Higgs Physics

Hannes Mildner

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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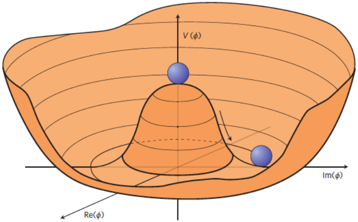
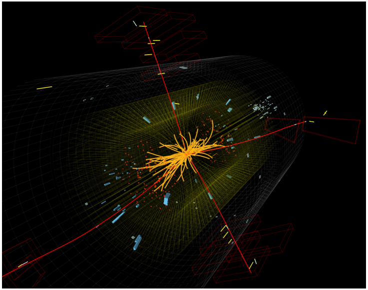
Introduction

- Introduction
- Theory
  - Fields, potential, and mass
  - Gauge theories (recap)
  - Symmetry breaking
  - The Standard Model
- Experiment
  - Search for the Higgs boson
  - Study of Higgs boson properties
  - Future of Higgs physics





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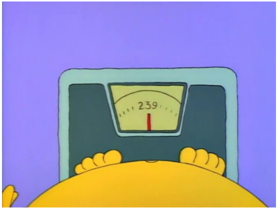

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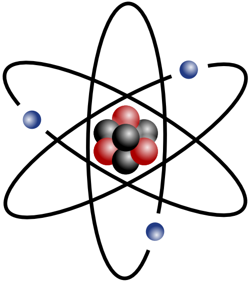

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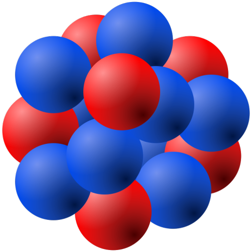

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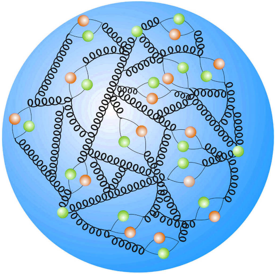

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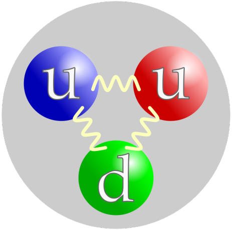
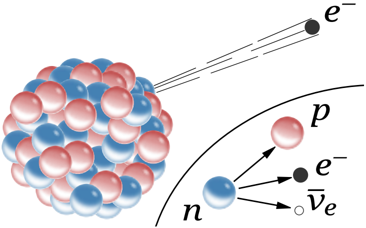
  - Rest mass of quarks only few MeV

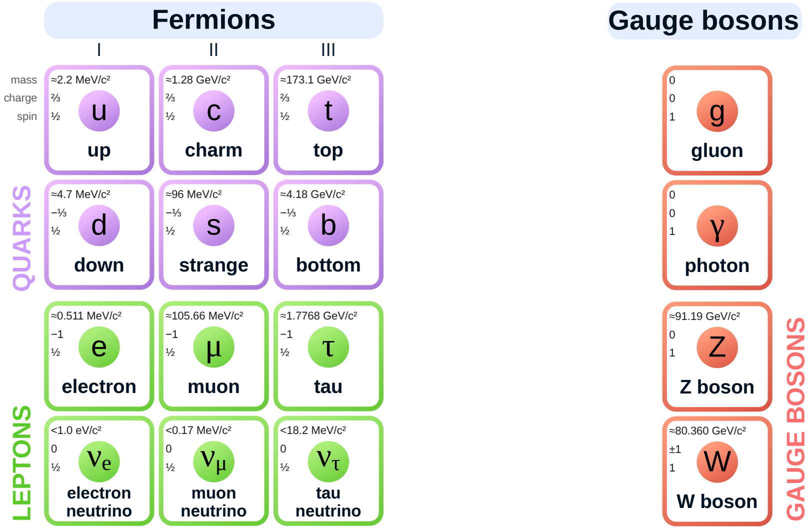


Elementary particle mass

- *Elementary* particle mass small but crucial, without it
  - Electrons would fly away ($r_{\text{atom}} \propto 1/m_e$)
  - Protons would decay ($m_p = m_n$)
  - Weak force wouldn't be ~~weak~~ short-ranged ($r \approx \frac{\hbar}{c m_W} \approx 10^{-18}$ m)
- So where does it come from?



Origin of elementary particle mass



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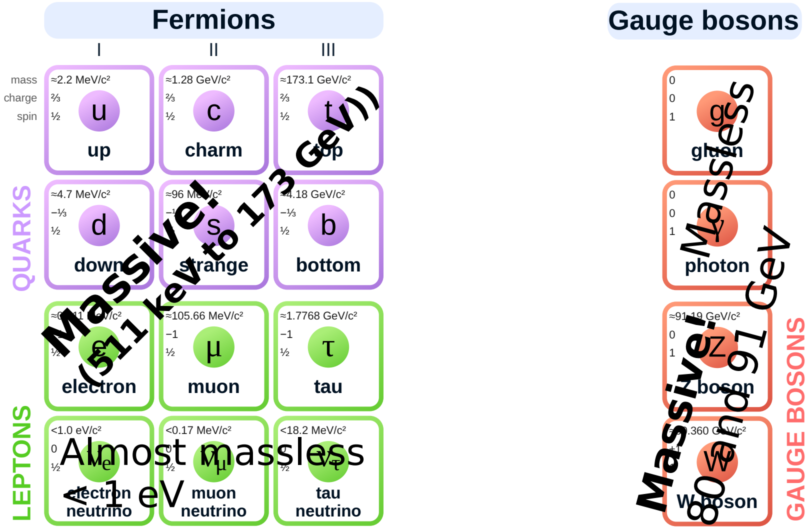

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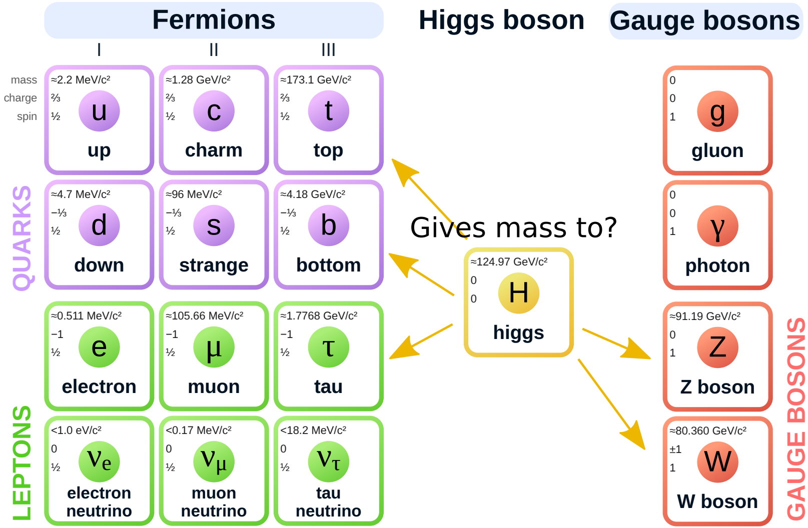

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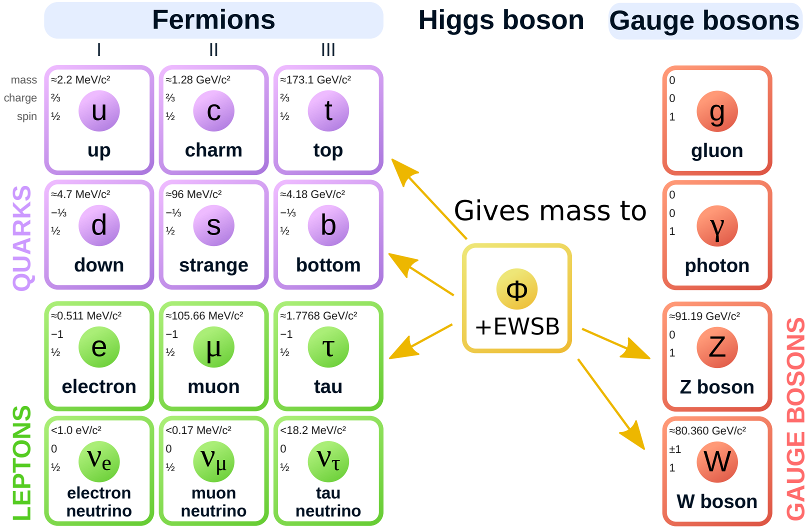

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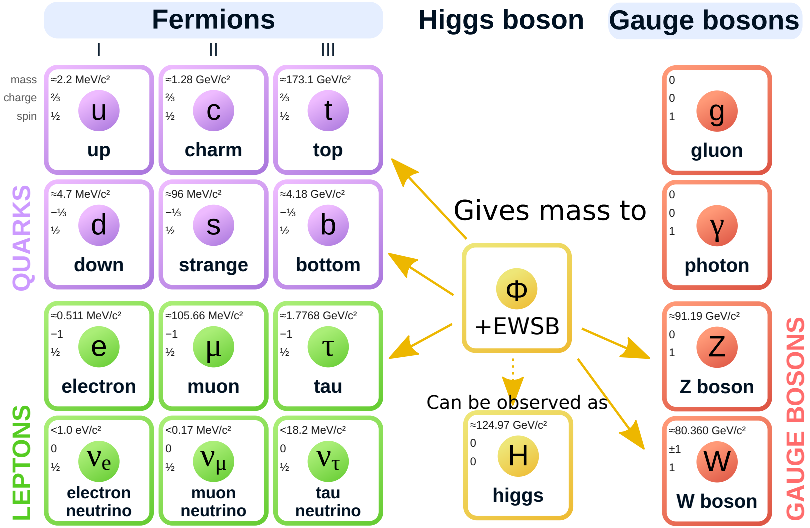

The Higgs mechanism – how does this actually work

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The Higgs mechanism – how does this actually work

- In the Standard Model, particle masses are introduced by electroweak symmetry breaking, using the Higgs Mechanism
- Will discuss a few things in more detail
  - Why do we need a field to “give mass”?
  - What is a (quantum) field?
  - How can it give particles mass?
  - How is it related to “electroweak symmetry breaking”?
  - How do we know it's there?

So... why do we need to give particles mass with a field

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  - Elegant
  - Analogue to EM force
  - Renormalizable (one can get rid of infinities)

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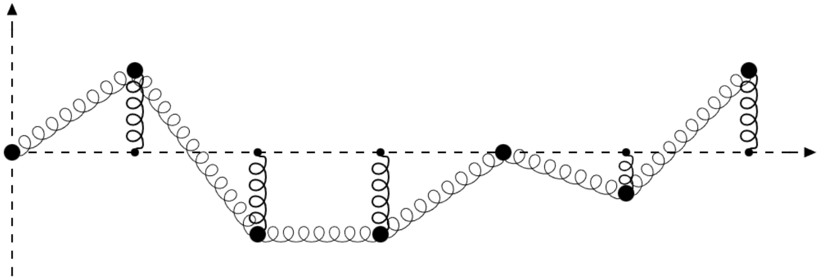
- And fermion mass also not compatible with SM gauge symmetry...
- The Higgs mechanism allows us to “work around” these issues

Fields, potential, and mass

A field and its potential

- Will recap first
  - What is a field
  - What is the potential of a field
- For that, I brought you the infinite spring model

Infinite spring model



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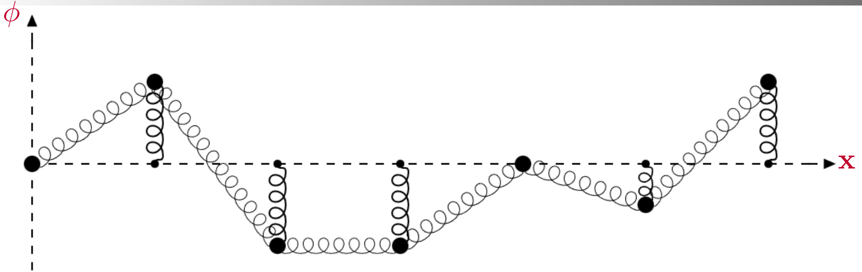

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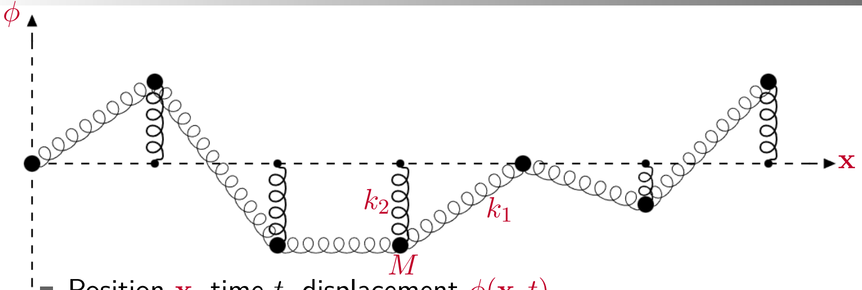

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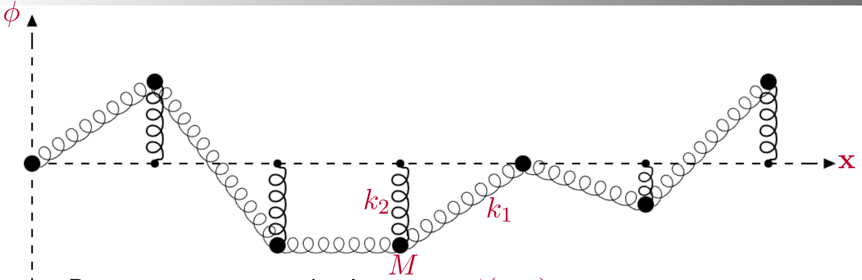

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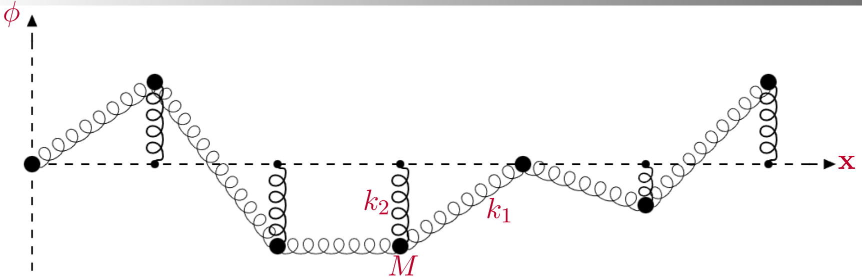

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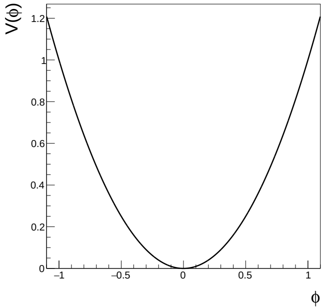
- Mass M , coupling to neighbor k_1, individual coupling k_2
- Kinetic energy: $\frac{1}{2}M(\frac{\partial\phi(\mathbf{x},t)}{\partial t})^2$
- Potential energy:

$$V = \frac{1}{2}k_1(\frac{\partial\phi(\mathbf{x},t)}{\partial\mathbf{x}})^2 + \frac{1}{2}k_2\phi(\mathbf{x}, t)^2$$



Towards a relativistic Lagrangian

Some simple algebra

$$L_{\text{springs}} = \underbrace{\frac{1}{2}M(\frac{\partial\phi(\mathbf{x},t)}{\partial t})^2}_{T} \underbrace{-\frac{1}{2}k_1(\frac{\partial\phi(\mathbf{x},t)}{\partial \mathbf{x}})^2 - \frac{1}{2}k_2\phi(\mathbf{x},t)^2}_{-V}$$

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- Replace M, k_1, k_2 with c, $\hbar$, m

$\leftrightarrow \frac{1}{2}\frac{1}{c^2}(\frac{\partial\phi(\mathbf{x},t)}{\partial t})^2 - \frac{1}{2}(\frac{\partial\phi(\mathbf{x},t)}{\partial \mathbf{x}})^2 - \frac{1}{2}m^2\frac{c^2}{\hbar^2}\phi^2(\mathbf{x},t)$

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- Four-vector notation and $c = 1$, $\hbar = 1$:

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- Lagrangian for relativistic wave equation (Klein–Gordon equation) $L_\phi = \frac{1}{2}(\partial_\mu\phi(x))(\partial^\mu\phi(x)) - \frac{1}{2}m^2\phi^2(x)$
- m^2 corresponds to individual spring coupling k_2 (not M) – related to *potential energy* from absolute displacement of ϕ

Klein–Gordon equation

Bonus: let's solve the field equation

- With Euler–Lagrange equation: $\partial_\mu(\frac{\partial L}{\partial(\partial_\mu \phi)}) - \frac{\partial L}{\partial \phi} = 0$

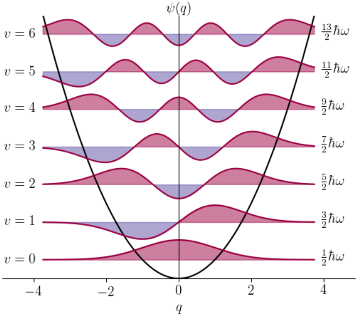
  $L = \frac{1}{2}\partial_\mu \phi(x) \partial^\mu \phi(x) - \frac{1}{2} m^2 \phi(x)^2$

  $\Rightarrow \partial_\mu \partial^\mu \phi + m^2 \phi = 0$
- Expand: $(i\frac{\partial}{\partial t})^2 \phi = ((-i\nabla)^2 + m^2)\phi \leftrightarrow E^2 = \boldsymbol{p}^2 c^2 + m^2 c^4$

- Take away: solutions of Klein–Gordon equation obey dispersion relation $E^2 = \boldsymbol{p}^2 c^2 + m^2 c^4$

Particles

- Nature is described by quantum field theory (QFT)
- In QFT: particles *discrete* excitations of field
- Energy of particles: $E^2 = p^2 + m^2$ (m^2 from quadr. potential term)
- m is minimum energy cost for particle creation
  - Photons can be generated with arbitrarily low energy (e.g. radio waves)
  - Electrons: need to pay at least 511 keV
- Reminiscent of minimum energy required to excite QM harmonic oscillator



Gauge theories

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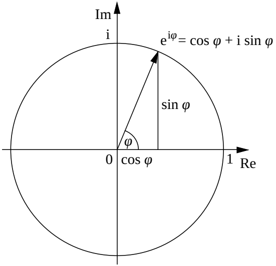

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- Conserved current – according to Noether's theorem – turns out to be electric charge

Local symmetry

- Recipe to introduce interaction: *demand* local symmetry!
  - Why? Will spit out a nice theory that describes nature.
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  - $A_\mu(x)$: a field, a Lorentz vector, with gauge invariance... it's the electromagnetic potential $A^\mu = (\phi_E, \mathbf{A})$

Reminder: gauge invariance of A^μ

EM potential: $A^\mu = (\phi_E, \mathbf{A})$

- $\mathbf{E} = -\nabla\phi_E - \frac{\partial \mathbf{A}}{\partial t}$, $\mathbf{B} = \nabla \times \mathbf{A}$
- $\phi_E \to \phi_E - \frac{\partial}{\partial_t}\alpha$, $\mathbf{A} \to \mathbf{A} + \nabla\alpha$

QED

Lagrangian for a vector field

$$L_A = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}M^2 A_\mu A^\mu$$

- First part: EM field strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, invariant under $A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x)$
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- Constructed QED for charged spin zero particle:

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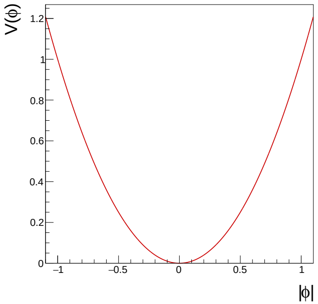
  - Massless gauge field, massive scalar
  - Fields are coupled through covariant derivative
- How to get a massive gauge field?

Symmetry Breaking

Mexican hat potential

- Let's try modifying the Lagrangian of the scalar (to make the gauge field massive...)
  $L_\phi = (D_\mu \phi)^* (D^\mu \phi) - m^2 \phi^* \phi$



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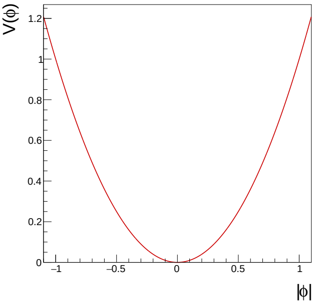

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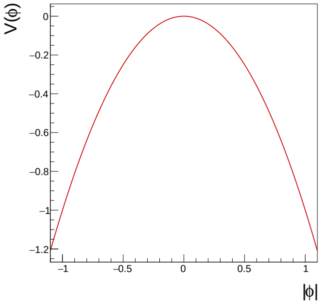

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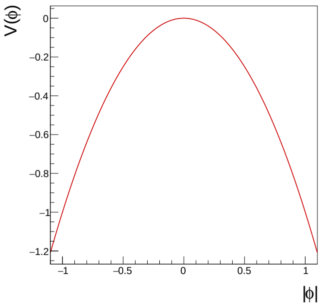

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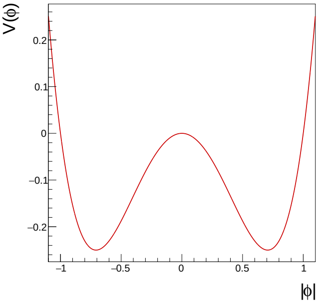
  - Add extra term $\lambda(\phi^*\phi)^2$, too (a four-boson "self-coupling")



Mexican hat potential

- Let's try modifying the Lagrangian of the scalar (to make the gauge field massive...) $L_\phi = (D_\mu\phi)^*(D^\mu\phi) - \mu^2\phi^*\phi - \lambda(\phi^*\phi)^2$
- Can we switch the sign of m^2
  - Just some parameter, why not
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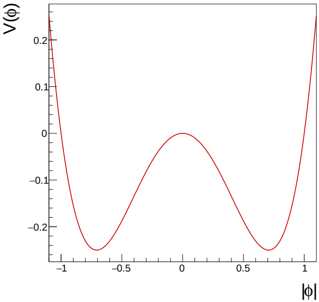

- Why these terms? Because we can: Gauge symmetry (✓), Lorentz invariance (✓), energy dimension of L is 4 (✓)
- Great feature of QFTs: greatly restrict our ability to add extra terms in a *fundamental* theory – this is one of the few we can add

Symmetry breaking... for the springs

- Again instructive to look at the infinite spring model
- Equivalent potential: $V = \frac{1}{2}k_1(\frac{\partial\phi(x)}{\partial x})^2 + \frac{1}{2}k_2\phi^2(x) + \frac{1}{4}k_3\phi^4(x)$
  - $k_2 < 0$: weird spring that pushes stronger the more you pull it
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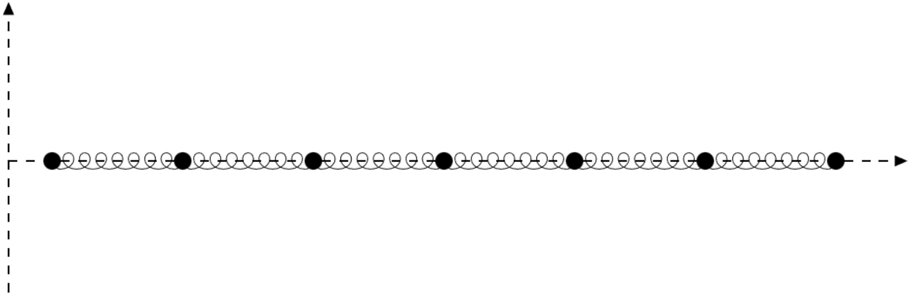

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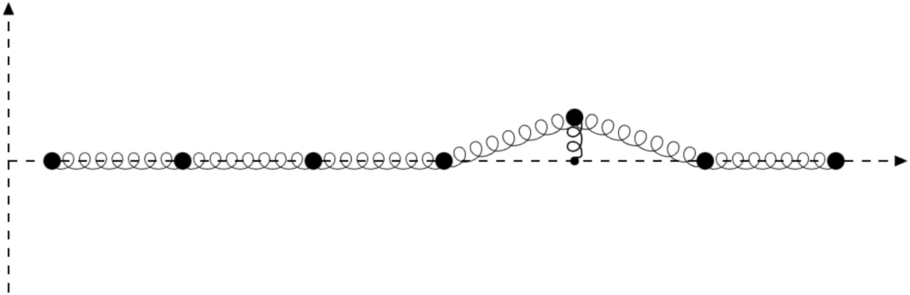

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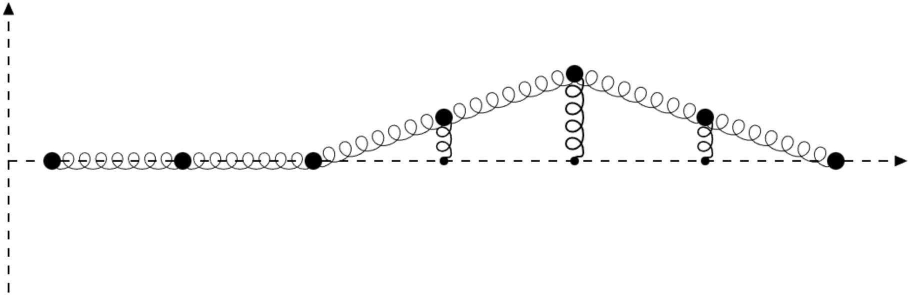

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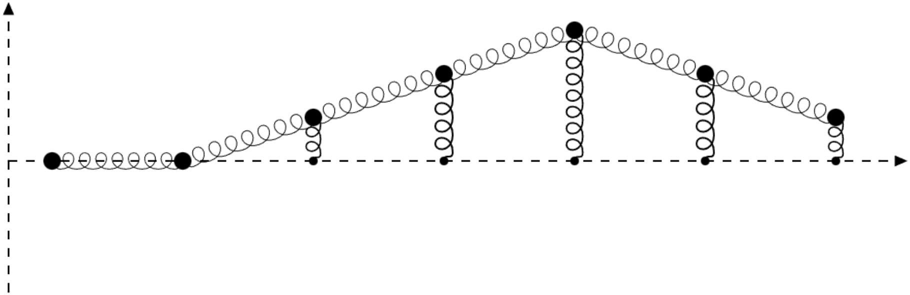

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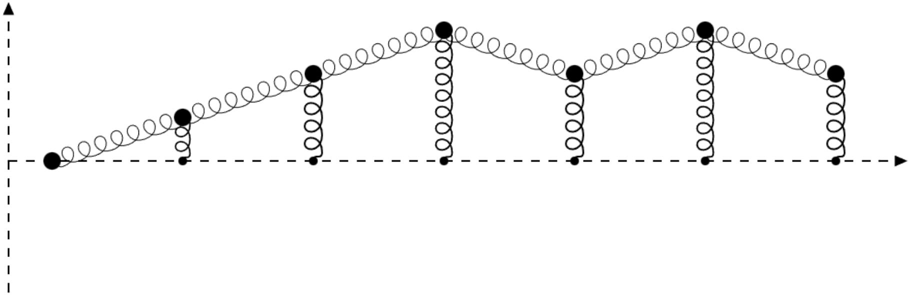

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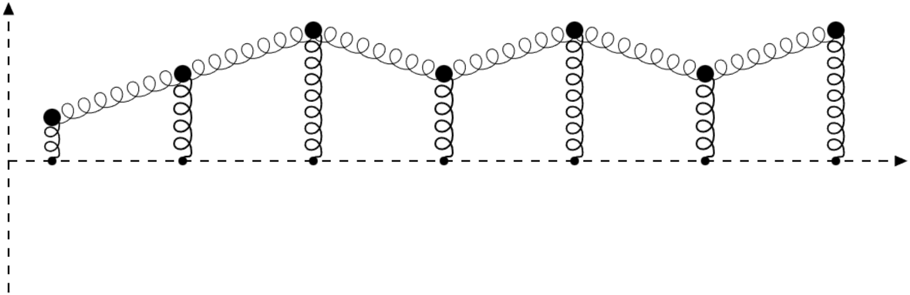

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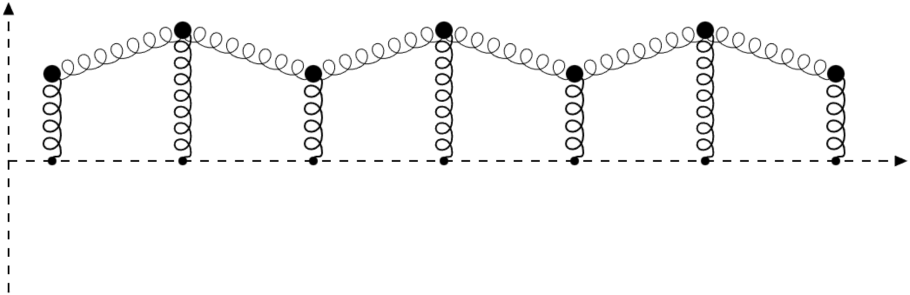

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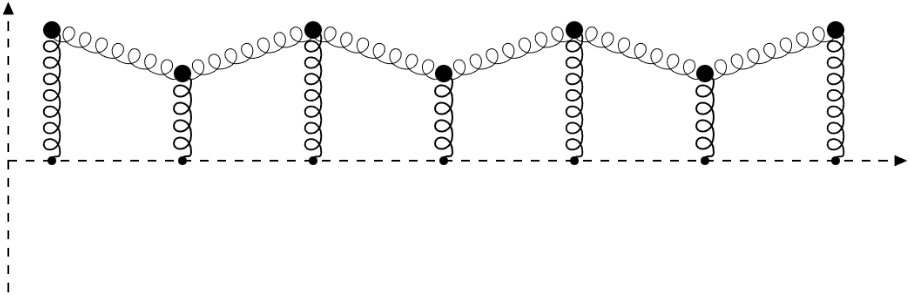

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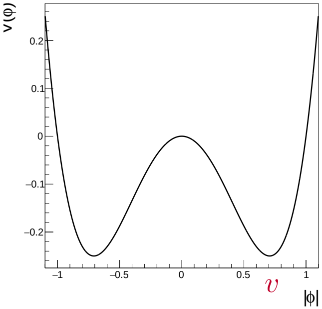

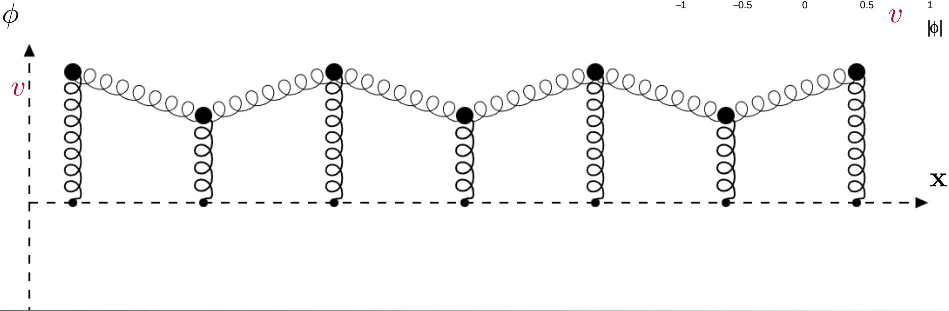

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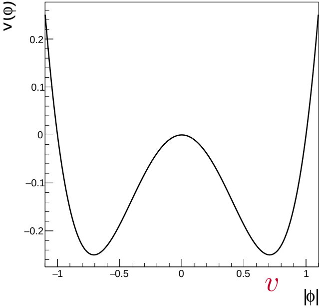

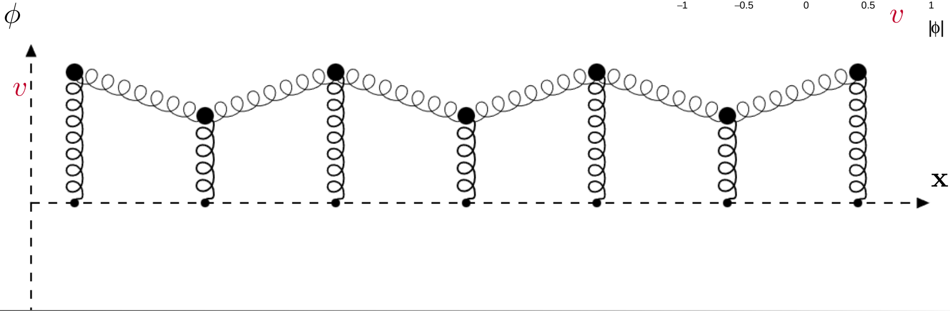

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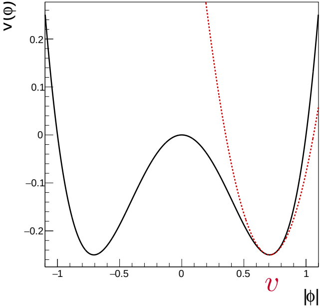
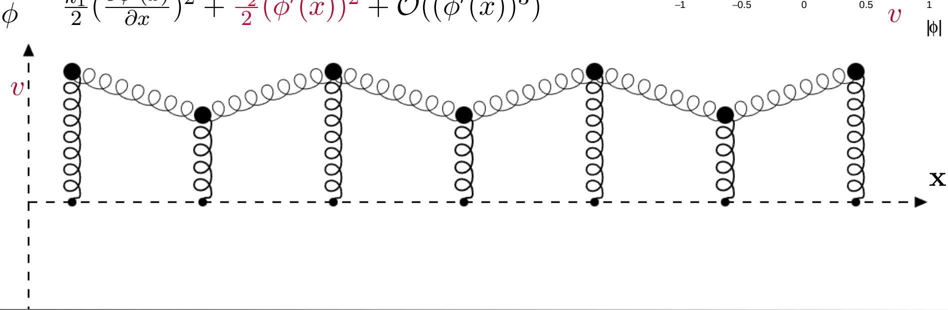
- Can approximate potential by $V(\phi'(x)) \approx \frac{k_1}{2}(\frac{\partial\phi'(x)}{\partial x})^2 + \frac{k_2'}{2}(\phi'(x))^2 + \mathcal{O}((\phi'(x))^3)$





Symmetry breaking for $U(1)$

- Back to our complex scalar field
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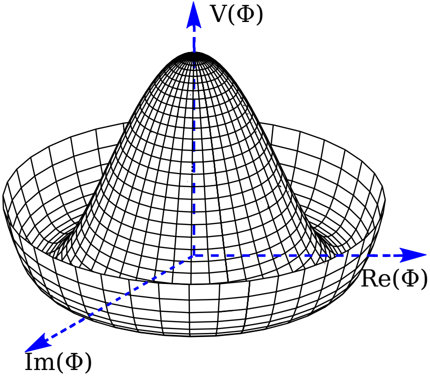

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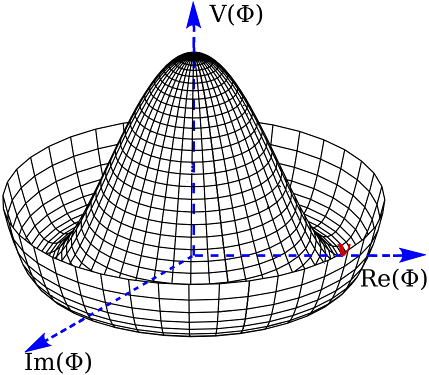

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- Expand field around minimum in terms of two real fields:
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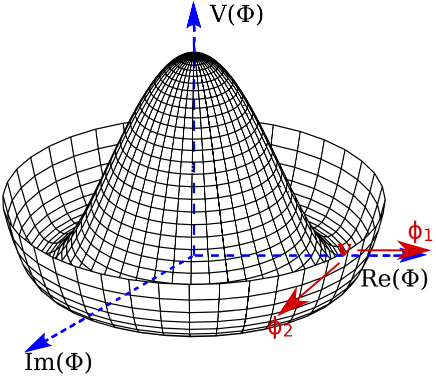
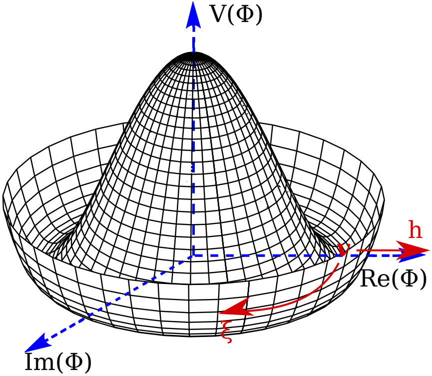


The would-be Goldstone boson

- To first order:
  $\phi(x) = \frac{1}{\sqrt{2}}(v+\phi_1(x)+i\phi_2(x)) \approx \frac{1}{\sqrt{2}}(v + h(x))e^{i\xi(x)/v}$



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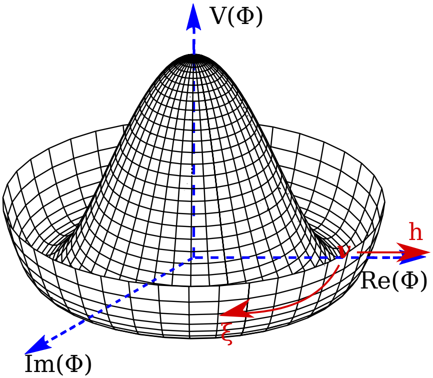

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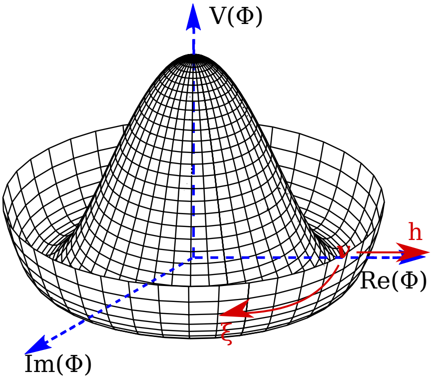

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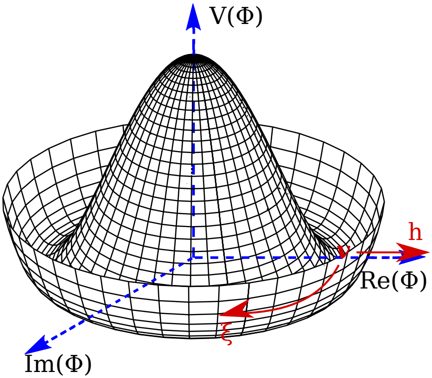
- Massless boson ξ? $\rightarrow$ would-be Goldstone boson
  - Remove massless boson everywhere by choosing gauge $\phi(x) \rightarrow \phi(x)e^{-i\xi(x)/v}$
  - No Goldstone boson, no (apparent) $U(1)$ symmetry: $\phi(x) = \frac{1}{\sqrt{2}}(v + h(x))$



Symmetry breaking: consequence for the gauge field

- Start out with scalar QED Lagrangian:
  $L = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + (D_\mu \phi)^* (D^\mu \phi) - V(\phi)$

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- Interacts with h proportional to mass, $g_{hAA} = g^2v = \frac{M_A}{v}$
- Massive vector field: 3 polarizations – degrees of freedom conserved (A_μ "eats" the Goldstone boson ξ and thus becomes massive)

Taking stock

- We've just seen the Higgs mechanism in action
- Ground state "spontaneously" breaks the $U(1)$ gauge symmetry
- Physics of the scalar field described by
  - One massive scalar field h (direction up the potential)
  - "Unphysical" massless scalar field – removed thanks to gauge symmetry
- Gauge field gets mass, function of gauge coupling g and vacuum epectation value v
- Gauge field couples to h proportional to mass
- SM is only slightly more complicated

Symmetry breaking in the Standard Model

SM gauge symmetries: reminder

Recall SM gauge sector:

- Electroweak symmetries: $U(1)_Y$ and $SU(2)_L$
- For $U \in SU(2)$
  - $U^\dagger U = 1$, $\det(U) = 1$
  - $U = e^{i\alpha^a \tau_a}$
  - τ_a: generators of $SU(2)$ ($a = 1, 2, 3$)
- Covariant derivative $D_\mu = \partial_\mu - ig_2 \frac{\tau_a}{2} W_\mu^a - ig_1 \frac{1}{2} Y B_\mu$
  - Gives us local $U(1)$ and $SU(2)$ gauge freedom
  - Gauge fields B_μ and W_μ^a
  - Gauge couplings g_1 and g_2, $g_1 \neq g_2$
  - Hypercharge Y and weak isospin T_3, $Q = T_3 + \frac{1}{2} Y$

The Higgs in the SM

- We need a scalar taking part in gauge interactions:
  Scalar doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, hypercharge $Y = 1$

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- "Gauge away" Goldstone bosons
- Expand $\Phi(x) = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$ to understand physics

The Higgs in the SM

Expanding the covariant derivative

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Expanding the covariant derivative

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The mass eigenstates

- Get fields with well-defined mass as linear combination of W^a and B
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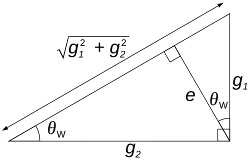

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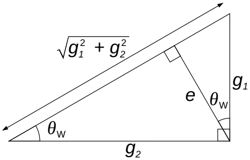

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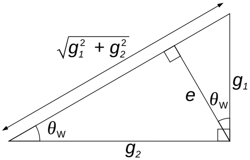

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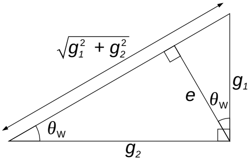

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- Results in $M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2}$, $M_W = \frac{1}{2} v g_2$, and $M_A = 0$
- Will give us the correct couplings (e.g. A_{μ} couples to e_L and e_R equally but not to ν_L), nice to figure out on a piece of paper...

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How to see this

- Fermions obey Dirac Lagrangian
  $L_D = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi$, $\bar{\psi} = \psi^\dagger\gamma^0$
- Can choose to write ψ in terms of *chiral* spinors $\psi = \begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix}$,

  $\gamma^0 = \begin{pmatrix} & 1 \\ 1 & \end{pmatrix}$, $\gamma^i = \begin{pmatrix} & \sigma_i \\ -\sigma_i & \end{pmatrix}$
- γ^0 flips ψ_L and ψ_R, $\gamma^0\gamma^i$ doesn't

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- Slightly more complicated for quarks (as well as massive ν...)

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- Vacuum expectation value v at the minimum of potential

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v from minimum of $V(\Phi)$

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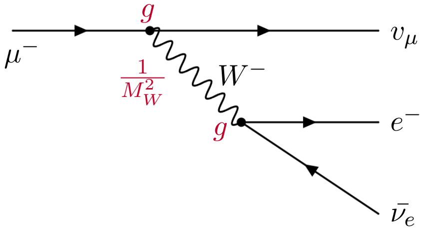

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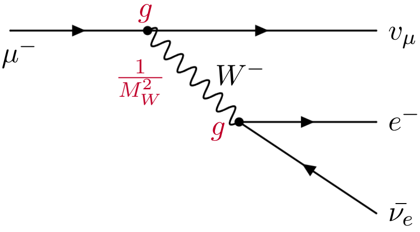
  - Turns out: $v = \frac{1}{\sqrt{\sqrt{2}G_\mu}} = 246\,\mathrm{GeV}$



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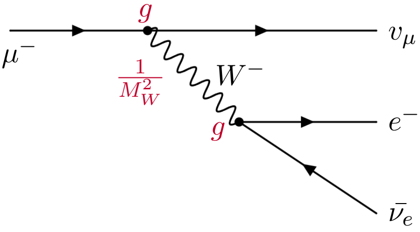

- v defines the “electroweak scale”
- SM particle mass: v multiplied with dimensionless coupling

Higgs mass and self couplings

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- Three-Higgs and four-Higgs interactions: $\propto \frac{M_H^2}{v}$ and $\propto \frac{M_H^2}{v^2}$
- Self-interaction only coupling requiring knowledge of M_H
  $\Rightarrow$ very hard to predict M_H (contrast to M_W, M_Z)

Higgs boson: predictions

- Higgs mechanism predicts an elementary scalar field (unheard of!)
- With a vacuum expectation value (outlandish!)
- This solves a lot of issues... (maybe there *is* something to it...)
- But how do we "prove" it's there? Generate Higgs bosons H! This gives us a huge number of testable hypotheses (selection):
  - New particle H
  - With spin zero
  - Couples to bosons like $g_{hVV} \propto \frac{m_V^2}{v}$, $g_{hhVV} \propto \frac{m_V^2}{v^2}$
  - Couples to fermions like $g_{hff} \propto \frac{m_f}{v}$
  - Couples to itself $g_{HHH} \propto \frac{M_H^2}{v}$, $g_{HHHH} \propto \frac{M_H^2}{v^2}$
  - Unfortunately, no idea about its mass...

Chronology

Quick chronology:

1962 Anderson: symmetry breaking not always with massless bosons

1964 Higgs: proposes the Higgs mechanism (relativistic variant)

1964 Brout and Englert as well as Guralnik, Hagen, Kibble: do so, too

1967 Weinberg: a model of leptons – the SM is born

1971 t Hooft and Veltman: SM is renormalizable

Only then the hunt for the Higgs boson really started...

Search for the Higgs boson

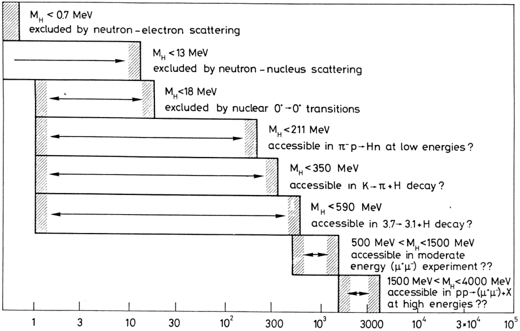
Higgs hunting: 70s

- An early discussion of a Higgs search in 1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva



- Excluding $< 18\,\mathrm{MeV}$
- Suggesting $\mathcal{O}(100\,\mathrm{MeV})$ searches

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- An early discussion of a Higgs search in 1976
- Not very optimistic

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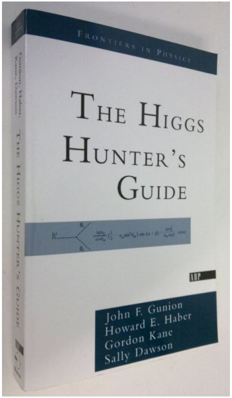
CERN -- Geneva

For $m_H > 4$ GeV the Higgs boson's production cross-section by any mechanism we have been able to think of is minute, and it decays predominantly to as yet conjectural [3)-5)] massive new particles.

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs hunting: 80s

- In 1989 books are filled... e.g., Higgs cross-sections calculated for M_H up to 1 TeV (at canceled SSC)



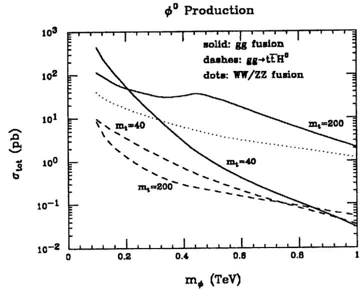
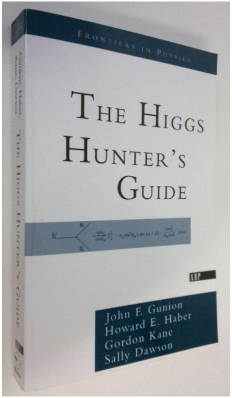


Figure 3.32 Cross sections for ϕ^0 production at the SSC deriving from reactions (3.95), (3.96), and (3.97) are given as a function of the Higgs mass for two extreme values of the top quark mass, $m_t = 40$ and $m_t = 200$ GeV. From ref. 173.

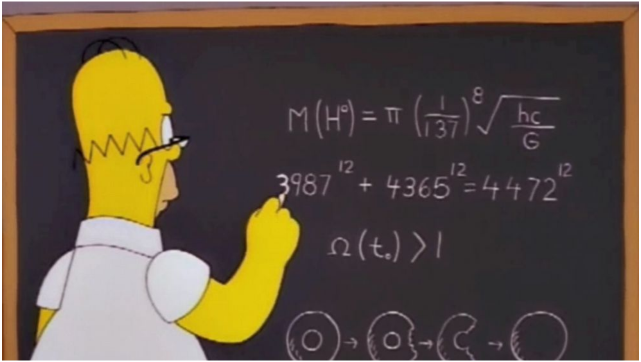
Higgs hunting: 80s

- In 1989 books are filled... e.g., Higgs cross-sections calculated for M_H up to 1 TeV (at canceled SSC)
- Much more pushy... make sure the LHC can handle high luminosity



cessible at the SSC. During the course of the SSC discussions we noted in several places that the LHC would have great difficulty in probing either type of Higgs sector, unless it can be designed to operate and experiments can be run at $\mathcal{L} \gtrsim 10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ without harming the detector's ability to study the relevant modes.

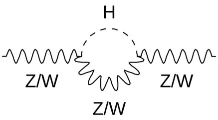
Higgs hunting: 90s

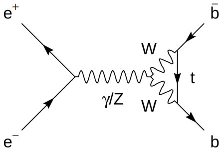


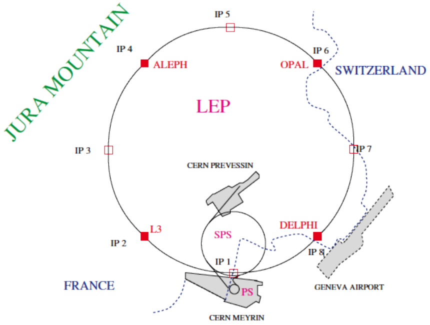
- Great decade for Higgs mass predictions
- $M_H^{\text{Homer}} = \pi\alpha^8 m_P \approx 300\,\text{GeV}$, not too bad

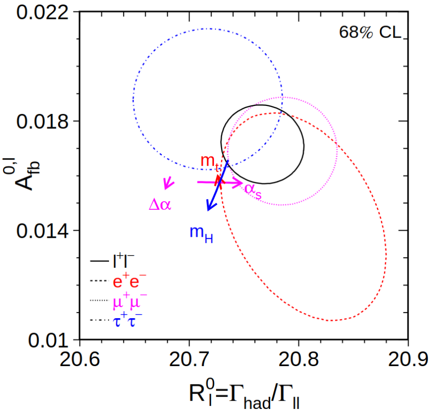
Higgs hunting: 90s LEP, SLD and Tevatron

- Precision measurements at LEP (and SLD) sensitive to Higgs trough virtual corrections



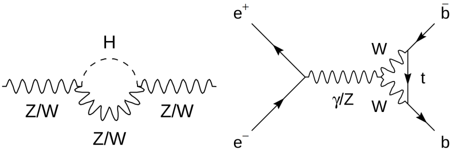


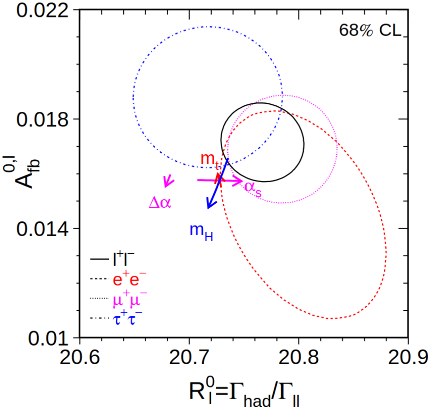


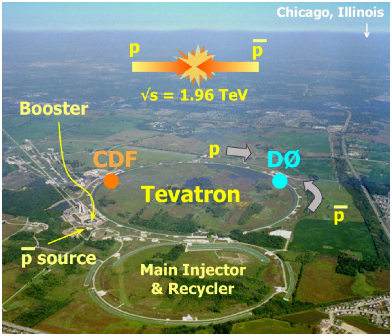


Higgs hunting: 90s LEP, SLD and Tevatron

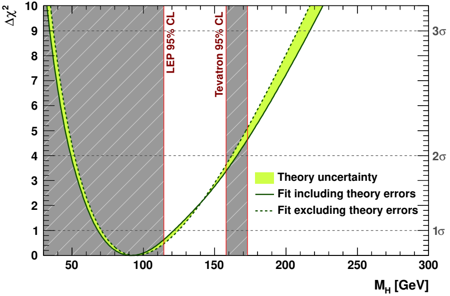
- Precision measurements at LEP (and SLD) sensitive to Higgs trough virtual corrections
- Tevatron measures m_t, direct searches at LEP and Tevatron







Higgs hunting: after LEP, SLD, and Tevatron (2011)



- Indirect constraint (combined fit of observables from LEP, SLD, and Tevatron): $91^{+30}_{-23}\mathrm{GeV}$

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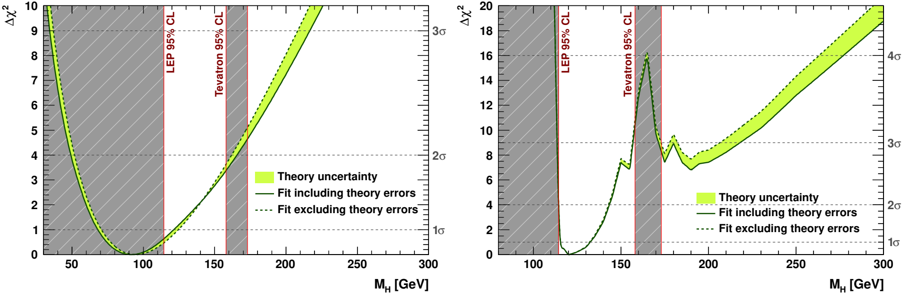

- Indirect constraint (combined fit of observables from LEP, SLD, and Tevatron): $91^{+30}_{-23}\mathrm{GeV}$
- Including direct searches (LEP, Tevatron, early LHC): $120^{+12}_{-5}\mathrm{GeV}$

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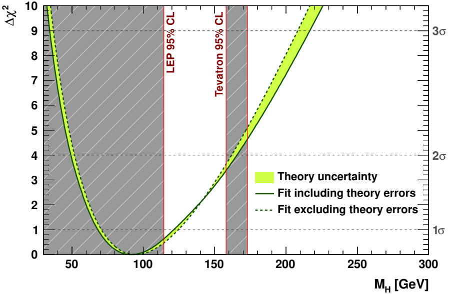
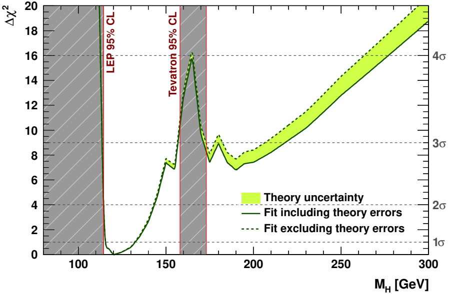
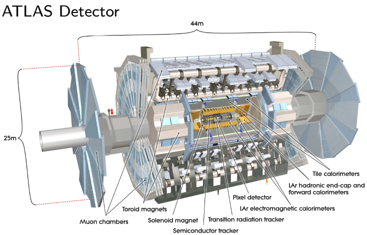
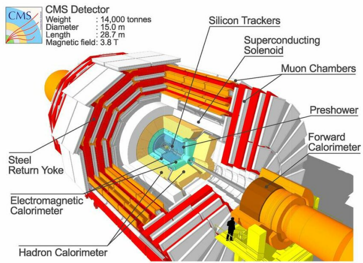




- Indirect constraint (combined fit of observables from LEP, SLD, and Tevatron): $91^{+30}_{-23}\mathrm{GeV}$
- Including direct searches (LEP, Tevatron, early LHC): $120^{+12}_{-5}\mathrm{GeV}$
- Doesn't mean Higgs with $M_H \approx 120\,\mathrm{GeV}$ exists – it's the most likely mass if it exists and is *exactly* as in the SM

LHC



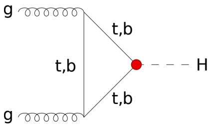


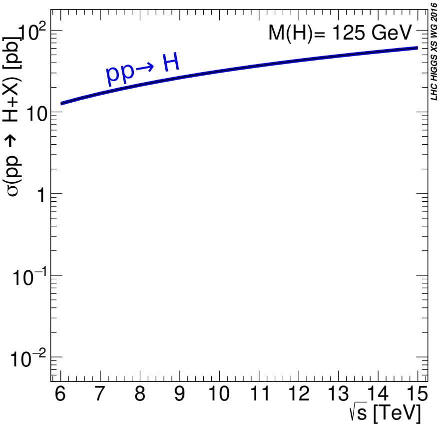
- From 2011 on, ATLAS and CMS were finally collecting large amounts of collision data at the LHC
- First at a centre-of-mass energy of 7 TeV, in 2012 at 8 TeV, later 13 TeV

Higgs production modes

- How do we produce the Higgs in proton collisions at the LHC?
- Quarks and gluons massless – need particles that couple to proton constituents and Higgs: weak bosons and top quark

Higgs production modes

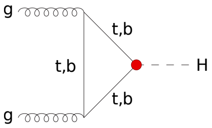


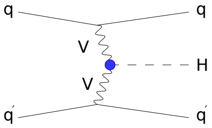


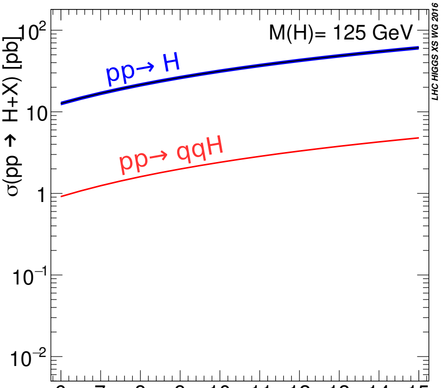
#1 $pp \to H$ ("ggH" or "ggF")

- Largest cross-section – loop-suppressed but
  - Large couplings: top Yukawa and α_S
  - Low-mass gluon final state preferred by parton distribution function (loads of gluons with small momentum fraction in proton)

Higgs production modes





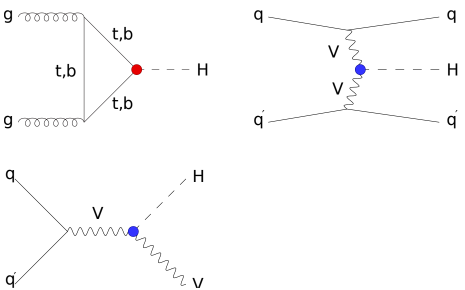


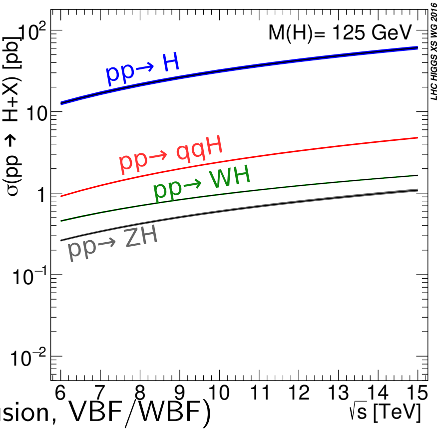
#1 $pp \to H$ ("ggH" or "ggF")

#2 $pp \to qqH$ (vector/weak boson fusion, VBF/WBF)

- Associated quarks generate forward and backward jets, helping to identify Higgs events
- Sensitive to boson coupling

Higgs production modes



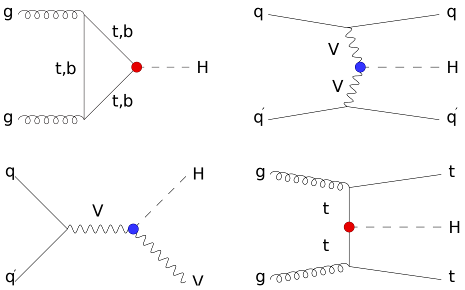


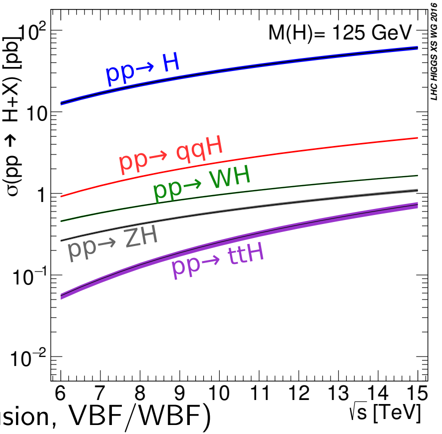
#1 $pp \to H$ (“ggH” or “ggF”)

#2 $pp \to qqH$ (vector/weak boson fusion, VBF/WBF)

#3 $pp \to VH$ (Higgs strahlung)

- Leptons from W or Z decay important for identification in jetty LHC environment





$\#1\ pp \to H$ ("ggH" or "ggF")

$\#2\ pp \to qqH$ (vector/weak boson fusion, VBF/WBF)

$\#3\ pp \to VH$ (Higgs strahlung)

$\#4\ pp \to t\bar{t}H$ (ttH)

- Spectacular but messy final state due to top quark decays

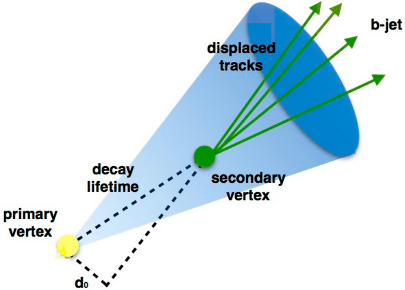
Higgs decays

Higgs boson branching ratios ($BR_i = \frac{\Gamma_i}{\Gamma_{\text{tot}}}$, with $\Gamma_{\text{tot}} = \sum_i \Gamma_i$):

Higgs decays

Higgs boson branching ratios ($BR_i = \frac{\Gamma_i}{\Gamma_{\text{tot}}}$, with $\Gamma_{\text{tot}} = \sum_i \Gamma_i$):

1. 58% $b\bar{b}$: Large rate due to b Yukawa coupling: $\Gamma_{H\to f\bar{f}} = \frac{N_c m_f^2 M_H \beta_f^3}{8\pi v^2}$
   - m_b largest fermion mass with $2m_b < M_H$, colour factor $N_c = 3$ for quarks, velocity $\beta_f \approx 1$
   - b-quarks form short-lived b-hadrons – decays after $\mathcal{O}(\text{cm})$ flight are identified with "b-tagging" algorithms



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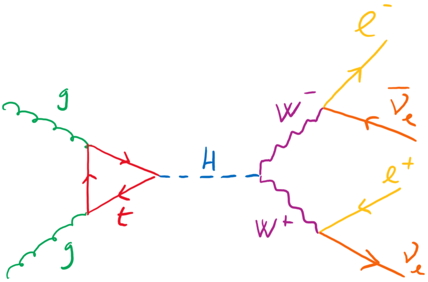
2. 21% WW^*: Useful if both Ws decay into leptons (5% of all cases)
   - Mediated by "off-shell" W^* boson with $m < M_W$
   - Poor mass resolution due to invisible neutrinos



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4. 6% $\tau^+\tau^-$: Characteristic one-prong and three-prong decays
   - Both leptonic decays ($\tau \to \ell\nu_\ell\nu_\tau$) and hadronic decays possible
   - Always missing mass due to neutrinos – poor resolution

Higgs decays

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6. 3% ZZ^*: Golden channel when both Z bosons decay into leptons
   - In that case, small background, can fully reconstruct mass
   - Only 0.5% of all ZZ^* decays (0.015% of Higgs decays)

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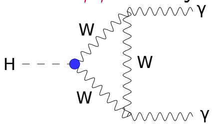
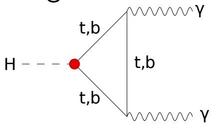
7. 0.2% $\gamma\gamma$: Fairly clean signal but relatively large background





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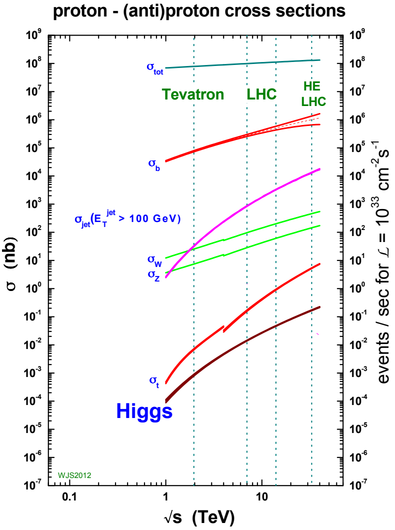
7. 0.2% $\gamma\gamma$: Fairly clean signal but relatively large background
8. 0.2% $Z\gamma$: Interesting if $Z \to \ell\ell$
9. 0.02% $\mu\mu$: Rarest decay we have a chance to find

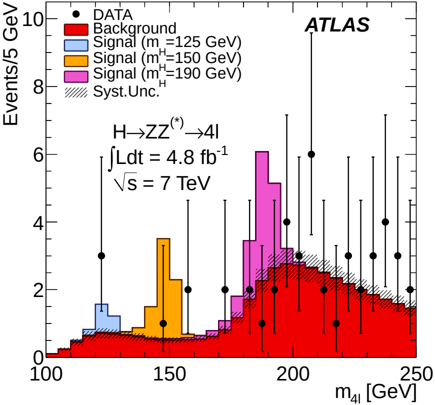
Number of signal and background events

- Higgs production is rare
  - pp cross-section $10^8\,\mathrm{nb}$: $> 10^{14}$ collisions in 2011
  - Most events: jet production
  - $10^2\,\mathrm{nb}$: W and Z production (main source of isolated leptons)
  - Higgs production: $< 10^{-2}\,\mathrm{nb}$!
- Higgs events in 2011 (until today)
  - $H(4\ell)$: 10 (1400)
  - $H(\gamma\gamma)$: 190 (25000)
  - $W(\ell\nu)H(b\bar{b})$: 240 (26000)
  - $qqH(\tau\tau)$: 370 (50000)



First hints in December 2011

- December 2011: first hints in the 4ℓ ($\ell = e, \mu$) channel
- How to read this plot?



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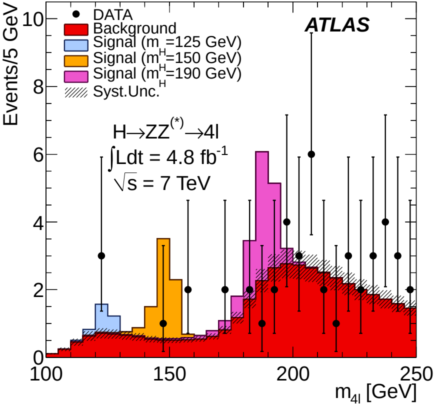

- x-axis: reconstructed four lepton invariant mass $m_{4\ell} = \sqrt{(\sum_\ell E_\ell)^2 - (\sum_\ell \mathbf{p}_\ell)^2} \approx M_H$

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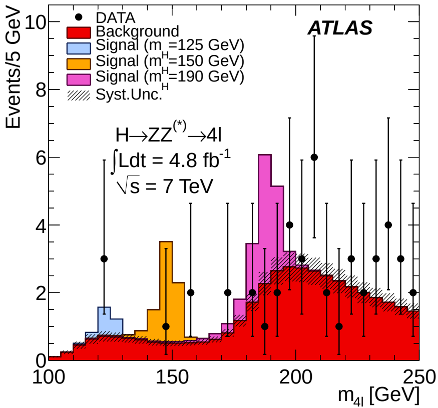

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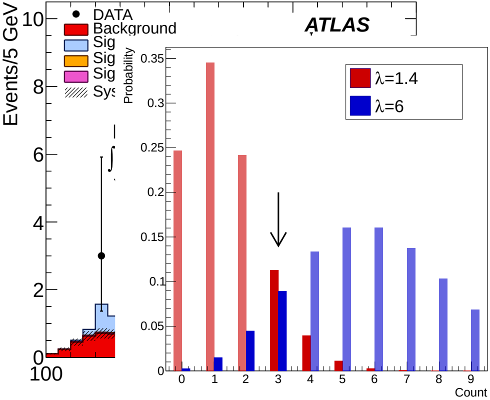

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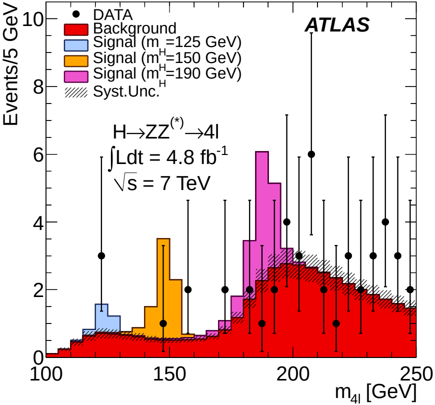

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- Background from simulation $(pp \to ZZ)$ and data-driven methods $(pp \to Z{+}\text{jets})$, with systematic uncertainty estimate

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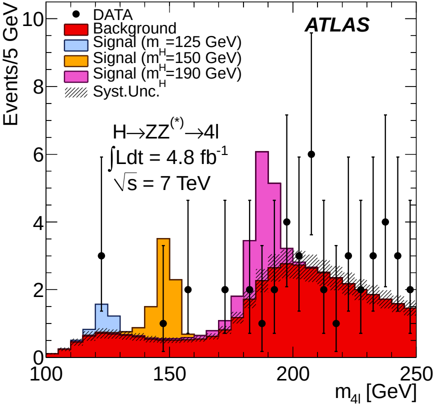

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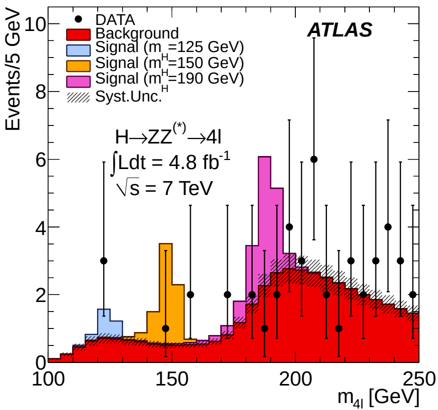
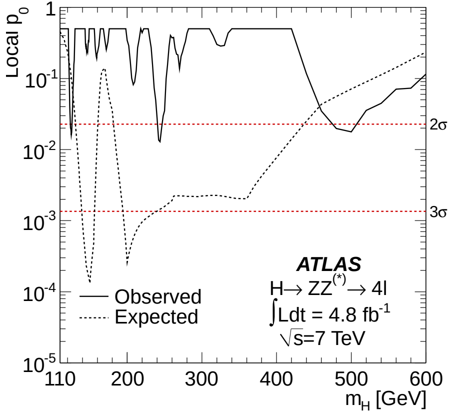
- Data with Poisson errors
- Background from simulation ($pp \to ZZ$) and data-driven methods ($pp \to Z$+jets), with systematic uncertainty estimate
- Signal expectation for various mass hypotheses (branching ratio increases with M_H)

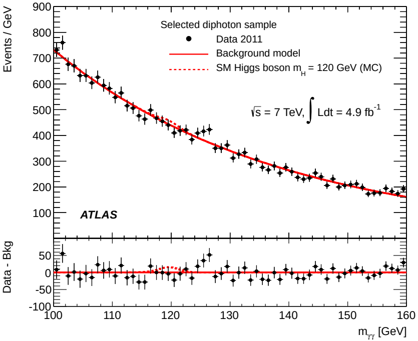
What are the odds?

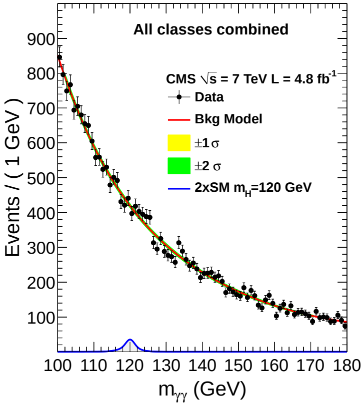




- About 2% probability for the background to fluctuate and look this signal-like, at 125 GeV and 240 GeV
- On its own that's nothing – we are testing many mass hypotheses

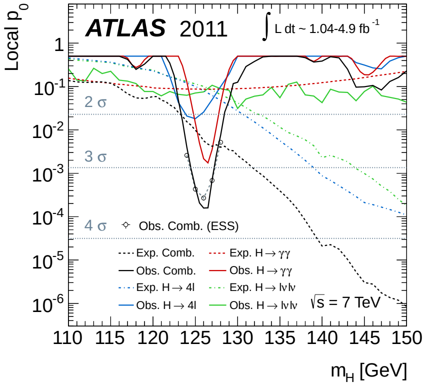
First hints in December 2011: $\gamma\gamma$

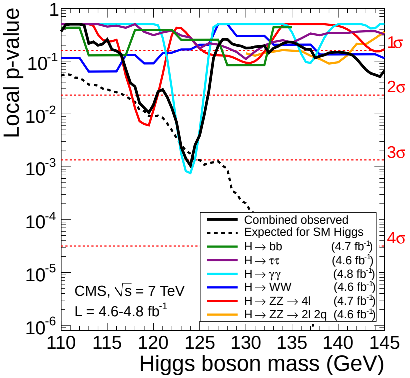




- Now it becomes interesting – ATLAS and CMS both see excesses at 125 GeV in the $H \to \gamma\gamma$ search
- Bump above background fit with smooth function

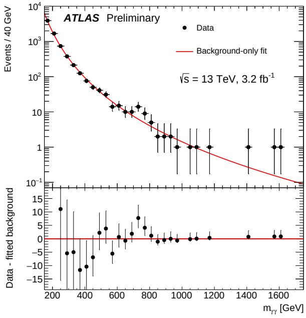
Higgs boson: status December 2011

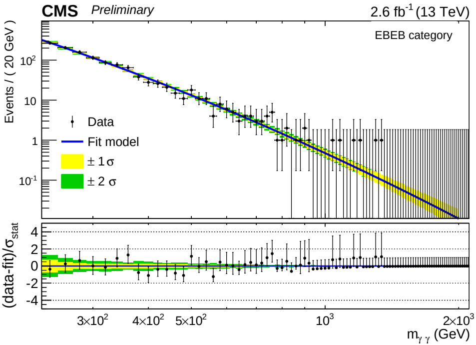




- Combined: both experiment excesses around 125 GeV ($p_0 < 0.001$)
- Mass and rate as expected for SM Higgs
- Why didn't we declare discovery then and there?

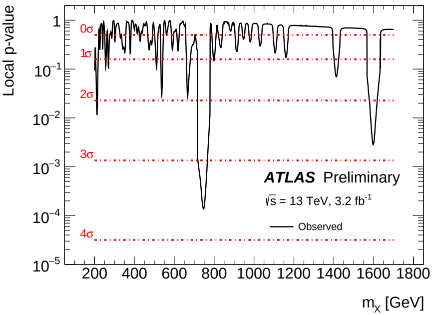
Fast forward December 2015

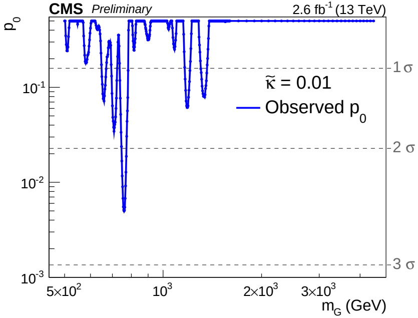




- We require 5σ for a discovery
- Many searches and many mass points, some fluctuations are expected (sometimes quantified as "look elsewhere effect")
- See here ATLAS and CMS high-mass $X \to \gamma\gamma$ search – both experiments see excess at 750 GeV after first year at 13 TeV

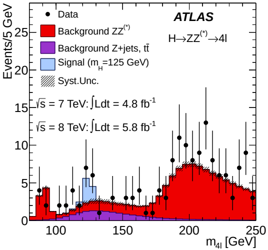
Fast forward December 2015

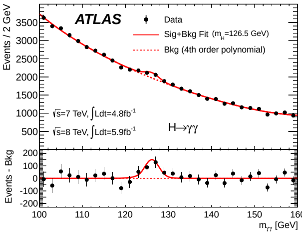


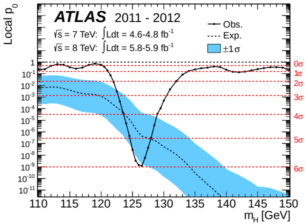


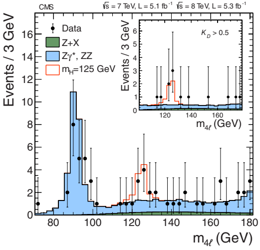
- Small p values – but turned out to be fluctuation!
- To be fair: experimental collaborations very cautious
- In contrast to Higgs: no one ordered this excess
- For the Higgs boson the story ended differently of course

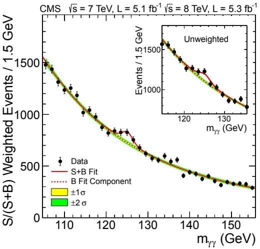
Higgs boson discovery 2012

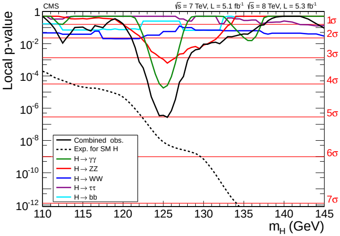












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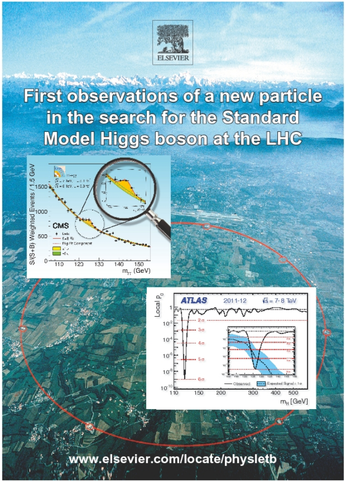

Study of Higgs boson properties

Higgs Properties – (is it really the SM Higgs boson?)

Remember:

- But how do we "prove" the Higgs mechanism exists? Generate Higgs bosons H! This gives us a huge number of testable hypotheses (selection):
  - New particle H
  - With spin zero
  - Couples to bosons like $g_{hVV} \propto \frac{m_V^2}{v}$, $g_{hhVV} \propto \frac{m_V^2}{v^2}$
  - Couples to fermions like $g_{hff} \propto \frac{m_f}{v}$
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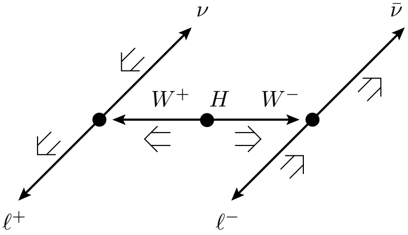

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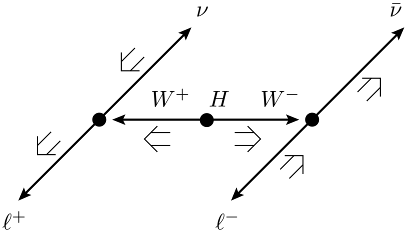

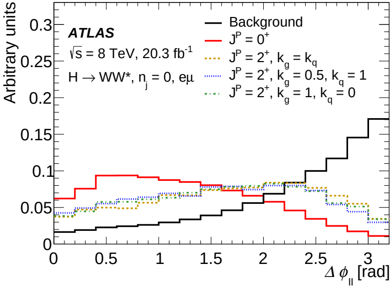

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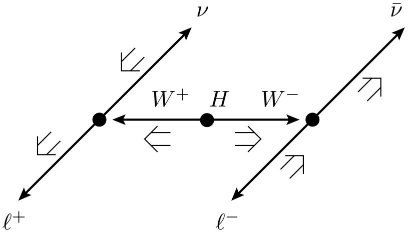
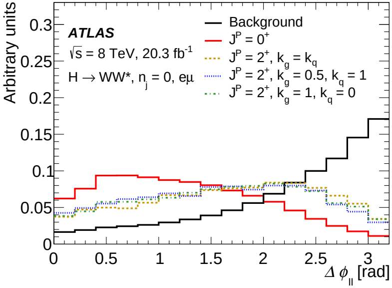
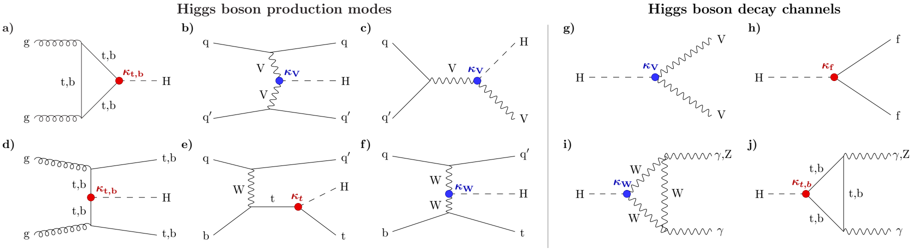
- Together with $H \to ZZ$: all tested hypotheses excluded with >99% CL





Towards couplings: cross-sections and branching ratios



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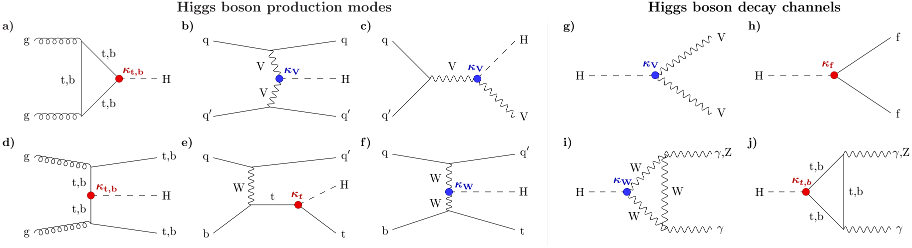

- Each measurement sensitive to a combination of couplings from production and decay (e.g. $ZH(b\bar{b})$: sensitive to g_{HZZ} and g_{Hbb})
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$$\sigma_{gg\to H\to 4\ell} = (\underbrace{1.040\kappa_t^2}_{\text{top-loop}} \underbrace{-0.038\kappa_b^2}_{\text{bottom-loop}} \underbrace{+0.002\kappa_t\kappa_b}_{\text{interference}}) \times \underbrace{\kappa_Z^2}_{\text{decay}} \times\sigma^{\text{SM}}_{gg\to H\to 4\ell}$$

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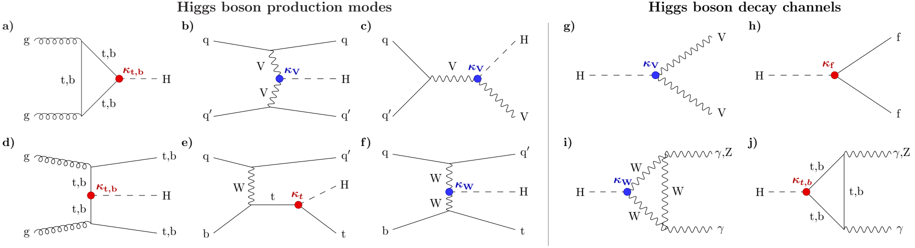

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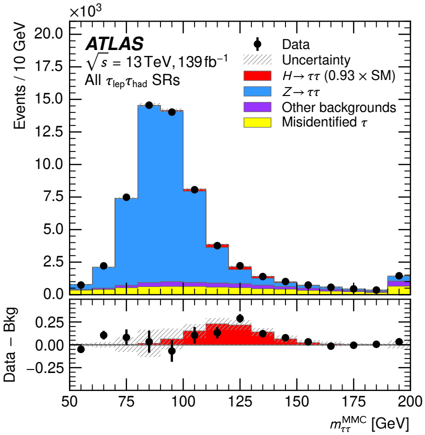
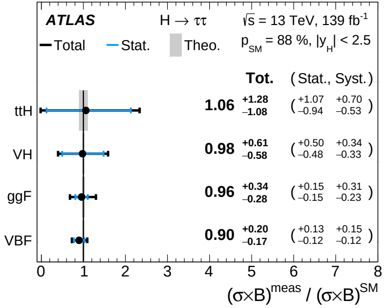
- Measurements of many channels needed untangle effect of couplings

Fermion decays: $\tau^+\tau^-$

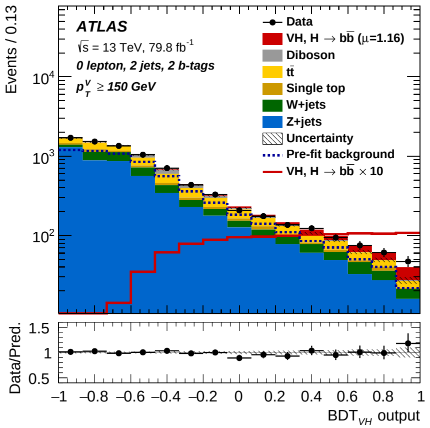


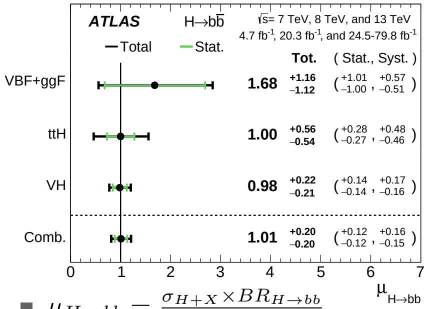


- VBF $H(\tau\tau)$ most sensitive, compromise of purity and event count

- We covered boson decays – $H(\tau\tau)$ first fermionic channel observed
- Broad peak (due to νs) around estimated M_H over $Z(\tau\tau)$ background

Fermion decays: $b\bar{b}$

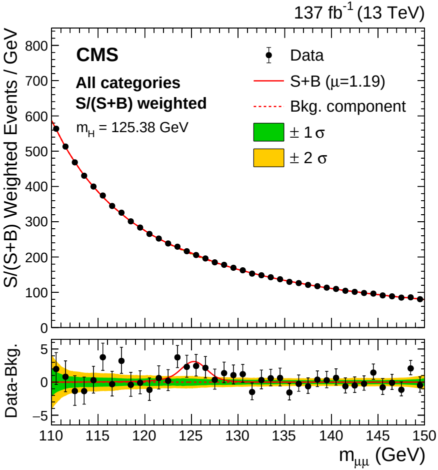


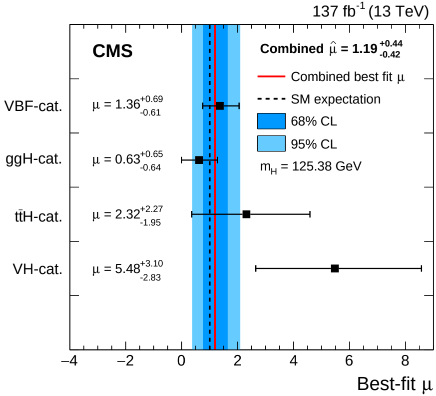


- $\mu_{H\to bb} = \dfrac{\sigma_{H+X} \times BR_{H\to bb}}{\sigma^{\text{SM}}_{H+X} \times BR^{\text{SM}}_{H\to bb}}$
- VH most sensitive

- In many cases, no single observable (e.g. m_{bb}) powerful enough
- For $H(b\bar{b})$: use machine learning (trained on simulation) to separate signal from background, combine many channels ⇒ observation

Fermion decays the 2nd generation: $H(\mu\mu)$





- $\mu = 1.2 \pm 0.4 \Rightarrow 3\sigma$ evidence!
- $H(\mu\mu)$ Buried under background of Drell–Yan $\mu^+\mu^-$ production
- 2nd gen quarks? $H(c\bar{c})$ maybe towards the end of the LHC program

All channels

- Four main production (ggF, VBF, VH, ttH) and five main decay channels ($\gamma\gamma$, ZZ, WW, $\tau\tau$, $b\bar{b}$) discovered by ATLAS and CMS

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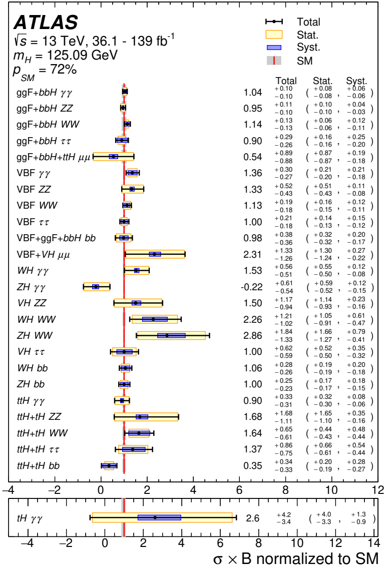
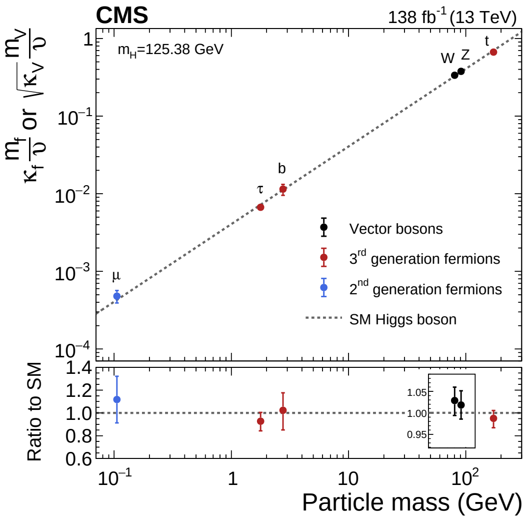
- Here ATLAS combined fit of 25 combinations of prod. and decay
- ggF measurements: 10% precision in $\gamma\gamma$, ZZ, and WW decays
- Fermion decay channels measured with up to 20% precision
- Compatible with SM ($p_{SM} = 72\%$)
- Systematic uncertainties sizable in most precise channels

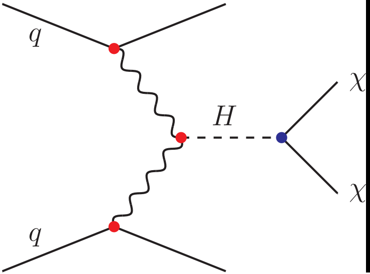


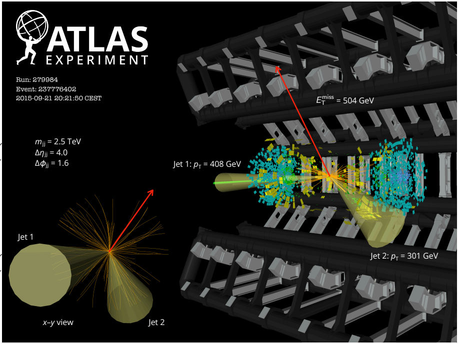
Coupling results

- CMS results on
  - $\kappa_f \times \frac{m_f}{v}$
  - $\sqrt{\kappa_V} \times \frac{m_V}{v}$
- Remember, SM prediction:
  - $g_{Hff} = \frac{m_f}{v}$
  - $g_{HVV} = \frac{M_V^2}{v}$
- Combined fit of ≈all measurements: excellent agreement with SM prediction, coupling proportional to mass



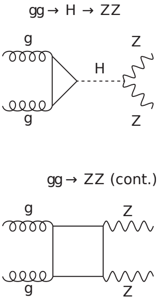
Invisible width

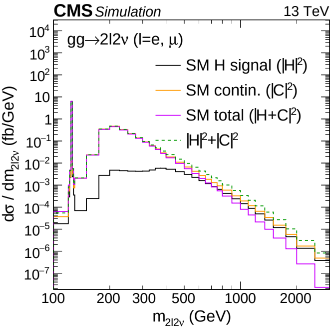


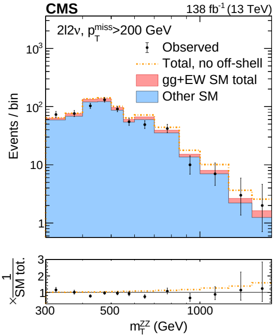


- Can also constrain decays into invisible particles (e.g. dark matter)
- Look for unbalanced events (with missing transverse energy, "MET")
- Best channel VBF (ggH: H decay at rest, no transverse momentum)
- CMS and ATLAS $\Gamma_{\text{inv.}} \lesssim 0.1$ at 95% CL

Total width

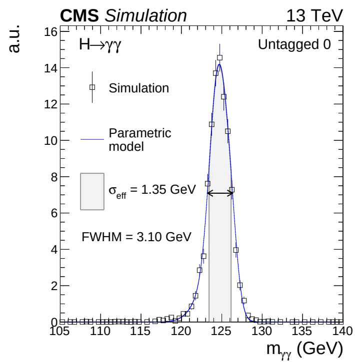


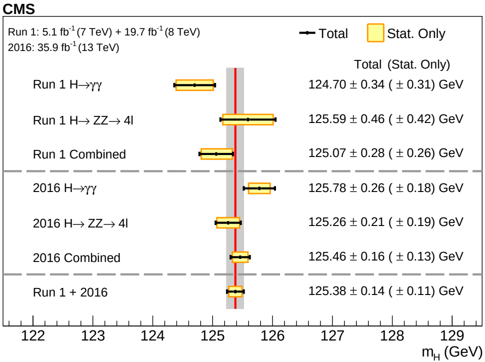




- Like all unstable particles, Higgs has a natural width of $\Gamma_H \approx \frac{\hbar}{\tau}$
- $\Gamma_H = 4.1$ MeV too small, $\tau = 1.6 \times 10^{-22}$ s too short for observation
- Constrain width in four-lepton events using events with $m_{\text{reconstr.}} \gg M_H$: large impact of interference with non-H events
- CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV, ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

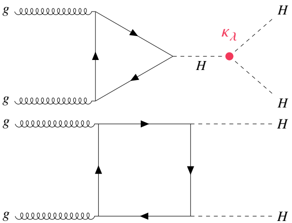
Higgs Mass

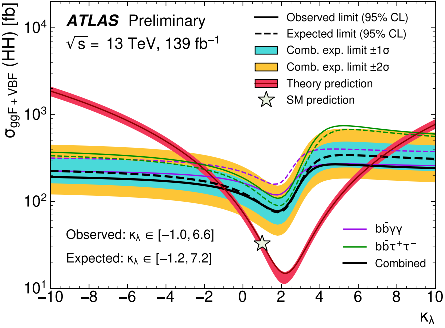




- Mass resolution in most precise channels (4ℓ and $\gamma\gamma$), at best 1-2 GeV
- Precise measurement of M_H from center of distribution
- Calibration of $\mathbf{p}_\mu$ and E_γ scale on $Z(\mu\mu)$ and $Z(ee)$ events
- CMS: $M_H = 125.38 \pm 0.14$ (stat) ± 0.08 (syst) statistically limited

Self couplings





- Self coupling: direct measurement with di-Higgs production
- Small cross-section due to destructive interference of dominant diagrams (Theory prediction smaller for $\kappa_\lambda = 1$ than $\kappa_\lambda = 0$)
- Search in $H(\gamma\gamma)H(b\bar{b})$ and $H(\tau\tau)H(b\bar{b})$ channels with multivariate methods
- Close to excluding $\kappa_\lambda = 0$, long way to SM sensitivity

Future of Higgs physics

Importance of the Higgs field

- Higgs at the heart of the Standard Model
  - Hard to overstate its importance for the theory
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  - But it is the crucial ingredient to make various parts of the SM work
- Also leaves many questions unanswered
  - Yukawa sector I: huge number of parameter (13/19 SM parameters)
  - Yukawa sector II: pattern and range of masses ($m_e = 511$ keV, $m_t = 173$ GeV)?
  - Origin of the potential?

Higgs and BSM physics

- Higgs very SM like – kills loads of (pre-LHC) BSM theories
  - Higgs-less models (duh)
  - 4th generation of quarks (due to ggH rate)
  - Many more... SM describes LHC physics annoyingly well

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- Another connection to new physics: M_H gets large quantum corrections and should be close to the scale of new physics (or even Planck mass) unless "accidentally light" – Why is it light? Coincidence or new physics at low scales?

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- But all terms with energy dimension 4 already in SM!
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- My favorite way to search for new physics: effective field theory (EFT)
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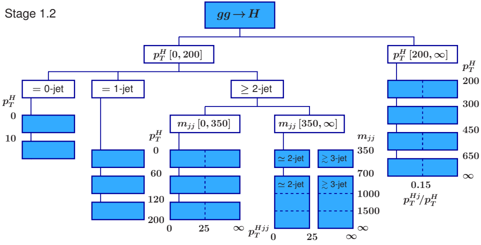
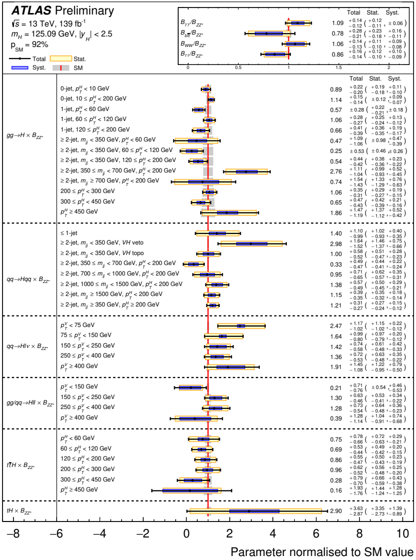
- At the *unknown* energy scale Λ this will break down

STXS: measuring kinematics

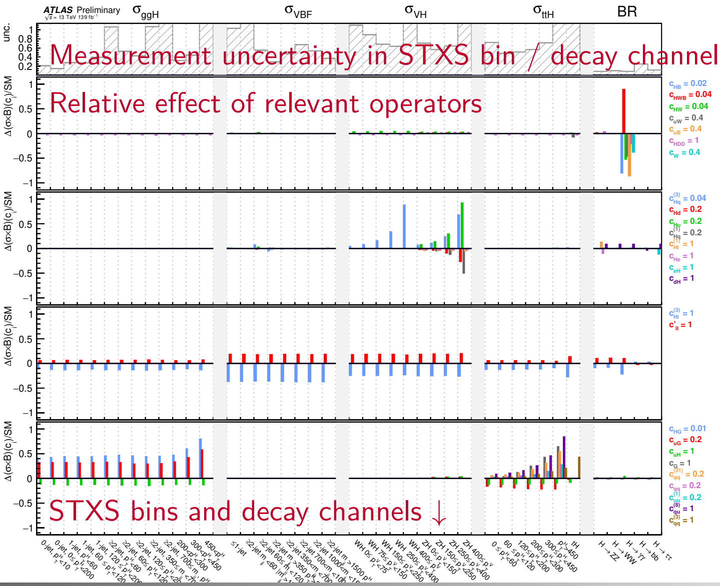
- How to measure Higgs production with modified interactions?
- Split measurements in many bins depending on kinematics
- For example ggH:



- ATLAS and CMS are measuring this already with ok precision →



STXS: EFT impacts



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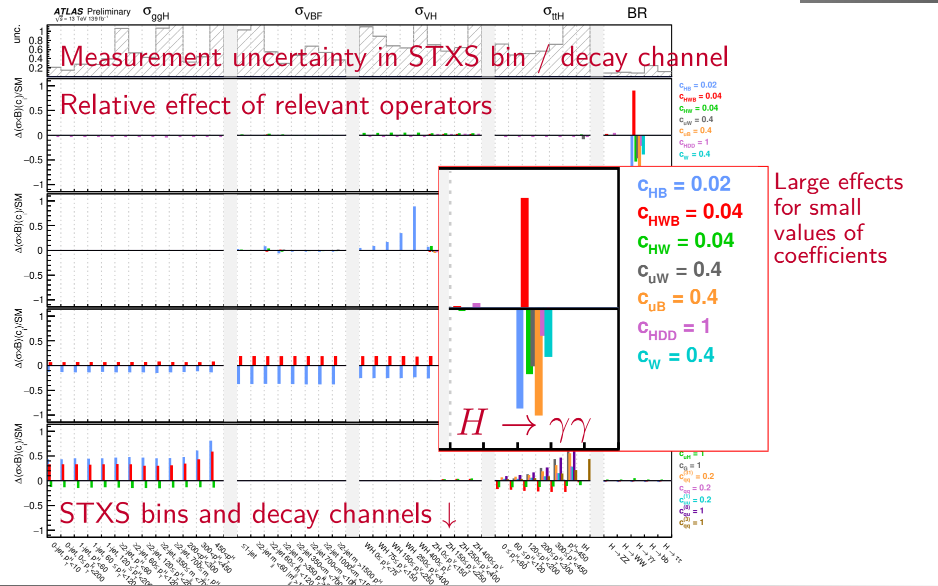

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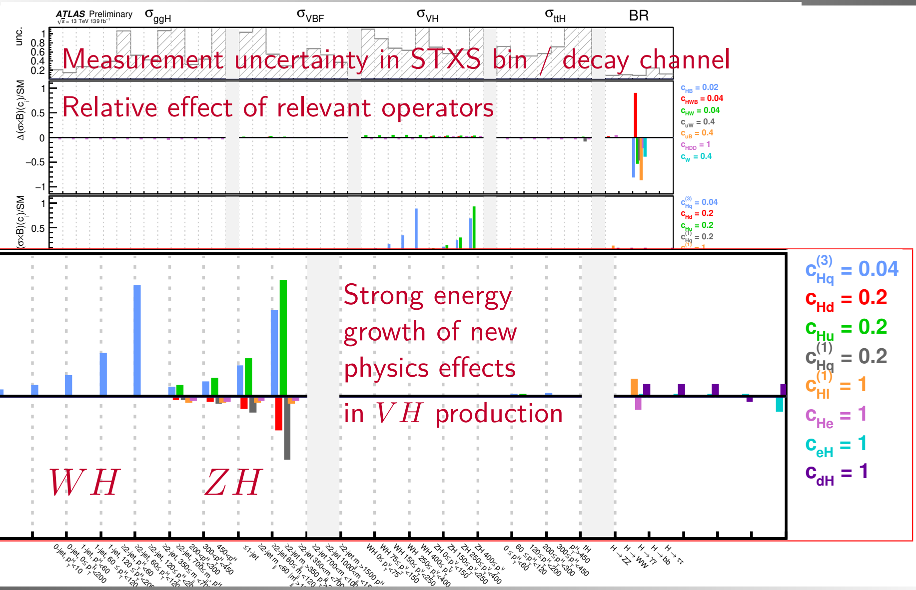

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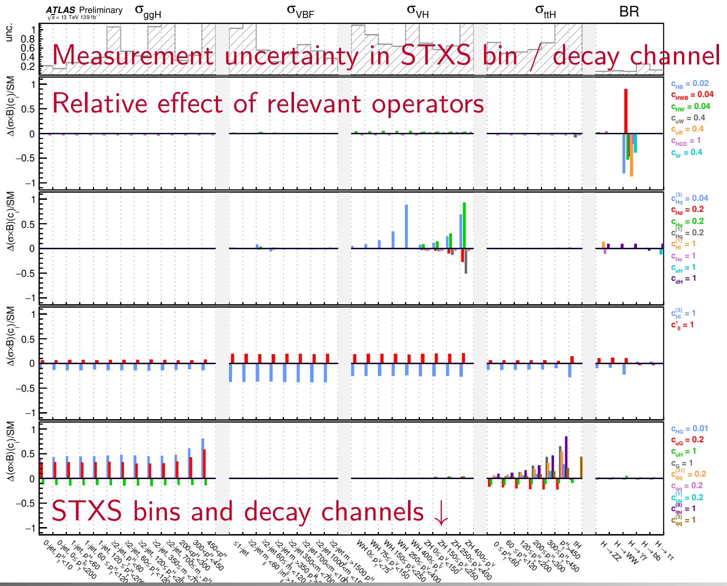
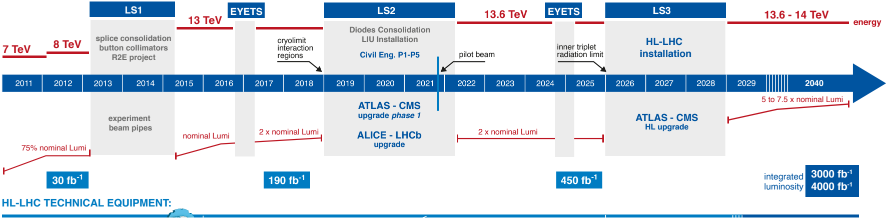


The future: high luminosity LHC



- Higgs discovery: 10 fb^{-1} at 7&8 TeV
- Now: 190 fb^{-1} at 13 TeV analyzed
- Next years: 450 fb^{-1} at 13.6 TeV
  $\Rightarrow$ improvement up to factor 2 possible
  $(\sigma_{\text{stat}} \propto (\int dtL)^{-0.5})$

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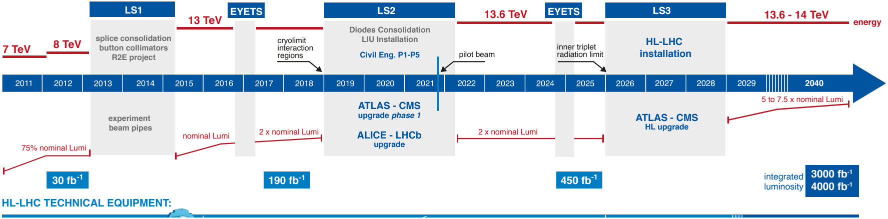

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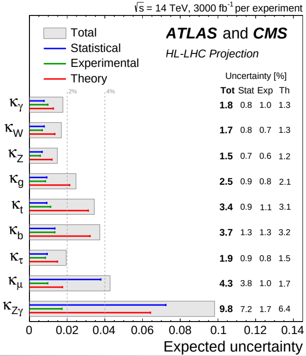
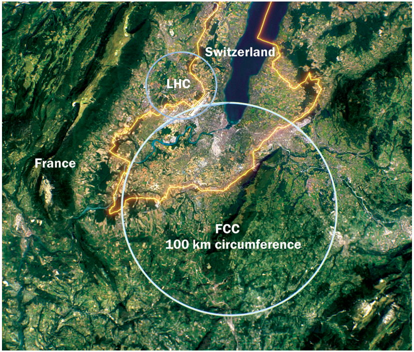
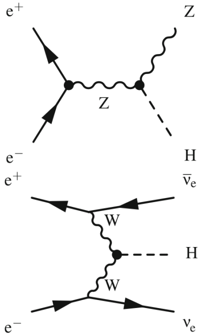
- From 2029: high luminosity LHC, high rates to further reduce statistical uncertainties



The far future: a Higgs factory





- LHC energy limited by radius and strength of magnets
- Long term goal: new collider with 100 km circumference
  - First as electron–positron collider "FCC-ee", precisely probing Higgs properties in clean environment
  - Eventually as new 100 TeV hadron collider "FCC-hh"

Conclusion

- Spontaneous breaking of electroweak symmetry crucial part of SM
- Gives mass to weak bosons and fermions without breaking symmetry of underlying theory
- Higgs boson discovered by ATLAS and CMS at the LHC in 2012
- So far, properties agree with SM expectation
- Higgs could be a tool to observe first hints of BSM physics
- Still only the beginning of experimental Higgs physics
    - Analysis of Run 3 dataset (maybe you will contribute to this?) can bring factor of 2 improvements
    - High luminosity LHC will increase dataset tenfold
    - Higgs physics also central consideration for future collider