Higgs Spin / Mixture Overview

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for

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Conclusion points

• The spin of the 126 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-odd fraction in $H \to ZZ^*$ cross-section (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 fermion 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 lepton colliders, and potentially hadron colliders. The photon and muon colliders are unique in their capability to probe CP violation directly with polarized beams.

• . . . The muon collider also has the potential for resonant production of heavy Higgs bosons. CP measurements are possible if a beam polarization option is included.

• A $\gamma\gamma$ collider is ideal to study CP mixture and violation in the Higgs sector. It can improve the precision of the effective $\gamma\gamma H$ coupling measurement through s-channel production.

CP Mixture / Spin Summary

Facility	LHC	HL-LHC	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\mu^+\mu^-$	$\gamma\gamma$	target
Energy (GeV)	14,000	14,000	250	350	500	1000	126	126	(theory)
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250	350	500	1000	?	?	
Measurement precision									
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	?	?	$>5\sigma$
...	...	...	...	...	...	...	...		
ZZH	0.07†	0.02†	0.0007	0.00011	0.00004	0.000007	✓	✓	$< 10^{-5}$
WWH	(?)	(?)	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
ggH	?	?	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	?	–	–	–	–	–	(?)	$< 10^{-2}$
$Z\gamma H$	–	?	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	?	?	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	(?)	(?)	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–		✓	–	$< 10^{-2}$
bbH	–	?	?	?	?	?	?	?	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

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(126)"

  (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)

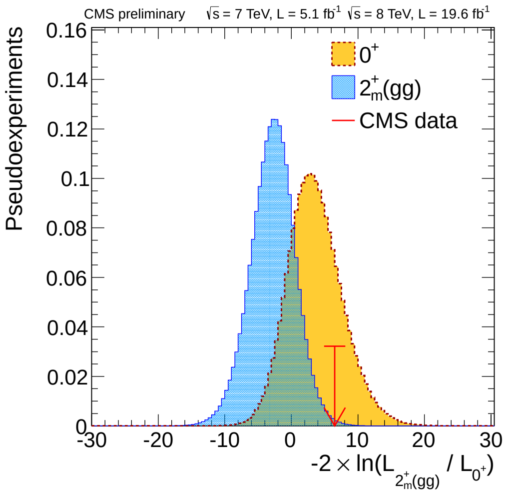
$$A_{VV} \propto \; a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

(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)

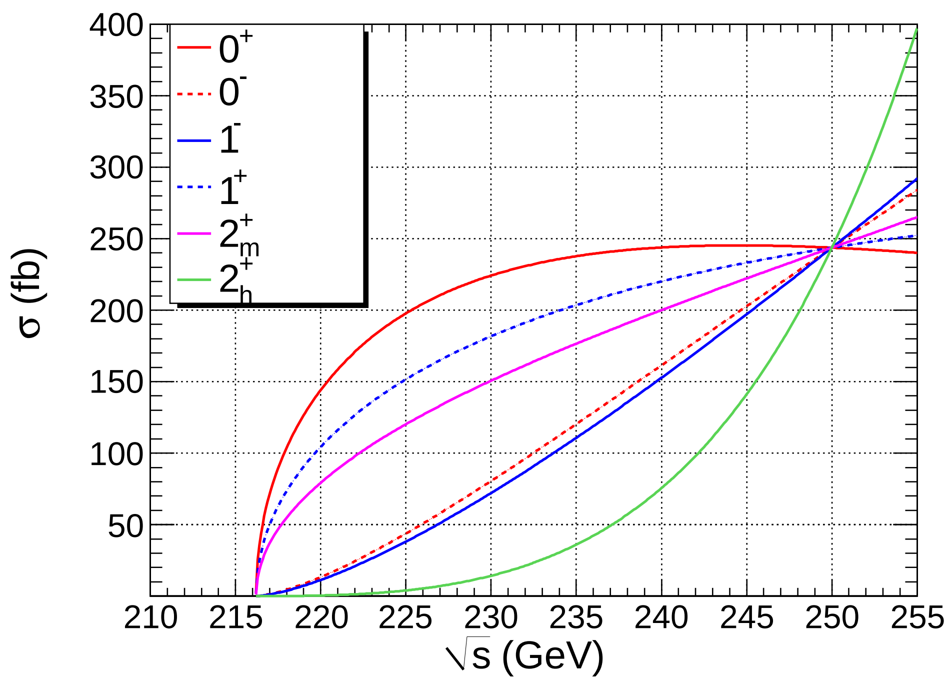


- LHC: MELA / BDT techniques, example:

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

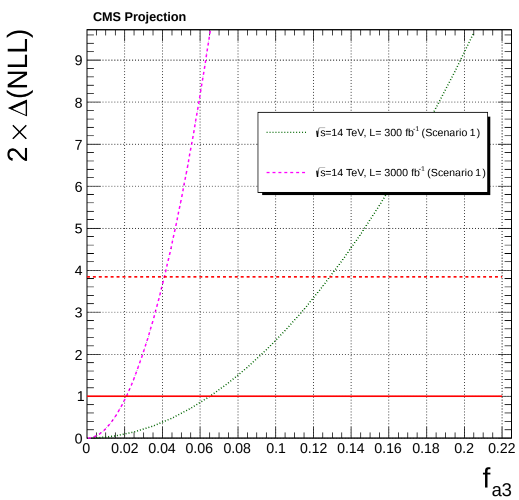
ZZH, WWH (SM a_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM a_2), or 0^- (a_3)

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

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

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

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



- CMS white paper: $H \to ZZ^* \to 4\ell$

300/fb: $f_{CP} < 0.07(0.14)$ at 68% (95%) CL

3000/fb: $f_{CP} < 0.02(0.04)$ at 68% (95%) CL

- CP in $e^+e^- \to Z^* \to ZH$

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

- Mixture $H \to \tau^+\tau^-$, summary from Stefan Berge, update:

  250 GeV (250/fb) $\Delta\theta = 5.9^\circ$

  350 GeV (350/fb) $\Delta\theta = 6.9^\circ$

  500 GeV (500/fb) $\Delta\theta = 8.8^\circ$

  1000 GeV (1000/fb) $\Delta\theta = 14^\circ$

- Mixture $t\bar{t}H$ at ILC

  short update today

- 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
  - measure interference of A_{++} vs A_{--} amplitudes $\Rightarrow$ CP fraction
  - $\sim$50k $\gamma\gamma \to H$ events in 5 years

(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 $\mathcal{A}1\neq0$, $\mathcal{A}2\neq0$ 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

Photon Collider

- From hep-ph/9206262, should measure at least two asymmetries:

$$\mathcal{A}_1 = \frac{|M_{++}|^2 - |M_{--}|^2}{|M_{++}|^2 + |M_{--}|^2} \qquad \mathcal{A}_2 = \frac{2\Im m M^*_{--} M_{++}}{|M_{++}|^2 + |M_{--}|^2} \qquad \mathcal{A}_3 = \frac{2\Re e M^*_{--} M_{++}}{|M_{++}|^2 + |M_{--}|^2}$$

$$M_{++} \propto (a_2 - i a_3);\ M_{--} \propto (a_2 + i a_3) \Rightarrow \mathcal{A}_1 \propto \Im m(a_2 a_3^*) \sim 0$$

need precision on $\mathcal{A}_2$ (e.g. run $\pm\frac{\pi}{4}$ linear polarization) $\propto \Re e(a_2 a_3^*)$

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 $\mathcal{A}1$≠0, $\mathcal{A}2$≠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

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