Stefania Gori
Perimeter Institute for Theoretical Physics

2014 CAP Congress / Congrès de l'ACP 2014

Sudbury,
June 17th 2014
The plan

1. Introduction: the discovery of a new boson

2. The Higgs in the Standard Model
   - Mass
   - Properties (production and decays)

3. Beyond the Standard Model Higgs bosons
   - Higgs couplings (loop and tree level)
   - Interplay with direct searches of New Physics particles
   - Exotic decays

Focus on
Supersymmetry
We have a new boson!

After 50 years from the theoretical proposal &
~40 years of experimental searches:

July 4\textsuperscript{th}, 2012: ATLAS and CMS: ”We have observed a new boson“

Francois Englert

Peter Higgs

2012: Last building block of the Standard Model found
We have a new boson!

After 50 years from the theoretical proposal &
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It gives mass to the fermions
\[ y_{ij} \propto m_f \]

It gives mass to the (massive) gauge bosons
\[ \text{coup}l \propto m_V \]

The Higgs couples to (almost) everything
What determines the Higgs characteristics?

The Higgs mass is not predicted by the Standard Model (SM).

However, once it is fixed, the full phenomenology of the Higgs is univocally determined.

The SM can only "predict indirectly" the Higgs mass:

Putting together all the info from the measurement at LEP and at Tevatron of the electroweak precision observables:

$$m_h = 91^{+30}_{-23} \text{ GeV}$$
The production of the Higgs...

125 GeV

\[ \sigma(p p \rightarrow H+X) [pb] \]

\[ M_H [GeV] \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\text{"Gluon fusion"}

\text{"V boson fusion"}

\text{"W,Z bremsstrahlung"}

\text{"t-t fusion"}
...and its decays

125 GeV

The Higgs decays very quickly:
\[ \Gamma_h \sim 4 \text{ MeV} \implies \tau_h \sim 2 \times 10^{-22} \text{s} \]

A „dreamland“ for experimentalists!

\[
\begin{align*}
\text{BR}(h \to bb) &= 58\%, \\
\text{BR}(h \to ZZ^*) &= 2.7\%, \\
\text{BR}(h \to WW^*) &= 21.6\%, \\
\text{BR}(h \to \tau\tau) &= 6.4\%, \\
\text{BR}(h \to \gamma\gamma) &= 0.22\%, \\
\text{BR}(h \to \gamma Z) &= 0.16\%, \\
\text{BR}(h \to \mu\mu) &= 0.022\%.
\end{align*}
\]
How well do we know?

State of the art for the SM computation

- $h \rightarrow ff$
  QCD up to NNNNLO
  Baikov, Chetyrkin, Kühn, Steinhauser ('97–'05)

- $h \rightarrow γγ / gg$
  full 2-loop result + h.o. improvements
  Spira, Djouadi, Graudenz, Zerwas '95; ...
  Actis, Passarino, Sturm, Uccirati '07,'08

- $h \rightarrow WW / ZZ$
  NLO for stable W/Z bosons
  Fleischer, Jegerlehner '81; Kniehl '91;
  Bardin, Vilenskii, Khristova '91
  NLO for off-shell/decaying W/Z bosons
  Bredenstein, Denner, Dittmaier., Weber '06

Parametric + theoretical uncertainty of BRs

<table>
<thead>
<tr>
<th>$m_h$ [GeV]</th>
<th>$h \rightarrow b\bar{b}$</th>
<th>$τ^+τ^-$</th>
<th>$c\bar{c}$</th>
<th>$gg$</th>
<th>$γγ$</th>
<th>$WW$</th>
<th>$ZZ$</th>
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<tbody>
<tr>
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<td>6%</td>
<td>12%</td>
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LHC Higgs XS WG '10–'13

Dominated by $δΓ_{h\rightarrow bb}$
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LHC Higgs XS WG ’10–’13

Dominated by $δΓ_{h→bb}$

**Numbers for the 7 TeV LHC:**

<table>
<thead>
<tr>
<th>$m_h = 126$ GeV</th>
<th>Uncertainties</th>
<th>NLO/NNLO/NNLO+</th>
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<tr>
<td></td>
<td>scale PDF4LHC</td>
<td>QCD EW</td>
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<tr>
<td>ggF</td>
<td>8 – 10%</td>
<td>8%</td>
</tr>
<tr>
<td>VBF</td>
<td>1%</td>
<td>2 – 3%</td>
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<tr>
<td>Wh</td>
<td>1%</td>
<td>4%</td>
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<tr>
<td>Zh</td>
<td>2%</td>
<td>4%</td>
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<td>tth</td>
<td>9%</td>
<td>9%</td>
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<table>
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<tr>
<th>QCD</th>
<th>EW</th>
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<tr>
<td>&gt; 100%</td>
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<td>5%</td>
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S.Gori
The discovery of the Higgs is the manifestation of the hierarchy problem

\[ m_h^2 \sim \mu^2 + c \Lambda^2, \quad c = \mathcal{O}(0.01) \]

\[ V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

**Fundamental scale** beyond the SM:
\[ \Lambda \approx M_{Pl} = 10^{19} \text{ GeV (Planck scale)} \]

**Needed a cancellation** to the precision of \(10^{-32}\)
to have \(m_h\) (physical) \(\approx 125 \text{ GeV}\)

\[ 14884157194850192375385501928538182559- \]
\[ 14884157194850192375385501928538166934 = 125^2 \]

Whatever cancels the quadratic sensitivity of the Higgs mass to the high energy scale must:

- couple to the Higgs
- be relatively light (TeV-scale?)

Testing the Higgs to discover New Physics (NP)
Beyond the Standard Model Higgs

- UnHiggs
- Littlest Higgs
- Portal Higgs
- Twin Higgs
- Composite Higgs
- Fat Higgs
- Simplest Higgs
- Phantom Higgs
- Intermediate Higgs
- Slim Higgs
- Private Higgs
- Supersymmetric Higgs
- Lone Higgs
- Gauge Higgs
- Gaugephobic Higgs
- Supersymmetric Higgs
Beyond the Standard Model Higgs

- UnHiggs
- Gaugephobic Higgs
- Twin Higgs
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- Supersymmetric Higgs
Supersymmetry and the hierarchy problem

An elegant way to keep quantum corrections to the Higgs mass under control

\[ m_h^2 = m_{h0}^2 + c\Lambda^2, \]

Quadratic corrections cancelled

\[ \delta m_h^2 = m_{\text{SUSY}}^2 \left( \frac{y_t^2}{8\pi^2} \log \left( \frac{\Lambda}{m_{\text{SUSY}}} \right) + \ldots \right) \]

The mass scale of the NP (susy) particles should be relatively low
The mass of the Higgs is predicted in concrete SUSY models

Example: in the Minimal Supersymmetric Standard Model (MSSM)
MSSM: a two Higgs doublet model.
In total: 2 scalar Higgs bosons, 1 pseudoscalar and 1 charged Higgs

\[ m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{X_t^2}{M_{\text{Susy}}^2} \left(1 - \frac{X_t^2}{12M_{\text{Susy}}^2}\right) + \log \frac{M_{\text{Susy}}^2}{m_t^2} \right] \]

At the tree level, the MSSM predicts a quite low Higgs mass

\[ M_{\text{stop}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L \\ m_t X_t \\ m_{u_3}^2 + m_t^2 + D_R \end{pmatrix} \]

Higgs mass directly connected to the stop spectrum
What are the implications?

The mass of the Higgs is predicted in concrete SUSY models.

Example: in the Minimal Supersymmetric Standard Model (MSSM)

Carena, SG, Shah, Wagner, 1112.3336
What are the implications?

The mass of the Higgs is predicted in concrete SUSY models

Different implications if we consider Susy models beyond the MSSM
Example:
The NMSSM: a two Higgs doublet + 1 singlet model. $\mathcal{W} \supset \lambda S H_1 H_2$
In total: 3 scalar Higgs bosons, 2 pseudoscalar and 1 charged Higgs

$\left( m_h^2 \right)_{\text{tree}} \lesssim m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

Hall, Pinner, Ruderman, 1112.2703
Higgs couplings (loop)

Hierarchy problem

Higgs pheno

QED (QCD)

beta functions

Indirect probe of Naturalness

recent studies:
Farina, Perelstein, Rey-Le Lorier, 1305.6068
Craig, Englert, McCullough, 1305.5251

Low energy Higgs theorem

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov, 1979
Higgs di-gluon/di-photon coupling

Stops & Higgs coupling to gluons

\[\text{Stops, } \tan \beta = 30, \ r = 0.9\]

\[m^2_S = \frac{m^2_L + m^2_R}{2}, \ r = \frac{m^2_L - m^2_R}{m^2_L + m^2_R}\]

SG, Low, 1307.0496
**Higgs di-gluon/di-photon coupling**

**Stops & Higgs coupling to gluons**

Stops, \( \tan \beta = 30, \ r = 0.9 \)

**Staus & Higgs coupling to photons**

Staus, \( \tan \beta = 30, \ r = 0 \)

\[
m_S^2 = \frac{m_L^2 + m_R^2}{2}, \quad r = \frac{m_L^2 - m_R^2}{m_L^2 + m_R^2}
\]

SG, Low, 1307.0496
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Stops & Higgs coupling to gluons

Stops, $\tan \beta = 30$, $r = 0.9$

Staus & Higgs coupling to photons

Staus, $\tan \beta = 30$, $r = 0$

CMS Projection

Expected uncertainties on Higgs boson couplings

SG, Low, 1307.0496
Measuring more and more precisely the coupling of the Higgs to gluons and photons gives us info on the Susy (stop/stau) spectrum.

Complementarity with direct searches:

**Stops**

- No bounds from direct searches of Drell-Yan produced staus

**Staus**

- (if promptly decaying)
Higgs couplings (tree)

\[
\begin{pmatrix}
H_u \\
H_d
\end{pmatrix} = \begin{pmatrix}
v \sin \beta \\
v \cos \beta
\end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix}
h \\
H
\end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix}
G \\
A
\end{pmatrix}
\]

\[
R_\alpha = \begin{pmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{pmatrix}, \quad R_\beta = \begin{pmatrix}
\sin \beta & \cos \beta \\
-\cos \beta & \sin \beta
\end{pmatrix}
\]

\[
\xi^h_u \sim \frac{\cos \alpha}{\sin \beta} \Rightarrow 1 + \frac{2m_Z^2}{m_H^2 \tan^2 \beta}
\]

\[
\xi^h_d \sim \xi^h_\ell \sim \frac{-\sin \alpha}{\cos \beta} \Rightarrow 1 - \frac{2m_Z^2}{m_H^2}
\]

\[
\xi^h_V \sim \sin(\beta - \alpha) \Rightarrow 1 - \frac{2m_Z^4}{m_H^4 \tan^2 \beta}
\]
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\]

\[
\xi^h_{V} \sim \sin(\beta - \alpha) \Rightarrow 1 - \frac{2m_Z^2}{m_H^2 \tan^2 \beta}
\]

The measurement of these couplings give information about the spectrum of the additional Higgs bosons
Looking for additional Higgs bosons

Complementarity with direct searches of additional Higgs bosons:

**CMS-PAS-HIG-12-033**

CMS preliminary 2.7-4.8 fb\(^{-1}\) \(\sqrt{s} = 7\) TeV

**CMS-PAS-HIG-13-021**

CMS Preliminary, \(H\rightarrow\tau\tau\), 4.9 fb\(^{-1}\) at 7 TeV, 19.7 fb\(^{-1}\) at 8 TeV

MSSM \(m_h^{\text{max}}\) scenario \(M_{\text{SUSY}} = 1\) TeV

95% CL Excluded:
- observed
- SM H injected
- expected
- \(\pm 1\sigma\) expected
- \(\pm 2\sigma\) expected
- LEP

\[ m_A \text{ [GeV/c}^2]\]

\[ \tan\beta \]

\[ H \rightarrow \text{bb} \]

\[ H \rightarrow \text{TT} \]
Beyond the SM theories can have particles lighter than the Higgs boson

A typical example:
models with a Dark Matter (DM) candidate with \( M_{DM} \leq M_h / 2 \sim 60 \text{ GeV} \)

These models can predict a non-zero \( \text{BR}(h \rightarrow \text{DM DM}) \)
Beyond the SM theories can have particles lighter than the Higgs boson.

A typical example:
models with a Dark Matter (DM) candidate with \( M_{\text{DM}} \leq M_h/2 \sim 60 \text{ GeV} \)

These models can predict a non-zero \( \text{BR}(h \rightarrow \text{DM DM}) \)

Searches for an “invisible Higgs boson” are already performed at ATLAS and CMS.

- Higgs produced in VBF: \( \text{BR}(h \rightarrow \text{inv}) \leq 69\% (53\%) \)  
  CMS PAS HIG-13-013

- Higgs produced in association with a leptonic \( Z \):
  \( \text{BR}(h \rightarrow \text{inv}) \leq 75\% (91\%) \)  
  CMS PAS HIG-13-018
  \( \text{BR}(h \rightarrow \text{inv}) \leq 75\% (62\%) \)  
  ATLAS 1402.3244

- Higgs produced in association with a \( Z \) decaying to bottom quarks:
  \( \text{BR}(h \rightarrow \text{inv}) \leq 1.82 (1.99) \)  
  CMS PAS HIG-13-028
1. **Well motivated**: very many models predict NP particles only very weakly coupled to the SM particles. The Higgs can give us access to the “dark sector“: ex. $|H|^2 |S|^2$

2. **Theoretically** it is easy to get sizable Higgs exotic branching ratios: it is sufficient a small coupling of the Higgs to NP particles, to get a sizable ($\geq 10\%$) branching ratio (the Higgs is very narrow)
Higgs exotic decays

1. **Well motivated**: very many models predict NP particles only very weakly coupled to the SM particles. The Higgs can give us access to the „dark sector“: ex. $|H|^2 |S|^2$

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3. **Experimentally** hidden if we do not look for them with dedicated searches
   Projections for the 13 TeV LHC show that, with 300 fb$^{-1}$ data, we will not determine the width of the Higgs with an accuracy better than $\sim 10\%$

**Exotic Decays of the 125 GeV Higgs Boson, 1312.4992**

A simple theory for a multitude of signatures

Example. Very simple extension of the SM: 
SM + singlet real scalar

$$\Delta \mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$
A simple theory for a multitude of signatures

Example. Very simple extension of the SM:
SM + singlet real scalar

\[ \Delta \mathcal{L} = \frac{\zeta}{2} s^2 |H|^2 \]

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<tbody>
<tr>
<td>(bb)</td>
<td>0.7(^R) [0.2(^L)]</td>
<td>(W)</td>
<td>0.8</td>
<td>0.9 [0.2]</td>
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<td>-</td>
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<tr>
<td>(bb\tau\tau)</td>
<td>&gt; 1 [0.15(^L)]</td>
<td>(V)</td>
<td>0.1</td>
<td>&gt; 1 [1]</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(bb\mu\mu)</td>
<td>((2 - 7) \cdot 10^{-4}^T) [((0.6 - 2) \cdot 10^{-4}^T)]</td>
<td>(G)</td>
<td>(3 \times 10^{-4})</td>
<td>0.6 - 1 [0.2 - 0.7]</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(\tau\tau\tau)</td>
<td>0.2 - 0.4(^R) [(U)]</td>
<td>(G)</td>
<td>0.005</td>
<td>40 - 80 [(U)]</td>
<td>1</td>
<td>0.2 - 0.4 [(U)]</td>
</tr>
<tr>
<td>(\tau\tau\mu\mu)</td>
<td>((3 - 7) \cdot 10^{-4}^T [(U)]</td>
<td>(G)</td>
<td>(3 \times 10^{-5})</td>
<td>10 - 20 [(U)]</td>
<td>0.007</td>
<td>0.04 - 0.1 [(U)]</td>
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<tr>
<td>(\mu\mu\mu\mu)</td>
<td>1 \cdot 10^{-4} ^[(U)]</td>
<td>(G)</td>
<td>1 \cdot 10^{-7}</td>
<td>1000 [(U)]</td>
<td>1 \cdot 10^{-5}</td>
<td>10 [(U)]</td>
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The Higgs is a unique laboratory to test New Physics

Not discussed in this talk, but of crucial importance:

- **BSM → Higgs**
  - Exotic production modes

- **Higgs & flavor**

- **Higgs → BSM**
  - Exotic decay modes

- **Higgs mass measurement**
- **Higgs SM coupling measurement**
  (including those couplings that are very suppressed in the SM e.g. $Z\gamma$)
Staus direct searches

At the LHC, direct searches for promptly decaying staus are difficult

- **Strong production**
  - Searches for staus NLSP produced from gluino & squark cascade decays. (GMSB models) At least one tau, jets and missing energy. ATLAS-CONF-2013-026, CMS-SUS-12-004
  - ATLAS: searches for staus NLSP produced from neutralino/chargino cascade decays. At least 2 taus and missing energy. ATLAS-CONF-2013-028

**Improved strategies** to look for our light staus?
Vacuum stability in the SM

@ NNLO:

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 1205.6497

We live in a metastable minimum
The mass of the Higgs

A mass that one could have expected?

Gfitters, 1107.0975