Higgs Searches and Properties
Measurement with ATLAS

杨海军（上海交通大学）

中国科学院大学
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Outline

- Introduction of SM
- Higgs Searches at Tevatron, LEP and EW measurements
- ATLAS Experiment at LHC
- Higgs Production and decays at LHC
- Major challenge for Higgs Searches
- Observation of Higgs-like particle
- Update results for Higgs searches (20.7fb$^{-1}$ at 8 TeV)
- Higgs Properties (Spin, CP, Couplings) Measurements
- Summary and Conclusions
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 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)
Higgs Mechanism (1964)

- 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

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

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

- 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 $\Rightarrow$ 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.
History of the Higgs Search

- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
  - Not taken too seriously until...
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - Closely linked to the Higgs boson
- 1993 CERN/LEP1 studies Z's and rules out $m_H < 53$ GeV
  - And indirectly excludes $m_H > 300$ GeV
- 2000 CERN/LEP2 lower limit reaches 114.4 GeV
- 2011 CERN/LHC excludes 130-550 GeV
- 2011 Fermilab/Tevatron excludes 156-175 GeV
- 2012 Fermilab/Tevatron observed $2.5\sigma$ excess at [120,130]
- **2012.7.4 New particle found at ~125 GeV**
  - $5\sigma$ for ATLAS/CMS, consistent with the SM Higgs
Results: exclude $m_H < 114.4 \text{ GeV/c}^2$ at 95% CL

Search for Higgs boson at Tevatron

Results (arXiv:1207.0449): $2.5\sigma$ excess at $m_H = 120-130$ GeV
Searches for Higgs Boson at LEP and LHC

- 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: \( m_H = 94^{+29}_{-24} \text{ GeV} \)

\[
M^2_W = M^2_Z (1 - \sin^2 \theta_W) (1 + \Delta \rho)
\]

Radiative correction: \( \Delta \rho (m_t, m_H, \alpha, \ldots) \)
CERN: Large Hadron Collider at CERN

- ATLAS
- ALICE
- CMS
- LHCb
- Where the WWW was born …

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

- Proton-proton collision at LHC
Proton-proton Collisions at LHC

Proton-Proton
Protons/bunch $10^{11}$
Beam energy 7 TeV ($7 \times 10^{12}$ eV)
Luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Crossing rate 40 MHz
Collisions $\approx 10^7 - 10^8 \text{ Hz}$

Selection of 1 in $10,000,000,000,000$
The ATLAS Detector: Huge Camera

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
- 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/γ identification and energy measurement

**Tracking system:** Charged particle momentum, vertexing
Gluon-gluon fusion $gg\rightarrow H$ and vector-boson fusion $qq\rightarrow qqH$ are dominant.

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

Inelastic pp cross section at 7 TeV is $\sim 60$ mb.
Higgs decay branching ratio at $m_H = 125$ GeV

- $\bar{b}b$: 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% (“gold-plated”, 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
Higgs Boson Width

- Strong mass dependent
  - \( \Gamma_H = 3.5 \text{ MeV} @ 120 \text{ GeV} \)
  - 1.4 GeV @ 200 GeV
  - 8.4 GeV @ 300 GeV
  - 68.0 GeV @ 500 GeV

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

- At high mass, intrinsic width becomes dominant
  \[
  \Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}} 
  \approx 500 \text{ GeV} \cdot \left( \frac{M_H}{1 \text{ TeV}} \right)^3
  \]
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)**
  - 20.7 fb$^{-1}$ for physics analysis
  - Peak luminosity $7.7 \times 10^{33}$ cm$^{-2}$s$^{-1}$

- **Data-taking efficiency: ~94%**

- **Significant pileup events**
Major Challenge (Large Pileup)

- Large pileup events result in big challenge to the detector, reconstruction and particle identification!
Observation of a new Particle (July 4, 2012)

- **H → γγ**
- **H → WW**
- **H → ZZ**

**ATLAS** Preliminary

- Data
- Background ZZ(∗)
- Background Z+jets, t̄t
- Signal (m_H = 125 GeV)
- Signal (m_H = 150 GeV)
- Signal (m_H = 190 GeV)
- Syst.Unc.

- Events/5 GeV
- Events/10 GeV
- m_γ [GeV]
- m_H [GeV]
- m_τ [GeV]
- m_V [GeV]
- m_μ [GeV]
- m_ν [GeV]
- m_γ [GeV]
- m_τ [GeV]
- m_V [GeV]
- m_μ [GeV]
- m_ν [GeV]

- Combined

**ATLAS** 2011 - 2012

- m_μ = 126.0 GeV
- μ = 1.4 ± 0.3

**ATLAS** Preliminary

- iS = 8 TeV, \(|Ldt| = 5.8 \text{ fb}^{-1}\)
- H → WW(∗) → 4l
- H → ZZ(∗) → 4l
Observation of a new Particle (5$\sigma$)!

Update Since July 4, 2012


<table>
<thead>
<tr>
<th>Higgs Boson Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
<th>$\int L , dt$ [fb$^{-1}$]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to ZZ^{(*)}$</td>
<td>4$\ell$</td>
<td>${4e, 2e2\mu, 2\mu2e, 4\mu}$</td>
<td>4.6</td>
<td>[8]</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$\ell\gamma\gamma$</td>
<td>${e\mu \otimes 0$-jet$} \oplus {\ell\ell} \oplus {1$-jet, 2-jet, $p_{T,\tau\tau} &gt; 100$ GeV, $VH}$</td>
<td>4.8</td>
<td>[7]</td>
</tr>
<tr>
<td>$H \to WW^{(*)}$</td>
<td>$\ell\nu\ell\nu$</td>
<td>${ee, e\mu, \mu\nu, \mu\mu} \otimes {0$-jet, 1-jet, 2-jet VBF$}$</td>
<td>4.6</td>
<td>[9]</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$\tau_{lep}\tau_{lep}$</td>
<td>${e\mu \otimes 0$-jet$} \oplus {\ell\ell} \oplus {1$-jet, 2-jet, $p_{T,\tau\tau} &gt; 100$ GeV, $VH}$</td>
<td>4.6</td>
<td>[10]</td>
</tr>
<tr>
<td></td>
<td>$\tau_{lep}\tau_{had}$</td>
<td>${e, \mu \otimes 0$-jet, 1-jet, $p_{T,\tau\tau} &gt; 100$ GeV, 2-jet$}$</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{had}\tau_{had}$</td>
<td>${1$-jet, 2-jet$}$</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>$VH \to Vbb$</td>
<td>$Z \to \nu\nu$</td>
<td>$E_{miss}^{T} \in {120 - 160, 160 - 200, \geq 200$ GeV$} \otimes {2$-jet, 3-jet$}$</td>
<td>4.6</td>
<td></td>
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<tr>
<td></td>
<td>$W \to \ell\nu$</td>
<td>$p_{T}^{W} \in {&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200$ GeV$}$</td>
<td>4.7</td>
<td>[11]</td>
</tr>
<tr>
<td></td>
<td>$Z \to \ell\ell$</td>
<td>$p_{Z}^{Z} \in {&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200$ GeV$}$</td>
<td>4.7</td>
<td></td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 7$ TeV

4.6-4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV

Full dataset

20.7 fb$^{-1}$ for $\gamma\gamma, ZZ, WW$

June 17, 2013

H. Yang - Discovery of the Higgs Boson
Update of $H \rightarrow \gamma\gamma$

**Higgs Significance**
- Expected $4.1\sigma$
- Observed $7.4\sigma$
Update of $H \to \gamma\gamma$

Best fitted mass:
$$M_H = 126.8 \pm 0.2 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV}$$

Best fitted signal strength:
$$1.65 \pm 0.24 \text{ (stat)}^{+0.25}_{-0.18} \text{ (syst)}$$
Evolution of Higgs $\rightarrow ZZ^* \rightarrow 4l$ Candidates
Update of $H \rightarrow ZZ^* \rightarrow 4l$

**Best fit mass:**

$M_H = 124.2 \pm 0.6\text{(stat)} \pm 0.3\text{(syst)}$ GeV

**Best fit signal strength:**

$\mu = 1.7 + 0.5 (-0.4) \text{ at } 124.2$ GeV

$\mu = 1.5 \pm 0.4 \text{ at } 125.5$ GeV
Update of $Z \rightarrow 4l$

Single resonant $Z \rightarrow 4l$ enhanced by relaxing mass, $P_T$ requirements

BR of $Z \rightarrow 4l$ is measured to be $(4.2 \pm 0.4) \times 10^{-6}$, consistent with SM prediction $(4.37 \pm 0.03) \times 10^{-6}$. 

June 17, 2013

H. Yang - Discovery of the Higgs Boson
Higgs Mass Measurements

Best fit mass for $H \rightarrow \gamma\gamma$:
$M_H = 126.6 \pm 0.2({\text{stat}}) \pm 0.7({\text{syst}}) \text{ GeV}$

Best fit mass for $H \rightarrow ZZ^* \rightarrow 4\ell$:
$M_H = 124.3 \pm 0.6({\text{stat}}) \pm 0.3({\text{syst}}) \text{ GeV}$

Best fit mass for combination:
$M_H = 125.5 \pm 0.2({\text{stat}}) \pm 0.6({\text{syst}}) \text{ GeV}$
Consistency Check of Higgs Mass Discrepancy

\[ \Delta \hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7} \text{ (stat)} \pm 0.6 \text{ (sys)} \text{ GeV} \]

The probability for a single Higgs boson-like particle to produce a value of the \( \Lambda \) test statistic disfavoring the \( \Delta M_H=0 \) hypothesis more than observed is found to be \( 1.2\% \) or \( 2.5\sigma \).
Update of $H \rightarrow WW^* \rightarrow ℓνℓν$

- Final discriminant

\[ m_T = \sqrt{\left( E_T^{ℓℓ} + E_T^{miss} \right)^2 + \left| p_T^{ℓℓ} + E_T^{miss} \right|^2} \]

Due to spin correlation between $W^+$ and $W^-$, the signal has the following properties:

**Large $P_T(ℓℓ)$, small $m_{ℓℓ}$, small $Δϕ_{ℓℓ}$**

**ATLAS best-fit signal strength:**

ICHEP (4.6+5.8 fb⁻¹): $μ = 1.3 \pm 0.5$

2012 (4.6+20.7 fb⁻¹): $μ = 1.0 \pm 0.3$

<table>
<thead>
<tr>
<th>$N_{jet}$</th>
<th>$N_{obs}$</th>
<th>$N_{bkg}$</th>
<th>$N_{sig}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= 0$</td>
<td>154</td>
<td>161 ± 11</td>
<td>25 ± 5</td>
</tr>
<tr>
<td>$= 1$</td>
<td>62</td>
<td>47 ± 6</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>$≥ 2$</td>
<td>2</td>
<td>4.6 ± 0.8</td>
<td>1.4 ± 0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$N_{WW}$</th>
<th>$N_{VV}$</th>
<th>$N_{ℓℓ}$</th>
<th>$N_{ℓ}$</th>
<th>$N_{Z/γ^∗}$</th>
<th>$N_{W+ jets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>113 ± 10</td>
<td>12 ± 2</td>
<td>5 ± 1</td>
<td>4 ± 1</td>
<td>6 ± 2</td>
<td>21 ± 5</td>
</tr>
<tr>
<td>16 ± 6</td>
<td>5 ± 1</td>
<td>10 ± 3</td>
<td>6 ± 2</td>
<td>5 ± 2</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>0.7 ± 0.2</td>
<td>-</td>
<td>0.7 ± 0.5</td>
<td>0.1 ± 0.1</td>
<td>2.4 ± 0.6</td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>
Update of $H \rightarrow \tau\tau$

- $H \rightarrow \tau\tau$ provide an unique opportunity to probe Yukawa coupling which gives mass to quarks and leptons
- It has one the largest branching ratios for low mass Higgs
- Three different $\tau\tau$ decay modes:
  - lep-lep: $\ell\ell4\nu$: (ee) + e$\mu$ + $\mu\mu$
  - lep-had: $\ell\tau_{had}3\nu$: e$\tau_{had}$ + $\mu\tau_{had}$
  - had-had: $\tau_{had}\tau_{had}\nu\nu$: $\tau_{had}\tau_{had}$
The largest deviation of observed from expected limit is in the 2-lepton channel.

The best fitted signal strength @ 125 GeV: $\mu = 0.8 \pm 0.7$

Due to the presence of MET, the complexity of each subchannel of $H \rightarrow \tau\tau$ is greater than $\gamma\gamma$ or $ZZ \rightarrow 4l$ channel.
Update of $H \rightarrow bb$

- Fit invariant mass of $M_{bb}$ distribution
- Validation $WZ, ZZ \rightarrow bb + X$: $\mu_{WZ, ZZ} = 1.09 \pm 0.30$ (4.0$\sigma$)
- On the Higgs search, data show no excess on top of expected backgrounds, expected limit $1.9 \sigma/\sigma_{SM} @ m_H = 125$ GeV, the observed limit is $1.8 \sigma/\sigma_{SM}$, signal strength is $\mu = -0.4 \pm 1.0$

![Graph showing data and limits for Higgs signal strength.](image-url)
Loop decay like $H \rightarrow \gamma\gamma$
- Could be enhanced if radion not Higgs (hep-ph/9907447)

Four channels combined to make limits
- $e^+e^-$, $\mu^+\mu^-$ at 7 TeV and 8 TeV
- Observed limit $18 \times \text{SM Higgs}$
- Expected limit $13 \times \text{SM Higgs}$
Expect suppressed by \((1.7778/0.1056)^2 \approx 280\) w.r.t. \(\tau\tau\)

Good efficiency and mass resolution improves things

- But SM sensitivity needs considerably more data
- Observed limit \(9.2 \times \text{SM}\)
- Expected limit \(8.2 \times \text{SM}\)
Update of Higgs Signal Strength

- Signal strength: $\mu = 1.3 \pm 0.2$ (ATLAS)
- $\mu = 0.8 \pm 0.14$ (CMS)

Higgs Boson Decay

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mu$ $m_H=125.5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VH \rightarrow Vbb$</td>
<td>$-0.4 \pm 1.0$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$0.8 \pm 0.7$</td>
</tr>
<tr>
<td>$H \rightarrow WW^{(*)}$</td>
<td>$1.0 \pm 0.3$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$1.6 \pm 0.3$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^{(*)}$</td>
<td>$1.5 \pm 0.4$</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.30 \pm 0.20$</td>
</tr>
</tbody>
</table>
Strong Evidence for a New Particle

2012 ICHEP
- Significance 6.0σ (exp 5.0σ)
- \( M_H = 126.0 \pm 0.4 \pm 0.4 \) GeV

2012 Full Datasets
- Significance 9.9σ (exp 7.5σ)
- \( M_H = 125.5 \pm 0.2 \pm 0.6 \) GeV
Is it the SM Higgs?

- Verify the new observed particle
  - Spin-0 particle
    - Spin-1: excluded by $H \rightarrow \gamma\gamma$
    - Spin-2: look at angular correlations
  - CP-nature
    - SM Higgs CP-even, extended Higgs sectors has CP-odd or mixed states
    - Look at angular correlations

- Couplings
  - Gauge / Yukawa couplings $\rightarrow g_{vvH}, g_{ffH} \propto m$
  - Unitarity in $W_L W_L$ scattering $\rightarrow g_{WWH} \propto m_W$
  - Higgs self-couplings, determine shape of Higgs potential via trilinear and quartic couplings, $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{constant}$
H $\to \gamma\gamma$ : Spin Analysis

- Using events in signal mass window [123.6, 128.6] GeV
- The photon polar angle in the resonance rest frame $|\cos\theta^*|$ is sensitive to the spin of Higgs.

$$
\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + (p_T^{\gamma \gamma}/m_{\gamma \gamma})^2}} \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma \gamma}^2}
$$
Observed data agree with spin $0^+$ hypothesis $(1-\text{CL}_b) \sim 58.8\%$.
Spin 2 hypothesis is disfavored at 99.3% C.L. (or $2.9\sigma$) assuming 100% gluon-gluon production.
Spin for $H \rightarrow WW$

- Combine several variables in a MVA discriminant (Boosted Decision Trees, BDT)
- Variables used: $m_{ll}$, $P_T^l$, $\Delta \phi_{ll}$, $m_T$

ATLAS Preliminary

$\sqrt{s} = 8$ TeV, $\int L dt = 20.7$ fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu + 0$ jets

ATLAS CONF-2013-031
The ATLAS data favors spin 0 with CP even.
H→ZZ*→4l : Spin and CP

- Fully reconstructed final state allows measuring Spin/CP:
  - Five kinematic angles (production, decay)
  - Invariant mass of the primary Z and the secondary Z

  - $\theta_1$ ($\theta_2$) is the angle between the negative final state lepton and the direction of flight of $Z_1$ ($Z_2$) in the Z rest frame.
  - $\Phi$ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
  - $\Phi_1$ is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the $Z_1$ in the four lepton rest frame and the positive direction of the parton axis.
  - $\theta^*$ is the production angle of the $Z_1$ defined in the four lepton rest frame.

- Discriminate $0^+$ (SM) hypothesis against:
  - $0^-$ (CP odd), $1^+, 1^-$
  - $2^-$ (pseudo-tensor)
  - $2^+_m$ (graviton-like tensor, minimal coupling)
H → ZZ* → 4l : Spin and CP

- **MVA: BDT vs J^p-MELA**

  - Data favour \( 0^+ \), \( 0^- \) hypothesis is excluded at 98.7% C.L. (2.23\( \sigma \))
  - \( 1^+ \) is excluded at 99% C.L., \( 2^+ \) is excluded at \( \sim 95.8\% \) C.L. (1.73\( \sigma \))

June 17, 2013

H. Yang - Discovery of the Higgs Boson
Observation of $H \to \gamma\gamma$ excludes spin-1

- Higgs has two types of couplings:
  - "Gauge" couplings (to bosons)
  - Yukawa couplings (to fermions)

Explore tension between SM value and observation from different Higgs production modes: $\mu_{VBF+VH}$ vs. $\mu_{ggF+ttH}$
Model independent coupling studies which are directly related to experimental observables.

2D contour: $\mu_{VBF+VH}$ vs. $\mu_{ggF+ttH}$

The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.
A determination of $\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}}$ provides evidence for VBF production at the 3.1σ level.

$$\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.2^{+0.7}_{-0.5}$$
Assumptions (LHC HXSWG, arXiv:1209.0040):

- The signal observed in different channels originate from a single narrow resonance with mass near 125 GeV.
- The width of the assumed Higgs boson near 125 GeV is neglected, hence the signal cross section can be decomposed in the following for all channels:

\[(\sigma \cdot \text{BR})(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}\]

- Only modifications of couplings strengths are taken into account, while the tensor structure of the couplings is assumed to be same as in the SM prediction (CP-even scalar). [ATLAS-CONF-2012-127]
Depending on the benchmark model, $\kappa_g$, $\kappa_\gamma$ and $\kappa_H$ are either functions of other couplings or independent parameters.

Notation for $gg \rightarrow H \rightarrow \gamma\gamma$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_H} = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \kappa_\gamma^2$$

$$\sigma_{ggF}^{SM} = \kappa_g^2 \sigma_{ggF}$$

$$\text{BR}_{SM}(H \rightarrow \gamma\gamma)$$

$$= \kappa_g^2 \sigma_{SM}(gg \rightarrow H) \cdot \frac{\kappa_\gamma^2}{\kappa_H^2} \text{BR}_{SM}(H \rightarrow \gamma\gamma)$$

Zero Width Approximation
Fermion and Vector Couplings

- Two coupling scale factors $\kappa_F$ for fermions and $\kappa_V$ for bosons
- Vector coupling ($\kappa_V$) measured in channels ($H \rightarrow \gamma\gamma$, WW, ZZ)
- Fermion coupling ($\kappa_F$) measured:
  - Directly in $H \rightarrow bb$ and $H \rightarrow \tau\tau$
  - Indirectly via loop $gg \rightarrow H$
- $\lambda_{FV} = \kappa_F / \kappa_V$, $\kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$
- Measured ratio of fermion to vector couplings: $\lambda_{FV} = 0.85^{+0.23}_{-0.13}$
- Fermion & vector couplings non-zero, consistent with SM.
- 2D compatibility of the SM hypothesis with the best fit point is 8%.
Probing custodial symmetry of the W/Z Coupling

- Similar to previous benchmark model, but $\kappa_V \rightarrow \kappa_W$ and $\kappa_Z$, so there are three free parameters $\kappa_W$, $\kappa_Z$ and $\kappa_F$. Identical couplings scale factors for the W and Z are required within tight bounds by SU(2) custodial symmetry and $\rho$ parameter.

- The VBF process is parametrized with $\kappa_W$ and $\kappa_Z$ according to the Standard Model.

\[
\begin{align*}
\lambda_{WZ} & = 0.80 \pm 0.15 \\
\lambda_{\gamma Z} & = 1.10 \pm 0.18 \\
\lambda_{FZ} & = 0.74^{+0.21}_{-0.17} \\
\kappa_{ZZ} & = 1.5^{+0.5}_{-0.4}
\end{align*}
\]

- 4D compatibility of the SM hypothesis with the best fit point is 9%.
Probing Potential Non-SM Particle Contributions

- For $H \rightarrow \gamma \gamma$ and $gg \rightarrow H$ vertices, effective scale factors $\kappa_\gamma$ and $\kappa_g$ are introduced (two free parameters). Non-SM particles can contribute to $H \rightarrow \gamma \gamma$ and $gg \rightarrow H$ loops or in new final states.

- Assuming only SM contributions to total width and $\kappa_i = 1$ for all SM particles.

- No assumption on total width, but $\kappa_i = 1$ for all SM particles.

\[
\begin{align*}
\kappa_g &= 1.08 \pm 0.14 \\
\kappa_\gamma &= 1.23^{+0.16}_{-0.13}
\end{align*}
\]

\[
\Gamma_H = \frac{\kappa_H^2(k_i)}{(1 - BR_{inv., undet.})} \Gamma_{H}^{SM}
\]

June 17, 2013

H. Yang - Discovery of the Higgs Boson
The compatibility of the measured yields for the studied channels with the prediction for the SM Higgs boson is tested under various benchmark assumptions proving salient features of the couplings.

For the different tested benchmarks the compatibility with the SM Higgs expectation ranges between 10%-20%.

No significant deviation from the SM prediction is observed in any of the fits performed.
### Summary of what we know now?

<table>
<thead>
<tr>
<th>Higgs Mass</th>
<th>125-126 GeV – agree with SM rough prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>Spin 0 fits well, spin 1 unlikely, spin (2^+) excluded at 99.9%</td>
</tr>
<tr>
<td>Parity</td>
<td>Reasonable evidence it is symmetric</td>
</tr>
<tr>
<td>Charge</td>
<td>Zero, as it should be</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Unknown, but narrow resonance and no obvious flight</td>
</tr>
<tr>
<td>Interaction with W/Z</td>
<td>Rates in WW and ZZ look as expected</td>
</tr>
<tr>
<td>Interaction with fermions</td>
<td>Direct evidence weak, gluon rate implies (~SM) coupling, Tevatron +CMS have evidence for (H \rightarrow bb)</td>
</tr>
<tr>
<td>Interaction with gluons</td>
<td>Total rate suggest it’s as expected</td>
</tr>
<tr>
<td>Interaction with photons</td>
<td>1.6 ± 0.2(stat) ± 0.2 (syst), &lt; 2(\sigma) deviation from SM !</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td><strong>SM Higgs with reasonable statistical fluctuations</strong></td>
</tr>
</tbody>
</table>
Summary and Conclusions

- A new Higgs-like particle was observed and confirmed.

\[
\text{Mass: } m_H = 125.5 \pm 0.2 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV}
\]

\[
\text{Signal strength @ 125.5 GeV : } \mu = 1.3 \pm 0.2
\]

- Higgs decays to $\gamma\gamma$, $ZZ^*$ and $WW^*$ (Gauge coupling) are established, but $H \rightarrow bb, \tau\tau, \mu\mu$ (Yukawa coupling) still lack of statistics to draw definitive conclusion.

- The spin-1 is excluded due to observation of $H \rightarrow \gamma\gamma$.

- Spin/CP: data favour $0^+$ (spin 0 and CP even, SM)

- Uncertainties of couplings parameters $\sim$10-20\%, no significant deviations from SM couplings are observed.

Please stay tuned!
Backup Slides

- $\gamma\gamma$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-012
- $\gamma\gamma$ spin: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-029
- $\tau\tau$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-160
- $\mu\mu$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-010
Figure 42: Event display of a $4\mu$ candidate. EventNumber: 71902630 RunNumber: 204769 $m_{4\ell} = 125.1$ GeV. $m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV. $\mu_1: p_T, \eta, \phi = 36.1$ GeV, 1.29, 1.33. $\mu_2: p_T, \eta, \phi = 47.5$ GeV, 0.69, -1.65. $\mu_3: p_T, \eta, \phi = 26.4$ GeV, 0.47, -2.51. $\mu_4: p_T, \eta, \phi = 71.7$ GeV, 1.85, 1.65. $p_T^{A\ell} = 27.0$ GeV. $E_T^{\text{miss}} = 41.8$ GeV.
CMS Higgs $\rightarrow$ $bb$

**Data Summary: VH $\rightarrow$ Vbb**

Summary

- seeing diboson production ($VV$), Higgs excess starting to build up
Results Summary: $H \rightarrow bb$

CMS result
- SM sensitivity reached
- mild excess is observed, channels consistent
- need more data

$\sigma/\sigma_{SM} = 1.0 \pm 0.5$
Summary

- Tevatron combination on $H \rightarrow b \bar{b}$ has been updated:
  - CDF $\nu \nu b \bar{b}$ with the latest $b$-tagger, 14% better sensitivity.
  - DZero $l \nu b \bar{b}$ small changes on treatment of scale factors.

- New preliminary result:

  $$\sigma(WH + ZH) \times Br(H \rightarrow b \bar{b})$$
  $$= 0.19 \pm 0.09 \text{ (stat+syst) pb}$$
  $$\Rightarrow \mu = 1.56 \pm 0.72_{-0.73}^{+0.72} \text{ @ } M_H = 125 \text{ GeV}$$

  Diboson $VZ X$ section measurement
  $$\sigma(WZ + ZZ) = 3.0 \pm 0.9 \text{ pb}$$
  (NLO exp. : $4.4 \pm 0.3 \text{ pb}$)

- Future

  - Extract Spin information based on kinematics of $V+H$ system (J. Ellis et al. arXiv:1208.6002)
Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$  
preliminary

1+2 b-Tagged Jets

- Data - Bkgd
- WZ
- ZZ
- Higgs Signal ($\sigma_H \times 1.5$)
  $m_H = 125 \text{ GeV/c}^2$

Dijet Mass (GeV/c$^2$)

Events / (20 GeV/c$^2$)

Thank you for your attention.
Higgs → γγ

- 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)

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

\~500 events in 2011+2012 sample!

- Irreducible background from γγ production

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

- Reducible background from γj 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

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

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
The decay properties of the Higgs boson are fixed, if the mass is known:

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

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

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

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

\[ \Gamma(H \rightarrow \gamma\gamma) = \frac{G_F}{128\sqrt{2}\pi^3} \frac{\alpha^2}{M_H^3} \left[ \frac{4}{3} N_C c_t^2 - 7 \right]^2 \]

**Higgs Boson:**

- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed
LHC physics is all about background rejection ($\sim 10^{10}$)

“Every event at a lepton collider is physics; every event at a hadron collider is background”

- By Samuel C.C. Ting