Theoretical overview of Higgs Physics

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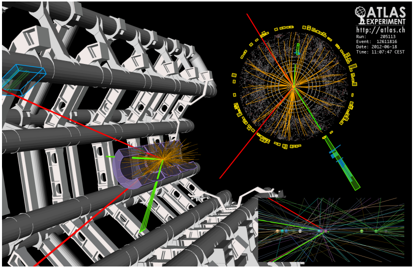
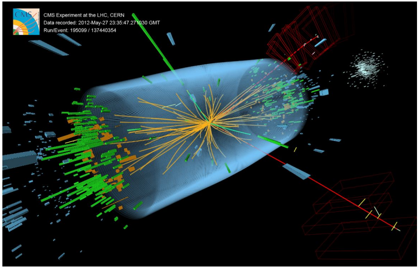
Summer School & Workshop
on the Standard Model and Beyond

August 31 - September 11, 2013





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"New results indicate that particle discovered at CERN is a Higgs boson"
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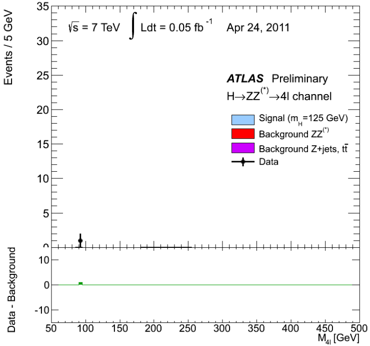
Introduction



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Outline

- First lecture: Higgs in the Standard Model
  - Quick review of the Higgs mechanism
  - Higgs properties
  - Higgs decays and production channels
- Second lecture: Higgs beyond the Standard Model
  - Two Higgs Doublet Model
  - Minimal Supersymmetric extension of the Standard Model
  - Implications

References

- "The Higgs Hunter's Guide", J. F. Gunion, H. E. Haber, G. Kane, S. Dawson, *Perseus Books*, 2000
- A. Djouadi, "The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model", Phys. Rept. 457 (2008) 1, hep-ph/0503172
- A. Djouadi, "The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model", Phys. Rept. 459 (2008) 1, hep-ph/0503173
- "Higgs cross section working group" website, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Original papers

- P. W. Anderson, "Plasmons, Gauge Invariance, and Mass", Phys. Rev. 130, 439 (8 Nov. 1963)
- F. Englert and R. Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons", Phys. Rev. Lett. 13, 321 (26 June 1964)
- P. W. Higgs, "Broken Symmetries and the Masses of Gauge Bosons", Phys. Rev. Lett. 13, 508 (31 Aug. 1964)
- G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble , "Global Conservation Laws and Massless Particles", Phys. Rev. Lett. 13, 585 (12 Oct. 1964)

Brief Review: QED and QCD

Electromagnetism: free electron → Dirac Lagrangian: $\mathcal{L} = \bar{\psi}(x)(i\gamma^\mu\partial_\mu - m)\psi(x)$

Invariance under $U(1)$ local symmetry, with $D_\mu = \partial_\mu - ie\,A_\mu$

→ conservation of electric charge

→ addition of a new field A_μ associated to the photon

→ e^- requires the photon!

→ QED: $$\mathcal{L} = \bar{\psi} i\gamma^\mu(\partial_\mu + ieA_\mu)\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2\xi}(\partial_\mu A^\mu)^2$$

Strong interaction: quarks with 3 colours → $SU(3)$ local symmetry

Similar to QED, but non abelian → more complicated

→ addition of 8 new fields A^a_μ associated to the gluons

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→ QCD: $\mathcal{L} = \bar{\Psi}(x)(i\gamma^\mu D_\mu - m)\Psi(x) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \mathcal{L}_{GF} + \mathcal{L}_{FP}$, $\Psi = (\psi_1, \psi_2, \psi_3)$

with $D_\mu = (\partial_\mu - ig_s T^a A^a_\mu)$ and $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$, $(a,b,c = 1\cdots 8)$

$\mathcal{L}_{GF}$: gauge fixing term, $\mathcal{L}_{FP}$: Faddeev-Popov term

In both QED and QCD, the gauge bosons need to be massless to respect gauge invariance

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Fermi wrote an Hamiltonian for β decay by analogy with electromagnetism

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$\rightarrow$ isospin doublets: $\begin{pmatrix} p \\ n \end{pmatrix}, \Psi_L^Q = \begin{pmatrix} u \\ d \end{pmatrix}, \Psi_L^\ell = \begin{pmatrix} \nu \\ e^- \end{pmatrix}$

$\rightarrow$ Lagrangian with isospin doublets: invariant under $SU(2)$

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\Psi}^Q_L (i\gamma^\mu(\partial_\mu + igT^a W^a_\mu) - M_Q)\Psi^Q_L + + \bar{\Psi}^\ell_L (i\gamma^\mu(\partial_\mu + igT^a W^a_\mu) - M_\ell)\Psi^\ell_L$$

where $M_{Q,L}$ are quark and lepton mass matrices, $T^a = \sigma^a/2$ and

$$F^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\epsilon_{abc} W^b_\mu W^c_\nu$$

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Similarities between QED and weak theory:

- in both theories, spin-1 gauge fields and spin-1/2 fermions
- γ and W^0 have identical quantum numbers
- electromagnetic coupling of charged $W^\pm$ bosons

$\rightarrow$ Assumption of a $SU(2)_L \times U(1)_Y$ symmetry

Covariant derivative:

$$D_\mu \psi = (\partial_\mu - i g_2 T_L^a W_\mu^a + i g_1 \frac{1}{2} Y B_\mu)\psi \equiv D_\mu^L \psi_L + D_\mu^R \psi_R$$

- $SU(2)_L$: weak isospin group with gauge bosons $W^\pm$, W^0
- $U(1)_Y$: weak hypercharge group with gauge boson B^0

$\rightarrow$ W^0 and B^0 mix to give γ and Z

Again, no mass term can be added for the gauge bosons without breaking the symmetry!

Fermion mass terms: $m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ not gauge invariant

1983: discovery of $W^\pm$ and Z bosons at CERN
However, $W^\pm$ and Z are massive!!!

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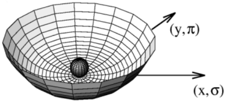
$SU(2)_L \times U(1)_Y$ to be spontaneously broken into $U(1)_{em}$

We introduce a complex scalar field doublet of $SU(2)$: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with the Lagrangian

$$\mathcal{L}_\Phi = (D^\mu \Phi)^\dagger D_\mu \Phi - V(\Phi) \quad , \quad V(\Phi) = \mu^2 \Phi^\dagger \Phi + \frac{1}{4}\lambda(\Phi^\dagger\Phi)^2 \quad (\lambda > 0)$$

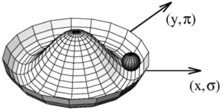
where $D_\mu = \partial_\mu - ig_2 \frac{\sigma^a}{2} W^a_\mu + i\frac{g_1}{2} B_\mu$, $\quad \begin{pmatrix} W^0_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$

$\mu^2 > 0$



Unique minimum: $\phi^\dagger\phi = 0$

$\mu^2 < 0$



Degenerate minima: $\phi^\dagger\phi = \dfrac{-2\mu^2}{\lambda}$

The potential is minimal for $|\Phi_0| = \left(\dfrac{-2\mu^2}{\lambda}\right)^{1/2} \equiv \dfrac{v}{\sqrt{2}} \longrightarrow \Phi_0 = \begin{pmatrix} 0 \\ \dfrac{v}{\sqrt{2}} \end{pmatrix}$

Higgs Mechanism

Rewriting the field Φ as

$$\Phi(x) = \left(\begin{array}{c} \phi^+(x) \\ \frac{1}{\sqrt{2}}\Big(v + H(x) + i\chi(x)\Big) \end{array} \right)$$

the Lagrangian becomes ($\phi^- = (\phi^+)^\dagger$)

$$\begin{aligned} \mathcal{L}_\Phi \;=\; & (\partial_\mu\phi^+)(\partial^\mu\phi^-) - \frac{iev}{2\sin\theta_W}(W^+_\mu\partial^\mu\phi^- - W^-_\mu\partial^\mu\phi^+) + \frac{e^2v^2}{4\sin^2\theta_W}W^+_\mu W^{-\mu} \\ & + \frac{1}{2}(\partial^\mu\chi)^2 + \frac{ev}{2\cos\theta_W\sin\theta_W}Z_\mu\partial^\mu\chi + \frac{e^2v^2}{4\cos^2\theta_W\sin^2\theta_W}Z^2 \\ & + \frac{1}{2}\partial^\mu H\,\partial_\mu H + \mu^2 H^2 \;+\; \text{trilinear and quadrilinear terms} \end{aligned}$$

Consequences:

- Z and W bosons receive masses: $M_W = \dfrac{ev}{2\sin\theta_W}$ and $M_Z = \dfrac{ev}{2\cos\theta_W\sin\theta_W}$
- massless photon
- physical Higgs boson of mass $M_H = \sqrt{-2\mu^2}$
- $\phi^\pm$ and χ: unphysical Goldstone bosons corresponding to unphysical d.o.f.
  $\rightarrow$ reabsorbed into the $W^\pm$ and Z longitudinal components.

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Yukawa interactions

The mass terms have to be generated by Higgs interaction

Lagrangian for Yukawa interactions:

$$\mathcal{L}_{\rm Yuk} = -\bar{\Psi}^{\ell}_{L} Y_{\ell} \psi^{\ell}_{R} \Phi - \bar{\Psi}^{Q}_{L} Y_{U} \psi^{U}_{R} \tilde{\Phi} - \bar{\Psi}^{Q}_{L} Y_{D} \psi^{D}_{R} \Phi + {\rm h.c.}$$

$\tilde{\Phi} = i\sigma^2 \Phi^* =$ charge conjugate Higgs doublet
$\Psi^{Q,\ell}_{L}$: $SU(2)$ doublets for quarks and leptons
$\psi^{U,D,\ell}_{R}$: $SU(2)$ singlets for quarks and leptons
Y_f: 3×3 Yukawa matrices

Mass terms obtained by setting $\Phi = \Phi_0$:

$$\mathcal{L}_{\rm mass} = -\frac{v}{\sqrt{2}} \bar{\psi}^{\ell}_{L} Y_{\ell} \psi^{\ell}_{R} - \frac{v}{\sqrt{2}} \bar{\psi}^{U}_{L} Y_{U} \psi^{U}_{R} - \frac{v}{\sqrt{2}} \bar{\psi}^{D}_{L} Y_{D} \psi^{D}_{R} + {\rm h.c.}$$

Diagonalisation of Y_f by unitary transformation: $\hat{\psi}^{f}_{L,R} \equiv U^{f}_{L,R} \psi^{f}_{L,R}$
such that: $(m_f)_i = \dfrac{v}{\sqrt{2}} (U^f_L Y_f (U^f_R)^\dagger)_{ii}$

$$\Rightarrow \mathcal{L}_{\rm mass} = -m_f \overline{\hat{\psi}^{f}_{L}} \hat{\psi}^{f}_{R} + {\rm h.c.} = -m_f \overline{\hat{\psi}^{f}} \hat{\psi}^{f}$$

$\Rightarrow$ standard mass term retrieved, coupling of Higgs to fermions $\propto m_f/v$

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Higgs particle properties

Higgs potential around the VEV:

$$V(H) = -\mu^2 H^2 + \frac{1}{4}\lambda v H^3 + \frac{1}{16}\lambda H^4$$

v is related to the W mass:

$$M_W = \frac{ev}{2\sin\theta_W}$$

measured precisely using $\mu^\pm$ decay widths:

$$v = \sqrt{\frac{-4\mu^2}{\lambda}} = 246\ \mathrm{GeV}$$

Higgs mass = free parameter related to the Higgs potential parameters:

$$M_H = \sqrt{-2\mu^2} = \sqrt{\frac{1}{2}\lambda v^2}$$

M_W and M_H measured $\Rightarrow$ all parameters of the Higgs theory fixed

Yukawa couplings determined by the measurement of all the fermion masses

Higgs couplings

- Higgs self-couplings: $V(H) = -\mu^2 H^2 + \frac{1}{4}\lambda v H^3 + \frac{1}{16}\lambda H^4$

$$\mathrm{HHH}: -3i\frac{M_H^2}{v} \qquad \mathrm{HHHH}: -3i\frac{M_H^2}{v^2}$$

- Higgs-gauge bosons: $\mathcal{L}_{\rm kin} = (D^\mu\Phi)^\dagger(D_\mu\Phi)$, $\quad D_\mu = \partial_\mu - ig_2\frac{\sigma^a}{2}W_\mu^a + i\frac{g_1}{2}B_\mu$

$$\mathrm{VVH}: 2i\frac{M_V^2}{v}g^{\mu\nu} \qquad \mathrm{VVHH}: 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

- Higgs-fermions: $\mathcal{L}_{\rm Yuk} = -\frac{y_f}{\sqrt{2}}\bar{\Psi}_L^f\psi_R^f H + \mathrm{h.c.}$

$$f\bar{f}\mathrm{H}: -i\frac{m_f}{v} = -i\frac{y_f}{\sqrt{2}}$$

- Higgs-gluon or photon (or neutrino):

no LO coupling

but can be generated at higher orders!

Theoretical constraints

λ changes with energy scale Q due to self-interaction of the scalar field through the RGE:

$$\frac{d\lambda}{dt} = \beta(\lambda) = \frac{3\lambda^2}{4\pi^2} \quad \text{where} \quad t = \ln(Q^2/Q_0^2)$$

- Triviality/perturbativity

  $\rightarrow$ At one loop, for large M_H:

$$\lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln(Q^2/Q_0^2)}$$

  A pole can be reached for large $Q \Rightarrow M_H \lesssim 160$ GeV

- Vacuum stability

  $\lambda(Q) > 0$ needed

  $\rightarrow$ Imposes a lower limit on the Higgs mass: $\Rightarrow M_H \gtrsim 130 + 2(\overline{m_t} - 170)$ GeV
  $\rightarrow$ close to the observed Higgs mass!

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Theoretical constraints

- Unitarity

  $2 \to 2$ scattering amplitude decomposition: $\mathcal{A} = 16\pi \sum_l (2l+1) P_l(\cos\theta) a_l$

  Optical theorem requires: $|\mathrm{Re}(a_l)| < 1/2$

  One can show:

$$a_0(W_L^+ W_L^- \to W_L^+ W_L^-) = -\frac{M_H^2}{16\pi v^2}\left[2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s}\ln\left(1 + \frac{s}{M_H^2}\right)\right]$$

  Unitary condition $|\mathrm{Re}(a_0)| < 1/2 \Rightarrow M_H < 870$ GeV

- Naturalness

  One loop corrections to the Higgs mass depend quadratically on a scale cut-off Λ:

$$\delta M_H^2 = \frac{3}{8\pi v^2}\Lambda^2(6M_W^2 + 3M_Z^2 + 3M_H^2 - 12m_t^2) \sim -\left(\frac{\Lambda}{0.35\ \mathrm{TeV}}\ 100\ \mathrm{GeV}\right)^2$$

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Higgs decays

Higgs decay channels

Definitions: $G_F = v^{-2}/\sqrt{2}, \quad \tau_i = 4m_i^2/M_H^2, \quad \beta_i = \sqrt{1-\tau_i}$

- Higgs to fermions

  At leading order ($N_c^{(q)} = 3, N_c^{(\ell)} = 1$):

$$\Gamma(H \to f\bar{f}) = \frac{G_F M_H}{4\sqrt{2}\pi} N_c^{(f)} m_f^2 \beta_f^3$$

  At higher orders, large QCD corrections to decays to quarks:

$$\Gamma(H \to q\bar{q}) = \frac{3 G_F M_H}{4\sqrt{2}\pi} \bar{m}_q^2 \beta_q^3 (1 + \Delta_{qq} + \Delta_H^2)$$

$$\Delta_{qq} = 5.67 \frac{\bar{\alpha}_s(M_H)}{\pi} + (35.94 - 1.36 N_f) \frac{\bar{\alpha}_s^2(M_H)}{\pi^2} + (164.14 - 25.77 N_f + 0.26 N_f^2) \frac{\bar{\alpha}_s^3(M_H)}{\pi^3}$$

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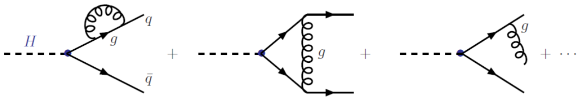

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- Higgs to ZZ and WW

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{16\sqrt{2}\pi} \, \delta_V \sqrt{1-4x}\,(1 - 4x + 12x^2) \; , \quad x = \frac{M_V^2}{M_H^2}$$

with $\delta_W = 2$ and $\delta_Z = 1$

If the channel is not open, we still can have one off-shell gauge boson):

$$\Gamma(H \to VV^*) = \frac{3 G_F^2 M_V^4}{16\pi^3} M_H \delta'_V R_T(x)$$

with $\delta'_W = 1$, $\delta'_Z = \frac{7}{12} - \frac{10}{9}\sin^2\theta_W + \frac{40}{9}\sin^4\theta_W$ and

$$R_T(x) = \frac{3(1-8x+20x^2)}{(4x-1)^{1/2}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2 - 13x + 47x^2) - \frac{3}{2}(1 - 6x + 4x^2)\log x$$

In fact: $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ and $H \to W^\pm W^{\mp *} \to \ell^+\bar{\nu}\ell^-\nu$

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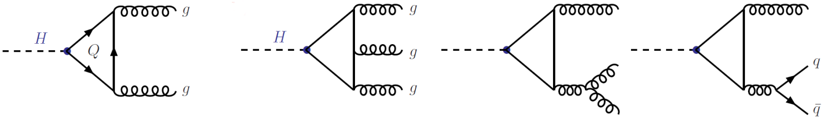
- Higgs to gluons



$$\Gamma_{\rm LO}(H \to gg) = \frac{G_F\, \alpha_s^2\, M_H^3}{36\,\sqrt{2}\,\pi^3} \left| \frac{3}{4} \sum_Q A_{1/2}^H(\tau_Q) \right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1) f(\tau)]\, \tau^{-2}$$

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} & \tau \leq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

NLO corrections:

$$\Gamma(H \to gg(g),\ gq\bar{q}) = \Gamma_{\rm LO}(H \to gg) \left[1 + E_H(\tau_Q)\frac{\alpha_s}{\pi}\right]$$

$$E_H(\tau_Q) = \frac{95}{4} - \frac{7}{6} N_f + \frac{33 - 2N_f}{6} \log \frac{\mu^2}{M_H^2} + \Delta E_H(\tau_Q)$$

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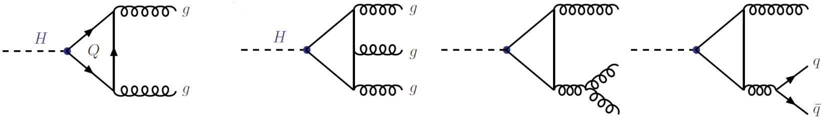

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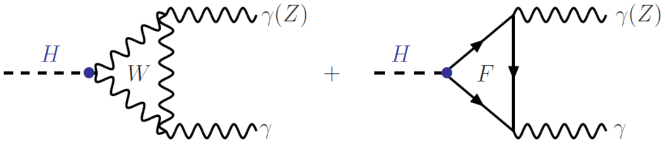


$$\Gamma(H \to \gamma\gamma) = \frac{G_F\,\alpha^2\,M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W)\right|^2$$

with the form factors for spin–$\frac{1}{2}$ and spin–1 particles given by

$$\begin{aligned} A_{1/2}^H(\tau) &= 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2} \\ A_1^H(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2} \end{aligned}$$

Higgs decay channels

- Higgs to $Z\gamma$

$$\Gamma(H \to Z\gamma) = \frac{G_\mu^2 M_W^2 \, \alpha \, M_H^3}{64\,\pi^4} \left(1 - \frac{M_Z^2}{M_H^2}\right)^3 \left| \sum_f N_f \frac{Q_f \hat{v}_f}{c_W} A_{1/2}^H(\tau_f, \lambda_f) + A_1^H(\tau_W, \lambda_W) \right|^2$$

with $\tau_i = 4M_i^2/M_H^2$, $\lambda_i = 4M_i^2/M_Z^2$ and the form factors

$$\begin{aligned} A_{1/2}^H(\tau,\lambda) &= [I_1(\tau,\lambda) - I_2(\tau,\lambda)] \\ A_1^H(\tau,\lambda) &= c_W \left\{ 4\left(3 - \frac{s_W^2}{c_W^2}\right) I_2(\tau,\lambda) + \left[\left(1 + \frac{2}{\tau}\right)\frac{s_W^2}{c_W^2} - \left(5 + \frac{2}{\tau}\right)\right] I_1(\tau,\lambda) \right\} \end{aligned}$$

with $\hat{v}_f = 2I_f^3 - 4Q_f s_W^2$ and

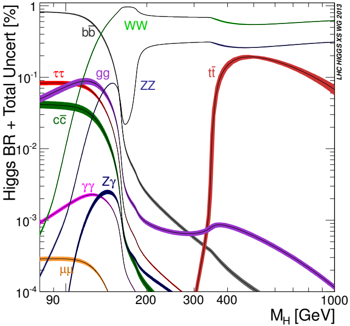
$$\begin{aligned} I_1(\tau,\lambda) &= \frac{\tau\lambda}{2(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}\left[f(\tau^{-1}) - f(\lambda^{-1})\right] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}\left[g(\tau^{-1}) - g(\lambda^{-1})\right] \\ I_2(\tau,\lambda) &= -\frac{\tau\lambda}{2(\tau-\lambda)}\left[f(\tau^{-1}) - f(\lambda^{-1})\right] \end{aligned}$$

with

$$g(\tau) = \begin{cases} \sqrt{\tau^{-1} - 1}\,\arcsin\sqrt{\tau} & \tau \geq 1 \\ \dfrac{\sqrt{1-\tau^{-1}}}{2}\left[\log\dfrac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right] & \tau < 1 \end{cases}$$

Higgs decay channels

Higgs decay branching fractions:



$H \to b\bar{b}$ main channel for $M_H \sim 125$ GeV

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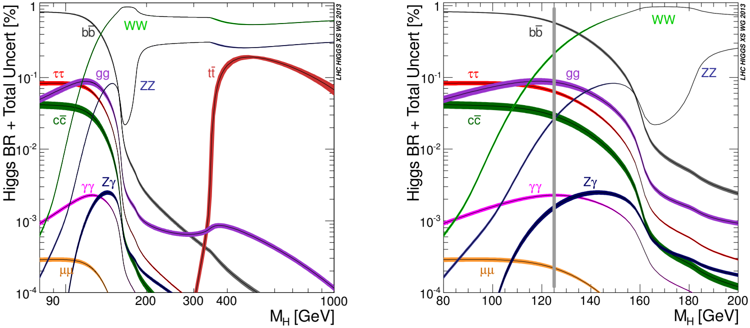

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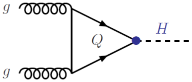
Higgs production

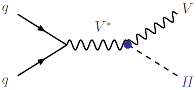
Higgs production channels

Main channels at the LHC

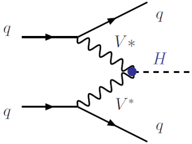
- gluon fusion:



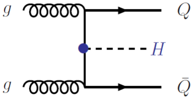
- associated production with Z or W:



- vector boson fusion:



- associated production with heavy quarks:



- (double Higgs production)

Gluon fusion

Gluon fusion process at partonic level:

$$\sigma_{\rm LO}(gg \to H) \equiv \sigma_0^H \, M_H^2 \, \delta(\hat{s} - M_H^2) \;=\; \frac{\pi^2}{8 M_H} \, \Gamma_{\rm LO}(H \to gg) \, \delta(\hat{s} - M_H^2)$$

In the narrow width approximation, the hadronic level is obtained by:

$$\sigma_{\rm LO}(pp \to H) = \int_\tau^1 \frac{dx}{x} \; \sigma_0^H \tau_H \, g(x, \mu_F^2) \, g(\tau/x, \mu_F^2)$$

where s being the invariant collider energy squared and $\tau_H = M_H^2/s$

$g(x, \mu_F^2)$ is the gluon parton density (PDF) at the factorisation scale μ_F

At higher orders, other diagrams appear $\to$ complicated, large uncertainties from PDFs

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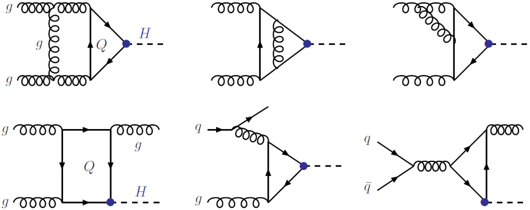
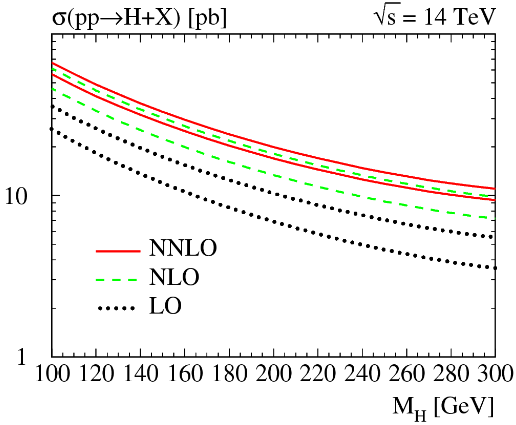


Gluon fusion

Importance of higher order corrections



Higher order calculation needed for precision Higgs searches

Associated production with a vector boson

Partonic level, at leading order:

$$\sigma_{\rm LO}(q\bar{q} \to VH) = \frac{G_F^2 M_V^4}{288\pi\hat{s}}(\hat{v}_q^2 + \hat{a}_q^2)\lambda^{1/2}(M_V^2, M_H^2; \hat{s})\frac{\lambda(M_V^2, M_H^2; \hat{s}) + 12M_V^2/\hat{s}}{(1 - M_V^2/\hat{s})^2}$$

with $\lambda(x, y; z) = (1 - x/z - y/z)^2 - 4xy/z^2$, $\hat{a}_f = 2I_f^3$, $\hat{v}_f = 2I_f^3 - 4Q_f s_W^2$ for $V = Z$ and $\hat{v}_f = \hat{a}_f = \sqrt{2}$ for $V = W$
to be convoluted with the PDF to obtain the hadronic cross section

More generally:

$$\frac{{\rm d}\sigma}{{\rm d}k^2}(pp \to HV + X) = \sigma(pp \to V^* + X) \times \frac{{\rm d}\Gamma}{{\rm d}k^2}(V^* \to HV)$$

$$\frac{{\rm d}\Gamma}{{\rm d}k^2}(V^* \to HV) = \frac{G_F M_V^4}{2\sqrt{2}\pi^2}\frac{\lambda^{1/2}(M_V^2, M_H^2; k^2)}{(k^2 - M_V^2)^2}\left(1 + \frac{\lambda(M_V^2, M_H^2; k^2)}{12M_V^2/k^2}\right)$$

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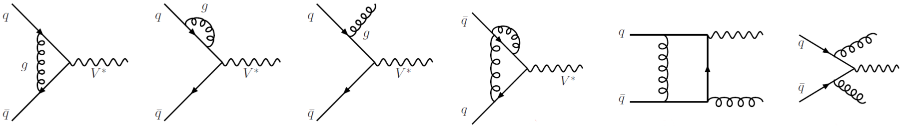

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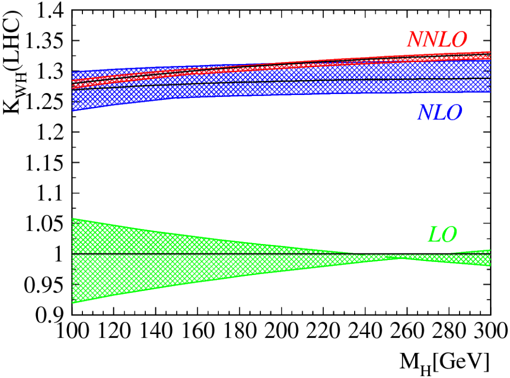
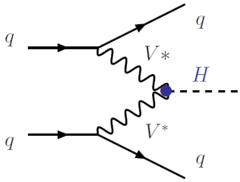
Importance of higher order corrections

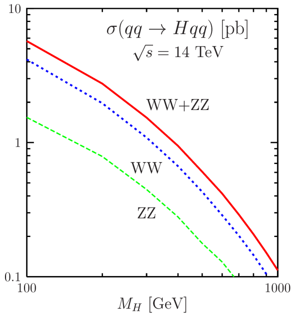
$$K_{WH} \equiv \frac{\sigma_{\rm HO}(pp \to H + W)}{\sigma_{\rm LO}(pp \to H + W)}$$



Vector boson fusion

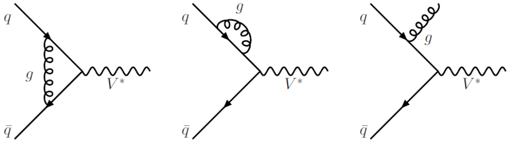


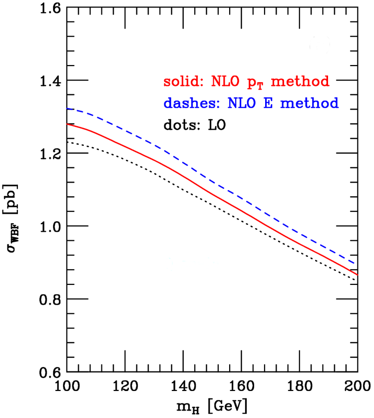
Calculation with off-shell vector bosons: $qq \to V^*V^*qq \to Hqq$



Vector boson fusion

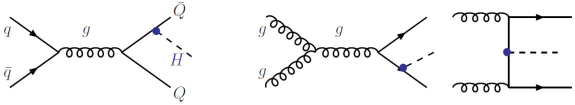
NLO corrections through vertex corrections:

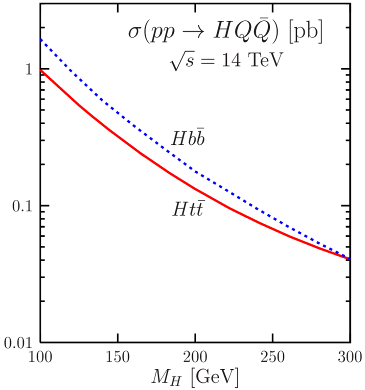




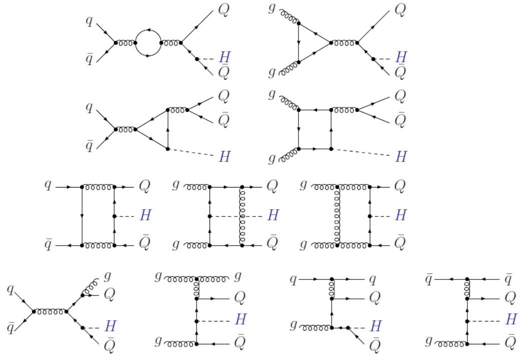
(NLO p_T/E methods: methods for tagging the forward jets, either with p_T or E)

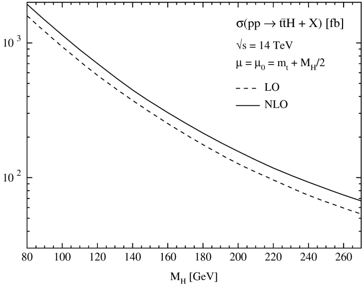
Associated production with heavy quarks



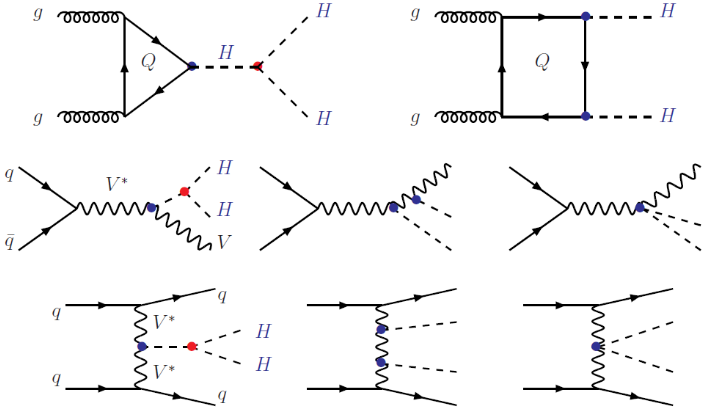


NLO corrections:



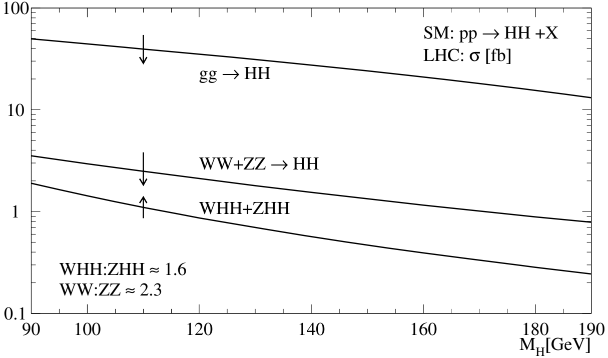


Double Higgs production



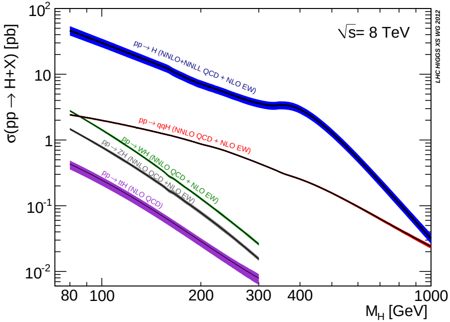
Very important processes to probe the triple Higgs coupling!

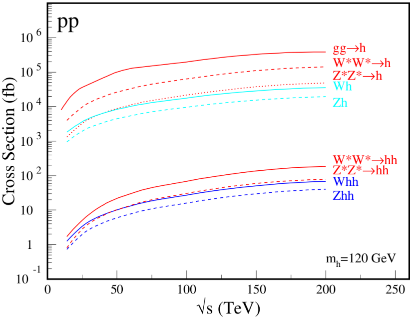
Double Higgs production



The vertical arrows correspond to a modification of the trilinear Higgs coupling from 0.5 to 1.5 times the SM value.

Main channels at the LHC





→ Uncertainties represented by the line widths

Higgs signal strengths at the LHC

Signal strength:

$$\mu_{XX} = \frac{\sigma(pp \to H)\,\mathrm{BR}(H \to XX)}{\sigma(pp \to H)_{\mathrm{SM}}\,\mathrm{BR}(H \to XX)_{\mathrm{SM}}}$$

Latest results:

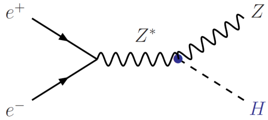
Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 0.4	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.20 ± 0.30	ATLAS+CMS
μ_{ZZ}	1.10 ± 0.22	ATLAS+CMS
μ_{WW}	0.77 ± 0.21	ATLAS+CMS
$\mu_{b\bar{b}}$	1.12 ± 0.45	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	1.01 ± 0.36	ATLAS+CMS

$\rightarrow$ diphoton decay mode $\Rightarrow$ massive neutral boson with spin $\neq 1$
$\rightarrow$ compatible with the SM Higgs
$\rightarrow$ still too early for conclusive information from couplings/rates

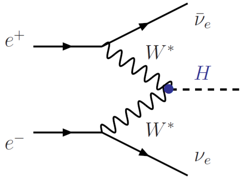
Higgs production channels at electron-positron colliders

Main channels at e^+e^- colliders

- Higgs-strahlung:



- WW fusion:

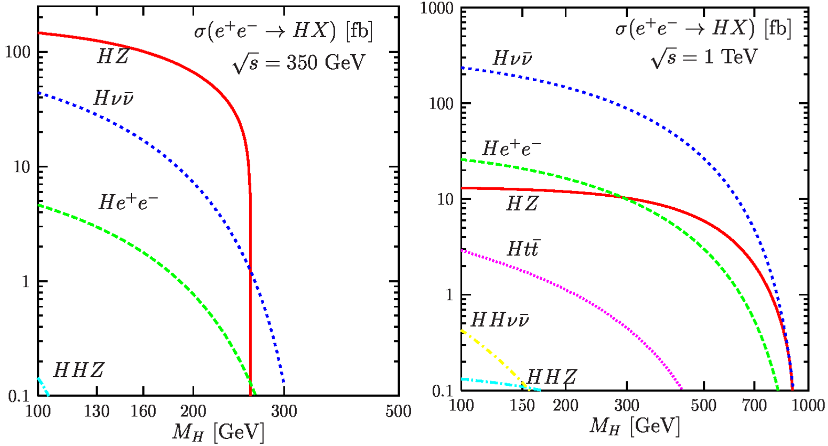


Other channels:

- ZZ fusion: $e^+e^- \to e^+e^-(Z^*Z^*) \to e^+e^-H$
- radiation of heavy fermions: $e^+e^- \to (\gamma^*, Z^*) \to f\bar{f}H$
- double Higgs production: $e^+e^- \to ZHH, \ell\ell HH$

Higgs production channels at electron-positron colliders

Main channels at e^+e^- colliders



Two Higgs doublet model

Two Higgs doublet model (2HDM)

General two Higgs doublet model:

- Based on the presence of two Higgs doublets
- Minimal extension of the SM Higgs sector
- Richer phenomenology by predicting several Higgs bosons
- Can even provide a Dark Matter candidate (Inert 2HDM): one Higgs stable thanks to D symmetry $\rightarrow$ dark matter
- Needed for the MSSM

Two Higgs doublet model: potential

Two Higgs doublets:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad\qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

General potential:

$$\begin{aligned} V_{\rm 2HDM} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ & + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\ & + \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\} \end{aligned}$$

$\rightarrow$ 10 parameters: m_{11}, m_{12}, m_{22} and λ_i $(i = 1 \cdots 7)$

m_{12}, λ_5, λ_6, λ_7 can have complex phases and generate CP violation

For simplicity reasons (or assuming a Z_2 symmetry), one can take $\lambda_6 = \lambda_7 = 0$

Two Higgs doublet model: parameters

2 VEV, minimum reached for:

$$\Phi_1 = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}$$

such as

$$v_1^2 + v_2^2 = v^2 \approx (246\ \mathrm{GeV})^2$$

Definition:

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

m_{11} and m_{22} can be accounted by v_1 and v_2, or by v and $\tan\beta$

$\rightarrow$ 7 parameters: m_{12}, λ_i $(i = 1 \cdots 5)$ and $\tan\beta$

2 complex scalar doublets $\rightarrow$ 8 degrees of freedom

$\rightarrow$ 3 d.o.f. used for the gauge bosons $\Rightarrow$ 5 d.o.f. remaining

$\rightarrow$ 5 scalar particles (3 neutral, 2 charged): h, H, A, H^+, H^-

h and H are CP-even, and A is CP-odd

Two Higgs doublet model: Higgs masses

With these definitions:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \cos\beta - H^+ \sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G^0 \cos\beta - A\sin\beta\right) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \sin\beta + H^+ \cos\beta\right) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G^0 \sin\beta + A\cos\beta\right) \end{pmatrix}$$

where G^0, G^+ (and G^-) are the unphysical Goldstone bosons

α: CP-even Higgs mixing angle

Higgs boson masses related to the model parameters:

$$m_A^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \lambda_5 v^2 \,, \qquad m_{H^+}^2 = m_A^2 + \frac{1}{2} v^2 (\lambda_5 - \lambda_4)$$

$$m_{H,h}^2 = \frac{1}{2}\left[\mathcal{M}_{11}^2 + \mathcal{M}_{22}^2 \pm \sqrt{(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2)^2 + 4\,(\mathcal{M}_{12}^2)^2}\right]$$

where $\mathcal{M}$ is the mass matrix:

$$\mathcal{M}^2 = m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 & (\lambda_3 + \lambda_4) s_\beta c_\beta \\ (\lambda_3 + \lambda_4) s_\beta c_\beta & \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 \end{pmatrix}$$

Two Higgs doublet model: Yukawa sector

Stability conditions:

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

The five λ_i parameters can be exchanged with the four Higgs masses and the α angle

General Yukawa Lagrangian assuming CP conservation:

$$\mathcal{L}_Y = \overline{Q}_L \widetilde{\Phi}_1 \eta_1^U U_R + \overline{Q}_L \Phi_1 \eta_1^D D_R + \overline{Q}_L \Phi_1 \eta_1^L L_R + \overline{Q}_L \widetilde{\Phi}_2 \eta_2^U U_R + \overline{Q}_L \Phi_2 \eta_2^D D_R + \overline{Q}_L \Phi_2 \eta_2^L L_R$$

where $\widetilde{\Phi}_i \equiv i\sigma_2 \Phi_i^*$, and η_i^F $(F = U, D, L)$ are real 3×3 Yukawa matrices related to the fermion mass matrices M^F by:

$$M^F = \frac{v}{\sqrt{2}} \left(\eta_1^F \cos\beta + \eta_2^F \sin\beta \right) \tag{1}$$

We introduce:

$$\kappa^F \equiv \eta_1^F \cos\beta + \eta_2^F \sin\beta$$

and

$$\rho^F \equiv -\eta_1^F \sin\beta + \eta_2^F \cos\beta$$

Two Higgs doublet model: Yukawa sector

With the physical scalars:

$$\begin{aligned}\mathcal{L}_{\rm Y} =& \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D\sin(\beta-\alpha)+\rho^D\cos(\beta-\alpha)\Big]Dh\\ &+\frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D\cos(\beta-\alpha)-\rho^D\sin(\beta-\alpha)\Big]DH+\frac{\rm i}{\sqrt{2}}\overline{D}\gamma_5\rho^D DA\\ &+\frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U\sin(\beta-\alpha)+\rho^U\cos(\beta-\alpha)\Big]Uh\\ &+\frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U\cos(\beta-\alpha)-\rho^U\sin(\beta-\alpha)\Big]UH-\frac{\rm i}{\sqrt{2}}\overline{U}\gamma_5\rho^U UA\\ &+\frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L\sin(\beta-\alpha)+\rho^L\cos(\beta-\alpha)\Big]Lh\\ &+\frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L\cos(\beta-\alpha)-\rho^L\sin(\beta-\alpha)\Big]LH+\frac{\rm i}{\sqrt{2}}\overline{L}\gamma_5\rho^L LA\\ &+\Big[\overline{U}\big(V_{\rm CKM}\rho^D P_R-\rho^U V_{\rm CKM}P_L\big)DH^+ +\overline{\nu}\rho^L P_R LH^+ +{\rm h.c.}\Big]\end{aligned}$$

$\kappa^F \propto M^F \Rightarrow \kappa^F$ diagonal

However, ρ^F in general is not diagonal

$\rightarrow$ flavour changing neutral currents (FCNC)

Two Higgs doublet model: types

Possible (general) assumption to suppress the FCNC:

each fermion type (U, D or L) couples only to one Higgs doublet

i.e. $\eta_1^F = 0$ or $\eta_2^F = 0 \Leftrightarrow \rho^F = \kappa^F \cot\beta$ or $\rho^F = -\kappa^F \tan\beta$

Usual assumption to avoid FCNC:

Z_2 symmetry under which one Higgs doublet and some right-handed fermions are odd

$\Rightarrow$ definition of the 2HDM *types*: 4 types (I–IV) by convention

Type	U_R	D_R	L_R	ρ^U	ρ^D	ρ^L
I	$+$	$+$	$+$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
II	$+$	$-$	$-$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$
III	$+$	$-$	$+$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$
IV	$+$	$+$	$-$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

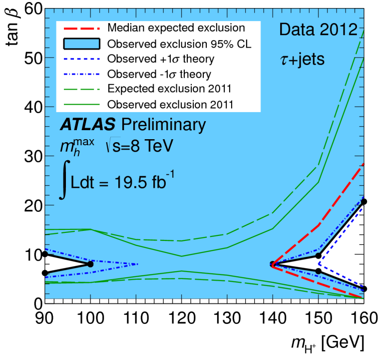
$+ =$ odd, $- =$ even

The Higgs sector of the MSSM corresponds to the 2HDM type II

Strong constraints due to the presence of a charged Higgs

$H^{\pm}$ has a flavour changing capability, as $W^{\pm}$

$\rightarrow$ Direct searches for example based on $t \rightarrow bH^{+}$ decay



ATLAS-CONF-2013-090

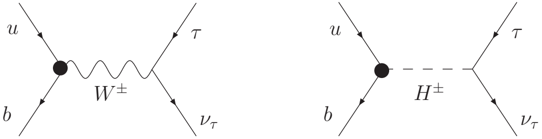
Limit on the MSSM charged Higgs also valid for the 2HDM type II

Two Higgs doublet model: flavour constraints

Very strong constraints from flavour physics through indirect effects

For example, $B \to \tau\nu$:

Tree level process, mediated by W^+ in the SM, and also H^+ in the 2HDM



$$\frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{2HDM-II}}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{SM}}} = \left[1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right]^2$$

$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (1.15 \pm 0.29) \times 10^{-4}$
Experimental average (ICHEP 2012): $\mathrm{BR}(B \to \tau\nu) = (1.14 \pm 0.23) \times 10^{-4}$

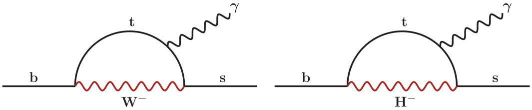
with $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ and $f_B = 194 \pm 10$ MeV

Similar processes: $B \to D\tau\nu_\tau$, $D_s \to \ell\nu_\ell$, $D \to \mu\nu_\mu$, $K \to \mu\nu_\mu$, ...

Two Higgs doublet model: flavour constraints

Inclusive branching ratio of $B \to X_s\gamma$

Contributing loops:



- SM contributions known to NNLO accuracy
- 2HDM contributions known to NNLO accuracy

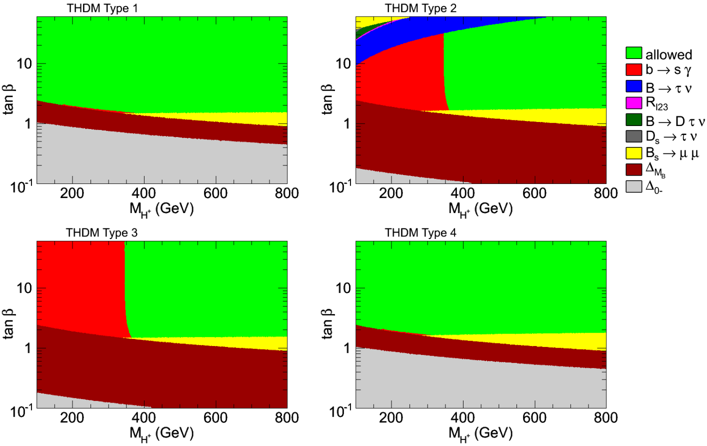
SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.08 \pm 0.24) \times 10^{-4}$

SuperIso v3.4

Experimental values (HFAG 2012): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$

$\rightarrow$ Strong constraints on the Higgs sector

Two Higgs doublet model: flavour constraints



SuperIso v3.4

- $M_{H^\pm} < 340$ GeV is excluded at 95% C.L. in Types 2 and 3 for any $\tan\beta$
- $\tan\beta < 2$ is excluded by several observables: $b \to s\gamma$, $\Delta_0(B \to K^*\gamma)$, ΔM_{B_d} and now even $B_s \to \mu^+\mu^-$!

Minimal Supersymmetric Standard Model (MSSM)

Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry: symmetry relating bosons and fermions ($\rightarrow$ Lie superalgebra)

Minimal Supersymmetric extension of the Standard Model (MSSM)

- Includes super partners of the SM particles:
  squarks, sleptons, gauginos and higgsinos

  gauginos + higgsinos mix to 2 charginos + 4 neutralinos

  2 Higgs doublets, 2HDM type II $\rightarrow$ 5 physical Higgs bosons

  $\rightarrow$ ensure anomaly cancellation
- Supersymmetry must be broken
- How SUSY is broken is irrelevant for phenomenology
- This is the mediation mechanism and the associated scale of SUSY breaking which is important
- Lightest SUSY particle (LSP) is stable if R-parity is conserved
  $R = (-1)^{2S-L+3B}$ $\quad S =$ spin, $L =$ lepton nb, $B =$ baryon nb
  $R = +1$ for SM particles and $R = -1$ for sparticles

Constrained MSSM scenarios

General MSSM

- Many free parameters
- Very difficult to perform systematic studies

A way out: Constrained MSSM scenarios

- Assume universality at GUT scale

  → Reduces the number of free parameters to a handful!

- Most well known scenario: CMSSM (or mSUGRA)

  Universal parameters: scalar mass m_0, gaugino mass $m_{1/2}$, trilinear soft coupling A_0 and Higgs parameters (sign of μ and $\tan\beta$)

  → Very useful for phenomenology, benchmarking, model discrimination, ...

  → But not representative of the whole MSSM!

Beyond constrained scenarios

Going beyond constrained scenarios

- CMSSM is a useful "exercise" but we need to go beyond!
- Some signatures can be overlooked and conclusions can be very different!
- Important to know how the results change when moving to general MSSM

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$
3 gaugino masses: M_1, M_2, M_3
3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$
3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

MSSM Higgs sector

Higgs part of the supersymmetric potential:

$$V_H = (|\mu|^2 + m_1^2)|\Phi_1|^2 + (|\mu|^2 + m_2^2)|\Phi_2|^2 - B\mu\epsilon_{ij}(\Phi_1^i \Phi_2^j + \mathrm{h.c.})$$
$$+ \frac{g_1^2 + g_2^2}{8}(|\Phi_1|^2 - |\Phi_2|^2) + \frac{g_1^2}{2}|\Phi_1^\dagger \Phi_2|^2$$

μ parameter: Higgsino mass term

B: SUSY breaking term parameter

$\tan\beta \equiv \frac{v_1}{v_2}$, α: CP-even Higgs mixing angle

All Higgs tree level masses can be re-expressed in terms of M_A and $\tan\beta$:

$$M_{H,h}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right)$$
$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

Problem (at tree level): $M_h^2 \leq M_Z^2 \cos^2 2\beta \leq M_Z^2$!

MSSM light Higgs mass

- At leading order:

$$M_h^2 = M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right]$$

- Large one-loop correction from top/stop loops:

$$(\Delta M_h^2)_{\tilde{t}} \approx \frac{3\sqrt{2}G_F}{2\pi^2}\, m_t^4 \left[-\log\left(\frac{m_t^2}{M_S^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

with $X_t = A_t - \mu/\tan\beta$ and $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

The maximal value can be reached for $X_t = \sqrt{6} M_S$ (maximal mixing)

- Contributions from sbottoms and staus in the large $\tan\beta$ limit

$$(\Delta M_h^2)_{\tilde{f}} \approx -\frac{N_c^{\tilde{f}}}{\sqrt{2}G_F}\, \frac{y_f^4}{96\pi^2}\, \frac{\mu^4}{m_{\tilde{f}}^4}$$

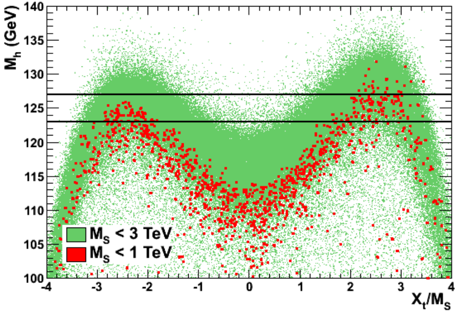
where $N_c^{\tilde{b}} = 3,\ N_c^{\tilde{\tau}} = 1,\ m_{\tilde{f}}^2 = m_{\tilde{f}_1} m_{\tilde{f}_2}$

MSSM light Higgs mass

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right] + \frac{3m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t = \sqrt{6} M_S$
- In contrast, much smaller M_h^{max} values for the no-mixing scenario, *i.e.* $X_t \approx 0$

MSSM light Higgs mass

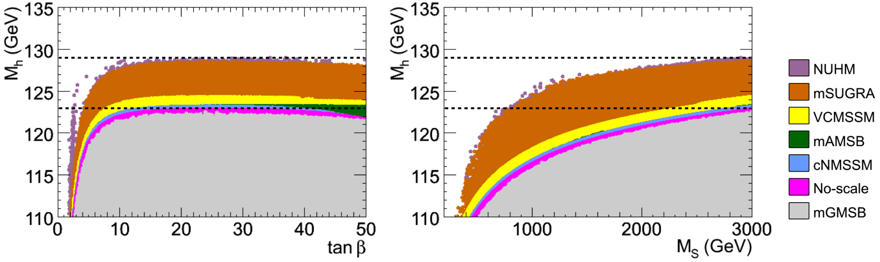


$M_h \sim 125$ GeV is easily satisfied in pMSSM

No mixing cases ($X_t \approx 0$) excluded for small M_S

Higgs mass and constrained MSSM scenarios

Maximal Higgs mass in constrained MSSM scenarios

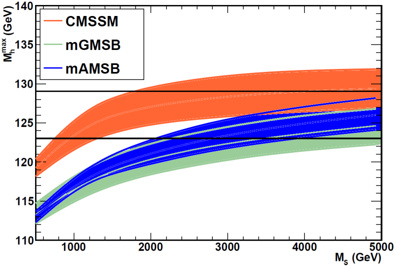


Several constrained models are excluded or about to be!
But CMSSM is still surviving!

MSSM Higgs mass and top mass

Impact of m_t on the Higgs mass:

m_t =170, 173 and 176 GeV



The variations in the top mass is directly transmitted to the Higgs mass!

That can even resurrect mGMSB!

MSSM Higgs boson couplings

Modified couplings with respect to the SM Higgs boson
($\rightarrow$ decoupling limit: $M_A \gg M_Z$):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha / \sin\beta \rightarrow 1$	$-\sin\alpha / \cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha / \sin\beta \rightarrow \cot\beta$	$\cos\alpha / \cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$\cot\beta$	$\tan\beta$	0

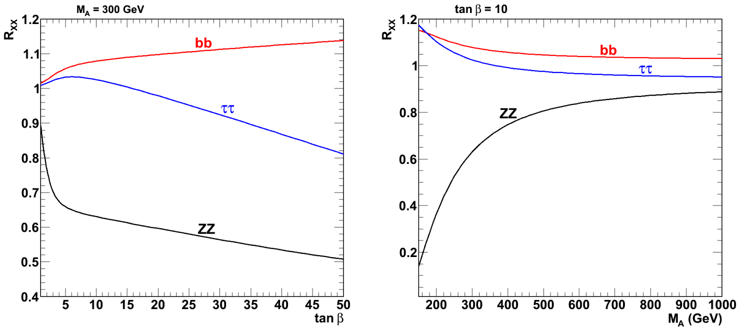
where:

$$\alpha = \frac{1}{2} \arctan\left(\tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\right)$$

Higher order corrections to the tree level couplings can be large for light SUSY particles

MSSM light Higgs couplings and decoupling limit

$$R_{XX} \equiv \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$



In the decoupling limit (large M_A, small $\tan\beta$), the light CP-even Higgs is SM-like

MSSM regimes

Particular benchmark scenario: maximal mixing ($X_t \approx \sqrt{6} M_S$):

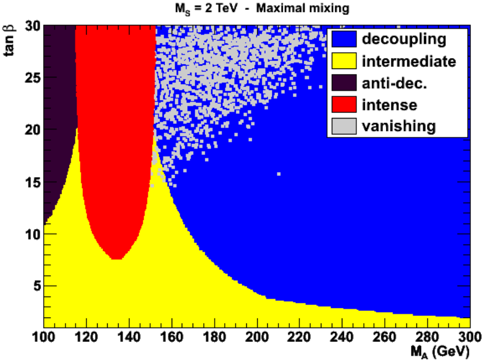
Decoupling regime:
large M_A, $\cos^2(\beta-\alpha) \leq 0.05$

Intermediate regime:
intermediate M_A

Anti-decoupling regime:
small M_A, $\cos^2(\beta-\alpha) \geq 0.95$

Intense coupling:
h, A, H rather close in mass,
g^2_{hbb} and $g^2_{Hbb} \geq 50$

Vanishing coupling:
g^2_{hbb} or $g^2_{hVV} \leq 0.05$



Green: LEP Higgs search limit

Solid black line: CMS $A/H \to \tau^+\tau^-$ search limit at 7+8 TeV with 17/fb

Dotted cyan line: ATLAS $t \to H^+ b$ search limit at 7 TeV with 4.6/fb

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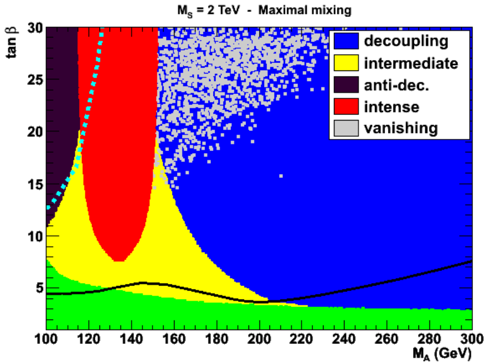

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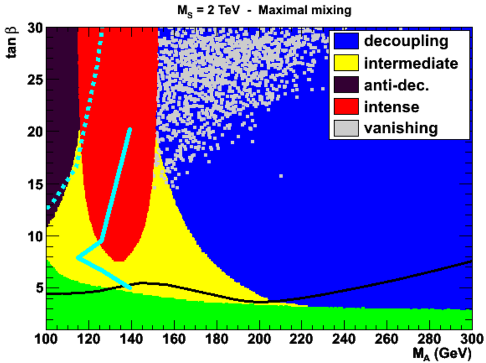

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Anatomy of MSSM light Higgs production

Main Higgs production channel at the LHC: $gg \to h$

$$R_h = \frac{\sigma(gg \to h)_{\rm MSSM}}{\sigma(gg \to h)_{\rm SM}} \approx \left(1 + \sum_{i=\tilde{t},\tilde{b}} \kappa_i\right)^2$$

where

$$\kappa_{\tilde{t}} \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

and

$$\kappa_{\tilde{b}} \approx -\frac{m_b^2 X_b^2}{4 m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2}$$

with where $X_b = A_b - \mu \tan\beta$.

A Higgs boson mass around 125 GeV calls for close to maximal mixing, natural to expect suppression of $gg \to h$.

Anatomy of MSSM light Higgs decays

$$\frac{\Gamma(h \to VV)_{\rm MSSM}}{\Gamma(h \to VV)_{\rm SM}} = (1+\kappa_V)^2 \qquad \frac{\Gamma(h \to \bar{f}f)_{\rm MSSM}}{\Gamma(h \to \bar{f}f)_{\rm SM}} = (1+\kappa_f)^2$$

The Higgs-boson couplings to massive gauge-boson pairs are affected in a universal and destructive way:

$$\kappa_Z \approx \kappa_W \approx -\frac{M_Z^4}{8M_A^4}\,\sin^2(4\beta)$$

The shifts in the tree-level couplings of the Higgs-boson to fermion pairs all fall off quadratically in the limit $M_A^2 \gg M_Z^2$:

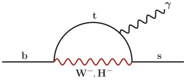
$$\kappa_b \approx \kappa_\tau \approx -\frac{2M_Z^2}{M_A^2}\,\sin^2\beta\,\cos(2\beta)$$

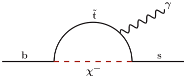
The diphoton channel receives contributions from stop, sbottom, stau, charged Higgs boson, and chargino loops:

$$\kappa_\gamma \approx \frac{1}{F_W - \frac{4}{3}}\left[-\frac{4}{3}\kappa_{\tilde{t}} - \frac{1}{3}\kappa_{\tilde{b}} - \kappa_{\tilde{\tau}} + \kappa_{H^\pm} + \kappa_{\chi^\pm}\right]$$

Interplay with flavour physics

- BR($B \to X_s \gamma$)



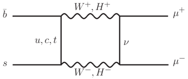


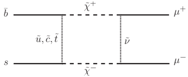
$$\frac{\mathrm{BR}(B \to X_s\gamma)_{\mathrm{MSSM}}}{\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}}} \approx 1 - 2.61\,\Delta C_7 + 1.66\,(\Delta C_7)^2$$

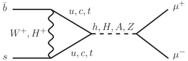
where $\Delta C_7^{H^\pm} \approx \frac{m_t^2}{3 M_{H^\pm}{}^2}\left(\ln \frac{m_t^2}{M_{H^\pm}{}^2} + \frac{3}{4}\right)$, $\quad \Delta C_7^{\chi^\pm} \approx -\mu A_t \tan\beta \frac{m_t^2}{m_{\tilde{t}}{}^4}\, g(x_{\tilde{t}\mu})$

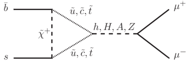
with $x_{\tilde{t}\mu} = m_{\tilde{t}}^2/\mu^2$ and $g(x) = -\frac{7x^2-13x^3}{12(1-x)^3} - \frac{2x^2-2x^3-3x^4}{6(1-x)^4}\ln x$

- BR($B_s \to \mu^+\mu^-$)







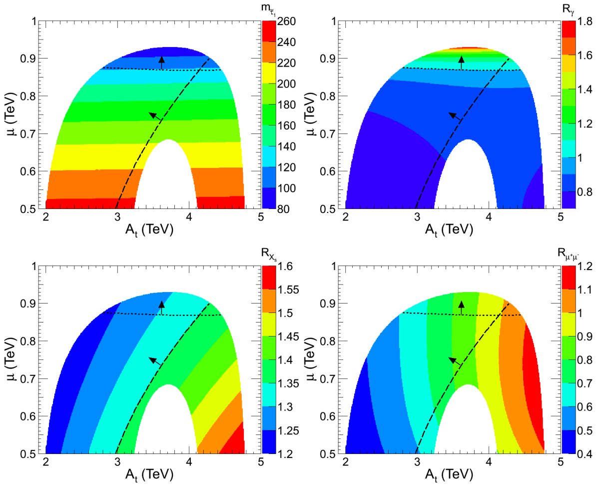


$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{MSSM}}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1 - 13.2\;C_P + 43.6\,(C_S^2 + C_P^2)$$

where $C_S \approx -C_P \approx -\mu A_t \frac{\tan^3\beta}{(1+\epsilon_b \tan\beta)^2}\frac{m_t^2}{m_{\tilde{t}}{}^2}\frac{m_b m_\mu}{4\sin^2\theta_W M_W^2 M_A{}^2} f(x_{\tilde{t}\mu})$

with $f(x) = -\frac{x}{1-x} - \frac{x}{(1-x)^2}\ln x$

Consequences in a scenario with light staus



Dotted line: $R_{\gamma\gamma} > 1$
Dashed line: constraint from $\text{BR}(\bar{B} \to X_s\gamma)$

Enhancement in diphoton rate strongly correlated with mass of lighter stau mass eigenstate and μ parameter.

In the preferred parameter space, $\text{BR}(B_s \to \mu^+\mu^-)$ smaller than SM.

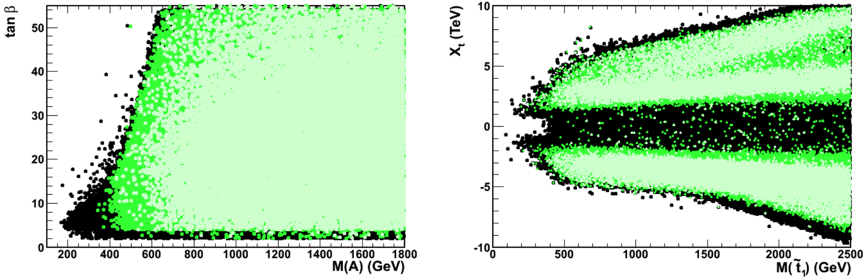
Signal strength is defined as:

$$\mu_{XX} \equiv \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

LHC results (+ theoretical uncertainty on Higgs mass):

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 2.1	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.20 ± 0.30	ATLAS+CMS
μ_{ZZ}	1.10 ± 0.22	ATLAS+CMS
μ_{WW}	0.77 ± 0.21	ATLAS+CMS
$\mu_{b\bar{b}}$	1.12 ± 0.45	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	1.01 ± 0.36	ATLAS+CMS

Consequences of the cross-section and decay rate measurements



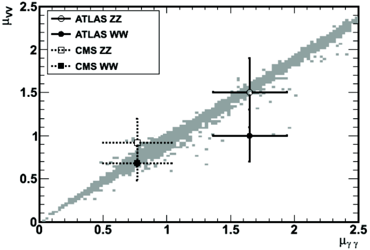
Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

→ $M_A < 350$ GeV disfavoured by the Higgs signal strengths (→ decoupling regime)
→ Still possible to have $M_{\tilde{t}} < 500$ GeV!
→ $|X_t| < 1.5$ TeV strongly disfavoured by the Higgs data

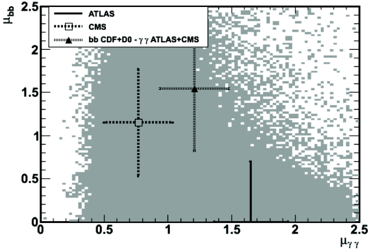
Consequences of the Higgs rate measurements in pMSSM

Correlations between the decay rates:

$\gamma\gamma - VV$



$\gamma\gamma - bb$



Experimental values compatible with the bulk of the pMSSM points

More statistics needed!

Heavy Higgs searches

MSSM Higgs sector can be strongly constrained also by Heavy Higgs searches

$\rightarrow$ In particular, $H/A \rightarrow \tau^+\tau^-$ searches are very constraining

However, the $M_h^{\max}$ scenario is assumed!

$\rightarrow$ Falsified if light SUSY particles and Higgs decays to MSSM particles open (i.e. decays to light staus)

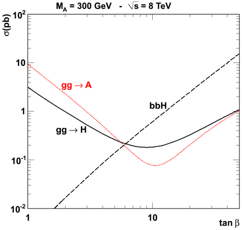
$\rightarrow$ Important to use several channels

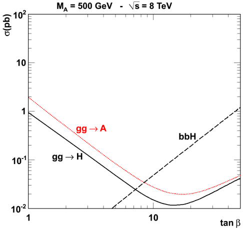
$\rightarrow$ **Look for other channels, with the largest strengths**

Heavy Higgs production in MSSM

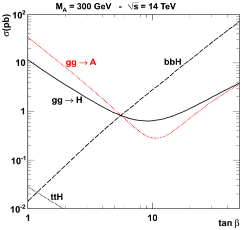
$M_A = 300$ GeV | $M_A = 500$ GeV

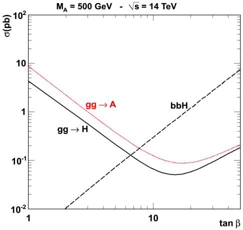
8 TeV





14 TeV



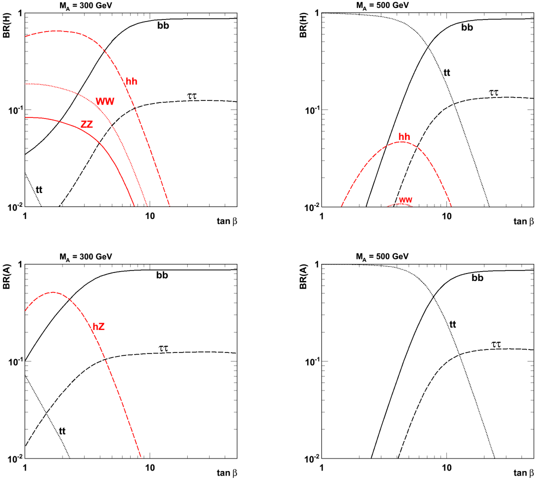


Heavy Higgs decays in MSSM

$M_A = 300$ GeV $\quad$ $M_A = 500$ GeV

H decays

A decays



Heavy Higgs search constraints

Decays of Heavy Higgs to $b\bar{b}$, ZZ, $t\bar{t}$ are also interesting!

→ Present search results for $H_{SM} \to ZZ$ and $H_{SM} \to b\bar{b}$ can be reinterpreted in MSSM

→ Future search limit predictions for $H_{SM} \to t\bar{t}, hh, Zh$ can also be derived

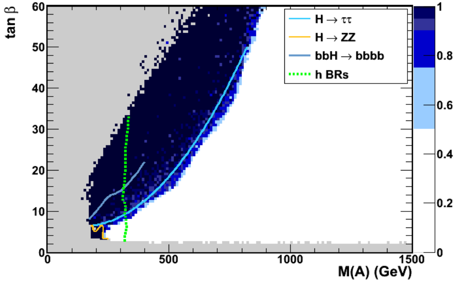
In the following, for each pMSSM point:

- Compute the MSSM signal strengths for the heavy Higgs bosons
- Compare the MSSM signal strengths to the current experimental measurements
- Determine if the point is excluded
- Derive limits in the $(M_A, \tan\beta)$ plane

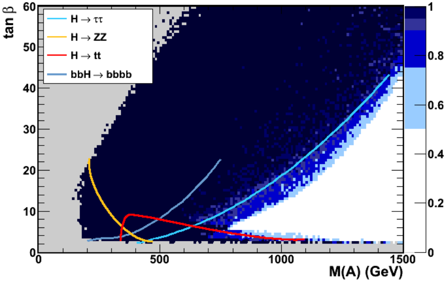
Heavy Higgs search constraints

Searches for heavy Higgs bosons mainly relies on $H/A \to \tau^+\tau^+$

8 TeV



14 TeV (150 fb^{-1})



lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
colour (blue) scale: fraction of excluded points

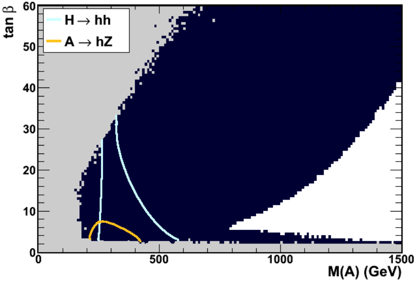
→ Some points inside the $H \to \tau\tau$ excluded region still survive

→ Other channels ($H \to ZZ$, $H \to t\bar{t}$, ...) will help probing the small $\tan\beta$ region

Heavy Higgs search constraints

Other future searches of interest: light Higgs production

14 TeV (150 fb^{-1})



lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
dark blue points: excluded by the other heavy Higgs searches

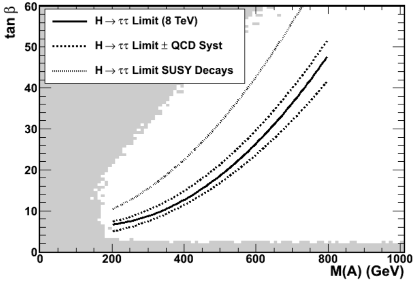
→ These channels will probe the small to intermediate $\tan\beta$ region

Heavy Higgs searches and uncertainties

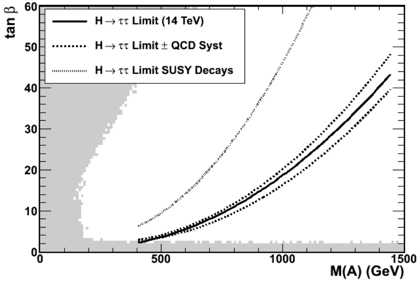
QCD uncertainties (PDF, α_s, m_t, ...) limiting factor for the $H/A \to \tau^+\tau^-$ constraints

Additional H to SUSY particle decays also limiting factor

8 TeV



14 TeV



Existence of SUSY decays much more limiting than QCD uncertainties

$\to$ **Exclusion limits should not be blindly applied**

Beyond pMSSM

- CP violating MSSM
  - CP phases in the MSSM Higgs sector
  - the 2 CP even and the CP odd Higgs bosons mix!
    $\rightarrow$ 3 Higgs bosons with CP even and CP odd components
  - Possibility of CP violating decays
- Next to Minimal Supersymmetric Standard Model (NMSSM)
  - one extra Higgs singlet
  - mixing of the singlet with the other Higgs bosons
  - 5 neutral Higgs bosons: 3 CP-even and 2 CP-odd bosons
  - charged Higgs bosons $H^{\pm}$
  - lightest Higgs can be much lighter than 126 GeV and escape detection
  - one extra neutralino
- ...

Conclusion

- SM Higgs mechanism: A great success story!
- Discovery of a Higgs boson turned a new page in the history of particle physics
- Important implications for beyond the SM scenarios
- Complementarity of the light and heavy Higgs searches for BSM models
- Of importance are also consistency checks using indirect searches

Precise measurement of all the Higgs couplings is of great importance to test fully the SM and pave the way to New Physics

Looking forward to the next LHC run data!

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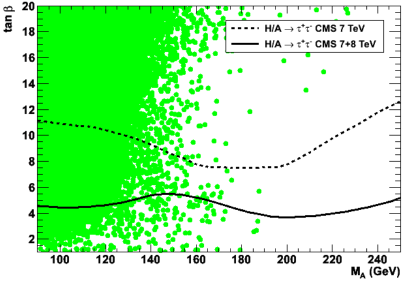
Extra slides

SM-like heavy CP-even Higgs

Light or heavy Higgs at 126 GeV??



Green: $122 < M_H < 129$ GeV

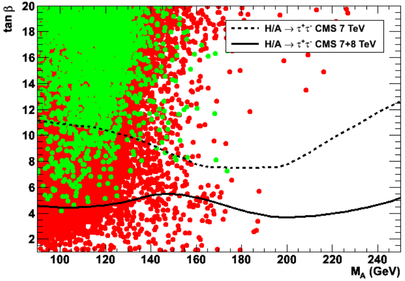
Red: + excluded by BR($B \to X_s \gamma$)

Blue: + excluded by BR($B \to \tau\nu$)

Yellow: + excluded by BR($B_s \to \mu^+\mu^-$)

→ 126 GeV heavy Higgs scenario excluded by flavour constraints

Light or heavy Higgs at 126 GeV??



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$\to$ **126 GeV heavy Higgs scenario excluded by flavour constraints**

SM-like heavy CP-even Higgs

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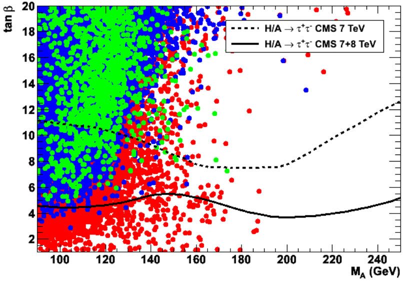

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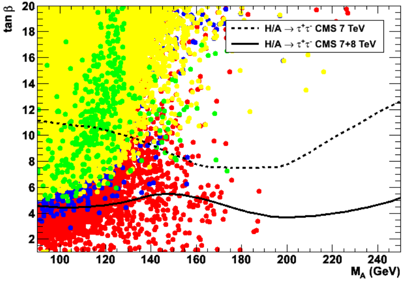
Light or heavy Higgs at 126 GeV??



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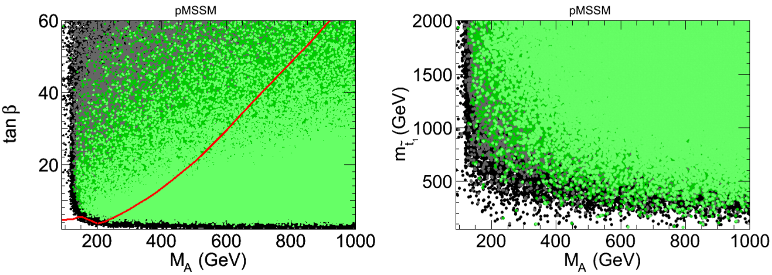
→ **126 GeV heavy Higgs scenario excluded by flavour constraints**

Constraints on pMSSM from BR($B_s \to \mu^+\mu^-$)

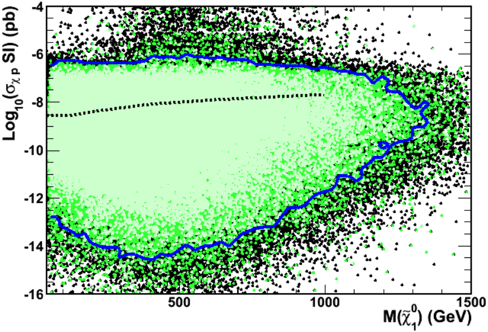
Same region also probed by BR($B_s \to \mu^+\mu^-$)...



Black points: all the valid pMSSM points
Gray points: $123 < M_h < 129$ GeV
Dark green points: in agreement with the latest BR($B_s \to \mu^+\mu^-$)
Light green points: in agreement with the ultimate LHCb BR($B_s \to \mu^+\mu^-$) measurement
Red line: excluded at 95% C.L. by the latest CMS $A/H \to \tau^+\tau^-$ searches

$\to$ **Strong constraints for small M_A and large $\tan\beta$**

... Same region also probed by dark matter direct detection



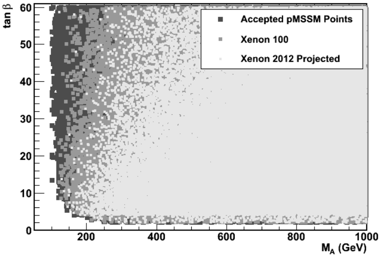
Black: all valid points
Dark green: points compatible at 90% C.L. with the LHC Higgs search results
Light green: points compatible at 68% C.L. with the LHC Higgs search results

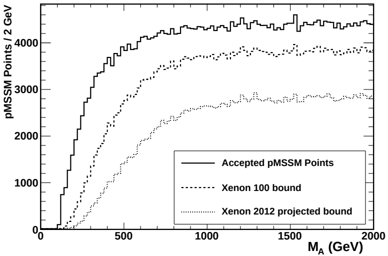
Dotted line: 2012 XENON-100 limit at 95% C.L.

28% of the valid points are excluded by XENON-100

Neutralinos and dark matter direct detection

pMSSM points and XENON dark matter exclusion limit





Results and sensitivity similar to those from $B_s \to \mu^+\mu^-$ and $A/H \to \tau^+\tau^-$, with different couplings/sectors probed

$\rightarrow$ **Strong constraints for small M_A and large $\tan\beta$**

MSSM with light staus and dark matter relic density

In this scenario:

$$\Omega_{\rm DM} h^2 \approx \frac{1.07 \cdot 10^9}{\rm GeV} \frac{x_f}{M_{\rm Pl} \sqrt{g_*}\, \hat{\sigma}_{\rm eff}} \,, \quad \hat{\sigma}_{\rm eff} \approx \alpha_{\chi\chi}\, a_{\chi\chi} + \alpha_{\chi\tilde{\tau}}\, a_{\chi\tilde{\tau}} + \mathcal{O}\left(1/x_f\right)$$

The relic density contributions can be split into two parts:
– neutralino annihilations

$$(\Omega_{\rm DM} h^2)_{\chi\chi} \approx 1.4 \cdot 10^{-2} \left(\frac{m_{\chi_1^0}}{0.1\,{\rm TeV}}\right)^2 (1 + r_{\tilde{\tau}\chi}^2)^2 \,,$$

– neutralino-stau co-annihilations:

$$(\Omega_{\rm DM} h^2)_{\tilde{\tau}\chi} \approx -2.5 \left(\frac{X_\tau}{50\,{\rm TeV}}\right)^2 e^{20.7\left(1 - r_{\tilde{\tau}\chi}\right)} \,.$$

where $r_{\tilde{\tau}\chi} = m_{\tilde{\tau}_1}/m_{\chi_1^0}$ and $X_\tau = A_\tau - \mu \tan\beta$.

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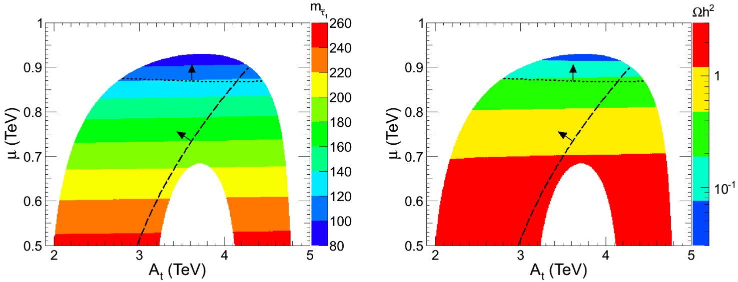

Relic density strongly correlated to the splitting with the NLSP mass

In the light stau scenario, clear correlation with the stau mass

Dotted line: $R_{\gamma\gamma} > 1$
Dashed line: constraint from BR($\bar{B} \to X_s \gamma$)