Higgs Physics
with ATLAS

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MPI Kolloquium, Werner-Heisenberg-Institut, November 29th 2005
the Higgs Mechanism and SM Higgs phenomenology at LHC
- discovery potential for SM Higgs boson
- investigation of the Higgs boson profile
- phenomenology of SUSY Higgs bosons
- discovery potential for MSSM Higgs bosons
- discriminating the SM from extended Higgs sectors
- conclusion and outlook
The Higgs Mechanism in the Nut Shell

The problem:
- consistent description of nature seems to be based on gauge symmetry
- $SU(2)_L \times U(1)$ gauge symmetry $\rightarrow$ no masses for $W$ and $Z$ and fermions
- "ad hoc" mass terms spoil
  - renormalisibility $\rightarrow$ no precise calculation of observables
  - high energy behaviour $\rightarrow$ $W_L W_L$ scattering violates unitarity at $E_{CM} \sim 1.2$ TeV

The "standard" solution:
- new doublet of complex scalar fields with appropriately chosen potential $V$
- $\rightarrow$ vacuum spontaneously breaks gauge symmetry
- $\rightarrow$ one new particle: the Higgs boson $H$
  $\Phi = v + H$
**Mass generation and Higgs couplings:** $\Phi = v + H$

**Interaction of particles with** $v = 247$ GeV

- **Effective mass** = friction of particles with omnipresent "Äther"
- $m_f \sim g_f v$ Yukawa coupling
- $M_V \sim g v$ gauge coupling

**Interaction of particles with Higgs $H$**

- Fermions $g_f \sim m_f / v$
- W/Z Bosons: $g_V \sim 2 M_V / v$

VVH coupling $\sim vev$

only present after EWSB breaking !!!

1 unknown parameter in SM: the mass of the Higgs boson
Higgs Boson Decays in SM

for $M < 135$ GeV: $H \to bb, \tau\tau$ dominant

for $M > 135$ GeV: $H \to WW, ZZ$ dominant

tiny: $H \to \gamma\gamma$ also important
Status of SM Higgs Searches I: LEP

Direct search:

- \( M_H < 114.4 \text{ GeV} \) excluded at 95% CL
- \( M_H < 114.4 \text{ GeV} \) at 95% CL, \( m_{\text{top}} = 172 \text{ GeV} \)

Electroweak fit:

- \( M_H < 186 \text{ GeV} \) at 95% CL, \( m_{\text{top}} = 172 \text{ GeV} \)

\((M_H < 216 \text{ GeV} \text{ for } m_{\text{top}} = 175 \text{ GeV})\)
Expected sensitivity:
95% CL exclusion up to 130 GeV with 4fb$^{-1}$ per experiment
3 sigma evidence up to 130 GeV with 8fb$^{-1}$ per experiment

Current sensitivity:
Cross section limits at level of
$\sim 10 \times$ SM cross section
Higgs Physics at LHC

- discovery of 1 neutral scalar Higgs boson
  (determination of mass, spin, CP)

- discrimination between SM and extended Higgs sectors

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LHC and ATLAS

- **LHC:** proton proton collisions at $E_{CM} = 14$ TEV, start in 2007
  - low luminosity running: $1(2) \times 10^{33} / (\text{cm}^2 \text{s}) \rightarrow 10(20) \text{ fb}^{-1}/\text{year}$
  - high luminosity running: $10^{34} / (\text{cm}^2 \text{s}) \rightarrow 100 \text{ fb}^{-1}/\text{year}$

- **A Toroidal LHC Aparatus**
  - $H \rightarrow 2$ photons, $H \rightarrow ZZ \rightarrow 4$ leptons
    - anticipated $\sigma_M/M_H \sim 1\%$
    - $\rightarrow$ em.-calorimetry, $\mu$–spectrometer
  - $ttH$, $H \rightarrow bb$
    - $\varepsilon_b = 60(50)\%$ $R_c > 10$ $R_{udsg} > 100$
    - $\rightarrow$ Si tracking detectors
  - $H \rightarrow \tau\tau$, $\rightarrow WW \rightarrow l\nu l\nu$, VBF prod.
    - missing E. resolution, hermiticity,
    - forward jets $\rightarrow$ calorimetry to $\eta = 5$

- MC studies with fast simulation of ATLAS detector
- key performance numbers from full sim.: $b$/tau/jet/el./$\gamma$/$\mu$ identification, isolation criteria, jet veto, mass resolutions, trigger efficiencies, ...
Production of the SM Higgs Boson at LHC

\[ \sigma(pp \rightarrow H + X) \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ m_t = 175 \text{ GeV} \]
CTEQ4M

M. Spira et al.
NLO QCD

Markus Schumacher  
Higgs Physics with ATLAS  
Munich, November 29th 2005
QCD corrections and Knowledge of Cross Sections

e.g.: Gluon Gluon Fusion

- $K = \sigma_{\text{NNLO}}/\sigma_{\text{LO}} \sim 2$
- $\Delta\sigma = 15\%$ from scale variations
- Error from PDF uncertainty $\sim 10\%$

Caveat: scale variations may underestimate the uncertainties!

- $ttH$: $K \sim 1.2$, $\Delta\sigma \sim 15\%$
- WH/ZH: $K \sim 1.3$ to $1.4$, $\Delta\sigma \sim 7\%$
- VBF: $K \sim 1.1$, $\Delta\sigma \sim 4\%$ + uncertainties from PDF (5 to 15%)

- but: rarely MC at NLO available (except gluon gluon fusion)
- background: NLO calculations often not available
  - need background estimate from data
  - ATLAS policy: use $K=1$ for signal
Cross sections for Background Processes

Background: mainly QCD driven

Signal: often electroweak interaction

→ photons, leptons, ...

overwhelming background

→ trigger: $10^{-7}$ reduction

on leptons, photons, missing $E_T$

Higgs 150 GeV: $S/B \leq 10^{-10}$
Discovery Potential for light SM Higgs boson

**discovery channels**

- **GGF:** $H \rightarrow \gamma\gamma$
- **GGF:** $H \rightarrow ZZ \rightarrow 4l^{\pm-}$
- **GGF:** $H \rightarrow WW \rightarrow 2l\nu\nu$
- **ttH:** $H \rightarrow bb$
- **VBF:** $H \rightarrow \tau\tau$
- **VBF:** $H \rightarrow WW$

For $M_H > 300$ GeV also:
- VBF: $H \rightarrow ZZ \rightarrow ll\nu\nu$
- VBF: $WW \rightarrow l\nuqq$

- no fully hadronic final states: eg. GGF, VBF: $H \rightarrow bb$
- Higgs Boson mass reconstruction possible?
- background controlable (S/B), estimate from data possible?
H → 2 Photons

- **signature:** two high $P_t\gamma$
- **background:** irreducible $pp\rightarrow \gamma\gamma + x$
  reducible $pp\rightarrow \gamma j, jj, \ldots$
- **exp issues (mainly for ECAL):**
  - $\gamma$, jet separation
  - energy scale, angular resolution
  - conversions/dead material

**ATLAS 100fb$^{-1}$**

- $S/BG \sim 1/20$
- mass resolution $\sigma_M$: $\sim 1\%$
- precise background estimate from sidebands (O(0.1%))

**preliminary NLO study:**
- increase of $S/\sqrt{B}$ by 50%
Gluon Fusion: $H \rightarrow ZZ(\ast) \rightarrow 4\text{ Leptons}$

- **signature**: 4 high $p_t$ isolated leptons
  1(2) dilepton mass $\sim M_Z$

- **irreducible BG**: $ZZ$
  $\rightarrow$ mass reconstruction

- **reducible BG**: $tt, Zbb \rightarrow 4\text{ leptons}$
  $\rightarrow$ rejection via
  lepton isolation and b-veto

- **good mass resolution $\sigma_M$: $\sim 1\%$**

- **small and flat background**
  $\rightarrow$ easy estimate from data

- **preliminary NLO study indicates**
  significance increase by 25%
Gluon Fusion: $H \rightarrow WW \rightarrow l^+ l^-$

- **signature:**
  - 2 high $p_t$ leptons + large missing $E_T$
  - lepton spin correlations

- no mass peak $\rightarrow$ transverse mass

$$m_T = \sqrt{2 \, P_T^{\ell \ell} E_T \, (1 - \cos \Delta \phi)}$$

- **BG:** WW, WZ, tt
  - lepton iso., missing $E$ resolution
  - jet (b-jet) veto against tt

- **BG estimate in data from** $\Delta \Phi_{ll}$
  - $\rightarrow$ NLO effect on spin corr.
  - $\rightarrow$ $gg \rightarrow WW$ contribution signal like

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**ATLAS**

- $M=170\text{GeV}$
- $L=30\text{fb}^{-1}$

**Dührssen, prel.**

- $m_H=170\text{ GeV}/c^2$
ttH with $H \rightarrow bb$

- **signature**: 1 lepton, missing energy
- **6 jets of which 4 b-tagged**
- **reducible BG**: $tt+\text{jets}, W+\text{jets} \rightarrow \text{b-tagging}$
- **irreducible BG**: $ttbb \rightarrow \text{reconstruct mass peak}$

- **exp. issue**: full reconstruction of ttH final state $\rightarrow$ combinatorics !!!
- **need good b-tagging + jet / missing energy performance**

- **mass resolution $\sigma_M$: ~ 15%**
- **50% correct $bb$ pairings**

- **very difficult background estimate from data with exp. uncertainty $\sim O(10\%)$**
- $\rightarrow$ normalisation from side band
- $\rightarrow$ shape from „re-tagged“ ttjj sample

**only channel to see $H \rightarrow bb$**
Vector Boson Fusion: $pp \rightarrow qqH$

- **signature:**
  - 2 forward jets with large rapidity gap
  - only Higgs decay products in central part of detector
Vector Boson Fusion: $pp \rightarrow q\bar{q}H$

- 2 forward tagging jets with rapidity

- **theory questions:**
  - jet distributions at NLO?
  - esp. direction of 3rd jet?
  - efficiency of central jet veto?

- need NLO MC generator for signal and BG

- **experimental issues:**

  - forward jet reconstruction
  - jet-veto fake rate due to pile up

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**Experimental Issues:**

Forward Jet Reconstruction

- Efficiency

- $p_T > 20$ GeV

- $\eta$ vs. Efficiency (ATLAS)

- $\Delta\eta$ vs. Efficiency (ATLAS)

Jet-Veto Fake Rate Due to Pile Up

- $p_T$ Veto Threshold vs. Fake Rate (%)

- High Lumi vs. Low Lumi (ATLAS)
**Weak Boson Fusion: H→WW→llνν (lνqq)**

- **signature:** tagging jets +
  - 2 high $p_t$ leptons + large missing $E_T$
  - lepton spin correlations (spin1↔0)
  - no mass peak $\rightarrow$ transverse mass

- **backgrounds:**
  - tt, Wt, WWjj, ...

- S/BG $\sim$ 3.5/1
- BG uncertainty $\sim$ 10 %

- shape from MC
- normalisation from side bands in $M_T$ and $\Delta \phi_{ll}$

### ATLAS

- **Higgs signal $m_H=160$ GeV/c²**
- **ATLAS**
- **10 fb$^{-1}$**

**Central jet veto**

**b-veto**

**Transverse mass**
Vector Boson Fusion: $H \to \tau \tau \to l \ell 4 \nu$ (I had 3 $\nu$)

- signature: tagging jets +
  - 2 high $p_t$ leptons + large missing $E_T$
  - mass reconstruction despite 4 $\nu$
  in collinear approximation

- backgrounds: $Zjj$, $tt$

- mass resolution $\sim 10\%$
  determined by missing $E_T$ resolution

- $BG$ uncertainty $\sim 5$ to $10\%$
  for $M_H > 125$ GeV: flat sideband
  for $M_H < 125$ normalisation from $Z$ peak

- $S/BG \sim 1$ to $2 / 1$

ATLAS
$H \to \tau \tau \to e\mu$
$M_H = 120$ GeV

central jet veto
reconstruction
of $m_{\tau\tau}$
Vector Boson Fusion, $H \rightarrow \tau\tau$: estimate of BG shape from data

- **Idea:** $jjZ \rightarrow \mu\mu$ and $jjZ \rightarrow \tau\tau \rightarrow \mu\mu$
  - look almost the same, esp. in calos
  - same missing energy
  - only $\mu$ momenta different
- **Method:** select $Z \rightarrow \mu\mu$ events
  - randomise $\mu$ momenta
  - apply "normal" mass reco.

Promising prel. results from ongoing diploma thesis in BN (M. Schmitz)
SM discovery potential depending on int. luminosity

- discovery from LEP exclusion until 1 TeV
  - from combination of search channels with 15 fb^{-1} of well understood data
  - with individual search channels with 30 fb^{-1} of well understood data
- for GGF: raise of significance by up to 50% at NLO
- results for cut based analysis → improvement by multivariate methods
Measurement of Higgs Boson Mass

- **Direct** from mass peak:
  \[ H \rightarrow \gamma\gamma \] \[ H \rightarrow bb \] \[ H \rightarrow ZZ \rightarrow 4l \]

- **“Indirect”** from Likelihood fit to transverse mass spectrum:
  \[ H \rightarrow WW \rightarrow l\nu l\nu \] \[ WH \rightarrow WWW \rightarrow l\nu l\nu l\nu \]

- **Uncertainties considered:**
  i) statistical
  ii) absolute energy scale
    \[ 0.1 (0.02) \% \] for \( l, \gamma, 1\% \) for jets
  iii) \( 5\% \) on BG + signal for \( H \rightarrow WW \)

VBF with \( H \rightarrow \tau\tau \) or WW not studied yet!

**Delta M/M: 0.1% to 1%**
Determination of Higgs boson couplings

Born level couplings:
- Fermions: \( g_f = \frac{m_f}{v} \)
- W/Z Bosons: \( g_V = 2 \frac{M_V^2}{v} \)

Loop induced effective couplings:
(sensitive to new physics)
- Photon: \( g_\gamma = g_W^+ + g_t^+ + \ldots \)
- Gluon: \( g_\gamma = g_t^+ + g_b^+ + \ldots \)

- couplings in production: \( \sigma_{Hx} = \text{const} \times \Gamma_{Hx} \) and decay \( \text{BR}(H\rightarrow yy) = \Gamma_H / \Gamma_{\text{tot}} \)
- experiment: \( \text{rate} = N_{\text{sig}} + N_{BG} \) \( N_{\text{sig}} = L \times \text{efficiency} \times \sigma_{Hx} \times \text{BR} \)
  \( \rightarrow \) need to know: luminosity, efficiency, background

\[ \sigma_{Hx} \times \text{BR} \sim \frac{\Gamma_{Hx}^{\text{prod}}\Gamma_{Hx}^{\text{decay}}}{\Gamma_{\text{tot}}} \]

- tasks: - disentangle contribution from production and decay
  - determine \( \Gamma_{\text{tot}} \)

Partial width: \( \Gamma_{Hz} \sim g_{Hz}^2 \)
**Ratio of Partial Widths**

- ratios of BRs = ratios of $\Gamma = $ ratios of $g$, if only Born level couplings

\[
\frac{\sigma_{\text{VBF}}}{} \times \text{BR}(H \rightarrow WW) = \frac{\Gamma_W \Gamma_W \Gamma_{tot}}{\Gamma_W \Gamma_W \Gamma_{tot}} = \frac{\Gamma_W}{\Gamma_W}
\]

13 analysis used
9 fit parameters:

\[
\begin{align*}
\Gamma_Z/\Gamma_W & \quad \Gamma_\gamma/\Gamma_W & \quad \Gamma_\tau/\Gamma_W & \quad \Gamma_b/\Gamma_W \\
\Gamma_W & \quad \Gamma_W & \quad \Gamma_W & \quad \Gamma_W
\end{align*}
\]

including various exp. and theo. errors

\[
(\sigma \cdot \text{BR})_{GF,H \rightarrow WW} \\
(\sigma \cdot \text{BR})_{VBF,H \rightarrow WW} \\
(\sigma \cdot \text{BR})_{ttH,H \rightarrow WW} \\
(\sigma \cdot \text{BR})_{WH,H \rightarrow WW} \\
(\sigma \cdot \text{BR})_{ZH,H \rightarrow WW}
\]

H$\rightarrow$ WW chosen as reference as best measured for $M_H > 120$ GeV

For 30fb$^{-1}$ worse by factor 1.5 to 2
Total Decay Width $\Gamma_H$

- for $M_H > 200$ GeV, $\Gamma_{tot} > 1$ GeV
  - measurement from peak width in $ZZ \rightarrow 4 l$
- for $M_H < 200$ GeV, $\Gamma_{tot} \ll$ mass resolution
  - no direct determination
  - have to use indirect constraints on $\Gamma_{tot}$
- lower limit from observable rates:
  $\Gamma_{tot} > \Gamma_W + \Gamma_Z + \Gamma_t + \Gamma_g + ...$
- upper limit needs input from theory:
  mild assumption: $g_V < g_V^{SM}$
  valid in models with only Higgs doublets and singlets
  rate(VBF, $H \rightarrow WW) \sim \Gamma_V^2 / \Gamma_{tot} < (\Gamma_V^2 \text{ in SM}) / \Gamma_{tot}$
  $\Rightarrow \Gamma_{tot} < \text{rate}/(\Gamma_V^2 \text{ in SM})$
Absolute couplings with $g_V < g_V^{\text{SM}}$ constraint

- Coupling to $W, Z, \tau, b, t$
- $\Gamma_{\text{inv}}$ for undetectable decays e.g. $c$, gluons, new
- $\Gamma_{\text{photon}}(\text{new}), \Gamma_{\text{gluon}}(\text{new})$: non SM contribution to loops

$\Delta g/g = \frac{1}{2} \Delta(g^2)/g^2$
Motivation for Supersymmetry from Higgs Sector

- “solves” hierarchy problem: why $v = 246 \text{ GeV} < < M_{\text{Pl}} = 10^{19} \text{GeV}$?
- Higgs problem in SM:
  - large corrections to the mass of the Higgs-Boson
  - $\Delta M_H^2 = \alpha \Lambda^2 = \alpha M_{\text{Planck}}^2$
  - natural value $\sim M_{\text{Pl}}$
  - electroweak fit $M_H \sim O(100 \text{GeV})$

- SUSY solution:
  - partner with spin difference by $\frac{1}{2}$ cancel divergence exactly if same $M$
  - SUSY broken in nature, but hierarchy still fine if $M_{\text{SUSY}} \sim 1 \text{ TeV}$

- SUSY breaking in MSSM:
  - parametrised by 105 additional parameters
  - too many $\Rightarrow$ constrained MSSM with 5 (6) additional parameters
The MSSM Higgs sector in a tiny Nut Shell

- SUSY: 2 Higgs doublets $\rightarrow$ 5 physical bosons
  - real MSSM: 2 CP even $h, H$, 1 CP odd $A$, charged $H^+, H^-$
- at Born level 2 parameters: $\tan\beta, m_A$, $m_h < M_Z$
- large loop corrections from SUSY breaking parameters
  - $m_h < 133$ GeV for $m_{top} = 175$ GeV, $M_{SUSY} = 1$ TeV
- corrections depend on 5 SUSY parameters: $X_t, M_0, M_2, M_{gluino}, \mu$
  - fixed in the benchmark scenarios e.g. MHMAX scenario
    $\rightarrow$ maximal $M_h$ $\rightarrow$ conservative LEP exclusion

- $g_{MSSM} = \xi g_{SM}$

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>$t$</th>
<th>$b/\tau$</th>
<th>$W/Z$</th>
</tr>
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<tbody>
<tr>
<td>$h$</td>
<td>$\cos\alpha/\sin\beta$</td>
<td>$-\sin\alpha/\cos\beta$</td>
<td>$\sin(\alpha-\beta)$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\sin\alpha/\sin\beta$</td>
<td>$\cos\alpha/\cos\beta$</td>
<td>$\cos(\alpha-\beta)$</td>
</tr>
<tr>
<td>$A$</td>
<td>$\cot\beta$</td>
<td>$\tan\beta$</td>
<td>-----</td>
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- no coupling of $A$ to $W/Z$
- small $\alpha$ $\rightarrow$ small BR($h \rightarrow \tau\tau, bb$)
- large $\beta$ $\rightarrow$ large BR($h, H, A \rightarrow \tau\tau, bb$)

$\alpha =$ mixing btw. CP-even neutral Higgs bosons
main questions for ATLAS:

- At least 1 Higgs boson observable in the entire parameter space?
- How many Higgs bosons can be observed?
- Can the SM be discriminated from extended Higgs sectors?

- LEP $\tan\beta$ exclusion:
  no exclusion for $m_t$ larger $\sim 183$ GeV!

- TEVATRON:
  so far exclusion for $\tan\beta > 50$, $M_A < 200$ GeV

- calculations with FeynHiggs
  (Heinemeyer, Hahn, et al.)

- no systematic uncertainties yet
The four CPC Benchmark Scenarios


- **MHMAX scenario**  \( m_h < 133 \) GeV \( \rightarrow \) conservative LEP exclusion
- **Nomixing scenario**  \( m_h < 116 \) GeV \( \rightarrow \) difficult for LHC
- **Gluophobic scenario**  \( g_{h,\text{gluon}} \)  \( m_h < 119 \) GeV
- **Small \( \alpha \) scenario**  \( \rightarrow \) small \( g_{hbb} \) and \( g_{h\tau\tau} \)  \( m_h < 123 \) GeV

**theo. goal:** harm discovery via
\( gg \rightarrow h, h \rightarrow \gamma\gamma \) and \( h \rightarrow ZZ \rightarrow 4l \)

**theo. goal:** harm discovery via
VBF, \( h \rightarrow \tau\tau \)  \( tth, h \rightarrow bb \)
Vector Boson Fusion: 30 fb$^{-1}$

MHMAX scenario

VBF: $h \rightarrow WW$

VBF: $h \rightarrow \tau\tau$

excluded by LEP (prel.)

VBF: $H \rightarrow WW$

VBF: $H \rightarrow \tau\tau$

h or H observable with 30 fb$^{-1}$

studied for $M_H > 110$ GeV at low lumi running
almost same conclusion for all 4 CP conserving benchmark scenarios
Light Higgs Boson $h: 30 \text{ fb}^{-1}$

observable channels: VBF $\rightarrow \mu\mu$ tth $\rightarrow bb$

- MHMAX scenario
  - VBF: $h \rightarrow WW$
  - VBF: $h \rightarrow \tau\tau$
  - bbh: $h \rightarrow \mu\mu$
  - excluded by LEP (prel.)

- No mixing scenario
  - VBF: $h \rightarrow \tau\tau$
  - bbh: $h \rightarrow \mu\mu$
  - excluded by LEP (prel.)
  - tth: $h \rightarrow bb$

- Gluophobic scenario
  - VBF: $h \rightarrow \tau\tau$
  - bbh: $h \rightarrow \mu\mu$
  - excluded by OPAL
  - tth: $h \rightarrow bb$

Difference mainly due to different $m_h$ in same $(\tan\beta, M_A)$ point (up to 17 GeV difference)
Small $\alpha$ scenario, $h$: 30 fb$^{-1}$

- hole due to reduced branching ratio for $H \rightarrow \tau\tau$

- covered by enhanced BR to gauge bosons

- complementarity of search channels almost guarantees observation of $h$
Light Higgs Boson $h: 300 \text{ fb}^{-1}$ (VBF only 30 fb$^{-1}$)

- also $h \rightarrow gg, h \rightarrow ZZ \rightarrow 4$ leptons, $tth \rightarrow bb$ contribute
- large area covered by several channels
  - sure discovery and parameter determination possible
- small area uncovered @ $m_h = 90$ to 100 GeV
- $h \rightarrow \gamma\gamma$ sensitive in gluophobic scenario due to $Wh, tth$ production
Heavy Neutral Higgs Bosons

large $\tan\beta$: $bbH/A, H/A \rightarrow \tau\tau, \mu\mu$

$\sigma \sim (\tan\beta)^2$

low mass $<$ 450 GeV: $\tau\tau \rightarrow$ lep. $\nu \nu$ had. $\nu$

trigger on lepton

large mass $>$ 450 GeV: also $\tau\tau \rightarrow$ had. $\nu$ had. $\nu$

larger rate, trigger on hard tau jets

Eff.(LV1TR) = 80% = 95% offline selected events

Tau ID: eff(tau) = 55% rejection(QCD) = 2500

Markus Schumacher  Higgs Physics with ATLAS  Munich, November 29th 2005
Charged Higgs Bosons

- **High mass**: $m_{H^+} > m_{top}$
  - $gb \rightarrow H^+ t$
  - $H^+ \rightarrow \tau \nu$
  - $t \rightarrow bqq$
  - **New**: $W \rightarrow qq$
  - $H^+ \rightarrow \tau \nu$

- **Low mass**: $m_{H^+} < m_{top}$
  - $gg \rightarrow tt$
  - $tt \rightarrow H^+ bW$
  - Only low lumi.
  - **Transition region around $m_{top}$**
    - Needs revised experimental analysis
    - Running bottom quark mass used
    - Xsec for $gb \rightarrow tH^+$ from T. Plehn's program

MHMAX scenario

- $30 \text{ fb}^{-1}$
- $300 \text{ fb}^{-1}$
- $gb \rightarrow tH^+, H^+ \rightarrow \tau \nu$
- $tt \rightarrow bH^+ bW, H^+ \rightarrow \tau \nu, W^- Iv$
- $30 \text{ fb}^{-1}$

Excluded by LEP (prelim.)

$gb \rightarrow tH^+, H^+ \rightarrow tb$

New $W \rightarrow qq$
Overall Discovery Potential: 300 fb$^{-1}$

- at least one Higgs boson observable for all parameters in all CPC benchmark scenarios
- significant area where only lightest Higgs boson $h$ is observable
- questions for future studies: can SUSY decay modes provide observation?
  e.g.: $H/A \rightarrow \chi_2 \chi_2 \rightarrow 2 \text{LSP} + 4 \text{lept.}$
  ongoing study in BN (N. Möser)

similar results in other benchmark scenarios

VBF channels, $H/A \rightarrow \tau\tau$ only used with 30fb$^{-1}$
SM or Extended Higgs Sector e.g. Minimal SUSY?

discrimination via rates from VBF

\[ R = \frac{\text{BR}(h \rightarrow WW)}{\text{BR}(h \rightarrow \tau\tau)} \]

compare expected measurement of \( R \) in MSSM with prediction from SM for same value of \( M_H \)

- assume Higgs mass well measured
- no systematic errors considered

\[ \Delta = \left| R_{\text{MSSM}} - R_{\text{SM}} \right| / \sigma_{\text{exp}} \]
The Higgs Sector in the CP Violating MSSM

- at Born level: CP symmetry conserved in Higgs sector
- complex SUSY breaking parameters \((\mu, A_t)\) introduce new CP phases
  - mixing between neutral CP eigenstates

mass eigenstates \(H_1, H_2, H_3\)

<> CP eigenstates \(h, A, H\)

Why consider such scenarios?

- no a priori reason for real SUSY parameters
- baryogenesis: 3 Sacharov conditions
  - B violation: via sphaleron processes
  - CP violation: SM too less, CPV MSSM new sources \(\rightarrow\) fine
  - No therm. Equ.: SM no strong 1st order electroweak phase transition
    - CPV MSSM still fine (even better NMSSM)
- evade dipole moments via spurious cancellations or split SUSY
Phenomenology in the CPX scenario

- maximise effect $\rightarrow$ CPX scenario (Carena et al., Phys.Lett B495 155(2000))
  \[ \arg(A_t) = \arg(A_b) = \arg(M_{\text{gluino}}) = 90 \text{ degree} \]

- scan of Born level parameters: \( \tan \beta \) and \( M_{H^+} \)

- \( H_1, H_2, H_3 \) couple to \( W, Z \)
  $\rightarrow$ all produced in VBF

- \( H_2, H_3 \rightarrow H_1 H_1, ZH_1, WW, ZZ \)
  decays possible

- no limit for mass of \( H_1 \) from LEP
  (compare CPC MSSM: \( M_h > M_Z \))

LHWG-Note 2005-01
CP-Violating MSSM: Overall Discovery Potential

- yet uncovered area
- size and location of "hole" depends on $M_{\text{top}}$ and program for calculation

$M_{H_1}$: < 70 GeV
$M_{H_2}$: 105 to 120 GeV
$M_{H_3}$: 140 to 180 GeV

Small masses below 70 GeV not yet studied in ATLAS

- most promising channel: $tt \rightarrow bW bH^+, H^+ \rightarrow W H_1, H_1 \rightarrow bb$
- final state: $4b 2j l \nu$ same as $ttH, H \rightarrow bb$ (study in Bonn)
- revised studies for $H_{2/3} \rightarrow H_2 H_1$ also interesting
Very first look at new promising MC study

- \( t\bar{t}\rightarrow H^+ b W b \quad H^+\rightarrow W H_1 \quad H_1\rightarrow bb \)
- 1 leptonic W decay \(\rightarrow\) lepton for trigger
- reconstruct top quarks \(\rightarrow\) combinatorics
- associate b quarks to H_1, H^+ \(\rightarrow\) \( M_{H_1} \) and \( M_{H^+} \)

\( M_{H^+} = 135 \text{ GeV}, \quad M_{H_1} = 54 \text{GeV}, \quad \tan\beta = 4.8 \) (diploma thesis M. Lehmacher, BN)

- estimate of background seems difficults
- coverage of hole area under study!

![Signal and background distributions](image)

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Higgs Physics with ATLAS
Munich, November 29th 2005
Conclusion and Outlook

- **Standard model**: discovery of SM Higgs boson with 15 fb$^{-1}$
  - requires good understanding of whole detector
  - multiple channels with larger luminosity → Higgs profile investigation

- **CP conserving MSSM**: at least one Higgs boson observable
  - only h observable in wedge area at intermediate tanβ
  - maybe Higgs to SUSY or SUSY to Higgs observable?
  - discrimination via Higgs parameter determination seems promising

- **CP violating MSSM**: probably a „hole“ with current MC studies
  - promising MC studies on the way

- **more realistic MC studies**:
  - influence of miscalibrated and misaligned detector
  - improved methods for background estimation from data
  - use of NLO calculations and MCs for signal and background

- **additional extended models + search channels**:
  - CPV MSSM, NMSSM, 2HDM
  - Higgs → SUSY, SUSY→Higgs
  - VBF, H→bb (b-trigger at LV2), VBF,H→inv. (add. forward jet trigger)
Let's wait and work for Higgs boson discovery ....

Thanks for your attention!