Production of Pseudoscalar Higgs Bosons at the LHC and Decays into Electroweak Gauge Bosons

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[arXiv:1003.5585]

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Introduction

- Higgs decays into electroweak gauge bosons yield very clean signals.
- For a sufficiently heavy (SM) Higgs the decay into WW and ZZ are the dominant decay modes.
- The CP eigenvalue of the Higgs can (in principle) be determined in these decay modes by measuring certain angular distributions.

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Pseudoscalar Higgs Bosons

- Most non-standard Higgs sectors also contain pseudoscalar particles.
- There are no tree-level couplings between a pseudoscalar Higgs and two gauge bosons.
- The bosonic sectors of most SM extensions conserve parity and cannot induce AVV' couplings at any order.

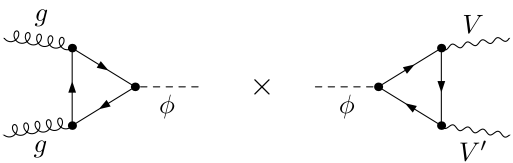
  $\Rightarrow$ AVV' couplings must be induced trough fermion loops.

  $\Rightarrow$ The branching ratios are usually expected to be small.

If we "see" a neutral spin-zero particle decaying to VV', does that mean it is scalar?

Production and Decays

- At the LHC the dominant production mode is gluon fusion.
- We compute $\sigma(pp \to \phi \to VV')$ (with $\phi = H, A$ and $VV' = WW,\ ZZ,\ Z\gamma,\ \gamma\gamma$) in the narrow width approximation



$$\sigma(pp \to \phi) \qquad \times \qquad B(\phi \to VV')$$

$\Rightarrow$ Strong couplings of ϕ to coloured particles enhances production cross section and branching ratio.

How large can the cross sections $\sigma(pp \to \phi \to VV')$ get in different SM extensions?

Adaptive Parameter Scans

How do we find, in a given model, the regions of the experimentally allowed parameter space, where a certain observable O is large?

Let $\mathbf{x} = (x_1, \ldots, x_n)$ be the unknown model parameters and

$$\theta_{\mathrm{exp}}(\mathbf{x}) = \begin{cases} 1, & \mathbf{x} \text{ is experimentally allowed} \\ 0, & \mathbf{x} \text{ is experimentally forbidden} \end{cases} \quad .$$

Then use the VEGAS algorithm to compute the integral

$$\int d^n\mathbf{x}\, O(\mathbf{x}) \theta_{\mathrm{exp}}(\mathbf{x}) \quad .$$

The algorithm will sample the desired parameter space regions with a higher density.

[O. Brein, hep-ph/0407340]

The Two Higgs Doublet Model

We consider a type-II two Higgs doublet model with no Higgs sector CP violation.

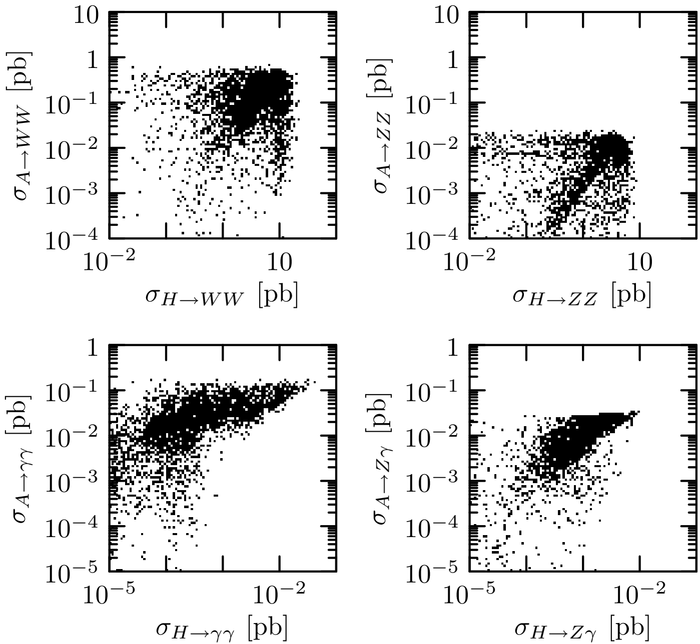
Theoretical constraints: [2HDMC, Eriksson, Rathsman, Stål]

- Positivity of the Higgs potential
- Perturbativity (Yukawa couplings $< 4\pi$)
- Tree-level unitarity of the S matrix

Experimental constraints (95% C.L.):

- Direct Higgs searches at LEP2 and Tevatron [HiggsBounds]
- Electroweak precision data (S and T parameters, R_b)
- b physics ($m_{H^\pm} > 350\,\mathrm{GeV}$) [Kaffas, Osland, Ogreid, arXiv:0706.2997]

Scan Results



Maximal Signal Cross Sections

$$\sigma(pp \to A \to WW) \lesssim 0.7\,\mathrm{pb} \quad , \quad \sigma(pp \to A \to ZZ) \lesssim 0.03\,\mathrm{pb} \quad ,$$
$$\sigma(pp \to A \to \gamma\gamma) \lesssim 0.2\,\mathrm{pb} \quad , \quad \sigma(pp \to A \to Z\gamma) \lesssim 0.04\,\mathrm{pb} \quad .$$

Maximal cross sections are reached simultaneously for

$$\tan\beta \approx 0.75 \quad , \quad m_A = 320\,\mathrm{GeV} \quad , \quad m_{H^\pm} > 370\,\mathrm{GeV} \quad ,$$
$$\beta - \alpha \approx \frac{\pi}{2} \quad \text{or} \quad m_h > m_A - m_Z \quad ,$$

- small $\tan\beta$ enhances production and decays mediated by top-loop
- $A \to b\bar{b}$ is suppressed by small $\tan\beta$
- $A \to t\bar{t}$ is not allowed kinematically
- $A \to Zh$ can be suppressed parametrically or kinematically

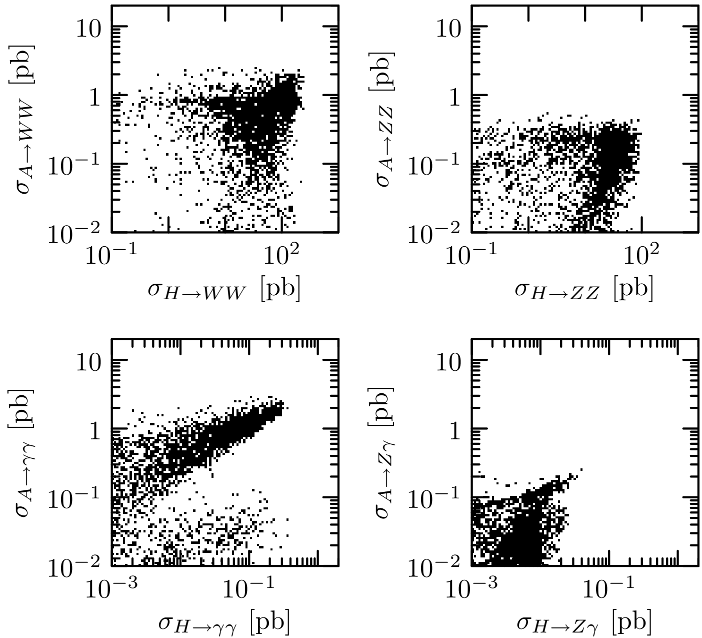
A fourth Generation of Fermions

- We consider a fourth generation of heavy chiral fermions $(u_4,\, d_4,\, \nu_4,\, \ell_4)$ with Dirac neutrinos.
- We neglect CKM mixing with the first three generations.
- Mass bounds from direct searches at LEP and TEVATRON:

$$m_{u_4} > 311\,\mathrm{GeV}\ ,\ m_{d_4} > 338\,\mathrm{GeV}\ ,$$
$$m_{\nu_4} > 100\,\mathrm{GeV}\ ,\ m_{\ell_4} > 100\,\mathrm{GeV}\ .$$

- The strongest constraints come from the oblique electroweak parameters S and T. [Kribs, Plehn et al. arXiv:0706.3718]
  - Large mass splittings within an $SU(2)$ doublet lead to a large ΔT.
  - Small mass splittings within an $SU(2)$ doublet lead to a large ΔS.

Scan Results



Maximal Signal Cross Sections

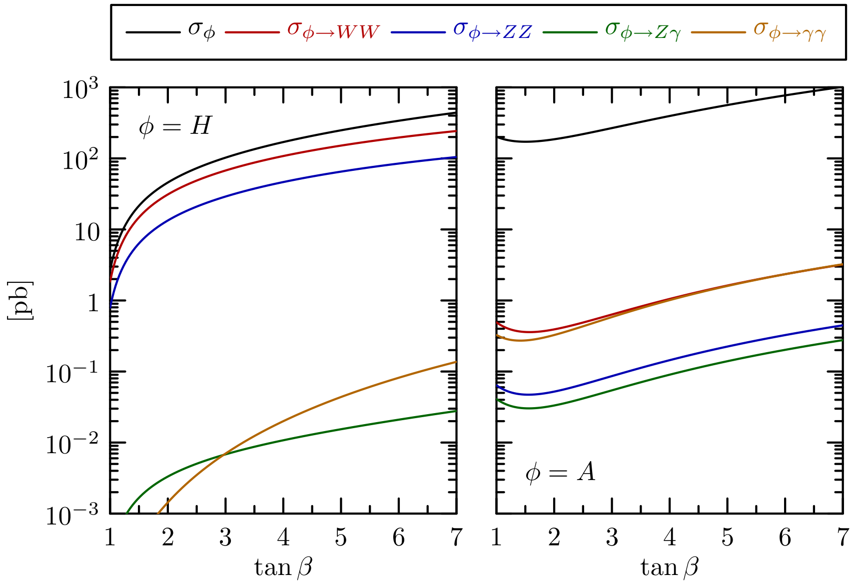
$$\sigma(pp \to A \to WW) \lesssim 3.2\,\mathrm{pb} \quad , \quad \sigma(pp \to A \to ZZ) \lesssim 0.40\,\mathrm{pb} \quad ,$$
$$\sigma(pp \to A \to \gamma\gamma) \lesssim 3.0\,\mathrm{pb} \quad , \quad \sigma(pp \to A \to Z\gamma) \lesssim 0.26\,\mathrm{pb} \quad .$$

Maximal cross sections are reached simultaneously for

$$\tan\beta \approx 6.3 \quad , \quad m_A \approx 260\,\mathrm{GeV} \quad , \quad m_{H\pm} \approx 360\,\mathrm{GeV} \quad ,$$
$$0 < \alpha \ll 1 \quad , \quad m_{\nu_4} \approx 100\,\mathrm{GeV} \quad , \quad m_{\ell_4} \approx m_A/2 \quad .$$

- The ℓ_4-loop contributions are maximised by putting m_A at the $\ell_4^+\ell_4^-$ threshold.
- At large $\tan\beta$ the $gg \to A$ production rates receive a large contribution from the d_4-loop.
- $\sigma(gg \to A) = 840\,\mathrm{pb}$ for the parameters above.

$\tan\beta$ Dependence



Light Higgs Production

The scalar Higgs couplings are

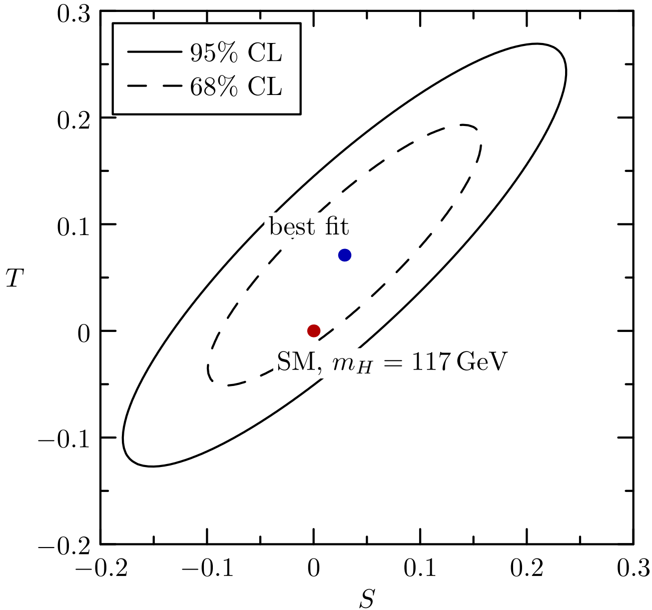
$$g^{\text{THDM}}_{hb\bar{b}} = -\frac{\sin\alpha}{\cos\beta} g^{\text{SM}}_{Hb\bar{b}} \quad , \qquad g^{\text{THDM}}_{ht\bar{t}} = +\frac{\cos\alpha}{\sin\beta} g^{\text{SM}}_{Ht\bar{t}} \quad ,$$

$$g^{\text{THDM}}_{Hb\bar{b}} = +\frac{\sin\alpha}{\sin\beta} g^{\text{SM}}_{Hb\bar{b}} \quad , \qquad g^{\text{THDM}}_{Ht\bar{t}} = +\frac{\cos\alpha}{\cos\beta} g^{\text{SM}}_{Ht\bar{t}} \quad .$$

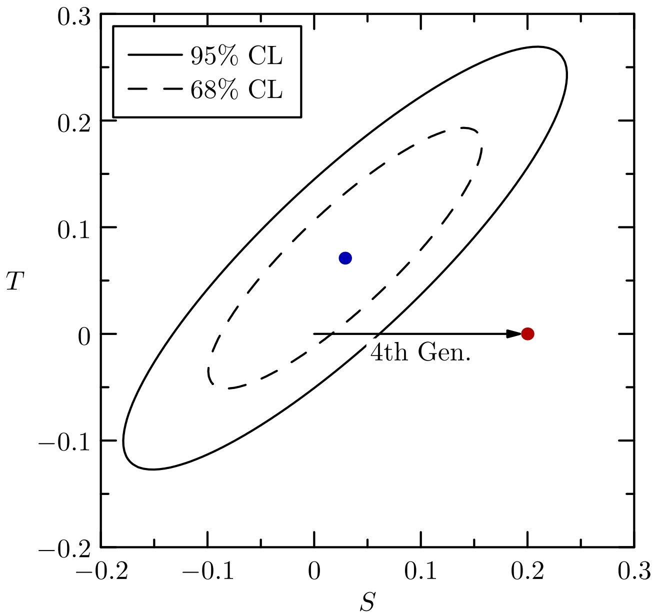
- $\alpha \ll 1$ leads to $\mathcal{O}(1)$ couplings for $hq\bar{q}$.
- $\alpha > 0$ leads to cancelleations between the u_4 and d_4 loop in $gg \to h$.

⇒ The $gg \to h$ production rate can still be similar to the SM.

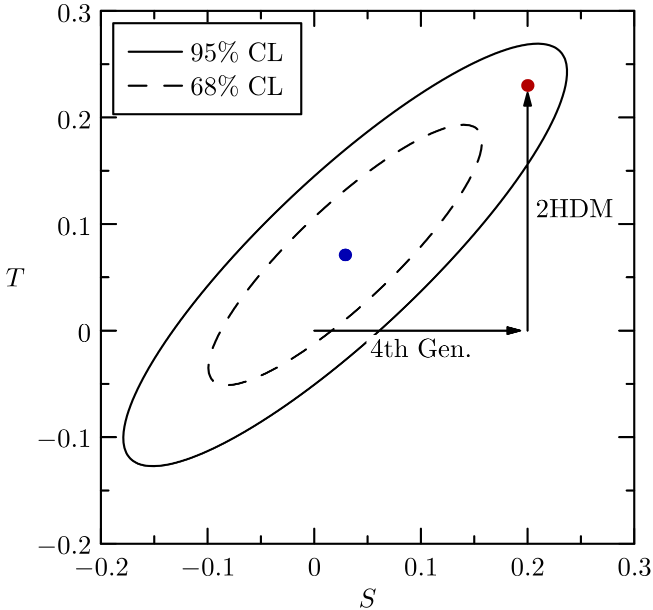
Oblique Electroweak Parameters



Oblique Electroweak Parameters



Oblique Electroweak Parameters



Extended Technicolour Models

- Electroweak symmetry is broken by a condensate of techni-quarks T.
- To obtain the right W and Z masses $v_T \equiv \langle T\bar{T} \rangle = 246\,\mathrm{GeV}$.
- SM fermion masses are generated by the breakdown of an extended technicolour gauge group.
- The top mass ends up too small.

Topcolour Models

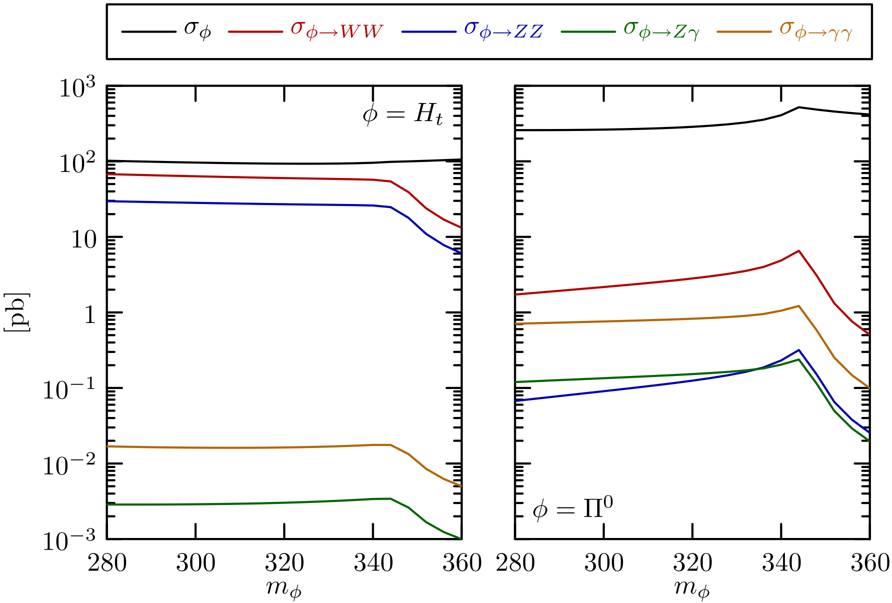
- The third generation feels a “stronger” strong interaction.
- Electroweak symmetry is broken by a $t\bar{t}$ codensate.
- To obtain the right W and Z masses $f_\pi = \langle t\bar{t} \rangle = 246\,\mathrm{GeV}$.
- f_π and the top mass m_t are related by the Pagels-Stokar formula
$$f_\pi = \frac{N_c}{16\pi^2} m_t^2 (\ln \frac{M^2}{m_t^2} + k) \quad .$$
- Without fine tuning m_t is too large ($\sim 600\,\mathrm{GeV}$).

Topcolour Assisted Technicolour (TC2)

- We have both (extended) technicolour and topcolour interactions.
- The spin-zero bound states form two $SU(2)_L$ doublets with VEVs f_π and v_T.
- To obtain the right W and Z masses $f_\pi^2 + v_T^2 = v^2 = (246\,\mathrm{GeV})^2$.
- The physical spin-zero particle content is
  - a top-pion triplet $\Pi^\pm$, Π^0 ($m_\Pi = \mathcal{O}(100\,\mathrm{GeV})$)
  - a scalar top-Higgs H_t ($m_{H_t} \approx 2m_t$)
  - a scalar techni-Higgs H_{TC} ($m_{H_{TC}} = \mathcal{O}(1\,\mathrm{TeV})$)
- The top mass gets only a small contribution from the ETC sector.

$$m_t = \frac{Y_t f_\pi + \varepsilon_t v_T}{\sqrt{2}} \quad , \quad \varepsilon_t \lesssim 0.1 \quad .$$

Cross Sections



Conclusions

- We have scanned the allowed parameter spaces of different SM extensions and determined the maximal size of the $pp \to A, H \to WW, ZZ, Z\gamma, \gamma\gamma$ cross sections.
- In a 3-generation (4-generation) 2HDM the largest possible $A \to VV'$ cross sections are found for $\tan\beta \approx 0.75$ ($\tan\beta \approx 6$).
- All studied models permit $pp \to A \to WW$ and $pp \to A \to \gamma\gamma$ cross sections of observable size.
- In these scenarios the A production cross sections are of $\mathcal{O}(100\,\mathrm{pb})$.

  $\Rightarrow$ Discovery will most likely happen in $A \to \tau^+\tau^-$ or $A \to b\bar{b}$.