Physics Program of the experiments at Large Hadron Collider

Lecture 11

- Higgs boson
  - Properties
  - MSSM sector
    - LEP, Tevatron, LHC

*parts based on slides from K. Jakobs, CERN, Academic Training, 2010*
Is it a Higgs Boson?
- can the LHC measure its parameters

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs self couplings

After the discovery of a “Higgs-like” resonance at the LHC one has to measure its parameters and consolidate the evidence for the Higgs boson.

- As many parameters as possible
- Discriminate between: SM like Higgs, MSSM like Higgs, composite Higgs,....
Measurement of the Higgs boson mass

- The mass value itself is important for precision tests of the Standard Model, but moderate precision seems to be adequate; (as compared to the anticipated $m_t$ and $m_W$ uncertainties)

- In addition: the Higgs mass value is important for the parameter measurements (in particular for the extraction of ratios of couplings) ….

… as many experimental observables / input values need to be compared to the theoretical predictions, which in turn depend -sometimes rather strongly- on $m_H$
LHC Higgs boson discovery potential
Measurement of the Higgs boson mass

Dominant systematic uncertainty: $\gamma / \ell$ energy scale.
assumed: $1\%$ (goal $0.2\%$)
Scale from $Z \to \ell\ell$ (close to light Higgs)

Precision below $1\%$ can be achieved over a large mass range for $30\ f{b}^{-1}$;
syst. limit can be reached for higher integrated luminosities $\to 100\ f{b}^{-1}$
Note: no theoretical errors, e.g. mass shift for large $\Gamma_H$ (interference resonant / non-resonant production) taken into account
Measurement of the Higgs boson mass

In case of exotic Higgs boson couplings (e.g. suppressed $H \rightarrow WW / ZZ$ couplings) the situation is more difficult

even the $\gamma\gamma$ decay mode would be affected, since the $WW$ loop contribution is dominant

Remaining channels at low mass: $H \rightarrow \tau\tau$

$H \rightarrow bb$

(difficult S:B situation, difficult as a discovery channel; mass value is most likely needed to extract a signal, if background and mass known, it might be useful and add to coupling measurements)

$qqH \rightarrow qq\tau\tau \rightarrow qq\ell\nu\nu$ hadrons

$ttH, H \rightarrow bb$

Requires good understanding of the detector ($\tau, E_{T}^{miss}$), resolution limited
Direct extraction of the Higgs boson width

- The decay width has strong dependence on the $m_H$
- For $m_H < 200$ GeV: no direct measurement
  - Indirect measurement: global maximum likelihood fit to determine the couplings parameters in mass range 110-190 GeV (ATLAS studies)
- For $m_H > 200$ GeV: measured with 35% precision for 30 fb$^{-1}$ (one experiment)
Spin, CP, couplings

- Spin and CP (and anomalous coupling)
  - “H→γγ” → spin = 0 or 2
  - H→WW ΔφΓ correlation → spin = 0
  - H→ZZ→4l → Spin and CP
  - Forward jets of VBF process

- Couplings
  - “Origin of mass” should be confirmed.
  - We expect that Yukawa coupling has a linearity with respect to the particle mass. That is the SM prediction.
  - top, bottom and tau Yukawa coupling measurement can be done at the LHC.
Higgs boson couplings to fermions and bosons

- Measure ratio of couplings
- With more theoretical assumptions measure also absolute values

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g g \rightarrow H$</td>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow WW \rightarrow lν lν$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow γγ$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>$w, z \rightarrow H$</td>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow WW \rightarrow lν lν$</td>
<td>110 GeV - 190 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow ττ \rightarrow lν lν$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow ττ \rightarrow lν hadν$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow γγ$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>$t t \bar{t}$</td>
<td>$H \rightarrow WW \rightarrow lν lν (lν)$</td>
<td>120 GeV - 200 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow bb$</td>
<td>110 GeV - 140 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow γγ$</td>
<td>110 GeV - 120 GeV</td>
</tr>
<tr>
<td>$w, z \rightarrow H$</td>
<td>$H \rightarrow WW \rightarrow lν lν (lν)$</td>
<td>150 GeV - 190 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow γγ$</td>
<td>110 GeV - 120 GeV</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$H \rightarrow γγ$</td>
<td>110 GeV - 120 GeV</td>
</tr>
</tbody>
</table>
Ratio of couplings

In the low mass region, we can measure event rates of Higgs with multi modes. So we can extract coupling information, particularly, determination of ratios is possible with a model-independent way.

ATLAS-PHYS-2003-030

With 300 fb⁻¹:
- Yukawa
  - $g_t^2$: 15-30%
  - $g_b^2$: 35-70%
  - $g_F^2$: 25-50%
- Gauge Boson
  - $g_Z^2$: 10-40%

This is slightly old result. (based on our old results)

Bottom Yukawa can be also measured by using WH/ZH, $H\rightarrow bb$ (high boosted Higgs). -> new technique, under investigation
Absolute coupling determination

- Need a help of theory to obtain the absolute values of couplings.

Assumption [hep-ph/0407190] :
- HVV (V=W,Z) couplings cannot be larger than the SM case, namely,
  - $g^2(H,W) < g^2_{SM}(H,W)$
  - $g^2(H,Z) < g^2_{SM}(H,Z)$

  This constraint is valid in generic multi-Higgs-doublet models. (eg. MSSM)

With 2x300fb$^{-1}$:
- **Yukawa**
  - $g_t^2 : 25-40\%$
  - $g_b^2 : 45-90\%$
  - $g_\tau^2 : 25-50\%$

- **Gauge Boson**
  - $g_Z^2 : 10-30\%$
  - $g_W^2 : 10-25\%$
  - Total Width : 15-50\%
## Summary of studies for SM

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>Mass region and purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gluon Fusion</strong></td>
<td><strong>H -&gt; γγ</strong></td>
<td>110-140 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; ZZ-&gt; 4l</strong></td>
<td>140-800 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; WW</strong></td>
<td>130-170 GeV</td>
</tr>
<tr>
<td><strong>Vector Boson Fusion</strong></td>
<td><strong>H -&gt; ττ</strong></td>
<td>110-140 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; WW</strong></td>
<td>130-200 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; γγ</strong></td>
<td>110-140 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; bb</strong></td>
<td>110-140 GeV</td>
</tr>
<tr>
<td><strong>ttH</strong></td>
<td><strong>H -&gt; bb</strong></td>
<td>110-130 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; ττ</strong></td>
<td>110-130 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; WW</strong></td>
<td>130-180 GeV</td>
</tr>
<tr>
<td><strong>WH/ZH</strong></td>
<td><strong>H -&gt; WW</strong></td>
<td>140-170 GeV</td>
</tr>
<tr>
<td></td>
<td><strong>H -&gt; bb</strong></td>
<td>110-130 GeV</td>
</tr>
</tbody>
</table>
Higgs boson self-coupling

To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

\[
\lambda_{HHHH}^{SM} = 3 \frac{m_H^2}{\nu}, \quad \lambda_{HHHH}^{SM} = 3 \frac{m_H^2}{\nu^2}
\]

Cross sections for HH production:

small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, ttt, Wtt,…

⇒ no significant measurement possible at the LHC
need Super LHC \[ L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}, 6000 \text{ fb}^{-1} \]
even there: a measurement is very difficult, needs more studies.
Summary: is it a Higgs boson?

1. Mass

Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ resonances

2. Couplings to bosons and fermions

- Ratios of major couplings can be measured with reasonable precision;
- Absolute coupling measurements need further theory assumptions

3. Spin and CP

Angular correlations in $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ and $\Delta\phi_{ij}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling

No measurement possible at the LHC;
Very difficult at the sLHC, there might be sensitivity in $HH \rightarrow WW WW$ for $m_H \sim 160$ GeV
Alternative models
Supersymmetry

- One of the most popular solutions for those open questions in the SM is the Supersymmetry (SUSY).
- In SUSY, every elementary particle has a super-partner differs by $\frac{1}{2}$ spin.
- This provides a natural solution for the Hierarchy problem of the SM.
- The minimal extension of the SM is called Minimal Supersymmetric Standard Model (MSSM)
Minimal Supersymmetric Standard Model

Superpartners for Standard Model particles:

\[
\begin{align*}
[u, d, c, s, t, b]_{L,R} & \quad [e, \mu, \tau]_{L,R} & \quad [\nu_{e, \mu, \tau}]_{L} \\
[\bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{t}, \bar{b}]_{L,R} & \quad [\bar{e}, \bar{\mu}, \bar{\tau}]_{L,R} & \quad [\bar{\nu}_{e, \mu, \tau}]_{L}
\end{align*}
\]

- Spin \(\frac{1}{2}\)
- Spin 0

\[g, W^\pm, H^\pm, \gamma, Z, H_1^0, H_2^0\]
- Spin 1 / Spin 0

\[\tilde{g}, \tilde{\chi}^\pm_{1,2}, \tilde{\chi}^0_{1,2,3,4}\]
- Spin \(\frac{1}{2}\)

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales
MSSM: Higgs sector

Enlarged Higgs sector: Two Higgs doublets

\[
\begin{align*}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{align*}
\]

\[
V = m_1^2 H_1 H_1 + m_2^2 H_2 H_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})
\]

\[
+ \frac{g'^2 + g^2}{8} (H_1 H_1 - H_2 H_2)^2 + \frac{g^2}{2} |H_1 H_2|^2
\]

gauge couplings, in contrast to SM

physical states: \(h^0, H^0, A^0, H^\pm\)

Goldstone bosons: \(G^0, G^\pm\)

Input parameters: (to be determined experimentally)

\[
\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)
\]
Neutral Higgses within MSSM

- At tree level, Higgs sector is described by $\tan\beta$ and $M_A$.
- Higher order corrections introduce dependency on additional SUSY parameters.

**Five additional, relevant parameters:**

- $M_{\text{SUSY}}$: Common Scalar mass
- $X_t$: Mixing Parameter
- $M_2$: SU(2) gaugino mass term
- $\mu$: Higgs mass parameter
- $m_g$: gluino mass

\[
m_{H,h}^2 = \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2m_A^2\cos^22\beta} \right)
\]

\[
m_h^2 \leq m_Z^2 \cos^22\beta \leq m_Z^2
\]

\[
m_h^2 \leq m_Z^2 + \frac{3g^2m_t^4}{8\pi^2m_W^2} \left[ \ln \left( \frac{M_Z^2}{m_t^2} \right) + x_t^2 \left( 1 - \frac{x_t^2}{12} \right) \right]
\]

where: $M_S^2 = \frac{1}{2} (M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)$ and $x_t = (A_t - \mu \cot\beta) / M_S$

→ upper mass bound depends on top mass and mixing in the stop sector
MSSM Higgs mass

- Benchmark scenario ($m_H^{\text{max}}$ scenario most popular)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$M_{\text{ SUSY}}$ (GeV)</th>
<th>$X_t^{\text{OS}}$ (GeV)</th>
<th>$\mu$ (GeV)</th>
<th>$M_2$ (GeV)</th>
<th>$M_\tilde{\chi}_1^0$ (GeV)</th>
<th>Upper bound on $m_H$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H^{\text{max}}$</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
<td>200</td>
<td>800</td>
<td>133</td>
</tr>
<tr>
<td>no mixing</td>
<td>2000</td>
<td>0</td>
<td>200</td>
<td>200</td>
<td>800</td>
<td>116</td>
</tr>
<tr>
<td>gluophobic</td>
<td>350</td>
<td>-750</td>
<td>300</td>
<td>300</td>
<td>500</td>
<td>119</td>
</tr>
<tr>
<td>small $\cdot_3$</td>
<td>800</td>
<td>-1100</td>
<td>2000</td>
<td>500</td>
<td>500</td>
<td>123</td>
</tr>
</tbody>
</table>

S. Heinemeyer, http://www.ifca.es/users/heinemey/uni/plots/

Search for neutral MSSM Higgs boson at LEP

\[ e^+ e^- \rightarrow Z h, Z H \]

\[ \sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}}) \sigma^{SM}_{hZ} \]

\[ \sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}}) \sigma^{SM}_{hZ} \]

\[ e^+ e^- \rightarrow A h, A H \]

\[ \sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}}) \sigma^{SM}_{hZ} \]

\[ \sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma^{SM}_{hZ} \]
Search for neutral MSSM Higgs boson at LEP

Constraints from the Higgs search at LEP  [LEP Higgs Working Group ’06]

Experimental search vs. upper $M_h$-bound (FeynHiggs 2.0)

$m_h^{\text{max}}$-scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):

$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

$M_A > 93.4$ GeV
(expected: 95.2 GeV)
Charged Higgs in $B$ decays

- Look for sensitive and theoretically clean modes

- Results from $B$-factories: Babar, Belle

![Diagram of charged Higgs in $B$ decays]
MSSM Higgs boson searches at Tevatron and LHC

Important channels in the MSSM Higgs boson search:

1. The Standard Model decay channels
   - $h \rightarrow \gamma\gamma$
   - $qq, h \rightarrow \tau\tau$
     evaluation of performance is based on SM results

2. Modes strongly enhanced at large $\tan \beta$:
   - $H/A \rightarrow \tau^+\tau^-$, $H^+ \rightarrow \tau\nu$
   - $H/A \rightarrow \mu^+\mu^-$

3. Other interesting channels:
   - $H/A \rightarrow Zh \rightarrow \ell\ell\gamma\gamma$
     $\rightarrow \ell\ell bb$
   - $H \rightarrow hh$
Production of MSSM Higgs bosons

- Agreement between the four and five flavour scheme calculations

![Graph showing production cross-section for MSSM Higgs bosons](image)
Branching ratios of MSSM Higgs bosons

[Graphs showing branching ratios for different Higgs bosons and mass ranges.]
Hadronic tau (τ_{had}) identification

- τ lepton properties:
  - Mass: 1.78 GeV ; Short lifetime: O(10^{-13}s)
  - Decay prior to reaching any detector component.
- Main decay channels:

<table>
<thead>
<tr>
<th>Decay products</th>
<th>BR (%)</th>
<th>Decay Type</th>
<th>e</th>
<th>Detect using standard e/μ ID algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + ν_μ + ν_τ</td>
<td>17.8</td>
<td>Leptonic (35.2%)</td>
<td>e</td>
<td></td>
</tr>
<tr>
<td>μ + ν_μ + ν_τ</td>
<td>17.4</td>
<td></td>
<td>μ</td>
<td></td>
</tr>
<tr>
<td>π^±/(K)+ν_τ</td>
<td>11.8</td>
<td>1-prong (48.7%)</td>
<td>τ_h</td>
<td>Need dedicated tau ID to measure narrow, low multiplicity jet object</td>
</tr>
<tr>
<td>π^±/(K)+≥1π^0+ν_τ</td>
<td>36.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π^±π^±π^±+≥0π^0+ν_τ</td>
<td>13.9</td>
<td>3-prong</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hadronic tau identification

- Identification usually optimised for each type of tau's.
- Using multi-variate techniques (LL, NN, BDT) usually gives significant improvement.
Inclusive $\Phi \rightarrow \tau\tau$ \quad ($\Phi=h/H/A$)

- Low BR $\sim 10\%$ but clean signature.
- Require $\geq 1$ leptonic tau decays: $\tau_\mu \tau_{\text{had}}, \tau_e \tau_{\text{had}}, \tau_\tau \tau_\mu$.
- Main backgrounds: $Z \rightarrow \tau\tau$, $W+$jets, QCD multijets.

\begin{align*}
M^{\text{vis}} &= \sqrt{(p_\mu^2 + p_\tau^2 + p_\tau^2)}
\end{align*}
$b(b) \Phi \rightarrow b(b)\tau\tau$

- Similar selection to inclusive $\Phi^0 \rightarrow \tau^+\tau^-$ search, requiring in addition $\geq 1$ b-tagged jet. 
  - reduced impact of $Z+jets$ background.
  - Higher sensitivity down to lower mass.
  - multivariate discriminant against ttbar, QCD multijets and $Z+jets$.

Elzbieta Richter-Was

Lectures on LHC physics
b(b) $\Phi \rightarrow bbb(b)$

- **Experimental signature:**
  - 3, 4 or $\geq 5$ jets; $\geq 3$ b-tags
  - Look for resonance in dijet mass
- Backgrounds dominated by heavy flavor-enriched QCD multijets:
  ➔ estimated from data.

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**DØ Preliminary, L=2.6 fb$^1$**

$m_h$ max, $\mu=-200$ GeV

$gb \rightarrow b\Phi$

---

**CDF Run II Preliminary**

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**95% C.L. upper limits CDF Run II Preliminary (2.2/fb)**

$m_b=140$ GeV; p-value: 0.9% (5.7% w/ trials factor)
Tevatron exclusions on MSSM Higgs bosons

Excluded cross section (95% C.L. limits)

Combination of the CDF and D0 results on $bb\Phi$, $\Phi \rightarrow \tau\tau$
\( Z \rightarrow \tau \tau \) in CMS

\( \int L dt = 1.7 \text{ pb}^{-1} \) analyzed

**Final selection applied**

- Muon \( P_T > 15 \text{ GeV/c} \)
- Tau \( P_T > 20 \text{ GeV/c} \)
- Loose HPS Tau Isolation
- Muon relative PF combined Isolation
- \( MT(\mu,\text{MET}) < 40 \text{ GeV/c}^2 \)

22 events expected (signal + background)

- 22 events observed
- Expected purity \( \sim 75\% \)

Clean \( Z \rightarrow \tau \tau \) signal observed
ATLAS analysis: invariant mass with collinear approximation

\[
m_{\tau\tau} = \frac{m_{lh}}{\sqrt{x_l x_h}} \quad x_h = \frac{E_h}{E_h + E_{vh}} \quad x_l = \frac{E_l}{E_l + E_{vh}}
\]

- \( m_{\tau\tau} \) can be reconstructed in the collinear approximation with good resolution (\( \delta m \approx 8 \text{ -- } 10 \text{ GeV/c}^2 \))
  - Assume \( \tau \) decays to be only source of \( E_{T\text{miss}} \)
  - Assume massless \( \tau \)'s

- Dominant background is \( Z/\gamma^* \rightarrow \tau\tau \)
Atlas analysis (simulation)

- Combined b-tagged and non b-tagged analyses

- Improvement for $M_A > 150$ GeV/c$^2$ over older ATLAS analysis of di-lepton final state $\tau_1\tau_1$ (CERN-OPEN-2008-020)

- Compares well with combined Tevatron results at 2.96 TeV obtained with 1.8 fb$^{-1}$ (CDF) and 2.2 fb$^{-1}$ (D0)
Projection for discovery and exclusion potential with 7 TeV and $L_{\text{int}}=1\text{fb}^{-1}$
The MSSM neutral Higgses: di-muon channel

- Not visible in SM, enhanced in MSSM
- Combine analyses: 0-bjet and at least 1 b-jet
- Z+jets bgd dominates at low masses, tt becomes at important at higher.
- Average muon $p_T$ resolution better than 3%, allows for excellent di-muon mass resolution.
- Theoretical uncertainty on the signal is up to 20% while the detector-related systematic uncertainties degrade signal significance by 5-10%.

Sensitivity not as good as in $\tau\tau$ channel but may be easier at the beginning.
The MSSM charged Higgs

- Naturally predicted in many non-minimal Higgs scenarios, here presented typeII-2HDM, mh-max.
- Light charged Higgs (below top mass)
  - dominant production is $t\bar{t}$, with $t \to H^\pm b$
  - dominant decay mode $H^\pm \to \tau\nu$
- Heavy charged Higgs (above top mass)
  - dominant production $gg/gb \to t(b)H^\pm$
  - dominant decay $H^\pm \to \tau\nu$ or $H^\pm \to tb$
- Final states: 2-4 b-jets, light jets from W decay, neutrinos, most channels with tau-lepton.
- Several topologies (i.e. five) studied.
- Profile Likelihood used for discovery or exclusion including 10% systematic uncertainties on bgd (data-driven control on tt background shape and normalisation).

Expect significant improvement of present day constraints already with $1fb^{-1}$. 

---assuming infMC---
MSSM Higgs boson searches at LHC

- best sensitivity from $A/H \rightarrow \tau\tau$, and $H^+ \rightarrow tb$ and $\tau\nu$  
- $A/H \rightarrow \mu\mu$ experimentally easier

$m_h < 135 \text{ GeV}$ \[ m_A \approx m_H \approx m_{H^\pm} \text{ at large } m_A \]
LHC discovery potential for SUSY Higgs bosons

\[ A, H, H^\pm \text{ cross-sections } \sim \tan^2 \beta \]

- best sensitivity from
  \[ A/H \rightarrow \tau\tau, \; H^\pm \rightarrow \tau\nu \]
  (not easy the first year ....)

- \( A/H \rightarrow \mu\mu \) experimentally easier
  (esp. at the beginning)

Here only SM-like \( h \) observable if SUSY particles neglected.

Coverage in the large \( m_A \) edge region can be improved (slightly) by:

- Higher luminosity: sLHC
- Additional SUSY decay modes (however, model dependent)
Different benchmark scenarios

Benchmark scenarios as defined by M. Carena et al. (h mainly affected)

ATLAS preliminary, 30 fb$^{-1}$, 5$\sigma$ discovery (2004)

**MHMAX scenario** ($M_{\text{SUSY}} = 1$ TeV/c$^2$)
maximal theoretically allowed region for $m_h$

**Nomixing scenario** ($M_{\text{SUSY}} = 2$ TeV/c$^2$)
(1 TeV almost excl. by LEP)
small $m_h \rightarrow$ difficult for LHC

**Gluophobic scenario** ($M_{\text{SUSY}} = 350$ GeV/c$^2$)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for $gg \rightarrow H, H \rightarrow gg$ and $Z \rightarrow 4\ell$

**Small a scenario** ($M_{\text{SUSY}} = 800$ GeV/c$^2$)
coupling to $b$ (and $t$) suppressed (cancellation of sbottom, gluino loops) for large tan $b$ and
$M_A = 100$ to $500$ GeV/c$^2$
MSSM Higgs sector in super-LHC

- Situation can be improved, in particular for $m_A < \sim 400$ GeV
- But: (s)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....
  .... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.
**Next topics**

- 5.01  - SUSY
- 12.01 - SUSY
- 19.01 - Wrapping up on data 2010:
  - SM physics: selected public results
  - Searches: new exclusion limits
How to make predictions

Comparison of precision observables with theory:

\[
\begin{align*}
\text{Precision data:} & \quad M_W, \sin^2 \theta_{\text{eff}}, a_\mu, \ldots & \leftrightarrow & \quad \text{Theory:} & \quad \text{SM, MSSM, \ldots}
\end{align*}
\]

\[\downarrow \quad \downarrow\]

Test of theory at quantum level: Sensitivity to loop corrections

\[\Rightarrow \text{Information about unknown parameters}\]

Very high accuracy of measurements and theoretical predictions needed
Predictions for $M_W$ in SM and MSSM

Theoretical prediction for $M_W$ in terms of $M_Z$, $\alpha$, $G_\mu$, $\Delta r$:

$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

$\updownarrow$

loop corrections

$\rightarrow$ can be approximated with the $\rho$-parameter:

$\rho$ measures the relative strength between neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta \rho}, \quad \Delta \rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}, \quad \Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta \rho$$

(leading, process independent terms)
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\[ \Delta \rho^{\text{SUSY}} \text{ from } \bar{t}/\bar{b} \text{ loops } > 0 \quad \Rightarrow \quad M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}} \]
Predictions for $M_W$ in SM and MSSM

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![Diagram](image.png)

$\Delta \rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops $> 0$ \Rightarrow $M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$
Predictions for $M_W$ in SM and MSSM

Example: Prediction for $M_W$ in the SM and the MSSM:

MSSM band:
scan over SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{SM}$