Discovery of Higgs boson at LHC

Haijun Yang

Colloquium at Department of Physics
Shanghai Jiao Tong University
September 12, 2012
Particle Physics studies the properties of fundamental building block of matters and their interactions.
Interactions of Particles

- Force is explained by exchange of force carriers between particles (Gravitational, Electromagnetic, Strong, Weak)
- Long-range force: light force carrier ($\gamma$, graviton)
- Short-range force: heavy force carrier ($W^\pm$, $Z^0$)
Elementary Particles

> 100 years’ discoveries

The SM is in excellent agreement with the numerous experimental measurements.

The only missing SM particle is the Higgs boson which is proposed to be responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.

Hunting for the Higgs boson is one of main goals in particle physics (LEP, Tevatron, LHC)
The potential in (a) is symmetric.

The potential in (b) the potential is still symmetric, but the symmetry of the ground state is spontaneously broken.

Spontaneously symmetry breaking → Nambu-Goldstone bosons (no spin, mass)

Peter Higgs showed that Goldstone bosons need not occur when a local symmetry is spontaneously broken in a relativistic theory. Instead, the Goldstone mode provides the third polarisation of a massive vector field. The other mode of the original scalar doublet remains as a massive spin-zero particle – the Higgs boson.
Cartoon Explanation of the Higgs Boson

Physicists
“Higgs field”
Cartoon Explanation of the Higgs Boson

A famous physicist

“Particle”

Physicists

“Higgs field”
A famous physicist is hard to move across the room. “Particle” → gain mass

Physicists “Higgs field”
A less popular physicist is easier to move across the room. “Particle” \(\rightarrow\) gain lower mass

A famous physicist is harder to move across the room. “Particle” \(\rightarrow\) gain higher mass

Source: Cern/UCL
Our Tool: High Energy Collider

- Energy is the currency in particle physics!
  - Shorter distance ↔ Higher energy ($\lambda = \hbar/p$)
  - Heavier matter particle ↔ Higher energy ($E = mc^2$)
- High energy beam and big machine to study the smallest scale

$$M_t = 173.2 \text{ GeV/c}^2$$

$$M_p = 0.938 \text{ GeV/c}^2$$

Energy = 0.98 TeV
Our Tool: High Energy Collider

- Higher energy beam collisions $\leftrightarrow$ higher temperature ($E = \kappa T$)
- Use high energy collider to recreate the conditions right after the Big Bang.

Shortest scale in particle physics

Largest scale in the Universe

$LHC$, time $\approx 10^{-13}$ s, Temp $\approx 10^{17}$ K, Energy $\approx 8$ TeV, distance $\approx 10^{-19}$ m
Large Electron Positron Collider at CERN

- Search for Higgs boson at LEP (e^+e^-, 26.7km)
- LEP1 (1989): \( \sqrt{s} = 91 \text{ GeV} \)
- LEP2 (2000): \( \sqrt{s} = 209 \text{ GeV} \)

where WWW was born in 1991...
Search for Higgs boson at LEP

Results: exclude $m_H < 114.4$ GeV/c$^2$ at 95% CL

Search for Higgs boson at Tevatron (1.96 TeV): 1983 – 2011

Proton-antiproton collision, 6.3km

CDF

D0
Search for Higgs boson at Tevatron

Results (arXiv:1207.0449): $2.5\sigma$ excess at $m_H=120-130$ GeV
Large Hadron Collider at CERN

LHC: 27 km, world’s largest proton-proton collider (7-14 TeV)
Tunnel (26.7 km)
Particle Acceleration and Collision

- Proton-proton collision at LHC
Collisions at LHC

Proton-Proton
Protons/bunch: $10^{11}$
Beam energy: 7 TeV ($7 \times 10^{12}$ eV)
Luminosity: $10^{34}$ cm$^{-2}$ s$^{-1}$
Crossing rate: 40 MHz

Collisions $\approx 10^7 - 10^9$ Hz

Selection of 1 in $10,000,000,000,000,000$

Search for Higgs boson
Tuesday 1 May 2007, 9pm, BBC Two

In the coming months the most complex scientific instrument ever built will be switched on. The Large Hadron Collider promises to recreate the conditions right after the Big Bang. By revisiting the beginning of time, scientists hope to unravel some of the deepest secrets of our Universe.

Within these first few moments the building blocks of the Universe were created. The search for these fundamental particles has occupied scientists for decades but there remains one particle that has stubbornly refused to appear in any experiment. The Higgs Boson is so crucial to our understanding of the Universe that it has been dubbed the God particle. It explains how fundamental particles acquire mass, or as one scientist plainly states: "It is what makes stuff stuff..."

- JOURNEY: Through space and time
- VOTE: Should we risk creating a black hole?
- VIEW: Highlights from the programme
A Giant Takes On Physics' Biggest Questions

Correction Appended

300 FEET BELOW MEYRIN, Switzerland — The first thing that gets you is the noise.

Multimedia

Physics, after all, is supposed to be a cerebral pursuit. But this cavern almost
ATLAS and CMS Collaborations

- **Detector: A Toroidal LHC ApparatuS (ATLAS)**
  - ~ 3000 physicists
  - ~ 1000 students
  - 175 institutes
  - 38 countries

- **Detector: Compact Muon Solenoid (CMS)**
  - ~ 3300 physicists
  - ~ 1500 students
  - 179 institutes
  - 41 countries

20+ years of worldwide collaborative efforts
### Academic Ranking of World Universities (Top-25)


<table>
<thead>
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## ATLAS Member Institutes


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The ATLAS Detector: Huge Camera

- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter

Taking pictures at a rate of 40 Million/s and recording pictures at a rate of ~1000/second

46 x 25 x 25 m, 7000 tons
~3000 collaborators

Solenoid Magnet
Pixel Detector
TRT Tracker
SCT Tracker
Toroid Magnets
The CMS Detector

Compact Muon Solenoid:
21 x 15 x 15 m, 14,500 tons

Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
Different particles have different signatures in detectors

- **Muon Spectrometer:** muon identification and momentum measurement
- **Hadronic calorimeter:** Measurement of jets and missing energy
- **Electromagnetic calo:** $e/\gamma$ identification and energy measurement
- **Tracking system:** Charged particle momentum, vertexing
Higgs Boson Mass Constraint

- Direct searches at LEP (2000):
  \[ m_H > 114.4 \text{ GeV} @ 95\% \text{ C.L.} \]

- Direct search at LHC (2012.3):
  \[ m_H < 127 \text{ GeV} @ 95\% \text{ C.L.} \]

- Precision electroweak data are sensitive to Higgs mass, global fit mass:
  \[ m_H = 94^{+29}_{-24} \text{ GeV} \]

Radiative correction:
\[ M^2_W = M^2_Z (1 - \sin^2 \theta_w)(1 + \Delta \rho) \]

\( \Delta \rho(m_t, m_H, \alpha, \ldots) \)
Higgs Boson Production at LHC

Gluon-gluon fusion $gg \rightarrow H$ and vector-boson fusion $qq \rightarrow qqH$ are dominant

@125 GeV: $\sigma_{ggH} = 19.5 \text{ pb}$, $\sigma_{VBF} = 1.6 \text{ pb}$, $\sigma_{WH} = 0.70 \text{ pb}$, $\sigma_{ZH} = 0.39 \text{ pb}$, $\sigma_{t\bar{t}H} = 0.13 \text{ pb}$

Inelastic pp cross section at 7 TeV is $\sim 60 \text{ mb}$
Higgs Boson Width

- **Strong mass dependent**
  \[ \Gamma_H = 3.5 \text{ MeV} \atop \text{at } 120 \text{ GeV} \]
  \[ 1.4 \text{ GeV} \atop \text{at } 200 \text{ GeV} \]
  \[ 8.4 \text{ GeV} \atop \text{at } 300 \text{ GeV} \]
  \[ 68.0 \text{ GeV} \atop \text{at } 500 \text{ GeV} \]

- At low mass region (<200 GeV), detector resolution dominates mass resolution

- At high mass, intrinsic width becomes dominant

\[ \Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}} \approx 500 \text{ GeV} \cdot \left(\frac{M_H}{1 \text{ TeV}}\right)^3 \]
Higgs Boson Decay

Higgs decay branching ratio at $m_H=125$ GeV

- $bb$: 57.7% (huge QCD background)
- $WW$: 21.5% (easy identification in di-lepton mode, complex background)
- $\tau\tau$: 6.3% (complex final states with $\tau$ leptonic and/or hadronic decays)
- $ZZ^*$: 2.6% (“golden-plate”, clean signature of 4-lepton, high S/B, excellent mass peak)
- $\gamma\gamma$: 0.23% (excellent mass resolution, high sensitivity)

Higgs boson production rate: 1 out of $10^{12}$ collision events
ATLAS Data Samples

- **7 TeV data samples (2011)**
  - 4.8 fb$^{-1}$ for physics analysis
  - Peak luminosity $3.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$

- **8 TeV data samples (2012)**
  - 5.8 fb$^{-1}$ for physics analysis
  - Peak luminosity $6.8 \times 10^{33}$ cm$^{-2}$s$^{-1}$

- **Data-taking efficiency:** ~94%
- **Significant pileup events**
Major Challenge

- Large pileup events result in big challenge to the detector, reconstruction and particle identification!
Higgs $\rightarrow \gamma\gamma$

- Very simple signature, but small rate $\text{Br}(H \rightarrow \gamma\gamma) \sim 2 \times 10^{-3}$;
- Important decay mode for the low mass region (100-140 GeV)

\[ \sigma_H \times \text{Br}(H \rightarrow \gamma\gamma) \sim 50 \text{ fb} \]
\[ @ \ m_H = 125 \text{ GeV} \]

- Decay through loops!

- Irreducible background from $\gamma\gamma$ production

\[ \sigma(\gamma\gamma) \sim 40 \text{ pb} \]

- Reducible background from $\gamma j$ and $jj$ productions

\[ \sigma(\gamma j) \sim 3 \times 10^5 \text{ pb} \]
\[ \sigma(jj) \sim 6 \times 10^8 \text{ pb} \]

Theoretical uncertainty $\Delta \sigma/\sigma \sim 30\%$, not reliable!
Higgs $\rightarrow \gamma\gamma$

Diphoton mass $m_{\gamma\gamma}$ as the final discriminant variable

$$m^2 = 2 E_{\gamma_1} E_{\gamma_2} \left( 1 - \cos \Delta \phi_{\gamma\gamma} \right)$$

Model signal and background using analytical functions:
Signal: Crystal-Ball function (core) + Gaussian (outlier)
Backgrounds: exponentials, polynomials, ...

A total 59059 events selected, expect $\sim 170$ signal events at 126 GeV
Consistent excesses in both 2011 and 2012 data

A minimum $p_0$ at 126.5 GeV

$$p_0 = 2 \times 10^{-6} \Rightarrow 4.5 \sigma$$

The measured signal strength, the excess relative to the SM expectation, at 126 GeV:

$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.8 \pm 0.5$$

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<th>p-value</th>
<th>Obs. Sig.</th>
<th>Exp. Sig.</th>
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<tr>
<td>2011</td>
<td>126</td>
<td>$3 \times 10^{-4}$</td>
<td>3.4$\sigma$</td>
<td>1.6$\sigma$</td>
</tr>
<tr>
<td>2012</td>
<td>127</td>
<td>$5 \times 10^{-4}$</td>
<td>3.2$\sigma$</td>
<td>1.9$\sigma$</td>
</tr>
<tr>
<td>Combined</td>
<td>126.5</td>
<td>$2 \times 10^{-6}$</td>
<td>4.5$\sigma$</td>
<td>2.5$\sigma$</td>
</tr>
</tbody>
</table>
Results from CMS (H → γγ)

Expected 2.5σ

Observed 4.1σ (LEE, 3.2σ)

Signal strength:

\( \sigma / \sigma_{SM} = 1.56 \pm 0.43 \)
Results from CMS (H$\rightarrow\gamma\gamma$)

September 12, 2012

Search for Higgs boson

$\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

Expected 2.5 $\sigma$

Observed 4.1 $\sigma$ (LEE, 3.2 $\sigma$)

Signal strength: $\sigma/\sigma_{\text{SM}} = 1.56 \pm 0.43$
Higgs $\rightarrow ZZ^* \rightarrow 4\ell$: the golden channel

The gold-plated channel over a wide range of potential Higgs mass.

**Clean signature:**
- 4 isolated leptons, full reconstruction;
- Mass peak over backgrounds, good mass resolution.

**Small backgrounds:**
Irreducible SM ZZ* production and reducible Z+jets, top, ...

But even smaller signal rate:
**@125 GeV**

$$\text{BR}(ZZ \rightarrow 4\ell) = 0.45\%, \quad \text{BR}(H \rightarrow ZZ^*) = 2.6\%$$
$$\Rightarrow \sigma_H \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell) = 2.6 \text{ fb}$$

$$\Rightarrow \sim 25 \text{ events in 2011+2012 samples}$$

**Selection efficiency to the 4th power of lepton efficiency:**
$$0.7^4 \sim 0.25, \quad 0.8^4 \sim 0.41 \Rightarrow \text{critical to improve lepton selection!}$$
Higgs $\rightarrow ZZ^* \rightarrow 4\ell$

A small cluster of events populates around 125 GeV

In the region $125 \pm 5$ GeV

<table>
<thead>
<tr>
<th>Dataset</th>
<th>2011</th>
<th>2012</th>
<th>2011+2012</th>
</tr>
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<tbody>
<tr>
<td>Expected B only</td>
<td>$2_{-0.3}^{+0.3}$</td>
<td>$3_{-0.5}^{+0.4}$</td>
<td>$5.1_{-0.8}^{+0.8}$</td>
</tr>
<tr>
<td>Expected S $m_H=125$ GeV</td>
<td>$2_{-0.3}^{+0.3}$</td>
<td>$3_{-0.5}^{+0.5}$</td>
<td>$5.3_{-0.8}^{+0.8}$</td>
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Observed in the data

<table>
<thead>
<tr>
<th>2011+ 2012</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>6</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Expected S/B</td>
<td>1.6</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Reducible/total background</td>
<td>5%</td>
<td>45%</td>
<td>55%</td>
</tr>
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Single resonant contributions
Enhanced by relaxing mass and pT requirements
Higgs → ZZ* → 4ℓ

Consistent excesses in both 2011 and 2012 data

A minimum $p_0$ at 125 GeV

$p_0 = 2 \times 10^{-4} \Rightarrow 3.6\sigma$

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<tr>
<td>2012</td>
<td>125.5</td>
<td>0.5%</td>
<td>2.6σ</td>
<td>2.1σ</td>
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<tr>
<td>Combined</td>
<td>125</td>
<td>0.02%</td>
<td>3.6σ</td>
<td>2.7σ</td>
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Signal strength at 126 GeV: $\mu=1.4 \pm 0.6$
Results from CMS (H$\rightarrow$ZZ$^*$\rightarrow$4$\ell$)

Single resonant Z$\rightarrow$4$\ell$ using loose selection cuts

Enrich the Higgs signal by tightening the selection cuts

Significance: 3.8$\sigma$ (expected), 3.2$\sigma$ (observed)
Candidate of $H \rightarrow ZZ^* \rightarrow 4l$ (CMS)

$M_{4l} = 126.9$ GeV

$\mu^+(Z_1) p_T : 43$ GeV
$\mu^-(Z_1) p_T : 24$ GeV
$e^+(Z_2) p_T : 21$ GeV
$e^-(Z_2) p_T : 10$ GeV
H → ZZ* → 4μ Candidate

- $M_{4μ} = 125.1$ GeV, $M_{12} = 86.3$ GeV, $M_{34} = 31.6$ GeV
Combined Results from ATLAS

- Observed significance $6.0\sigma$ (expected $5.0\sigma$)
- Fitted mass: $126.0 \pm 0.4$ (stat) $\pm 0.4$ (syst) GeV
Observed significance $5.1\sigma$ (expected $5.2\sigma$)
Fitted mass: $125.3 \pm 0.4$ (stat) $\pm 0.5$ (syst) GeV
Observation of a New Particle

Model Higgs Boson with the ATLAS Experiment at the LHC

Abstract

A search for the Standard Model Higgs boson using 4.8 fb$^{-1}$ collected at $\sqrt{s} = 7$ TeV in 2011 and 5.0 fb$^{-1}$ collected at $\sqrt{s} = 8$ TeV in 2012 at the LHC is presented. The datasets used correspond to integrated luminosities of up to 5.1 fb$^{-1}$ at 7 TeV and 5.0 fb$^{-1}$ at 8 TeV. The observed significance of deviations from background expectations is greater than 5 standard deviations for the mass range 115 to 135 GeV. This observation has a significance of 5.3 standard deviations, corresponding to a probability of 0.003%. This is a significant deviation from the Standard Model expectations, which are consistent with a signal from a Higgs boson with mass in the range of 115 to 135 GeV.


“We have now found the missing cornerstone of particle physics. We have a discovery. We have observed a new particle that is consistent with a Higgs boson.”

- Rolf Heuer
CERN Director

“It is an extraordinary achievement for the lab, and I am glad that it happened in my lifetime.” – Peter Higgs

Fabiola Gianotti
ATLAS Spokesperson

It is a historic milestone, but only the beginning……
Physicists Find Elusive Part

The Higgs boson discovery is another giant leap for humankind

The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of

Themis Bowcock

guardian.co.uk, Wednesday 4 July 2012 12.45 BST

Jump to comments (…)

Scientists in Geneva on Wednesday applauded the discovery.

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

Scientists gather at Cern. Formal confirmation of the Higgs boson discovery is expected to follow in the next few months. Photograph: Denis Balibouse/Reuters
Prize for Higgs Mechanism

- **J. J. Sakurai Prize for Theoretical Particle Physics (2011)**

Peter W. Higgs
Phys. Lett. 12 (1964.9.15) 132
PRL 13 (1964.10.19) 508

F. Englert, R. Brout
PRL 13 (1964.8.31) 321

G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, PRL 13 (1964.11.16) 585

Who will win the Nobel Prize?
Thank You！
谢谢大家！
A $p$-value (shaded green area) is the probability of an observed (or more extreme) result arising by chance.
Standard Deviation

- Probability density function (PDF): Gaussian distribution
- $\mu$: mean value
- $\sigma$: standard deviation

$$
\frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
$$
What’s Next?

We have now discovered a Higgs-like new particle at 126 GeV
- Only observed in bosonic final states so far, its decay to fermonic final states has yet to be established;
- The overall production rate appears to be consistent with the Standard Model expectation, but is the higher than expected $H\rightarrow\gamma\gamma$ rate a statistical fluctuation? Or something new in the loop?

Some current activities:
- Complete the analyses in $H\rightarrow\tau\tau$ and $H\rightarrow bb$ final states (Kracow?);
- Observe the particle in the VBF production mode
  - Separate ggF and VBF processes, coupling measurements;
- Measurements of the particle properties: mass, spin and CP, ...
- Improve the precision of the rate measurements;
- Continue the search for other Higgs-like particles
Higgs has two types of coupling:
- To gauge bosons;
- Yukawa coupling to fermions

Isolating the two couplings through the study of both production and decay processes

- "gauge" coupling
- Yukawa coupling
Higgs Spin and Parity

H→ZZ*→4l final state is ideal for Higgs property measurement thanks to full reconstruction, good resolution, low background.

With 30 fb⁻¹, expect a ~3σ separation between $0^+$ and $0^-$. 

JHU generator: $0^+$  $0^-$

Antonelli et al.
Combined Results from ATLAS

The best estimate of the mass:
\[ m = 126.0 \pm 0.4 \text{(stat)} \pm 0.4 \text{(sys)} \text{ GeV} \]

The signal strength at 126 GeV
\[ \mu = 1.4 \pm 0.3 \]
Higgs $\rightarrow$ WW* $\rightarrow$ $\ell\nu\ell\nu$

The SM WW is said to be “irreducible”

However, WW from the scalar Higgs is expected to have different kinematics

$\sigma(H \rightarrow WW* \rightarrow \ell\nu\ell\nu) \approx 220$ fb

(8 TeV, $m_H=125$ GeV)

$\Rightarrow \sim 2300$ events in 2011+2012 samples

Main background:
$WW, t\bar{t}, W/Z$+jets, $WZ/ZZ/W\gamma,...$

The spin correlation leads to a smaller average opening angle between the two leptons
Higgs → WW* → ℓνℓν

0-jet selections
- $p_T^{\ell\ell} > 30$ GeV;
- $m_{\ell\ell} < 50$ GeV;
- $\Delta\phi_{\ell\ell} < 1.8$

The transverse mass as the final discriminant

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\vec{p}_T^{\ell\ell} + \vec{E}_T^{miss})^2}$$

Fit $m_T$ to improve sensitivity

125 GeV: $0.75m_H < m_T < m_H$ (illustration only)

<table>
<thead>
<tr>
<th>Signal</th>
<th>WW</th>
<th>WZ/ZZ/Wγ</th>
<th>$t\bar{t}$</th>
<th>$tW/tb/tqb$</th>
<th>$Z/\gamma^* + \text{jets}$</th>
<th>$W + \text{jets}$</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H + 0$-jet</td>
<td>20 ± 4</td>
<td>101 ± 13</td>
<td>12 ± 3</td>
<td>8 ± 2</td>
<td>3.4 ± 1.5</td>
<td>1.9 ± 1.3</td>
<td>15 ± 7</td>
<td>142 ± 16</td>
</tr>
<tr>
<td>$H + 1$-jet</td>
<td>5 ± 2</td>
<td>12 ± 5</td>
<td>1.9 ± 1.1</td>
<td>6 ± 2</td>
<td>3.7 ± 1.6</td>
<td>0.1 ± 0.1</td>
<td>2 ± 1</td>
<td>26 ± 6</td>
</tr>
<tr>
<td>$H + 2$-jet</td>
<td>0.34 ± 0.07</td>
<td>0.10 ± 0.14</td>
<td>0.10 ± 0.10</td>
<td>0.15 ± 0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.35 ± 0.18</td>
</tr>
</tbody>
</table>

Significant excess over estimated background in both 0-jet and 1-jet channels!
A minimum $p_0$ value at 125 GeV

$$p_0 = 3 \times 10^{-3} \Rightarrow 2.8\sigma$$

(Expected: $p_0 = 0.01$ and 2.3\sigma)

$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.3 \pm 0.5$

2011: $\mu = 0.5 \pm 0.6$; 2012: $\mu = 1.9 \pm 0.7$

Compatible within 1.5\sigma
### Higgs Search Overview

High resolution channels: clean signature, full reconstruction, good mass resolution. *updated with 2012 data for the July 4th seminar.*

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass range (GeV)</th>
<th>Key detector requirements</th>
<th>Main backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>photon</td>
<td>$\gamma\gamma, \gamma j, jj$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110-600</td>
<td>lepton</td>
<td>$ZZ, Z+\text{jets}, \text{top}$</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (WH/ZH)</td>
<td>110-130</td>
<td>jets, b-tagging</td>
<td>$W/Z+\text{jets}, \text{top}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ ($ll, \tau_\tau_\tau, \tau_\tau$)</td>
<td>100-150</td>
<td>lepton, jets, ETmiss</td>
<td>$Z+\text{jets}, \text{jets}$</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow llvv$</td>
<td>110-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$WW, W/Z+\text{jets}, \text{top}, W\gamma$</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow lvqq$</td>
<td>300-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$W+\text{jets}, \text{jets}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow llvv$</td>
<td>200-600</td>
<td>lepton, ETmiss</td>
<td>$Z+\text{jets}, ZZ, \text{top}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow llqq$</td>
<td>200-600</td>
<td>lepton, jets, ETmiss, b-veto</td>
<td>$Z+\text{jets}, ZZ, \text{top}$</td>
</tr>
</tbody>
</table>

Low resolution channels: poor mass resolution, strong dependence on jet and ETmiss performance, *only WW*→lvlv *updated with 2012 data.*
<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRACKER</strong></td>
<td>Si pixels + strips&lt;br&gt;TRT → particle identification&lt;br&gt;( \sigma/p_T \approx 5 \times 10^{-4} ) ( p_T \pm 0.01 )</td>
<td>Si pixels + strips&lt;br&gt;No particle identification&lt;br&gt;( \sigma/p_T \approx 1.5 \times 10^{-4} ) ( p_T \pm 0.005 )</td>
</tr>
<tr>
<td><strong>EM CALO</strong></td>
<td>Pb-liquid argon&lt;br&gt;( \sigma/E \approx 10%/\sqrt{E} ) uniform&lt;br&gt;longitudinal segmentation</td>
<td>PbWO₄ crystals&lt;br&gt;( \sigma/E \approx 2-5%/\sqrt{E} )&lt;br&gt;no longitudinal segmentation</td>
</tr>
<tr>
<td><strong>HAD CALO</strong></td>
<td>Fe-scint. + Cu-liquid argon (( \geq 10 \lambda ))&lt;br&gt;( \sigma/E \approx 50%/\sqrt{E} ) ( \pm 0.03 )</td>
<td>Brass-scint. (( \geq 5.8 \lambda + \text{catcher} ))&lt;br&gt;( \sigma/E \approx 100%/\sqrt{E} ) ( \pm 0.05 )</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td>MDT, CSC, RPC, TGC&lt;br&gt;( \sigma/p_T \approx 7% ) at 1 TeV&lt;br&gt;standalone</td>
<td>DT, CSC, RPC&lt;br&gt;( \sigma/p_T \approx 5% ) at 1 TeV&lt;br&gt;combining with tracker</td>
</tr>
</tbody>
</table>
The decay properties of the Higgs boson are fixed, if the mass is known:

\[ \Gamma(H \to f \bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2 (M_H^2) M_H \]

\[ \Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2) \beta_V \]

where: \( \delta_2 = 1, \delta_W = 2, \ x = M_V^2/M_V^2, \ \beta = \text{velocity} \)

\[ \Gamma(H \to gg) = \frac{G_F}{36\sqrt{2}\pi^3} \alpha_s^2 (M_H^2) M_H^3 \left[ 1 + \left( \frac{95}{4} - \frac{7N_f}{6} \right) \alpha_s \right] \]

\[ \Gamma(H \to \gamma\gamma) = \frac{G_F}{128\sqrt{2}\pi^3} \alpha_s^2 M_H^3 \left[ \frac{4N_c}{3N_c e_t^2} - 7 \right]^2 \]

**Higgs Boson:**

- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed
Yukawa Couplings

- Higgs couples to fermion mass

\[
L_{\text{Yukawa}} = -\lambda_d Q_L \Phi d_R + hc
\]

\[
= -\lambda_d \left( \frac{v + h}{\sqrt{2}} \right) \bar{d}d h \rightarrow -\frac{m_d}{v} \bar{d}d h
\]

- \( m_f = \lambda_f v/\sqrt{2} \)
- Yukawa ffh coupling doesn’t vanish for \( v=0 \)
- Measuring Yukawa coupling doesn’t prove VEV exists!
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

\[
(D^\mu \Phi)(D^\nu \Phi) \rightarrow \left( \frac{gv}{2} \right)^2 W^{\mu\nu} W^\nu_{\mu} \left( 1 + \frac{h}{v} \right) + \ldots
\]

- WWh coupling vanishes for $v=0$! Tests the connection of $M_W$ to non-zero VEV
Selected $H \rightarrow ZZ^* \rightarrow 4l$ Candidates

- Observed candidates with $M_{4l}$ between 120 and 130 GeV

Signal $m_H = 125$ GeV

Total background: $ZZ^*$, $Z$+jets and $t\bar{t}$

**ATLAS**

$m_{ll}=125$ GeV

Data ($120<m_{4l}<130$ GeV)

$\sqrt{s}=7$ TeV: $\int Ldt = 4.8$ fb$^{-1}$

$\sqrt{s}=8$ TeV: $\int Ldt = 5.8$ fb$^{-1}$
H → ZZ* → eeee Candidate

- $M_{4e} = 124.6$ GeV, $M_{12} = 70.6$ GeV, $M_{34} = 44.7$ GeV
H → ZZ* → 2e2µ Candidate

- $M_{2e2\mu} = 123.9$ GeV, $M_{12} = 87.9$ GeV, $M_{34} = 19.6$ GeV
About 28K JHU H(0+) and 28K H(0-) events, one half for BDT training and another half and SM ZZ for test.

**Selection Cuts:**
- $50 \text{ GeV} < M_{Z1} < 106 \text{ GeV}$
- $17.5 \text{ GeV} < M_{Z2} < 115 \text{ GeV}$
- Lepton pT:
  - $p_{T1} > 20 \text{ GeV}$, $p_{T2} > 15 \text{ GeV}$,
  - $p_{T3} > 10 \text{ GeV}$, $p_{T4} > 7 \text{ GeV}$
- $|\eta| < 2.5$
- $dR > 0.1$ ($0.2$) for same (different) flavor di-lepton
- $120 \text{ GeV} < M_{ZZ} < 130 \text{ GeV}$
Using Binned Log-likelihood Ratio method to determine the separation power between Higgs 0+ and 0-

1M MC trials based on Poisson statistics

Log-likelihood Ratio distributions

Expected significance vs int. luminosity

<table>
<thead>
<tr>
<th>Int. Luminosity (fb⁻¹)</th>
<th>Significance (no ZZ, BDT)</th>
<th>Significance (with ZZ, BDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (N_s=6, N_b=5.5)</td>
<td>1.97 σ</td>
<td>1.45 σ</td>
</tr>
<tr>
<td>20 (N_s=12, N_b=11)</td>
<td>2.74 σ</td>
<td>1.98 σ</td>
</tr>
<tr>
<td>30 (N_s=18, N_b=16.5)</td>
<td>3.36 σ</td>
<td>2.40 σ</td>
</tr>
<tr>
<td>40 (N_s=24, N_b=22)</td>
<td>3.85 σ</td>
<td>2.77 σ</td>
</tr>
<tr>
<td>50 (N_s=30, N_b=27.5)</td>
<td>4.26 σ</td>
<td>3.10 σ</td>
</tr>
</tbody>
</table>
Discovery of SM Particles

- 1897 – e discovery, by J.J. Thompson (cathode ray tube, UK)
- 1919 – proton, Ernest Rutherford (UK)
- 1930 – neutron, James Chadwick (UK)
- 1936 – μ, Carl D. Anderson at Caltech
- 1947 – strange quark (K+ = usbar, K- = subar)
- 1956 – ν_e discovery (nuclear reactor)
- 1962 – ν_μ discovery at BNL
- 1968 – u and d quark (quark model)
- 1974 – c quark (BNL, SLAC, J/ψ = ccbar)
- 1977 – τ discovery (SLAC)
- 1977 – b quark (Upsilon, FNAL)
- 1979 – gluon (DESY)
- 1983 – W and Z (CERN)
- 1995 – top quark
- 2000 – ν_τ discovery (Fermilab)