Higgs Spin / Mixture Overview

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for

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For the conclusion points

(•) The spin of the 125 GeV boson will be constrained by the LHC. A limited parameter space of spin-two couplings may be left to be constrained by the data from the future facilities. Potential CP admixture in spin-zero $H \to ZZ^*$ decay amplitude squared (f_{a3}) will be measured by LHC to a few percent precision. The e^+e^- machines can measure this to a greater precision in the $ee \to ZH$ mode. CP admixture in lepton couplings is not expected to suffer from loop suppression and can be studied in $H \to \tau\tau$ decay and ttH production, leading to interesting measurements on both proton and lepton colliders. The photon and muon colliders are unique in their capability to probe CP violation directly with polarized beams.

- Next important milestone: have first draft report by July 15

CP Violation in the Higgs Sector

- CP mixture could arise for example in 2HDM neutral Higgs sector:

$$H = \cos\alpha_1 \cos\alpha_2 \; H_1 + \sin\alpha_1 \cos\alpha_2 \; H_2 + \sin\alpha_2 \; A$$

  - ideally we want to measure α_1 and α_2
  - but we measure decay/production amplitudes
    such as $H \to VV$ or $H \to f\bar{f}$
  - additional model-dependent suppression (e.g. loop in $A \to VV$)
    e.g. $\sin\alpha_2 \sim 0.1$, if loop $\times 0.03 \Rightarrow |A_{CP-\mathrm{odd}}|^2 \sim 10^{-5}\,|A_{\mathrm{even}}|^2$

- Therefore two parts in the report:

(I) experimental projection on CP-odd fraction (and spin)
in decay (production) amplitude

  - basis for comparison of facility performance

(II) connect CP-odd fraction to theoretical models

  - relate to models (e.g. 2HDM), baryogenesis, other meas. (EDM)

Two main paths: spin and mixture

- Two main paths to study “H(125)”

  (1) test of exotic spin > 0 assignments / hypothesis testing

  LHC is excluding already $\Rightarrow$ interest may be reducing

  nonetheless, identify benchmark models for comparison

  (2) measure mixture: tensor structure of interactions (spin-0)

  equivalent effective Lagrangian or scattering amplitude approaches

(2a) ZZH, WWH (SM a_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM a_2), or 0^- (a_3)

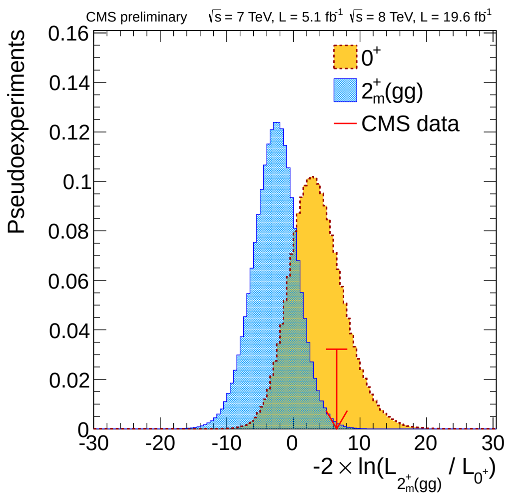
$$A_{VV} \propto \; a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

(2b) $\tau^+\tau^- H, \mu^+\mu^- H, b\bar{b}H, t\bar{t}H, ..$ $\qquad A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$

(field strength tensor $V^{\mu\nu} \Leftrightarrow f^{(i),\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$)

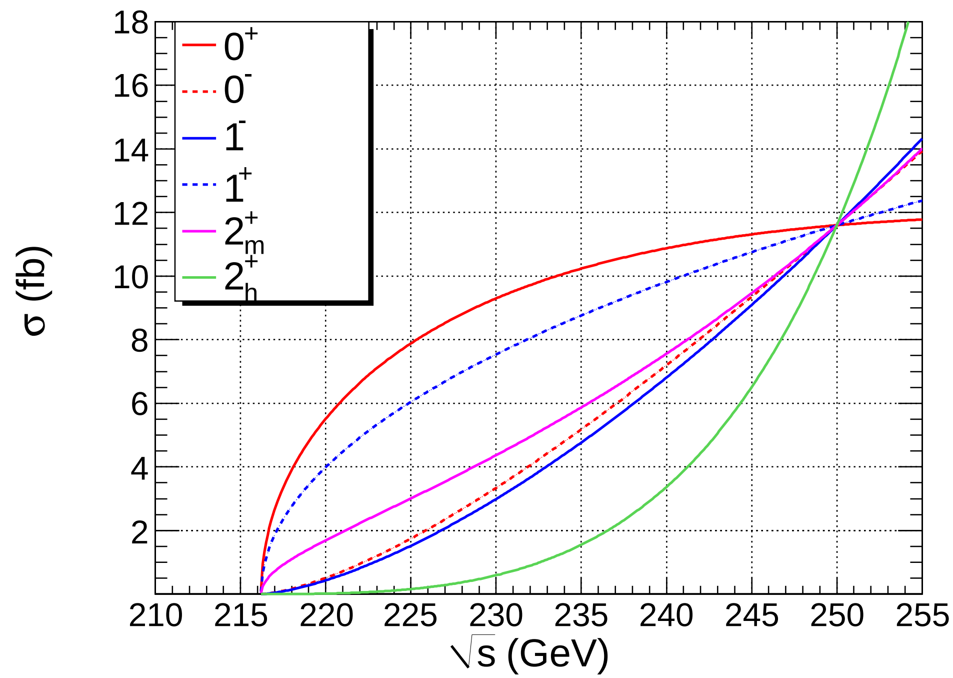
Path 1: Spin > 0

- Several test models adopted by LHC for ZZH, WWH, $\gamma\gamma H$, ggH
  - may use min. coupling KK graviton as an example 2^+_m
- Possible measure tensor structure (less motivated than spin-0)



- LHC: MELA / BDT techniques, example:
  LHC expect 2^+_m vs SM 0^+: $>2\sigma$
  scales to 300/fb LHC $\sim 10\sigma$

- Measure at $e^+e^- \to ZH$
  - energy scan (m_{Z^*} scan)
  - kinematics



Path 2 (a): Mixture in VVH

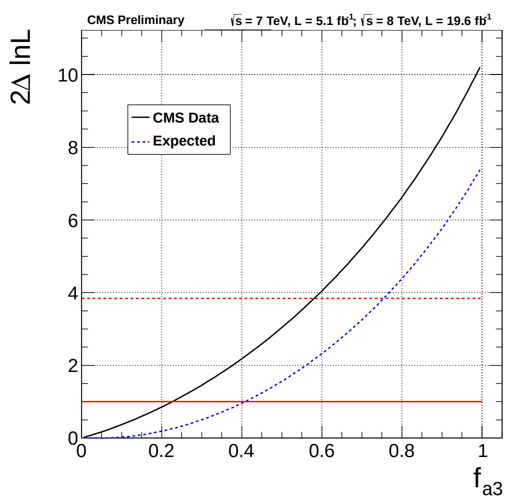
ZZH, WWH (SM a_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM a_2), or 0^- (a_3)

$$A_{VV} \propto \; a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

When a_1 dominates, f_{a3} is CP-violating fraction (here $a_i = 1 \leftrightarrow \sigma_i$):

$$f_{CP} = f_{a3} = \frac{|a_3|^2 \sigma_4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_4}\,; \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2 \sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_4}\,; \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$



- LHC: assuming SM

CMS expect (observe) $f_{CP} = 0.00 \pm 0.40$ (± 0.23)

scales to 300/fb LHC $f_{CP} = 0.00 \pm 0.08$ (?)

may include f_{a2}, phases in projections

Path 2 (b): Mixture in $f\bar{f}H$

- Mixture $\tau^+\tau^-H, \mu^+\mu^-H, b\bar{b}H, t\bar{t}H$ harder to measure on $e^+e^- \& \, pp$
  - possible if polarization of fermion decay (production) is measured
    $e^\pm$ beam polarization may help
  - feasibility in $H \to \tau^+\tau^-$
    arXiv:hep-ph/0307331: $\Delta\theta \sim 6^\circ$ with 1000/fb at $E_{e^+e^-} = 350$ GeV
    $\Delta f_{CP}^{\tau} \sim 0.01$ (?) (more discussion today)
  - feasibility in $e^+e^-(pp) \to t\bar{t}H$ (?)
- Similar parameterization:

$$A_{f\bar{f}} \propto \frac{m_f}{v}\bar{u}_2\left(\rho_1 + \rho_2\,\gamma_5\right)v_1 = \frac{m_f}{v}\bar{u}_2\,\rho\left(\cos\theta + e^{i\phi_{\rho 2}}\sin\theta\,\gamma_5\right)v_1$$

$$f_{CP} = f_{\rho 2} = \frac{|\rho_2|^2\sigma_2}{|\rho_1|^2\sigma_1 + |\rho_2|^2\sigma_2} \simeq \frac{|\rho_2|^2}{|\rho_1|^2 + |\rho_2|^2} = \sin^2\theta$$

Photon and Muon Colliders

- Polarized beams on $\mu^+\mu^-$ and $\gamma\gamma$ colliders with s-channel production
  - would allow to measure A_{++} vs A_{--} amplitudes $\Rightarrow$ CP fraction
  - need to quantify f_{CP} in $\mu^+\mu^-H$ and $\gamma\gamma H$

    (not "easily" possible on LHC and e^+e^-)

ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

In s-channel production of Higgs:

Only with C

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2}\left\{[1+\zeta_2\tilde{\zeta}_2] + \mathcal{A}_1\left[\zeta_2+\tilde{\zeta}_2\right] + \mathcal{A}_2\left[\zeta_1\tilde{\zeta}_3+\zeta_3\tilde{\zeta}_1\right] - \mathcal{A}_3\left[\zeta_1\tilde{\zeta}_1-\zeta_3\tilde{\zeta}_3\right]\right\}$$

== 0 if CP is conserved

== +1 (-1) for CP is conserved for A CP-Even (CP-Odd) Higgs

→ If $\mathcal{A}1 \neq 0$, $\mathcal{A}2 \neq 0$ and/or $|\mathcal{A}3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

→ Possible to search for CP violation in Ž H Ž fermions without having to measure their polarization

→ In bb, a ≤1% asymmetry can be measure with 100 fb-1 that is, in 1/2 years

arXiv:0705.1089v2

Spin and Mixture for Snowmass-2013

- We already know many things, but need to focus on projections:
  - VVH $(V = W, Z)$ on LHC covers $H \to ZZ^*$
  - e^+e^- expectations and fermion couplings need to quantify better
  - quantify $\mu^+\mu^- \to H$ and $\gamma\gamma \to H$ feasibility of CP measurements

f_{CP}	LHC 300/fb	LHC 3000/fb	e^+e^- 250 GeV	e^+e^- 500 GeV	$\mu^+\mu^-$ 125	$\gamma\gamma$ 125
spin-2 ...	$\sim 10\sigma$ ...	$\gg 10\sigma$ ...	$>10\sigma$ ...	$>10\sigma$ ...	? ...	? ...
VVH	± 0.08 (?)	± 0.03 (?)	0.0008 (?)	0.00005 (?)	?	?
$\tau\tau H$	?	?	~ 0.01 (?)	~ 0.01 (?)	?	?
ttH	?	?	–	?	–	–
$\mu\mu H$	–	–	–	–	?	–
$\gamma\gamma H$	–	(?)	–	–	–	?