STANDARD MODEL

John Ellis, King’s College London (& CERN)
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

<table>
<thead>
<tr>
<th>L_L</th>
<th>(ν_e, e^-)_L, (ν_μ, μ^-)_L, (ν_τ, τ^-)_L</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_R</td>
<td>(1,2,-1), (1,1,-2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q_L</th>
<th>(u, d)_L, (c, s)_L, (t, b)_L</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_R</td>
<td>(3,2,+1/3), (3,1,+4/3)</td>
</tr>
<tr>
<td>D_R</td>
<td>(3,1,-2/3)</td>
</tr>
</tbody>
</table>

- Lagrangian:

\[
\mathcal{L} = -\frac{1}{4} F^\alpha_{\mu\nu} F^{\alpha\mu\nu} + i\bar{\psi} \not\!D\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)
\]

  gauge interactions
  matter fermions
  Yukawa interactions
  Higgs potential
Open Questions beyond the Standard Model

- What is the origin of particle masses due to a Higgs boson?
- Why so many flavours of matter particles?
- What is the dark matter in the Universe?
- Unification of fundamental forces?
- Quantum theory of gravity?
Has the Higgs been Excluded?

Interesting hints around $M_h = 125$ GeV?

**ATLAS** excludes

$< 122.5, > 129, < 539$ GeV

**CMS** excludes

$> 127.5, < 600$ GeV
Has the Higgs been Discovered?

Interesting hints around $M_h = 125$ GeV?

CMS prefers $< 125$ GeV

ATLAS prefers $> 125$ GeV
Unofficial Combination of Higgs Search Data from March 7th

Is this the Higgs Boson?

No Higgs here!

Philip Gibbs
The Particle Higgsaw Puzzle

Is LHC finding the missing piece?
Is it the right shape?
Is it the right size?
Do we already know the ‘Higgs’ has Spin Zero?

- Decays into $\gamma\gamma$, so cannot have spin 1
- 0 or 2?
- If it decays into $\tau\tau$ or b-bar: spin 0 or 1 or orbital angular momentum
- Can diagnose spin via
  - angular distribution of $\gamma\gamma$
  - angular correlations of leptons in WW, ZZ decays
- Does selection of WW events mean spin 1?
Does the ‘Higgs’ have Spin Zero?

- Polar angle distribution: \( X_2 \rightarrow \gamma \gamma \) (flat for \( X_0 \))
- Azimuthal angle distribution: \( X_0 \rightarrow WW \) (flat for \( X_2 \))

Does the ‘Higgs’ have Spin Zero?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$
  
  (for $\varphi = \pi$)

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …

- Quark FCNC bounds exclude observability of quark-flavour-violating $h$ decays

- Lepton-flavour-violating $h$ decays could be large: $\text{BR}(\tau\mu)$ or $\text{BR}(\tau\text{e})$ could be $O(10)\%$

$\text{BR}(\mu\text{e})$ must be $< 2 \times 10^{-5}$

Blankenburg, JE, Isidori: arXiv:1202.5704
There must be New Physics Beyond the Standard Model

Higgs potential collapses

Higgs coupling less than in Standard Model

Precision Electroweak data??

Higgs coupling blows up!!
Elementary Higgs or Composite?

- Higgs field: $\langle 0|H|0 \rangle \neq 0$
- Quantum loop problems
  - Fermion-antifermion condensate
  - Just like QCD, BCS superconductivity
  - Top-antitop condensate? needed $m_t > 200$ GeV
- New technicolour force?
  - Heavy scalar resonance?
  - Inconsistent with precision electroweak data?

Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

Cutoff $\Lambda = 10$ TeV

$m_h^2 \sim (200 \text{ GeV})^2$
Heretical Interpretation of EW Data

Do all the data tell the same story? e.g., $A_L$ vs $A_H$

What attitude towards LEP, NuTeV?

- Two $3\sigma$ Anomalies
  - $CL(\text{Fit A}) = 0.02$
  - $\nu N$ Systematic error
- $CL(\text{Fit B}) = 0.17$
- $CL(\text{Fit B}') = 0.067$
- $CL(A_L \oplus A_H) = 0.004$
- $A_H$ Systematic error
- $CL(m_H > 114) = 0.05$

Unknown New Physics

No $m_H$ Prediction

SM
$m_H < 205$ 95%
Higgs + Higher-Order Operators

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)} \]

Precision EW data suggest they are small: why?

But conspiracies are possible: \( m_H \) could be large, even if believe EW data …?

<table>
<thead>
<tr>
<th>Dimension six operator</th>
<th>( c_i = -1 )</th>
<th>( c_i = +1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{O}<em>{WB} = (H^+ \sigma^a H)W^a</em>{\mu\nu}B_{\mu\nu} )</td>
<td>9.0</td>
<td>13</td>
</tr>
<tr>
<td>( \mathcal{O}_H =</td>
<td>H^+D_\mu H</td>
<td>^2 )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{LL} = \frac{1}{2}(\bar{L}\gamma</em>\mu\sigma^a L)^2 )</td>
<td>8.2</td>
<td>8.8</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{HL} = i(H^+D</em>\mu H)(\bar{L}\gamma_\mu L) )</td>
<td>14</td>
<td>8.0</td>
</tr>
</tbody>
</table>

95% lower bounds on \( \Lambda/\text{TeV} \)

But conspiracies are possible: \( m_H \) could be large, even if believe EW data …?

Do not discard possibility of heavy Higgs

Barbieri, Strumia
Interpolating Models

- Combination of Higgs boson and vector $\rho$

  Two main parameters: $m_\rho$ and coupling $g_\rho$

  Equivalently ratio weak/strong scale:
  
  $$g_\rho / m_\rho$$

Grojean, Giudice, Pomarol, Rattazzi
What if the Higgs is not quite a Higgs?

- Tree-level Higgs couplings ~ masses
  - Coefficient ~ 1/v
- Couplings ~ dilaton of scale invariance
- Broken by Higgs mass term – $\mu^2$, anomalies
  - Cannot remove $\mu^2$ (Coleman-Weinberg)
  - Anomalies give couplings to $\gamma\gamma$, $gg$
- Generalize to pseudo-dilaton of new (nearly) conformal strongly-interacting sector
- Pseudo-Goldstone boson of scale symmetry
A Phenomenological Profile of a Pseudo-Dilaton

- Universal suppression of couplings to Standard Model particles: $a = c = \nu/V$
- Effective potential:
  \[ V(\chi) = \frac{m^2}{\gamma V^2} \left[ \frac{1}{4 + \gamma \left( \frac{\chi}{V} \right)^\gamma} - \frac{1}{4} \right] + \mathcal{O} \left( \frac{m^2}{V^2} \right)^2 \]
- Self-couplings:
  \[ g_3 \bar{\chi} = (5 + \gamma + \ldots) \frac{m^2}{V} \]
  \[ g_4 \bar{\chi} = (11 + 6\gamma + \gamma^2 + \ldots) \frac{m^2}{V^2} \]
- $\Gamma(gg)$ may be enhanced
- $\Gamma(\nu\nu)$ may be suppressed

Pseudo-baryons as dark matter?


Updated with Dec. 11 constraints
General Analysis of ‘Less Higgs’ Models

- Parameterization of effective Lagrangian:

\[
\mathcal{L}^{(2)} = \frac{1}{2} (\partial_{\mu} h)^2 + \frac{v^2}{4} \text{Tr} \left( D_{\mu} \Sigma^\dagger D^{\mu} \Sigma \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \cdots \right) \\
- \frac{v}{\sqrt{2}} \lambda_{i j} \left( \bar{u}_L^{(i)}, \bar{d}_L^{(i)} \right) \Sigma \left( u_R^{(i)}, 0 \right)^T \left( 1 + c_u \frac{h}{v} + c_{2u} \frac{h^2}{v^2} + \cdots \right)
\]

- Fits

\[a = c = \sqrt{1 - \xi}\]

Azatov, Contino, Galloway: arXiv:1202.3415
You & JE: in preparation
Pseudo-Baryonic Dark Matter?

- Nonlinear Lagrangians have soliton solutions = baryons (à la Skyrme)
- Produced at electroweak transition (first-order)

Theoretical Constraints on Higgs Mass

- Large $M_h \to$ large self-coupling $\to$ blow up at low-energy scale $\Lambda$ due to renormalization
- Small: renormalization due to $t$ quark drives quartic coupling $< 0$ at some scale $\Lambda$ $\to$ vacuum unstable
- Vacuum could be stabilized by supersymmetry

Espinosa, JE, Giudice, Hoecker, Riotto, arXiv0906.0954

LHC 95% exclusion
The LHC will Tell the Fate of the SM

Examples with LHC measurement of \( m_H = 120 \) or \( 115 \) GeV
How to Stabilize a Light Higgs Boson?

• Top quark destabilizes potential: introduce stop-like scalar:
  \[ \mathcal{L} \supset M^2 |\phi|^2 + \frac{M_0}{\nu^2} |H|^2 |\phi|^2 \]

• Can delay collapse of potential:
• But new coupling must be fine-tuned to avoid blow-up:
• Stabilize with new fermions:
  – just like Higgsinos
• Very like Supersymmetry!
Loop Corrections to Higgs Mass $^2$

- Consider generic fermion and boson loops:

- Each is quadratically divergent: $\int d^4k/k^2$

\[
\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]
\]

\[
\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]
\]

- Leading divergence cancelled if

Supersymmetry! $\lambda_S = \xi \times 2$
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 130$ GeV

As suggested by EW data
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible. Dark Matter and Supersymmetric particles?

We shall look for them with the LHC.
Classic Supersymmetric Signature

Missing transverse energy carried away by dark matter particles
Supersymmetry Searches in CMS

Jets + missing energy (+ lepton(s))
Impact of LHC on the CMSSM

Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by $b \rightarrow s$ gamma

WMAP constraint on CDM density

Preferred (?) by latest $g - 2$
Impact if $m_H = 125$ GeV

- Need large $m_{1/2}$
- Prefer big $\tan \beta$
- Find small dark matter scattering rate

JE, Olive; arXiv:1202.3262
MasterCode

- Combines diverse set of tools
  - different codes: all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- Compatibility is crucial! Ensured by
  - close collaboration of tools authors
  - standard interfaces

Favoured values of gluino mass significantly above pre-LHC, > 2 TeV

--- pre-Higgs
— Higgs @ 125
... H@125, no g-2

Favoured values of squark mass significantly above pre-LHC, > 2 TeV

--- pre-Higgs
— Higgs @ 125
… H@125, no g-2


Favoured values of squark mass significantly above pre-LHC, > 2 TeV
Favoured values of $B_s \rightarrow \mu^+\mu^-$ above Standard Model

--- pre-Higgs
— Higgs @ 125
... H@125, no g-2

Searches with $\sim 5/fb$

**Razor Inclusive**

Hybrid CLs 95% C.L. Limits
- Median Expected Limit
- Expected Limit ±1σ
- Observed Limit
- Observed ±1σ (theory)

**ATLAS Preliminary**

- $\int L dt = 4.71 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$
- Combined
  - $\text{CL}_S$ observed 95% C.L. limit
  - $\text{CL}_S$ median expected limit
- ATLAS EPS 2011
- $\tilde{\tau}$ LSP
- LEP Chargino
- No EWSB

**Jets + missing energy**
Latest News on $B_s \rightarrow \mu^+\mu^-$

- Upper limit approaching Standard Model
- Pressuring supersymmetric models
The Stakes in the Higgs Search

• How is gauge symmetry broken?
• Is there any elementary scalar field?
• Would have caused phase transition in the Universe when it was about $10^{-12}$ seconds old
• May have generated then the matter in the Universe: electroweak baryogenesis
• A related inflaton might have expanded the Universe when it was about $10^{-35}$ seconds old
• Contributes to today’s dark energy: $10^{60}$ too much!
Conversation with Mrs Thatcher: 1982

What do you do?

Think of things for the experiments to look for, and hope they find something different.

Wouldn’t it be better if they found what you predicted?

Then we would not learn anything!
Lightest Supersymmetric Particle

• Stable in many models because of conservation of R parity:
  \[ R = (-1)^{2S - L + 3B} \]
  where \( S = \) spin, \( L = \) lepton #, \( B = \) baryon #

• Particles have \( R = +1 \), sparticles \( R = -1 \):
  - Sparticles produced in pairs
  - Heavier sparticles \( \rightarrow \) lighter sparticles

• Lightest supersymmetric particle (LSP) stable
Possible Nature of LSP

• No strong or electromagnetic interactions
  Otherwise would bind to matter
  Detectable as anomalous heavy nucleus

• Possible weakly-interacting candidates
  Sneutrino
    (Excluded by LEP, direct searches)
  Lightest neutralino $\chi$ (partner of Z, H, $\gamma$)
  Gravitino
    (nightmare for detection)
Limits on Heavy MSSM Higgses
**XENON100 Experiment**
Latest News from LHCb: $B_s \rightarrow \mu^+\mu^-$

- LHCb upper limit approaching Standard Model
- Pressuring supersymmetric models
- Updates soon from ATLAS & CMS
Favoured values of $M_h \sim 119$ GeV:

Range consistent with evidence from LHC!

$\chi^2$ price to pay if $M_h = 125$ GeV is $< 2$

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb⁻¹ of LHC Data

68% & 95% CL contours

pre-Higgs
— Higgs @ 125

CMSSM
60 million points sampled

NUHM1
70 million points sampled


Red and blue curves represent Δχ² from global minimum, located at ⭐

Preferred region “opens up” at cost of worsening global χ² value!
Favoured dark matter scattering rate well below XENON100 limit

--- pre-Higgs
— Higgs @ 125

Spin-independent Dark matter scattering

Be careful what you wish for!
The Spin of the Higgs Boson @ LHC

Low mass: if $H \to \gamma\gamma$, It cannot have spin 1

Higher mass: angular correlations in $H \to ZZ$ decays

Significance for exclusion of other $J^{CP}$ states than $0^+$

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$J^{CP} = 1^+$</th>
<th>$J^{CP} = 1^-$</th>
<th>$J^{CP} = 0^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>6.5 σ</td>
<td>4.8 σ</td>
<td>40 σ</td>
</tr>
<tr>
<td>250</td>
<td>20 σ</td>
<td>19 σ</td>
<td>80 σ</td>
</tr>
<tr>
<td>300</td>
<td>23 σ</td>
<td>22 σ</td>
<td>70 σ</td>
</tr>
</tbody>
</table>

ATLAS + CMS, 2 x 300 fb⁻¹
Measuring Higgs Couplings @ LHC

Current LHC hint @ $M_h = 125$ GeV
Flavour-Changing Couplings?

- Constraints on quark-flavour-changing couplings from FCNC

<table>
<thead>
<tr>
<th>Operator</th>
<th>Eff. couplings</th>
<th>95% C.L. Bound</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_R d_L$, $s_L d_R$</td>
<td>$c_{ds}^* c_{ds}$</td>
<td>$1.1 \times 10^{-10}$</td>
<td>$\Delta m_K$, $\epsilon_K$</td>
</tr>
<tr>
<td>$s_R d_L$, $s_L d_R$</td>
<td>$c_{ds}^* c_{ds}$</td>
<td>$2.2 \times 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>$s_R u_L$, $s_L u_R$</td>
<td>$c_{cu}^* c_{cu}$</td>
<td>$0.9 \times 10^{-9}$</td>
<td>$\Delta m_D$, $</td>
</tr>
<tr>
<td>$s_R u_L$, $s_L u_R$</td>
<td>$c_{cu}^* c_{cu}$</td>
<td>$1.4 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$b_R d_L$, $b_L d_R$</td>
<td>$c_{bd}^* c_{bd}$</td>
<td>$9.0 \times 10^{-8}$</td>
<td>$\Delta m_{B_d}$, $S_{B_d} \to K$</td>
</tr>
<tr>
<td>$b_R d_L$, $b_L d_R$</td>
<td>$c_{bd}^* c_{bd}$</td>
<td>$1.0 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$b_R s_L$, $b_L s_R$</td>
<td>$c_{sb}^* c_{sb}$</td>
<td>$9.0 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$b_R s_L$, $b_L s_R$</td>
<td>$c_{sb}^* c_{sb}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

- Constraints on lepton-flavour-changing couplings

<table>
<thead>
<tr>
<th>Operator</th>
<th>Eff. couplings</th>
<th>Bound</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\bar{\nu}_R \nu_L)(q_L q_R)$, $(\bar{\mu}_L \nu_R)(q_L q_R)$</td>
<td>$</td>
<td>c_{\mu e}</td>
<td>^2$, $</td>
</tr>
<tr>
<td>$(\tau_R h_L)(h_L h_R)$, $(\tau_L h_R)(h_L h_R)$</td>
<td>$</td>
<td>c_{\tau l}</td>
<td>^2$, $</td>
</tr>
<tr>
<td>$(\tau_R h_L)(h_L h_R)$, $(\tau_L h_R)(h_L h_R)$</td>
<td>$</td>
<td>c_{\tau e}</td>
<td>^2$, $</td>
</tr>
<tr>
<td>$(\tau_R h_L)(h_L h_R)$, $(\tau_L h_R)(h_L h_R)$</td>
<td>$</td>
<td>c_{\tau e}</td>
<td>^2$, $</td>
</tr>
<tr>
<td>$(\tau_R h_L)(h_L h_R)$, $(\tau_L h_R)(h_L h_R)$</td>
<td>$</td>
<td>c_{\mu e}</td>
<td>^2$, $</td>
</tr>
</tbody>
</table>

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Blankenburg, JE, Isidori: arXiv:1202.5704
For $M_h = 120$ GeV
Quo Vadis $g_\mu - 2$?

- Strong discrepancy between BNL experiment and $e^+e^-$ data:
  - now $\sim 3.6 \sigma$
  - Better agreement between $e^+e^-$ experiments

- Increased discrepancy between BNL experiment and $\tau$ decay data
  - now $\sim 2.4 \sigma$
  - Convergence between $e^+e^-$ experiments and $\tau$ decay

- More credibility?
Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

\[
\begin{pmatrix}
\frac{1}{2} \\
0
\end{pmatrix}
\text{ e.g., } \begin{pmatrix}
\ell \text{ (lepton)} \\
\tilde{\ell} \text{ (slepton)}
\end{pmatrix}
\text{ or }
\begin{pmatrix}
q \text{ (quark)} \\
\tilde{q} \text{ (squark)}
\end{pmatrix}
\begin{pmatrix}
\frac{1}{2}
\end{pmatrix}
\text{ e.g., } \begin{pmatrix}
\gamma \text{ (photon)} \\
\tilde{\gamma} \text{ (photino)}
\end{pmatrix}
\text{ or }
\begin{pmatrix}
g \text{ (gluon)} \\
\tilde{g} \text{ (gluino)}
\end{pmatrix}
\]

- 2 Higgs doublets, coupling $\mu$, ratio of v.e.v.’s = $\tan \beta$

- Unknown supersymmetry-breaking parameters:
  Scalar masses $m_0$, gaugino masses $m_{1/2}$,
  trilinear soft couplings $A_\lambda$, bilinear soft coupling $B_\mu$

- Often assume universality:
  Single $m_0$, single $m_{1/2}$, single $A_\lambda$, $B_\mu$: not string?

- Called constrained MSSM = CMSSM

- Minimal supergravity also predicts gravitino mass
  
  $m_{3/2} = m_0$, $B_\mu = A_\lambda - m_0$
Latest News from CDF: $m_W$
Are ATLAS & CMS seeing the Same Thing?

Both compatible with $m_H = 125$ GeV
Combining the Information from Previous Direct Searches and Indirect Data

Assuming the Standard Model

\[ m_H = 125 \pm 10 \text{ GeV} \]

\[ m_H = 124.5 \pm 0.8 \text{ GeV} \]
Supersymmetry Searches in ATLAS

Jets + missing energy + 0 lepton
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

Volume 13, Number 16

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik, † C. R. Hagen, † and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)
The Englert-Brout-Higgs Mechanism

- **Vacuum expectation value of scalar field**
- Englert & Brout: June 26\(^{th}\) 1964
- First Higgs paper: July 27\(^{th}\) 1964
- Pointed out loophole in argument of Gilbert if gauge theory described in Coulomb gauge
- Accepted by Physics Letters
- Second Higgs paper with explicit example sent on July 31\(^{st}\) 1964 to Physics Letters, rejected!
- Revised version (Aug. 31\(^{st}\) 1964) accepted by PRL
- Guralnik, Hagen & Kibble (Oct. 12\(^{th}\) 1964)
We consider, as our example, a theory which was partially solved by Englert and Brout, and bears some resemblance to the classical theory of Higgs. Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

\[ \mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi} i D\mathbf{\gamma} \psi + m^2 \psi^2 \]

With no loss of generality, we can take \( \eta_2 = 0 \), and find

\[ (-\partial^2 + \eta_1^2)\varphi_1 = 0, \]
\[ -\partial^2 \varphi_2 = 0, \]
\[ (-\partial^2 + \eta_1^2)A_\mu^T = 0, \]

where the superscript \( T \) denotes the transverse part. The two degrees of freedom of \( A_\mu^T \) combine with \( \varphi_1 \) to form the three components of a
The Higgs Boson

• **Higgs pointed out a massive scalar boson**

\[
\left\{ \partial^2 - 4\varphi_0^2 V''(\varphi_0^2) \right\}(\Delta \varphi_2) = 0, \quad (2b)
\]

Equation (2b) describes waves whose quanta have
(bare) mass \(2\varphi_0\sqrt{V''(\varphi_0^2)}\)

• “… an essential feature of [this] type of theory
… is the prediction of incomplete multiplets of vector and scalar bosons”

• Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence

• **Discussed in detail by Higgs in 1966 paper**