MSSM $\phi \rightarrow \tau \tau$

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Agenda

Standard model
- Gauge theories
- Higgs mechanism
- Yukawa coupling

Higgs discovery

Extensions of the SM
- SUSY
- MSSM

Higgs searches $\phi \rightarrow \tau\tau$
- Model independent
- Model dependent (MSSM)
Recap – The Standardmodel

- QED Lagrangian and Gauge Invariance

\[
L_{\text{Dirac}} = \overline{\Psi} \left( i \gamma^\mu \partial_\mu - m \right) \Psi
\]

Invariant under global U(1) transformation

\[
L \to L' = L \quad \checkmark
\]

Demand invariance under local U(1) transformation!

\[
\begin{align*}
\partial_\mu & \to D_\mu = \partial_\mu + iqA_\mu \\
A_\mu & \to A'_\mu = A_\mu - \frac{1}{q} \partial_\mu \Theta(x)
\end{align*}
\]

\[
L_{\text{QED}} = \overline{\Psi} (i \gamma^\mu D_\mu - m) \Psi = \overline{\Psi} (i \gamma^\mu \partial_\mu) \Psi - m \overline{\Psi} \Psi - q(\overline{\Psi} \gamma^\mu \Psi) A_\mu + \frac{1}{4} F_{\mu\nu} F^{\mu\nu}
\]

\[
L \to L' = L \quad \checkmark
\]

Full QED lagrangian
Recap – The Standardmodel

The demand of gauge invariance under local U(1) transformation gives rise to the covariant derivative $D_\mu$ and a new field $A_\mu$ which works as a massless messenger particle between different points in spacetime.

Massless?

- Terms like $m^2 A_\mu A^\mu$ are not gauge invariant
- Euler-Lagrange equation for $A_\mu$ leads to massless Klein-Gordon equation

$$ (\partial_\mu \partial^\mu) A_\mu = 0 $$

$\rightarrow$ Gauge field is a boson with zero mass
Recap – The Standardmodel

- **U(1)** use same procedure to **non-abelian** Lie groups **SU(N)** (generators of the group don't commute)

- **SM**: **SU(3)_C x SU(2)_L x U(1)_Y**

- **SU(3)**: **QCD**
  - 8 massless gluons
  - No need for spontaneous symmetry breaking

- **SU(2) x U(1)**: Electroweak sector
  - Parity violation (weak force couples only to lh particles and rh antiparticles)
  - Massterms of the form $m^2\bar{\psi}\psi / m^2W_\mu W^\mu$ not invariant under symmetry transformations (lh and rh fields transform differently)

**Solution → Yukawa Coupling**

**Solution → Higgs Mechanism**

**SpecialUnitary**

- $G \in SU(N)$
- $G_{fin} = (I + i\frac{\vartheta^a}{m}T^a)^m \to e^{i\vartheta^aT^a}$
- $\vartheta^a$ Continuous parameter
- $T^a$ Generator of the group
- $(N^2 - 1)$ Generators
Higgs Mechanism

- **Sponateous symmetry breaking** + local Gauge theory
  - Groundstate has less symmetries than the corresponding e.o.m
  - Breaking of global symmetries → Goldstone theorem

There is one massless scalar particle (goldstone boson) for every spontaneously broken symmetry
Higgs Mechanism

- e.g. Lagrangian for complex scalar field (global U(1) symmetry)
  \[ L = (\partial_\mu \Phi)^* (\partial^\mu \Phi) - \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 \]

- Groundstate for \( \mu^2 < 0 \) \( \rightarrow \) \( \Phi^* \Phi = -\frac{\mu^2}{2\lambda} \)

- Expand around minima \( |\Phi| = \sqrt{-\frac{\mu^2}{2\lambda}} = v \)

\[ \Phi = v + \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2) \]

\[ \rightarrow L = \frac{1}{2} (\partial_\mu \phi_1)^2 + \frac{1}{2} (\partial_\mu \phi_2)^2 - 2\lambda v^2 \phi_1^2 - \sqrt{2} v \lambda \phi_1 (\phi_1^2 + \phi_2^2) - \frac{\lambda}{4} (\phi_1^2 + \phi_2^2)^2 \]

Interaction terms: \( \phi^4 \phi^3 \)

Massterms: \( m_{\phi_1} = 2v\sqrt{\lambda} \quad m_{\phi_2} = 0 \) (Goldstone Boson)
Higgs mechanism for U(1) gauge theory

\[ L = (D_\mu \phi)^*(D^\mu \phi) - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

- Spontaneous symmetry breaking: expand \( \phi \) around \( v = \sqrt{-\frac{\mu^2}{2\lambda}} \)

\[ \phi(x) = v + \frac{1}{\sqrt{2}} (\varphi_1 + i \varphi_2) = \left( v + \frac{H(x)}{\sqrt{2}} \right) \exp \left( \frac{i \chi(x)}{\sqrt{2}v} \right) \]

- Kinetic term changes to

\[ |D_\mu \phi|^2 = \frac{1}{2} \partial_\mu H \partial^\mu H + e^2 v^2 A'_\mu A'^\mu \left( 1 + \frac{H}{v\sqrt{2}} \right)^2 \quad \text{with} \quad A'_\mu = A_\mu + \frac{\partial_\mu \chi}{\sqrt{2}ve} \]

- Which leads to the lagrangian

\[ L = \frac{1}{2} (\partial_\mu H)(\partial^\mu H) - 2\lambda v^2 H^2 - \lambda \sqrt{2}v H^3 - \frac{\lambda}{v} H^4 - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + e^2 v^2 A'_\mu A'^\mu + e^2 A'_\mu A'^\mu \left( \sqrt{2}v H + \frac{H^2}{2} \right) \]

Massive scalar particle (Higgs)

Massive gauge boson

In this case a massive photon
Higgs Mechanism

- Sponateous symmetry breaking + local Gauge theory
  - Groundstate has less symmetries than the corresponding e.o.m
  - Breaking of global symmetries $\rightarrow$ Goldstone theorem
  - No Goldstone bosons but one more d.o.f (longitudinal polarization) for the gauge fields
  - In SU(2)xU(1) gauge theory W and Z gauge bosons aquire mass
  - Photon stays massless

- This shuffling of d.o.f is the Higgs mechanism
Yukawa coupling

- $m\overline{\Psi}\Psi$ not gauge invariant under $SU(2)_L \times U(1)_Y$ (different charges)
  \[ m\overline{\Psi}\Psi = m(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L) \]
- Idea is to write interaction between $\Psi_L$, $\Psi_R$ and $\phi$ (for simple down type electron case)

\[ L_Y = g\left( \overline{\Psi}_L \phi \, e_R + h.c \right) \]

- $L_Y$ invariant under $SU(2)_L \times U(1)_Y$
- May become a mass term after ssb

\[ \phi = \begin{pmatrix} 0 & \\ v + h & \sqrt{2} \end{pmatrix} \]

Charges w.r.t $U(1)_Y$
- $Y_R = -2$
- $Y_\phi = 1$
- $Y_L = -1$

Lorentz invariant
Gauge invariant
Renormalizable
Dimension 4

\[ \checkmark \]
Yukawa coupling

\[ \phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Rightarrow \]

\[ L_Y = g[(\bar{\nu} \bar{e}_L) \left( \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \right) e_R + h.c] = g(\bar{e}_L \cdot e_R + h.c) \frac{v + h}{\sqrt{2}} \]

\[ = \frac{gv}{\sqrt{2}}(\bar{e}_Le_R + \bar{e}_Re_L) + \frac{gh}{\sqrt{2}}(\bar{e}_Le_R + \bar{e}_Re_L) \]

\[ = m_e(\bar{e}_Le_R + \bar{e}_Re_L) + \frac{m_e}{v} h(\bar{e}_Le_R + \bar{e}_Re_L) \]

\[ L_Y = m_e\bar{e}e + \frac{m_e h\bar{e}e}{v} \]

- Fermion mass
- Higgs fermion interaction \( \sim \frac{m_e}{v} \)

- Quark masses: same procedure but need Higgs doublet with \( Y = -1 \) for down type quarks \( \phi^\dagger \) (later)
SM Lagrangian

\[ L_{SM} = L_F + L_{gauge} + L_\phi + L_Y \]

\[ L_F = \sum_\Psi \overline{\Psi} i \gamma^\mu D_\mu \Psi \quad D_\mu \Psi = (\partial_\mu - ig_s T^a G^a_\mu) - ig^i \frac{\tau^i}{2} W^i_\mu - ig' \frac{1}{2} B_\mu \Psi \]

\[ L_{gauge} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \]

\[ L_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) \]

\[ D_\mu \phi = (\partial_\mu - ig^i \frac{\tau^i}{2} W^i_\mu - ig' \frac{1}{2} B_\mu) \phi \]
Higgs Discovery

P-value:

\[ p = \int_{t_m}^{\infty} g(t | H_0) \, dt \]

Probability to measure values \( t > t_m \) if \( H_0 \) is true

..so there's a chance of less than \( 10^{-6} \)
First LHC run 2010-2012

- It is a boson
- Spin 0 (Landau Yang Theorem)
- Mass at ~125 GeV
- CP even: \( J^P=0^+ \) (very likely)
- BUT: Is it THE SM Higgs Boson or could it be something else?

\[
H \rightarrow \gamma\gamma
\]

\[
H \rightarrow ZZ
\]

\[\text{arXiv:1312.5353} \]

\[\text{arXiv:1407.0558} \]
Problems of the SM

- Higgs mechanism “deus ex machina”
- Gravitation not included
- Dark Matter
- Neutrino masses
- Matter anti-matter asymmetry
- No strong & weak & em unification
- ...

Extensions of the SM - SUSY

- every boson as a fermion as superpartner and vice versa
- Same mass, same quantum numbers (except spin)
- Must be broken (same mass particles not observed)

- Hidden sector and visible sector → what is the messenger?
- R-Parity: LSP possible DM candidate
MSSM

- Same symmetry group, SU(3)xSU(2)xU(1), as SM
- Need second Higgs doublet with Y=-1 for down type quark masses in Yukawa coupling

\[ L_Y = g \overline{\Psi} \Phi \Psi \]  
\[ H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \]  
\[ H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \]

\[ \text{VEV}_1 = v_1, \text{VEV}_2 = v_2 \]

- In SM $H_2^+$ gives rise to down type quark masses. But is not allowed in SUSY.
- 8 d.o.f – 3 (W,Z) → 5 physical states
- 2 CP-even neutral Higgs bosons: H, h
- 1 CP-odd neutral Higgs boson: A
- 2 charged Higgs bosons: $H^+, H^-$
MSSM

- Two free parameters: \( \tan \beta = \frac{v_1}{v_2} \quad m_A \)

\[
\tan \beta = \frac{v_2}{v_1}, \quad v_1^2 + v_2^2 = v^2 = 4 \frac{m_Z^2}{g^2 + g'^2} \approx 246 \text{GeV}
\]

- All MSSM Higgs masses can be expressed through \( \tan \beta = \frac{v_1}{v_2} \quad m_A \)

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

- Other parameters fixed to benchmark scenarios

- **Tree level**: e.g. upper bound on \( m_h \) (light scalar Higgs boson mass)

\[
m_h \leq m_Z \cos 2\beta \quad \text{After radiative corrections:} \quad m_h \approx 135 \text{ GeV}
\]

- e.g. Benchmark scenario \( m_h^{\text{max}} \): allow \( m_h \) to reach 135 GeV

- More benchmark scenarios.. (e.g. \( m_H, m_h \) compatible with SM Higgs mass)
Production and decay

- LHC: Upper mass bound on SM like Higgs ($h$) with higher order corrections
  \[ m_h^2 \approx M_Z^2 \cos^2(2\beta) + \Delta m_h^2 \quad m_h \approx 125\text{GeV} \rightarrow \Delta m_h \approx 85\text{GeV} \rightarrow \text{large } \tan \beta \]

- Gluon fusion dominant at small $\tan \beta$

- Large $\tan \beta (\gg 1) \rightarrow$ stronger Yukawa coupling to down type fermions $\rightarrow$ b-quark associated production dominant


\[
\begin{align*}
(gg\Phi) & \quad \quad (bb\Phi) \\
\begin{tikzpicture}
\begin{scope}[every node/.style={scale=0.7}]
\node[anchor=south east] (1) at (0,0) {$t, \bar{t}$};
\node[anchor=south east] (2) at (1,0) {$b, \bar{b}$};
\node[anchor=south east] (3) at (2,0) {$h, H, A$};
\node[anchor=south east] (4) at (3,0) {$h, H, A$};
\node[anchor=south east] (5) at (4,0) {$b$};
\node[anchor=south east] (6) at (5,0) {$b$};
\node[anchor=south east] (7) at (6,0) {$g$};
\node[anchor=south east] (8) at (7,0) {$g$};
\node[anchor=south east] (9) at (8,0) {$t, \bar{t}$};
\node[anchor=south east] (10) at (9,0) {$b, \bar{b}$};
\node[anchor=south east] (11) at (10,0) {$h, H, A$};
\node[anchor=south east] (12) at (11,0) {$h, H, A$};
\node[anchor=south east] (13) at (12,0) {$b$};
\node[anchor=south east] (14) at (13,0) {$b$};
\node[anchor=south east] (15) at (14,0) {$g$};
\node[anchor=south east] (16) at (15,0) {$g$};
\node[anchor=south east] (17) at (16,0) {$t, \bar{t}$};
\node[anchor=south east] (18) at (17,0) {$b, \bar{b}$};
\node[anchor=south east] (19) at (18,0) {$h, H, A$};
\node[anchor=south east] (20) at (19,0) {$h, H, A$};
\node[anchor=south east] (21) at (20,0) {$b$};
\node[anchor=south east] (22) at (21,0) {$b$};
\node[anchor=south east] (23) at (22,0) {$g$};
\node[anchor=south east] (24) at (23,0) {$g$};
\node[anchor=south east] (25) at (24,0) {$t, \bar{t}$};
\node[anchor=south east] (26) at (25,0) {$b, \bar{b}$};
\node[anchor=south east] (27) at (26,0) {$h, H, A$};
\node[anchor=south east] (28) at (27,0) {$h, H, A$};
\node[anchor=south east] (29) at (28,0) {$b$};
\node[anchor=south east] (30) at (29,0) {$b$};
\node[anchor=south east] (31) at (30,0) {$g$};
\node[anchor=south east] (32) at (31,0) {$g$};
\node[anchor=south east] (33) at (32,0) {$t, \bar{t}$};
\node[anchor=south east] (34) at (33,0) {$b, \bar{b}$};
\node[anchor=south east] (35) at (34,0) {$h, H, A$};
\node[anchor=south east] (36) at (35,0) {$h, H, A$};
\node[anchor=south east] (37) at (36,0) {$b$};
\node[anchor=south east] (38) at (37,0) {$b$};
\end{scope}
\end{tikzpicture}
\end{align*}
\]

- Interesting decay channels (for large $\tan \beta$)

\[
\begin{align*}
H & \rightarrow \tau\tau \\
H & \rightarrow bb
\end{align*}
\]
Experimental setup **Compact MUON Selenoid**

- CMS detector can detect $e, \mu, p, n, \gamma, K, \pi \rightarrow$ no $\tau$

- One needs to reconstruct $\tau$ events from decay products
\( \tau \) decays

- Decays in lighter leptons and hadrons \( m_\tau \approx 1776 \text{ GeV} \)
  \[
  \begin{align*}
  \tau &\rightarrow e + \nu_e + \nu_\tau \\
  \tau &\rightarrow \mu + \nu_\mu + \nu_\tau \\
  \tau^- &\rightarrow \pi^- + \pi^0 + \nu_\tau \\
  \tau^- &\rightarrow \pi^- + \nu_\tau
  \end{align*}
  \]

- Important decay modes for two \( \tau \)-leptons
  \[
  \tau_h \tau_h, \quad \mu \tau_h, \quad e \tau_h, \\
  e\mu, \quad \mu\mu, \quad ee
  \]

- Hadronic decays \( \rightarrow \text{Jets} \)
Searches for $A/H/h \rightarrow \tau\tau$

- Expect two isolated high $p_T$ leptons $(e, \mu, \tau_h)$

  - $\tau$ From Higgs decays should be isolated (not inside jets)

  - Trigger objects

- Reduce backgrounds

- Reconstruct $m_{\tau\tau}$
  - ML technique
  - Distinguish Higgs signal from bkg

- Enhance sensitivity to MSSM Higgs bosons with b-tag associated Higgs production (large $\tan \beta$)
Background

- Largest source of bkg $Z \rightarrow \tau \tau$

  Embedding method

  Take $Z \rightarrow \mu \mu$ from data
  Replace reconstructed $\mu$ by simulated $\tau$ decays
  (lepton universality)

- QCD multijet events:
  - 2J misidentified as $\tau_h$ decays
  - 1J misidentified as $\tau_h$ decay

- $W+$Jets: contributes to $e\tau_h$ and $\mu\tau_h$ channel

- Drell-Yan production of $\mu$ pairs

arXiv:1401.5041
<table>
<thead>
<tr>
<th>Process</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no b-tag</td>
<td>b-tag</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>26838 ± 244</td>
<td>284 ± 8</td>
</tr>
<tr>
<td>QCD</td>
<td>5495 ± 258</td>
<td>131 ± 18</td>
</tr>
<tr>
<td>W+jets</td>
<td>2779 ± 201</td>
<td>55 ± 14</td>
</tr>
<tr>
<td>$Z$+jets (e, $\mu$ or jet faking $\tau$)</td>
<td>716 ± 109</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>82 ± 6</td>
<td>36 ± 5</td>
</tr>
<tr>
<td>Di-bosons + single top</td>
<td>94 ± 11</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Total background</td>
<td>36004 ± 205</td>
<td>530 ± 18</td>
</tr>
<tr>
<td>$A+H+h \rightarrow \tau\tau$</td>
<td>226 ± 23</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>Observed data</td>
<td>36055</td>
<td>542</td>
</tr>
</tbody>
</table>

**Efficiency × acceptance**

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon fusion Higgs</td>
<td>$2.34 \cdot 10^{-2}$</td>
<td>$2.49 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>b-quark associated Higgs</td>
<td>$1.96 \cdot 10^{-2}$</td>
<td>$3.54 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

arXiv:1408.3316
Signal extraction

CMS $h, H, A \rightarrow \tau\tau$ 19.7 fb$^{-1}$ (8 TeV) + 4.9 fb$^{-1}$ (7 TeV)

- $h \rightarrow \tau\tau$
- $H \rightarrow \tau\tau$
- $A \rightarrow \tau\tau$
- $Z \rightarrow \tau\tau$
- $t\bar{t}$
- Electroweak
- QCD
- Bkg. uncertainty

MSSM $m_{\chi}^{\text{max}}$ scenario
$m_{\chi}=160$ GeV, $\tan\beta=8$

**b-tag**

**No b-tag**
Model independent searches

- Search for a narrow $\phi$ resonance

- Test statistic $q$ based on profile likelihood ratio

\[ q_\mu = -2 \ln \frac{L(N_{obs} | \mu \cdot s + b, \hat{\theta}_\mu)}{L(N_{obs} | \hat{\mu} \cdot s + b, \hat{\theta})}, \quad 0 \leq \hat{\mu} \leq \mu \]

- $\hat{\theta}_\mu$ maximizes likelihood in the numerator for given $\mu$

- $\hat{\theta}$ and $\hat{\mu}$ define the point where the likelihood reaches its global maximum

$\rightarrow$ Upper limits on $\sigma \cdot B(\phi \rightarrow \tau\tau)$ for $\sigma(gg\phi)$ and $\sigma(bb\phi)$
Model independent searches 1D

- Treat other production channel as nuisance parameter
Model independent searches 2D

- Likelihood contour plots for SM Higgs mass
- Result compatible with SM Higgs

\[ \sigma(bb\phi) \cdot B(\phi \rightarrow \tau\tau) \text{ [pb]} \]

CMS \( \phi \rightarrow \tau\tau \)

- 95\% CL
- 68\% CL
- Best fit
- Expected for SM H(125 GeV)

arXiv:1408.3316
MSSM model dependent searches

- Modified CL approach (MSSM vs bkg only is not valid anymore)
- Test compatibility of the data to $h$, $H$, $A$ signal compared to SM Higgs signal

\[
M(\mu) = [\mu \cdot s(\text{MSSM}) + (1 - \mu) \cdot s(\text{SM})] + b
\]

Physical model

\[
q_{\text{MSSM/SM}} = -2 \ln \frac{L(N_{\text{obs}} | M(1), \hat{\theta}_{\mu})}{L(N_{\text{obs}} | M(0), \hat{\theta}_0)}
\]

Maximized by finding the Corresponding nuisance parameters for $M(1)$ and $M(0)$

- Expectation for every benchmark scenario is determined at each point of the parameter space $\tan \beta$, $m_A$
MSSM model dependent searches

$\tan \beta$ vs. $m_A$ [GeV]

$CL_s(MSSM,SM)<0.05$

- Observed
- Expected
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

$MSSM m_h^{max}$ scenario

$MSSM m_{h,H,A} \neq 125\pm 3$ GeV

arXiv:1408.3316
Uncertainties

• Experimental uncertainties
  – Integrated Luminosity ~2%
  – Jet energy scale 1-10%
  – Identification and trigger efficiencies ~2%
  – $\mathcal{T}$ Uncertainty ~8%
  – B-tagging 2-7%
  – Mistag for light flavor partons 10-20%

• Theoretical uncertainties
  – $\sigma$ depends on $\tan\beta$, $m_A$ and benchmark scenario
  – up to 20%
Summary

- No BSM physics in run 1
- Run 2?
- No evidenz in run 2 → What will happen to SUSY?
Backup