Nucleon & Electron EDMs at 10^{-29}-10^{-30} e-cm Sensitivity!

In Search Of A New Source of CP Violation

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September 15, 2020

Two Loops Bigger Than One?

Baryogenesis: $N_B - N_{Bbar}/N_\gamma \approx 10^{-10}$

1957 - **Parity Violation in Weak Interactions (Maximal!)**
Lee & Yang **Why is nature left-handed (Chiral)?**

1964- CP Violation Discovered in Kaon Decays
CKM Model of Quark Mixing

1967 Sakharov Conditions:

1) Baryon Number Violation
2) CP Violation (strong early Universe source)
3) Non-Equilibrium 1st Order Phase Transition

(Leptogenesis – Very Early Universe Alternative)

Some Current Dipole Moments (Bounds)

fermion	a_f^{exp}	$|d_f^{exp}|$ e-cm
$a_\mu =$ **0.00116592091(33)**		
$a_e =$ 0.00115965218073(28)		$<1.1\times10^{-29}$ (ACME)
$a_n =$ -1.91304273(45)		$<1.3\times10^{-26}$
$a_p =$ 1.79284734462(82)		$<2\times10^{-25}$ (from d_{Hg})

$|d_{Hg}| < 7.4\times10^{-30}$ e-cm

electron, Hg atom & neutron bounds
(Very Powerful BSM Constraints)

Atomic, Molecular, Nuclear Physics
HEP/Nuclear SR Entry $|d_p| \approx 10^{-29}$ e-cm?

3

Complex Formalism: $F_D = F_2 + iF_3$

$$H_{dipole} = -1/2[F_D f_L \sigma_{\mu\nu} f_R + F_D^* f_R \sigma_{\mu\nu} f_L]F^{\mu\nu}$$

$F_D = |F_D|e^{i\phi}$ $f_{R,L} = (1 \pm \gamma_5)/2f$

$|F_D| = (F_2^2 + F_3^2)^{1/2}$, $\tan\phi = F_3/F_2$

$\tan\phi =$ Relative Degree of CP Violation

egs. $|\tan\phi_e|^{SM} \approx 10^{-24}$ $|\tan\phi_n|^{SM} \approx 10^{-20}$

Can ϕ be removed by a chiral rotation?

   $f \rightarrow \exp(i\gamma_5\phi/2) f$ (Dirac Confusion)

No, not if it makes the mass m_f complex (CP Viol.)

EDM (relative phase!)

Induced by complex interaction eg Hee, Htt…

4

Proton edm SR goal: $d_p \sim 10^{-29}$e-cm

Improvement by more than 4 orders!
Sensitivity similar to $d_e < 10^{-30}$e-cm

In a renormalizable quantum field theory, at
lowest order $d_p = 0$ (No dim. 5 operators)

$d_p \sim em/\Lambda_{NP}^2 \sin\phi^{NP}$ quantum loop induced

Λ_{NP} scale of "new physics"

ϕ^{NP} = Complex CP violation phase of New Physics

phase misalignment with m_p

$\sim 10^{-22}(1\text{TeV}/\Lambda_{NP})^2 \sin\phi^{NP}$e-cm

If ϕ^{NP} is of O(1), $\Lambda_{NP} \sim \underline{3000\text{TeV}}$ Probed! (very roughly)
If $\Lambda_{NP} \sim$O(1TeV), $\phi_{NP} \sim 10^{-6}$ Probed!

Standard Model Success

Many Elementary Particles!

SU(3)$_C$xSU(2)$_L$xU(1)$_Y$ Standard Model (SM)

8 gluons + W$^\pm$, Z, γ ***gauge bosons*** *(spin 1)*

3 generations of ***quarks & leptons (mix->CP violation)***

e,ν_e,u,d μ,ν_μ,c,s τ,ν_τ,t,b   (m$_t$/m$_e$ =3.4x10^5!!) *(spin ½)*

Complex Scalar Doublet: S$^\pm$,S^0,H source of mass

SM Spectrum Now Complete m$_H$=125 GeV

Is that all there is? Additional Particles? Interactions?

Supersymmetry - Something Else

*Multi-Higgs (2 doublets?) (Singlets?)

* Heavy (Vector-like) Leptons, Quarks etc .

LHC Higgs Discovery

- **Elementary** *SM Higgs Scalar Exists!*: m_H=125 GeV

Great Discovery reopens old Issues.

λΦ⁴ theory: Quadratic Divergences (Natural?),

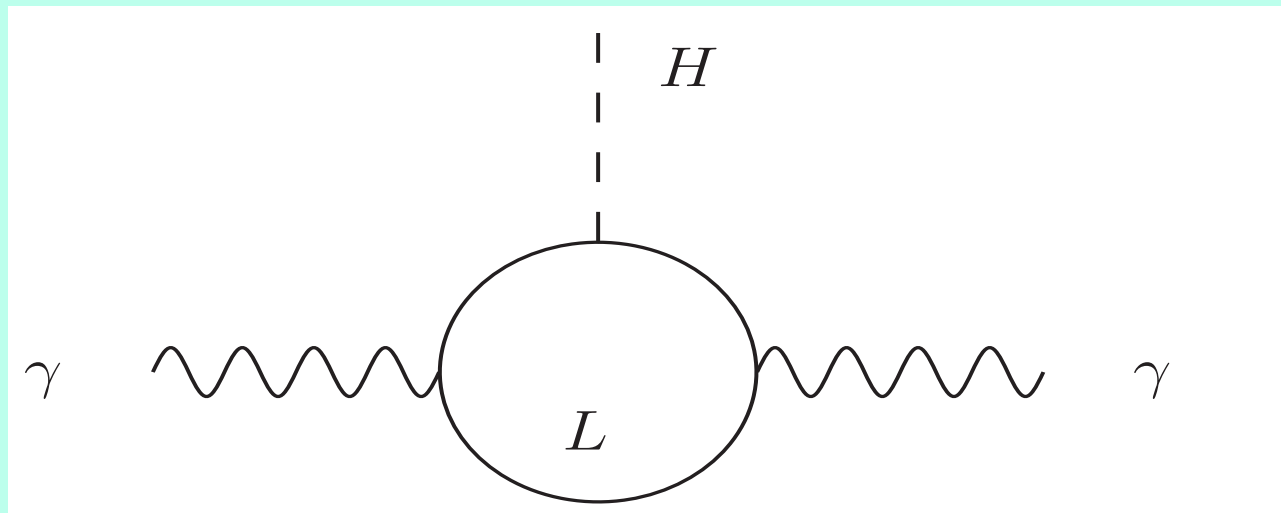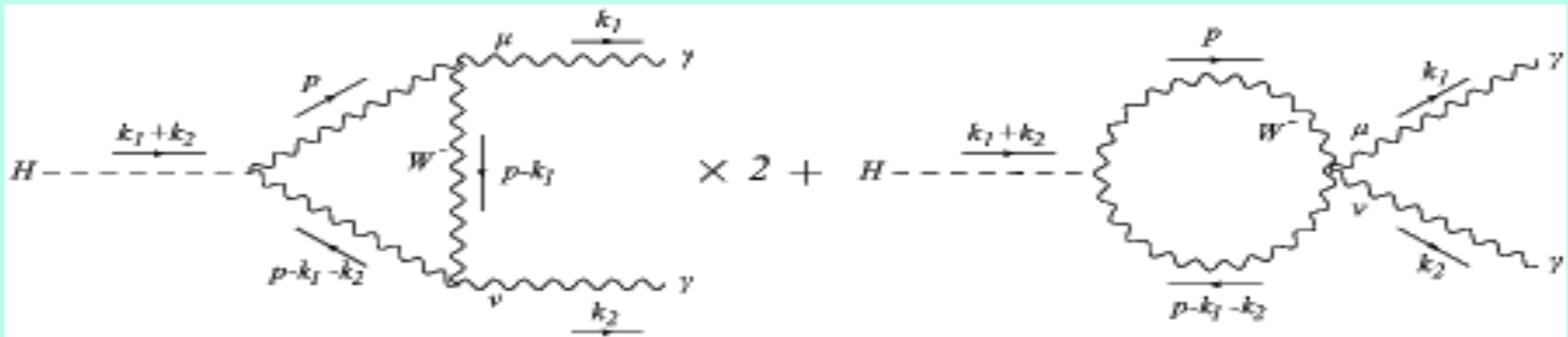Vacuum stability?…

Higgs Properties become a primary probe

Branching Ratios (Couplings), Precision! Anomalies?

Loop Induced BR(H➜γγ) ≈ BR(H➜γγ) $_{SM}$

Several Higgs CP Violation Opportunities?

Implications for edms! d_e, d_n, d_p, d_μ…

W & Top Loop Contributions to H➔γγ
(top quark loop, opposite sign)

Higgs (125GeV) Properties

- ATLAS and CMS Experiments undisputable evidence for a
- Higgs (spin 0) new particle with mass 125GeV

Expected Higgs SM Properties

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \rightarrow ZZ^* \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$	1.2×10^{-4}
$H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \nu \bar{\nu}$	3.6×10^{-4}

- **_5 sigma SM LHC Higgs evidence presented (July 4, 2012)_**

  RUN I > 1,000,000 H already produced at the LHC!

  gluon + gluon ➜ H   through top quark loop

  H➜$\gamma\gamma$ ≈ **_SM Expectation_**

  H➜ZZ*(virtual)➜4 leptons

  H➜WW*➜4 leptons (includes Neutrinos)

  H➜$\tau^+\tau^-$

  H➜bb

  BR(H➜$\mu^+\mu^-$)~2×10^{-4} (5σ sensitivity expected from 14TeV Run)

  H decays to e, u, d expected to be unobservably small

 **_BR(H➜e+e-) ~ O(5×10^{-9})! Higgs Factory Needed_**

  edms may be **unique** window to e, u, d Higgs couplings**!**

One Loop Higgs (m_h=125GeV) Contribution to Dipole Moments
$|d_l| = m_l^3/m_h^2 m_W^2$ highly suppressed!!
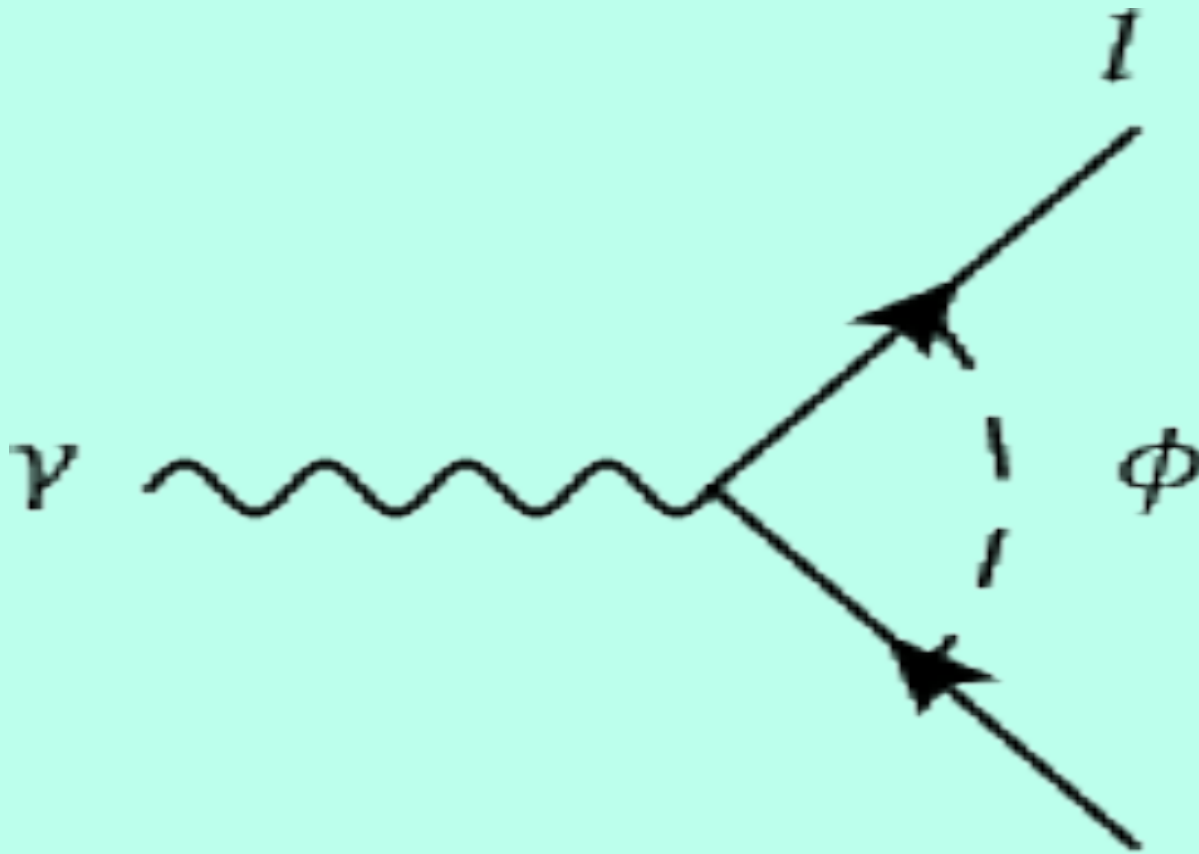
Complex Hee or Htt Interaction

- SM Scalar coupling $gm_e/2m_W$ **modified** by New Physics
- Eg. Several sources of electron mass ➜ misalignment
  coupling multiplied by $A(\cos\phi + i\gamma_5\sin\phi)$
  complex part violates P & T (CP) CP misalignment
  similar possibility for Htt coupling (larger?)
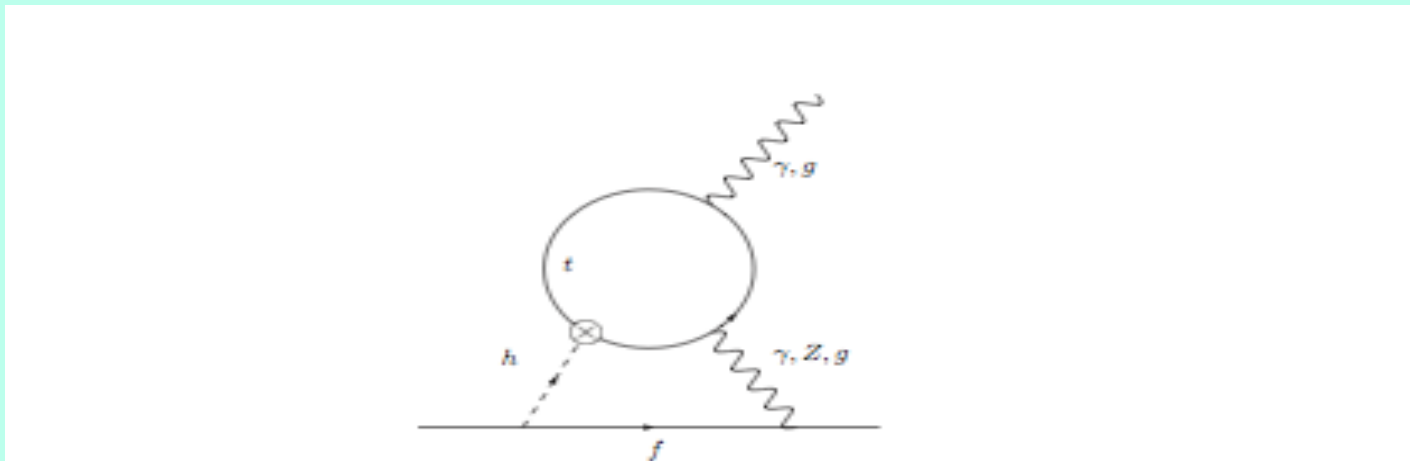
Induces fermion edm!! In Higgs loops

Great Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28} e-cm Neutron Spallation/Reactor Sources

- $d_e \rightarrow 10^{-30}$ e-cm or better!   (Molecules) ACME

- d_p & $d_D \rightarrow 10^{-29}$ e-cm Storage Ring Proposal (BNL/COSY)

  Pave the way for a new generation of storage ring experiments d_e, d_p, d_D, $d(^3\text{He})$, d(radioactive nuclei), d_μ

  Several orders of magnitude improvement expected

  All Very Well Motivated – Must Do Exps.

Example Hγγ vs edms
McKeen, Pospelov & Ritz; Voloshin

H➡γγ   Dim. 5 Operator (Scalar Analog of Dipole Moments)

$$aHF_{\mu\nu}F^{\mu\nu} + bH*F_{\mu\nu}F^{\mu\nu} \quad (*F_{\mu\nu}=F_{\mu\nu} \text{ dual } =1/2\varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$$

second term violates P & T (much like edm)

New Source of CP Violation!

Higgs **pseudoscalar** Coupling

$$\tan\phi_{H➡\gamma\gamma}= b/a \qquad \Gamma(H➡\gamma\gamma) \; \alpha \; a^2 +b^2$$
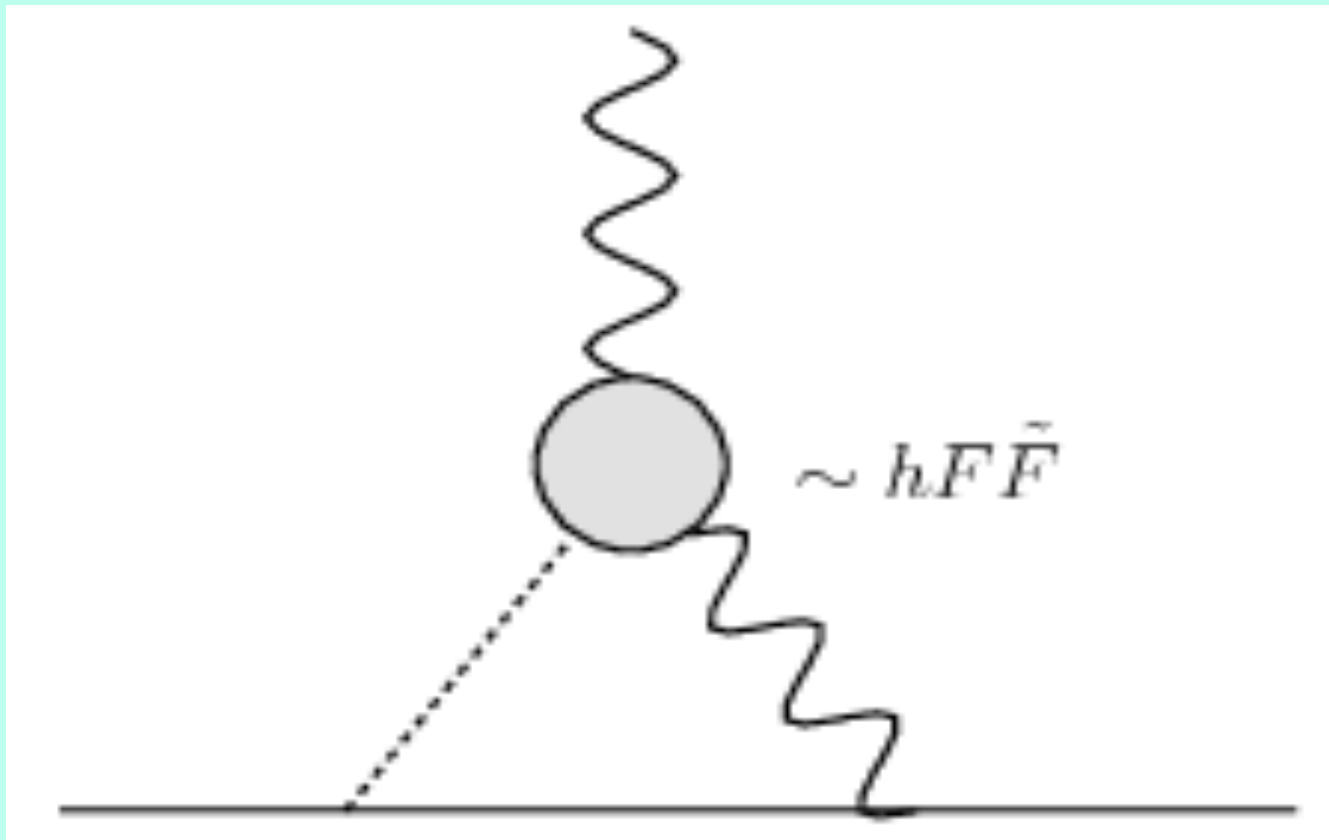
Could the Higgs violate CP? Source of Baryogenesis?
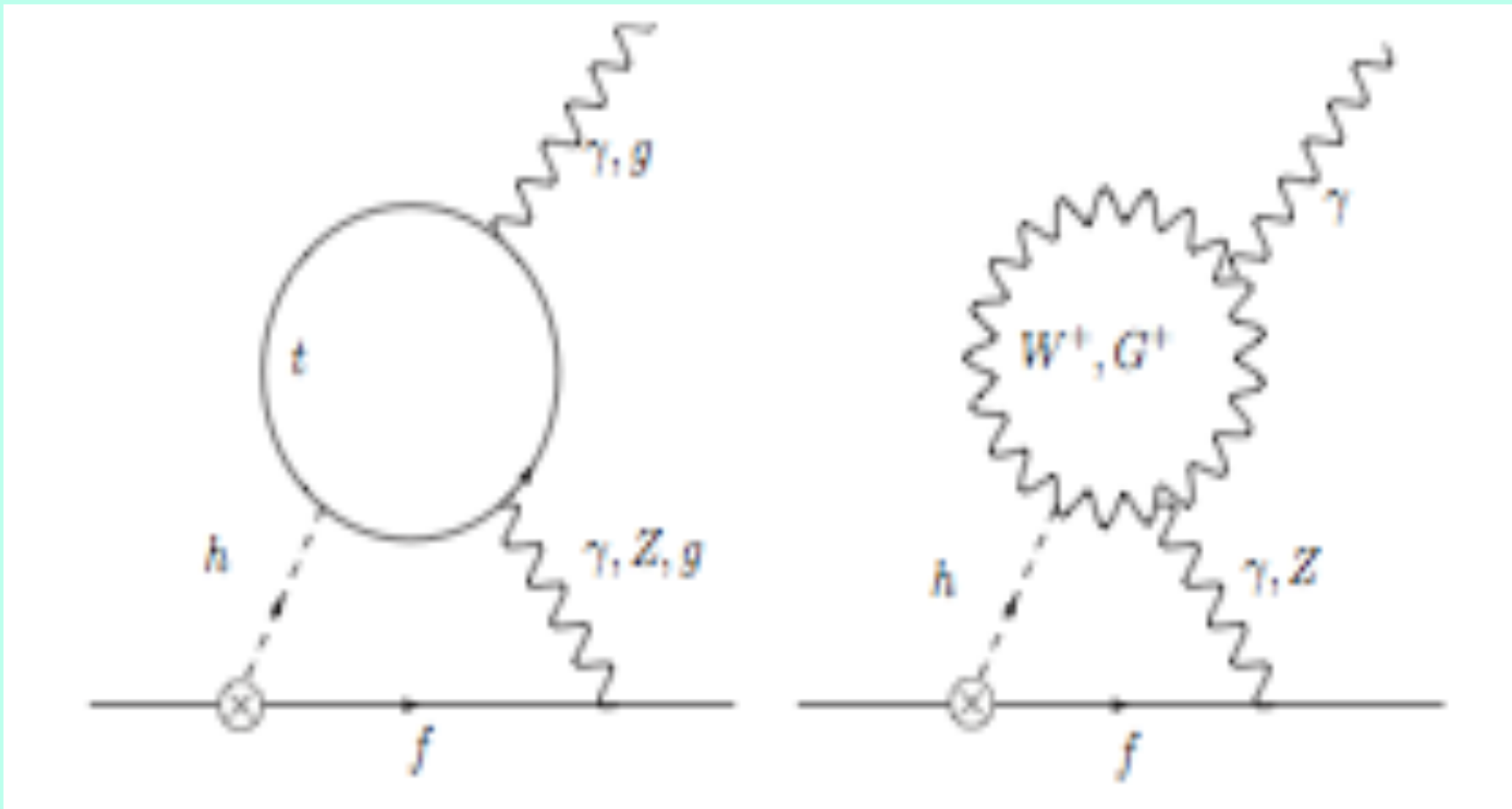
Measure γγ   planes of polarizaton (Voloshin)

Max. at $\theta=\phi_{H➡\gamma\gamma}= b/a$ (instead of 0)

Very Difficult, particularly for b<<a

Generic CP Violating higgs 2 loop
(McKeen, Pospelov, Ritz)
several potential complex phases

$\sim h F \tilde{F}$

2 loop dipole moment sources: McKeen, Pospelov, Ritz
earlier Huber, Pospelov, Ritz

a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx few \times 10^{-11}$
  Both **_Unobservably Small_** $a_e(H) \approx 5 \times 10^{-16}$

  EDM Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e−cm
  $$|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-25} \sin\phi \, e-cm$$
  Already d_e bound implies $\sin\phi_e \leq 0.002$ (smaller?)
  Altmannshofer, Brod, Schmaltz JHEP (updated)

CP violation in BR($H \to \gamma\gamma$) $\gamma\gamma$ Collider?

**_Unlikely to be observable, but edm experiments can
Explore down to $\tan\phi \approx O(10^{-4})$! Unique!_**

Physics Reach of $d_p \sim 10^{-29}$ e-cm
2 loop Barr-Zee Higgs Effect

$$d_p \sim 3 \times 10^{-25} \tan\phi^{Higgs} \text{ e-cm}$$

$$\sim 3 \times 10^{-25} (\phi^{Hqq} + \phi^{Htt} + \phi^{H\gamma\gamma} \ldots) \text{ e-cm}$$

$$\tan\phi^{Hqq} = \text{ImHqq/ReHqq etc}$$

Angles of $O(10^{-4})$ probed!!

Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources

- d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring (BNL/COSY)
  Probes New Physics(NP) at $(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-6}$!
  for $\phi_{NP} \sim O(1) \rightarrow \Lambda_{NP} > \underline{3000\text{TeV}}$! (**well beyond LHC**)
  Paves the way for a **new generation** of storage ring
  experiments d_p, d_D, $d(^3\text{He})$, d(radioactive nuclei), d_μ

$d_e \rightarrow 10^{-30}$e-cm or better!
$d_p \rightarrow 10^{-29}$e-cm Storage Ring Proposal
Complementary

19

Outlook

EDMs will eventually be discovered: $d_e, d_n, d_p \dots d_D$

Magnitudes of $\approx 10^{-28}$ expected for Baryogenesis

Atomic, Molecular, Neutron, *Storage Ring* (All important)

CP violation phase in*: Hee, Hγγ, Htt, 2HD Model…*

Uniquely explored by 2 loop edms! **Barr-Zee effect**

May be our only window to Hee, Huu and Hdd couplings

The Higgs Mechanism critical for our existence!

Early Universe and Beyond

Must Be Fully Explored