since 1887

# Electric Dipole Moment and Dark Matter in a CP Violating Minimal Supersymmetric SM

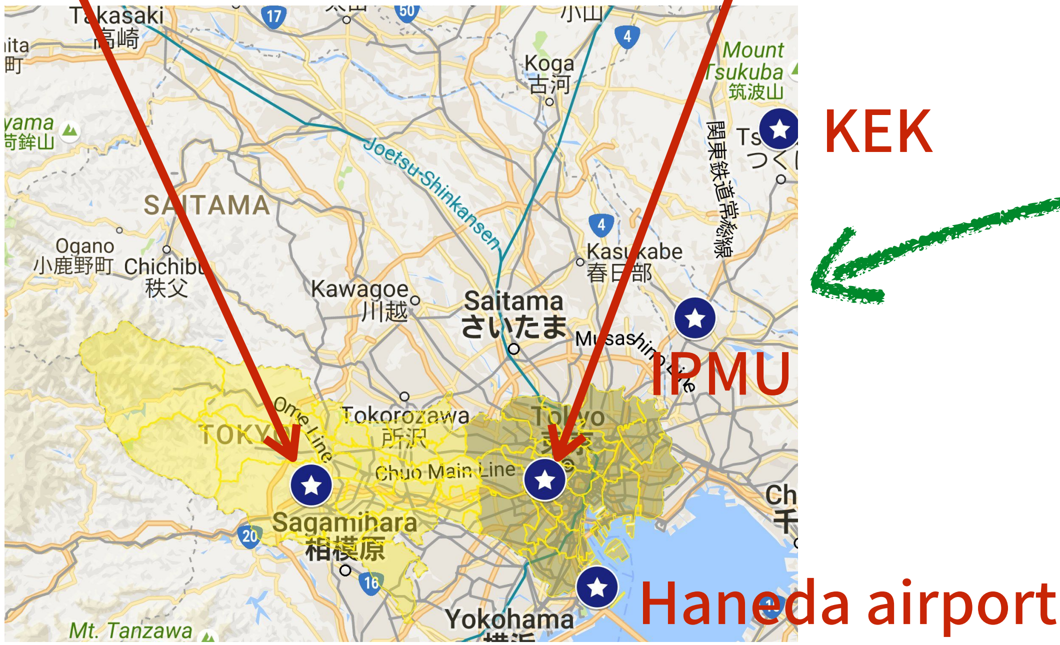
Tetsuo Shindou (Kogakuin Univ.)

**Based on 1805.09537 with T. Abe, N. Omoto, O. Seto**

26&27.06.2018 “What comes beyond the SMs”, Bled, Slovenia

# The University was established in 1887

Kogakuin Univ.





In the physics group: 5 faculties (incl. me)

- 2 Particle theorists
- 1 ILC experimentalist
- 2 Astrophysicists (Theorist & ALMA)

# Physics beyond the SM

The Higgs boson was discovered (2012)

&

Its properties are consistent with a SM Higgs boson

↓

The SM seems to be established

However, it's not the end of the story

We still require the NP beyond the SM

- Baryon asymmetry of the Universe?
- What's the Dark Matter?
- Origin of tiny neutrino mass?
- Charge quantisation?← Unified theory ? (Hierarchy problem)
- Some excess might be found (muon g-2, …)
- …

# Defeats of extended Higgs models

Two strong constraints on BSM models

- ☆ No significant contribution to FCNC

no new flavour mixing

- ☆ Rho parameter is very close to one

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \simeq 1$$

custodial symmetric

Extended Higgs sector $\longrightarrow$ either conditions is broken

e.g.

- doublet extension leads to new flavour mixing

Softly broken $Z_2$ rescues it

- triplet extension leads to the breaking of custodial sym.

Singlet extension is safe

# SUSY

No signal has been discovered at LHC

↓

SUSY may not be a solution to the “naturalness problem”

But it may still be an attractive candidate of BSM

- ☆ Gauge coupling unification is realised
- ☆ Quadratic divergence is cancelled
- ☆ Spin-0 fields are naturally introduced
- ☆ Well-defined UV picture of type-II 2HDM
- ☆ LSP can be a DM with R-parity

# SUSY from flavour point of view

It is good to consider MSSM with rather large ~~SUSY~~ mass

Supersymmetric sector is very beautiful

$$W = y_u U^c H_2 \cdot Q + y_d D^c H_1 \cdot Q + y_\ell E^c H_1 \cdot L + \mu H_1 \cdot H_2$$

It naturally leads to type-II 2HDM

dangerous FCNC is suppressed

SUSY breaking sector is not good

So many sources of flavour mixings and CP

If SUSY breaking masses are heavy enough, they don't cause problems.

↑

Consistent with SUSY search and Higgs mass (125 GeV)

# High scale SUSY?

- Let's consider the case with large SUSY breaking mass
- If everything are heavy, the model does not solve any problem in the SM
- Some SUSY particles may be light as ~1TeV
  - For DM, which should be light?
  - In such a case, how to probe the model?

# Neutralino DM scenarios in MSSM

Neutralino DM in MSSM is thermally produced too much

significant enhancement of annihilation is necessary

- ☆ Neutralinos annihilate significantly through SU(2) gauge interaction
  - ☆ e.g. Higgsino-like DM with $m_\chi \sim 1\ \mathrm{TeV}$

N. Nagata&S. Shirai, arXiv:1410.4549

- ☆ Annihilation cross section of Bino-like neutralino is enhanced with a particular mass spectrum of other associated particles
  - ☆ Higgs resonance (funnel), coannihilation, …

# Funnel scenario

We focus on the scenario

$$\chi\chi \rightarrow H^0, A^0 \rightarrow \bar{f}f \xrightarrow[2m_{\rm DM} \simeq m_{H,A}]{} \text{DM annihilation is enhanced}$$

↓

Observed relic abundance can be explained

In this scenario, Bino mass is less than a few TeV

Some parameters are fixed such as heavy Higgs mass

We analyse this scenario in MSSM with CP phases

↓

electric dipole moments are useful

# CP violation in MSSM

## Soft SUSY breaking terms:

$$\begin{aligned}\mathcal{L}_{\rm soft} = &-\frac{M_1}{2}\tilde{B}\tilde{B} - \frac{M_2}{2}\tilde{W}^\alpha\tilde{W}^\alpha - \frac{M_3}{2}\tilde{G}^A\tilde{G}^A \\ &- m_{H_1}^2 H_{1a}^* H_1^a + m_{H_2}^2 H_{2a}^* H_2^a - \tilde{q}_{iLa}^*(M_{\tilde{q}}^2)_{ij}\tilde{q}_{jL}^a - \tilde{\ell}_{iLa}^*(M_{\tilde{\ell}}^2)_{ij}\tilde{\ell}_{jL}^a \\ &- \tilde{u}_{iR}(M_{\tilde{u}}^2)_{ij}\tilde{u}_{jR}^* - \tilde{d}_{iR}(M_{\tilde{d}}^2)_{ij}\tilde{d}_{jR}^* - \tilde{e}_{iR}(M_{\tilde{e}}^2)_{ij}\tilde{e}_{jR}^* \\ &- \epsilon_{ab}\left[(T_e)_{ij}H_1^a\tilde{\ell}_{iL}^b\tilde{e}_{jR} + (T_d)_{ij}H_1^a\tilde{q}_{iL}^b\tilde{d}_{jR} + (T_u)_{ij}H_2^a\tilde{q}_{iL}^b\tilde{u}_{jR} + m_3^2 H_1^a H_2^b + \text{h.c.}\right]\end{aligned}$$

Some phases can be rotated out

All the physical quantities are described by

$$\arg(M_i M_j^*)\ , \quad \arg\left(M_i (T_{u,d,e})_{k\ell}^*\right)\ , \quad \arg(\mu M_i)\ , \quad \arg\left(\mu (T_{u,d,e})_{k\ell}^*\right)$$

★ When flavour mixings are neglected,

$(T_u)_{33} = A_t y_t\ ,\quad (T_d)_{33} = A_b y_b\ ,\quad (T_e)_{33} = A_\tau y_\tau$ are sometimes used

# Higgs mass in MSSM

SM-like Higgs mass is predicted in MSSM

At the tree level: $m_h^2 = m_Z^2 \cos^2 2\beta \longleftrightarrow m_h = 125\ \mathrm{GeV}$

Significant 1-loop contributions are required

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3}{2\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{M^2}{m_t^2} + \frac{X_t^2}{M^2} - \frac{X_t^4}{12M^4}\right]$$

$$M = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \quad X_t = A_t - \mu \cot\beta$$

Large stop mass is necessary! $m_{\tilde{t}} \sim 10\ \mathrm{TeV}$

# Our parameter choice

We neglect flavour mixings in the sfermion sector

$M_1$ (~DM mass) is taken as a free parameter

$m_{H^\pm} = 2M_1$ ⟵ DM relic abundance(tuned also by $|\mu|$)

$M_{\tilde{q}_3} = M_{\tilde{t}} = 7$ TeV

$A_t = 10$ TeV, $\phi_{A_t} = 0$

} SM-like Higgs mass $m_h = 125$ GeV

$\tan\beta = 30$

$|M_2| = |M_3| = 10\mathrm{TeV}$

$M_{\tilde{q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{\ell}_{1,2}} = M_{\tilde{e}_{1,2,3}} = 100$ TeV

Other $A$ terms are set to be zero

For CP phases, we take $(\phi_{M_1}, \phi_{M_2}, \phi_\mu)$ as free parameters

By rephasing, we can set $\phi_{M_3} = 0$

# Observables

- ☆ Relic abundance of DM $\Omega h^2 = 0.12$
- ☆ SM-like Higgs mass $m_h = 125\ \mathrm{GeV}$
- ☆ EDMs — electron, neutron, Hg
- ☆ Spin-independent cross section

} Prediction

# Electric Dipole Moments

Relevant terms in the effective Lagrangian:

$$\mathcal{L} \supset -d_f \frac{i}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu} - g_s d_q^C \frac{i}{2} \bar{q} \sigma^{\mu\nu} \gamma_5 q G_{\mu\nu} - \frac{w}{6} f^{abc} G^a_{\mu\nu} G^{b\nu}{}_{\rho} G^c_{\alpha\beta} \epsilon^{\rho\mu\alpha\beta}$$

EDM's of electron, mercury, and neutron are estimated as

$$d_e = d_e$$

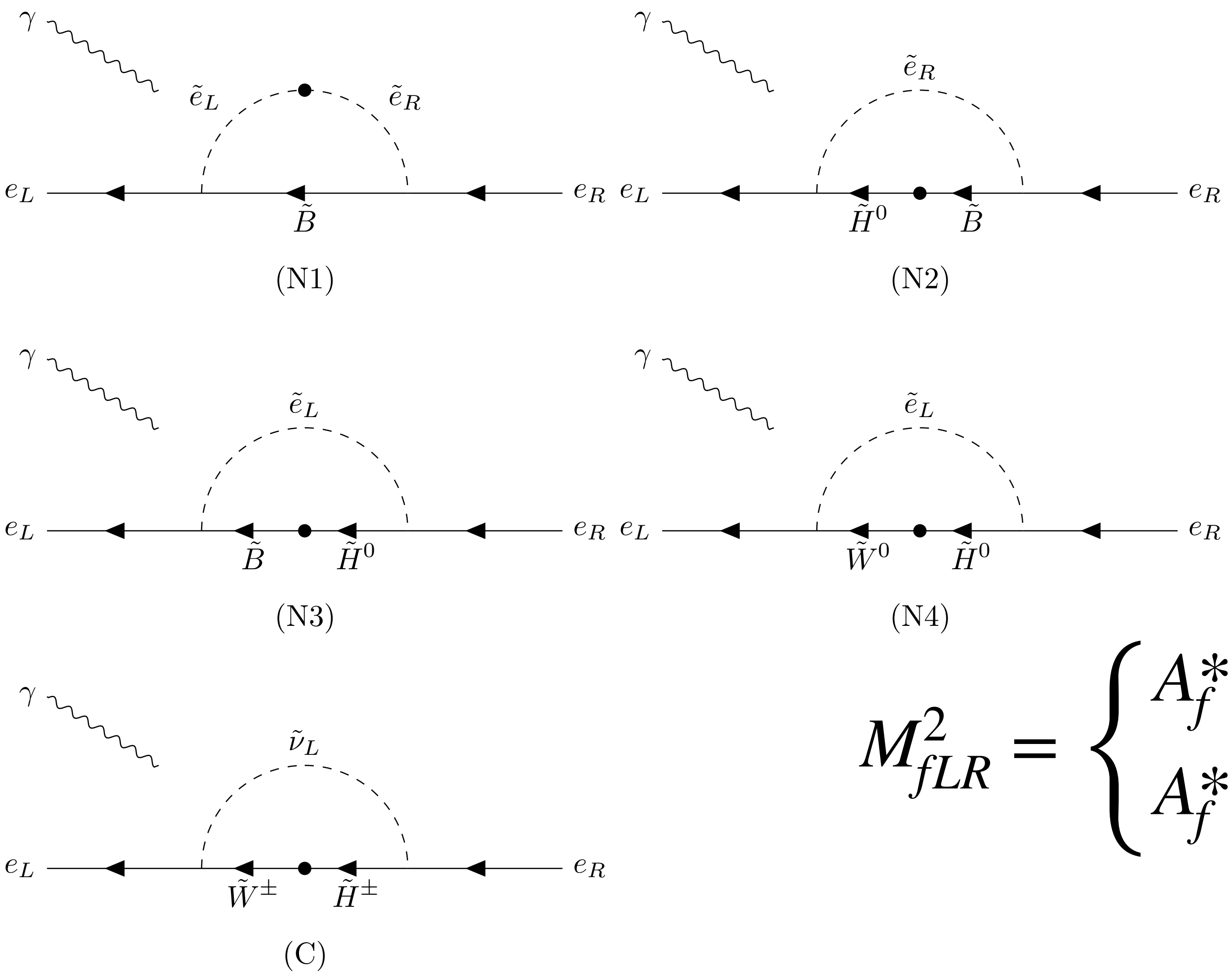
$$d_{\mathrm{Hg}} = 7 \times 10^{-3} \times e(d_u^C - d_d^C) - 10^{-2} d_e$$

$$d_n = 0.79 d_d - 0.20 d_u + e(0.30 d_u^C + 0.59 d_d^C) \pm (10 - 30)\ \mathrm{MeV} w$$

Dependence on electron/quark/chromo EDMs is different between these observables

# EDM in MSSM — 1 loop

## One loop contributions



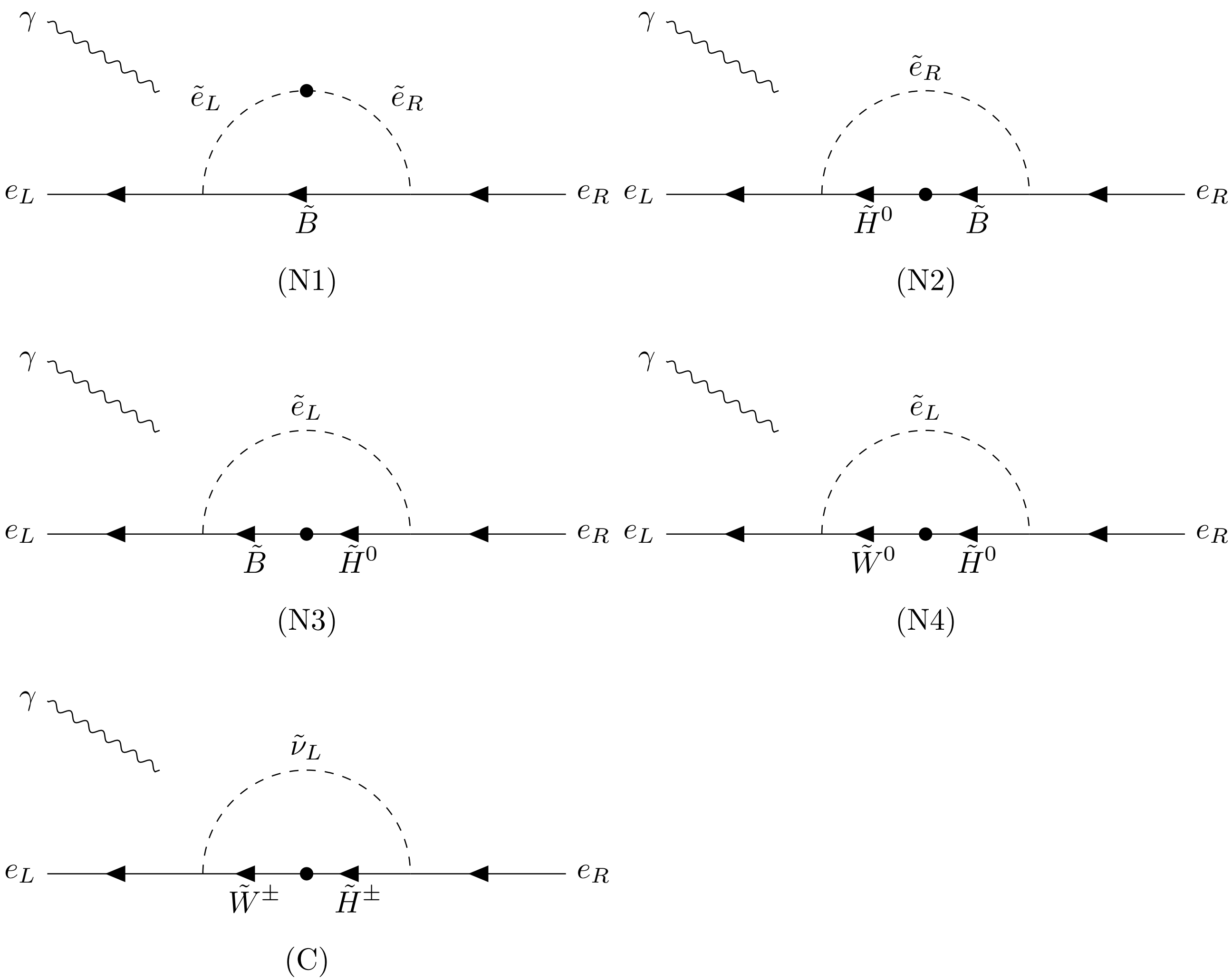

$$d_e^{\mathrm{N1}} \propto \mathrm{Im}(M_{eLR}^2 M_1)$$
$$d_e^{\mathrm{N2}} \propto \mathrm{Im}(\mu M_1)$$
$$d_e^{\mathrm{N3}} \propto \mathrm{Im}(\mu M_1)$$
$$d_e^{\mathrm{N4}} \propto \mathrm{Im}(\mu M_1)$$
$$d_e^{\mathrm{C}} \propto \mathrm{Im}(\mu M_2)$$

$$M_{fLR}^2 = \begin{cases} A_f^* m_f - \mu m_f \cot\beta & f = t \\ A_f^* m_f - \mu m_f \tan\beta & f = b, \tau \end{cases}$$

They are quickly decoupled when sfermions are heavy

# EDM in MSSM — 1 loop

## One loop contributions




$$d_e^{\mathrm{N1}} \simeq 0$$

$$d_e^{\mathrm{N2}} \propto \sin(\phi_\mu + \phi_{M_1})$$

$$d_e^{\mathrm{N3}} \propto \sin(\phi_\mu + \phi_{M_1})$$

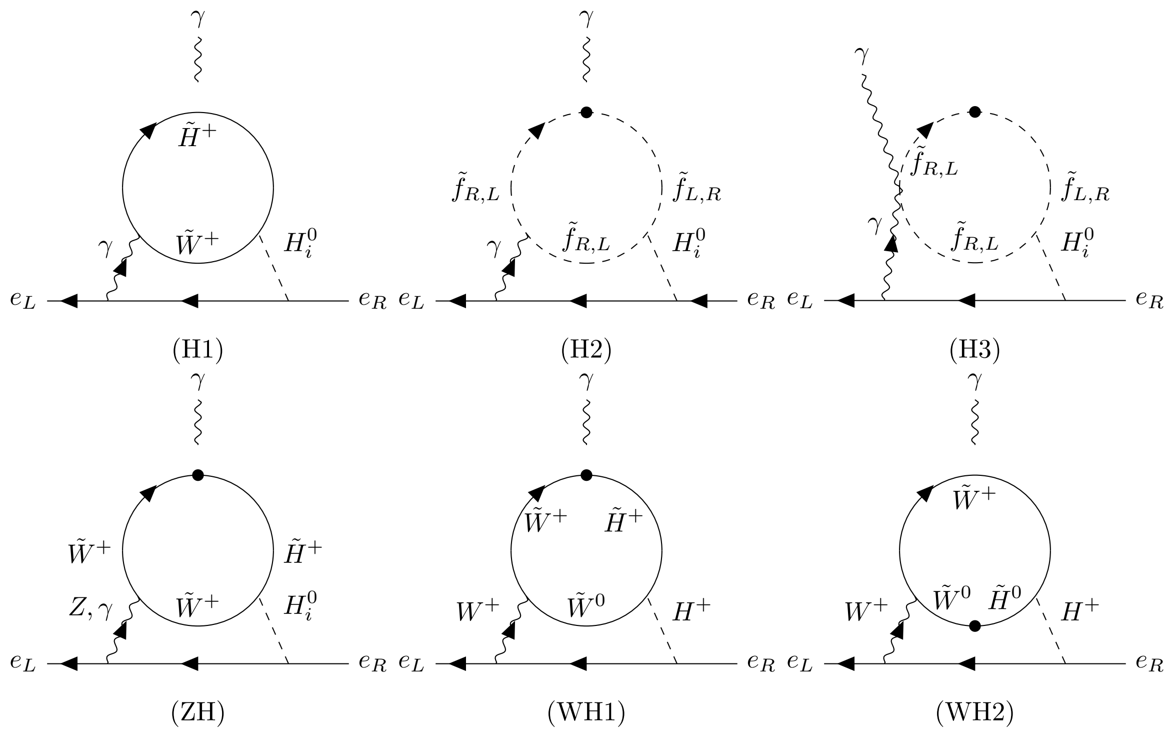
$$d_e^{\mathrm{N4}} \propto \sin(\phi_\mu + \phi_{M_1})$$

$$d_e^{\mathrm{C}} \propto \sin(\phi_\mu + \phi_{M_2})$$

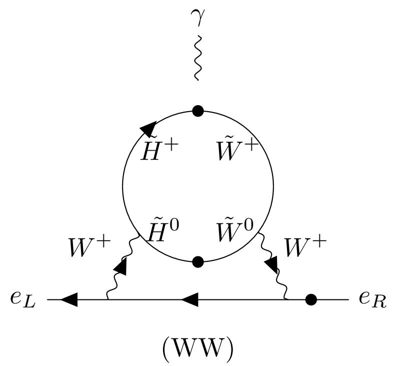
They are quickly decoupled when sfermions are heavy

# EDM in MSSM — 2 loop

## When relevant sfermions are heavy, two loop is dominant




$$d_E^{\mathrm{H1}} \propto \mathrm{Im}(\mu M_2)$$
$$d_E^{\mathrm{H1}} \propto \mathrm{Im}(M_{fLR}^{2*}\mu)$$
$$d_E^{\mathrm{H3}} \propto \mathrm{Im}(M_{fLR}^{2*}\mu)$$
$$d_E^{\mathrm{ZH}} \propto \mathrm{Im}(\mu M_2)$$
$$d_E^{\mathrm{WH1}} \propto \mathrm{Im}(\mu M_2)$$
$$d_E^{\mathrm{WH2}} \propto \mathrm{Im}(\mu M_2)$$
$$d_E^{\mathrm{WW}} \propto \mathrm{Im}(\mu M_2)$$




(WW) is suppressed compared to the others

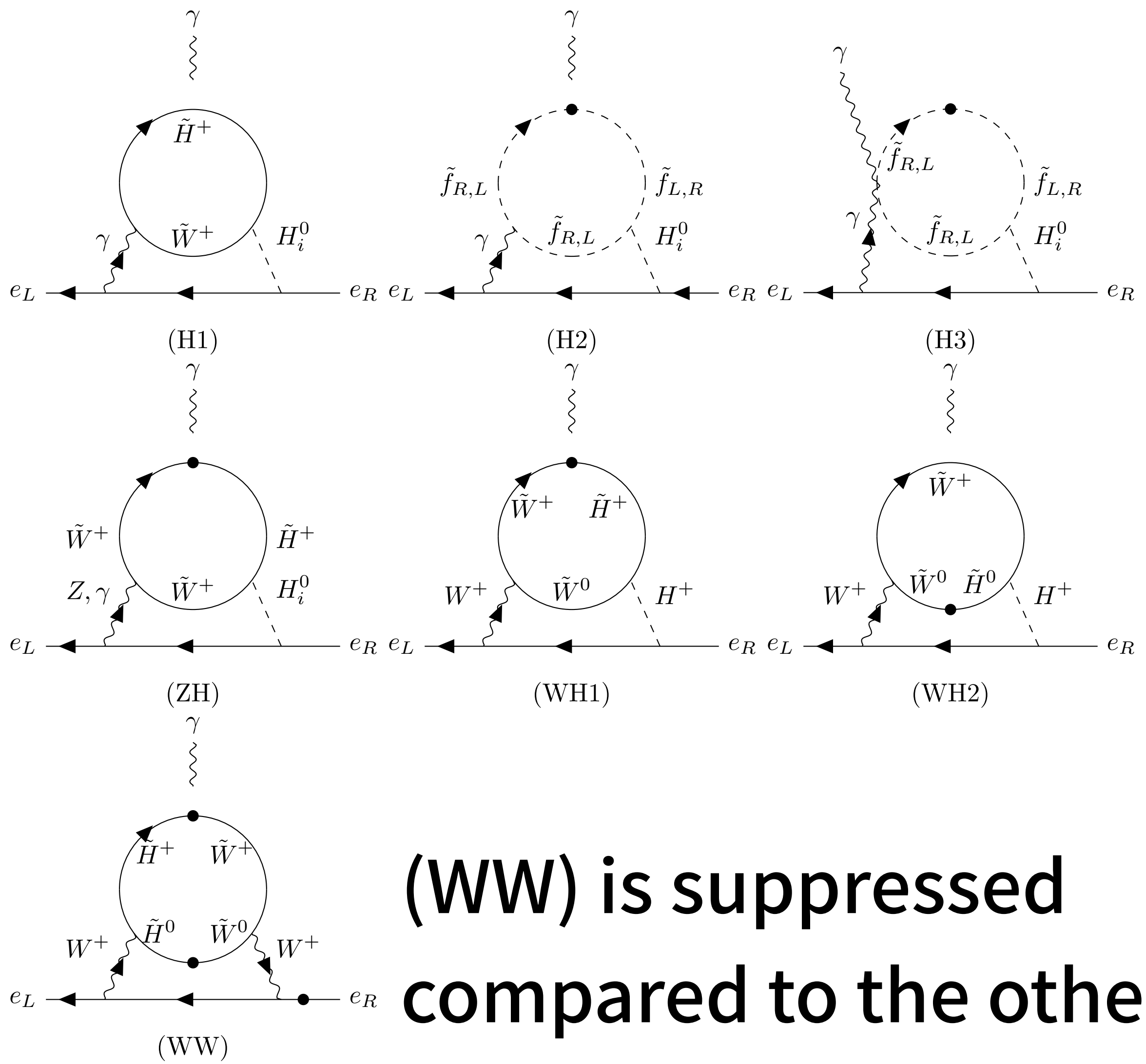
Wino, stop, sbottom are heavy

↓

decoupled!

# EDM in MSSM — 2 loop

## When relevant sfermions are heavy, two loop is dominant




$$d_E^{\mathrm{H1}} \propto \sin(\phi_\mu + \phi_{M_2})$$
$$d_E^{\mathrm{H1}} \propto \sin \phi_\mu$$
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$$d_E^{\mathrm{WH2}} \propto \sin(\phi_\mu + \phi_{M_2})$$
$$d_E^{\mathrm{WW}} \propto \sin(\phi_\mu + \phi_{M_2})$$

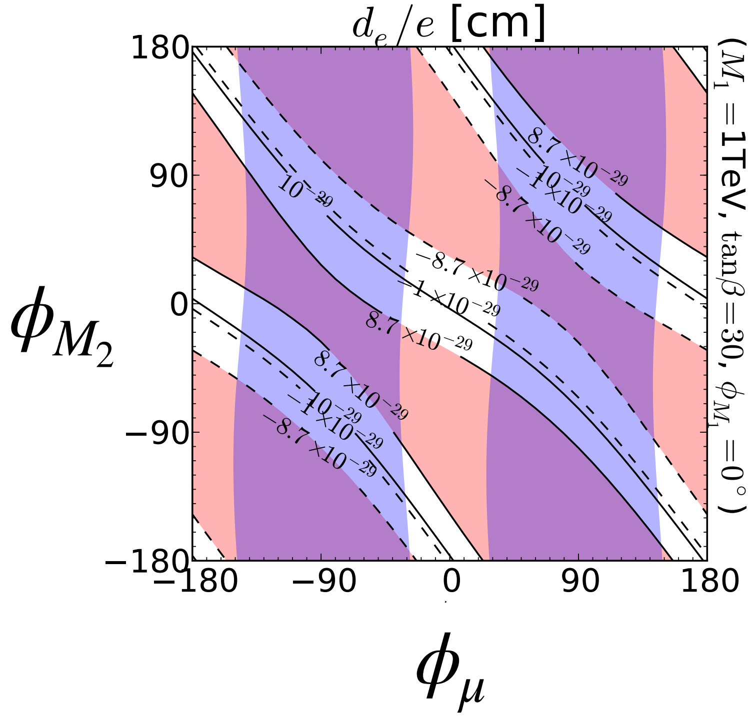
(WW) is suppressed compared to the others

Wino, stop, sbottom are heavy
↓
decoupled!

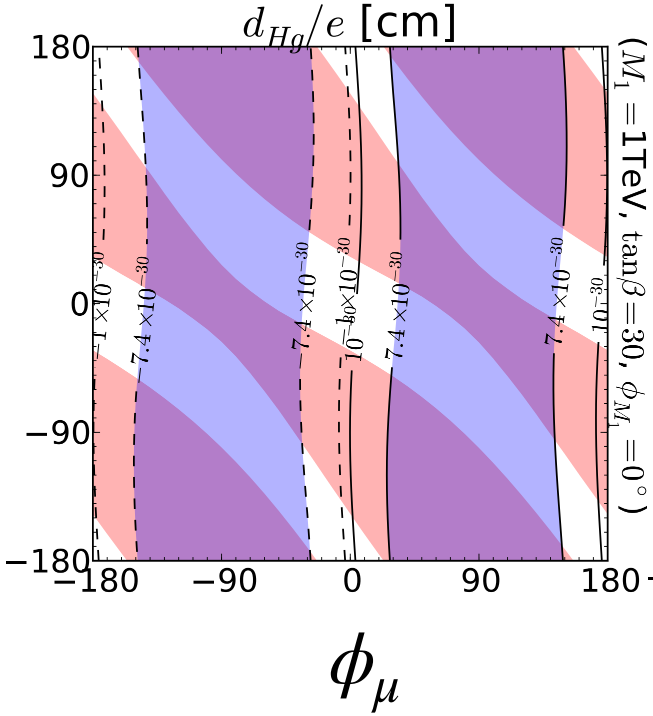
# Numerical results

$$M_1 = 1\ \text{TeV}, \quad \phi_{M_1} = 0, \quad M_2 = 10\ \text{TeV}$$

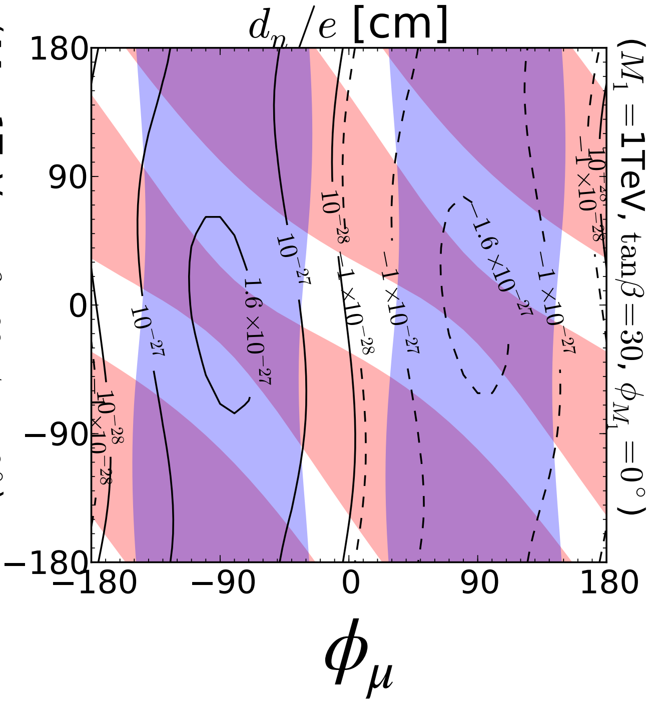
**electron**




**mercury**




**neutron**



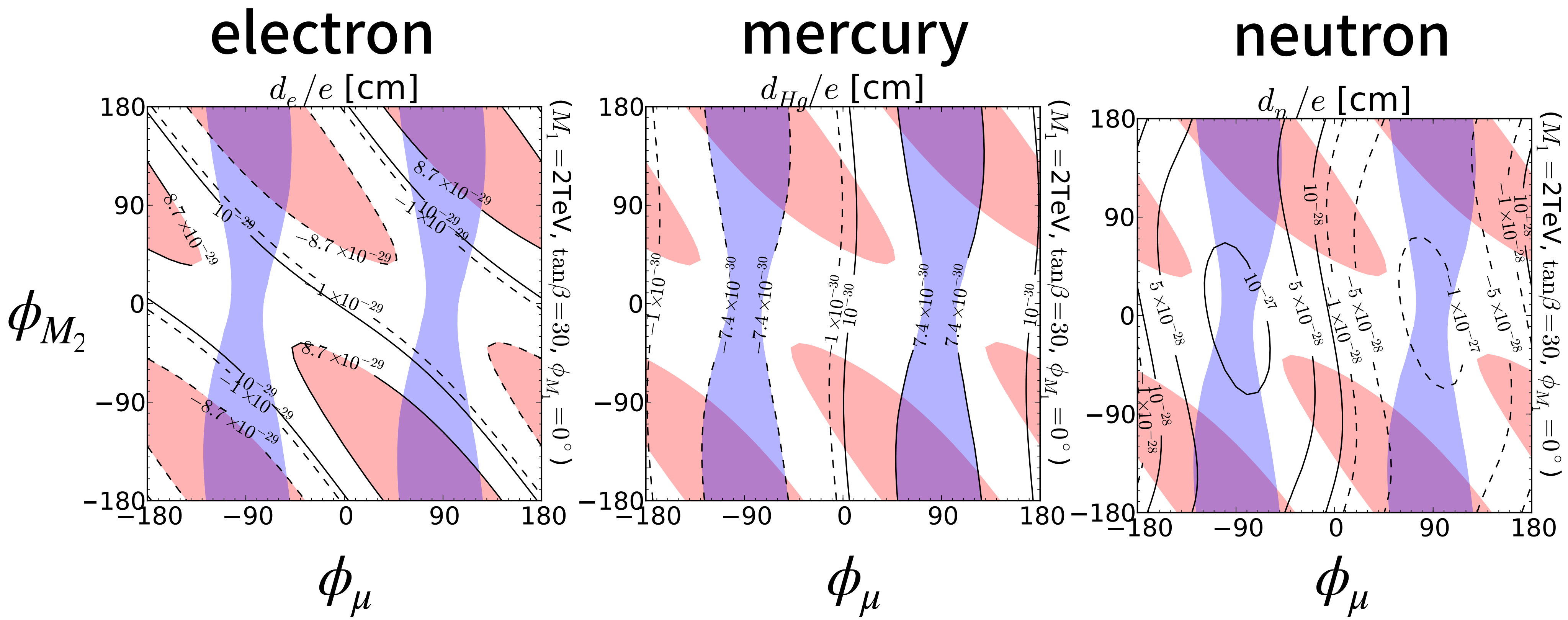

$|d_e| < 8.7\times10^{-29} e\cdot\text{cm}$ ↓ $1\times10^{-30} e\cdot\text{cm}$

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

$|d_n| < 2.9\times10^{-26} e\cdot\text{cm}$ ↓ $2.5\times10^{-29} e\cdot\text{cm}$

# Numerical results

$M_1 = 2$ TeV, $\phi_{M_1} = 0$, $M_2 = 10$ TeV




When M1 (DM mass) becomes larger,

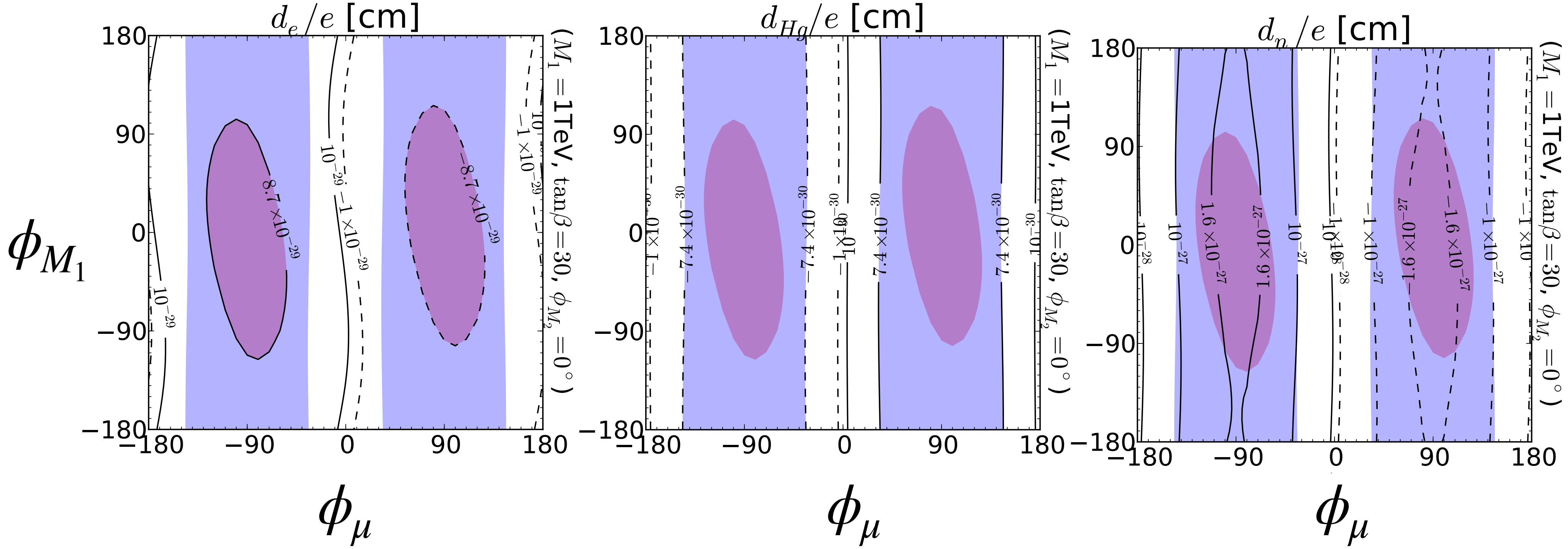
contributions are smaller.

But still significant.

# Numerical results

$M_1 = 2\ \mathrm{TeV}, \quad \phi_{M_2} = 0, \quad M_2 = 10\ \mathrm{TeV}$

**electron** **mercury** **neutron**

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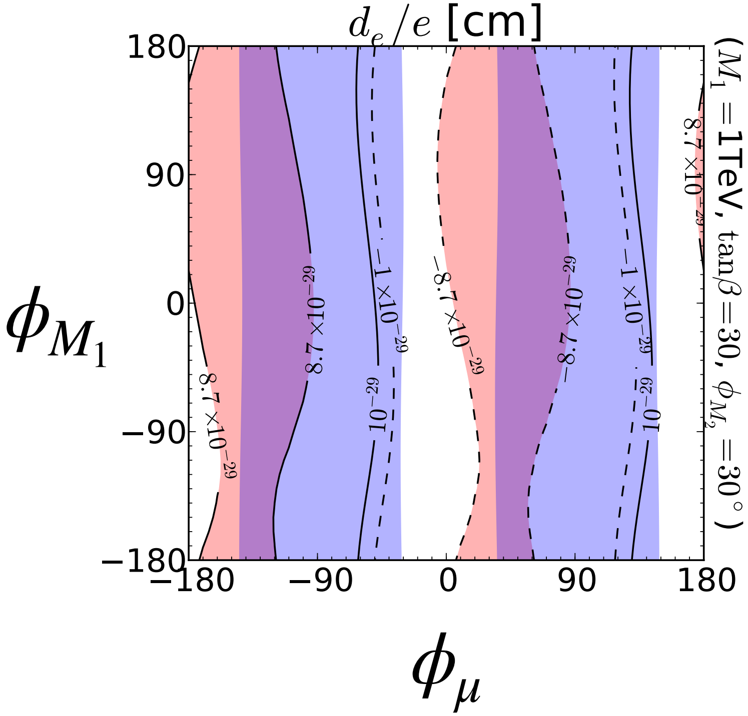
$\downarrow$ $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $\downarrow$

$1 \times 10^{-30} e \cdot \mathrm{cm}$ $\quad\quad\quad\quad\quad\quad\quad\quad$ $2.5 \times 10^{-29} e \cdot \mathrm{cm}$

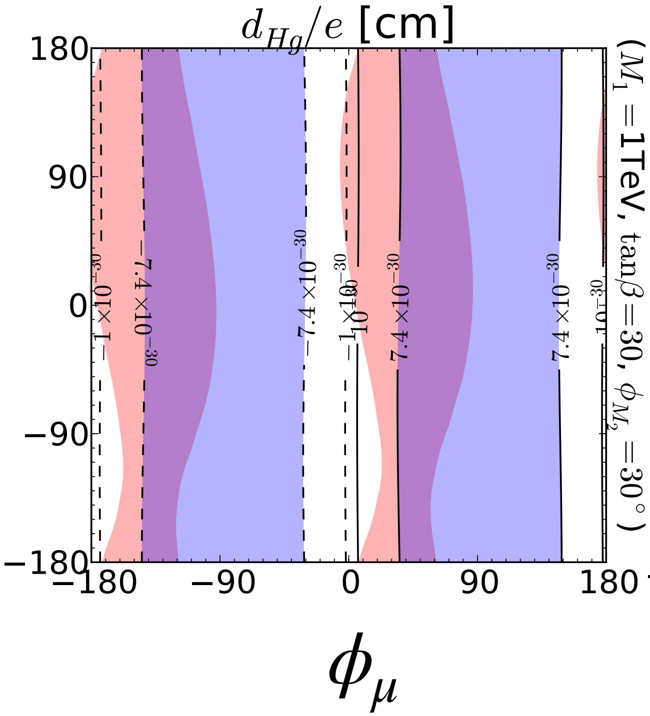
# Numerical results

$M_1 = 2$ TeV, $\phi_{M_2} = 30^\circ$, $M_2 = 10$ TeV

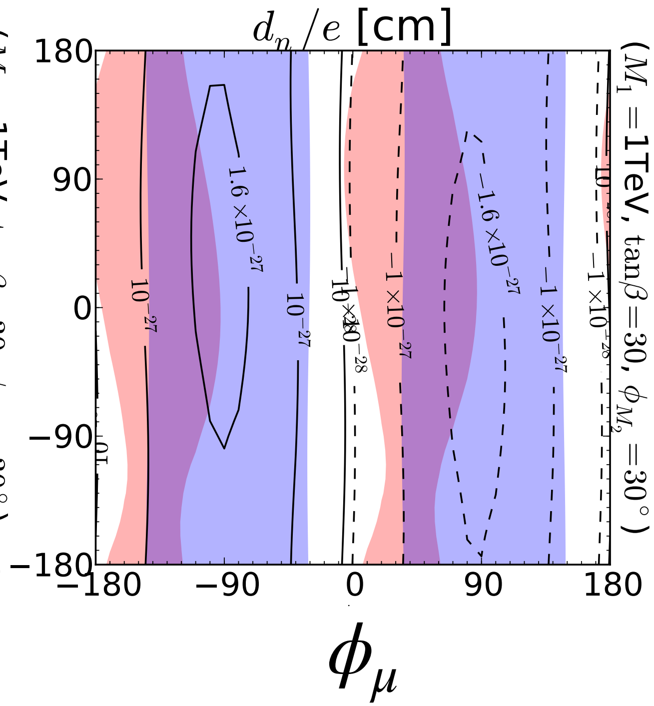
**electron**




**mercury**




**neutron**

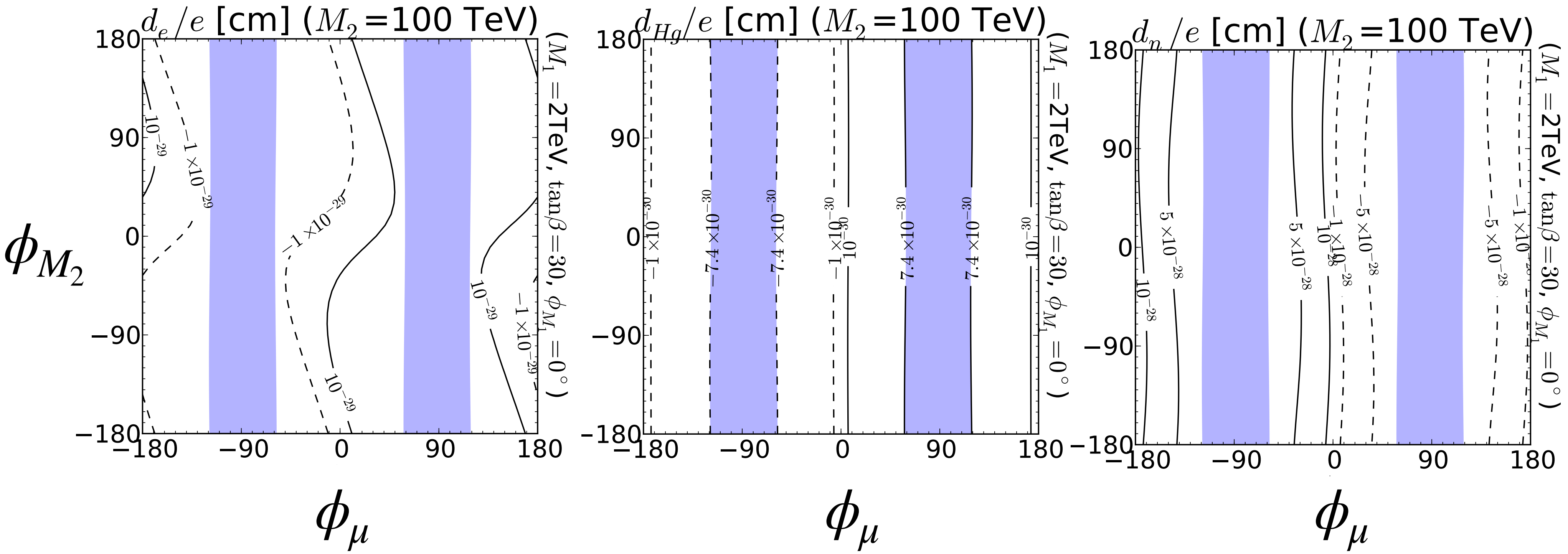



**Dependence on $\phi_{M_1}$ is rather weak**

# Numerical results

$$M_1 = 2\ \text{TeV}, \quad \phi_{M_1} = 0^\circ, \quad M_2 = 100\ \text{TeV}$$

**electron** | **mercury** | **neutron**

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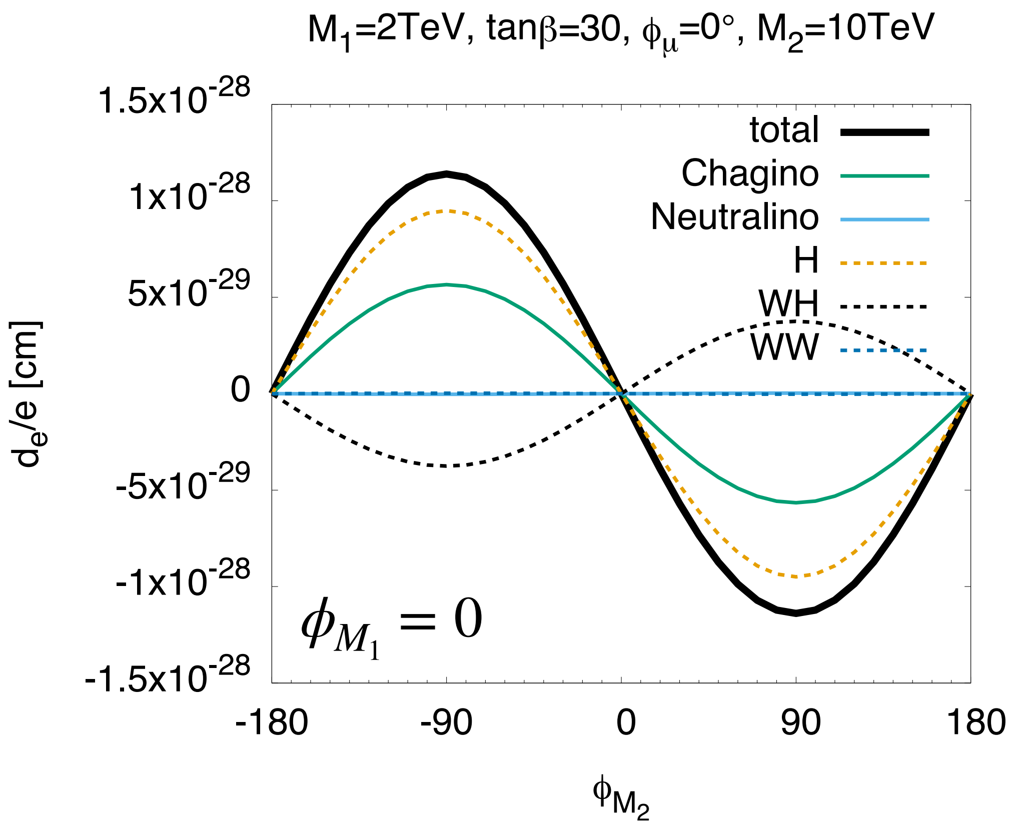
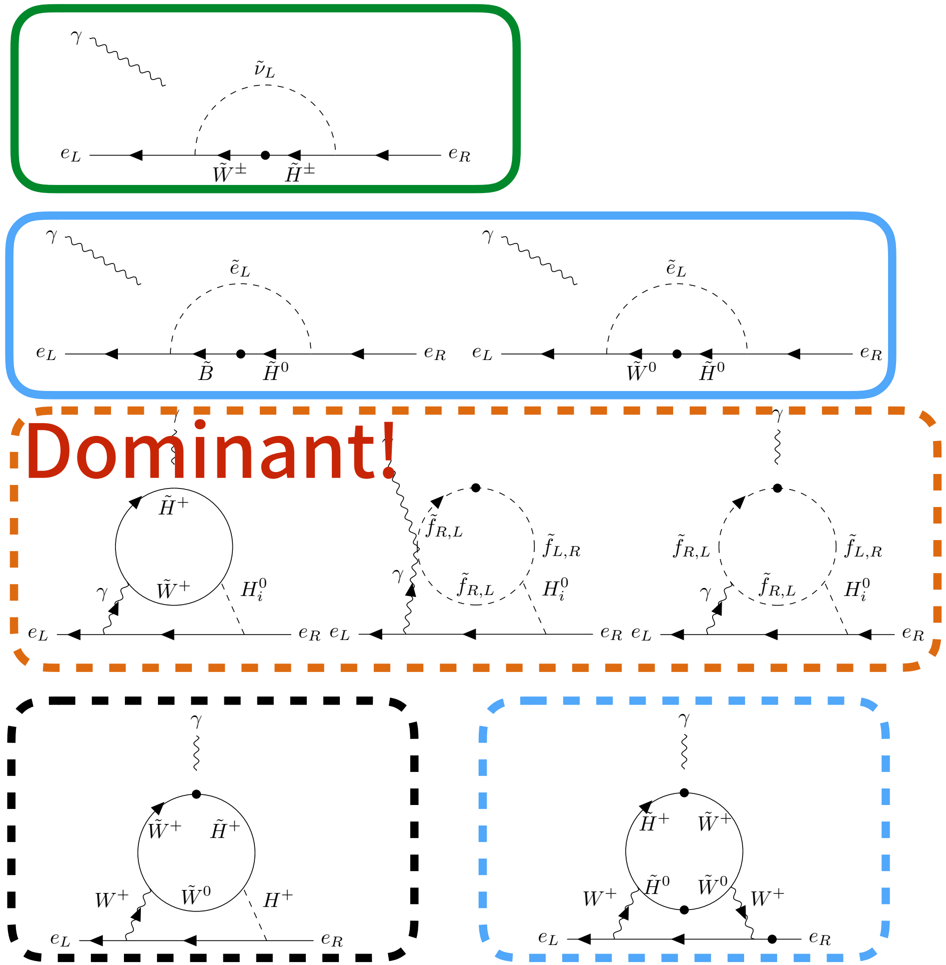
↓

$2.5 \times 10^{-29} e \cdot \text{cm}$

# Anatomy of $d_e$

## Which contribution is dominant?



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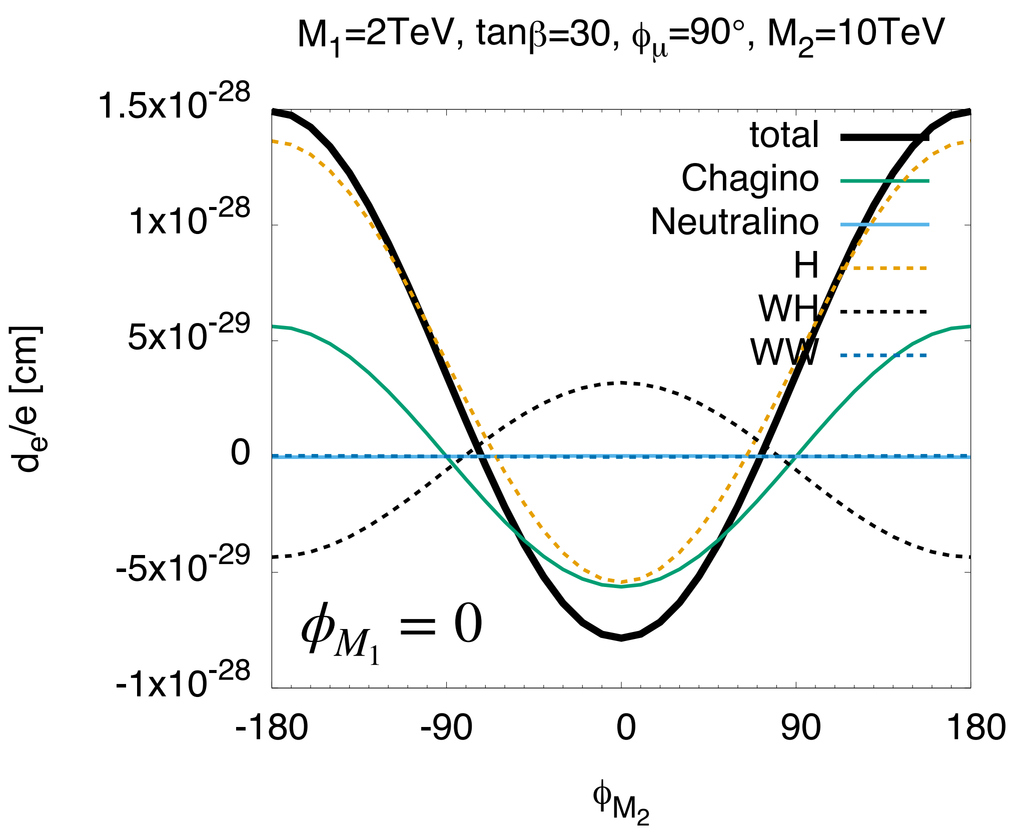


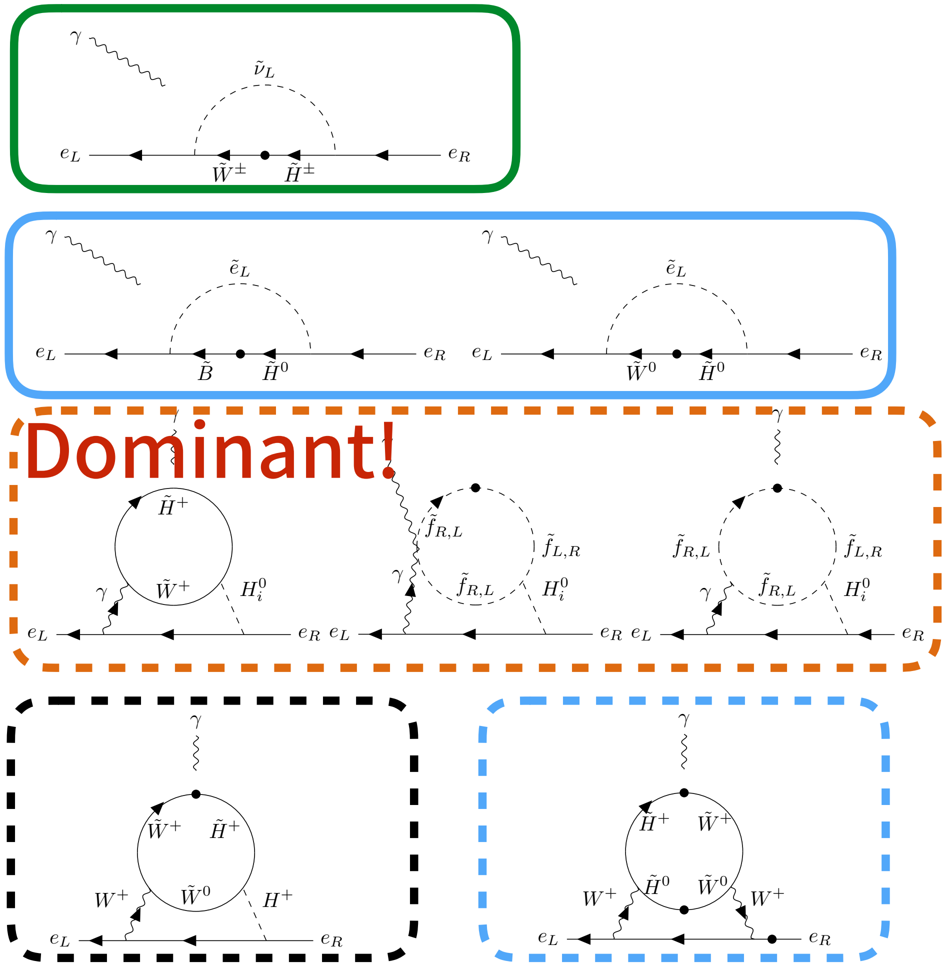

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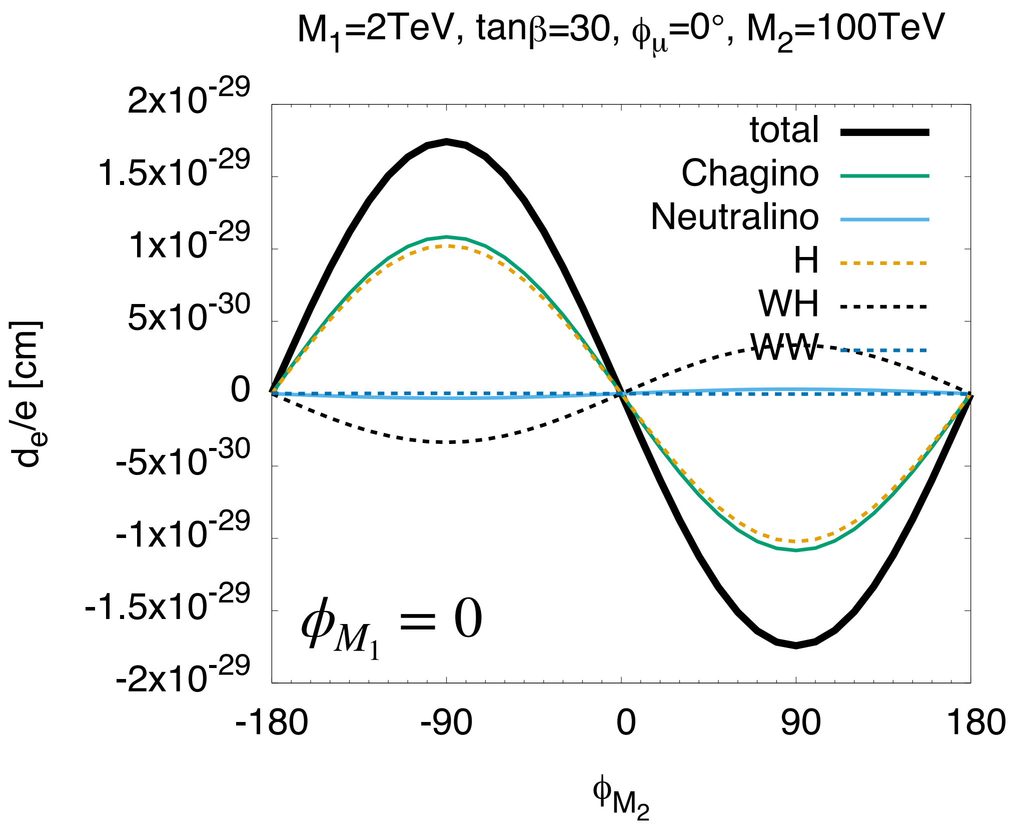


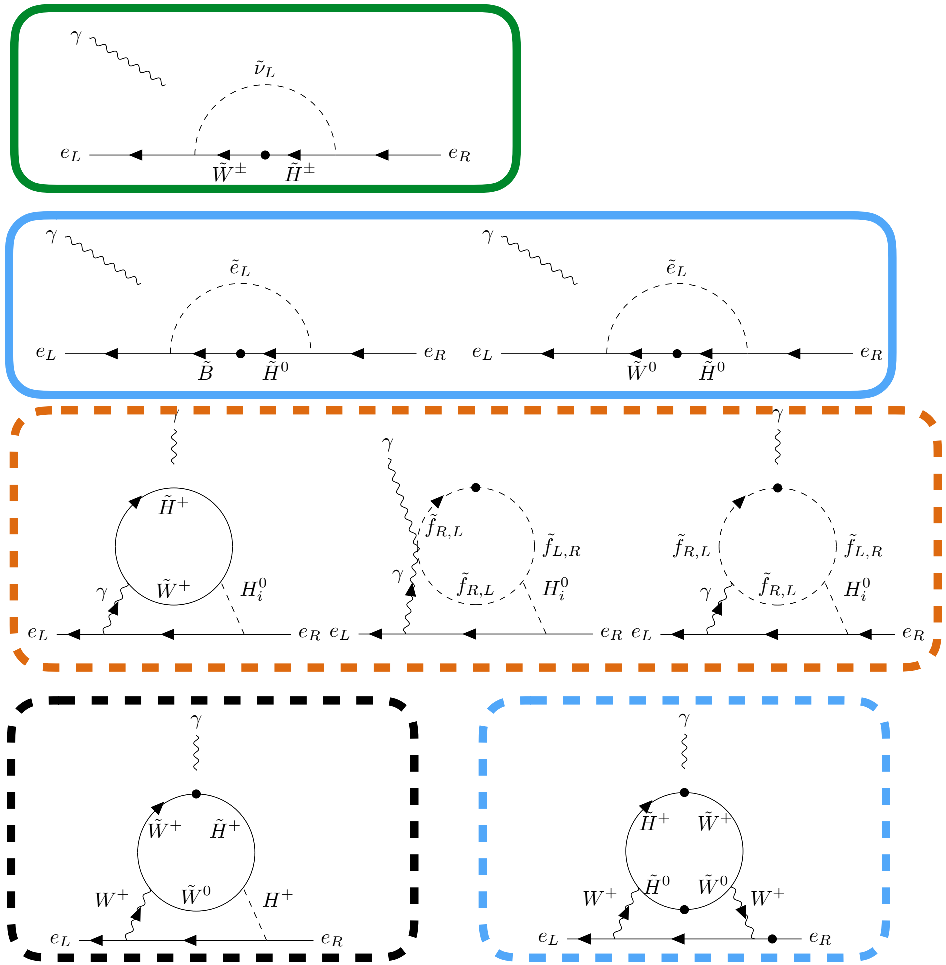

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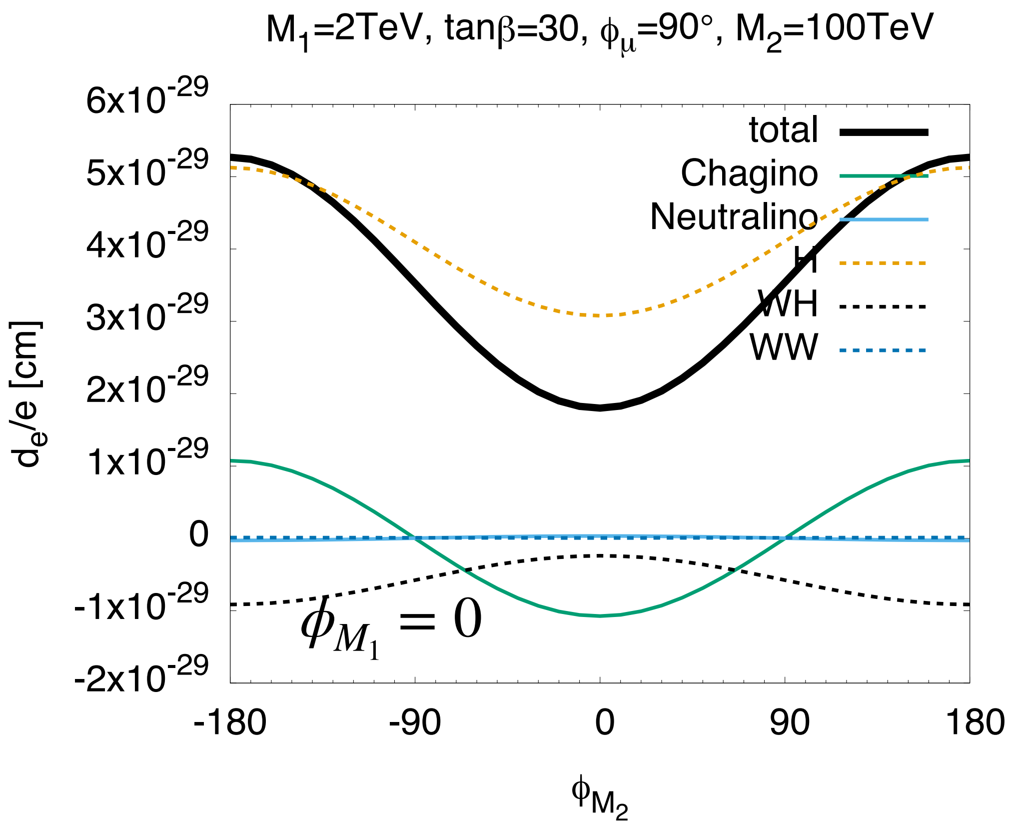


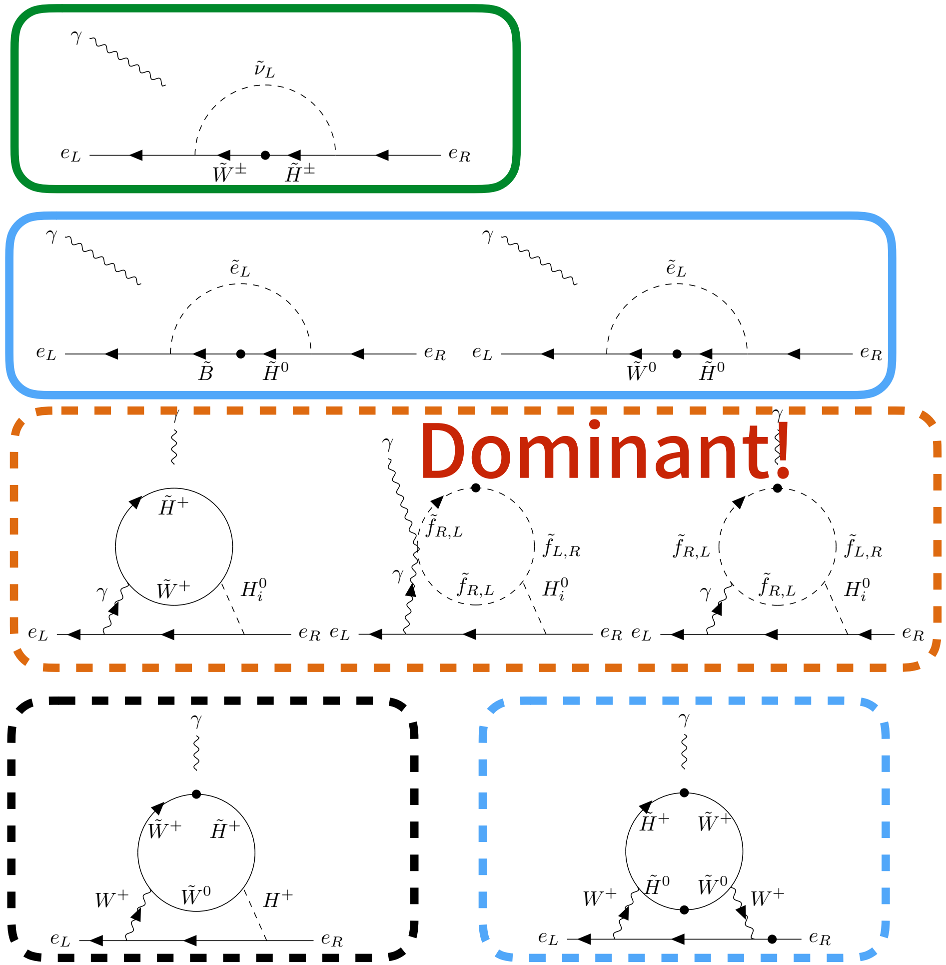

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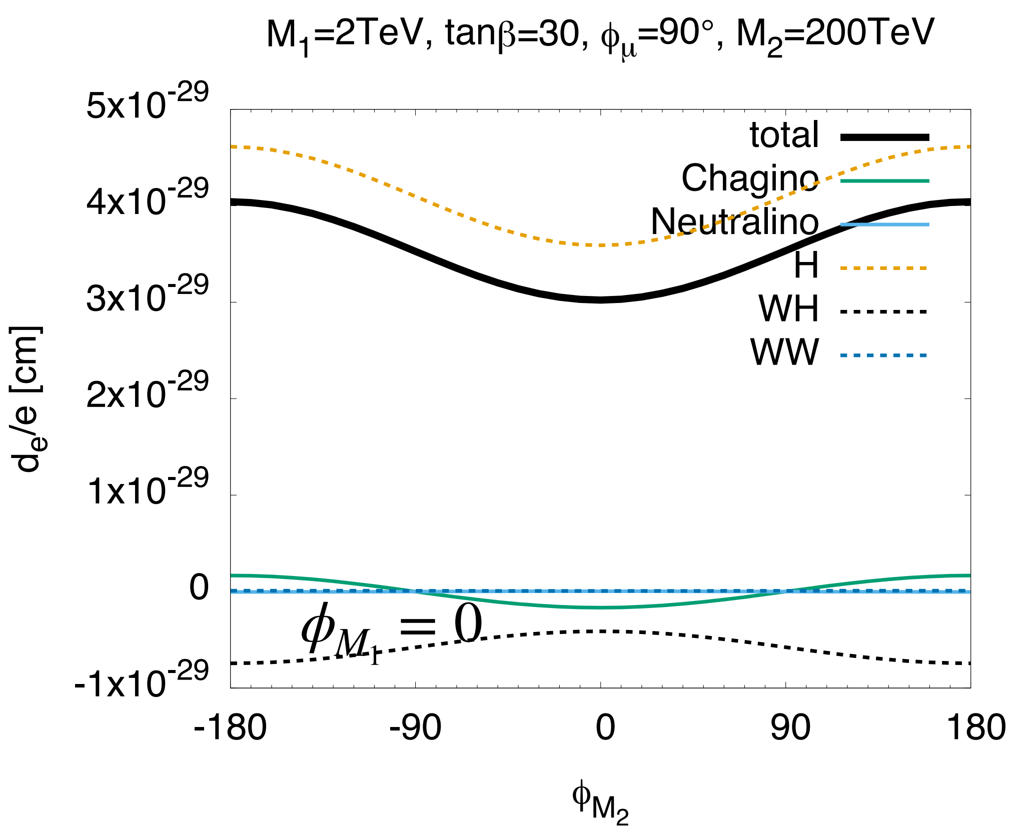
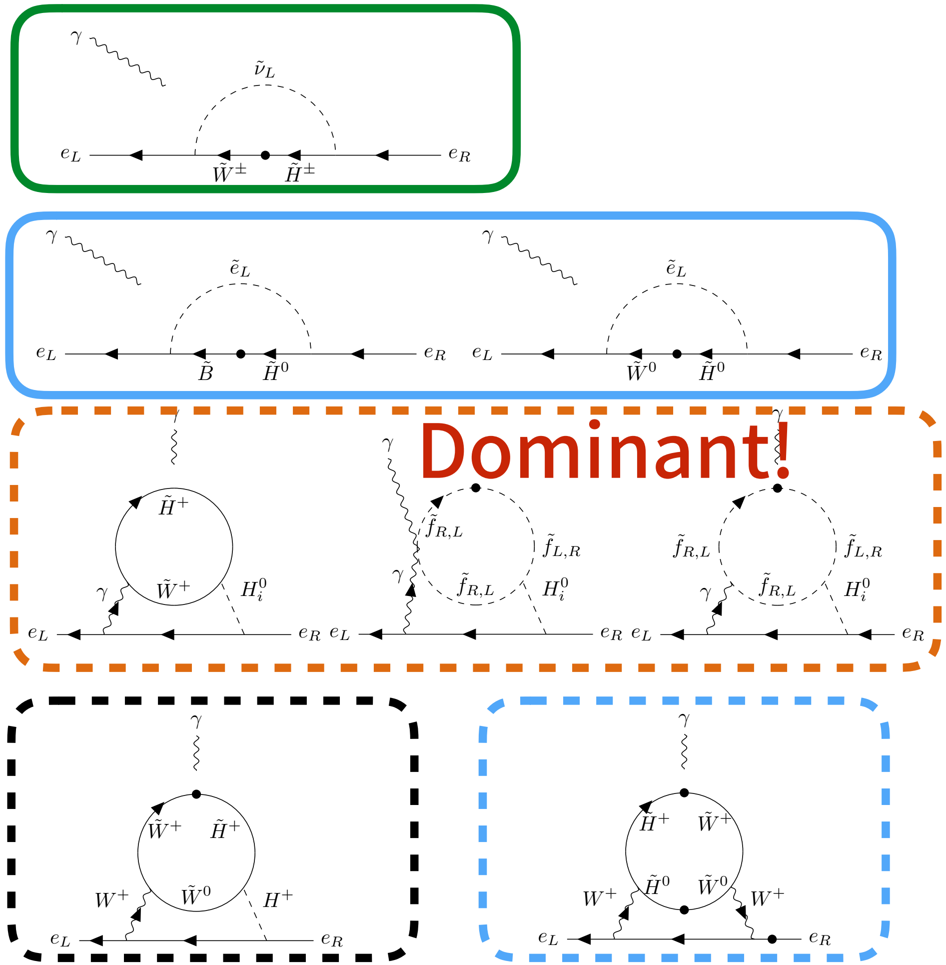
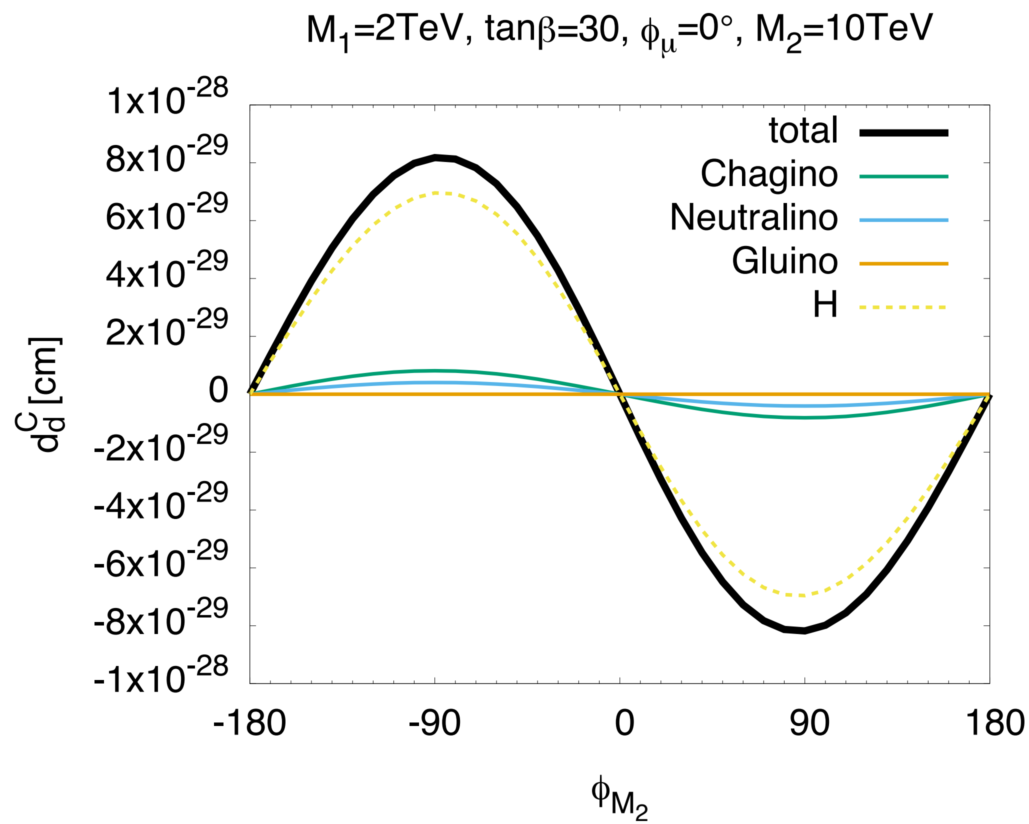
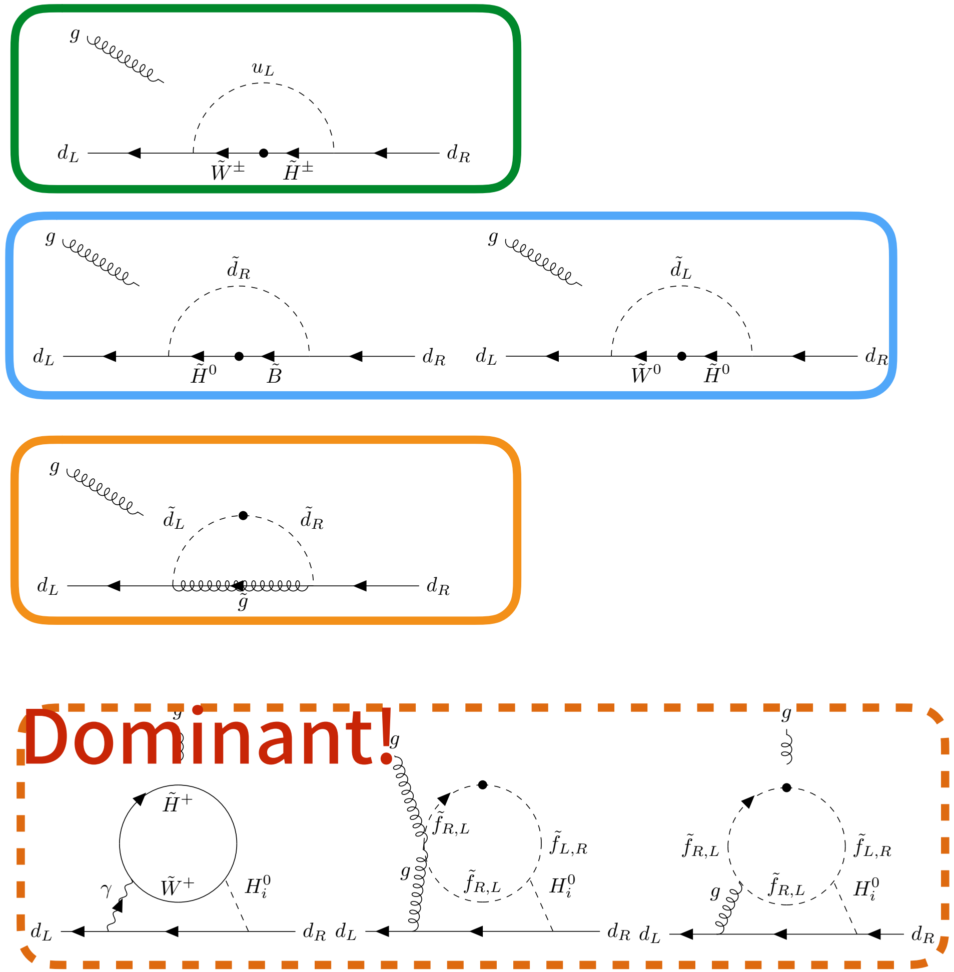


# Anatomy of $d_f^C$

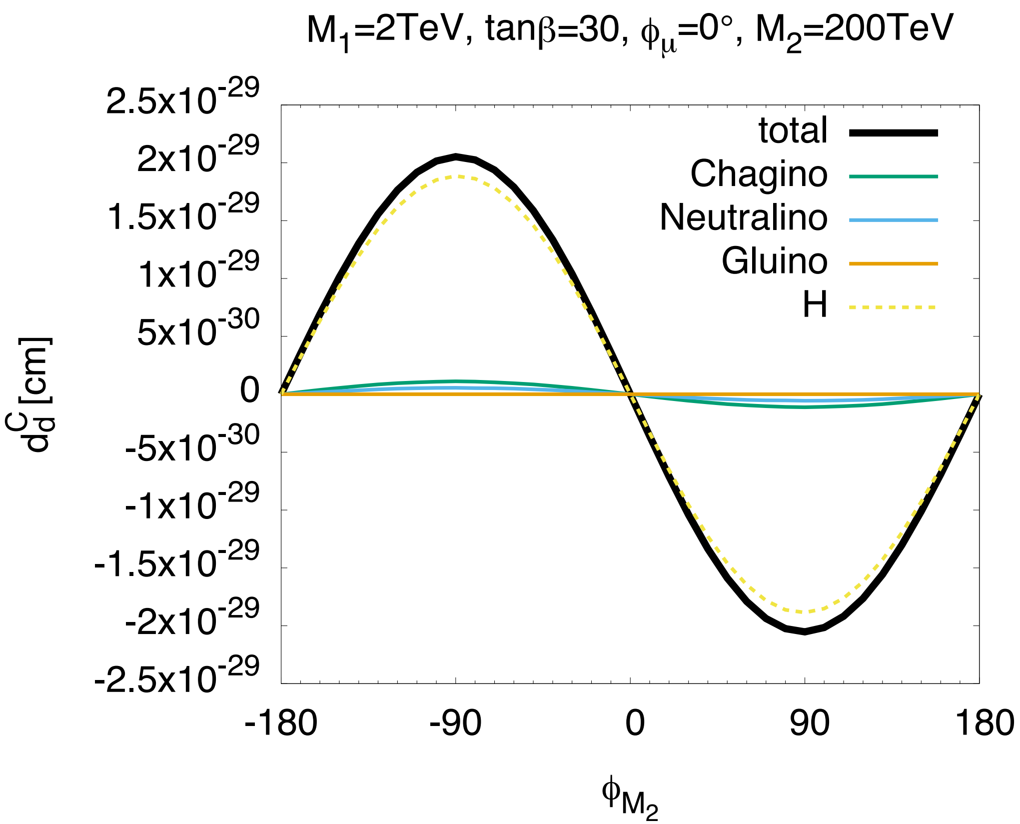
## Which contribution is dominant?

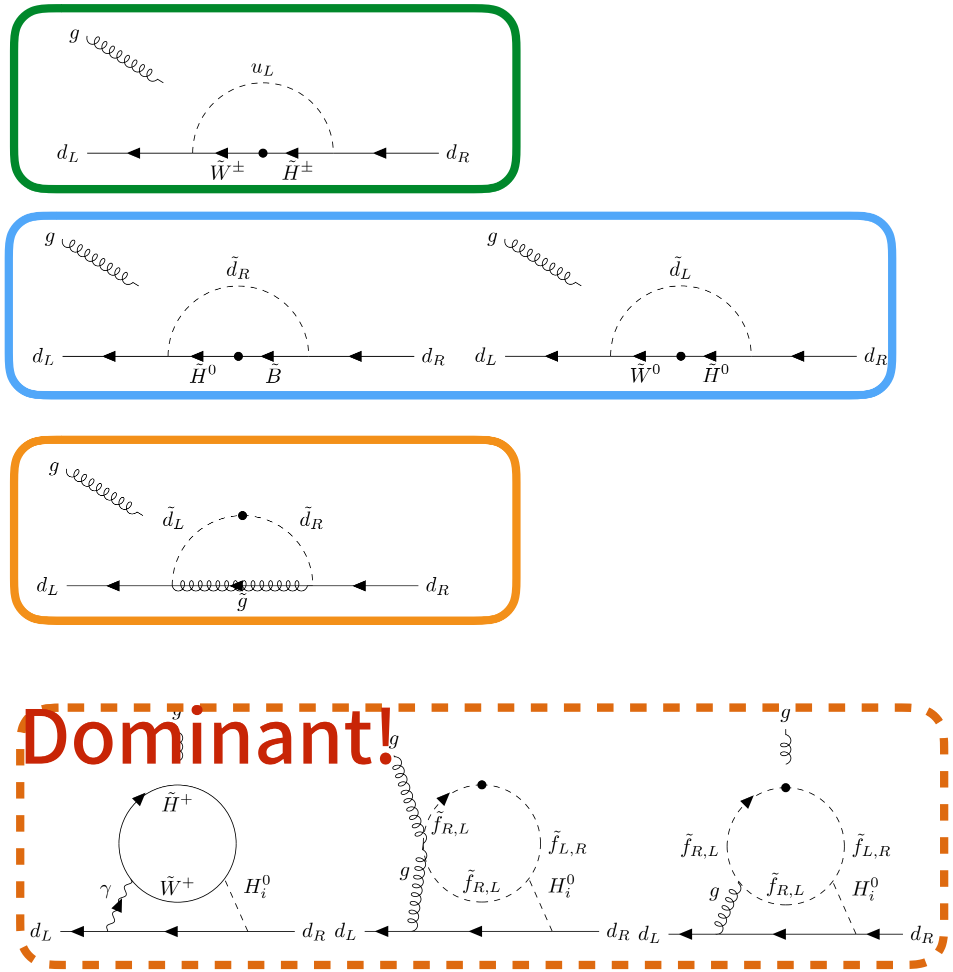


# Anatomy of $d_f^C$

## Which contribution is dominant?

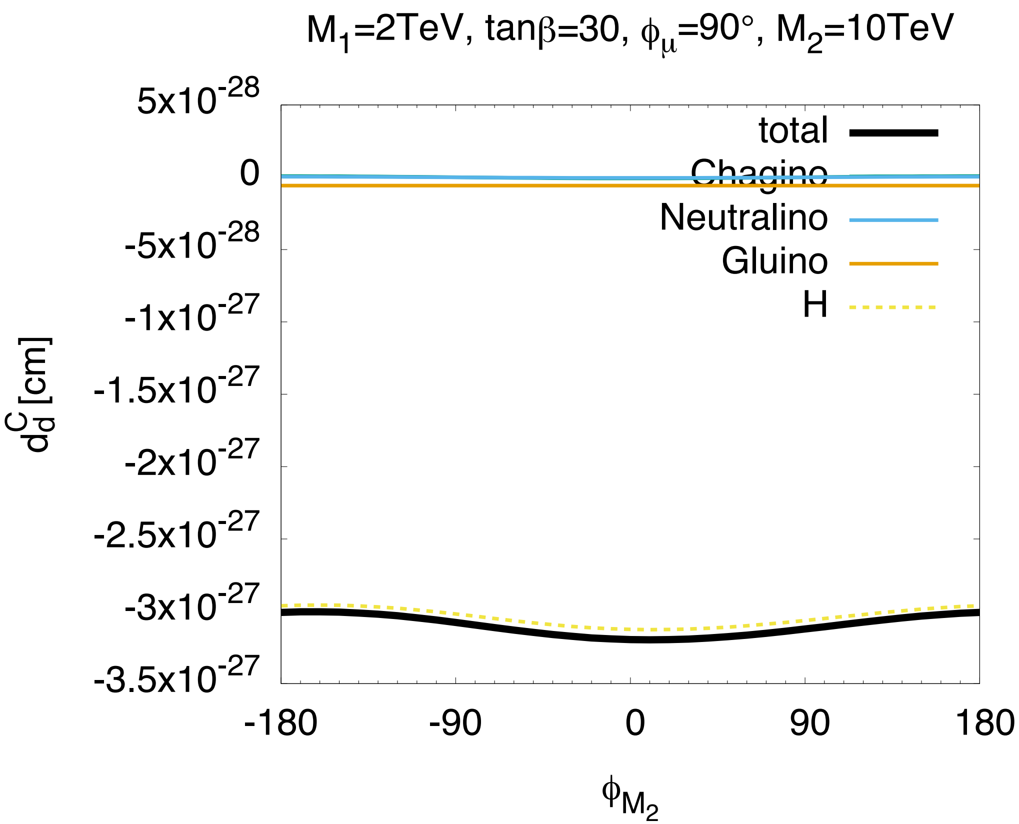


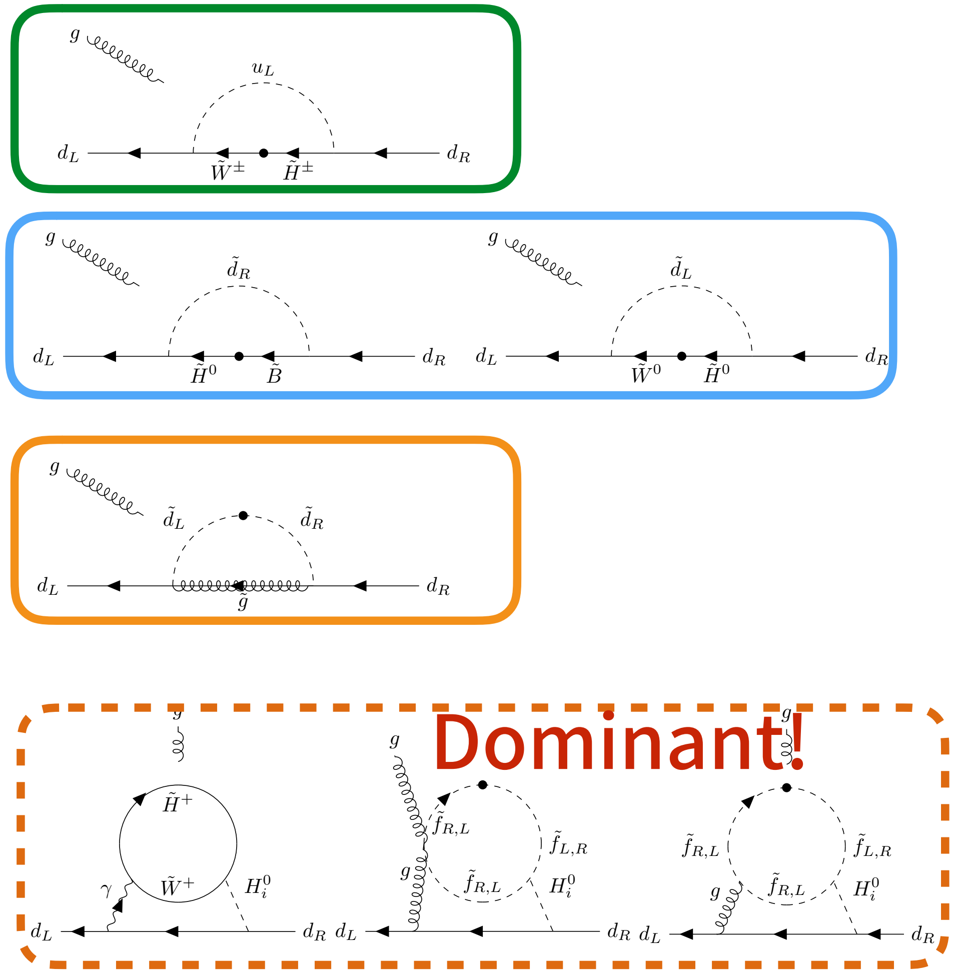



**Dominant!**

# Anatomy of $d_f^C$

## Which contribution is dominant?



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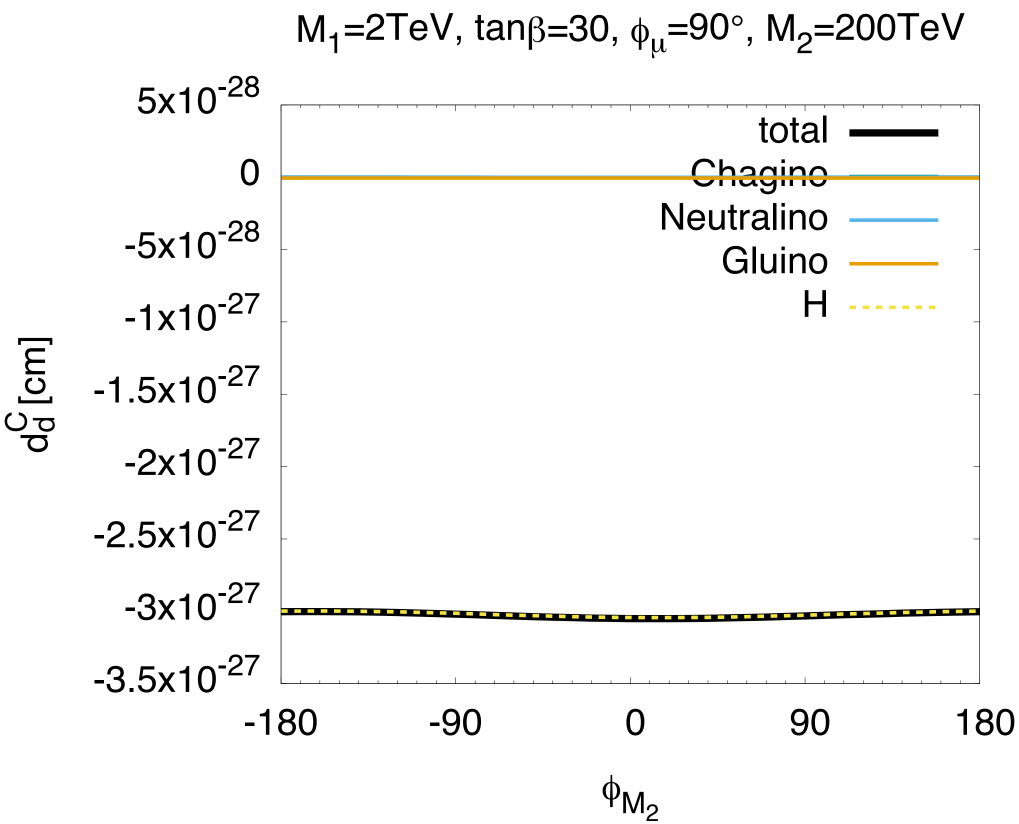
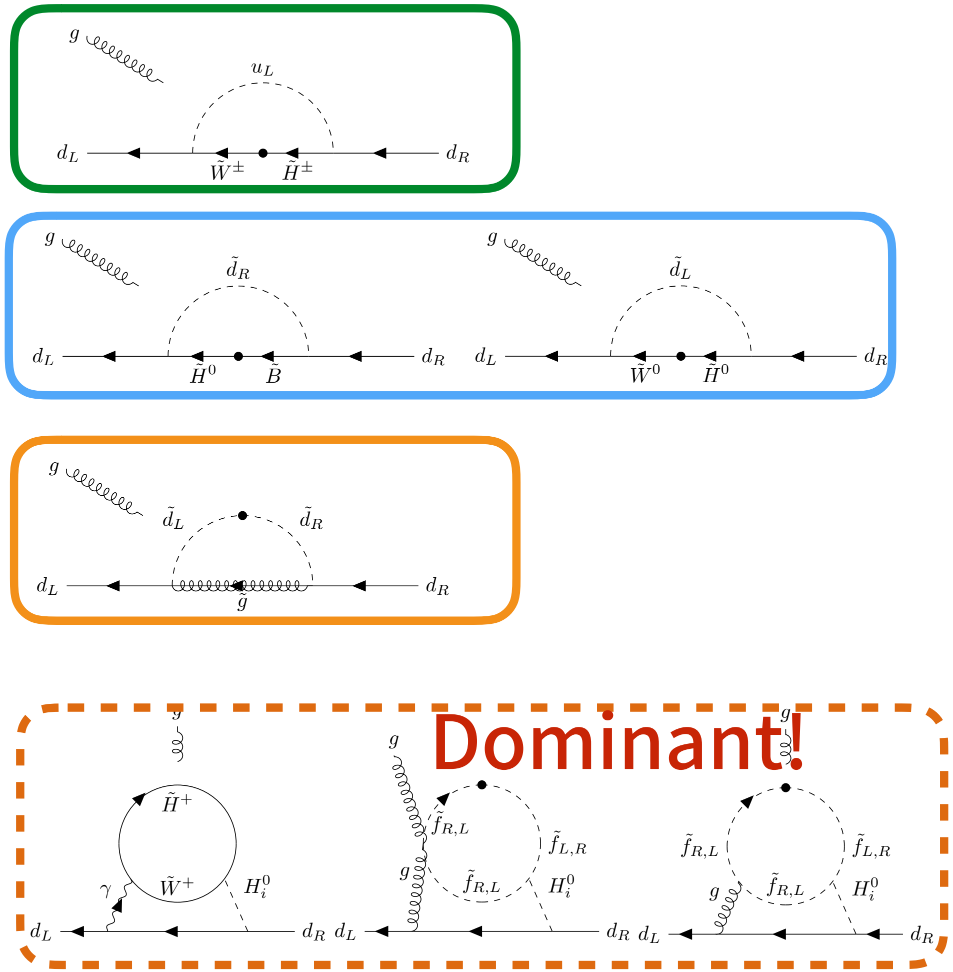


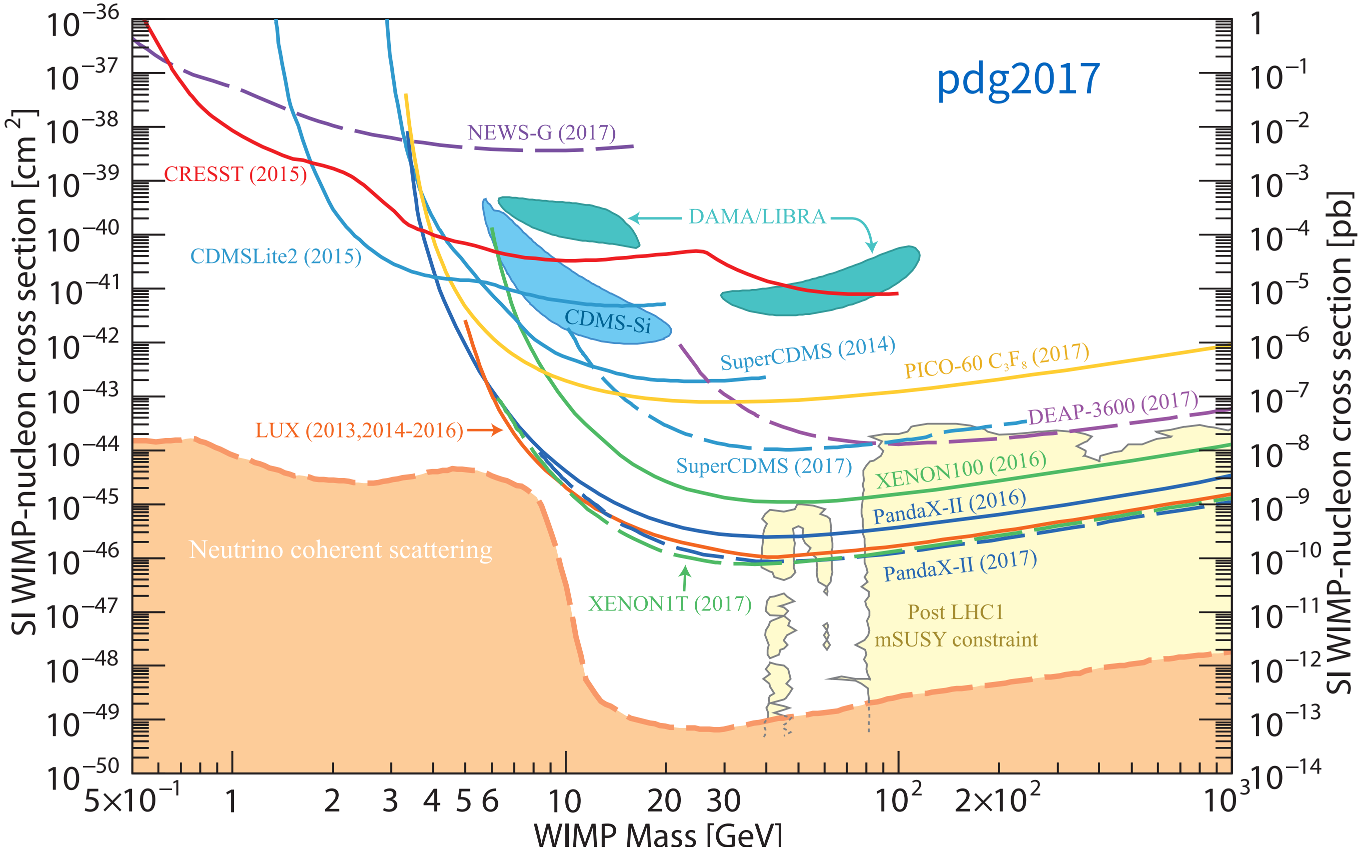



# Spin-Independent cross section

DM-nucleon scattering cross section

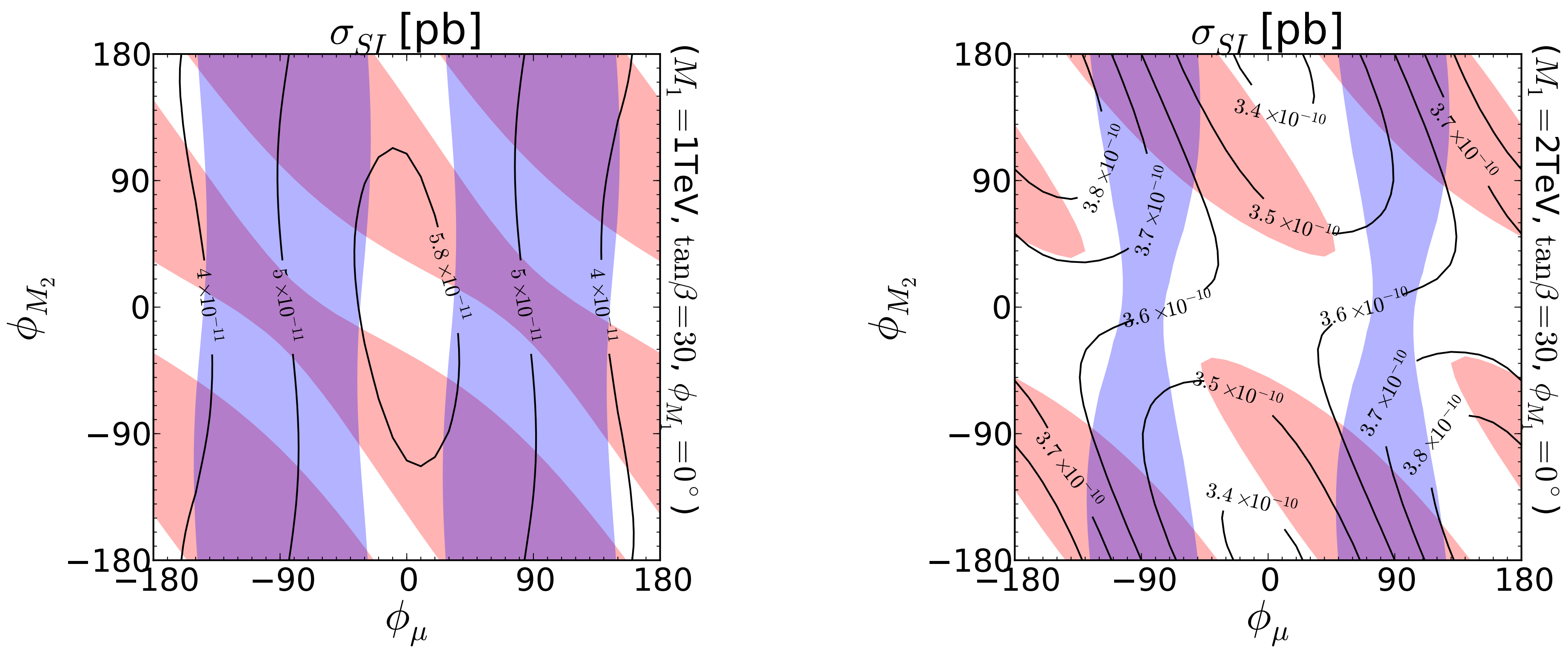
↓

relevant to direct detection of DM




Sensitivity will go down two orders of magnitude in future

# Spin-Independent cross section

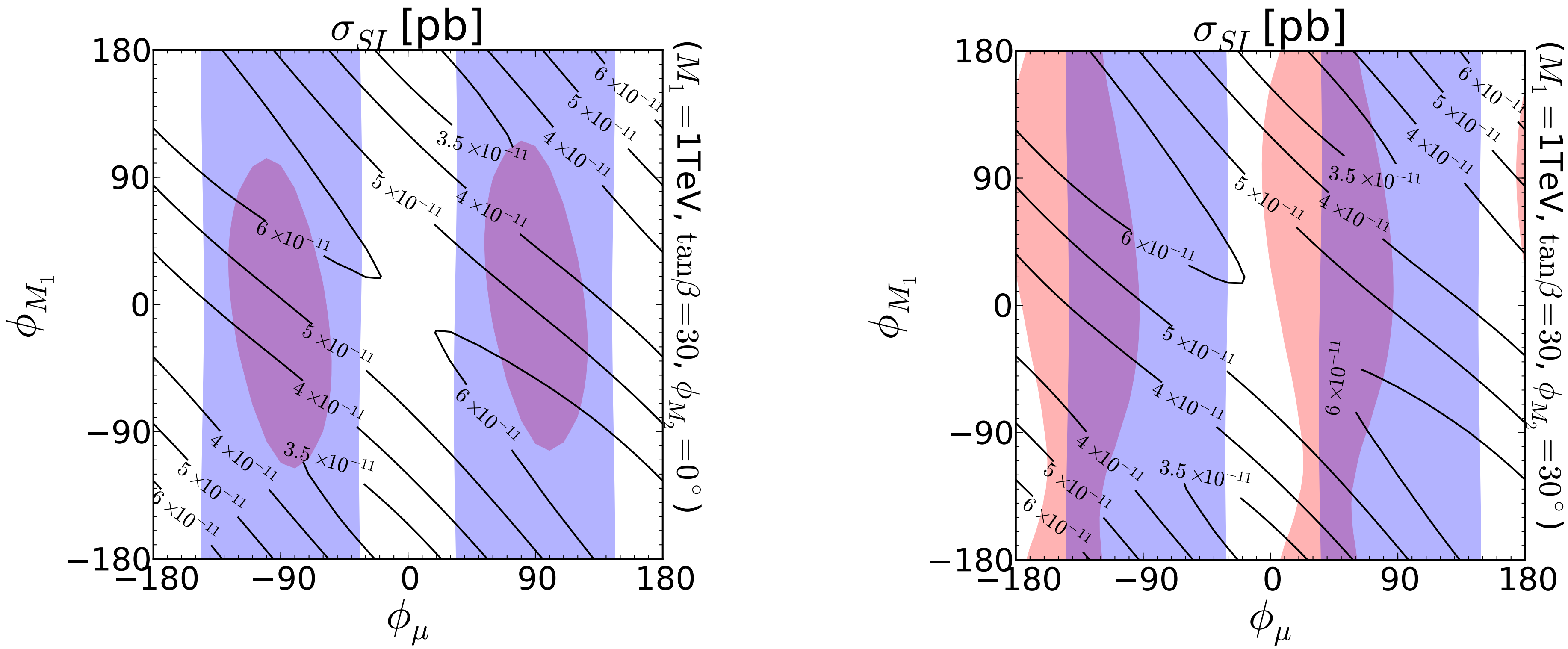



$|d_e| > 8.7 \times 10^{-29} e \cdot \mathrm{cm}$ $|d_{\mathrm{Hg}}| > 7.4 \times 10^{-30} e \cdot \mathrm{cm}$

The cross section has weak dependence on phases

Smaller than the current limit, but within the prospects of DARWIN, DarkSide-20k, and LZ

# Spin-Independent cross section




$|d_e| > 8.7\times10^{-29} e\cdot\text{cm}$ $|d_{\text{Hg}}| > 7.4\times10^{-30} e\cdot\text{cm}$

The cross section has weak dependence on phases

Smaller than the current limit, but within the prospects of DARWIN, DarkSide-20k, and LZ

# Summary

- We consider Bino-like DM scenario in CPV MSSM
- EDM experiments are powerful tools to explore this scenario
- SI cross section weakly depends on CP phases
    - Below current experimental limit, but larger than the future prospects of experiments.