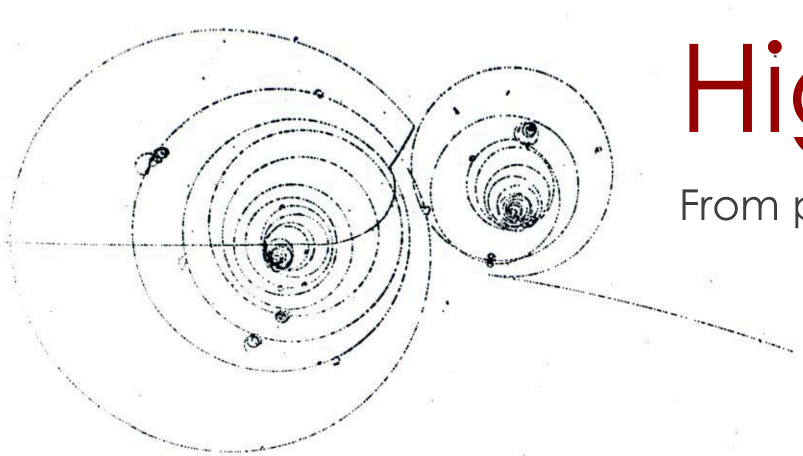
Arthur, Ludo, Michael, Robbie and Sam

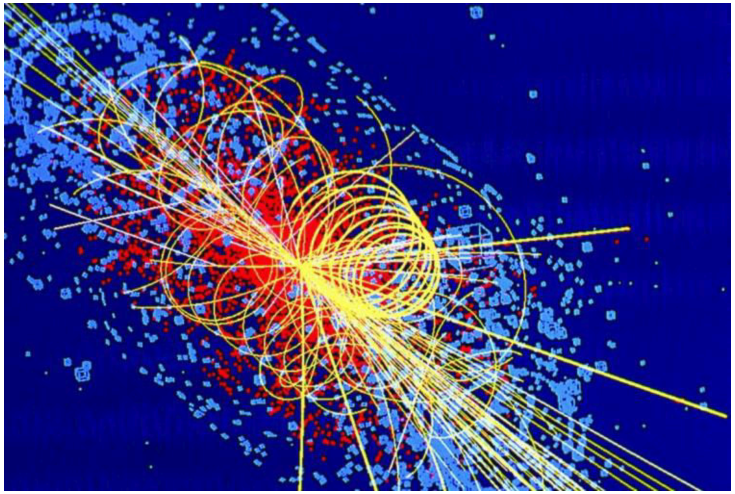
Higgs

From prediction to discovery and beyond



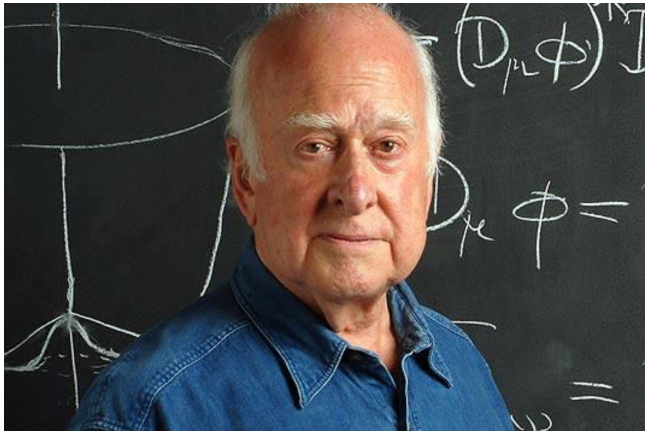
Content

- Theory
- Search for Higgs at LHC
- Experimental verification of Higgs
- Higgs beyond the standard model



Theory

- Electroweak model
- Problems
- Higgs mechanism
- Higgs decay channels



The gauge principle

- QFT framework: inherent redundancy
- Demand: local gauge invariance
- Led to QED

QED

- Dirac Lagrangian

$$L_{Dirac} = \overline{\psi}(i\not{\partial} - m)\psi$$

Euler Lagrange

- Dirac Equation

$$\left(i\not{\partial} - m\right)\psi = 0$$

QED

$$L_{Dirac} = \overline{\psi}(i\not{\partial} - m)\psi$$

- Demand invariance of Lagrangian under the local U(1) rotation

$$\psi(x) \rightarrow e^{iea(x)}\psi(x)$$

- Introduce covariant derivative

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} + eA^{\mu}(x)$$

- With the field A_{μ} , which transforms as:

$$A^{\mu} \rightarrow A^{\mu}{}' = A^{\mu} - \frac{1}{e}\partial_{\mu}\alpha(x)$$

QED

$$L_{Dirac} = \overline{\psi}(i\not{\partial} - m)\psi$$

- Minimal substitution leads to local gauge invariant (interacting) theory:

$$L_{Dirac} = L_{freeDirac} + L_{interaction}$$

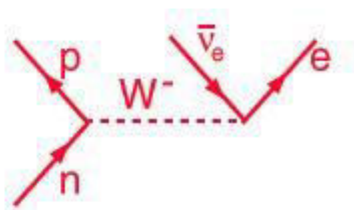
$$L_{Dirac} = \overline{\psi}\left(i\not{D} - m\right)\psi$$
$$= \overline{\psi}\left(i\not{\partial} - m\right)\psi + e\overline{\psi}\gamma_{\mu}A^{\mu}(x)\psi$$

Introducing the electroweak model

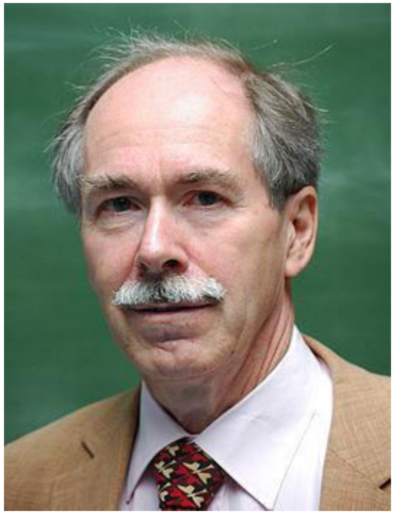
Main Ingredients:

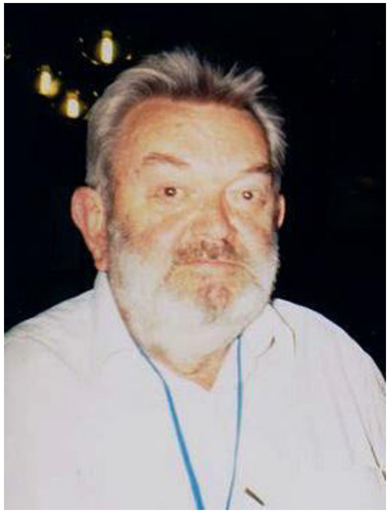
- Local (non-abelian) gauge invariance
- Renormalizability (puts restrictions on the possible terms in Lagrangian)
- Spontaneous symmetry breaking

Electromagnetic



Weak





Massless electroweak model

$SU(2)_L \times U(1)_Y$

- Weak interaction on LH doublets (maximal violation of parity).
- Fermionic content:

$$\psi_L = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}_L \qquad \psi_R$$

- Action of SU(2) and U(1):

$$\psi_L \xrightarrow{SU(2)_L \times U(1)_Y} e^{i\vec{\beta}\cdot\vec{T}} e^{i\alpha Y} \psi_L$$

$$\psi_R \xrightarrow{SU(2)_L \times U(1)_Y} 1 \cdot e^{i\alpha Y} \psi_R$$

From global to local SU(2)xU(1)

- For each symmetry generator of the gauge group, a gauge fields to construct a covariant derivative is introduced:

- For doublets (L): $\partial_\mu \rightarrow D_\mu = \partial_\mu - W_\mu + B_\mu$

- For singlets (R): $\partial_\mu \rightarrow \nabla_\mu = \partial_\mu + B_\mu$

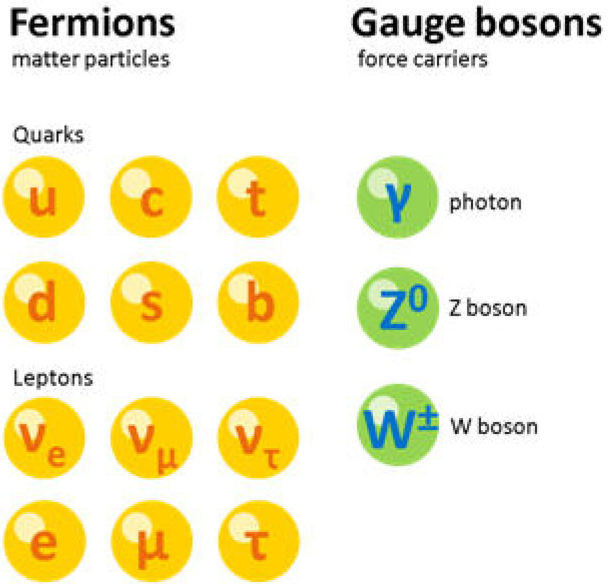
Electroweak Lagrangian

- Minimal substitution in free electroweak theory:

$$L_{EW} = \bar{\psi}_L \not{D}_\mu \psi_L + \bar{\psi}_R \not{\nabla}_\mu \psi_R$$

- Kinetic gauge terms:

$$L_{kinetic} = -\tfrac{1}{4} W_a^{\mu\nu} W_{\mu\nu}^a - \tfrac{1}{4} B^{\mu\nu} B_{\mu\nu}$$



Two main problems

- Mass terms lead to explicit breaking of symmetry:
- Fermion mass -> global (thus local) gauge variance
- Gauge boson mass -> Non-renormalizability +global gauge variance

Problems with SM

- Fermion mass term:

$$m\bar{\psi}\psi = m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$$

$$\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R \rightarrow$$

$$(\bar{\psi}_R e^{-i\beta Y})(e^{i\vec{\alpha}\cdot\vec{T}} e^{i\beta Y}\psi_L) + (\bar{\psi}_L e^{-i\beta Y} e^{-i\vec{\alpha}\cdot\vec{T}})(e^{i\beta Y}\psi_R)$$

- Gauge boson mass term:

$$m\vec{W}_\mu \cdot \vec{W}^\mu + mB^\mu B_\mu$$

$$W_\mu^a \rightarrow W_\mu^a + g\varepsilon_{abc}W_\mu^b\alpha^c + \partial_\mu\alpha^a$$

$$B_\mu \rightarrow B_\mu + \partial_\mu\beta$$

Non-renormalizability

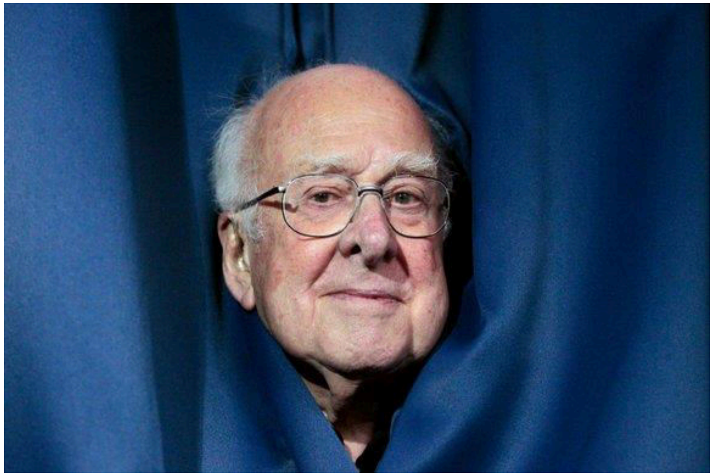
- Interatctions of longitudinal polarizations of W bosons lead to divergences
- Divergence soothened by exchange of Higgs boson

Solution of problems

Spontaneous symmetry breaking

- Spontaneous = ground state is not invariant under (gauge) symmetry of theory
- Hidden gauge symmetry in stead of broken gauge symmetry

$$\phi(x) = v + h(x)$$



Goldstones

- Global spontaneously broken symmetries lead to the appearance of massless goldstone bosons
- Local broken symmetries give massless gauge bosons mass. The massless gauge bosons ‘eat’ the massless goldstones to provide for the missing degree of freedom.

Global breakdown

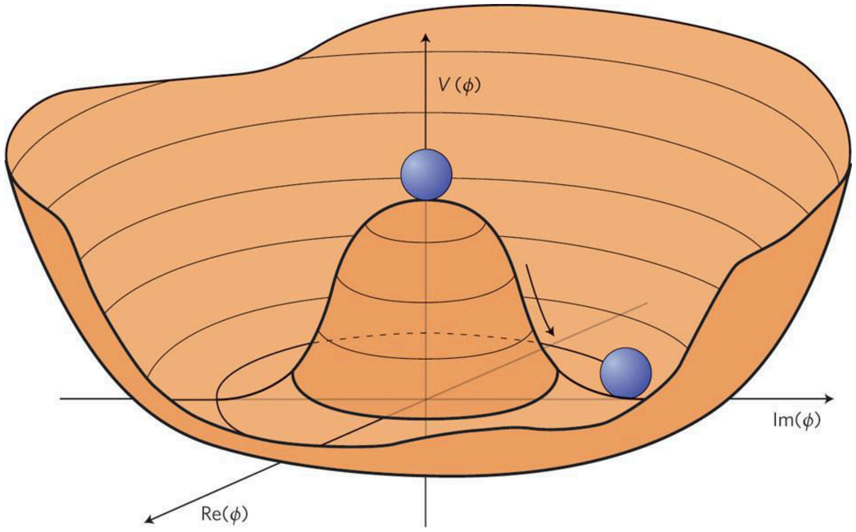
- Start with theory of a complex scalar

$$L = \partial_\mu \phi \partial_\mu \phi^* - V(|\phi|)$$

- Assume the complex scalar has non zero vev (potential has a global minimum at the non-zero expectation value)

$$<|\phi|> = a \quad \text{with} \quad V(a) = 0$$

- Famous mexican hat potential



Global breakdown

- Naturally expanding

$$\phi(x) = a + \eta_1(x) + i\eta_2(x)$$

- This leads to a lagrangian with a massive η_1 and massless η_2
- Goldstone not observed in nature!

Abelian Higgs model

- Consider a charged scalar minimally coupled to an abelian gauge field:

$$L = D_\mu \phi D_\mu \phi^* - V(|\phi|)$$

- Assume the complex scalar has non zero vev (potential has a global minimum at the non-zero expectation value)

- Local U(1) invariance can be used to make ϕ real (unitary gauge) :

$$\phi^*(x) = \phi(x)$$

- Massless goldstone is 'eaten' by gauge field

Abelian Higgs model

- Spontaneous breaking: $<\phi>=v \text{ with } V(v)=0$
- To analyze the particle spectrum of the theory, it is natural to redefine our field:

$$\phi(x)=v+h(x)$$

- Expanding Lagrangian leads to:

$$L_{U(1)+higgs}=D_\mu\phi D_\mu\phi^* - V(\phi)$$

$$=\ldots+(\partial_\mu+B_\mu)(v+h)(\partial_\mu+B_\mu)(v+h)-V(v+h)$$

Conclusion

- Massless goldstone is eaten and the massless goldstone has been eaten by the Higgs
- Coupling scalar to gauge fields with non-zero vev, we can create massive gauge bosons, while respecting gauge symmetries of theory.

Massive electroweak sector

- Analogous to Abelian Higgs model now the Higgs SU(2) doublet couples to an abelian field

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} 0 \\ v + h \end{pmatrix} \qquad L = D_\mu \Phi \, D_\mu \Phi^* - V(|\Phi|)$$

- Use SU(2) gauge freedom to gauge in one direction of 4-space.

  3 goldstones dissappear from doublet, but reappear as parameters of rotated (gauged) gauge fields.

- Higgs doublet transforms sunder SU(2)xU(1) in order to make fermion mass terms invariant as we will see later

Degrees of freedom

- Degrees of freedom are redistributed:

4 massless gauge bosons	s = 1	4x2
4 Higgs scalars	s = 0	4x1
3 massive gauge bosons	s = 1	3x3
1 massless gauge boson	s = 1	1x2
1 massive higgs scalar	s = 0	1

Masses of the Gauge bosons

- Local gauge invariant Lagrangian with mass:

$$L_{Higgs} = D_\mu \Phi^\dagger D_\mu \Phi + h.c.$$

$$= (\partial_\mu - W_\mu + B_\mu)\begin{pmatrix} 0 & v+h \end{pmatrix}(\partial_\mu - W_\mu + B_\mu)\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$= \frac{1}{8} v^2 (W_\mu{}^{+2} + W_\mu{}^{-2} + Z_\mu{}^2 + 0 \cdot A_\mu) + hVV + h^3 + h^4$$

- Assuming $v = 246\,GeV$

$$Mw+ = Mw- = \frac{1}{2} vg = 80.4\,GeV$$

$$Mz = \frac{1}{2} v\sqrt{g^2 + g'^2} = 91.2\,GeV$$

Yukawa Lagrangian

Bonus of Higgs theory:

- Massive fermions AND fermion - higgs interaction
- However the mass value is not predicted in SM.

$$L_{Yukawa} = \bar{\psi}_L \Phi \psi_R + h.c.$$
$$= \bar{\psi}_L \begin{pmatrix} 0 \\ v + h \end{pmatrix} \psi_R + h.c.$$

Yukawa Lagrangian

$$\begin{aligned}
\mathcal{L}_e &= -\lambda_e \frac{1}{\sqrt{2}} \left[(\bar{\nu}, \bar{e})_L \begin{pmatrix} 0 \\ v+h \end{pmatrix} e_R + \bar{e}_R (0, v+h) \begin{pmatrix} \nu \\ e \end{pmatrix}_L \right] \\
&= -\frac{\lambda_e (v+h)}{\sqrt{2}} [\bar{e}_L e_R + \bar{e}_R e_L] \\
&= -\frac{\lambda_e (v+h)}{\sqrt{2}} \bar{e} e \\
&= - \underbrace{\frac{\lambda_e v}{\sqrt{2}} \bar{e} e}_{\text{electron mass term}} - \underbrace{\frac{\lambda_e}{\sqrt{2}} h \bar{e} e}_{\text{electron-higgs interaction}}
\end{aligned}$$

$$m_e = \frac{\lambda_e v}{\sqrt{2}} \qquad \frac{\lambda_e}{\sqrt{2}} \propto m_e$$

The Standard model is a QFT with a Lagrangian invariant under local symmetries:

Gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Fermionic sector
5 representations of the zoo of particles (s=1/2)
Scalar sector
Higgs particle (s=0)
LGI requires 3 gauge boson fields
G, W, B (s=1)

Extra observed global symmetries
B Baryon number L Lepton number

SM Lagrangian

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \qquad \text{(U(1), SU(2) and SU(3) gauge terms)}$$
$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} \qquad \text{(lepton dynamical term)}$$
$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] \qquad \text{(electron, muon, tauon mass term)}$$
$$-\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] \qquad \text{(neutrino mass term)}$$
$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} \qquad \text{(quark dynamical term)}$$
$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] \qquad \text{(down, strange, bottom mass term)}$$
$$-\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] \qquad \text{(up, charmed, top mass term)}$$
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. \qquad \text{(Higgs dynamical and mass term)} \quad (1)$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar{\psi} = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad (2)$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \quad (3)$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T = (0, v+h)/\sqrt{2}, \qquad <\phi>_0^T = \text{(expectation value of } \phi) = (0, v)/\sqrt{2}, \quad (5)$$

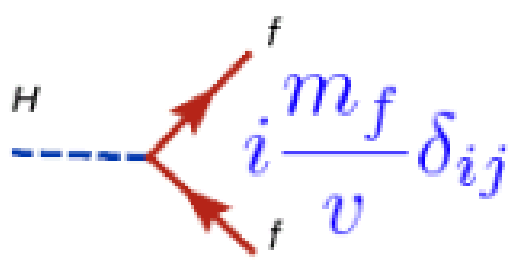
where v is a real constant such that $\mathcal{L}_\phi = \overline{(\partial_\mu\phi)}\partial^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu). \quad (6)$$

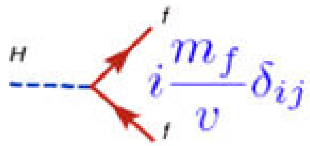
Couplings to higgs $\quad h \to f\,\overline{f}$

$$\frac{d\Gamma}{d\Omega} = \frac{M^2}{32\pi^2} P_f S \qquad\qquad -iM = \bar{u}(p_1)\frac{im_f}{v}v(-p_2)$$

$$\Gamma = (\frac{m_f}{v})^2 \frac{m_h N_c}{8\pi}[1-x]^{\frac{3}{2}} \qquad x = \frac{4m_f^{\ 2}}{m_h^{\ 2}}$$

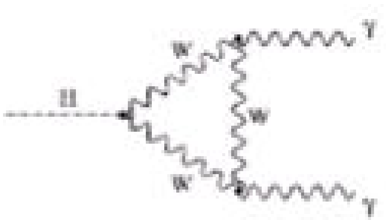


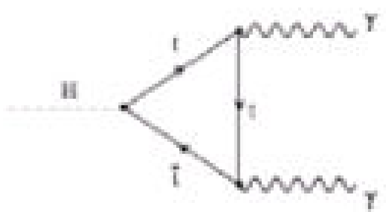
The end of a Higgs boson



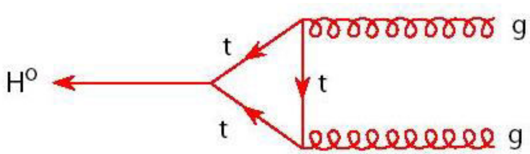
$$\Gamma(h \to f\bar{f}) = (\frac{m_f}{v})^2 \frac{m_h N_c}{8\pi}[1-x]^{\frac{3}{2}}$$

$$\Gamma(h \to V\bar{V}) \sim S_{vv} g^2 \frac{{m_V}^4}{m_h}$$

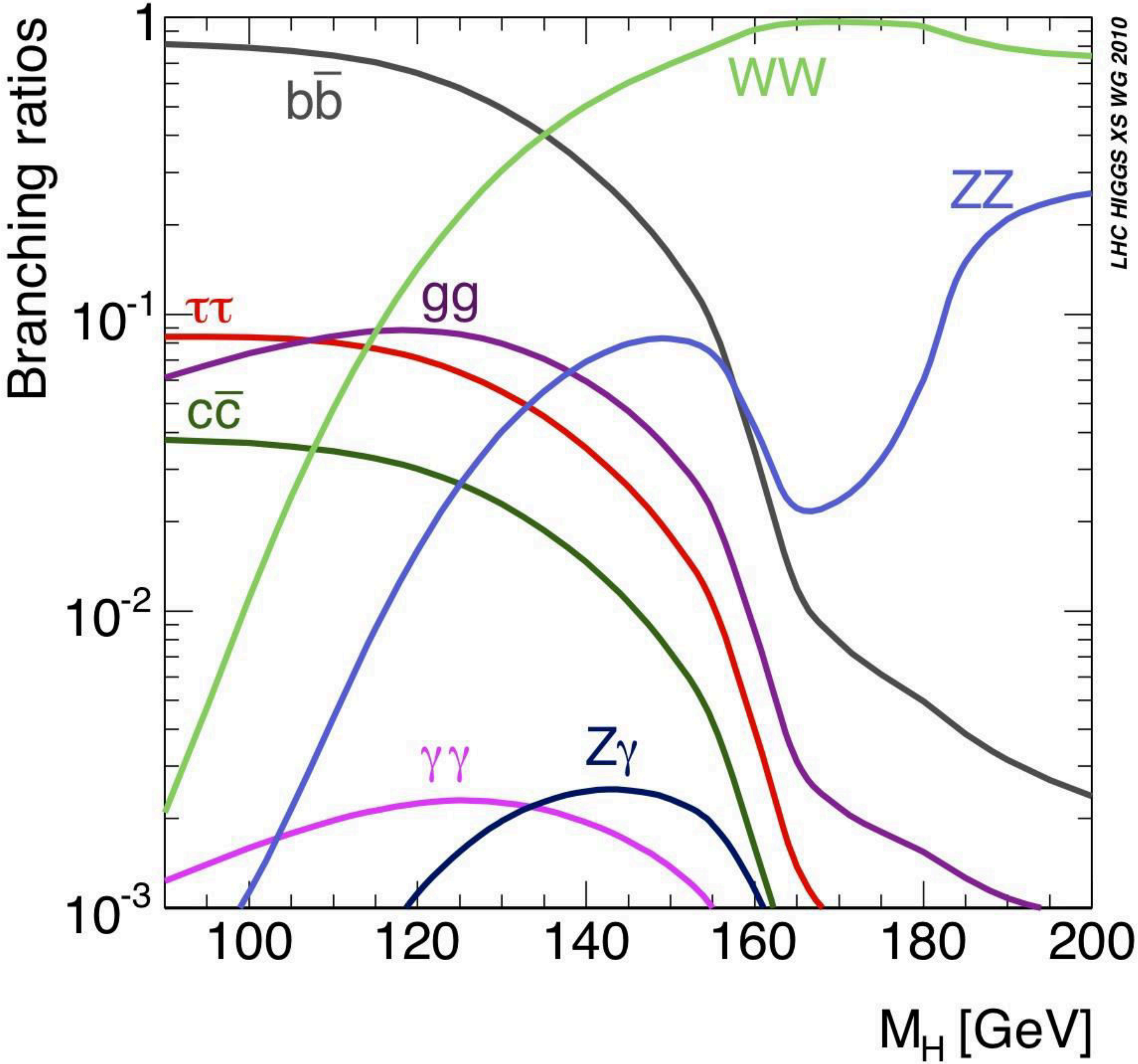




$$\Gamma(h \to loop \to \gamma\bar{\gamma}) \sim \alpha^2 N_c \frac{{m_l}^3}{m_h}$$



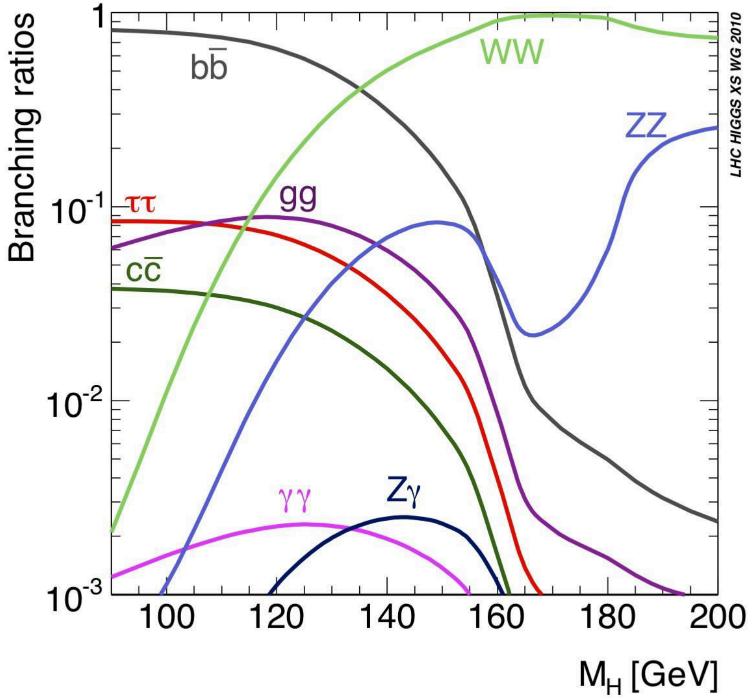
$$\Gamma(h \to q.loop \to g\bar{g}) = {\alpha_s}^2 N_c \frac{{m_l}^3}{m_h}[1+\alpha_s+..]^2$$



Branching ratios
1
10-1
10-2
10-3
100
120
140
160
180
200
MH [GeV]
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
LHC HIGGS XS WG 2010

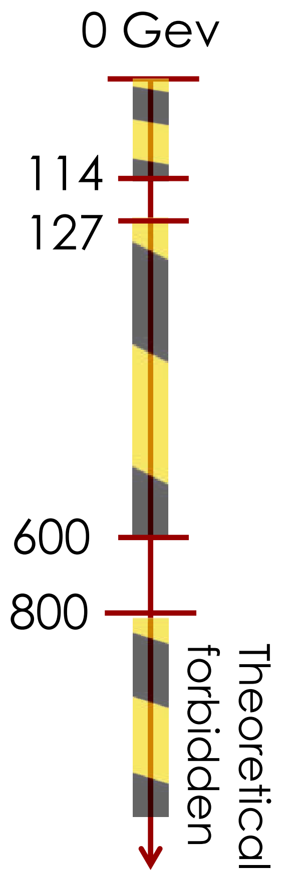
Implication of branching ratios

- They strongly depends on higgsmass
- Strongly influences the detectability along certain channels
- WW for example can be not present or most dominant



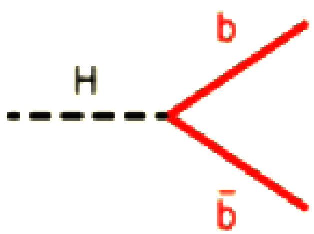
Experimental constraints

- The Large Hadron Collider (LHC) have excluded the mass region below 114.4 GeV
- Tevatron and the LHC excluded a boson below 600 GeV, apart from mass regions 116 to 127 GeV.
- The CDF and DØ experiments at the Tevatron have also recently reported a broad excess in the mass region 120–135 GeV



Decay of 125 GeV Higgs

- For M_h = 125 GeV we can calculate branching ratios
- All 5 decay channels are significantly pressent



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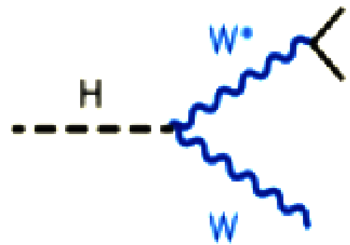

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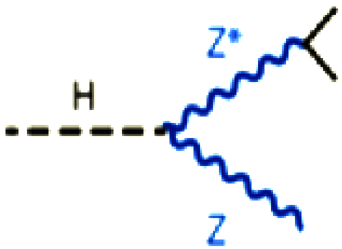

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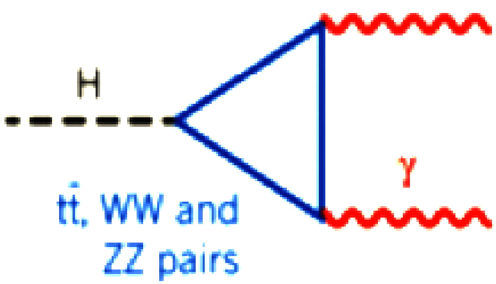

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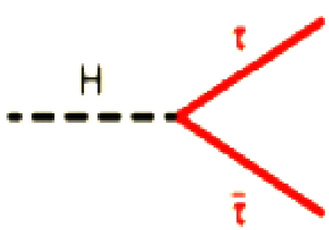
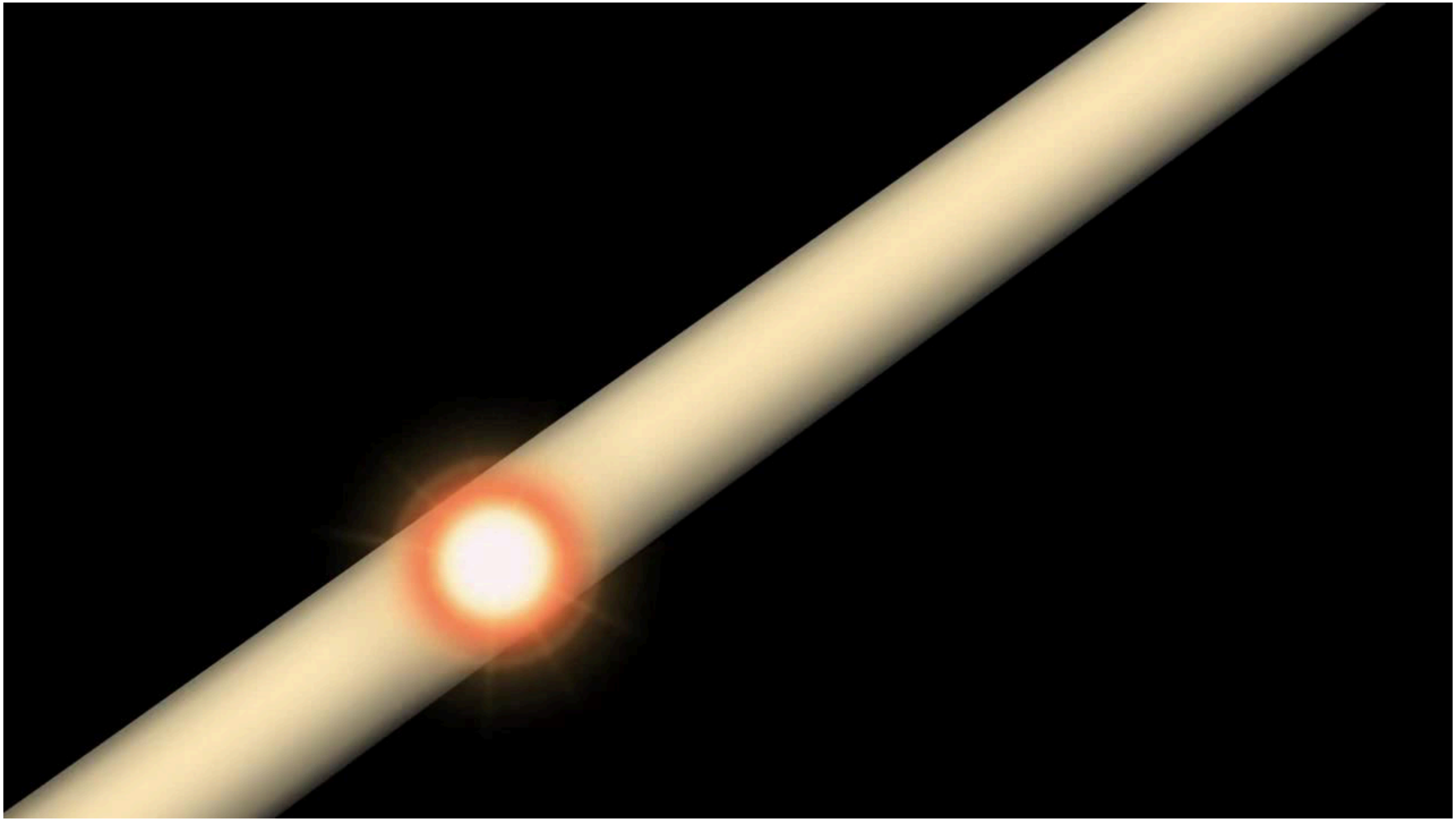


6.3%

Properties of the channels

- H $\rightarrow ZZ^* \rightarrow$ 4l and $H\rightarrow\gamma\gamma$give narrow mass peaks
- H $\rightarrow ZZ^* \rightarrow$ 4l, $H\rightarrow\gamma\gamma$ and $H\rightarrow WW^*\rightarrow e\nu\mu\nu$ more sensitive than bb and tt (less background)
- Diphoton final state implies that the boson has an integer spin different from unity.
- Decay to W bosons are harder to precisely reconstruct because of undected neutrino's

Large Hadron Collider (LHC)



Properties LHC

- The energy $\sqrt{s}$ is distributed statistically over six quarks
- What particles can actually be measure?
- Each detection indentifies the energy, impuls and charge of the particle.
- In all directions particle can be measured except In longitudinal direction for angles smaller than .8 deg

Higgs production at LHC

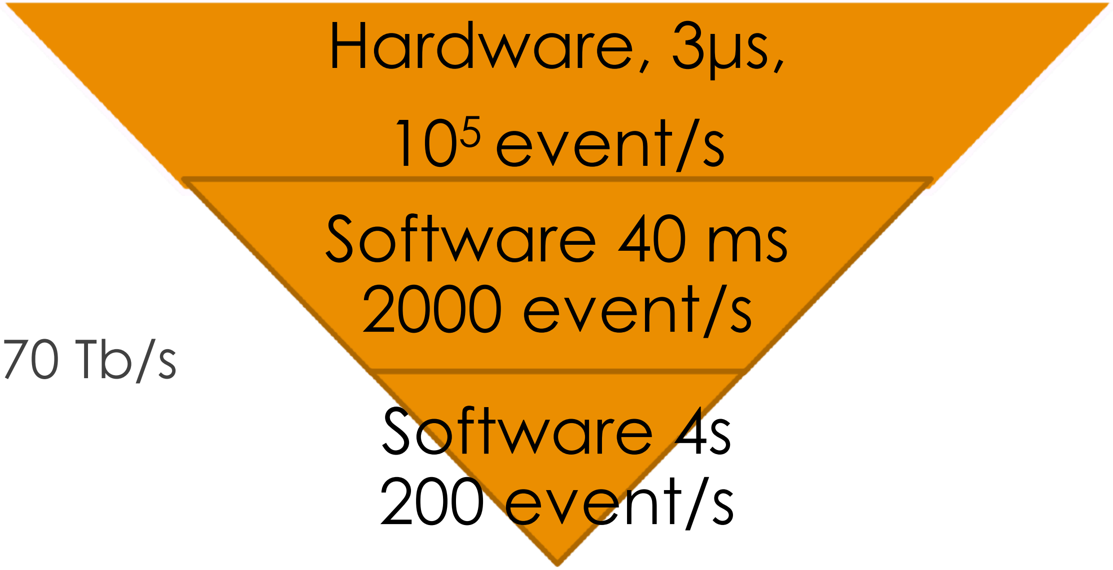
- Largest SM higgs production cross sections:
  - Gluon fusion gg -> H (ggF)
  - W or Z boson fusion qq -> qqH (VBF)
  - Associated production production with W or Z bosons qq -> VH (VH)
- All production processes add up to a total cross section for Higgs .

How many collisions

- Integrated luminosity of 5.3 fb^{-1} (7.6 10^{33} cm^{-2} s^{-1}, $\int L dt$)
- Integrated luminosity multiplied with total cross section gives expected number Higgs creations
- 10^5 Higgs particles expected for 5.3 fb^{-1} including all channels

Trigger

- From 10^9 events/s to 200 event/s
- Multi levels of triggering
- Using 1 hardware trigger and 2 software triggers



- Now 300Mb/s otherwise 70 Tb/s

Background at the LHC

- Reducible Vs Irreducible
- Processes contributing to background events

Table 1: Event generators used to model the signal and background processes. "PYTHIA" indicates that PYTHIA6 and PYTHIA8 are used for simulations of $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV data, respectively.

Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W+jets, Z/γ^*+jets	ALPGEN [59]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \to WW$	MC@NLO+HERWIG
$gg \to WW$	gg2WW [62]+HERWIG
$q\bar{q} \to ZZ$	POWHEG [63]+PYTHIA
$gg \to ZZ$	gg2ZZ [64]+HERWIG
WZ	MadGraph+PYTHIA, HERWIG
$W\gamma$+jets	ALPGEN+HERWIG
$W\gamma^*$ [65]	MadGraph+PYTHIA
$q\bar{q}/gg \to \gamma\gamma$	SHERPA

How to estimated background

- Background estimated by running a Monte Carlo simulation
- Simulated a poisson distributed energy distribution over the quark and calculated the outcome of a collision
- Simulations were also experimental validated first

Reconstruction of event

- Approximately 20 collisions at one time
- Indentify those different collisions
- Make use of momentum, energy and charge conservation and the laws of particle physics

Missing transverse momenta

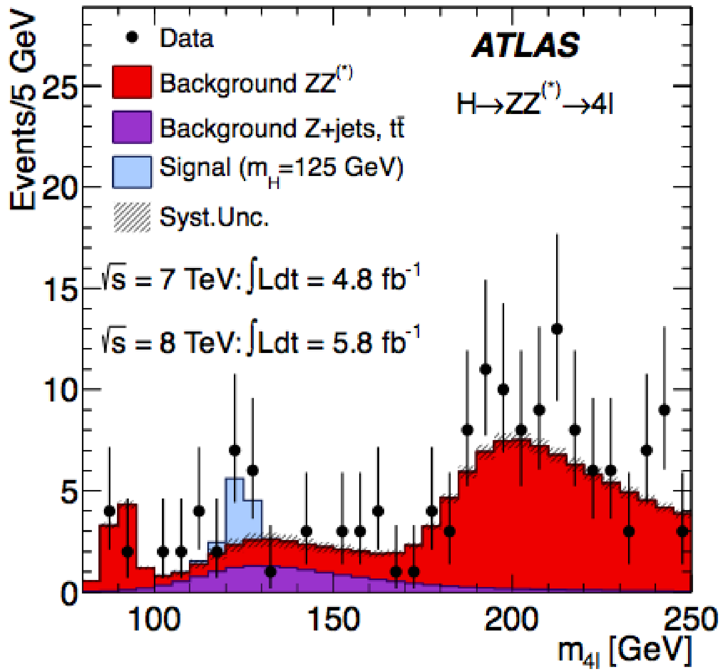
- Due to neutrino losses
- Neutrinos from decay channels:

  Leads to broad distribution of higgs mass peak

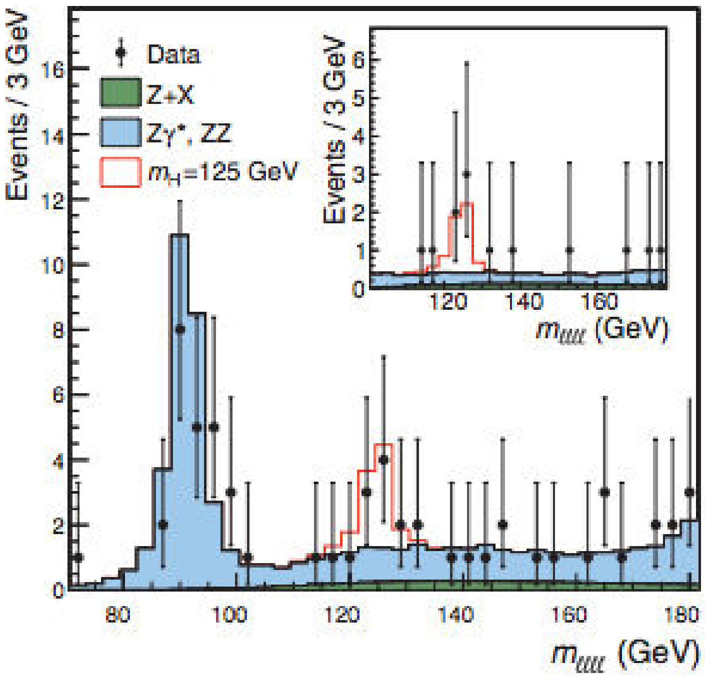
Detection ZZ->4l decay

- Data is measured, signal is expected value for Higgs

Atlas

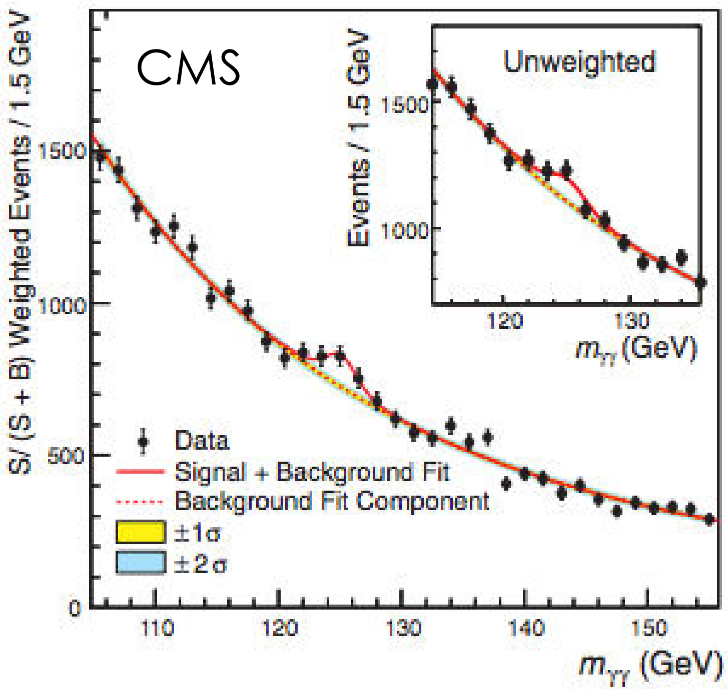


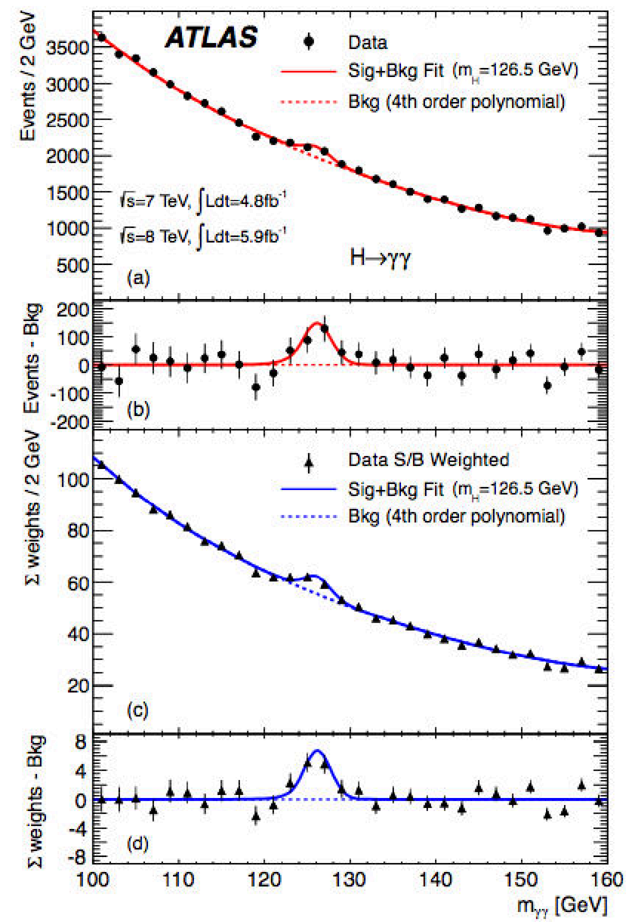
CMS



Detection di-photon decay

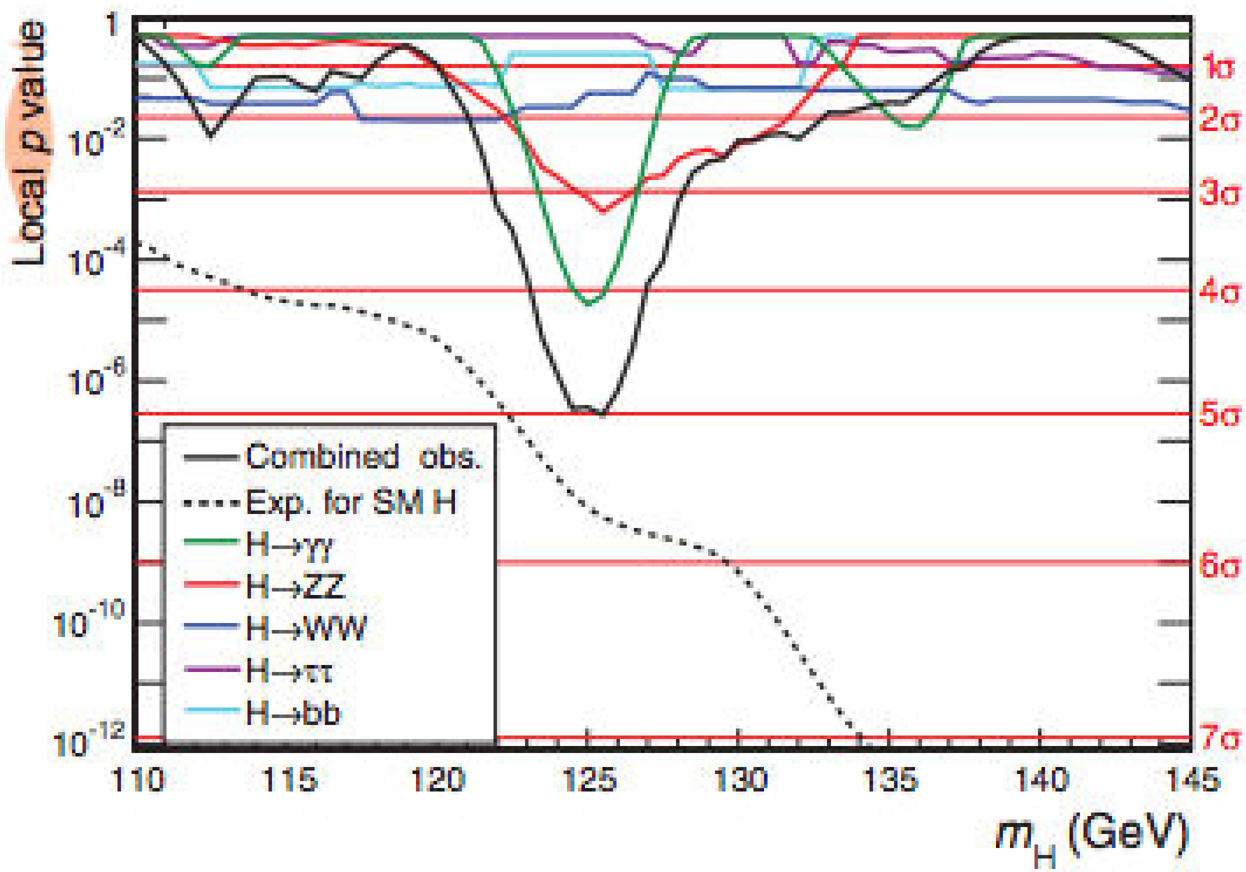
- Relative strong signal
- Rescaled, why ?





Combined data CMS

Overview of excess events of the different channels



Combined data CMS

- ZZ-> 4l and diphoton channels show a clear excessive amount of event around the mass of 125 GeV
- The other channels show to much background compared to signal

Conclusion experiment

- In 2011 at 7 Tev 4.6–4.8 fb^{-1}, a mass of 124–126 GeV with significances of 2.9 and 3.1 ATLAS and CMS
- Combing this with data from 2012 running at 8 Tev and 5.8–5.9 fb^{-1}

A Boson is found at

- Atlas: 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV
  significances 5.1 σ
- CMS: 125.3 ± 0.4 (stat) ± 0.5 (sys) GeV.
  significicances 4.6 σ

Is it a Higgs particle?

How to verify the SM Higgs

- An investigation into the properties the SM demands for the Higgs particle

SM Higgs

- Couples to all particles with mass
- Spin-0
- Parity +

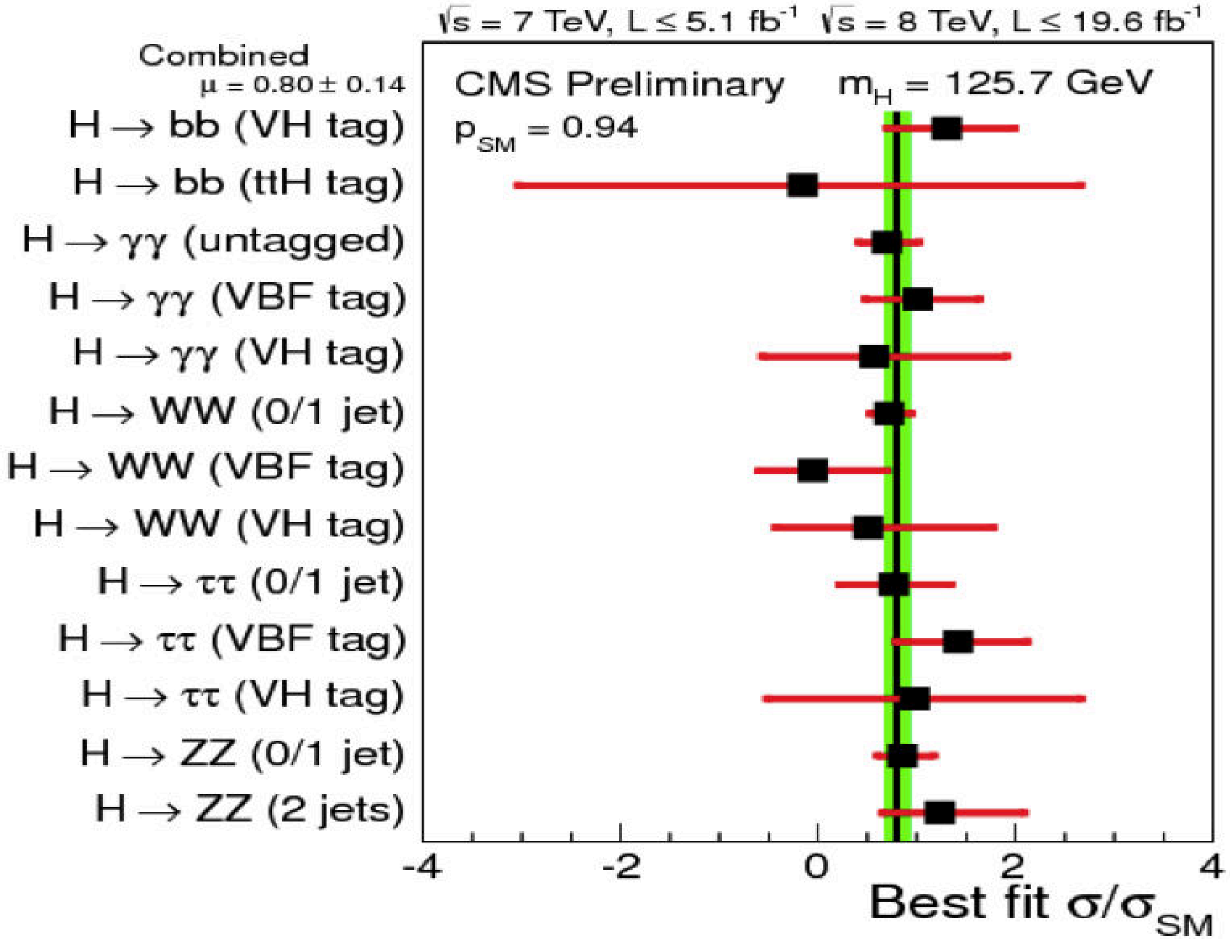
SM couplings

- Five Higgs decay channels: $\gamma\gamma$, $WW^{(*)}$, $Z Z^{(*)}$, $\tau^+\tau^-$, bb-bar
- Determine signal strength for all these. Hard for some:
- $WW^{(*)}$ -> lvlv : missing p_T from neutrinos
- $\tau^+\tau^-$: decays in many particles, also missing p_T
- bb-bar: much SM noise and big uncertainty due to high energetic jets

- Differentiating between Higgs production modes helps to bypass the SM noise
- ggF, gluon-gluon fusion: gg –-т loop--> H
- VBF, vector boson fusion: WW, ZZ -> H
- VH, associated production: W, Z -> H + W, Z

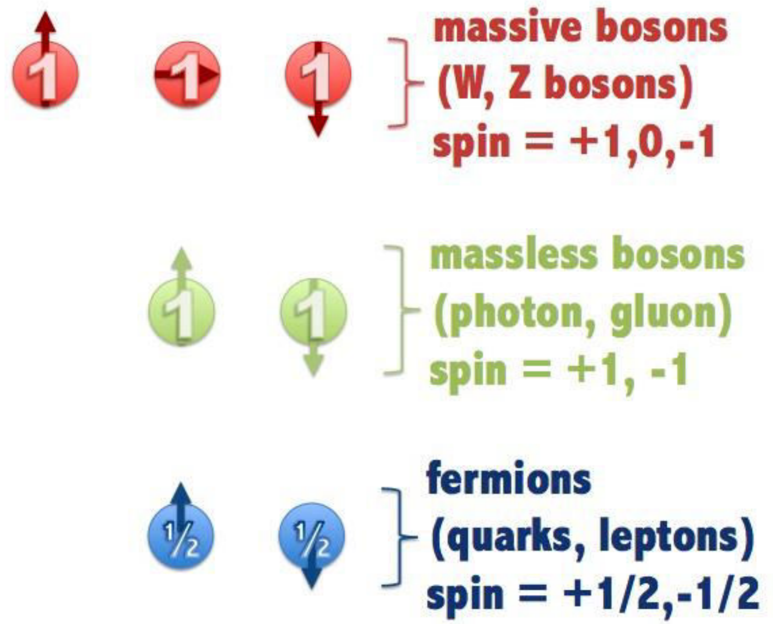
SM: Branching ratios

April 2013 CMS preliminary results



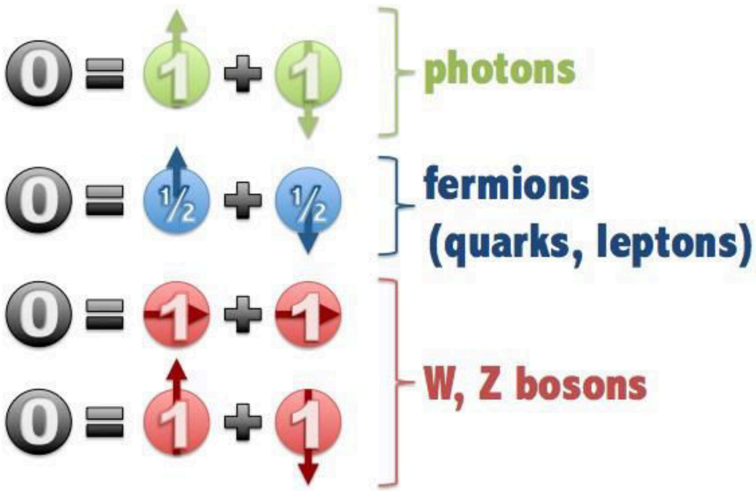
Spin

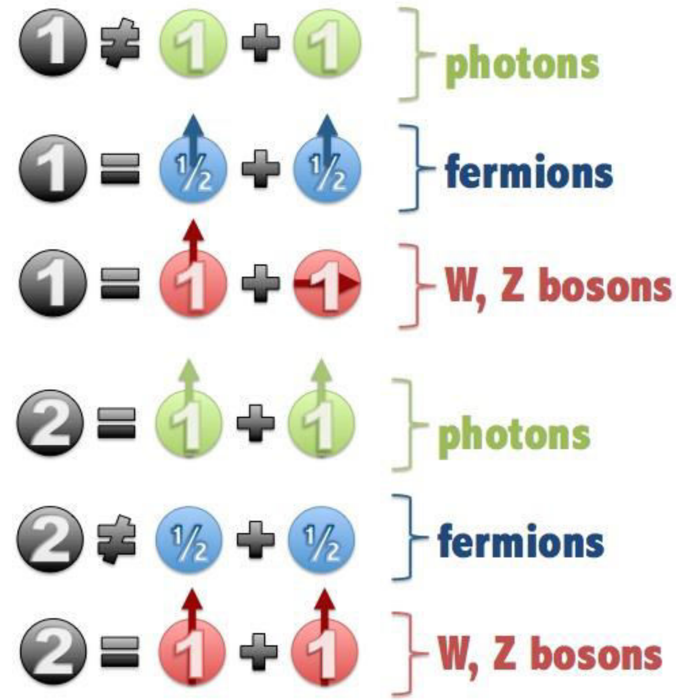
- Using observed decays, spin can be determined by exclusion
- Spin-0 can also be concluded
  From isotropic higgs decay
  *full knowledge of decay
  Kinematics and production is
  required
- spin of decay elementary
  particles:



Spin Scenarios

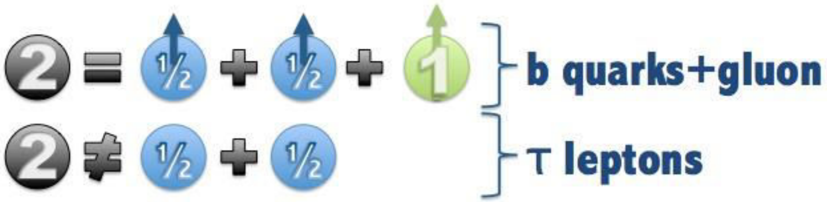
How source particle-spin is reconstructed





Observing fermionic decay modes will rule out spin-2
and therefore will prove spin-0 scenario

Spin Scenarios



- b quark decay not sufficient
- H -> $\tau^+\tau^-$ will prove conclusive
- Currently, data of H -> $\tau^+\tau^-$ channel is still inconclusive

ATLAS note

- ATLAS note 16 april 2013
- Spin and parity can be determined by reconstructing kinematics in channels
  - H -> $ZZ^{(*)}$ -> 4l,
  - H -> γγ,
  - H -> $WW^{(*)}$ -> lνlν
- Spin-parity hypotheses J^p: 0^+ compared to other scenarios
- The data strongly favour the $J^p = 0^+$ hypothesis
- Although $J^p = 0^+$ is likely, results are not conclusive

concluding

- Exact coupling of new boson to other particles must be further determined
- Spin-parity seems to be in accordance to SM, but too early to tell
- LHC operation will resume in 2015, reaching 14 TeV CME
- Future data will prove affirm Higgs boson or otherwise investigate any aspects of EW symmetry breaking

Why beyond the standard model

Higgs mass not predicted in SM $m_H = \sqrt{2\lambda}v$
Hierachy problem/fine tuning of the Higgs mass
Higgs vev on comological constant
Number of families and higgs implications
Charge quantization and unconnected lepton quark content
Neutrino oscillations, right handed neutrino?
Dark matter
Matter antimatter assymetry
Fermion masses and mixing angles
Gauge coupling unification

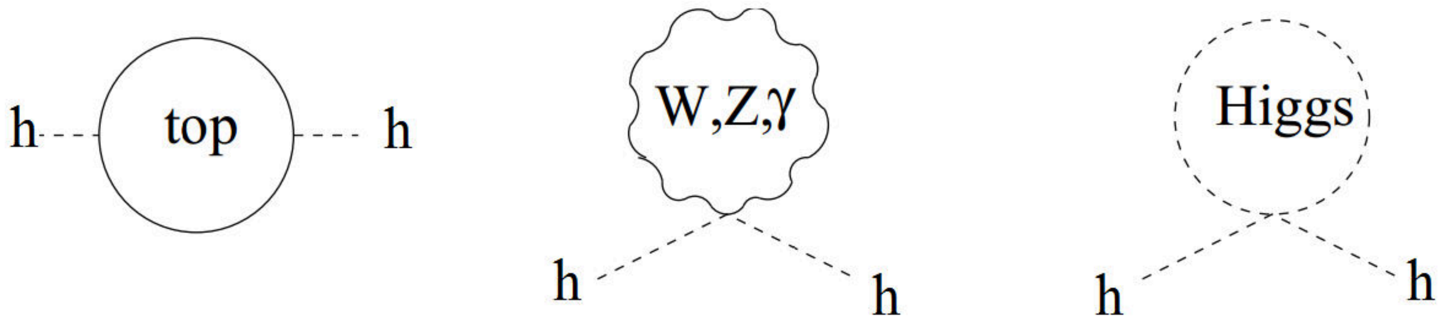
Hierachy problem

- The standard model has a drawback.
- Introduce an energy cut off scale Λ, beyond this the standard model is not more valid.
- $\Lambda \to \infty$ is some sense not really a problem.
- But this is where the hierachy problem comes in.

Hierachy problem

- The Higgs mass is determined by it's propagator
- The propgator is a sum of the tree mass and quantum corrections in the form of one loop diagrams
- So $m_h^2 \sim m_{tree}^2$ + (quantum corrections)^2
- This tree mass is a free paramater but must be chosen large to cancel the main quantum correction loop.

The main quantum correction contributions to the Higgs mass



$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \;\sim\; -(2\,TeV)^2 \qquad \frac{1}{16\pi^2}g^2\Lambda^2 \;\sim\; (700\,GeV)^2 \qquad \frac{1}{16\pi^2}\lambda^2\Lambda^2 \;\sim\; (500\,GeV)^2$$

$\Lambda = 10$ TeV

Quadratic divergence

- The main contributions to the mass term are all quadratically convergent in Λ
- with $\Lambda \sim 10TeV$ the main contributions are

$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \;\sim\; -(2\,TeV)^2 \text{ from the top loop,}$$

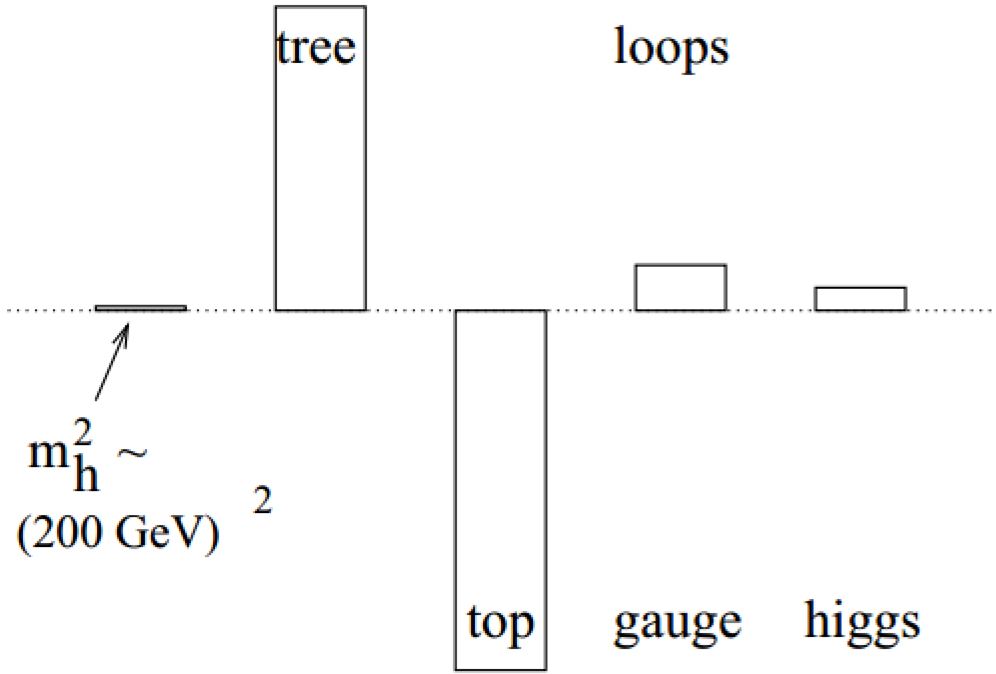
$$\frac{1}{16\pi^2}g^2\Lambda^2 \;\sim\; (700\,GeV)^2 \text{ from the gauge loop, and}$$

$$\frac{1}{16\pi^2}\lambda^2\Lambda^2 \;\sim\; (500\,GeV)^2 \text{ from the Higgs loop.}$$

- The free parameters λ_t λ and g determine the precise values of the contributions.

Higgs mass is "unnaturally" small

- The following graph show estimates of the ratios between the loop corrections.



Fine tuning

- So we see that the fine tuning of the paramters $\lambda_t, \lambda \text{ and } g$ must be extremely precise, about 1 part in 100
- Setting $\Lambda \sim 1TeV$ reduces the magnitude of the corrections to the same scale as the Higgs boson and hence there is no hierachy or fine tuning problem.
- This would however mean there should be some new physics beyond the standard model. Any such physics would arise at a energy scale above Λ

Vacuum energy density

- The higgs vev impies is a 10^{54} order too large?

$$V\min = V(v) = \frac{-1}{8} m_h{}^2 v^2$$

$$\Lambda_h = \frac{1}{8} m_h{}^2 v^2 = 10^8 GeV^4$$

$$\Omega_\Lambda = 10^{-46} GeV^4$$

Beyond the standard model physics

saving hierarchy

- We will discuss theories which will either completely solve the hierarchy problem or shift Λ to a higher energy.

- The most well known and studied beyond the standard model (BSP) is **supersymmetry**, which takes care of the hierarchy on any energy scale.

- The little Higgs model solves the hierarchy problem on up to scales of $\Lambda \sim 10 TeV$

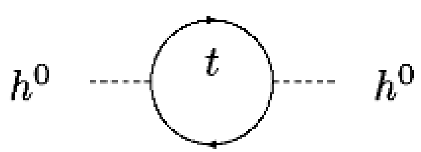
Susy

- Spin opposide partners & spartners
- MSSM Minimal SuSy Model is the minimal extension of SM
- N=1; Bosons and fermions have 1 superpartner from opposite sector

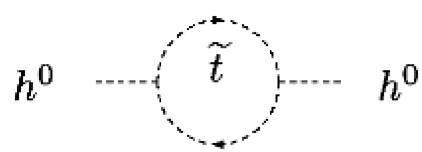
- In unbroken susy; superpartners have equal mass.
- Quantum loops of supersymmetric partners have an opposite sign.
- These means that the hierarchy problem is solved.
- However this would also imply that the Higgs mass is zero
- No Susy particles found yet.

Susy breaking

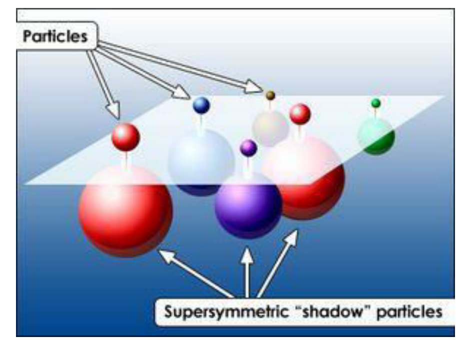
- Susy as a broken symmetry ~1TeV in the Early universe
- For every loop correction diagram in SM we can introduce a SUSY



$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$



$$\frac{3}{8\pi^2}\tilde{\lambda}_t^2\Lambda^2$$



- Broken symmetry; non equal masses of the superpartners.
- Almost 100% cancellation. Higgs obtains natural small mass
- Hierarchy problem solved...?

Particles in Susy L_{SM}

5 fermion (spin ½) representations
$Q_L(3,2)$, $u_R(3,1)$, $d_R(3,1)$, $L_L(1,2)$, $e_R(1,1)$
12 massless gauge boson (spin 1) fields 1B, 3W, 8G.

In susy a supersymmetric partner of higgs fields (complex duplet) introduced: 8 dof.

After spontaneous breaking with Higgs mechanism:

W^+ ,W^-,Z^0	massive (3 dof)
γ , 8 G	massless

5 massive scalar higgs particles!

h^0, H^0	CP even higgs bosons
A^0	CP odd
H^+, H^-.	Charged higgs

Particles in Susy L_{susy}

5 'sfermion' (spin 1) representations
12 gauge (spin ½) fields:
Bino, $Wino^+$, $Wino^-$,$Wino^0$ and 8 Gluinos.

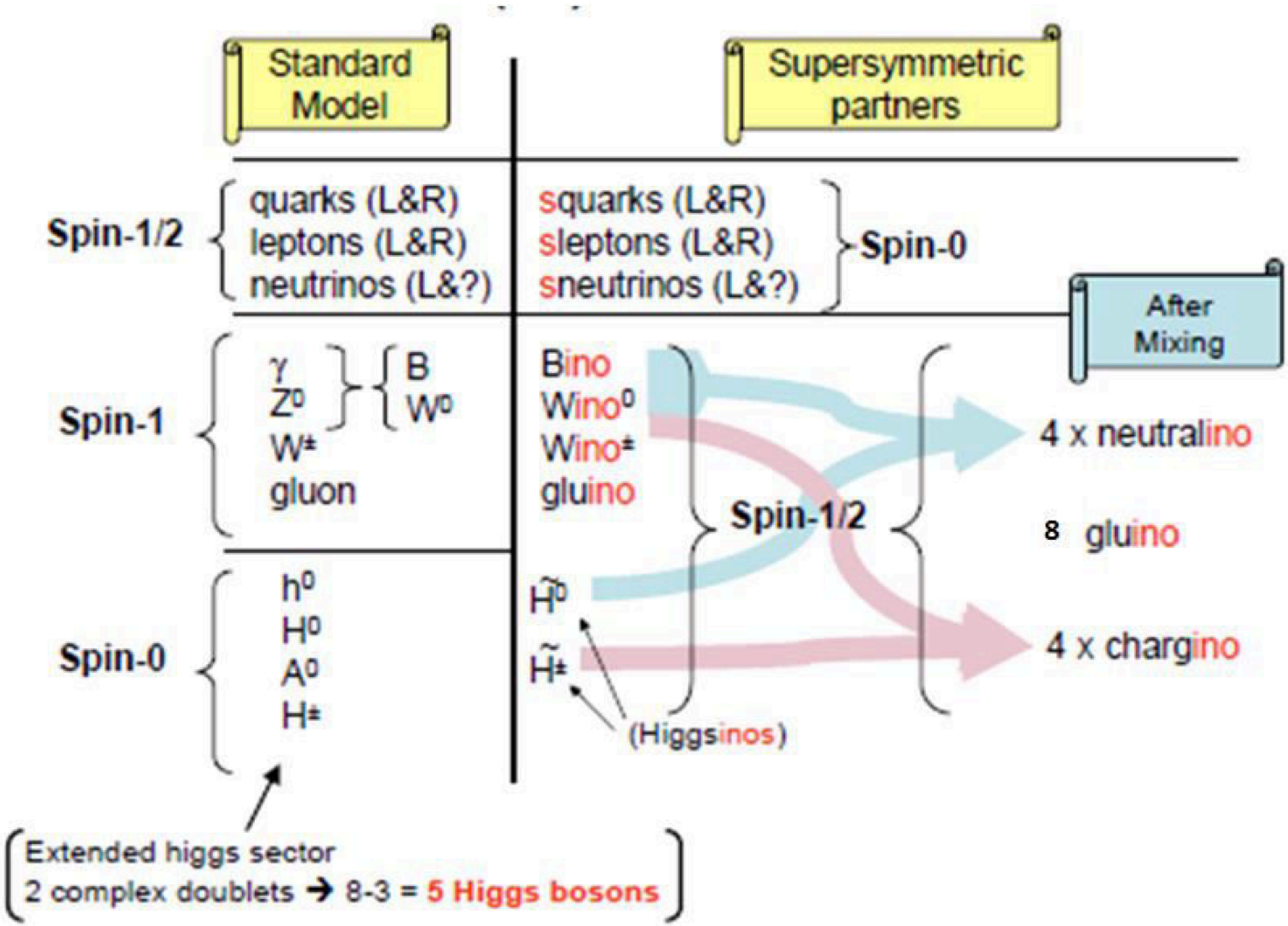
The 2 higgs fields introduce again 8 dof.
After spontaneous symmetry breaking:

1 Bino	massless	B
3 Winos	massive	W^+ ,W^-,W^0
5 Higgsinos	massive	$\underline{h}^0$, $\underline{H}^0$,$\underline{A}^0$, $\underline{H}^+$, $\underline{H}^-$.
8 Gluinos	massless	G

The Bino, neutral Wino and neutral Higgsinos mix to create 4 Neutralinos $X_{1,2,3,4}$

The charged Winos and charged Higgsinos mix to create 4 Charginos x_1^+, x_1^-, x_2^+, x_2^-

The 8 Gluinos remain massless.



In R-parity conserving models; stable neutralino!

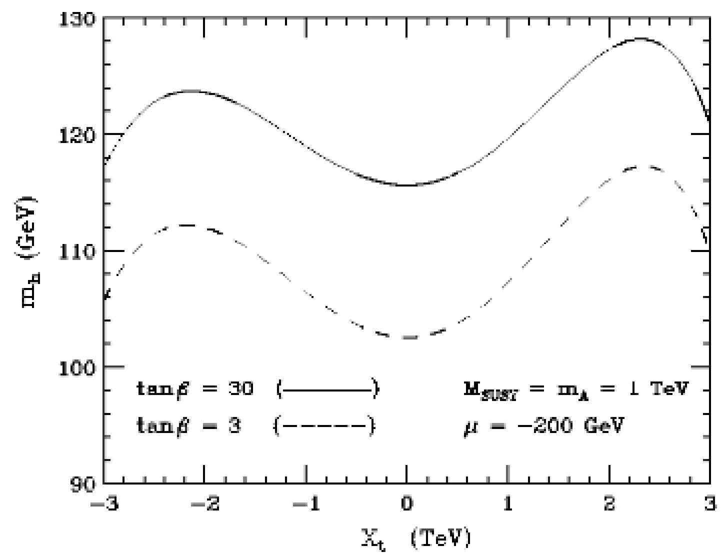
[

Higgs mass in MSSM

- MSSM Higgs Decoupling limit
- $m_A >> m_{Z.}$ 1 light higgs scalar particle h^0 $m \sim M_{Hsm}$
- The other 4 higgs particles have a mass ~1TeV: discovery difficult

$$m^2_{h^0,H^0} = \frac{1}{2}\left(m^2_{A^0} + m^2_Z \mp \sqrt{(m^2_{A^0} + m^2_Z)^2 - 4m^2_Z m^2_{A^0}\cos^2 2\beta}\right.$$

$$M_h^2 \stackrel{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] .$$



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Questions?

Little Higgs

- A viable model is the Little Higgs
- The little Higgs theory cancells the loop corrections to a higher energy scale $\Lambda \sim 10 TeV$
- s

Backup slides

Higgs mass

Not predicted in the SM. $m_H = \sqrt{2\lambda} v$

The higgs propagator receives loop corrections from gauge bosons, higgs self interactions
For large Mh SI dominate at relative low energies.

$m_h < 700$ GeV Perbutation theory breaks down (soft limit)

Higgs mass

The requirement that λ remains positive in order to keep a global minima in the higgs quartic polynomial for the potential $V=\mu^2\varphi^2 + \lambda^2\varphi^4$, up to the GUT energy scale $\Lambda=10^{16}$ GeV puts a lower limit on λ and m_h,

$m_h > 135$ GeV

Vacuum stability $\lambda>0$

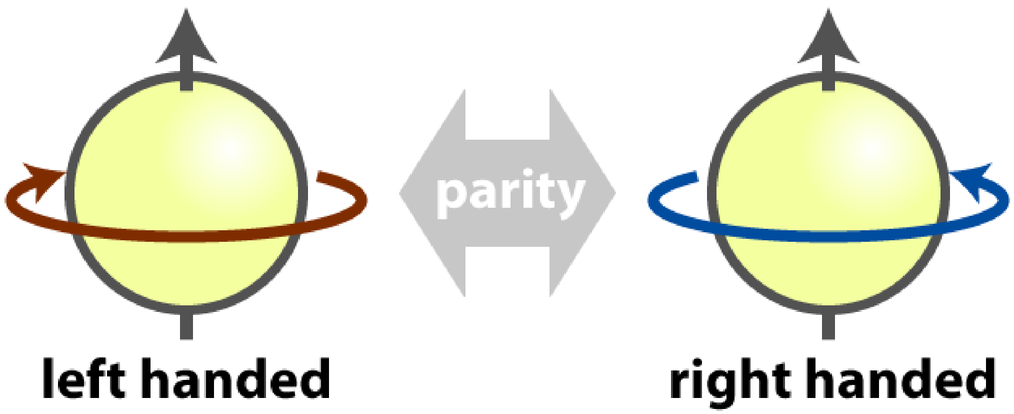
Higgs mass

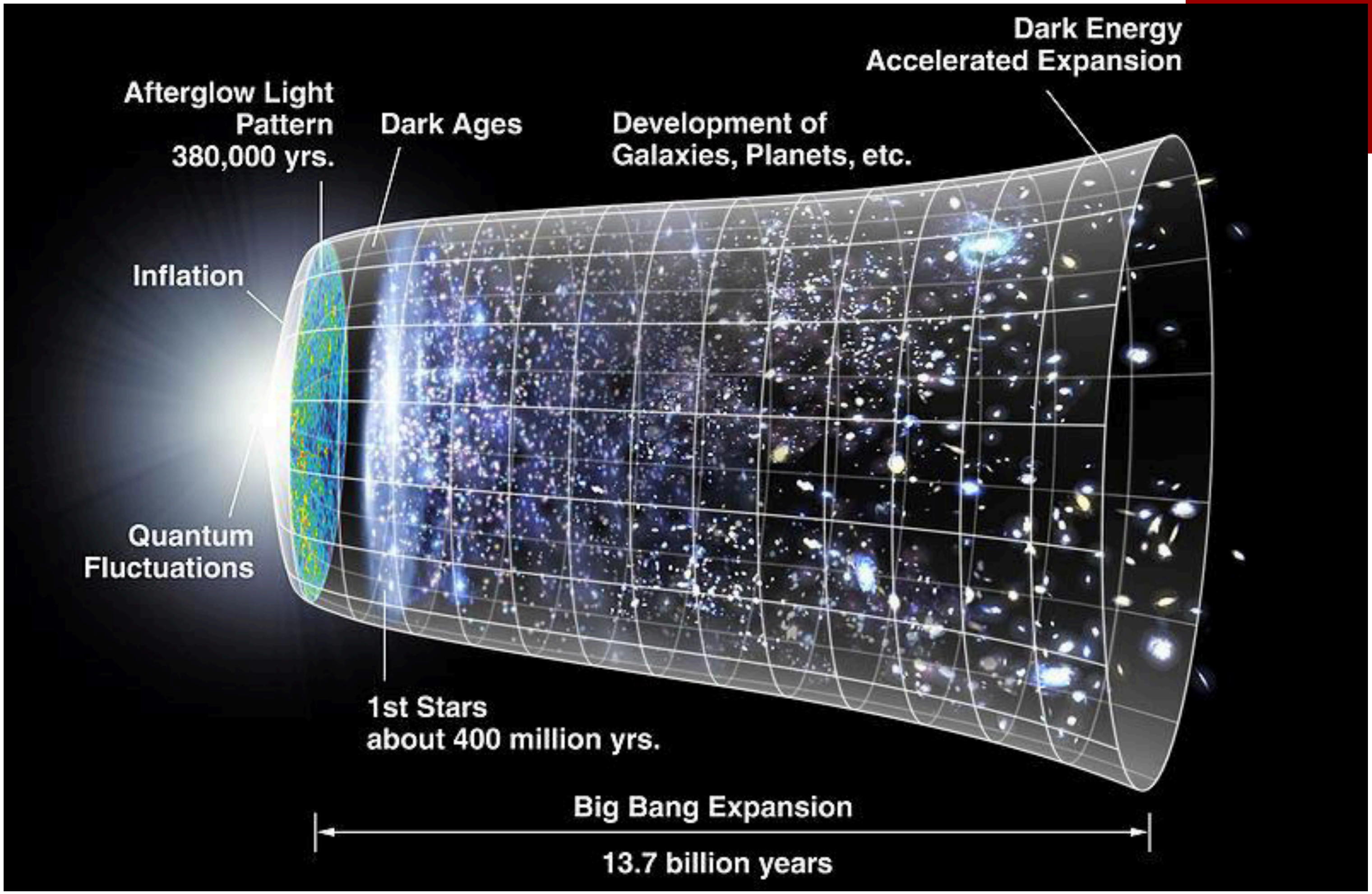
The higgs coupling constant λ depends like all gauge coupling constants on energy, $d\lambda / dt = \beta_\lambda$ with $t = \ln(Q^2)$. The evolution of the β function sets a limit on the higgs mass, if we require that $\lambda<\infty$ up to the GUT scale $\Lambda=10^{16}$ GeV,

$m_h < 160$ GeV

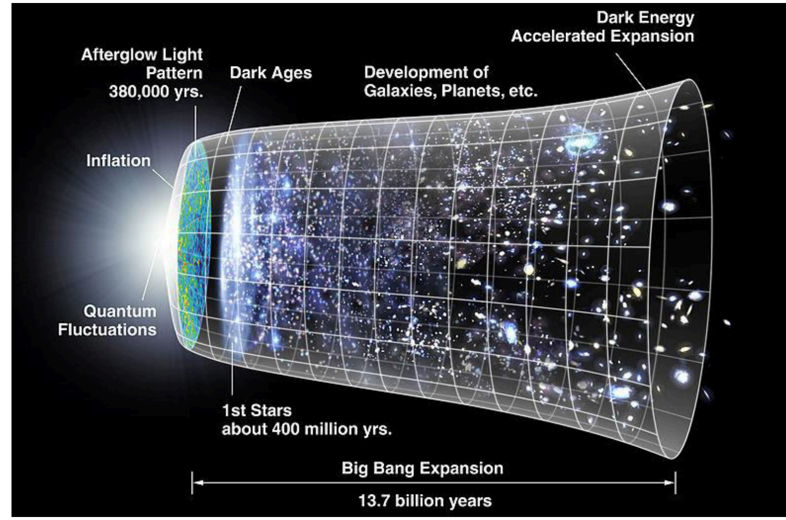
Landau pole $\lambda<\infty$

Hh-graviton-hh needed!!


parity
left handed
right handed



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



Planck 10^19
Baryogenesis? Matter/antimatter assymetry
GUT 10^14 Mx 10^{14}GeV Gut breaking. SU5->SU3 xSU2. Quarks en leptons.
Susy breaking 1TeV Mass difference. Sarticles not observed
Elektroweak breaking Mh~246GeV Strong en SU2xU1 apart
?Inflation? Decay to particles. Reheating
Quark/gluon plasma filles universe
Hadron p,n
Lepton
Photon
Nucleosynthesis He4
Recombination Free streaming. CMB Acoustic oscc.

Stars, Galaxies, Clusters

$$
\begin{aligned}
(D_\mu \phi) &= \frac{1}{\sqrt{2}}\left[ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}YB_\mu\right]\begin{pmatrix}0\\ v\end{pmatrix}\\
&= \frac{i}{\sqrt{8}}\left[g(\tau_1 W_1 + \tau_2 W_2 + \tau_3 W_3) + g^{'}YB_\mu\right]\begin{pmatrix}0\\ v\end{pmatrix}\\
&= \frac{i}{\sqrt{8}}\left[g\left(\left(\begin{smallmatrix}0 & W_1\\ W_1 & 0\end{smallmatrix}\right) + \left(\begin{smallmatrix}0 & -iW_2\\ iW_2 & 0\end{smallmatrix}\right) + \left(\begin{smallmatrix}W_3 & 0\\ 0 & -W_3\end{smallmatrix}\right)\right) + g^{'}\left(\begin{smallmatrix}Y_{\phi_0}B_\mu & 0\\ 0 & Y_{\phi_0}B_\mu\end{smallmatrix}\right)\right]\begin{pmatrix}0\\ v\end{pmatrix}\\
&= \frac{i}{\sqrt{8}}\begin{pmatrix} gW_3 + g^{'}Y_{\phi_0}B_\mu & g(W_1 - iW_2)\\ g(W_1 + iW_2) & -gW_3 + g^{'}Y_{\phi_0}B_\mu\end{pmatrix}\begin{pmatrix}0\\ v\end{pmatrix}\\
&= \frac{iv}{\sqrt{8}}\begin{pmatrix} g(W_1 - iW_2)\\ -gW_3 + g^{'}Y_{\phi_0}B_\mu\end{pmatrix}
\end{aligned}
$$

We can then also easily compute $(D^\mu\phi)^\dagger$: $(D^\mu\phi)^\dagger = -\frac{iv}{\sqrt{8}}\left(g(W_1 + iW_2)\ ,\ (-gW_3 + g^{'}Y_{\phi_0}B_\mu)\right)$ and we get the following expression for the kinetic part of the Lagrangian:

$$
(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{1}{8}v^2\left[g^2(W_1^2 + W_2^2) + (-gW_3 + g^{'}Y_{\phi_0}B_\mu)^2\right] \tag{7}
$$

Couplings to higgs $h \rightarrow f\overline{f}$

$$\frac{d\Gamma}{d\Omega} = \frac{M^2}{32\pi^2} P_f S \qquad -iM = \bar{u}(p_1)\frac{im_f}{v} v(-p_2)$$

$$M^2 = (\frac{m_f}{v})^2[-4p1p2 - 4m_f{}^2]$$

$$M^2 = (\frac{m_f}{v})^2[2m_h{}^2 - 8m_f{}^2] = (\frac{m_f}{v})^2[1-x]N_c$$

$$d\Gamma = (\frac{m_f}{v})^2 \frac{m_h N_c}{8\pi}[1-x]^{\frac{3}{2}}$$

$$\Gamma_{H\to\gamma\gamma} = \frac{\alpha^2 g^2 m_H^3}{1024\pi^3 m_W^2} \left| \sum_i N_c e_i^2 F_i \right|$$

$$\Gamma_{H\to gg} = \frac{\alpha_s^2 g^2 m_H^3}{512\pi^3 m_W^2} \left| \sum_i F_i \right|$$