The Higgs Particle

CERN Academic Training

Lecture III

Properties, Implications and Prospects

Marumi Kado

Laboratoire de l’Accélérateur Linéaire (LAL)
And CERN
Outline

I.- The roadmap to the discovery  (Lecture I)

   From theoretical foundations to the discovery

II.- An (early) experimental profile of the Higgs boson  (Lecture II)

   Measurement of properties of the Higgs particle

III.- Implications and future projects  (Lecture III)

   1.- Comments on Statistical Methods (Part III)
   2.- Rare and invisible decays
   3.- Measurement of spin/CP properties of the discovered state
   4.- Search for BSM Higgs and extended sectors
   5.- Implications of the discovered state
   6.- Future Higgs programs
   7.- Conclusion
How to Read Higgs Exclusion Limits Plots

\[
\lambda_\mu = \lambda(\mu, \theta) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \quad q_\mu = -2 \ln \lambda_\mu
\]
Statistical Interpretation
How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio...

Relate to Higgs mass hypothesis

Not a measurement of mass
Not a measurement of cross section

Expected Signal

Excess

Deficit

Inclusive diphoton sample

\( \hat{\mu} \)

\( \sqrt{s} = 7 \text{ TeV}, \int Ldt = 4.9 \text{ fb}^{-1} \)

\( m_H = 120 \text{ GeV (MC)} \)

\( \pm 1 \sigma \)

\( \int Ldt = 4.9 \text{ fb}^{-1} \)

\( \sqrt{s} = 7 \text{ TeV} \)

2011 Data

ATLAS Preliminary
How to Read Higgs Exclusion Limits Plots

\[ \lambda_\mu = \lambda(\mu, \theta) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \]

\[ q_\mu = -2 \ln \lambda_\mu \]

Background likeliness

\[ CL_{s+b} \text{ Probability that a signal-plus-background experiment be more background-like than observed} \]
The Higgs Natural Width Problem

At LHC no direct access to the Higgs total cross section (unlike e+e- collider from recoil mass spectrum)

- Total width (4 MeV) too tiny to be meaningfully measured experimentally from lineshape

- New observed state can decay invisibly. Direct search possible at LHC

- New observed state can decay to a priori visible decay products but not distinguishable from background. In this case no experimental handle

The total width cannot be measured without further assumptions on the couplings of the visible states.
Invisible and rare decays
Invisible and rare decays

<table>
<thead>
<tr>
<th>Channel categories</th>
<th>ATLAS</th>
<th>CMS</th>
<th>TeVatron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ggF</td>
<td>VBF</td>
<td>VH</td>
</tr>
<tr>
<td>γγ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ (llll)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WW (lνlν)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ττ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>H (bb)</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zγ</td>
<td>(inclusive) ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>µµ</td>
<td>(inclusive) ✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invisible</td>
<td>(√)</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Invisible Higgs Channels I

- Indirect constraints on the invisible and undetected Branching
  
  \( (a \text{ fortiori} \text{ on the invisible branching}) \)

- Re-interpretation of mono-jet and mono-W or Z analyses

\[ \kappa_g, \kappa_\gamma, B_{\text{inv, undet}} \]

For a 125 GeV Higgs: \( \sigma B_{\text{inv}} / \sigma_{\text{SM}} < 1.6 \) at 95%CL (obs)
Invisible Higgs Channels I

- Search for a dilepton pair compatible with a Z and missing transverse energy
- Analyses using fits to MET (ATLAS) or MT (CMS)

For a 125 GeV Higgs:
- **ATLAS**
  \[ \text{Br}_{\text{inv}} < 65\% \text{ at } 95\%\text{CL} \text{ (obs)} \]
  \[ \text{Br}_{\text{inv}} < 84\% \text{ at } 95\%\text{CL} \text{ (exp)} \]
- **CMS**
  \[ \text{Br}_{\text{inv}} < 75\% \text{ at } 95\%\text{CL} \text{ (obs)} \]
  \[ \text{Br}_{\text{inv}} < 91\% \text{ at } 95\%\text{CL} \text{ (exp)} \]
Invisible Higgs Channels II

- Associated production with a Z in bb (CMS only)
- Search following closely VH(bb)
- Contribution from VH(bb) has very little impact

For a 125 GeV Higgs:

$$\frac{\sigma_{\text{Br}_{\text{inv}}}}{\sigma_{\text{SM}}} < 1.8 \text{ at } 95\%\text{CL (obs)}$$

$$\frac{\sigma_{\text{Br}_{\text{inv}}}}{\sigma_{\text{SM}}} < 2.0 \text{ at } 95\%\text{CL (exp)}$$

CMS-PAS-HIG-13-028
Invisible Higgs Channels IV

- Search in the VBF production mode
- Main selection on \( M_{jj}, \Delta \eta_{jj}, \) and large MET

For a 125 GeV Higgs:
- CMS
  \[ \text{Br}_{\text{inv}} < 69\% \text{ at } 95\% \text{CL (obs)} \]
  \[ \text{Br}_{\text{inv}} < 53\% \text{ at } 95\% \text{CL (exp)} \]
Higgs width determination

- Direct measurement will only be possible at muon collider... what can be done at the LHC?

- Direct measurement at LHC from the Higgs lineshape in diphoton and 4l will be limited by systematics and in particular the modeling of the resolution systematic uncertainties (See CMS result)

- Direct measurement through decay length in the 4l channel has also very limited sensitivity.

- Very indirect estimates through coupling fit (with various assumptions)

- New trends in trying to constrain the Higgs width (still indirect, but little to no assumptions):
  - Width through mass differences
  - Width through precise high mass VV cross section measurements
Interferometry and mass shift

- Adding detector resolution effects, mass shift induced: ~70 MeV at NLO
- Interference dependent on $\Gamma_H \rightarrow$ measure of the shift could allow to bound the width.
- Measurement of the shift can be done:
  
  - by comparing the masses in $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$
  
  - by exploiting dependence with Higgs boson $p_T$

---

ZZ High Mass cross section

(From N. Kauer)

- Off shell
- Interference in the high mass range

First study by Fabrizio Caola, Kirill Melnikov (arXiv:1307.4935) for $M_H = 126$ GeV

using CMS data (LHC7: 5.1 fb$^{-1}$, LHC8: 19.6 fb$^{-1}$) and gg2VV (NK)

Signal process: $pp \rightarrow H \rightarrow ZZ \rightarrow 2e2\mu, 4e, 4\mu$

resonance contribution to signal cross section ("on-peak"): $M_{ZZ} < 130$ GeV

off-resonance contribution to signal cross section ("off-peak"): $M_{ZZ} > 130$ GeV

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\sigma_{on-peak}^H$</th>
<th>$\sigma_{off-peak}^H$</th>
<th>$\sigma_{interference}^{off-peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>0.203</td>
<td>0.044 (21%)</td>
<td>-0.108</td>
</tr>
<tr>
<td>8 TeV</td>
<td>0.255</td>
<td>0.061 (24%)</td>
<td>-0.166</td>
</tr>
<tr>
<td>$N_{2e2\mu}^{SM}$</td>
<td>9.8 (CMS)</td>
<td>1.73</td>
<td>-4.6</td>
</tr>
<tr>
<td>$N_{2e2\mu+4e+4\mu}^{SM}$</td>
<td>21.1 (CMS)</td>
<td>3.72</td>
<td>-9.91</td>
</tr>
</tbody>
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ZZ High Mass cross section

(From N. Kauer)

rescale Higgs couplings and Higgs width keeping $\sigma_{\text{peak}}$ fixed to SM

$$N_{4l}^{\text{off}} = 3.72 \times \frac{\Gamma_H}{\Gamma_{H}^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_{H}^{\text{SM}}}}$$

CMS in $pp \rightarrow ZZ \rightarrow 4\ell$: 451 evts observed, 432 ± 31 evts expected (on-peak only/ZWA)

expected total number of events with rescaled Higgs couplings/width:

$$N_{\text{exp}} = 432 + 3.72 \times \frac{\Gamma_H}{\Gamma_{H}^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_{H}^{\text{SM}}}} \pm 31$$

95% CL (2$\sigma$) upper limit: $\Gamma_H \leq 38.8 \frac{\Gamma_{H}^{\text{SM}}}{\Gamma_H} \approx 163$ MeV

(Caola and Melnikov)

Ultimately (assuming 3% uncertainty) the limit ~20-40 MeV
Rare decays I

Search for the Higgs boson decaying to a di-muon pair
Rare decays II

Search for the Higgs boson decaying to $Z \gamma$
Exotic decays

Search for the Higgs boson decaying to hidden sector particles in electron jets

Signature of electron jets

Another analysis search using displaced muonic lepton jets...
Using the Higgs Particle for rare FCNC in Top to Higgs Decays

<table>
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<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
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<tr>
<td>$t \to u\gamma$</td>
<td>$3.7 \cdot 10^{-16}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
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<tr>
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<tr>
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<tr>
<td>$t \to cH$</td>
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To be compared to ~30% from WW in CMS
« The outcome of the spin analysis has as much suspense as a football game between Brazil and Tonga »

C.G.
Main Quantum Numbers

A large number of options to probe the spin directly from angular (or threshold behavior) distributions.

- From the associated production modes (VH, VBF or ggF+jets)
- From the production angle $\cos \theta^*$ distribution
- From the decay angles and the spin correlation when applicable

The philosophy of the approach:

- Measure compatibility with the $0^+$ hypothesis
- Try to exclude alternative hypotheses simulated using an effective Lagrangian including higher order couplings.
What are we trying to exclude?

Event definition directly from general amplitudes

**Spin 0**

\[ A(X \to V_1 V_2) = v^{-1} \left( g_1^{(0)} m_v^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f^{* (1)}_{\mu \nu} f^{* (2), \mu \nu} + g_3^{(0)} f^{* (1), \mu \nu} f^{* (2)}_{\mu \alpha} \frac{q_\nu q_\alpha}{\Lambda^2} + g_4^{(0)} f^{* (1)} f^{* (2), \mu \nu} \right) \]

**Spin 1**

\[ A(X \to V_1 V_2) = b_1 \left[ (\epsilon_1^* q)(\epsilon_2^* \epsilon_x) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_x) \right] + b_2 \epsilon_\alpha \mu \nu \beta \epsilon_x^* \epsilon_1^* \epsilon_2^* \nu \tilde{q}^\beta \]

**Spin 2**

\[ A(X \to V_1 V_2) = \Lambda^{-1} \left[ 2g_1^{(2)} t_{\mu \nu} f^{* (1) \mu \alpha} f^{* (2) \nu \alpha} + 2g_2^{(2)} t_{\mu \nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{* (1) \mu \alpha} f^{* (2) \nu \beta} + g_3^{(2)} \frac{q_\alpha q_\beta}{\Lambda^2} t_{\beta \nu} \left( f^{* (1) \mu \nu} f^{* (2)}_{\mu \alpha} + f^{* (2) \mu \nu} f^{* (1)}_{\mu \alpha} \right) \right. \\
+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} \frac{t_{\mu \nu} f^{* (1) \alpha \beta} f^{* (2) \alpha \beta}}{t_{\nu \mu}} + m_v^2 \left( 2g_5^{(2)} t_{\mu \nu} \epsilon_1^* \epsilon_2^* \nu + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu \nu} (\epsilon_1^* \epsilon_2^* \alpha - \epsilon_1^* \epsilon_2^* \nu) + g_7^{(2)} \frac{\tilde{q}^\mu q_\nu}{\Lambda^2} t_{\mu \nu} \epsilon_1^* \epsilon_2^* \nu \right) \\
\left. + g_8^{(2)} \frac{\tilde{q}^\mu q_\nu}{\Lambda^2} t_{\mu \nu} f^{* (1) \alpha \beta} f^{* (2) \alpha \beta} + m_v^2 \left( g_9^{(2)} \frac{t_{\mu \alpha} q_\alpha}{\Lambda^2} \epsilon_{\mu \nu \rho \sigma} \epsilon_1^* \epsilon_2^* \nu q_\sigma + g_{10}^{(2)} \frac{t_{\mu \alpha} q_\alpha}{\Lambda^4} \epsilon_{\mu \nu \rho \sigma} q_\rho q_\sigma (\epsilon_1^* \nu (q \epsilon_2^*) + \epsilon_2^* \nu (q \epsilon_1^*)) \right) \right] \]
### What are we trying to exclude?

Event definition directly from general amplitudes

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$X$ production</th>
<th>$X \rightarrow VV$ decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_m$</td>
<td>$gg \rightarrow X$</td>
<td>$g_1^{(0)} \neq 0$</td>
</tr>
<tr>
<td>$0^+_h$</td>
<td>$gg \rightarrow X$</td>
<td>$g_2^{(0)} \neq 0$</td>
</tr>
<tr>
<td>$0^-$</td>
<td>$gg \rightarrow X$</td>
<td>$g_4^{(0)} \neq 0$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>$b_2 \neq 0$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>$b_1 \neq 0$</td>
</tr>
<tr>
<td>$2^+_m$</td>
<td>$g_1^{(2)} \neq 0$</td>
<td>$g_1^{(2)} = g_5^{(2)} \neq 0$</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$g_4^{(2)} \neq 0$</td>
<td>$g_4^{(2)} \neq 0$</td>
</tr>
<tr>
<td>$2^-_h$</td>
<td>$g_8^{(2)} \neq 0$</td>
<td>$g_8^{(2)} \neq 0$</td>
</tr>
</tbody>
</table>

Nothing on the rates !!!
Analysis of Parity in the $H \rightarrow 4l$ Channel

Using the distributions of 2 production and 3 decay angles and $Z_1$ and $Z_2$ masses combined in BDT or Matrix Element (MELA)

$H \rightarrow ZZ$ Spin and Parity analyses

- Probes $0^-, 1^+, 1^-$, and spin-2 hypotheses as WW and $\gamma\gamma$
- Not very sensitive for spin
Analysis of Spin in the $H \rightarrow \gamma\gamma$ Channel

Using the inclusive analysis

- Sensitive variable is dihoton $\cos \theta^*$ distribution
- Use events within $1.5\sigma$ of the peak ($m_H=126.5$ GeV)

Expected sensitivity and observation are quite close $\sim 99\%$ CL and good compatibility with SM
**H → WW Spin analysis**

- Use Spin correlation (from V-A W decays) and a BDT analysis using all kinematic variables probing the same hypotheses as H → γγ analysis.
- Analysis done inclusively with very different preselection cuts.
**H → WW Spin analysis**

- Use Spin correlation (from V-A W decays) and a BDT analysis using all kinematic variables probing the same hypotheses as H → \( \gamma \gamma \) analysis.
- Analysis done inclusively with very different preselection cuts.

Excludes \( 2^+_{(m)} \) at more than 99% CL_{s}
**H → WW Spin analysis**

- Use Spin correlation (from V-A W decays) and a BDT analysis using all kinematic variables probing the same hypotheses as H → γγ analysis.
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**Spin Combination**

Excludes 2^{+}_{(m)} at more than 99% CL_{s}
H → WW Spin analysis

- Use Spin correlation (from V-A W decays) and a BDT analysis using all kinematic variables probing the same hypotheses as $H \to \gamma\gamma$ analysis.
- Analysis done inclusively with very different preselection cuts.

Spin Combination

Excludes $2^{+}(m)$ at more than 99% CL$_{s}$
Overview of Spin and Parity Results

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$CL_S$</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ZZ*(4l)</td>
<td>$\gamma\gamma$</td>
<td>WW*</td>
</tr>
<tr>
<td>0^-</td>
<td>2.2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0^-_h</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1^-</td>
<td>6.0%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1^+</td>
<td>0.2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2^+_m(gg)</td>
<td>16.9%</td>
<td>0.7%</td>
<td>5%</td>
</tr>
<tr>
<td>2^+_m(qq)</td>
<td>&lt;0.1%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>2^-</td>
<td>&lt;0.1%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Compatibility with 0^+ is essential!
- No VH or VBF threshold distribution analysis yet at LHC.
Using Threshold Distributions in VH(bb) at D0

Strong signal hypotheses separation

\[ J^P = 0^- \text{ excluded at } 98\% \text{ CL} \]

\[ J^P = 2^+ \text{ excluded at } 99.9\% \text{ CL} \]
CP mixing

Measuring possible CP violating components of the amplitude

$$A = v^{-1} \epsilon_1^\mu \epsilon_2^\nu \left( a_1 g_{\mu\nu} m_H^2 + a_2 q_{\mu} q_{\nu} + a_3 \epsilon_{\mu\nu\alpha\beta} q_{1}^\alpha q_{2}^\beta \right) = A_1 + A_2 + A_3$$

- SM case $a_1 = 1$ and $a_2 = a_3 = 0$
- $a_3$ is a CP-odd amplitude
- Measure $f_{a_3} = a_3 / a_1$ (assuming $a_2 = 0$)

Check of a mixing with CP-odd component

CMS: $f_{a_3} = 0.00^{+0.23}_{-0.00}$
$f_{a_3} < 0.56$ at 95% CL (exp 0.76)
Extending...

The Higgs sector

- Not governed by gauge symmetry
- Bears the Flavor Hierarchy problem (responsible for most free parameters of the Standard Model)
- ...and there is more!
The Gauge Hierarchy Problem

The Higgs potential is fully renormalizable, but...

Loop corrections to the Higgs boson mass...

...are quadratically divergent:

\[ \Delta m^2 \propto \int_{\Lambda} d^4k \frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2} \]

If the scale at which the standard model breaks down is large, the Higgs natural mass should be of the order of the cut-off. e.g. the Planck scale

\[ m = m_0 + \Delta m + \ldots \] Higher orders

This can be achieved by fine tuning the \( m_0 \) (at all orders)...

Inelegant...

(note that composite/technicolor models are not concerned by this problem)
Supersymmetry

\[ \Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2} (-2\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f} + ...) \quad \rightarrow \quad \text{Contribution of fermions} \]

\[ \Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2} (\Lambda^2 + 2m_s^2 \ln \frac{\Lambda}{m_s} + ...) \quad \rightarrow \quad \text{Contribution of scalars} \]

Therefore in a theory where for each fermion there are two scalar fields with

SUSY: each fermionic degree of freedom has a symmetric bosonic correspondence

The field content of the standard model is not sufficient to fulfill this condition

(fulfilled if the scalars have same couplings as the fermions and not too large mass split)

- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)
- Natural candidate for Dark Matter
Extented Higgs Sectors

1.- Why should it be minimal?

2.- Additional doublets (2 HDMs)?

**SUSY:** Two doublets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

2 HDMs in general: 5 Higgs bosons
- Two CP even $h$ and $H$
- One CP odd $A$
- Two charged Higgs bosons

3.- Additional singlets?

$\mu$ parameter (of the superpotential) problem in SUSY, can be solved by the introduction of a singlet field in the NMSSM

4.- Additional triplet(s)?

In order to generate Majorana mass terms for neutrinos
Nano Review of BSM Channels I

- Charged Higgs
  - Main current analysis $H^\pm \to \tau \nu$
  - $H^\pm \to cs$
  - High mass specific $H^\pm \to AW$
  - High mass specific $H^\pm \to tb$

![Graph](image-url)

**ATLAS Preliminary**

Data 2012

$\tau+\text{jets}$

$\int L dt = 19.5 \text{ fb}^{-1}$

### Median expected exclusion

- $m_h^\text{max}$
- $\sqrt{s} = 8 \text{ TeV}$

### Observed exclusion

- 95% CL
- $\pm 1\sigma$ theory
- $\pm 1\sigma$ theory
- Expected exclusion 2011
- Observed exclusion 2011
- **Charged Higgs**
  - Main current analysis $H^\pm$ to $\tau\nu$
  - $H^\pm$ to $cs$
  - High mass specific $H^\pm$ to $AW$
  - High mass specific $H^\pm$ to $tb$

- **MSSM h, H, and A**
  - Main current analysis $\tau\tau$
  - Also searched for in $\mu\mu$
  - Also searched for in $bb(b)$
  - New open channel in the intermediate-high mass: $hh$, $hZ$
Nano Review of BSM Channels III

- Charged Higgs
  - Main current analysis $H^\pm$ to $\tau\nu$
  - $H^\pm$ to $c\bar{s}$
  - High mass specific $H^\pm$ to $A\bar{W}$
  - High mass specific $H^\pm$ to $t\bar{b}$

- MSSM $h$, $H$, and $A$
  - Main current analysis $\tau\tau$
  - Also searched for in $\mu\mu$
  - Also searched for in $b\bar{b}(b)$
  - New open channel in the intermediate-high mass: $hh$, $hZ$
- Singlet interpretation with unitarity constraint (High mass analyses)
  - ZZ to llνν channel (most powerful, overlap with invisible search)
  - ZZ to llqq channel (potentially interesting lower mass reach)
  - ZZ to llll: Interesting to fit all h and H simultaneously
  - WW to lvlv can also fit h and H simultaneously
  - WW to lvqq high mass only
    - γγ See latest CMS result and extending mass domain

- 2HDM Interpretation
  - ZZ to llll simultaneous fit
  - WW to lnln simultaneous fit
    - γγ simultaneous fit

- Doubly charged Higgs
  Like sign dilepton final states
Nano Review of BSM Channels V

- Singlet interpretation with unitarity constraint (High mass analyses)
  - ZZ to llνν channel (most powerful, overlap with invisible search)
  - ZZ to llqq channel (potentially interesting lower mass reach)
  - ZZ to llll: Interesting to fit all h and H simultaneously
  - WW to lvlv can also fit h and H simultaneously
  - WW to lvqq high mass only
  - γγ See latest CMS result and extending mass domain

- 2HDM Interpretation
  - ZZ to llll simultaneous fit
  - WW to lnln simultaneous fit
  - γγ simultaneous fit

- Doubly charged Higgs
  Like sign dilepton final states
Nano Review of BSM Channels VI

- Singlet interpretation with unitarity constraint (High mass analyses)
  - ZZ to llνν channel (most powerful, overlap with invisible search)
  - ZZ to llqq channel (potentially interesting lower mass reach)
  - ZZ to llll: Interesting to fit all h and H simultaneously
  - WW to lvlv can also fit h and H simultaneously
  - WW to lvqq high mass only
  - γγ See latest CMS result and extending mass domain

- 2HDM Interpretation
  - ZZ to llll simultaneous fit
  - WW to llnl simultaneous fit
  - γγ simultaneous fit

- Doubly charged Higgs
  Like sign dilepton final states
Future projects
The Higgs particle and LHC future prospects

High Luminosity scenarios of 300 fb\(^{-1}\) and 3 ab\(^{-1}\)
The LHC timeline

**LS1** Machine Consolidation

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb⁻¹ int. lumi

2013/14 Prepare LHC for design E & lumi

Collect ~30 fb⁻¹ per year at 13/14 TeV

**LS2** Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS: Pixel upgrade, FTK, and new small wheel

2018 Phase-1 upgrade ultimate lumi

Twice nominal lumi at 14 TeV, ~100 fb⁻¹ per year

~2022 Phase-2 upgrade to HL-LHC

~300 fb⁻¹ per year, run up to > 3 ab⁻¹ collected

**LS3** Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

~2022

Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.
**HL-LHC Beam Parameters**

Two HL-LHC scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>Nominal</th>
<th>HL-LHC (25 ns)</th>
<th>HL-LHC (50 ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C.O.M Energy</strong></td>
<td>8 TeV</td>
<td>13-14 TeV</td>
<td>14 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td><strong>N_p</strong></td>
<td>1.2 (10^{11})</td>
<td>1.15 (10^{11})</td>
<td>2.0 (10^{11})</td>
<td>3.3 (10^{11})</td>
</tr>
<tr>
<td>Bunch spacing / k</td>
<td>50 ns / 1380</td>
<td>25 ns / 2808</td>
<td>25 ns / 2808</td>
<td>50ns / 1404</td>
</tr>
<tr>
<td><strong>(\varepsilon) (mm rad)</strong></td>
<td>2.5</td>
<td>3.75</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>(\beta^*) (m)</strong></td>
<td>0.6</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>L (cm^{-2}s^{-1})</strong></td>
<td>(\sim 7 \times 10^{33})</td>
<td>(10^{34})</td>
<td>7.4 (10^{34})</td>
<td>8.4 (10^{34})</td>
</tr>
<tr>
<td><strong>Pile up</strong></td>
<td>(\sim 25)</td>
<td>(\sim 20)</td>
<td>(\sim 140)</td>
<td>(\sim 260)</td>
</tr>
</tbody>
</table>

\[ L = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \varepsilon_n} F \]

Pile up is a crucial issue!

CMS event with 78 reconstructed vertices
Reaching ttH Production in (robust) rare modes

Analyses not relying on more intricate decay channels (bb, tt and WW)

- $\gamma\gamma$ channel: more than 100 Events expected with $s/b\sim 1/5$

- $\mu\mu$ channel: approximately 30 Events expected with $s/b\sim 1$

Analyses (rather) robust to PU

$\mu\mu$ decay mode should reach more than 5 standard deviation
Completing the Picture WBS
*Weak Boson Scattering*

Only taking into account the cleanest signals: $ZZjj$ in the 4 leptons final state

Very clean signature for a TeV resonance (in anomalous WBS models)

Sensitivities for 300 fb$^{-1}$ and 3 ab$^{-1}$:

<table>
<thead>
<tr>
<th>Model (anomalous WBS)</th>
<th>300 fb$^{-1}$</th>
<th>3 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV and $g=1$</td>
<td>2.4 $\sigma$</td>
<td>7.5 $\sigma$</td>
</tr>
<tr>
<td>1 TeV and $g=1.75$</td>
<td>1.7 $\sigma$</td>
<td>5.5 $\sigma$</td>
</tr>
<tr>
<td>1 TeV and $g=2.5$</td>
<td>3.0 $\sigma$</td>
<td>9.4 $\sigma$</td>
</tr>
</tbody>
</table>
LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses

**ATLAS Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}; \int \text{L} \text{d}t = 300 \text{ fb}^{-1} ; \int \text{L} \text{d}t = 3000 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Same as current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2</td>
<td>50% TH systematics</td>
</tr>
</tbody>
</table>

Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5\% level
LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses

Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level
Self Couplings

Determination of the scalar potential, essential missing ingredient: **self couplings**!

Are they as predicted: $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$

$\lambda_4$: hopeless in any planned experiment (?)

$\lambda_3$: **very very** hard in particular due to the double H production, which also interferes with the signal...

... but some hope, in (rather) robust

$pp \rightarrow HH \rightarrow bb\gamma\gamma$

($S \sim 15$, $B \sim 21$ for $3\text{ ab}^{-1}$ and some faith...) $bb\tau^+\tau^-$

(under study)
New Trends

Interferometry

CP properties

Exploring the complexe structure of couplings

Limits at 3 ab$^{-1}$ around 200 MeV on total width
Beyond LHC Programs

$e^+e^-$ colliders

**ILC**

Three scenarios

- 250 GeV
- 500 GeV
- 1000 GeV

Lumi 0.7 to 5 $10^{34}$ cm$^{-2}$s$^{-1}$

**CLIC**

Three scenarios

- 500 GeV
- 1500 GeV
- 3000 GeV

Lumi 1.3 to 6 $10^{34}$ cm$^{-2}$s$^{-1}$
Beyond LHC Programs

Future circular collider VHE-LHC including $e^+e^-$ collider

**TLEP**

Two scenarios

- 240GeV
- 350GeV

Lumi 5 to 7 cm$^{-2}$s$^{-1}$
(but 4 IPs)

**VHE-LHC**

100 TeV Collider
(~20T magnets)
Beyond LHC Programs
\textbf{e^+e^- colliders}

<table>
<thead>
<tr>
<th>Facility</th>
<th>ILC</th>
<th>ILC(LumiUp)</th>
<th>TLEP (4 IP)</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>250</td>
<td>500</td>
<td>1000</td>
<td>250/500/1000</td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>250</td>
<td>+500</td>
<td>+1000</td>
<td>1150+1600+2500$^\dagger$</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>12%</td>
<td>5.0%</td>
<td>4.6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>18%</td>
<td>8.4%</td>
<td>4.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>6.4%</td>
<td>2.3%</td>
<td>1.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4.9%</td>
<td>1.2%</td>
<td>1.2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>1.3%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\kappa_{\mu}$</td>
<td>91%</td>
<td>91%</td>
<td>16%</td>
<td>10%</td>
</tr>
<tr>
<td>$\kappa_{\tau}$</td>
<td>5.8%</td>
<td>2.4%</td>
<td>1.8%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>6.8%</td>
<td>2.8%</td>
<td>1.8%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>5.3%</td>
<td>1.7%</td>
<td>1.3%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$-$</td>
<td>14%</td>
<td>3.2%</td>
<td>2.0%</td>
</tr>
<tr>
<td>$BR_{inv}$</td>
<td>0.9%</td>
<td>$&lt;$ 0.9%</td>
<td>$&lt;$ 0.9%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

- Reaching few permil to percent level precision on the couplings
- Direct measurement of branching fractions
Beyond LHC Programs

Further Programs

**ep Collider**

**γγ Collider**

Ultimate Higgs factory

**μμ Collider**
Conclusions and Outlook
Three Years of LHC at the Energy Frontier

Two fundamental observations

- The discovery of the 126 GeV (Standard Model-like) Higgs boson: The main missing key piece of the Standard Model!

- Nothing else!
Naturalness

- Naturalness is a property of theories with free parameters of similar orders of magnitude
- SUSY Undoubtedly a beautifully Natural solution... But it hasn’t been observed yet!
- The larger the mass of the superpartners the less natural a solution...

- Naturalness, has been a guiding principle for theory in the past decades
The other striking observation of the LHC: Nothing else anywhere... so far

Unlike unitarity (no loose theorem), naturalness is a conceptual request and the degree of acceptable fine-tuning subjective!

Should Naturalness as a guiding principle be dropped?
Knowing the Higgs mass and assuming the structure of the Higgs potential we also know that...

\[ \lambda = 0.126 \]

Very peculiar value...
Running of the Quartic Coupling, Metastability

\[ \lambda \sim 0 \]
(at the high scale)

Large dependence on top mass and of course Higgs boson mass

Could this be a guiding principle?
Outlook

From the theory point of view
- Is the Higgs a fundamental scalar? Could symmetry breaking be dynamic?
- Is the SM minimal? Is there only one Higgs responsible for vector boson and fermion masses?
- Does the Higgs particle couple to dark matter?
- What is responsible for the flavor hierarchy?

From the experimental point of view
- New horizons and measurements possible involving the Higgs boson
  - Precision in measuring coupling and spin/CP properties!
  - New trends to measure natural width
  - Rare decay modes (charm, J/Psi $\gamma$, WD, etc...)
  - Using the Higgs particle to probe FCNCs
  - Decays to exotic particles (hidden valley pions, dark Zs, etc...)
  - Exciting new analysis techniques (jet substructure)
- Searches for new physics involving the Higgs particle
- Focal point for the future large scale projects
Thank You !