기초과학연구원
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Renormalization Effects on EDMs in ElectroWeakly Interacting Massive Particle Models

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Based on

arXiv:1902.05360 (to be published in PRD)

with W.Kuramoto (Nagoya), R.Nagai (ICRR)

Electroweakly Interacting Massive Particles (EWIMPs)

- well-motivated dark matter candidates
- single n-plet EWIMP fermion appears in well-motivated UV physics

(split/pure gravity mediated) supersymmetry

$\mathbf{3}_0$ Majorana triplet (wino)

Arkani-Hamed, Dimopoulos (2004)
Giudice, Romanino (2004)
Ibe, Yanagida (2011)

spread supersymmetry

$\mathbf{2}_{1/2}$ Dirac doublet (higgsino)

Hall, Nomura (2011)

- accidentally stable

$\mathbf{5}_0$ Majorana quintuplet (minimal dark matter)

Cirelli, Fornengo, Strumia (2005)

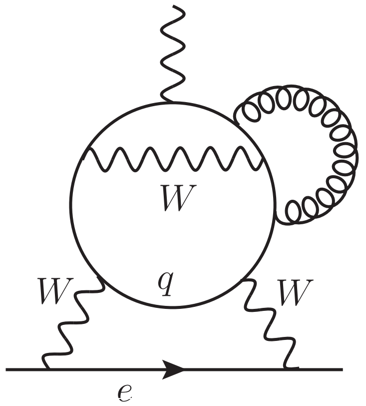
Electric Dipole Moments

EDMs in the SM,

$$d_n \sim 10^{-32}\ e\,\mathrm{cm}\,, \qquad d_e \sim 10^{-38}\ e\,\mathrm{cm}$$

Pospelov, Ritz (2013)

Gavela, et al (1982), Khriplovich, Zhitnitsky (1982)
Khriplovich (1986), McKellar et al (1987)



electron EDM

$$|d_e| \leq 1.1 \times 10^{-29}\ e\,\mathrm{cm} \longrightarrow |d_e| \simeq 1.0 \times 10^{-31}\ e\,\mathrm{cm}$$

ACME collab. (2018) — ACME-III final goal

nucleon EDMs

$$|d_n| \leq 3.0 \times 10^{-26}\ e\,\mathrm{cm} \longrightarrow |d_n| \simeq 10^{-27}\text{-}10^{-28}\ e\,\mathrm{cm}$$

C. A. Baker et al. (2006)
J. M. Pendlebury et al. (2015)

Several UCN experiments

$$|d_p| \leq 7.9 \times 10^{-25}\ e\,\mathrm{cm} \longrightarrow |d_p| \simeq 1.0 \times 10^{-29}\ e\,\mathrm{cm}$$

W. C. Griffith et al. (2009)

Strage-ring experiments

SM predictions are still beyond future prospect.

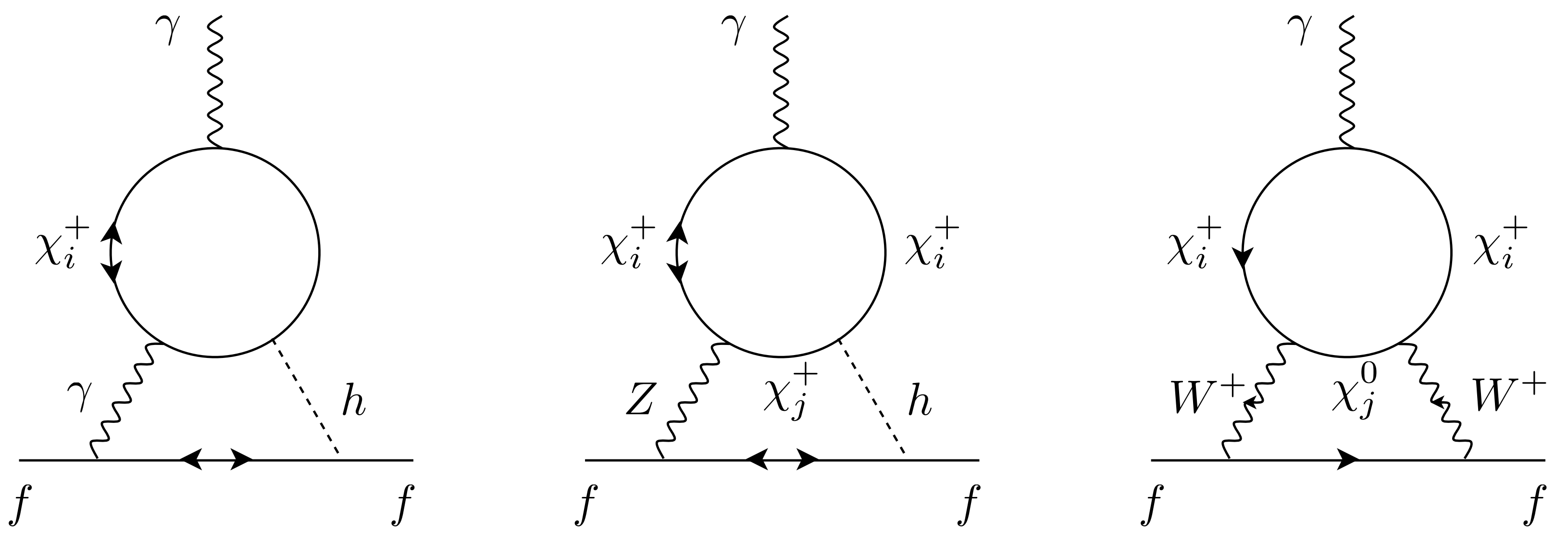
Future exps are sensitive to the new-physics CPV.

CP Violation in Split Supersymmetry (example: EDMs from EWIMP fermion)

Giudice, Romanino (2005)

Split Supersymmetry

- Heavy scalars (sfermions+additional Higgs) are decoupled
  Low-energy spectrum: SM + chargino+neutralino (= gauginos+higgsinos)
- Charginos and Neutralinos only contribute to fermion EDMs (Barr-Zee)



- BZ contributions are computed at m_Z ~ gaugino/higgsino mass scale
- CPV: phases of mass/gaugino couplings

What happens if higgsinos have the similar mass as sfermions?
At which scale should we compute the parton EDMs?

CP Violation from D=5 Operators

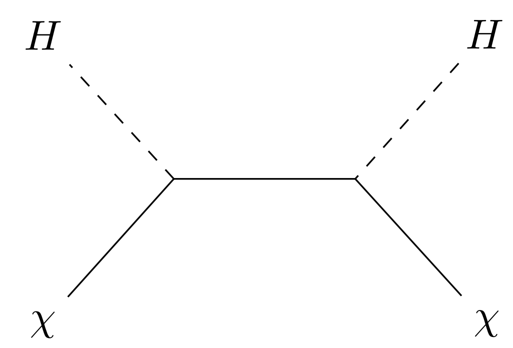
We focus on the single EWIMP fermion models.

Possible CP Violation from the D=5 operators @ scale M_{phys}

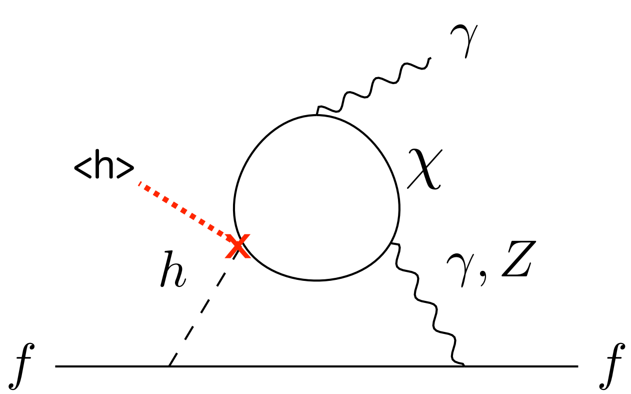
$$\mathcal{L}_\chi = \begin{cases} \frac{1}{2}\tilde{C}_s H^\dagger H \overline{\chi}^C i\gamma_5\chi & \text{(Majorana)} \\ \tilde{C}_s H^\dagger H \overline{\chi} i\gamma_5\chi + \tilde{C}_t H^\dagger t^a H \overline{\chi} i\gamma_5 T^a\chi & \text{(Dirac)} \end{cases}$$

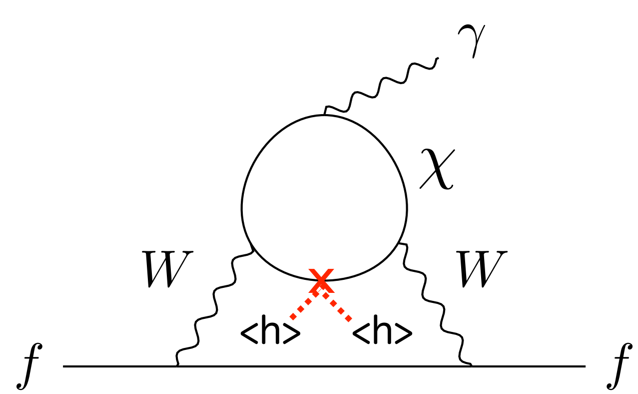
UV completion

fermionic mediator w/ M_{phys}



Fermionic EDMs arise from the operators @ EW scale





Resultant fermionic EDMs:

$$d_f \sim \frac{e\alpha}{(4\pi)^3}\frac{m_f}{M}\tilde{C}_{s,t}$$

- ⋆ two-loop factor
- ⋆ chirality flip (M: EWIMP mass)
- ⋆ CP violation

Renormalization Flow of CPV D=5 Operators

$$\mathcal{L}_\chi = \begin{cases} \frac{1}{2}\tilde{C}_s H^\dagger H \overline{\chi}^C i\gamma_5 \chi & \text{(Majorana)} \\ \tilde{C}_s H^\dagger H \overline{\chi} i\gamma_5 \chi + \tilde{C}_t H^\dagger t^a H \overline{\chi} i\gamma_5 T^a \chi & \text{(Dirac)} \end{cases}$$

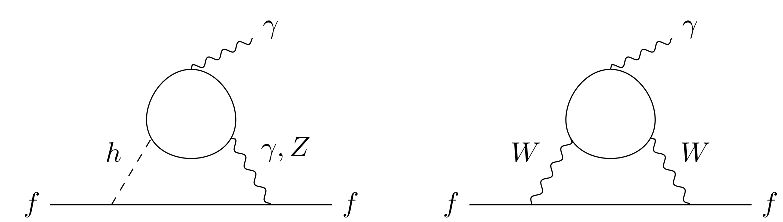
Energy scale

M_{phys} >> 10TeV — D=5 Operators are generated

↓ RG running of D=5 operators

Kuramoto, TK, Nagai (2019): THIS work!

m_Z — Matching with parton EDMs



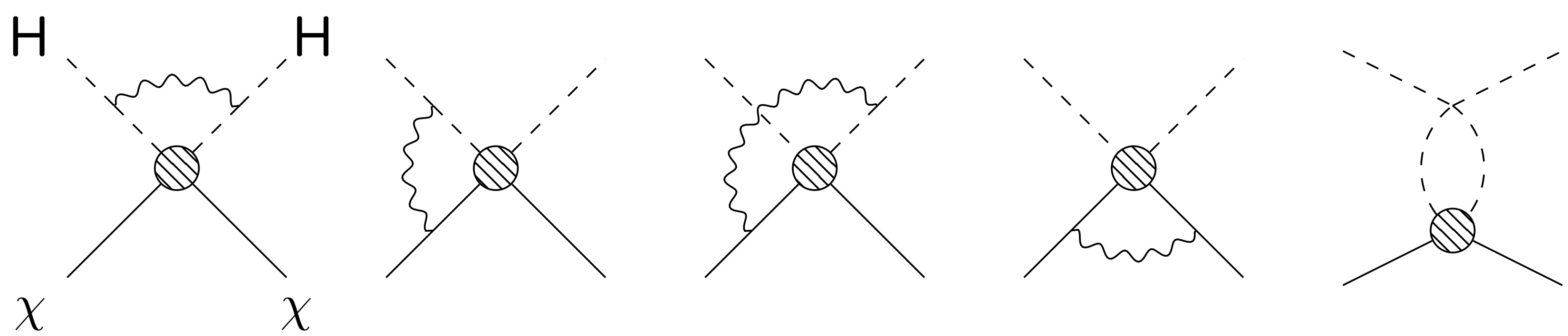
↓ RG running of quark EDMs

Degrassi, Franco, Marchetti, Silvestrini (2005)

Λ_{QCD} — Matching with hadronic EDMs

One-Loop Anomalous Dimension for D=5 Operators

One-loop vertex corrections



gauge interactions

Higgs[4] interaction

RG equation for Wilson coefficients

Kuramoto, TK, Nagai (2019)

$$\frac{d}{d\ln\mu}\begin{pmatrix}\tilde{C}_s(\mu)\\ \tilde{C}_t(\mu)\end{pmatrix} = \begin{pmatrix}(\gamma_{\mathcal{O}})_{ss} & (\gamma_{\mathcal{O}})_{st}\\ (\gamma_{\mathcal{O}})_{ts} & (\gamma_{\mathcal{O}})_{tt}\end{pmatrix}^T \begin{pmatrix}\tilde{C}_s(\mu)\\ \tilde{C}_t(\mu)\end{pmatrix}$$

$$(\gamma_{\mathcal{O}})_{ss} = -\frac{1}{(4\pi)^2}\left[6g^2\left(C_2(H)+C_2(\chi)\right)+6g'^2\left(Y_H^2+Y_\chi^2\right)-3\lambda-6y_t^2\right]$$

$$(\gamma_{\mathcal{O}})_{tt} = -\frac{1}{(4\pi)^2}\left[6g^2\left(C_2(H)+C_2(\chi)-\frac{1}{2}C_2(G)\right)+6g'^2\left(Y_H^2+Y_\chi^2\right)-\lambda-6y_t^2\right]$$

$$(\gamma_{\mathcal{O}})_{st} = (\gamma_{\mathcal{O}})_{ts} = 0$$

Quadratic Casimir invariant

$$T^aT^a = C_2(\chi)\mathbf{1}$$

$$C_2(\chi) = \frac{1}{4}(n^2-1)$$

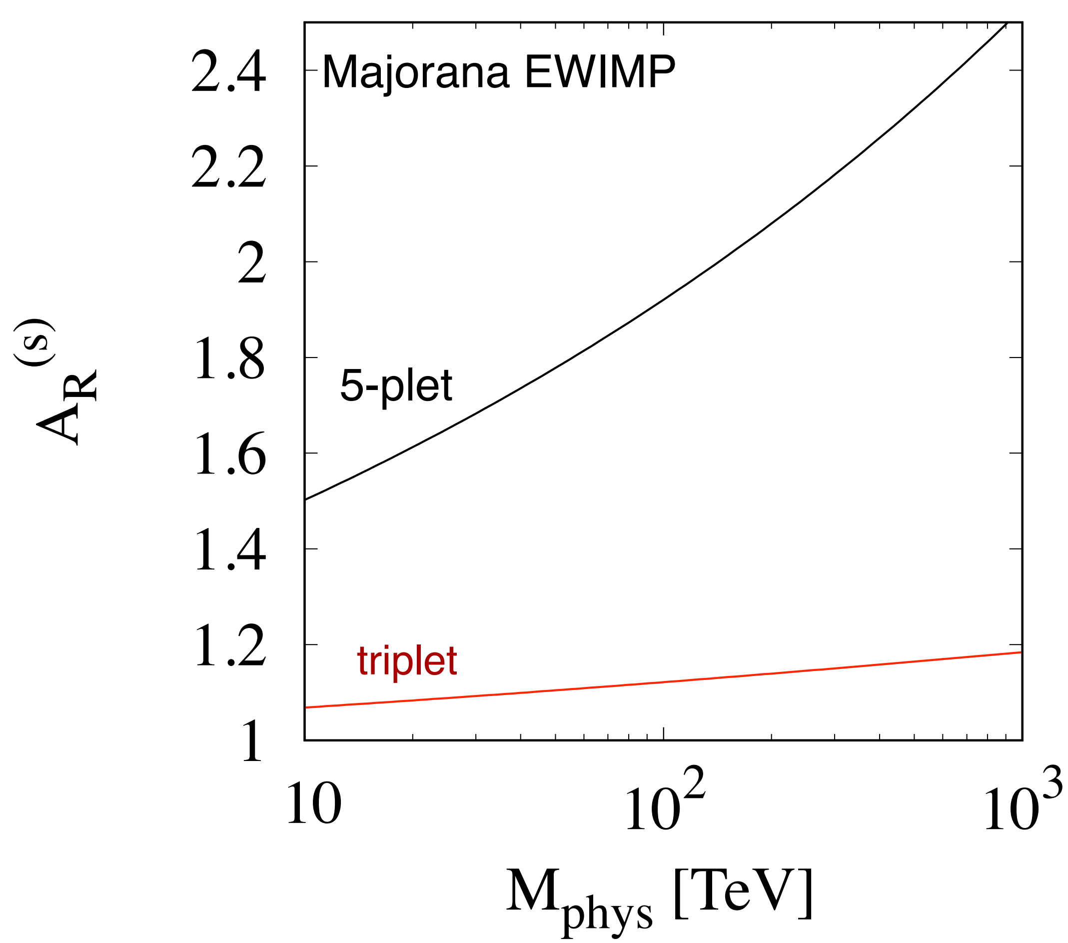
$C_2(\chi)$: large for a large multiplet

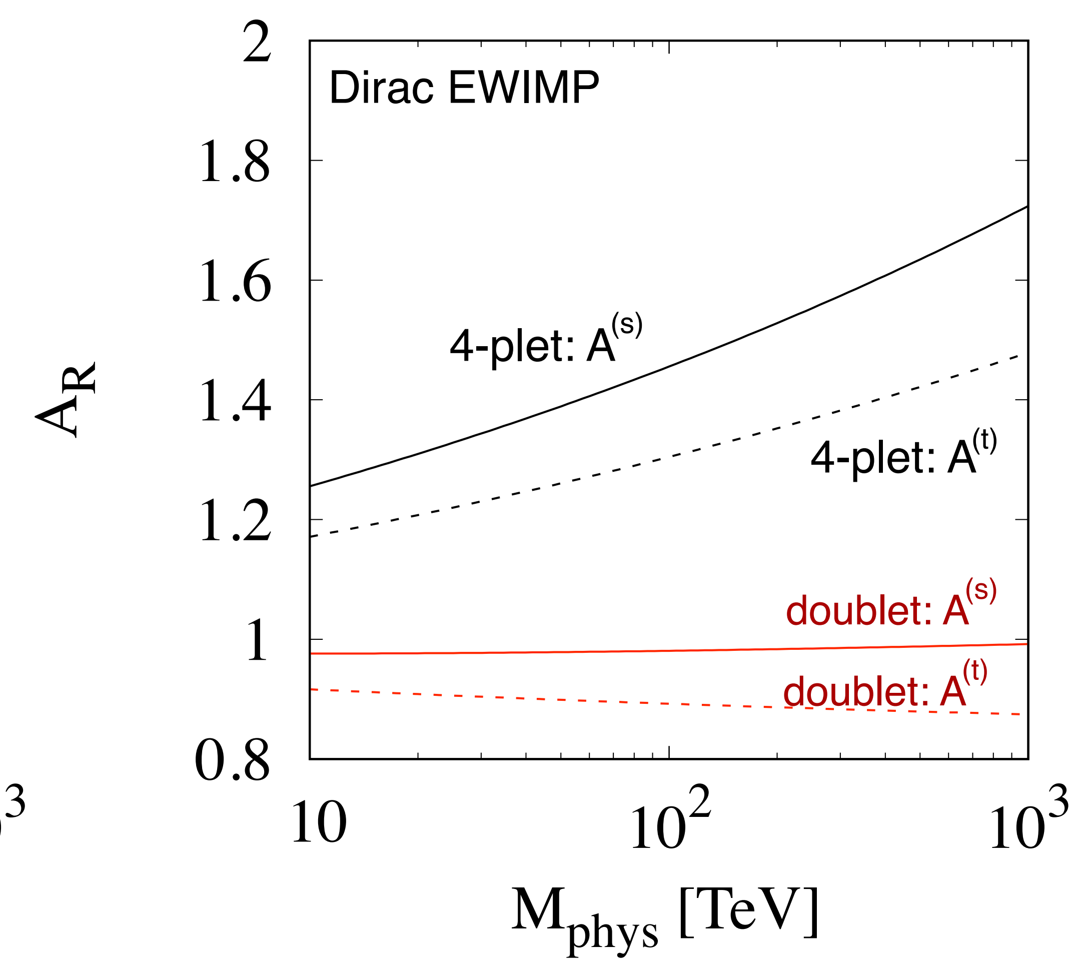
Wilson coefficients can be large @ low-energy for a large multiplet

Results

Renormalization Factor $A_R^{(s,t)} \equiv \tilde{C}_{s,t}(m_Z)/\tilde{C}_{s,t}(M_{\rm phys})$

b/w the weak scale and the input scale $M_{\rm phys}$

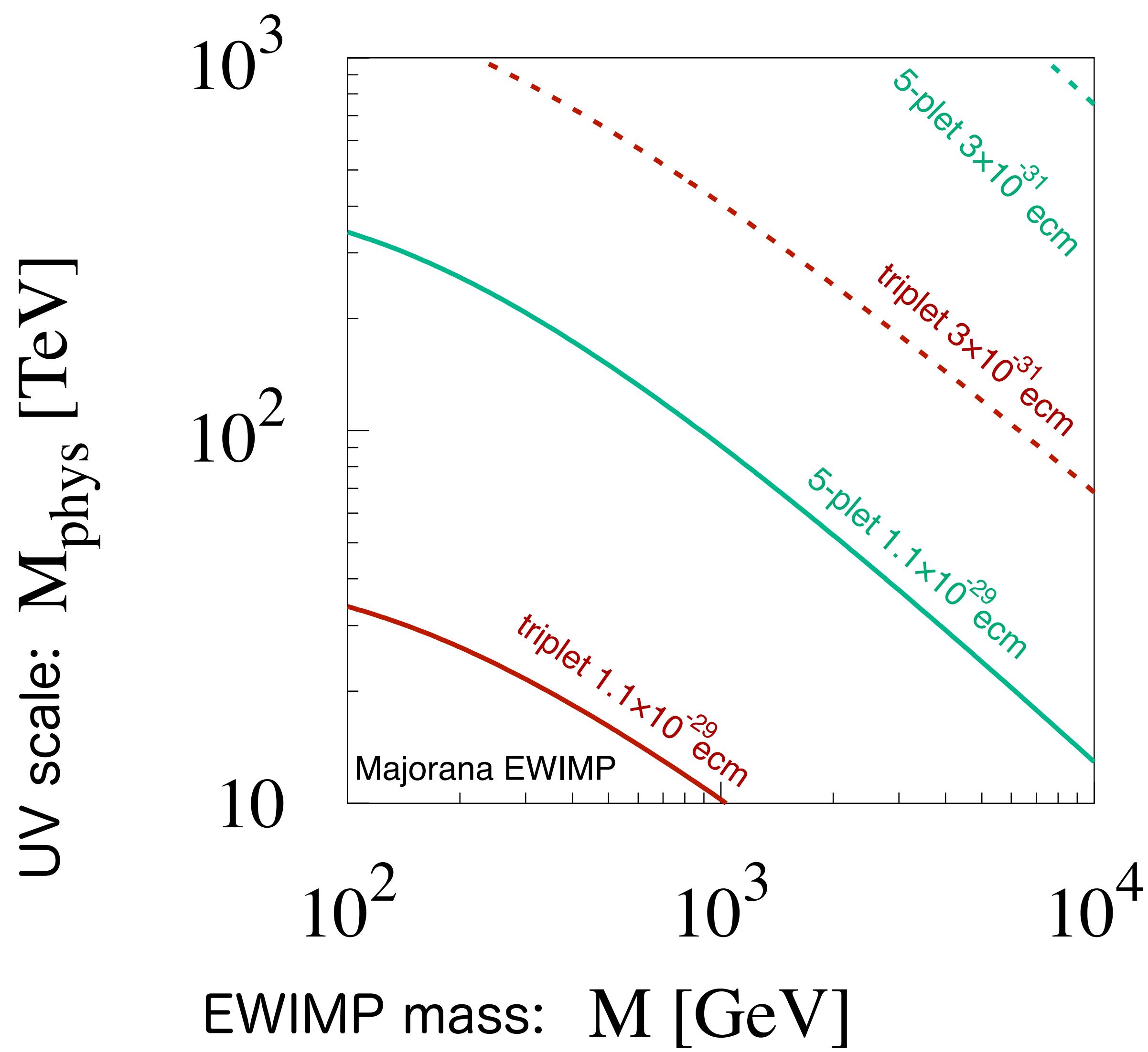




$M_{\rm phys}$: scale where effective operators are induced

$A^{(s)}$ and $A^{(t)}$:
AD of $A^{(t)}$ is smaller than that of $A^{(s)}$.

Electron EDM from Majorana EWIMPs



Wilson coefficients @ input scale

$$\tilde{C}_{s,t}(M_{\rm phys}) = \frac{\xi}{M_{\rm phys}}$$

- ξ is determined by the fundamental parameters in UV.
  - Couplings
  - CPV in the EWIMP sector

  we take $\xi = 0.1$
- Assuming no relevant CP violation in the SM(EFT)

Electron EDM is proportional to $d_f \propto n(n^2-1)$

more severe constraint for EDM from 5-plet for the same M & $M_{\rm phys}$

Summary and Discussion

- ☑ We derived the one-loop ADM for CPV d=5 operators in SM+single EWIMP model.
- ☑ We evaluated the enhancement factor from RGE (from M_{phys} to M_Z).
- ☑ One-loop RG flow enhancement factor:
  5-plet (MDM like): 1.6 - 2.4 (for M_{phys} = 10TeV-10^3TeV)
  triplet (wino like): 1.1 - 1.2 (for M_{phys} = 10TeV-10^3TeV)

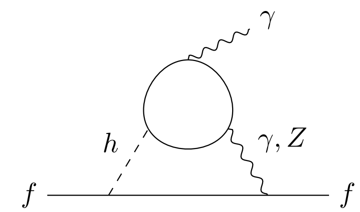
Comments:

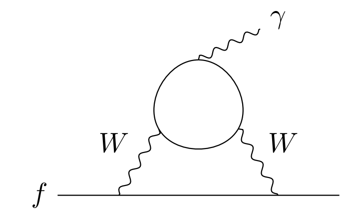
- ☑ Multi-EWIMP system (ex. wino-higgsino system):
  additional Yukawa couplings (free parameters) to the SM Higgs
  -> highly depends on models
- ☑ nucleon EDMs: similarly obtained
  $|d_n/d_e| \sim 15$
  $|d_p/d_e| \sim 10$
  ratio of parton masses/d_{ZH} contribution/QCD corrections

Backup

CP Violation from D=5 Operators

Barr-Zee (1990)
Hisano, Kobayashi, Mori, Senaha (2014)
Nagata, Shirai (2014)





Resultant EDMs from an EWIMP fermion (n-plet with mass M)

Majorana fermion

$$\frac{d_f^{\gamma H}}{e} = \frac{\alpha_e m_f Q_f}{6(4\pi)^3} \frac{n(n^2-1)}{M} \tilde{C}_s f_0\left(\frac{M^2}{m_h^2}\right),$$

$$\frac{d_f^{ZH}}{e} = \frac{\alpha m_f}{12(4\pi)^3}(T_f^3 - 2Q_f \sin^2\theta_W)\frac{n(n^2-1)}{M}\tilde{C}_s f_1\left(\frac{m_Z^2}{m_h^2}, \frac{M^2}{m_h^2}\right),$$

$$\frac{d_f^{WW}}{e} = 0\,.$$

f_0 and f_1:loop functions

d_{ZH} for electron
accidentally small
$\sin^2\theta_W = 0.23122$

Dirac fermion (Y_χ: hypercharge)

$$\frac{d_f^{\gamma H}}{e} = \frac{\alpha_e m_f Q_f}{3(4\pi)^3}\frac{n}{M} f_0\left(\frac{M^2}{m_h^2}\right)\left[(n^2-1+12Y_\chi^2)\tilde{C}_s - Y_\chi(n^2-1)\tilde{C}_t\right],$$

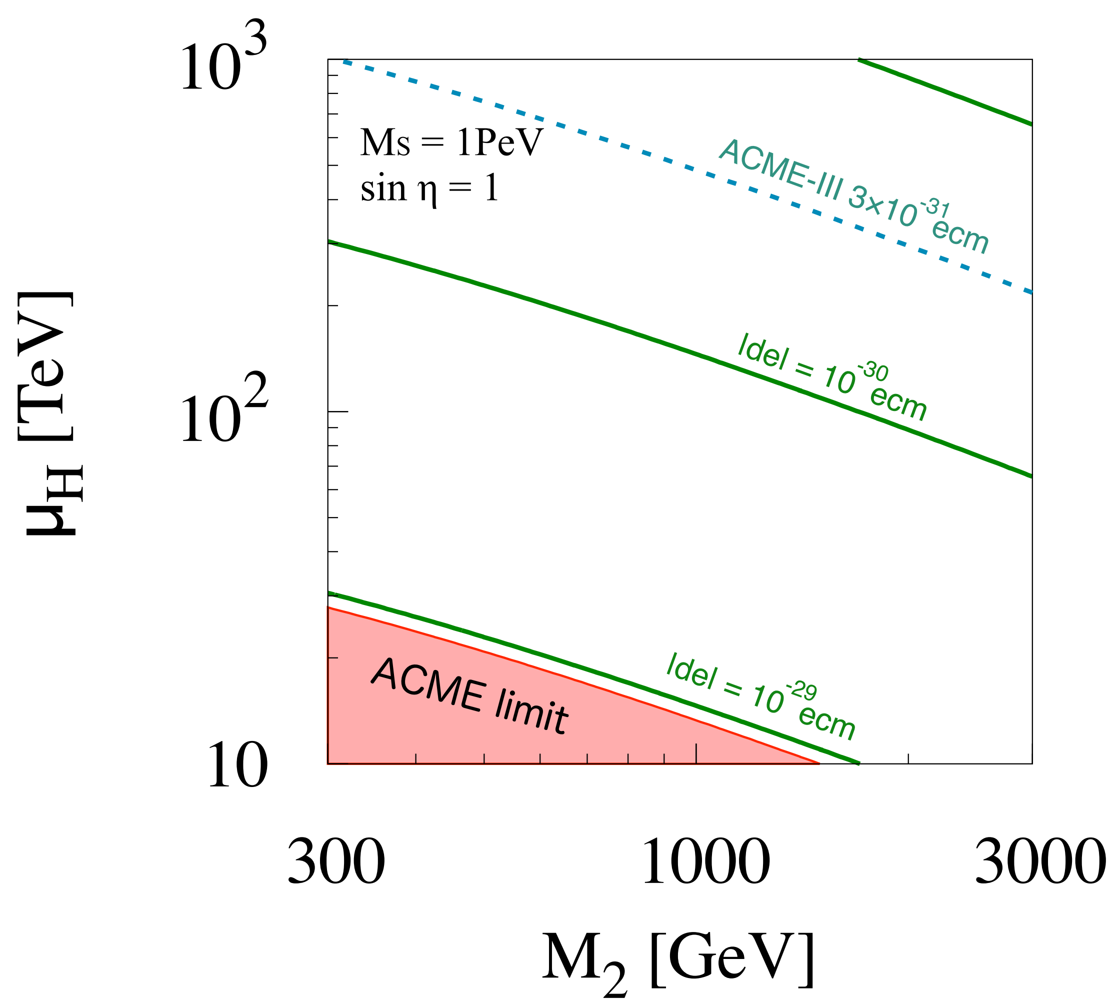
$$\frac{d_f^{ZH}}{e} = \frac{\alpha m_f}{12(4\pi)^3}\frac{n}{M}(T_f^3 - 2Q_f\sin^2\theta_W) f_1\left(\frac{m_Z^2}{m_h^2}, \frac{M^2}{m_h^2}\right)$$
$$\times\left[2(n^2-1-12Y_\chi^2\tan^2\theta_W)\tilde{C}_s - Y_\chi(n^2-1)(1-\tan^2\theta_W)\tilde{C}_t\right],$$

$$\frac{d_f^{WW}}{e} = \frac{\alpha m_f T_f^3}{6(4\pi)^3}\frac{n}{M} f_0\left(\frac{M^2}{m_W^2}\right) Y_\chi(n^2-1)\tilde{C}_t\,.$$

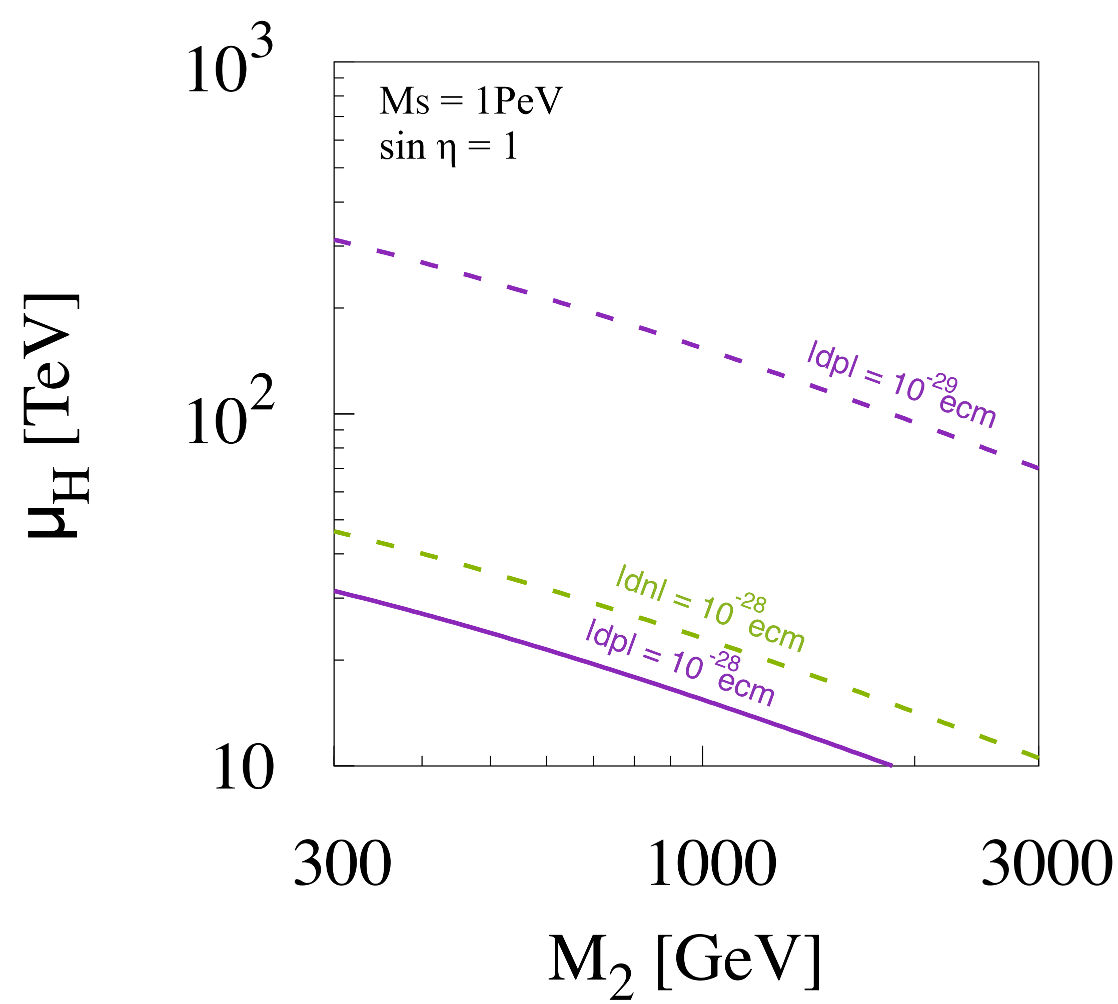
High-scale Supersymmetric Model

Wino mass M_2- Higgsino mass μ_H contour plots $\quad \widetilde{C}_s(\mu_H) = \frac{|g_u||g_d|}{|\mu_H|}\sin\eta\,, \qquad \eta = \arg(g_u^* g_d^* M_2 \mu_H)$

electron EDM



nucleon EDM



Future exps: probe a broad region when sin eta = 1

d_N/d_e is predicted in this model: $|d_p/d_e| \sim 10$, $|d_n/d_e| \sim 15$

QCD correction
d_{ZH} contribution
mass/charges

High-scale Supersymmetric Model (η-dependence)

$$\widetilde{C}_s(\mu_H) = \frac{|g_u||g_d|}{|\mu_H|}\sin\eta\,, \qquad \eta = \arg(g_u^* g_d^* M_2 \mu_H)$$