RG effects on the CEDM via CP violating four-Fermi operators

Masaki J.S. Yang (梁　正樹)
D3 @ U. of Tokyo

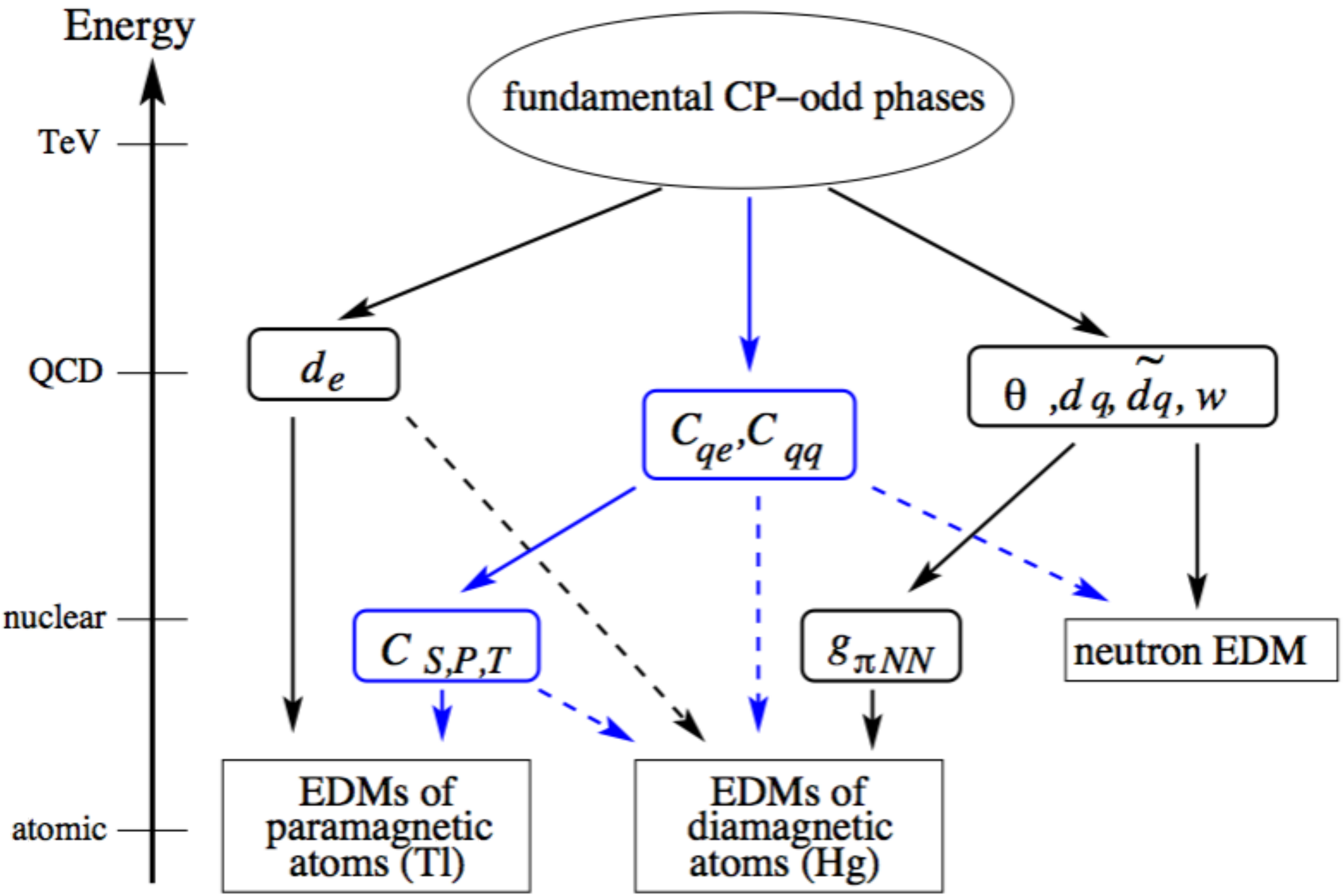
Collab. with J. Hisano and K. Tsumura @ Nagoya U.

Physics Letters B 713 (2012) 473, arxiv/1205.2212

12/07/02 Flasy12＠Dortmund

An overlooking of EDM

Pospelov and Ritz,
"EDM as probes of New Physics"
Annals Phys. 318 (2005) 119-169
hep-ph/0504231



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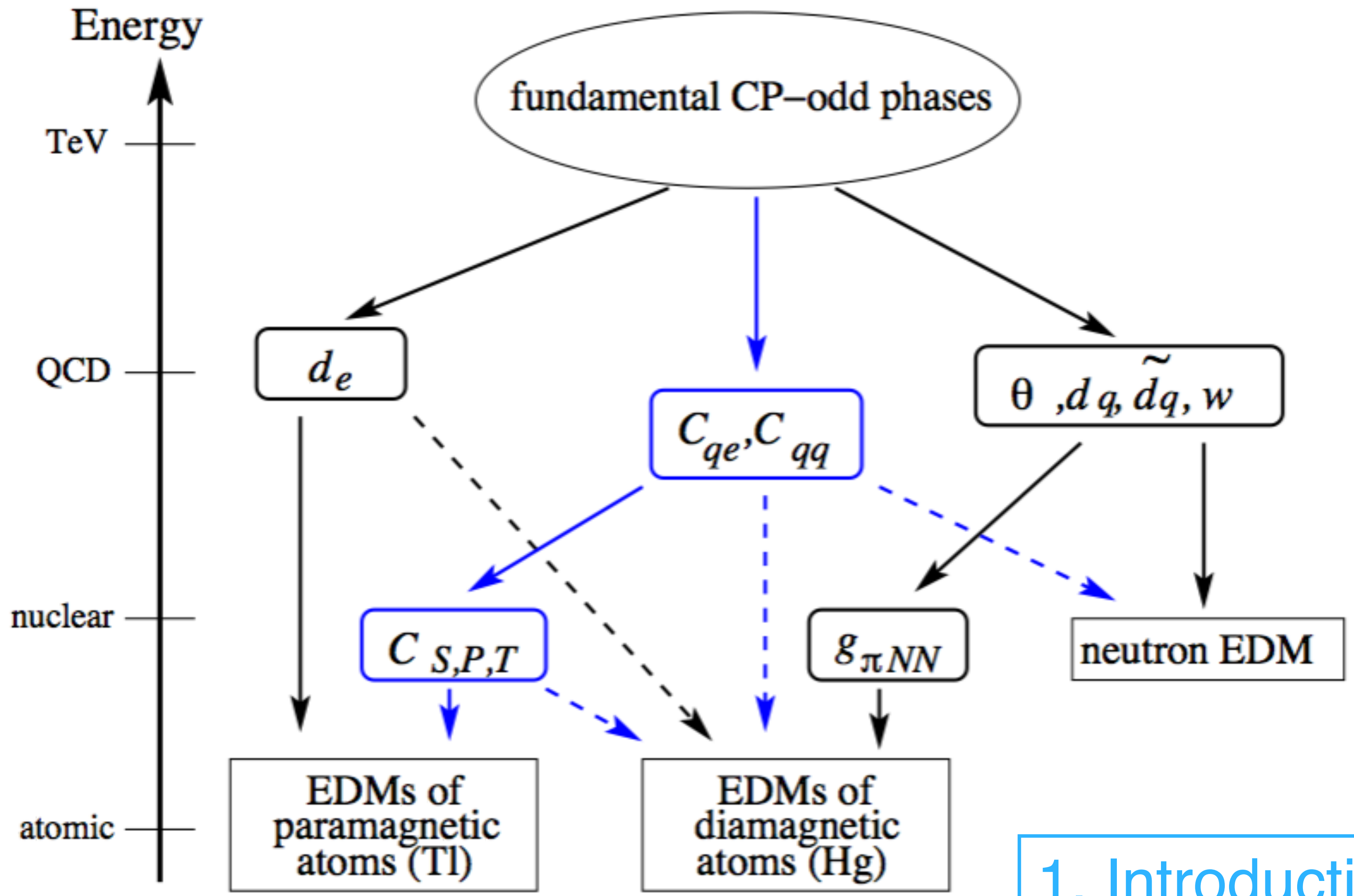

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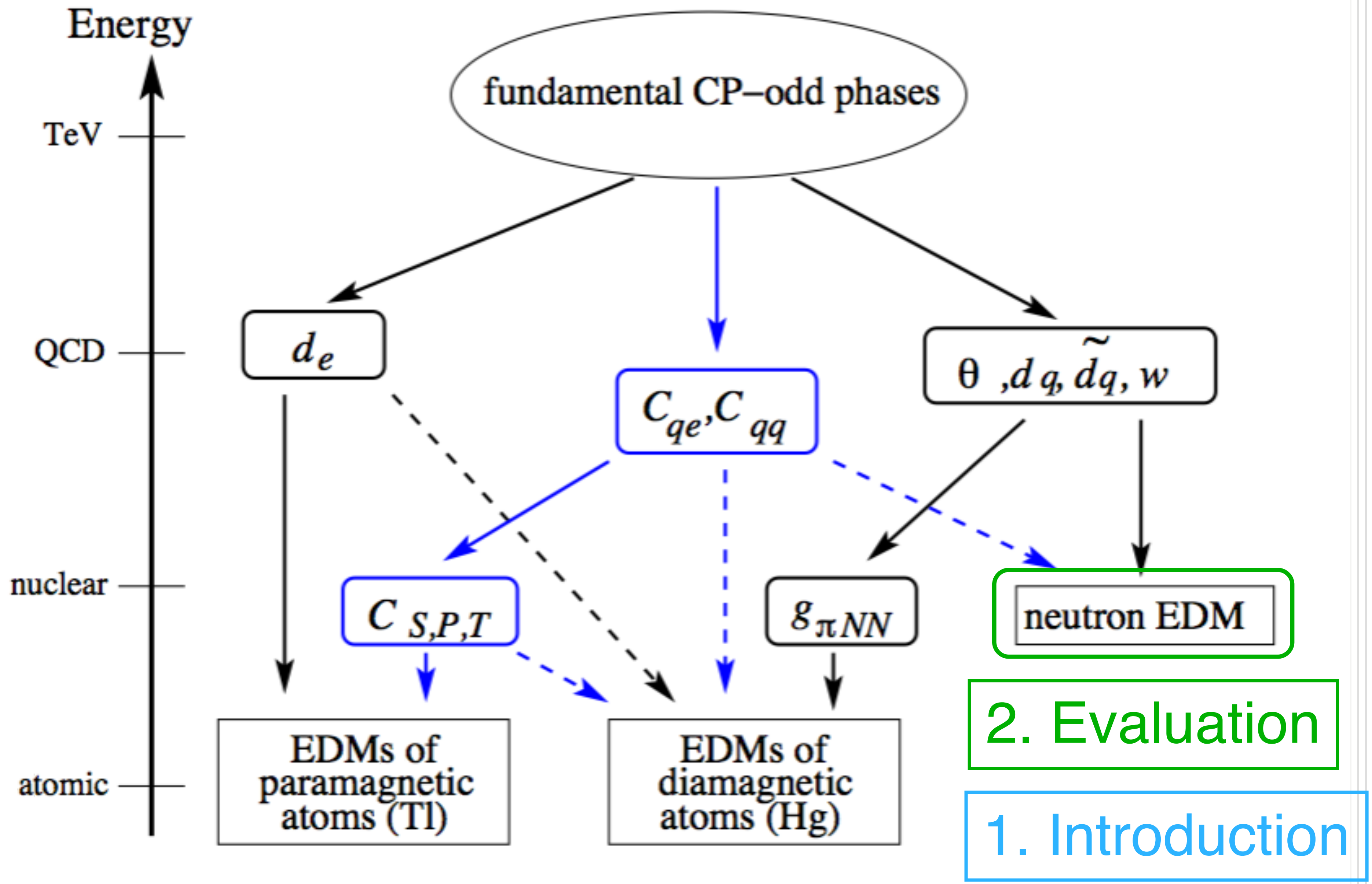

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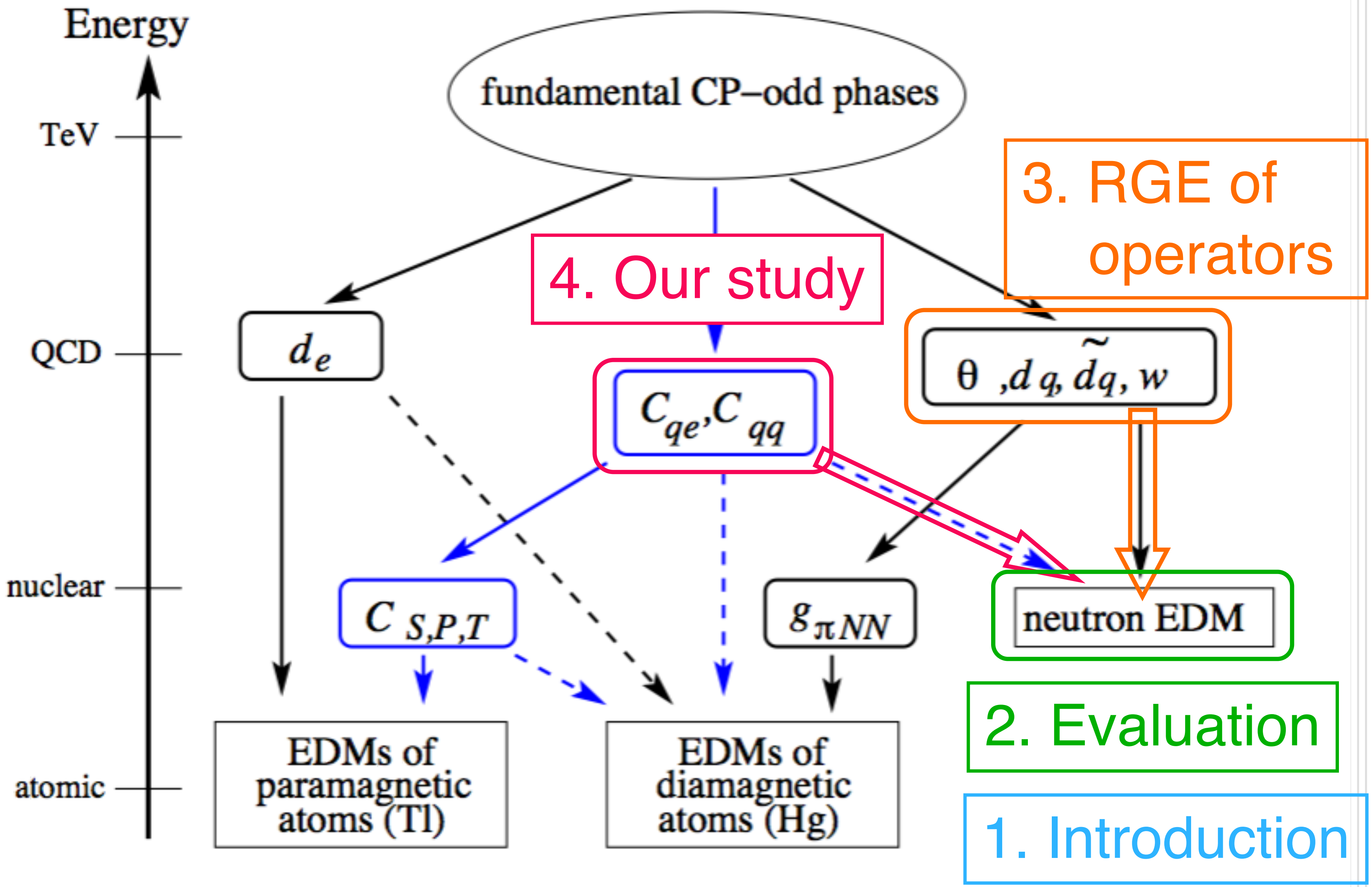

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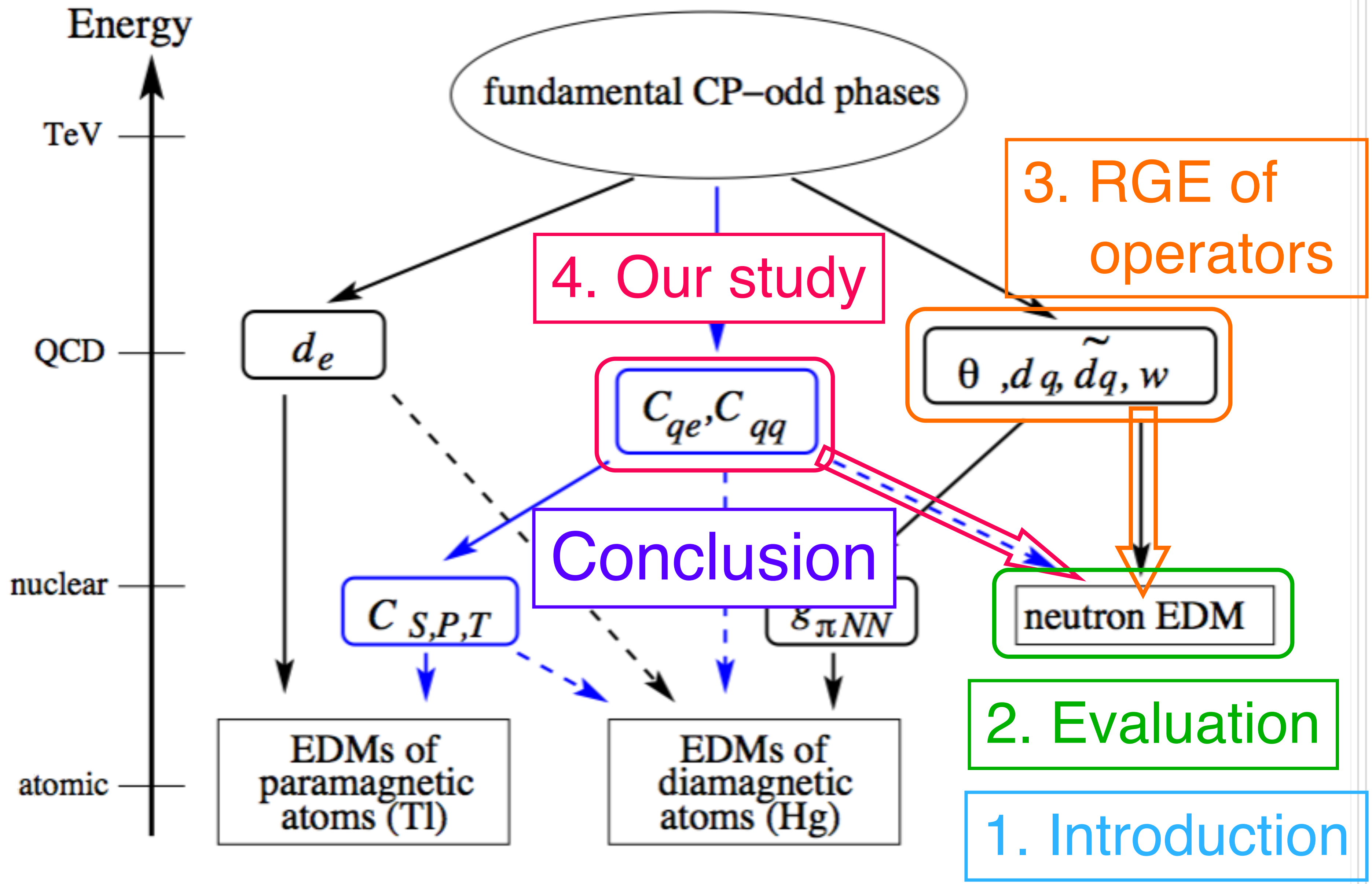

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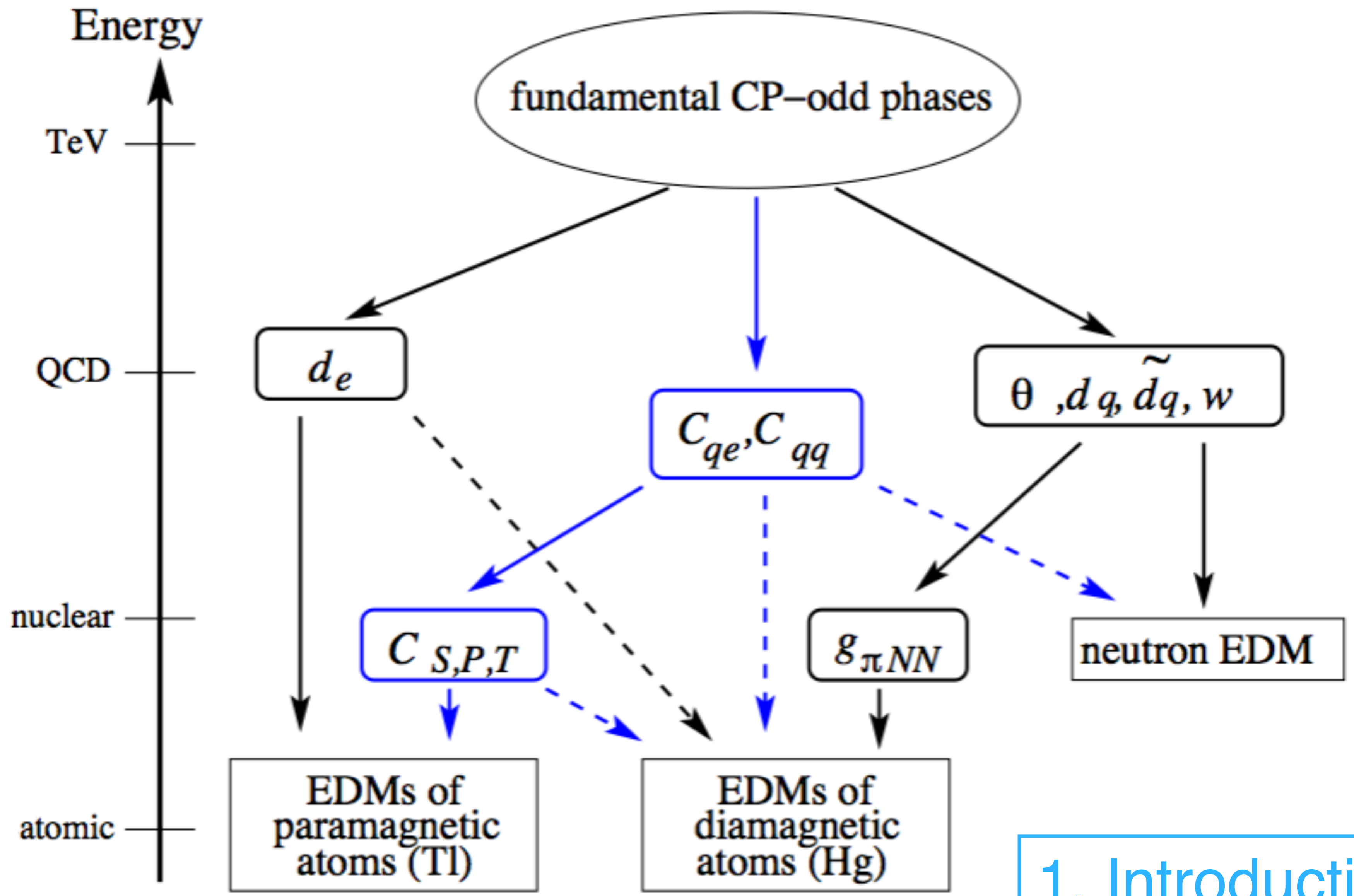
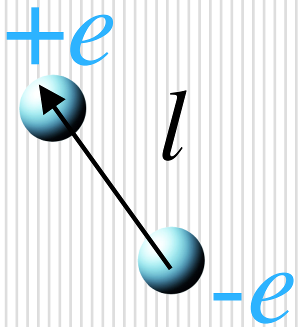


1. Introduction

Introduction : What is EDM?

Electric dipole moment (EDM)



$$d = el,$$

violates P and T

$$H_{\mathrm{T,P\ odd}} = -d\mathbf{E}\cdot\frac{\mathbf{S}}{S}$$

CPT theorem ⇒ T-violation = CP-violation

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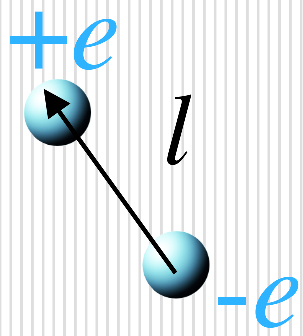

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CPT theorem ⇒ T-violation = ~~CP~~ -violation

Motivation

- □ SM EDM is very tiny ⇒ A probe of new physics
- □ Baryon from SM CPV is too small ⇒ Baryogenesis

Current experimental situation

- **Current bound**

B. C. Regan, et al., PRL88 (2002) 071805;
W. C. Griffith, et al., PRL102 (2009) 101601;
C. A. Baker et al., PRL97 (2006) 131801;

$$|d_{\text{Tl}}| < 9 \times 10^{-25} e \text{ cm}, \quad |d_{\text{Hg}}| < 3.1 \times 10^{-29} e \text{ cm}, \quad |d_n| < 2.9 \times 10^{-26} e \text{ cm},$$

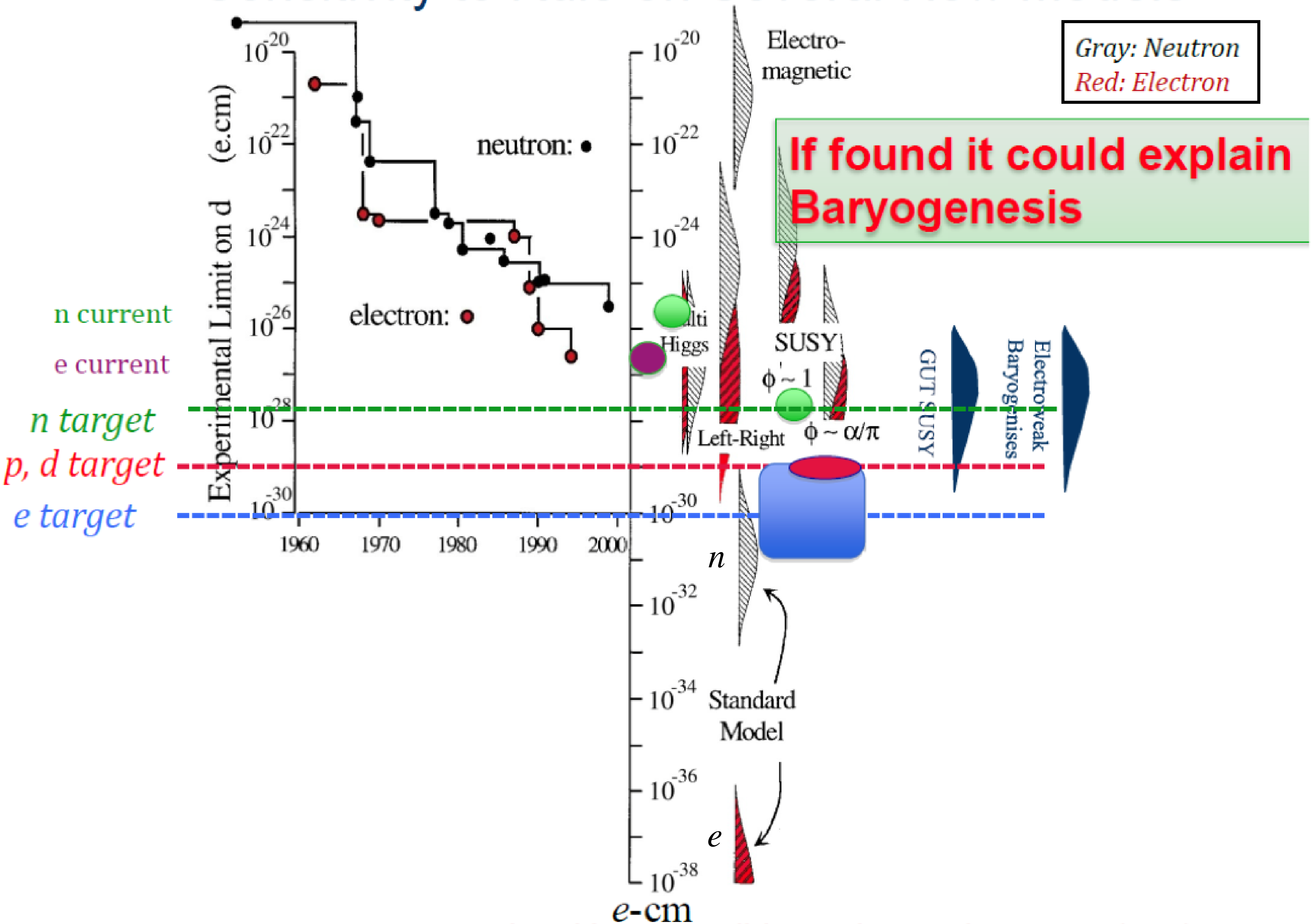
From molecule YbF (1 year ago)

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

J.J. Hudson, et al., Nature 473 (2011) 493-496

- **Next generation exp. (for several years)**
  - n : nEDM (SNS & PSI), CryoEDM, etc. ∼10^{-28} e cm
  - μ : muon g-2 / EDM collab. ∼10^{-20} e cm (proposal) ⇒ 10^{-25} e cm ?
  - p : storage ring EDM collab. ∼ 10^{-29} e cm
  - D : storage ring EDM collab. ∼10^{-29} e cm
  - Ra, Xe, Rn, ???

Sensitivity to Rule on Several New Models



Adopted from J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

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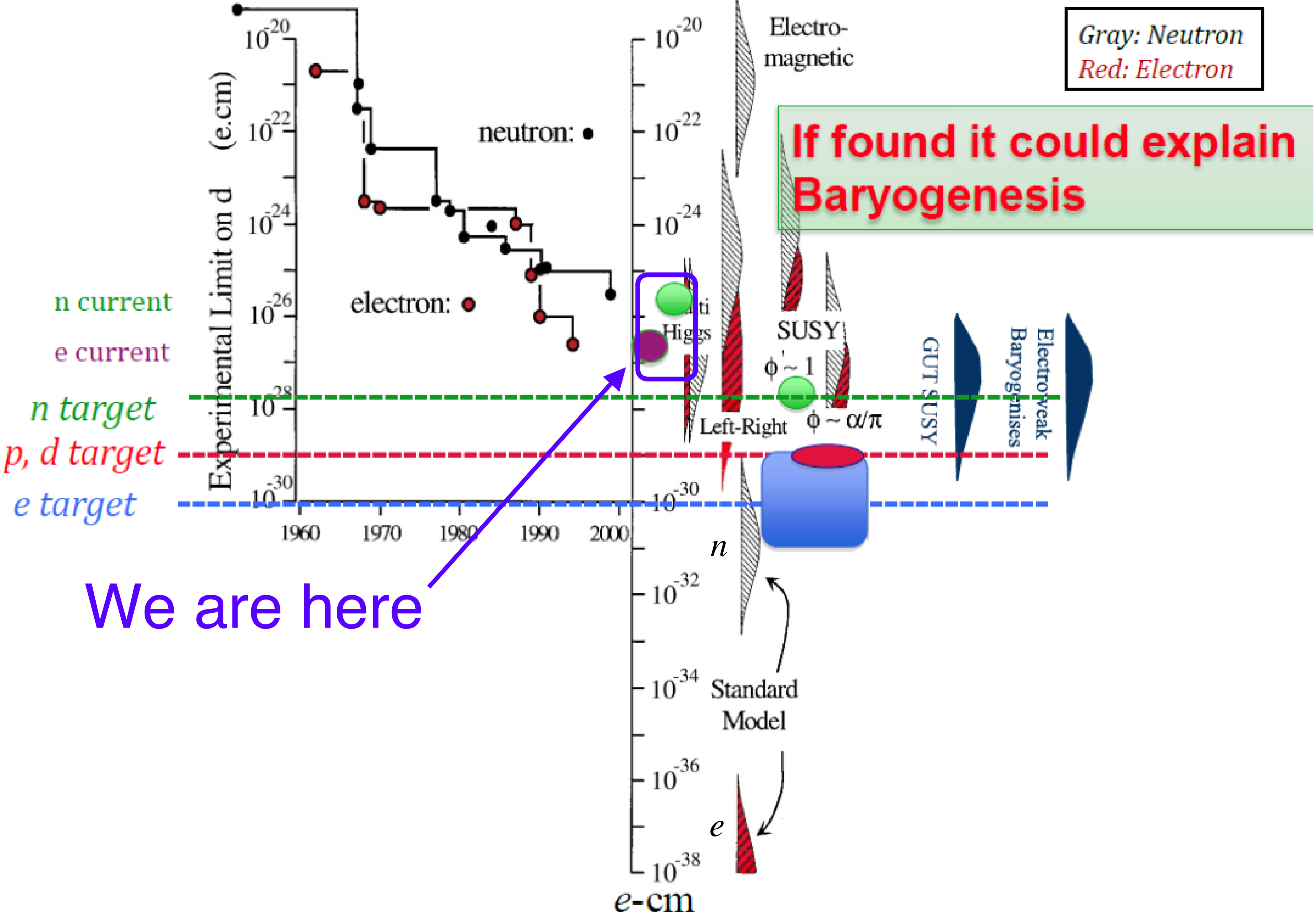

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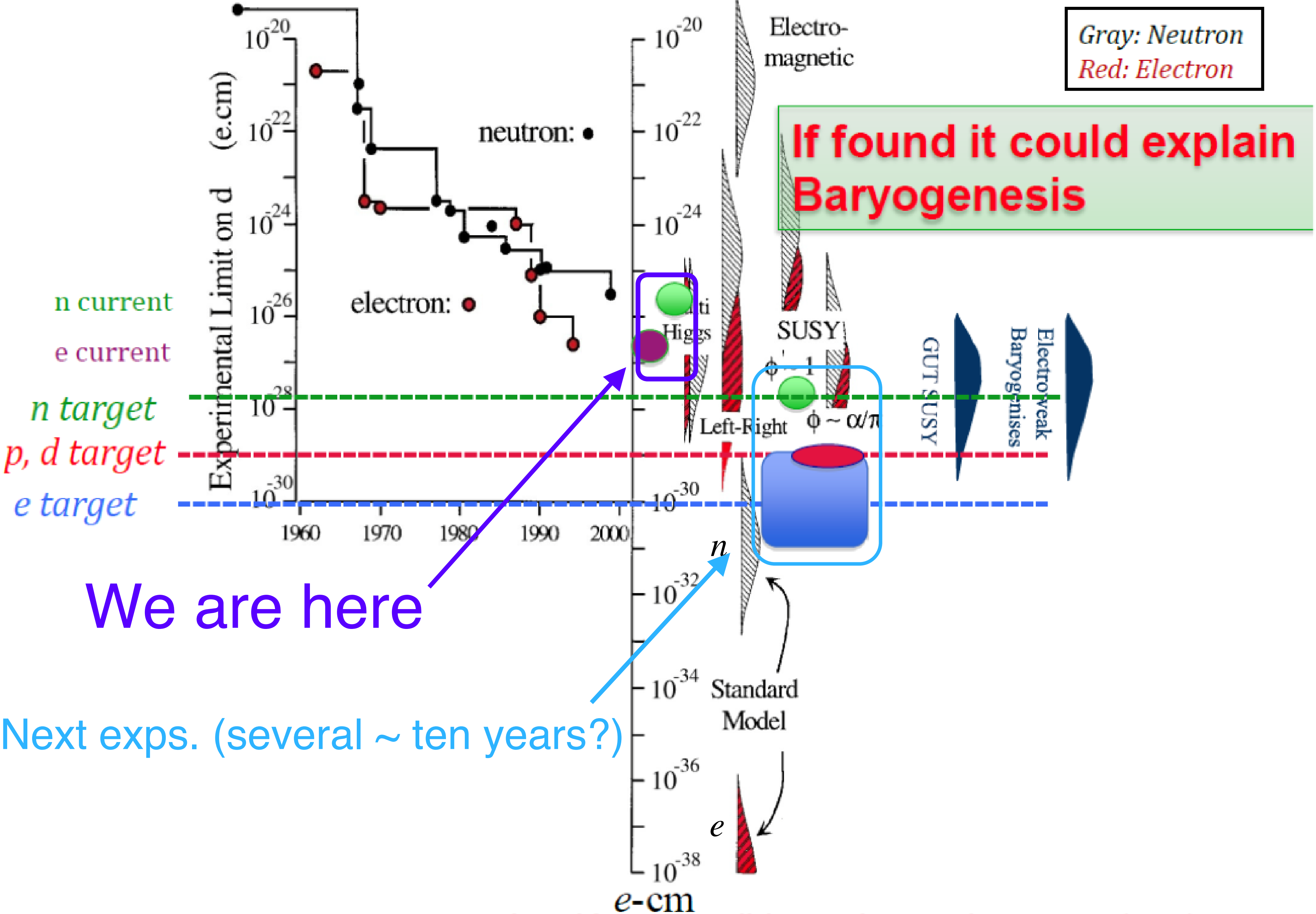

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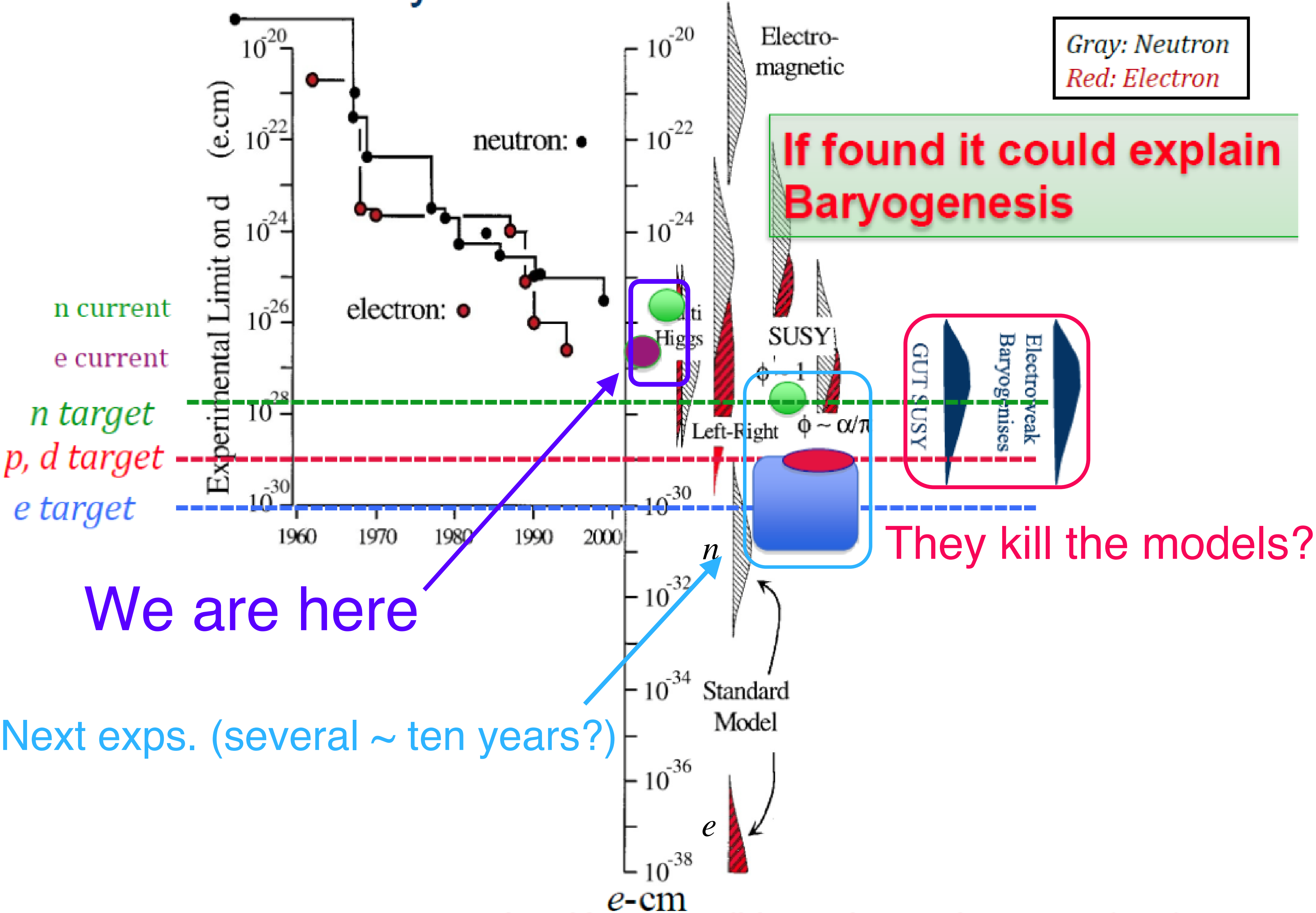

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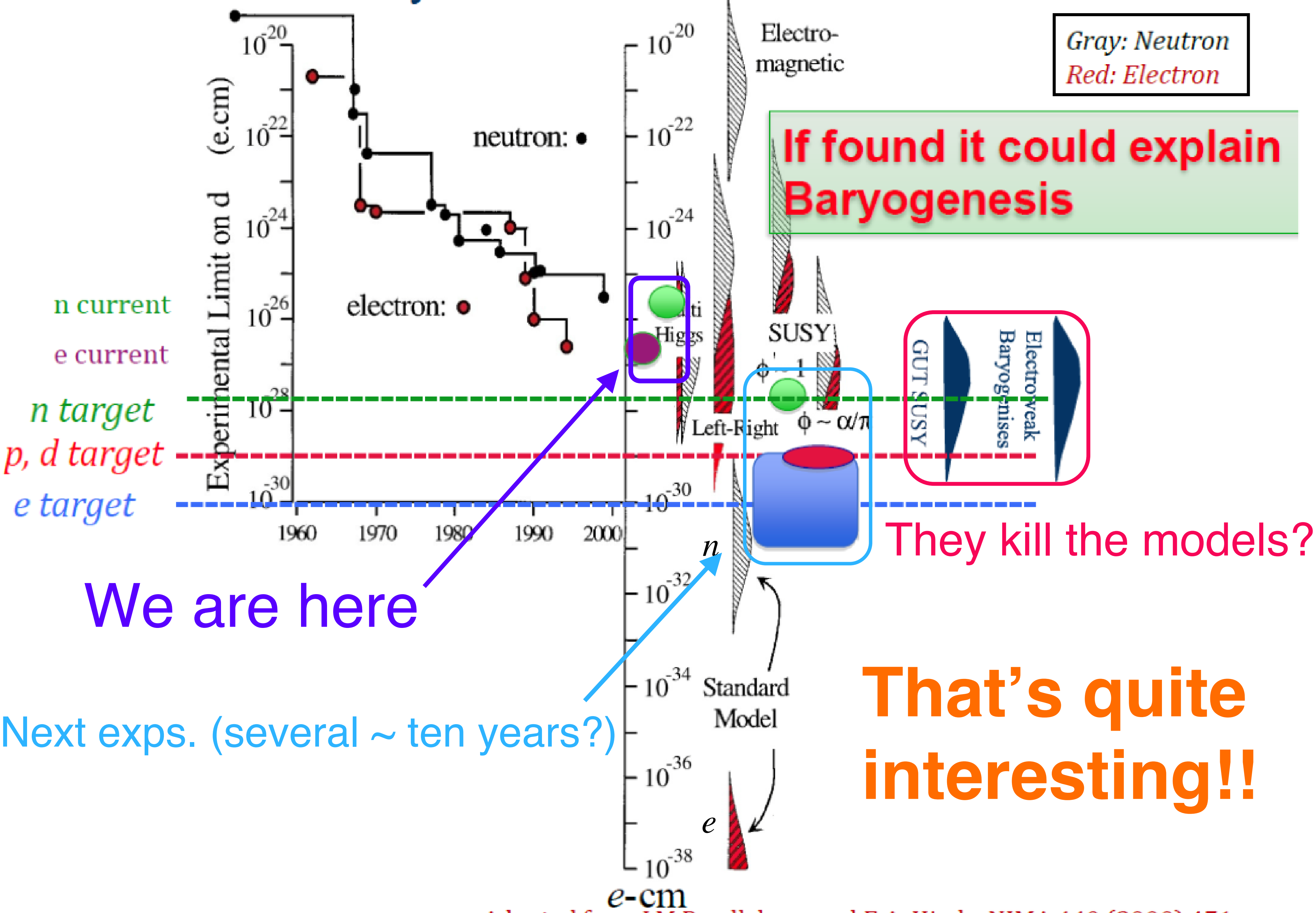

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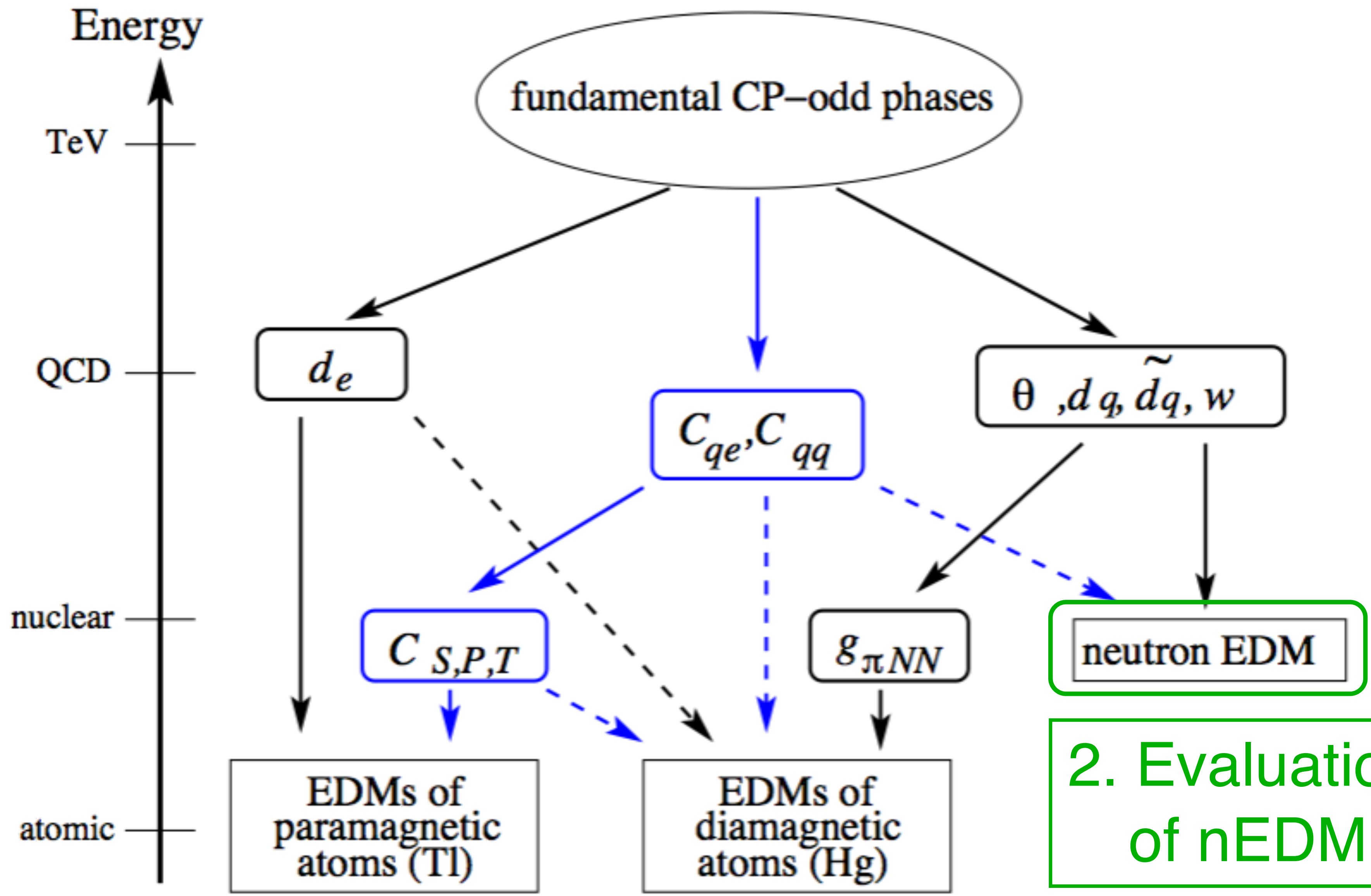


2. Evaluation of nEDM

Theoretical evaluation of NEDM

To evaluate nEDM, there are some methods different in treatment of non-perturbativity.

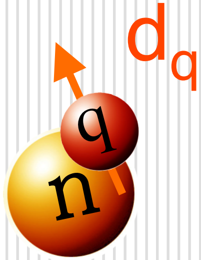
- quark model
- chiral tech.
- sum rule
- lattice

↓ Non-perturbativity

□ SU(6) quark model

$$d_n = \frac{1}{3}(4d_d - d_u)$$

A. Manohar, H. Georgi Nucl.Phys. B234 (1984) 189



□ Chiral techniques

□ QCD sum rules

□ Lattice estimation

} Theoretical uncertainty is not small…

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Non-perturbativity

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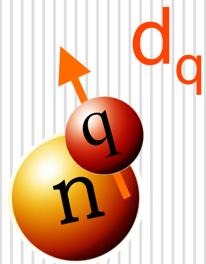

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□ Chiral techniques

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□ Lattice estimation

Theoretical uncertainty is not small…

□ The QCD sum rule for nEDM

$$\lambda_n^2 d_n m_n - AM^2 = -\Theta\langle\bar{q}q\rangle \frac{M^4}{8\pi^2} e^{\frac{m_n^2}{M^2}}$$

The coupling between physical n state and neutron (interpolating) field

$$\langle \Omega_{\not{C}\not{P}} | \eta_n(x) | N_{\not{C}\not{P}}(\boldsymbol{p}, s)\rangle = \lambda_n e^{\frac{i}{2}\alpha_n \gamma_5}\ u_n(\boldsymbol{p}, s)\ e^{-ip\cdot x}\ .$$

$M \doteqdot m_n$, and using other sum rule (Ioffe formula), B. L. Ioffe, Z. Phys. C 18 (1983) 67.

$$\frac{1}{8}\frac{1}{(2\pi)^4} M^6 \simeq \lambda_N^2\, e^{-M_N^2/M^2}\,,$$

$$\lambda_n = 0.022 \pm 0.007\ \mathrm{GeV}^3$$

leads to Pospelov and Ritz, '99 and '01

$$d_n = (2.5 \pm 1.3) \times 10^{-16}\bar{\theta}\ [e\ \mathrm{cm}] + (1 \pm 0.5)\left[1.4(d_d - 0.25 d_u) + 1.1 e(\tilde{d}_d + 0.5\tilde{d}_u)\right]$$

□ The QCD sum rule for nEDM

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The coupling between physical n state and neutron (interpolating) field

From the HME of neutron (Composite picture)

the HME of quark (elemental picture)

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Recent calculation J. Hisano, J. Y. Lee, N. Nagata and Y. Shimizu, arXiv:1204.2653 [hep-ph].

λ_n from lattice; larger and precise value $\lambda_n = -0.0436\ \mathrm{GeV}^3$, Y. Aoki at. Al. (2008)

$$d_n = 4.2 \times 10^{-17} \bar{\theta}\ [e\ \mathrm{cm}] + 0.47 d_d - 0.12 d_u + e(-0.18\tilde{d}_u + 0.18\tilde{d}_d - 0.008\tilde{d}_s) .$$

They obtain more precise and conservative (∽ 20%) constraint.

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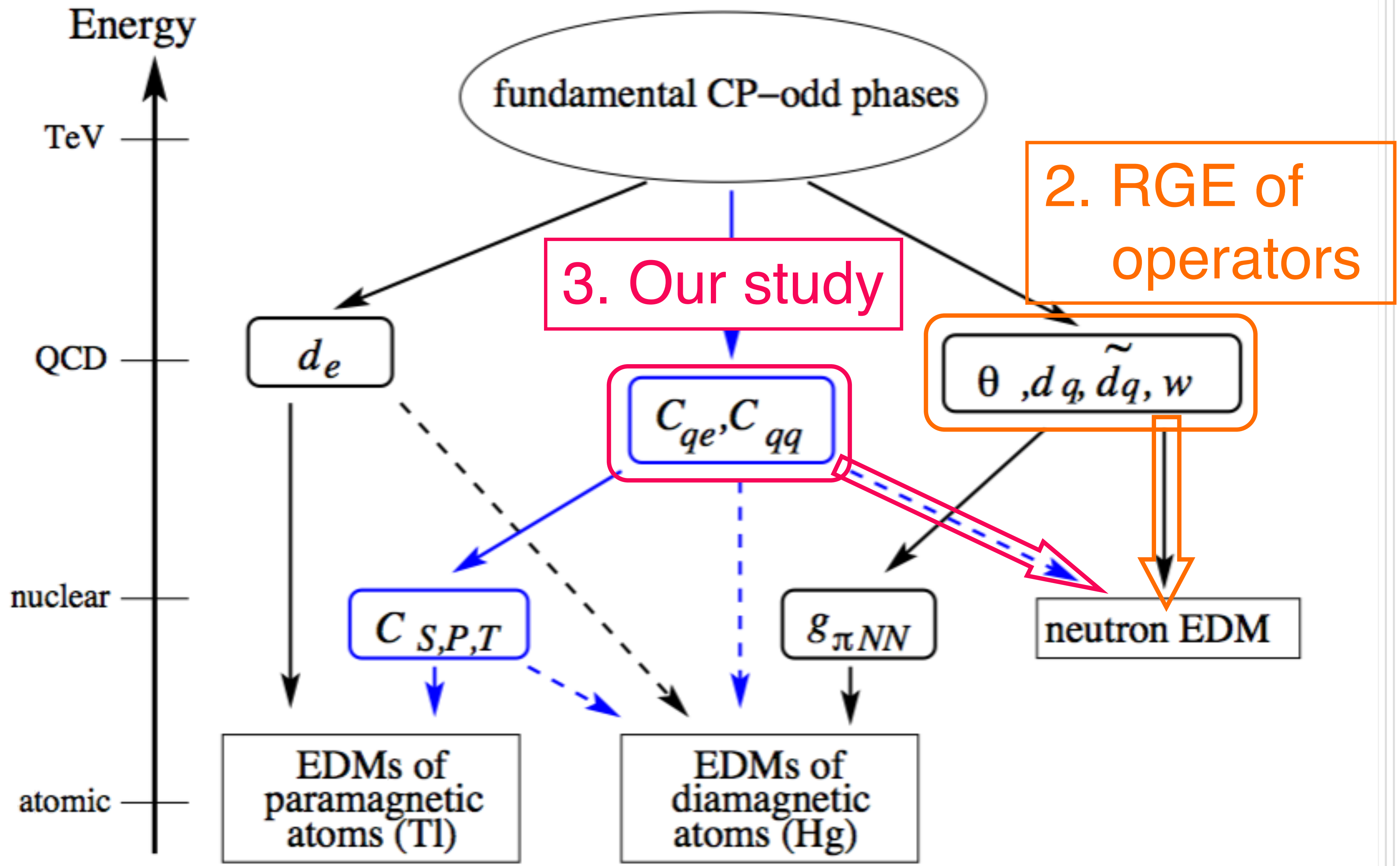


The CP violating effective operators

We describe effects of CPV BSM by effective operator.

$$\mathcal{L}_4 = \frac{g_s^2}{32\pi^2}\bar{\theta} G^a_{\mu\nu} G^{\mu\nu a}$$

θ term

$$\mathcal{L}_5 = -\frac{i}{2}\sum_i d_i \bar{\psi}_i F^{\mu\nu}\sigma_{\mu\nu}\gamma^5\psi_i - \frac{i}{2}\sum_i \tilde{d}_i \bar{\psi}_i g_s G^{\mu\nu}\sigma_{\mu\nu}\gamma^5\psi_i$$

EDM CEDM

$$\mathcal{L}_6 = \frac{1}{3} w f^{abc} G^a_{\mu\nu}\tilde{G}^{\nu\lambda b} G_\lambda^{\ \mu c} + \sum_{i,j} C_{ij}(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma^5\psi_j) + \cdots$$

Weinberg op. CPV 4 fermi op.

For NEDM evaluation, we must include the running of α_s and these operators to low energy around m_N ⇒RGE

The previous studies

□effective operator ⇒ light quark EDM

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Rev. D 18, 2583 (1978).
M. Ciuchini, E. Franco, L. Reina and L. Silvestrini, Nucl. Phys. B 421 (1994) 41. (O1 & O2 from b->sγ)
E. Braaten, C. S. Li and T. C. Yuan, Phys. Rev. Lett. 64 (1990) 1709; Phys. Rev. D 42 (1990)276. (O2 & O3)
G. Degrassi, E. Franco, S. Marchetti and L. Silvestrini, JHEP 0511, 044 (2005). (NLO)

EDM CEDM Weinberg op.

$$H_{CPV} = \sum_q C_1^q(\mu) O_1^q(\mu) + \sum_q C_2^q(\mu) O_2^q(\mu) + C_3(\mu) O_3(\mu)$$

RGE

$$\frac{d\vec{C}(\mu)}{d\ln\mu} = \gamma^T \vec{C}(\mu)$$

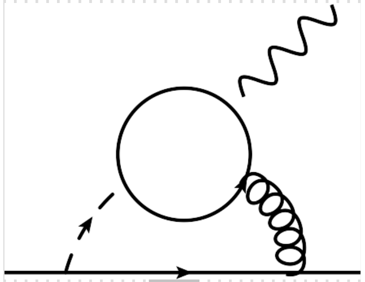
$$\gamma(\alpha_s) = (\alpha_s/4\pi)\,\gamma^{(0)}$$

anomalous dimension matrix at $\alpha_s^{\,1}$ order

$$\gamma^{(0)} \equiv \begin{pmatrix} \gamma_e & 0 & 0 \\ \gamma_{qe} & \gamma_q & 0 \\ 0 & \gamma_{Gq} & \gamma_G \end{pmatrix} = \begin{pmatrix} 8\,C_F & 0 & 0 \\ 8\,C_F & 16\,C_F - 4\,N & 0 \\ 0 & -2\,N & N + 2n_f + \beta_0 \end{pmatrix}$$

The previous studies

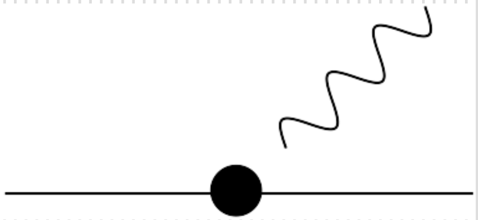
$>$1TeV



$iM_{\rm NP}$

Integrated out NP

$m_{\rm NP}$



$C^q_{1-3}(m_{\rm NP})O^q_{1-3}(m_{\rm NP})$

Introducing
op. mixing and α_s evolution

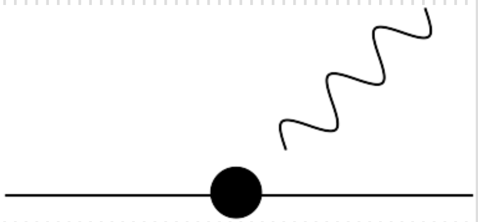
LO
RGE

$$C^q_1(m_H) = \eta^{\gamma_e/2\beta_0} C^q_1(m_{\rm NP}) + \cdots$$

$$\eta = \alpha_s(m_{\rm NP})/\alpha_s(m_H)$$

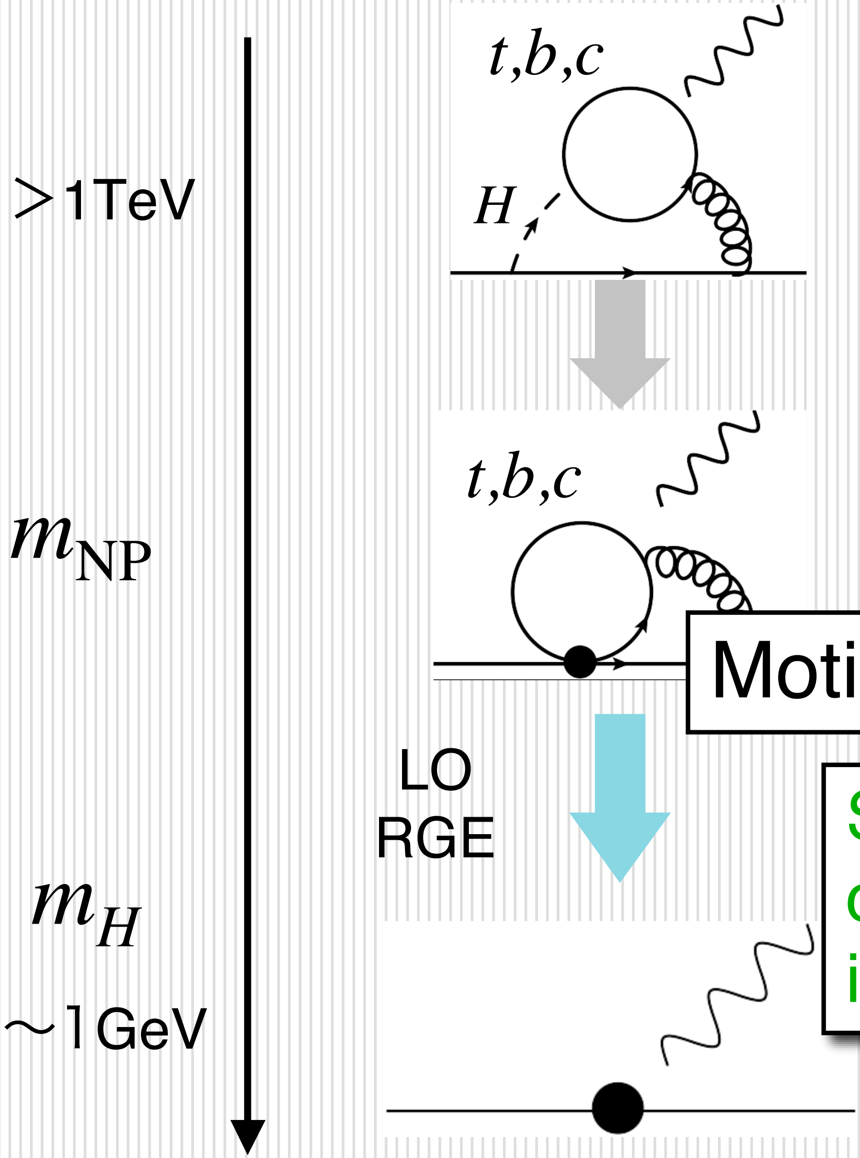
m_H

$\sim$1GeV



Non. Pert. Eval.
NEDM

However…



- In the case yukawa int. has CPV,
  ⇒ when Higgs is integrated out,
  ⇒ 4 fermi operators emerge,
  ⇒ and **they mix with (C)EDM ops.**

$$C^q_{1-3}(m_{\rm NP})O^q_{1-3}(m_{\rm NP}) + \underline{C^q_{4f}(m_{\rm NP})O^q_{4f}(m_{\rm NP})}$$

Motivation

Since this effect has never been considered, we would like to take in these mixing and RG evolution.

Non. Pert. Eval.
NEDM

Our operator basis

The previous framework
EDM, CEDM, Weinberg op.

+ same flavor 4F op.

$$\mathcal{O}_4^q = \overline{q_\alpha} q_\alpha \overline{q_\beta}\, i\gamma_5 q_\beta,$$

$$\mathcal{O}_5^q = \overline{q_\alpha} \sigma^{\mu\nu} q_\alpha \overline{q_\beta}\, i\sigma_{\mu\nu}\gamma_5 q_\beta,$$

+ different flavor 4F op.

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

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

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

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

RGE

$$\mu \frac{\partial}{\partial \mu} \mathbf{C} = \mathbf{C}\boldsymbol{\Gamma},$$

Wilson coefficients

$$\mathbf{C} = (C_1^q, C_2^q, C_3, C_4^q, C_5^q, \widetilde{C}_1^{q'q}, \widetilde{C}_2^{q'q}, \widetilde{C}_1^{qq'}, \widetilde{C}_2^{qq'}, \widetilde{C}_3^{q'q}, \widetilde{C}_4^{q'q}).$$

Anomalous dimension matrix

Known results
(C)EDM & Weinberg op.

We cal'd here

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

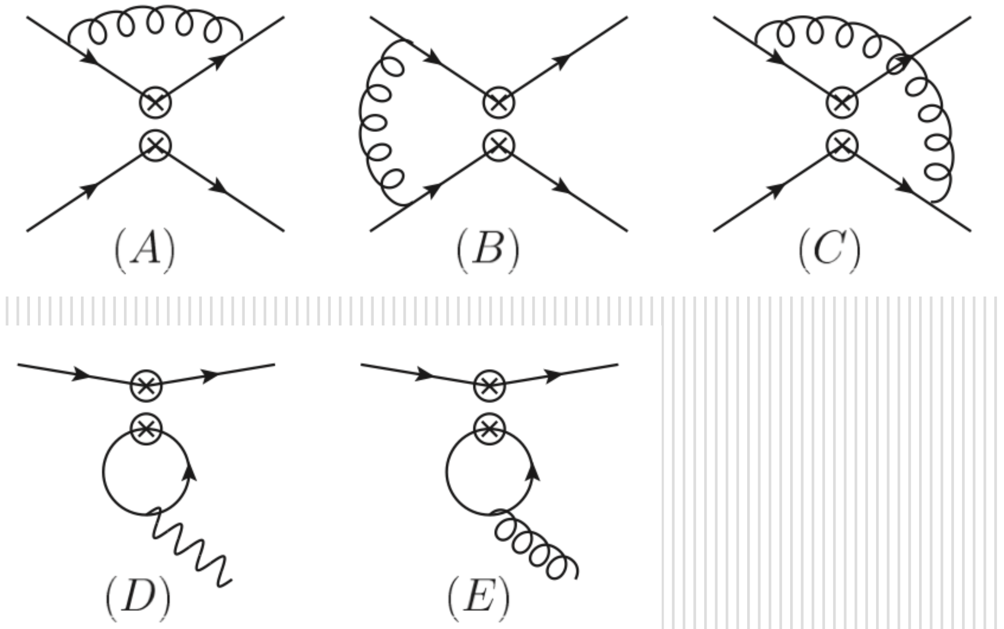
same

different

We derived these components from one-loop divergence.

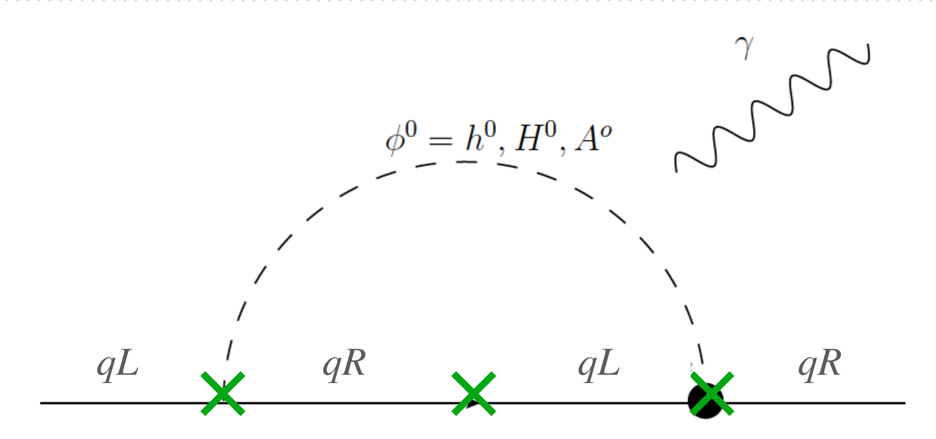
4F⇔4F γ_f γ'_f

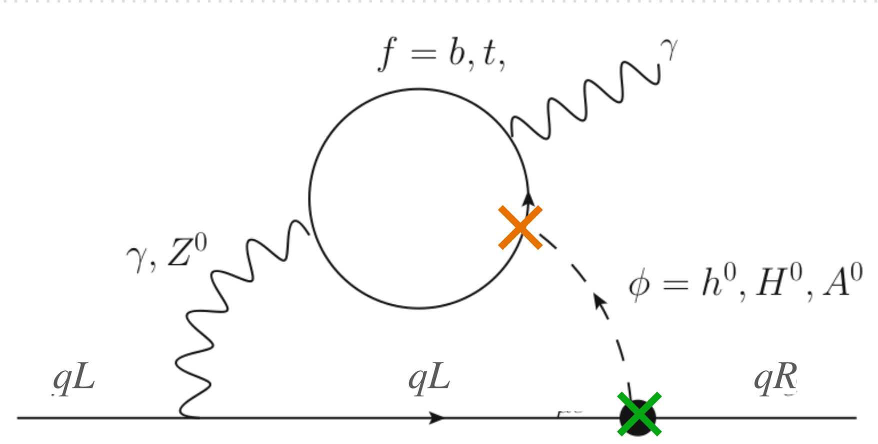
4F⇒EDM γ_{sf} γ'_{sf}



An application

- EDM from Barr - Zee dgms.





- 1-loop processes are highly suppressed by small fermion mass
- 2-loop Barr-Zee dgm. can becomes dominant because of the large higgs couplings from heavy particles

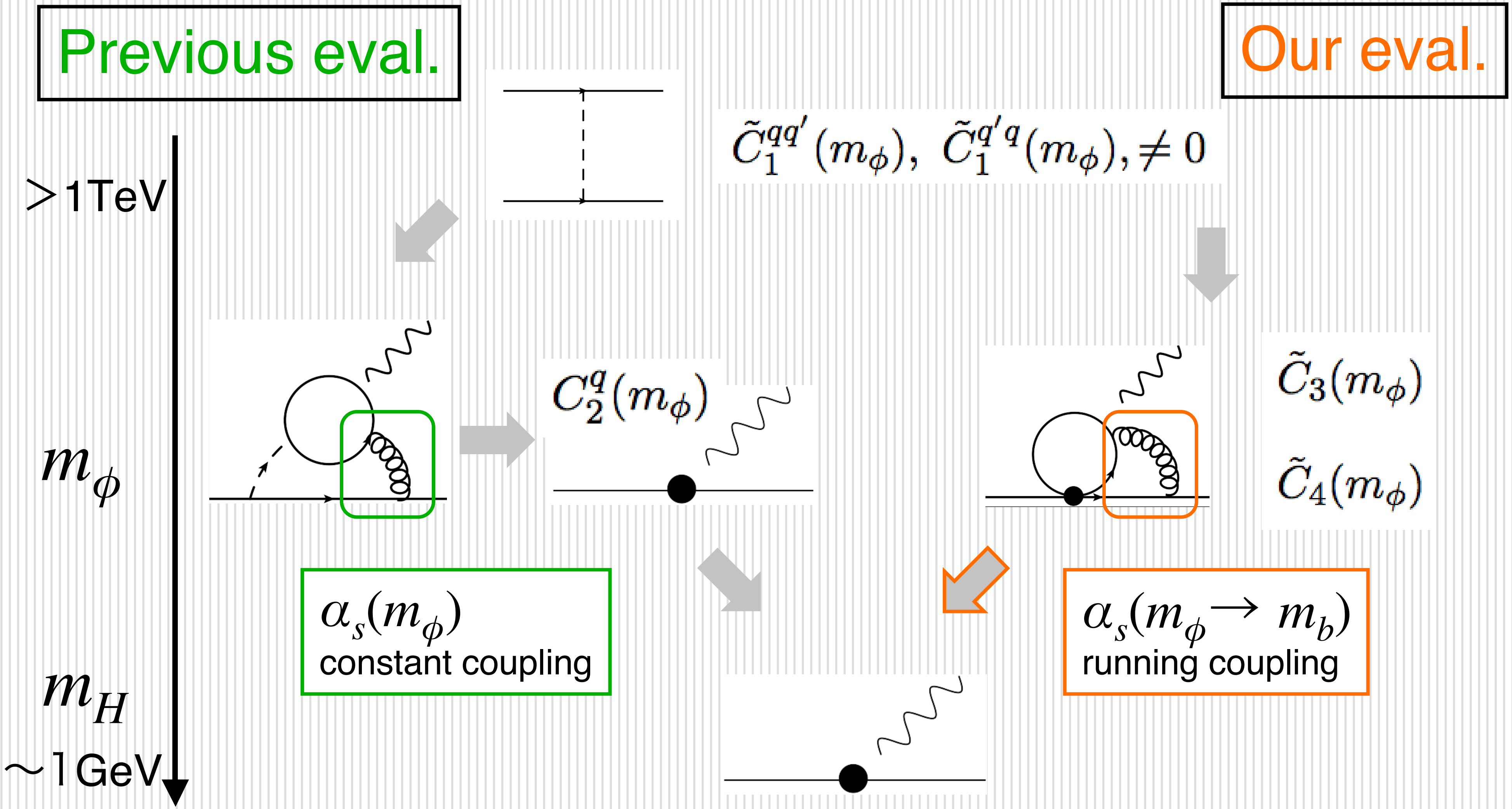
$$\frac{A^{(2-loop)f}_{l_i \to l_j \gamma}}{A^{1-loop}_{l_i \to l_j \gamma}} \sim \frac{\alpha_{em}}{4\pi} \frac{m_f^2}{m_{l_i}^2} \log\left(\frac{m_f^2}{m_H^2}\right)$$

Barr, Zee(1990),
Chang, Keung, Pilaftsis(1998)

Numerical evaluation

For a illustration,

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



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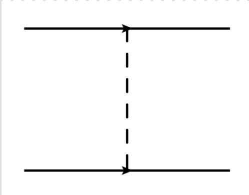
For a illustration, $\mathcal{L}_\phi = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\alpha \phi,$

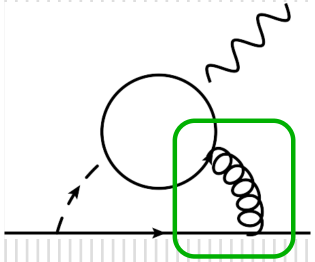
Previous eval. | **Our eval.**

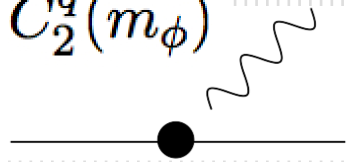
>1TeV



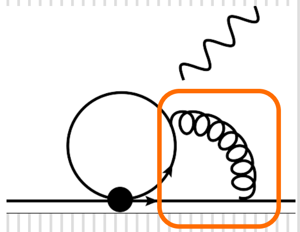
$\tilde{C}_1^{qq'}(m_\phi),\ \tilde{C}_1^{q'q}(m_\phi), \neq 0$

m_ϕ





$C_2^q(m_\phi)$



$\tilde{C}_3(m_\phi)$

$\tilde{C}_4(m_\phi)$

m_H

$\alpha_s(m_\phi)$
constant coupling

$\alpha_s(m_\phi \rightarrow m_b)$
running coupling

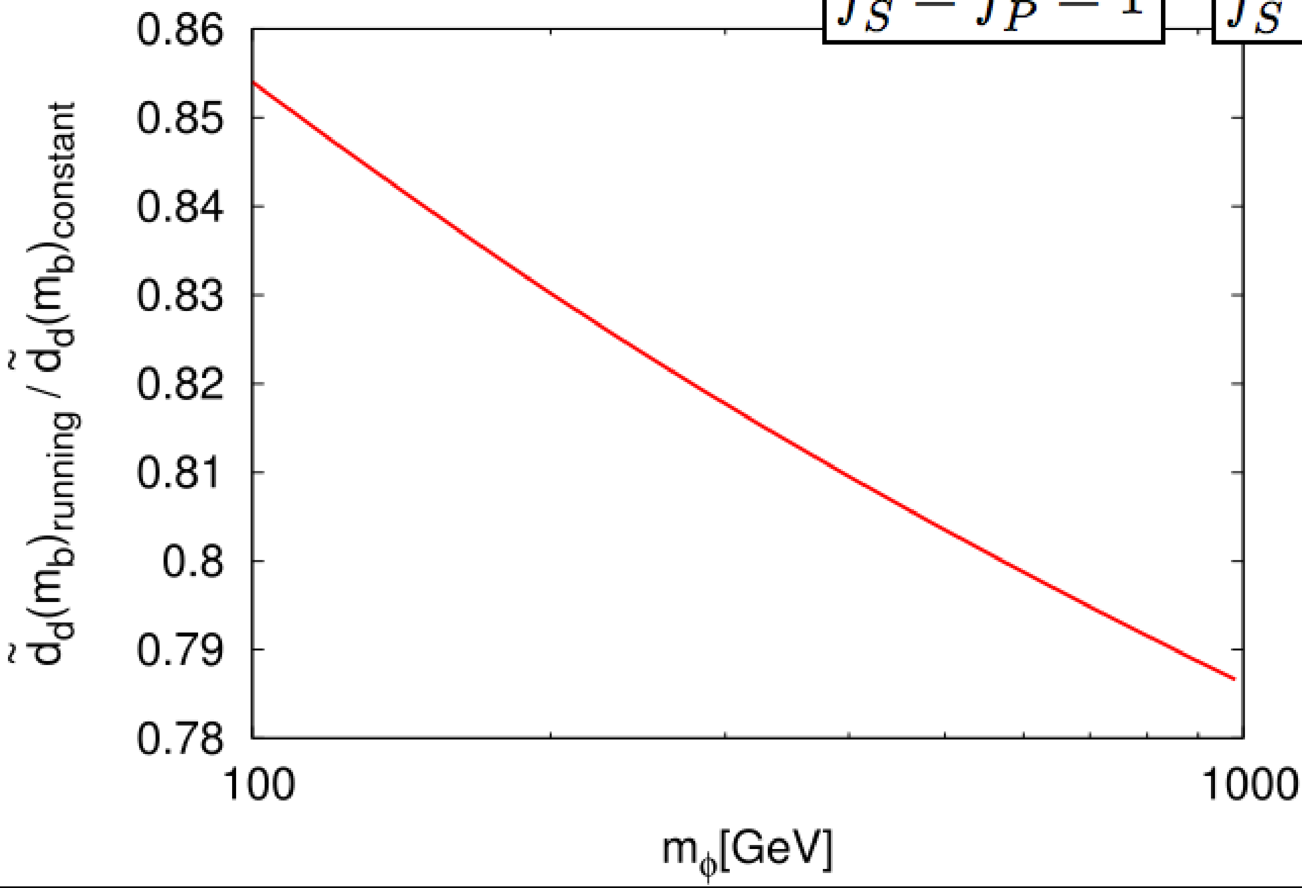
~ 1GeV

We compare the constant and running coupling.

Ratio of CEDM for down quark

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

$f_S^d = f_P^d = 1$ $f_S^b = f_P^b = 1$



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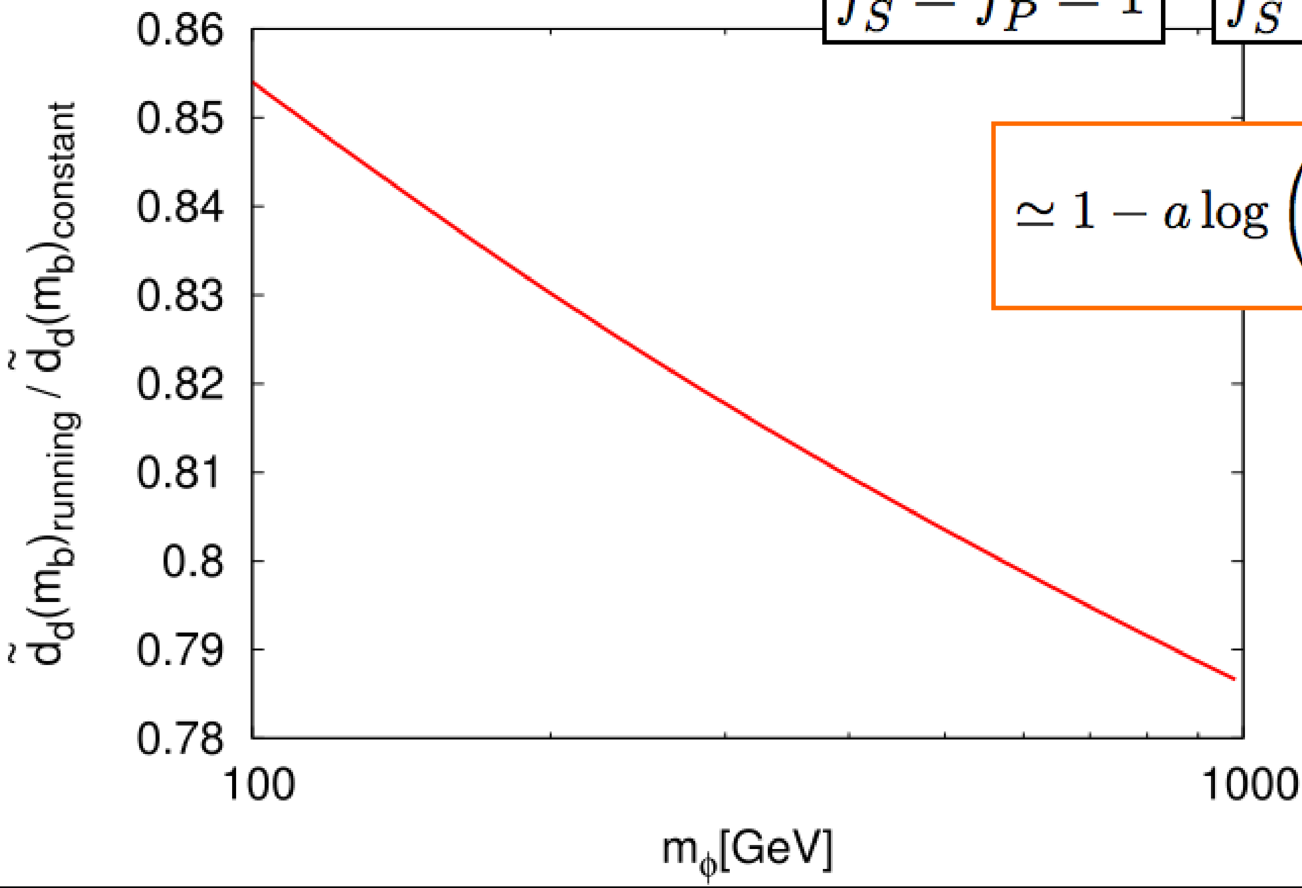
Ratio of CEDM for down quark

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

$f_S^d = f_P^d = 1$ $\quad$ $f_S^b = f_P^b = 1$



$\simeq 1 - a \log\left(\frac{m_\phi}{m_b}\right)$

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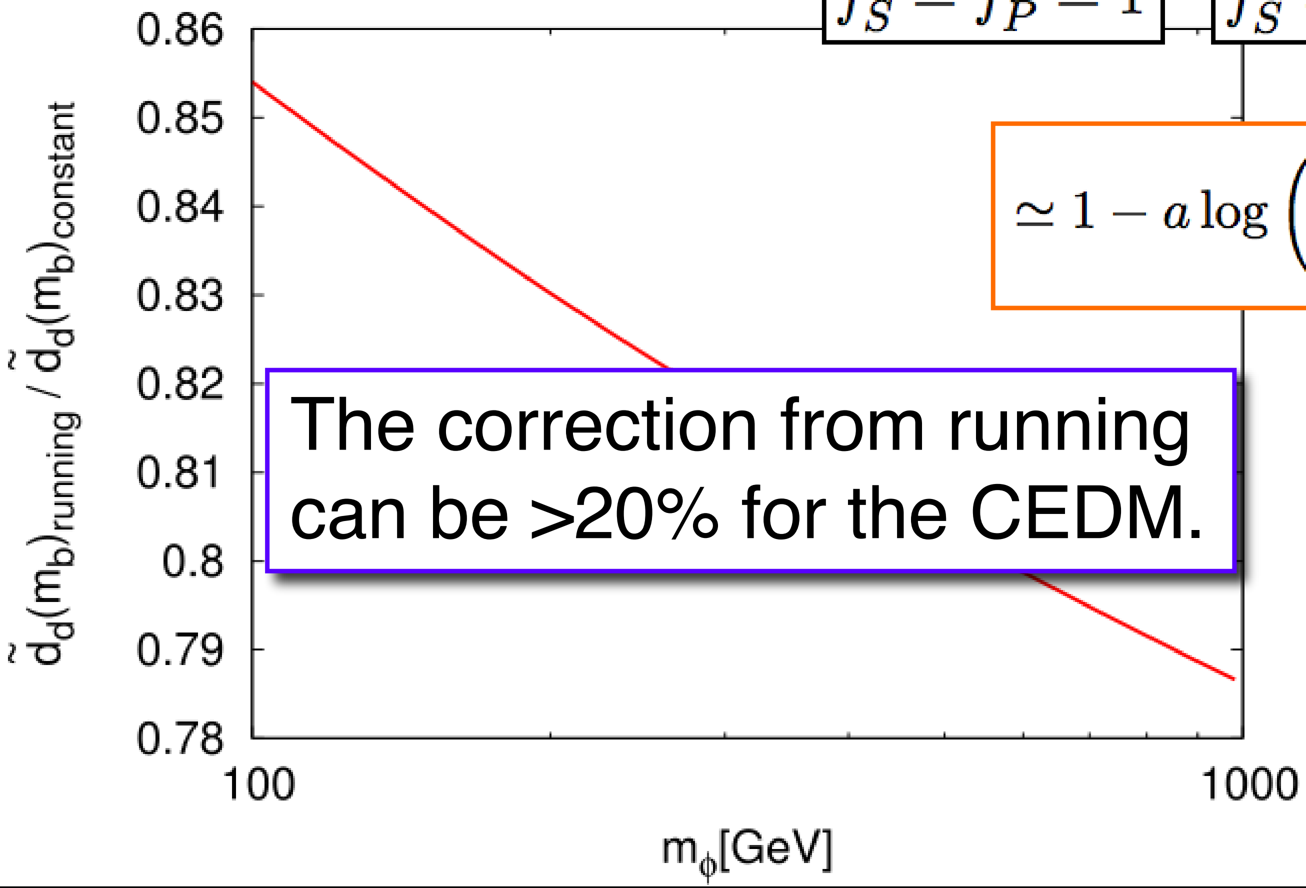


$\simeq 1 - a \log \left(\frac{m_\phi}{m_b} \right)$

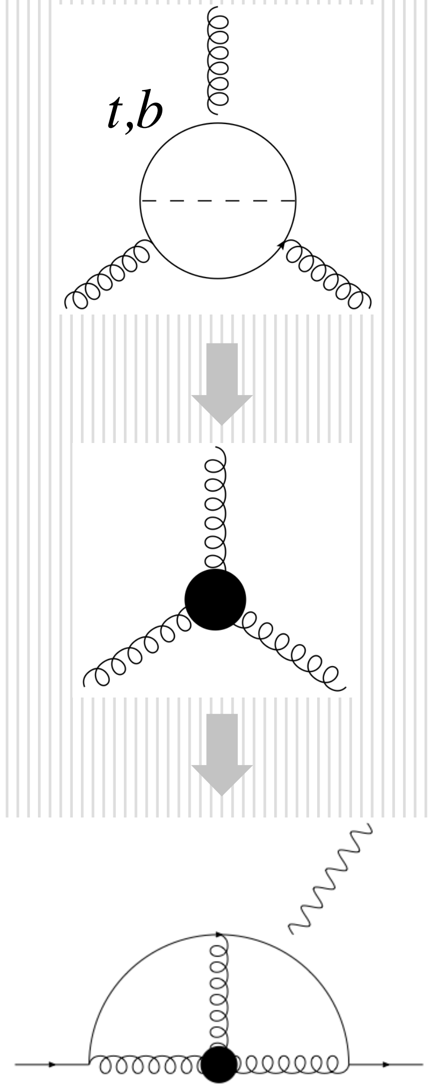
The correction from running can be >20% for the CEDM.

We compare the constant and running coupling.

The Weinberg operator

- When the same-flavor 4F op. of heavy quark is integrated out, the Weinberg operator emerges.

$$\frac{1}{3} w f_{ABC} G^{A}_{\mu\nu} \tilde{G}^{B\nu\lambda} G^{C\mu}_{\lambda} .$$



■ matching condition

$$C_3(m_q) = \frac{\alpha_s(m_q)}{8\pi} C_2^q(m_q) .$$

D. Chang, T. W. Kephart, W. -Y. Keung and T. C. Yuan,
Phys. Rev. Lett. 68, 439 (1992); Nucl. Phys.B 384, 147 (1992).

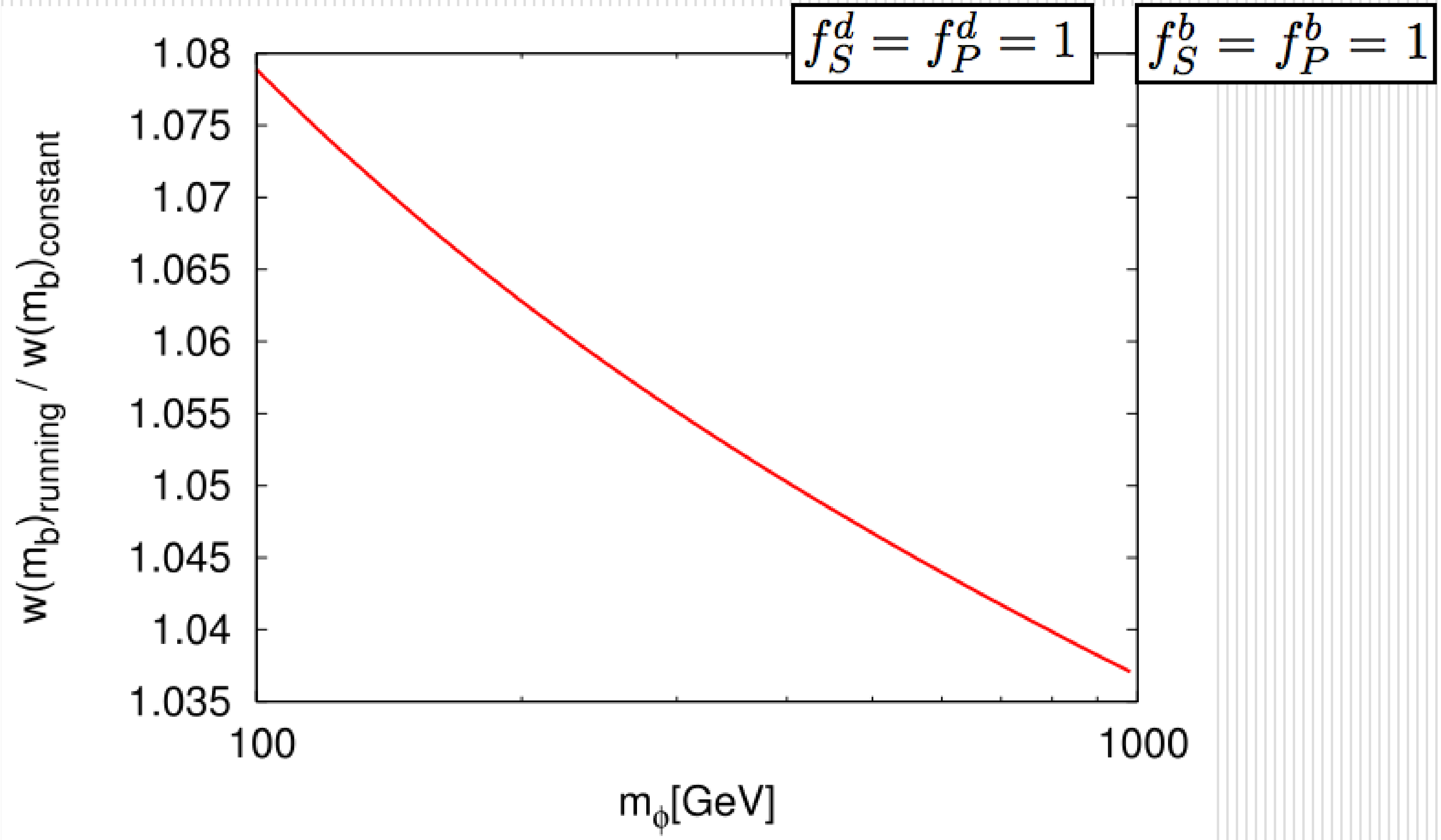
■ Its effect to the NEDM (sum rule cal.)

$$d_n(w) \sim (10 - 30)\, \mathrm{MeV} \times e w .$$

D. A. Demir, M. Pospelov and A. Ritz, Phys. Rev. D 67, 015007 (2003).

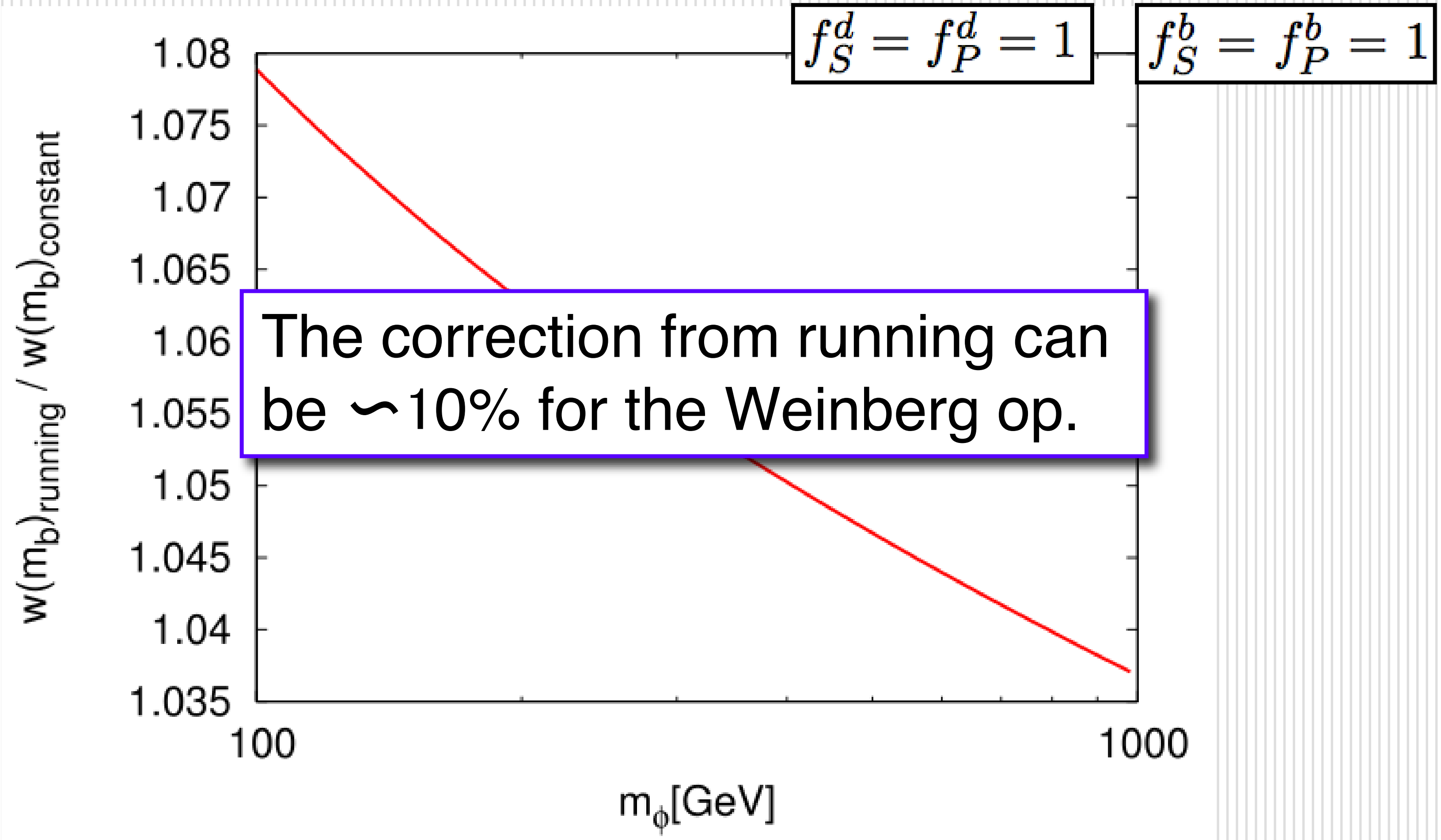
Ratio of Weinberg operator

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



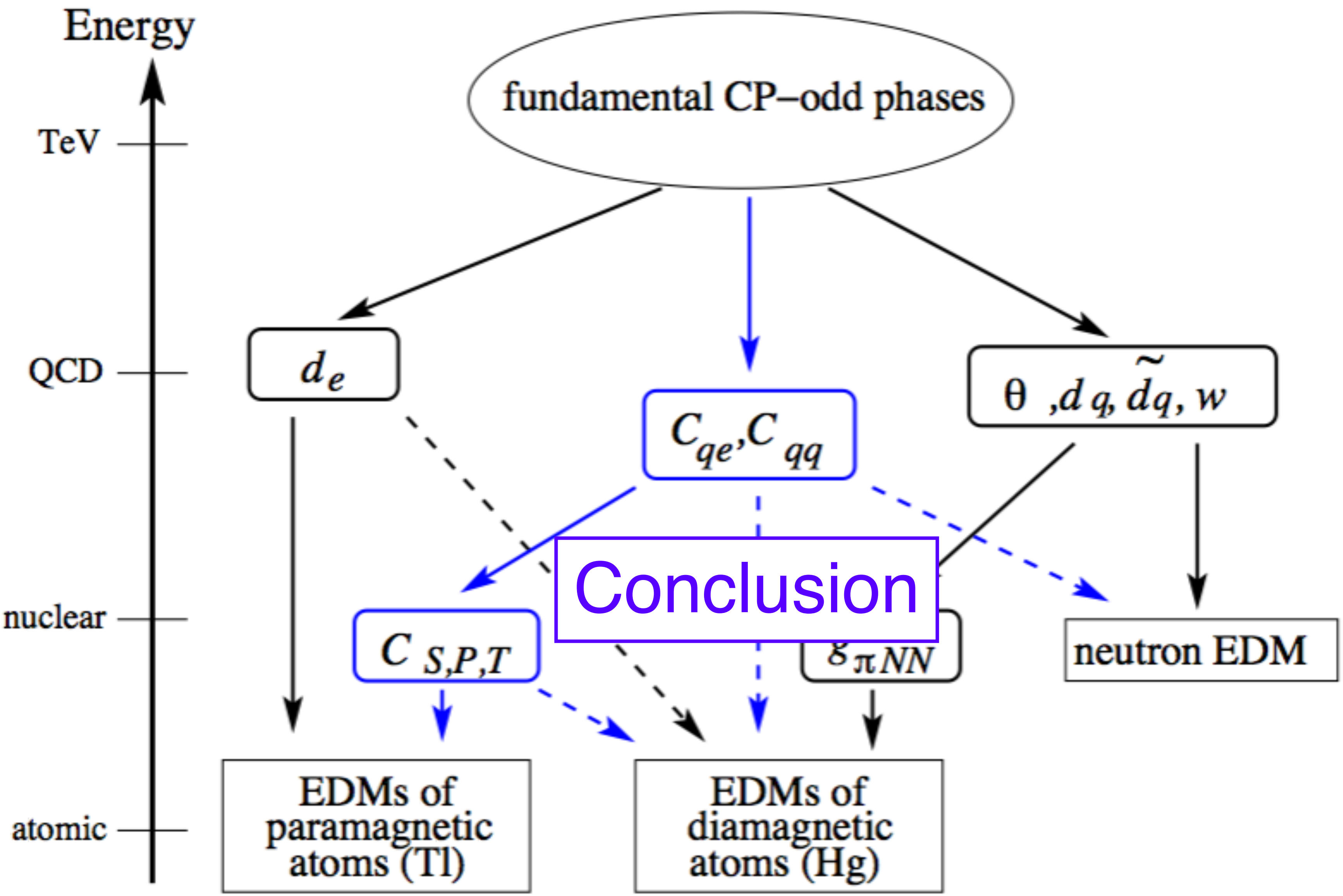
Ratio of Weinberg operator

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



An overlooking of EDM

Pospelov and Ritz,
"EDM as probes of New Physics"
Annals Phys. 318 (2005) 119-169
hep-ph/0504231



Conclusion

- EDMs are sensitive to new CPV sources, and become the good probes for NP. It is also expected from sufficient baryogenesis.
- In this study, we derived the RGE for CPV ops. up to the dim. 6, including operator mixings between the (C)EDM and the 4-fermi operators, at the one-loop level.
- The perturbation theory improved by RGE, and the evaluation of NEDM becomes more accurate (10 ∽ 20 %).

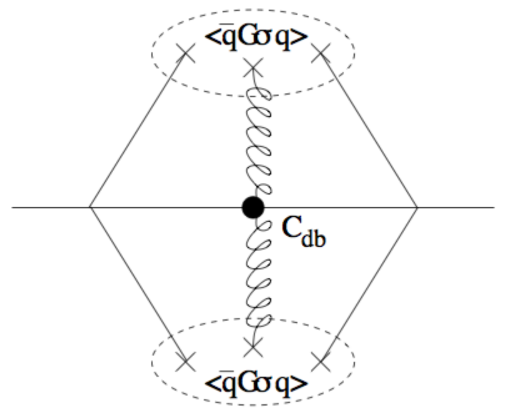
That's all.

Thank you.

Back up

Durmus A. Demir , Oleg Lebedev , Keith A. Olive , Maxim Pospelov , Adam Ritz . Nucl.Phys. B680 (2004) 339-374, hep-ph/0311314

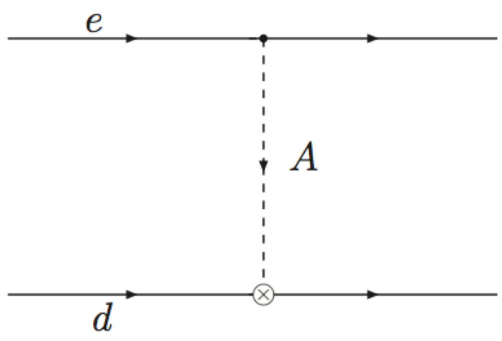
- Potentially many CP-odd four Fermi interactions also contribute to the neutron EDM, but are more difficult to handle within the sum-rule framework.



$$d_n(C_{bd}) \sim \frac{e2.6\times10^{-3}\mathrm{GeV}^2}{m_b}(C_{bd}+0.75C_{db}).$$

This effect is smaller than our results.

Also it contributes Tl EDM.



$$\frac{d_{\mathrm{Tl}}}{[d_{\mathrm{Tl}}]_{\mathrm{exp}}} \simeq \frac{\tan^3\beta}{330}\left(\frac{100\mathrm{GeV}}{m_A}\right)^2\left[\sin\theta_\mu + 0.04\sin(\theta_\mu+\theta_A)\right].$$

QCD sum rule (very short review)

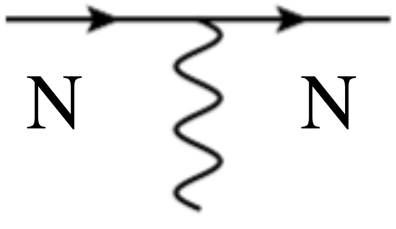
- Calculate neutron correlator by two methods.

$$\Pi(q) \equiv i \int d^4x \, e^{iq\cdot x} \langle \Omega_{\not{CP}} | T\{\eta_n(x)\bar{\eta}_n(0)\} | \Omega_{\not{CP}} \rangle_F \;,$$

$$\eta_1 = 2\epsilon_{abc}(d_a^T C\gamma_5 u_b) d_c,$$
$$\eta_2 = 2\epsilon_{abc}(d_a^T C u_b)\gamma_5 d_c,$$

・Phenomenological cal. ・OPE cal.

$$\Pi^{\text{phen}}_{(d)} = \frac{i}{2}\{F\sigma\gamma_5, \not{p}\}\left(\frac{\lambda^2 d_n}{(p^2 - m_n^2)^2} + \frac{A}{p^2 - m_n^2} + \cdots\right) ; = \Pi^{\text{OPE}} = \frac{-i}{16\pi^2}\{F\sigma\gamma^5, \not{p}\}\, \Theta\langle\bar{q}q\rangle \log\left(\frac{-p^2}{\Lambda^2}\right)$$



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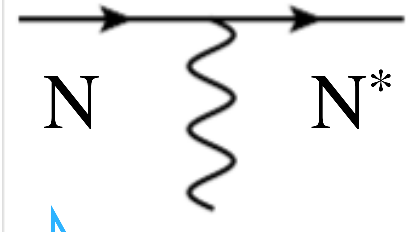

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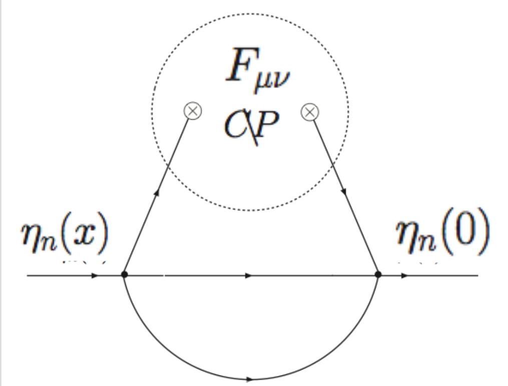


Double pole Single pole

Borel trf.
Suppress the N* contribution

$$\lambda_n^2 d_n m_n - AM^2 = -\Theta\langle\bar{q}q\rangle \frac{M^4}{8\pi^2} e^{\frac{m_n^2}{M^2}}$$

M : Borel mass
Arbitrary parameter

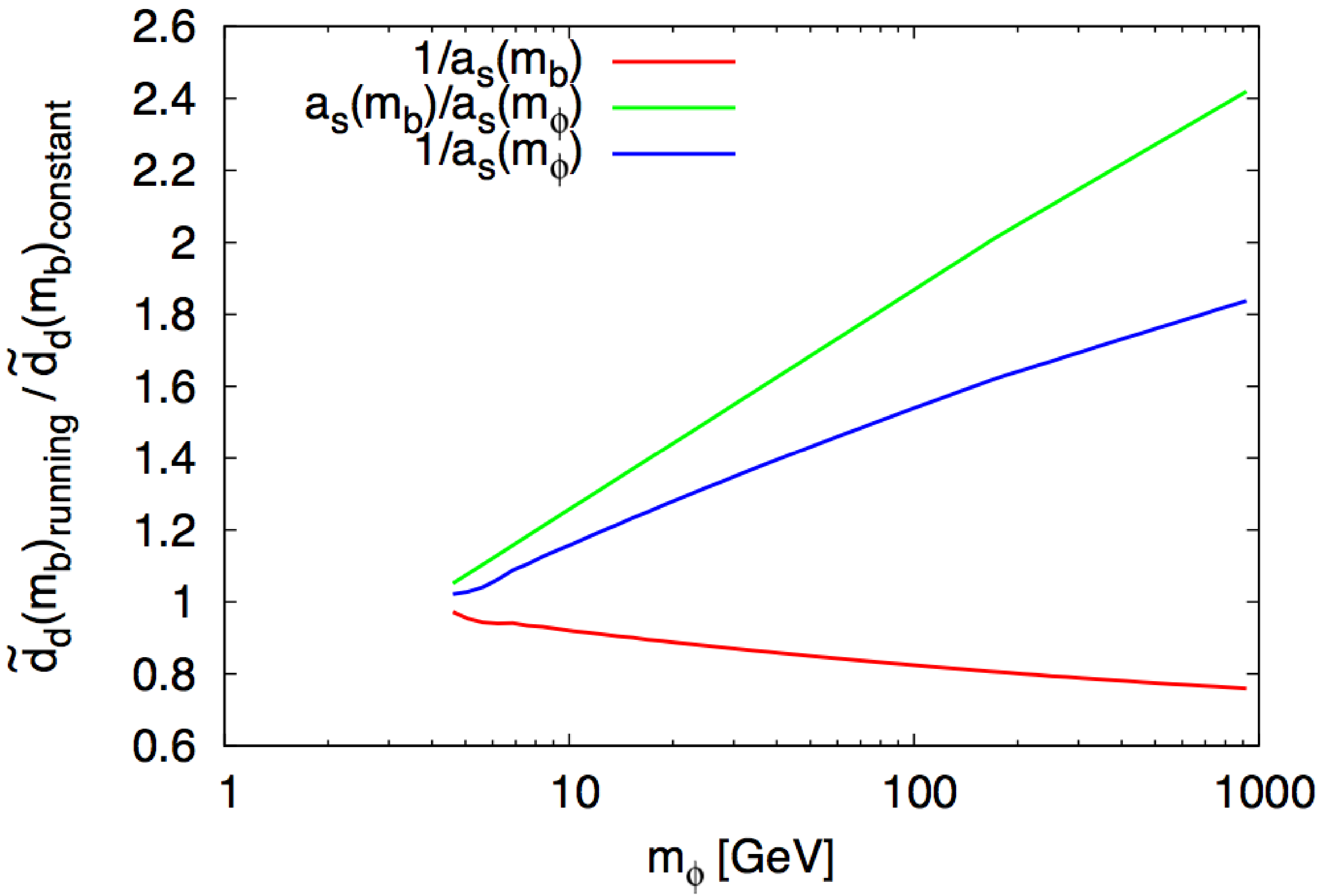
Insurance

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

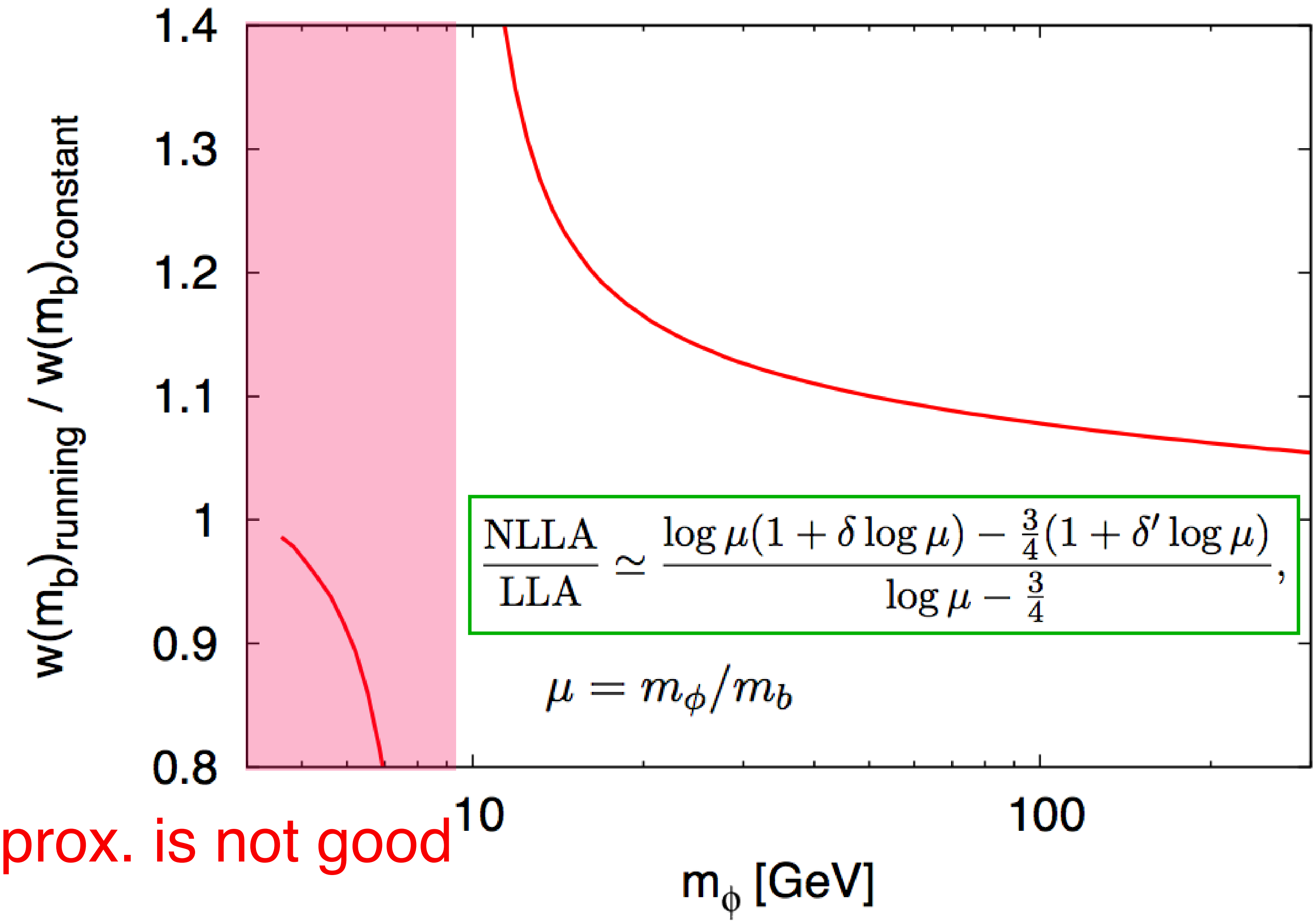
$$\gamma_s = \begin{bmatrix} +8C_F & 0 & 0 \\ +8C_F & +16C_F - 4N & 0 \\ 0 & +2N & N + 2n_f + \beta_0 \end{bmatrix}$$

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

The effect from running coupling



Asymptotic behavior of weinberg op.

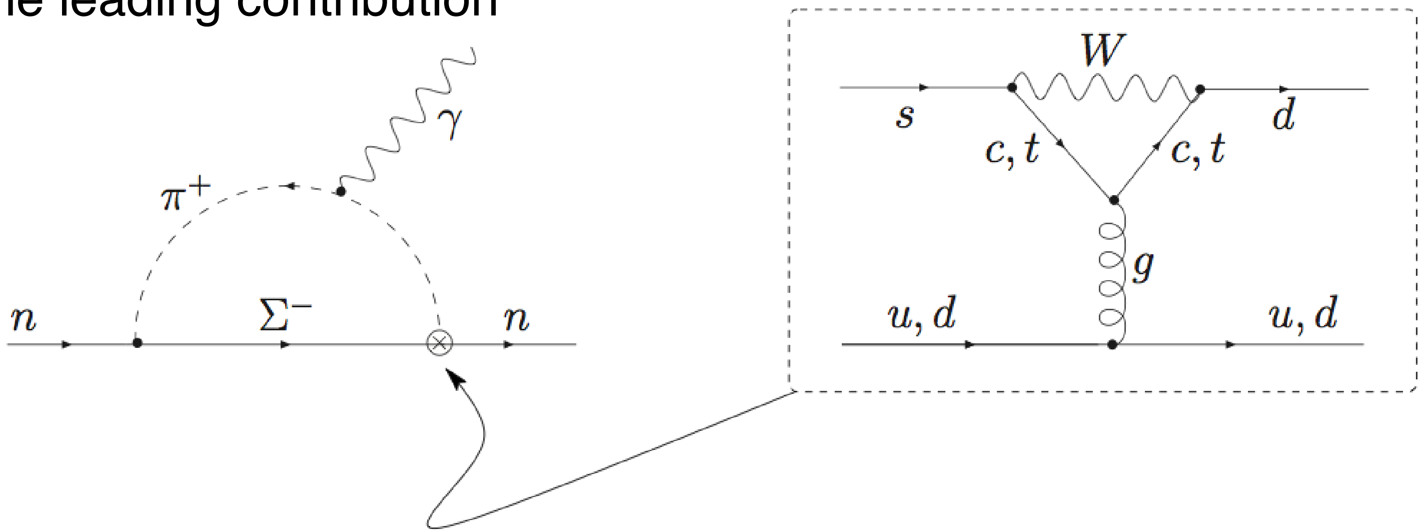


Approx. is not good

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.

QCD Crrections to NEDM from Dimension-six Four-Quark operators

Collab. with J. Hisano and K. Tsumura
arxiv/1205.2212

Masaki J.S. Yang (梁　正樹)
D3 @ Univ. of Tokyo