Physics 129: Particle Physics
Lecture 26: The Higgs: Giving mass to the W and Z

Nov 24, 2020

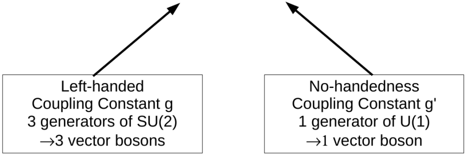
- Suggested Reading:
  - Thomson Chapter 17
  - Griffiths 11.6-11.9
- Final Projects posted
  - Due Friday Dec 18, 5PM No extensions possible
  - Pick 1 of the 4 possible projects
- Homework 12 posted. Due Wed Dec 2 typo in announcement, now fixed

Particle physics based on quantum gauge theories

- Simplest such theory: Quantum Electrodynamics (QED)
  - Developed in the 1950's
  - Tested to 7 significant digit precision
  - Exhibits a number of remarkable properties that are typical of all gauge theories
    - Built on postulate of "local gauge invariance"
    - Identification of spin 1 field as force carrier
    - Need for renormalization: process of subtracting unobservable infinities and retaining small, finite observable corrections
    - Strength of interaction depends on universal coupling constant (α)
- SM built in analogy with QED
  - QFT theory based on gauge symmetry
  - Choice of gauge group determines interactions among the bosons
  - Interactions among bosons (3 and 4 boson vertices) due to non-commuting generators of SU(3) (color) and $SU(2)_L$ (weak isospin)
  - Posulate of local gauge invariance determines interaction of bosons with the fermions
- Electroweak unification: $SU(2)_L \times U(1)$
- Today: Review the electroweak interaction and add the final wrinkle
  - Giving mass to the fundamental particles

Weak Interactions (I)

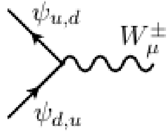
- Like Strong Interactions, EW interaction described as “gauge theory” where vertices determined by choice of “gauge” group
  - But wrinkles different from the Strong Interaction case
- Attempt to unify electromagnetic and weak interactions, but in fact there are two coupling constants
  - Gauge group is SU$(2)_L \times$ U(1)

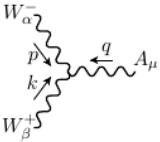


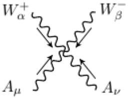
  - However, g and g' are not the EM and weak couplings
    - Two neutral fields that are degenerate until mass terms introduced
    - Interaction that gives mass to the weak bosons breaks the degeneracy and determines choice of basis
    - EM basis is a combination of neutral components of SU$(2)_L$ and U(1) chosen to couple to charge

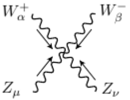
Weak Interactions (I): The Force Carriers

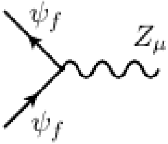
- Three vector bosons': W^+, W^-, Z^0
- $W^\pm$ responsible for β-decay: changes quark and lepton flavor
- Z also couples to quarks and leptons (similar to photon)
- Triple and Quartic couplings of gauge bosons to each other

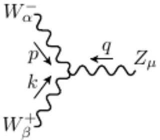


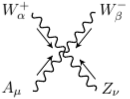












The weak bosons have mass

- Weak interactions not mediated by a massless field
  - Short range force and small coupling at q^2
- "Weakness" at low energy comes from mass of force mediator
  - Propagator $\frac{-ig(g_{\mu\nu}-q_\mu q_\nu)}{q^2-m2}$ as $q^2 \to 0$ acts like a 4-fermi interaction

$$G_F \sim 10^{-5}\ \mathrm{GeV}^{-2} \Rightarrow g_W/M_W^2$$

- But how to incorporate massive boson into gauge theory?
  - Gauge invariance does not allow addition of a mass term directly into the LaGrangian
  - The solution: Electroweak Symmetry Breaking and the Higgs mechanism
    - Keep the Lagrangian invariant under gauge transformations but break the invariance in the choice of inital state (the vacuum)
    - This is called Electroweak Symmetry Breaking (EWSB)
  - M_W and M_Z predicted in terms of e and 1 additional parameter $(\sin^2\theta_W)$

We'll walk through that story today

Why the Higgs?

- Without Higgs, Lagrangian does not contain mass terms for the gauge bosons or the fermions
- If we introduce a mass term "by hand" for the gauge fields, it violates gauge invariance

  $\rightarrow$ That's why the photon is massless in QED
- For the fermions, a mass term would have the form

$$-m_\ell \left(\bar{e}_R e_L + \bar{e}_L e_R\right)$$

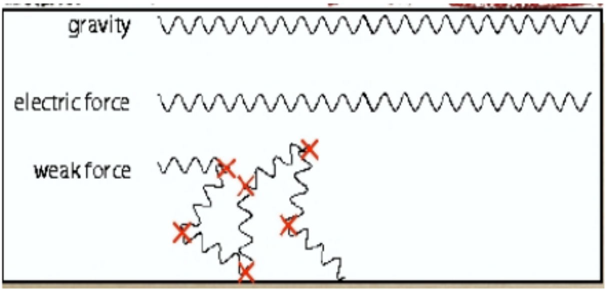
  But e_L is a weak isodoublet and e_R is a weak isosinglet: this term violates weak isospin symmetry
- The trick around this: dynamic symmetry breaking (aka spontaneous symmetry breaking)
  - Maintain gauge invariance of $\mathcal{L}$
  - Introduce a new field that has self interactions
  - These interactions induce a non-zero vacuum expectation value of one component of the field
  - Change of coordinate system to reinterpret this field in terms of physical states

Does spontaneous symmetry breaking make sense?

- We all know of an example of spontaneous symmetry breaking in nature: the ferromagnet
  - Fundamental Hamiltonian for a magnet is symmetric with respect to rotations
  - But a ferromagnet has its spins aligned in one direction
  - Choice of direction is arbitrary: Picked "by chance" or from a small imperfection when magnet created
- No one would argue that the existence of magnets violations rotation symmetery
- It is possible to have initial states that break the symmetry even if the fundamental interaction observes it
- In SM, it is the vacuum itself that breaks the symmetry through a field we call the Higgs field
  - Existence of a particle called the Higgs boson is a manefestation of that field
- Note: the SM with one Higgs boson is just the simplest example of spontaneous symmetry breaking
- Nature could give us a richer phenomenology (and does if Supersymmetry is correct)

Overview

- There is a field filling our Universe
- It doesn't disturb strong, EM or gravitational interactions
- It interacts with weak bosons to generate mass dynamically
- Also generates fermion masses



Courtesy of H Murayama

The Simplest Choice: A scalar field with weak isospin

- Introduce a complex $SU(2)_L$ doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad Y_\phi = +1$$

with the following Lagrangian

$$\begin{aligned} \mathcal{L}_{scalar} &= \mathcal{D}^\mu \phi \mathcal{D}_\mu \phi - V(\phi^\dagger \phi) \\ \mathcal{D}_\mu &\equiv \partial_\mu + \frac{ig'}{2} a_\mu Y + \frac{ig}{2} \vec{\tau} \cdot \vec{b}_\mu \\ V(\phi^\dagger \phi) &= \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2 \end{aligned}$$

- Introduce interactions between scalar field and the fermions

$$\mathcal{L}_{yukawa} = -\frac{g_f}{\sqrt{2}} \left(\overline{\chi}_L \phi R + \overline{\chi}_R \phi L \right)$$

couples fermion states of opposite helicity (as mass term in QED did)

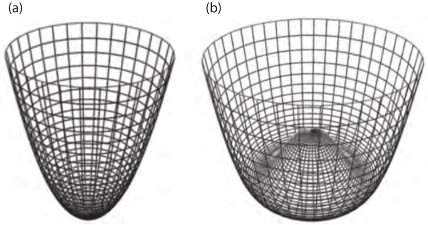
Each fermion has own g_f: m_f remain free parameters!

Two choices for the shape

- Notice: Lagrangian on previous page is symmetric under $SU(2)_L \times U(1)$
- But let's examine scalar self-coupling:

$$V(\phi^\dagger \phi) = \mu^2(\phi^\dagger \phi) + |\lambda|(\phi^\dagger \phi)^2$$

Potential is symmetric under rotations in ϕ space



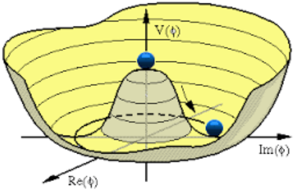
- If μ^2 positive, V is minimum at $\phi^\dagger \phi = 0$.
- If μ^2 negative, V is minimum at $\phi^\dagger \phi \neq 0$.

Introducing the VeV

$$V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|(\phi^\dagger\phi)^2$$

- Now, suppose μ^2 is negative

  Form of potential in complex space:



- Minimum not at $< \phi >= 0$
- Define minimum as “vacuum expectation value” (VeV) v:

$$v = \frac{|\mu|}{\sqrt{\lambda}}$$

Chosing a direction for the VeV

- $V(\phi^\dagger\phi)$ has a degenerate ground state
- Pick vacuum to make $<\phi>_0$ real

$$<\phi>_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}; \quad v = \sqrt{-\mu^2/|\lambda|}$$

- Spontaneous symmetry breaking in choice of ground state similar to how ferromagnet spontaneously chooses direction of B field
- Our choice conserves charge but breaks $SU(2)_L \times U(1)$ symmetry (see next page)

How operators act on $< \phi >$

$$\begin{aligned}
\tau_1 < \phi >_0 &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \\
\tau_2 < \phi >_0 &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \\
\tau_3 < \phi >_0 &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \\
Y < \phi >_0 &= +1 < \phi >_0 \\
\text{Therefore :} & \\
Q < \phi >_0 &= \frac{1}{2} (\tau_3 + Y) < \phi >_0 \\
&= \frac{1}{2} \begin{pmatrix} Y+1 & 0 \\ 0 & Y-1 \end{pmatrix} < \phi >_0 \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ 0 \end{pmatrix}
\end{aligned}$$

Excitations

- Examine small excitations about the ground state

$$\phi(x) = \phi_0 + h(x) = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v + \eta(x) \end{array} \right)$$

- Substituting into $\mathcal{L}_{scalar}$:

$$\begin{aligned} \mathcal{L}_{scalar} &= \mathcal{D}^{\mu}\phi\mathcal{D}_{\mu}\phi - V(\phi^{\dagger}\phi) \\ &= \frac{1}{2}(\partial_{\mu}\eta)^2 - \lambda v^2\eta^2 - \lambda v\eta^3 - \frac{1}{4}\lambda\eta^4 + const \end{aligned}$$

- 1^{st} term is kineteic energy term, 2^{nd} looks like mass term, others look like self interactions

  Interpret field η as particle (the Higgs) with mass $m_{\eta} = \sqrt{2\lambda v}$

Vector Boson Masses

- Coupling of ϕ to gauge bosons determined by

$$\mathcal{D}_\mu \equiv \partial_\mu + \frac{ig'}{2} a_\mu Y + \frac{ig}{2} \vec{\tau} \cdot \vec{b}_\mu$$

- Taking covariant derivative gives interaction term

$$\begin{aligned} \mathcal{L}_H &= \left(\frac{g'}{2} a + \frac{g}{2} \vec{\tau} \cdot \vec{b} \right) \phi_0 \\ &= \frac{1}{8} \left| \begin{pmatrix} g b^3 + g' a & g(b^1 - i b^2) \\ g(b^1 + i b^2) & -g b^3 + g' a \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \right| \end{aligned}$$

- Writing mass term in basis of W and Z fields:

$$\left(\frac{gv}{2} \right)^2 W^+ W^- + \frac{v^2}{8} Z^0 Z^0$$

- With

$$Z^0 = -g W^3 + g' a$$

- Giving mass

$$M_W = \frac{vg}{2} \quad M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

Calculating the W and Z Masses

- Using

$$M_W = \frac{vg}{2} \quad M_Z = \frac{v\sqrt{g^2+g'^2}}{2}$$

we find

$$\begin{aligned} M_Z &= \frac{\sqrt{g^2+g'^2}}{g} M_W = \frac{M_Z}{\cos\theta_W} \\ M_W &= \cos\theta_W M_Z \end{aligned}$$

- Also using fact that G_F measures W coupling at low q^2

$$\begin{aligned} \frac{g^2}{8} &= \frac{G_F M_W^2}{\sqrt{2}} = G_F \frac{g^2 v^2}{4\sqrt{2}} \\ v &= \frac{1}{2\sqrt{2} G_F} = 246 \text{ GeV} \end{aligned}$$

- Also can prove (see Thomson):

$$e = \frac{gg'}{\sqrt{g^2+g'^2}}$$

so

$$\begin{aligned} M_W^2 &= \frac{g^2 v^2}{4} = \frac{e^2 v^2}{4\sin^2\theta_W} \\ &= \frac{(37.3 \text{ GeV})^2}{\sin^2\theta_W} \sim 80 \text{ GeV} \end{aligned}$$

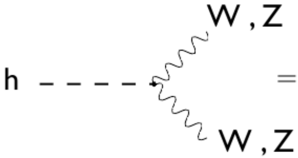
Some Observations

- Single fundamental Higgs is only simplest possible theory
- Important aspect is *dynamic* symmetry breaking where vacuum state breaks the symmetry rather than the Lagrangian
- SM predicted W and Z mass using values of G_F and $\sin\theta_W$ measured in β-decay and ν-scattering respectively
  - Predicted before W and Z decays observed experimentally
  - Gave motivation to build accelerators able to reach these energies
- Higgs mass not predicted by SM
  - $m_\eta = \sqrt{2\lambda v^2}$
  - We know v but not λ
- Fermion masses "explained" but masses themselves are just parameters of the theory

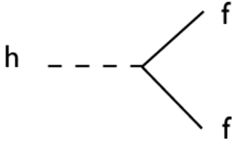
$$\mathcal{L}_{Yukawa} = -\frac{g_f}{\sqrt{2}}\left(\overline{\chi}_L \phi \chi_R + \overline{\chi}_R \phi \chi_L\right)$$

with unknown g_f

Couplings of the Higgs Completely Specified in SM



$$= \; gM_W \;,\; \frac{gM_Z}{\cos\theta_W}$$



$$= \frac{gM_f}{2M_W}$$

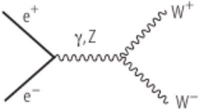
- Coupling to W^+W^- and ZZ defined by $\mathcal{L}$
- Coupling to fermions with strength that depends on fermion mass

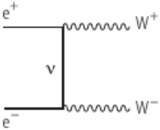
Counting Degrees of Freedom

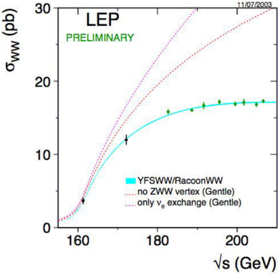
- Introduced a complex doublet field: 4 degrees of freedom
- Redefined this field through a change of variables
  - One component becomes the Higgs (a scalar)
  - When $W^{\pm}$ and Z were massless, only transverse polarizations allowed
  - When they gain mass, longitudinal polarizations also possible
  - 3 additional degrees of freedom become these longitudinally polarized states

Evidence for the Triple Gauge Coupling

- LEP-2 was above threshold for W^+W^- production
- Relevant Feynman diagrams:





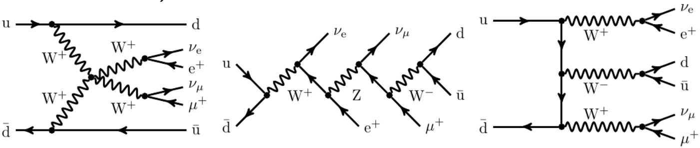


Higgs diagram negligable due to small electron mass

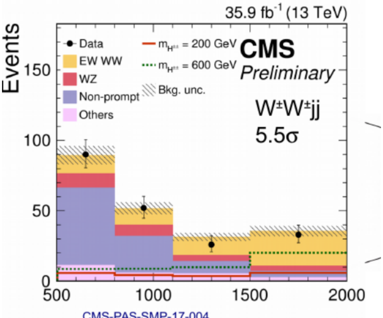
- Sum of all amplitudes has better high energy behavour than individual components
  - Cancellations among amplitudes due to gauge invariance
  - Connected to renormalizability

Quartic Coupings and Vector Boson Scattering

- LEP-2 not sensitive to quartic couplings; accessible at LHC
- $pp \to W^\pm W^\pm$ especially sensitive (other production mechanisms small)

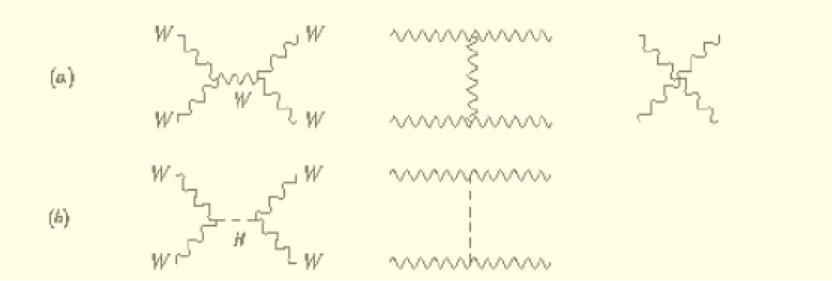


- Observed both by ATLAS and CMS
  - Statistical uncertainties still substantial



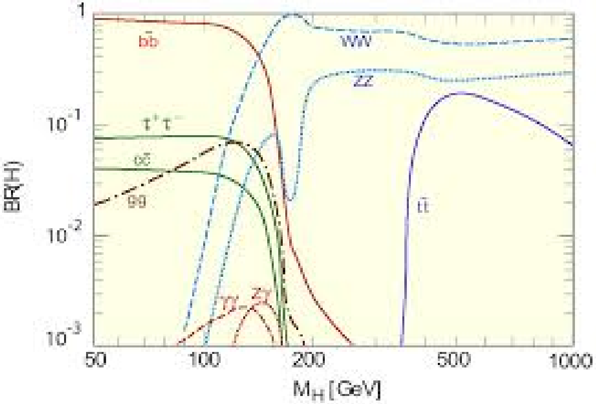
Longitudinal WW Scattering and the Higgs Mass

- The Higgs gives the W longitudinal polarization states
- Higgs diagrams important for longitudinal W scattering
- Without Higgs, cross section would rise with E_{cm}
- Unitary violation if no Higgs and no other new physics above the TeV scale
- Important argument for construction of the LHC



How does the Higgs Decay?

- Higgs mass not predicted by SM
- Higgs couples to EW bosons and to fermions
- Fermion couplings depend on m_f
- Higgs will decay to heaviest states it can

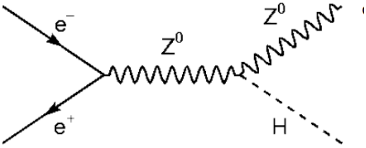


- Search strategy mass dependent

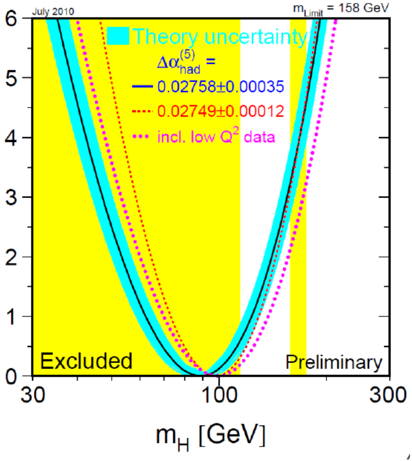
History of W/Z/Higgs Measurements

- Discovery of W (UA1 at $Sp\overline{p}S$) 1983
- Discovery of Z (UA1, UA2 at $Sp\overline{p}S$) 1983
- First Z observed from e^+e^- annihilation (Mark-II at SLC) 1989
- LEP turn-on 1989
- Lep-II reaches W-pair threshold 1996
- Higgs discovered at LHC 2012
- Since 2012, exploration of the Higgs at LHC

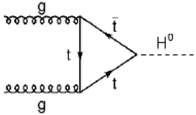
The Higgs and LEP



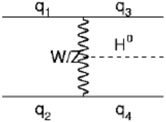
- Direct searches via Higgs-strahlung
- Indirect searches via radiative corrections
- No direct evidence for the Higgs constrains $m_H > 114$ GeV
- Indirect constraints suggest Higgs < 240 GeV if SM is correct



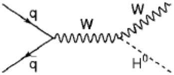
Higgs Production at the LHC



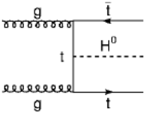
Gluon fusion: Largest cross-section



Vector Boson Fusion (VBF)

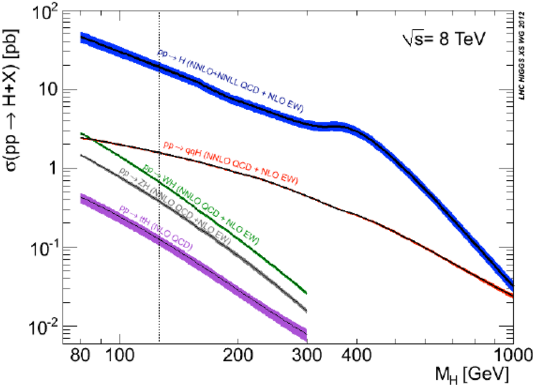


Associated production (VH)



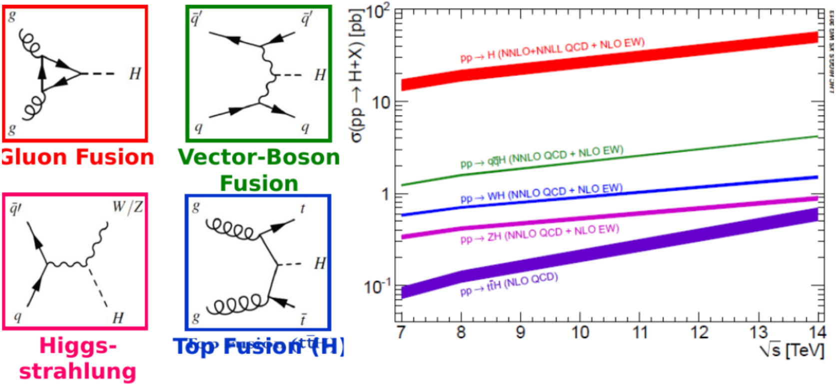
tth production

Cross Sections Calculated to NNLO



- At low mass, gluon fusion dominates
- Importance of VBF increases with m_H
- Associated production falls rapidly with m_H
- $t\bar{t}H$ always small

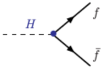
Dependence on Center of Mass Energy



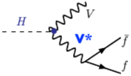
J. Olsen

Higgs Branching Fractions

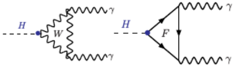
h → bb,ττ

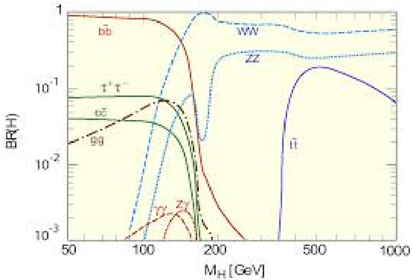


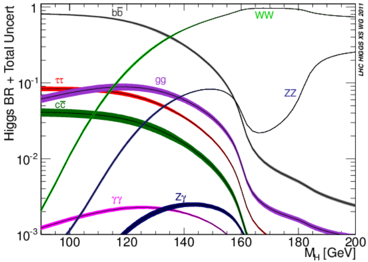
h → VV* → Vff



h → γγ

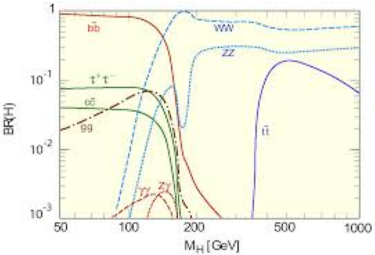






- Higgs likes to decay to the heaviest available states
- Once diboson channels open, they dominate
- Low mass: $h \to b\bar{b}$ largest mode
- $h \to VV^*$ significant for $m_h > 120$ GeV

Search Strategy (I)



- Before Higgs discovered, mass could be anywhere below ~ 1 TeV
- Indirect measurements favored light Higgs ($m_h <\sim 240$ GeV)
- Broad search strategy for all masses, production and decay modes
- If $m_h > 2M_Z$, $h \to ZZ$ is the golden mode
- For $m_h < 2M_Z$ look in multiple modes
  - Largest BR ($h \to b\bar{b}$) has huge background from QCD HF production
  - $h \to ZZ^*$ with leptonic decays clean but low rate ($BR(Z \to \ell\ell) \sim 3\%$ per species)
  - $h \to \gamma\gamma$ has good mass resolution but large continuum background
  - $h \to \tau\tau$ requires good τ identification

Search Strategy (II)

- Independent search in each decay mode
- For given mode, categorize events into categories with different S:B
  - These categories will also tell us about production mechanism
  - Important for measuring coupling
- Measure rate relative to SM prediction

$$\mu \equiv \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

- Initial discovery presented as p-value plot vs m_h
- Construct likelihood function from Poisson probabilities

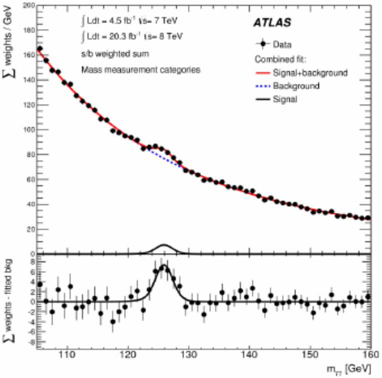
$$L(data|\mu,\theta) = \prod_i L(data_i|\mu,\theta_i)$$

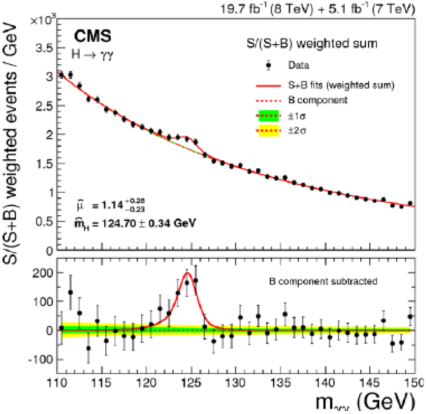
where i are the categories and θ are "nuisance parameters" representing systematic uncertainties

$h \to \gamma\gamma$

- Narrow peak over large continuum background
- Determine background from fit to data itself
- Depends critically on mass resolution
- Latest results more than 5σ each for ATLAS and CMS

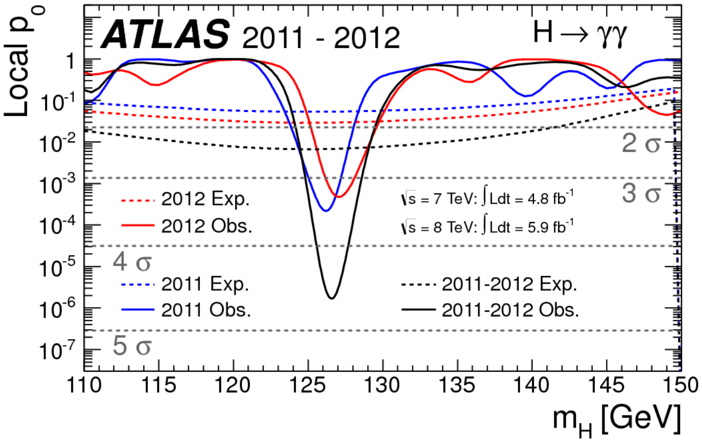
arXiv:1406.3827 (ATLAS)





arXiv:1407.0558 (CMS)

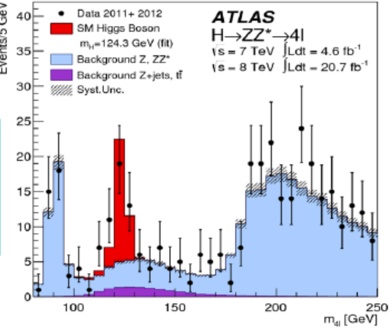
p-Value for $h \to \gamma\gamma$ from initial discovery paper

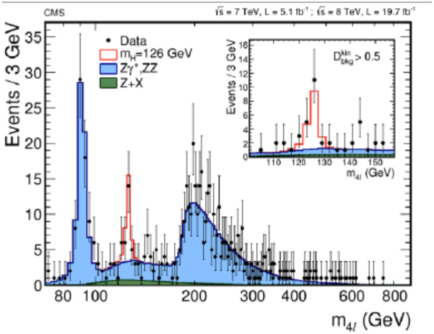


$h \to ZZ^* \to 4\ell$

- Clean signature with narrow peak
- SM background largely from ZZ
- Current measurement $\sim 6.5\sigma$ each in ATLAS and CMS

arXiv:1307.1427





arXiv:1312.5353 (CMS)

p-Value for $h \to ZZ^*$ from initial discovery paper