Gauge invariant Barr-Zee type contributions to fermionic EDMs in the two-Higgs doublet models

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In collaboration with
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Maskawa institute
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Introduction

- LHC found a Higgs boson around 126 GeV
- where is the next scale?

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- where is the next scale?

~O(1) TeV

naturalness requires new physics here

- susy
- composite Higgs
- etc

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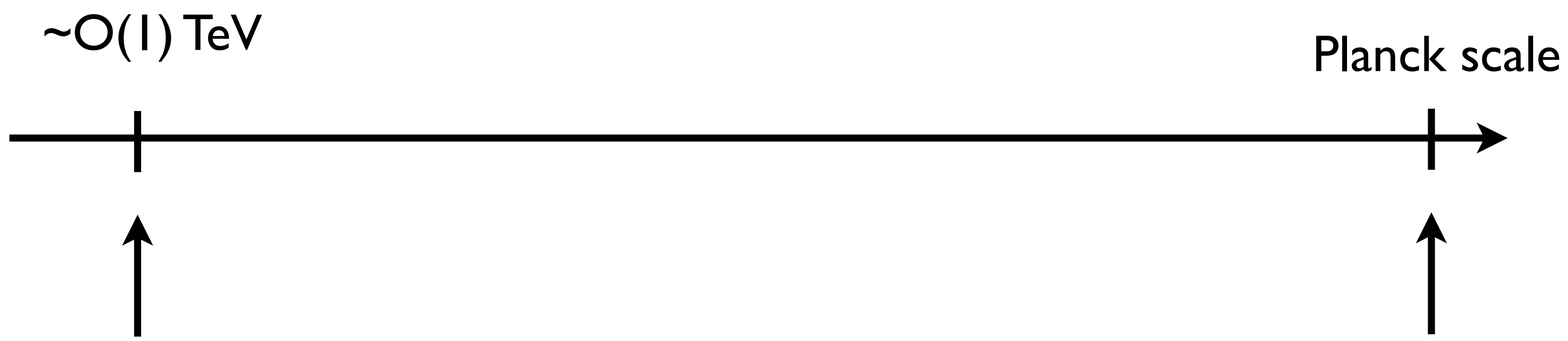

naturalness requires new physics here

- susy
- composite Higgs
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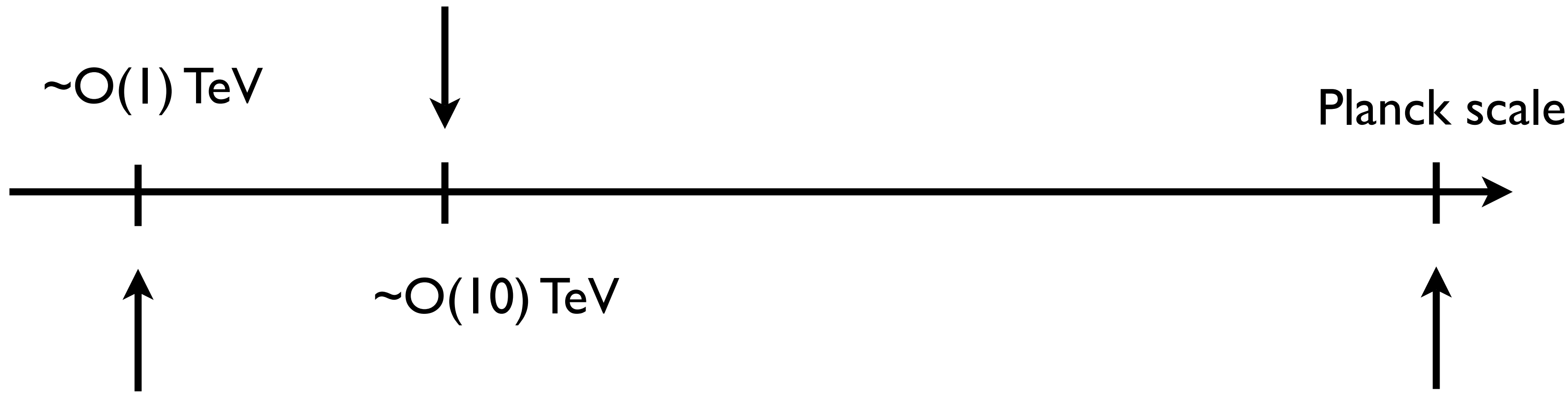
too high scale to do experiments

Introduction

- LHC found a Higgs boson around 126 GeV
- where is the next scale?

- too high scale for direct detection with LHC
- but indirect search can reach here (flavor physics etc.)



naturalness requires new physics here

- susy
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too high scale to do experiments

electric dipole moment (EDM)

EDM has capability to seek high scale physics indirectly

$$\mathcal{L}_{EDM} = -i\frac{\mathbf{d_f}}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f F^{\mu\nu}$$

- dim. 5 operator
- pick up CP violation
- need chirality flip

particle	exp. bound $[\mathrm{e\,cm}]$	SM prediction (δ_{KM})	BSM expectations
neutron	$\lvert d_n\rvert < 2.9 \times 10^{-26}$	$\sim 10^{-32}$	$\lesssim 10^{-26}$
proton	$\lvert d_p\rvert < 5.4 \times 10^{-24}$	$\sim 10^{-32}$	$\lesssim 10^{-26}$
electron	$\lvert d_e\rvert < 1.6 \times 10^{-27}$	$\lesssim 10^{-38}$	$\lesssim 10^{-27}$
muon	$\lvert d_\mu\rvert < 2.8 \times 10^{-19}$	$\lesssim 10^{-36}$	$\lesssim 10^{-22}$

talk by Bernreuther

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$$\lvert d_e\rvert < 8.7\times 10^{-29} e\ \mathrm{cm}$$

talk by Bernreuther

2HDM with softly broken Z_2 symmetry

two-Higgs-Doublet-Model (2HDM)

- extra CP violation source in Higgs potential
- often appear in BSM (SUSY, top see-saw, W' model, ...)
- good bench mark model for BSM
- (electroweak baryogenesis?)

- we impose Z_2 symmetry to avoid FCNC

Type	H_1	H_2	u_R	d_R	e_R	q_L / l_L
I	+	-	-	-	-	+
II	+	-	-	+	+	+
X	+	-	-	-	+	+
Y	+	-	-	+	-	+

Type I, II ,X, Y

$$\mathcal{L}_{\text{Yukawa}} = -\overline{q}_L \widetilde{H}_2 y_u u_R - \overline{q}_L H_i y_d d_R - \overline{\ell}_L H_j y_e e_R + h.c.$$

Type	I	II	X	Y
u	H_2	H_2	H_2	H_2
d	H_2	H_1	H_2	H_1
ℓ	H_2	H_1	H_1	H_2

$\widetilde{H}_2 = \epsilon H_2^*$

CPV source in Higgs potential

$$
\begin{aligned}
V =& m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 \\
& - \left(m_3^2 H_1^\dagger H_2 + (h.c.) \right) \\
& + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 \\
& + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
& + \frac{1}{2}(\lambda_5 (H_1^\dagger H_2)^2 + (h.c.)).
\end{aligned}
$$

CPV source in Higgs potential

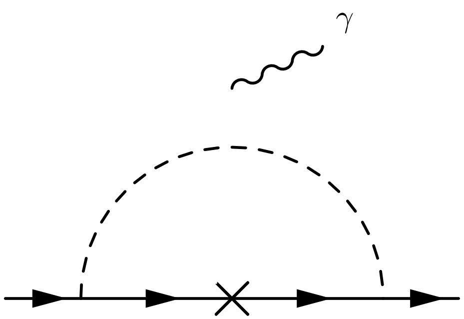
$$\begin{aligned} V =& m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 \\ & - \left(m_3^2 H_1^\dagger H_2 + (h.c.) \right) \\ & + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 \\ & + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \frac{1}{2}(\lambda_5 (H_1^\dagger H_2)^2 + (h.c.)). \end{aligned}$$

- m_3 and λ_5 are complex and have CP phase
- they can be a source of EDM

two loop give larger contributions

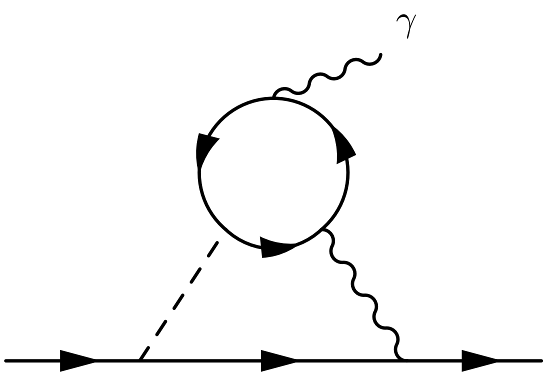
<u>one loop (O(y³))</u>

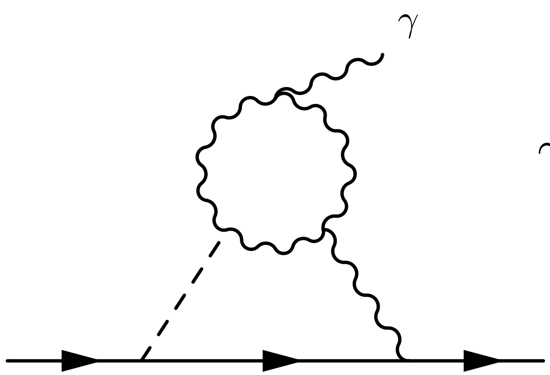
$$\mathcal{L}_{EDM} = -i\frac{\mathbf{d_f}}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f F^{\mu\nu}$$



$$\sim \frac{1}{(4\pi)^2}\frac{m_e^3}{v^4} \sim 10^{-42}\mathrm{cm}$$

<u>two loop (O(y)) (Barr-Zee diagrams)</u>





$$\sim \frac{1}{(4\pi)^4}\frac{m_e}{v^2} \sim 10^{-29}\mathrm{cm}$$

Goal of this talk

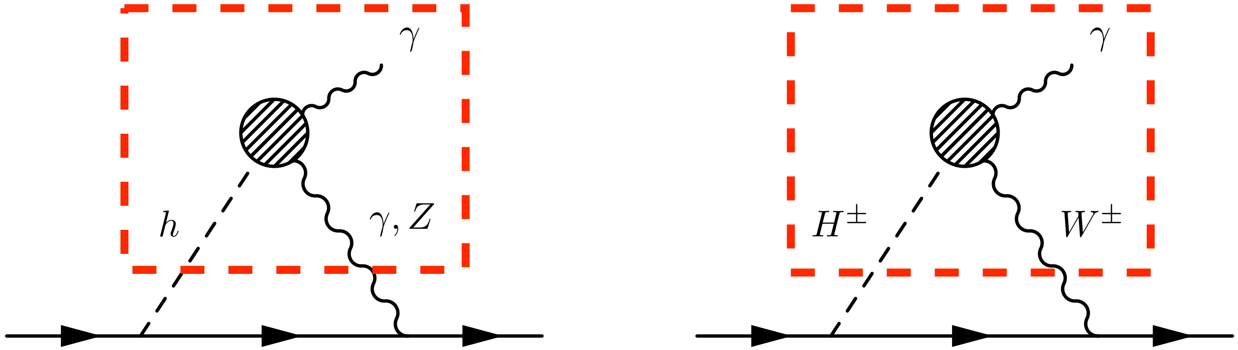
- we study EDM in 2HDM with softly broken Z_2 symmetry
- focus on Barr-Zee diagram
- take into account of the gauge invariance
- show numerical result of type-I, -II, -X, and -Y.

Contents

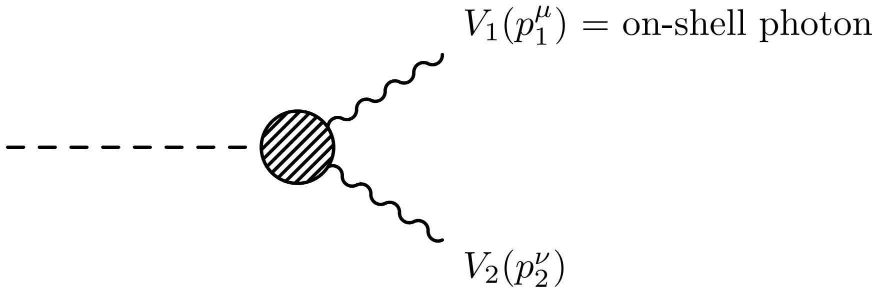
Contents

subdiagram in Barr-Zee diagram

- Barr-Zee diagram includes hγγ, hZγ, and HWγ loop subdiagrams

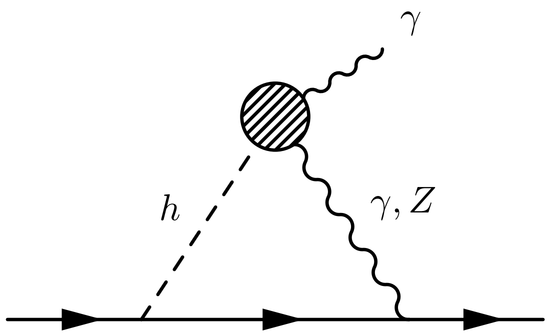


- we start by calculating hγγ, hZγ, and HWγ effective vertex



subdiagram in Barr-Zee diagram

- If effective vertex is gauge invariant, Barr-Zee diagram is gauge invariant



gauge boson propagator:

$$\propto g_{\mu\nu} - A(q^2, \xi) q_\mu q_\nu$$

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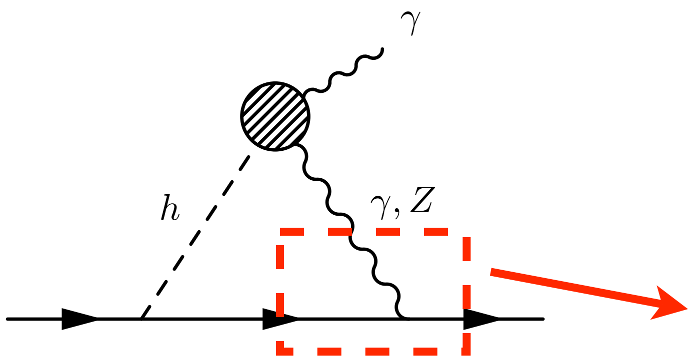

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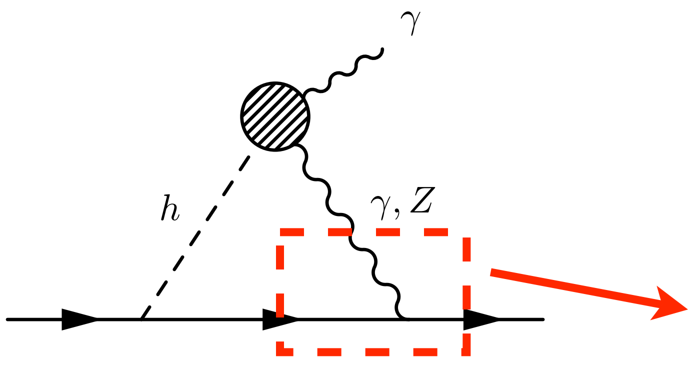

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$q_\mu q_\nu$ part: $\bar{u}(p)\not{q}\frac{1}{\not{p} - \not{q}}$

$$= \bar{u}(p)((\not{q} - \not{p}) + \not{p})\frac{1}{\not{p} - \not{q}}$$

$$= -\bar{u}(p)$$

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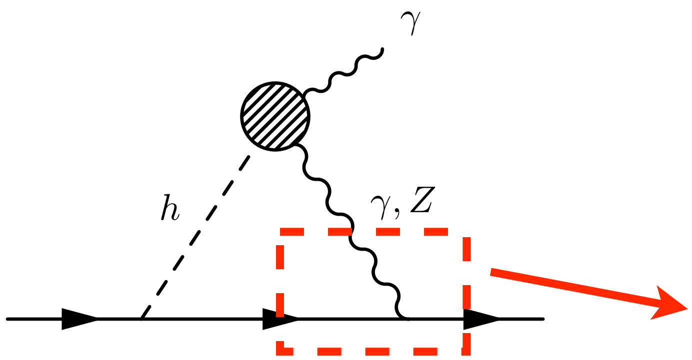

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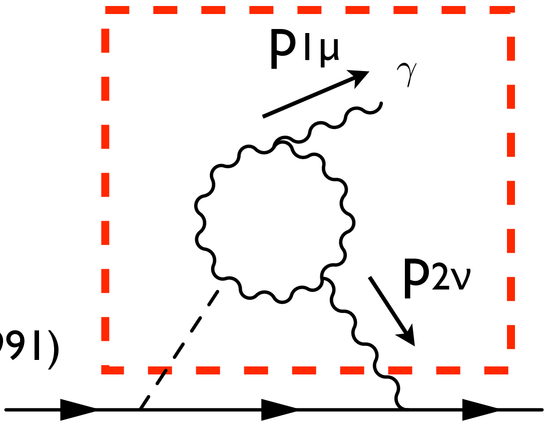
- no $\sigma_{\mu\nu}\gamma_5$ term
- do not contribute to EDM

gauge invariance of the effective vertex

- effective vertex is not gauge invariant



Leigh, Paban, Xu (1991)

$$\Gamma_n^{\mu\nu} = -\tfrac{1}{2}\sum_m \frac{i\alpha}{4\pi}\frac{g^2 V_m^*}{m_W^2}\Big[8\delta_{mn}(2J_1 - 3J_2)\left(p_2^\mu p_1^\nu - p_1\cdot p_2 g^{\mu\nu}\right)$$

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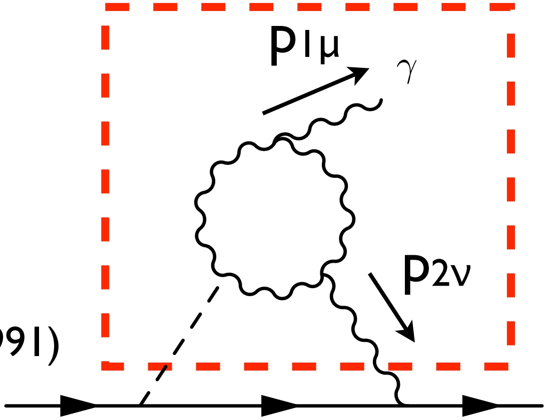

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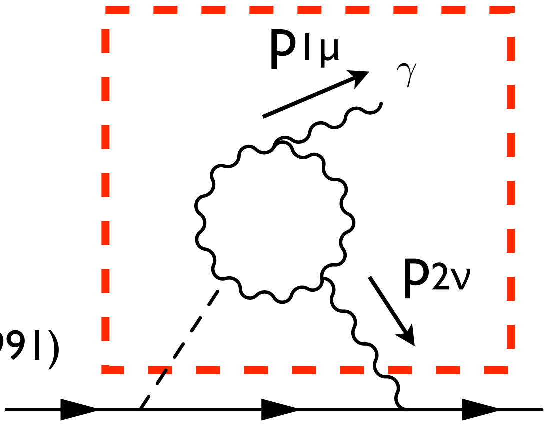

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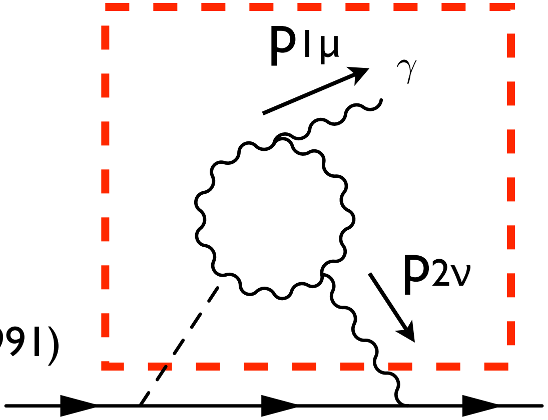

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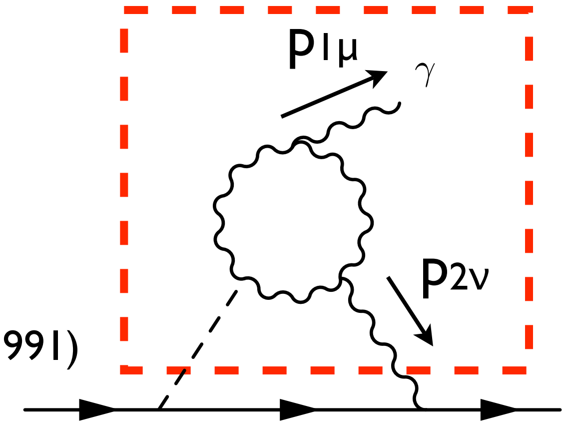

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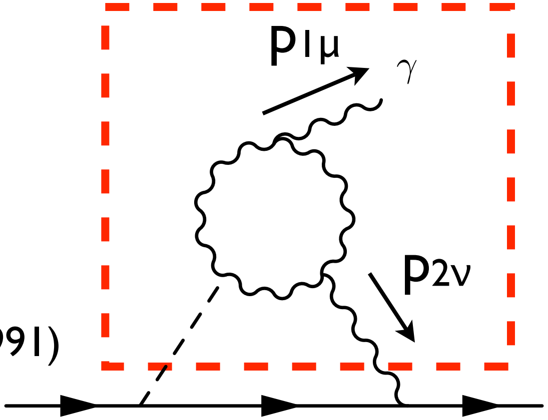

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NOT gauge invariant

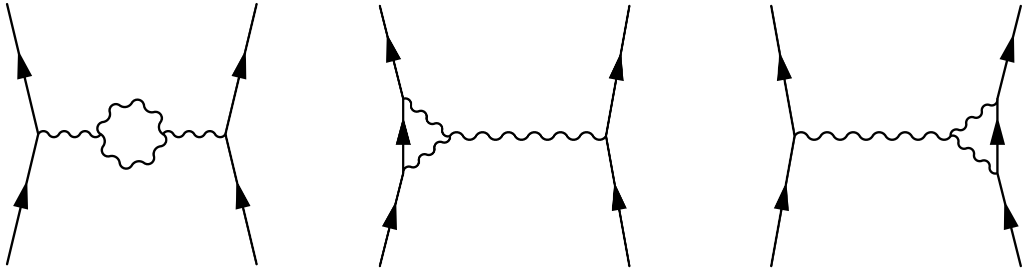
- previous works did not care the gauge invariance
- we improve this point

Contents

pinch technique (review)

example: gauge boson self-energy (γZ) are not gauge invariant

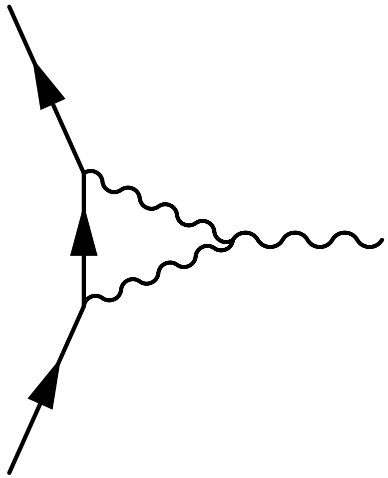
$$i\Pi_{\mu\nu}^{Z\gamma} = i\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Pi_T(q^2) + i\frac{q_\mu q_\nu}{q^2}\Pi_L(q^2)$$



+ (wave functions)

- sum of all relevant diagrams are gauge invariant
- pinch technique: barrow some terms from vertex corrections
- then self-energy are made gauge invariant

pinch technique (review)



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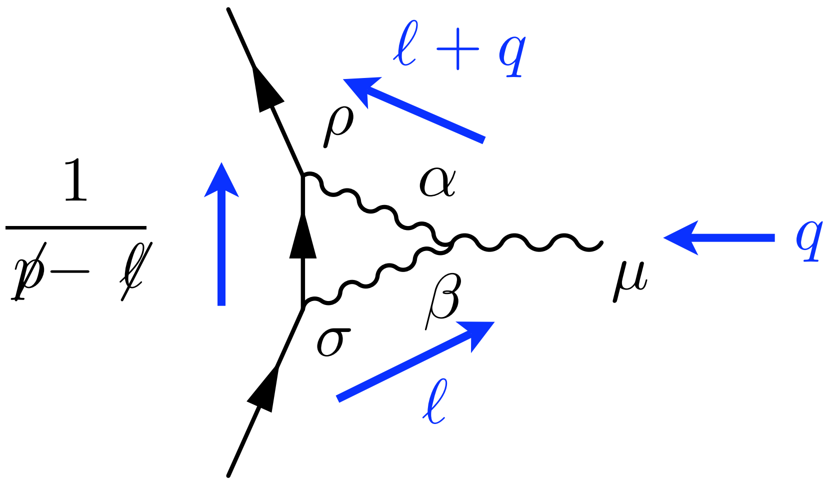

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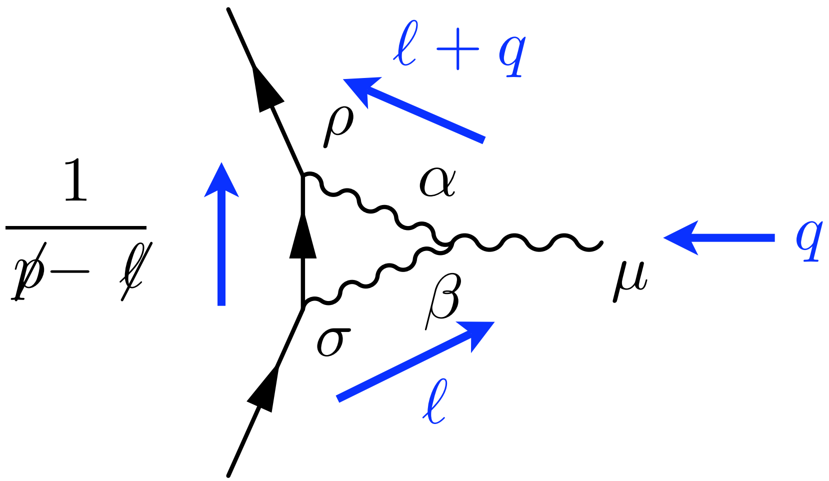

derivative coupling:

$$[(l-p)+(p+q)-2q]_\alpha \, g_{\mu\beta} + [(l-p)+p+2q]_\beta \, g_{\mu\alpha} + (-(l+q)-l)_\mu g_{\alpha\beta}.$$

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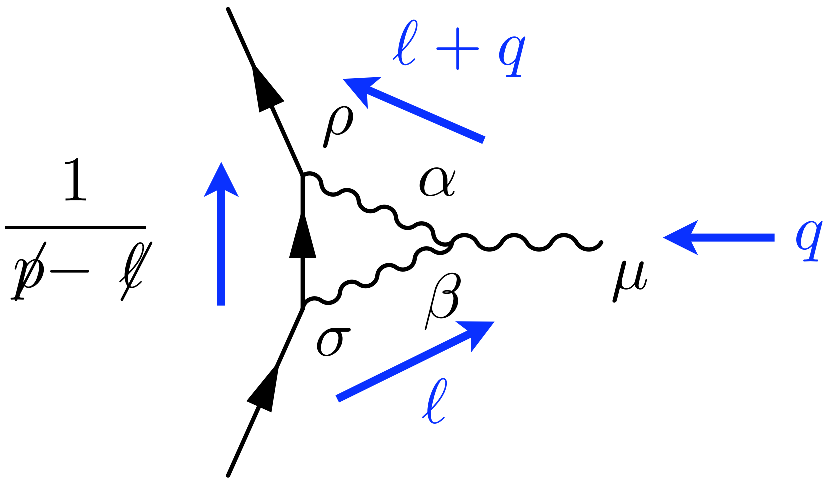

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cancel the fermion propagator

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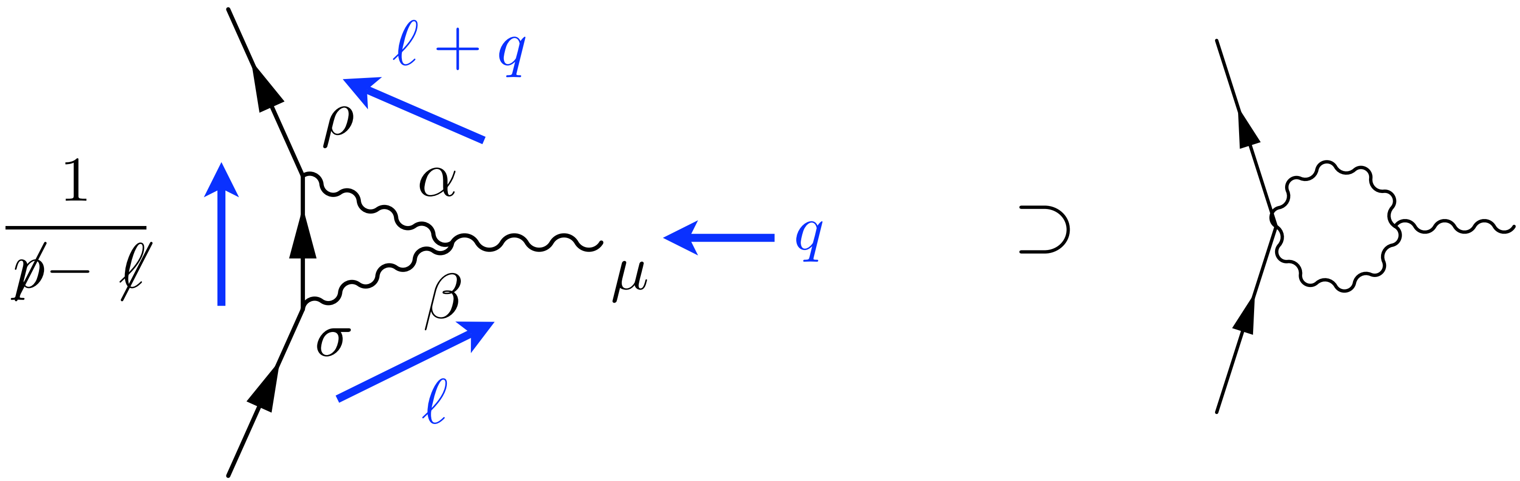

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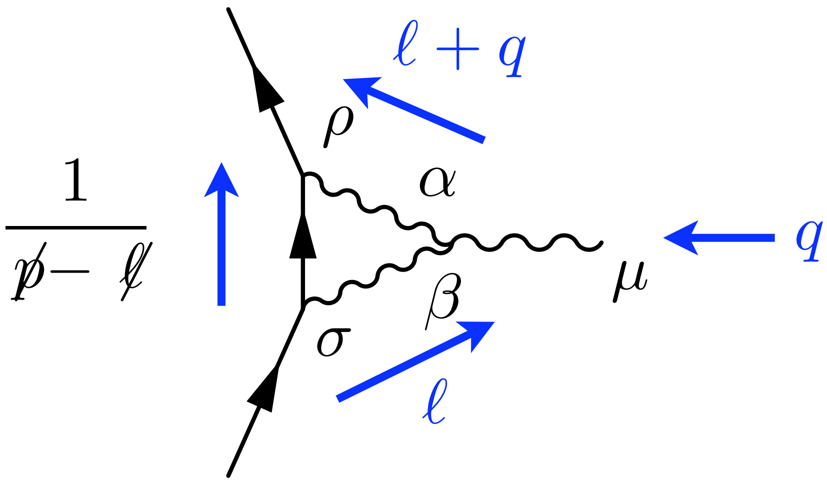
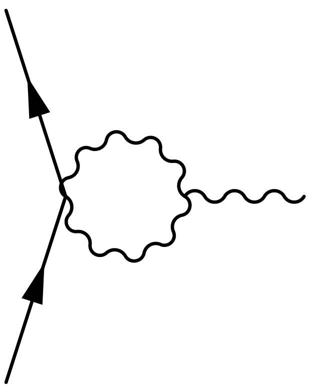


$\supset$



- almost self-energy diagram
- make self-energy gauge invariant

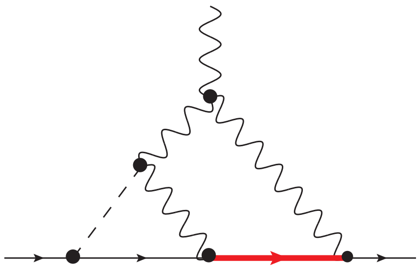
derivative coupling:

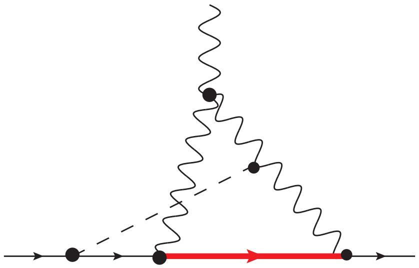
$$\underline{[(l-p)} + (p+q) - 2q]_\alpha \, g_{\mu\beta} + \underline{[(l-p)} + p + 2q]_\beta \, g_{\mu\alpha} + (-(l+q) - l)_\mu g_{\alpha\beta}.$$

cancel the fermion propagator

pinch technique for Barr-Zee

- we have the following non-Barr-Zee diagrams





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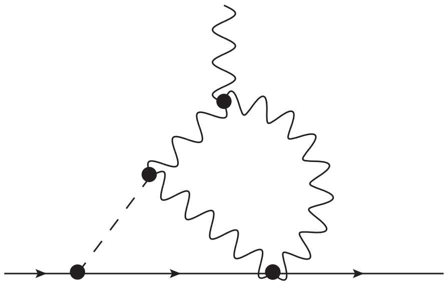

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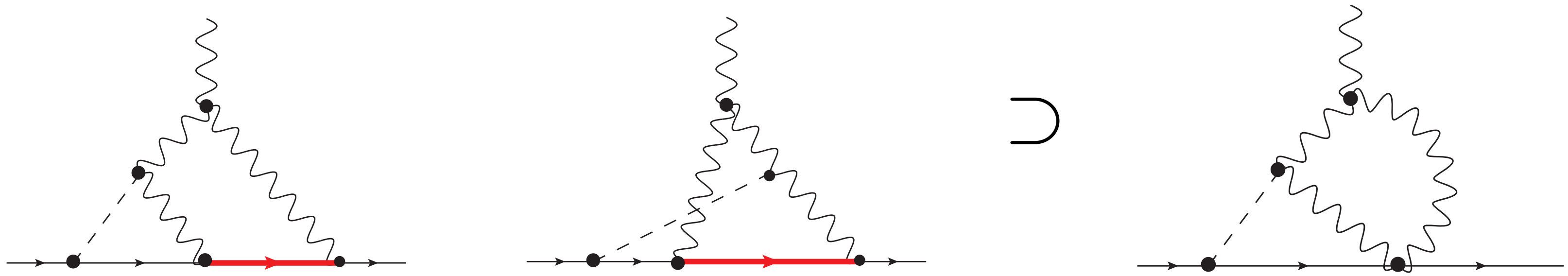
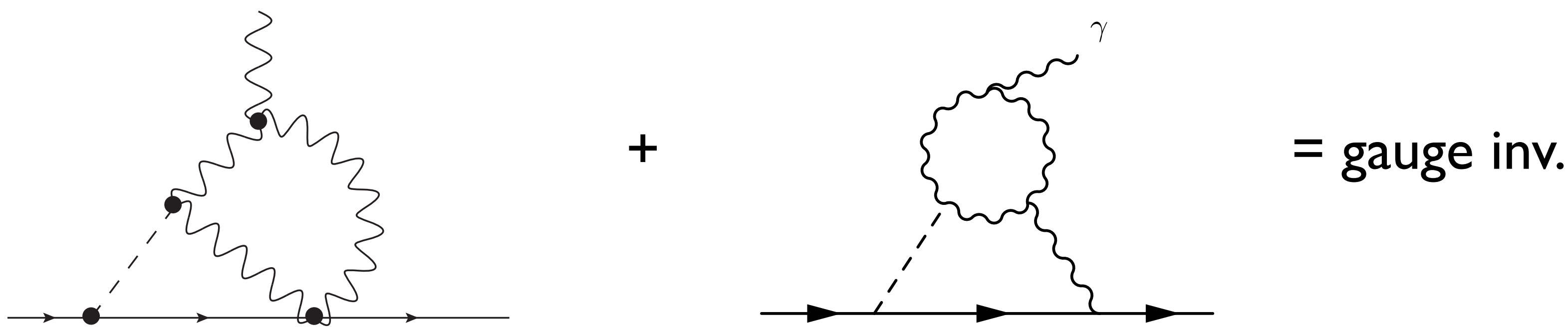
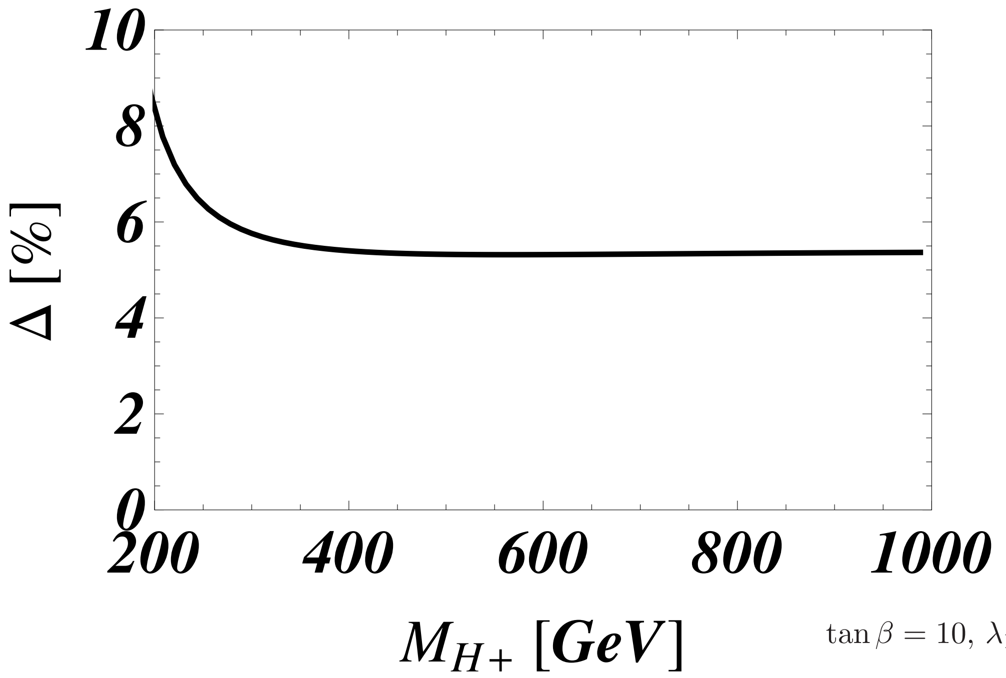


- we have checked this diagram certainly work for the gauge invariance



EDM w/ and w/o pinch contributions

Δ = (gauge no inv - gauge inv)/gauge inv

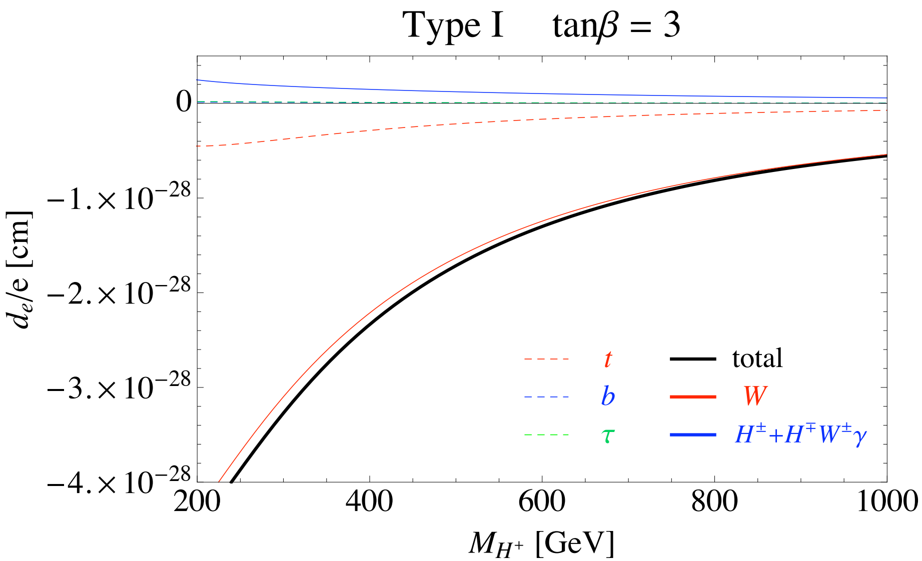


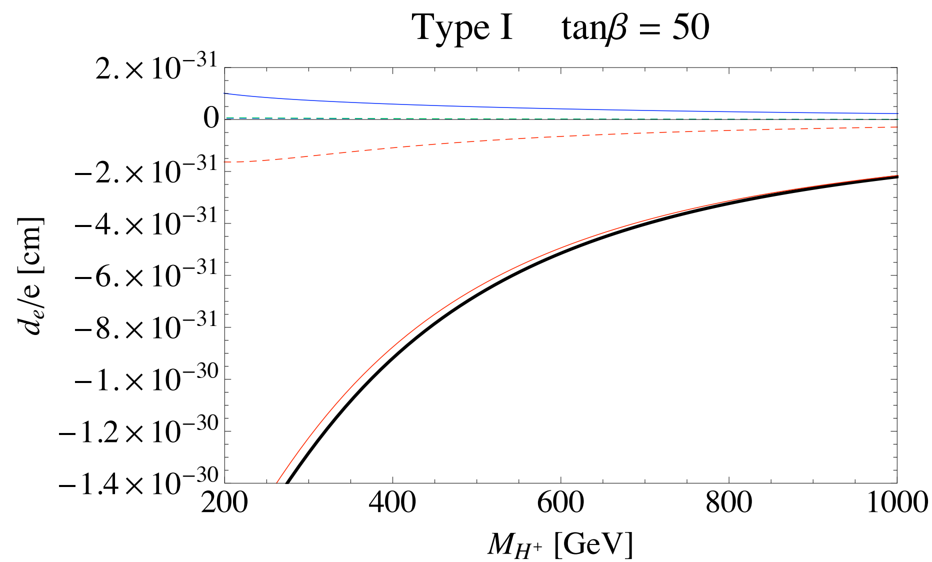
$\tan\beta = 10,\ \lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 \sin 2\phi = 0.5$

- Not too big difference, but not too small difference
- Anyway, result is now gauge invariant and reliable

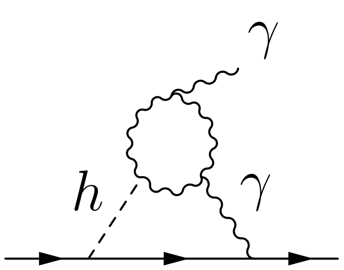
Contents

electron EDM (type I)



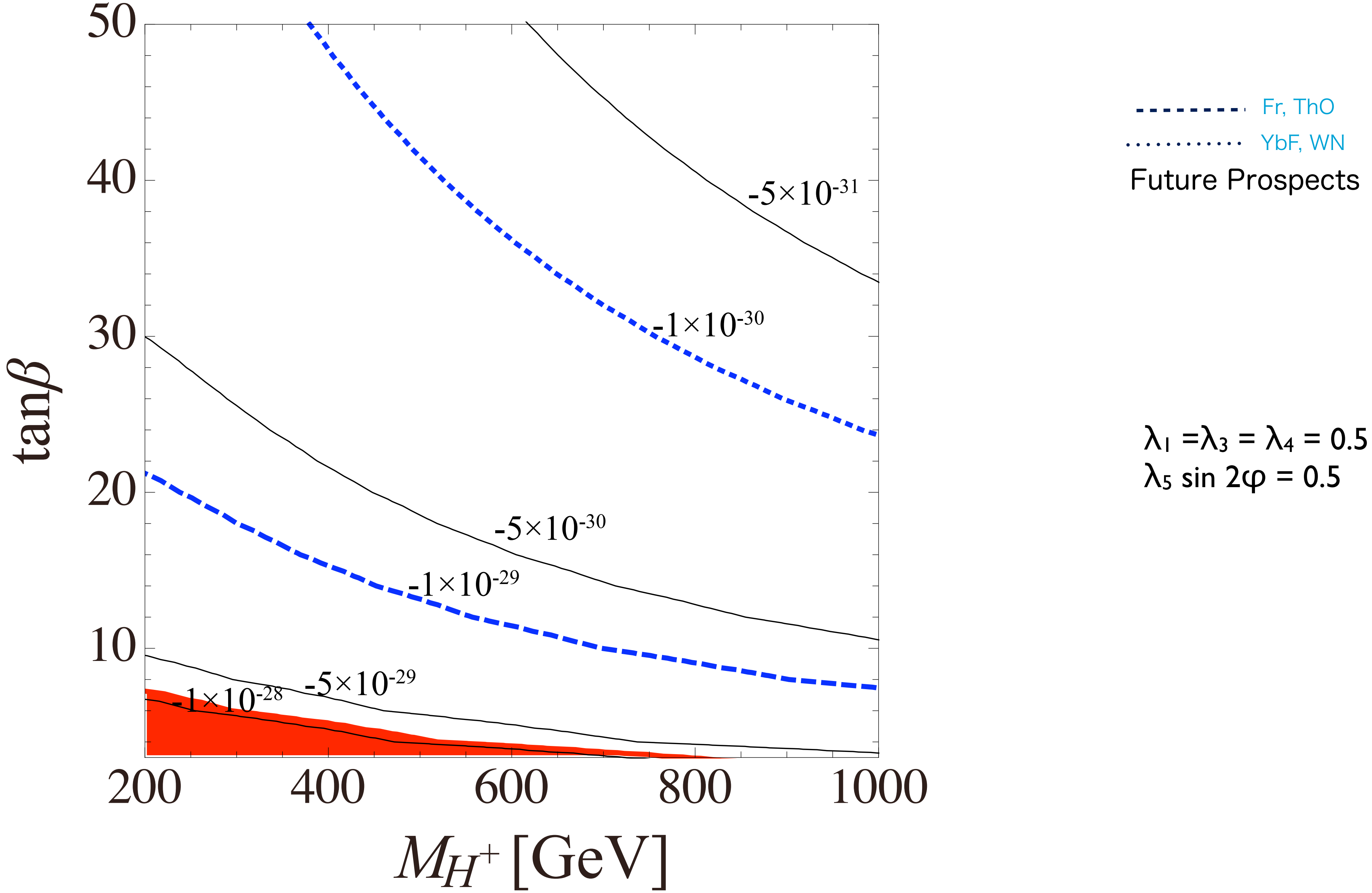


- The dominant contribution comes from



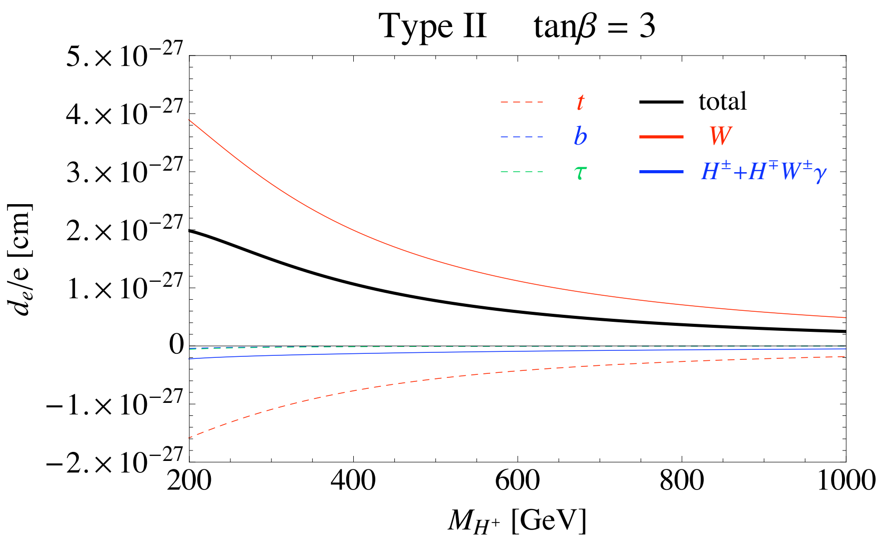
- tanB dependence $$\frac{1}{1+\tan^2\beta}$$

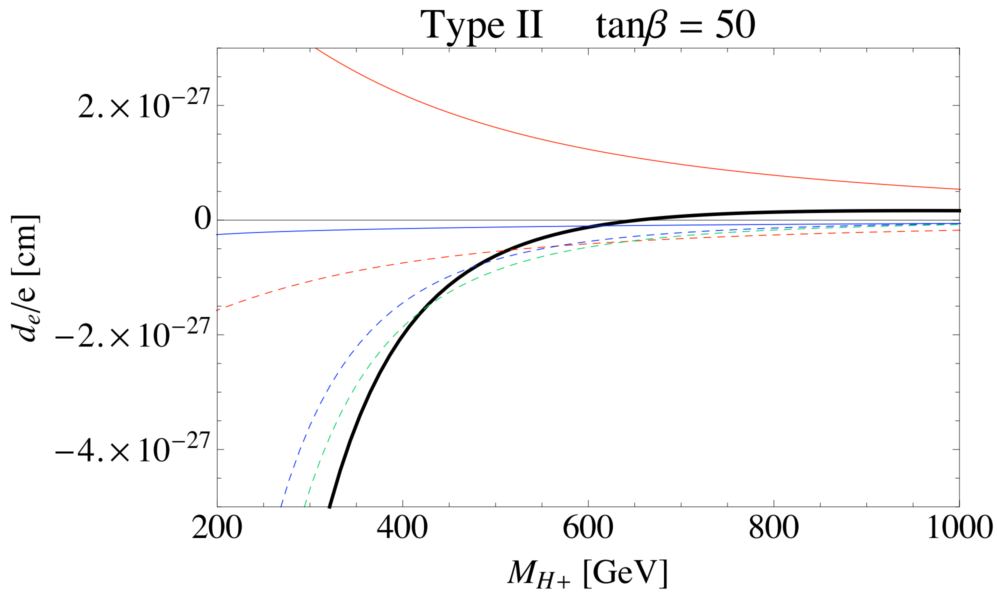
eEDM Type I



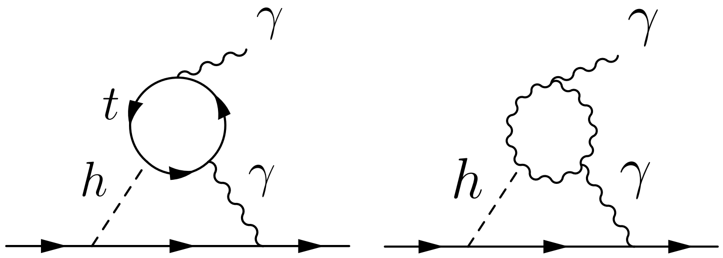
50
40
30
20
10
tanβ
200
400
600
800
1000
M_{H^+} [GeV]
-5×10^{-31}
-1×10^{-30}
-5×10^{-30}
-1×10^{-29}
-5×10^{-29}
-1×10^{-28}
Fr, ThO
YbF, WN
Future Prospects
λ$_1$ =λ$_3$ = λ$_4$ = 0.5
λ$_5$ sin 2φ = 0.5

electron EDM (type II)

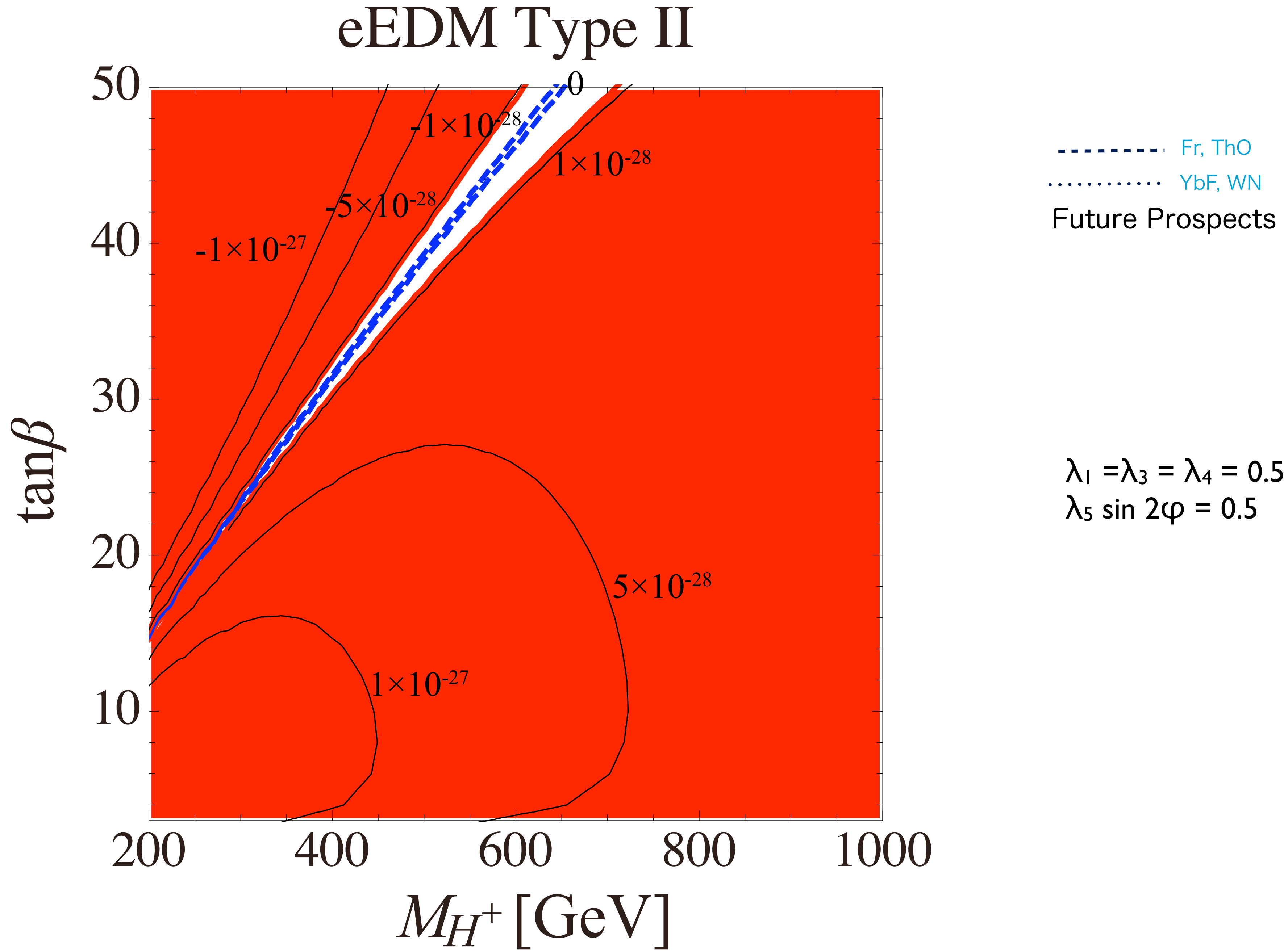




- The dominant contribution comes from



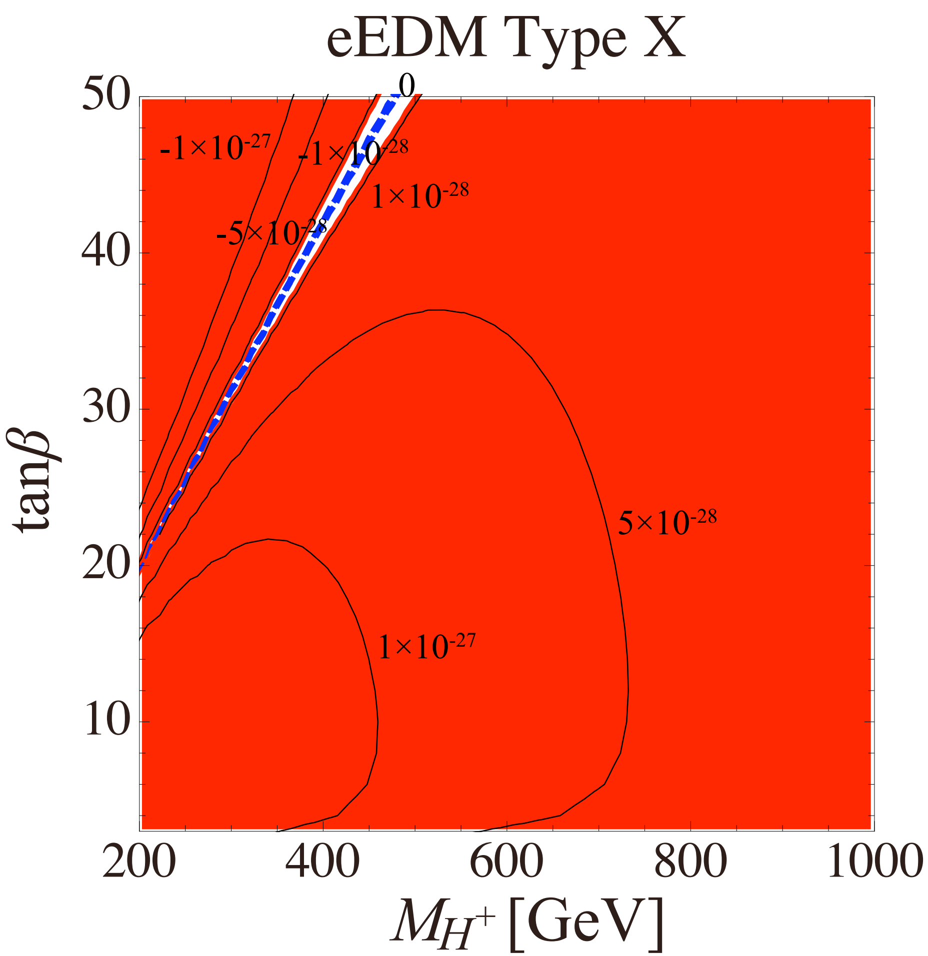
- In large tanB region, bottom and tau also contribute

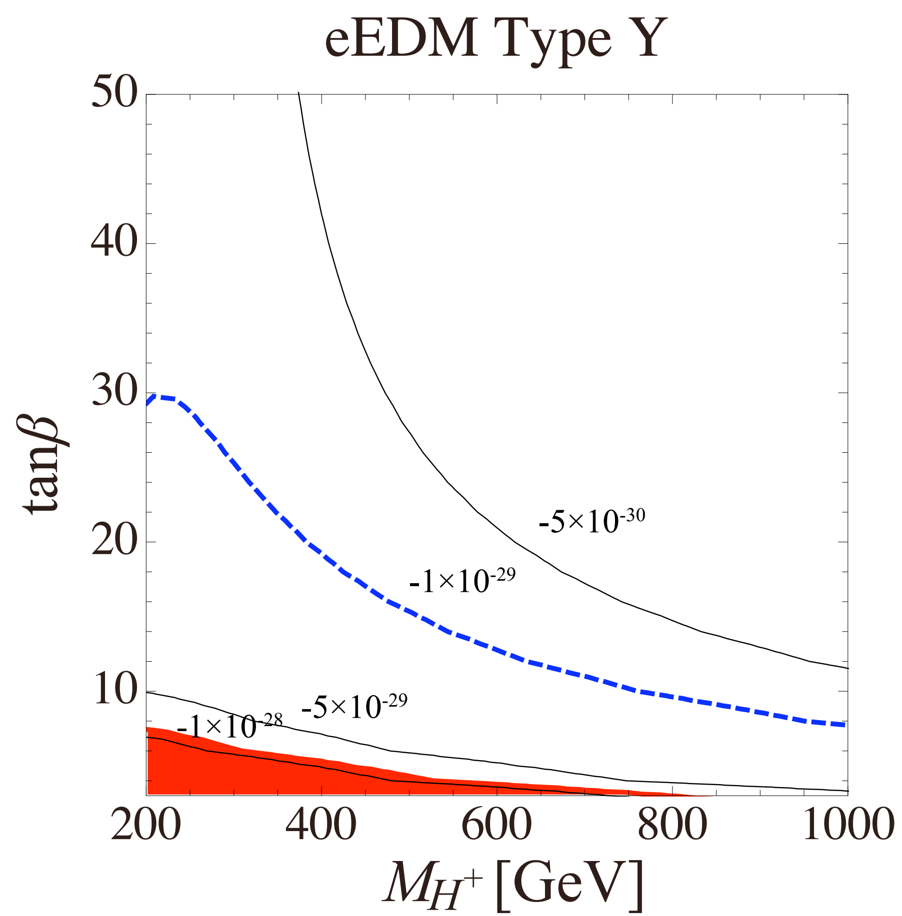

eEDM Type II
50
40
30
20
10
200
400
600
800
1000
tanβ
M_{H^+} [GeV]
0
-1×10^{-28}
1×10^{-28}
-5×10^{-28}
-1×10^{-27}
5×10^{-28}
1×10^{-27}
Fr, ThO
YbF, WN
Future Prospects
$\lambda_1 = \lambda_3 = \lambda_4 = 0.5$
$\lambda_5 \sin 2\varphi = 0.5$

electron EDM (type X and Y)

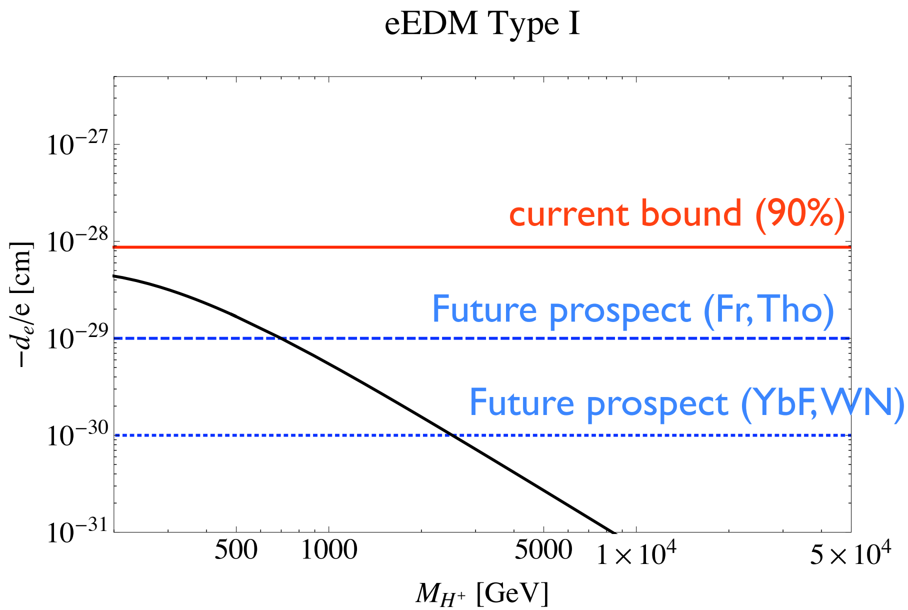
$\lambda_1 = \lambda_3 = \lambda_4 = 0.5$
$\lambda_5 \sin 2\varphi = 0.5$

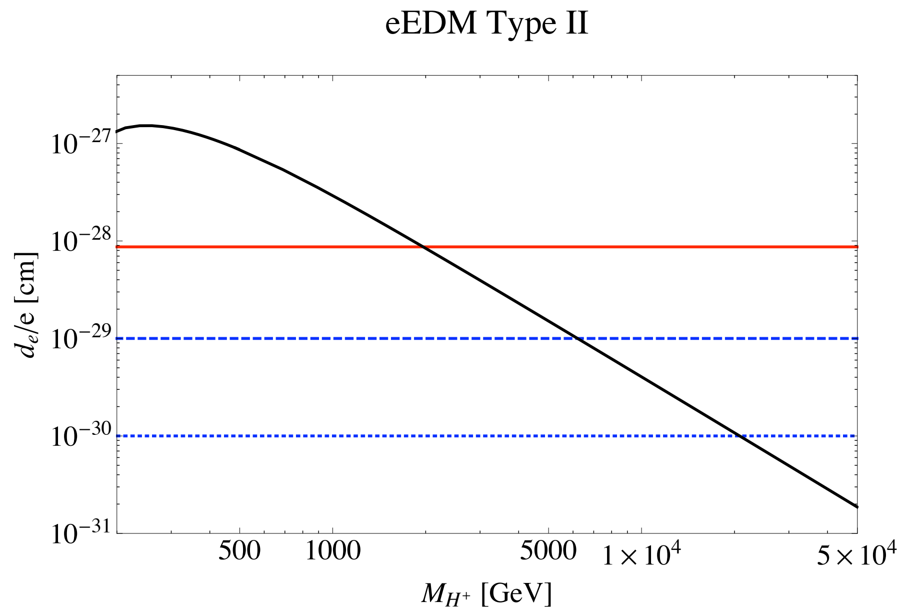
- Type X is similar to type II
- Type Y is similar to Type I





electron EDM in heavy M limit

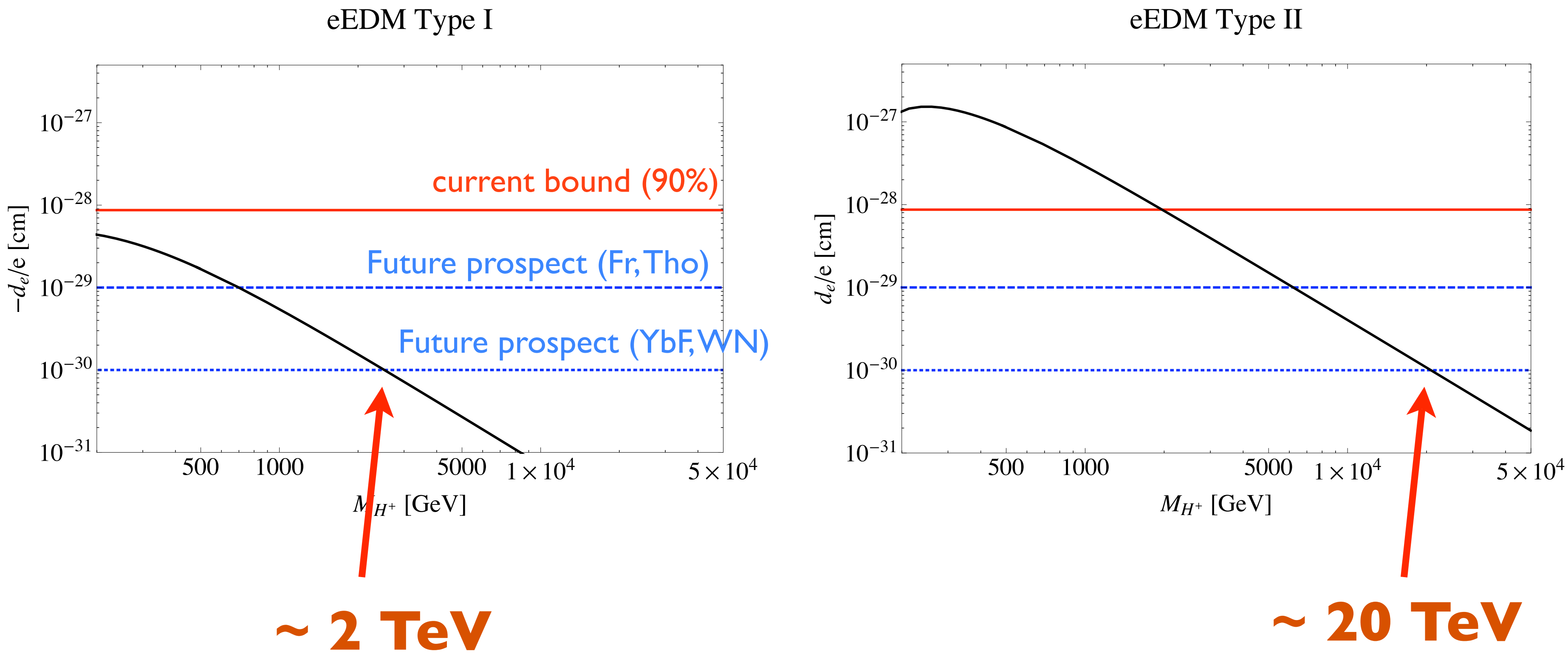




$$\tan\beta = 10,\ \lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 \sin 2\phi = 0.5$$

Chance to seek O(10) TeV scale

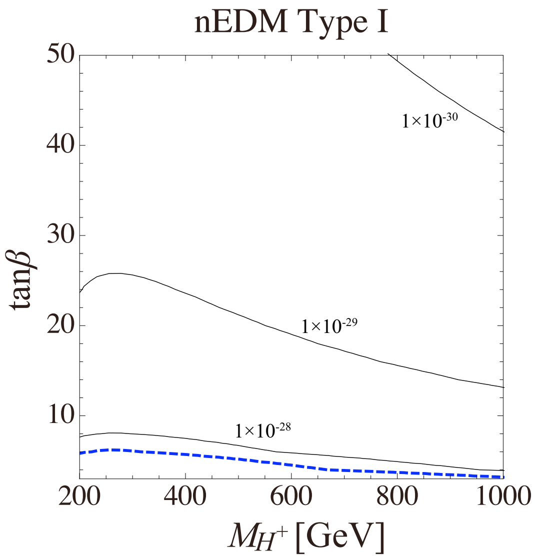
electron EDM in heavy M limit

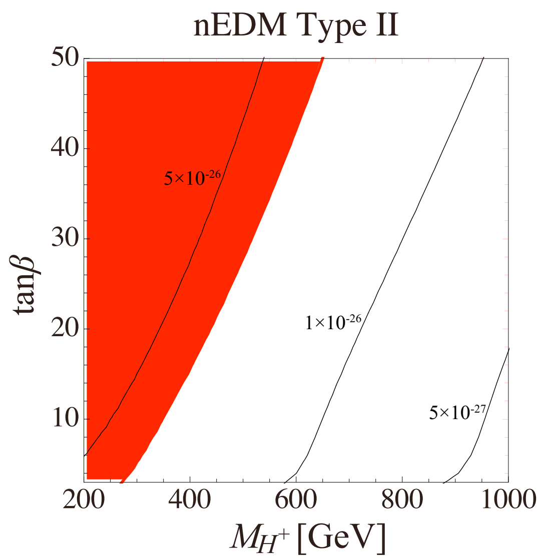


$\tan\beta = 10,\ \lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 \sin 2\phi = 0.5$

Chance to seek O(10) TeV scale

neutron EDM





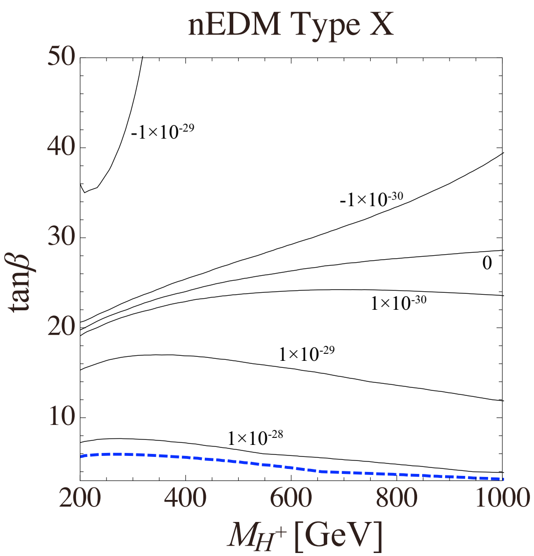
Fr, ThO

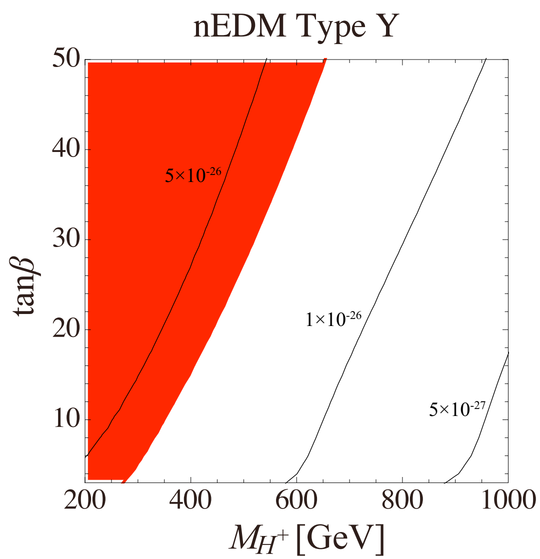
YbF, WN

Future Prospects

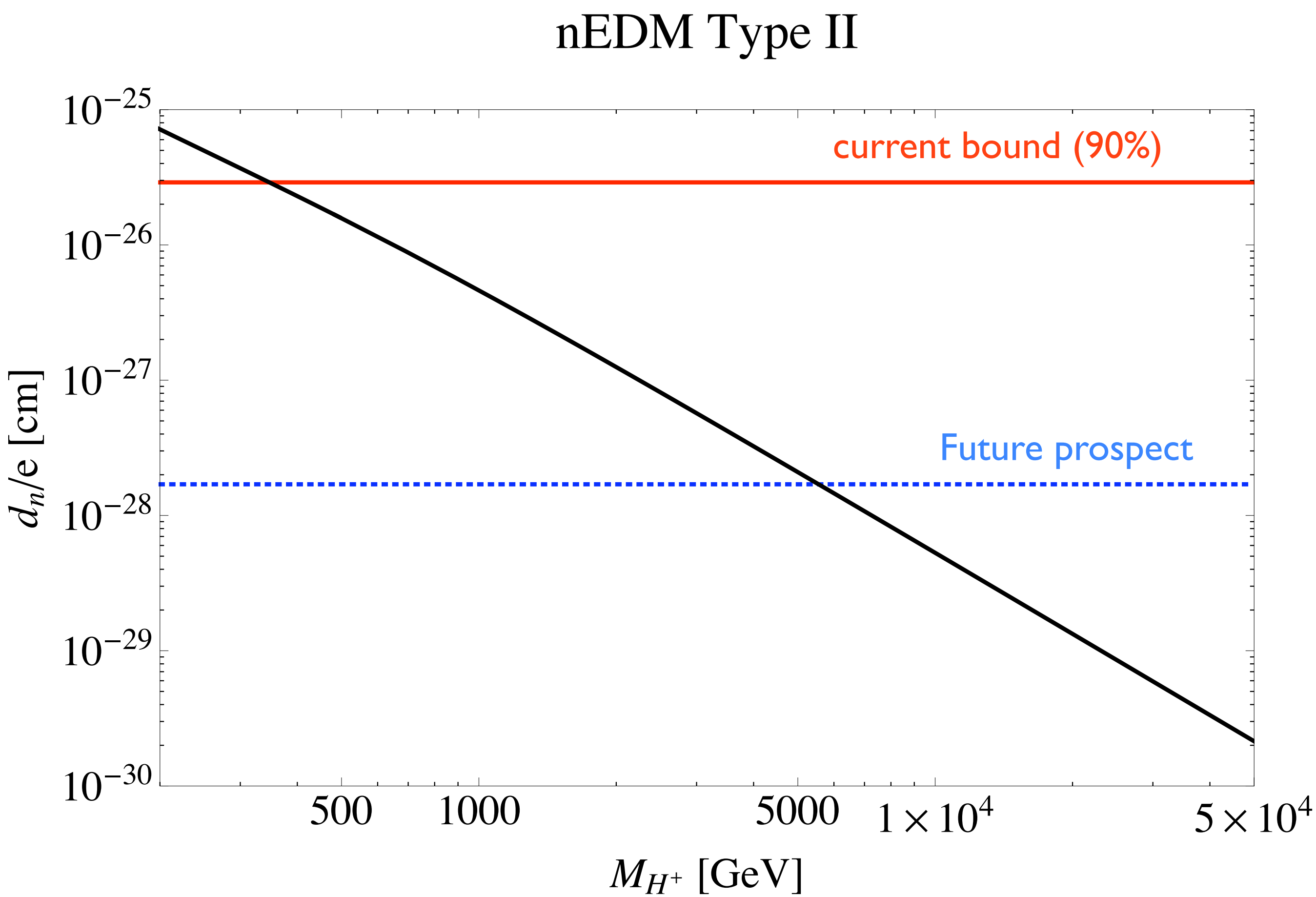
$\lambda_1 = \lambda_3 = \lambda_4 = 0.5$

$\lambda_5 \sin 2\varphi = 0.5$





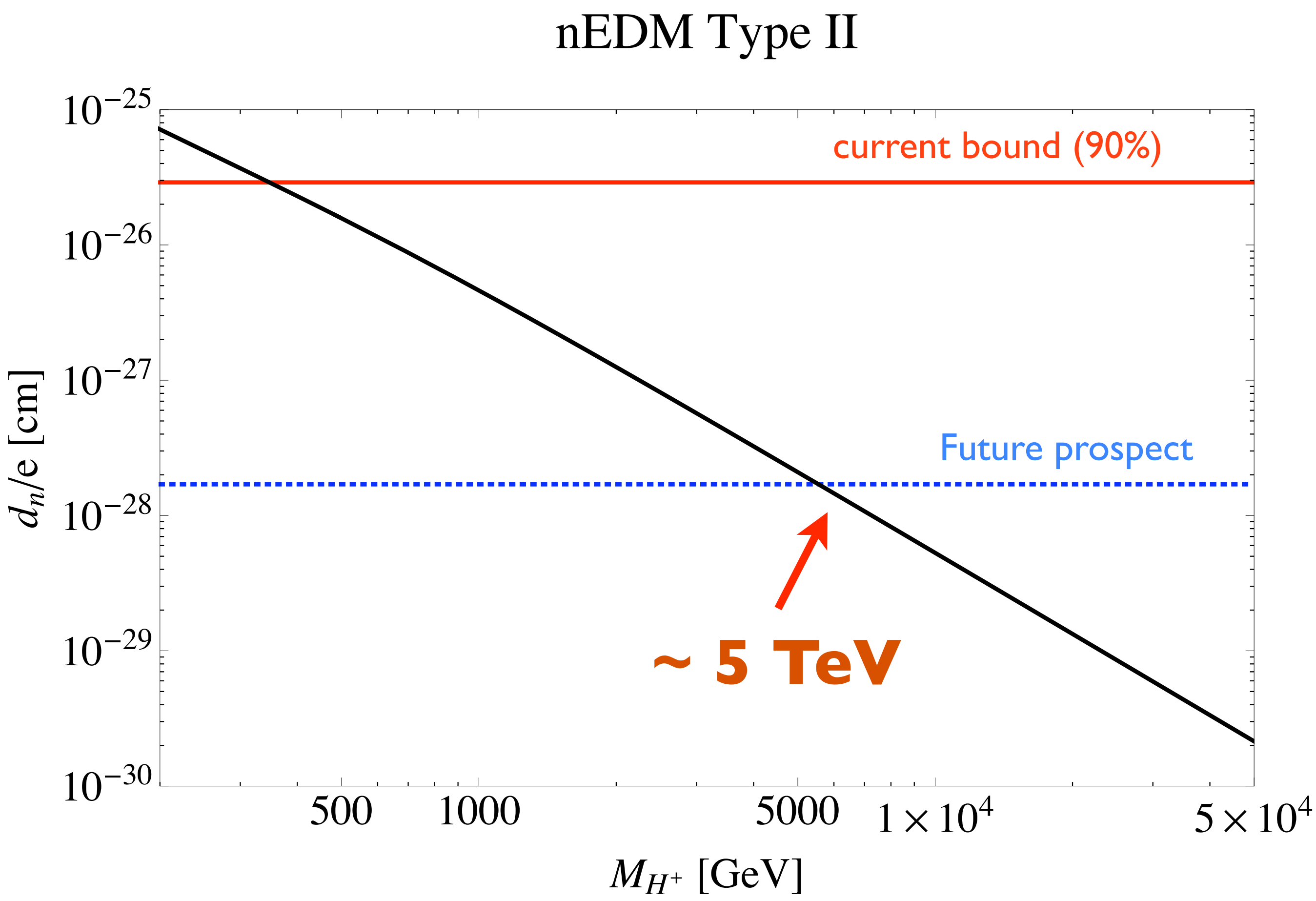
neutron EDM



- Type Y is same
- Type I and X are too small.

$\tan\beta = 10,\ \lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 \sin 2\phi = 0.5$

neutron EDM



- Type Y is same
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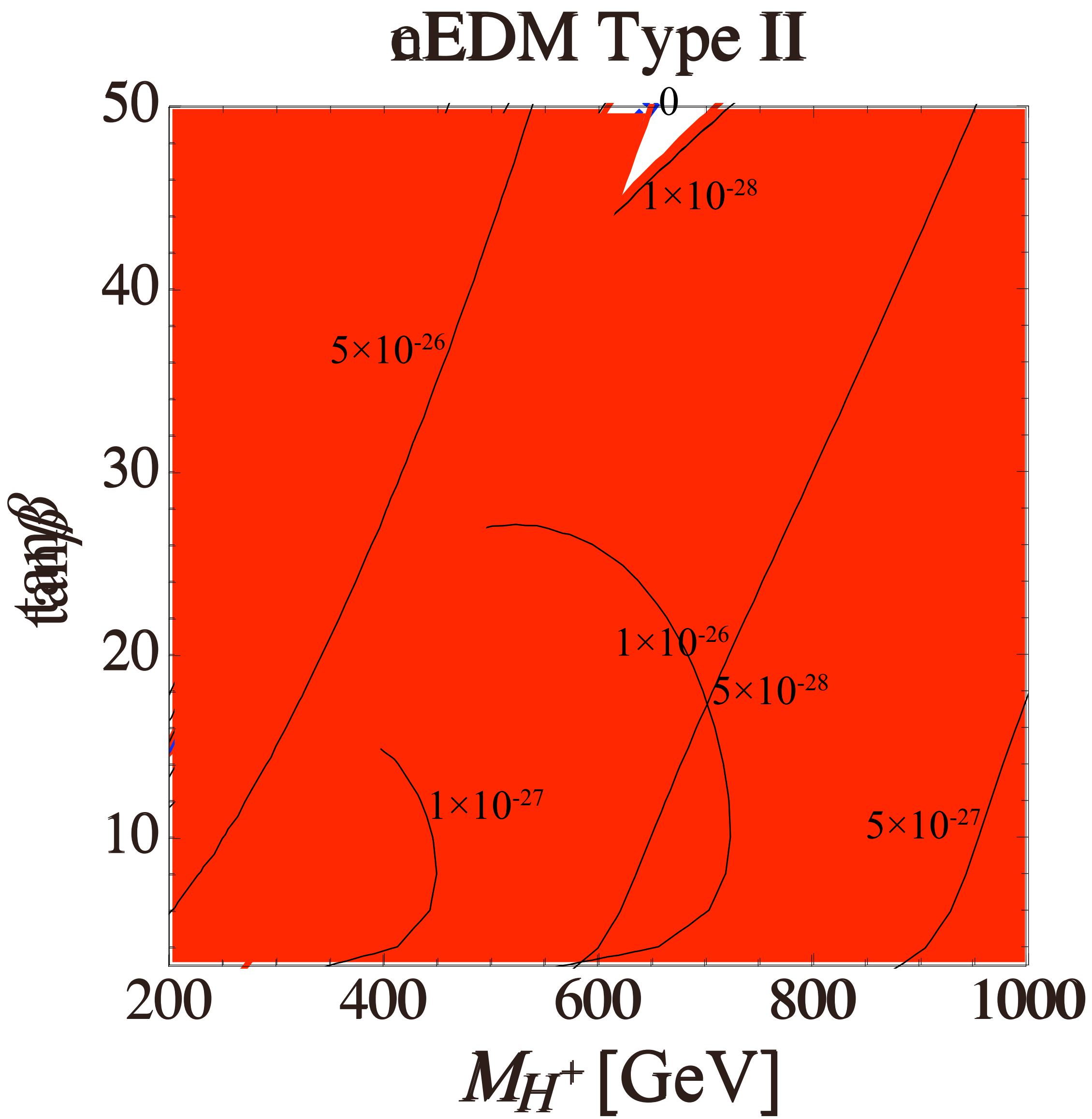
eEDM and nEDM (type II)



$\lambda_1 = \lambda_3 = \lambda_4 = 0.5$

$\lambda_5 \sin 2\varphi = 0.5$

Contents

Summary

✓EDM is a good window for high scale physics

✓we have studied EDM in 2HDM

✓Barr-Zee diagram is now gauge invariant thanks to the pinch terms

✓numerical results:

- ⋆ we might reach O(10) TeV scale by future experiments

BACKUP SLIDES

why not gauge invariant?

- Barr-Zee diagrams are not the all diagrams at two-loop level
- After taking non-Barr-Zee diagrams, gauge invariance of EDM is recovered

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