g-2, LFV, EDMと
フレーバー対称性

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Based on Morimitsu Tanimoto(Niigata U.), KY 2310.16325 [hep-ph]

話すこと

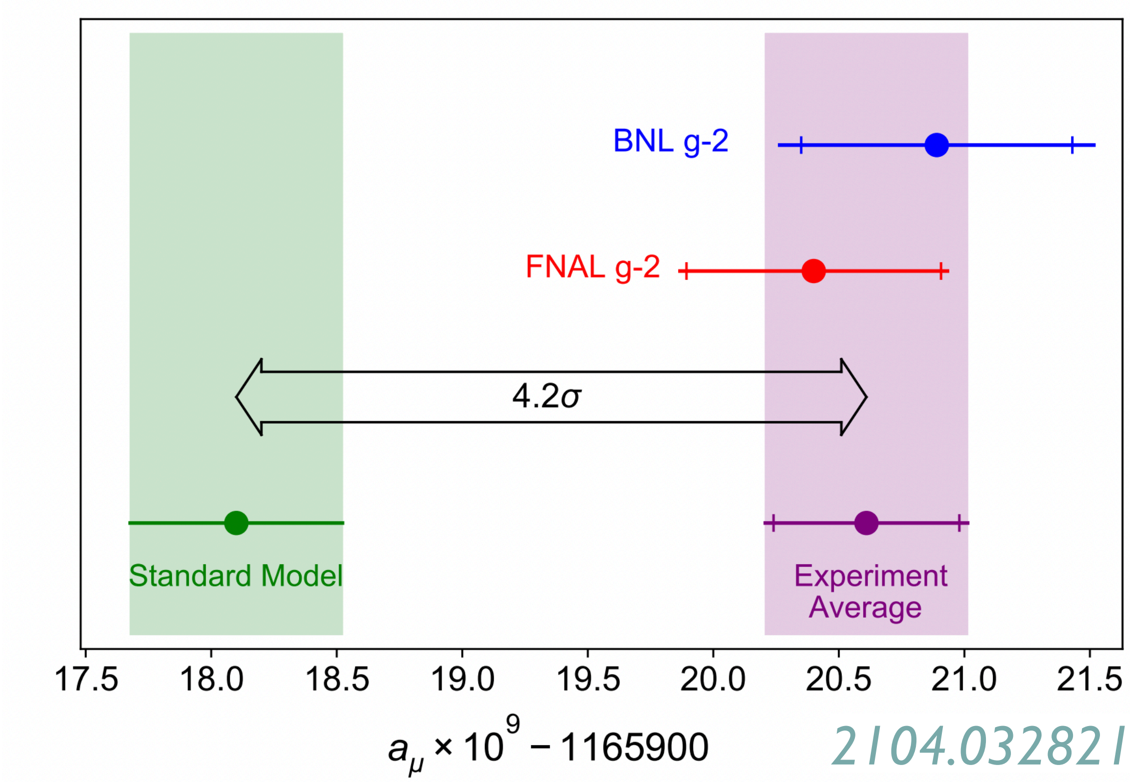
Muon $(g-2)_\mu$ anomaly が新物理の寄与によるものであったとき

- 新物理のレプトンフレーバー構造に与える示唆は何か？
- フレーバー対称性との整合性は？
- 他の物理量への予言は？

Muon $(g-2)_\mu$ anomaly

anomalous magnetic dipole moment of the muon $a_\mu \equiv \frac{(g-2)_\mu}{2}$

SM Exp



2104.03282l

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$$

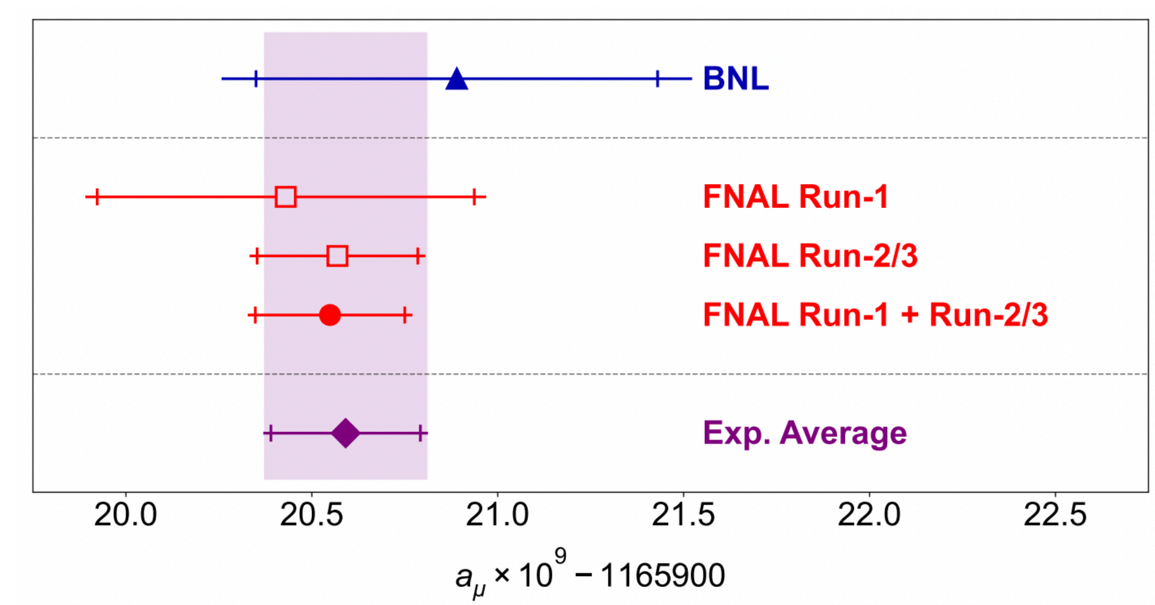
Muon $(g-2)_\mu$ anomaly ?

<u>Lattice QCD result</u>

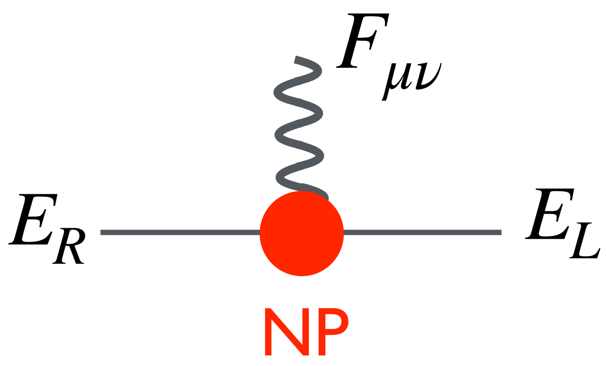
on Hadron Vacuum Polarization

→ smaller discrepancy

<u>New FNAL result</u> 2308.06230



新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM



Dipole operator

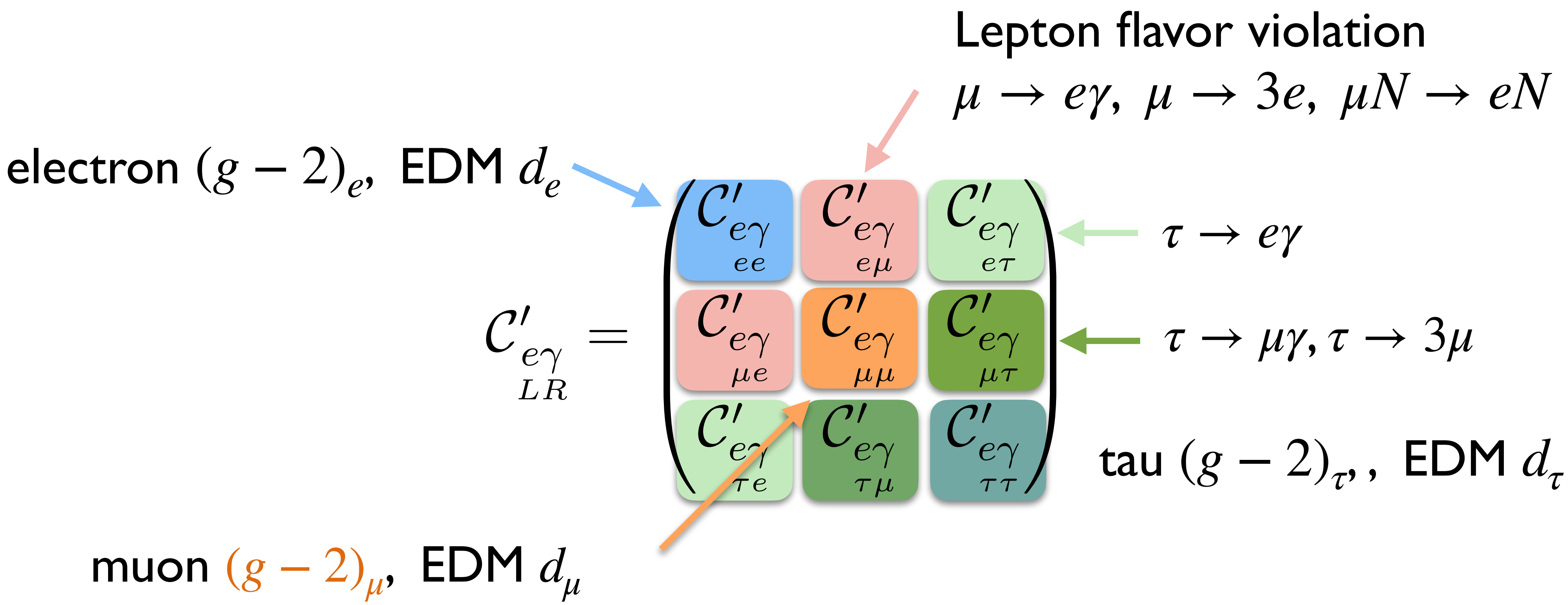
$$\mathcal{O}_{\substack{e\gamma\\LR}} = \frac{v}{\sqrt{2}} \overline{E}_L \sigma^{\mu\nu} E_R F_{\mu\nu} \qquad \mathcal{L}_{\text{dipole}} = \frac{1}{\Lambda^2}\left(\mathcal{C}'_{\substack{e\gamma\\LR}} \mathcal{O}_{\substack{e\gamma\\LR}} + \mathcal{C}'_{\substack{e\gamma\\RL}} \mathcal{O}_{\substack{e\gamma\\RL}}\right)$$

$e \quad \mu \quad \tau$

$$\mathcal{C}'_{\substack{e\gamma\\LR}} = \begin{pmatrix} \mathcal{C}'_{\substack{e\gamma\\ee}} & \mathcal{C}'_{\substack{e\gamma\\e\mu}} & \mathcal{C}'_{\substack{e\gamma\\e\tau}} \\ \mathcal{C}'_{\substack{e\gamma\\\mu e}} & \mathcal{C}'_{\substack{e\gamma\\\mu\mu}} & \mathcal{C}'_{\substack{e\gamma\\\mu\tau}} \\ \mathcal{C}'_{\substack{e\gamma\\\tau e}} & \mathcal{C}'_{\substack{e\gamma\\\tau\mu}} & \mathcal{C}'_{\substack{e\gamma\\\tau\tau}} \end{pmatrix} \begin{matrix} e \\ \mu \\ \tau \end{matrix}$$

新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

Muon $(g-2)_\mu$ 以外も様々な現象が引き起こされる



新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

muon $(g-2)_\mu$

Lepton flavor violation
$\mu \to e\gamma,\ \mu \to 3e,\ \mu N \to eN$

electron $(g-2)_e$, EDM d_e

$\tau \to e\gamma$

$\tau \to \mu\gamma, \tau \to 3\mu$

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

muon $(g-2)_\mu$, EDM d_μ

$$\Delta a_\mu = \frac{4m_\mu}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\mathrm{Re}\left[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}\right]$$

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\mathrm{Re}\left[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}\right] \approx 1.0 \times 10^{-5}\ \mathrm{TeV}^{-2}$$

新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

muon $(g-2)_\mu$& $\mu \to e\gamma$

Lepton flavor violation

$\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$

electron $(g-2)_e$, EDM d_e

$$\mathcal{C}'_{\substack{e\gamma\\LR}} = \begin{pmatrix} \mathcal{C}'_{\substack{e\gamma\\ee}} & \mathcal{C}'_{\substack{e\gamma\\e\mu}} \\ \mathcal{C}'_{\substack{e\gamma\\\mu e}} & \mathcal{C}'_{\substack{e\gamma\\\mu\mu}} \\ \mathcal{C}'_{\substack{e\gamma\\\tau e}} & \mathcal{C}'_{\substack{e\gamma\\\tau\mu}} \end{pmatrix}$$

$$\mathcal{B}(\ell_r \to \ell_s\gamma) = \frac{m_{\ell_r}^3 v^2}{8\pi\Gamma_{\ell_r}}\frac{1}{\Lambda^4}\left(|\mathcal{C}'_{\substack{e\gamma\\rs}}|^2 + |\mathcal{C}'_{\substack{e\gamma\\sr}}|^2\right)$$

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}\ (90\%\ \text{C.L.})$$

MEG

$$\longrightarrow \frac{1}{\Lambda^2}|\mathcal{C}'_{\substack{e\gamma\\e\mu(\mu e)}}| < 2.1 \times 10^{-10}\,\text{TeV}^{-2}$$

muon $(g-2)_\mu$, EDM d_μ

$$\Delta a_\mu = \frac{4m_\mu}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\text{Re}\left[\mathcal{C}'_{\substack{e\gamma\\\mu\mu}}\right]$$

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

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新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

muon $(g-2)_\mu$& $\mu \to e\gamma$ → 特徴的なフレーバー構造 (対角成分 ≫ 非対角成分)

electron $(g-2)_e$, EDM d_e

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} \end{pmatrix}$$

Lepton flavor violation

$\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$

$$\mathcal{B}(\ell_r \to \ell_s \gamma) = \frac{m_{\ell_r}^3 v^2}{8\pi \Gamma_{\ell_r}} \frac{1}{\Lambda^4} \left(|\mathcal{C}'_{\underset{rs}{e\gamma}}|^2 + |\mathcal{C}'_{\underset{sr}{e\gamma}}|^2 \right)$$

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13} \ (90\% \text{ C.L.})$$

MEG

$$\longrightarrow \frac{1}{\Lambda^2} |\mathcal{C}'_{\underset{e\mu(\mu e)}{e\gamma}}| < 2.1 \times 10^{-10}\, \text{TeV}^{-2}$$

muon $(g-2)_\mu$, EDM d_μ

$$\Delta a_\mu = \frac{4m_\mu}{e} \frac{v}{\sqrt{2}} \frac{1}{\Lambda^2} \text{Re}\left[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}\right]$$

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

$$\longrightarrow \frac{1}{\Lambda^2} \text{Re}\left[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}\right] \approx 1.0 \times 10^{-5}\, \text{TeV}^{-2}$$

Strong flavor alignment

$$\left| \frac{\mathcal{C}'_{\underset{e\mu(\mu e)}{e\gamma}}}{\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}} \right| < 2.1 \times 10^{-5}$$

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

Isidori, Pages and Wilsch[2111.13724]

造 from $(g-2)_\ell$, LFV and EDM

$$\Delta a_e = \frac{4m_e}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{ee}$$

$$\Delta a_e^{Cs} = a_e^{\rm Exp} - a_e^{\rm SM,CS} = (-8.8 \pm 3.6) \times 10^{-13}$$
$$\Delta a_e^{Rb} = a_e^{\rm Exp} - a_e^{\rm SM,Rb} = (4.8 \pm 3.0) \times 10^{-13} \quad .$$

electron $(g-2)_e$

11 vs 22

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

$\tau \to e\gamma$

$\tau \to \mu\gamma, \tau \to 3\mu$

muon $(g-2)_\mu$

$$\Delta a_\mu = \frac{4m_\mu}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu}$$

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu} \approx 1.0 \times 10^{-5}\ \mathrm{TeV}^{-2}$$

新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

$$[\mathcal{C}'_{e\gamma}]_{\mu\mu} \xrightarrow{\mathrm{Re}} (g-2)_\mu, \qquad [\mathcal{C}'_{e\gamma}]_{\mu\mu} \xrightarrow{\mathrm{Im}} \text{EDM } d_\mu$$

Lepton flavor violation
$\mu \to e\gamma,\ \mu \to 3e,\ \mu N \to eN$

electron $(g-2)_e$, EDM d_e

$$\mathcal{C}'_{\substack{e\gamma \\ LR}} = \begin{pmatrix} \mathcal{C}'_{\substack{e\gamma \\ ee}} & \mathcal{C}'_{\substack{e\gamma \\ e\mu}} & \mathcal{C}'_{\substack{e\gamma \\ e\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \mu e}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \tau e}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\tau}} \end{pmatrix}$$

$\tau \to e\gamma$

$\tau \to \mu\gamma, \tau \to 3\mu$

muon $(g-2)_\mu$

$$\Delta a_\mu = \frac{4m_\mu}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\,\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu}$$

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\,\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu} \approx 1.0 \times 10^{-5}\ \mathrm{TeV}^{-2}$$

EDM d_μ

$$d_\mu = -\sqrt{2}\,\frac{v}{\Lambda^2}\,\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu}$$

$$|d_\mu/e| < 1.8 \times 10^{-19}\ \mathrm{cm}$$

BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\,\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu} < 2.7 \times 10^{-2}\ \mathrm{TeV}^{-2}$$

$$\Delta a_e = \frac{4m_e}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\,\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{ee}$$

$$\Delta a_e^{Cs} = a_e^{\rm Exp} - a_e^{\rm SM,CS} = (-8.8 \pm 3.6)\times 10^{-13}$$
$$\Delta a_e^{Rb} = a_e^{\rm Exp} - a_e^{\rm SM,Rb} = (4.8 \pm 3.0)\times 10^{-13}\ .$$

electron $(g-2)_e$

$$d_e = -\sqrt{2}\,\frac{v}{\Lambda^2}\,\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{ee}$$

$$|d_e/e| \lesssim 1.1\times 10^{-29}\,\mathrm{cm} = 5.6\times 10^{-13}\,\mathrm{TeV}^{-1}$$

ACME

$$\frac{1}{\Lambda^2}\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{ee} < 1.6\times 10^{-12}\,\mathrm{TeV}^{-2}$$

EDM d_e

$$\mathcal{C}'_{\substack{e\gamma\\LR}} = \begin{pmatrix} \mathcal{C}'_{e\gamma,ee} & \mathcal{C}'_{e\gamma,e\mu} & \mathcal{C}'_{e\gamma,e\tau} \\ \mathcal{C}'_{e\gamma,\mu e} & \mathcal{C}'_{e\gamma,\mu\mu} & \mathcal{C}'_{e\gamma,\mu\tau} \\ \mathcal{C}'_{e\gamma,\tau e} & \mathcal{C}'_{e\gamma,\tau\mu} & \mathcal{C}'_{e\gamma,\tau\tau} \end{pmatrix}$$

$\leftarrow \tau \to e\gamma$

$\leftarrow \tau \to \mu\gamma, \tau \to 3\mu$

muon $(g-2)_\mu$

EDM d_μ

$$\Delta a_\mu = \frac{4m_\mu}{e}\frac{v}{\sqrt{2}}\frac{1}{\Lambda^2}\,\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu}$$

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (251 \pm 59)\times 10^{-11}$$

FNAL, BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\mathrm{Re}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu} \approx 1.0\times 10^{-5}\,\mathrm{TeV}^{-2}$$

$$d_\mu = -\sqrt{2}\,\frac{v}{\Lambda^2}\,\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu}$$

$$|d_\mu/e| < 1.8\times 10^{-19}\,\mathrm{cm}$$

BNL

$$\longrightarrow \quad \frac{1}{\Lambda^2}\mathrm{Im}\,[\mathcal{C}'_{e\gamma}]_{\mu\mu} < 2.7\times 10^{-2}\,\mathrm{TeV}^{-2}$$

新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

$$\mathcal{B}(\ell_r \to \ell_s \gamma) = \frac{m_{\ell_r}^3 v^2}{8\pi \Gamma_{\ell_r}} \frac{1}{\Lambda^4} \left(|\mathcal{C}'_{\underset{rs}{e\gamma}}|^2 + |\mathcal{C}'_{\underset{sr}{e\gamma}}|^2 \right)$$

$$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma) < 4.4 \times 10^{-8} \ (90\% \ \mathrm{CL})$$

BaBar

$$\to \frac{1}{\Lambda^2} |\mathcal{C}'_{\underset{\mu\tau(\tau\mu)}{e\gamma}}| < 2.7 \times 10^{-6}\, \mathrm{TeV}^{-2}$$

electron $(g-2)_e$, EDM d_e

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}' \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

$\leftarrow$ $\tau \to \mu\gamma, \tau \to 3\mu$

muon $(g-2)_\mu$, EDM d_μ

$$\Delta a_\mu = \frac{4 m_\mu}{e} \frac{v}{\sqrt{2}} \frac{1}{\Lambda^2} \mathrm{Re} [\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}]$$

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

FNAL, BNL

$$\to \frac{1}{\Lambda^2} \mathrm{Re} [\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}] \approx 1.0 \times 10^{-5}\, \mathrm{TeV}^{-2}$$

$$\left| \frac{\mathcal{C}'_{\underset{\mu\tau(\tau\mu)}{e\gamma}}}{\mathcal{C}'_{\underset{\tau\tau}{e\gamma}}} \right| < 1.6 \times 10^{-2} \times \left| \frac{y_\tau\, \mathcal{C}'_{\underset{\mu\mu}{e\gamma}}}{y_\mu\, \mathcal{C}'_{\underset{\tau\tau}{e\gamma}}} \right|$$

natural expectation

$$|\mathcal{C}'_{\underset{\tau\tau}{e\gamma}}|/y_\tau \sim |\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}|/y_\mu$$

Isidori, Pages and Wilsch[2111.13724]

新物理のフレーバー構造 from $(g-2)_\ell$, LFV and EDM

Dipole operator によって様々な現象が引き起こされる

Lepton flavor violation

$\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$

electron $(g-2)_e$, EDM d_e

$$C'_{\substack{e\gamma\\ LR}} = \begin{pmatrix} C'_{\substack{e\gamma\\ ee}} & C'_{\substack{e\gamma\\ e\mu}} & C'_{\substack{e\gamma\\ e\tau}} \\ C'_{\substack{e\gamma\\ \mu e}} & C'_{\substack{e\gamma\\ \mu\mu}} & C'_{\substack{e\gamma\\ \mu\tau}} \\ C'_{\substack{e\gamma\\ \tau e}} & C'_{\substack{e\gamma\\ \tau\mu}} & C'_{\substack{e\gamma\\ \tau\tau}} \end{pmatrix}$$

$\tau \to e\gamma$

$\tau \to \mu\gamma, \tau \to 3\mu$

muon $(g-2)_\mu$, EDM d_μ

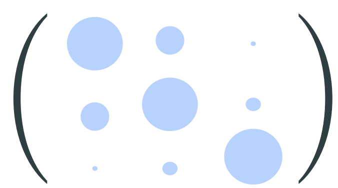
muon $(g-2)_\mu$& $\mu \to e\gamma$ → 特徴的なフレーバー構造 (対角成分 $\gg$ 非対角成分)

このようなフレーバー構造はどのようにして出すことができるか？

→ フレーバー対称性

フレーバー対称性

SM flavor problem

$M_{u,d,e} \sim$  $V_{CKM} \sim$ 

階層的構造　なぜ？

NP flavor problem

現在、フレーバー物理量において有意なずれは見つかっていない

→ 新物理に対して厳しい制限

新物理は特殊なフレーバー構造を持っている？

その背後には**フレーバー対称性**があるかもしれない

imposing *flavor symmetry*
- *U(2) flavor symmetry* — Isidori, Pages and Wilsch[2111.13724], Tanimoto, KY 2310.16325
- *A4 modular flavor symmetry* — Kobayashi, Otsuka, Tanimoto, KY [2204.12325]

NP
- realize muon $(g-2)_\mu$ anomaly
- satisfy constraint from LFV

→ EDM d_e, d_μ　electron $(g-2)_e$

$U(2)^5$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

- $U(2)^5$フレーバー対称性は、3世代目湯川結合がなぜ大きいのか自然な説明を与える

  1st & 2nd 世代のみに作用する

  3rd 世代目は対称性によって許される

$$\psi = (\underbrace{\psi_1, \psi_2}_{\text{SU(2) doublet}}, \underbrace{\psi_3}_{\text{singlet}})$$

- SM Yukawa が良い近似で保っている対称性

  exact symmetry for $m_u, m_d, m_c, m_s = 0$ & $V_{CKM} = 1$

  ⇒ small breaking terms を導入するのみでOK

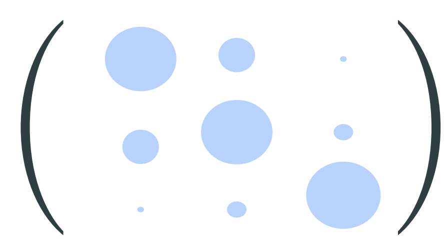
The SM flavor puzzle

Striking hierarchy

Mass : 3rd > 2nd > 1st

$M_{u,d} \sim$ 

Almost diagonal CKM matrix

$V_{CKM} \sim$ 

$U(2)^5$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

Under $U(2)^3 = U(2)^q \times U(2)^u \times U(2)^d$ symmetry

$$\psi = (\psi_1, \psi_2, \psi_3)$$

SU(2) doublet (ψ_1, ψ_2) singlet (ψ_3)

$$\mathcal{L}_{\rm Yuk} = \begin{pmatrix} \bar{Q}^{(2)} & \bar{q}^3 \end{pmatrix} Y_u \begin{pmatrix} u^{(2)} \\ t \end{pmatrix} + \begin{pmatrix} \bar{Q}^{(2)} & \bar{q}^3 \end{pmatrix} Y_d \begin{pmatrix} d^{(2)} \\ b \end{pmatrix}$$

$$Q^{(2)} = (Q^1, Q^2) \sim (2,1,1) \qquad Q^3 \sim (1,1,1)$$
$$u^{(2)} = (u^1, u^2) \sim (1,2,1) \qquad t \sim (1,1,1)$$
$$d^{(2)} = (d^1, d^2) \sim (1,1,2) \qquad b \sim (1,1,1)$$

Unbroken symmetry

$$Y_u = y_t \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$U(2)_q$ (upper two rows), $U(2)_u$ (left two columns)

After U(2) breaking

$$\left(\begin{array}{cc|c} \multicolumn{2}{c|}{\Delta_u} & V_q \\ \hline 0 & 0 & 1 \end{array}\right)$$

U(2) breaking (Spurion)

$$V_q \sim (2,1,1),$$

$$\Delta_u \sim (2,\bar{2},1),$$

$$\Delta_d \sim (2,1,\bar{2})$$

$U(2)^5$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

Under $U(2)^3 = U(2)^q \times U(2)^u \times U(2)^d$ symmetry

$$\psi = (\psi_1, \psi_2, \psi_3)$$

SU(2) doublet   singlet

$$\mathcal{L}_{\rm Yuk} = \begin{pmatrix} \bar{Q}^{(2)} & \bar{q}^3 \end{pmatrix} Y_u \begin{pmatrix} u^{(2)} \\ t \end{pmatrix} + \begin{pmatrix} \bar{Q}^{(2)} & \bar{q}^3 \end{pmatrix} Y_d \begin{pmatrix} d^{(2)} \\ b \end{pmatrix}$$

$Q^{(2)} = (Q^1, Q^2) \sim (2,1,1)$ $Q^3 \sim (1,1,1)$

$u^{(2)} = (u^1, u^2) \sim (1,2,1)$ $t \sim (1,1,1)$

$d^{(2)} = (d^1, d^2) \sim (1,1,2)$ $b \sim (1,1,1)$

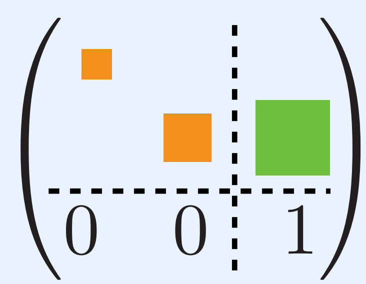
Unbroken symmetry

$$Y_u = y_t \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$U(2)_q$

$U(2)_u$

After U(2) breaking



U(2) breaking (Spurion)

$: |V_q| \sim |V_{ts}| \sim \mathcal{O}(10^{-1})$

$: |\Delta_u| \sim \begin{pmatrix} y_u/y_t & \\ & y_c/y_t \end{pmatrix} \sim \begin{pmatrix} \mathcal{O}(10^{-3}) & \\ & \mathcal{O}(10^{-2}) \end{pmatrix}$

spurion order : $1 \gg$ ■ $\gg$ ■ $\gg$ ■ > 0

$\mathcal{O}(10^{-1})$ $\mathcal{O}(10^{-2})$ $\mathcal{O}(10^{-3})$

NP LR flavor structure in U(2)

新物理のレプトンフレーバー構造もU(2)フレーバー対称性でコントロールされていると考える　→新物理の高次元オペレーターのフレーバー構造をU(2) breaking spurionで記述する

$U(2)_{L_L} \otimes U(2)_{E_R}$ breaking (Spurion)　　$V_\ell \sim (2,1)$,　$\Delta_e \sim (2,\bar{2})$

LR flavor structure at order $\mathcal{O}(V_\ell^2 \Delta_e)$　　$X^n_{\alpha\beta}(\bar{\ell}_\alpha \Gamma e_\beta)\eta^n$　　$(n = Y, e\gamma)$

$$X^n = \left(\begin{array}{c|c} (2,\bar{2}) & (2,1) \\ \hline (1,2) & (1,1) \end{array} \right)_{LR}$$

NP LR flavor structure in U(2)

新物理のレプトンフレーバー構造もU(2)フレーバー対称性でコントロールされていると考える　→新物理の高次元オペレーターのフレーバー構造をU(2) breaking spurionで記述する

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LR flavor structure at order $\mathcal{O}(V_\ell^2 \Delta_e)$　　$X^n_{\alpha\beta}(\bar{\ell}_\alpha \Gamma e_\beta)\eta^n$　　$(n = Y, e\gamma)$

$$X^n = \left(\begin{array}{c|c} C^n_\Delta (\Delta_e)_{\alpha\beta} + C^n_{VVV} (V_\ell)_\alpha (V_\ell^\dagger)_\gamma (\Delta_e)_{\gamma\beta} & C^n_V (V_\ell)_\alpha + C^n_{VVV} (V_\ell)(V_\ell^\dagger)(V_\ell)_\alpha \\ \hline C^n_{V\Delta} (V_\ell^\dagger)_\alpha (\Delta_e)_{\alpha\beta} & C^n + C^n_{VV} (V_\ell^\dagger V_\ell) \end{array} \right)_{LR}$$

$C, C_V, C_\Delta, C_{VV}, C_{V\Delta}, C_{VV\Delta}$: $\mathcal{O}(1)$ NP coefficients

NP LR flavor structure in U(2)

新物理のレプトンフレーバー構造もU(2)フレーバー対称性でコントロールされていると考える　→新物理の高次元オペレーターのフレーバー構造をU(2) breaking spurionで記述する

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$$X^n = \left(\begin{array}{c:c} C^n_\Delta (\Delta_e)_{\alpha\beta} + C^n_{VVV}(V_\ell)_\alpha (V_\ell^\dagger)_\gamma (\Delta_e)_{\gamma\beta} & C^n_V (V_\ell)_\alpha + C^n_{VVV}(V_\ell)(V_\ell^\dagger)(V_\ell)_\alpha \\ \hdashline C^n_{V\Delta}(V_\ell^\dagger)_\alpha (\Delta_e)_{\alpha\beta} & C^n + C^n_{VV}(V_\ell^\dagger V_\ell) \end{array} \right)_{LR}$$

$C, C_V, C_\Delta, C_{VV}, C_{V\Delta}, C_{VV\Delta}$: $\mathcal{O}(1)$ NP coefficients

parametrization

$$V_\ell = \begin{pmatrix} 0 \\ \epsilon_\ell \end{pmatrix}, \quad \Delta_e = O_e^T \begin{pmatrix} \delta'_e & 0 \\ 0 & \delta_e \end{pmatrix}, \quad O_e = \begin{pmatrix} c_e & s_e \\ -s_e & c_e \end{pmatrix}$$

$$= \begin{pmatrix} C^{e\gamma}_\Delta c_e \delta'_e & -C^{e\gamma}_\Delta s_e \delta_e & 0 \\ s_e \delta'_e (C^{e\gamma}_\Delta + C^{e\gamma}_{VV\Delta}\epsilon_\ell^2) & c_e \delta_e (C^{e\gamma}_\Delta + C^{e\gamma}_{VV\Delta}\epsilon_\ell^2) & (C^{e\gamma}_V \epsilon_\ell + C^{e\gamma}_{VVV}\epsilon_\ell^3) \\ C^{e\gamma}_{V\Delta}(s_e \epsilon_\ell \delta'_e) & C^{e\gamma}_{V\Delta}(c_e \epsilon_\ell \delta_e) & C^{e\gamma} + C^{e\gamma}_{VV}\epsilon_\ell^2 \end{pmatrix}_{LR}$$

parameters : $\dfrac{\delta'_\ell}{\delta_\ell} \simeq \dfrac{y_e}{y_\mu}$　　ϵ_ℓ and s_e are not constrained, but presume from quark sector

$s_e = 0.01 - 0.1\,,\qquad \epsilon_\ell = 0.01 - 0.1$

$(g-2)_\mu$ & $\mu \to e\gamma$ in U(2)

$$\mathscr{C}^{e\gamma}_{\mu\mu} \simeq |C^{e\gamma}_{\Delta}|\,\delta_e \left[\frac{1}{c_e} + c_e\epsilon_\ell^2\left(\left|\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_{\Delta}}\right|\cos(\arg C^{e\gamma}_{VV\Delta}) - \left|\frac{C^{y}_{VV\Delta}}{C^{y}_{\Delta}}\right|\frac{s_e^2}{c_e^2}\cos(\arg C^{y}_{VV\Delta})\right)\right]$$

$$\mathscr{C}^{e\gamma}_{e\mu} = [U_L^\dagger X^{e\gamma} U_R]_{12} \simeq |C^{e\gamma}_{\Delta}|\,s_e\delta_e\epsilon_\ell^2\left(\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_{\Delta}} - \frac{C^{y}_{VV\Delta}}{C^{y}_{\Delta}}\right)$$

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

muon $(g-2)_\mu$ and $\mu \to e\gamma$

strong flavor alignment

$$\left|\frac{\mathcal{C}'_{\underset{e\mu}{e\gamma}}}{\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}}\right| \approx \left|\frac{s_\theta}{c_\theta}\epsilon_\ell^2\left(\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_{\Delta}} - \frac{C^{y}_{VV\Delta}}{C^{y}_{\Delta}}\right)\right| < 2.1\times10^{-5}$$

$s_e = \mathcal{O}(\sqrt{m_e/m_\mu}) \sim 10^{-1}$ $\quad \epsilon_\ell \sim 10^{-1}$

$\to 10^{-3}$ suppression by U(2) spurions

from $\mu \to e\gamma$

$$\frac{1}{\Lambda^2}|\mathcal{C}'_{\underset{e\mu(\mu e)}{e\gamma}}| < 2.1\times10^{-10}\,\mathrm{TeV}^{-2}$$

from muon $(g-2)_\mu$

$$\frac{1}{\Lambda^2}\mathrm{Re}\,[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}] \approx 1.0\times10^{-5}\,\mathrm{TeV}^{-2}$$

$$\left|\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_{\Delta}} - \frac{C^{y}_{VV\Delta}}{C^{y}_{\Delta}}\right| \lesssim 10^{-2}$$

tight alignment condition

Isidori, Pages and Wilsch [2111.13724]

$(g-2)_\mu$ & $\mu \to e\gamma$ in U(2)

$$\mathscr{C}^{e\gamma}_{\mu\mu} \simeq |C^{e\gamma}_\Delta|\,\delta_e \left[\frac{1}{c_e} + c_e\epsilon_\ell^2\left(\left|\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_\Delta}\right|\cos(\arg C^{e\gamma}_{VV\Delta}) - \left|\frac{C^{y}_{VV\Delta}}{C^{y}_\Delta}\right|\frac{s_e^2}{c_e^2}\cos(\arg C^{y}_{VV\Delta})\right)\right]$$

$$\mathscr{C}^{e\gamma}_{e\mu} = [U_L^\dagger X^{e\gamma} U_R]_{12} \simeq |C^{e\gamma}_\Delta|\, s_e\delta_e\epsilon_\ell^2\left(\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_\Delta} - \frac{C^{y}_{VV\Delta}}{C^{y}_\Delta}\right) + s_e\delta_e\epsilon_\ell^2\, C_{3rd}$$

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

3世代目を含んだ対角化で出てくる効果

$$C_{3rd} = \frac{C^{y*}_\Delta C^y_V + C^{y*}_{V\Delta} C^y}{|C^y|^2}\left(\frac{C^{e\gamma}}{C^y}C^y_V - C^{e\gamma}_V\right) + \frac{C^y_V}{C^y}\left(\frac{C^{e\gamma}_V}{C^y_V}C^y_{V\Delta} - C^{e\gamma}_{V\Delta}\right)$$

muon $(g-2)_\mu$ and $\mu \to e\gamma$

strong flavor alignment

$$\left|\frac{\mathcal{C}'_{\underset{e\mu}{e\gamma}}}{\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}}\right| \approx \left|\frac{s_\theta}{c_\theta}\epsilon_\ell^2\left(\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_\Delta} - \frac{C^{y}_{VV\Delta}}{C^{y}_\Delta}\right)\right| < 2.1\times 10^{-5}$$

from $\mu \to e\gamma$

$$\frac{1}{\Lambda^2}|\mathcal{C}'_{\underset{e\mu(\mu e)}{e\gamma}}| < 2.1\times 10^{-10}\ \mathrm{TeV}^{-2}$$

from muon $(g-2)_\mu$

$$\frac{1}{\Lambda^2}\mathrm{Re}\left[\mathcal{C}'_{\underset{\mu\mu}{e\gamma}}\right] \approx 1.0\times 10^{-5}\ \mathrm{TeV}^{-2}$$

$s_e = \mathcal{O}(\sqrt{m_e/m_\mu}) \sim 10^{-1}$ $\epsilon_\ell \sim 10^{-1}$

→ 10^{-3} suppression by U(2) spurions

→ $$\left|\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_\Delta} - \frac{C^{y}_{VV\Delta}}{C^{y}_\Delta}\right| \lesssim 10^{-2}$$

C_{3rd} の効果で、たとえ $\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_\Delta} = \frac{C^{y}_{VV\Delta}}{C^{y}_\Delta}$ であったとしても $\mathcal{C}'_{\underset{e\mu(\mu e)}{e\gamma}}$ はsupressされない

$(g-2)_\mu$ & EDM d_e in U(2)

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

muon $(g-2)_\mu$ and EDM d_e

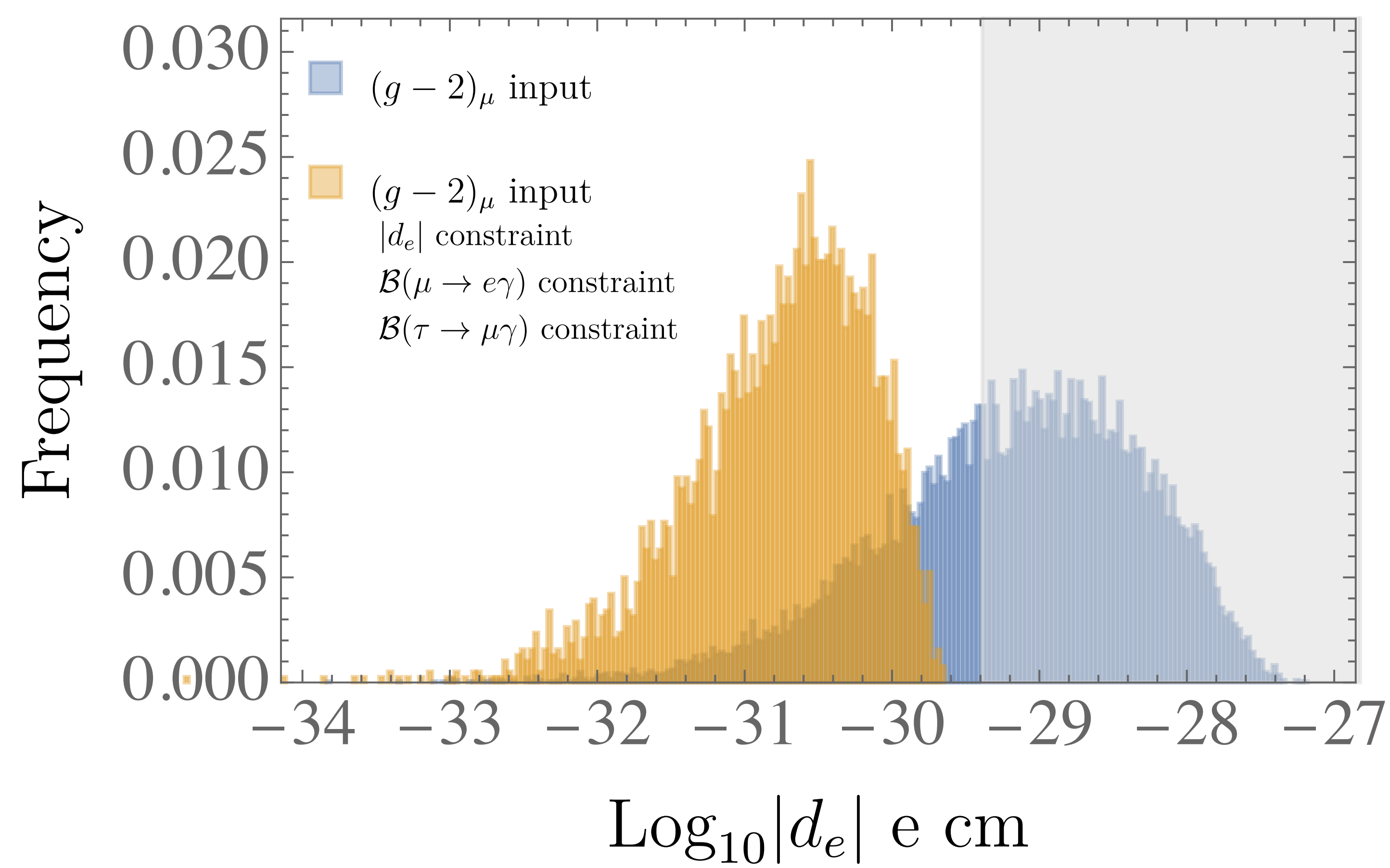
$$\left| \frac{\mathrm{Im}\ \mathcal{C}'_{\underset{ee}{e\gamma}}}{\mathrm{Re}\ \mathcal{C}'_{\underset{\mu\mu}{e\gamma}}} \right| \simeq s_e^2 \frac{\delta'^{\,2}}{\delta} \epsilon_\ell^2\, \mathrm{Im} \left(\frac{C^{e\gamma}_{VV\Delta}}{C^{e\gamma}_{\Delta}} - \frac{C^{y}_{VV\Delta}}{C^{y}_{\Delta}} + \frac{C_{3rd}}{|C^{e\gamma}_{\Delta}|} \right) < 1.8 \times 10^{-8}$$

$\sim 4 \times 10^{-9}$

constraint from $\mu \to e\gamma$ more tight

$\vee$

constraint from EDM d_e in U(2)



$(g-2)_\mu$ & $(g-2)_e$ in U(2)

$$\mathcal{C}'_{\substack{e\gamma \\ LR}} = \begin{pmatrix} \mathcal{C}'_{\substack{e\gamma \\ ee}} & \mathcal{C}'_{\substack{e\gamma \\ e\mu}} & \mathcal{C}'_{\substack{e\gamma \\ e\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \mu e}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \tau e}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\tau}} \end{pmatrix}$$

muon $(g-2)_\mu$ and electron $(g-2)_e$

U(2) relation $\dfrac{\mathrm{Re}\,\mathcal{C}'_{\substack{e\gamma \\ ee}}}{\mathrm{Re}\,\mathcal{C}'_{\substack{e\gamma \\ \mu\mu}}} \approx \dfrac{\blacksquare}{\blacksquare} = \dfrac{m_e}{m_\mu} \simeq 5 \times 10^{-3}$

$$\Delta a_e = \Delta a_\mu \frac{m_e}{m_\mu} \frac{\mathrm{Re}\,\mathcal{C}'_{\substack{e\gamma \\ ee}}}{\mathrm{Re}\,\mathcal{C}'_{\substack{e\gamma \\ \mu\mu}}} \approx \Delta a_\mu \times \left(\frac{m_e}{m_\mu}\right)^2 \sim 5.7 \times 10^{-14}$$

naive scaling

vs.

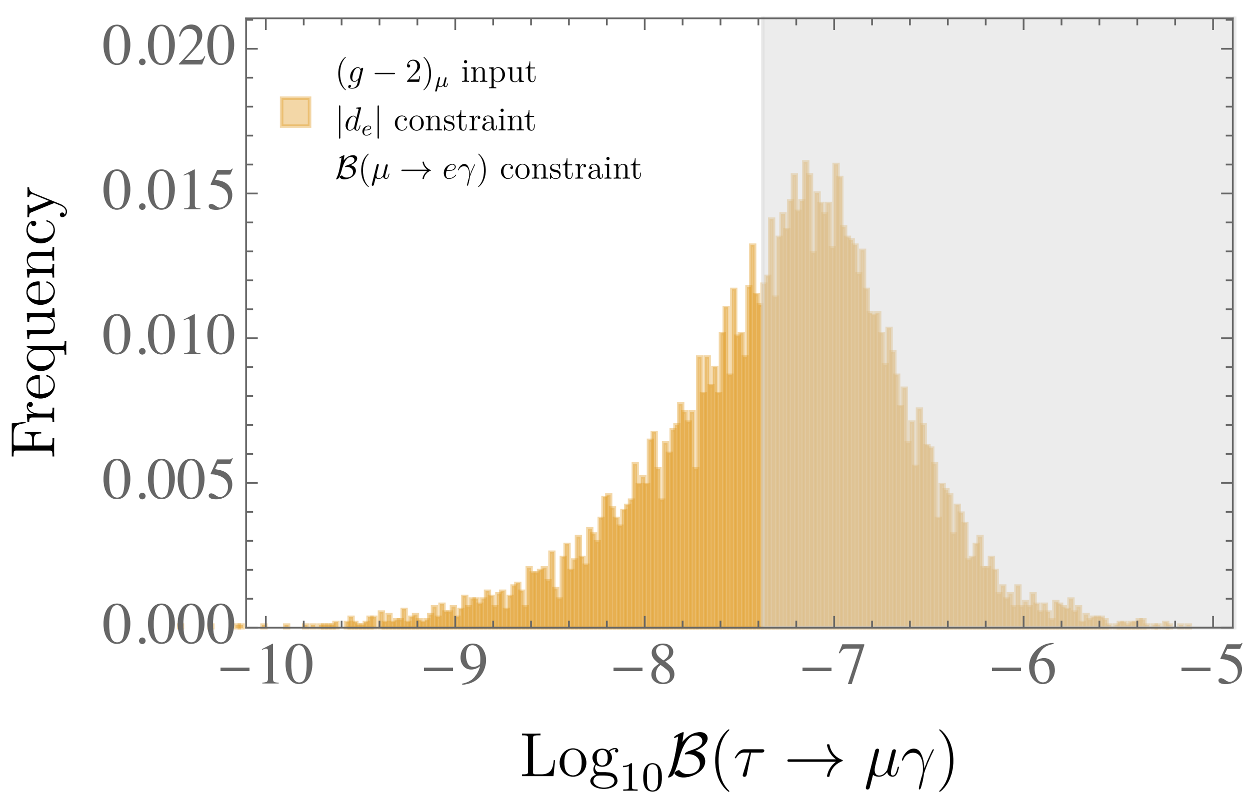
$$\Delta a_e^{Cs} = a_e^{\mathrm{Exp}} - a_e^{\mathrm{SM,CS}} = (-8.8 \pm 3.6) \times 10^{-13}$$
$$\Delta a_e^{Rb} = a_e^{\mathrm{Exp}} - a_e^{\mathrm{SM,Rb}} = (4.8 \pm 3.0) \times 10^{-13} \quad .$$

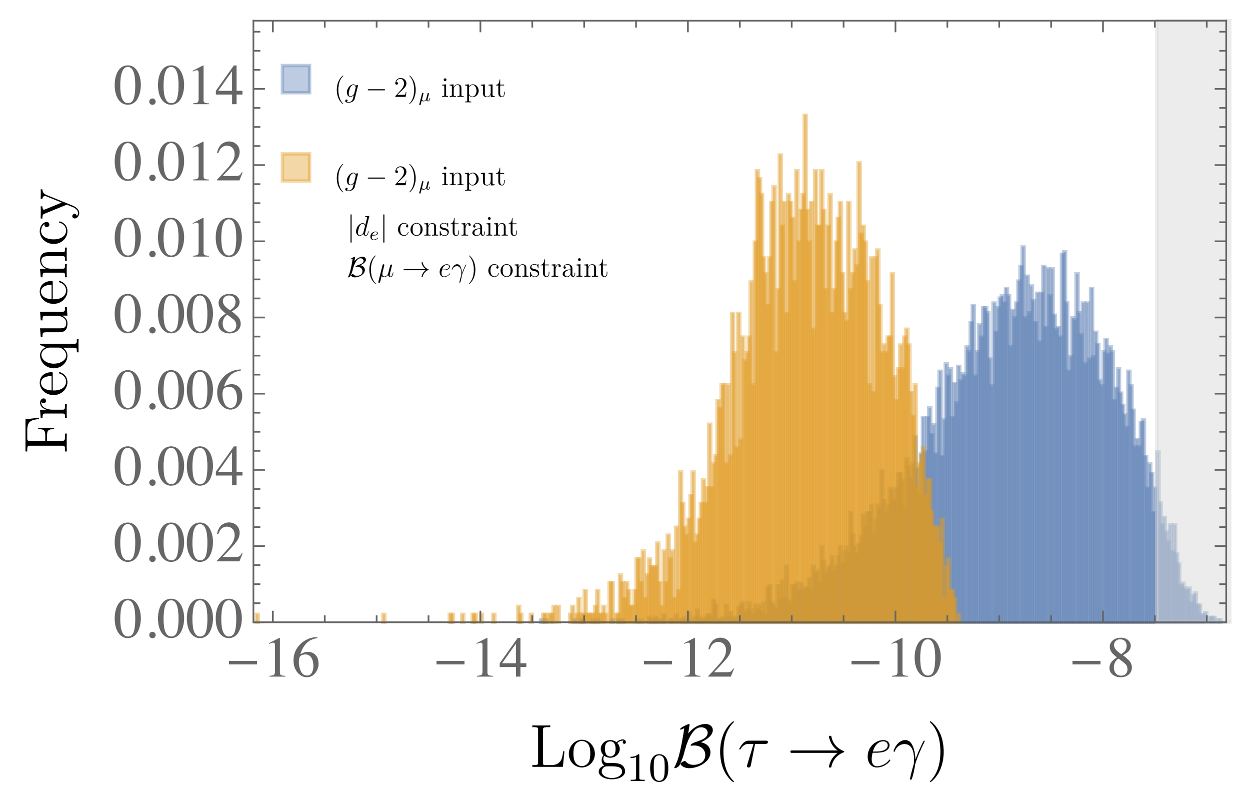
Predicted value is small of one order compared with the present observed one at present
Wait for the precise observation of the fine structure constant to test the framework

$(g-2)_\mu$ & $\tau \to \mu\gamma$, $\tau \to e\gamma$ in U(2)

$$\mathcal{C}'_{\underset{LR}{e\gamma}} = \begin{pmatrix} \mathcal{C}'_{\underset{ee}{e\gamma}} & \mathcal{C}'_{\underset{e\mu}{e\gamma}} & \mathcal{C}'_{\underset{e\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\mu e}{e\gamma}} & \mathcal{C}'_{\underset{\mu\mu}{e\gamma}} & \mathcal{C}'_{\underset{\mu\tau}{e\gamma}} \\ \mathcal{C}'_{\underset{\tau e}{e\gamma}} & \mathcal{C}'_{\underset{\tau\mu}{e\gamma}} & \mathcal{C}'_{\underset{\tau\tau}{e\gamma}} \end{pmatrix}$$

muon $(g-2)_\mu$ and $\tau \to \mu\gamma$, $\tau \to e\gamma$





→ Belle II

Summary

- Muon $(g-2)_\mu$& $\mu \to e\gamma$ → 新物理のフレーバー構造

Tight bound on flavor alignment $\mathcal{C}'_{\substack{e\gamma \\ LR}} = \begin{pmatrix} \mathcal{C}'_{\substack{e\gamma \\ ee}} & \mathcal{C}'_{\substack{e\gamma \\ e\mu}} & \mathcal{C}'_{\substack{e\gamma \\ e\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \mu e}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \mu\tau}} \\ \mathcal{C}'_{\substack{e\gamma \\ \tau e}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\mu}} & \mathcal{C}'_{\substack{e\gamma \\ \tau\tau}} \end{pmatrix}$

- そのフレーバー構造の背後にはフレーバー対称性があるかも

U(2) flavor symmetry

input $(g-2)_\mu$ anomaly

	$\mu \to e\gamma$	EDM d_e	EDM d_μ	$(g-2)_e$
U(2)	input	$\lvert d_e/e \rvert \lesssim 10^{-30}$cm	$\lvert d_\mu/e \rvert \lesssim 10^{-26}$cm	$\Delta a_\mu \times \left(\frac{m_e}{m_\mu}\right)^2$
Modular	$BR(\mu \to e\gamma) \lesssim 10^{-16}$	input	$\lvert d_\mu/e \rvert \lesssim 10^{-25}$cm	$\Delta a_\mu \times \left(\frac{m_e}{m_\mu}\right)^2$

naive scaling

- もしmuon $(g-2)_\mu$が新物理のシグナルであるならば、フレーバー対称性に依って、物理量間の相関が異なる形で出てくる