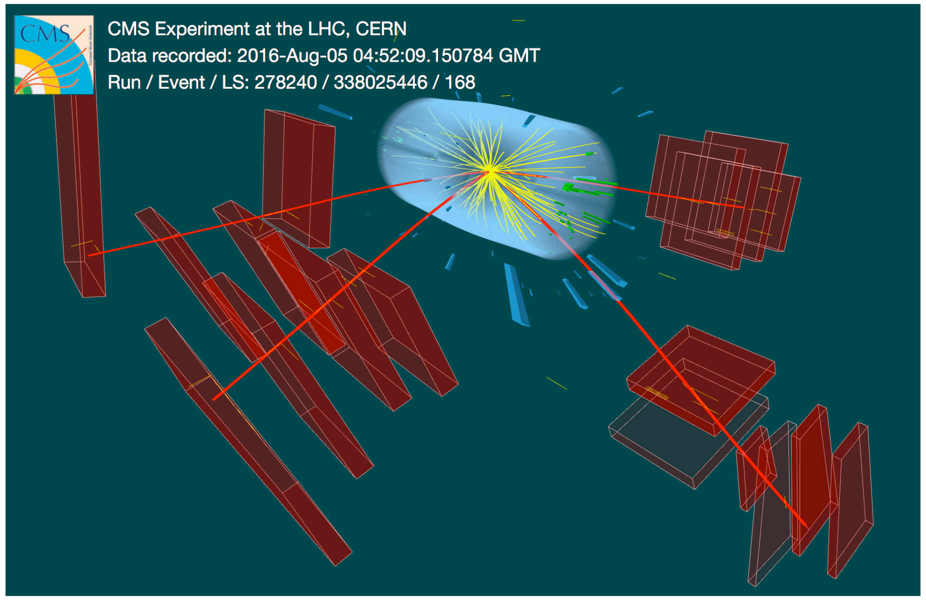
Higgs Physics



HASCO Summer School

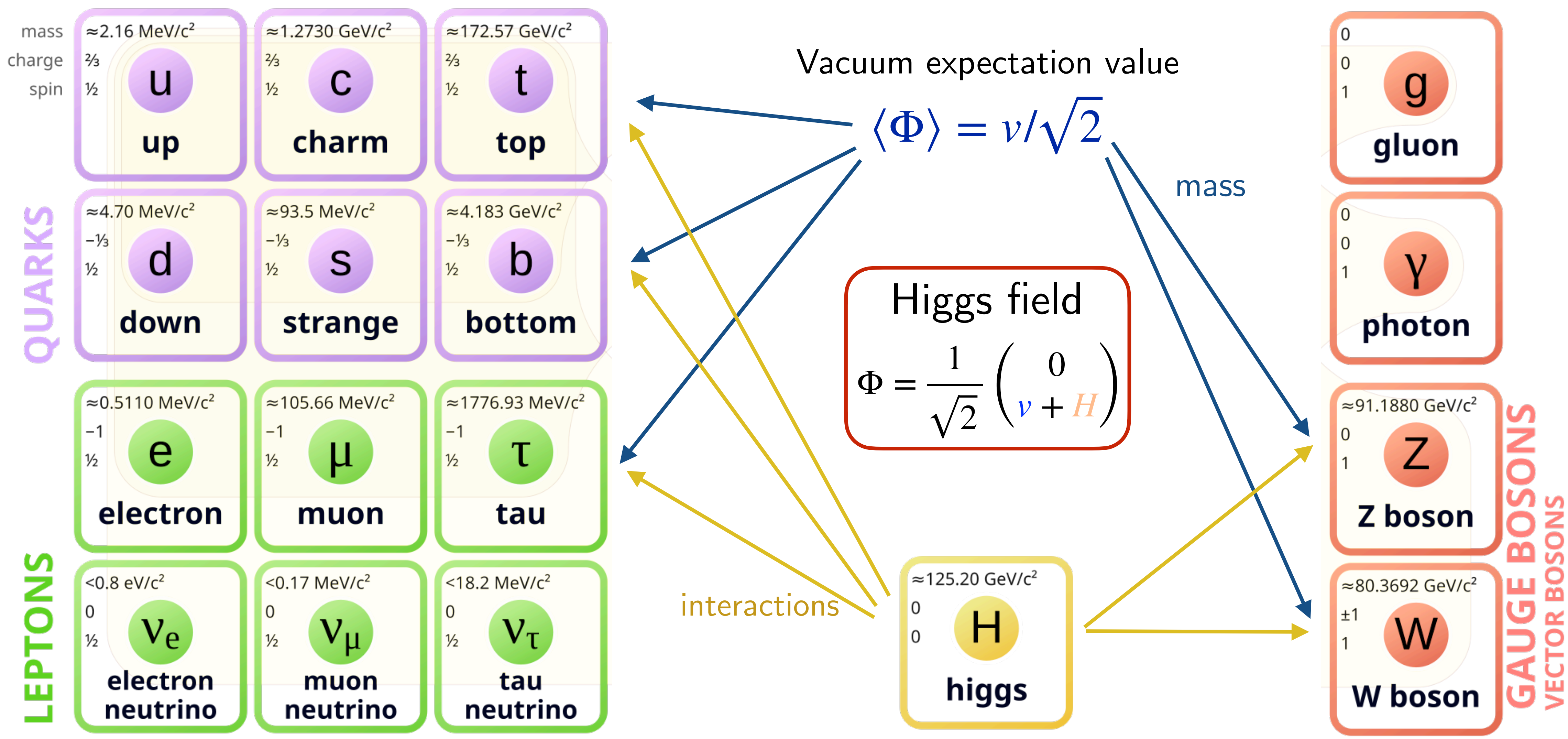
Göttingen — 29. July 2024

Matthias Kerner

Karlsruhe Institute of Technology — ITP

The Standard Model

Particle content:



Central role of Higgs field in SM:

→ Obtains Vacuum Expectation Value v due to Electroweak Symmetry Breaking (EWSB)

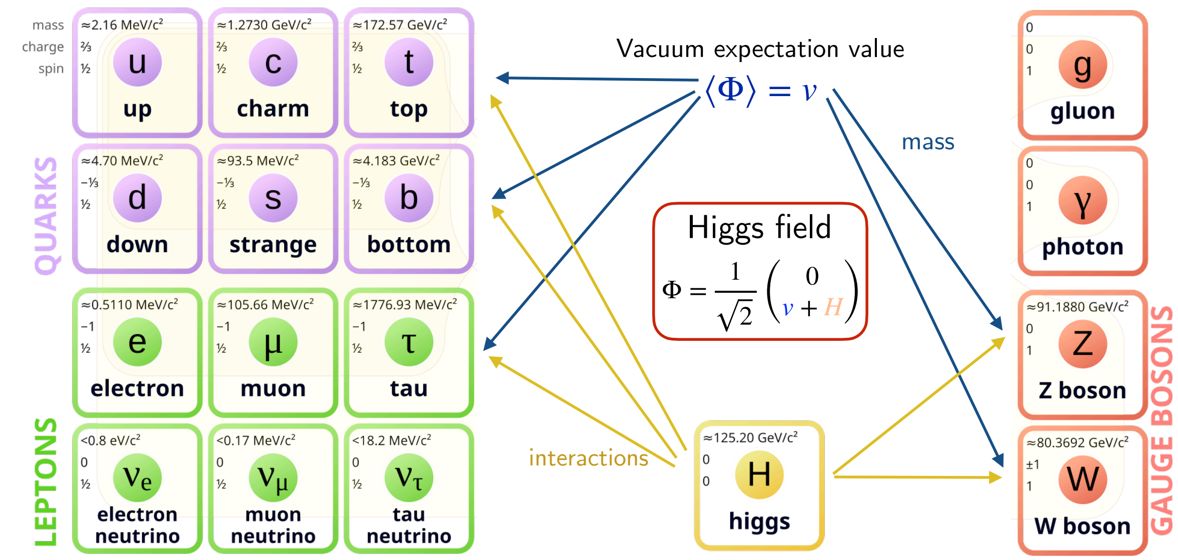
→ Generates masses of elementary particles

The Standard Model

Central role of Higgs field in SM:

→ Generates masses of <u>elementary</u> particles, e.g.

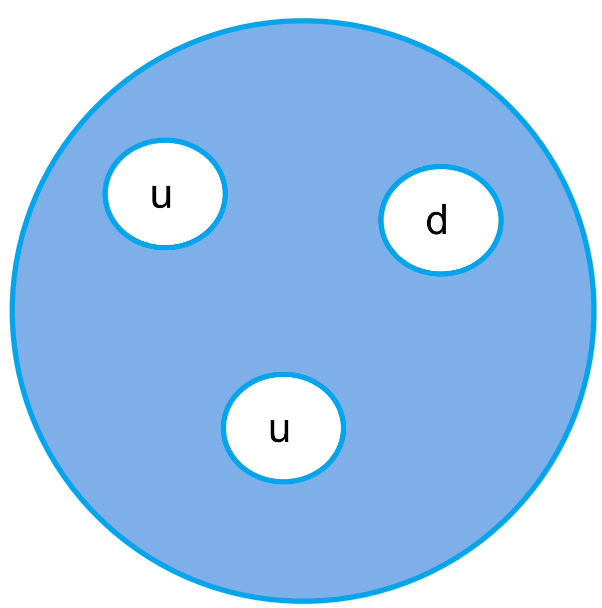
$$m_u = 2.16\,\mathrm{MeV/c^2}$$
$$m_d = 4.70\,\mathrm{MeV/c^2}$$



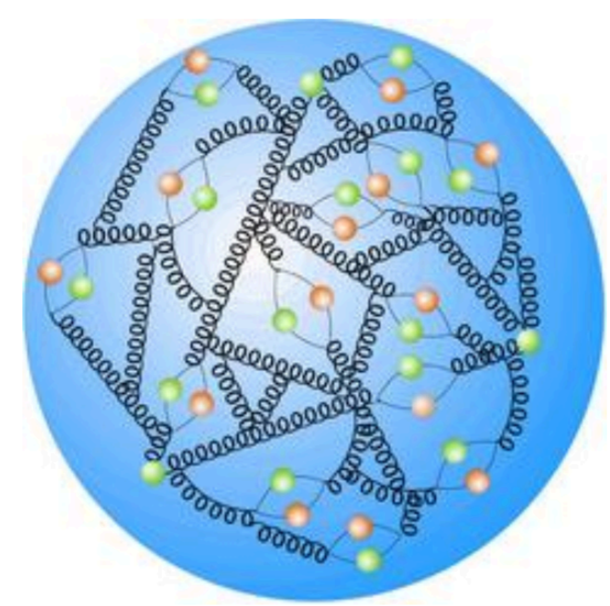
note, however:

only small contribution of hadron masses due to constituent quarks,
(1% for protons/neutrons)

mass largely generated by dynamics of QCD interaction



$$2m_u + m_d \approx 9\,\mathrm{MeV/c^2}$$

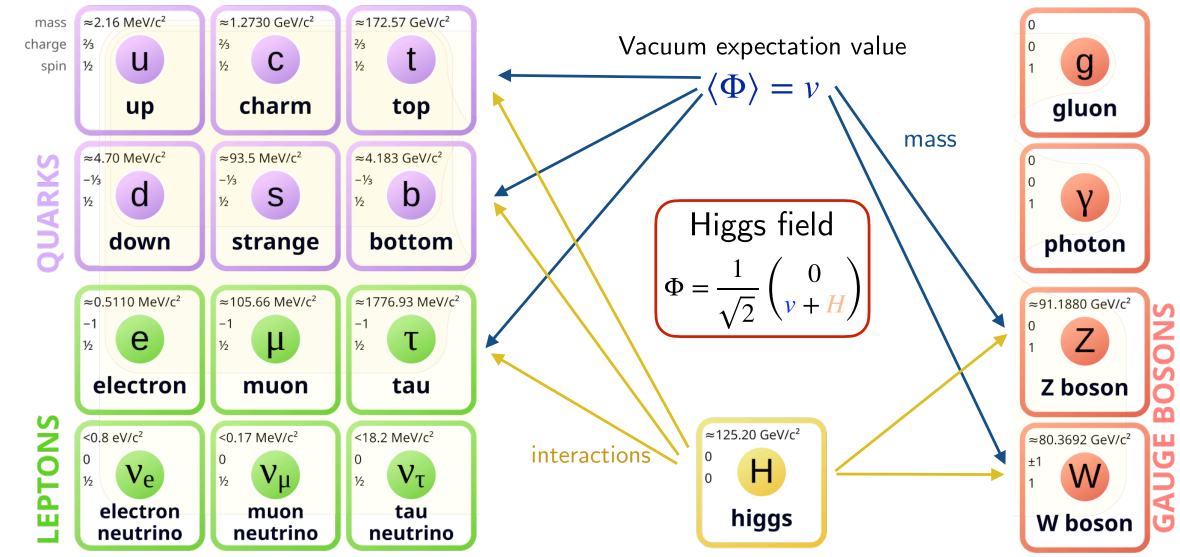


$$m_{proton} \approx 938\,\mathrm{MeV/c^2}$$

The Standard Model

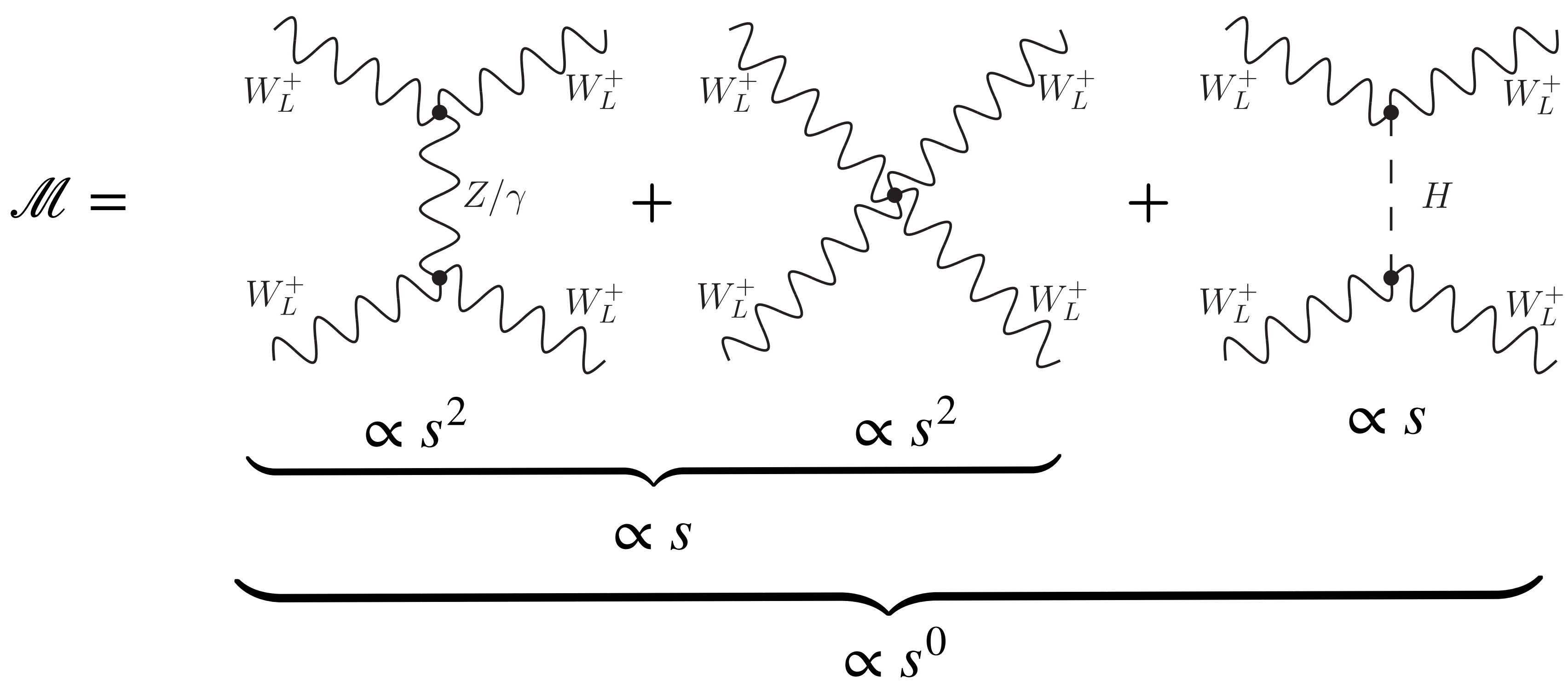
Central role of Higgs field in SM:

→ Generates masses of elementary particles,



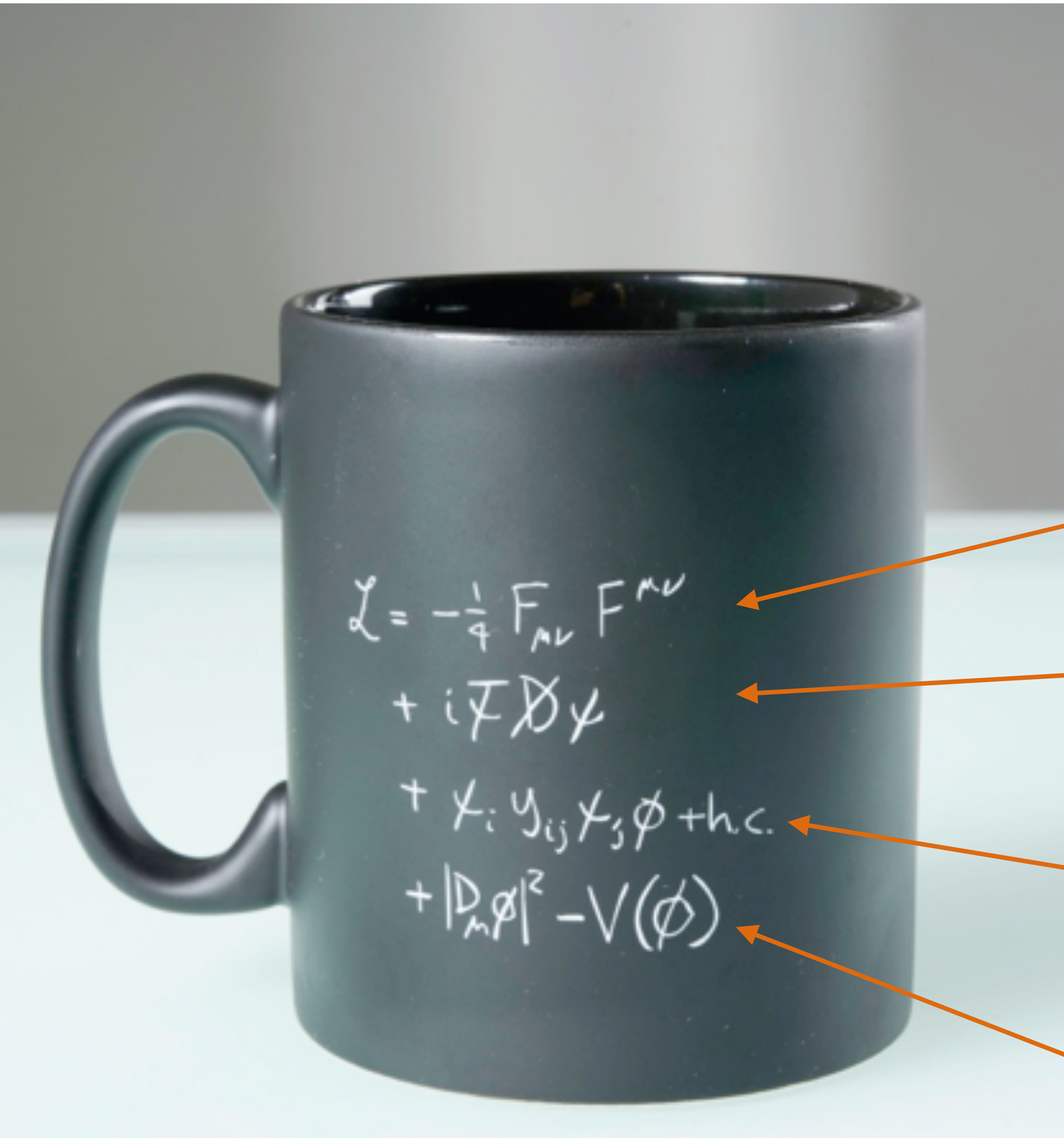
→ Solves some issues of the electroweak sector:

- generates masses of W- and Z-bosons without violating underlying symmetry
- avoids unitarity violation in longitudinal vector boson scattering



The Standard Model

Lagrangian



Kinematic terms of gauge bosons

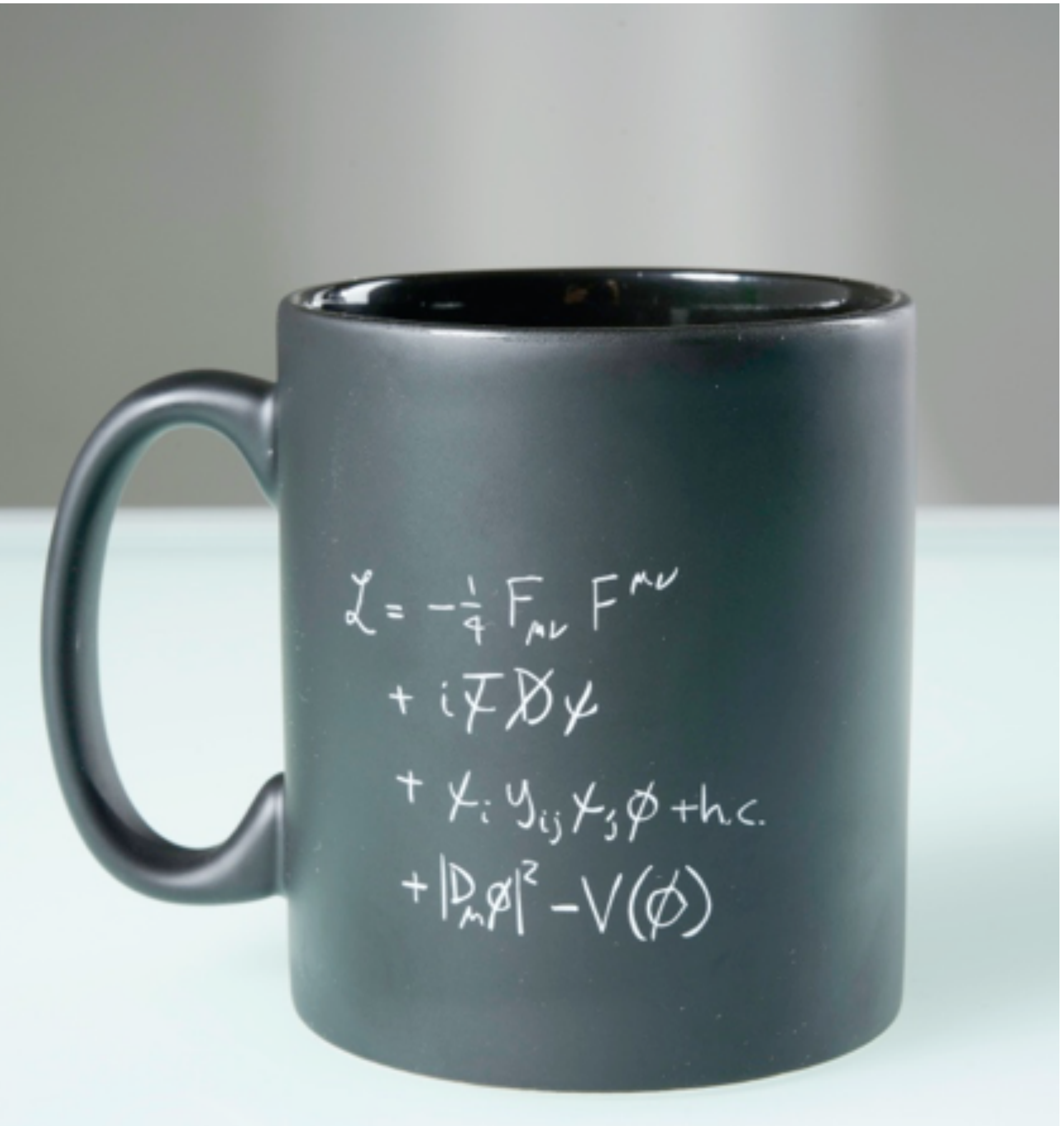
Kinematic terms of fermions
& Interactions of Fermions with Gauge Bosons

Fermion masses/mixing
& Interaction with Higgs boson

Kinematic term & Potential of Higgs

The Standard Model

Lagrangian & Symmetry Group



particles assigned to multiplets of the group

$$SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}$$

color $\rightarrow$ QCD

electroweak sector:

L: left-handed interactions

Y: hypercharge

EWSB

$$SU(3)_C \otimes U(1)_Q$$

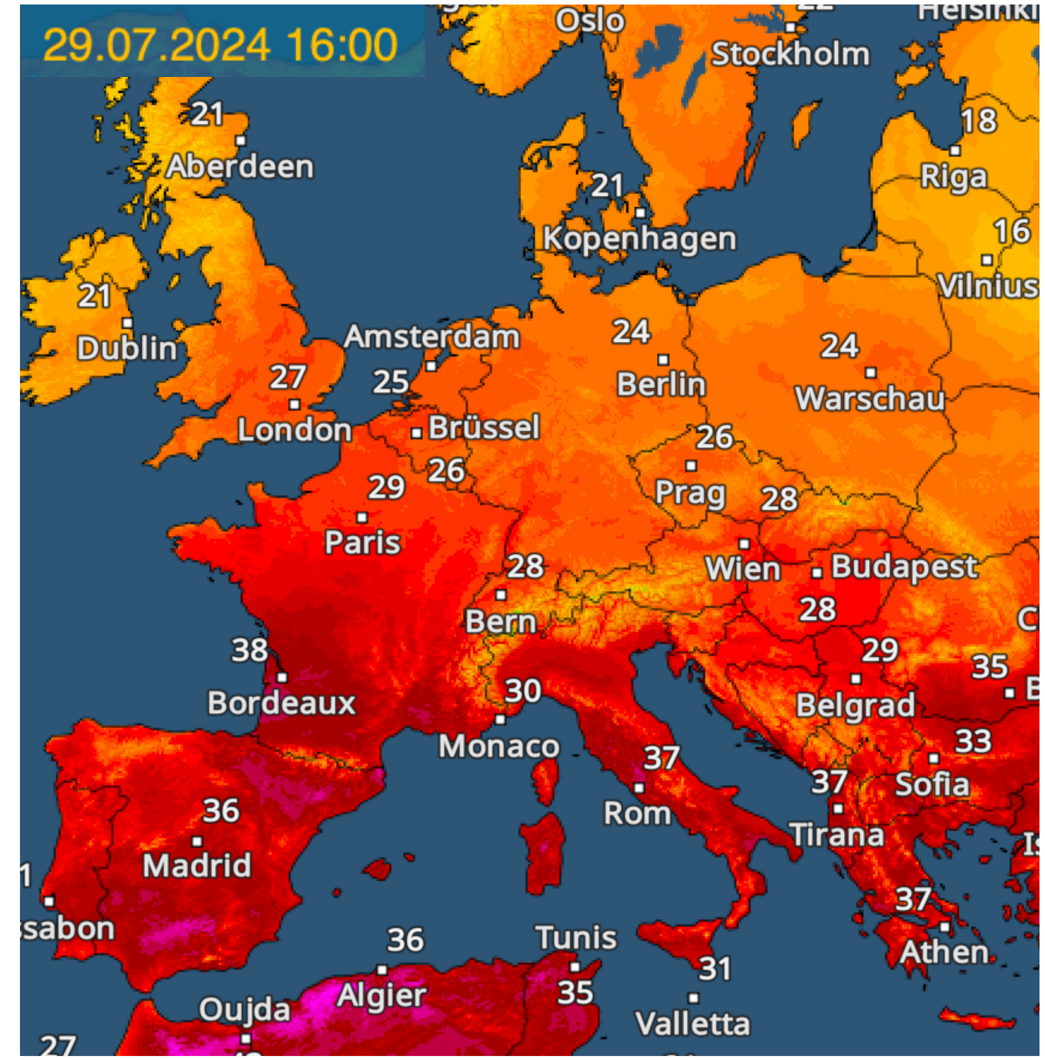
electric charge

Fields, Particles
& Gauge Symmetries

Field Theory

Fields: Assign number(s) to each point in space(-time)

e.g.:
- Temperature T($\overrightarrow{x}$, t)
- Electromagnetic potential $A^\mu = (\Phi, \overrightarrow{A})$
- Scalars $\Phi(\overrightarrow{x}, t)$, Spinors $\Psi(\overrightarrow{x}, t)$, …



Dynamics governed by Lagrangian density $\mathscr{L}$

$\rightarrow$ Euler Lagrange equations:

$$\partial_\mu \frac{\partial \mathscr{L}}{\partial(\partial_\mu \phi_i)} - \frac{\partial \mathscr{L}}{\partial \phi_i} = 0$$

e.g. for Electrodynamics:

$$\mathscr{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

with field-strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$\rightarrow$ equations of motion:

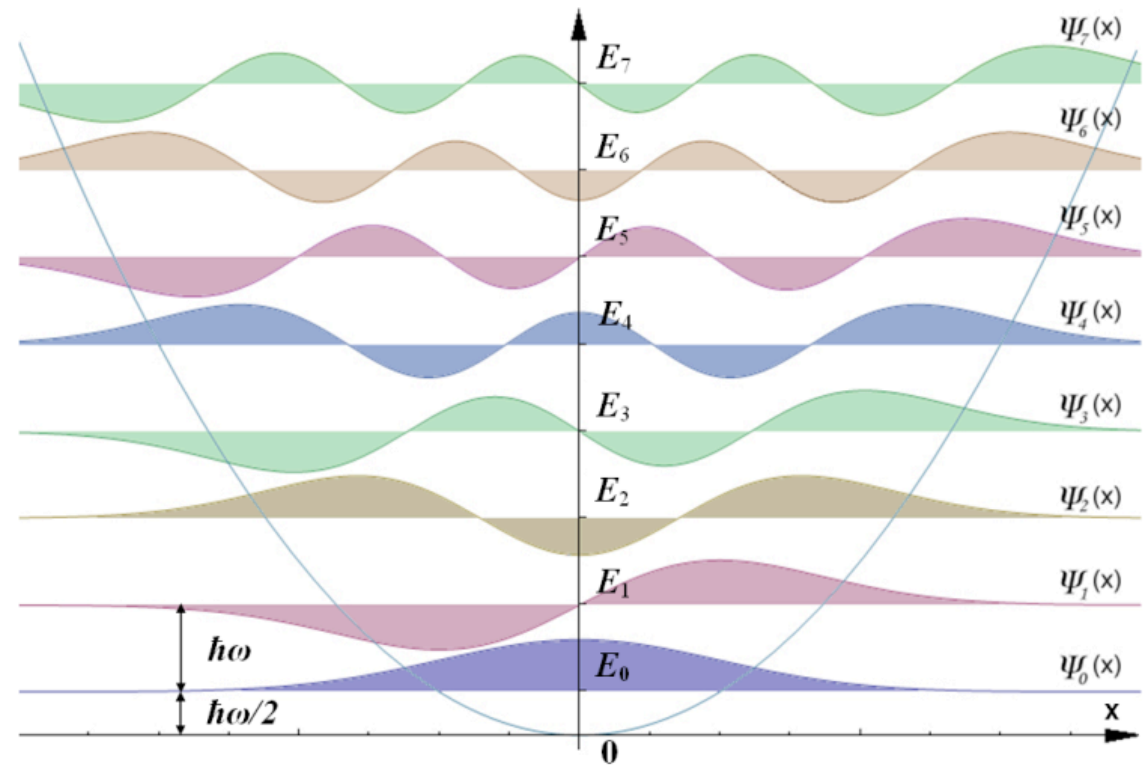
- Dirac equation: $(i\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu - m)\psi = 0$
- Maxwell equations: $\partial_\mu F^{\mu\nu} = j^\nu$ with $j^\nu = e\,\bar{\psi}\gamma^\nu\psi$

Quantum Field Theory & Particles

Equations of Motion for free fields
solved by plane-wave decomposition

Klein Gordon Equation $(\partial_\mu \partial^\mu + m^2)\Phi = 0$
(eq. of motion of a scalar field)

$$\Phi(\vec{x}, t) = \int \frac{d^3\vec{p}}{2E\,(2\pi)^3} \left(a(\vec{p}) e^{-ipx} + a^+(\vec{p}) e^{ipx} \right)$$



Quantization via canonical commutation relations

$$\left[\Phi(\vec{x}, t),\, \Pi(\vec{x}', t)\right] = i\hbar\, \delta(\vec{x} - \vec{x}')$$

field Φ — conjugate momentum

$$\Pi = \frac{\partial \mathscr{L}}{\partial(\partial_0 \phi)}$$

$\rightarrow$ can identify: ground state $\hat{=}$ vacuum

excitations $\hat{=}$ particles

From Global Symmetries to Gauge Theories

Karlsruhe Institute of Technology

Let's start with the Lagrangian of a free Dirac Fermion ψ (e.g. electron)

$$\mathcal{L} = \bar{\psi}\, i\gamma^{\mu}\partial_{\mu}\psi - m\,\bar{\psi}\psi$$

kinematics mass

This Lagrangian is invariant under the global U(1) transformation (≙ multiplication with complex phase)

α constant

$$\psi \to e^{i\alpha}\psi$$

(since $\bar{\psi} = \psi^{+}\gamma^{0}$, we have $\bar{\psi} \to e^{-i\alpha}\bar{\psi}$)

What happens if we instead consider local U(1) transformations ?

$$\psi \to e^{iq\alpha(x)}\psi$$

$\rightarrow$ $\mathcal{L}$ not invariant due to extra terms with $iq\partial_{\mu}\alpha(x)$

Solution: introduce additional gauge field A^{μ}

with covariant derivative $D_{\mu} = \partial_{\mu} + iqA_{\mu}$

$\rightarrow$ $i\partial_{\mu}\alpha(x)$ terms cancelled by gauge transformation of A^{μ}

From Global Symmetries to Gauge Theories

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Lagrangian of Quantum-Electrodynamics (QED):

$$\mathscr{L} = \bar{\psi} i \gamma^{\mu} (\partial_{\mu} + ieA_{\mu}) \psi - m\bar{\psi}\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

kinematic terms of gauge field
$F_{\mu\nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu}$

is invariant under the gauge transformation

$$\psi \rightarrow e^{iq\alpha(x)} \psi$$
$$A_{\mu} \rightarrow A_{\mu} - \partial_{\mu} \alpha(x)$$

gauge transformation of $A^{\mu} = (\phi, \overrightarrow{A})$
known from classical electrodynamics:
$\phi \rightarrow \phi - \partial_t \alpha, \qquad \overrightarrow{A} \rightarrow \overrightarrow{A} + \overrightarrow{\nabla} \alpha$

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Can we modify the QED Lagrangian to describe electroweak interactions?

We need:

- massive W and Z gauge bosons

  → mass terms

$$\frac{1}{2}m_Z^2 Z_\mu Z^\mu, \quad m_W^2 W_\mu^+ W^{-\mu}$$

not invariant!

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  not invariant!
- different interaction/transformation of left- and right-handed fermions $\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \to \begin{pmatrix} e^{q_L \alpha(x)} \psi_L \\ e^{q_R \alpha(x)} \psi_R \end{pmatrix}$
  $\rightarrow$ mass terms
  $$m\bar{\psi}\psi = m(\psi_L^+ \psi_R + \psi_R^+ \psi_L)$$
  not invariant!
  mix left-/right-handed fields
  even worse for $SU(2)_L$: ψ_L is doublet, ψ_R singlet

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  not invariant!
  even worse for $SU(2)_L$: ψ_L is doublet, ψ_R singlet
  mix left-/right-handed fields

Solution:
Generate mass terms dynamically
via Spontaneous Symmetry Breaking

Spontaneous Symmetry Breaking & The Higgs Mechanism

Spontaneous Symmetry Breaking

We consider a complex scalar doublet

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

ϕ^+, ϕ^0: complex scalar fields, each with 2 degrees of freedom

with Lagrangian

$$\mathscr{L}_{\text{Higgs}} = (\partial_\mu \Phi)^+ (\partial^\mu \Phi) - V(\Phi^+\Phi),$$

where

$$V(\Phi^+\Phi) = -\mu^2 \Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

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$V(\Phi^+\Phi)$ needs to be bounded from below $\leftrightarrow$ Theory has a ground state

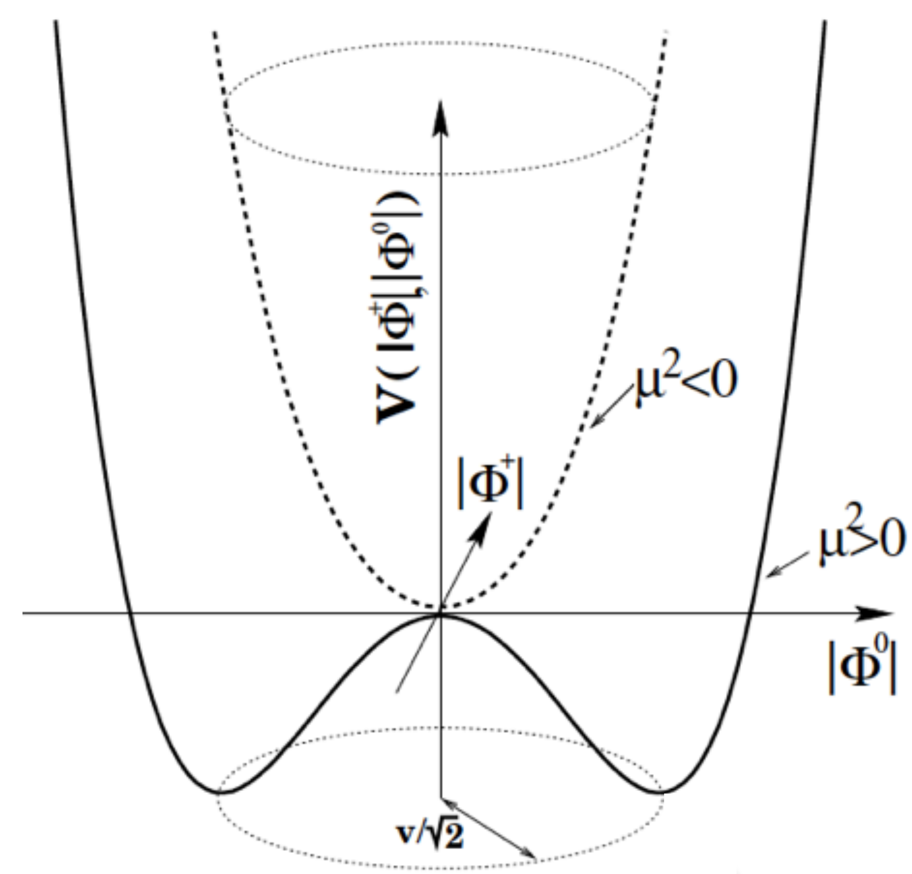
$\rightarrow \; \lambda > 0,$ but what about μ^2 ?

- $\mu^2 < 0$: ground state at $|\langle\Phi\rangle| = 0$
- $\mu^2 > 0$: non-zero vacuum expectation value

$$|\langle\Phi\rangle| = \sqrt{\frac{\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}}$$

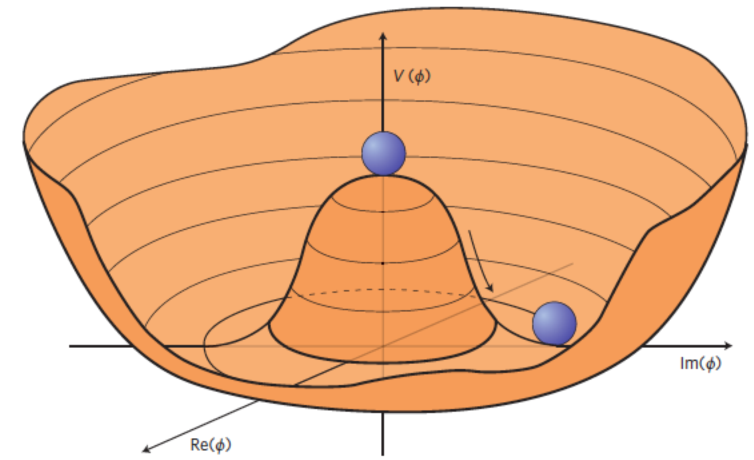
Nature/We choose one of the possible vacuum states as 'true' vacuum:

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$



Spontaneous Symmetry Breaking

Expanding Φ around the minimum:



$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H(x) + i\chi(x)) \end{pmatrix} = \frac{1}{\sqrt{2}} e^{\frac{i\sigma^i \theta^i(x)}{v}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$\rightarrow \quad \mathscr{L}_{\text{Higgs}} = (\partial_\mu \Phi)^+ (\partial^\mu \Phi) + \mu^2 \Phi^+ \Phi - \lambda(\Phi^+ \Phi)^2$$

$$= \sum_i \underbrace{\frac{1}{2}(\partial\theta^i)^2 + \frac{1}{2}(\partial H)^2}_{\text{kinematic terms}} \underbrace{- \frac{1}{2}(2\lambda v^2) H^2}_{\text{mass term}} - \lambda v H^3 - \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$

$\rightarrow$ We obtain:

- 3 massless 'Goldsone bosons'
- 1 massive 'Higgs boson' with

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

Spontaneous Symmetry Breaking

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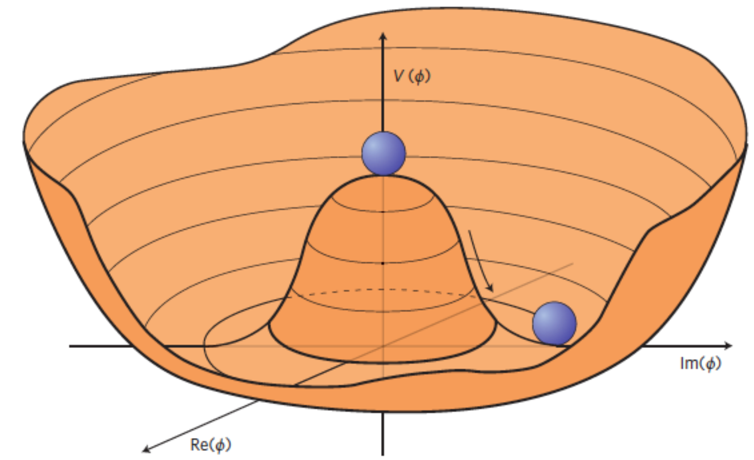

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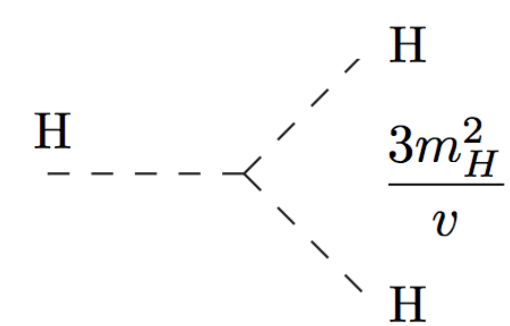
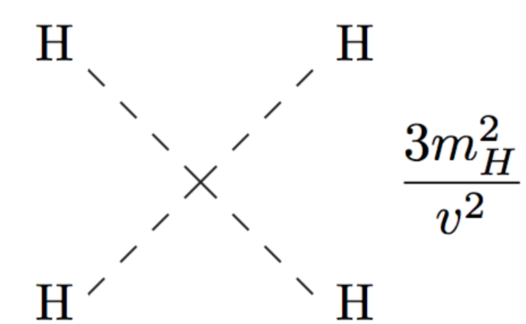
interactions

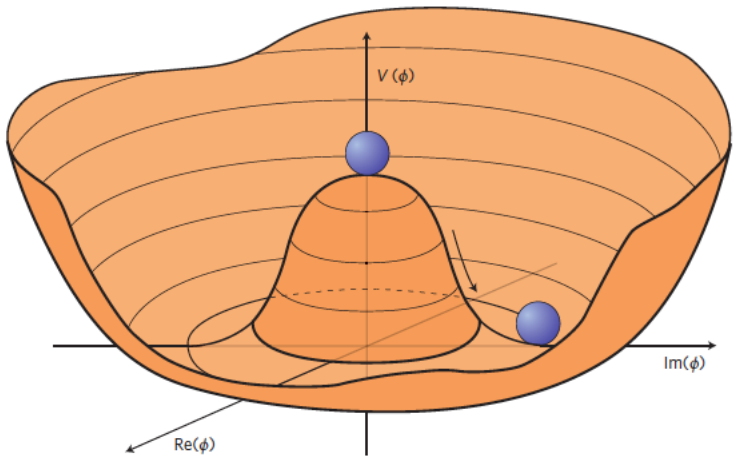




Spontaneous Symmetry Breaking

Let us investigate the symmetries of our theory:
The Lagrangian

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \Phi)^+(\partial^\mu \Phi) + \mu^2 \Phi^+ \Phi - \lambda (\Phi^+ \Phi)^2$$



is invariant under the $SU(2)_L \otimes U(1)_Y$ transformation

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \rightarrow \quad e^{i\frac{\sigma^a}{2}\beta^a(x)} e^{i\frac{Y}{2}\alpha(x)} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

What about the ground state $\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$?

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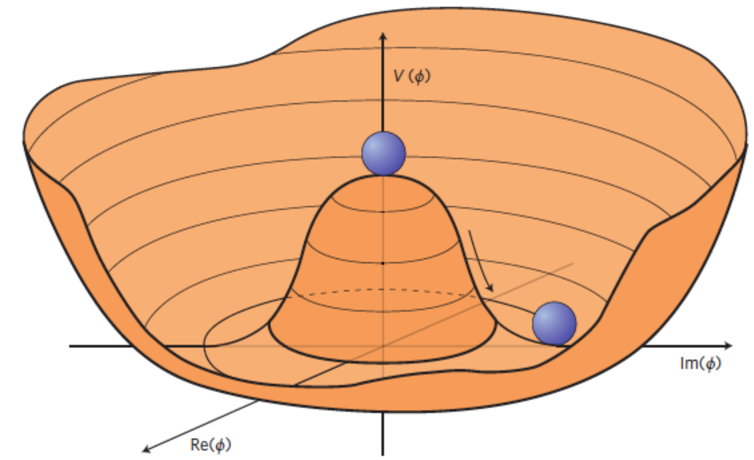

A state $\tilde{\Phi}$ is invariant under a transform $e^{iT^a\beta^a(x)}$ if

$$e^{iT^a\beta^a(x)}\Phi = \Phi \quad \Longleftrightarrow \quad T^a\Phi = 0$$

We have e.g.:

$$T_3\Phi_0 = \frac{\sigma^3}{2}\Phi_0 = \frac{1}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}0\\ -v/\sqrt{2}\end{pmatrix} \neq 0$$

$$Y\Phi_0 = Y(\Phi)\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix} \neq 0$$

Ground state not invariant under $SU(2)_L \otimes U(1)_Y$

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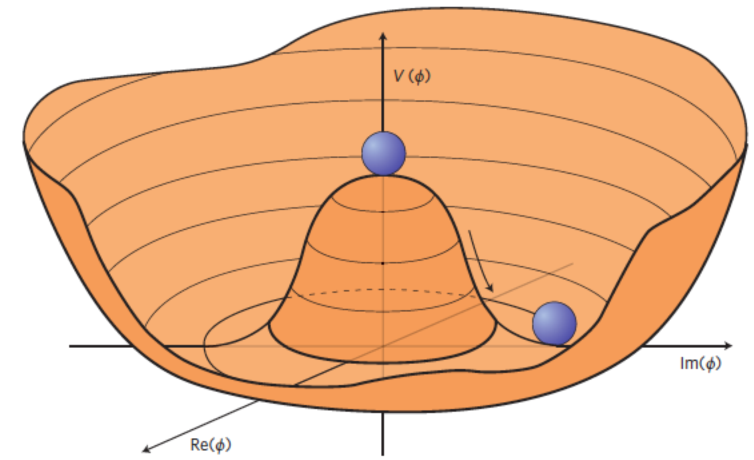

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Ground state not invariant under $SU(2)_L \otimes U(1)_Y$

but we can identify the electric charge operator $Q = Y/2 + T_3$

$$Q\Phi_0 = \frac{1}{2}(\sigma^3 + Y)\Phi_0 = \frac{1}{2}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}0\\ 0\end{pmatrix}$$

$Y(\Phi) = 1$

electric charge Q is symmetry of ground state Φ_0 (and of the full theory)

Spontaneous Symmetry Breaking, due to non-vanishing vacuum expectation value

$$SU(2)_L \otimes U(1)_Y \longrightarrow U(1)_Q$$

The Higgs Mechanism

We now consider the Higgs Lagrangian within the SM:

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

where we now have the covariant derivative

$$D_\mu \Phi = (\partial_\mu + ig \frac{\sigma^i}{2} W^i_\mu + ig' \frac{Y_H}{2} B_\mu) \Phi$$

- gauge couplings: g, g'
- $U(1)_Y$ Hypercharge of Higgs doublet ($Y_H = 1$)
- σ^i: since Φ is $SU(2)_L$ doublet
- gauge fields: W^i_μ, B_μ

When acting on the ground state Φ_0, this leads to

$$(D_\mu \Phi_0)^+ (D^\mu \Phi_0) = \left| \left(ig\frac{\sigma^i}{2} W^i + ig' \frac{Y}{2} B \right) \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \right|^2 = \frac{1}{2}\frac{v^2}{4} \begin{pmatrix} W_1 \\ W_2 \\ W_3 \\ B \end{pmatrix}^T \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \\ W_3 \\ B \end{pmatrix}$$

$$= \frac{1}{2}\frac{g^2 v^2}{4} (W_{1\mu} W_1^\mu + W_{2\mu} W_2^\mu) + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z^\mu$$

$$= m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu$$

with

$$W^\pm = \frac{1}{\sqrt{2}} (W_1 \mp i W_2)$$

$$m_W = \frac{v}{2} g, \quad m_Z = \frac{v}{2} \sqrt{g^2 + g'^2}$$

Rotation to mass eigenstates:

$$\begin{pmatrix} A \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

→ Weinberg angle $\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$

→ 3 massive gauge bosons Z, W^+, W^-; photon A remains massless

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So far considered: $(D_\mu \Phi_0)^+ (D^\mu \Phi_0) \; = m_W^2 \, W^+_\mu W^{-\mu} \; + \; \frac{1}{2} m_Z^2 \, Z_\mu Z^\mu$

But we actually need:

$$(D_\mu \Phi)^+ (D^\mu \Phi) = \left| \left(\partial_\mu + ig\frac{\sigma^i}{2} W^i + ig' \frac{Y}{2} B\right) \frac{1}{\sqrt{2}} e^{\frac{i\sigma^i \theta^i(x)}{v}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \right|^2$$

can be absorbed by gauge transformations of W, Z
→ 'unitary gauge'

3 'would-be Goldstone bosons eaten by W and Z'
→ gives longitudinal degree of freedom

polarizations of vector bosons

with momentum $k = (\sqrt{k^2 + m^2}, 0, 0, k)$

- transverse: $\varepsilon_{T,1} = (0, 1, 0, 0)$
  $\varepsilon_{T,2} = (0, 0, 1, 0)$
- longitudinal: $\varepsilon_L = \frac{1}{m}(k, 0, 0, \sqrt{k^2 + m^2})$
  (only if $m \neq 0$)

The Higgs Mechanism

We now consider the Higgs Lagrangian within the SM:

$$\mathscr{L}_{\text{Higgs}} = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi^+ \Phi)$$

where we now have the covariant derivative $\quad D_\mu \Phi = (\partial_\mu + ig\frac{\sigma^i}{2} W^i_\mu + ig'\frac{Y_H}{2} B_\mu)\Phi$

So far considered: $\quad (D_\mu \Phi_0)^+ (D^\mu \Phi_0) \; = m_W^2 \, W^+_\mu W^{-\mu} \; + \; \frac{1}{2} m_Z^2 \, Z_\mu Z^\mu$

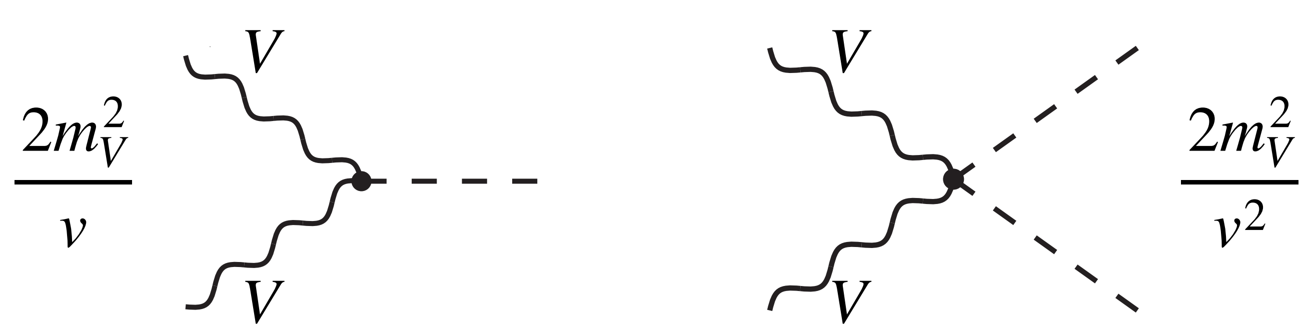
But we actually need:

$$(D_\mu \Phi)^+ (D^\mu \Phi) = \left| \left(\partial_\mu + ig\frac{\sigma^i}{2} W^i + ig'\frac{Y}{2} B \right) \frac{1}{\sqrt{2}} e^{\frac{i\sigma^i \theta^i(x)}{v}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \right|^2$$

$$v + H(x) = v(1 + H/v)$$

$$= m_W^2 \, W^+_\mu W^{-\mu} \cdot (1 + \frac{H}{v})^2 \; + \; \frac{1}{2} m_Z^2 \, Z_\mu Z^\mu \cdot (1 + \frac{H}{v})^2 \; + \text{kinematic terms}$$

$\rightarrow$ couplings of Higgs boson to W & Z bosons



Yukawa Sector

Karlsruhe Institute of Technology

Coupling of Fermion fields ψ_i to Higgs doublet via Yukawa couplings

$$\mathscr{L}_{Yukawa} = y_{ij}\,\bar{\psi}_{i,L}\,\Phi\,\psi_{j,R} + \mathrm{h.c.} \qquad i,j = \{e,\mu,\tau;\ u,c,t;\ d,s,b\}$$

The details get a bit messy, but some things to remember are:

- ψ_L, Φ: doublets of $SU(2)_L$ $\rightarrow$ $\bar{\psi}_L \Phi \psi_R$ invariant
  ψ_R: singlet
- invariance under $U(1)_Y$ $\rightarrow$ only certain combinations of i, j allowed
  $\rightarrow$ y_{ij} can be grouped into blocks
  $y_{ij}^L, y_{ij}^U, y_{ij}^D$ for leptons, up- & down-type quarks
- y_{ij}^k : in total 3x3x3=27 complex parameters:
  - 3 lepton masses (neutrinos are massless)
  - 6 quark masses
  - 3 angles & 1 physical phase $\rightarrow$ quark-mixing given by CKM matrix

  all other parameters are unphysical phases (and can be absorbed into a redefinition of the fermion fields)

Yukawa Sector

Coupling of Fermion fields ψ_i to Higgs doublet via Yukawa couplings

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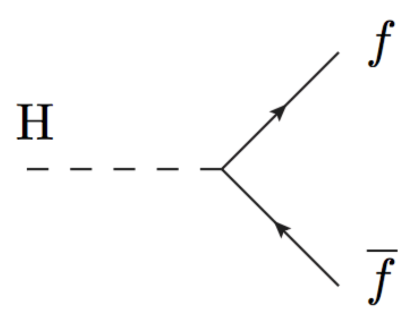
$i, j = \{e, \mu, \tau;\ u, c, t;\ d, s, b\}$

inserting $$\Phi = \frac{1}{\sqrt{2}} e^{\frac{i\sigma^i\theta^i(x)}{v}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

(and rotating to mass eigenstates)

$$\rightarrow \mathscr{L}_{Yukawa} = m_i\,\bar{\psi}_i\psi_i \cdot (1 + \frac{H}{v})$$

$\rightarrow$ Fermion-Higgs couplings



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

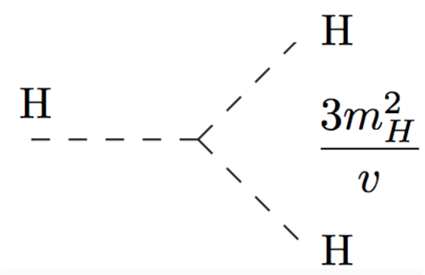
Theory Summary

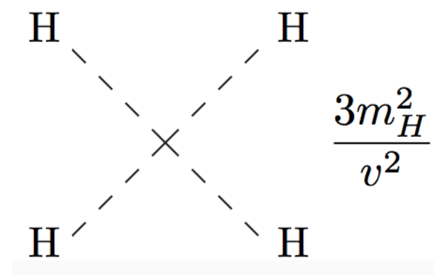
- Ground state of Higgs potential

$$V(\Phi^+\Phi) = -\mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

  breaks symmetry $SU(2)_L \otimes U(1)_Y$ to $U(1)_Q$

- $V(\Phi^+\Phi)$ contains Higgs self interactions





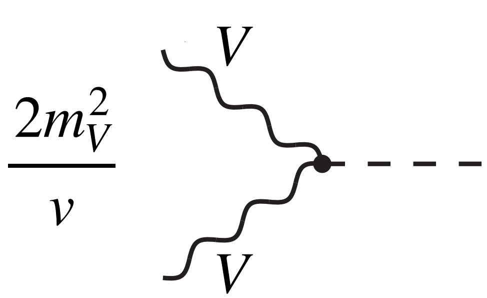
- $(D_\mu\Phi)^+(D^\mu\Phi)$

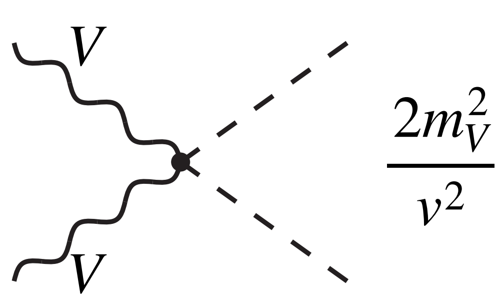
  generates masses

$$m_W = \frac{v}{2}g = 80.38\,\mathrm{GeV}$$

$$m_Z = \frac{v}{2}\sqrt{g^2 + g'^2} = 91.19\,\mathrm{GeV}$$

  & couplings

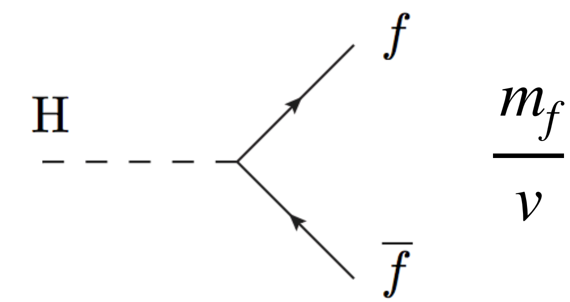




- $\mathscr{L}_{Yukawa} = y_{ij}\,\bar{\Psi}_{i,L}\,\Phi\,\psi_{j,R} + \mathrm{h.c.}$

  generates fermion masses m_f

  & couplings



Theory Summary

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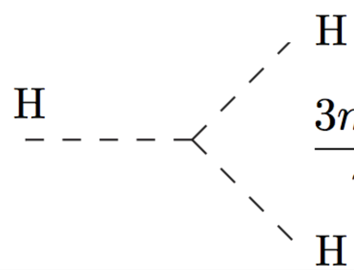
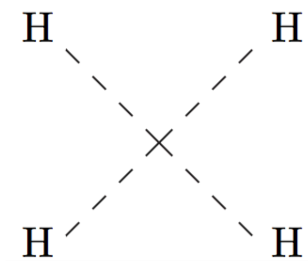


$$\frac{3m_H^2}{v}$$



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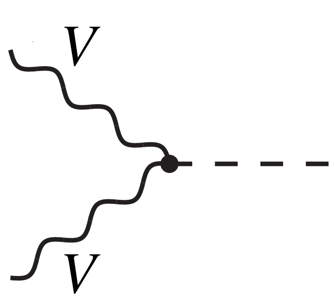
generates masses

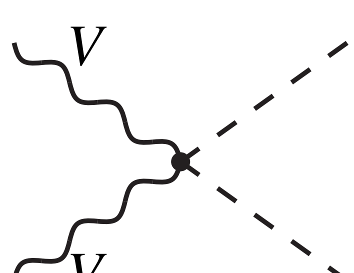
$$m_W = \frac{v}{2}g = 80.38\,\text{GeV}$$

$$m_Z = \frac{v}{2}\sqrt{g^2 + g'^2} = 91.19\,\text{GeV}$$

& couplings

$$\frac{2m_V^2}{v}$$



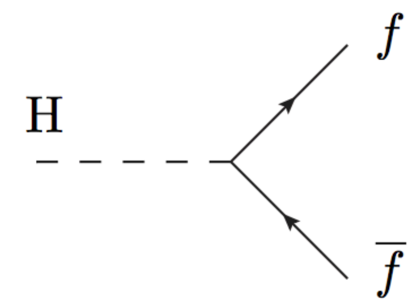


$$\frac{2m_V^2}{v^2}$$

- $\mathscr{L}_{Yukawa} = y_{ij}\bar{\Psi}_{i,L}\,\Phi\,\psi_{j,R} + \text{h.c.}$

generates fermion masses m_f

& couplings



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

with Fermi's constant

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.16638 \cdot 10^{-5}\,\text{GeV}^{-2}$$

$\rightarrow$ vacuum expectation value

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

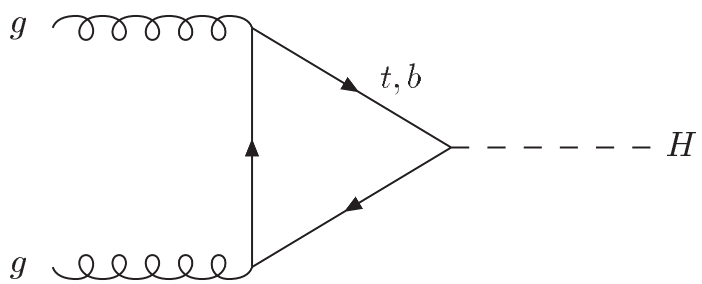
All Higgs couplings determined by particle masses!

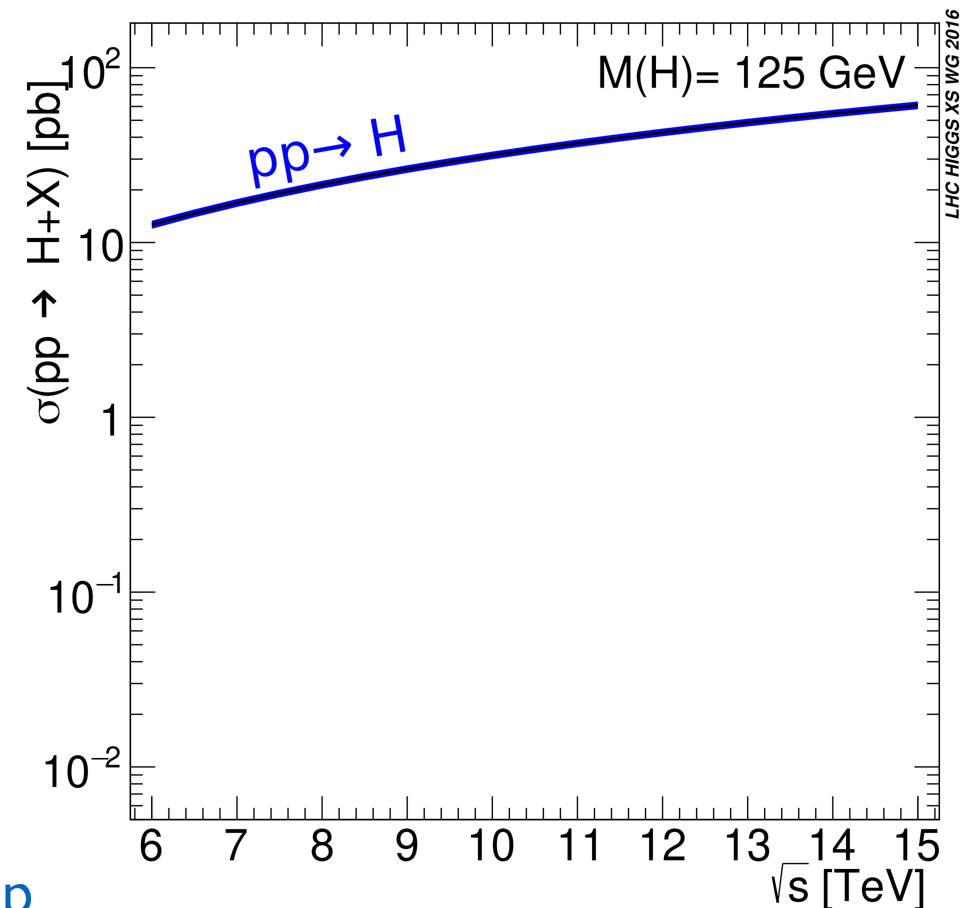
Only free parameter at this point: m_H

Higgs Production & Decay

Higgs Production at the LHC

Higgs couplings given by particle masses $\rightarrow$ need to produce heavy particle first !





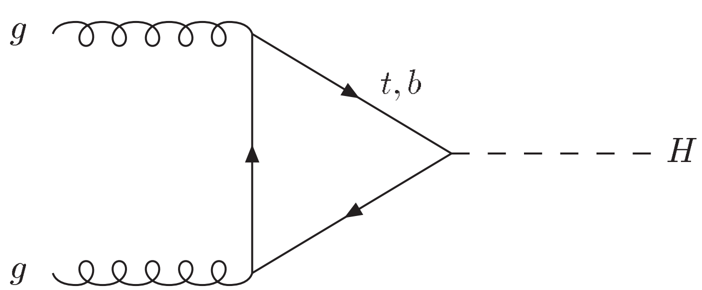
1) Gluon Fusion $\quad$ gg $\rightarrow$ H via heavy-quark loop

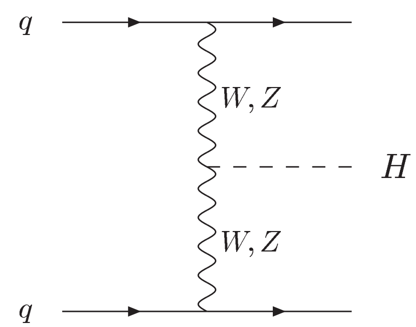
loop suppressed, but:

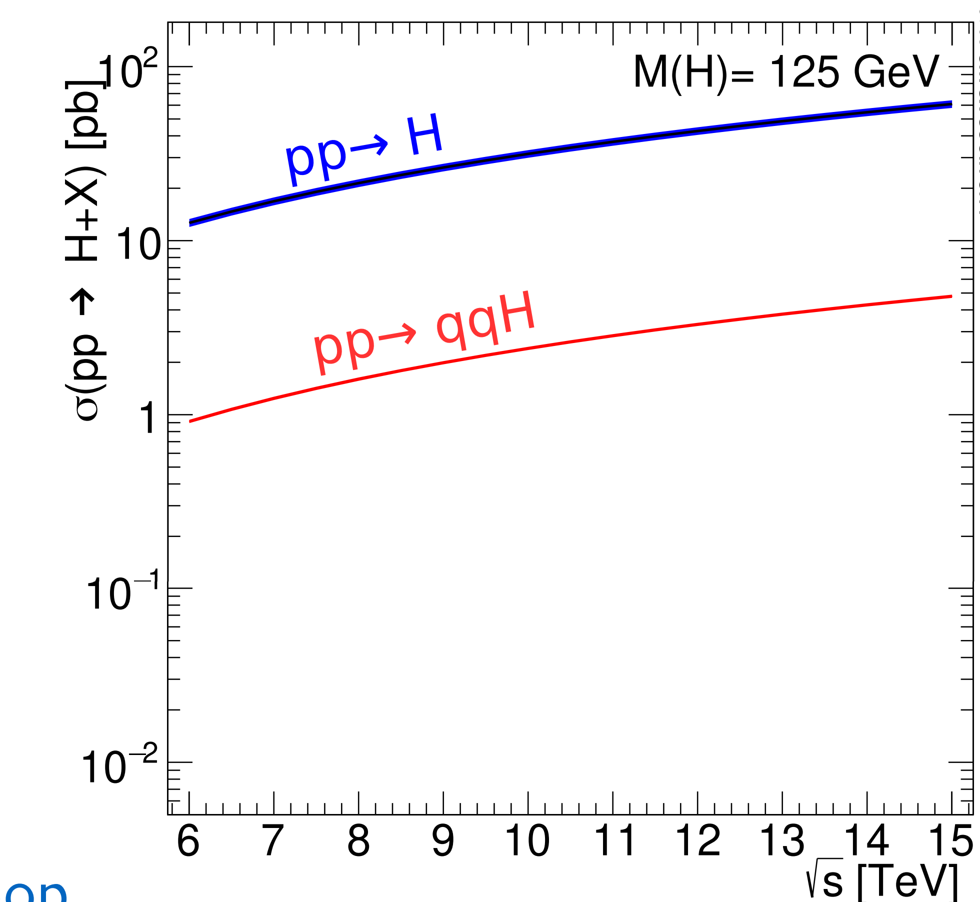
- large couplings: top Yukawa & α_s
- large gluon content of the proton

Higgs Production at the LHC

Higgs couplings given by particle masses $\rightarrow$ need to produce heavy particle first !







1) Gluon Fusion $\quad$ gg $\rightarrow$ H via heavy-quark loop

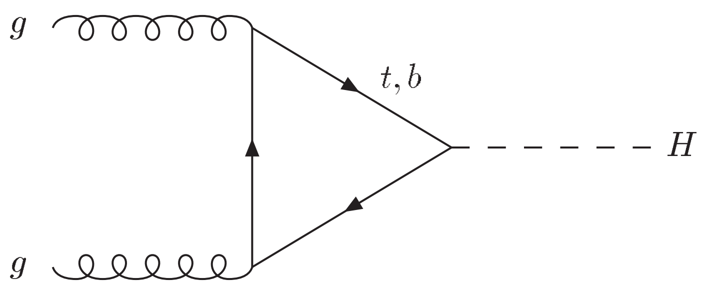
2) Vector Boson Fusion (VBF) $\quad$ qq $\rightarrow$ qqVV $\rightarrow$ qqH

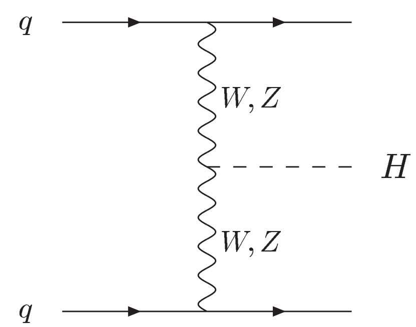
- characteristic detector signature:
  quarks generate forward & backward jet
  $\rightarrow$ helps to identify Higgs event

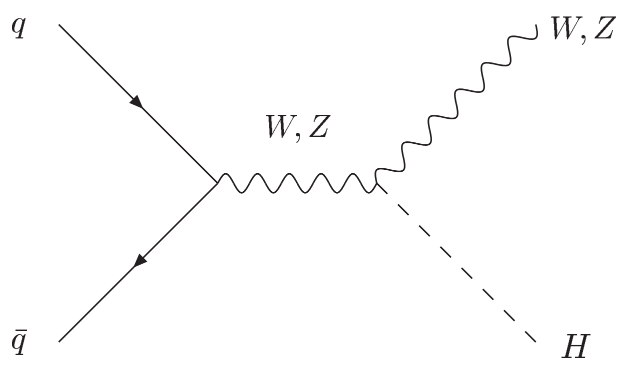
- direct probe of HVV coupling

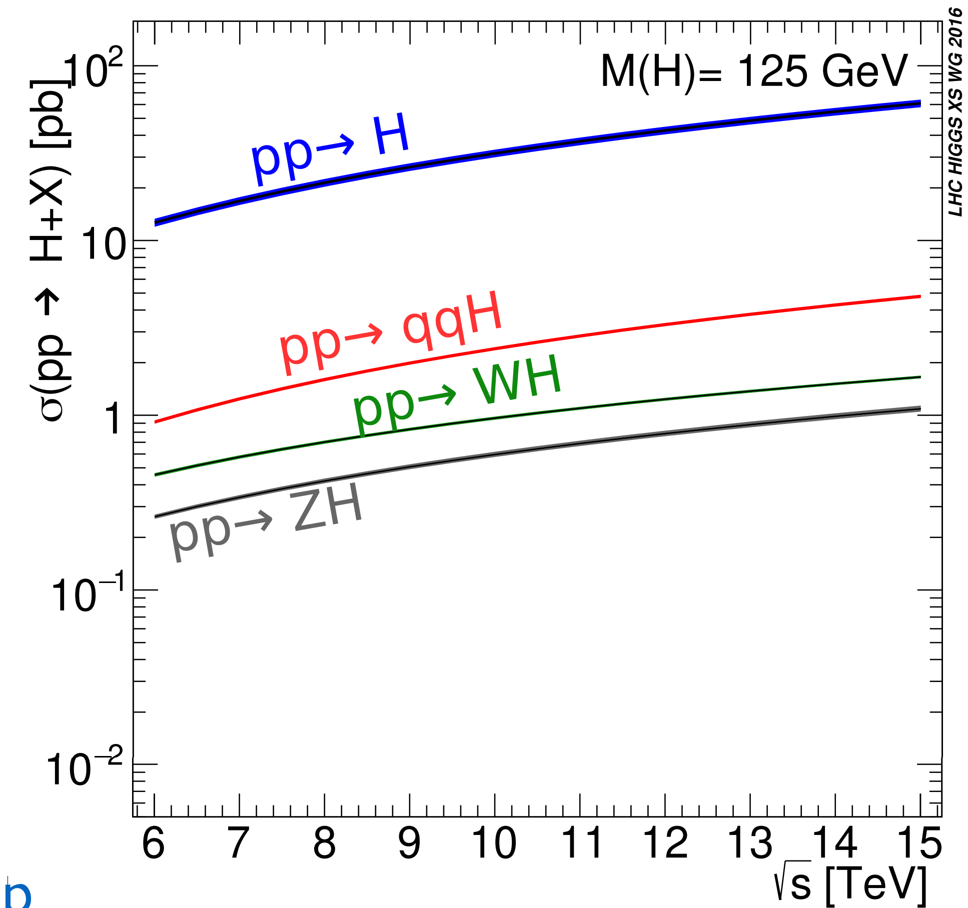
Higgs Production at the LHC

Higgs couplings given by particle masses $\rightarrow$ need to produce heavy particle first !









1) Gluon Fusion $gg \rightarrow H$ via heavy-quark loop

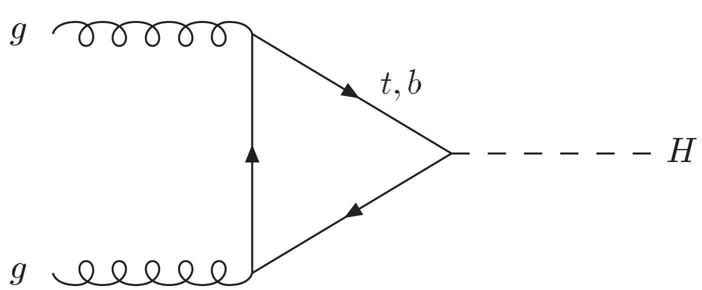
2) Vector Boson Fusion (VBF) $qq \rightarrow qqVV \rightarrow qqH$

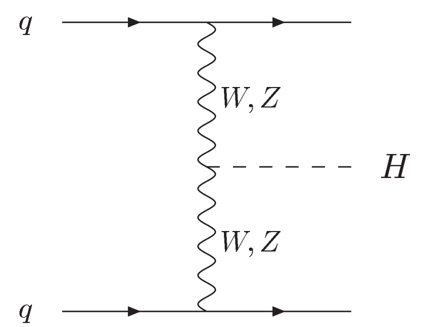
3) Higgs Strahlung $qq \rightarrow VH$

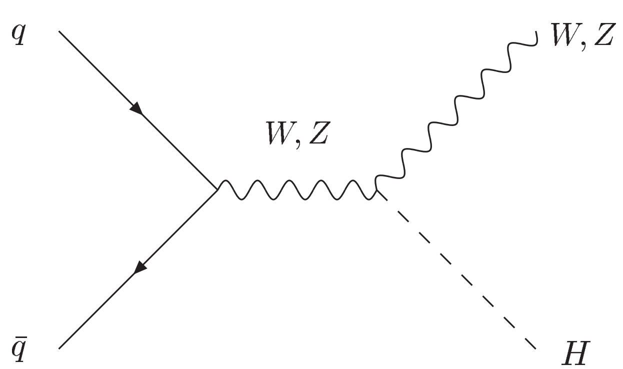
- leptons from W/Z decay help with event identification
- direct probe of HVV coupling

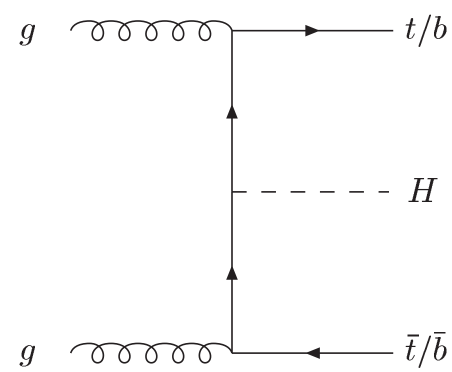
Higgs Production at the LHC

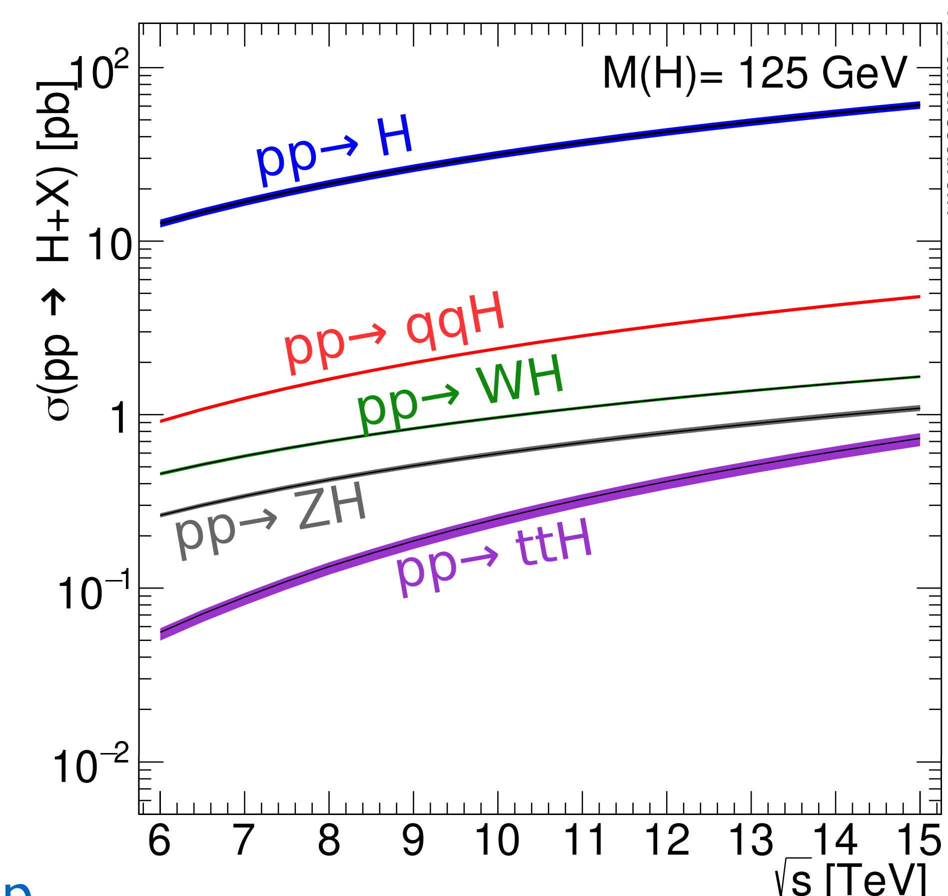
Higgs couplings given by particle masses $\rightarrow$ need to produce heavy particle first !











1) Gluon Fusion $\quad$ gg $\rightarrow$ H via heavy-quark loop

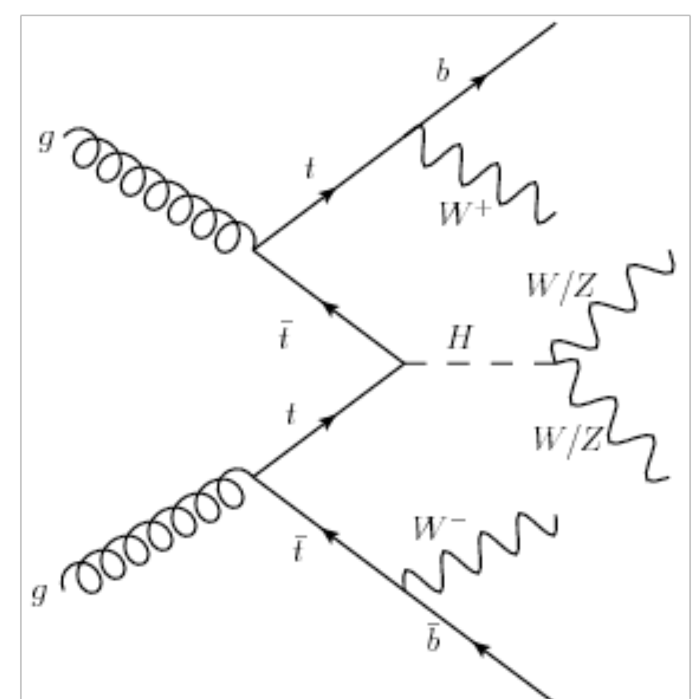
2) Vector Boson Fusion (VBF) $\quad$ qq $\rightarrow$ qqVV $\rightarrow$ qqH

3) Higgs Strahlung $\quad$ qq $\rightarrow$ VH

4) Top Associated Prod. $\quad$ pp $\rightarrow$ ttH

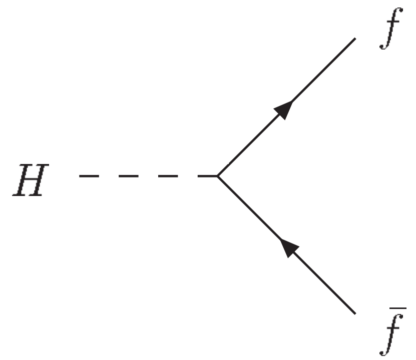
- challenging final state
  due to decays of top quarks and Higgs boson

- direct probe of ttH coupling



Higgs Decays

- to fermions

$\Gamma \propto \Big|$  $\Big|^2$

$$= N_{C,f} \frac{m_H^2 \beta^3}{8\pi v^2} m_f^2$$

velocity $\beta \approx 1$

$N_{C,f} =$ color factor:
3 for quarks
1 for leptons

$$BR = \frac{\Gamma_i}{\Gamma_{tot}}, \quad \Gamma_{tot} = \sum_i \Gamma_i$$

assuming $m_H = 125\,\mathrm{GeV}$:

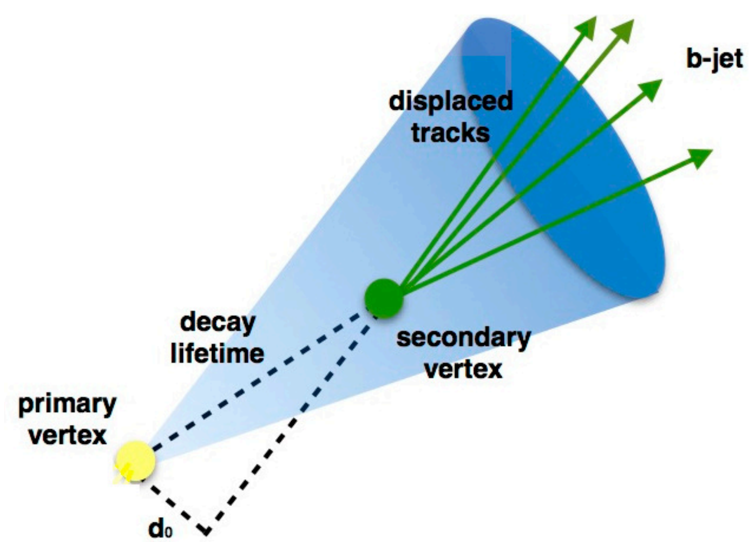
	$\Gamma\,[\mathrm{MeV}]$	BR [%]
$t\bar{t}$	0	0
$b\bar{b}$	2.38	58.1
$\tau^+\tau^-$	0.26	6.3
$c\bar{c}$	0.12	2.9
$\mu^+\mu^-$	<0.01	0.02
$s\bar{s}$	<0.01	0.02

$\Gamma_{tot} = 4.1\,\mathrm{MeV}$

$\rightarrow$ life time $\tau = 10^{-22}\,\mathrm{s}$

- 58% of Higgs bosons decay to $b\bar{b}$

  b quarks form short-lived B hadrons
  $\rightarrow$ can be identified by displaced tracks



  but large QCD backgrounds

- 0.02% of Higgs bosons decay to $\mu^+\mu^-$

  small benching fraction, but
  very clear detector signature

Higgs Decays

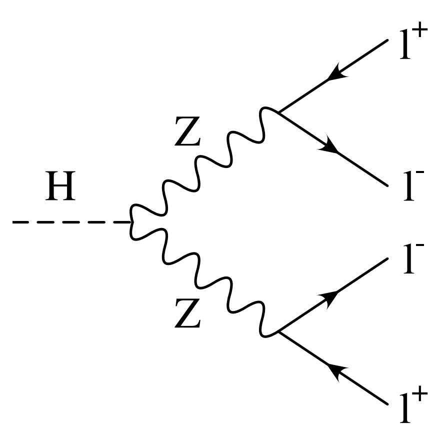
- to fermions
- to vector bosons (ZZ*, WW*)

BR: 3% (ZZ*) 21% (WW*)

$$BR = \frac{\Gamma_i}{\Gamma_{tot}}, \quad \Gamma_{tot} = \sum_i \Gamma_i$$

$m_H < 2m_V \rightarrow$ one of the V has to be off-shell (indicated by V*)

vector bosons decay to quarks or leptons:



BR $Z \rightarrow l^+l^- \approx 10\,\%$

BR $W \rightarrow l\nu \approx 30\,\%$

$\rightarrow$ small event rates when including decays to leptons, but clean detector signature

assuming $m_H = 125\,\text{GeV}$:

	$\Gamma\,[\text{MeV}]$	BR [%]
$t\bar{t}$	0	0
$b\bar{b}$	2.38	58.1
WW	0.88	21.5
$\tau^+\tau^-$	0.26	6.3
$c\bar{c}$	0.12	2.9
ZZ	0.11	2.6
$\mu^+\mu^-$	<0.01	0.02
$s\bar{s}$	<0.01	0.02

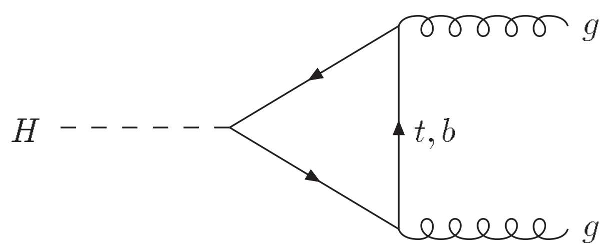
$\Gamma_{tot} = 4.1\,\text{MeV}$

$\rightarrow$ life time $\tau = 10^{-22}\,\text{s}$

Higgs Decays

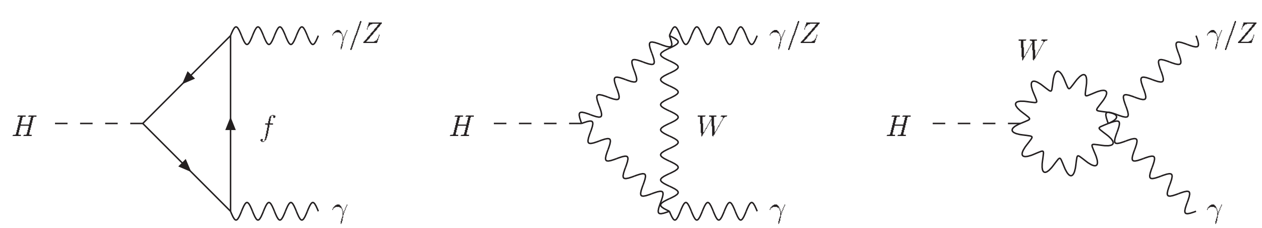
$$BR = \frac{\Gamma_i}{\Gamma_{tot}}, \quad \Gamma_{tot} = \sum_i \Gamma_i$$

- to fermions
- to vector bosons (ZZ*, WW*)
- loop induced decays
  - to gluons (BR: 8.2%)



→ phenomenologically irrelevant, due to huge QCD backgrounds at LHC

  - to photons $\gamma\gamma$ or $Z\gamma$ (BR: 0.2% each)



→ small BR compared to $H \to gg$ due to
- coupling α instead of α_s
- destructive interferences of the 3 diagrams

→ clear detector signature (in particular $H \to \gamma\gamma$)

assuming $m_H = 125\,\mathrm{GeV}$:

	$\Gamma\,[\mathrm{MeV}]$	BR [%]
$t\bar{t}$	0	0
$b\bar{b}$	2.38	58.1
WW	0.88	21.5
gg	0.33	8.2
$\tau^+\tau^-$	0.26	6.3
$c\bar{c}$	0.12	2.9
ZZ	0.11	2.6
$\gamma\gamma$	0.01	0.23
$Z\gamma$	<0.01	0.15
$\mu^+\mu^-$	<0.01	0.02
$s\bar{s}$	<0.01	0.02

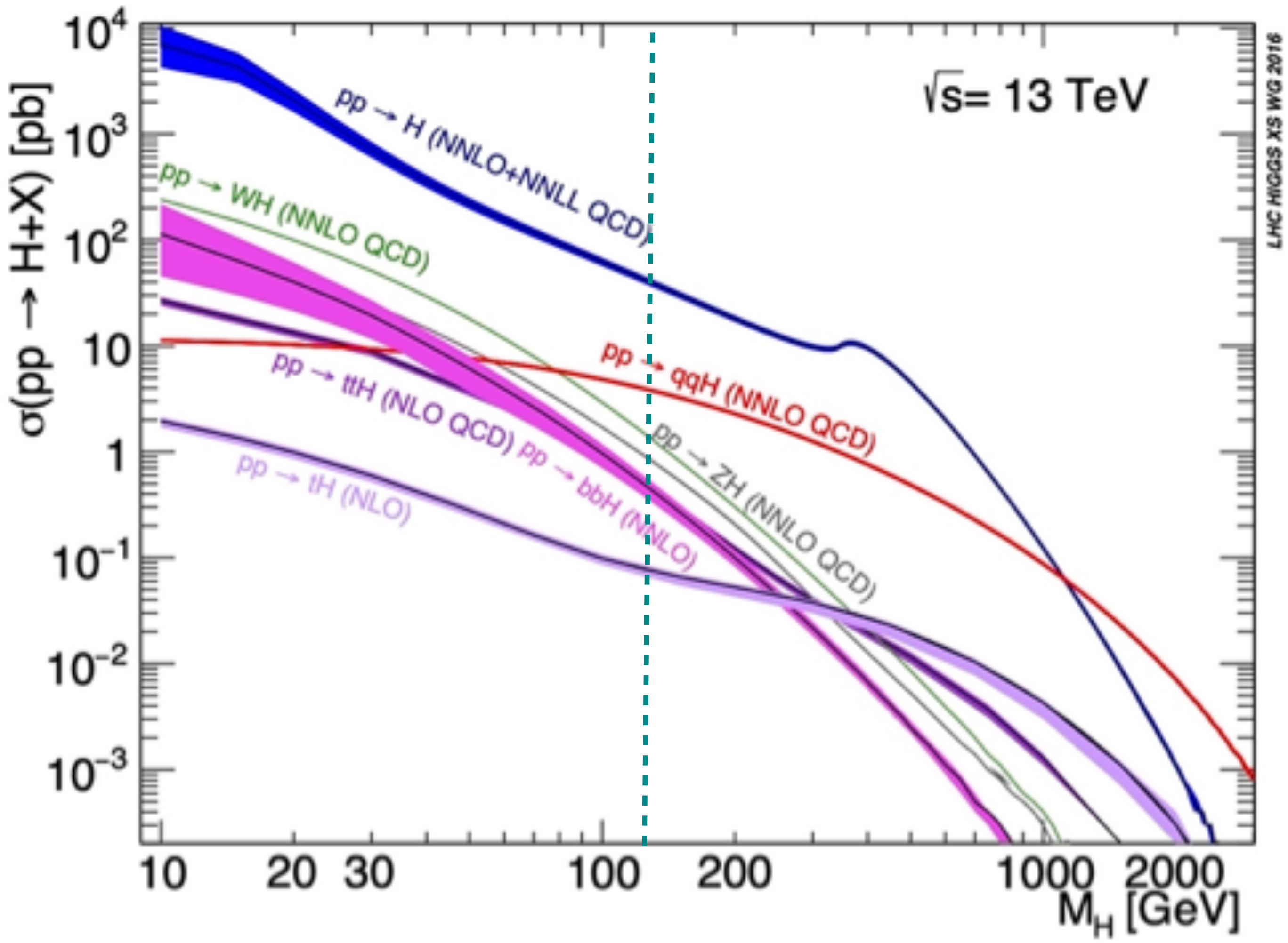
$$\Gamma_{tot} = 4.1\,\mathrm{MeV}$$

→ life time $\tau = 10^{-22}\,\mathrm{s}$

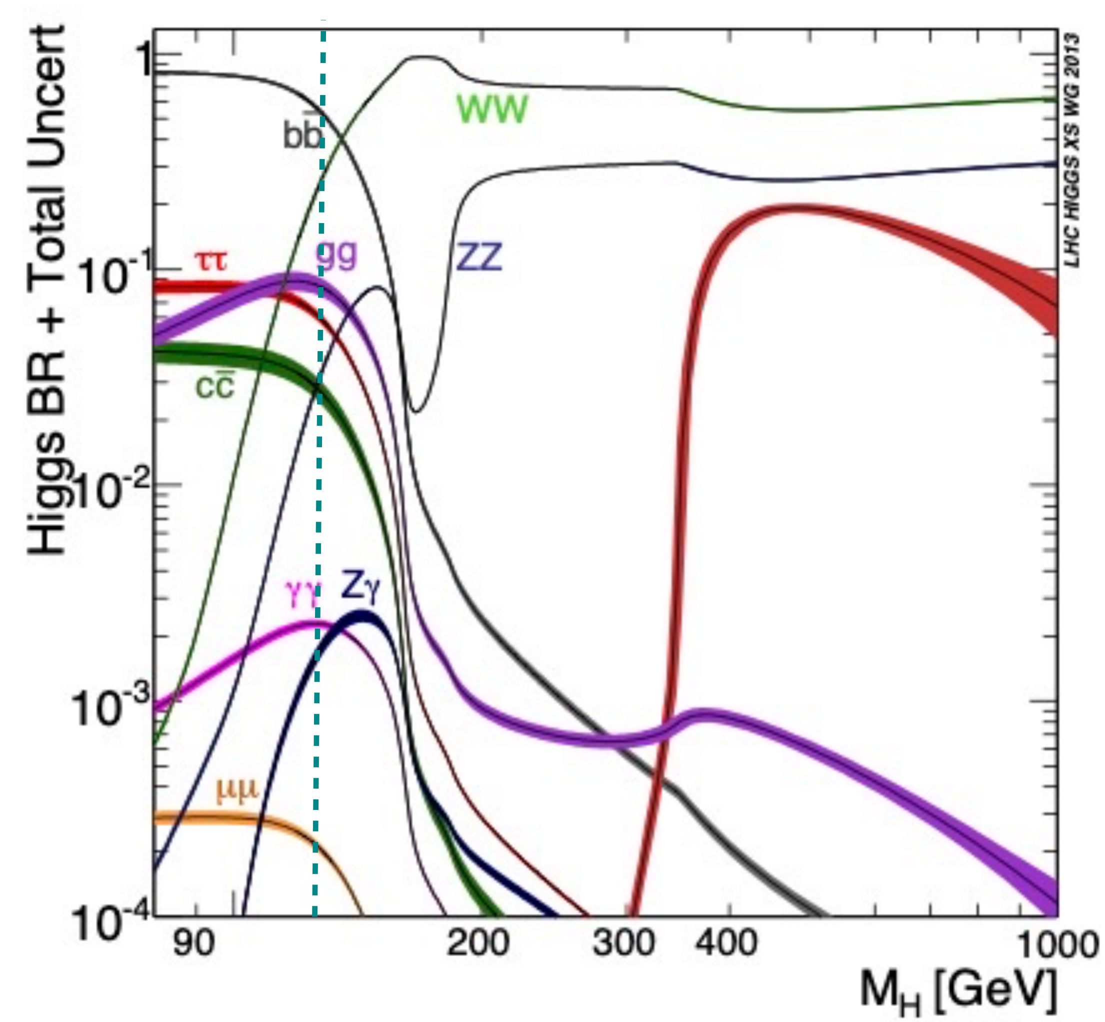
Higgs Production & Decay

In another world (where $m_H \neq 125$ GeV) ...

production cross section



branching ratio



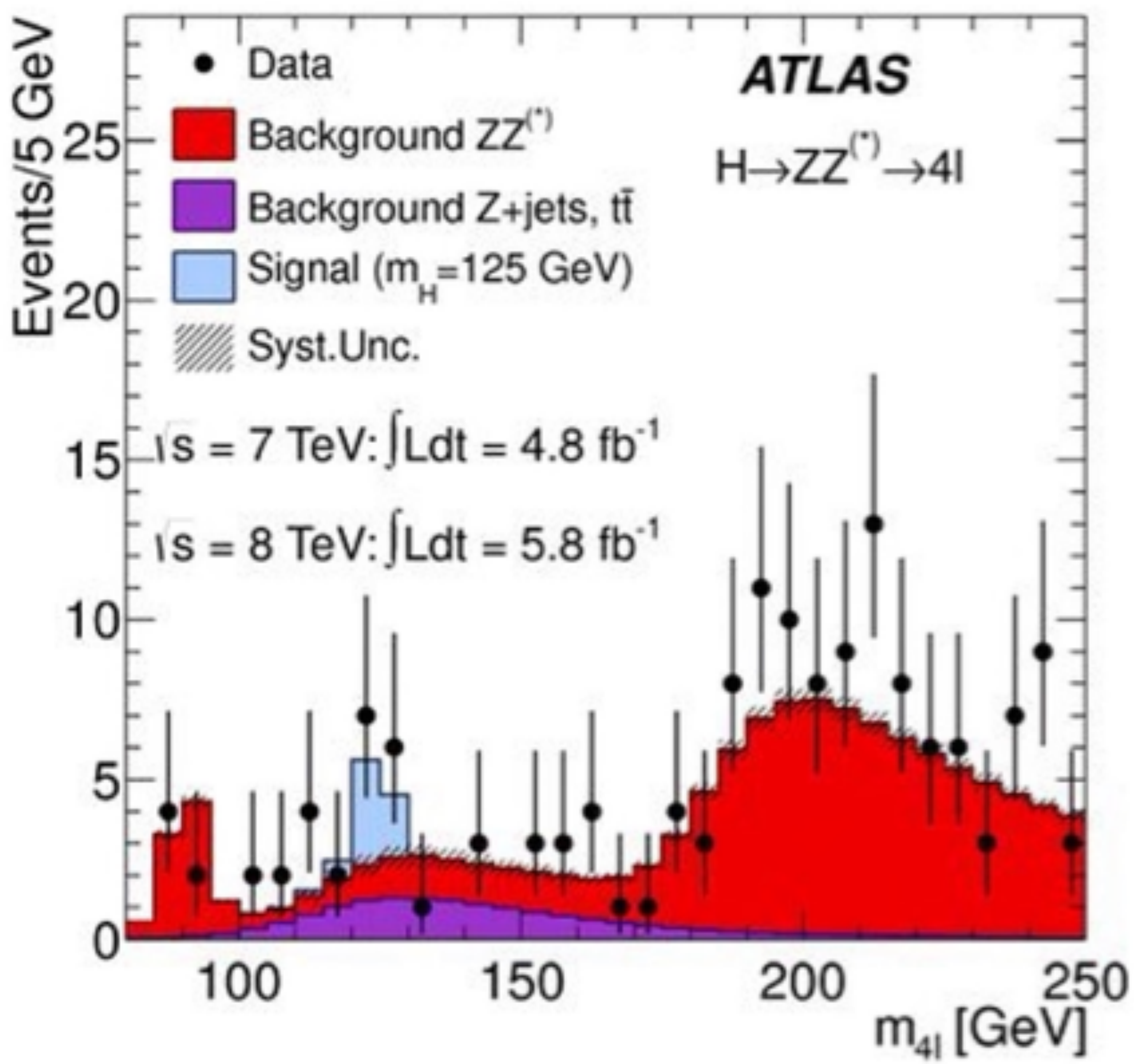
for $m_H = 125$ GeV: large variety of production channels and decay modes relevant!

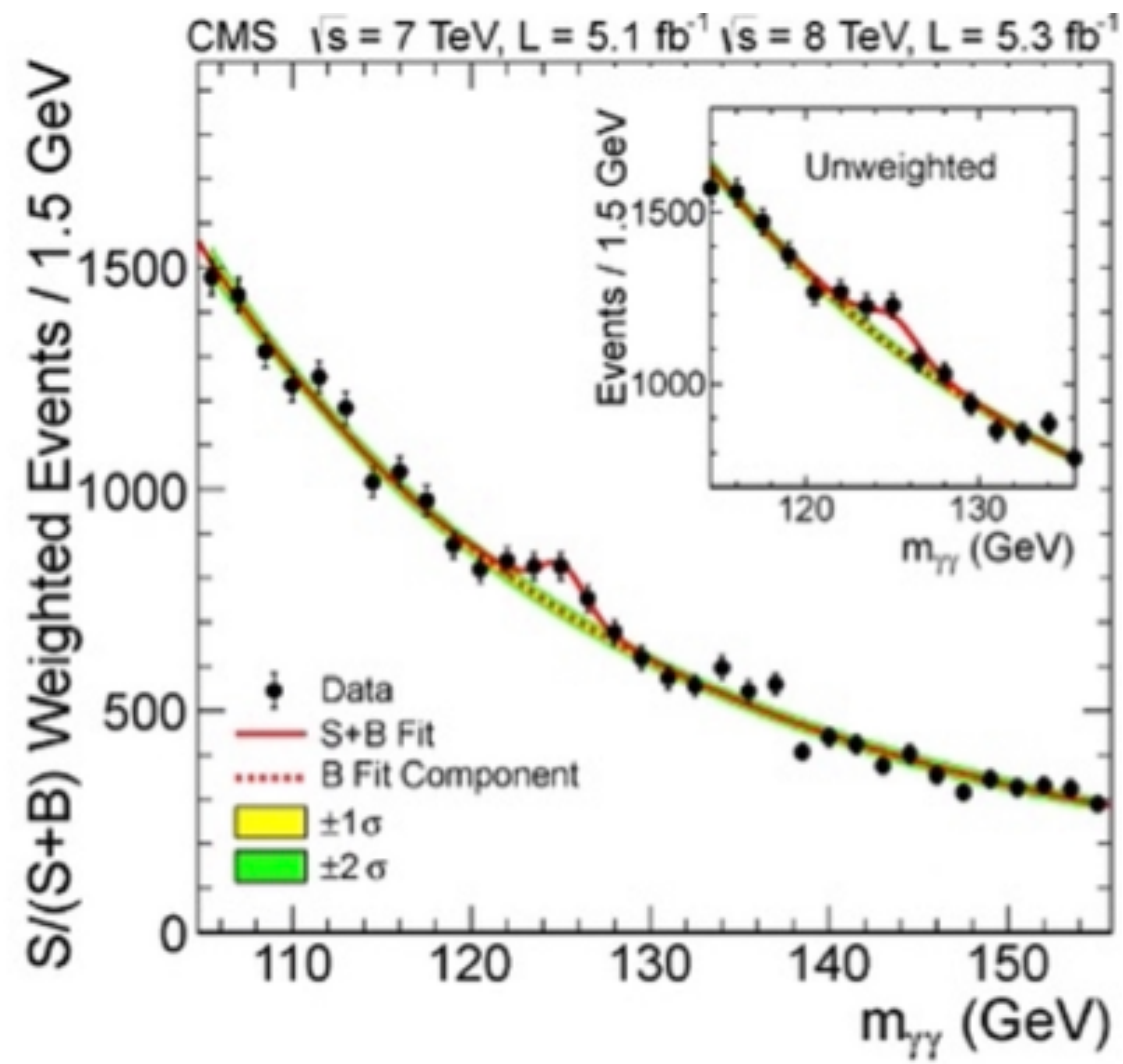
Experimental Results

Higgs Discovery

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ resonance in the m_{4l} $(H \to ZZ^* \to 4l)$ and $m_{\gamma\gamma}$ $(H \to \gamma\gamma)$ spectrum





Higgs Discovery

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ many happy faces ...

Higgs Discovery

Karlsruhe Institute of Technology

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ many happy faces ...

... and a year later:

Nobel Prize awarded to François Englert (*1932) & Peter Higgs (1929-2024)

Higgs Discovery

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

But is this new particle the Higgs Boson?

Need to measure:

- spin
- parity
- couplings to other SM particles

Higgs Discovery

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

But is this new particle the Higgs Boson?

Need to measure:
- spin
- parity
- couplings to other SM particles

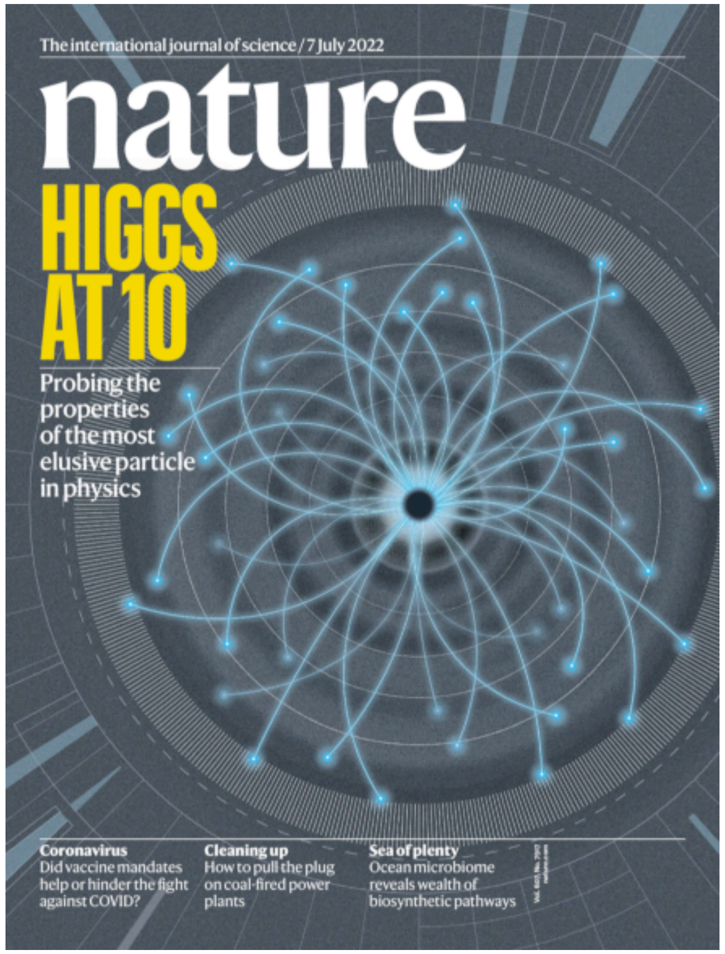
10th anniversary in July 2022

Article

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Article

A portrait of the Higgs boson by the CMS experiment ten years after the discovery



More Higgs Data

LHC Run 3
(2015-1018)

integrated luminosity:
139 fb^{-1}

→ 8M Higgs bosons produced (per exp.)

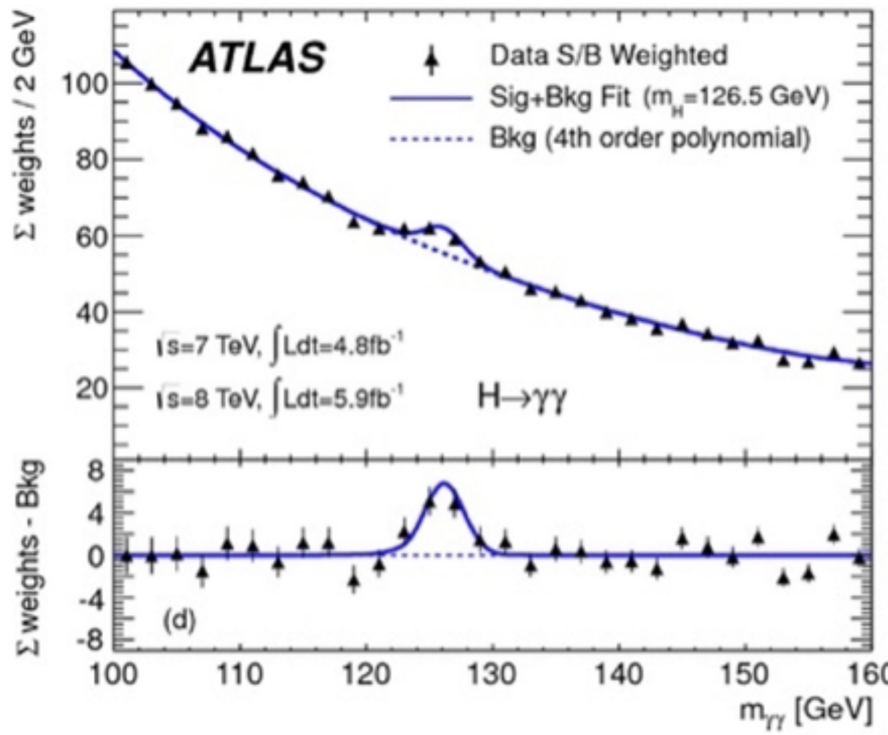
→ 20.000 $H \rightarrow \gamma\gamma$ decays

→ 2.000 $H \rightarrow ZZ^* \rightarrow 4l$ decays

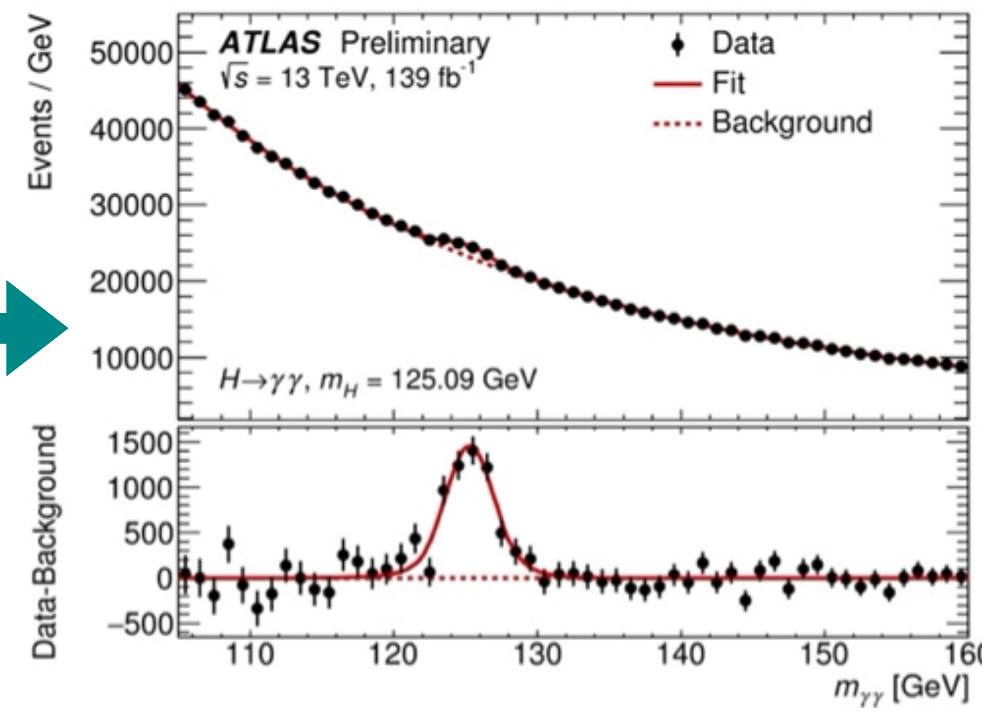
Higgs mass (PDG comb.)

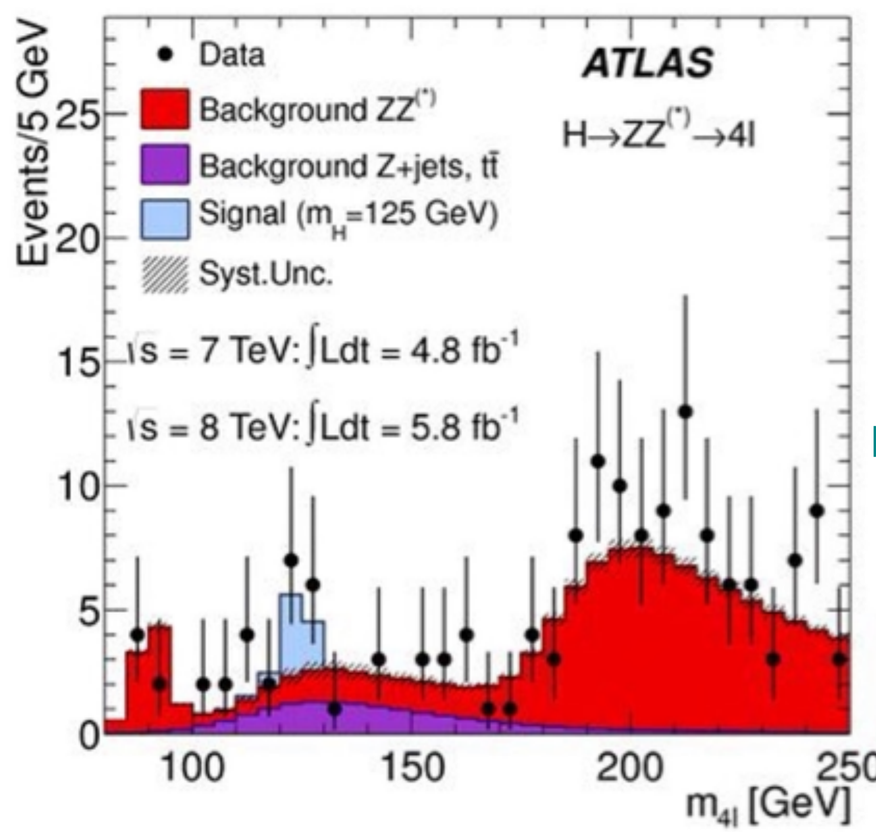
$m_H = 125.25 \pm 0.17\,\text{GeV}$

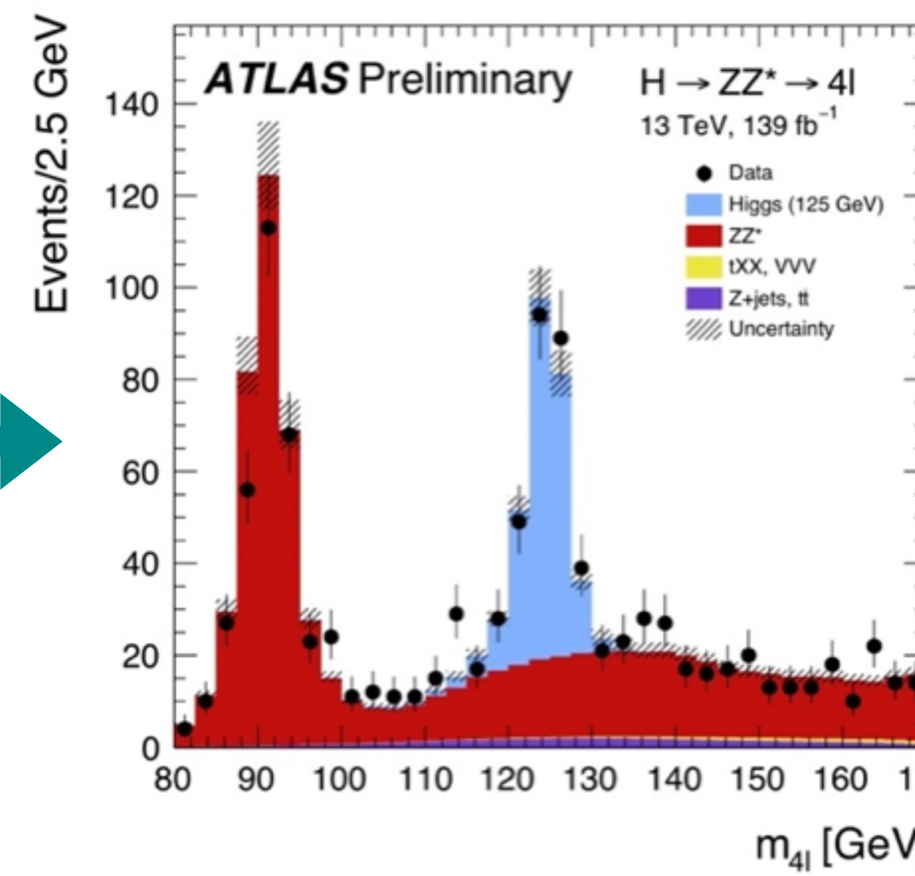
2012:



2022:





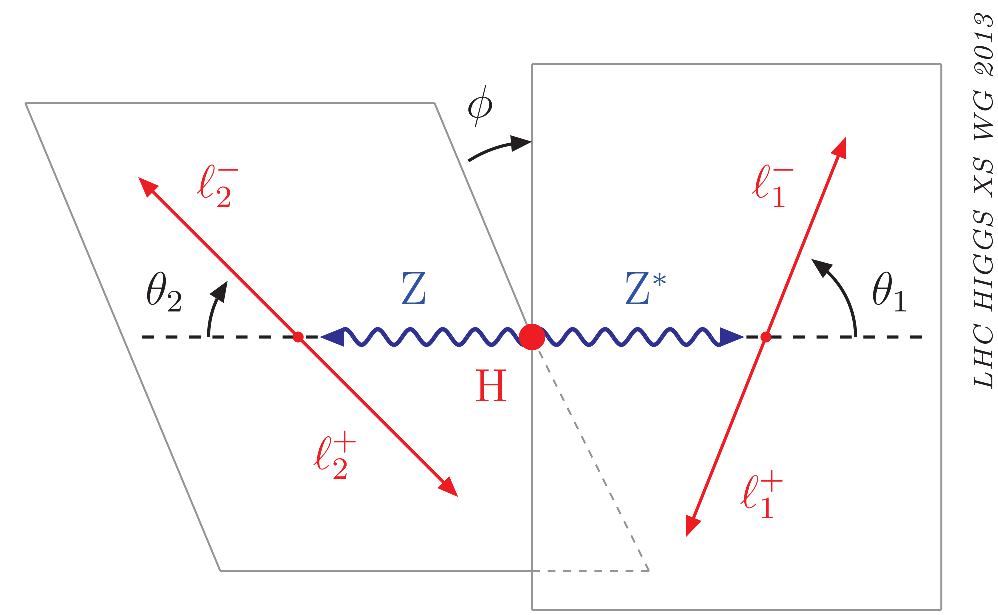


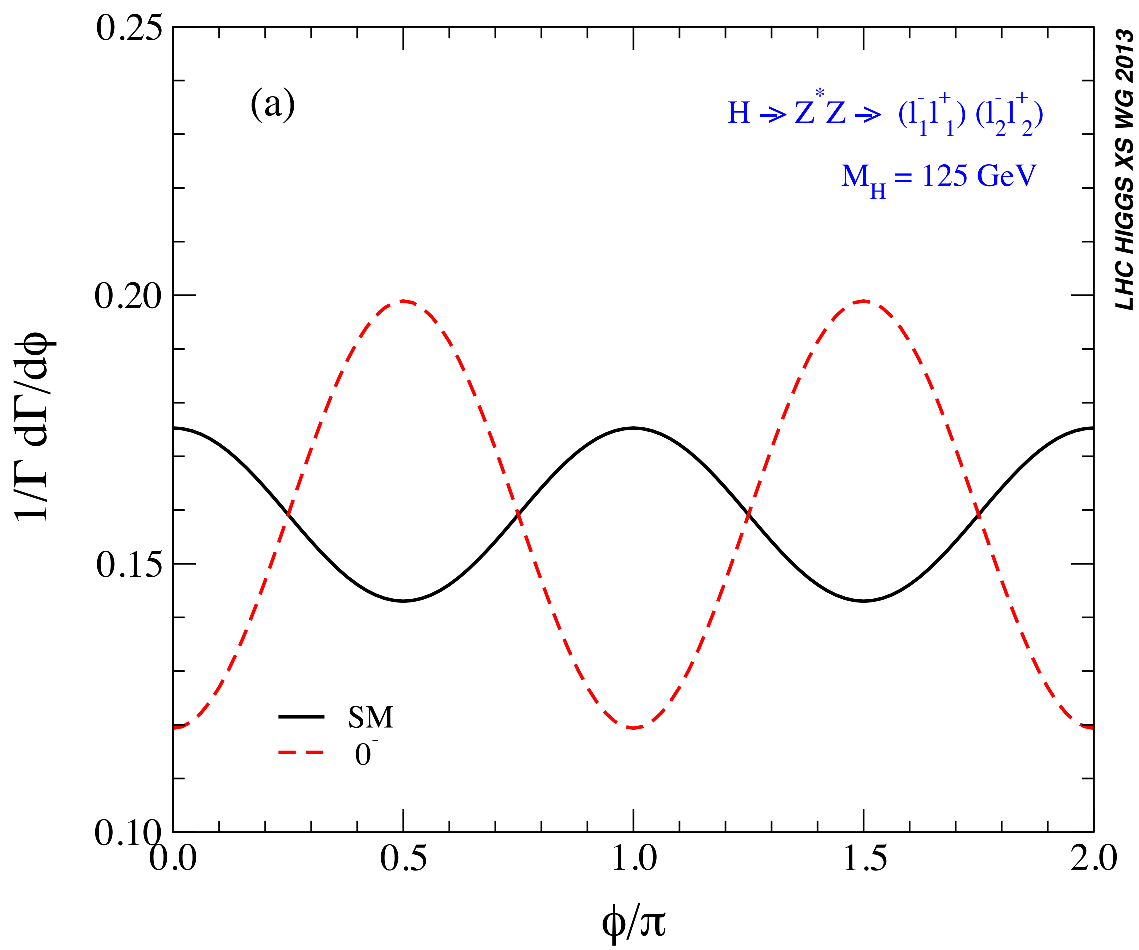
Higgs Spin & Parity

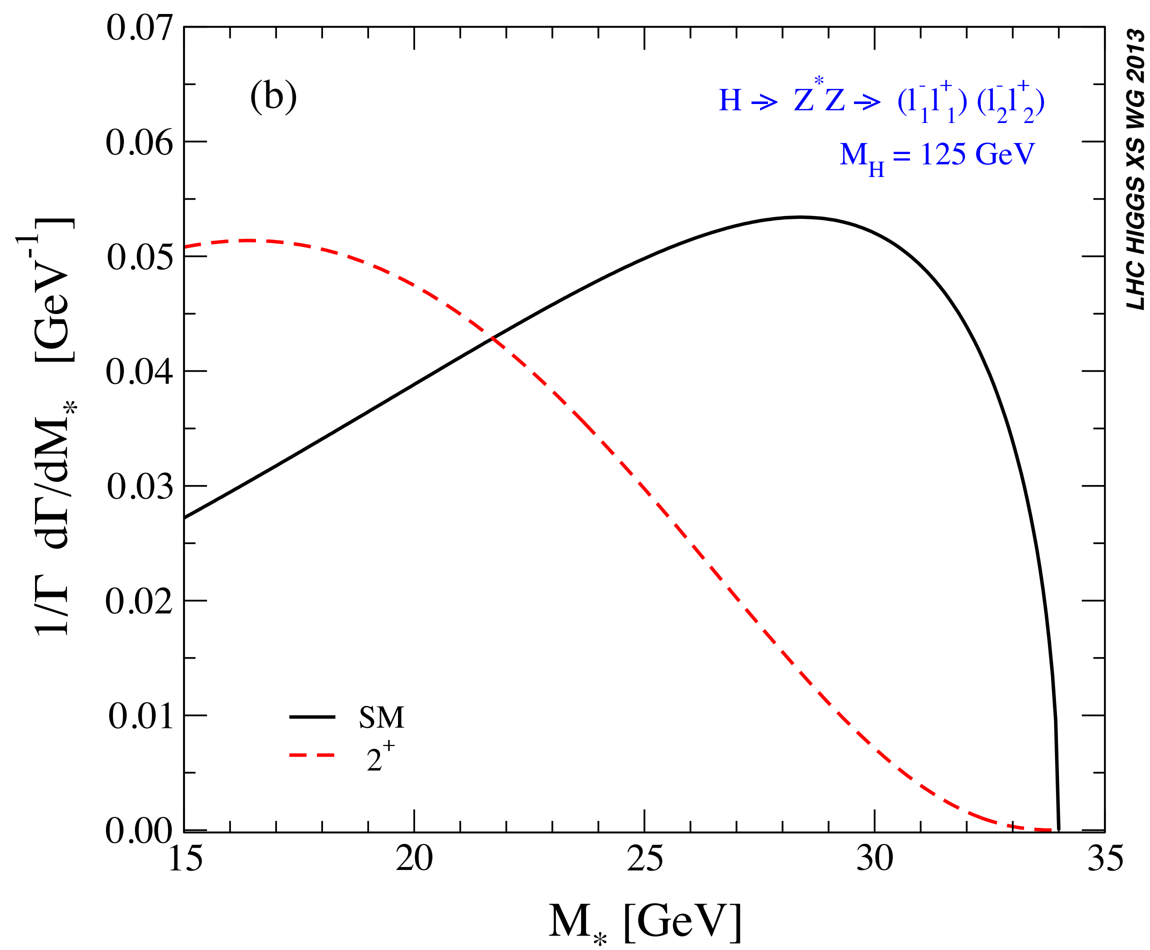
Higgs has spin 0 and is CP-even

confirmed by study of decay distributions in 2013

(spin-1/2 & spin-1 hypothesis already excluded by observation of $H \to \gamma\gamma$ in 2012)





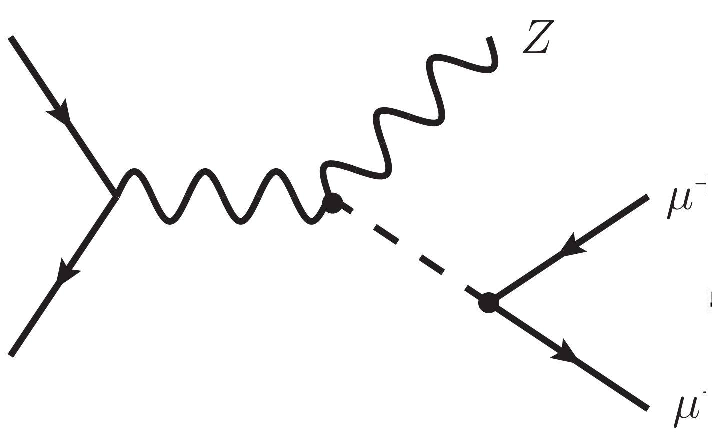


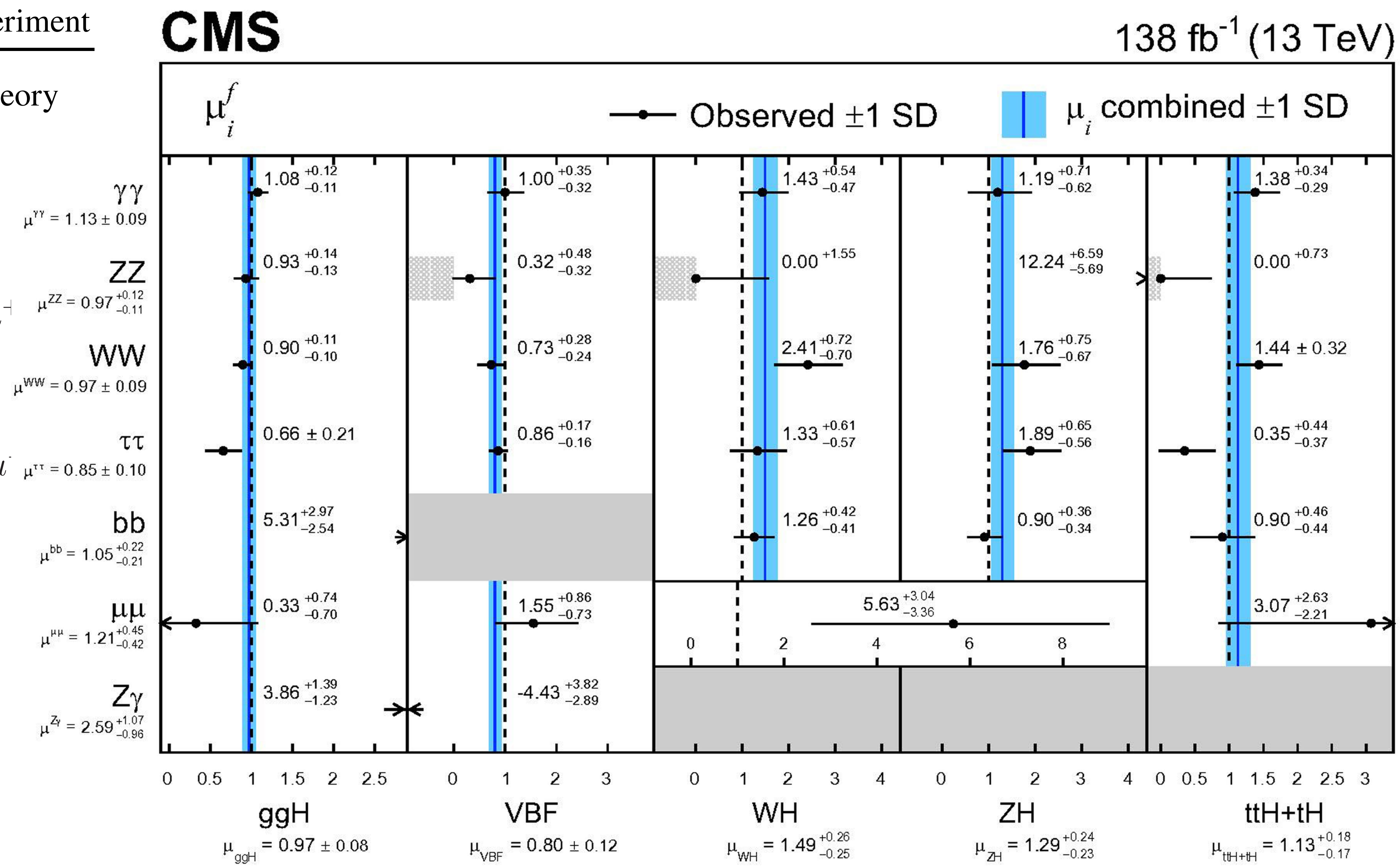
invariant mass of the $Z^* \to ll$ decay

Higgs Couplings

Can measure 'signal strength' for each production & decay channel ...

$$\mu = \frac{\sigma(pp \to H \to XX)_{\text{experiment}}}{\sigma(pp \to H \to XX)_{\text{theory}}}$$





all measurements in good agreement with SM predictions

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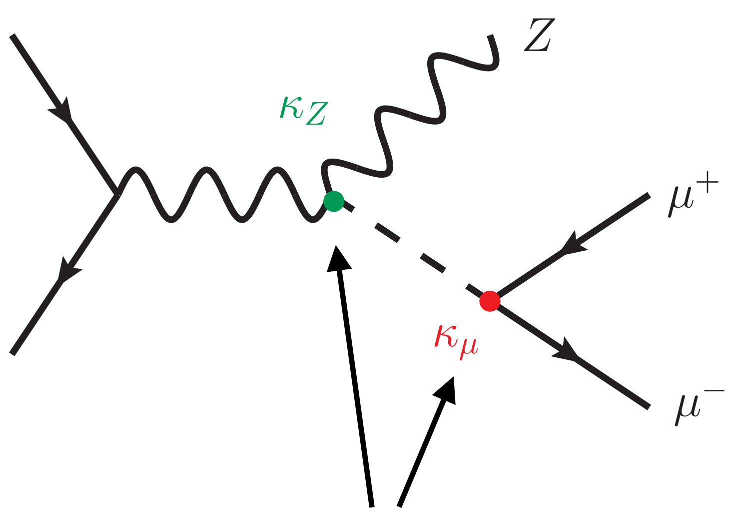
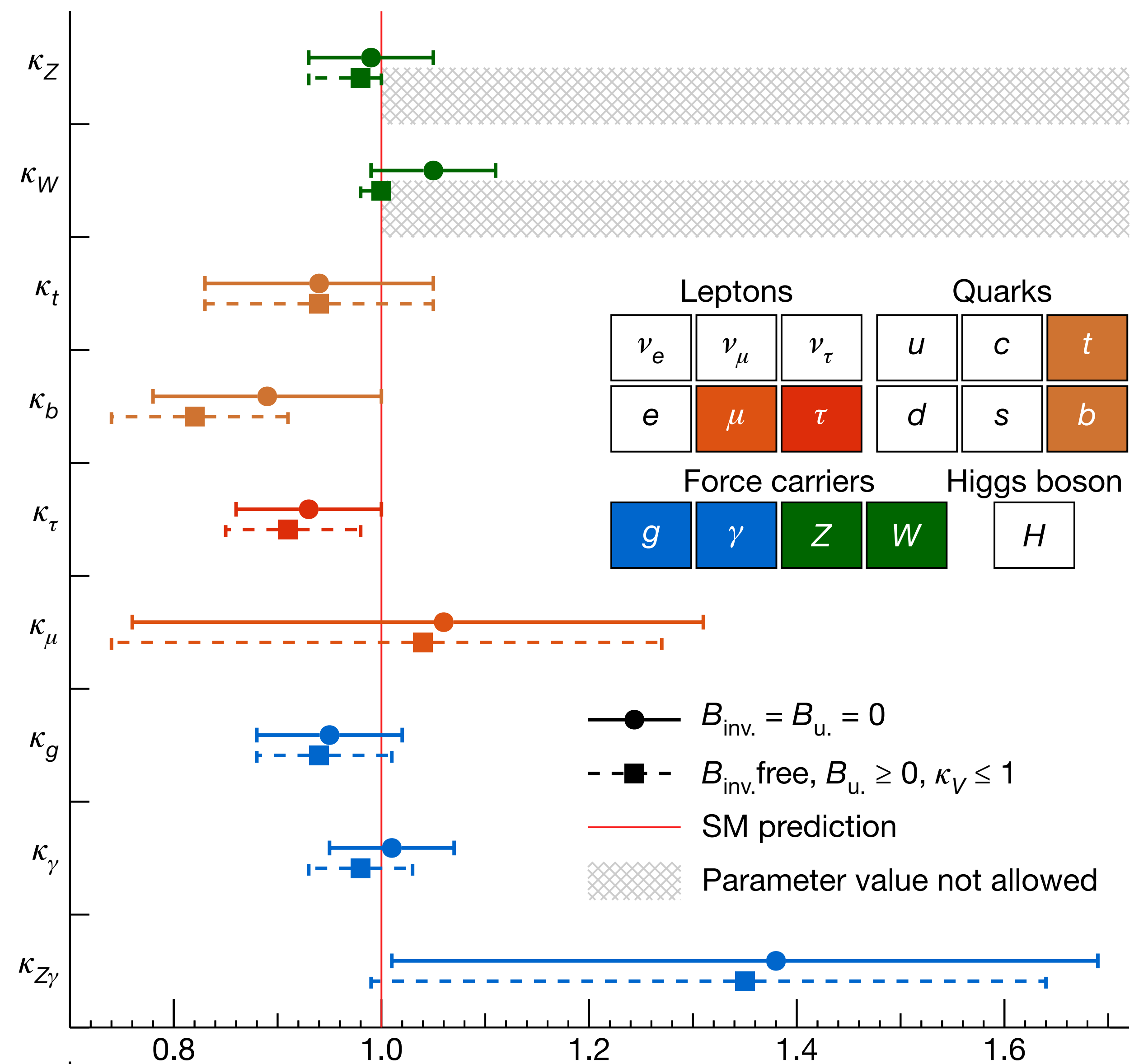
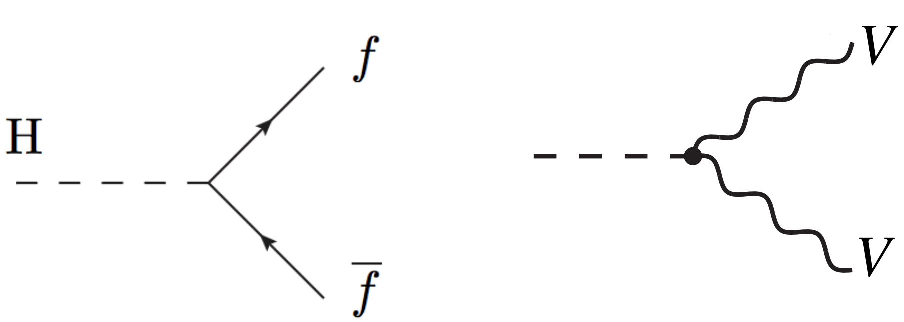


... and extract coupling modifiers $g_{HX} = \kappa_X \cdot g_{HX}^{SM}$



→ test of couplings to SM particles



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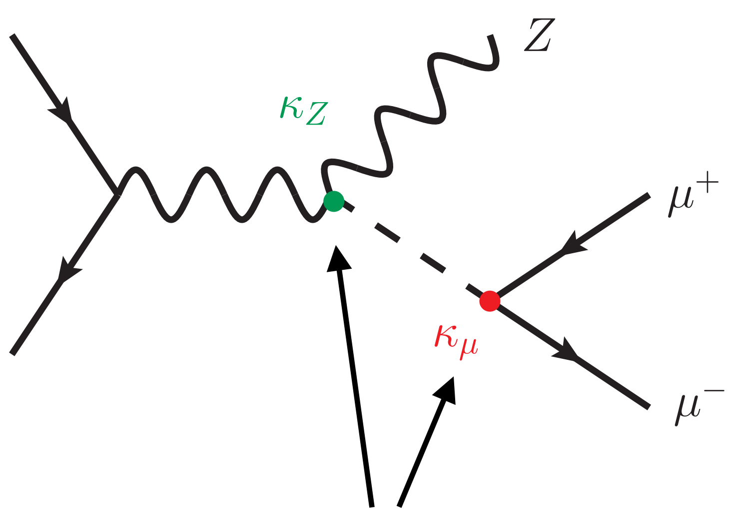

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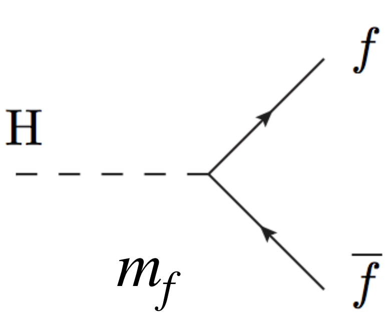
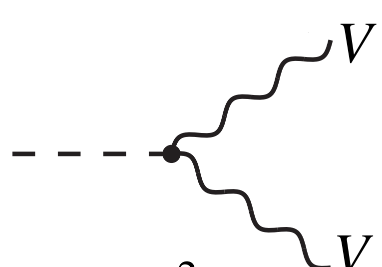
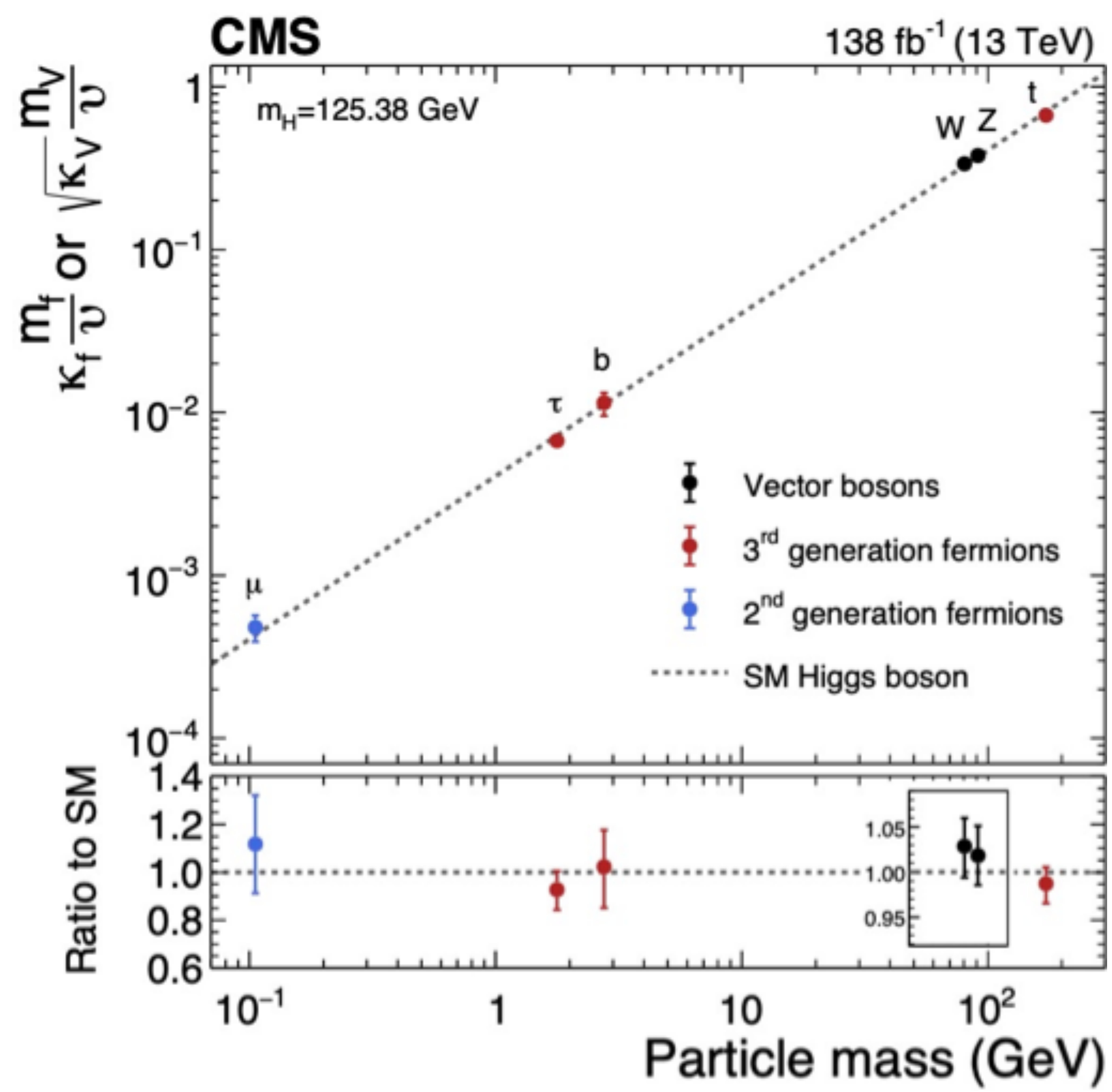


$\frac{m_f}{v}$



$\frac{2m_V^2}{v}$



and confirmation that Higgs couplings determined by particle masses

Probing the Higgs Potential

Back to the question:

Is the particle discovered in 2012 the Higgs Boson?

Need to measure:
- spin
- parity
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$$\mathscr{L}_{\text{Higgs}} = (\partial_\mu \Phi)^+ (\partial^\mu \Phi) + \mu^2 \Phi^+ \Phi - \lambda (\Phi^+ \Phi)^2$$

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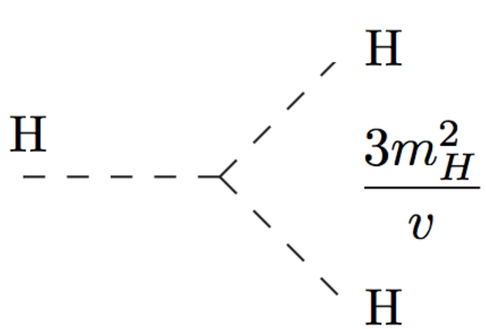
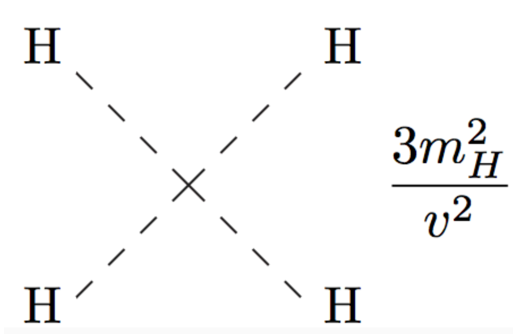
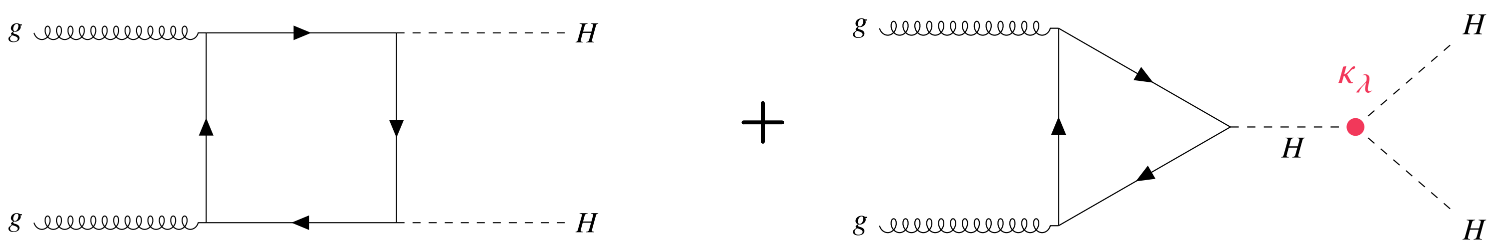
$\rightarrow$ need to measure self interactions of the Higgs boson to probe Higgs potential





Double Higgs Production

Trilinear Higgs coupling can be proved via Double Higgs Production



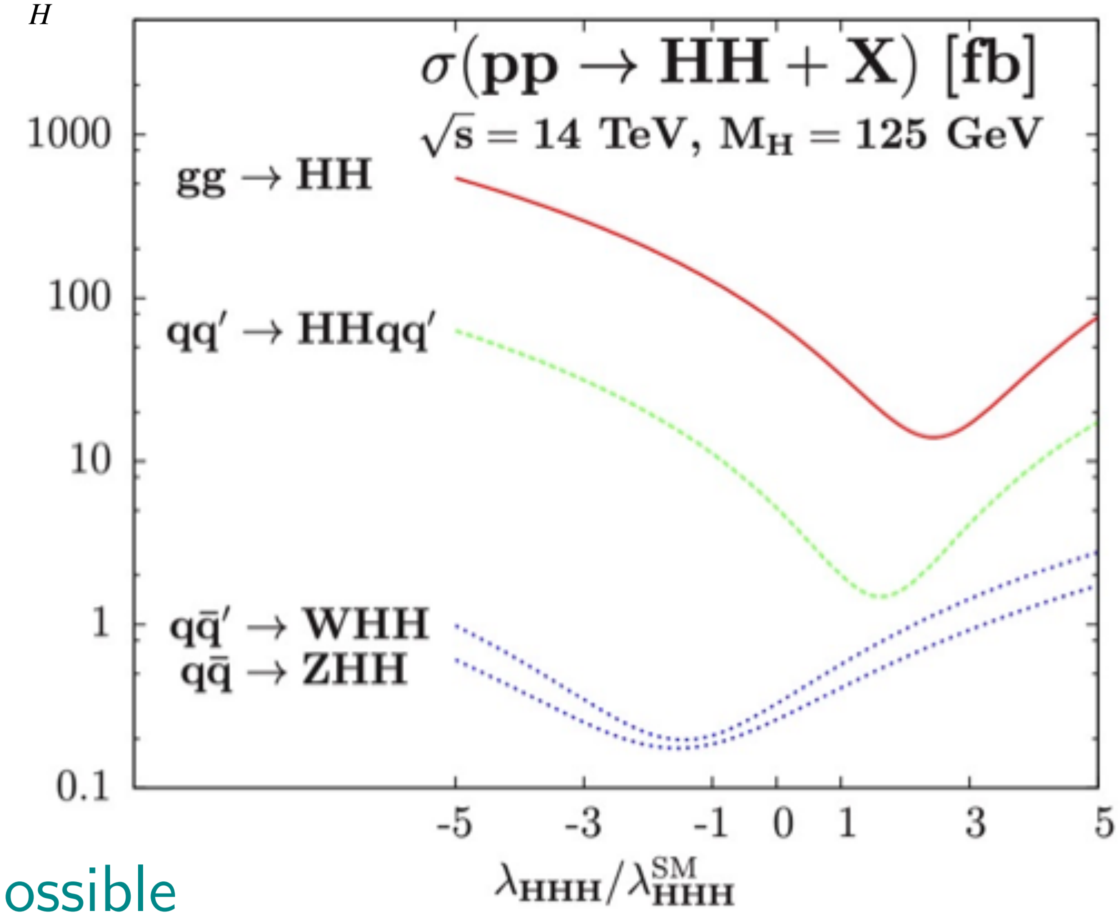
Same production mechanism as single-H production
(gluon fusion, VBF, Higgs strahlung, assoc. production)

but much smaller production cross sections, e.g.

$$\sigma(gg \to H) \approx 52\,\text{pb}$$

$$\sigma(gg \to HH) \approx 0.034\,\text{pb} = 34\,\text{fb}$$

due to
- heavier final state
- destructive interference of box and triangle diagrams



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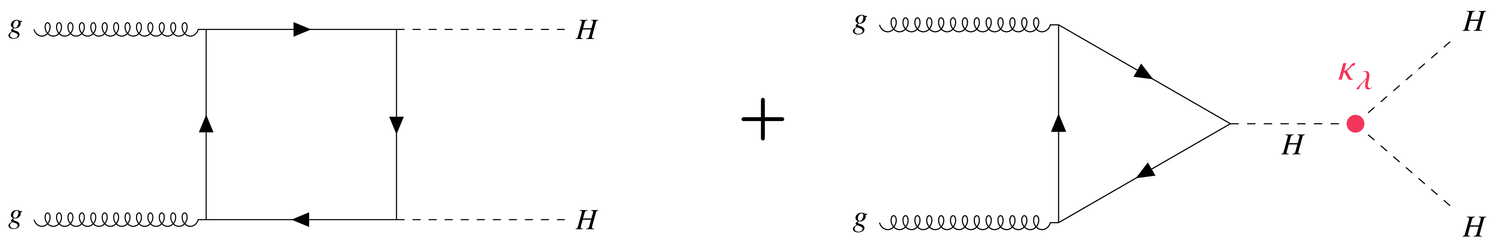

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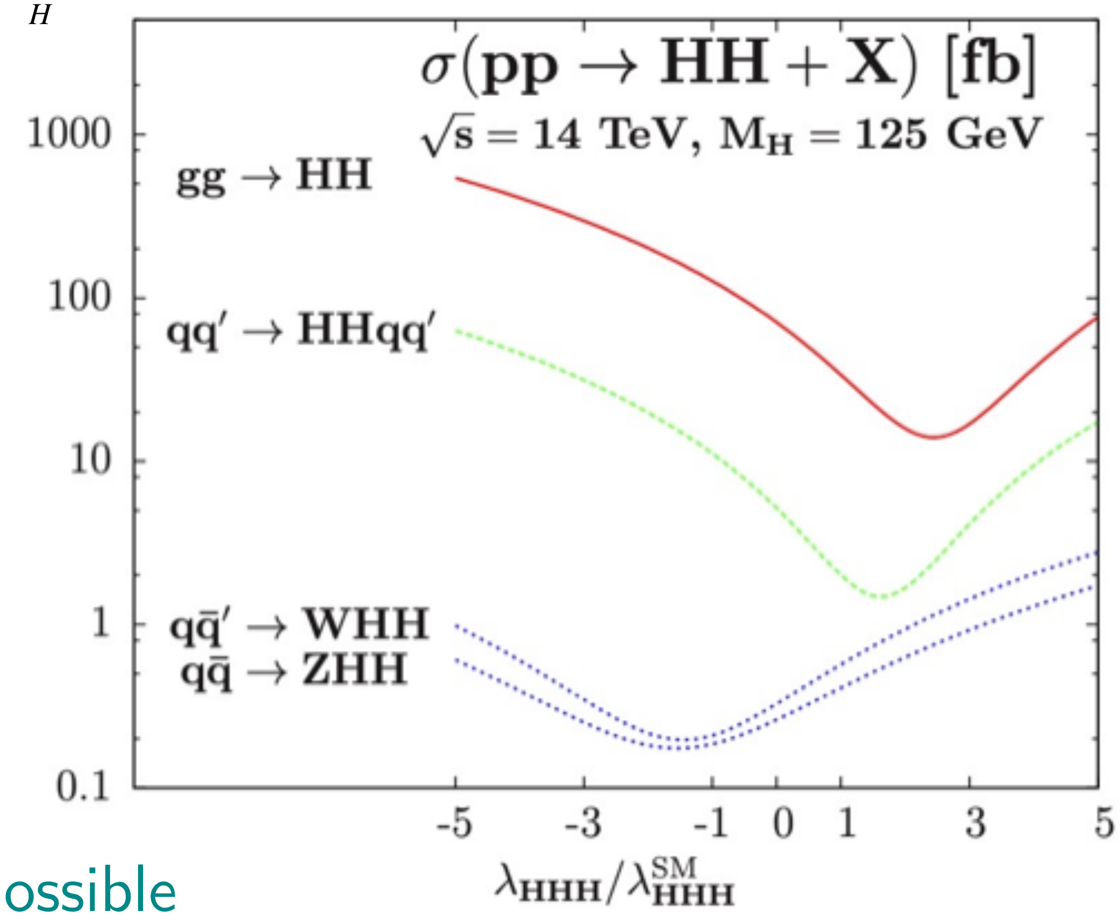
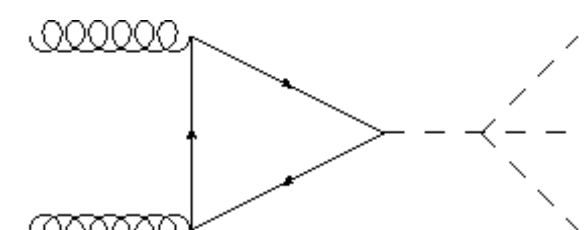


→ study of HH production at LHC challenging, but possible

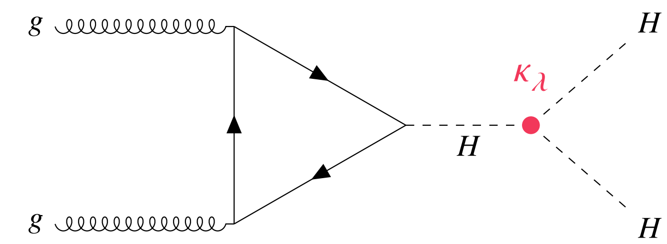
... and what about HHH production to probe quartic coupling?

$$\sigma(gg \to HHH) \approx 0.1\,\mathrm{fb}$$



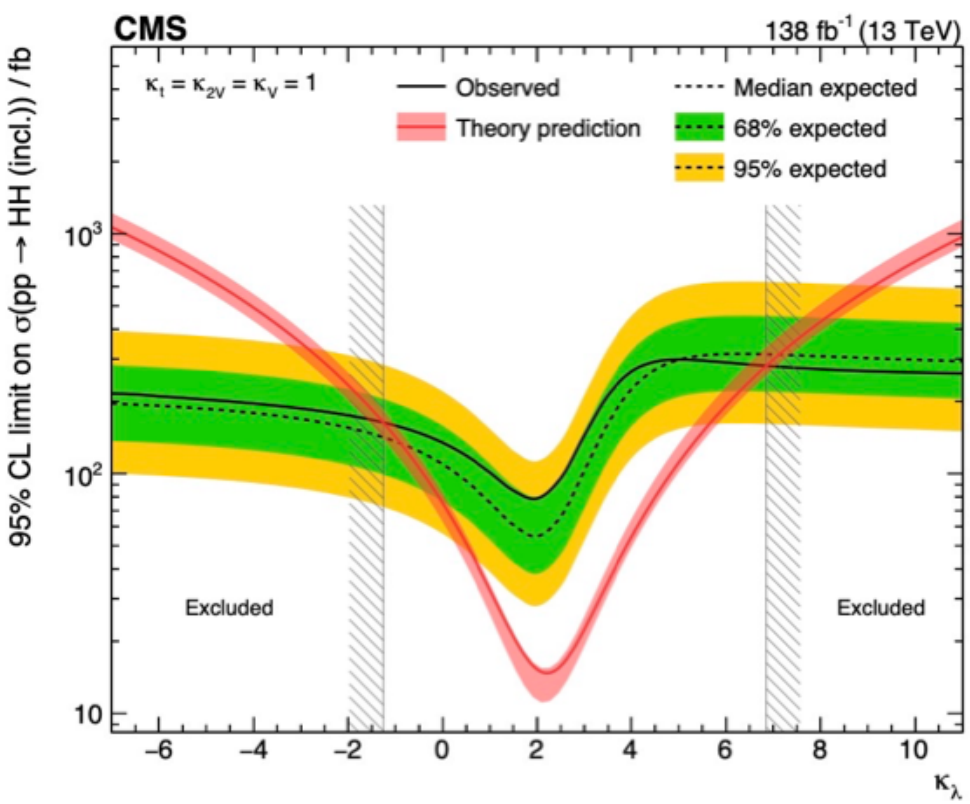
→ unlikely to be observed at LHC (if not enhanced by BSM physics)

Double Higgs Production



Double Higgs production not observed yet,
but limits on coupling modifier κ_λ:

$$-1.24 < \kappa_\lambda < 6.49 \quad \text{(CMS)}$$



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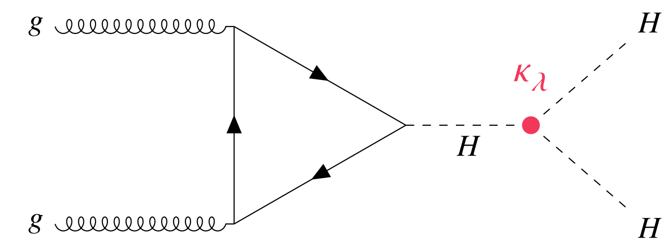

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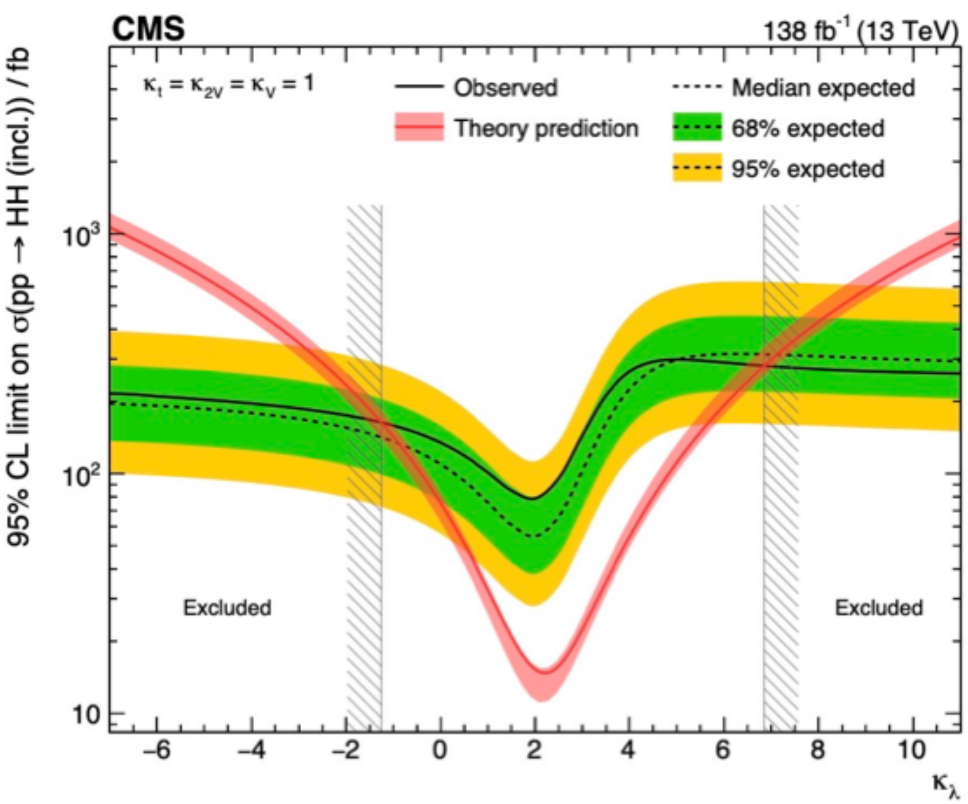
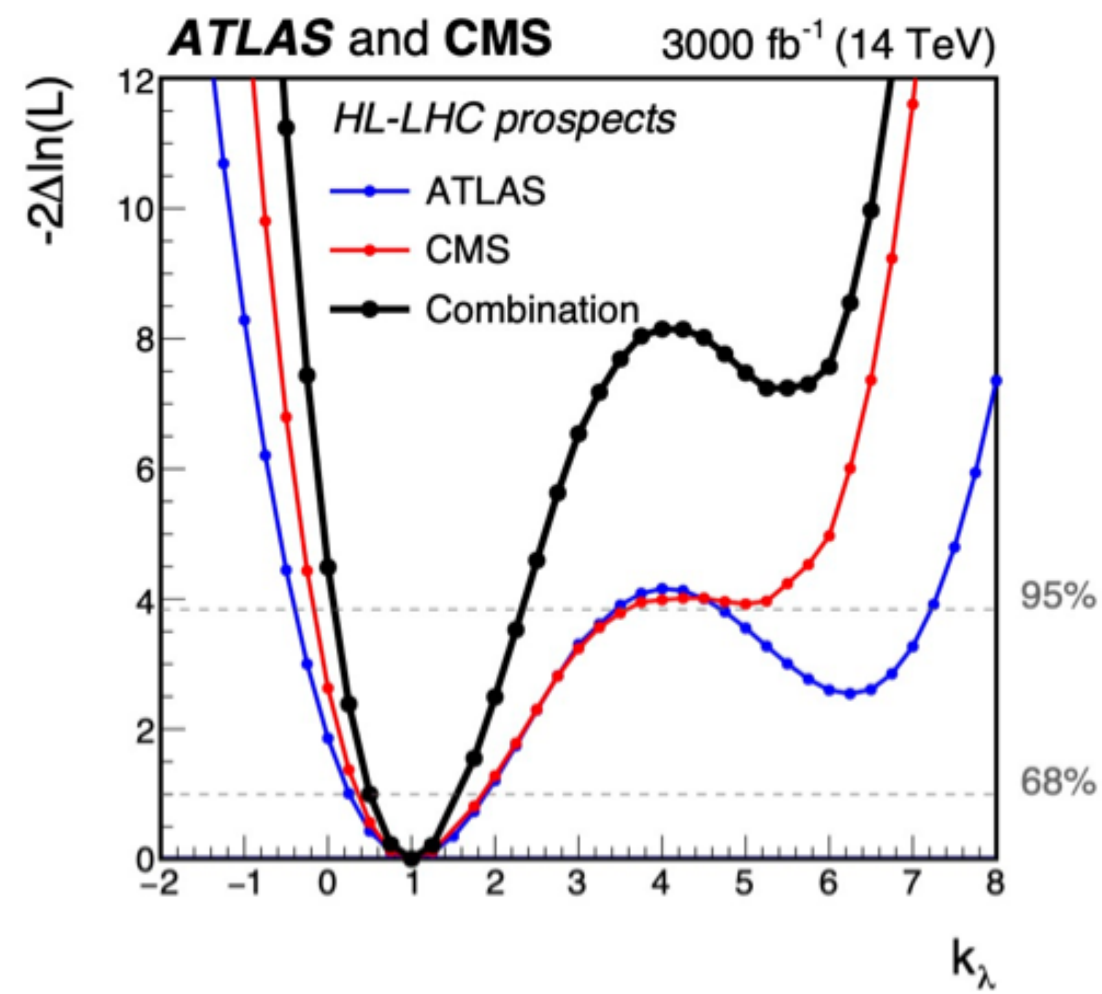


Projections for High-Luminosity LHC:

$0.52 < \kappa_\lambda < 1.5$ $\rightarrow$ can exclude $\kappa_\lambda = 0$



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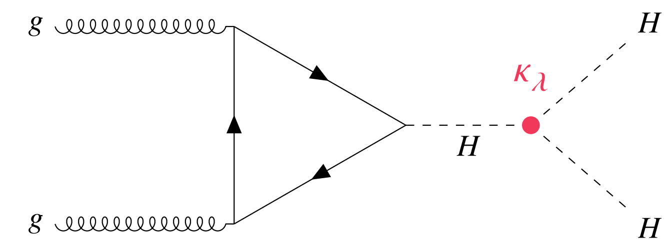

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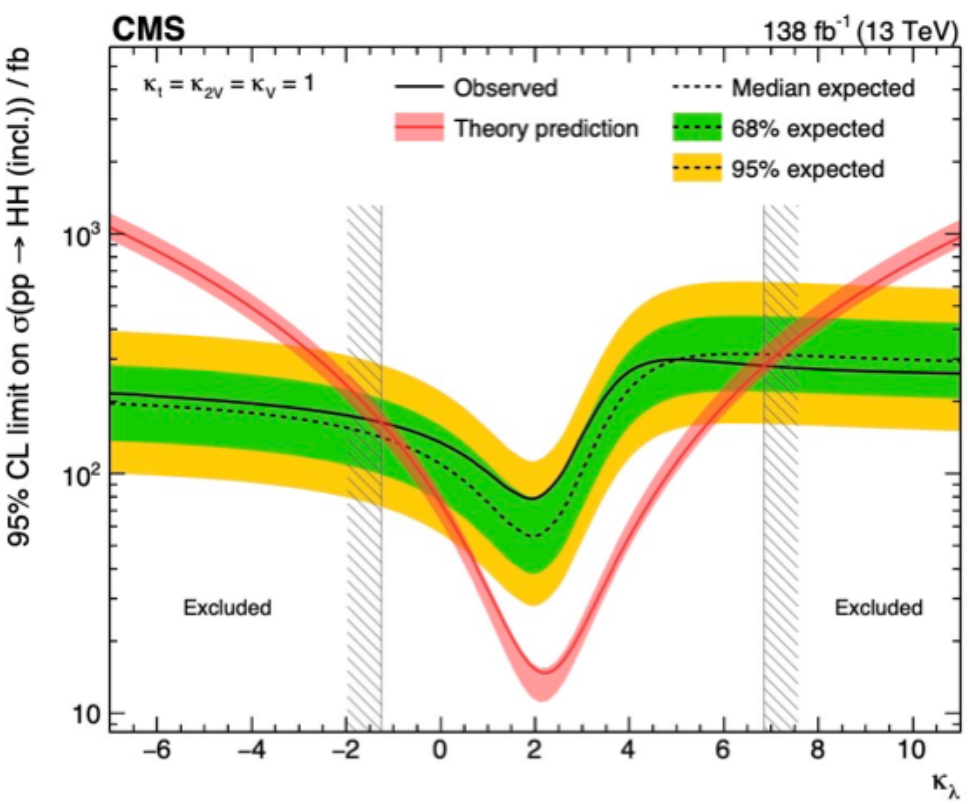

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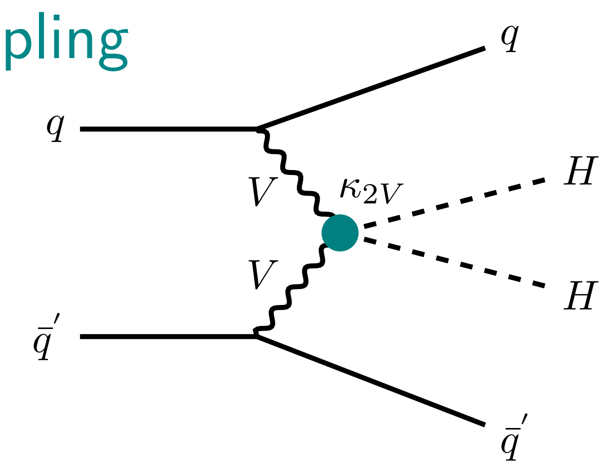
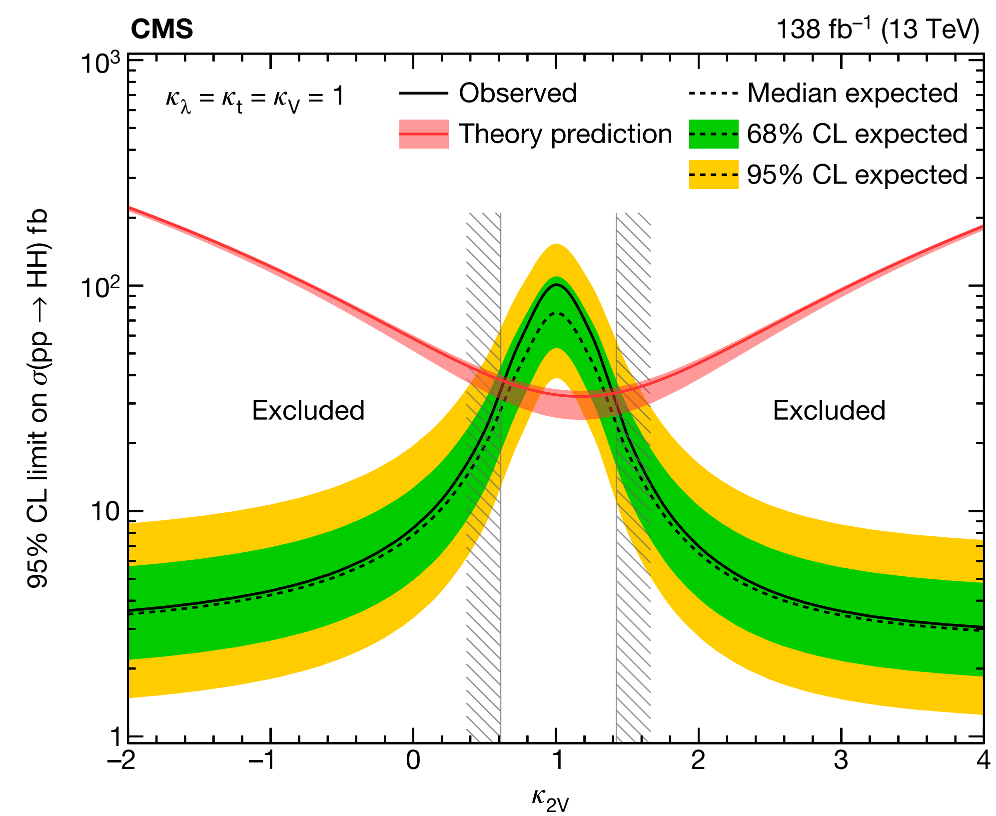
Double Higgs production also sensitive to *HHVV* coupling





$$0.67 < \kappa_{2V} < 1.38 \quad \text{(CMS)}$$

Questions?