A short overview on Higgs physics at the LHC and LHeC

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Outline

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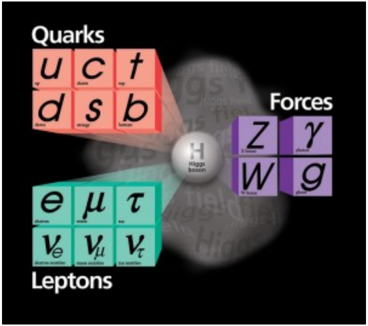
   - Why Do We Need a Higgs Boson?
   - Standard Model
   - Higgs mass constraints
2. Beyond Standard Model: MSSM
3. Collider Aspects
4. Our work:
   - ttH in SM
   - Higgs Bosons in (Next-to-) MSSM
   - Charged Higgs Flavor violating decays in 2HDM-III
5. Summary

Introduction

Fundamental Particles and Forces



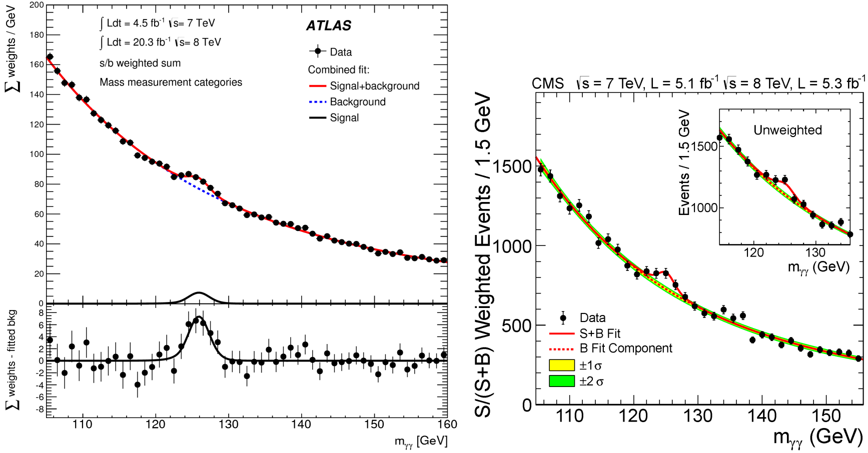
- Matter
  is made out of fermions
- Forces
  are mediated by bosons
- Higgs boson

breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

What we know

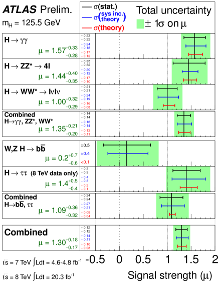
- The photon and gluon appear to be massless
- The W and Z gauge bosons are heavy
- There are 6 quarks
- There appear to be 3 distinct neutrinos with small but non-zero masses
- The pattern of fermions appears to replicate itself 3 times

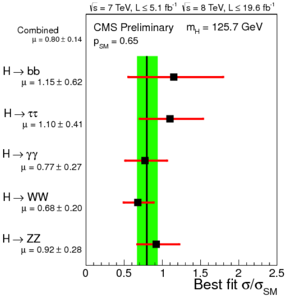
LHC results: 4th July 2012



ATLAS: 125.5 $\pm$ 0.2 (ATLAS-CONF-2013-014)
CMS: 125.3 $\pm$ 0.4 (arXiv:1207.7235)

R: Signal Strength

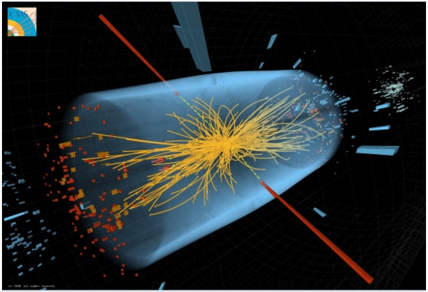


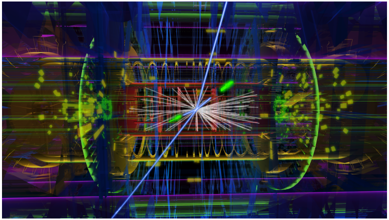


$R(\gamma\gamma)_{\text{ATLAS}} = 1.57 + 0.33 - 0.28$

$R(\gamma\gamma)_{\text{CMS}} = 0.77 \pm 0.27$

What we know





- CMS: Higgs to di-photon
- ATLAS: Higgs to ZZ to $ee\mu\mu$
- Combined significances more than 6σ for each experiments

Why Do We Need a Higgs Boson?

- Why are the W and Z boson masses non-zero?
- $U(1)$ gauge theory with single spin-1 gauge field, A_μ
  $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
  $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$
- $U(1)$ gauge transformation: $A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$
- Mass term for A would look like:
  $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$
- Mass term violates local gauge invariance

Gauge invariance is the guiding principle

Abelian Higgs Model

- Add complex scalar field ϕ with charge $-e$:
  $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$
- where $D_\mu = \partial_\mu - ieA_\mu$; $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$
- $V(\phi) = \mu^2 \mid \phi \mid^2 + \lambda(\mid \phi \mid^2)^2$
- $U(1)$ transformations:
  $A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$
  $\phi(x) \to e^{-ie\eta(x)}\,\phi(x)$

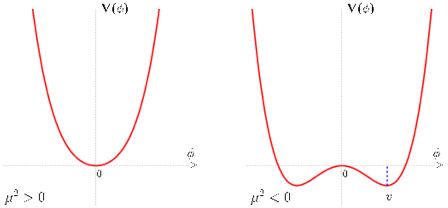
L is Gauge invariant

Abelian Higgs Model contd.

$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$
$D_\mu = \partial_\mu - ieA_\mu;$
$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \mu^2 \mid \phi \mid^2 + \lambda(\mid \phi \mid^2)^2$

By convention: $\lambda > 0$

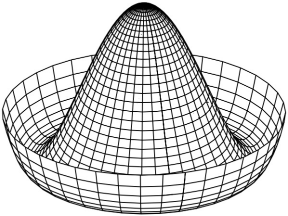
Case 1: $\mu^2 > 0$
QED with M_A=0 and $m_\phi = \mu$
Unique minimum at ϕ=0
Case 2: $\mu^2 < 0$
Minimum energy state at:
$\langle\phi^0\rangle = \sqrt{-\frac{\mu^2}{2\lambda}} = v/\sqrt{2}$



Vacuum breaks $U(1)$ symmetry

Aside: What fixes sign (μ^2)?

Mexican hat potential



Abelian Higgs Model

$$\phi(x) = \frac{e^{i\frac{\chi(x)}{v}}}{\sqrt{2}}(v + H(x)) \quad \overset{U(1)}{\longrightarrow} \quad \frac{1}{\sqrt{2}}(v + H(x)) \ , \tag{1}$$

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2 v^2}{2} A^\mu A_\mu + \frac{1}{2}\left(\partial^\mu H \partial_\mu H + 2\mu^2 H^2\right) + \ldots \tag{2}$$

$$m_A^2 = g^2 v^2$$
$$m_H^2 = -2\mu^2 = 2\lambda v^2$$

Massive Gauge boson!

Standard Model(SM)

- 1961 – Glashow, Salam and Weinberg proposed Electro-weak theory of weak left-handed isospin, $SU(2)_L$, and hypercharge $U(1)_Y$.
- 1964 – Gellman, 1973 – Gross, Politzer and Wilczek proposed theory of Strong interaction based on $SU(3)_C$
- SM: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Gauge couplings: g_s, g, $g^{'}$
- 1964–1967 $\rightarrow$ Complex $SU(2)$ Higgs doublet: ϕ
  1. P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508; ibid. Phys. Rev. 145 (1966) 1156;
  2. F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321;
  3. G.S. Guralnik, C.R. Hagen and T. Kibble, Phys. Rev. Lett. 13 (1965) 585;
  4. T. Kibble, Phys. Rev. 155 (1967) 1554.

Standard Model contd.

SM field	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
Q	3	2	$\frac{1}{6}$	(u_L, d_L)
U^c	$\overline{3}$	1	$-\frac{2}{3}$	$\overline{u}_R$
D^c	$\overline{3}$	1	$\frac{1}{3}$	$\overline{d}_R$
L	1	2	$-\frac{1}{2}$	(ν_L, e_L)
E^c	1	1	1	$\overline{e}_R$
H_1	1	2	$-\frac{1}{2}$	$(\phi^+ \phi^0)$
G^a	8	1	0	G^μ
W^i	1	3	0	W_i^μ
B	1	1	0	B^μ

Standard Model contd.

- SM includes complex Higgs $SU(2)$ doublet
  $\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$,
- $\mathcal{L}_\phi = (D^\mu \phi)^\dagger D_\mu \phi - V(\phi)$ where
  $V(\phi) = \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$
  $D_\mu \phi = (\partial_\mu - igA_\mu^a \tau^a - ig' Y_\phi B_\mu)$, $[\tau^a = \sigma^a/2]$
- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at:
  $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

Choice of minimum breaks gauge symmetry

More on SM Higgs Mechanism

$$(D^\mu\phi)^\dagger D_\mu\phi \longrightarrow \cdots + \frac{1}{8}(0\ \ v)\left(gA^a_\mu\sigma^a + g'B_\mu\right)\left(gA^{b\mu}\sigma^b + g'B^\mu\right)\begin{pmatrix}0\\ v\end{pmatrix} +$$

$$\cdots \longrightarrow \cdots + \frac{1}{2}\frac{v^2}{4}\left[g^2(A^1_\mu)^2 + g^2(A^2_\mu)^2 + (-gA^3_\mu + g'B_\mu)^2\right] + \cdots$$

$$W^\pm_\mu = \frac{1}{\sqrt{2}}(A^1_\mu \pm A^2_\mu) \quad \longrightarrow \quad M_W = g\frac{v}{2}$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gA^3_\mu - g'B_\mu) \quad \longrightarrow \quad M_Z = \sqrt{g^2+g'^2}\frac{v}{2}$$

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'A^3_\mu + gB_\mu) \quad \longrightarrow \quad M_A = 0$$

Masses vanish when $v = 0$

$$\phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}}\begin{pmatrix}0\\ v+H(x)\end{pmatrix} \overset{SU(2)}{\longrightarrow} \phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H(x)\end{pmatrix}\,, \tag{3}$$

$$\mathcal{L}_\phi = \mu^2 H^2 - \lambda v H^3 - \frac{1}{4}H^4 = -\frac{1}{2}M_H^2 H^2 - \sqrt{\frac{\lambda}{2}}M_H H^3 - \frac{1}{4}\lambda H^4\ . \tag{4}$$

χ=3 d.o.f $\rightarrow$ $W^\pm$ and Z

$m_H^2 = -2\mu^2 = 2\lambda v^2$

Recap of SM Higgs Mechanism

- Generate mass for W,Z using Higgs mechanism
  –Higgs VEV breaks $SU(2) \times U(1)$
  –Single Higgs doublet is **minimal** case
- Before spontaneous symmetry breaking:
  –Massless W_i, B, Complex ϕ
- After spontaneous symmetry breaking:
  –Massive $W^{\pm}$,Z, massless γ, physical Higgs boson h

Easy to add more scalars

Higgs coupling with Gauge Bosons:

$$\mathcal{L} = gM_W W^{+\mu} W^-_\mu h + \frac{gM_Z}{cos\theta_W} Z^\mu Z_\mu h$$

Yukawa coupling: Fermion mass

- In SM, like other particle fermion is also massless.
- However, electron has mass (0.5 MeV).
- If add: m$\bar{\psi}_R \psi_L$ + m$\bar{\psi}_L \psi_R \rightarrow$ Gauge Symmetry (in particular isospin) is explicitly broken.
- Question: Fermion masses without violating gauge invariance?

$$\mathcal{L}_{Yukawa} = -\Gamma_u^{ij} \bar{Q}_L^i \phi^c u_R^j - \Gamma_d^{ij} \bar{Q}_L^i \phi d_R^j - \Gamma_e^{ij} \bar{L}_L^i \phi l_R^j + h.c. \quad (5)$$

where $\phi^c = -i\sigma^2 \phi^\star$

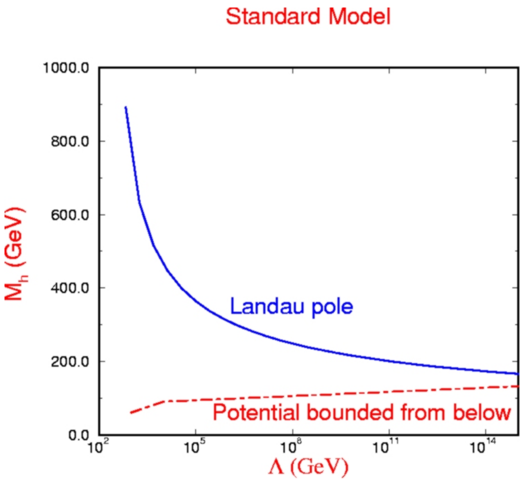
$$m_f = \Gamma_f \frac{v}{\sqrt{2}} \quad (6)$$

where $f = u, d, l$

Final form of Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi \quad \text{[Gauge-sector]}$$
$$+ \psi_i\lambda_{ij}\psi_j + h.c. \quad \text{[Flavour sector]}$$
$$+ |D_\mu\phi|^2 - V(\phi) \quad \text{[EWSB sector]}$$
$$+ \frac{1}{M} L_i\lambda^{\nu}_{ij}L_j h^2 \text{or} L_i\lambda^{\nu}_{ij}N_j \quad [\nu \text{ mass sector}]$$

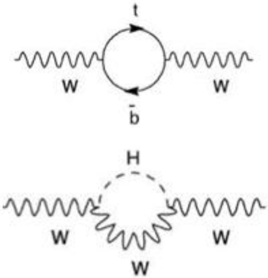
Now History: Unitarity, Triviality and Perturbativity

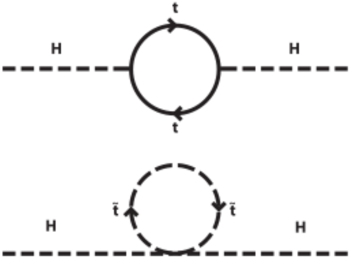


→ if there is no new physics beyond that of the SM before Planck scale:

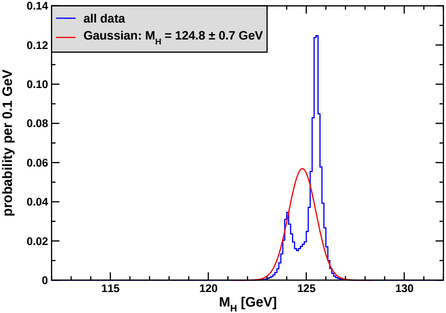
$$130 \text{ GeV} < M_h < 170 \text{ GeV}$$

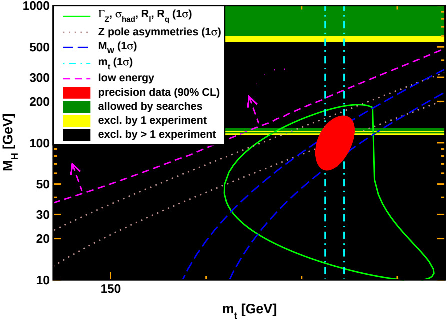
SM loop correction: m_W and m_H





EW precision data and LEP2 limit (plus Tevatron)





→ Global EW fit $m_H = 102^{+24}_{-20}$ GeV (w/o Collider data)

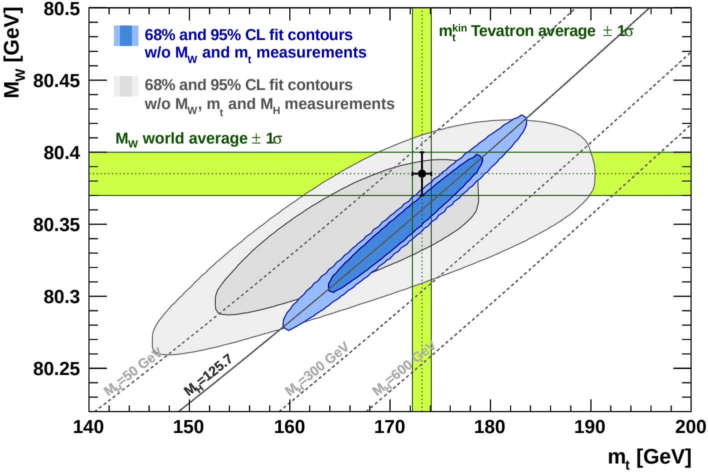
→ Tevatron and LHC:m_t=173.2±1.0 GeV

→ m_t=169.6±3.5 GeV(pole mass) gives $m_H = 81^{+32}_{-24}$ GeV

→ LEP2 direct searches (114.4 GeV) : $<$ 185 GeV (95% C.L.)

Tevatron: 90% preferred range (95% C.L. lower and upper) 115 $\lesssim m_H \lesssim$ 148 GeV

M_W vs m_t

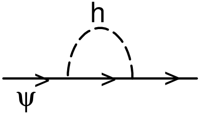


GFitter Group

Observation of m_H=125 GeV in agreement with global fits is triumph for SM... consistent theory!

Quadratic Divergences

$$\mathcal{L}_\phi = \overline{\psi}(i\gamma^\mu\partial_\mu)\psi + \mid \partial_\mu\phi \mid^2 - m_S^2 \mid \phi \mid^2 - \left(\frac{\lambda_F}{2}\overline{\psi}\psi\phi + \text{h.c.}\right) \quad . \qquad (7)$$



$$-i\Sigma_F(p) = \left(\frac{-i\lambda_F}{\sqrt{2}}\right)^2 (i)^2 \int \frac{d^4k}{(2\pi)^4} \frac{(k+m_F)}{[k^2-m_F^2][(k-p)^2-m_S^2]} \quad . \qquad (8)$$

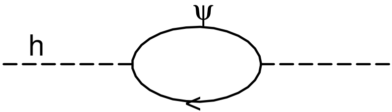
The renormalized fermion mass is $m_F^r = m_F + \delta m_F$, with $\delta m_F = \Sigma_F(p) \mid_{p=m_F}$

= i $\lambda_F^2/32\pi^4 \int_0^1 dx \int d^4k' \frac{m_F(1+x)}{[k'^2-m_F^2x^2-m_S^2(1-x)]^2}$.

$\delta m_F = -\frac{\lambda_F^2 m_F}{32\pi^2} \int_0^1 dx(1+x) \int_0^{\Lambda^2} \frac{ydy}{[y+m_F^2x^2+m_S^2(1-x)]^2}$

= -3 $(\lambda_F^2 m_F/64\pi^2) \log\left(\frac{\Lambda^2}{m_F^2}\right) + ...$

Quadratic Divergences



$$-i\Sigma_S(p^2) = \left(\frac{-i\lambda_F}{\sqrt{2}}\right)^2 (i)^2(-1)\int \frac{d^4k}{(2\pi)^4}\frac{Tr[(k+m_F)((k-p)+m_F)]}{(k^2-m_F^2)[(k-p)^2-m_F^2]} \quad . \tag{9}$$

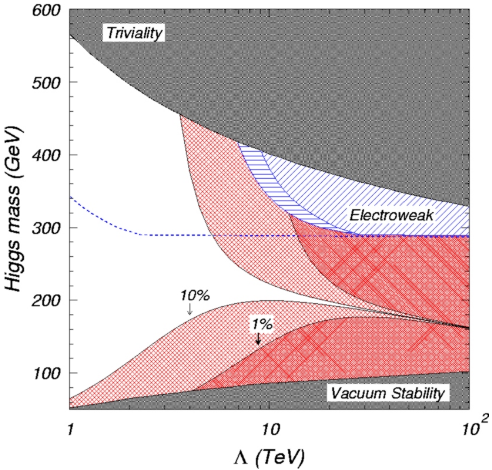
$$(\delta M_h^2)_a = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 + (m_S^2 - 6m_F^2)\log\left(\frac{\Lambda}{m_F}\right)\right.$$
$$\left. + (2\mathrm{m}_F^2 - \frac{m_S^2}{2})\left(1 + I_1\left(\frac{m_S^2}{m_F^2}\right)\right)\right] + \mathcal{O}\left(\frac{1}{\Lambda^2}\right),$$

So, we have

$$M_h^2 = M_{h,0}^2 + \delta M_h^2 + \text{counterterm}, \tag{10}$$

To get the correct Higgs mass the counterterm must be adjusted!

Hierarchy problem



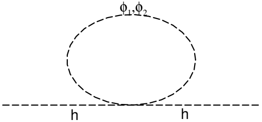
For example: 125 GeV Higgs at 2(10) TeV reqd. 10(1)% fine-tunning.

large Λ more fine-tunning, $1/10^{15}$ at M_{Pl}

[Kolda and Murayama, hep-ph/0003170]

Solving the Hierarchy problem

$$L= \mid \partial_\mu \phi_1 \mid^2 + \mid \partial_\mu \phi_2 \mid^2 - m_{s_1}^2 \mid \phi_1 \mid^2 - m_{s_2}^2 \mid \phi_2 \mid^2$$
$$+\lambda_S \mid \phi \mid^2 \left(\mid \phi_1 \mid^2 + \mid \phi_1 \mid^2 \right) + \mathcal{L}_\phi \quad .$$



$$(\delta M_h^2)_b = -\lambda_S \int \frac{d^4k}{(2\pi)^4} \left[\frac{i}{k^2 - m_{s_1}^2} + \frac{i}{k^2 - m_{s_2}^2} \right]$$
$$= (\lambda_S/16\pi^2) \left\{ 2\Lambda^2 - 2m_{s_1}^2 \log\left(\frac{\Lambda}{m_{s_1}}\right) - 2m_{s_2}^2 \log\left(\frac{\Lambda}{m_{s_2}}\right) \right\}$$
$$+O\left(\frac{1}{\Lambda^2}\right).$$

Solving the Hierarchy problem contd.

$$(\delta M_h^2)_a = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 + (m_S^2 - 6m_F^2)\log\left(\frac{\Lambda}{m_F}\right)\right.$$

$$\left.+ (2m_F^2 - \frac{m_S^2}{2})\left(1 + I_1\left(\frac{m_S^2}{m_F^2}\right)\right)\right] + \mathcal{O}\left(\frac{1}{\Lambda^2}\right),$$

$$(\delta M_h^2)_b = -\lambda_S \int \frac{d^4k}{(2\pi)^4}\left[\frac{i}{k^2 - m_{s_1}^2} + \frac{i}{k^2 - m_{s_2}^2}\right]$$

$$= (\lambda_S/16\pi^2)\left\{2\Lambda^2 - 2m_{s_1}^2 \log\left(\frac{\Lambda}{m_{s_1}}\right) - 2m_{s_2}^2 \log\left(\frac{\Lambda}{m_{s_2}}\right)\right\}$$

$$+O\left(\frac{1}{\Lambda^2}\right).$$

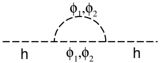
Thus, if

$$\lambda_S = \lambda_F^2$$

The Quadratic divergences cancells!

- independent of the masses, m_F and m_{s_i}
- magnitude of λ_S and λ_F^2
- also need two Higgses (for anomaly cancellation)

One more thing for completeness: after SSB



$$(\delta M_h^2)_c = \frac{\lambda_S^2 v^2}{16\pi^2}\left\{-1+2\log\left(\frac{\Lambda}{m_{s_1}}\right)-I_1\left(\frac{M_h^2}{m_{s_1}^2}\right)\right\}+(m_{s_1}\to m_{s_2})+\mathcal{O}\left(\frac{1}{\Lambda^2}\right). \quad (11)$$

Combing the three contributions:
If $\Lambda_S = \Lambda_F^2$ and $m_{s_1} = m_{s_2}$,

$$(\delta M_h^2)_{tot} = \frac{\lambda_F^2}{4\pi^2}\left\{m_{s_1}^2 \log\left(\frac{\Lambda}{m_{s_1}}\right) - m_F^2 \log\left(\frac{\Lambda}{m_F}\right)\right\} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right). \quad (12)$$

As long as the mass splitting between the fermion and scalarïs small, $\delta m^2 \equiv m_F^2 - m_{s_1}^2$,

$$(\delta M_h^2)_{tot} = \frac{\lambda_F^2}{4\pi^2}\delta^2 \quad . \quad (13)$$

Supersymmetry: Cancels the divergences in all order!

L= $-\partial_\mu S^* \partial^\mu S - i\bar{\zeta}\bar{\sigma}^\mu \partial_\mu \zeta - \frac{1}{2}m(\zeta\zeta + \overline{\zeta\zeta}) - cS\zeta\zeta - c^* S^* \overline{\zeta\zeta} - \mid mS + cS^2 \mid^2$

Chiral Superfiled:

$$\Phi(x) = S(x) + \sqrt{2}\theta\zeta(x) + \theta\theta F(x)$$

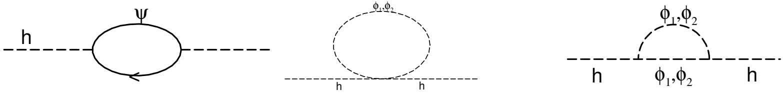
$$V(S, S^*) = \mid mS + cS^2 \mid^2$$

$c^2 = \lambda_S$ **and** $c = \lambda_F$

$$\lambda_S = \lambda_F^2$$

Beyond SM: Supersymmetry

- WW scattering: Higgs Mass $<$ TeV
- What is the problem then?
  1. Why $\mu^2 < 0$ in SM?
  2. Radiative corrections leads Higgs mass [wants close to the largest mass scale] diverges. Counterterm must be adjusted 1 part in 10^{15} at each order [**Hierarchy problem**]
- Supersymmetry:
  1. $m^2_{H_u}$ running (REWSB)
  2. fermion and boson into a Superfields (m_F and m_{s_i}; λ_S,λ_F) cancel the quadratic growth (each order) and independent of masses and couplings



$$(\delta M_h^2)_{tot} = \frac{\lambda_F^2}{4\pi^2}(m_F^2 - m_{s_1}^2) \quad (14)$$

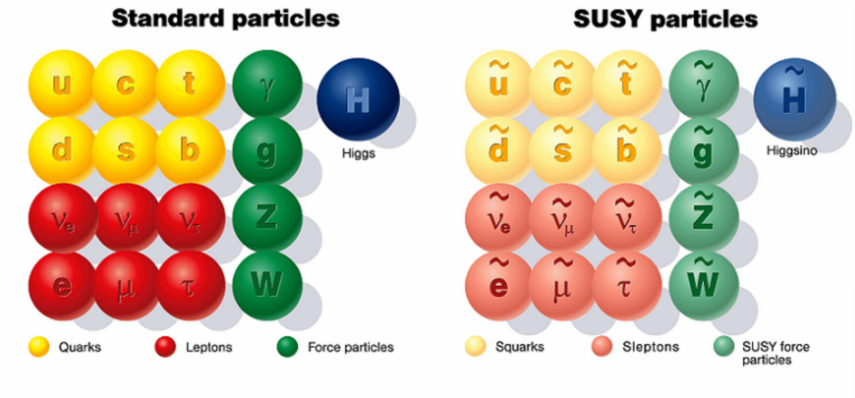
Mass difference "small", no unnatural cancellations required and theory is "natural".

[Drees, hep-ph/9611409; Martin,hep-ph/9709356, Dawson, hep-ph/9712464]

MSSM particle content

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{Q}$	3	2	$\frac{1}{6}$	$(u_L, d_L), (\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{2}{3}$	$\overline{u}_R, \tilde{u}_R^*$
$\hat{D}^c$	$\overline{3}$	1	$\frac{1}{3}$	$\overline{d}_R, \tilde{d}_R^*$
$\hat{L}$	1	2	$-\frac{1}{2}$	$(\nu_L, e_L), (\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	1	$\overline{e}_R, \tilde{e}_R^*$
$\hat{H}_1$	1	2	$-\frac{1}{2}$	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	$\frac{1}{2}$	$(H_2, \tilde{h}_2)$
$\hat{G}^a$	8	1	0	$G^\mu, \tilde{g}$
$\hat{W}^i$	1	3	0	$W_i^\mu, \tilde{\omega}_i$
$\hat{B}$	1	1	0	$B^\mu, \tilde{b}$

SM and Supersymmetric Particle Content



→ The particle contents are doubled.
→ Same Gauge Quantum Number Partcicles are mixed, e.g.,Wino,Bino,Higgsinos

→ Large number of free parameters($\sim$ 100) compare to SM(18) [constrained model, e.g., mSUGRA 5 parameters].

CP-conserving Higgs sector

The Higgs sector of the MSSM consists of two doublets:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} ; \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} . \tag{15}$$

$$H_1^0 = \frac{1}{\sqrt{2}}(\phi_1 - ia_1) , \quad H_2^0 = \frac{1}{\sqrt{2}}(\phi_2 + ia_2) \tag{16}$$

- After EWSB , $\langle\phi_1\rangle = v\cos\beta$ and $\langle\phi_2\rangle = v\sin\beta$
- 1 charged and 3 neutral(2 CP-even and 1 CP-odd)
- CP-odd state, $A = -a_1 \sin\beta + a_2\cos\beta$,
- 2 CP-even , h and H mixes, α:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_2 \\ \phi_1 \end{pmatrix} . \tag{17}$$

MSSM Higgs Potential

$$V_H = \left(|\mu|^2 + m_1^2 \right) |H_1|^2 + \left(|\mu|^2 + m_2^2 \right) |H_2|^2 - \mu B \epsilon_{ij} \left(H_1^i H_2^j + \mathrm{h.c.} \right)$$
$$+ \frac{(g^2 + g'^2)}{8} \left(|H_1|^2 - |H_2|^2 \right)^2 + \frac{1}{2} g^2 |H_1^* H_2|^2$$

$\rightarrow$ 3 independent parameters: $|\mu|^2 + m_1^2$, $|\mu|^2 + m_2^2$ and μB
$\rightarrow$ must be non-zero for EWSB to take place
$\rightarrow$ quartic couplings are not free and fixed from gauge couplings
$\rightarrow$ CP-conserving, as any phase in μB can be absorbed in Higgs fields.

$$M_W^2 = \frac{g^2}{2} (v_1^2 + v_2^2) \tag{18}$$

$$\tan \beta \equiv \frac{v_2}{v_1} \tag{19}$$

tree-level $\tan \beta$ **and** μB

Higgs boson Masses

Scalars:

$$M_{h,H}^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 \mp \left((M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta\right)^{1/2}\right\} \quad (20)$$

Pseudoscalar:

$$M_A^2 = \frac{2 \mid \mu B \mid}{\sin 2\beta}, \quad (21)$$

Charged scalar:

$$M_{H^\pm}^2 = M_W^2 + M_A^2 \quad (22)$$

$\rightarrow$ $\tan\beta$ and M_A are inputs and at tree level:

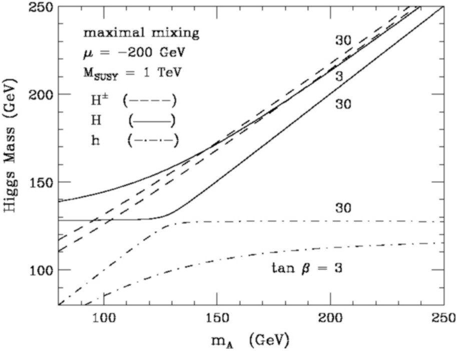
$$M_{H^\pm} > M_W$$
$$M_H > M_Z$$
$$M_h < M_A$$
$$M_h < M_Z \mid \cos 2\beta \mid < M_Z$$

The lightest neutral Higgs boson must be observable at LEP(but not!)

Higgs boson Masses contd.

Loop corrections (top and scalar-top, always +ve) [monotonically increasing with M_A]

$$M_h^2 < M_Z^2 \cos^2 2\beta + \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\frac{\tilde{M}^2}{M_T^2}\right) \quad (23)$$



→ $tan\beta$ fixed: max. m_h for $m_A >> m_Z$
→ 122 GeV (min. mix.) < m_h-max < 135 GeV (max. mix.)

MSSM predicts $m_h < 135$ GeV

Higgs couplings in MSSM

- $g_{hVV} = g_V M_V \sin(\beta - \alpha) g^{\mu\nu}$, $g_{HVV} = g_V M_V \cos(\beta - \alpha) g^{\mu\nu}$
  [$g_V = \frac{2M_V}{v}$]
- $m_\gamma = 0 \Rightarrow$ $\gamma\gamma H_i$**=0** , $\gamma Z^0 H_i$**=0** at tree-level (at loop level non-zero!)
- Decoupling limit: $M_h \simeq M_h^{max}$, while $M_H \simeq M_{H^\pm} \simeq M_A \gg M_Z$
  $\cos(\beta - \alpha) \to 0 \Rightarrow \sin(\beta - \alpha) \to 1$
  the couplings of h^0 to the gauge bosons tend to the SM like.

The **lightest CP-even MSSM Higgs boson** will be hardly distinguishable from the SM Higgs boson

This is true for any extension of SM

Collider Physics in brief
(relevant for this discussion)
Han,hep-ph/0508097
Perelstein,arXiv:1002.0274[hep-ph]

LHC Experiments

- ALICE : A Large Ion Collider Experiment
- ATLAS :A-Toroidal-LHC-Apparatus
- CMS :The Compact Muon Solenoid
- LHCb :Large Hadron Collider beauty Experiment
- LHCf :measurement of forward neutral particle production for cosmic ray research
- MoEDAL:Monopole and Exotics Detector at the LHC
- TOTEM :Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC

Collison variables

$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). \end{cases}$$

$$E_{CM} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \mathbf{p}_2 = 0. \end{cases}$$

KE fixed-target frame ($\vec{p}_2 = 0$) $T \approx E_1$
KE c.m. frame ($\vec{p}_1 + \vec{p}_2 = 0.$) $T = 0$

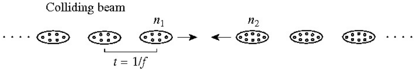
Beam energies maximally converted to reach a higher threshold
Designing principle: LEP and LHC at CERN and Tevatron at FNAL

Energy loss per revolution:

$$\Delta E \propto \frac{1}{R} \left(\frac{E}{m} \right)^4 \quad (24)$$

more efficient larger radius and/or more massive particle

Collider Parameters



Luminosity:

$$\mathcal{L} \propto f n_1 n_2 / a \tag{25}$$

cm^{-2} s^{-1}, *f* beam crossing freq.; *a* transverse profile of the beams
The reaction rate, i.e., number of events per unit time:

$$R(s) = \sigma(s)\mathcal{L}, \tag{26}$$

$$\sigma \sim \frac{1}{E_{\rm cm}^2}\ . \tag{27}$$

Larger the energies of the colliders must also have higher luminosity

Colliders	$\sqrt{s}$ (GeV) (GeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (kHz)	#/bunch (10^{10})	L (km)
LEP II	~ 210	10^{32}	$\sim 0.1\%$	45		26.7
Tevatron	1960	2.1×10^{32}	9×10^{-5}	2500	p: 27, $\bar{p}$: 7.5	6.28
LHC	14000	10^{34}	0.01%	40000	10.5	26.66

Luminosity

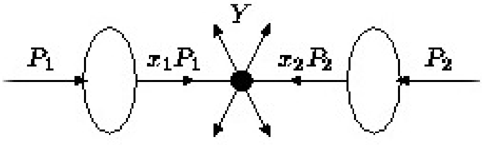
Rate of physics processes directly related:

$$N_{obs} = \int L dt . \epsilon . \sigma$$

ϵ: Optimized by experimentalist
σ: Cross-section using Feynman diagram

Ability to observe something depends on N_{obs}

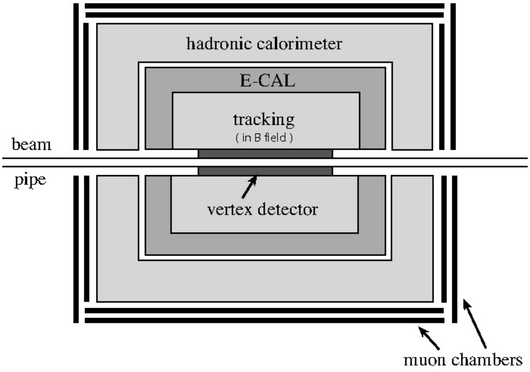
Hadron Collider: Hard scattering of partons



$$\sigma(AB \to Y\,X) = \sum_{a,b} \int dx_1 dx_2\; P_{a/A}(x_1, Q^2) P_{b/B}(x_2, Q^2)\; \hat{\sigma}(ab \to Y), \qquad (28)$$

- P_1, P_2: Proton beams
- X: inclusive scattering remnant
- Q^2: factorization scale (momentum transfer) $>> \Lambda^2_{QCD} \approx (200\ \mathrm{MeV})^2$
- $\hat{\sigma}(ab \to Y)$: Perturbation theory
- $P_{a/A}(x_1, Q^2)$: Non-perturbation, data fitting [e.g.,Tevatron($p\bar{p}$),HERA(ep)]

Detector

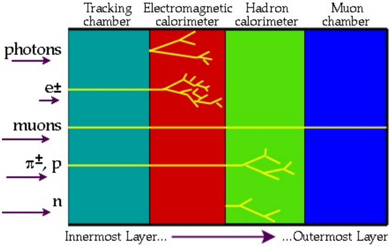


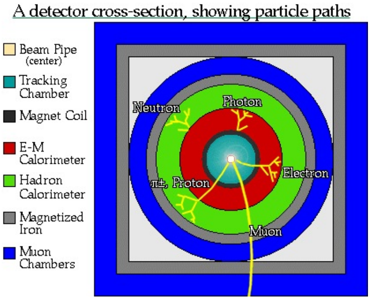
Z, W, t prompt decay lepton, quarks: $1/\Gamma \sim 1/(2\ \mathrm{GeV}) \approx 3.3 \times 10^{-25}$s
Other quarks fragment into hadrons: $t_h \sim 1/\Lambda_{QCD} \approx 1/(200\ \mathrm{MeV}) \approx 3.3 \times 10^{-24}$s
Quasi-stable: fast-moving $\tau > 10^{-10}$ s, e.g., n, Λ, K_L^0, $\ldots$ $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$,Ω
Short-lived resonances: π^0, $\rho^{0,\pm}$... and Z, $W^{\pm}$, t, $(H\ldots)$ (decay prompt)
Displaced vertex: $\tau \sim 10^{-12}$ **s** $B^{0,\pm}$, $D^{0,\pm}$, $\tau^{\pm}$,, **travel approx.** $c\tau \sim 100\ \mu$**m.**

Things not "seen": no em and strong interaction , e.g., ν, $\tilde{\chi}^0$ in SUSY $\rightarrow \not{E}_T$

Cross and End view

Detector designed to separate electrons, photons, muons, neutral and charged hadrons



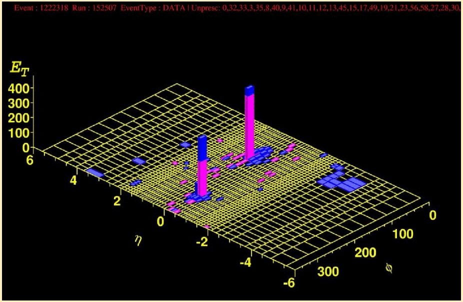


Most often, electromagnet and hadronic calorimeters provide the energy measurements for (essentially) massless particles, e.g., $e^{\pm}$, γ, and light quark(q) or gluon(g)jets

Kinematic Constraints and Variables

- Transverse momentum, **p_T= p sinθ**:
  Particles that escape detection if ($\theta < 3^\circ$) have $p_T \approx 0$
  Visible transverse momentum conserved $\sum p_T = 0$ for all particles
  Very useful variables
- Polar angle θ: not Lorentz invariant
  Rapidity: y and Pseudorapidity: η
  $y = \frac{1}{2} ln \frac{E+p_z}{E-p_z}$
  For m=0, $y = \eta = -ln(tan\frac{\theta}{2})$

Independent variables to describe events



Separation between two objects (di-jet at CDF):

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \qquad (29)$$

Isolation (resolving) criterion: **Invariant under longitudinal boosts**

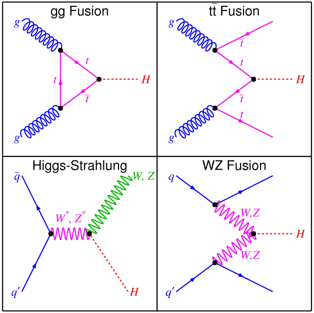
p_T, η and ϕ: are independent variables that describe an event

How to make a Discovery:

Lot's of complicated statistical tools used by experimentalists
But the ideas in a nutshell:

- Need to show that we have a signal that is inconsistent with being background
  Number of observed data events: N_{Data}
  Number of estimated background: N_{Bg}
  Excess: N_{Data} - N_{Bg}
- Need number of observed data events to be inconsistent with background fluctuation: $\sqrt{N_{Bg}}$
- **Significance: S/$\sqrt{B}$=(N_{Data} - N_{Bg})/$\sqrt{N_{Bg}}$**
  Require typically 5σ, corresponds to probability of statistical fluctuation of 5.7×10^{-7}
  Increases with increasing luminosity: S/$\sqrt{B} \approx \sqrt{L}$

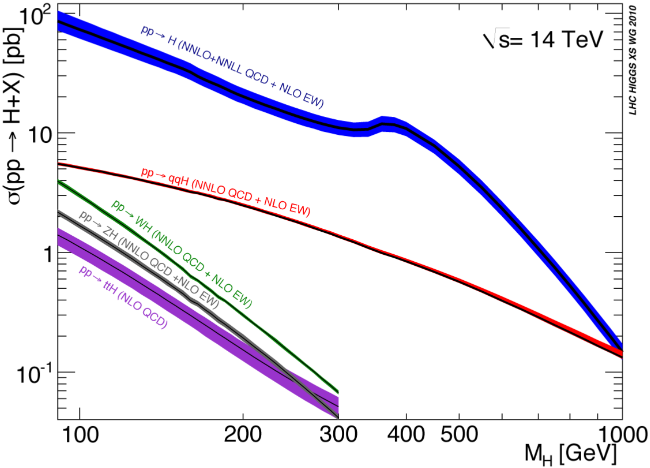
Higgs production at Hadron Colliders



- gluon-gluon fusion (gluon PDF as well as large top Yukawa; **New physics in loop**)
- Higgs-strahlung (WH/ZH: **vanishes if v=0 fundamental test of EWSB**)
- Vector Boson Fusion (t-channel: **vanishes if v=0 fundamental test of EWSB**)
- Associated Production($t\bar{t}H$:**Direct measurement of top-Yukawa**)

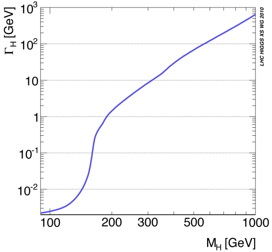
gluon-gluon > VBF > Higgs-strahlung >ttH

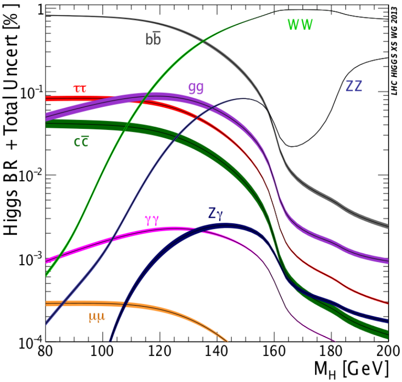
Higgs cross-section at Hadron Colliders



For m_H=125 GeV LHC@14 TeV: $t\bar{t}H \approx$ 0.4pb

Higgs Decay width and Branching





For m_H=125.6 GeV: Γ= 4.21 MeV;

$\tau = 6.58 \times 10^{-16} eV.s/\Gamma = 1.6 \times 10^{-22} s$

$H \rightarrow b\bar{b}$ = 56.0 %[recall: large Yukawa couplings; top threshold closed]

$H \rightarrow \tau\bar{\tau}$=6.0%

$H \rightarrow WW$=23.0%

$H \rightarrow ZZ$=3.0%

$H \rightarrow gg$=8.0% (top triangle loop)

$H \rightarrow \gamma\gamma$=2.0 $\times$ 10^{-3} % (W and top triangle loop)

ttH at LHC

in collaboration with

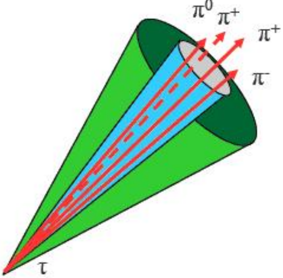
Pankaj Agrawal, Somnath Bandyopadhyay and SPD arXiv: 1308.3043, PRD 88(093008)2013
Pankaj Agrawal, Somnath Bandyopadhyay and SPD arXiv: 1308.6511, PRD submitted
Pankaj Agrawal and SPD work in progress

τ-decays

Higgs[125-130 GeV]:
$\tau\bar{\tau}$=5-7%;WW=14-30%;$b\bar{b}$=80-60%

τ decay modes:

- Leptonic decay modes:(35%)
  $\tau \rightarrow \nu_\tau \nu_e e$(17.4%)
  $\tau \rightarrow \nu_\tau \nu_\mu \mu$(17.4%)
- Hadronic decay modes:
  1-prong decays:(50%)
  $\tau \rightarrow \nu_\tau \pi^\pm$ (11.0%)
  $\tau \rightarrow \nu_\tau \pi^0 \pi^\pm$ (25.4%)
  $\tau \rightarrow \nu_\tau \pi^0 \pi^0 \pi^\pm$ (10.8%)
  $\tau \rightarrow \nu_\tau \pi^0 \pi^0 \pi^0 \pi^\pm$ (1.4%)
  $\tau \rightarrow \nu_\tau K^\pm \pi^0$ (1.6%)
  3-prong decays:(15%)
  $\tau \rightarrow \nu_\tau \pi^\pm \pi^\pm \pi^\pm \pi^0$ (15.2%)



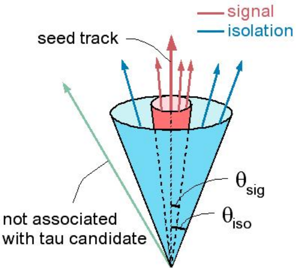
τ-jets

Tau-lepton:cτ=90 μm, life-time: 2.9 $\times 10^{-3}$s m_τ=1.78 GeV
Leptonically decaying Tau-lepton is indistinguishable from prompt lepton (due to small life-time)
Because of its light mass compared to the collider energy scale, produced tau is highly boosted and its decay products are collimated.

tau jets(hadronic decay) at LHC:

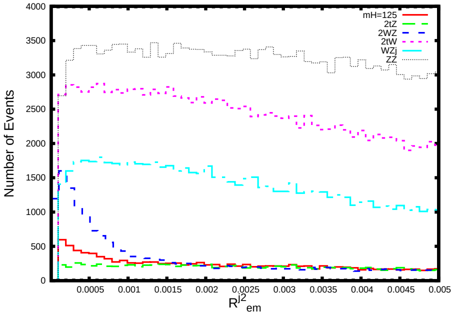
- very collimated: 90% of the energy is contained within code radius R=0.2 around the jet-direction (for ET>50 GeV)
- Low multiplicity: One, three prongs
- Hadronic, large amount of EM energy deposition: Charged pions, Photons from π^0

For such candidates a set of topological variables is computed:
Mass of calorimetric clusters
Mass of associated tracks
Track radius : pT of tracks weighted by its distance to tau candidate axis



Electro-Magentic Area: How “wide” is the energy deposition?

$$R^{j^2}_{em} = \sum_\alpha p_{T,\alpha}\, R^2(\alpha, j) \Big/ \sum_\alpha p_{T,\alpha}\,,$$

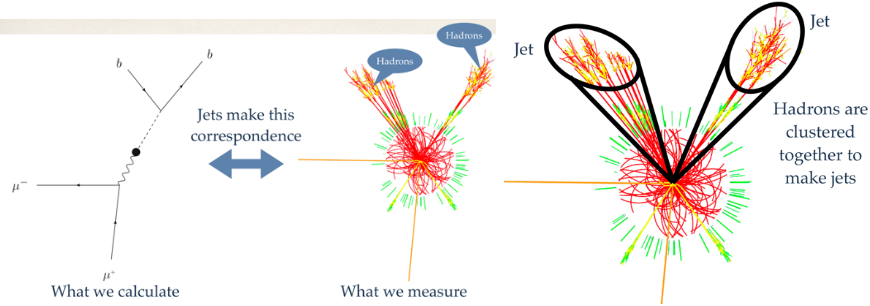


$R^{j^2}_{em} \lesssim 10^{-4}$:$\epsilon_\tau \approx 0.30\%$

$\epsilon_{j\to\tau} \approx$3.0%

4 e/μ;
3 e/μ+1j;
3 $e/\mu+\tau_j$;
3 $e/\mu+b$;
3 e/μ
SM bgs: $t\bar{t}Z$, WWZ,ZZ,$t\bar{t}$,$t\bar{t}W$,$Z2j$,$WWZj$,ZZW etc
ALPGEN: $p_T^{j,b} > 20\ \mathrm{GeV},\ |\eta^{\mathrm{j,b}}| < 2.5,\ \mathrm{R(jj, bj, bb)} > 0.4$
PYTHIA: showering, fragmentation,hadronization
Lepton selection: $p_T^{\mu} > 20\ \mathrm{GeV},\ |\eta^{\mu}| < 2.5,\ \mathrm{R}(\mu\mathrm{j}, \mu\mathrm{b}) > 0.4$,
Three different choices:
Low Tau Tagging(LTT):$\epsilon_\tau \approx$ 0.25% $\epsilon_{j\to\tau}$ $\approx$0.1%
High Tau Tagging(HTT): $\epsilon_\tau \approx$ 0.50% $\epsilon_{j\to\tau}$ $\approx$1.0%
Our Tau Tagging: $R_{em}^{j^2} \lesssim 10^{-4}$:$\epsilon_\tau \approx$ 0.30% $\epsilon_{j\to\tau}$ $\approx$3.0%

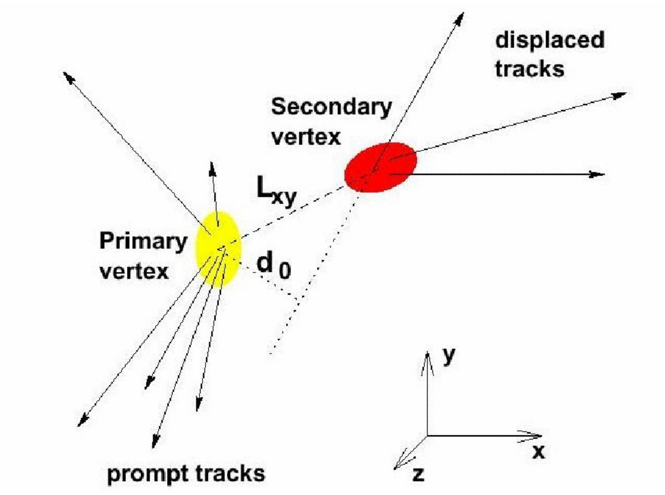
Hadronization



tau-jet: narrow due to low mass and contains few hadrons(as it decays to 1/3 prong decays)

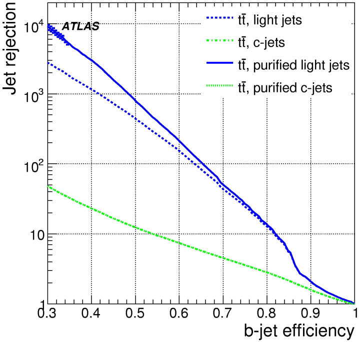
b-jet: travelled a distances after production, a bit fatter and contains large hadrons

b-tagging and mistagging at LHC



b-tagging and mistagging at LHC

→Identification of jets/hadrons which contains a b-quark.



[ATLAS arXiv:0901.0512 [hep-ex]]

B-meson ($m \sim$ 5 GeV) typical ($p_T >$ 5 GeV) decay length $\sim$ 0.5 mm

⇒Matching:ΔR(j-q) and Et ratio: identify the flavor of the jets(b,c,q)

⇒For $\epsilon_b \approx 50\% \rightarrow \epsilon_c \approx 10\%$ and $\epsilon_j \approx 0.25\%$

3 e/μ + τ-jet [ϵ_b=55%, $\epsilon_{j\to b}$=1%].

τ jets id	Signal, M_H (GeV)			Backgrounds					$S/\sqrt{B}$, M_H (GeV)		
	120	125	130	$t\bar{t}Z$	WWZ	$t\bar{t}W$	WZj	ZZ	120	125	130
R-cut	26	24	23	19	3	16	31	9	2.9	2.7	2.6
LTT	24	22	20	18	3	1	3	8	4.2	3.8	3.5
HTT	44	40	38	31	5	5	13	16	5.1	4.6	4.4
B-tag/HTT	36	32	31	24	0	4	0	0	6.8	6.0	5.9

ttH: Multi-lepton analysis at LHC@14TeV with 100 fb^{-1}

3 e/μ + b-jet [ϵ_b=55%, $\epsilon_{j\to b}$=1%].

Signal, M_H (GeV)			Backgrounds			$S/\sqrt{B}$, M_H (GeV)		
120	125	130	$t\bar{t}Z$	$t\bar{t}W$	WZj	120	125	130
50	41	31	35	421	8	2.3	**1.9**	1.4

4 e/μ [ϵ_b=55%, $\epsilon_{j\to b}$=1%].

b-jet id	Signal, M_H (GeV)			Backgrounds			$S/\sqrt{B}$, M_H (GeV)		
	120	125	130	$t\bar{t}Z$	WWZ	ZZ	120	125	130
no extra b	19	23	26	20	3	4	3.6	4.4	5.0
extra b	16	19	22	16	0	0	4.0	**4.8**	5.5

$e\mu\tau b$; $e\mu 2\tau$; $e\mu\tau 2b$; $e\mu 2\tau b$[Phys.Rev.D submitted]

$\epsilon_{j\to\ell} \approx$ 0.01% – 0.001% (jet fake–rate as a lepton)

$\epsilon_{j\to b} \approx$ 1.0% (jet fake–rate as a *b*-jet)

2 e/μ + *tau*-jet + *b*-jet [ϵ_b=55%, $\epsilon_{j\to b}$=1%].

τ jets id	Signal, M_H (GeV)			Backgrounds				$S/\sqrt{B}$, M_H (GeV)		
	120	125	130	$t\bar{t}Z$	$t\bar{t}$	$t\bar{t}W$	$Z2j$	120	125	130
LTT	333	333	330	336	8228	567	30	3.4	3.4	3.4
HTT	555	552	549	561	32889	942	120	2.9	2.9	2.9
SS/LTT	111	111	111	111	9	189	0	6.3	6.3	6.3
SS/HTT	186	183	183	186	3	315	0	8.3	**8.2**	8.2

ttH: Di-lepton analysis at LHC@14TeV with 300 fb^{-1}

$e\mu\tau b$; $e\mu 2\tau$; $e\mu\tau 2b$; $e\mu 2\tau b$[Phys.Rev.D submitted]

$\epsilon_{j\to\ell} \approx 0.01\% - 0.001\%$ (jet fake–rate as a lepton)

$\epsilon_{j\to b} \approx 1.0\%$ (jet fake–rate as a b-jet)

2 e/μ + 2 *tau*-jet

τ jets id	Signal, M_H (GeV)			Backgrounds						$S/\sqrt{B}$, M_H (GeV)		
	120	125	130	$t\bar{t}Z$	WWZ	$t\bar{t}W$	$t\bar{t}$	$Z2j$	ZZ	120	125	130
LTT	42	41	37	36	6	3	9	9	30	4.4	4.3	3.8
HTT	117	114	104	111	15	9	147	276	84	4.6	4.5	4.1
SS/LTT	14	14	12	12	3	0	0	0	0	3.6	3.6	3.1
SS/HTT	39	38	35	36	6	3	0	0	0	5.8	5.7	5.2

2 e/μ + 2 *tau*-jet + *b*-jet

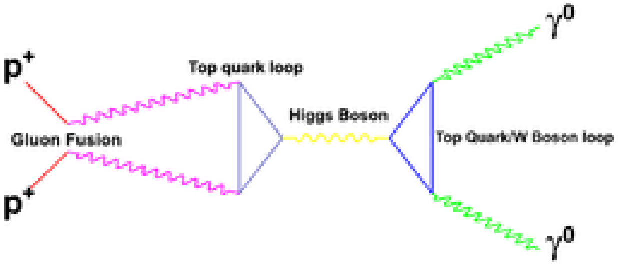
τ jets id	Signal, M_H (GeV)			Backgrounds			$S/\sqrt{B}$, M_H (GeV)		
	120	125	130	$t\bar{t}Z$	$t\bar{t}W$	$t\bar{t}j$	120	125	130
LTT	34	33	30	30	3	6	5.4	5.3	4.8
HTT	93	91	83	90	6	81	6.9	6.8	6.2
SS/LTT	11	11	10	10	0	0	3.5	3.5	3.2
SS/HTT	31	30	28	30	3	0	5.4	5.2	4.9

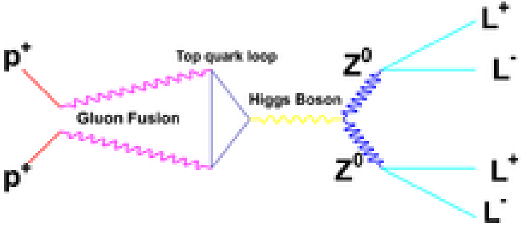
ttH summary

The cut–and–count experiments shows that the significances is more than 5–8σ at LHC@14TeV with 100/300 fb^{-1}

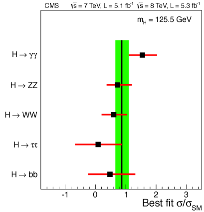
We are working in the full hadronic mode (and with 1-lepton) using FastJET, Delphes Detector simulator

Signal channels





R: Signal Strength contd.



$$R(X) \equiv \frac{\sigma(pp \to h) BR(h \to X)}{\sigma(pp \to h)_{SM} BR(h \to X)_{SM}}$$

$$= \frac{\sigma(pp \to h)}{\sigma(pp \to h)_{SM}} \times \frac{\Gamma(h \to \mathrm{All})_{SM}}{\Gamma(h \to \mathrm{All})} \times \frac{\Gamma(h \to X)}{\Gamma(h \to X)_{SM}}, \quad (30)$$

X: $b\bar{b}$, WW and $\gamma\gamma$.
R = 0(1) is the background-only (SM) hypothesis
$R(\gamma\gamma)_{\mathrm{ATLAS}}{=}1.57{+}0.33{-}0.28$
$R(\gamma\gamma)_{\mathrm{CMS}}{=}0.77{\pm}0.27$

Three ways to enhance R:

1. enhance cross-section,
2. total decay-width suppression (mainly the $b\bar{b}$),
3. enhancing the partial width in X channel.

Models beyond SM

What are the models beyond SM and in particular MSSM where these features can be realised?

In MSSM

The model parameter space is highly constrained and only occur in a very fine-tunned model spaces

Large region in

Next-to-MSSM

in collaboration with
Stefano Moretti, Andrew Akeroyd (Southampton, UK)
and
Jaime Hernandez Sanchez(Puebla, Mexico)

NMSSM

What is the value of μ in the MSSM superpotential: $\mu H_u H_d$?

μ=0 $\rightarrow$ no mixing (i.e., any breaking in up-sector could not be communicated to down-sector)
Also hints from LEP limit on Chargino mass (105 GeV)

μ=M_{pl} $\rightarrow$ Higgs and Higgsions $\sim$ Planck scale(problem of Perturbativity)

This contradiction is known as μ problem

However, for phenomenological acceptable solutions:

$\mu \sim$ **electro-weak scale**

NMSSM contd...

This problem can be solved by adding extra singlet:
$\mu H_u H_d \rightarrow \lambda S H_u H_d + \frac{1}{3}\kappa S^3$
$B\mu H_u H_d \rightarrow \lambda A_\lambda S H_u H_d + \frac{1}{3}\ \kappa A_\kappa S^3$

Assuming SSB terms are approx. $\mathcal{O}(M_{SUSY})$ leads
$\langle S \rangle \sim M_{SUSY}/\kappa$
$\mu_{eff} \equiv \lambda \langle S \rangle \sim \lambda/\kappa\ M_{SUSY}$ and if $\lambda/\kappa \sim \mathcal{O}(1)$

$$\mu_{eff} \equiv M_{SUSY}$$

SUSY breaking scale is the only scale and that generate EWSB scale

Soft-breaking parameters

H_u, H_d, S, squarks $\tilde{q}_i \equiv (\tilde{u}_{iL}, \tilde{d}_{iL})$, $\tilde{u}^c_{iR}$, $\tilde{d}^c_{iR}$ and sleptons $\tilde{\ell}_i \equiv (\tilde{\nu}_{iL}, \tilde{e}_{iL})$ and $\tilde{e}^c_{iR}$

$$\begin{aligned} -\mathcal{L}_0 &= m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + m^2_{\tilde{q}_i}|\tilde{q}_i|^2 + m^2_{\tilde{u}_i}|\tilde{u}^c_{iR}|^2 + m^2_{\tilde{d}_i}|\tilde{d}^c_{iR}|^2 \\ &\quad + m^2_{\tilde{\ell}_i}|\tilde{\ell}_i|^2 + m^2_{\tilde{e}_i}|\tilde{e}^c_{iR}|^2 , \end{aligned} \tag{31}$$

$$\begin{aligned} -\mathcal{L}_3 &= \Big(h_t A_t\, Q \cdot H_u\, \tilde{u}^c_{3R} + h_b A_b\, H_d \cdot Q\, \tilde{d}^c_{3R} + h_\tau A_\tau\, H_d \cdot L\, \tilde{e}^c_{3R} \\ &\quad + \lambda A_\lambda\, H_u \cdot H_d\, S + \frac{1}{3}\kappa A_\kappa\, S^3 \Big) + \text{h.c.} , \end{aligned} \tag{32}$$

$$-\mathcal{L}_{1/2} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a \right] + \text{h.c.} . \tag{33}$$

Higgses: Doublet-Singlet Mixing

$$\begin{aligned} H_1 &= S_{1,d}\, H_d + S_{1,u}\, H_u + S_{1,s}\, S\,, \\ H_2 &= S_{2,d}\, H_d + S_{2,u}\, H_u + S_{2,s}\, S\,, \\ H_3 &= S_{3,d}\, H_d + S_{3,u}\, H_u + S_{3,s}\, S\,. \end{aligned} \quad (34)$$

$$\begin{aligned} \frac{g_{H_i bb}}{g_{H_{SM} bb}} = \frac{g_{H_i \tau\tau}}{g_{H_{SM}\tau\tau}} &= \frac{S_{i,d}}{\cos\beta}\,, \qquad \frac{g_{H_i tt}}{g_{H_{SM} tt}} = \frac{S_{i,u}}{\sin\beta}\,, \\ \bar{g}_i \equiv \frac{g_{H_i VV}}{g_{H_{SM} VV}} &= \cos\beta\, S_{i,d} + \sin\beta\, S_{i,u}\,. \end{aligned} \quad (35)$$

- Square of the Couplings are Unity
- Recall: suppression of the $b\bar{b}$ decay width (we need to enhance R)
- **low tan-beta top quark is dominant (again gamma-gamma enhancement through top-loop)**
- Doublet-singlet mixing proportional to λ, and can be sizeable for $\lambda \gtrsim 0.3$

Input Parameters

$$\lambda\ ,\ \kappa\ ,\ A_\lambda\ ,\ A_\kappa,\ \tan\beta \equiv v_u/v_d\ ,\ \mu_{\rm eff}\ . \tag{36}$$

(for this inputs: $m^2_{H_u}$, $m^2_{H_d}$ and m^2_S from M_Z, $\tan\beta$ and $\mu_{\rm eff}$. NUH-NMSSM: Non-universality in the Higgs soft masses)
cNMSSM: soft SUSY breaking terms are identical GUT scale:

$$M_1 = M_2 = M_3 \equiv M_{1/2}\ , \tag{37}$$

$$m^2_{\tilde{q}_i} = m^2_{\tilde{u}_i} = m^2_{\tilde{d}_i} = m^2_{\tilde{\ell}_i} = m^2_{\tilde{e}_i} \equiv m^2_0\ , \tag{38}$$

$$A_t = A_b = A_\tau \equiv A_0\ . \tag{39}$$

6+3=9 parameters:

$$\lambda\ ,\ \kappa\ ,\ \tan\beta\ ,\ \mu_{\rm eff}\ ,\ A_\lambda\ ,\ A_\kappa\ ,\ A_0\ ,\ M_{1/2}\ ,\ m_0\ , \tag{40}$$

Higgses masses in NMSSM

In addition to MSSM,
$\rightarrow$ one extra scalar Higgs Boson(total 3)
$\rightarrow$ one extra pseudoscalar Higgs Boson(total 2)
$\rightarrow$ one extra neutral Higgsino (total 5 neutralinos)
$\rightarrow$ Charged Higgs and Chargino content is the same as of MSSM

MSSM: $M^2_{H_1}$ = tree-level + loop $\lesssim$ $(130 - 135 GeV)^2$
NMSSM: $M^2_{H_1}$ = MSSM + $1/2(\lambda v)^2 sin^2(2\beta) \lesssim (140 GeV)^2$

This extra contribution from the new scalar raises the lightest Higgs mass bound, but only by a little.

Constrained imposed

Constraints from SUSY searches at Colliders:

$$m_0 \gtrsim 140 \text{ GeV} , \qquad M_{1/2} \gtrsim 270 \text{ GeV}$$
$$m_{\tilde{q}} \gtrsim 580 \text{ GeV} , \qquad M_{\tilde{g}} \gtrsim 640 \text{ GeV} . \qquad (41)$$

Chargino (from LEP)

$$105 < \mu_{\text{eff}} < 205 \text{ GeV} \qquad (42)$$

Charged (resp. CP-odd) Higgs masses as low as ~ 250 (resp. 160) GeV
Dark matter relic density: $0.094 < \Omega h^2 < 0.136$
We required:

$$123 \text{ GeV} < M_{H_2} < 129 \text{ GeV}$$
$$R_2^{\gamma\gamma} \equiv \sigma^{\gamma\gamma}_{obs}(H_2)/\sigma^{\gamma\gamma}_{SM} > 1.04 \qquad (43)$$

U. Ellwanger and C. Hugonie, arXiv:1203.5048 [hep-ph].

and the Masses of the Higgses such that

- S1:Production:$H^{\pm}a_1$:
  $H^+ \to t\bar{b}$ and $a_1 \to b\bar{b}$ **e11**
  $H^+ \to Wa_1$ and $a_1 \to b\bar{b}$ **e12**
- S2:Production:$H^{\pm}h_1$:
  $H^+ \to t\bar{b}$ and $h_1 \to b\bar{b}$ **e21**
  $H^+ \to Wa_1$ and $h_1, a_1 \to b\bar{b}$ **e22**
- S3:Production:$H^{\pm}h_2$:
  $H^+ \to t\bar{b}$ and $h_2 \to b\bar{b}$ **e31**
  $H^+ \to Wa_1$ and $h_2, a_1 \to b\bar{b}$ **e32**

are possible and
some handful of W4b events at LHC@14 TeV to discover multiple Higgses

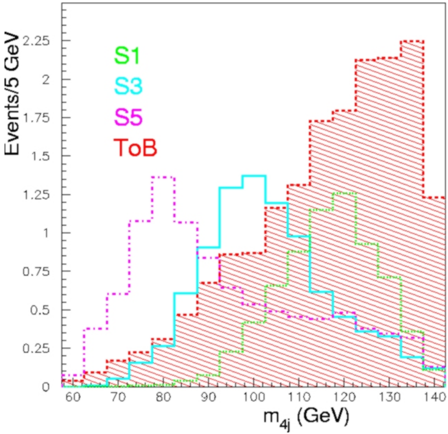
Analysis

Markov Chain Monte Carlo(MCMC)
non-universal Higgs NMSSM (NUH-NMSSM)
125,000 MCMC $\rightarrow$ 58 good points $\rightarrow$ 30 points decays occur simultaneously
with subject to following constraints:
$\rightarrow$ 123 $\mathrm{GeV} < M_{H_2} < 129$ GeV and
$\rightarrow R^{H_2}_{gg}(\gamma\gamma) > 1.04$, and $R^{H_2}_{VBF}(\gamma\gamma) > 1.04$

$$R^{H_2}_{gg}(\gamma\gamma) \equiv \sigma^{\gamma\gamma}_{gg}(H_2)/\sigma^{\gamma\gamma}_{SM} \ . \tag{44}$$

and similarly for the VBF.

CPV Higgs:(m_{h_2}=$m_{j_1 j_2 j_3 j_4}$) reco. at LHC@14TeV 60/fb

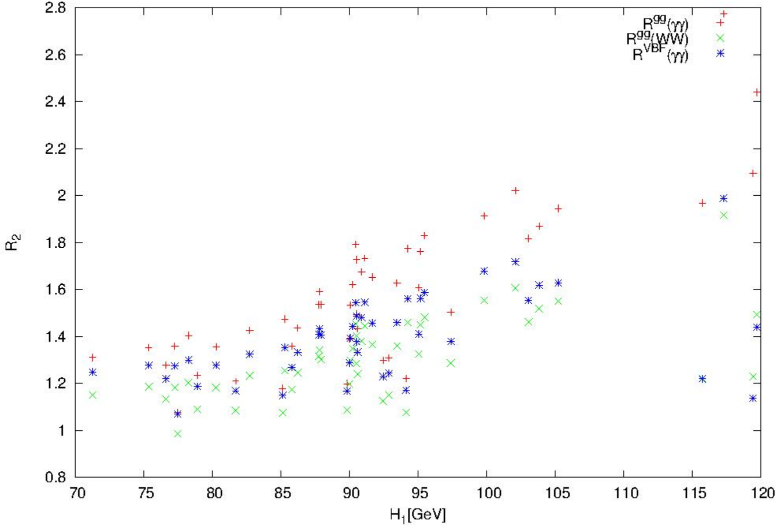


Wh2→h1h1:W4b signatures in CP-violating MSSM

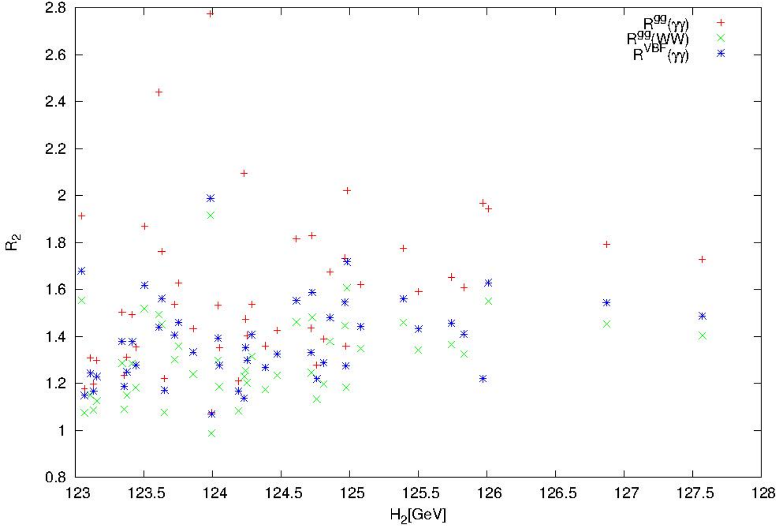
AIP Conf. Proc. **1078**, 223 (2009) with Amitava Datta and Manuel Drees

Phys.Rev.D83:035003,2011 with Manuel Drees(PI,Bonn)

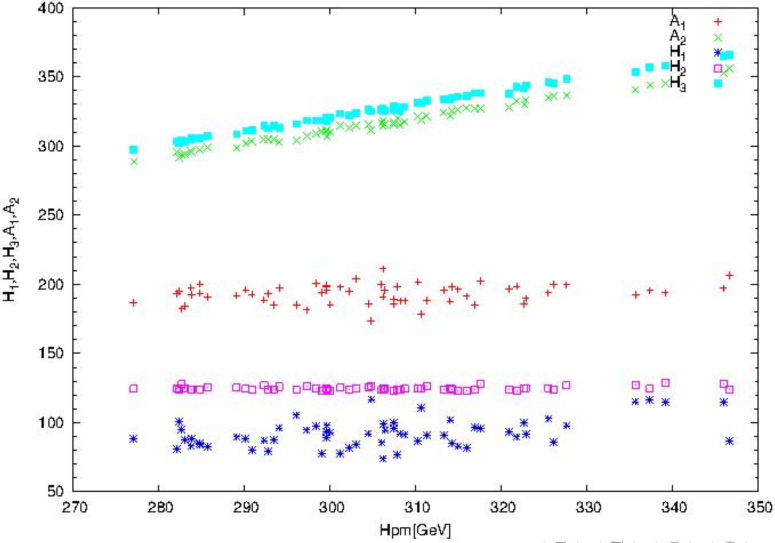
Signal Strength with H1 for R2 > 1.04



Signal Strength with H2 for R2 > 1.04



Masses with R2 >1.04



Event Rate 13 TeV@LHC for 300/fb for R2 > 1.04

- C1: $N_j \gtrsim 4$ with $Pt_j \gtrsim 15$, $\eta_j \lesssim 5$
- C2: C1 $\otimes\ n_\ell \gtrsim 1$, where ℓ=e,μ with $Pt_\ell \gtrsim$ 20 GeV
- C3: C2 $\otimes\ \not{E}_T > 20$ GeV
- C4,5,6,7: C3 $\otimes\ N_{b-tag} \gtrsim$ 1,2,3,4 (with the inclusion of the mis-tagging of cjet and low flavored jets.)

	Process	Raw	C1	C2	C345	C6	C7
BP-19	$H^\pm h_1$	28.1	24.53	16.67	10.78	4.11	0.69
BP-19	$H^\pm h_2$	22.9	19.46	12.65	7.53	2.69	0.45
BP-30	$H^\pm h_1$	92.27	77.90	51.49	33.29	12.49	1.97
BP-30	$H^\pm h_2$	6.18	5.18	3.34	1.97	0.69	0.12
BP-50	$H^\pm h_1$	26.7	23.16	15.48	10.00	3.80	0.63
BP-50	$H^\pm h_2$	25.8	21.71	14.07	8.37	2.97	0.48
	$t\bar{t}$	40471788.8	28337537.1	13804522.4	4279486.9	195074.0	809.4

Event Rate 14 TeV@LHC for 3000/fb for R2 > 1.04

- C1: $N_j \gtrsim 4$ with $Pt_j \gtrsim 15$, $\eta_j \lesssim 5$
- C2: C1 $\otimes$ $n_\ell \gtrsim 1$, where ℓ=e,μ with $Pt_\ell \gtrsim$ 20 GeV
- C3: C2 $\otimes$ $\not{E}_T > 20$ GeV
- C4,5,6,7: C3 $\otimes$ $N_{b-tag} \gtrsim$ 1,2,3,4 (with the inclusion of the mis-tagging of cjet and low flavored jets.)

	Process	Raw	C1	C2	C345	C6	C7
BP-19	$H^\pm h_1$	318.7	279.11	229.17	121.25	45.96	7.37
	$H^\pm a_1$	0.026	0.02	0.02	0.01	0.00	0.00
	$H^\pm h_2$	259.3	221.59	181.77	83.83	29.51	4.65
BP-30	$H^\pm h_1$	1040.6	880.71	712.25	369.09	138.57	22.29
	$H^\pm a_1$	0.09	0.08	0.07	0.04	0.01	0.00
	$H^\pm h_2$	69.7	58.66	47.58	21.66	7.64	1.19
BP-50	$H^\pm h_1$	302.3	263.51	215.27	113.70	42.93	6.87
	$H^\pm a_1$	0.021	0.02	0.02	0.01	0.00	0.00
	$H^\pm h_2$	291.6	247.23	202.21	93.66	32.41	5.20
$t\bar{t}$	100K	483482693.0	342620010.4	268632653.9	50562620.0	2132158.6	19339.3
$t\bar{t}c\bar{c}$	500K	2050450.0	2023253.5	1633073.2	398226.2	56719.5	3666.2
$b\bar{b}b\bar{b}W^\pm$	100K	27721.2	13321.4	9570.4	4244.9	1509.7	231.20
$t\bar{t}b\bar{b}$	100K	3144823.6	3058561.1	2474032.9	1137325.4	381530.0	58493.7
$ggggW^\pm$	300K	17471378.2	13034114.0	9499130.1	873.5	0.0	0.0
$b\bar{b}c\bar{c}W^\pm$	300K	56093.6	33361.3	23764.6	5155.5	655.9	30.4

Event Rate 100TeV@VLHC for 3000/fb for R2 > 1.04

- C1: $N_j \gtrsim 4$ with $Pt_j \gtrsim 50$, $\eta_j \lesssim 5$
- C2: C1 $\otimes$ $n_\ell \gtrsim 1$, where ℓ=e,μ with $Pt_\ell \gtrsim$ 50 GeV
- C3: C2 $\otimes$ $\not{E}_T > 75$ GeV
- C4,5,6,7: C3 $\otimes$ $N_{b-tag} \gtrsim$ 1,2,3,4 (with the inclusion of the mis-tagging of cjet and low flavored jets.)

	Process	Raw	C1	C2	C345	C6	C7
$H^\pm h_1$	50K	19241.33	519.89	124.30	14.24	3.08	0.38
$H^\pm h_2$	25K	7.01	0.40	0.13	0.02	0.01	0.00
$H^\pm a_1$	50K	4.30	0.41	0.14	0.03	0.01	0.00
$t\bar{t}$	7.2M	22699845131.6	201234127.0	92233884.6	4779578.5	195470.8	3152.7

NMSSM multiple Higgs boson searches

With all recent experimental bounds, in NMSSM model parameters, different Higgs boson production can leads to W4b signatures however is not very promising even with VLHC@100TeV with 3000 fb^{-1}. We are thinking to write a short note and go for the Gauge decay modes: for example, $h_1, h_2 \to a_1 Z, ZZ$, where the cross-sections are large.

Charged Higgs Flavor violating decays in 2HDM-III

in collaboration with

Alfonso Rosado, Reyna Xoxocotzi Aguilar and Jaime Hernandez Sanchez(Puebla, Mexico)

2HDM-III

$$V = \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) - \left(\mu_{12}^2(\Phi_1^\dagger\Phi_2) + \text{H.c.}\right) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2$$
$$+\frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left(\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right)(\Phi_1^\dagger\Phi_2) + \text{H.c.}\right),$$

$\Phi_1^\dagger = (\phi_1^-, \phi_1^{0*})$ $\Phi_2^\dagger = (\phi_2^-, \phi_2^{0*})$ (Hypercharge=+1)

$$-\mathcal{L}_Y = Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R + Y_2^d \bar{Q}_L \Phi_2 d_R + Y_1^l \bar{L}_L \Phi_1 l_R + Y_2^l \bar{L}_L \Phi_2 l_R,$$

$\Phi_{1,2} = (\phi_{1,2}^+, \phi_{1,2}^0)^T$ $\tilde{\Phi}_{1,2} = i\sigma_2\Phi_{1,2}^*$.

2HDM-III contd.

$M_f^{ij} = \frac{1}{\sqrt{2}}(v_1 Y_1^{ij} + v_2 Y_2^{ij})$, $f = u, d, l$
In SM: diagonalizing the mass matrices automatically diagonalize Yukawa interaction.
This is important for absence of FCNC!
In 2HDM: the above structure is not allowed to diagonalize Mass matrices and Yukawas simultaneously!
This leads to the tree-level FCNC (e.g.,$\bar{d}s\phi$!)

2HDM-III contd.

- Impose some discrete symmetry (to remove those FCNC terms!)
- Even w/o discrete symmtery, however with some speacial structures of Yukawas (assuming hermitians) could also do the same thing (i.e., not eliminating in a ture sense but the elements in the mass matrices are very small!)

$\bar{M}_f = V_{fL}^\dagger M_f V_{fR}$
$\bar{M}_f = \frac{1}{\sqrt{2}}(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f)$, where $\tilde{Y}_i^f = V_{fL}^\dagger Y_i^f V_{fR}$.
One can derive a better approximation for the product $V_q\, Y_n^q\, V_q^\dagger$, expressing the rotated matrix $\tilde{Y}_n^q$ as:

$$\left[\tilde{Y}_n^q\right]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{v}\left[\tilde{\chi}_n^q\right]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{v}\left[\chi_n^q\right]_{ij} e^{i\vartheta_{ij}^q}, \tag{45}$$

These are called four-texture form!

Harald Fritzsch, Zhi-zhong Xing, S. Moretti, A. Cordero-Cid, J. HernandezSanchez, O. Felix-Beltran, F. Gonzalez-Canales, C. G. Honorato, M. A. Perez, R. Noriega-Papaqui, J. J. Toscano, J.L. Diaz-Cruz, A. Rosado

2HDM-III contd.

$$\mathcal{L}^{\bar{f}_i f_j \phi} = -\left\{ \frac{\sqrt{2}}{v} \overline{u}_i \left(m_{d_j} X_{ij} P_R + m_{u_i} Y_{ij} P_L \right) d_j \, H^+ + \frac{\sqrt{2} m_{l_j}}{v} Z_{ij} \overline{\nu_L} l_R H^+ + H.c. \right\}$$
$$-\frac{1}{v} \left\{ \bar{f}_i m_{f_i} h^f_{ij} f_j h^0 + \bar{f}_i m_{f_i} H^f_{ij} f_j H^0 - i \bar{f}_i m_{f_i} A^f_{ij} f_j \gamma_5 A^0 \right\}, \quad (46)$$

where ϕ^f_{ij} ($\phi = h, H, A$), X_{ij}, Y_{ij} and Z_{ij} are defined as:

$$\phi^f_{ij} = \xi^f_\phi \delta_{ij} + G(\xi^f_\phi, X), \quad \phi = h, H, A,$$
$$X_{ij} = \sum_{l=1}^{3} (V_{\rm CKM})_{il} \left[X \frac{m_{d_l}}{m_{d_j}} \delta_{lj} - \frac{f(X)}{\sqrt{2}} \sqrt{\frac{m_{d_l}}{m_{d_j}}} \tilde{\chi}^d_{lj} \right],$$
$$Y_{ij} = \sum_{l=1}^{3} \left[Y \delta_{il} - \frac{f(Y)}{\sqrt{2}} \sqrt{\frac{m_{u_l}}{m_{u_i}}} \tilde{\chi}^u_{il} \right] (V_{\rm CKM})_{lj},$$
$$Z^l_{ij} = \left[Z \frac{m_{l_i}}{m_{l_j}} \delta_{ij} - \frac{f(Z)}{\sqrt{2}} \sqrt{\frac{m_{l_i}}{m_{l_j}}} \tilde{\chi}^l_{ij} \right]. \quad (47)$$

With this structure in different limits one can have different 2HDM

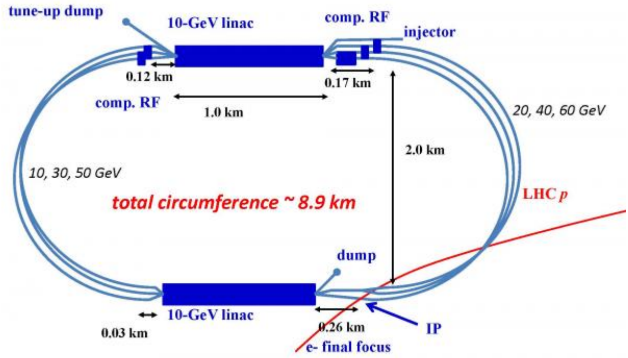
2HDM-III contd.

2HDM-III	X	Y	Z	ξ_h^u	ξ_h^d	ξ_h^l	ξ_H^u	ξ_H^d	ξ_H^l
2HDM-I-like	$-\cot\beta$	$\cot\beta$	$-\cot\beta$	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β
2HDM-II-like	$\tan\beta$	$\cot\beta$	$\tan\beta$	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β
2HDM-X-like	$-\cot\beta$	$\cot\beta$	$\tan\beta$	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β
2HDM-Y-like	$\tan\beta$	$\cot\beta$	$-\cot\beta$	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β

- $\mu - e$ universality in τ decays
- Leptonic meson decays $B \to \tau\nu$, $D \to \mu\nu$, $D_s \to \mu\nu, \tau\nu$ and semileptonic decays $B \to D\tau\nu$
- $B \to X_s\gamma$ decays
- $B^0 - \bar{B}^0$ mixing
- Eelectro-weak precision test(including S,T,U oblique parameters)

Finally with all these above constraints one can find: $\chi^f_{kk} \sim 1$ and $|\chi^f_{ij}| \leq 0.5$,

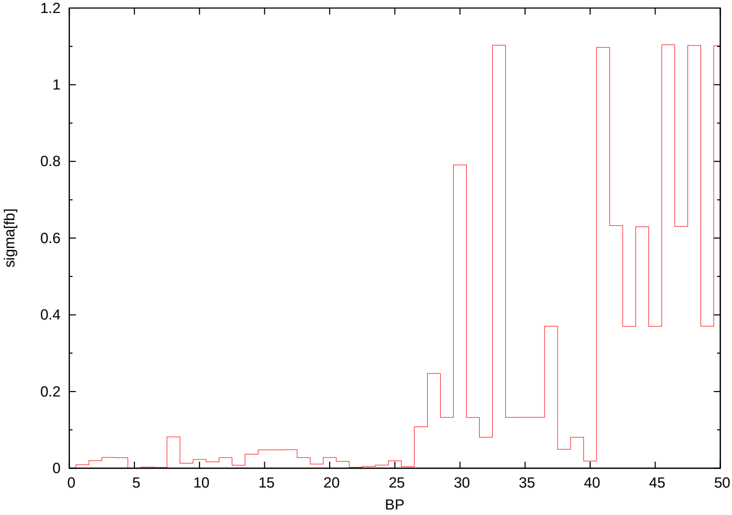
LHeC Collider



$\sqrt{s} = \sqrt{(E_e E_p)} = 1.296$ TeV (e-=60GeV p=7000 GeV) with 100/fb

J. L. Abelleira Fernandez [arXiv:1206.2913 [physics.acc-ph]]

Process: $e-p \to e-H^{+}\bar{t}$+h.c.



Flavor violating Signal: $e-p \to e-H^+\bar{t}$+h.c.

$H^\pm$ (for $m_{H^\pm} < m_t - m_b$ with $|X| >> |Y|, |Z|$) gives rise to a "leptophobic" with BR($H^\pm \to cs$)+BR($H^\pm \to cb$) $\sim$ 100%

Signal: 2-lepton+ 3-jet+$\not{E}_T$ with 100 fb^{-1}

- C1: $N_j \gtrsim 3$ with $Pt_j \gtrsim 15$, $\eta_j \lesssim 5.0$
- C2: C1 $\otimes$ $n_\ell \gtrsim 2$, where ℓ=e,μ with $Pt_\ell \gtrsim$ 15 GeV
- C3: C2 $\otimes$ $\not{E}_T > 20$ GeV
- C4: C3 $\otimes$ $N_{b-tag} \gtrsim$ 1 (with the inclusion of the mis-tagging of cjet and low flavored jets, with ϵ_b=0.50, ϵ_c=0.10 and ϵ_j=0.01, where j=u,d,s,g)

Process	Raw	C1	C2	C3	C4	C4 $\otimes$ ee	C4 $\otimes e\mu$	C4 $\otimes \mu\mu$
BP30	6.1	3.8	2.4	2.2	1.0	0.0	0.9	0.1
BP33	7.7	4.8	3.1	2.7	1.2	0.1	1.1	0.1
BP48	7.8	4.8	3.1	2.8	1.3	0.1	1.2	0.1
$et\bar{t}$	52.03	38.03	23.31	20.71	12.00	1.22	9.71	1.06
$\nu_e b\bar{t}$	3167.3	84.78	6.65	5.91	4.22	0.00	2.11	2.11
$etbq$	0.74	0.43	0.26	0.23	0.15	0.01	0.12	0.01
$ettq$	12.04	10.07	6.18	5.57	3.24	0.45	2.48	0.30
$ettZ$	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00

With full luminosity option(1000 fb^{-1}): 10/$\sqrt{(150)}$ =0.9σ

We're working on Multi-Variate Analysis to get the best sensitivity

Summary:

- Recent observations from LHC@8TeV found a mass peaks in the di-photon (also in other mode, WW,ZZ,$\tau\tau$, $b\bar{b}$) channel in the ranges $124 < m_H < 128$ with more than 5σ at 125.6 GeV.
- In SM, by exploiting the tau-jet tagging in $t\bar{t}H$ alone, the Higgs signal will show up in 5-8σ at LHC@14 TeV.
- In MSSM (with CP-conserving) predicts $m_H < 135$ GeV, however explaing the observed signal strength needs extreme fine-tunning.
- NMSSM solves the μ problem (of MSSM) naturally and due to Singlet-Doublet mixing, the enhanced decay rates into di-photon channel (mainly due to suppresion of $b\bar{b}$, and by other means implicitly) is quite natural.
- For this allowed NMSSM parameter spaces of R2, many production and decays of multiple Higgses leads to many different signal topology that can be studied.
- Our study in W4b mode withing CP-violating MSSM are motivate us to explore within NMSSM.
- Reconstructing multiple Higgses simultaneously, can hint for some new physics beyond MSSM.
- Flavor–violating decays of Charged Higgs could be observable at LHeC can hint for signature of 2HDM-III.