Title: Using the Higgs as a Direct Probe of New Physics

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Abstract: The discovery of the Higgs boson marks the first direct probe into the mechanism of electroweak symmetry breaking. All evidence currently points to the fact that electroweak symmetry is broken by at least one fundamental scalar, and naturalness remains the most compelling reason to expect additional degrees of freedom at the weak scale. This talk will describe some ideas for how to utilize powerful and proven experimental techniques, in conjunction with the fact that observables directly related to the Higgs boson are now experimentally accessible, to make concrete statements about the existence of possible new degrees of freedom at the weak scale.

Using the Higgs as a Direct Probe of New Physics

Michael Park
NHETC
Rutgers University

1112.2298, 1207.6794, 1210.0559, 1308.0845

In Collaboration With: Emmanuel Contreras-Campana, Nathaniel Craig, Jared A. Evans, Richard Gray, Can Kilic, Jessie Shelton, Sunil Somalwar, Scott Thomas, Matthew Walker

Perimeter Institute
12/05/13

Thoughts from Run I

Run I of LHC a fantastic success

Arguably interesting anomalies

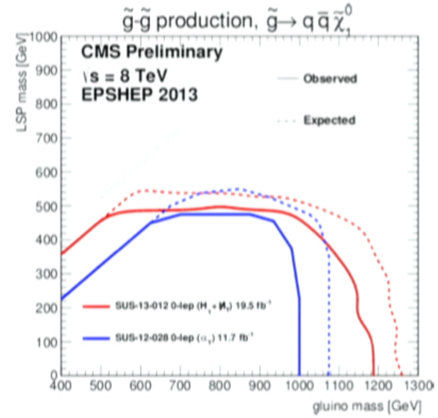
→ No compelling sign of new physics

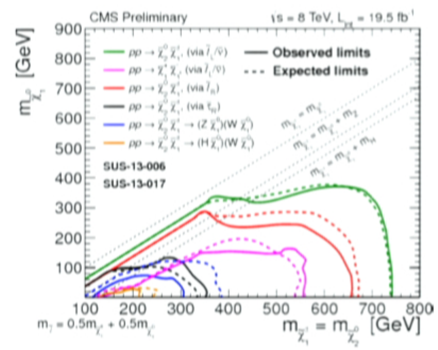
→ Still much room for discovery

Lessons from Run I

→ Electroweak symmetry broken by at least one fundamental scalar

→ New colored states appear absent





From Run I to Run II

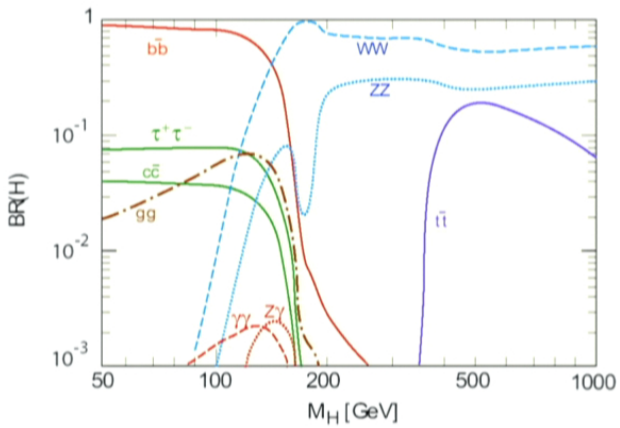
Higgs discovery marks first direct probe of EWSB

Implications of the ~125 GeV mass

Theorists nightmare

$$m_h^2 \leq m_Z^2 \ \cos^2 2\beta$$

Experimentalists dream



Motivates a bottom up approach for Run II

Thoughts for Run II

Phenomenologically motivated approach

→ Exploit presence of diverse Higgs decay modes

→ Utilize powerful experimental tools

Supersymmetry is still a useful parameterization

Natural questions addressable in early Run II

1) Extended Higgs sectors? 2HDM? Beyond?

2) Rare flavor processes involving the Higgs

3) (Discrete) symmetries of the Higgs sector

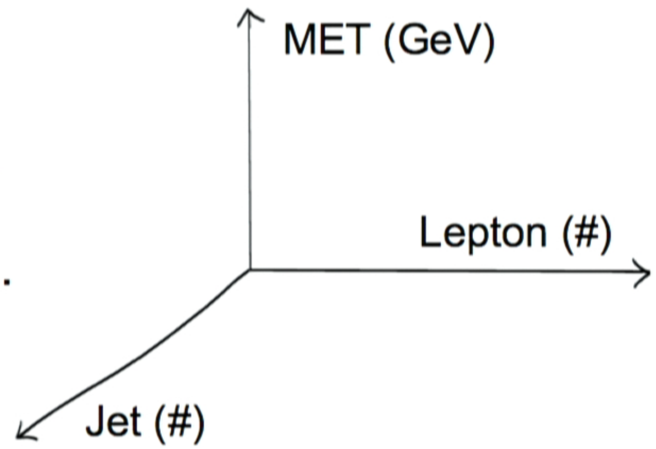
The Experimentalists Event

Signature Space

Discrete: Lepton #, Jet #, ...

Continuous: MET, ST, HT, ...

Signature operator mapping



Standard Model event density concentrated at origin

Cut-and-count methods result in lost information

Don't cut! Always bin!

The Experimentalists Event

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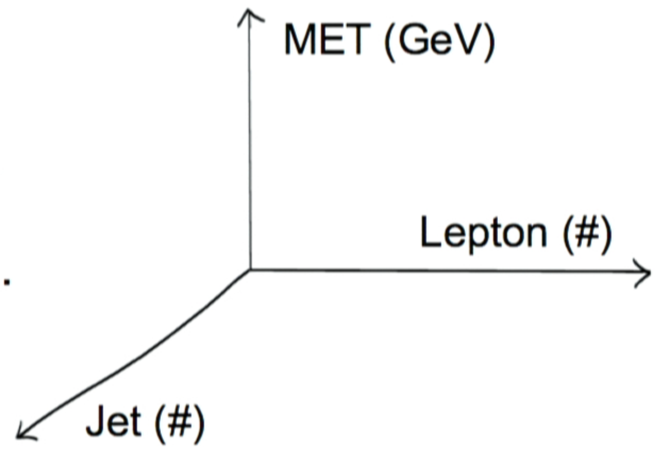

Standard Model event density concentrated at origin

Cut-and-count methods result in lost information

Don't cut! Always bin!

Multi-Leptons in a Nutshell

Signature subspaces with lepton # are of particular interest

Theoretical perspective:

→ New EW degrees of freedom are a natural expectation

Experimental perspective:

→ Cleanest objects measured by the detector

→ Relative insensitivity to pile-up (modulo isolation)

→ Weak processes not subject to QCD tuning

Multi-Leptons in a Nutshell

"Multi-lepton" means 3 or more electrons/muons

Irreducible contribution from $\tau \rightarrow e/\mu$

One-prong hadronic $\tau \rightarrow \pi$ treated separately

Orthogonality, SM separability, tractability

- Axes: Lepton #, Drell-Yan #, Z #, HT, MET

Discretize bins and order by SM contamination

arXiv:1204.5341 – The CMS Collaboration

Multi-Leptons: Extended Higgs

The Higgs has many multi-lepton final states

Resonant channels → gluon fusion

Decay: h → ZZ* (non resonant if one Z → $\tau\tau$)

Non resonant channels → associated production

Production: Wh, Zh, tth

Decay: h → WW*, ZZ*, $\tau\tau$ (at low mass)

arXiv:1112.2298 – E. C-Campana, N. Craig, R. Gray, C. Kilic, S. Somalwar, S. Thomas, MP

The Multi-Lepton Menu

Extended Higgs Sectors – arXiv:1210.0559, 1308.0845

Top to Charm and Higgs - arXiv: 1207.6794

T-Violation in Higgs Decays - arXiv: To Appear

Multi-Leptons: Extended Higgs

Canonical 2HDM parameterization with assumptions

→ CP conservation

→ Glashow-Weinberg models

→ PQ symmetry: forbids terms with odd # of Hu or Hd

Free parameters reduced to masses and mixing angles

Full parameter scan is computationally intractable

arXiv:1210.0559 – N. Craig, J. Evans, R. Gray, C. Kilic, S. Somalwar, S. Thomas, MP

Multi-Leptons: Extended Higgs

Consider a few benchmark spectra

	SM (GeV)	Spectrum 1 (GeV)	Spectrum 2 (GeV)	Spectrum 3 (GeV)	Spectrum 4 (GeV)
h	125	125	125	125	125
H	–	300	140	500	200
A	–	500	250	230	80
$H^{\pm}$	–	500	250	230	250

	2HDM I	2HDM II	2HDM III	2HDM IV
u	H_u	H_u	H_u	H_u
d	H_u	H_d	H_u	H_d
e	H_u	H_d	H_d	H_u

Reduced parameter space is factorizable

Multi-Leptons: Extended Higgs

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d	H_u	H_d	H_u	H_d
e	H_u	H_d	H_d	H_u

Reduced parameter space is factorizable

Multi-Leptons: Extended Higgs

Huge number of additional multi-lepton final states

Maximize sensitivity by combining channels

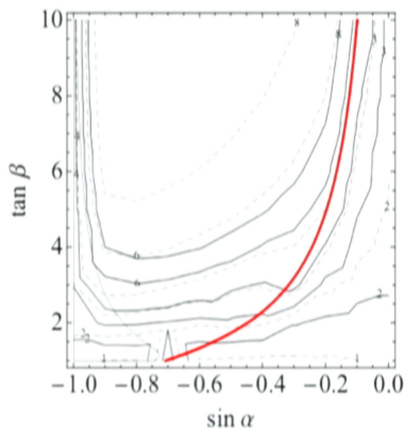
Production	Decay
$gg \to h$	$h \to 4\ell$
$\mathrm{VBF} \to h$	$h \to 4\ell$
$gg \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
$\mathrm{VBF} \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
	$A \to ZH \to ZWW, Z\tau\tau, ZZZ$
	$A \to ZH \to Zhh \to ZWWWW, ZWW\tau\tau, Z\tau\tau\tau\tau, ZZZb\bar{b}, ZZZWW, 5Z, ZZZ\tau\tau$
$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau$

Multi-Leptons: Extended Higgs

Example of binning in signature space

Bins ordered by SM contamination

7 TeV Limits



			Observed	Expected	SM Higgs Signal
4 Leptons					
†MET HIGH	HT HIGH	No Z	0	0.018 ± 0.005	0.03
†MET HIGH	HT HIGH	Z	0	0.22 ± 0.05	0.01
†MET HIGH	HT LOW	No Z	1	0.20 ± 0.07	0.06
†MET HIGH	HT LOW	Z	1	0.79 ± 0.21	0.22
†MET LOW	HT HIGH	No Z	0	0.006 ± 0.001	0.01
†MET LOW	HT HIGH	Z	1	0.83 ± 0.33	0.01
†MET LOW	HT LOW	No Z	1	2.6 ± 1.1	0.36
†MET LOW	HT LOW	Z	33	37 ± 15	1.2
3 Leptons					
†MET HIGH	HT HIGH	DY0	2	1.5 ± 0.5	0.15
†MET HIGH	HT LOW	DY0	7	6.6 ± 2.3	0.67
†MET LOW	HT HIGH	DY0	1	1.2 ± 0.7	0.04
†MET LOW	HT LOW	DY0	14	11.7 ± 3.6	0.63
†MET HIGH	HT HIGH	DY1 No Z	8	5.0 ± 1.3	0.38
†MET HIGH	HT HIGH	DY1 Z	20	18.9 ± 6.4	0.19
†MET HIGH	HT LOW	DY1 No Z	30	27.0 ± 7.6	1.8
MET HIGH	HT LOW	DY1 Z	141	134 ± 50	1.6
†MET LOW	HT HIGH	DY1 No Z	11	4.5 ± 1.5	0.13
†MET LOW	HT HIGH	DY1 Z	15	19.2 ± 4.8	0.09
MET LOW	HT LOW	DY1 No Z	123	144 ± 36	1.8
MET LOW	HT LOW	DY1 Z	657	764 ± 183	4.3

Multi-Leptons: Resonant Extensions

Beyond 2HDM, consider additional production modes

Non-resonant tth associated production

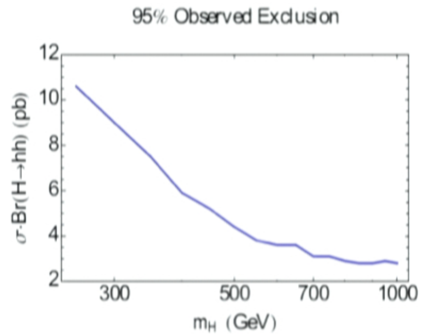
arXiv:1308.0845 – N. Craig, J. Shelton, MP

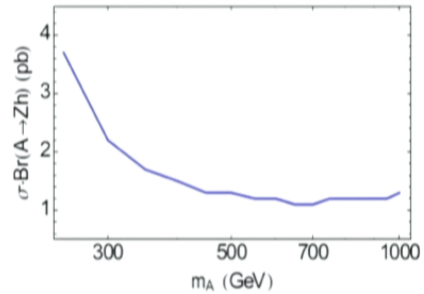
Resonant production: Two possibilities

→ CP-even: H to hh

→ CP-odd: A to Zh

arXiv:(Imminent) – N. Craig, J. Evans, S. Thomas, MP





Multi-Leptons: Rare Flavor

Multi-Leptons sensitive to rare Higgs FCNC decays

→ Production of tt with t → ch, t → W b

Standard Model suffers suppression from GIM and mixing

→ No symmetry forbids this process

$$\mathrm{Br}(t \to ch)_{\mathrm{SM}} \sim 10^{-13} - 10^{-15}$$

Phys.Rev.D 44 – G. Eilam, J. Hewitt, A. Soni
arXiv:9805498 – B. Mele, S. Petrarca, A. Soddu

In some 2HDM variants ("type III"), BR ~ 0.1%

Phys.Lett.B 296 – W. Hou

Multi-Leptons: Rare Flavor

Most relevant higher order effective operator comes at d=6

$$\lambda_{ij} Q_i H \overline{u}_j + \frac{\xi_{ij}}{M^2} H^\dagger H Q_i H \overline{u}_j + h.c.$$

Effective Yukawa at this order is given by

$$m_{ij} u_i \overline{u}_j + \lambda^h_{ij} h u_i \overline{u}_j + h.c. \qquad \lambda^h_{ij} = \frac{\partial m_{ij}}{\partial v} = \frac{1}{\sqrt{2}} \left[\lambda_{ij} + \frac{v^2}{M^2} \xi_{ij} \right]$$

Express branching fraction in terms of ξ or λ

$$\mathrm{Br}(t \to ch) \sim (|\xi_{tc}|^2 + |\xi_{ct}|^2) \frac{150 \text{ GeV}}{M^4} \sim 0.29 (|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2)$$

arXiv:1207.6794 – N. Craig, J. Evans, R. Gray, S. Somalwar, S. Thomas, M. Walker, MP

The Multi-Lepton Menu

Extended Higgs Sectors - arXiv: 1210.0559, 1308.0845

Top to Charm and Higgs - arXiv: 1207.6794

T-Violation in Higgs Decays - arXiv: To Appear

T-Violation in the Higgs Sector

Novel test of CP-even scalar hypothesis

The Golden Channel: $pp \to h \to ZZ' \to l_+ l_- l'_+ l'_-$

Pros: Preserves all kinematic information, most accurately measured decay mode

Cons: Low statistics

Standard model

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

Leading Order
Pseudo-scalar operator

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

arXiv:(To Appear) – S. Thomas, MP

T-Violation in the Higgs Sector

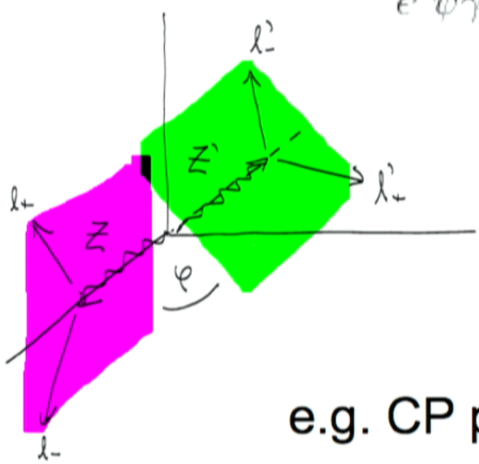
Infer operator structure from final state kinematics

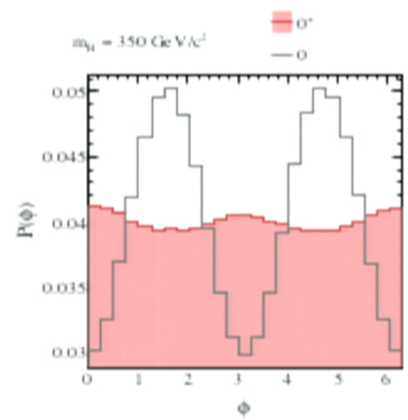
$$Z^{\mu\nu}\widetilde{Z}_{\mu\nu} \sim \epsilon_{\mu\nu\rho\sigma} p^{\mu}_{Z} \epsilon^{\nu}_{Z} p^{\rho}_{Z'} \epsilon^{\sigma}_{Z'}$$

Leptonic decay plane determined
by polarization

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

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





e.g. CP properties of Kaon system

T-Violation in the Higgs Sector

Unique T-odd observable $$\tau \equiv \frac{\epsilon_{\mu\nu\rho\sigma} p^{\mu}_{l_+} p^{\nu}_{l_-} p^{\rho}_{l'_+} p^{\sigma}_{l'_-}}{m_h^4}$$

Must be proportional to plane angle

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

Vanishes for pure scalar or pure pseudo-scalar:

Must arise as an interference effect

Proportionality of cross term → asymmetry

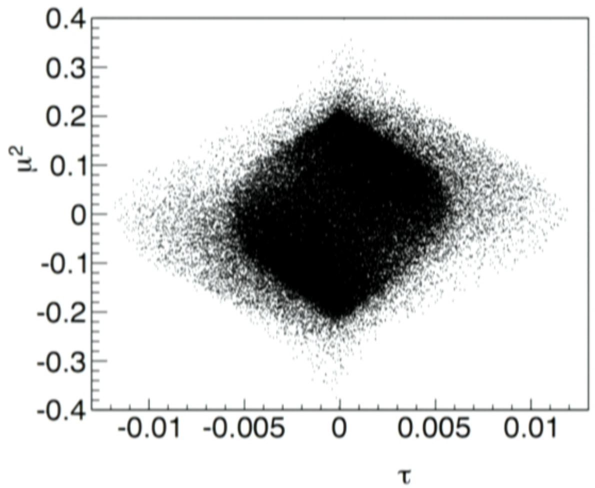
$$|\mathcal{M}_{total}|^2 = |\mathcal{M}_h|^2 + |\mathcal{M}_-|^2 + \mathcal{M}_h^* \mathcal{M}_- + h.c.$$

T-Violation in the Higgs Sector

Plotting τ shows no observable asymmetry

Full matrix element reveals
kinematic factor

Extra kinematic structure
washes out asymmetry



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

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

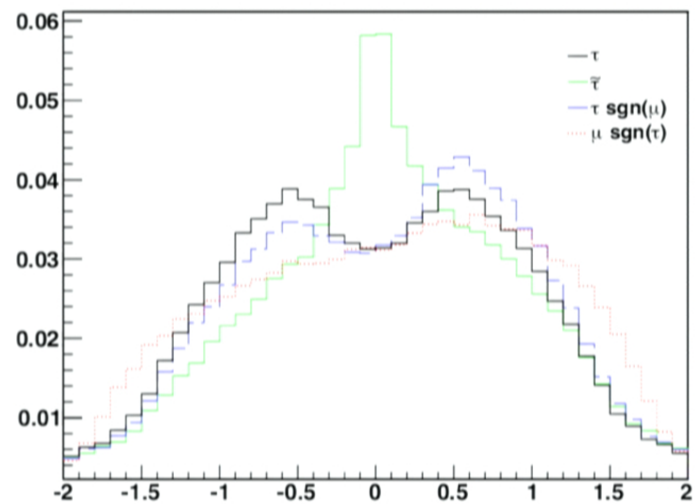
T-Violation in the Higgs Sector

Define new observable sensitive to sgn(μ)

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

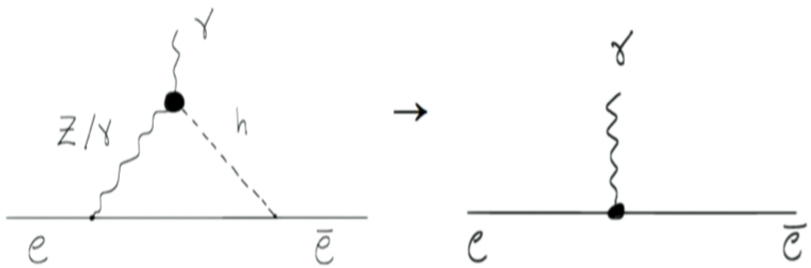
Many conceivable variables sensitive to sgn(μ) → roughly same asymmetry

Plot of signed and unsigned variables



T-Violation in the Higgs Sector

Contributions to electron EDM



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

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

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

Bound on the linear combination of couplings

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

Expectations from naturalness?

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

Phys.Rev.Lett 65 – S. Barr, A. Zee

T-Violation in the Higgs Sector

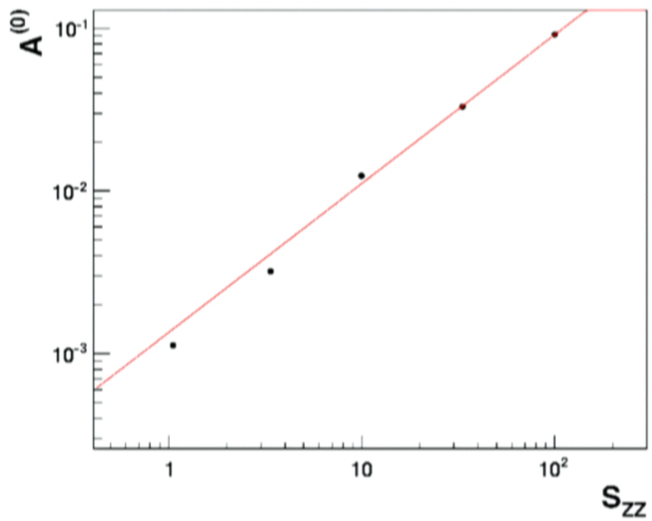
Quantify the asymmetry by defining

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

Plot asymmetry with varying coupling strengths

Sensitivity comparable to EDM's will require many $O(\mathrm{ab}^{-1})$'s

We can wait (nothing but time)



Conclusions

It is a unique time for particle physics

Much information has been gleaned from Run I of the LHC

Data motivates a bottom up approach to exploring structure in the electroweak sector

Many definitive answers await us very early on in Run II