Seminar slide for Berkeley week

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

New Contributions to Lepton Dipole Moments in Vector-like Lepton Models

2024/3/15

Genta Osaki (D1, U-Tokyo phys.)

About the title

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to Lepton Dipole Moments
in Vector-like Lepton Models

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magnetic dipole moment → muon g-2
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→ muon EDM
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new contribution

measured by future exp!?

Summary

- SM has a problem of “**muon g-2 anomaly**”.
- Vector-like leptons can explain this problem.
- We calculated **new contributions for muon/electron EDMs**.
- There is a possibility that **muon/electron EDMs will be measured by future experiments**.

Today’s menu

- **Lepton dipole moments** (15 min)
- **Vector-like leptons** (10 min)
- **Method** (5 min)
- **Result** (10 min)

Lepton dipole moments

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$$H = -\vec{m} \cdot \vec{B} \; - \vec{d} \cdot \vec{E}$$

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In the lecture of classical electrodynamics…

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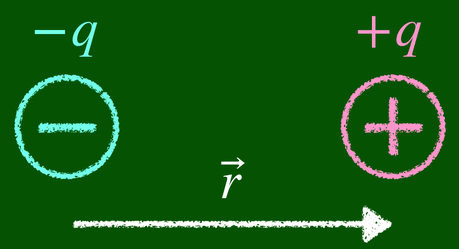

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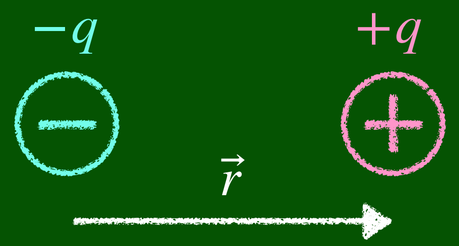

$$\vec{d} \equiv q\,\vec{r}$$

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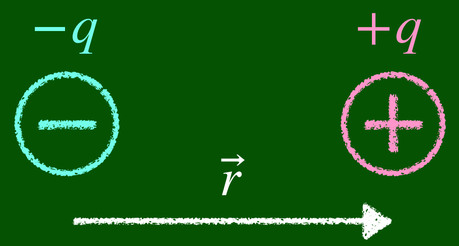

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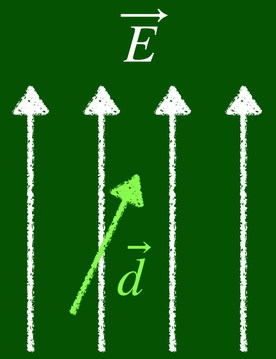

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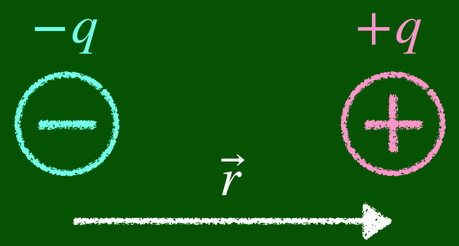

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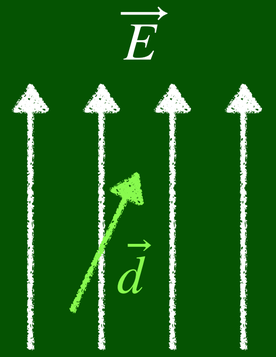

$$U = -\vec{d}\cdot\vec{E}$$

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← value from Dirac equation

: anomalous magnetic moment

Discrete symmetry

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T:

C:

Discrete symmetry

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We can calculate C, P, T transformation of $\vec{E}$, $\vec{B}$, $\vec{s}$

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CPT theorem: physics is invariant under CPT transformation.

EDM from CP violation

$$H = -\vec{m} \cdot \vec{B} \; - \vec{d} \cdot \vec{E}$$

修士論文 表3.1

EDM from CP violation

$$H = -\vec{m} \cdot \vec{B} \; - \vec{d} \cdot \vec{E}$$

	$\boldsymbol{E}$	$\boldsymbol{B}$	$\boldsymbol{d}$ or $\boldsymbol{m}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

表 3.1　電磁場および電気/磁気双極子モーメントの離散対称性

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→ CP violation

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Standard model prediction

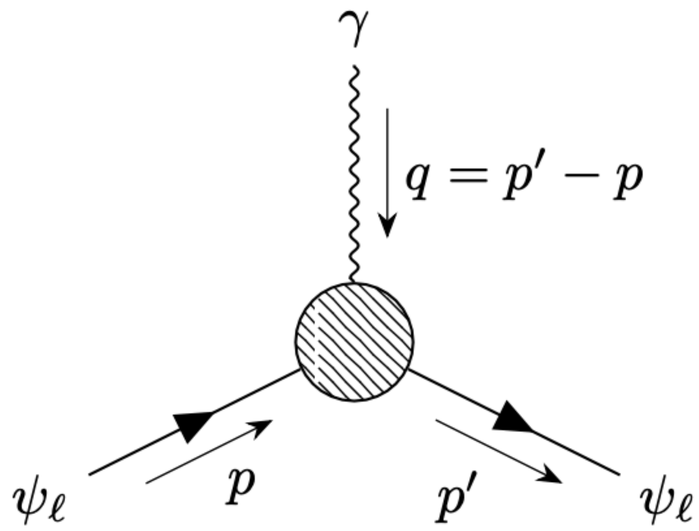

図 3.1　3 点関数の Feynman diagram

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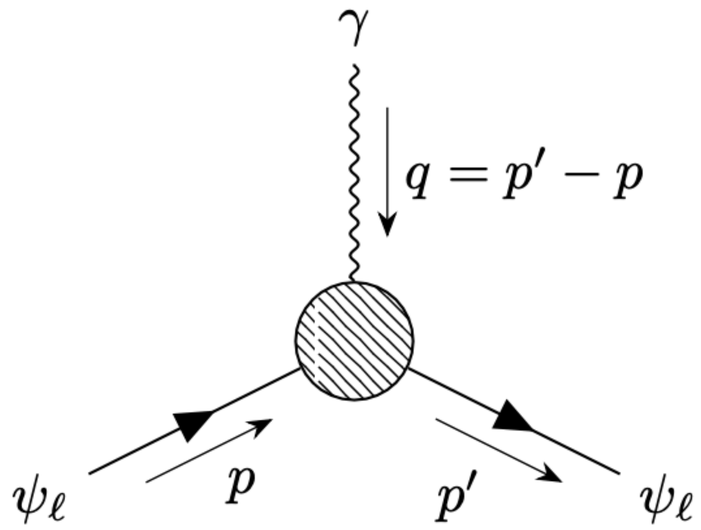

図 3.1　3 点関数の Feynman diagram

$$a_\mu^{\mathrm{SM}} = 116\ 591\ 810(43) \times 10^{-11}$$

Phys. Rept. **887** (2020)

$$d_e^{\mathrm{SM}} \leq 10^{-38}\ e \cdot \mathrm{cm}$$

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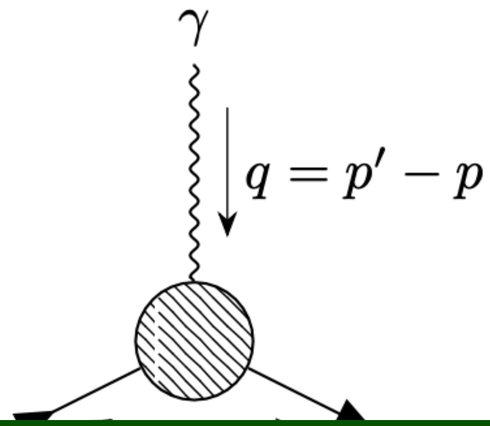

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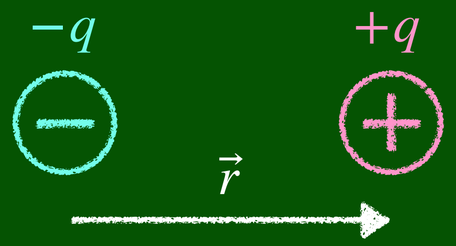
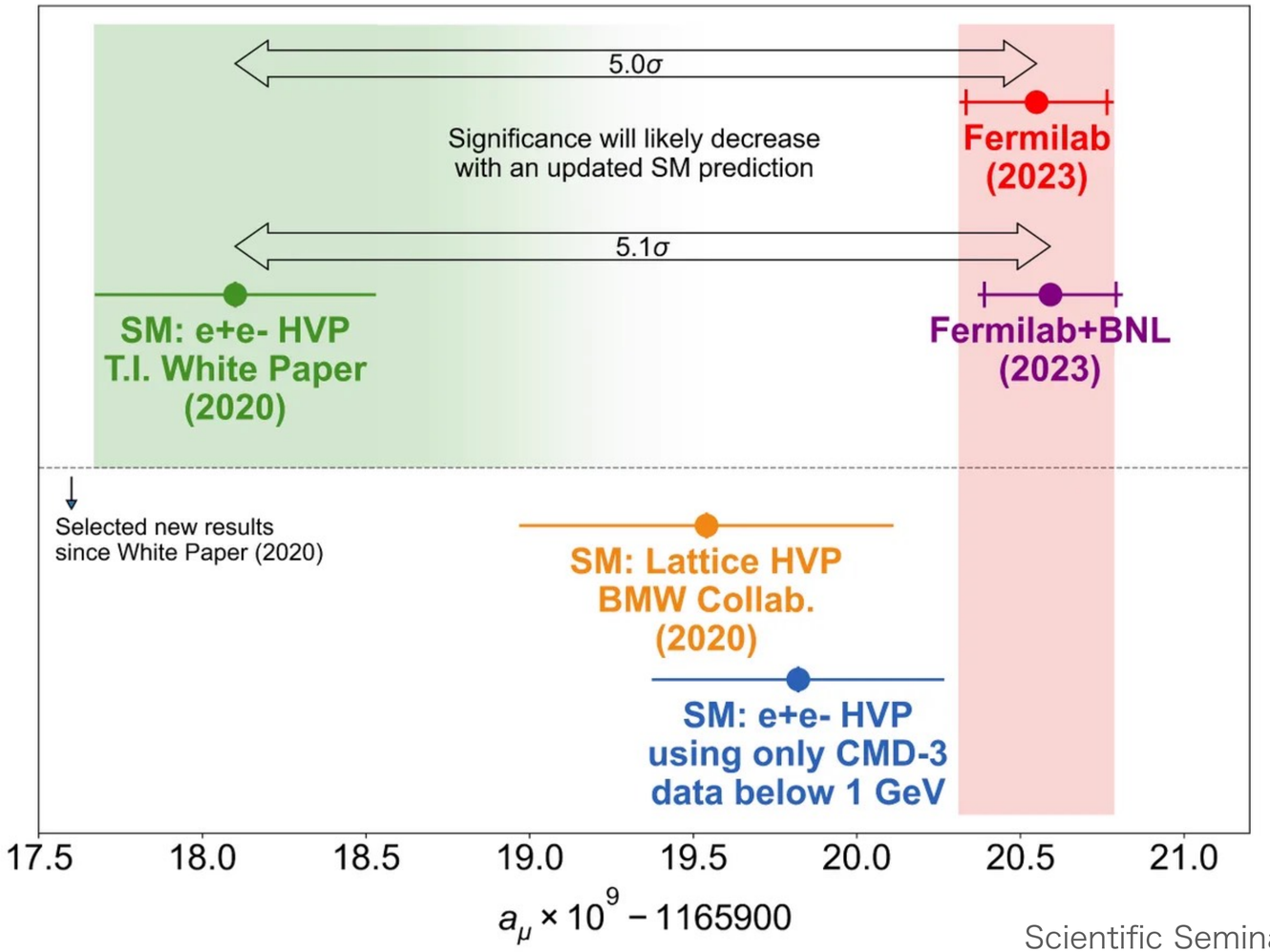


$$\vec{d} \equiv q\,\vec{r}$$

e cm

修士論文 図3.1

Muon g-2 experiment



Scientific Seminar: 2023 results from the Muon g-2 experiment at Fermilab

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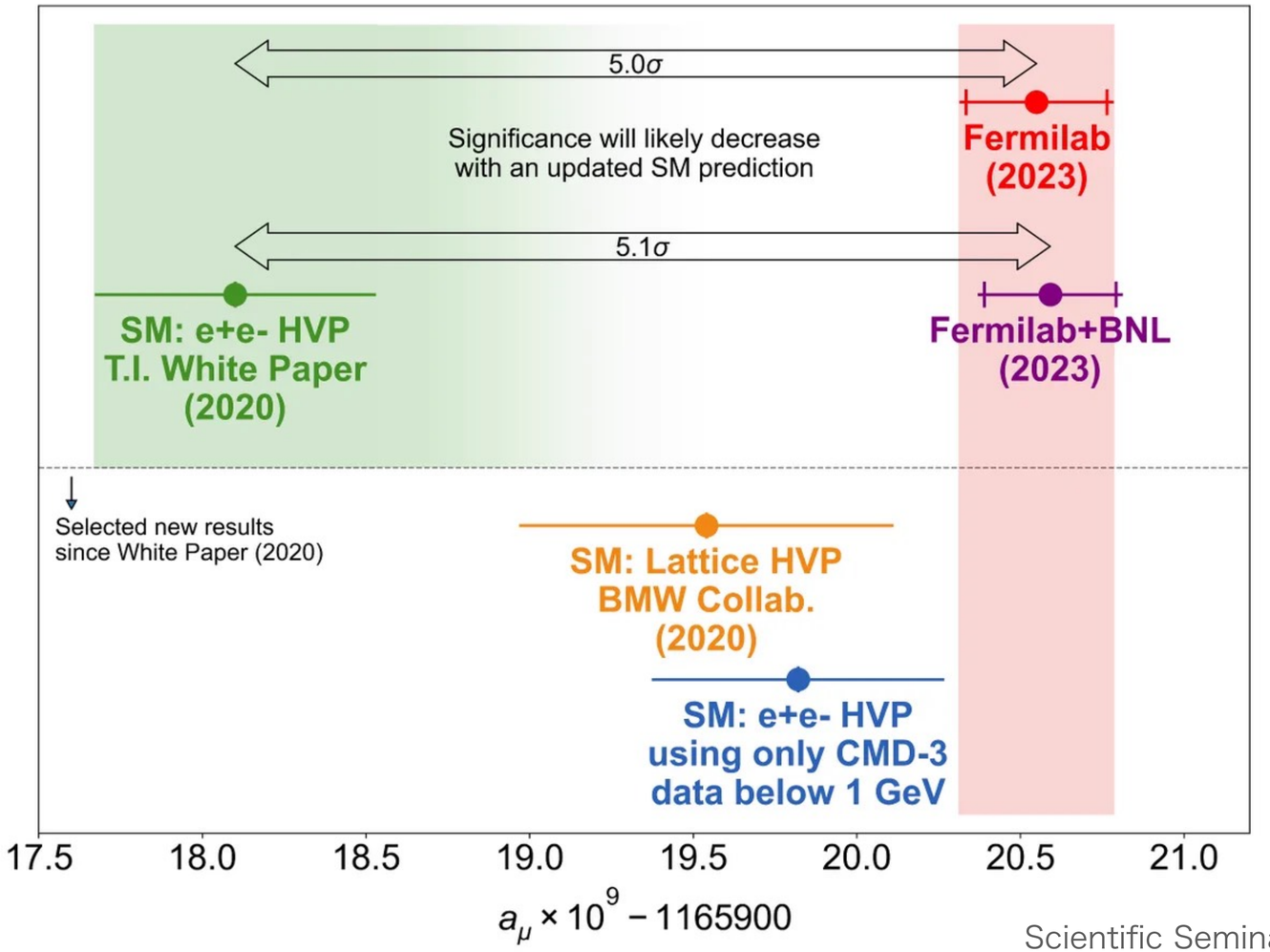

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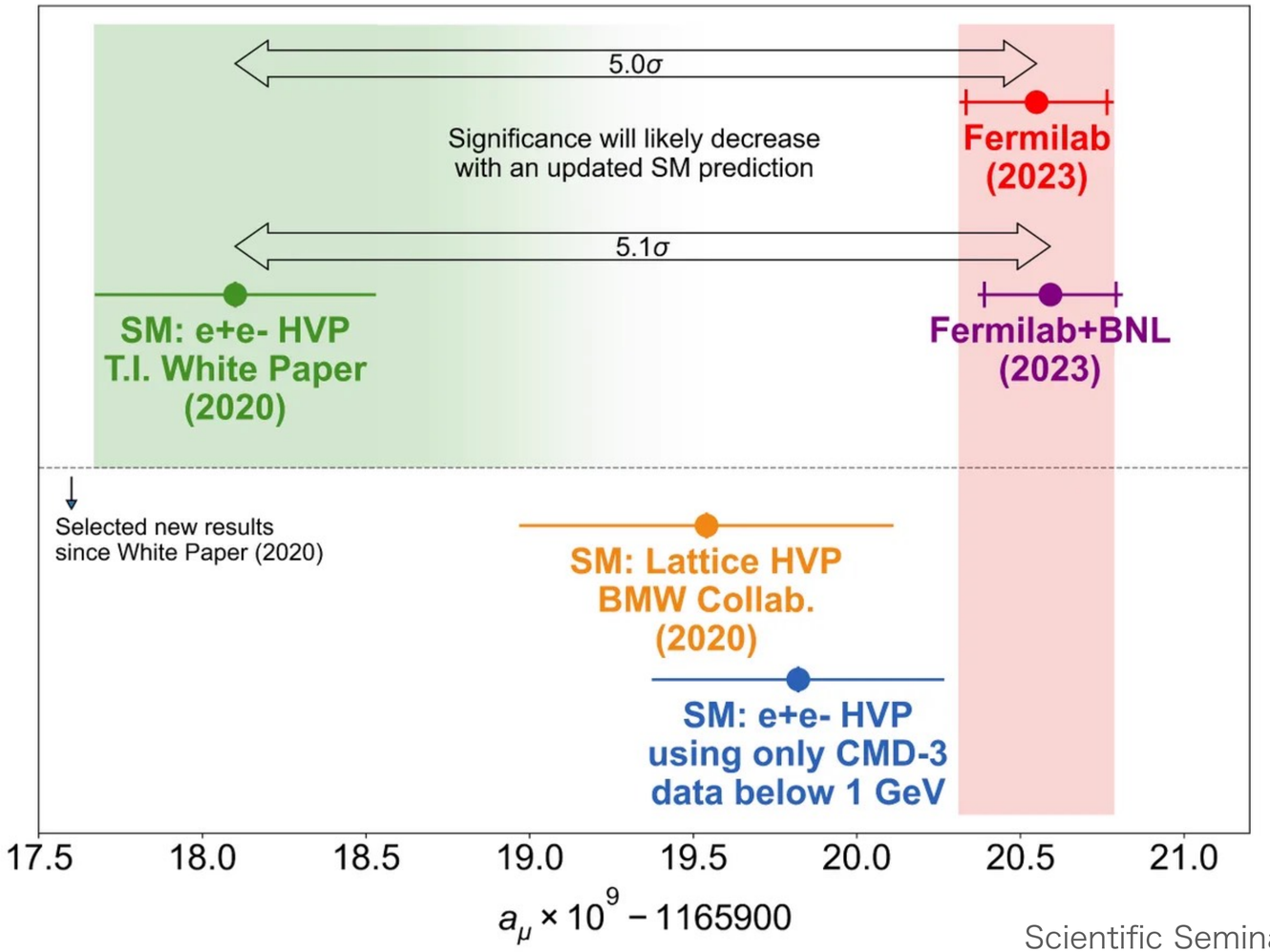

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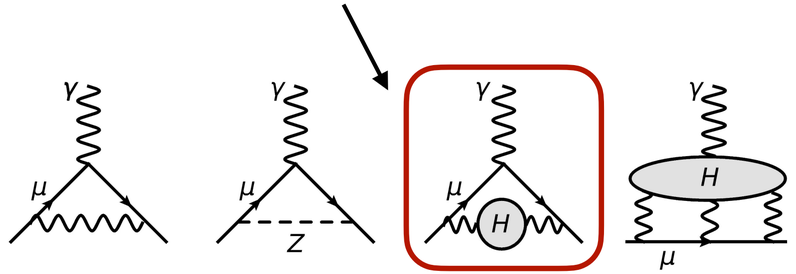
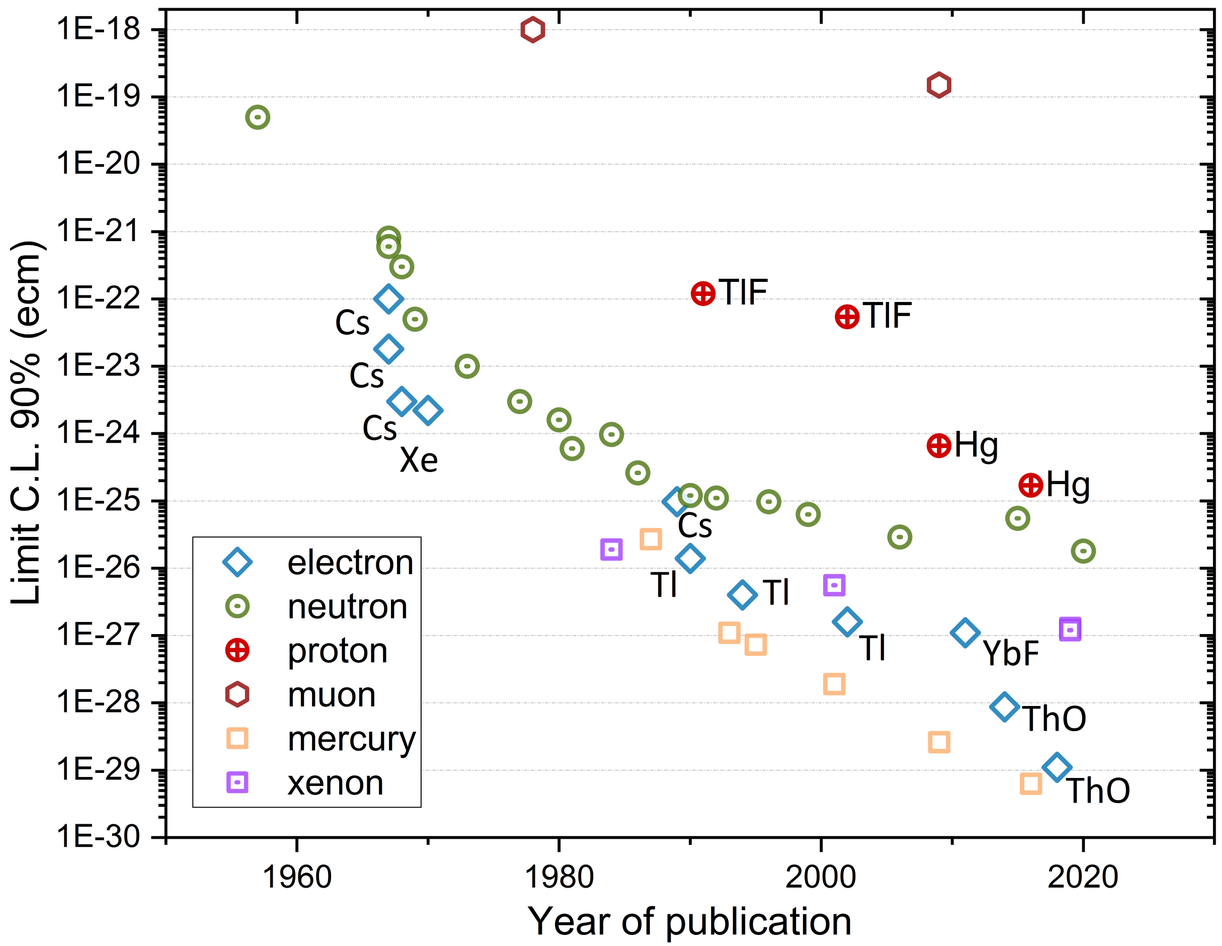
The calculation of HVP is different.



Phys. Rev. Lett. 126 (2021) 141801

Scientific Seminar: 2023 results from the Muon g-2 experiment at Fermilab

Muon, electron EDM experiment



arXiv:2102.08838 (2021)

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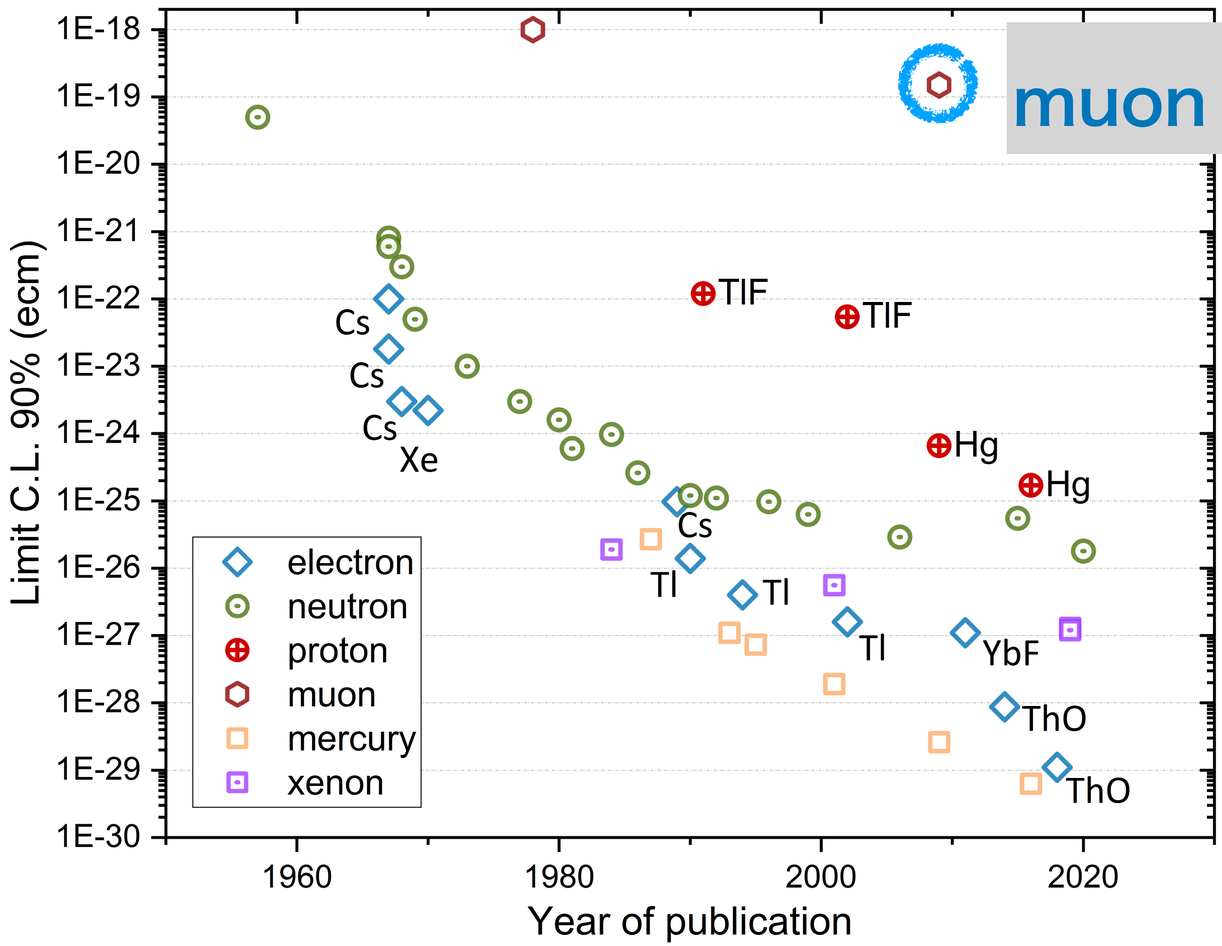

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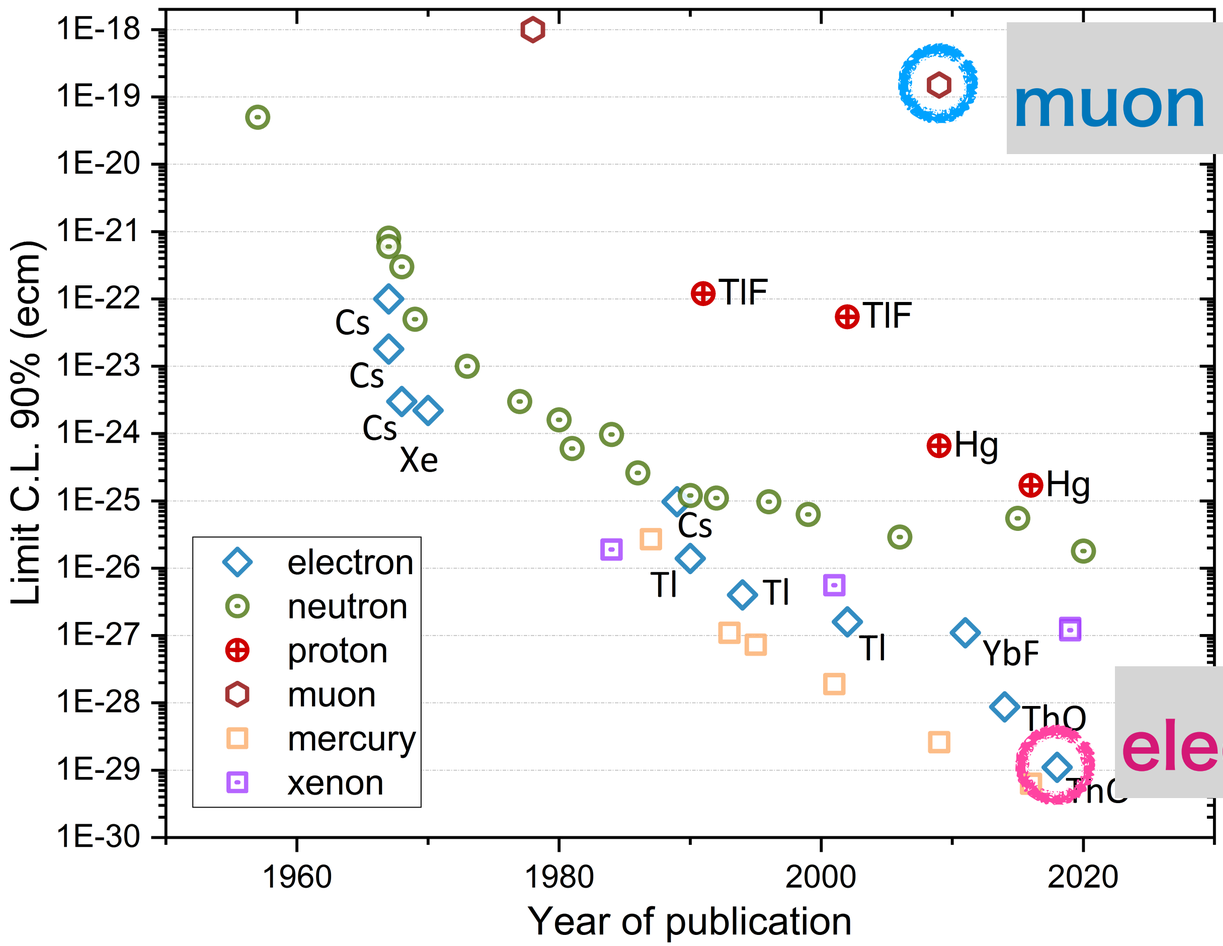

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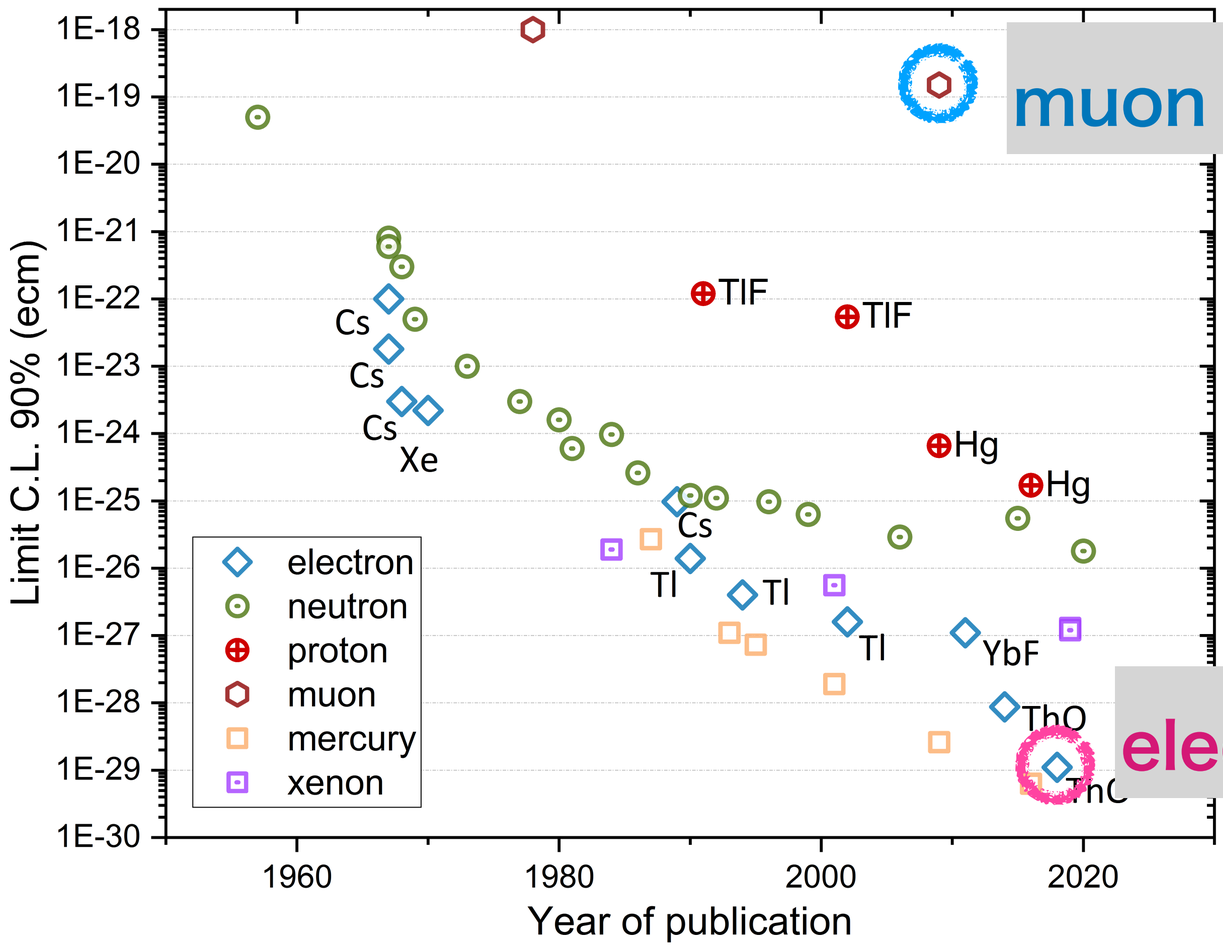

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updated!

$|d_\mu^{2022}| < 4.1 \times 10^{-30}\ e \cdot \mathrm{cm}$

arXiv:2212.11841 (2022)

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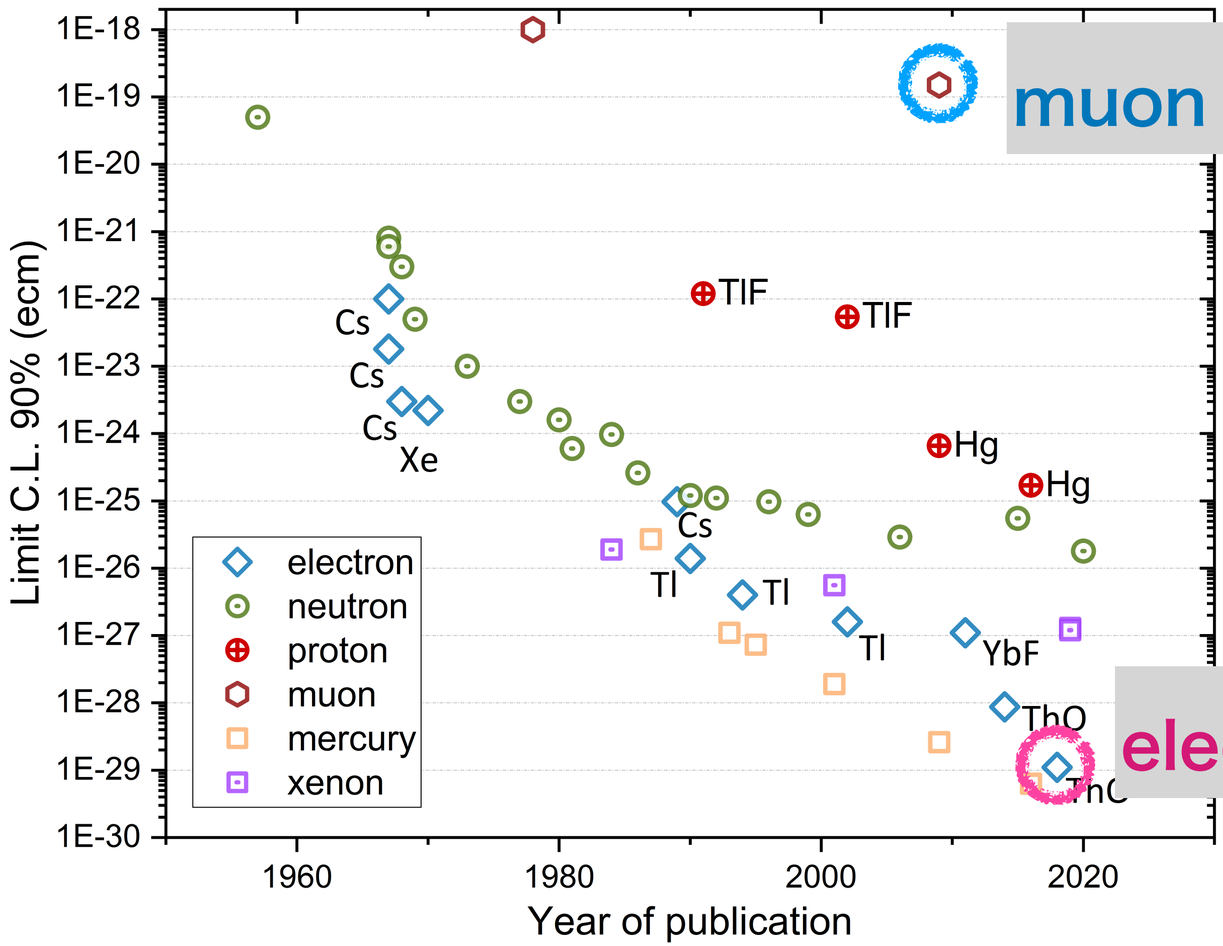

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$$d_{e,\mu}^{\mathrm{SM}} \leq 10^{-38,\,36}\ e \cdot \mathrm{cm}$$

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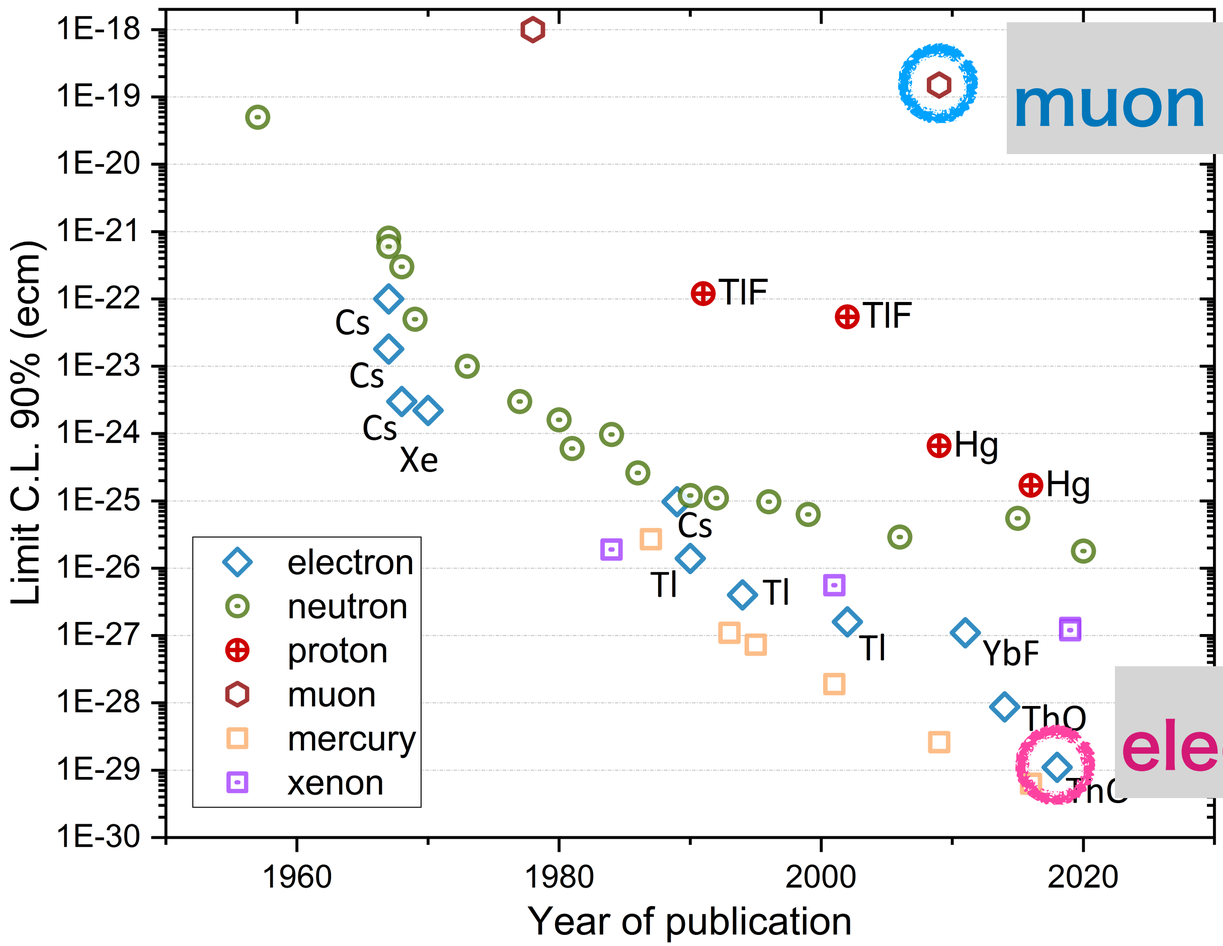

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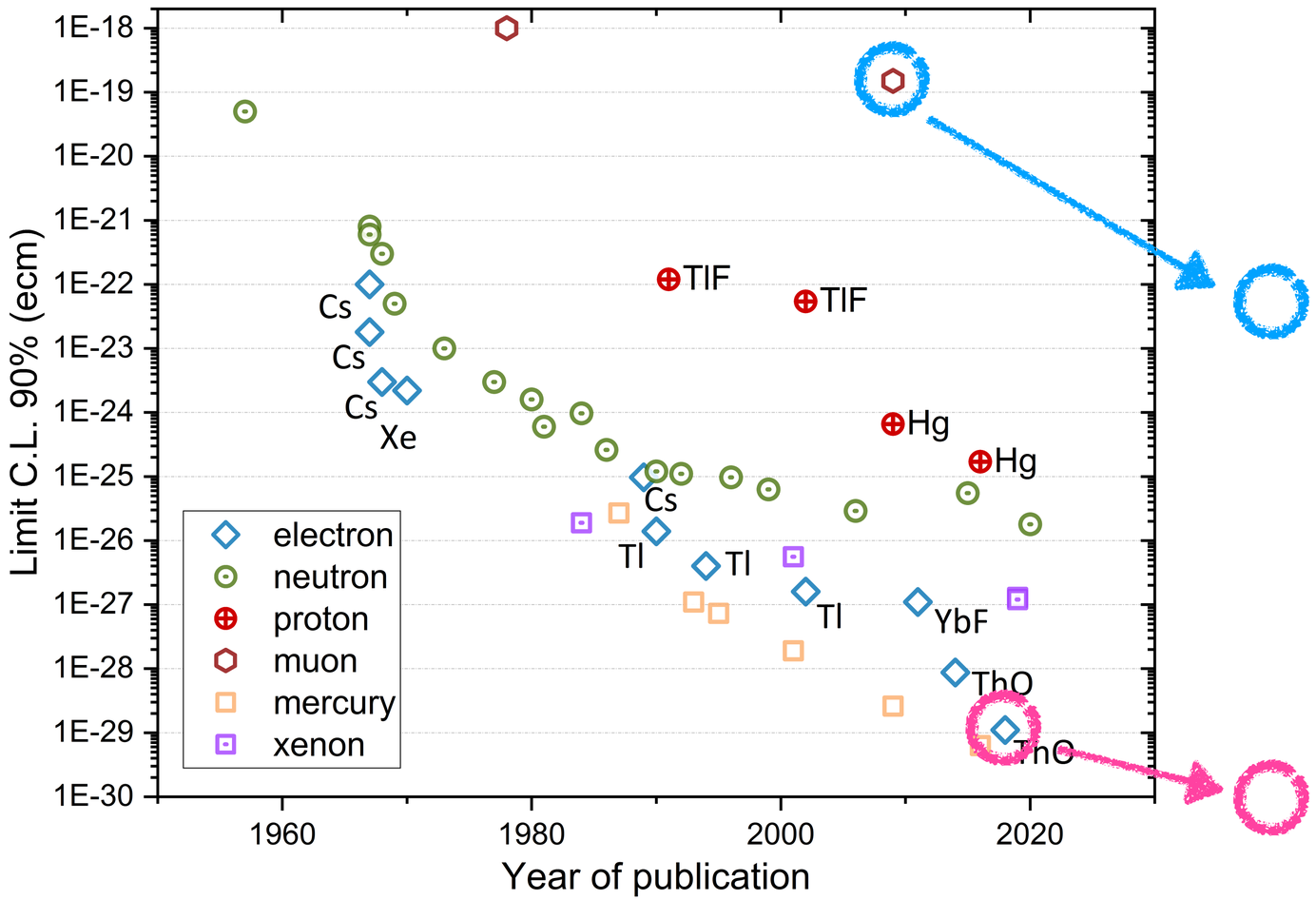
SM value is very very small …

arXiv:2102.08838 (2021)

Future experiment (~2030)



$$|d_\mu^{\mathrm{PSI}}| < 6 \times 10^{-23}\ e \cdot \mathrm{cm}$$

arXiv:2102.08838 (2021)

$$|d_e^{\mathrm{future}}| < 1 \times 10^{-30}\ e \cdot \mathrm{cm}$$

arXiv:2203.08103 (2022)

arXiv:2102.08838 (2021)

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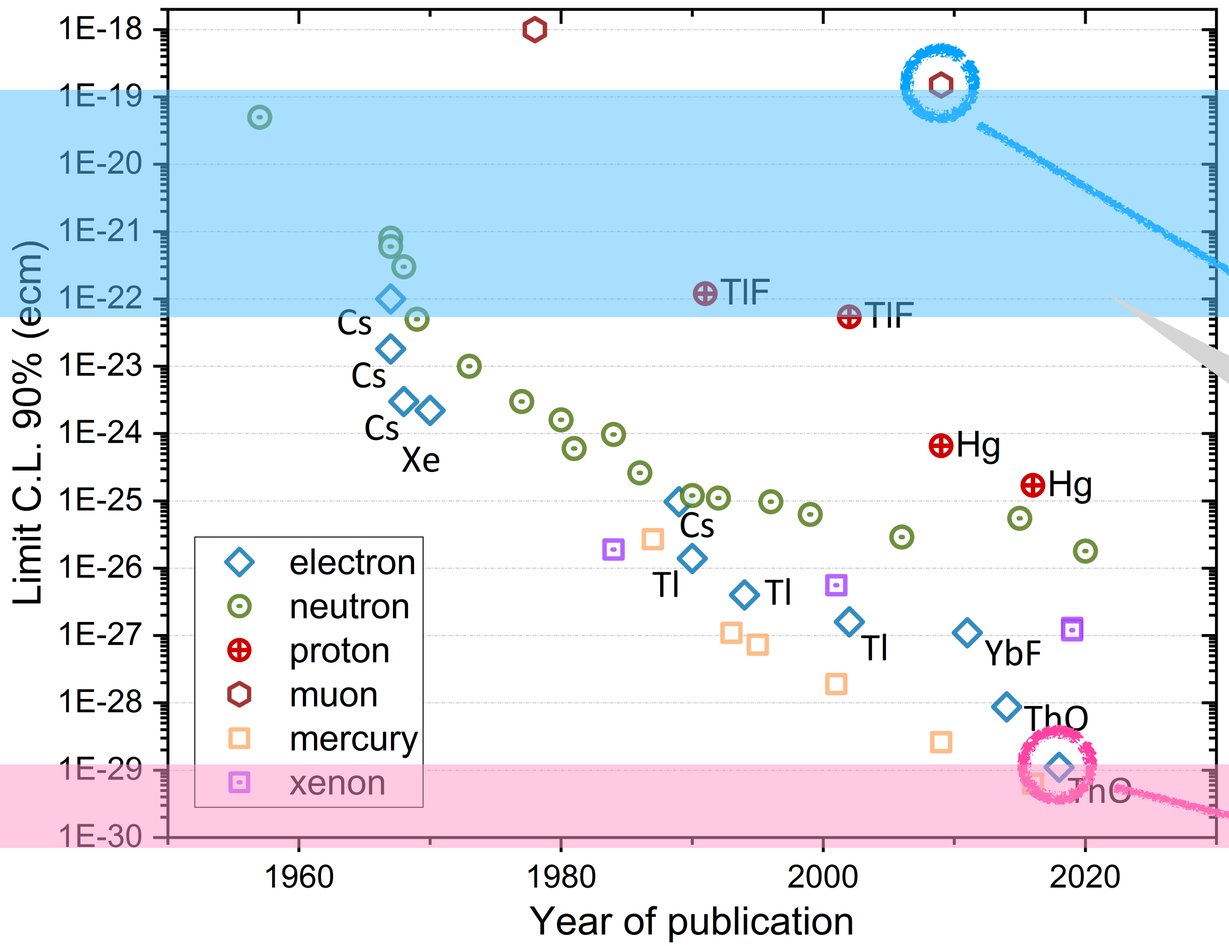

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if you find in this region…

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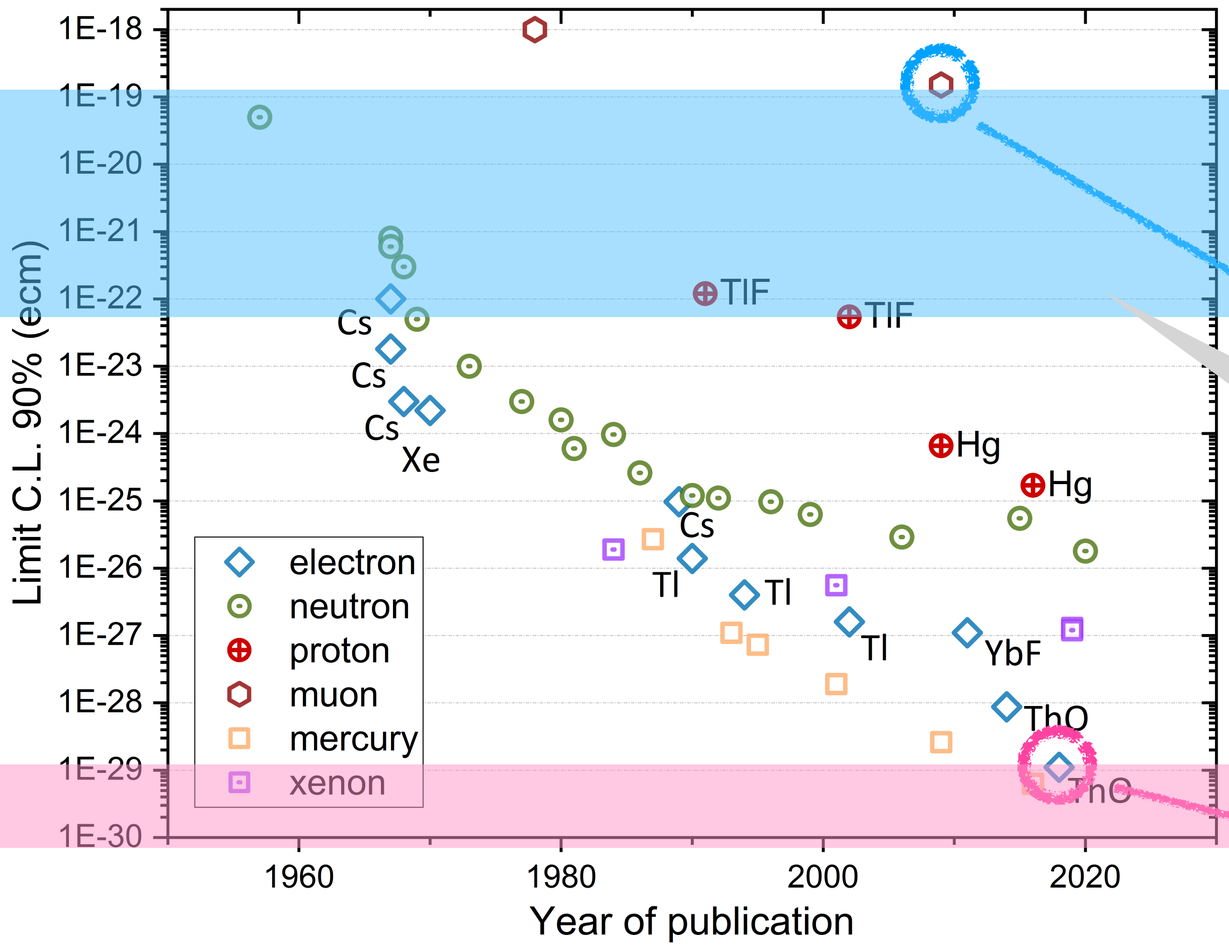

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if you find in this region…

→ **New physics!?**

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arXiv:2203.08103 (2022)

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Vector-like leptons

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$-\frac{1}{2}$	-1

表 4.1　Vector-like Leptons の変換性

$$\begin{aligned}\mathcal{L} \supset & -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$-\frac{1}{2}$	-1

表 4.1　Vector-like Leptons の変換性

$$\begin{aligned}\mathcal{L} \supset & -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**
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表 4.1　Vector-like Leptons の変換性

Vector-like leptons

$$\begin{aligned}\mathcal{L} \supset & -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
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表 4.1　Vector-like Leptons の変換性

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修士論文 表4.1

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
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表 4.1　Vector-like Leptons の変換性

Vector-like leptons

=

gauge transformations for L/R are equivalent

$$\mathcal{L} \supset -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

修士論文 表4.1

Lagrangian

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
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表 4.1　Vector-like Leptons の変換性

Vector-like leptons

=

gauge transformations for L/R are equivalent

couples to 2nd leptons

$$\mathcal{L} \supset -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \tag{4.1}$$

修士論文 表4.1

CP-violating phase

	ℓ_L	μ_R	H	$L_{L,R}$	$E_{L,R}$
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$-\frac{1}{2}$	-1

表 4.1　Vector-like Leptons の変換性

There are two CP phases (independent of phase transition)

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$

$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$$\begin{aligned}\mathcal{L} \supset & - y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

CP-violating phase

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$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$

$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

CP violation → **origin of EDM**

$$\begin{aligned}\mathcal{L} \supset & - y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

CP-violating phase

ex. $E_R \to e^{i\theta} E_R$

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$$\begin{aligned}\mathcal{L} \supset & - y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}\end{aligned} \tag{4.1}$$

修士論文 表4.1

CP-violating phase

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$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$e^{i\theta} E_R$ $e^{i\theta} E_R$ $e^{i\theta} E_R$

$$\mathcal{L} \supset - y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

修士論文 表4.1

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$e^{i\theta} E_R$ $e^{i\theta} E_R$ $e^{i\theta} E_R$

修士論文 表4.1

CP-violating phase

ex. $E_R \to e^{i\theta} E_R$

$\lambda_E \to e^{i\theta}\lambda_E,\ \lambda \to e^{i\theta}\lambda,\ M_E \to e^{i\theta} M_E$

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$$\mathcal{L} \supset - y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

$e^{i\theta} E_R$ $e^{i\theta} E_R$ $e^{i\theta} E_R$

修士論文 表4.1

CP-violating phase

ex. $E_R \to e^{i\theta} E_R$

$\lambda_E \to e^{i\theta}\lambda_E,\ \lambda \to e^{i\theta}\lambda,\ M_E \to e^{i\theta} M_E$

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
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$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

$e^{i\theta}E_R$ $e^{i\theta}E_R$ $e^{i\theta}E_R$

修士論文 表4.1

CP-violating phase

ex. $E_R \to e^{i\theta} E_R$

$\lambda_E \to e^{i\theta}\lambda_E,\ \lambda \to e^{i\theta}\lambda,\ M_E \to e^{i\theta} M_E$

$\phi_\lambda \to \phi_\lambda,\ \phi_{\bar{\lambda}} \to \phi_{\bar{\lambda}}$

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$$\mathcal{L} \supset -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

$e^{i\theta}E_R$ $e^{i\theta}E_R$ $e^{i\theta}E_R$

修士論文 表4.1

CP-violating phase

ex. $E_R \to e^{i\theta} E_R$

$\lambda_E \to e^{i\theta}\lambda_E,\ \lambda \to e^{i\theta}\lambda,\ M_E \to e^{i\theta} M_E$

$\phi_\lambda \to \phi_\lambda,\ \phi_{\bar{\lambda}} \to \phi_{\bar{\lambda}}$

independent of phase transition!

$$\phi_\lambda = \arg(y_\mu \lambda_L^* \lambda_E^* \lambda)$$
$$\phi_{\bar{\lambda}} = \arg(y_\mu \lambda_L^* \lambda_E^* M_L M_E \bar{\lambda}^*)$$

$$\mathcal{L} \supset -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \qquad (4.1)$$

$e^{i\theta}E_R$ $e^{i\theta}E_R$ $e^{i\theta}E_R$

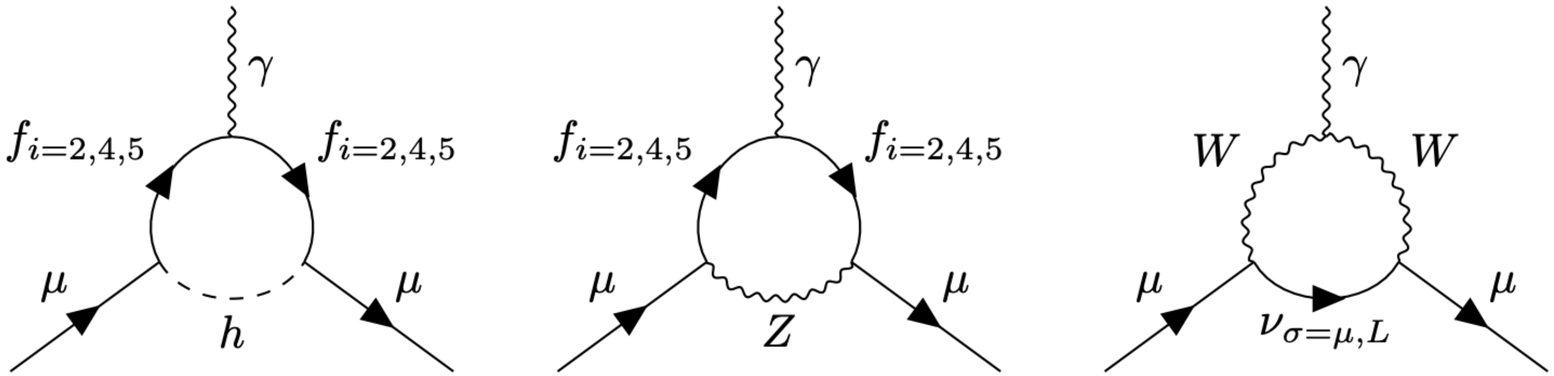
修士論文 表4.1

Method

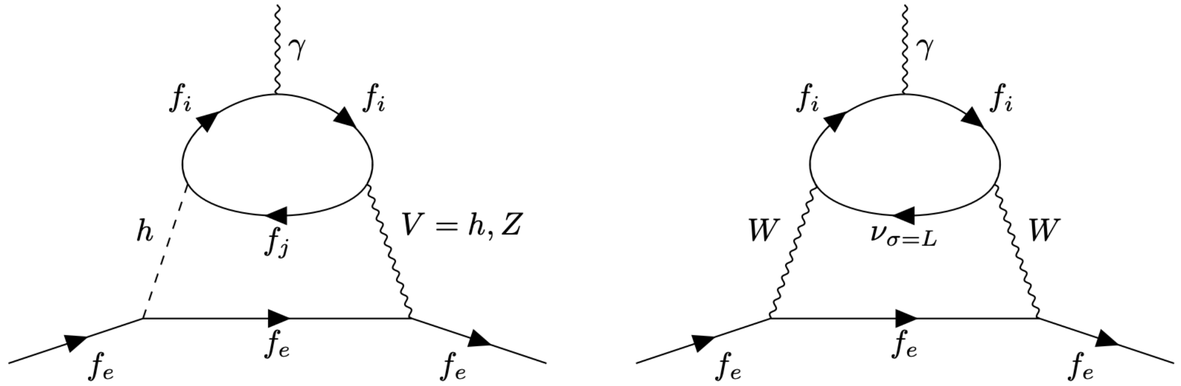
K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

Calculation of diagrams

muon g-2/EDM
(one loop)



electron EDM
(two loop)



修士論文 図4.1, 4.2

Generating sample points

$$\mathcal{L} \supset -y_\mu \bar{\ell}_L \mu_R H - \lambda_E \bar{\ell}_L E_R H - \lambda_L \bar{L}_L \mu_R H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.} \tag{4.1}$$

パラメータ	範囲
M_L, M_E	$1 - 5$ TeV
$\lvert\lambda_L\rvert, \lvert\lambda_E\rvert$	式 (4.56)
$\lvert\lambda\rvert, \lvert\bar{\lambda}\rvert$	$0 - 1$
$\phi_\lambda, \phi_{\bar{\lambda}}$	$0 - 2\pi$
y_μ	$m_{i=2} = m_\mu$ の解

表 4.3　サンプル点をランダムに生成する際のパラメータ範囲

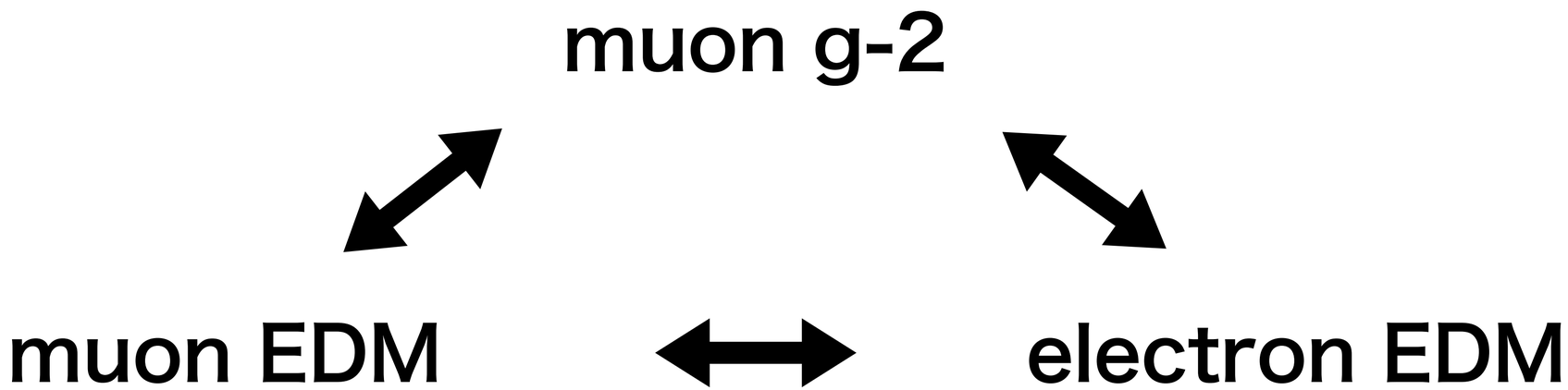
experimental restrictions

- $R(h \to \mu^+\mu^-)$
- Electroweak precision
- g-2/EDM experiments

修士論文 表4.3

Making scatter plot

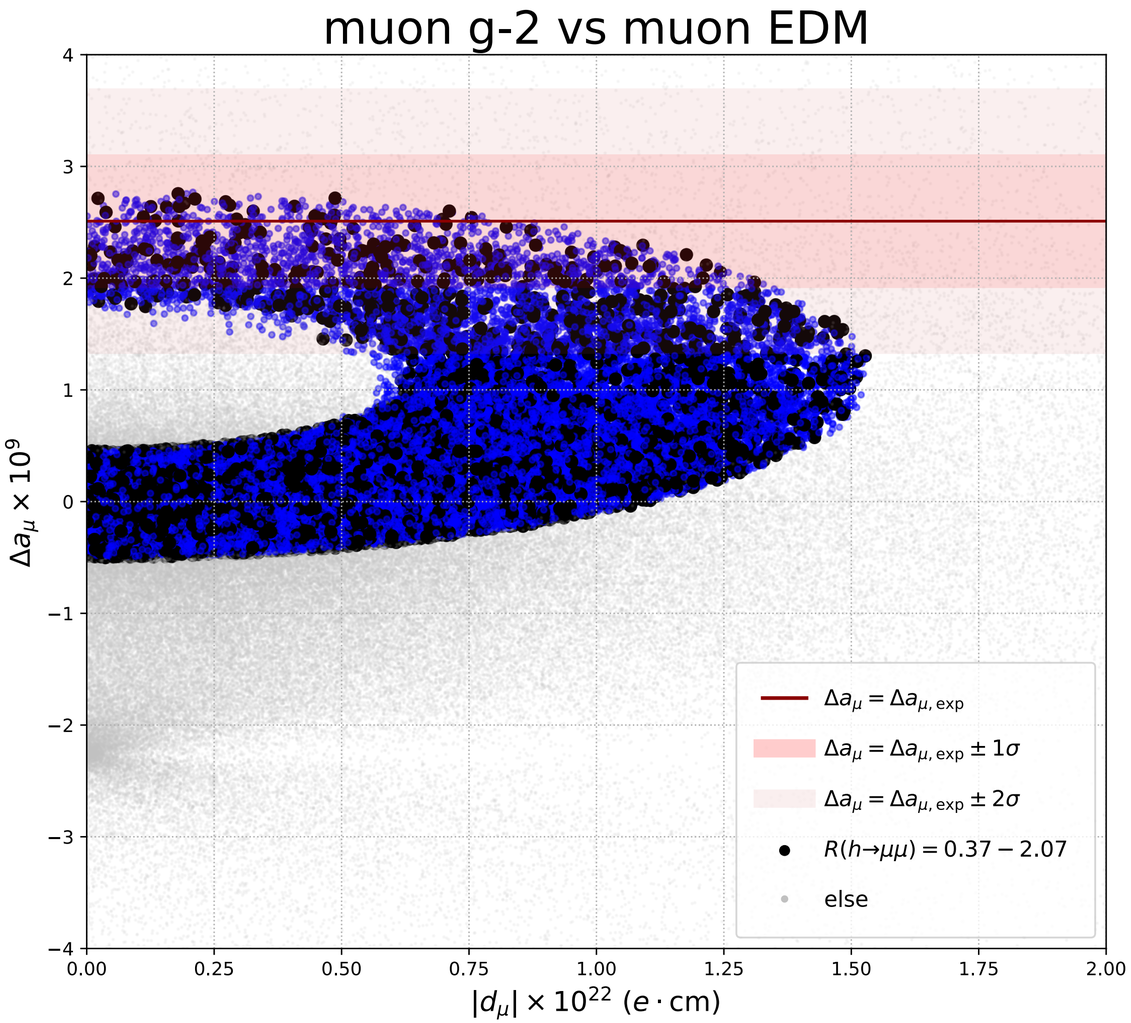
3 scatter plots for these pairs



Result

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

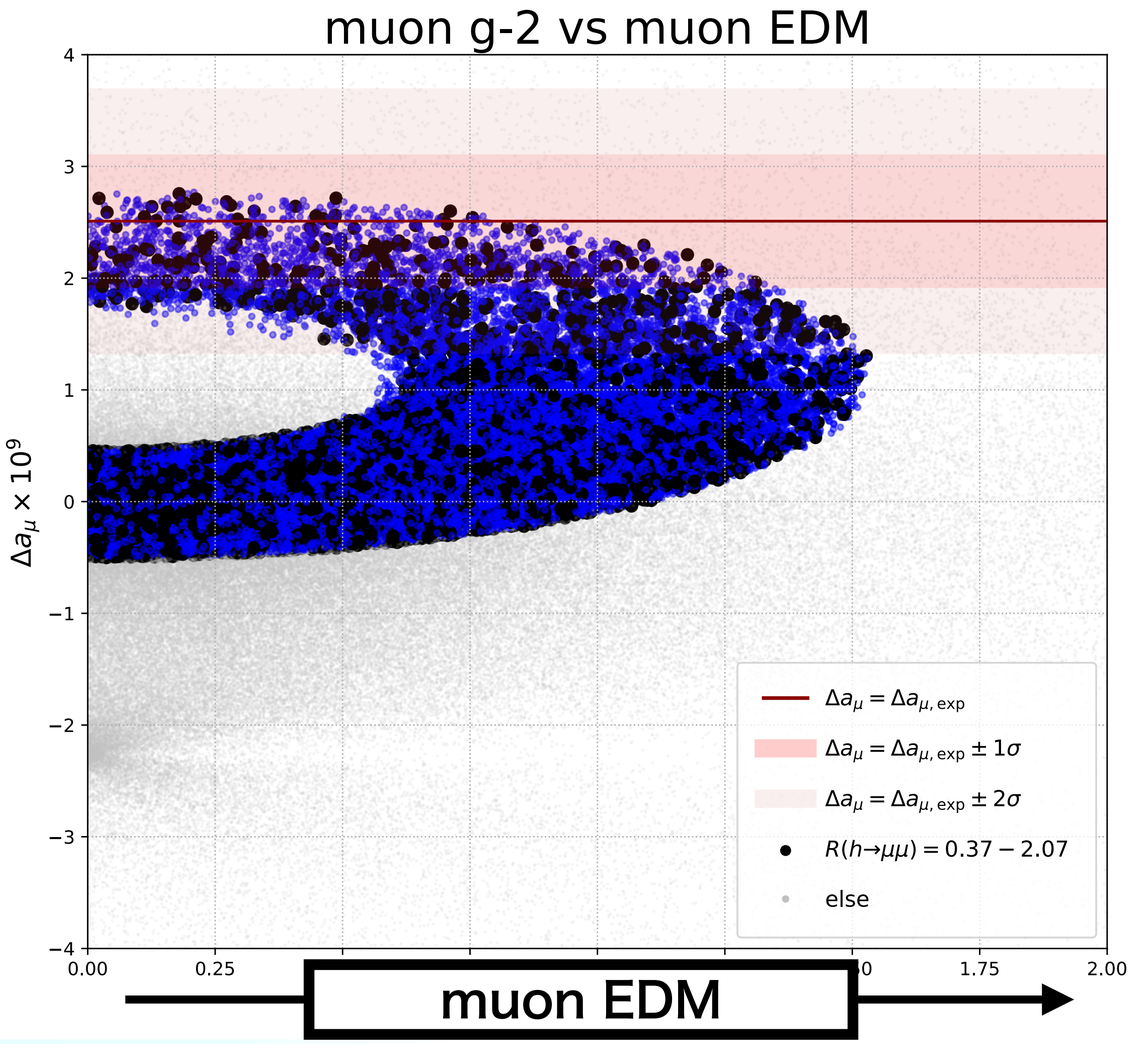
muon g-2 vs muon EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (左)

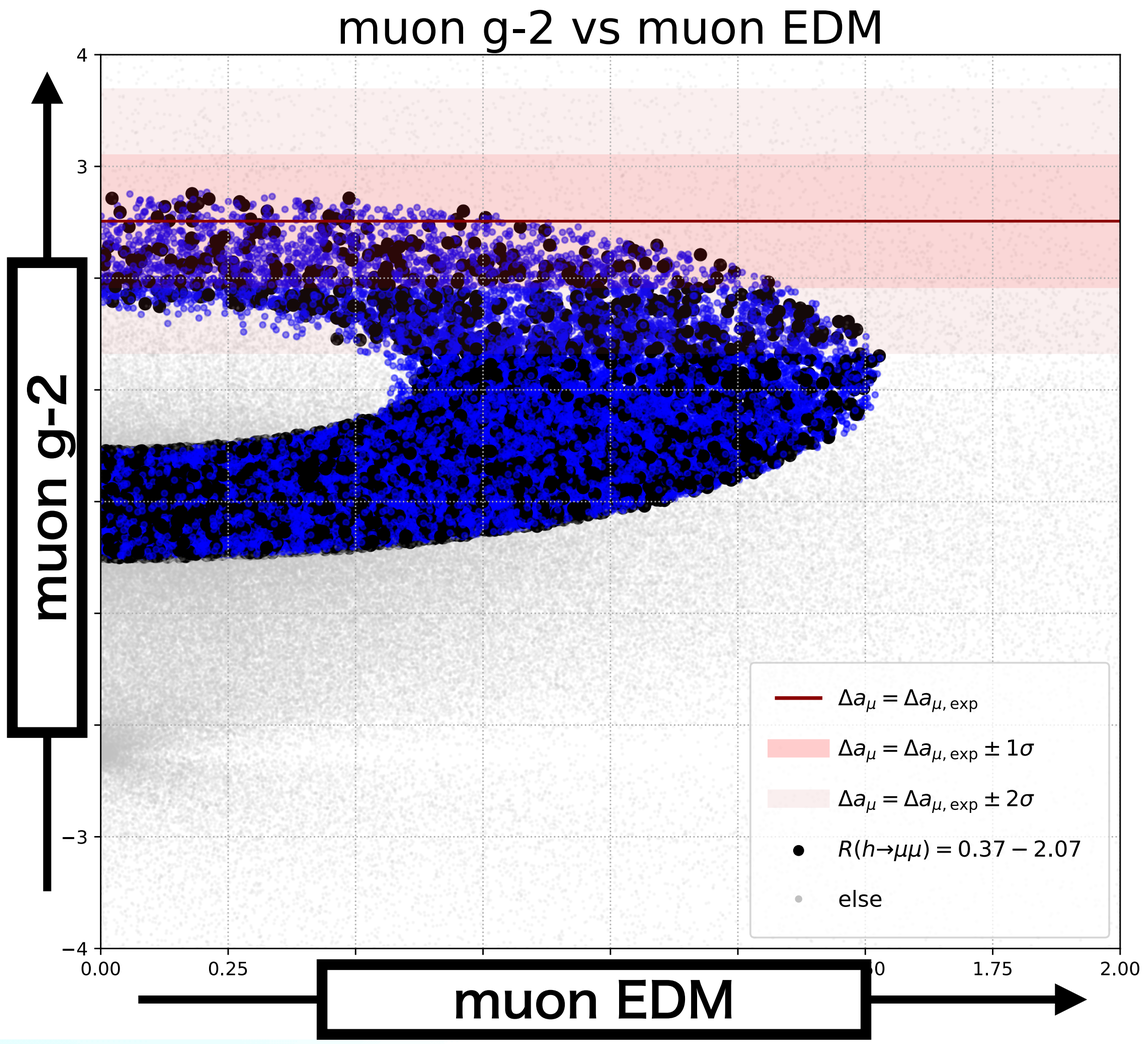
muon g-2 vs muon EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (左)

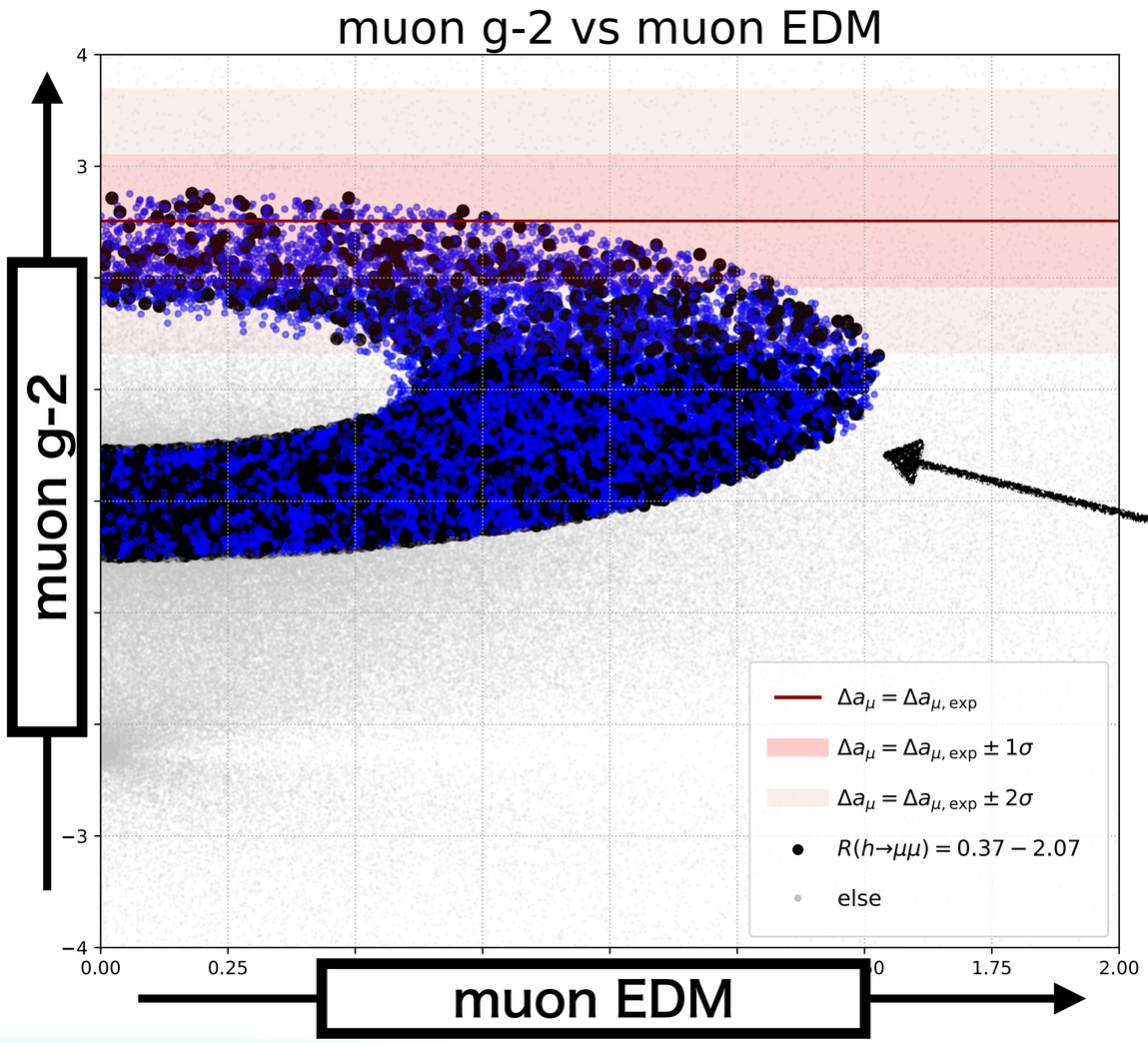
muon g-2 vs muon EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (左)

muon g-2 vs muon EDM

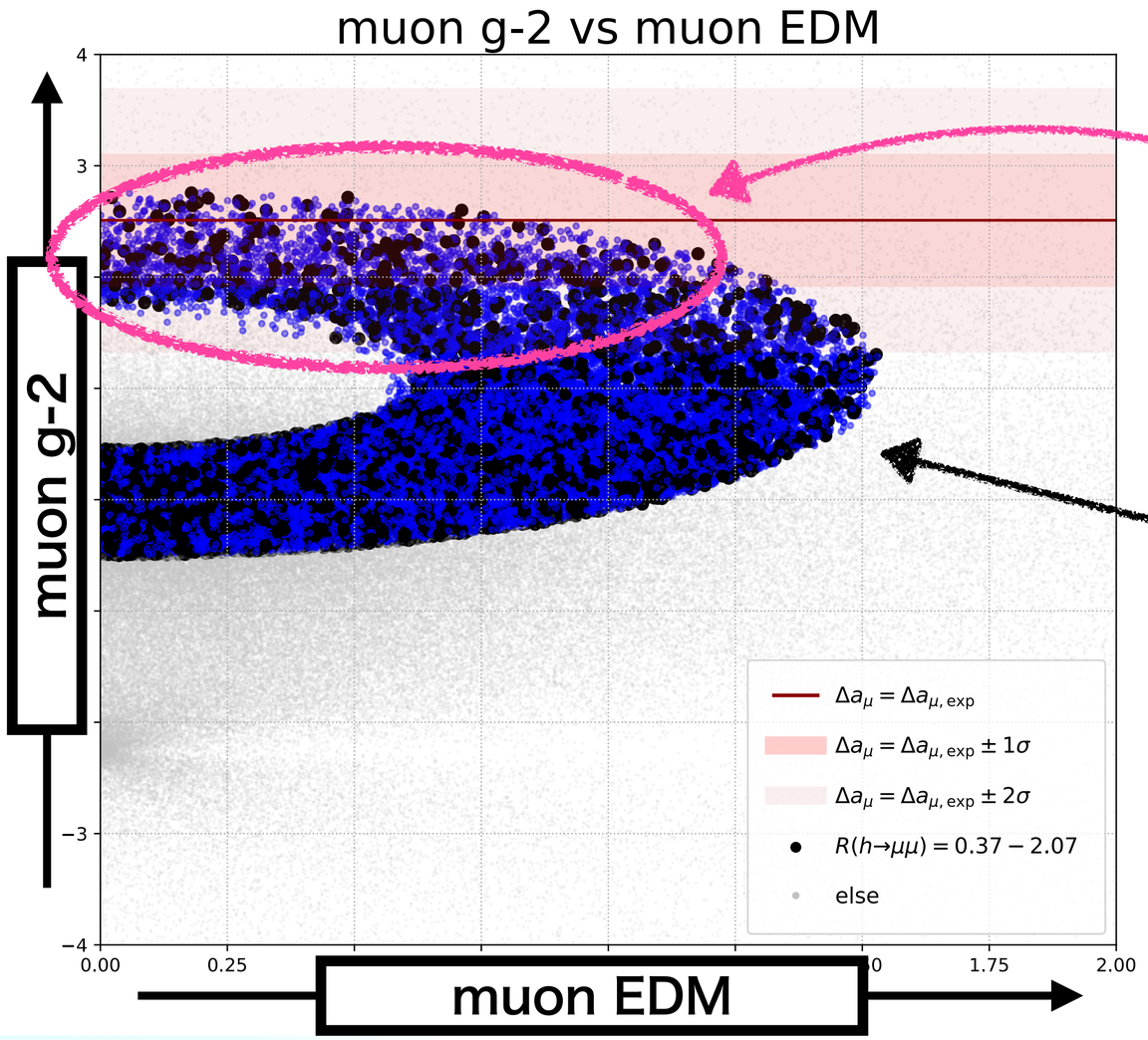


agree with $R(h \to \mu^+\mu^-)$

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (左)

muon g-2 vs muon EDM



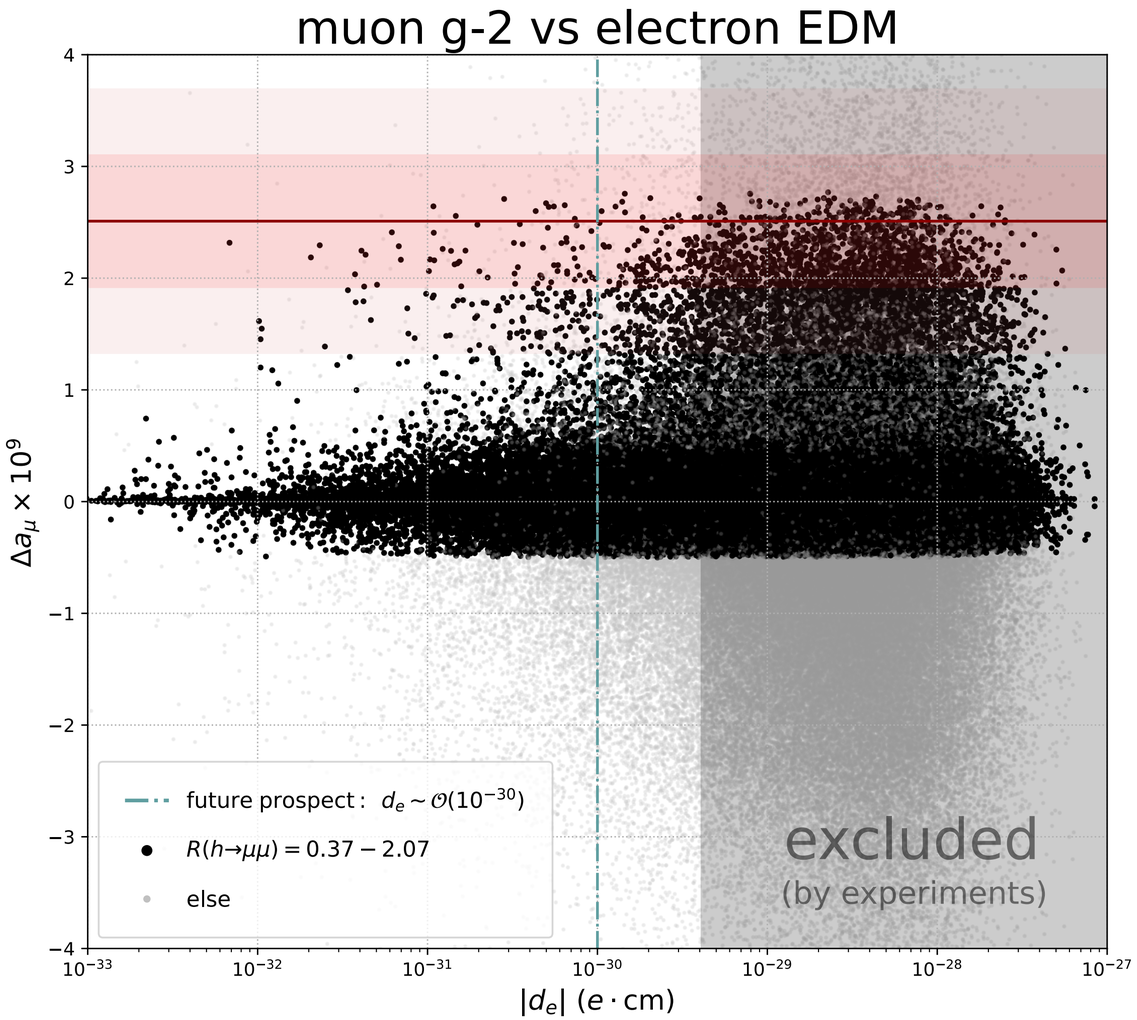
muon g-2 can be explained

agree with $R(h \to \mu^+\mu^-)$

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (左)

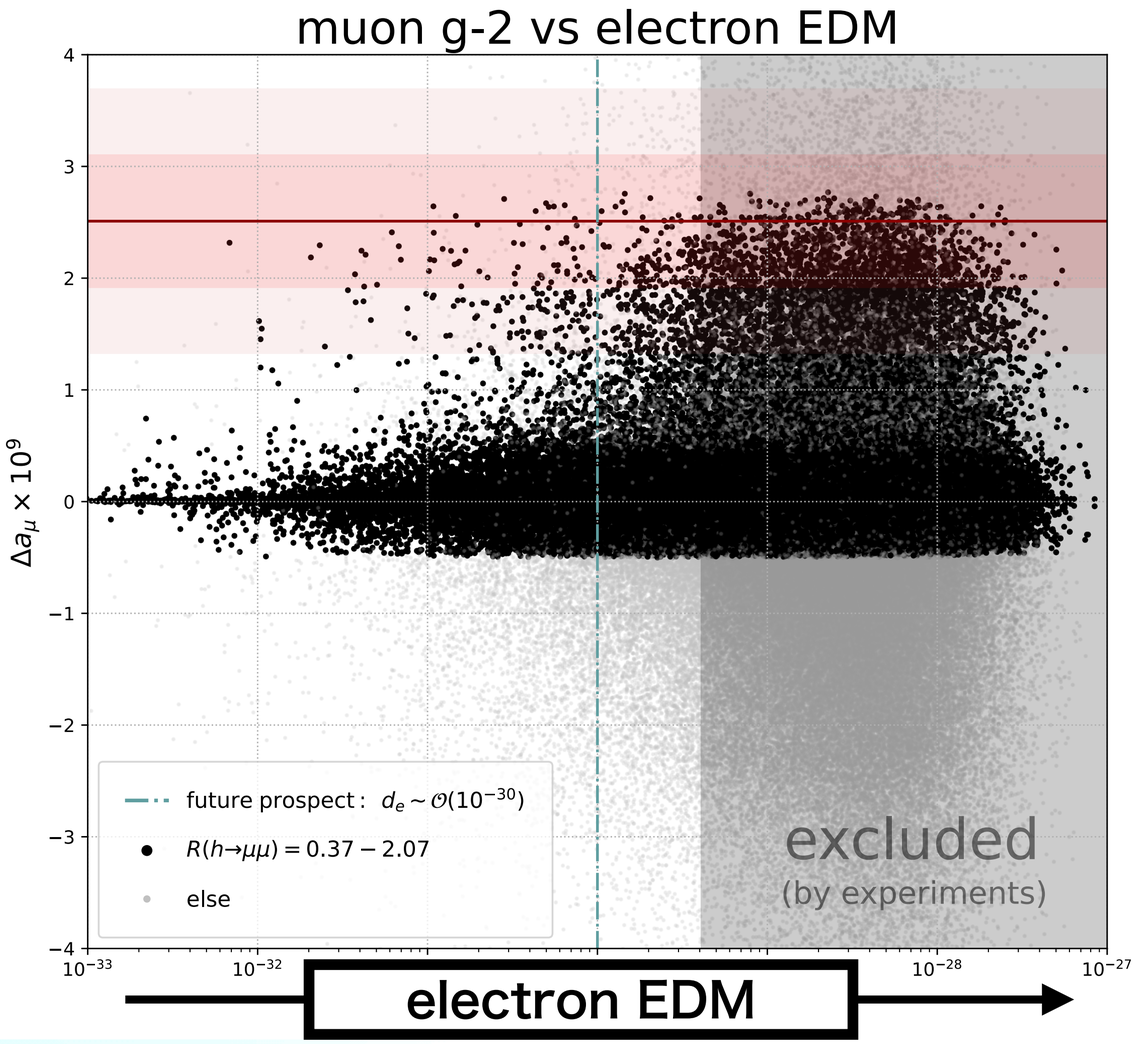
muon g-2 vs electron EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

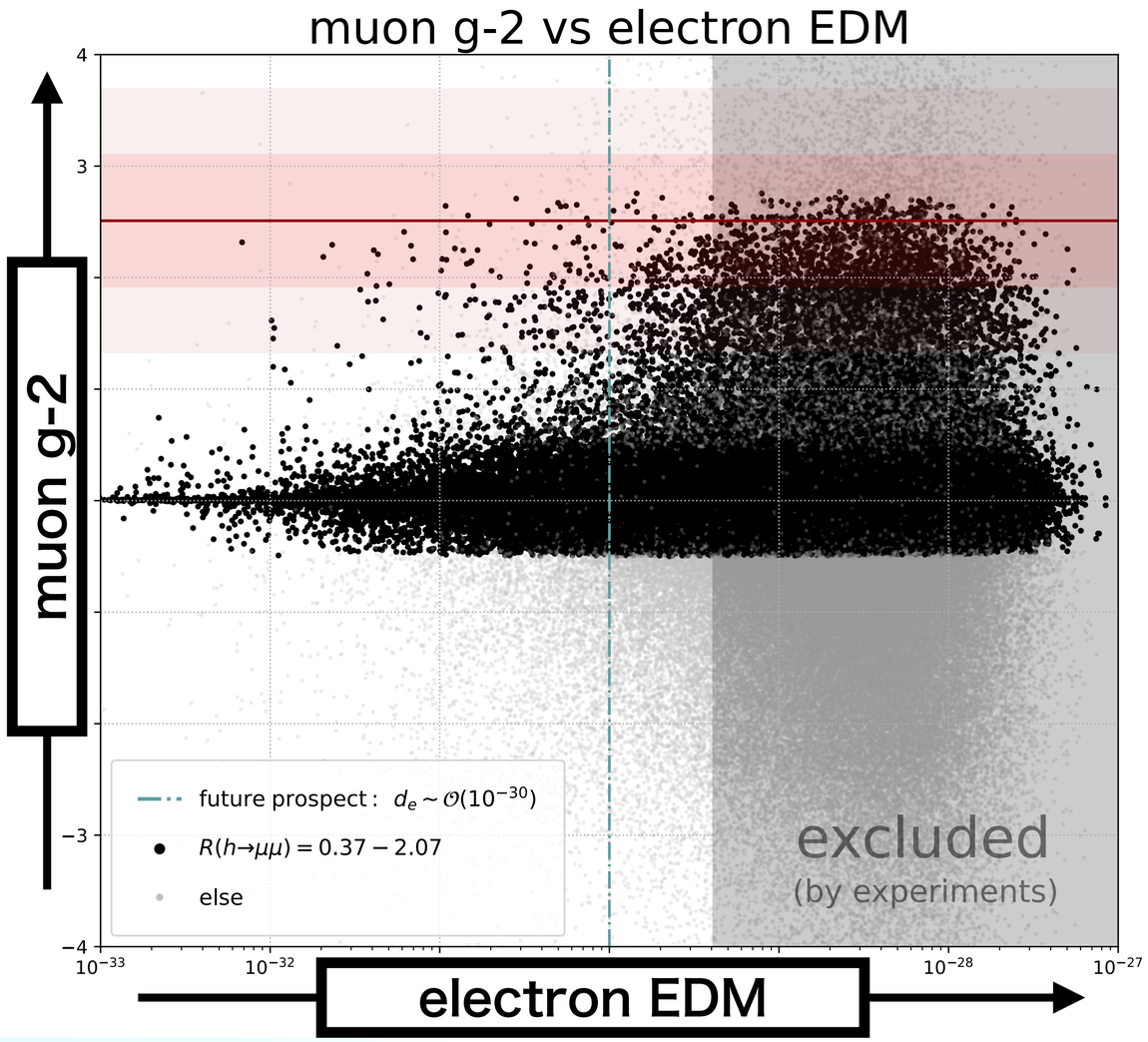
muon g-2 vs electron EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

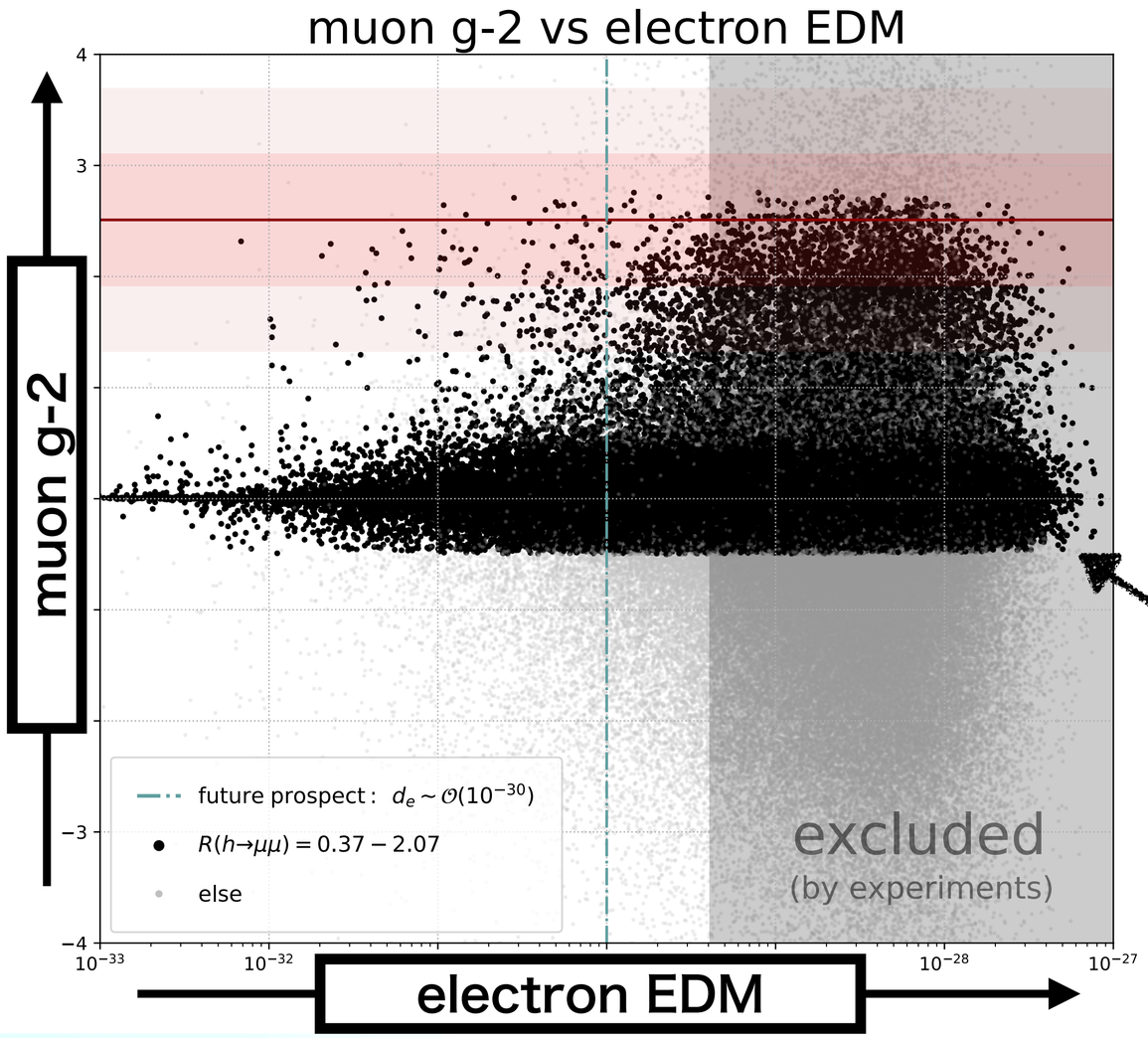
muon g-2 vs electron EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

muon g-2 vs electron EDM

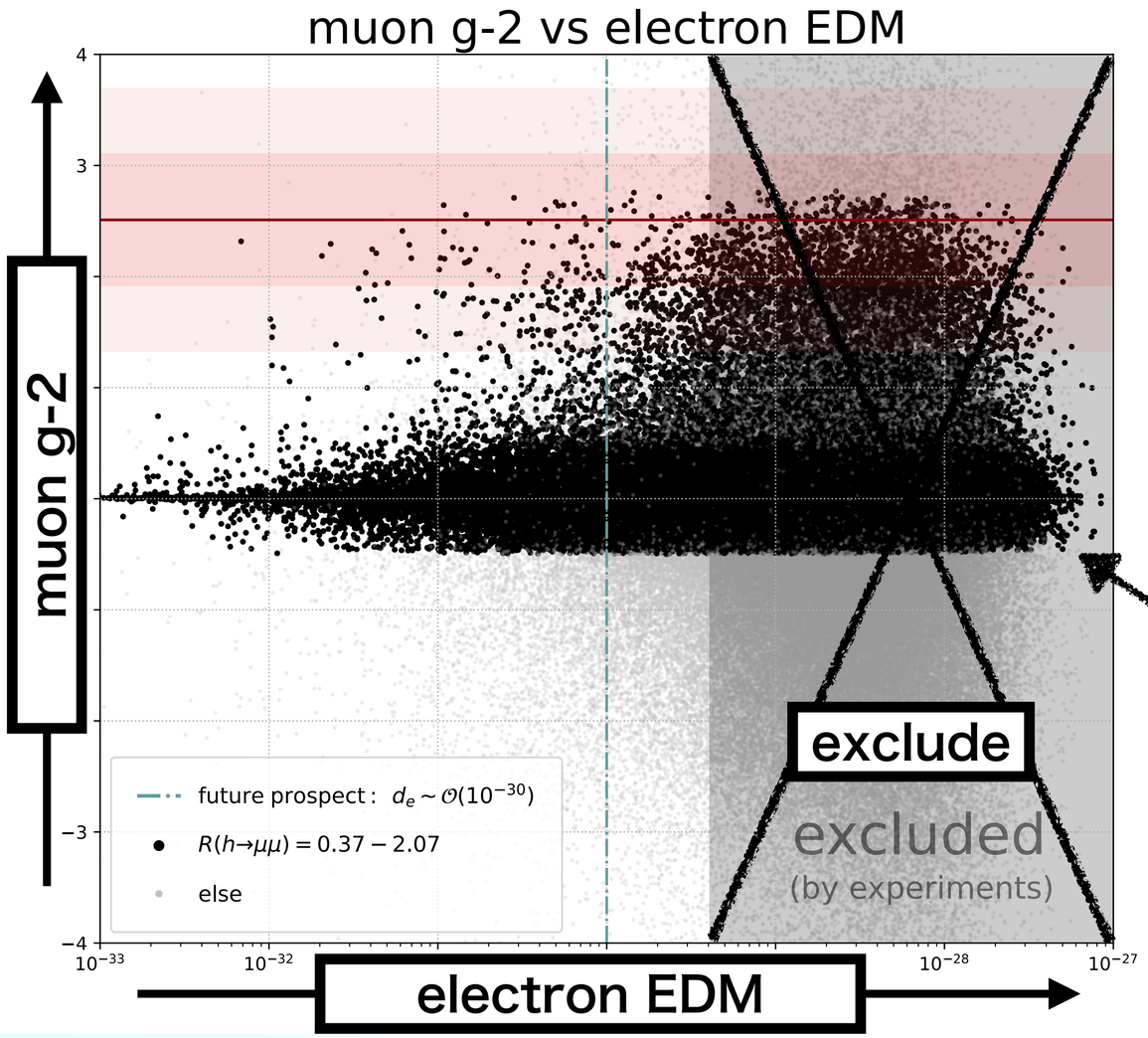


agree with $R(h \to \mu^+\mu^-)$

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

muon g-2 vs electron EDM

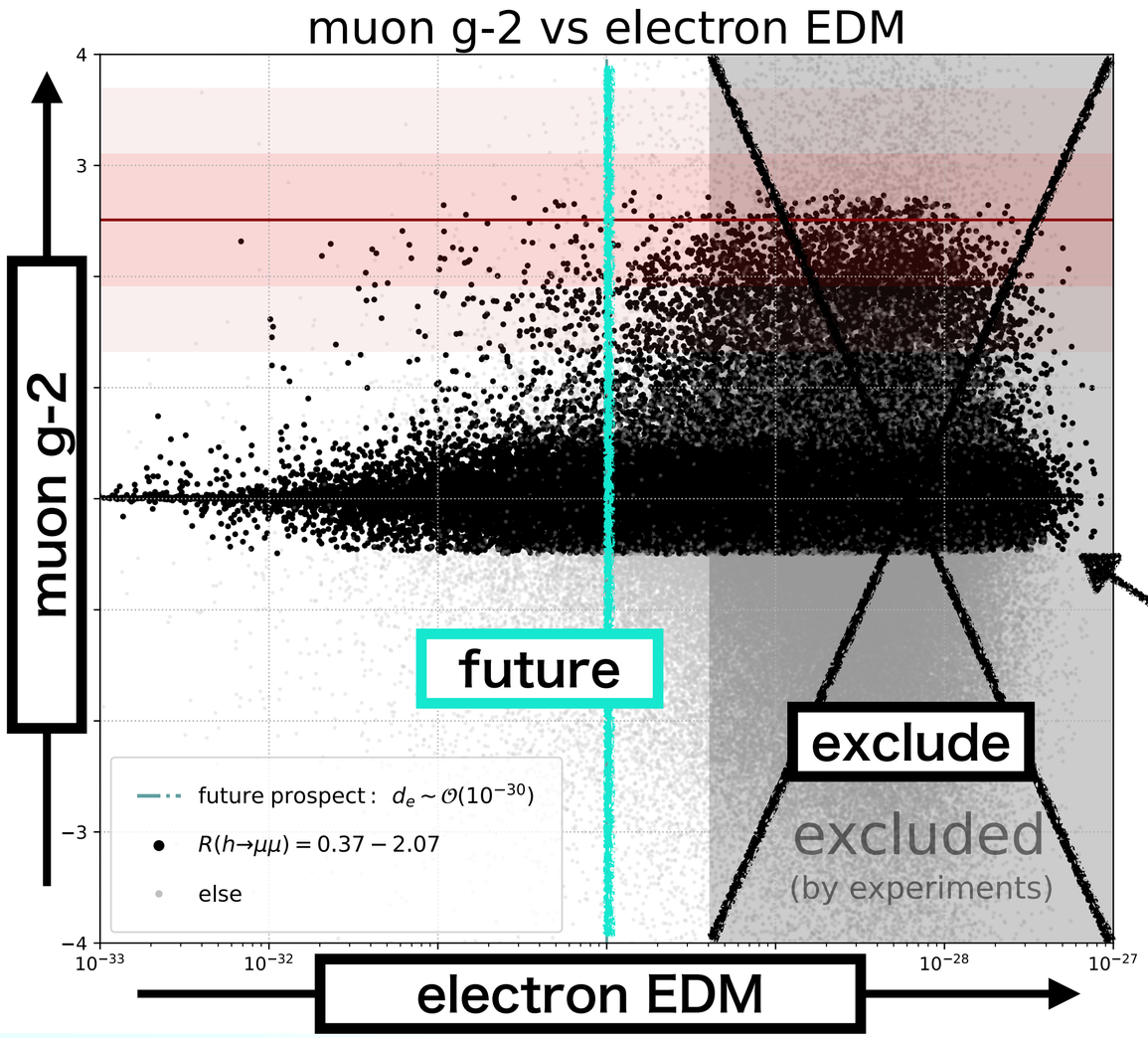


agree with $R(h \to \mu^+\mu^-)$

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

muon g-2 vs electron EDM



agree with $R(h \to \mu^+\mu^-)$

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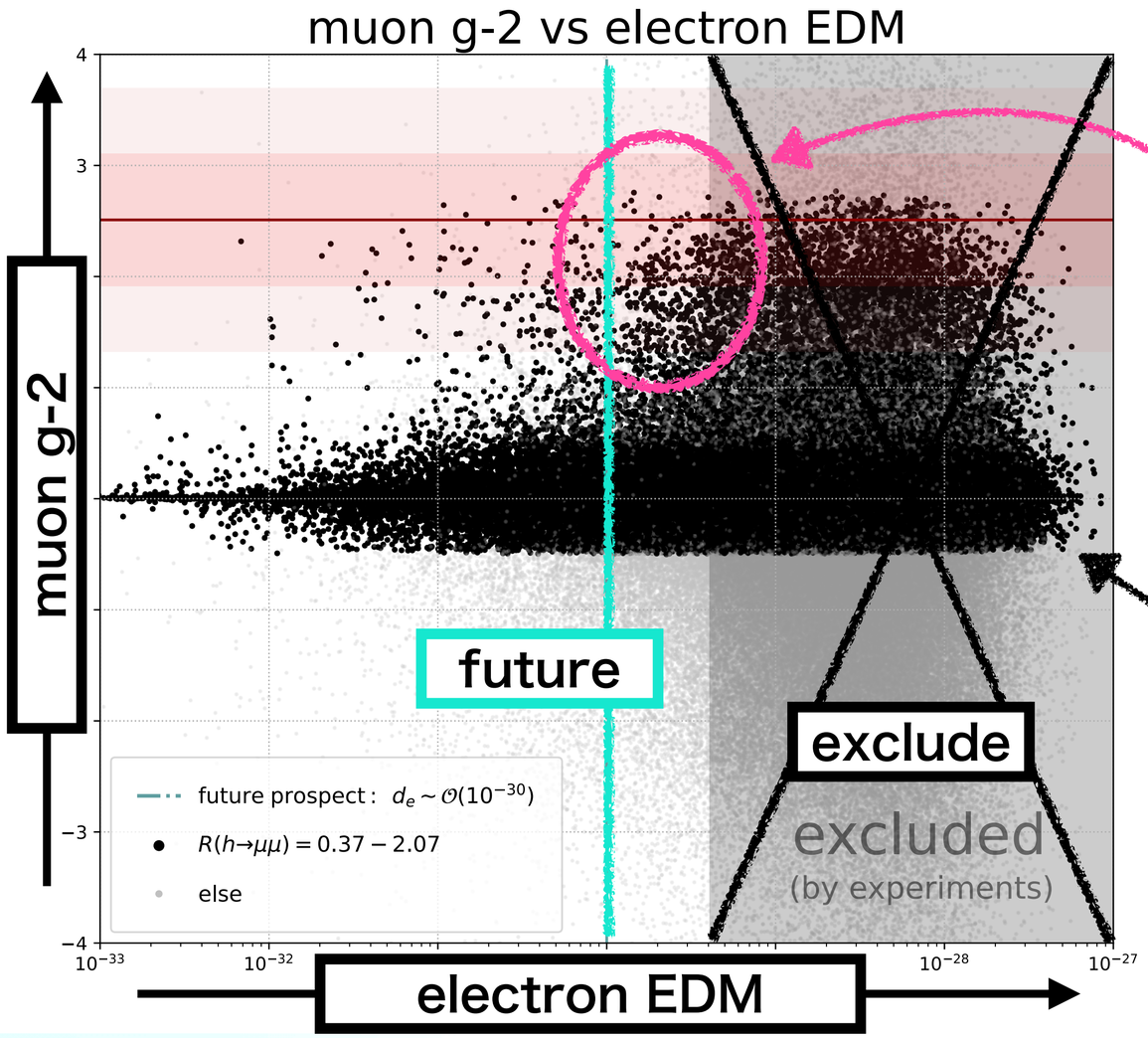
修士論文 図4.3 (右)

muon g-2 vs electron EDM



muon g-2 can be explained

&

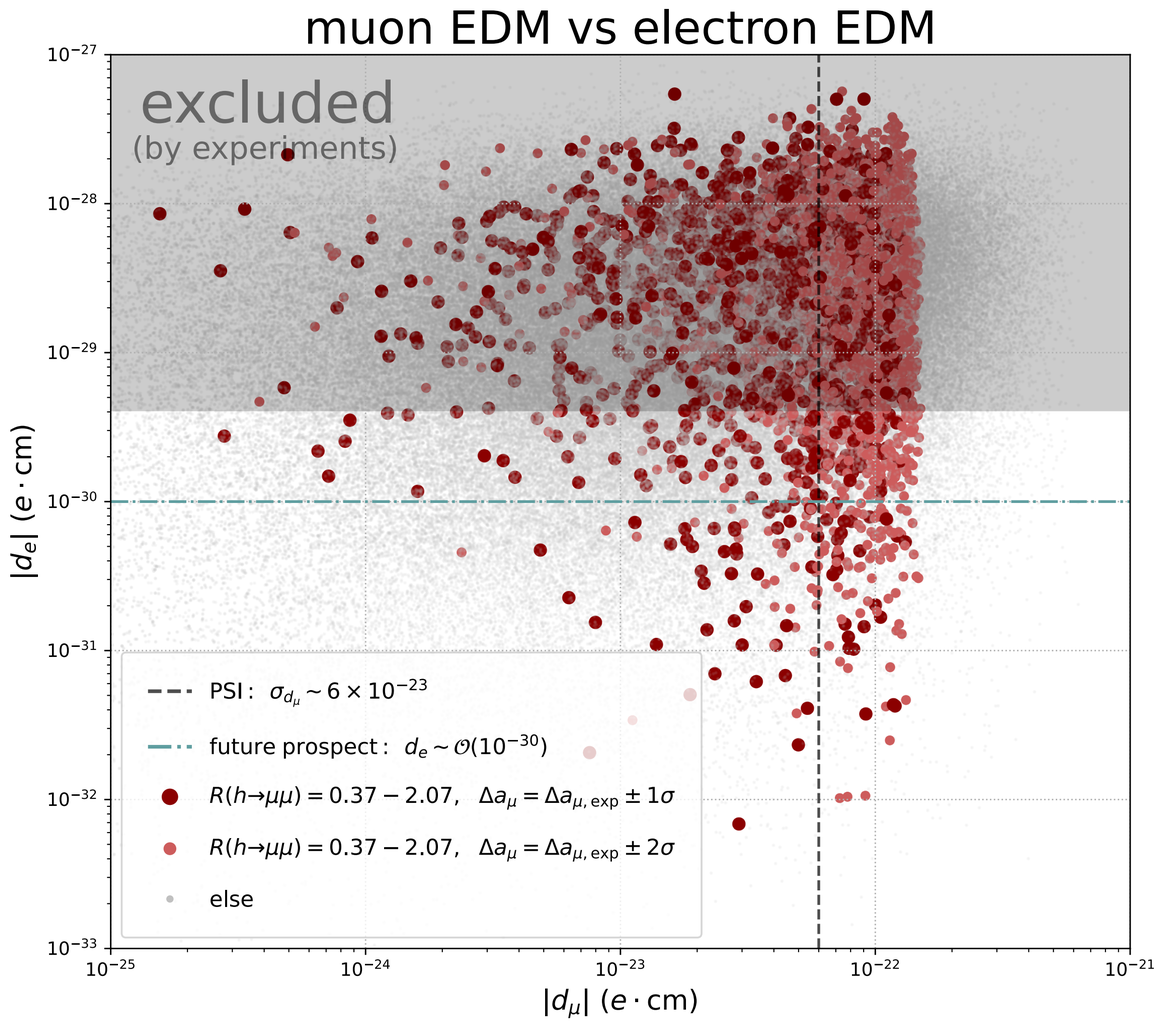
electron EDM will be found by future experiments

agree with $R(h \to \mu^+\mu^-)$

K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.3 (右)

muon EDM vs electron EDM



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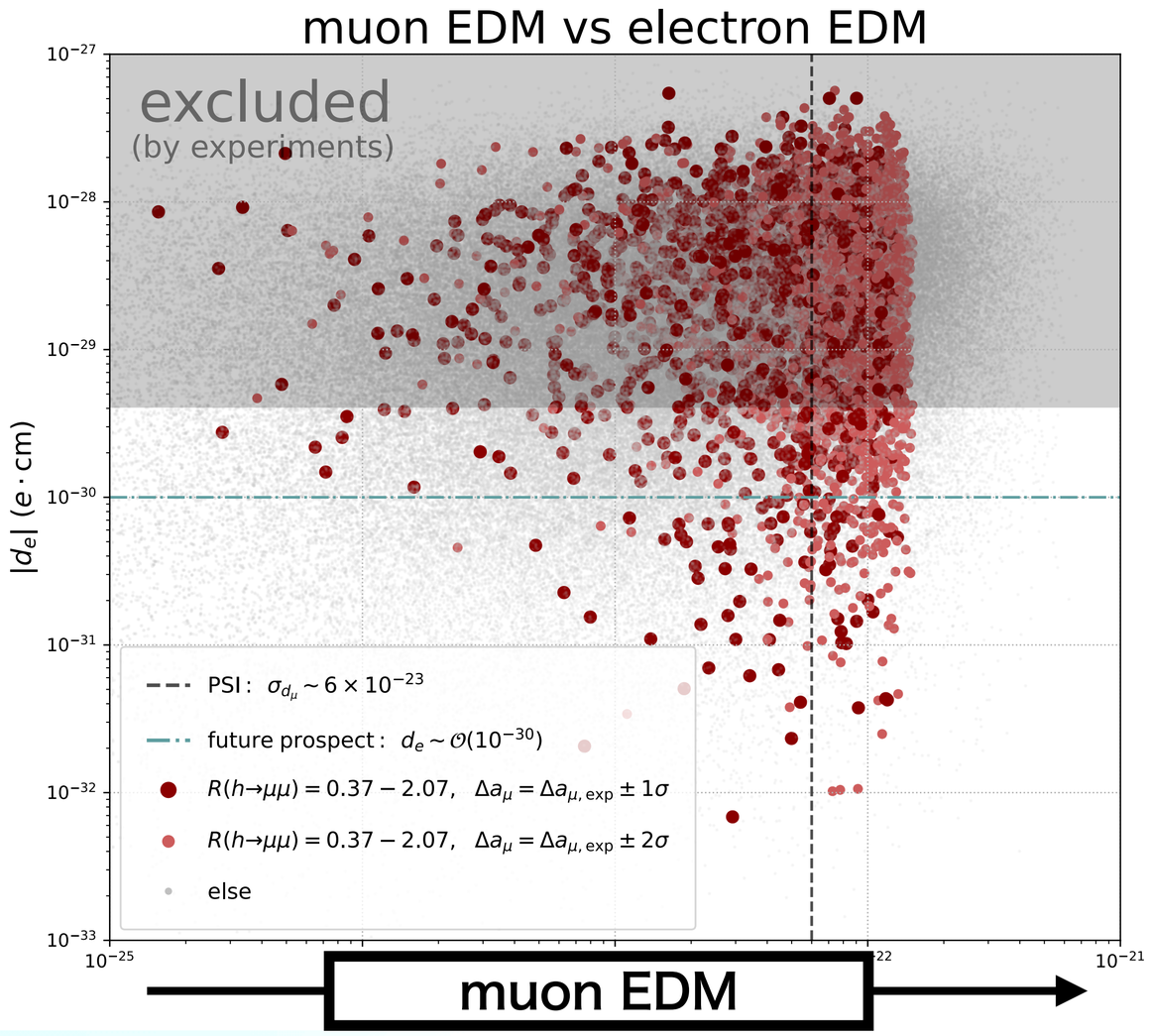
修士論文 図4.4

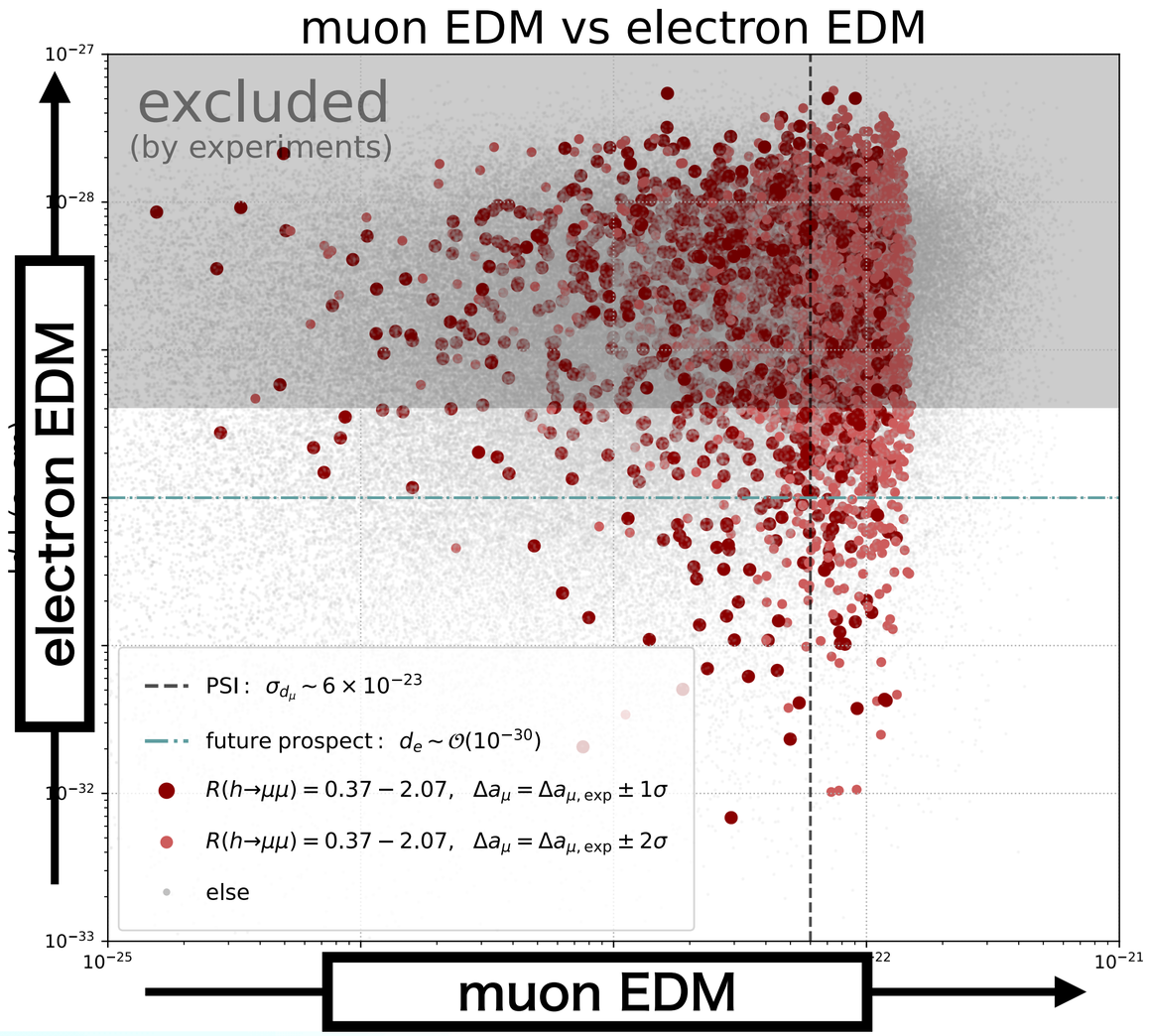
muon EDM vs electron EDM



K. Hamaguchi, N. Nagata, G. Osaki, and S.-Y. Tseng, JHEP 01 (2023) 100.

修士論文 図4.4

muon EDM vs electron EDM



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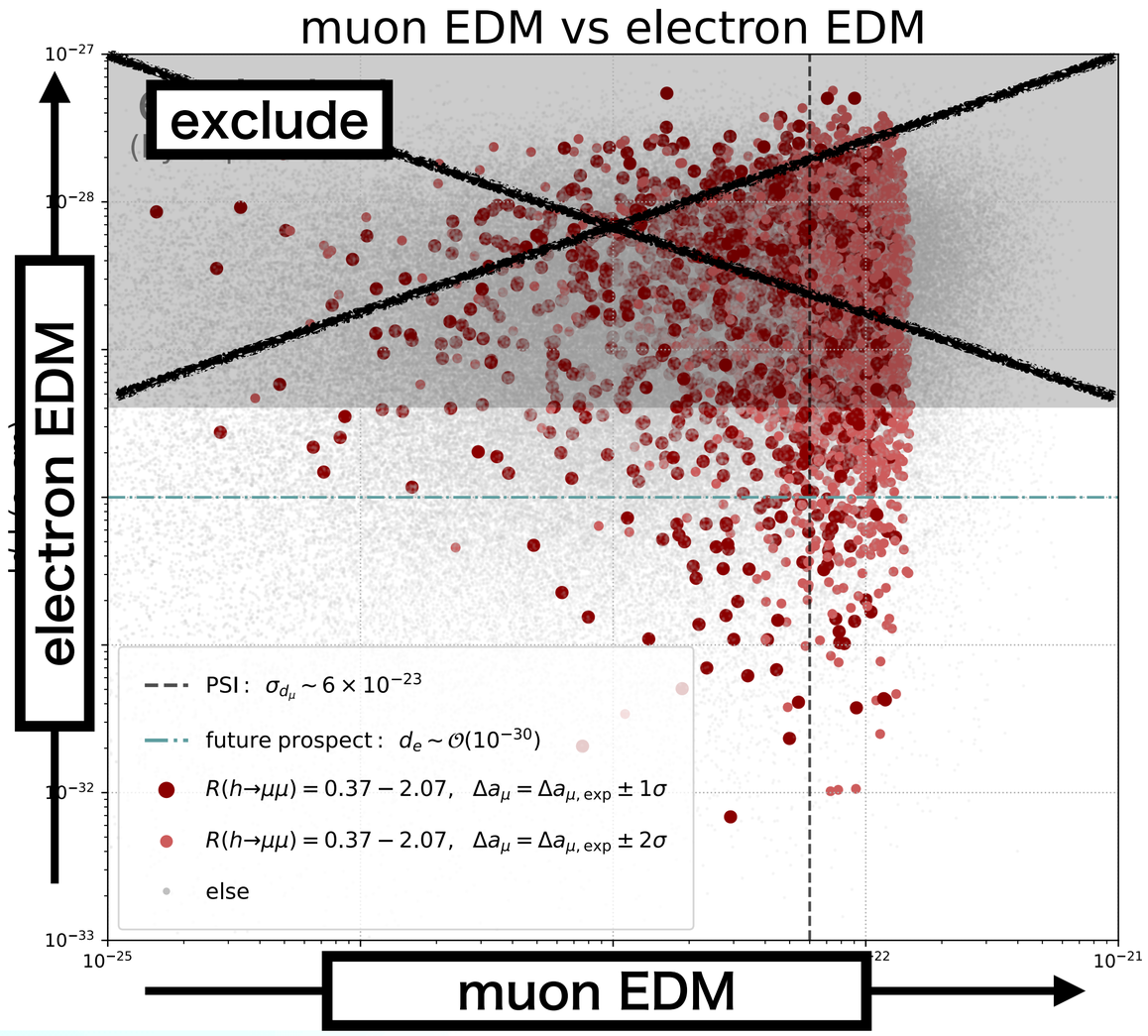

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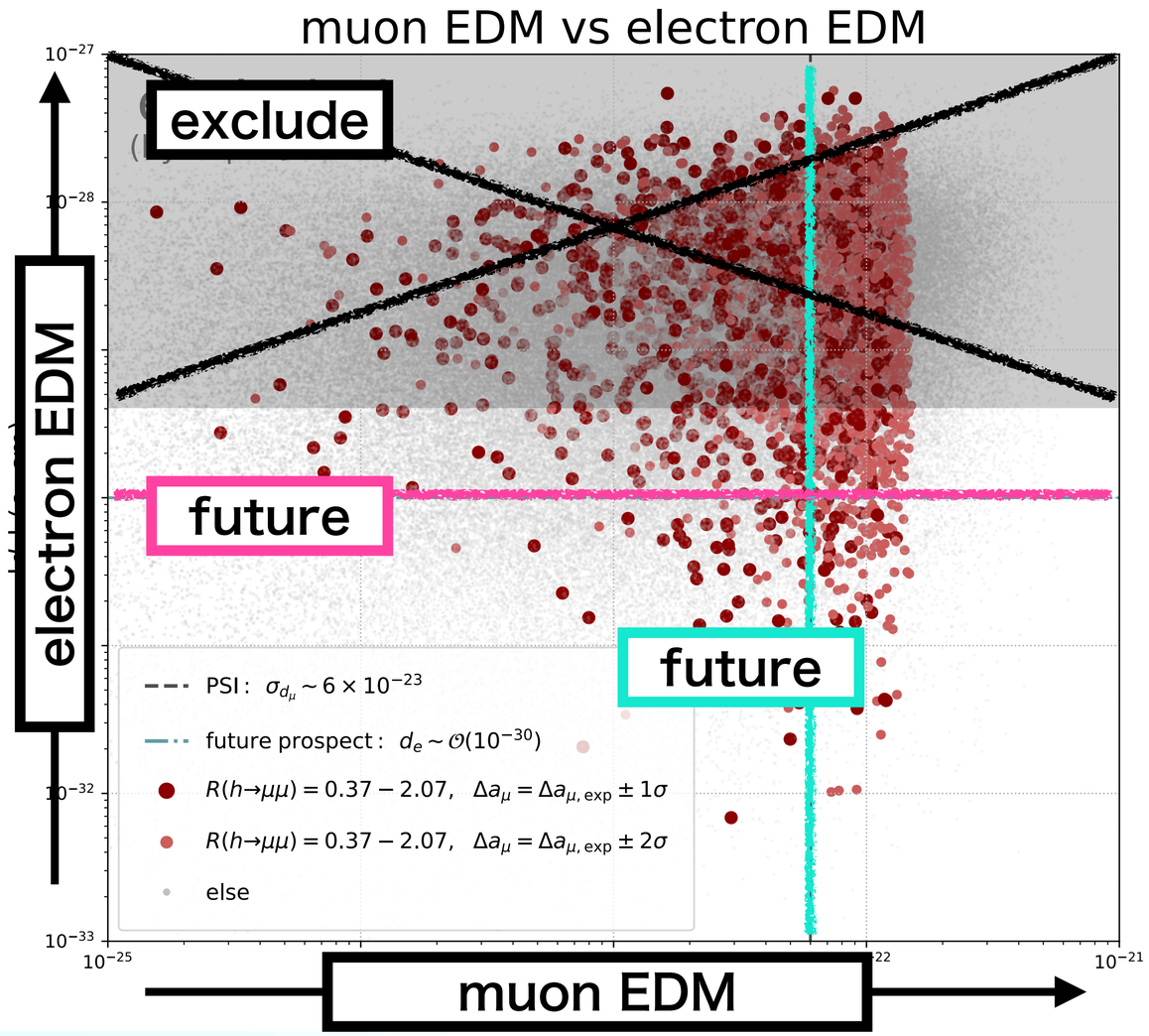

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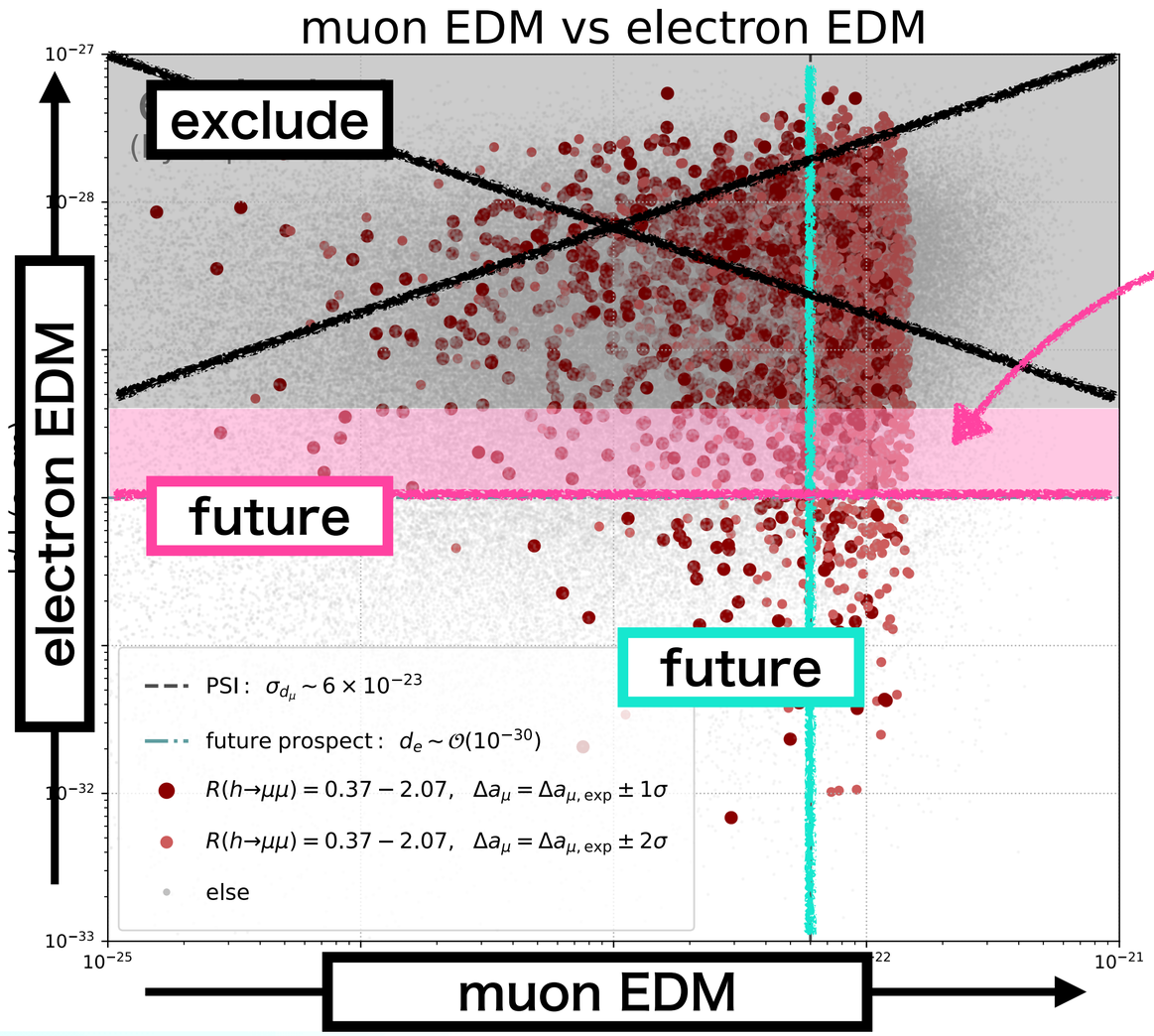

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electron EDM will be found
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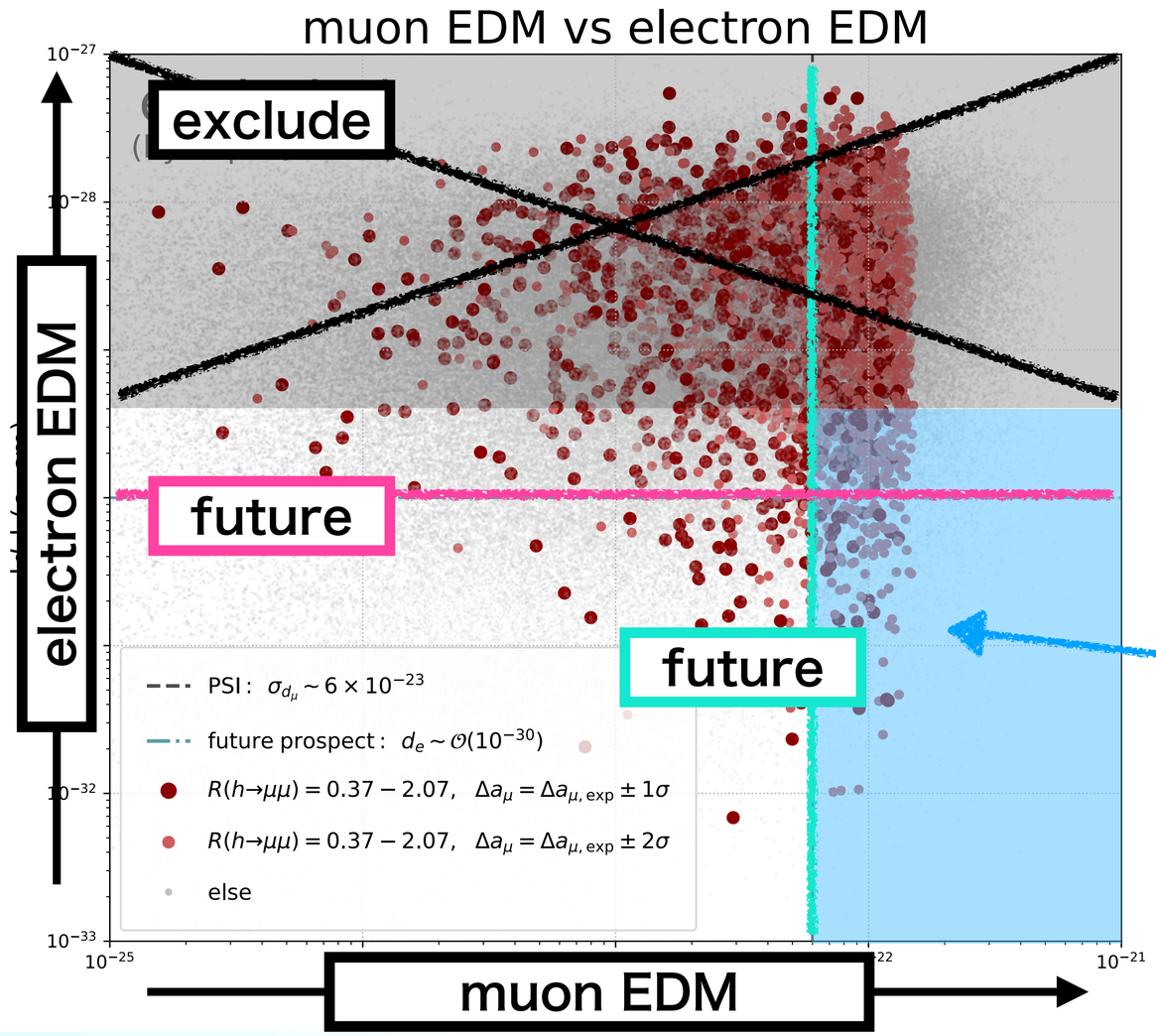

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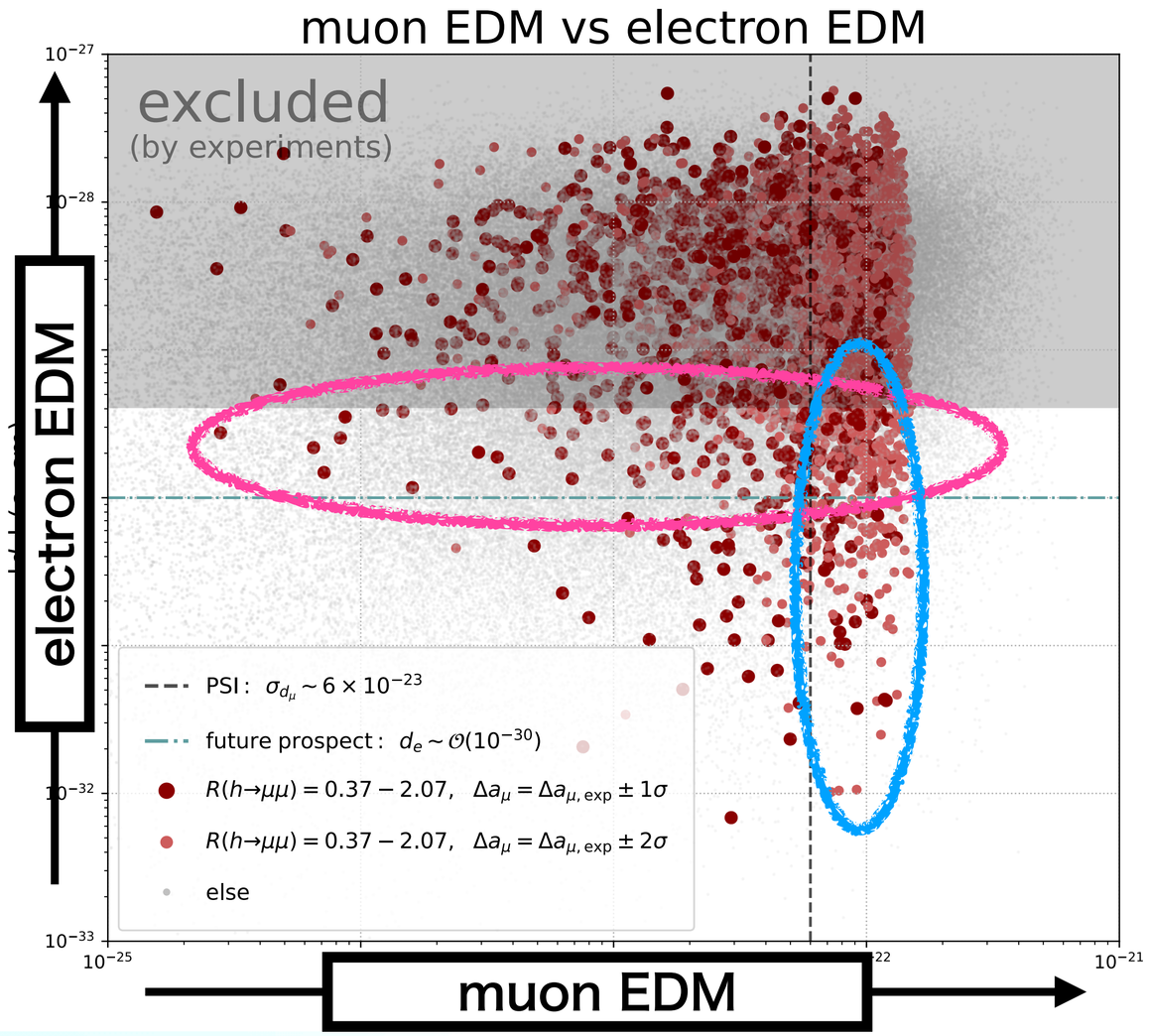

sample points exist !

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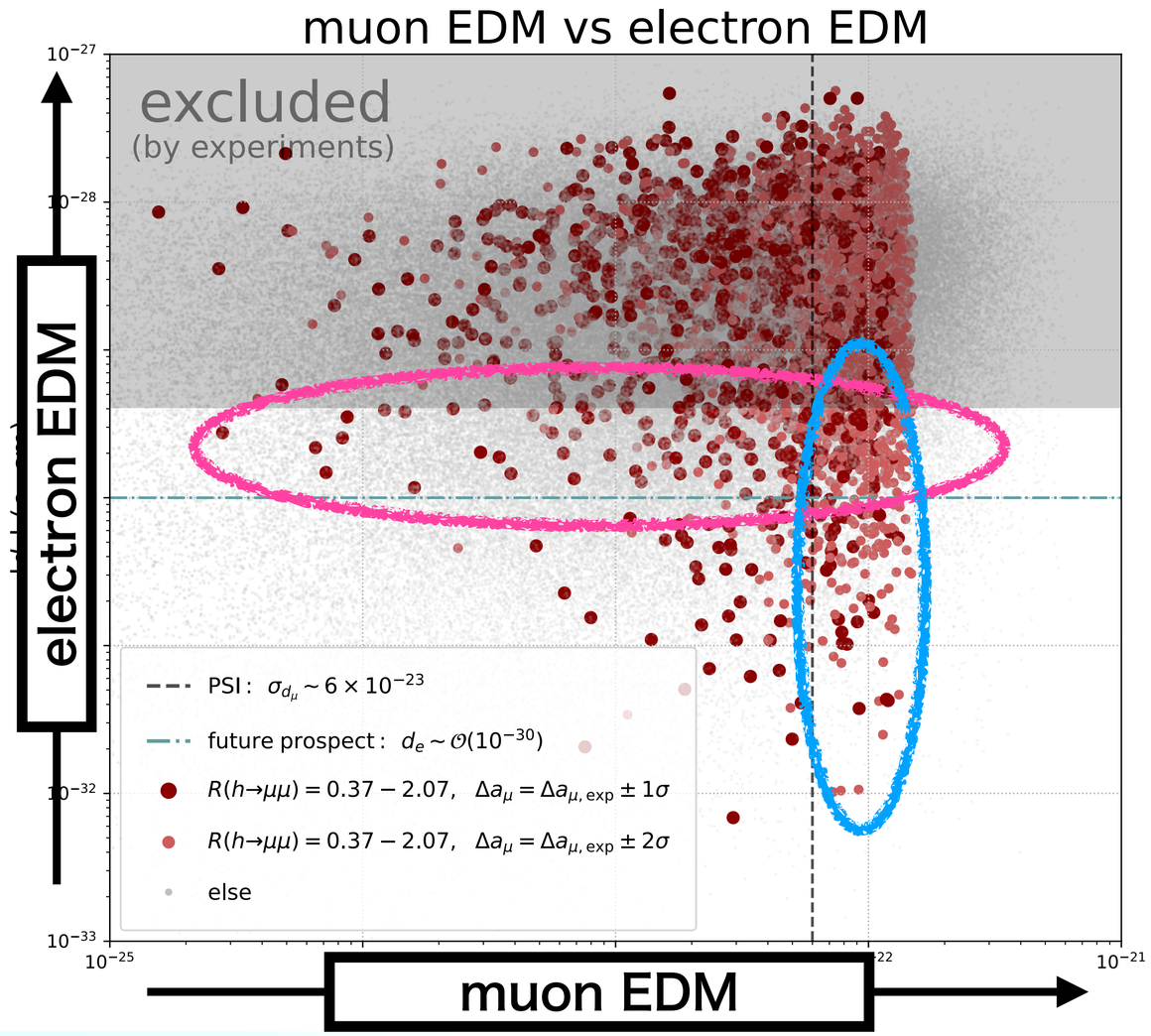

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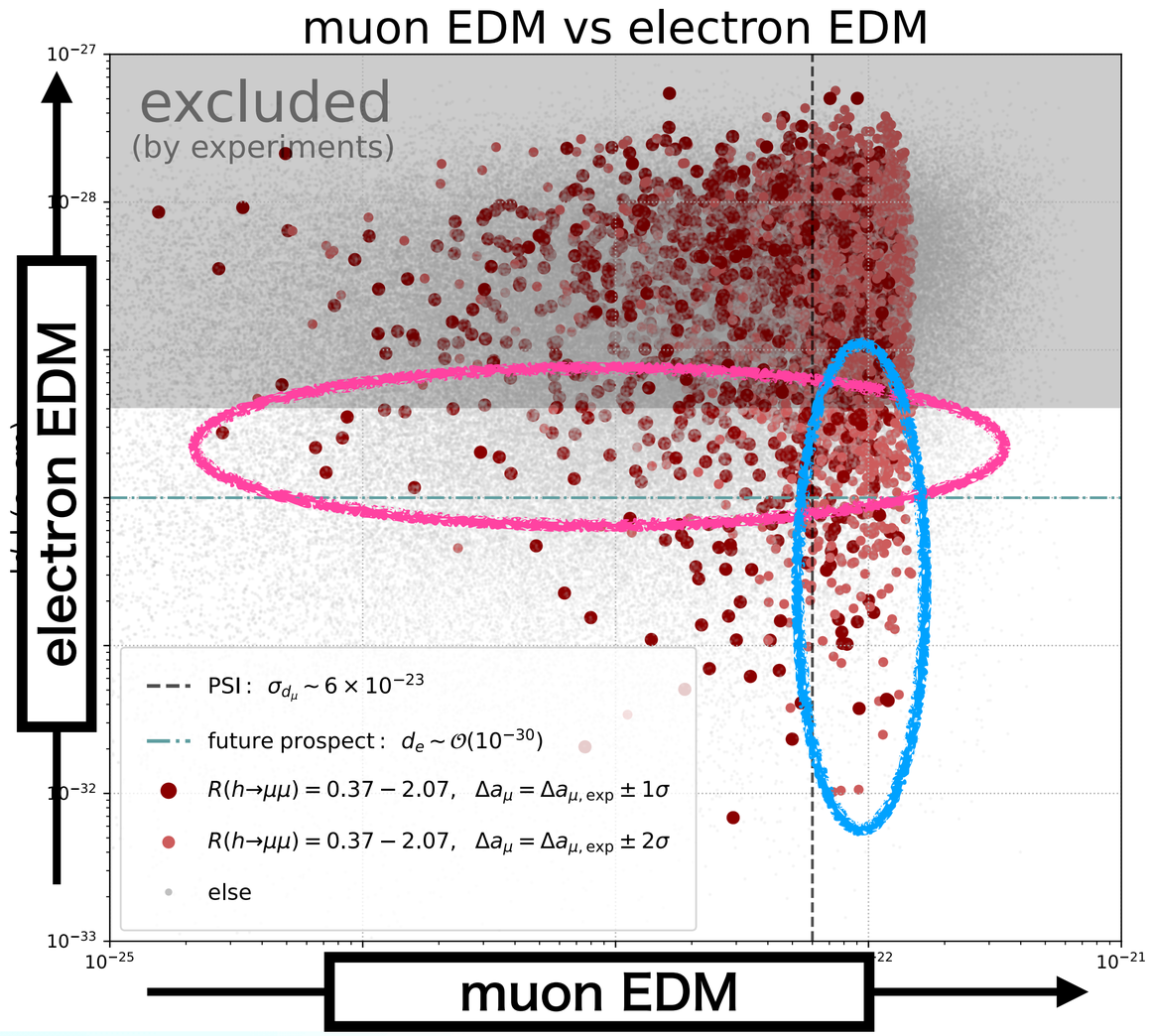

sample points exist !

if vector-like lepton models are true,

there is a possibility that lepton EDM will be found near future!!

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Summary

- SM has a problem of “**muon g-2 anomaly**”.
- Vector-like leptons can explain this problem.
- We calculated **new contributions for muon/electron EDMs**.
- There is a possibility that **muon/electron EDMs will be measured by future experiments**.

Summary

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Thank you for listening!