4体フェルミ演算子の中性子EDMへ与えるQCD補正

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PRESENTATION

基研研究会 素粒子物理学の進展
18-21/7/2012

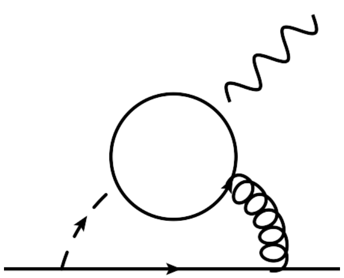
QCD Corrections to Neutron Electric Dipole Moment from Dimension-six Four-Quark Operators

J. Hisano, K. Tsumura and M. J.S. Yang, Phys. Lett. B713 (2012) 473

Outline

- EDM and CP violation
- What's new ?
- RG improvement
- Numerical evaluation

Purpose: Proper treatment of EDM by RGE



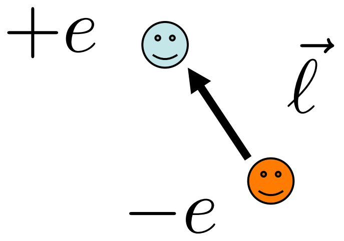
What is the EDM?

◻ Electric dipole moment (EDM)

Classical picture:

a measure of the separation of positive and negative electrical charges in a system of charges

$$\vec{d} = e\,\vec{\ell}$$



For point-like particle:

Spin is only the **vector** quantity for spin ½ particle

$$\vec{d} = d\,\vec{s}$$

- **A neutral non-relativistic particle w/ spin S in EM fields**

$$\mathcal{H} = -\mu\,\mathbf{B}\cdot\mathbf{s} - d\,\mathbf{E}\cdot\mathbf{s}$$

  - μ is Magnetic dipole moment (MDM)
  - **d is Electric dipole moment (EDM)**

→ **d** breaks **P** and **T** reflections.

$$\mathbf{P}(\mathbf{B}\cdot\mathbf{s}) = \mathbf{B}\cdot\mathbf{s}, \qquad \mathbf{P}(\mathbf{E}\cdot\mathbf{s}) = -\mathbf{E}\cdot\mathbf{s}$$

$$\mathbf{T}(\mathbf{B}\cdot\mathbf{s}) = \mathbf{B}\cdot\mathbf{s}, \qquad \mathbf{T}(\mathbf{E}\cdot\mathbf{s}) = -\mathbf{E}\cdot\mathbf{s}$$

↕

$$\mathbf{CP}(\mathbf{E}\cdot\mathbf{s}) = -\mathbf{E}\cdot\mathbf{s}$$

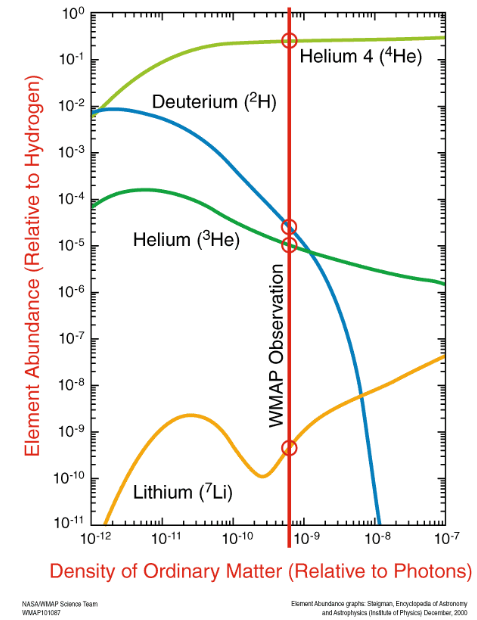
EDM is a CPV (via CPT theo.) **observable!!**

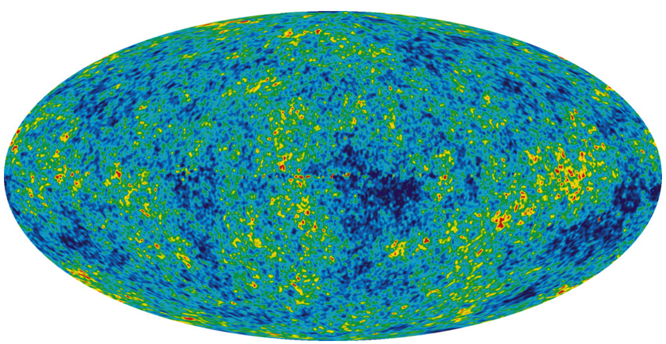
Why CP violation?

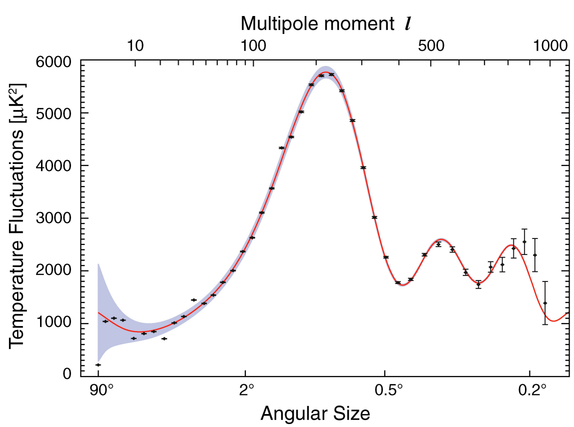
New source of CP violation?

Baryon asymmetry

$$\eta = \frac{n_B}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}$$







Baryon asymmetry

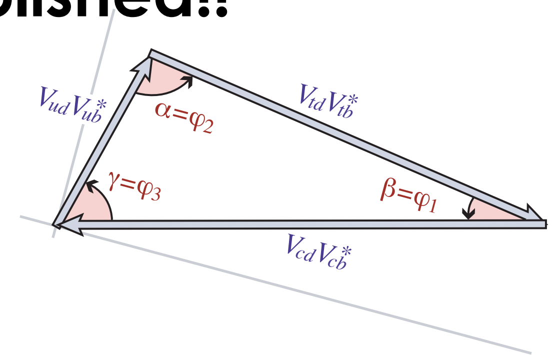
Sakharov conditions:

- B# violation
- C and **CP violation**
- Interactions out of thermal equilibrium

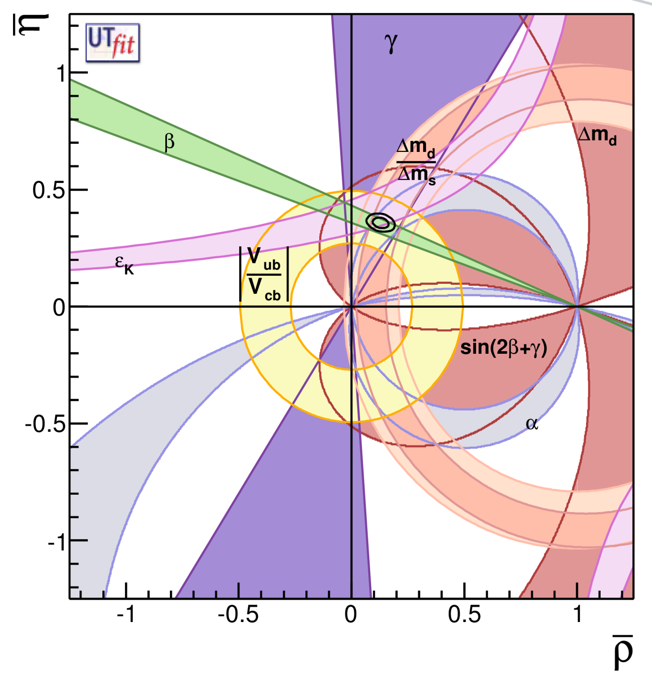
$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \simeq \arg\left(-\frac{1-\rho-i\eta}{\rho+i\eta}\right),$$
$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \simeq \arg\left(\frac{1}{1-\rho-i\eta}\right),$$
$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \simeq \arg(\rho+i\eta).$$

- **KM (Kobayashi-Maskawa) phase has been established!!**

A unique source of CP violation in the SM



$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$



Consistent with most of flavor data,

however…

Baryon asymmetry

Measure of CPV:

$$J = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)A$$

$$A = 2 \times (\text{Unitarity triangle})$$

Too small CP violation in the SM

$$\frac{J}{T_c^{12}} \sim 10^{-20}$$

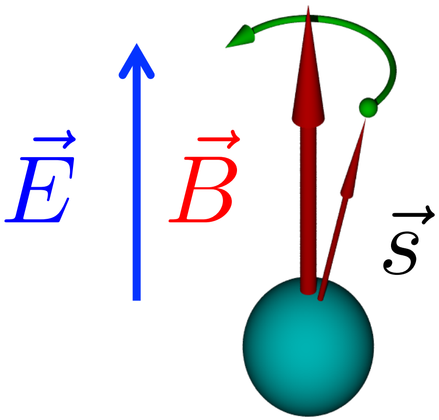
KM phase is not sufficient to explain BAU!!

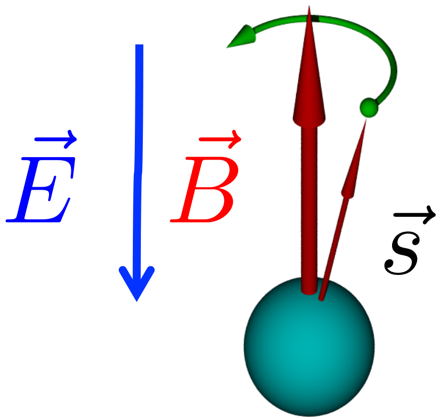
Need new source of CPV

◻ How do we measure EDMs?

Larmor precession

$$\frac{d\vec{s}}{dt} = -\mu\,\vec{B}\times\vec{s} - d\,\vec{E}\times\vec{s}$$





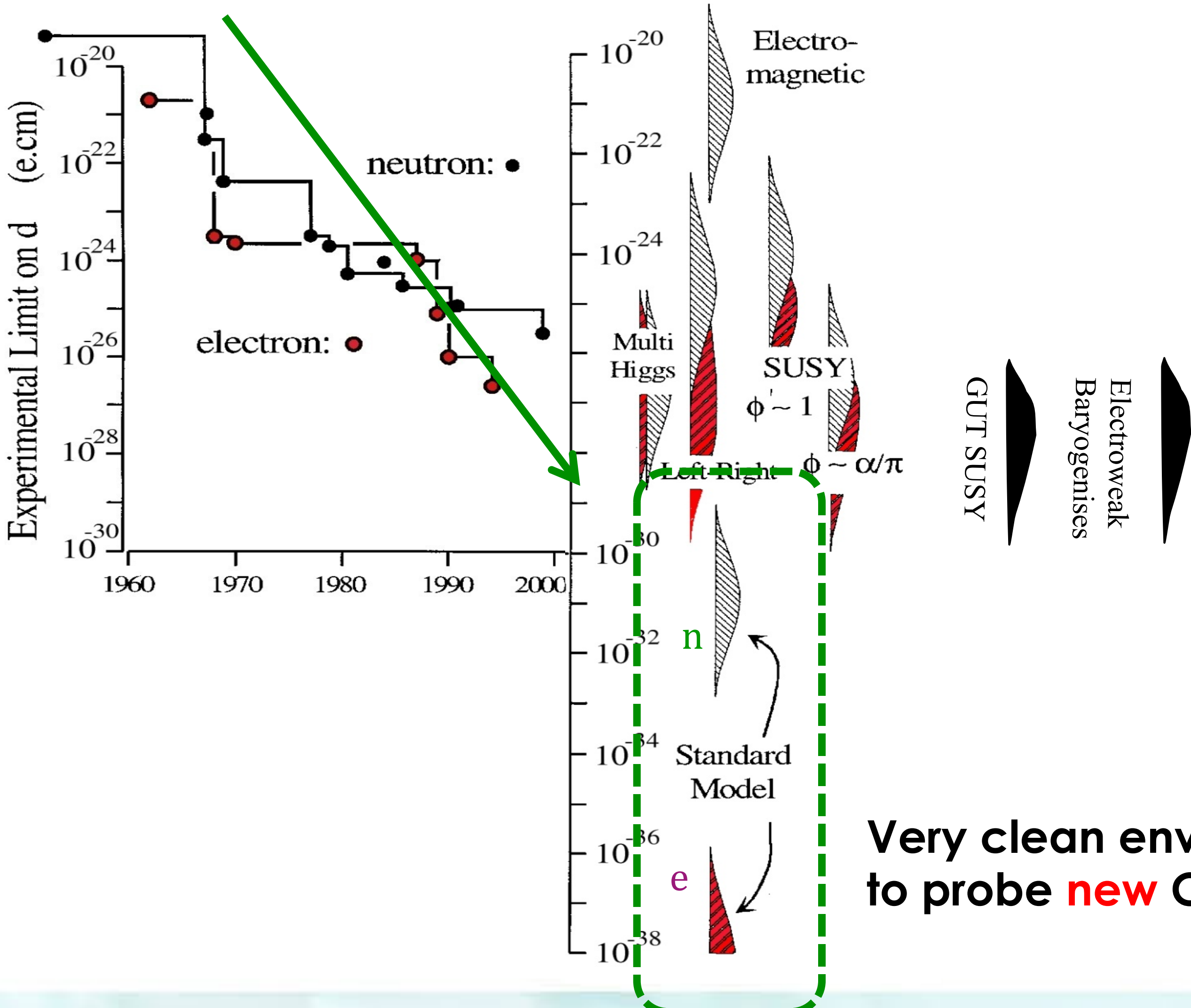
$$\omega_+ = \frac{+2\mu B + 2d E}{\hbar}$$

$$\omega_- = \frac{+2\mu B - 2d E}{\hbar}$$

$$d = \frac{\hbar\Delta\omega}{4E}$$

Measure the difference of angular frequency!!

◻ SM prediction



Very clean environment to probe new CP violation

□ Current experimental bounds

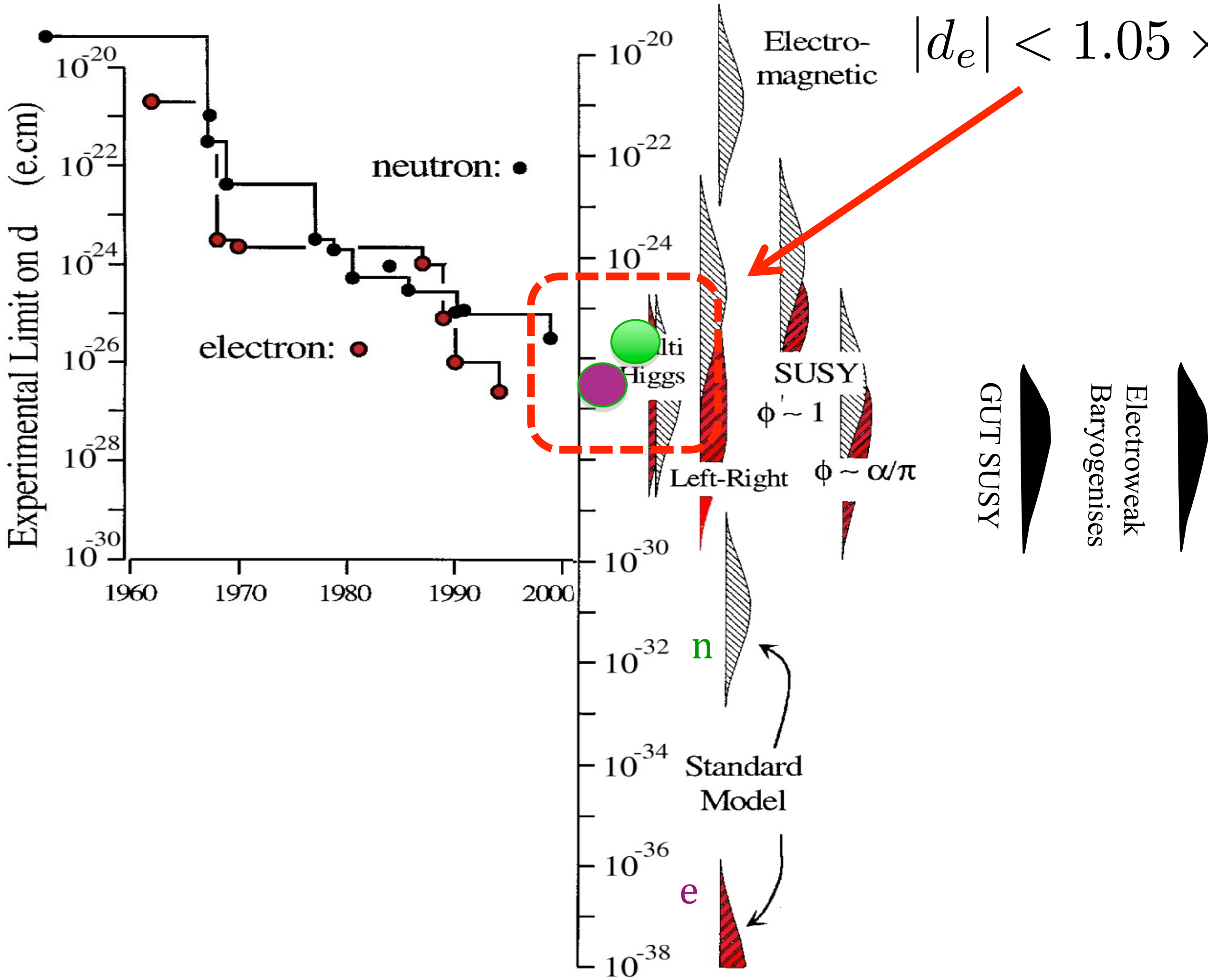
$$|d_n| < 2.9 \times 10^{-26} e \text{ cm}$$

$$|d_e| < 1.05 \times 10^{-27} e \text{ cm}$$

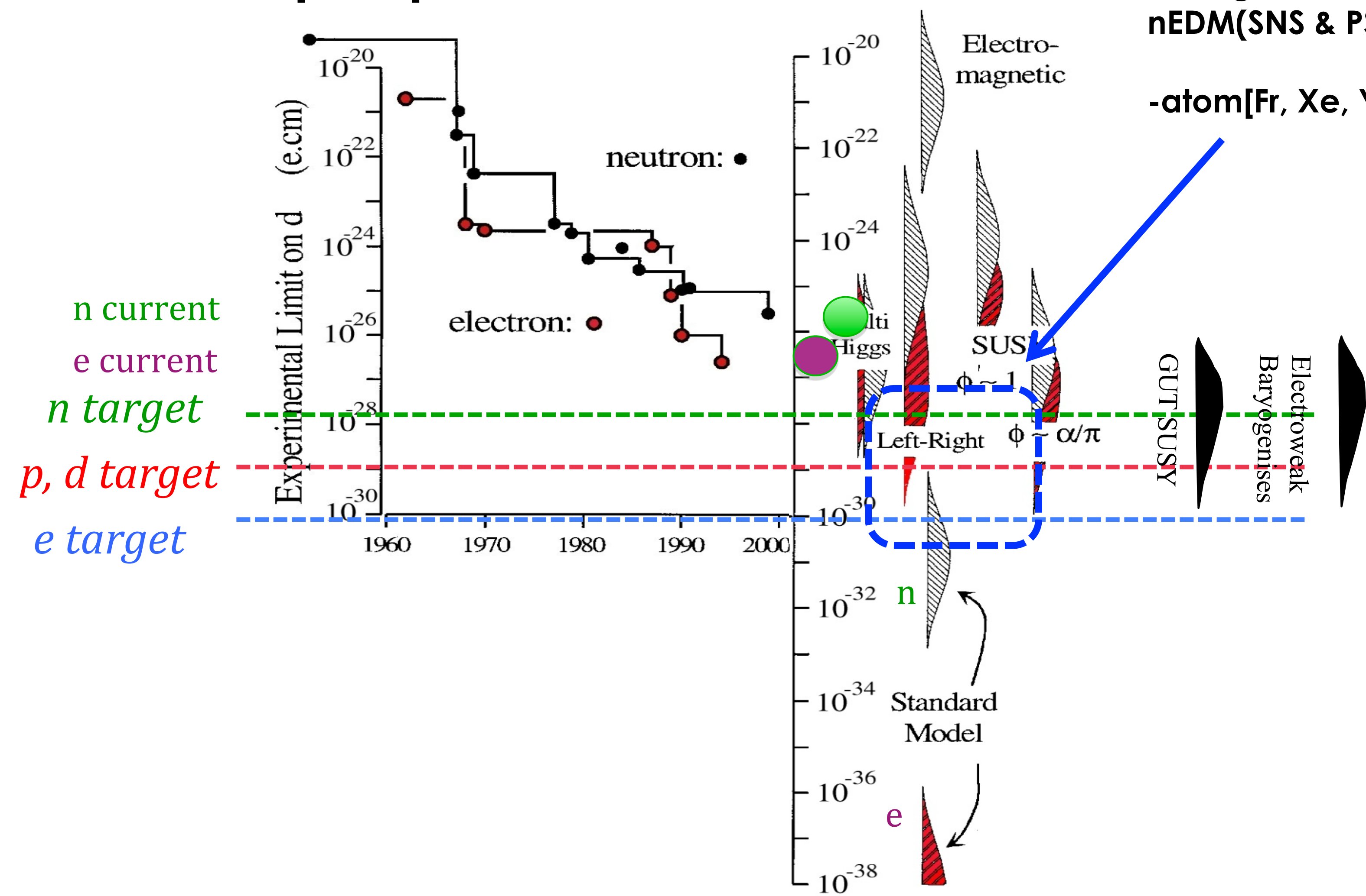
[Tl, YbF]

n current

e current



▫ Future prospects



Next Generations

-n target;

nEDM(SNS & PSI), CryoEDM

~10^{-28}

-atom[Fr, Xe, Yb, …](→ d_e,d_n);

CPV operators

Strong CP (D=4)

$$+\frac{g_s^2}{32\pi^2}\,\bar{\theta}\,G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu}$$

→**can induce d** (neglect the following discussions)

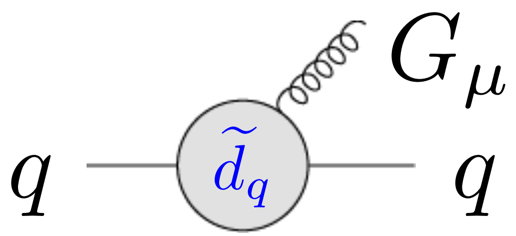
- It can be controlled by adopting PQ sym.

EDM and ChromoEDM (D=5)

$$-\frac{i}{2}\sum_f d_f\,\overline{f}\gamma^5\sigma^{\mu\nu}f\,F_{\mu\nu} = d_f\overline{f}\left[+i\begin{pmatrix}\sigma\cdot\mathbf{E} & 0\\ 0 & \sigma\cdot\mathbf{E}\end{pmatrix} - \begin{pmatrix}0 & \sigma\cdot\mathbf{B}\\ \sigma\cdot\mathbf{B} & 0\end{pmatrix}\right]f$$

$$-\frac{i}{2}\sum_q \widetilde{d}_q\,\overline{q}\gamma^5\sigma^{\mu\nu}T^a q\,G^a_{\mu\nu}$$

→ **Induce neutron EDM**



$$\mathcal{H} = -\mu\,\mathbf{B}\cdot\mathbf{s} - d\,\mathbf{E}\cdot\mathbf{s}$$

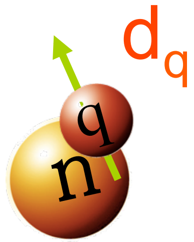
- CPV operators
  - Weinberg's three gluon (D=6)

$$+\frac{1}{3}w f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$$

  - 4 Fermi (D=6)

$$+C^S_{ij}(\overline{\psi}\psi)(\overline{\psi}i\gamma_5\psi) + C^T_{ij}(\overline{\psi}\sigma_{\mu\nu}\psi)(\overline{\psi}i\gamma_5\sigma_{\mu\nu}\psi)$$

Evaluation of neutron EDM



There are some methods to evaluate nEDM

w/ relatively large uncertainties

- SU(6) quark model (w/o QCD corr.)

$$d_n = \frac{1}{3}(4d_d - d_u)$$ Manohar, Georgi, NPB234 (1984) 189

- Chiral techniques Crewther, Vecchia, Veneziano, Witten PLB88 (1979) 123

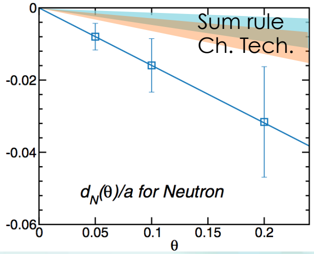
$$d_n = \frac{e}{4\pi^2 m_n} g_{\pi NN} \bar{g}^{(0)}_{\pi NN} \ln \frac{\Lambda}{m_\pi}$$

- QCD sum rules Pospelov, Ritz, PRL83 (1999) 2526

$$d_n = 2.9 \times 10^{-17}\bar{\theta} + 0.32 d_d - 0.08 d_u + e(-0.12\tilde{d}_u + 0.12\tilde{d}_d - 0.006\tilde{d}_s)$$

Hisano, Lee, Nagata, Shimizu, PRD85 (2012) 114044

- Lattice estimation



Shintani et.al. PRD75 (2007) 034507

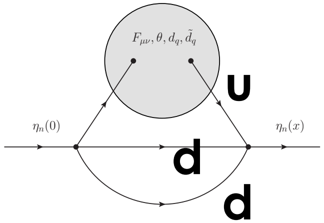
永田くん→

- **QCD sum rules**
  - Calculate neutron correlation function by 2 method
    - OPE:

      Expand neutron interpolating field by **parton**

$$\eta_n(x) = j_1(x) + \beta j_2(x)$$

$$j_1 = 2\epsilon_{abc}(d_a^T C\gamma_5 u_b)d_c\,, \quad j_2 = 2\epsilon_{abc}(d_a^T C u_b)\gamma_5 d_c$$

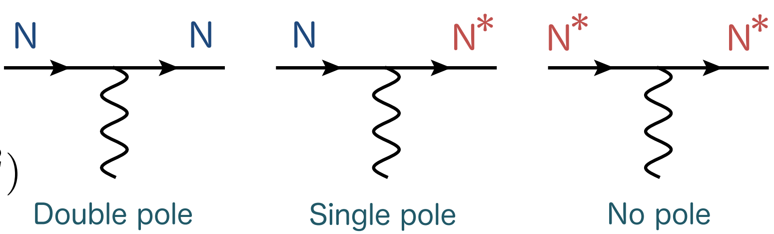


    - phenomenological model

      Expand around neutron pole mass

$$\Pi^{(\mathrm{phen})}(q) = \frac{1}{2} f(q^2)\{\tilde{F}\sigma, \not{q}\} + \cdots$$

$$f(q^2) = \frac{\lambda_n^2 d_n m_n}{(q^2 - m_n^2)^2} + \frac{A(q^2)}{q^2 - m_n^2} + B(q^2)$$



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永田くん→

- QCD sum rules

PLEASE ASK 永田くん

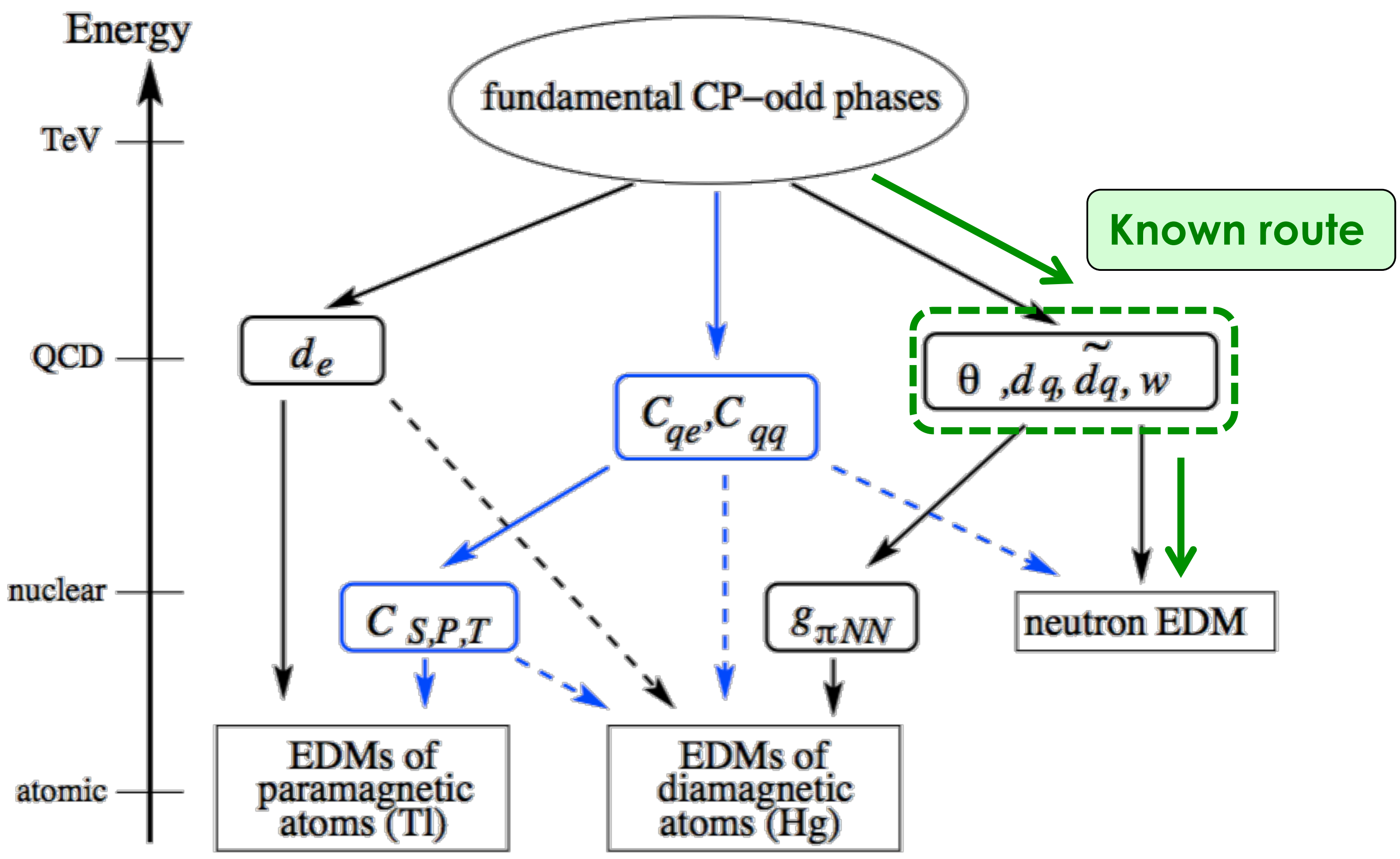
For our numerical evaluation we use;

Hisano, Lee, Nagata, Shimizu, PRD85 (2012) 114044

$$d_n = 2.9 \times 10^{-17}\bar{\theta} + 0.32 d_d - 0.08 d_u + e(-0.12\tilde{d}_u + 0.12\tilde{d}_d - 0.006\tilde{d}_s)$$

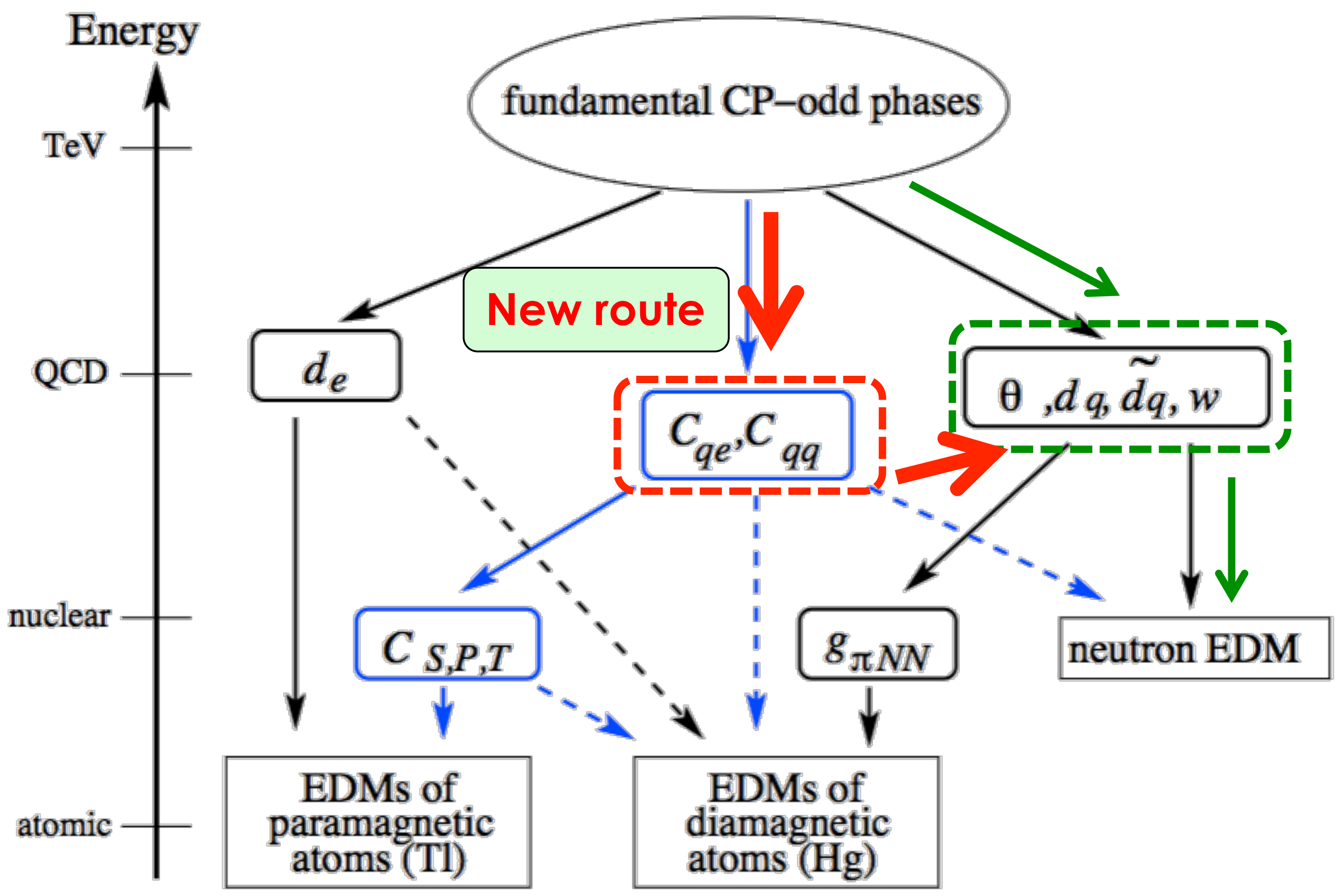
What’s new?

▫ Over view



Energy
TeV
QCD
nuclear
atomic
fundamental CP–odd phases
Known route
d_e
C_{qe}, C_{qq}
θ , d_q, $\tilde{d}_q$, w
$C_{S,P,T}$
$g_{\pi NN}$
neutron EDM
EDMs of paramagnetic atoms (Tl)
EDMs of diamagnetic atoms (Hg)

◻ Over view



Energy
TeV
QCD
nuclear
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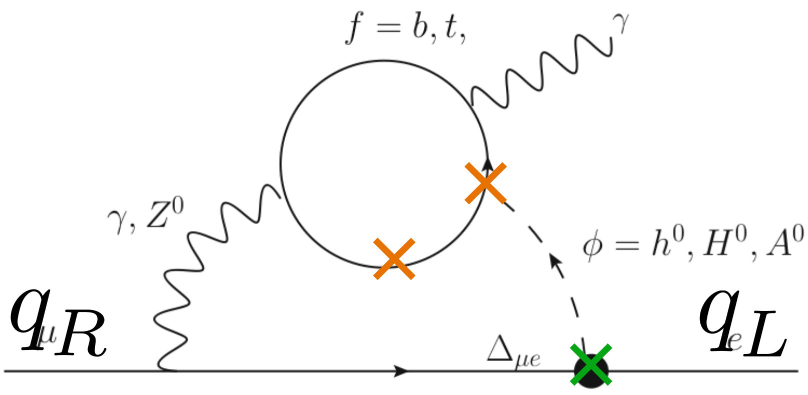
fundamental CP–odd phases
New route
d_e
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
$C_{S,P,T}$
$g_{\pi NN}$
neutron EDM
EDMs of paramagnetic atoms (Tl)
EDMs of diamagnetic atoms (Hg)

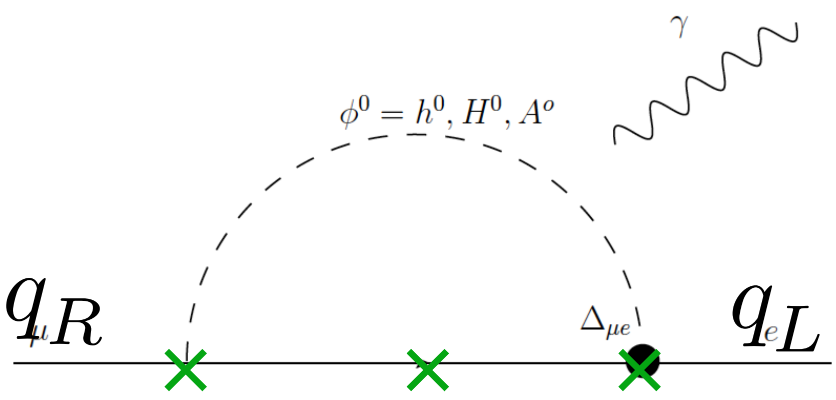
□ Barr-Zee diagram (an example)



An important 2-loop contribution to EDM.

$$\frac{A^{\text{2-loop}}}{A^{\text{1-loop}}} \sim \frac{\alpha}{4\pi} \frac{m_F^2}{m_q^2} \ln \frac{m_F^2}{m_H^2}$$

The effect can be as large as 1-loop.



-"2-loop" is enhanced by large Yukawa and heavy mass.

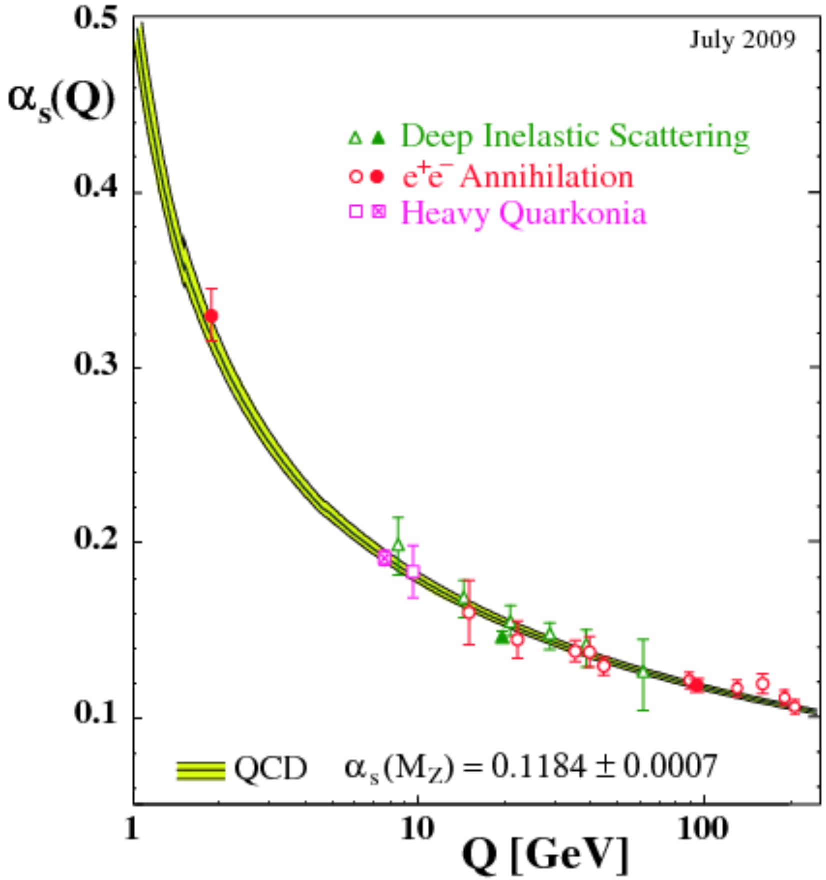
$$cf. \quad m_F \to m_b \tan\beta$$

-"1-loop" is suppressed by multi-mq insertions.

QCD corrections

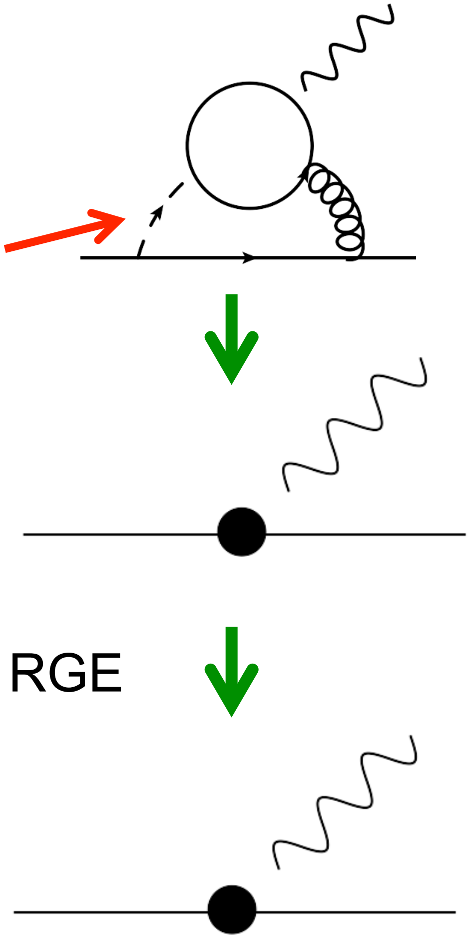
Running effect is potentially large

- Running α_s



$$\frac{d\alpha_s}{d\ln\mu^2} = \beta$$

□ Previous calculations:



$$\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}$$

Integrate NP particles

$$\mathcal{L}_{\rm SM} + \delta\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm Dim\geq 5}$$

$$\leftrightarrow d_i, \tilde{d}_i(m_{\rm NP})$$

Introduce Running α_s, Operators mixing

and then, evaluate

$$d_i, \tilde{d}_i(\sim 1\,{\rm GeV})$$

However…

- Our calculations:

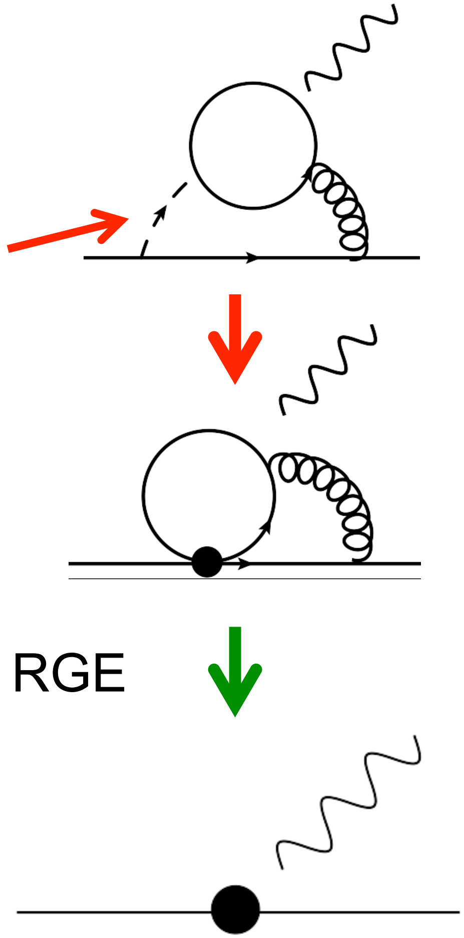
>1TeV

CPV Higgs

$m_{\rm NP}$

RGE

$\sim$1GeV



$$\mathcal{L}_{\rm SM}+\mathcal{L}_{\rm NP}$$

Integrate NP particles

$$\mathcal{L}_{\rm SM}+\delta\mathcal{L}_{\rm SM}+\mathcal{L}_{{\rm Dim}\geq 5}$$

$$\leftrightarrow d_i,\tilde{d}_i,C_{ij}(m_{\rm NP})$$

Introduce Running α_s, Operators mixing

and then, evaluate

$$d_i,\tilde{d}_i(\sim 1\,{\rm GeV})$$

- CPV effect is described by
  - **Theta term**: $\mathcal{L}_4 = \frac{g_s^2}{32\pi^2}\bar{\theta}\, G^a_{\mu\nu} G^a_{\mu\nu}$
  - **EDM** and **CEDM**:

$$\mathcal{L}_5 = -\frac{i}{2}\sum_i d_i \overline{\psi}_i \sigma_{\mu\nu}\gamma_5 \psi F_{\mu\nu} \; - \frac{i}{2}\sum_i \tilde{d}_i \overline{\psi}_i \sigma_{\mu\nu}\gamma_5 \psi G_{\mu\nu}$$

  - **Weinberg's** and **4-Fermi**:

$$\mathcal{L}_6 = \frac{1}{3} w\; f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \; + \sum_{ij} C^S_{ij} (\overline{\psi}_i \psi_i)(\overline{\psi}_j i\gamma_5 \psi_j) + \sum_{ij} C^T_{ij} (\overline{\psi}_i \sigma_{\mu\nu} \psi_i)(\overline{\psi}_j i\gamma_5 \sigma_{\mu\nu} \psi_j)$$

Eff. Hamiltonian in the previous studies

$$\mathcal{H}_{\rm CPV} = +\sum_q C_1^q(\mu)\mathcal{O}^q_{\rm EDM}(\mu) + \sum_q C_2^q(\mu)\mathcal{O}^q_{\rm CEDM}(\mu) + C_3(\mu)\mathcal{O}^q_{\rm Weinberg}(\mu)$$

Renormalization Group

$$\vec{C} = (C_1^q, C_2^q, C_3)^T$$

$$\frac{d\vec{C}(\mu)}{d\ln\mu} = \vec{C}(\mu)\Gamma$$

$$\Gamma = \frac{\alpha_s}{4\pi}\gamma_s = \frac{\alpha_s}{4\pi}\begin{pmatrix} +8C_F & 0 & 0 \\ +8C_F & +16C_F - 4N & 0 \\ 0 & -2N & N + 2n_f + \beta_0 \end{pmatrix}$$

Eff. Hamiltonian in the previous studies

$$\mathcal{H}_{\rm CPV} = +\sum_q C_1^q(\mu)\mathcal{O}^q_{\rm EDM}(\mu) + \sum_q C_2^q(\mu)\mathcal{O}^q_{\rm CEDM}(\mu) + C_3(\mu)\mathcal{O}^q_{\rm Weinberg}(\mu)$$

Renormalization Group

$$\vec{C} = (C_1^q, C_2^q, C_3)^T$$

$$\frac{d\vec{C}(\mu)}{d\ln\mu} = \vec{C}(\mu)\Gamma$$

Ex. $C_1^q(m_\phi) = C_3(m_\phi) = 0$

Induced by operator mixing

$$C_1^q(m_b) = (+8\eta^{16/23} - 8\eta^{14/23})C_2^q(m_\phi) \sim -0.28C_2^q(m_\phi)$$

$$C_2^q(m_b) = \eta^{14/23}C_2^q(m_\phi) \sim +0.70C_2^q(m_\phi)$$

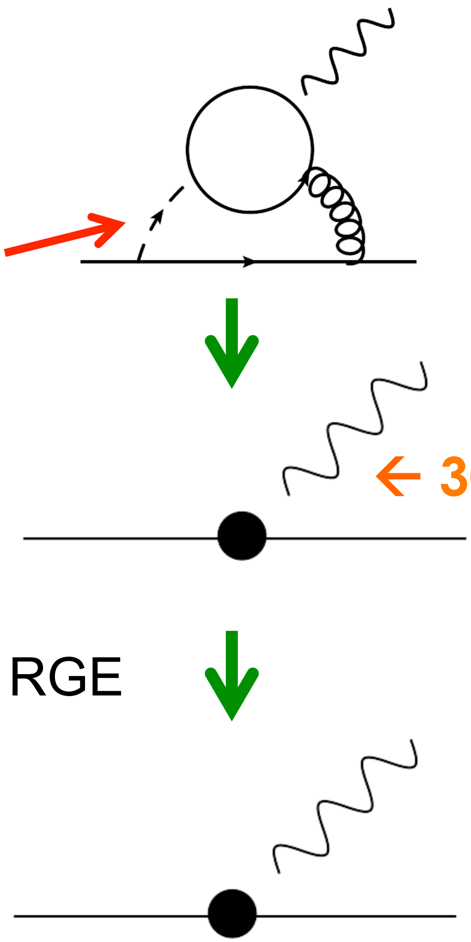
$$\eta = \alpha_s(m_\phi)/\alpha_s(m_b)$$

Corrected 30% by QCD

□ Previous calculations:

$>$1TeV

CPV Higgs



$$\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}$$

Integrate NP particles

$m_{\rm NP}$

← 30% correction to CEDM

Introduce Running α_s, Operators mixing

and then, evaluate

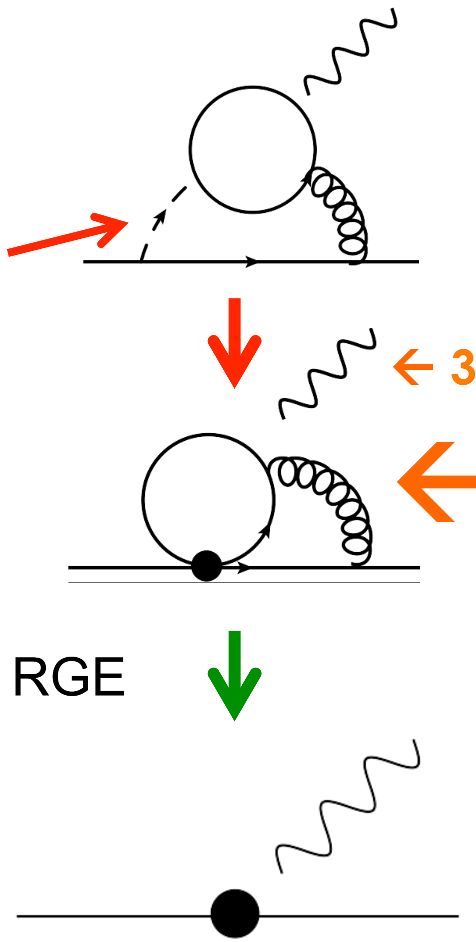
$$d_i\,,\,\tilde{d}_i(\sim 1\,\mathrm{GeV})$$

∼1GeV

- Our calculations:

$>$1TeV

CPV Higgs



m_{NP}

～1GeV

$$\mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{NP}}$$

Integrate NP particles

← 30% correction to CEDM

← **How BIG?** (same QCD order)

Introduce Running α_s, Operators mixing

and then, evaluate

$$d_i\,,\,\tilde{d}_i(\sim 1\,\mathrm{GeV})$$

- **A full set of operators**
  - EDM, CEDM, Weinverg
  - +same flavor 4-Fermi ops.
  - +diff. flavor 4-Fermi ops.

$$O_4^q = \overline{q_\alpha} q_\alpha \overline{q_\beta} i\gamma_5 q_\beta$$

$$O_5^q = \overline{q_\alpha} \sigma_{\mu\nu} q_\alpha \overline{q_\beta} i\gamma_5 \sigma_{\mu\nu} q_\beta$$

$$\widetilde{O}_1^{q'q} = \overline{q'_\alpha} q'_\alpha \overline{q_\beta} i\gamma_5 q_\beta$$

$$\widetilde{O}_2^{q'q} = \overline{q'_\alpha} q'_\beta \overline{q_\beta} i\gamma_5 q_\alpha$$

diff. in color structure

$$\widetilde{O}_3^{q'q} = \overline{q'_\alpha} \sigma_{\mu\nu} q'_\alpha \overline{q_\beta} i\gamma_5 \sigma_{\mu\nu} q_\beta$$

$$\widetilde{O}_4^{q'q} = \overline{q'_\alpha} \sigma_{\mu\nu} q'_\beta \overline{q_\beta} i\gamma_5 \sigma_{\mu\nu} q_\alpha$$

$$\frac{d\vec{C}(\mu)}{d\ln\mu} = \vec{C}(\mu)\Gamma$$

$$\vec{C} = (C_1^q, C_2^q, C_3, C_4^q, C_5^q, C_1^{q'q}, C_2^{q'q}, C_1^{qq'}, C_2^{qq'}, C_3^{q'q}, C_4^{q'q})^T$$

What's new?

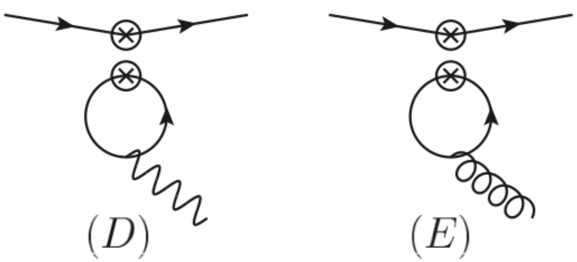
- RGE up to D=6

Known part for (C)EDM & Weinberg's

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_s & \mathbf{0} & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma_{sf} & \frac{\alpha_s}{4\pi}\gamma_f & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma'_{sf} & \mathbf{0} & \frac{\alpha_s}{4\pi}\gamma'_f \end{pmatrix}$$

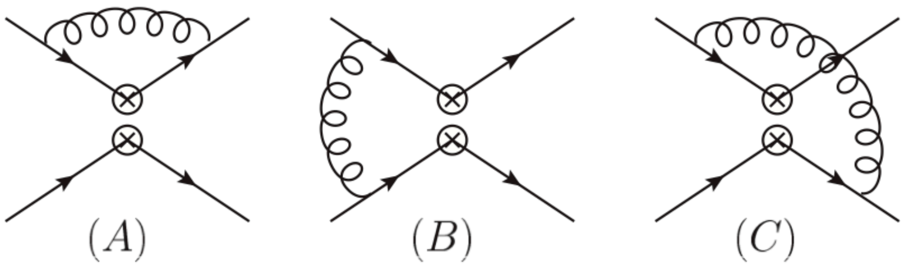
New parts!!

4F⇒EDM



4F⇔4F

1 gluon exchange



$$\vec{C} = (C_1^q, C_2^q, C_3, C_4^q, C_5^q, C_1^{q'q}, C_2^{q'q}, C_1^{qq'}, C_2^{qq'}, C_3^{q'q}, C_4^{q'q})^T$$

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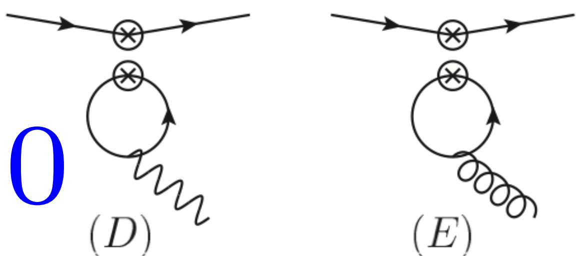
- RGE up to D=6

Known part for (C)EDM & Weinberg's

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_s & 0 & 0 \\ \frac{1}{(4\pi)^2}\gamma_{sf} & \frac{\alpha_s}{4\pi}\gamma_f & 0 \\ \frac{1}{(4\pi)^2}\gamma'_{sf} & 0 & \frac{\alpha_s}{4\pi}\gamma'_f \end{pmatrix}$$

New parts!!

4F⇒EDM

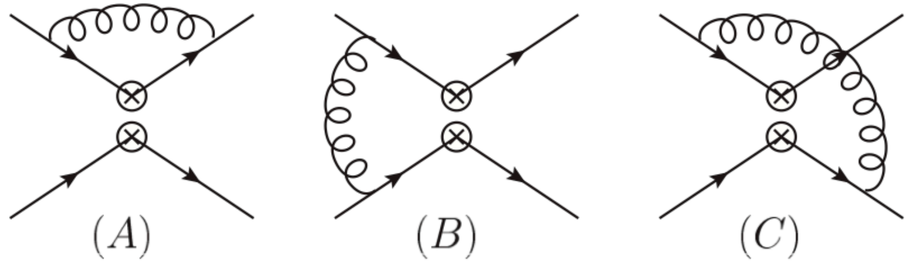


α_s^0

0 gluon exchange

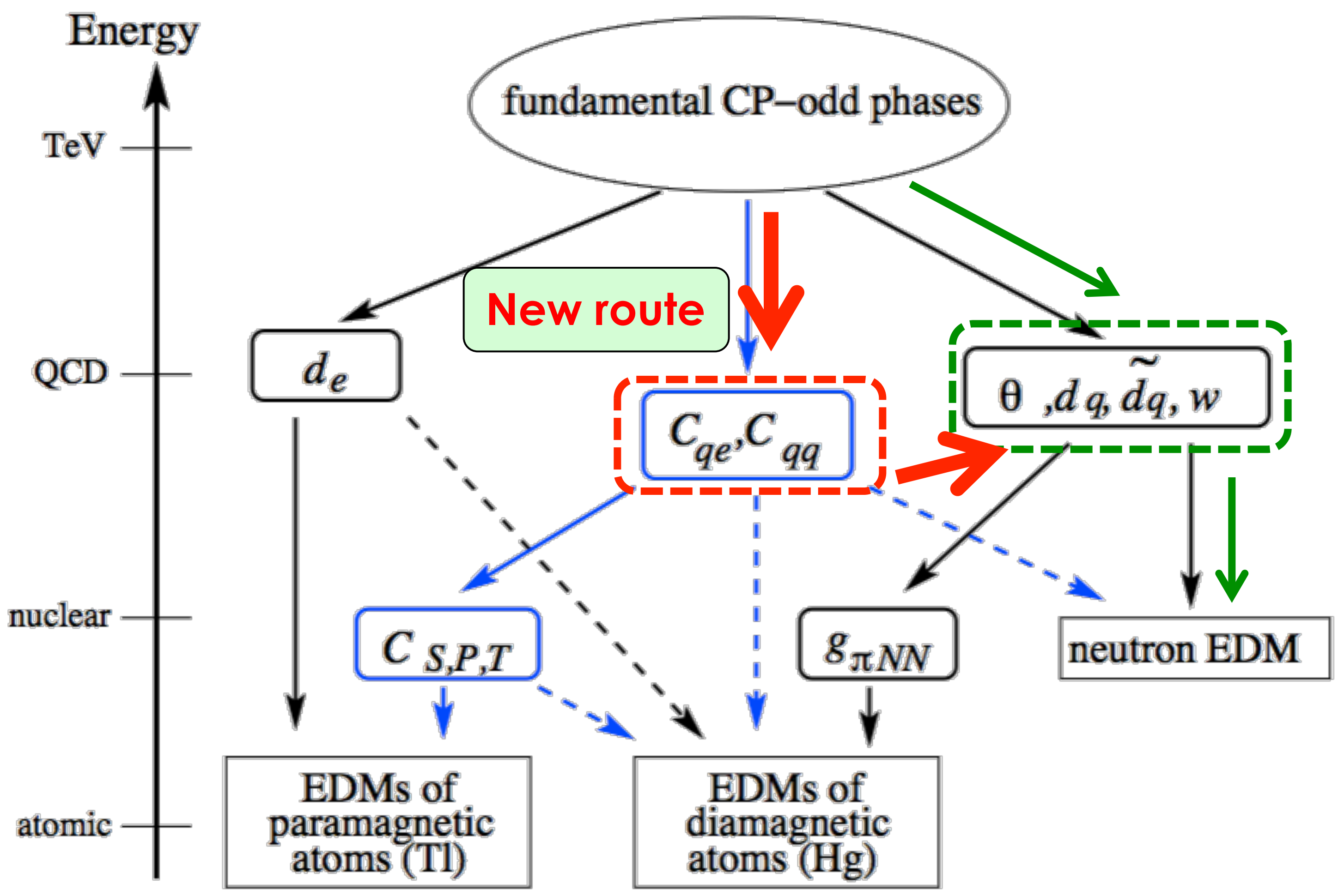
4F⇔4F

1 gluon exchange



$$\vec{C} = (C_1^q, C_2^q, C_3, C_4^q, C_5^q, C_1^{q'q}, C_2^{q'q}, C_1^{qq'}, C_2^{qq'}, C_3^{q'q}, C_4^{q'q})^T$$

▫ Over view


Energy
TeV
QCD
nuclear
atomic
fundamental CP–odd phases
New route
d_e
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
$C_{S,P,T}$
$g_{\pi NN}$
neutron EDM
EDMs of paramagnetic atoms (Tl)
EDMs of diamagnetic atoms (Hg)

▫ Numerical evaluation

- ▫ **Consider: a real scalar with CPV Yukawa**

$$\mathcal{L}_\phi = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\alpha \phi$$

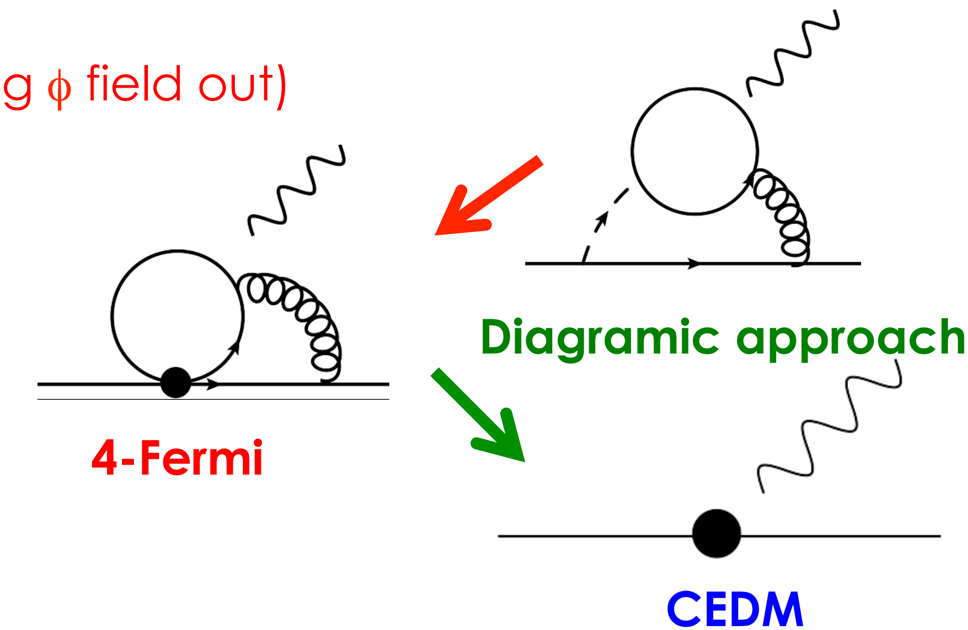
- ▫ **Induce 4-Fermi int.** (integrating ϕ field out)

Boundary cond. @ mϕ

$$C_4^q(m_\phi) = \sqrt{2} G_F \frac{m_q^2}{m_\phi^2} f_S^q f_P^q$$

$$\widetilde{C}_1^{q'q}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^q f_P^{q'}$$

$$\widetilde{C}_1^{qq'}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^{q'} f_P^q$$



$$C_2^q(\mathrm{CEDM}) = \frac{\alpha_s(m_\phi)}{8\pi^3} \frac{m_{q'}}{m_q} \left(\ln \frac{m_\phi}{m_{q'}} \right)^2 \left[\widetilde{C}_1^{q'q} + \widetilde{C}_1^{qq'} \right]$$

Numerical evaluation

- $$\frac{A^{2\text{-loop}}}{A^{1\text{-loop}}} \sim \frac{\alpha}{4\pi}\frac{m_F^2}{m_q^2}\ln\frac{m_F^2}{m_H^2}$$

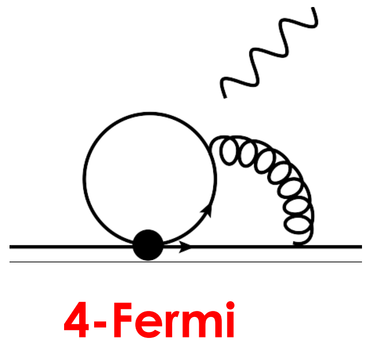
- **Induce 4-Fermi int.** (integrating ϕ field out)

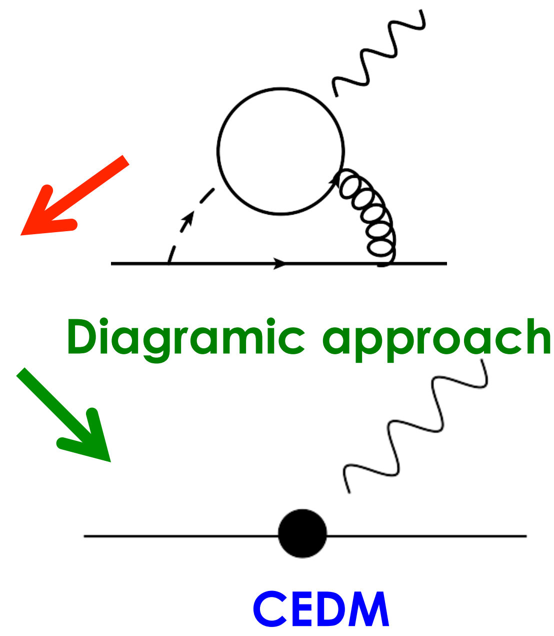
Boundary cond. @ mϕ

$$C_4^q(m_\phi) = \sqrt{2}G_F\frac{m_q^2}{m_\phi^2}f_S^q f_P^q$$

$$\widetilde{C}_1^{q'q}(m_\phi) = \sqrt{2}G_F\frac{m_q m_{q'}}{m_\phi^2}f_S^q f_P^{q'}$$

$$\widetilde{C}_1^{qq'}(m_\phi) = \sqrt{2}G_F\frac{m_q m_{q'}}{m_\phi^2}f_S^{q'} f_P^q$$





$$C_2^q(\text{CEDM}) = \frac{\alpha_s(m_\phi)}{8\pi^3}\frac{m_{q'}}{m_q}\left(\ln\frac{m_\phi}{m_{q'}}\right)^2\left[\widetilde{C}_1^{q'q} + \widetilde{C}_1^{qq'}\right]$$

- **Numerical evaluation**
  -

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_s & \mathbf{0} & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma_{sf} & \frac{\alpha_s}{4\pi}\gamma_f & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma'_{sf} & \mathbf{0} & \frac{\alpha_s}{4\pi}\gamma'_f \end{pmatrix}$$

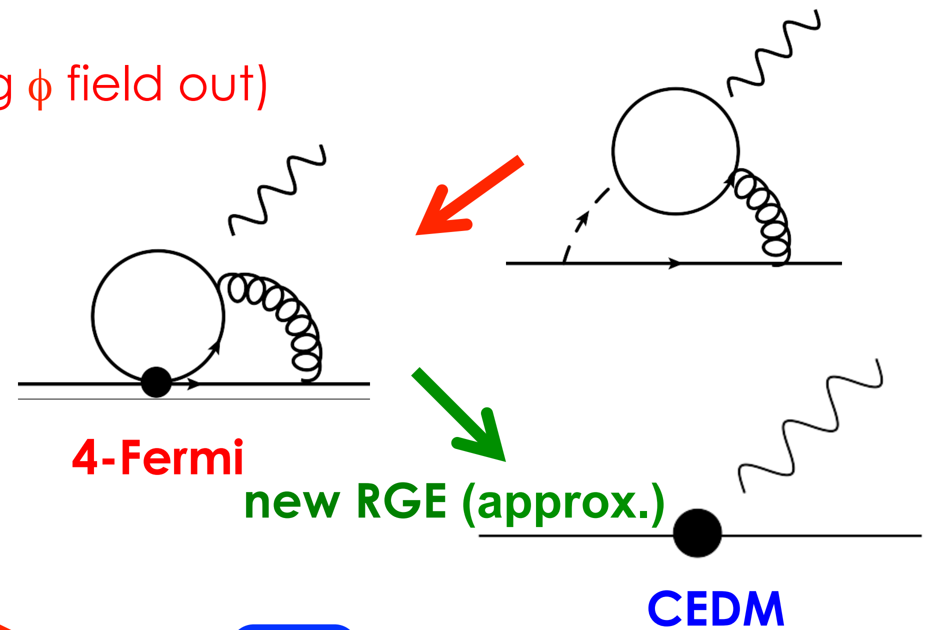
  - **Induce 4-Fermi int.** (integrating ϕ field out)

Boundary cond. @ mϕ

$$C_4^q(m_\phi) = \sqrt{2}G_F \frac{m_q^2}{m_\phi^2} f_S^q f_P^q$$

$$\widetilde{C}_1^{q'q}(m_\phi) = \sqrt{2}G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^q f_P^{q'}$$

$$\widetilde{C}_1^{qq'}(m_\phi) = \sqrt{2}G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^{q'} f_P^q$$



Cancel light-q Yukawa

$$C_2^q(\mathrm{CEDM}) = \frac{\alpha_s(m_\phi)}{8\pi^3}\frac{m_{q'}}{m_q}\left(\ln\frac{m_\phi}{m_{q'}}\right)^2\left[\widetilde{C}_1^{q'q} + \widetilde{C}_1^{qq'}\right]$$

Factor come froms γ

Numerical evaluation

- Consider: a real scalar with CPV Yukawa

$$\mathcal{L}_\phi = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\alpha \phi$$

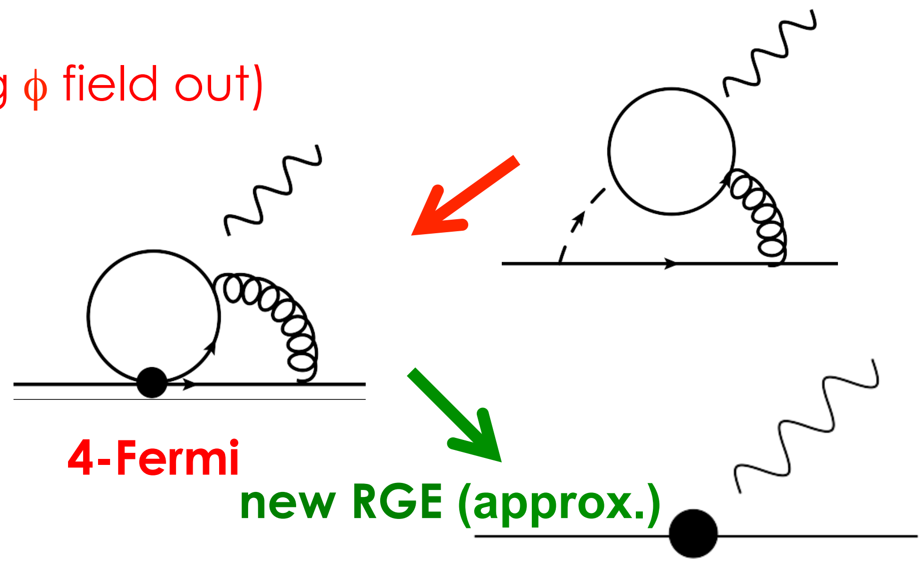
- Induce 4-Fermi int. (integrating ϕ field out)

Boundary cond. @ mϕ

$$C_4^q(m_\phi) = \sqrt{2} G_F \frac{m_q^2}{m_\phi^2} f_S^q f_P^q$$

$$\widetilde{C}_1^{q'q}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^q f_P^{q'}$$

$$\widetilde{C}_1^{qq'}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^{q'} f_P^q$$



RGE result is consistent with Diagramic one!!

$$C_2^q(\mathrm{CEDM}) = \frac{\alpha_s(m_\phi)}{8\pi^3} \frac{m_{q'}}{m_q} \left(\ln \frac{m_\phi}{m_{q'}} \right)^2 \left[\widetilde{C}_1^{q'q} + \widetilde{C}_1^{qq'} \right]$$

Numerical evaluation

- Consider: a real scalar with CPV Yukawa

$$\mathcal{L}_\phi = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\alpha \phi$$

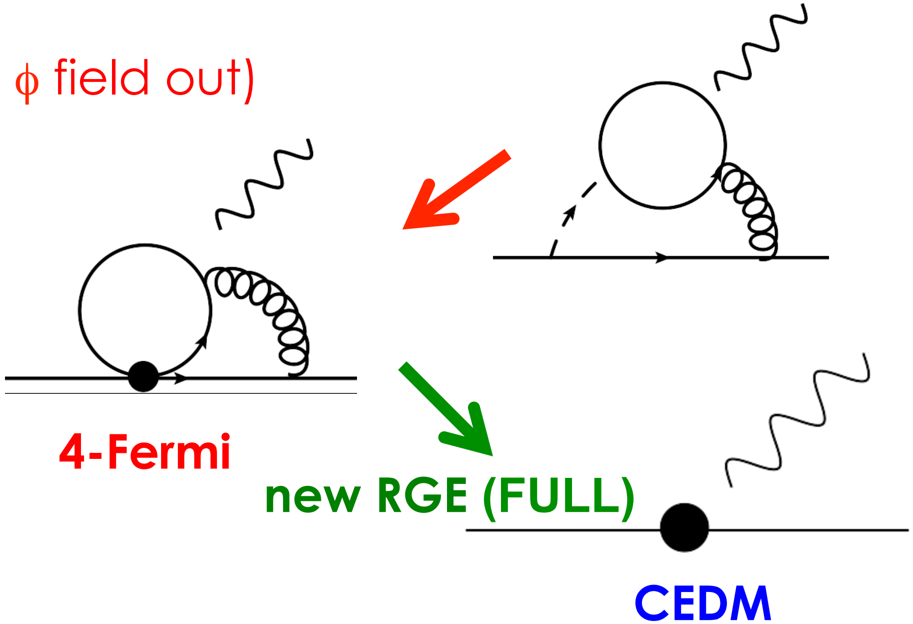
- Induce 4-Fermi int. (integrating ϕ field out)

Boundary cond. @ mϕ

$$C_4^q(m_\phi) = \sqrt{2} G_F \frac{m_q^2}{m_\phi^2} f_S^q f_P^q$$

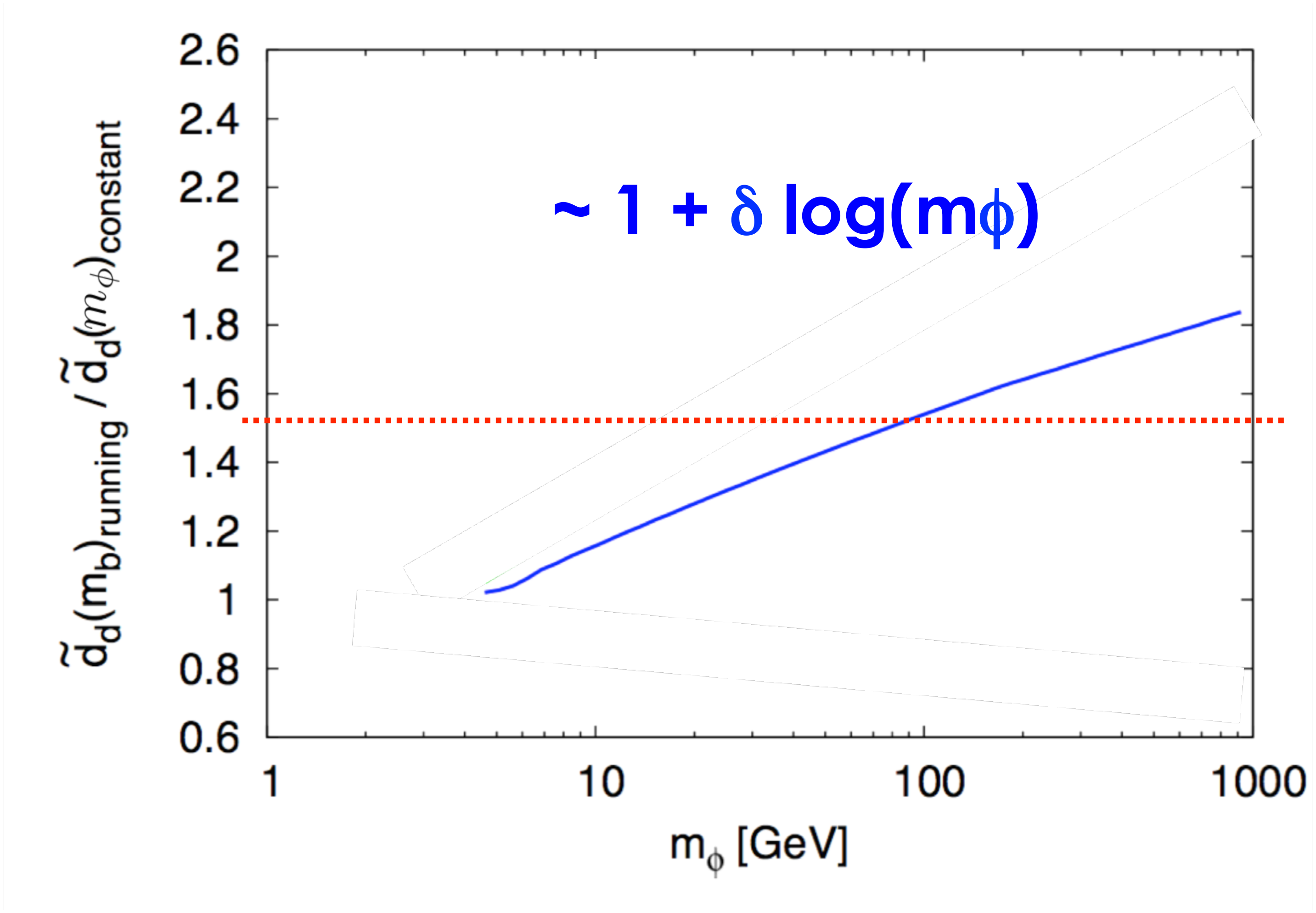
$$\widetilde{C}_1^{q'q}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^q f_P^{q'}$$

$$\widetilde{C}_1^{qq'}(m_\phi) = \sqrt{2} G_F \frac{m_q m_{q'}}{m_\phi^2} f_S^{q'} f_P^q$$

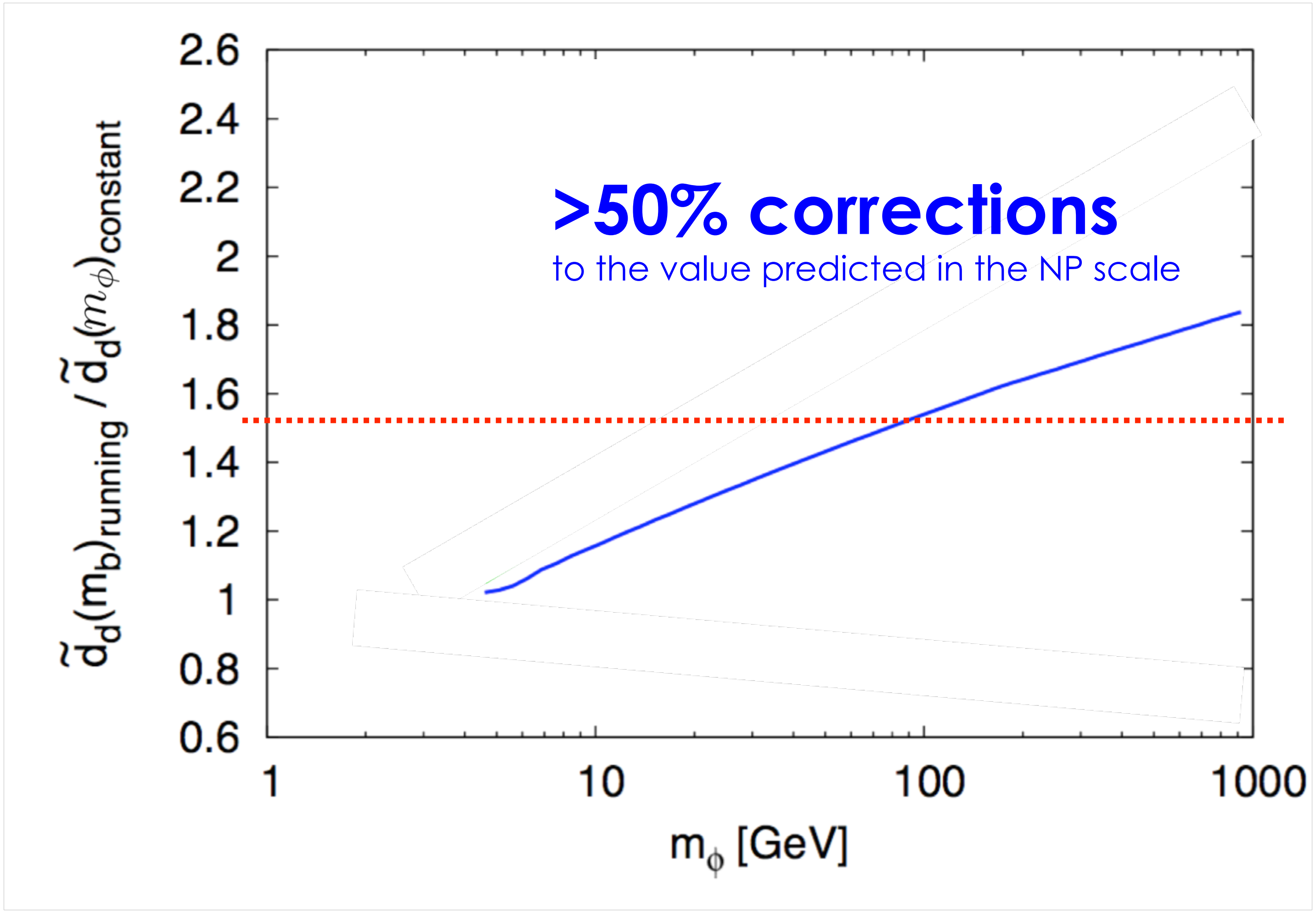


Numerically evaluation of $C_2^q(m_b) = \widetilde{d}_d / m_d$ **via full RGE.**

- **Numerical evaluation** (running effect on the CEDM)



▫ **Numerical evaluation** (running effect on the CEDM)



Conclusion

- EDM is CPV observable, and experiments are ongoing.

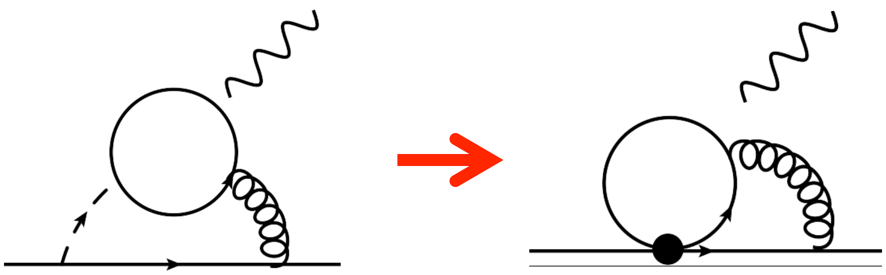
- RGEs including 4-Fermi up to D=6 are derived.

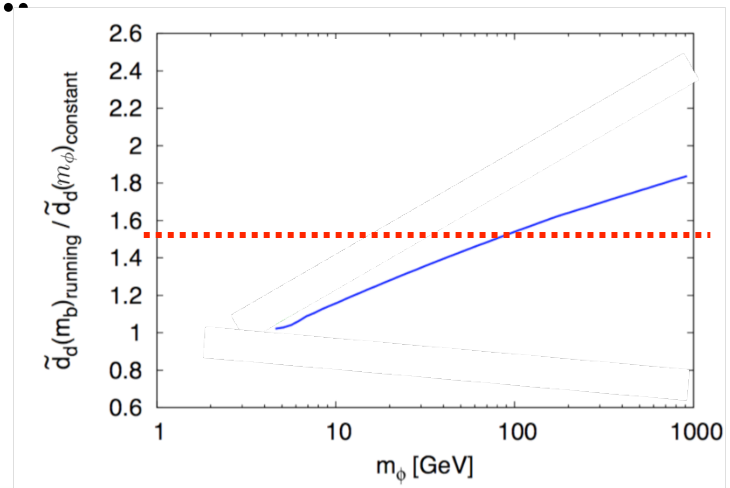
$$\frac{d\vec{C}(\mu)}{d\ln\mu} = \vec{C}(\mu)\Gamma$$

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_s & \mathbf{0} & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma_{sf} & \frac{\alpha_s}{4\pi}\gamma_f & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma'_{sf} & \mathbf{0} & \frac{\alpha_s}{4\pi}\gamma'_f \end{pmatrix}$$

- Using new RGE, the contribution especially from Barr-Zee diagram is properly evaluated.

The QCD corr. can be >50% effect!!

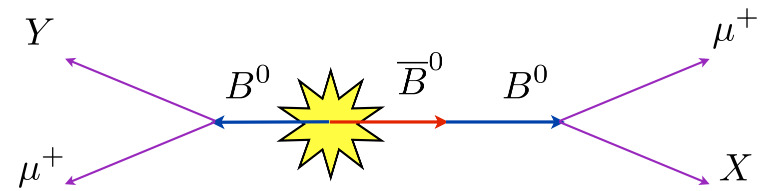





話は
聞かせてもらった!!
Backup

New source of CP violation?

D0 – anomalous μμ charge asymmetry



$$A^b_{sl} = (-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst}))\,\%$$

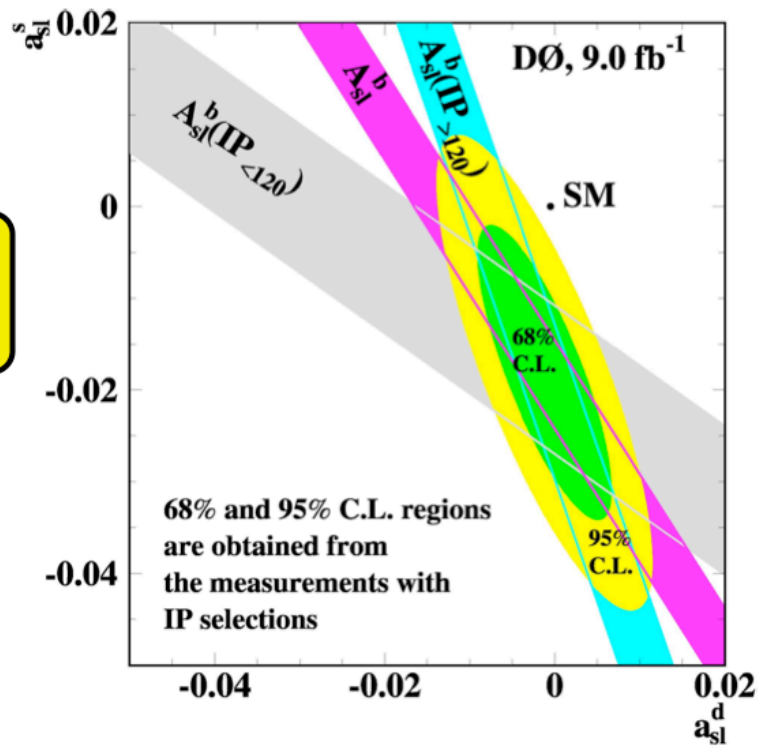
- Anomalous Dimuon - 3.9σ deviation from SM expectations
- Split the data (blue band, grey band):

$$a^d_{\text{sl}} = (-0.12 \pm 0.52)\%,$$
$$a^s_{\text{sl}} = (-1.81 \pm 1.06)\%.$$

- Need to investigate in as many different ways as possible.

SM Prediction

$$a^d_{\text{sl}} = (-4.1 \pm 0.6) \times 10^{-4},$$
$$a^s_{\text{sl}} = (1.9 \pm 0.3) \times 10^{-5}.$$



(arXiv:1102.4274)
A. Lenz & U. Nierste, JHEP06 072 (2007)

New source of CP violation?

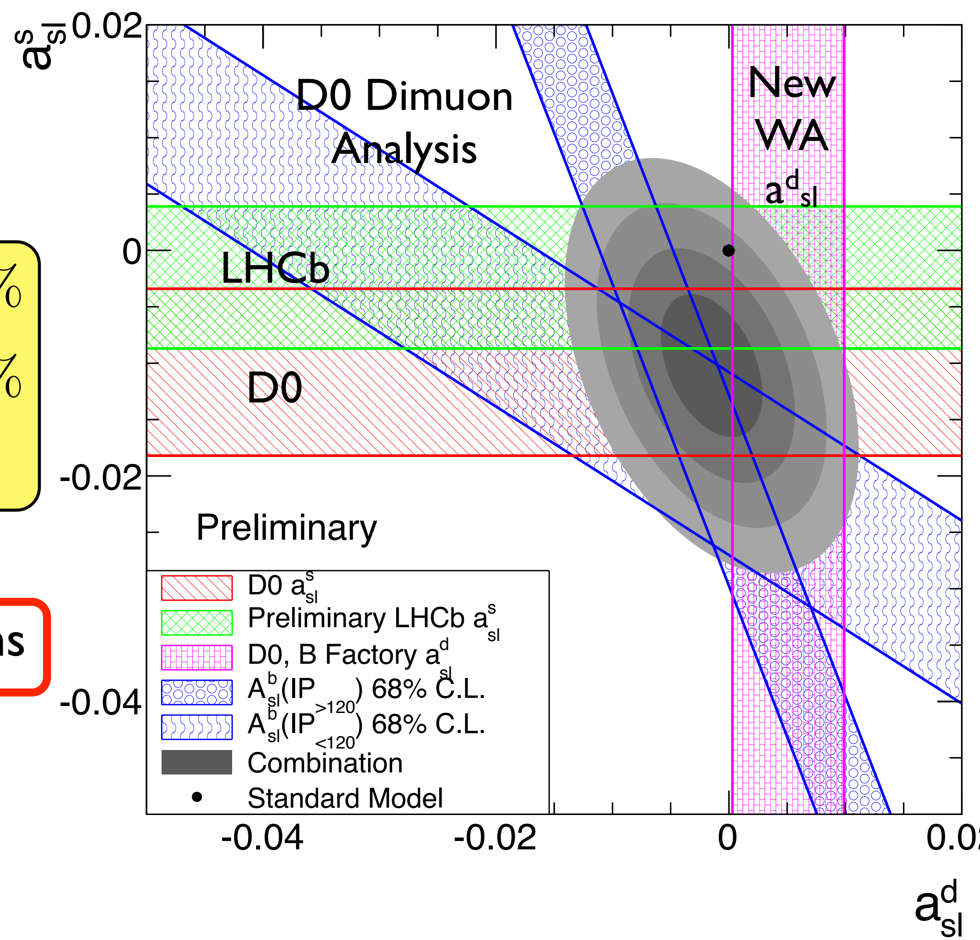
May not be anomalous?

LHCb – No new CPV in Bs

- Combine with D0 and B-Factory average a^d_{sl}.

$$a^s_{\mathrm{sl}} = (-1.02 \pm 0.42)\ \%$$
$$a^d_{\mathrm{sl}} = (-0.15 \pm 0.29)\ \%$$
$$\rho = -0.40$$

- p-value(SM) = 1.3%
  2.5 standard deviations
  χ^2 = 4.00/2 dof
- a^s_{sl} is 2.5 standard deviations from zero

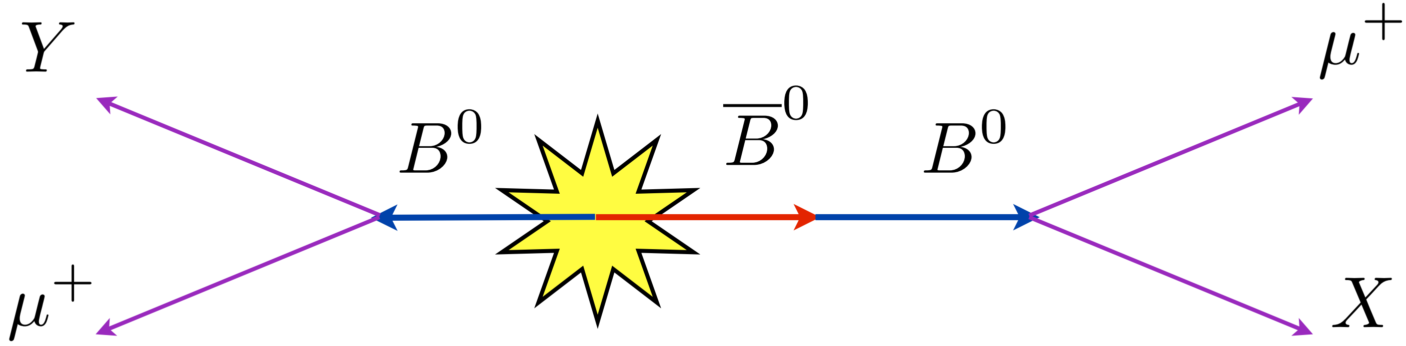


Anyway,

CPV is a probe of New physics

Go back to EDM

D0 – anomalous Dimuon charge asymmetry



$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$= C_d a^d_{sl} + C_s a^s_{sl}$$

where $a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$

arxiv.org:1106.6308 PRD **84** 052007 (2011)

$C_{d(s)}$ is the fraction of $B_d(B_s)$ events in the data sample.

▫ EDM in the SM

One more example:

Back up

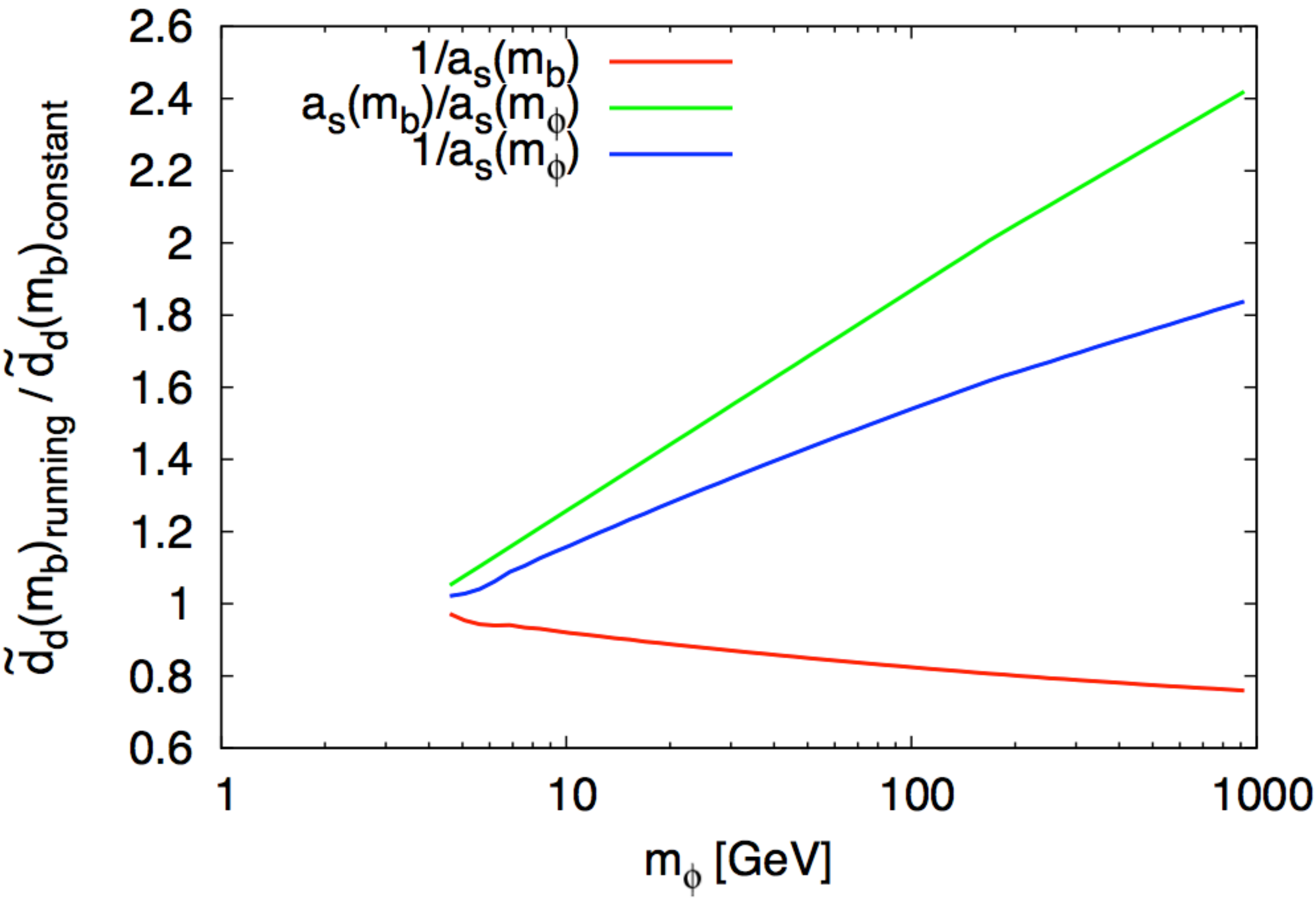
- RGE up to D=6

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_s & \mathbf{0} & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma_{sf} & \frac{\alpha_s}{4\pi}\gamma_f & \mathbf{0} \\ \frac{1}{(4\pi)^2}\gamma'_{sf} & \mathbf{0} & \frac{\alpha_s}{4\pi}\gamma'_f \end{pmatrix}$$

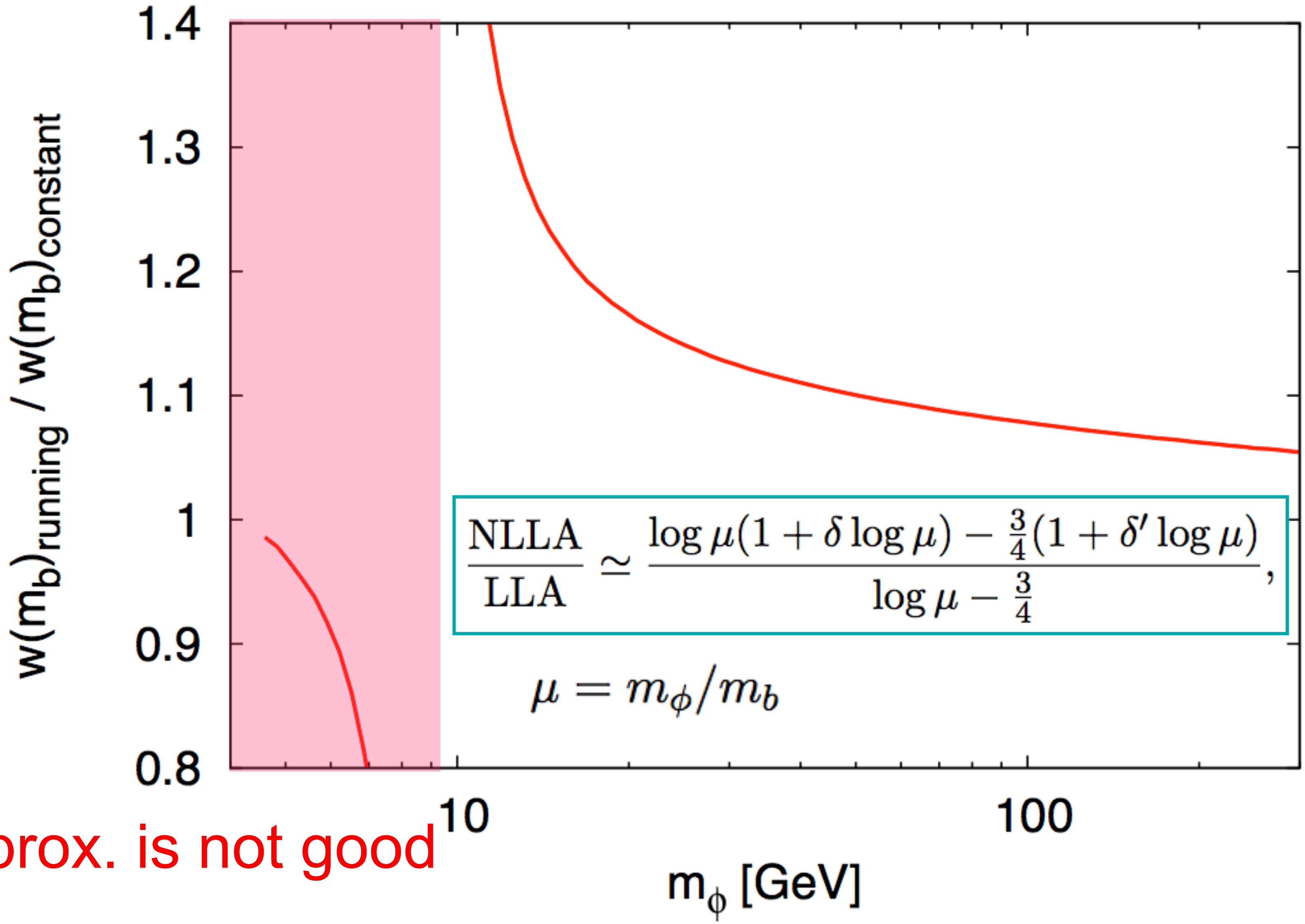
$$\gamma_{sf} = \begin{bmatrix} +4 & +4 & 0 \\ -32N - 16 & -16 & 0 \end{bmatrix} \qquad \gamma_f = \begin{bmatrix} -12C_F + 6 & +\frac{1}{N} - \frac{1}{2} \\ +\frac{48}{N} + 24 & +4C_F + 6 \end{bmatrix}$$

$$\gamma'_{sf} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -16N\frac{m_{q'}}{m_q}\frac{Q_{q'}}{Q_q} & 0 & 0 \\ -16\frac{m_{q'}}{m_q}\frac{Q_{q'}}{Q_q} & -16\frac{m_{q'}}{m_q} & 0 \end{bmatrix} \gamma'_f = \begin{bmatrix} -12C_F & 0 & 0 & 0 & +\frac{1}{N} & -1 \\ -6 & +\frac{6}{N} & 0 & 0 & -\frac{1}{2} & -C_F + \frac{1}{2N} \\ 0 & 0 & -12C_F & 0 & +\frac{1}{N} & -1 \\ 0 & 0 & -6 & +\frac{6}{N} & -\frac{1}{2} & -C_F + \frac{1}{2N} \\ +\frac{24}{N} & -24 & +\frac{24}{N} & -24 & +4C_F & 0 \\ -12 & -24C_F + \frac{12}{N} & -12 & -24C_F + \frac{12}{N} & +6 & -8C_F - \frac{6}{N} \end{bmatrix}$$

The effect from running coupling



Asymptotic behavior of weinberg op.

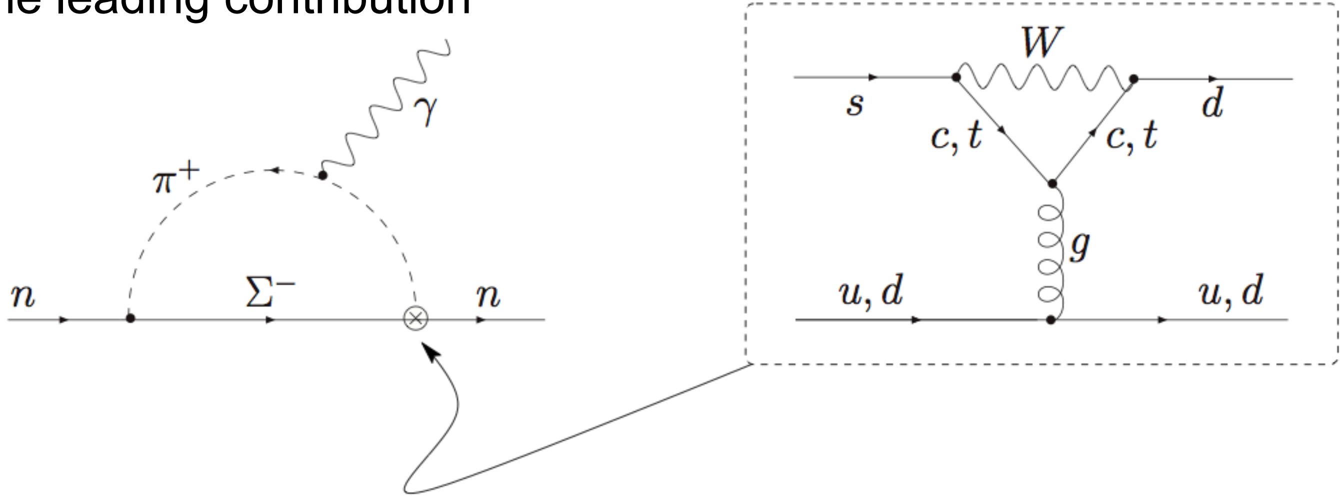


Approx. is not good

NEDM in the Standard Model

Induced by KM phase $d_n^{\mathrm{KM}} \simeq 10^{-32} e \text{ cm.}$

The leading contribution



$10^{-(6-7)}$ smaller than present exp. bound

If New physics have CP violation,
We can probe that by EDM.