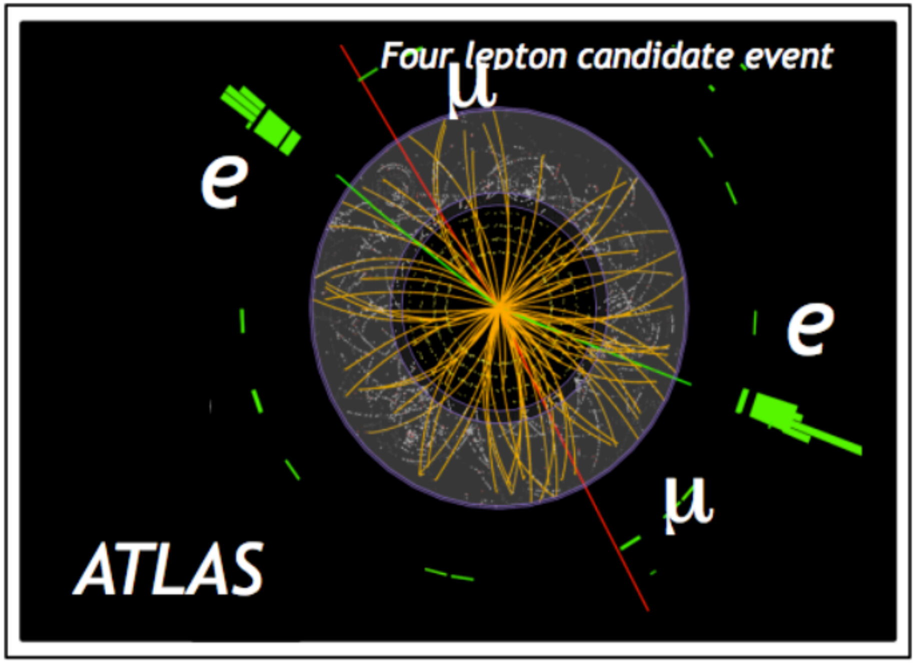

Reconstruct electron and muon four momentum
From measured tracks and calorimeter clusters

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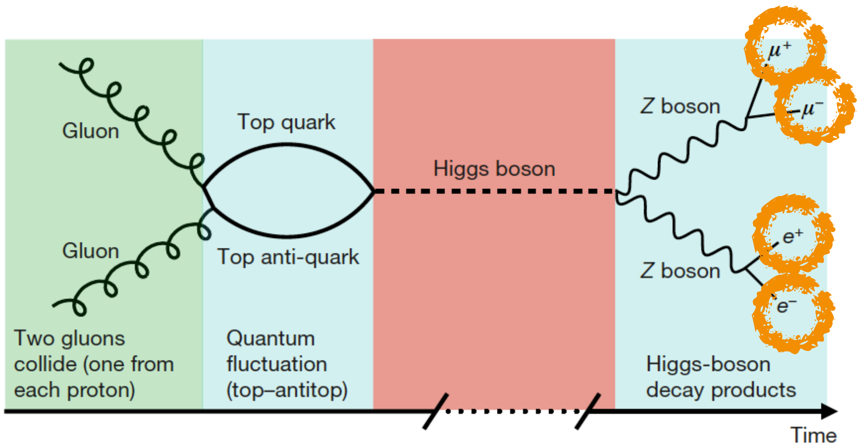

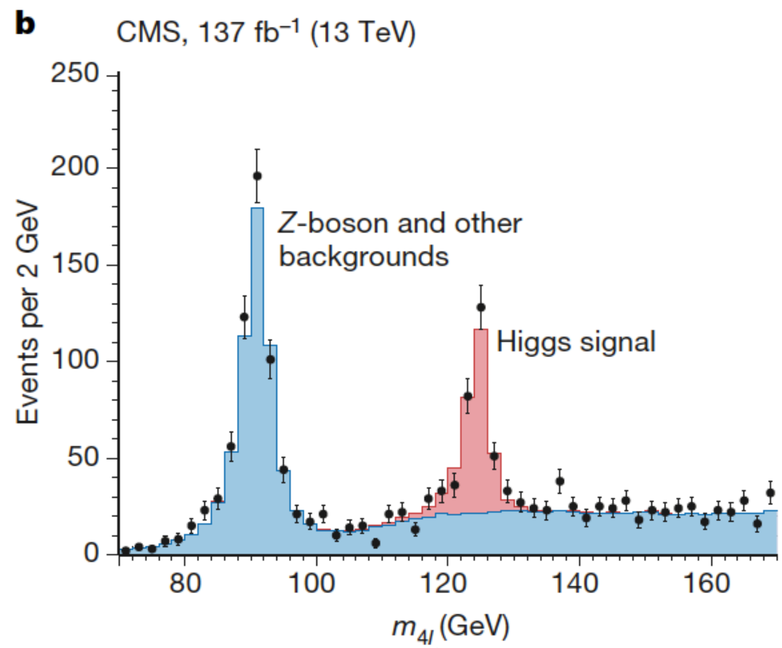

Mass reconstructed from 4 leptons ($e^+e^-\mu^+\mu^-$ or $e^+e^-e^+e^-$ or $\mu^+\mu^-\mu^+\mu^-$)

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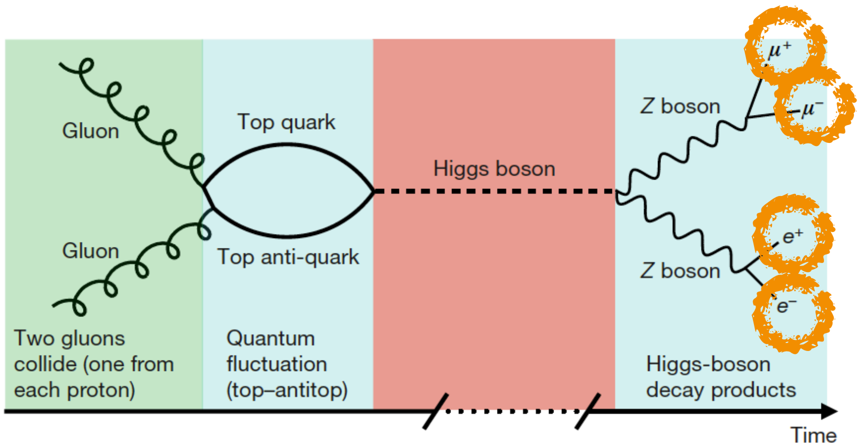

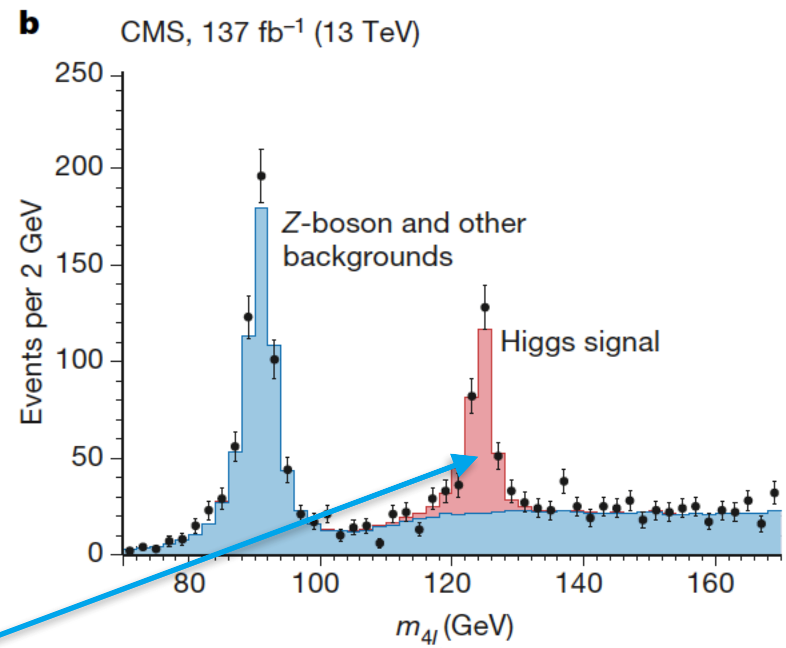

Resonance in reconstructed mass
= there is a particle decaying into leptons

Mass reconstructed from 4 leptons
($e^+e^-\mu^+\mu^-$ or $e^+e^-e^+e^-$ or $\mu^+\mu^-\mu^+\mu^-$)

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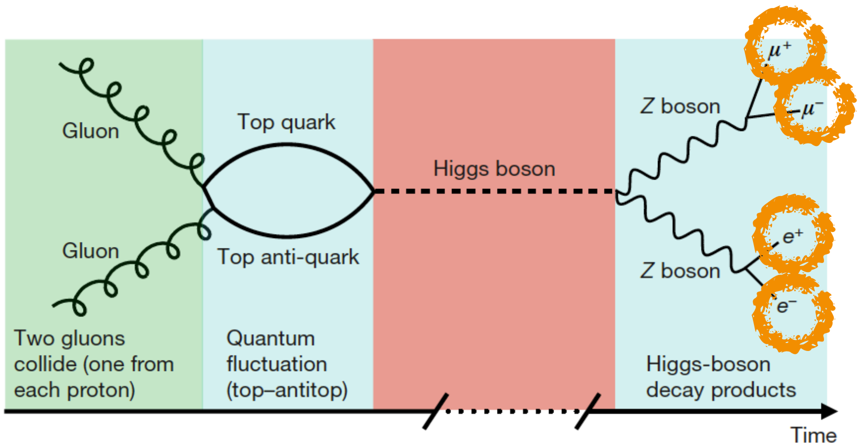

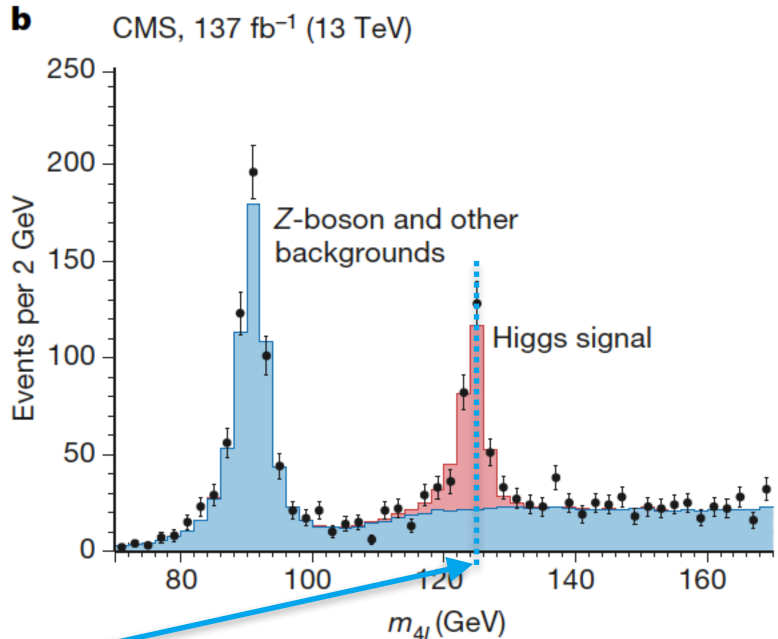

Particle has mass of ~125 GeV

Mass reconstructed from 4 leptons ($e^+e^-\mu^+\mu^-$ or $e^+e^-e^+e^-$ or $\mu^+\mu^-\mu^+\mu^-$)

Not shown: relative angular distribution of leptons sensitive to spin of particle => confirmed Higgs is Spin-0

Measurement of Higgs

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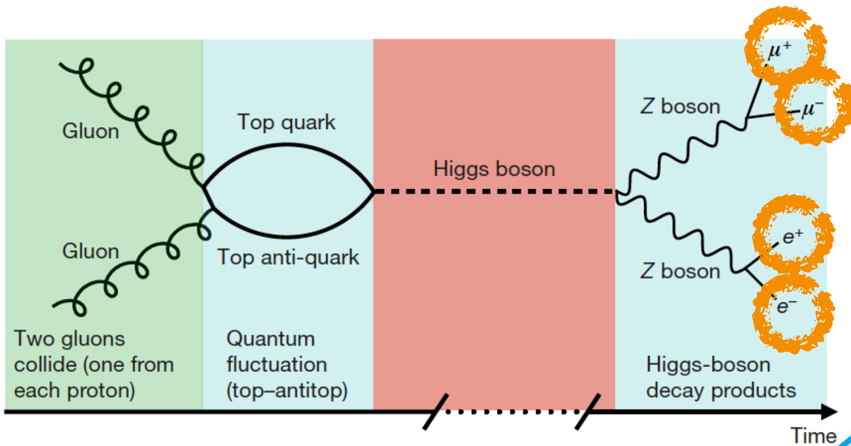
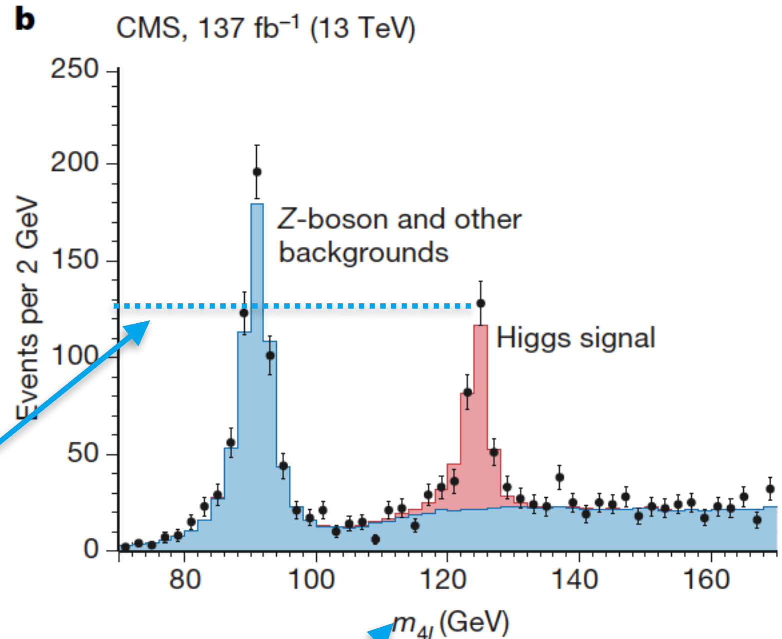




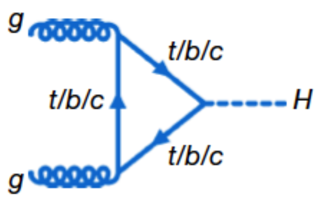
Rate of observed Higgs Bosons related to interaction strength between Top quark pair and Higgs and Z Boson and Higgs Both are predicted by SM

Mass reconstructed from 4 leptons ($e^+e^-\mu^+\mu^-$ or $e^+e^-e^+e^-$ or $\mu^+\mu^-\mu^+\mu^-$)

Higgs production modes

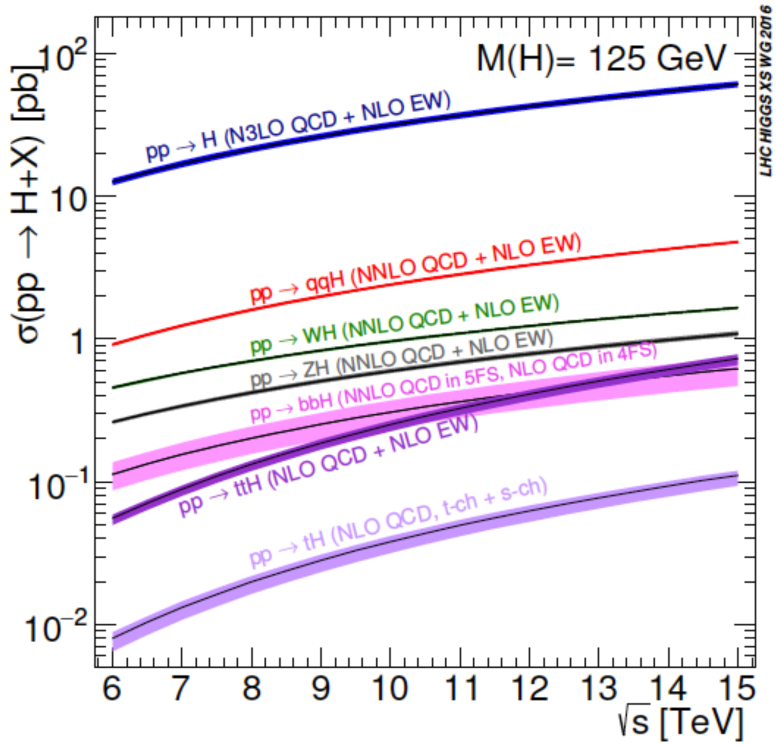
- Interaction in one measurement related to Higgs interaction in production * decay
- To get interactions separately per particle probe all possible decay and production modes with complementary sensitivity
  - Each mode has special experimental challenges

Higgs production modes



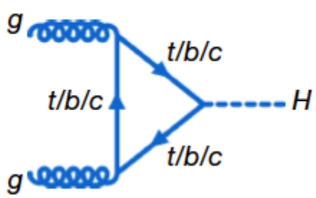
Gluon Fusion (ggF)
7M Higgs produced

N(Higgs) = N(events) = Lumi * σ



LHC center of mass energy

Higgs production modes



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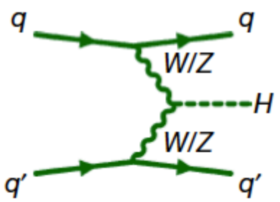
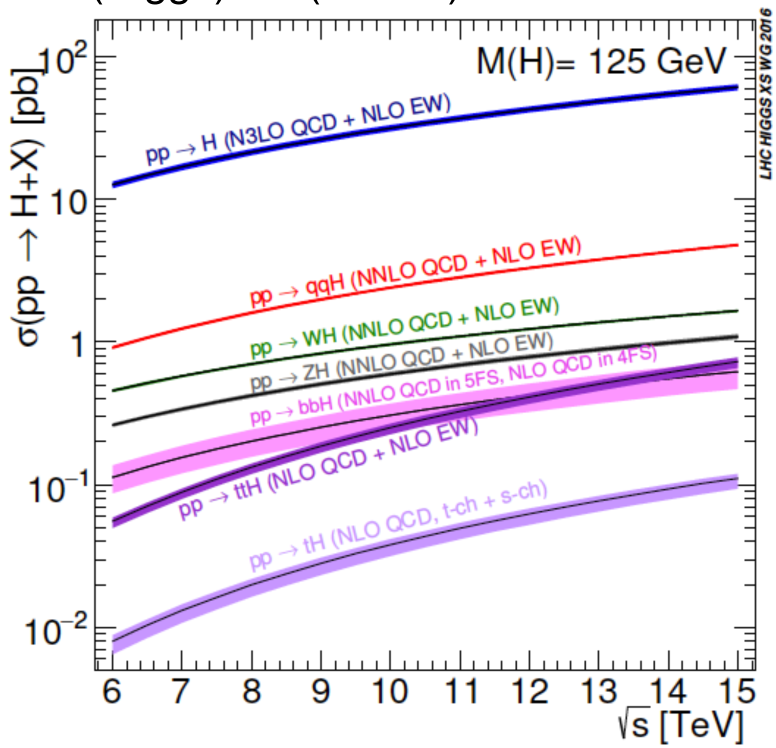
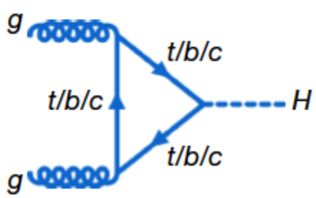


Vector Boson Fusion (qqH)
~0.5M Higgs produced

N(Higgs) = N(events) = Lumi * σ



Higgs production modes



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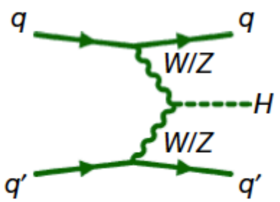

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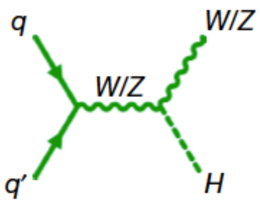
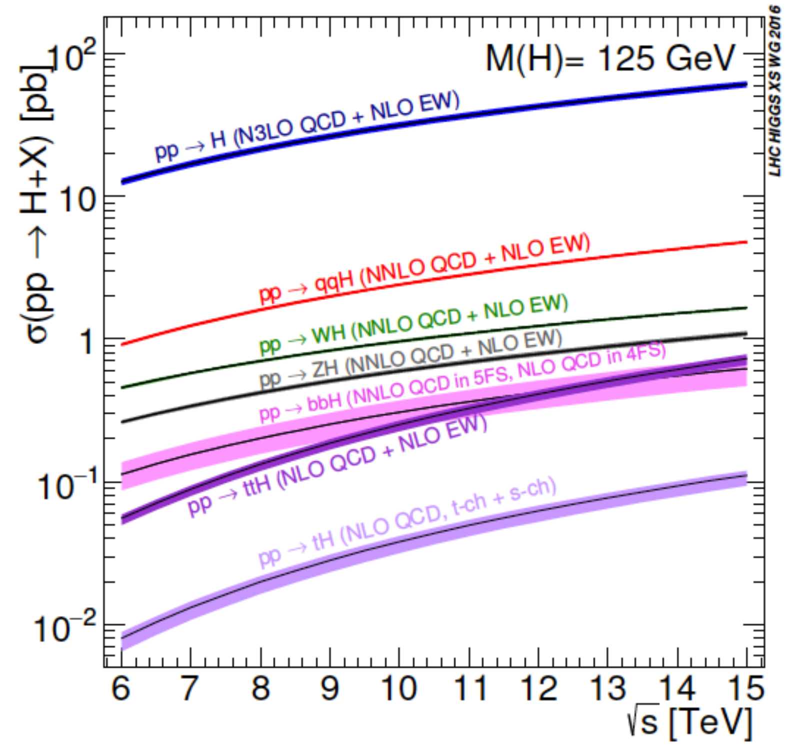
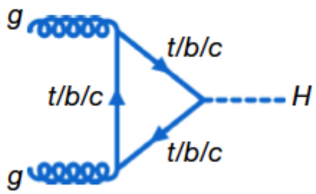


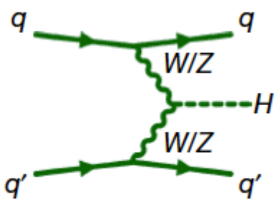
W and Z associated prod.
~0.35M Higgs produced



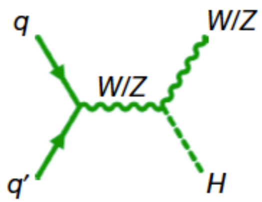
Higgs production modes at the LHC



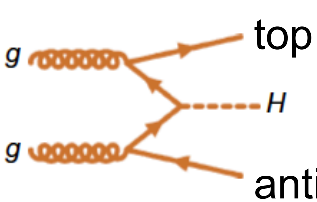
Gluon Fusion (ggF)
7M Higgs produced



Vector Boson Fusion (qqH)
~0.5M Higgs produced

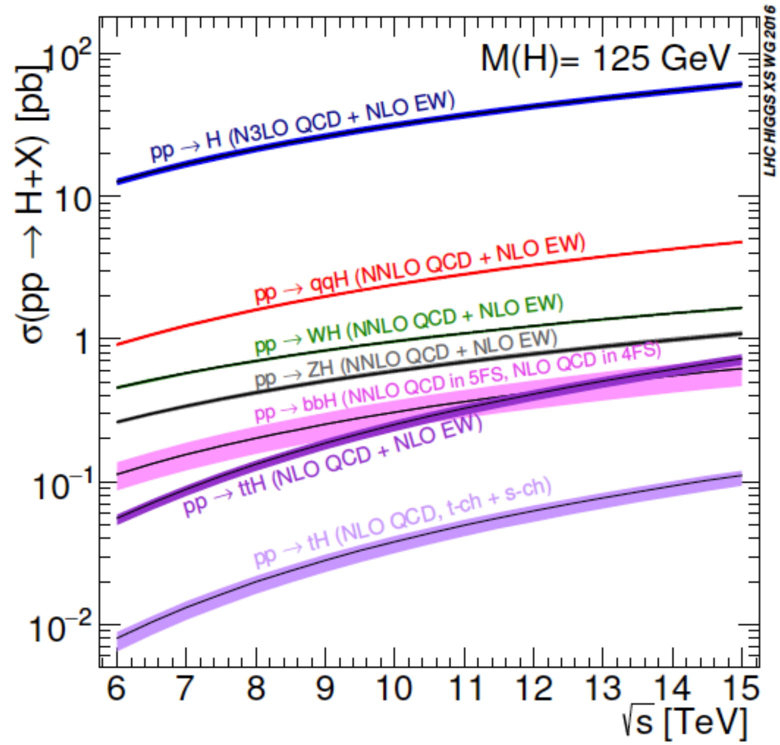


W and Z associated prod.
~0.35M Higgs produced

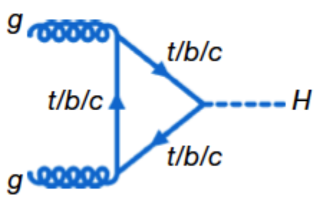


top associated prod.
~70k Higgs produced

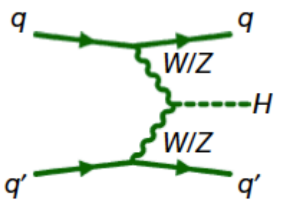
No (top) loop involved!



Higgs production modes at the LHC



Gluon Fusion (ggF)
7M Higgs produced



Vector Boson Fusion (qqH)
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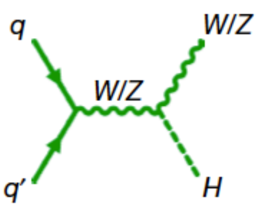

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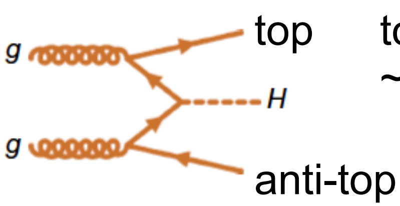
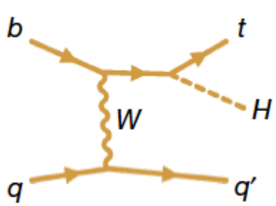
~0.35M Higgs produced

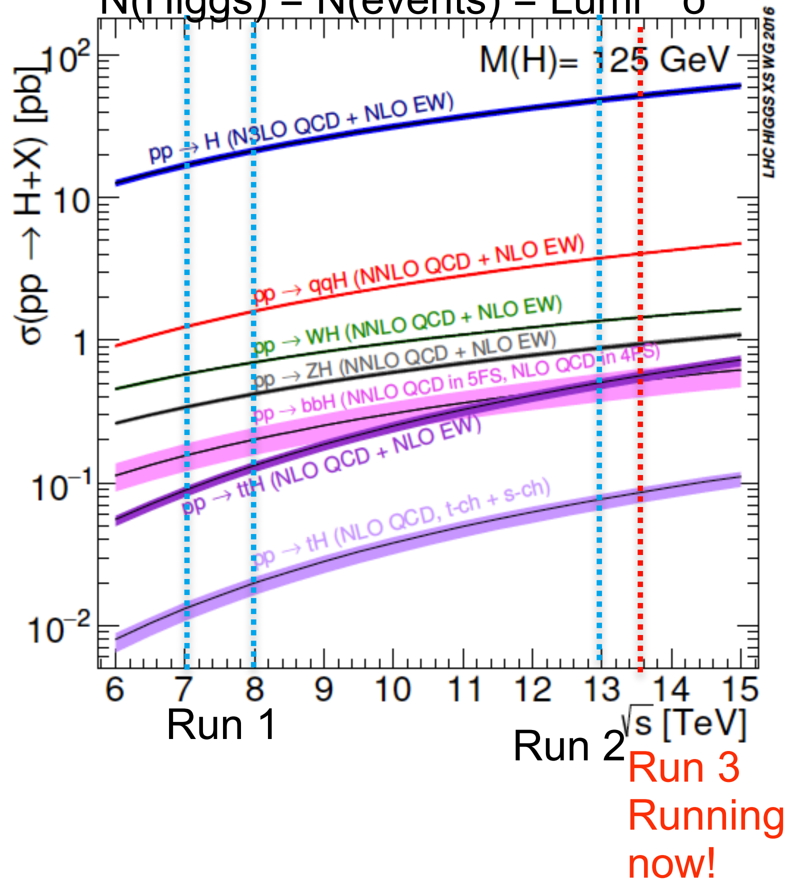


top associated prod.
~70k Higgs produced



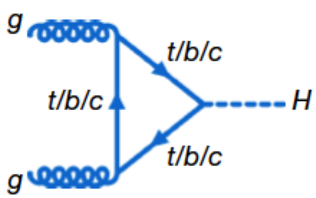
Single top associated prod.
~12k Higgs produced

N(Higgs) = N(events) = Lumi * σ

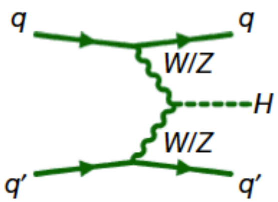


Cross sections increase with center of mass energy
-> note in particular for ttH and tH

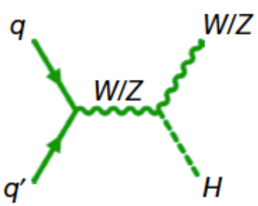
Higgs production modes at the LHC



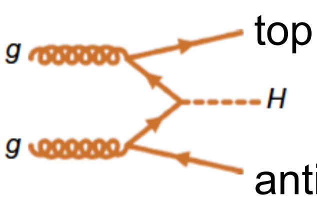
Gluon Fusion (ggF)
7M Higgs produced



Vector Boson Fusion (qqH)
~0.5M Higgs produced



W and Z associated prod.
~0.35M Higgs produced



top associated prod.
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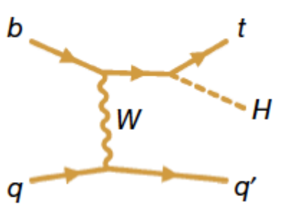

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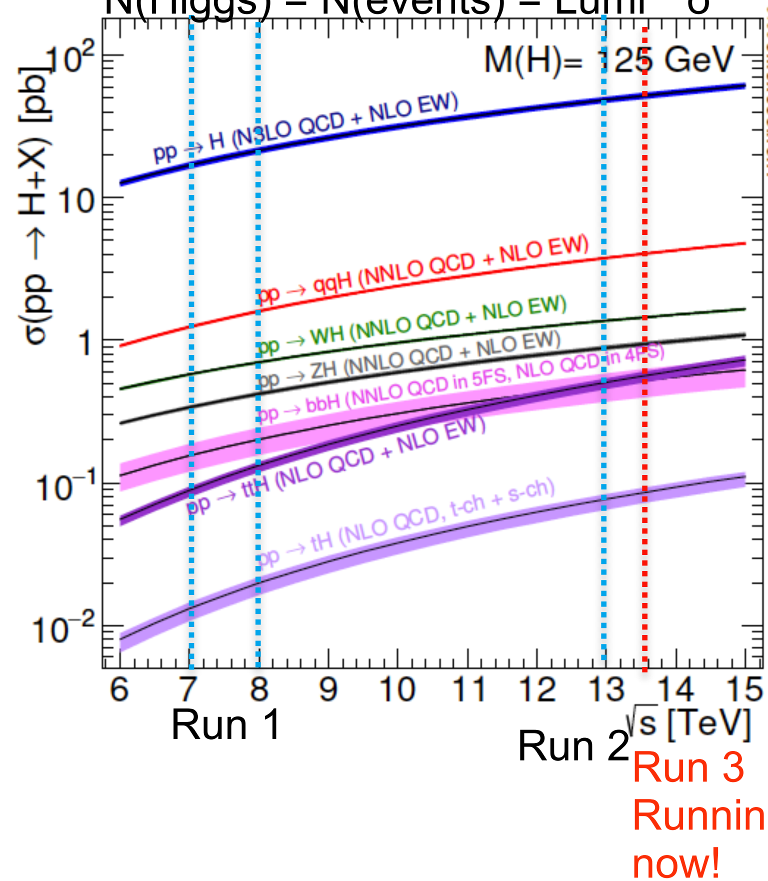
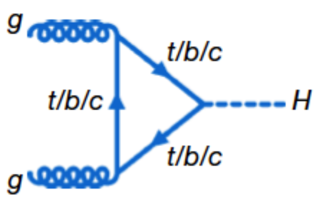


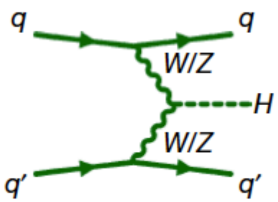
Cross sections increase with center of mass energy
-> note in particular for ttH and tH

Measure Higgs production modes at the LHC



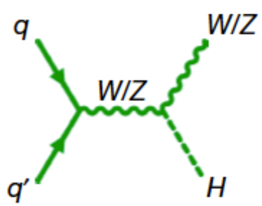
Gluon Fusion (ggF)
7M Higgs produced

Detect Higgs Peak



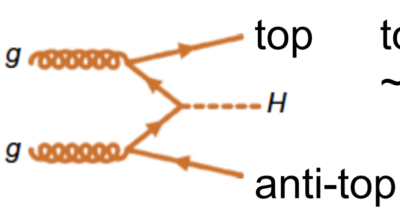
Vector Boson Fusion (qqH)
~0.5M Higgs produced

Detect Higgs + Jet in forward Direction



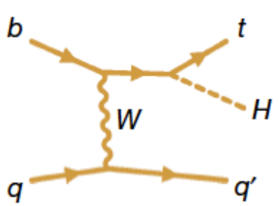
W and Z associated prod.
~0.35M Higgs produced

Detect Higgs + W or Z Boson



top associated prod.
~70k Higgs produced

Detect Higgs + top quark pair



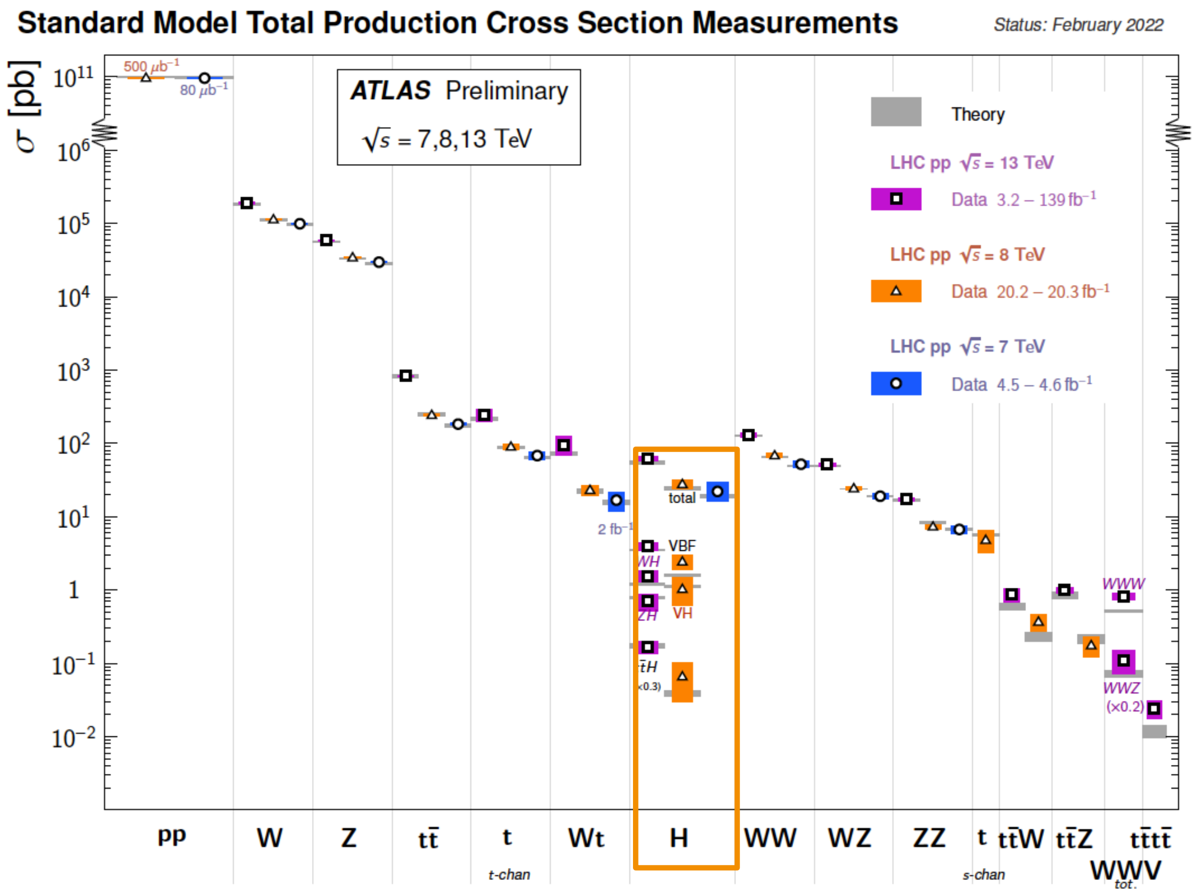
Single top associated prod.
~12k Higgs produced

Detect Higgs + top quark + jet in Forward direction

Particles need to be within detector acceptance
=> reduces rate significantly!

Rate of Physics processes at the LHC

$\sigma_{QCD} \sim 10^9\ \sigma_{Higgs}$

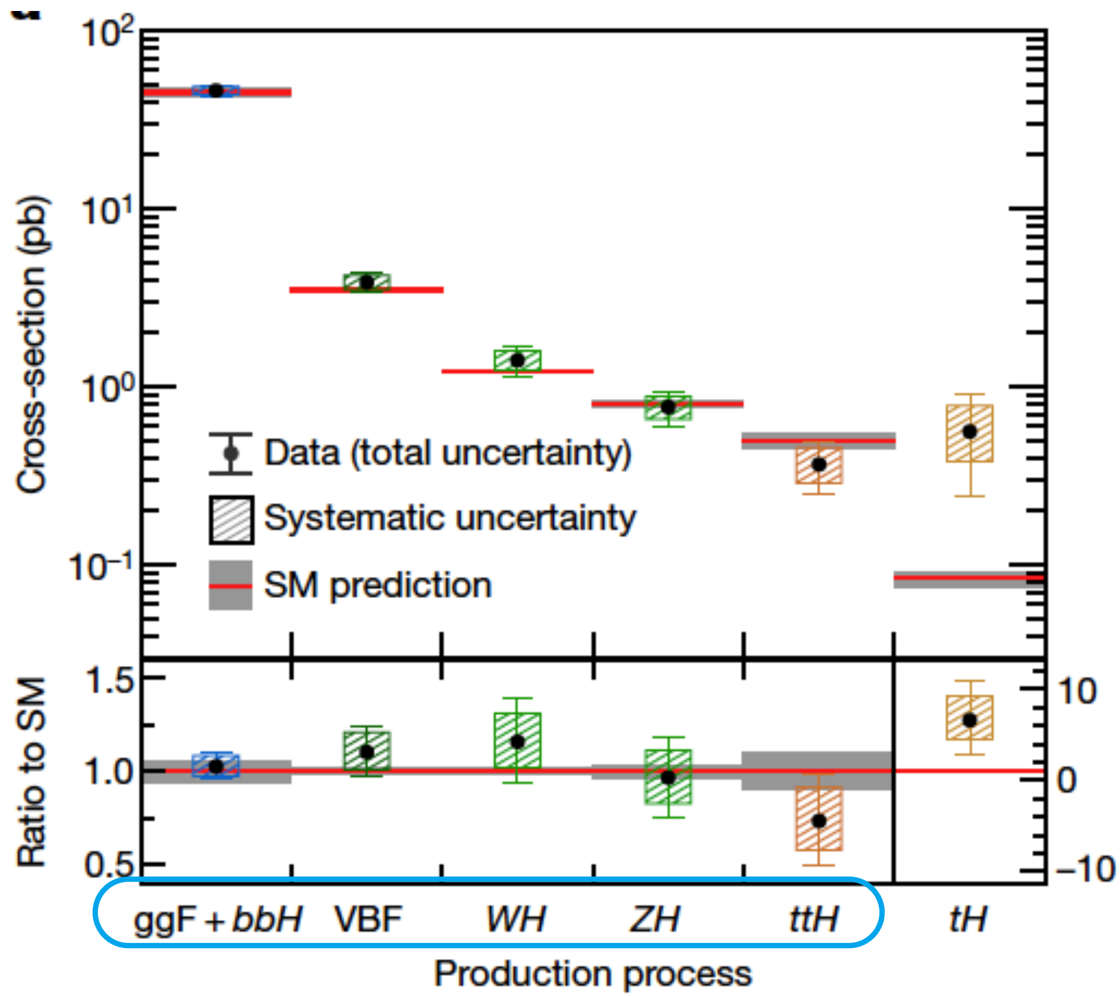


Lots of background to suppress!

-> stringent requirements to select events fast during data taking (trigger) and during offline data analysis

Reduce rate of selected Higgs events significantly!

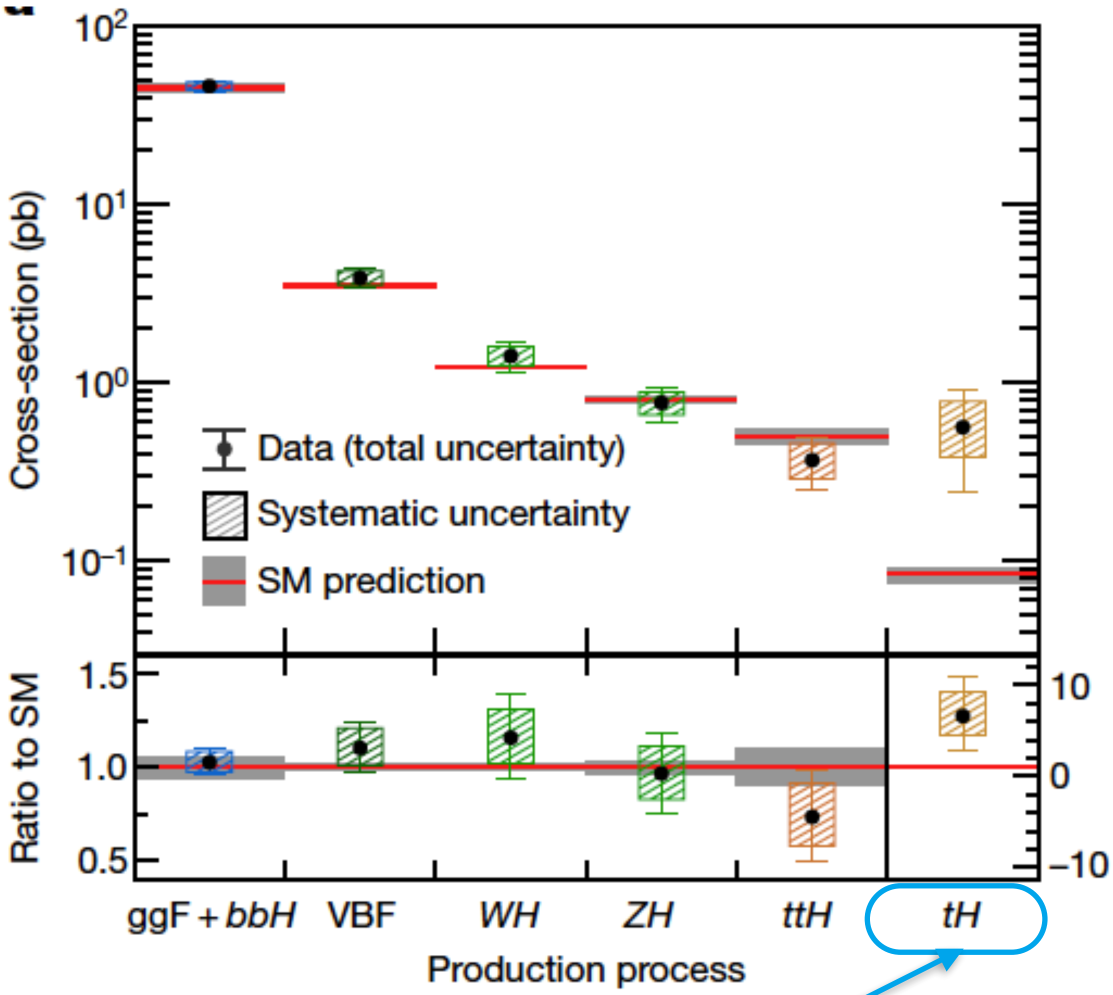
In total ~27000 Higgs events recorded



Processes observed

Good agreement with Standard Model predictions for existence of processes and their rate!

Measured production cross section



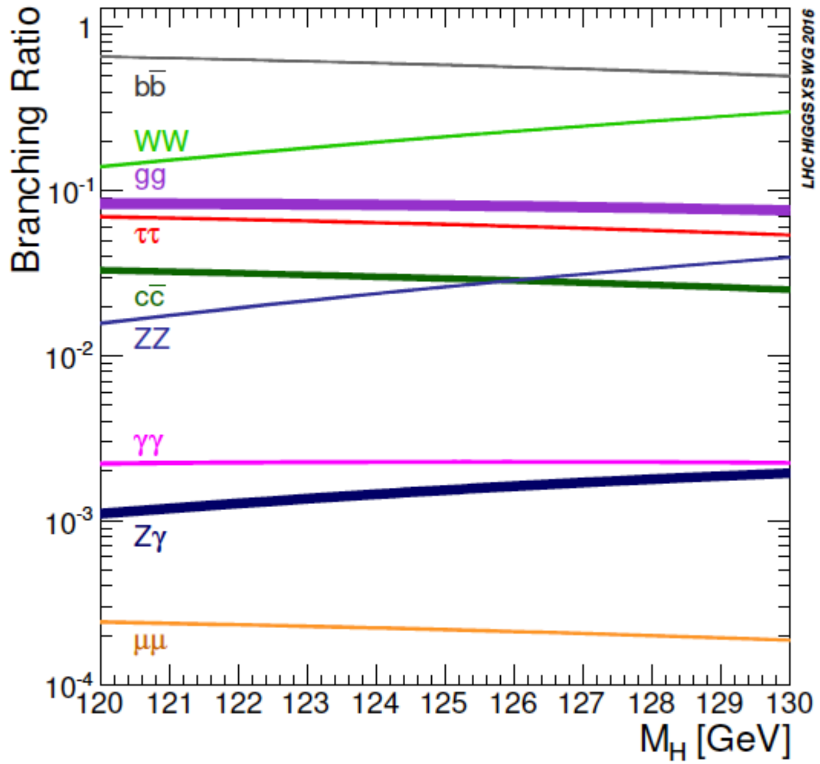
Processes not yet observed
Rate of the process < 8 times SM prediction
(so maybe it is equal to SM prediction?)
Something to discover with LHC Run 3

Higgs decays - third generation quarks

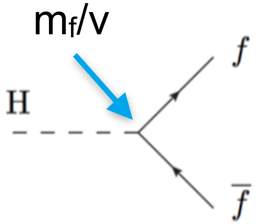
- Higgs lifetime 10^{-22} sec -> total decay width Γ_{tot}: 4.1 MeV
- Higgs decays into a pair of fermions or bosons

$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$



Example decay to bb:

$\Gamma_{H\rightarrow bb} \propto \Sigma_{colors} \Big|$  $\Big|^2$

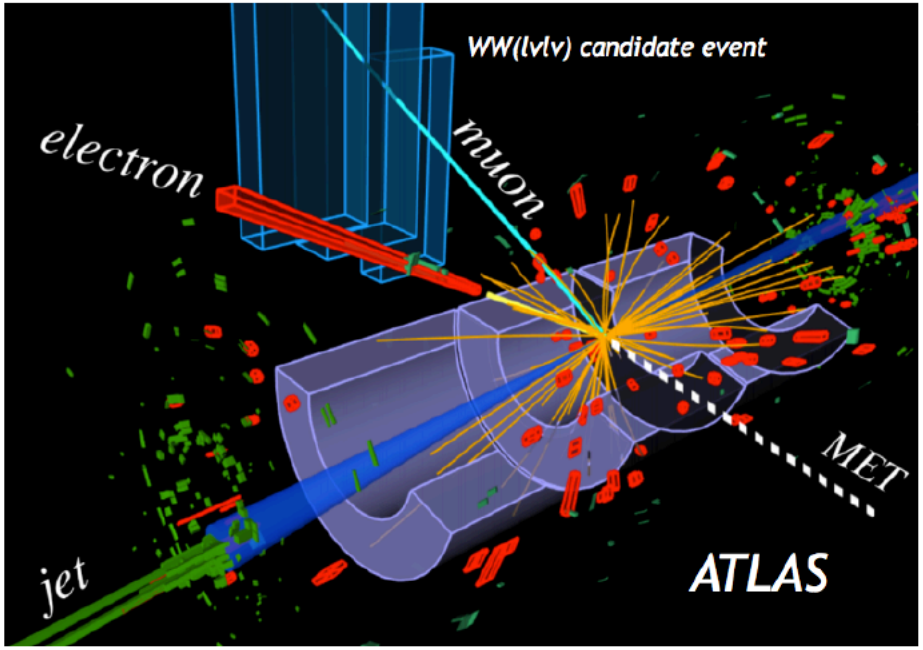
Decay mode	Expected BR for m_H=125 GeV
bb	57%

Higgs decays - W-bosons

- Higgs lifetime 10^{-22} sec -> total decay width Γ_{tot}: 4.1 MeV
- Higgs decays into a pair of fermions or bosons

$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$



Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%

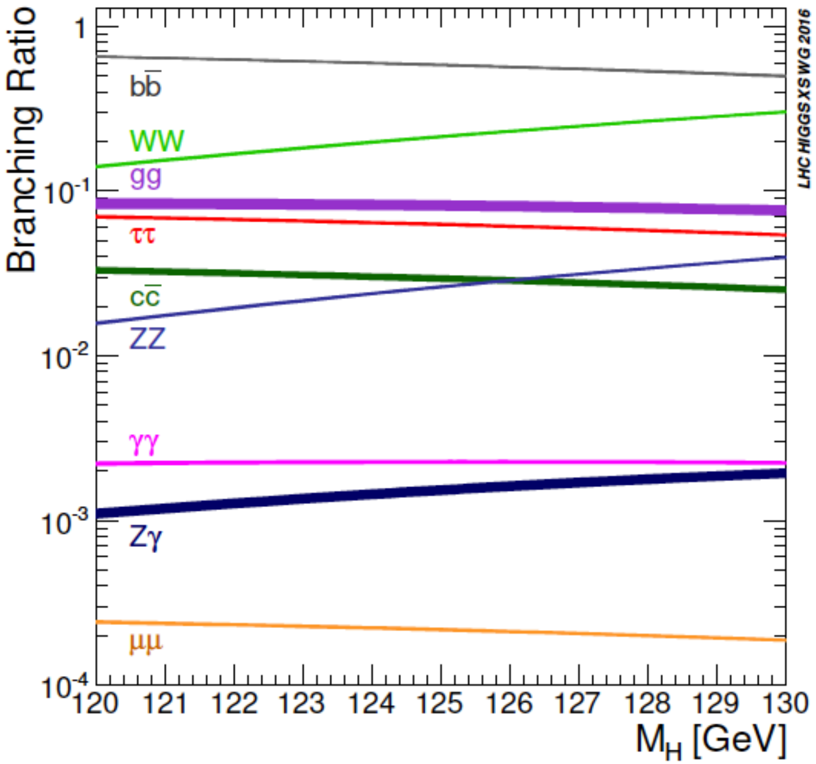
Question round: why is WW BR lower than bb? After all, W is much heavier?

Higgs decays - third generation leptons

- Higgs lifetime 10^{-22} sec -> total decay width Γ_{tot}: 4.1 MeV
- Higgs decays into a pair of fermions or bosons

$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma \Gamma_i$



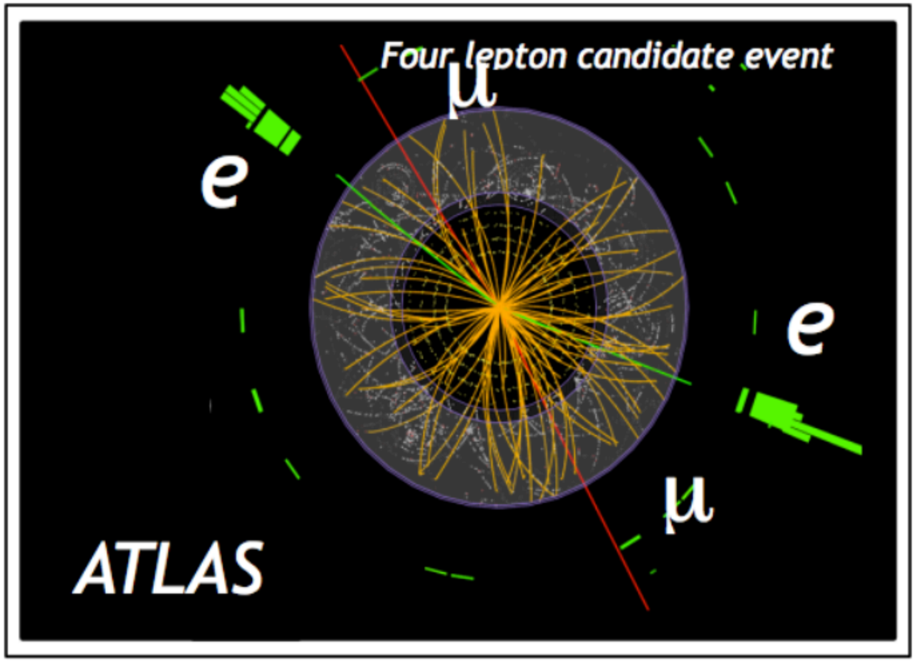
Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %

Higgs decays - Z-bosons

- Higgs lifetime 10^{-22} sec -> total decay width Γ_{tot}: 4.1 MeV
- Higgs decays into a pair of fermions or bosons

$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$



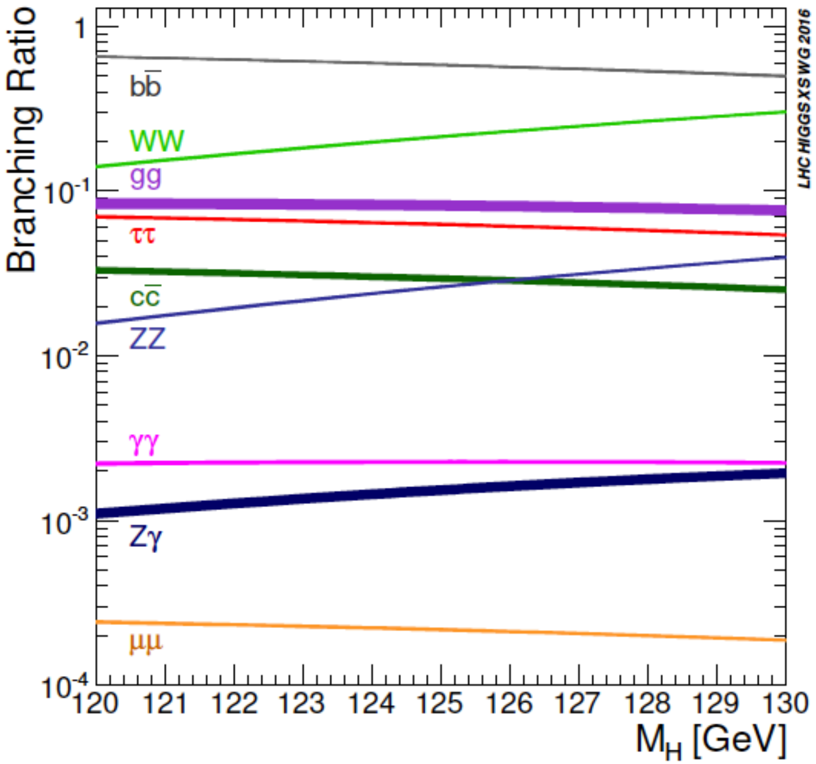
Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %
ZZ	3%

Higgs decays - 2nd generation quarks

- Higgs lifetime 10^{-22} sec -> total decay width Γ_{tot}: 4.1 MeV
- Higgs decays into a pair of fermions or bosons

$BR_i = \Gamma_i / \Gamma_{tot}$

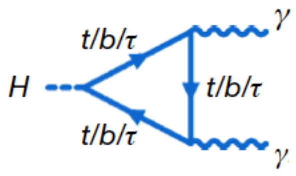
$\Gamma_{tot} = \Sigma\, \Gamma_i$

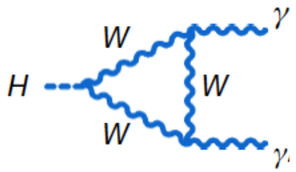


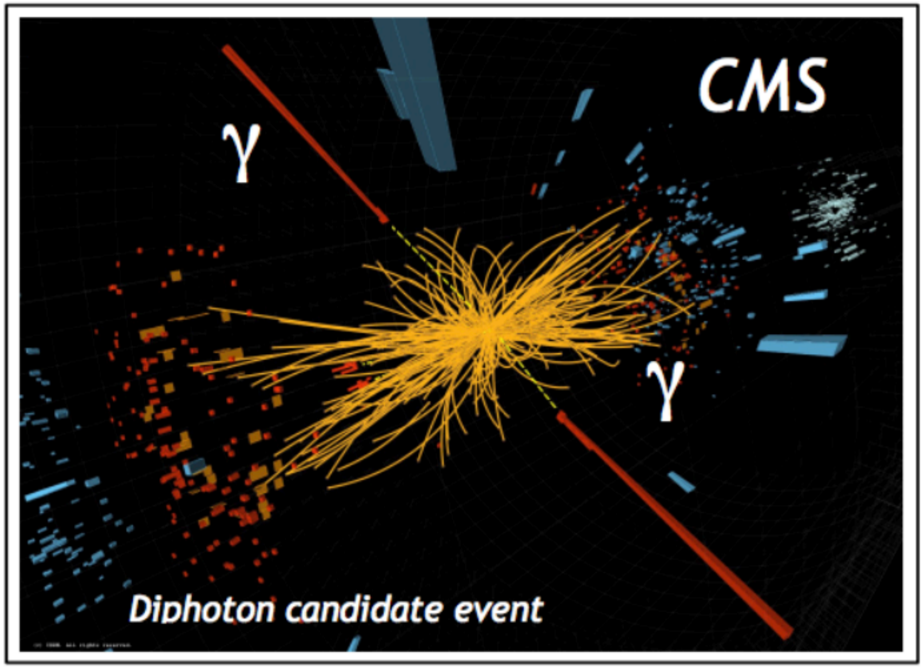
Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %
ZZ	3%
cc	3%

Higgs decays - photons

How? - Loop again!







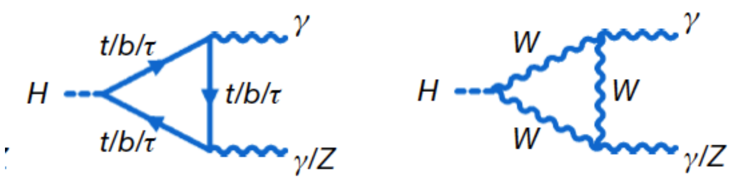
$BR_i = \Gamma_i / \Gamma_{tot}$

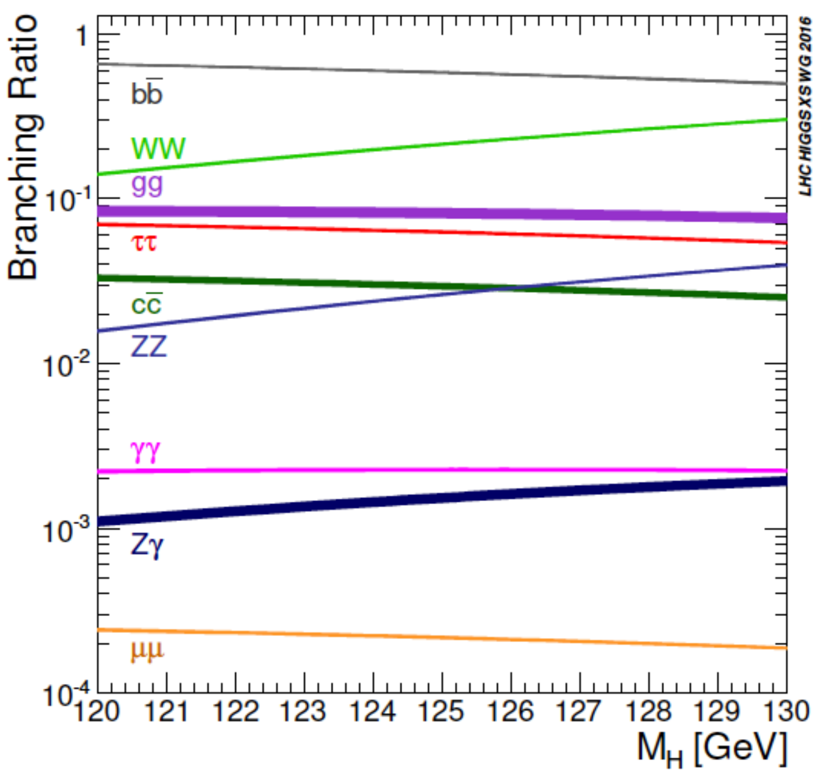
$\Gamma_{tot} = \Sigma \Gamma_i$

Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %
ZZ	3%
cc	3%
γγ	0.2 %

Higgs decays - Z + photon

How? - Loop again!





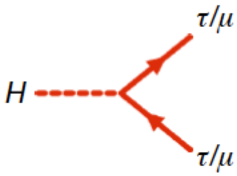
$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %
ZZ	3%
cc	3%
γγ	0.2 %
Zγ	0.2 %

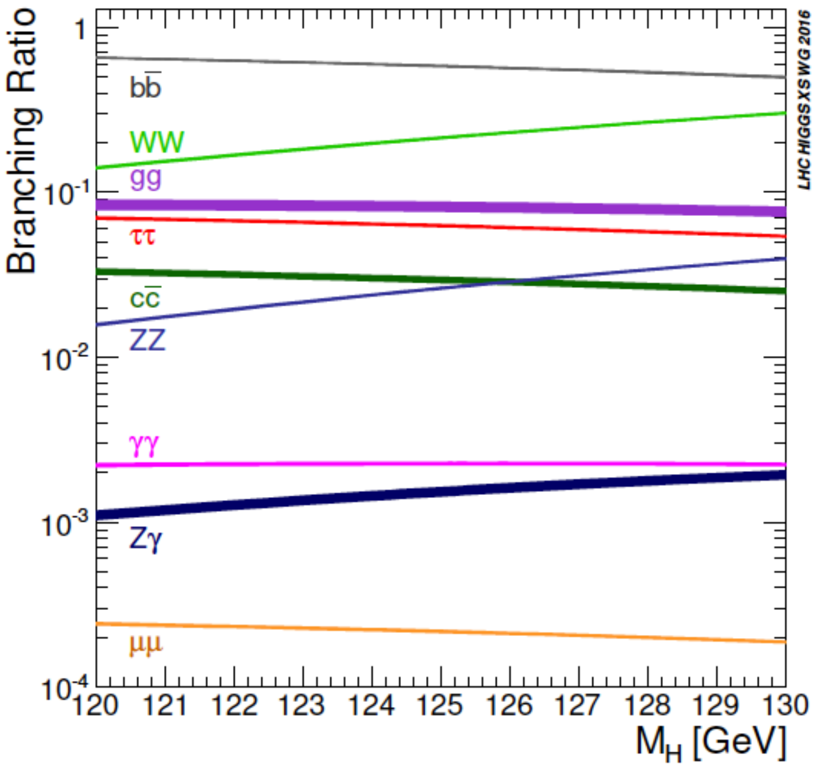
Question: why do the BR for WW, ZZ and Zgamma depend more on Higgs mass than the other BR?

Higgs decays - 2nd generation fermions



$BR_i = \Gamma_i / \Gamma_{tot}$

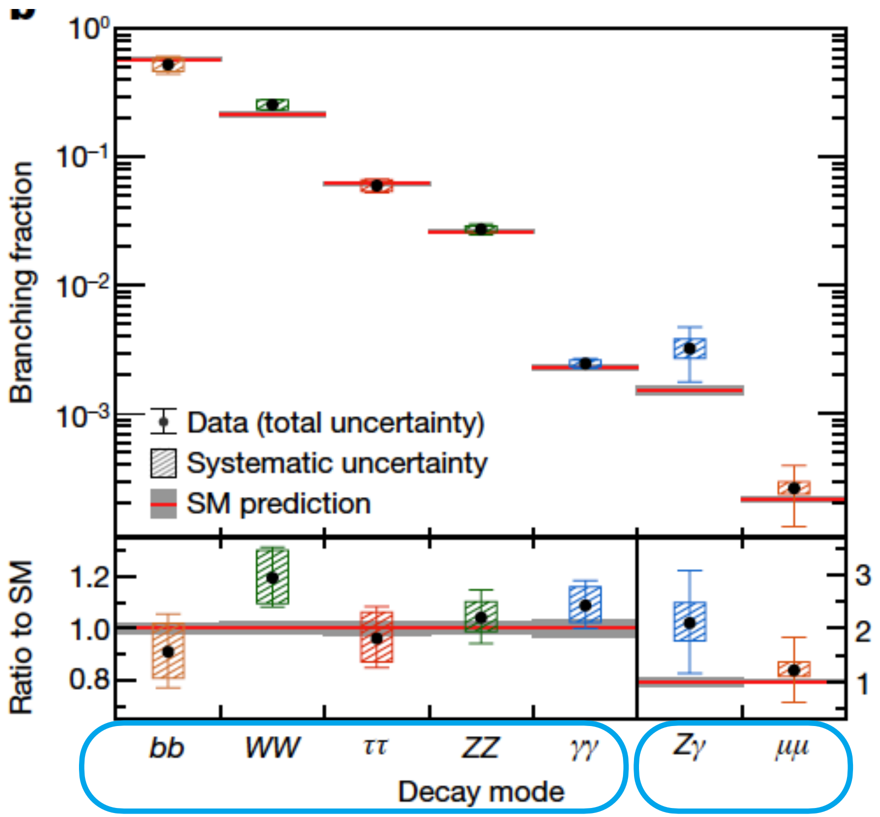
$\Gamma_{tot} = \Sigma\, \Gamma_i$



Decay mode	Expected BR for m_H=125 GeV
bb	57%
WW	22%
ττ	6.3 %
ZZ	3%
cc	3%
γγ	0.2 %
Zγ	0.2 %
μμ	0.02 %

Measured Higgs branching ratios

Assume Higgs production follows. Standard Model -> get BR from data

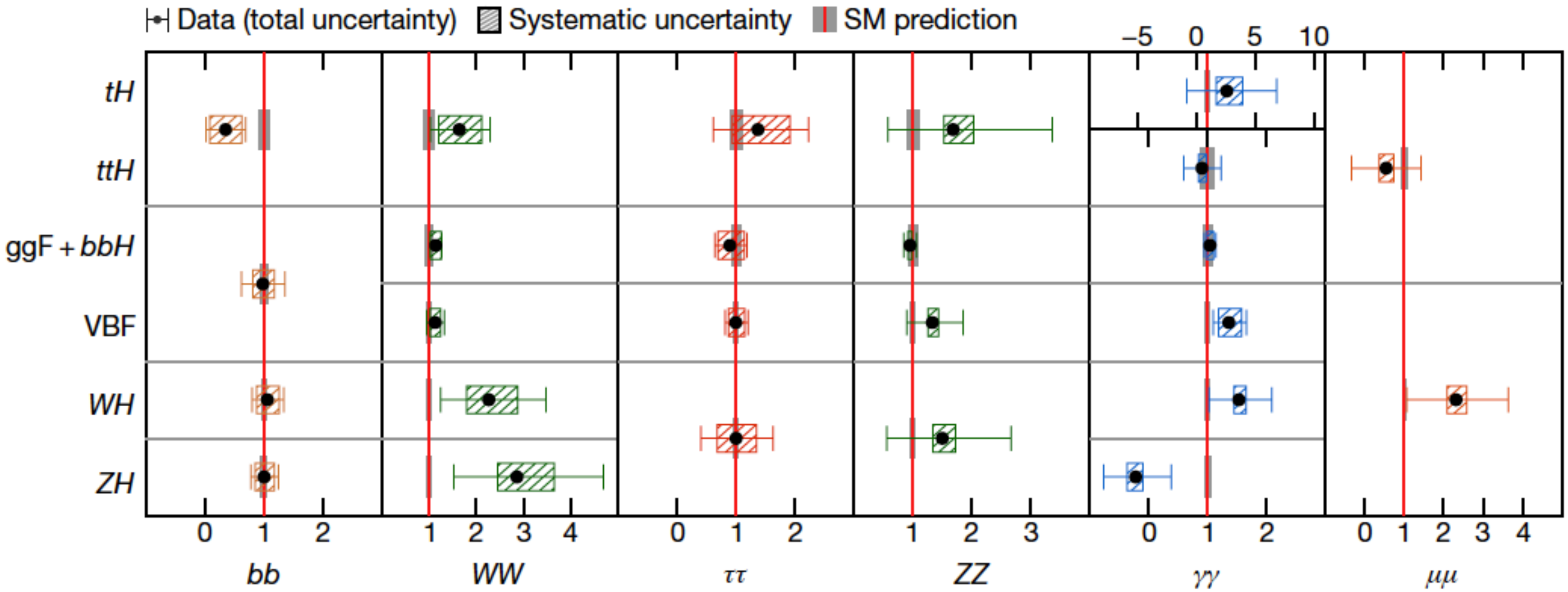


Measured to be in agreement with SM within ~20%

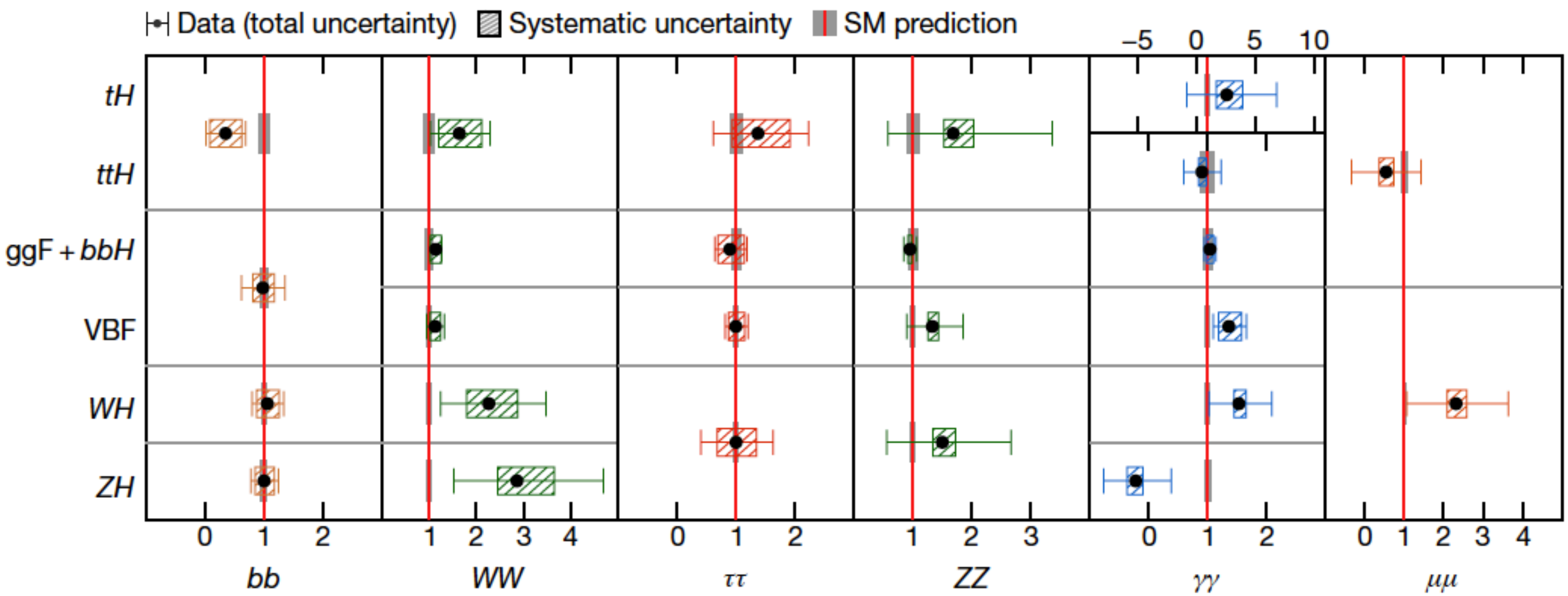
Very rare decays measured with SM within 2-300%

Many decay modes experimentally proven to exist
= strong evidence to establish resonance at m=125 GeV as Higgs

Production and decay modes combinations



Production and decay modes combinations



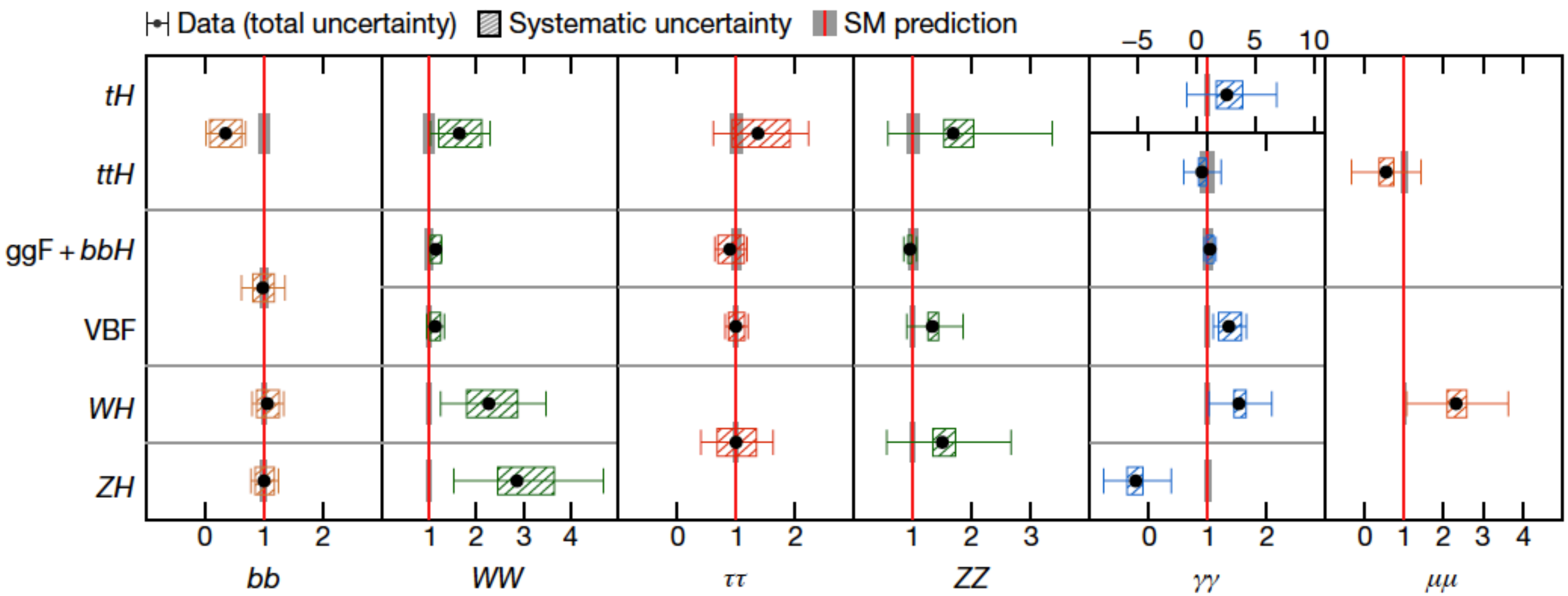
Measure inclusive Higgs production rate including all measurements into a single fit
Parameterising each individual production and decay mode as

$$\mu_{if} = (\sigma_i/\sigma_i^{SM})(B_f/B_f^{SM})$$

Assume all processes scale with the same parameter $\mu = \mu_{if}$, get possible correction factor
To Higgs production cross section $\mu = \sigma_{measured} / \sigma_{SMpredicted}$

$$\mu = 1.05 \pm 0.06$$
$$= 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$$

Production and decay modes combinations



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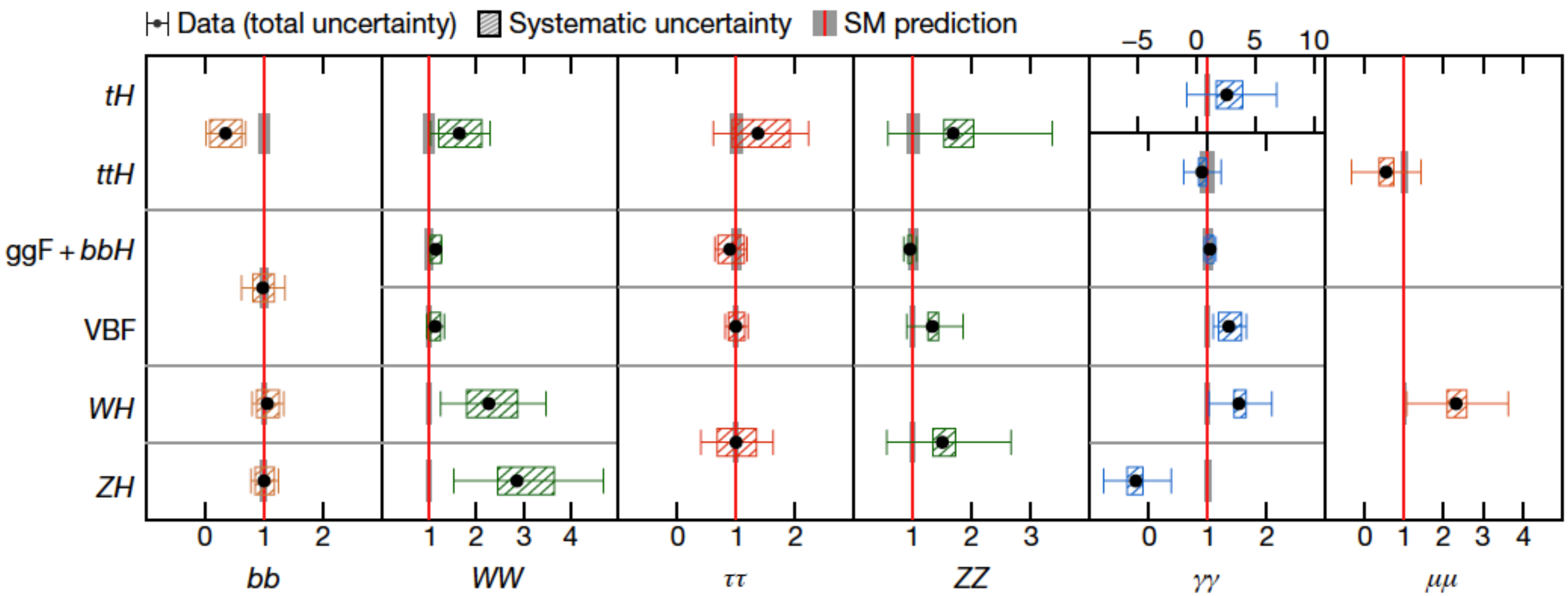
Room for better theory

Production and decay modes combinations



Measure inclusive Higgs production rate including all measurements into a single fit
Parameterising each individual production and decay mode as

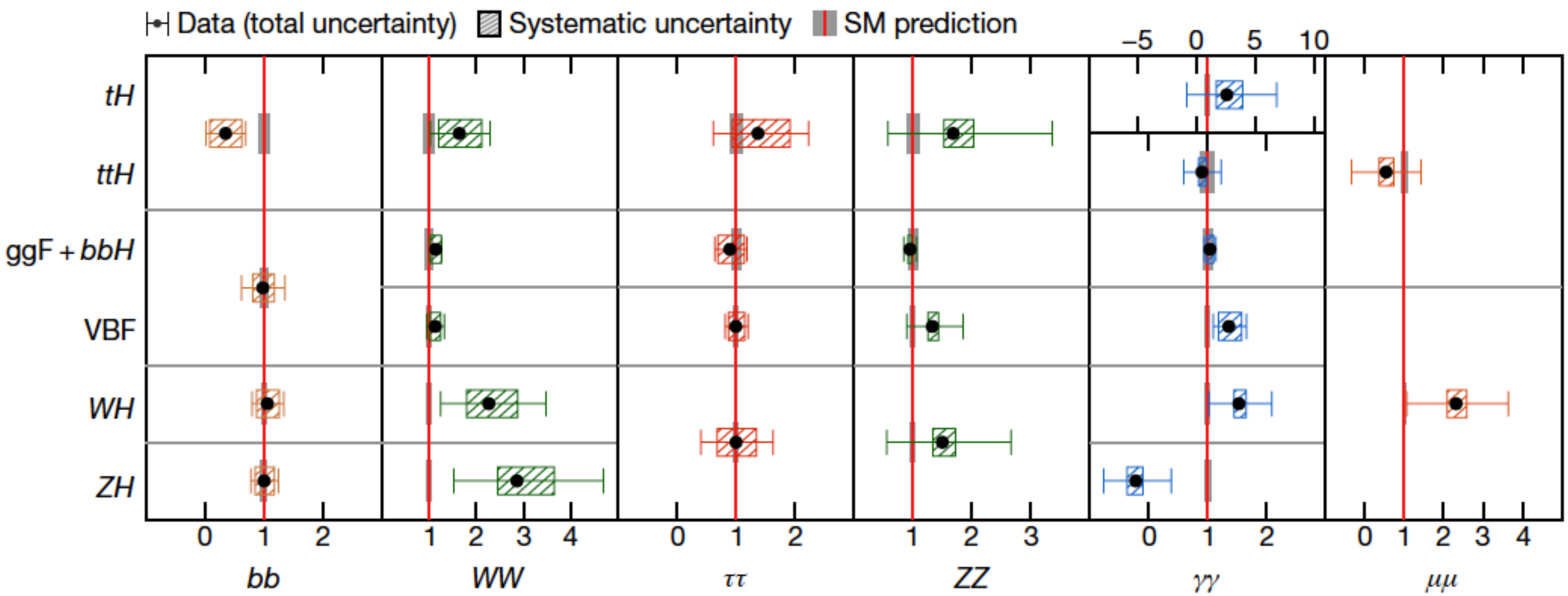
$$\mu_{if} = (\sigma_i/\sigma_i^{SM})(B_f/B_f^{SM})$$

Assume all processes scale with the same parameter μ = $\mu_{if,}$ get possible correction factor
To Higgs production cross section μ = $\sigma_{measured}$ / $\sigma_{SMpredicted}$

$\mu =$ More data will help

$= 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$

Production and decay modes combinations



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Parameterising each individual production and decay mode as

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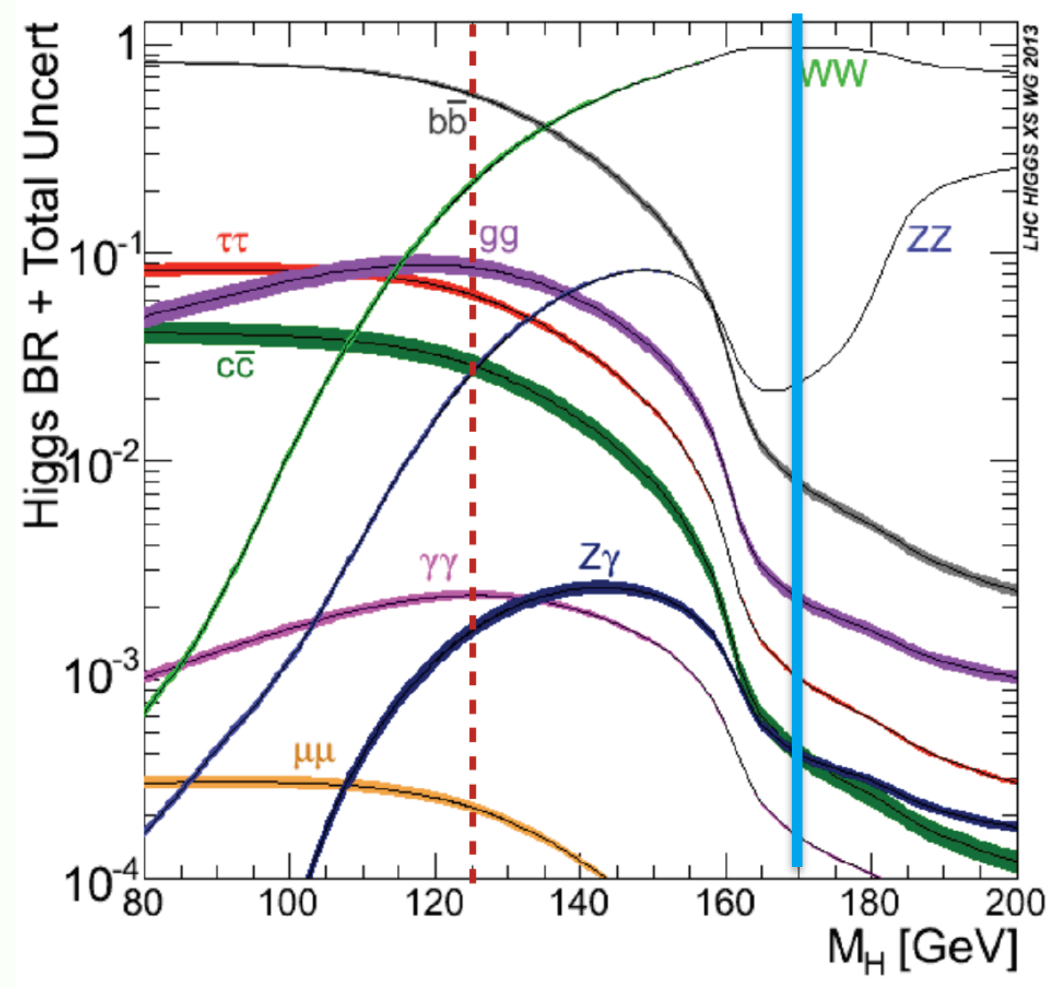
$$\mu = 1.05 \pm 0.06$$
$$= 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$$

Room for improved calibrations and object reconstruction

What if…..?



If Higgs were 50 GeV heavier, most of the decay channels would have been Out of reach for current LHC data. In particular $\gamma\gamma$ channel!

DESY

Measure coupling strength

- Probe coupling to the Higgs for each particle type
- Technical implementation: κ framework

Measure coupling strength

- Probe coupling to the Higgs for each particle type
- Technical implementation: κ framework
- Take production cross section and decay width and allow it to vary as the prediction is fitted to data

  $\kappa_p^2 = \sigma_p / \sigma_p^{\mathrm{SM}}$ or $\kappa_p^2 = \Gamma_p / \Gamma_p^{\mathrm{SM}}$,

  p: particle, e.g. γ, b, W, Z,…
- K = 1 means agreement with SM

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- Coupling of vector bosons and fermions follow Higgs mechanism
- Make assumptions on the other couplings

Measure coupling strength

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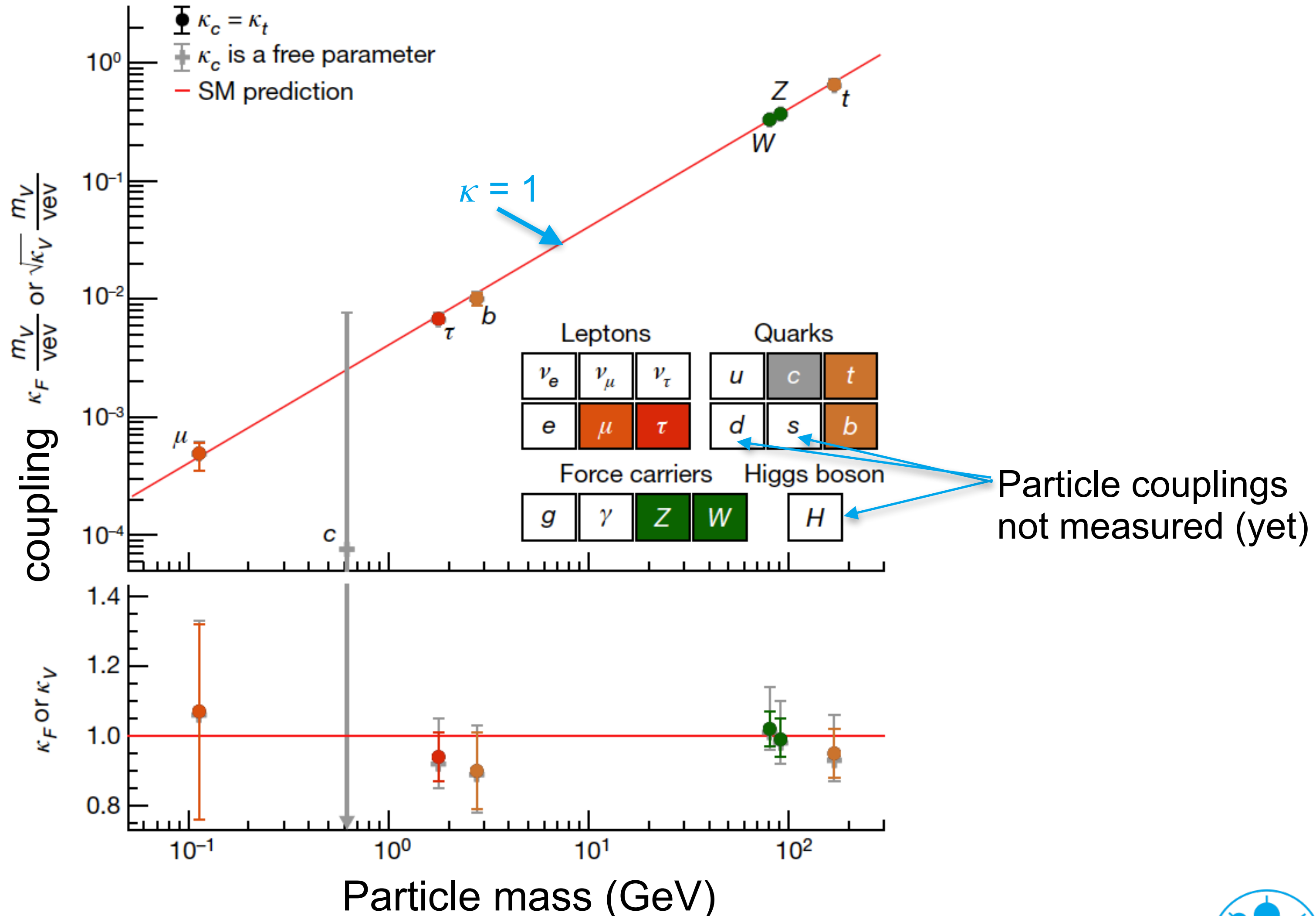
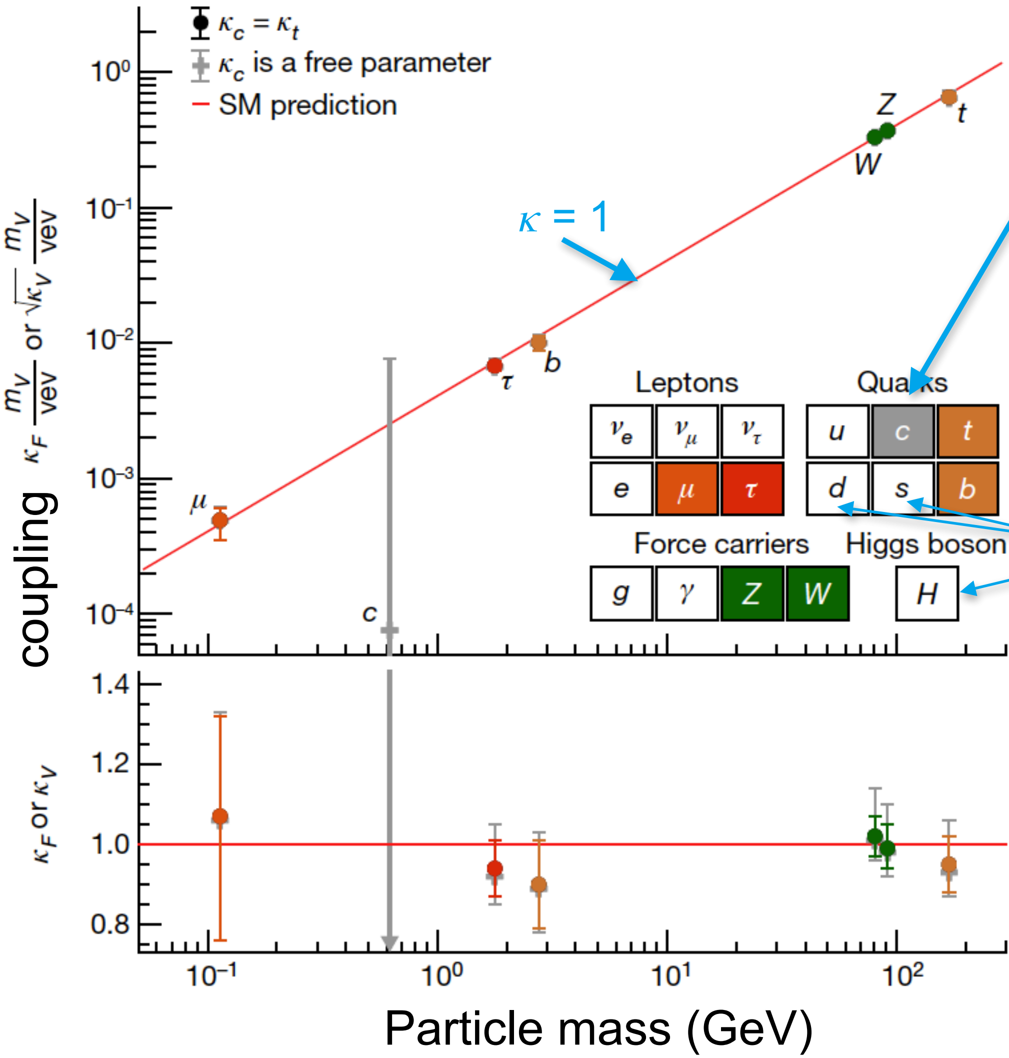
  p: particle, e.g. γ, b, W, Z,…

- K = 1 means agreement with SM
- Coupling of vector bosons and fermions follow Higgs mechanism
- Make assumptions on the other couplings not being probed
  - Being SM or being free
  - fermions couple the same way (one modifier for $\kappa_c = \kappa_t$)
  - …

Measure coupling strength as function of mass



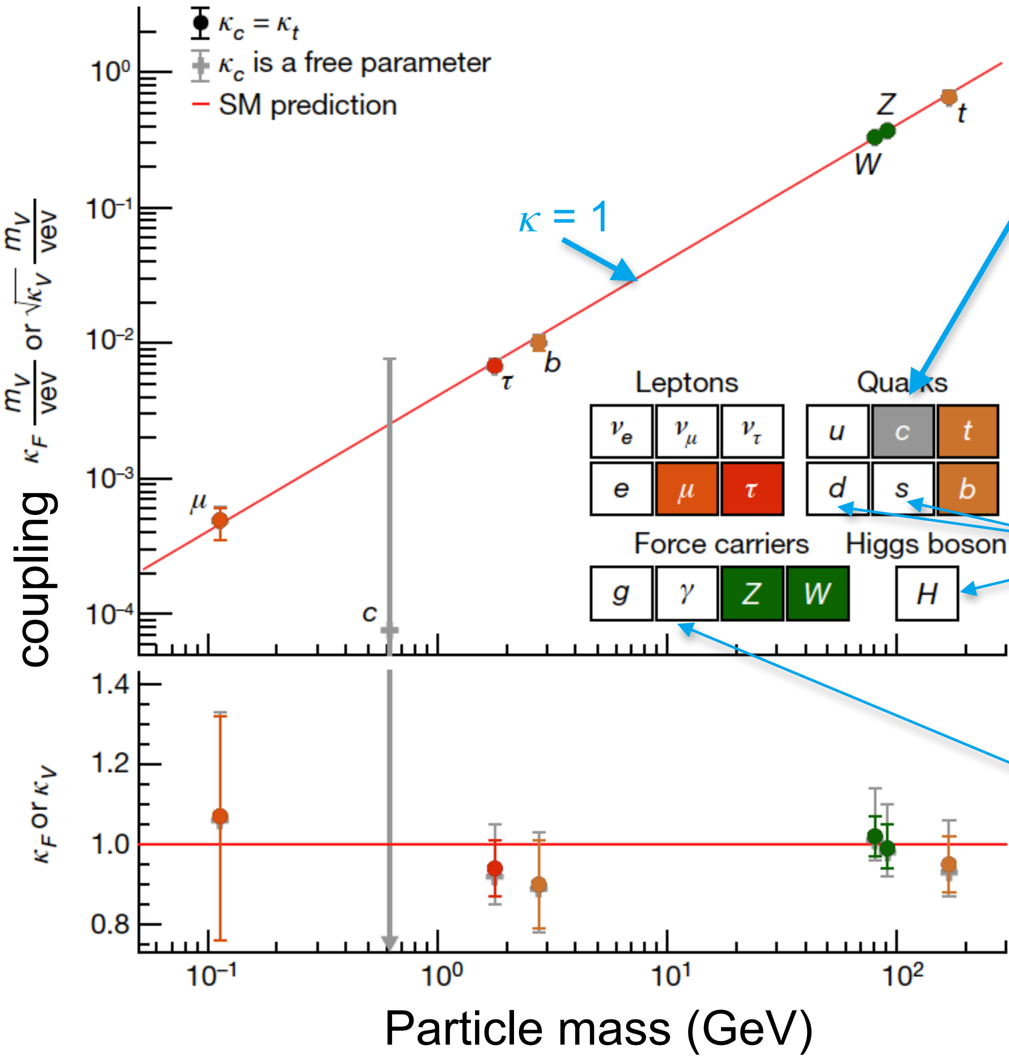
Measure coupling strength as function of mass



Particle coupling measured but not observed yet (too large uncertainty)

Particle couplings not measured (yet)

Measure coupling strength as function of mass

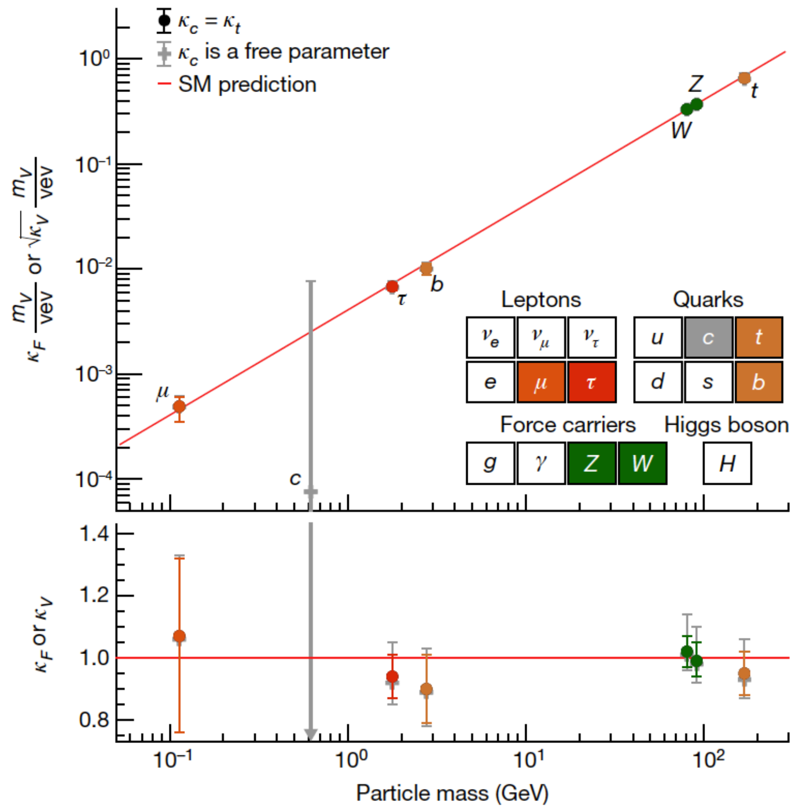


Particle coupling measured but not observed yet (too large uncertainty)

Particle couplings not measured (yet)

Couplings through loop assumed to be SM. choose not to test them here

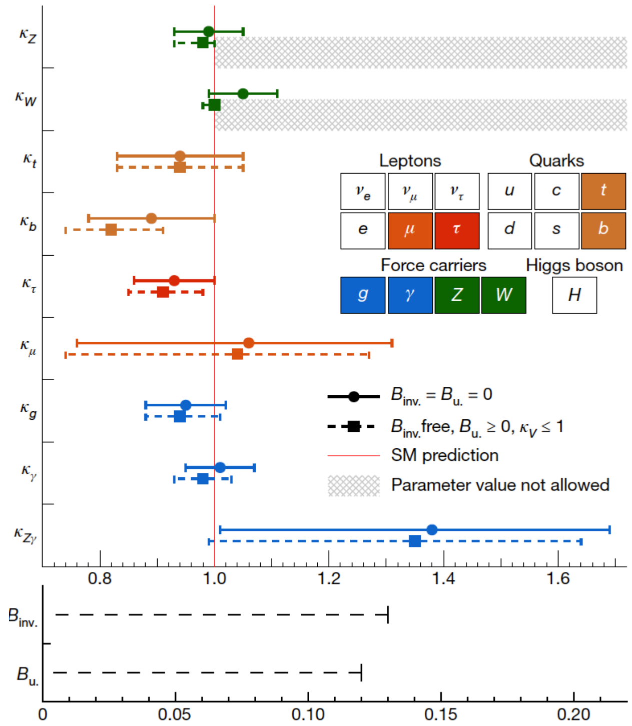
Measure coupling strength as function of mass



- Higher mass leads to more precise measurements
- Knowledge about Higgs mostly from vector boson couplings (5% precision) and 3rd generation fermions (7-12% precision)
- 2nd generation fermions probed with large uncertainties

Measure coupling strength

- Maybe there is coupling to a (new) particle that has just not been observed yet?
  - Probe data under this assumption (B_{inv} free)
  - Some decays might be undetected due to large backgrounds, let's include these as well ($B_u >= 0$)



Higgs Summary

- Demonstrated Higgs mechanism and what we know today about the resonance observed at ~125 GeV on 4.7.2012
  - It is spin-0
  - It has mass of 125 GeV
  - It couples to 3rd generation fermions and heavy vector bosons according to the Standard model prediction within (5-12% precision)
  - It couples to 2nd generation fermions
  - It decays to photons
- **It looks like the Higgs in the Standard Model Higgs Boson!**

Higgs Outlook

- Room for new physics to appear?
- Not all couplings have been observed yet:
  - Decay to charm quarks (hopefully with Run 3 data)
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  - Measure CP properties of Higgs in fermionic interactions
    - Deviation might explain Baryon asymmetry in Universe
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Back-up

MASS TERMS

- quadratic in fields with a constant

$$\frac{g_W^2}{8}(W_\mu^1 + iW_\mu^2)(W^{1\mu} - iW^{2\mu})(v+h)^2$$

$$\frac{g_W^2 v^2}{8}(W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) = \frac{m_W^2}{2}(W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu})$$

$$\boxed{m_W = \frac{1}{2} g_W v}$$

$$\frac{v^2}{8}(A_\mu, Z_\mu)\begin{pmatrix} 0 & 0 \\ 0 & g_W^2 + g'^2 \end{pmatrix}\begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$m_A = 0 \qquad \boxed{m_Z = \frac{v}{2}\sqrt{g_W^2 + g'^2}}$$

Spontaneous symmetry breaking in the SM

We give mass to the gauge bosons through the Higgs mechanism: generate mass terms from t
kinetic energy term of a scalar doublet field Φ that undergoes a broken-symmetry process.

Introduce a complex scalar doublet: four scalar real fields (why will become clear later)

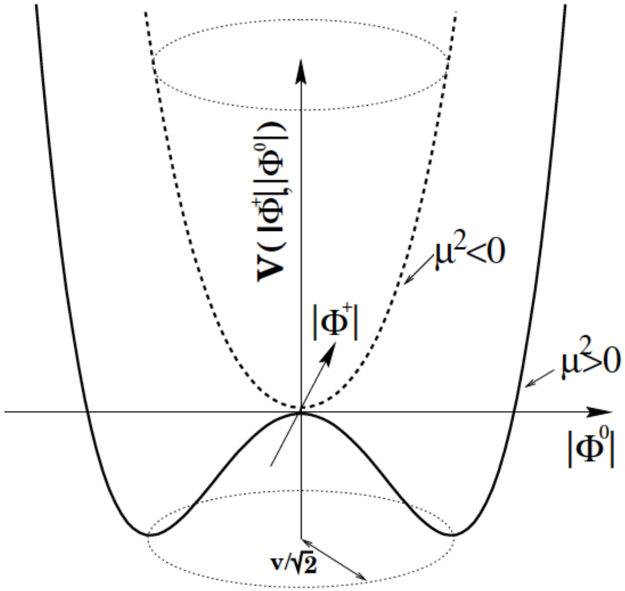
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad Y(\Phi) = 1$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V\left(\Phi^\dagger \Phi\right)$$

$$D^\mu = \partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{Y(\Phi)}{2} B^\mu$$

$$V\left(\Phi^\dagger \Phi\right) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2, \qquad \mu^2, \lambda > 0$$

Notice the "wrong" mass sign.



$V\left(\Phi^\dagger \Phi\right)$ is $SU(2)_L \times U(1)_Y$ symmetric.

- The reason why $Y(\Phi) = 1$ is not to break electric-charge conservation.
- Charge assignment for the Higgs doublets is done according to $Q = T_3 + Y/2$.

Fermion mass generation

A direct mass term is not invariant under $SU(2)_L$ or $U(1)_Y$ gauge transformation

$$m_f \bar{\psi}\psi = m_f \left(\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R\right)$$

Generate fermion masses through Yukawa-type interactions terms

$$\begin{aligned}
\mathcal{L}_{\mathrm{Yukawa}} &= -\Gamma_d^{ij} \bar{Q}'^{i}_L \Phi d'^{j}_R - \Gamma_d^{ij*} \bar{d}'^{i}_R \Phi^\dagger Q'^{j}_L \\
&\quad -\Gamma_u^{ij} \bar{Q}'^{i}_L \Phi_c u'^{j}_R + \mathrm{h.c.} \\
&\quad -\Gamma_e^{ij} \bar{L}^{i}_L \Phi e^{j}_R + \mathrm{h.c.} \\
&\quad -\Gamma_\nu^{ij} \bar{L}^{i}_L \Phi_c \nu^{j}_R + \mathrm{h.c.}
\end{aligned}$$

$$\Phi_c = i\sigma_2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

where Q', u' and d' are quark fields that are generic linear combination of the mass eigenstates u and d and Γ_u, Γ_d and Γ_e are 3×3 complex matrices in generation space, spanned by the indices i and j.

$\mathcal{L}_{\mathrm{Yukawa}}$ is Lorentz invariant, gauge invariant and renormalizable, and therefore it can (actually it must) be included in the Lagrangian.

Notice: neutrino masses can be implemented via the Γ_ν term. Since $m_\nu \approx 0$, we neglect it.

Expanding around the vacuum state

In the unitary gauge we have

$$\bar{Q}'^{\,i}_L\, \Phi\, d'^{\,j}_R \;=\; \left(\bar{u}'^{\,i}_L \;\; \bar{d}'^{\,i}_L\right) \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} d'^{\,j}_R = \frac{v+H}{\sqrt{2}}\, \bar{d}'^{\,i}_L\, d'^{\,j}_R$$

$$\bar{Q}'^{\,i}_L\, \Phi_c\, u'^{\,j}_R \;=\; \left(\bar{u}'^{\,i}_L \;\; \bar{d}'^{\,i}_L\right) \begin{pmatrix} \frac{v+H}{\sqrt{2}} \\ 0 \end{pmatrix} u'^{\,j}_R = \frac{v+H}{\sqrt{2}}\, \bar{u}'^{\,i}_L\, u'^{\,j}_R$$

and we obtain

$$\begin{aligned}\mathcal{L}_{\rm Yukawa} &= -\Gamma^{ij}_d \frac{v+H}{\sqrt{2}}\, \bar{d}'^{\,i}_L\, d'^{\,j}_R - \Gamma^{ij}_u \frac{v+H}{\sqrt{2}}\, \bar{u}'^{\,i}_L\, u'^{\,j}_R - \Gamma^{ij}_e \frac{v+H}{\sqrt{2}}\, \bar{e}^{i}_L\, e^{j}_R + \text{h.c.} \\ &= -\left[M^{ij}_u\, \bar{u}'^{\,i}_L\, u'^{\,j}_R + M^{ij}_d\, \bar{d}'^{\,i}_L\, d'^{\,j}_R + M^{ij}_e\, \bar{e}^{i}_L\, e^{j}_R + \text{h.c.}\right]\left(1 + \frac{H}{v}\right)\end{aligned}$$

$$M^{ij} = \Gamma^{ij} \frac{v}{\sqrt{2}}$$

W and Z masses and Weinberg angle θ_W

Electroweak mixing angle (rotating W0 and B0 vector boson plane to get Z0 and photon)

Gives relationship between W and Z Boson masses

$$\cos\theta_W = \frac{m_W}{m_Z}$$

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}},$$