Probing P and T Violation in The Higgs Sector

Michael Park

in collaboration with

Scott Thomas

Rutgers University

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Motivation

Standard Model Higgs found, spin measured, coupling-to-mass ratios checked

No compelling evidence for BSM physics from direct searches

Should look for effects of new virtual/intermediate particle states

Weak scale new physics could give percent level deviations to SM Higgs observables

Violations of P and T could arise from pseudoscalar interference

Issues

Fortuitous Higgs mass - many channels available but many difficulties

Higgs to diphoton?

$$\mathcal{O}_{-}^{AA} = \frac{g^2 \widetilde{S}_{AA}}{16\pi v} h A^{\mu\nu} \widetilde{A}_{\mu\nu}$$

- Detectors cannot measure spins, only 4-vectors

Higgs to WW?

- Hadronic decays muddled by background

- Leptonic decays lose information

The Golden Channel

Pros:

- **Preserves all kinematic information**
- **Best measured final state**

Cons:

- **Low statistics**

$$pp \to h \to ZZ' \to l_+ l_- l'_+ l'_-$$

In the Standard Model, the contributing operator is

$$\mathcal{O}_h = \frac{m_Z^2}{v} h Z^\mu Z_\mu$$

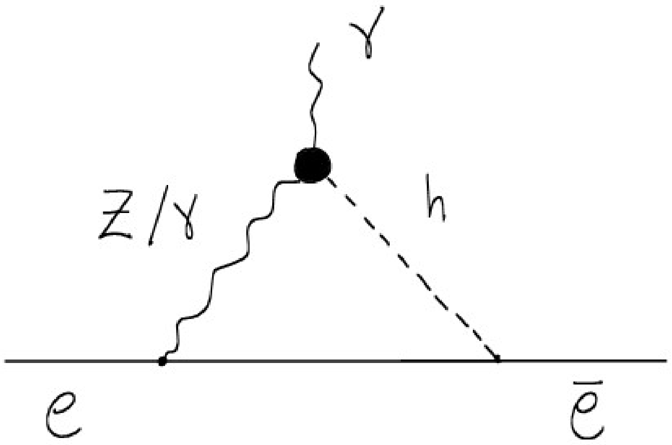
The lowest order pseudoscalar effective operator after EWSB is

$$\mathcal{O}_- = \frac{g_Z^2 \widetilde{S}_{ZZ}}{16\pi v} h Z^{\mu\nu} \widetilde{Z}_{\mu\nu}$$

Bounds from EDM's

Similar operators would contribute to electron EDM

$$\mathcal{O}_-^{AA} = \frac{g^2\widetilde{S}_{AA}}{16\pi v} h A^{\mu\nu}\widetilde{A}_{\mu\nu} \qquad \mathcal{O}_-^{AZ} = \frac{g g_Z \widetilde{S}_{AZ}}{16\pi v} h Z^{\mu\nu}\widetilde{A}_{\mu\nu}$$



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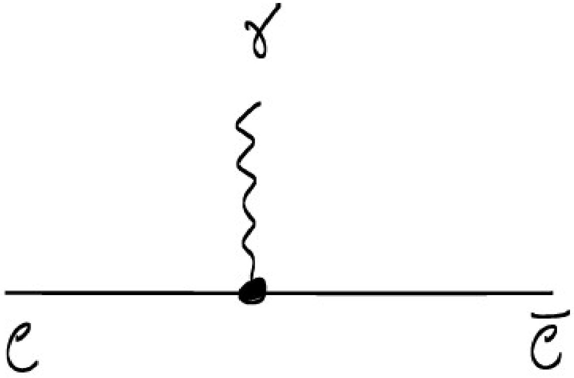


$$\mathcal{O}_{EDM} = \frac{d_e}{2}\overline{\Psi}\sigma^{\mu\nu}\Psi\widetilde{A}_{\mu\nu}$$

Bounds from EDM's

Really it is a specific linear combination that is bounded by the EDM

$$\frac{d_e}{e} = \frac{\alpha}{32\pi^2}\frac{m_e}{v^2}\left[\widetilde{S}_{AA}\log\left(1+\frac{\Lambda^2}{m_h^2}\right) - \frac{1-4s_W^2}{2s_W^2 c_W^2}\widetilde{S}_{AZ}\frac{m_h^2\log\left(1+\frac{\Lambda^2}{m_h^2}\right) - m_Z^2\log\left(1+\frac{\Lambda^2}{m_Z^2}\right)}{m_h^2 - m_Z^2}\right]$$

$$\frac{d_e}{e} < 1\times 10^{-26}$$

Ignoring considerations of naturalness, the operator

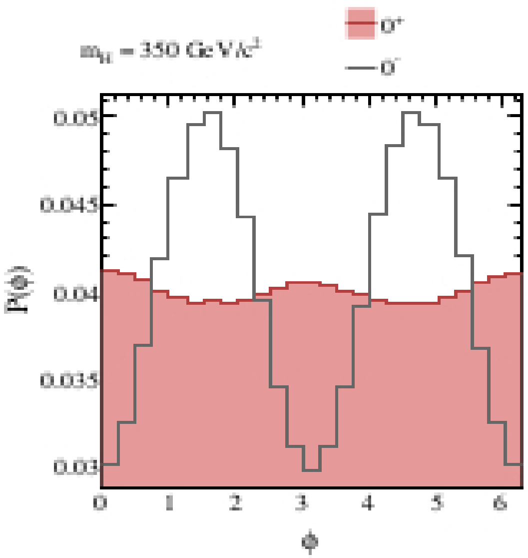
$$\mathcal{O}_- = \frac{g_Z^2\widetilde{S}_{ZZ}}{16\pi v} h Z^{\mu\nu}\widetilde{Z}_{\mu\nu}$$ **remains unbounded**

Kinematic Structures

Operators determine kinematic behavior of decay products

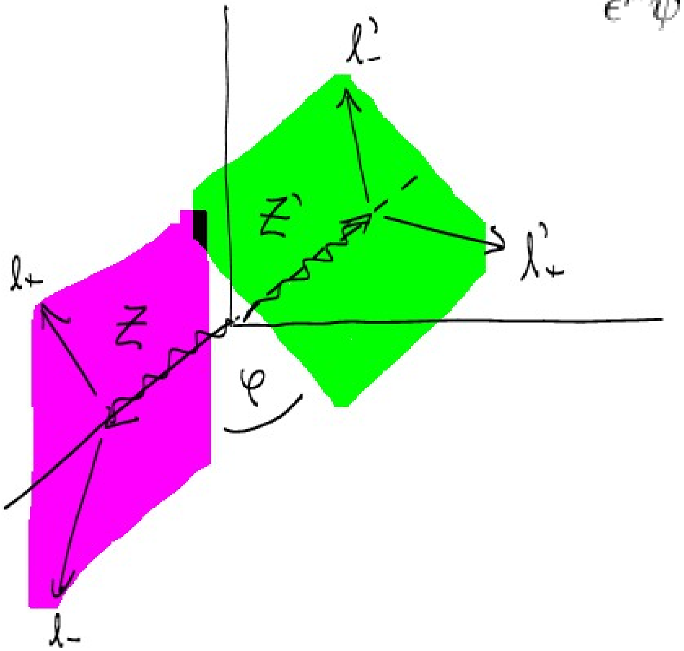
$$Z^{\mu} Z_{\mu} \sim \epsilon_Z \cdot \epsilon_{Z'}$$

$$Z^{\mu\nu} \widetilde{Z}_{\mu\nu} \sim \epsilon_{\mu\nu\rho\sigma} p_Z^{\mu} \epsilon_Z^{\nu} p_{Z'}^{\rho} \epsilon_{Z'}^{\sigma}$$



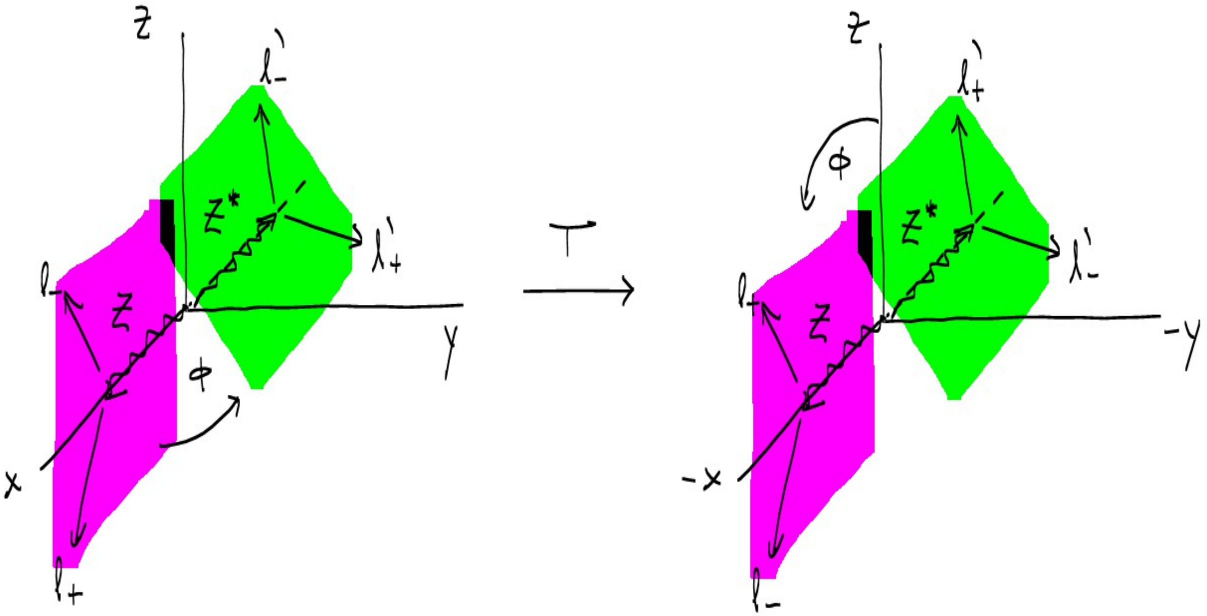
The leptonic decay plane determined by polarization

$$\epsilon^{\mu} \overline{\psi} \gamma_{\mu} \psi$$



T Violation

Signed plane angle is sensitive to T violation



T violation should show up as an interference effect

Should vanish for pure scalar or pure pseudoscalar couplings

T-odd Observable

The unique T-odd observable for this four body final state is given by

$$\tau \equiv \frac{\epsilon_{\mu\nu\rho\sigma} p^{\mu}_{l_+} p^{\nu}_{l_-} p^{\rho}_{l'_+} p^{\sigma}_{l'_-}}{m_h^4}$$

It is related to the plane angle by

$$\sin\varphi = -\frac{1}{2}\tau \frac{\lambda^{1/2}(m_h^2, m_Z^2, m_{Z'}^2)}{\sqrt{m_Z^2 m_{Z'}^2 (p_{l_+} \cdot p_{Z'})(p_{l_-} \cdot p_{Z'})(p_{l'_+} \cdot p_Z)(p_{l'_-} \cdot p_Z)}}$$

We expect a cross term proportional to tau resulting in a deficit amplitude when tau is negative

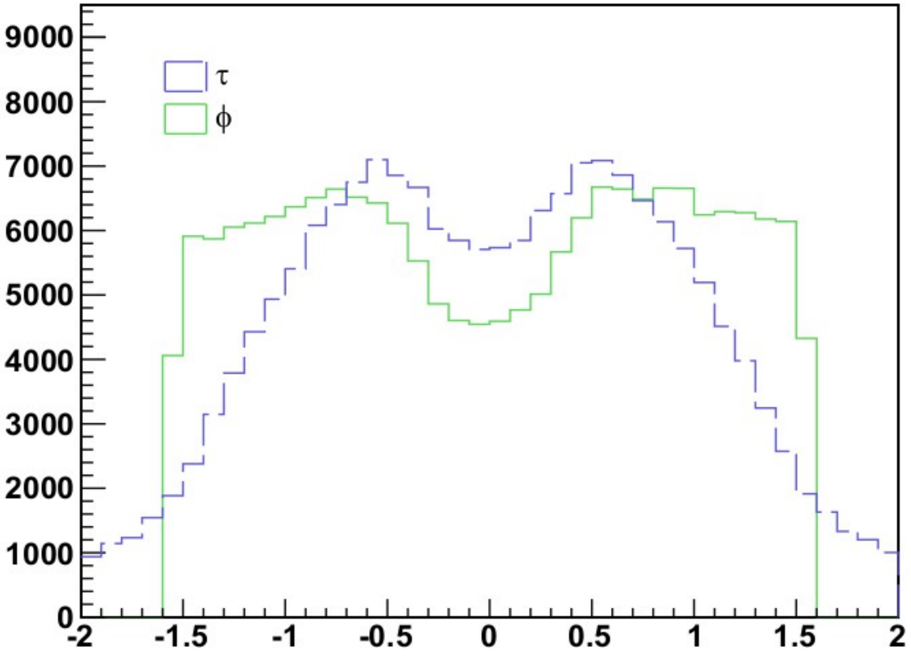
$$|\mathcal{M}_{total}|^2 = |\mathcal{M}_h|^2 + |\mathcal{M}_-|^2 + \mathcal{M}_h^* \mathcal{M}_- + h.c.$$

T-odd Observable

Plot of tau shows almost no noticeable asymmetry

Maybe the asymmetry is too small

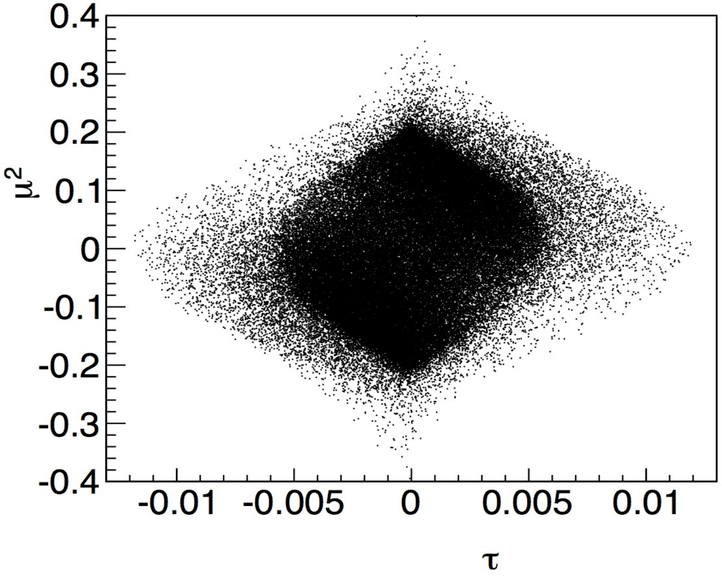
Give up?



Matrix Elements

Interference term contains extra kinematic structure

$$\mathcal{M}_h^*\mathcal{M}_- + h.c. \sim \frac{4g_Z^2\widetilde{S}_{ZZ}m_Z^2(g_V^2+g_A^2)^2}{\pi v}\tau(p_{l_+}-p_{l_-})^\mu(p_{l'_+}-p_{l'_-})_\mu$$

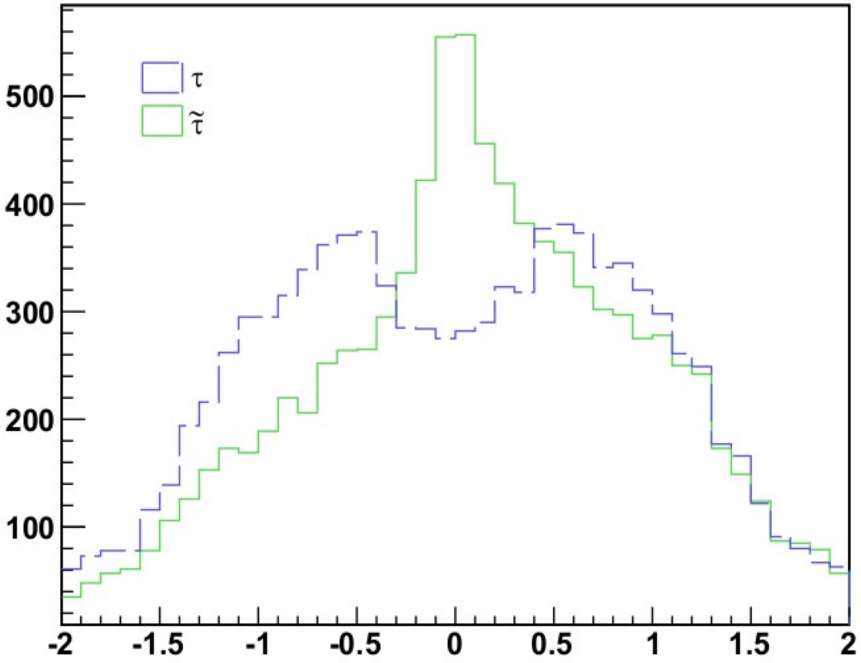


$$\tilde{\mu} \equiv \frac{(p_{l_+}-p_{l_-})^\mu(p_{l'_+}-p_{l'_-})_\mu}{m_h^2}$$

Enhancing the Asymmetry

Define a new observable that untangles the asymmetry

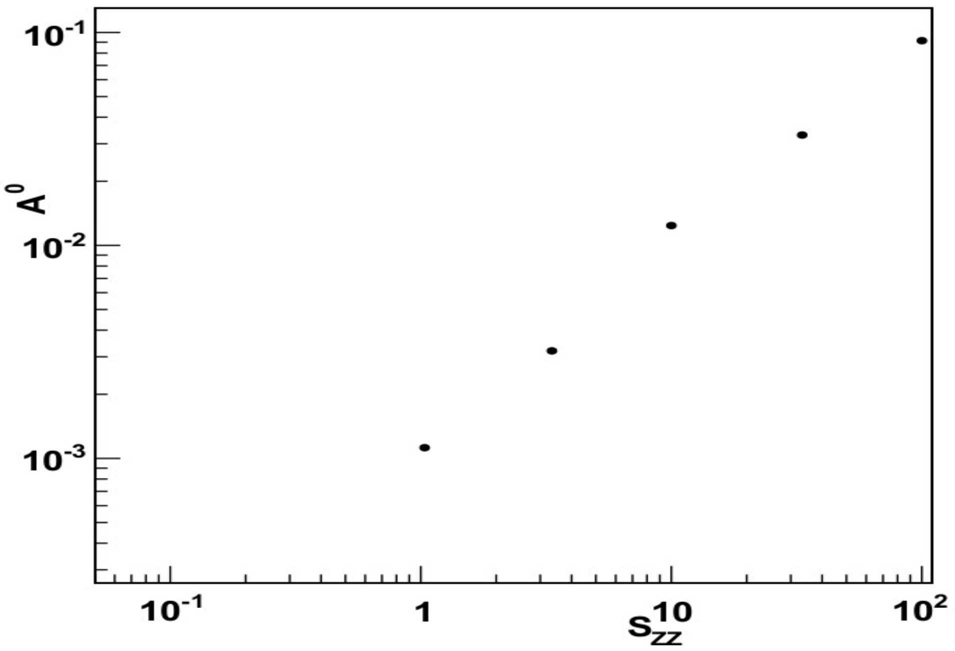
$$\widetilde{\mathcal{T}} \equiv \tau\tilde{\mu} = \frac{\epsilon_{\mu\nu\rho\sigma} p^{\mu}_{l_+} p^{\nu}_{l_-} p^{\rho}_{l'_+} p^{\sigma}_{l'_-} \left(m^2_{l_+ l'_+} - m^2_{l_+ l'_-} - m^2_{l_- l'_+} + m^2_{l_- l'_-}\right)}{m_h^6}$$



Quantifying the Asymmetry

The simplest way to quantify the asymmetry is

$$\mathcal{A}^{(\theta)}_{\widetilde{\mathcal{T}}} = \int d\widetilde{\mathcal{T}}\ \left(\theta(\widetilde{\mathcal{T}}) - \theta(-\widetilde{\mathcal{T}})\right)\ \frac{d\mathcal{P}(h \to \ell^+\ell^-\ell'^+\ell'^-)}{d\widetilde{\mathcal{T}}}$$



Conclusion

The era of precision Higgs measurements has begun

A novel evaluation of discrete symmetries in Higgs interactions

The measurement of a new coupling

Large integrated luminosity to compete with EDM

Yet still an interesting probe of T-violation in the Higgs sector