CP violation and electric dipole moment

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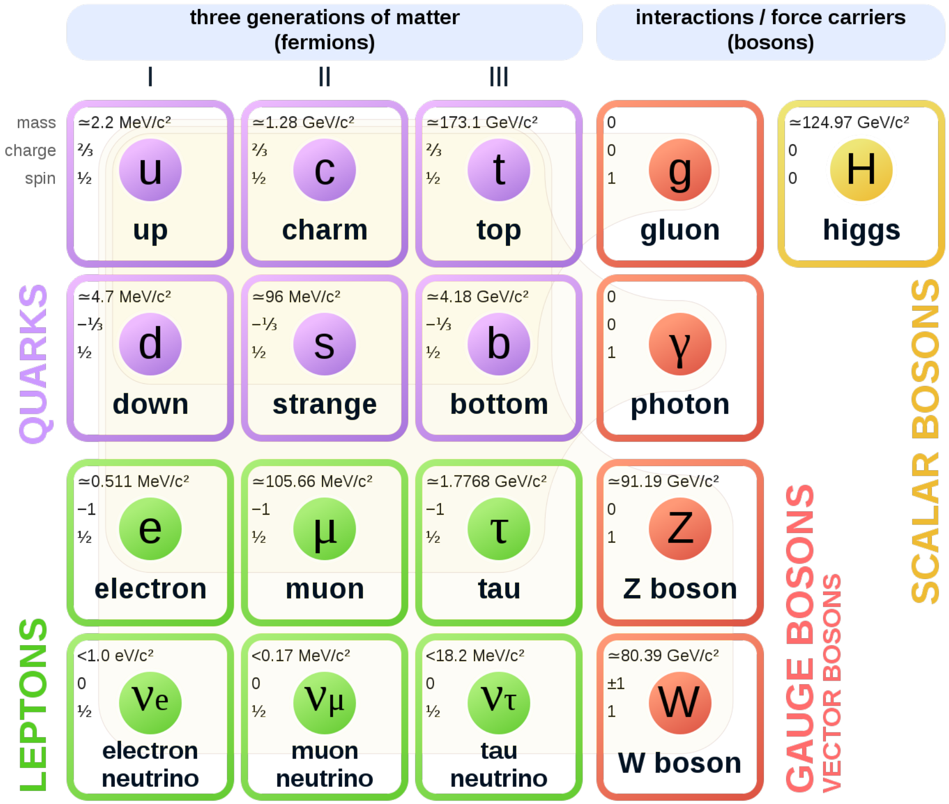
Lectures at
IBS-CTPU

Standard model and search for new physics

Standard model of particle physics



Standard model = QCD ($SU(3)_c$)+electroweak theory ($SU(2)_L xU(1)_Y$)

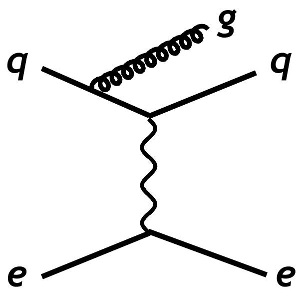
Matter fields : quarks and leptons (3 generations)

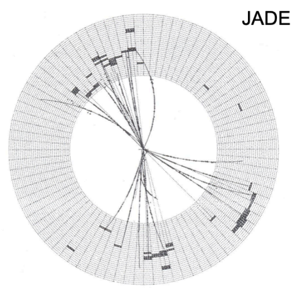
Higgs field : spontaneous breaking of EW gauge symmetry

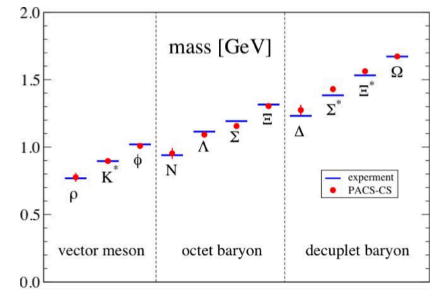
Standard model of particle physics

SM is very successful in describing high energy experimental data

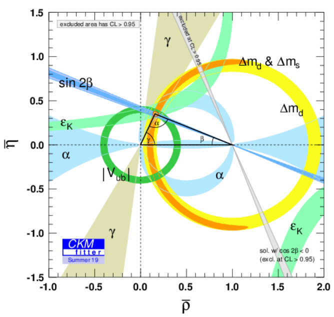
- QCD confirmed by accelerator experiments and lattice QCD

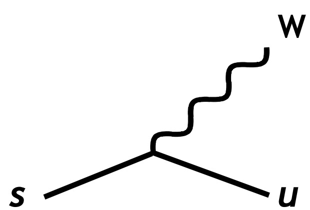






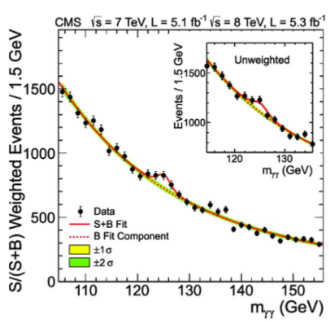
- CKM, almost unitary

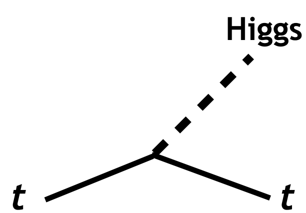




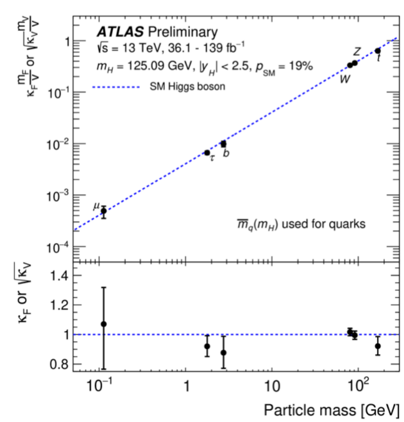
Flavor change

- Higgs boson, Yukawa couplings discovered





Yukawa interaction

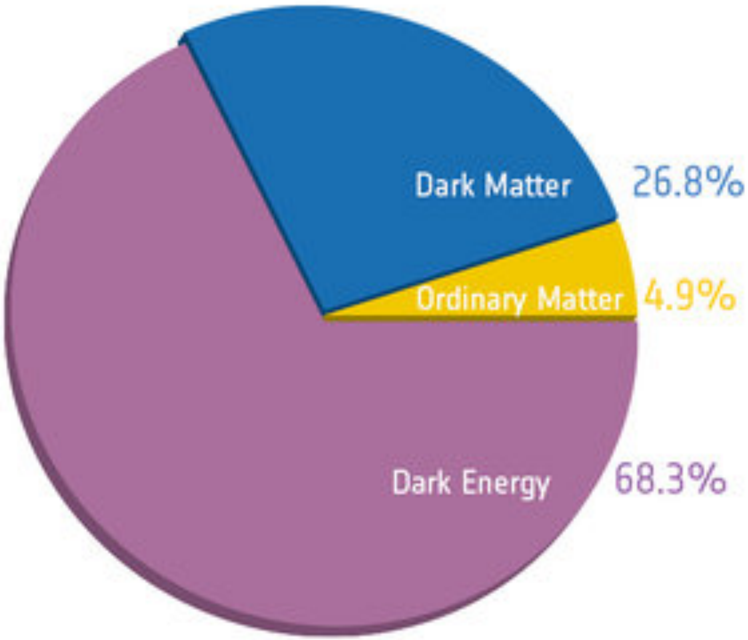


Theoretical problems of the standard model

SM is having several problems:

- **Origin of Higgs, hierarchy problem ($m_H << \Lambda_{Planck}$)**
- **Small neutrino mass (m_ν = O(0.01eV) << m_H)**
- **Hierarchy of Yukawa couplings (Y_e = O(10^{-6})<<Y_t = O(1))**
- **Charged lepton flavor conserved? (or small violation?)**
- **Strong CP problem ← Resolved?? (see later)**
- **Grand unification of gauge couplings?**
- **Does not include gravity, general relativity**

Problems of standard model with the Universe

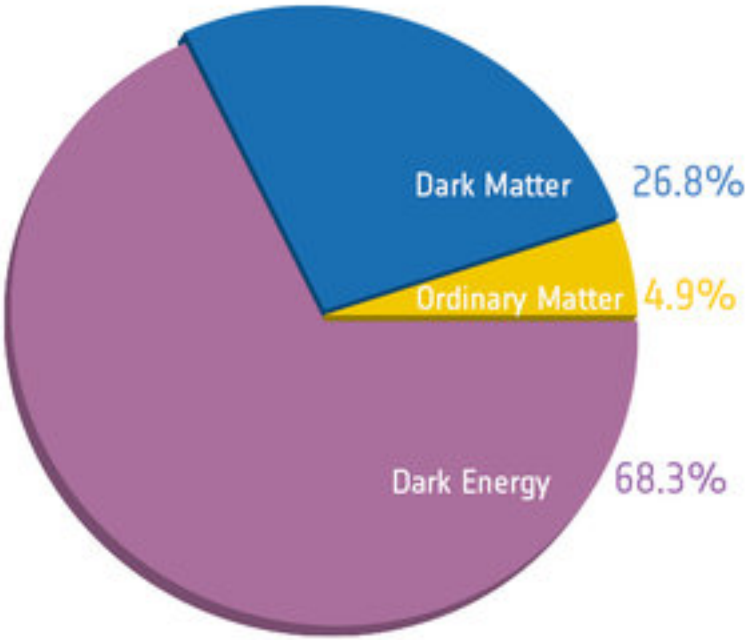


All components are difficult to explain in the SM!!

- Matter (baryon) cannot exist within the SM
- No candidates of dark matter particle in the SM
- Dark energy and inflation are not possible with SM fields??

Other notable problems such as lithium problem, Hubble tension, etc.

Problems of standard model with the Universe



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Other notable problems such as lithium problem, Hubble tension, etc.

Sakharov's three conditions

To generate the baryon number asymmetry of our Universe, 3 conditions must be satisfied:

- Baryon number violating interaction

  Baryon number must be created from null

- Departure from equilibrium

  Creation and annihilation must be asymmetric

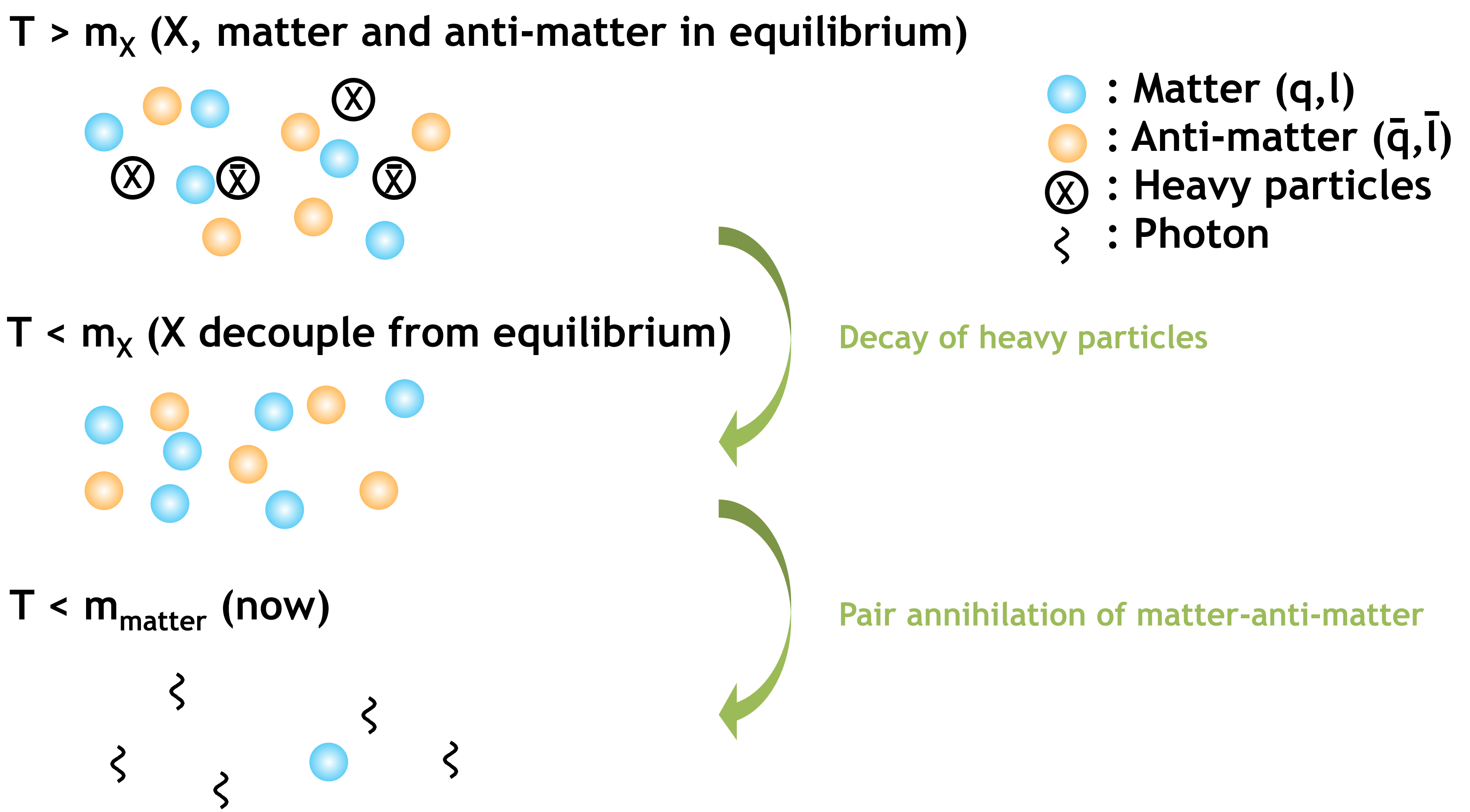
- Violations of charge conjugation (C) and charge conjugation-parity (CP)

  Particle and antiparticle properties must be asymmetric

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32.

Why did antimatter disappear (baryon number excess)?

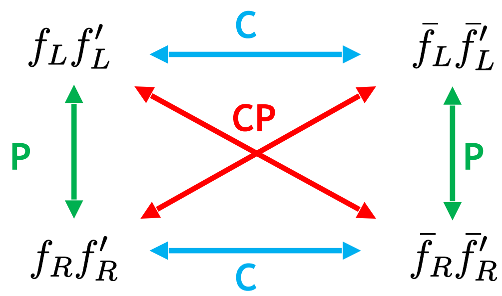
Asymmetric decays generates excess of matters in the early Universe



Matter/photon ratio
= baryon number asymmetry

C, CP violations and baryon number asymmetry

P, C and CP transformations of initial & final states:



Baryon number asymmetry:

$$\epsilon \propto \Gamma(X \to f_L f'_L) + \Gamma(X \to f_R f'_R) - \Gamma(\bar{X} \to \bar{f}_L \bar{f}'_L) - \Gamma(\bar{X} \to \bar{f}_R \bar{f}'_R)$$

Similar relations hold for decays of other particles, other interactions

C & CP violations are both needed for baryon number asymmetric decays

No baryon number asymmetry in SM

ratio matter : photon (∼entropy)

Observation: $1 : 10^{10}$

Standard model prediction: 0 !!

In the SM, we have
* no strong 1st order phase transition (Higgs)
* not enough CP violation (CKM)
* no baryon/lepton number violation? (NY, see later)

⇒ Do not fulfill any Sakharov's criteria...

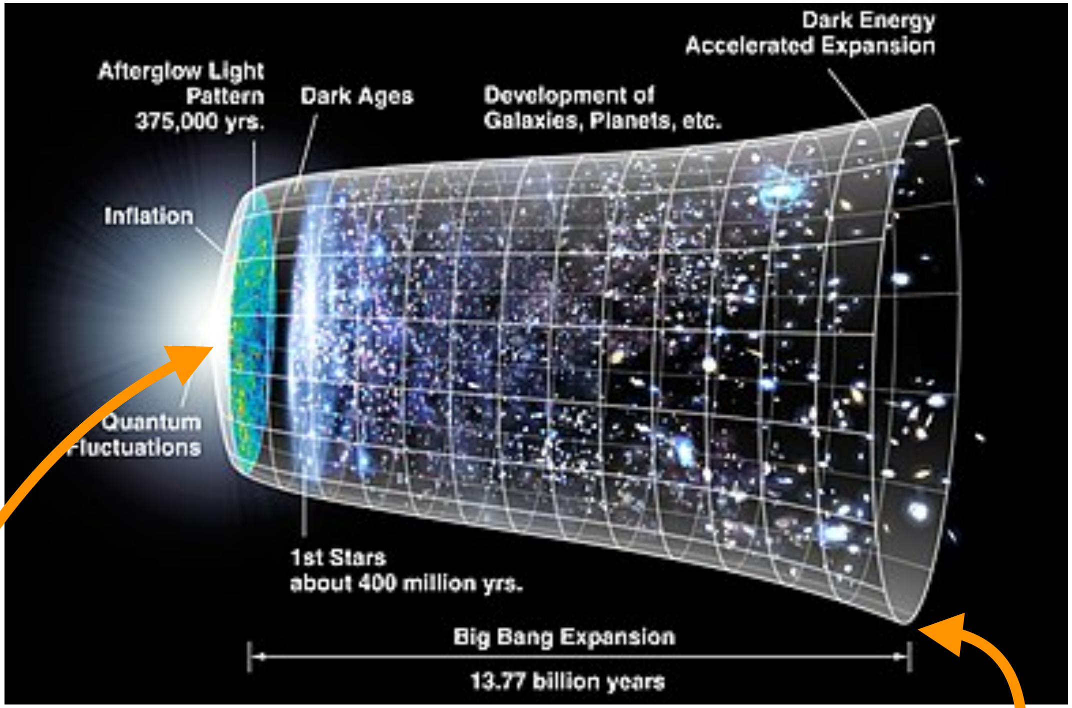
➡ **We need new physics and CP violation beyond the standard model !**

Why not baryon number asymmetry as initial condition?

No, because the inflation dilutes baryon number asymmetry

(Inflation is needed to solve horizon problem, flatness, …)

E-folding number ∼ 60



Suppose initial condition

$B/s \sim 1 : 1$

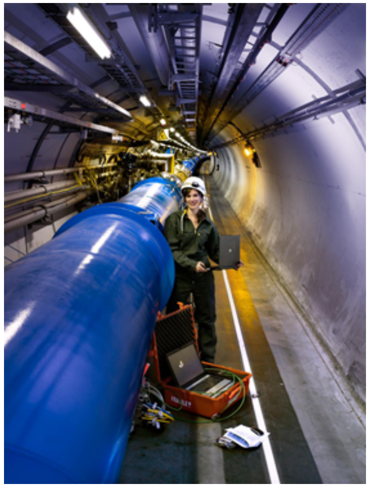
You would have now

$B/s \sim 1 : 10^{25}$!

Search for new physics : High energy frontier

Meaning : use accelerators

Current frontier : LHC experiments @ CERN



27 km circumference

Detect new particles with high energy particle collisions

Very difficult to upgrade accelerator experiments

Next generation experiments (ILC, FCC, etc) are not approved…

Precision test frontier

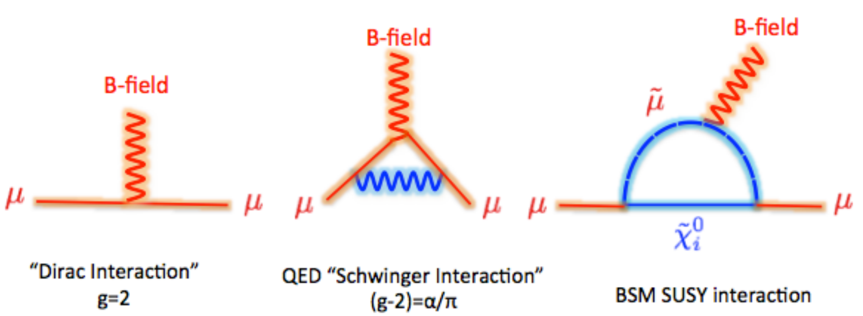
Principle:

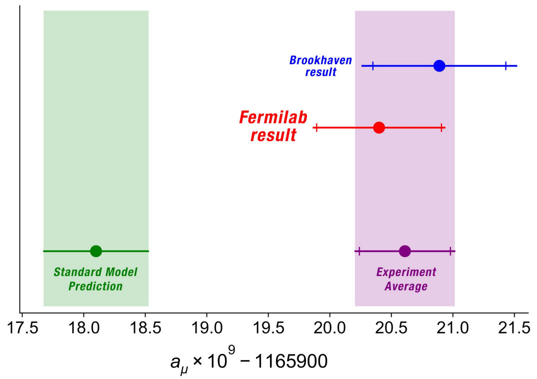
In quantum mechanics, high energy particles/interactions contribute to low energy phenomena due to the uncertainty principle

Effects of heavy particles are of course small, but nonzero!

⇒ Very precise measurements can unveil new high energy particles!

Example : muon anomalous magnetic moment (g-2)





⇒ Difference from standard model prediction is new physics!

In this lecture, I will mainly focus on CP violation and EDM

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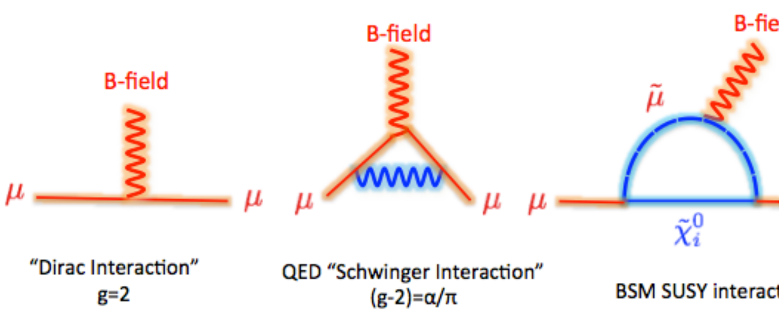

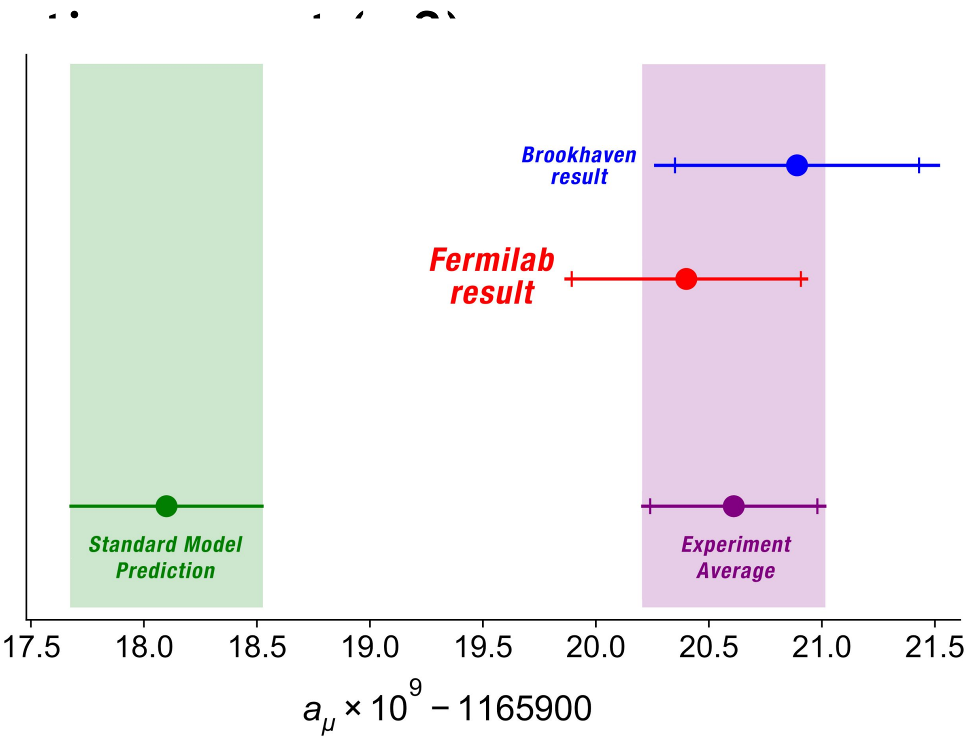

⇒ Difference from standard

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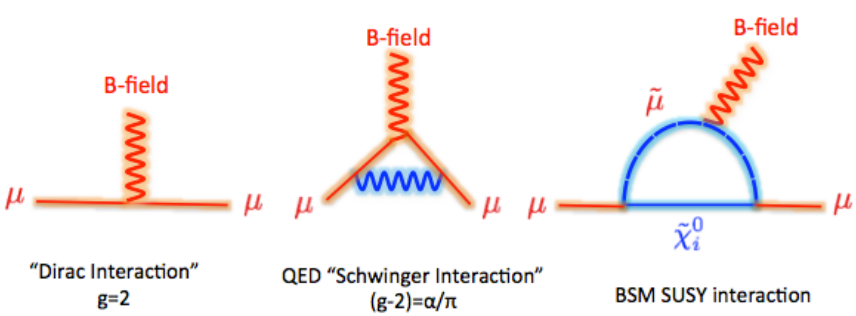

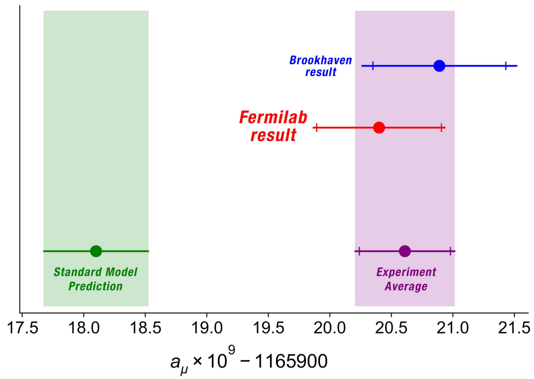

⇒ Difference from standard model prediction is new physics!

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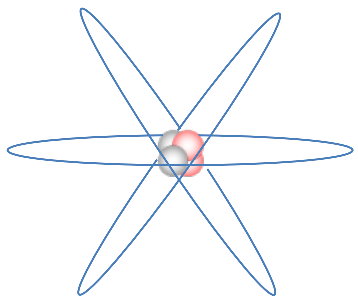
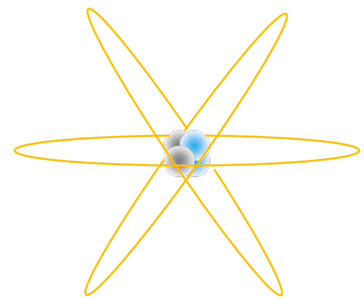
CP violation

Do you know antiparticle?

**Antiparticle: particle with opposite electric charge,
and with almost the same properties as particles**



particle (atom)



antiparticle (anti-atom)

Anti-matter (matter made of anti-particles) annihilates with matter and emit a huge amount of energy (gamma rays)

Anti-matter ??
(photo from *Angels & Demons*, Dan Brown)

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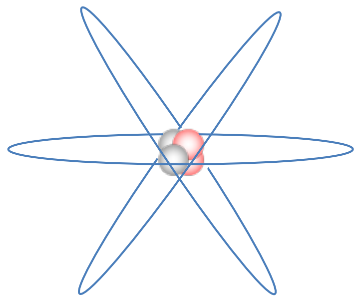
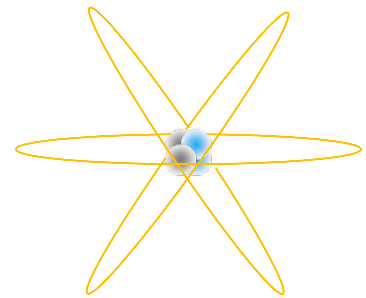


particle (atom)



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Anti-matter ??
(photo from *Angels & Demons*, Dan Brown)

Discrete symmetries : P and C

Parity transformation (P):

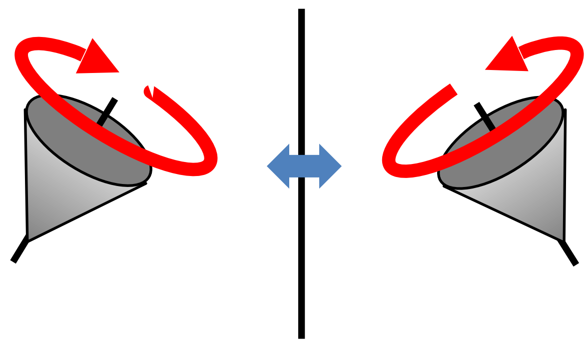
Invert all spatial coordinates

$$\vec{\mathbf{x}} \to -\vec{\mathbf{x}}$$

$\Rightarrow$ Mirror

For Dirac spinors,

$$\psi_L \leftrightarrow \psi_R \quad \Longleftrightarrow \quad \psi \to \gamma_0 \psi$$



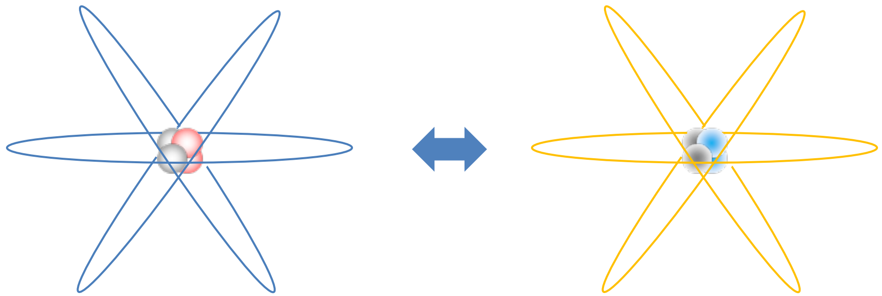
Charge conjugation (C):

Invert sign of all charges

$$\psi = e^{i\theta}|\psi|$$

$$\to \psi^* = e^{-i\theta}|\psi|$$

$\Rightarrow$ Invert complex phases



Matter (atom)   Antimatter (anti-atom)

CP symmetry

C inverts complex phases of field operators

Antifermions have opposite parity, so we need to also invert P
(because spin is rotation of charge, opposite current for antiparticle)

⇒ Left-handed quark and right-handed antiquark
have same properties if CP conserved (if no interactions)

⇒ This is the genuine symmetry between particles and antiparticles
for <u>massless and noninteracting</u> fermions !

(Not C , probably because C was formulated in nonrelativistic physics)

CPT theorem

CPT is not violated in local field theory with Lorentz symmetry

Why is CPT conserved?

CPT is a convention of “all signs”

We are free to define the signs of space-time axes and charges

What if CPT is broken?

⇒ Lorentz violation

⇒ $m_{e^-} \neq m_{e^+}$ Different particle and antiparticle masses!

(Motivation for anti-atom experiments)

⇒ Non-Hermite? (Breakdown of probabilistic interpretation)

CP = T

Time reversal : take complex conjugate of coupling constants

(because $Te^{iHt}\psi(x)|0\rangle = e^{-iHt}T\psi(x)|0\rangle$ **)**

From CPT theorem, CP=T. Let us show this :

CP inverts the phase of operators

$$c_1\phi^n\psi^m + c_2\phi^l\psi^k + \cdots \to c_1(\phi^\dagger)^n(\psi^\dagger)^m + c_2(\phi^\dagger)^l(\psi^\dagger)^k + \cdots$$

Since Lagrangian is Hermite, $\mathcal{L} = \mathcal{L}^\dagger$

$$\mathcal{L}^{(\mathrm{CP})} = c_1(\phi^\dagger)^n(\psi^\dagger)^m + c_2(\phi^\dagger)^l(\psi^\dagger)^k + \cdots$$

$$= \mathcal{L}^{(\mathrm{CP})\dagger} = c_1^*\phi^n\psi^m + c_2^*\phi^l\psi^k + \cdots = \mathcal{L}^{(\mathrm{T})}$$ **⇒ CP = T is OK**

⇒ CP is not conserved if coupling constants are complex

But generic couplings are complex, unless some symmetry forbids complex phases (naturalness argument)

… General Lagrangian is CP violating?

⇒ No ! Because operator phases may be redefined (next slide)

CP violating interactions

CP is violated if fermion and antifermion do not have same interaction

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CP is violated if fermion and antifermion do not have same interaction

⇒ Lagrangian with complex coupling constants (e.g. vector interaction)

$$\mathcal{L}_V = \underline{g_V} V_\mu \bar{\psi}_1 \gamma^\mu \psi_2 + \underline{g_V^*} V_\mu^\dagger \bar{\psi}_2 \gamma^\mu \psi_1$$

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HOWEVER, complex phases may be removed by field redefinition $\psi' = e^{i\theta}\psi$
(absorb complex phase of couplings into fields)

➡ $$\mathcal{L}_V = |g_V| V_\mu \bar{\psi}_1' \gamma^\mu \psi_2 + |g_V| V_\mu^\dagger \bar{\psi}_2 \gamma^\mu \psi_1'$$

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➡ **More interactions (coupling constants) are required than fields**

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⇒ **More interactions (coupling constants) are required than fields**

⇒ **To completely fix the phases, we need interactions which change chirality (e.g. mass term or Yukawa interaction)**

$$\psi = \begin{pmatrix} e^{i\theta_L}\psi_L \\ e^{i\theta_R}\psi_R \end{pmatrix}$$

$$\mathcal{L}_Y = \underline{g_Y} \phi \bar{\psi}_1 \psi_2 + \underline{g_Y^*} \phi^\dagger \bar{\psi}_2 \psi_1$$

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$$\mathcal{L}_Y = \underline{g_Y} \phi \bar{\psi}_1 \psi_2 + \underline{g_Y^*} \phi^\dagger \bar{\psi}_2 \psi_1$$

We could fix all 3 relative phases of $\psi_{1L}, \psi_{2L}, \psi_{1R}, \psi_{2R}$

CP violating interactions

CP is violated if fermion and antifermion do not have same interaction

⇒ Lagrangian with complex coupling constants (e.g. vector interaction)

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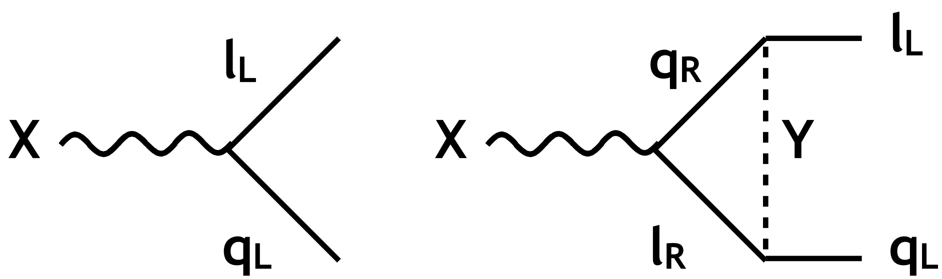
⇒ 1 remaining phase violates CP !

Toy model for fermion number asymmetry generation

Consider the decay of heavy particles (X,Y) with CP violation

(Leptons and quarks are massless)



$$\Gamma(X \to ql) \neq \Gamma(\bar{X} \to \bar{q}\bar{l})$$

Thanks to the appearance of different interactions with X and Y,
all 3 relative phases between l_L, l_R, q_L, q_R are exhausted, 1 remaining

We need interference with 1-loop to generate asymmetry, because

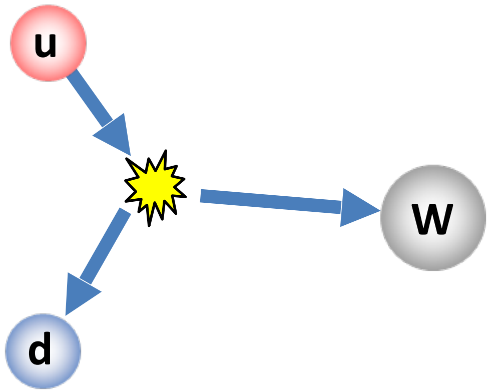
- Complex phases of couplings cancel for |tree|^2 cross section
- Loops with on-shell fermions generate imaginary parts $\dfrac{i}{\not{p} - m + i\epsilon}$

Prototype of GUT baryogenesis!

J. A. Harvey et al., Nucl. Phys. B **201**, 16 (1982).

CPV of Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



W boson exchange may change generation (flavor)

3 x 3 complex elements ⇒ 18 real parameters

But not all are free! (given that masses have already fixed θ_L-θ_R)

M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

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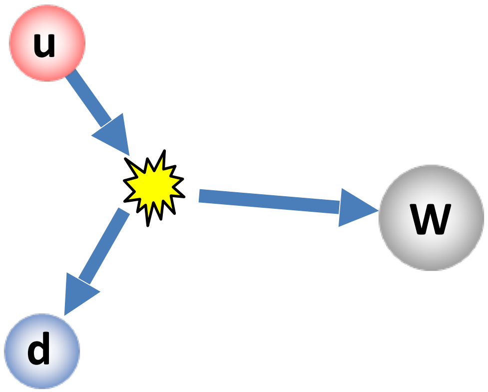

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9 equations, reduce to 9 free parameters

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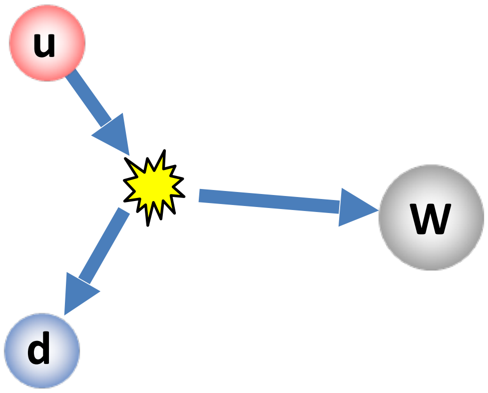

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9 equations, reduce to 9 free parameters

Field redefinition : $\psi_q \to e^{i\theta_q} \psi_q$

We can absorb 5 relative complex phases between quarks

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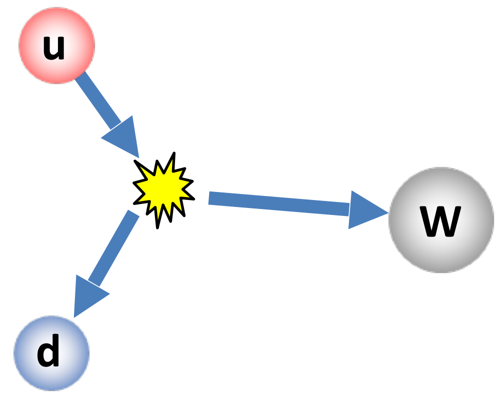

W boson exchange may change generation (flavor)

3 x 3 complex elements ⇒ 18 real parameters

But not all are free! (given that masses have already fixed θ_L-θ_R)

Unitarity : $V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = \hat{1}$

9 equations, reduce to 9 free parameters

Field redefinition : $\psi_q \to e^{i\theta_q} \psi_q$

We can absorb 5 relative complex phases between quarks

Remaining degree of freedom

- 3 mixing angles (flavor change)
- 1 complex phase : CP violation !

M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

Jarlskog invariant and relevant CKM CP violation

Parametrize CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

δ : CP violating phase

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δ : CP violating phase

To pick up $i\delta$, we need the following combination :

$$J = \mathrm{Im}[V_{ts}^* V_{td} V_{us} V_{ud}^*] = -\mathrm{Im}[V_{cs}^* V_{cd} V_{us} V_{ud}^*]$$ (**Jarlskog invariant**)

$$= (3.06 \pm 0.21)\times 10^{-5} \text{ (PDG value)}$$

C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).

Jarlskog invariant and relevant CKM CP violation

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Estimation : $CPV \propto \frac{m_t^2 m_b^2 m_c^2 m_s^2}{m_W^8} J$ = $O(10^{-16})$ (m^2 because L→R→L)

Jarlskog invariant and relevant CKM CP violation

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⇒ SM CP violation is very small !!

(we may have some enhancement due to kinematics, QCD effects, etc)

Complex phases of fermion mass

$$\mathcal{L} = m\bar{\psi}_R\psi_L + \text{h.c.}$$

(Total Lagrangian is Hermite, real)

$e^{i\theta_m}$ $\quad$ $e^{i\theta_R}$ $\quad$ $e^{-i\theta_L}$

Fermion mass may have CP phase

Phases of left- and right-handed fermions may be rotated independently

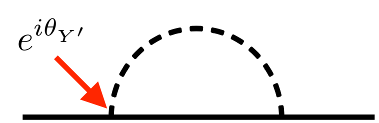
$$\begin{cases} \psi_L & \rightarrow & e^{i(\theta_L - \theta_m/2)}\psi_L \\ \psi_R & \rightarrow & e^{i(\theta_R + \theta_m/2)}\psi_R \end{cases}$$

($U(1)_L$ x $U(1)_R$ symmetry)

⇒ We can remove CP phase …

But, conversely, we can also <u>generate</u> CP phase, definition-dependent?

Also, BSM theory can generate CP phase via loops



How much is the true CP violation…?

Chiral symmetry and CP phases

We can factorize the mass for chirality flipping interactions:

Dipole moment (MDM and EDM):

$$\mathcal{L}_F = A\bar{\psi}_R\sigma^{\mu\nu}F_{\mu\nu}\psi_L + \text{h.c.} \qquad = a\underline{m}\bar{\psi}_R\sigma^{\mu\nu}F_{\mu\nu}\psi_L + \text{h.c.}$$

4-fermion interaction (CP-even and CP-odd):

$$\mathcal{L}_2 = B(\bar{\psi}_R\psi_L)^2 + \text{h.c.} \qquad = b\underline{m^2}(\bar{\psi}_R\psi_L)^2 + \text{h.c.}$$

CP phase of *m* is also factorized because chiral symmetry is protected,
***m* has a global $U(N_f)_L$x $U(N_f)_R$ charge**

- **Factorized couplings (*a* and *b*) are independent of chiral $U(N_f)_L$x $U(N_f)_R$ transformation!**
- **CP phase of mass is an overall phase, unphysical!**
- **Factorized couplings (and their phases) are physical!**

Schematically

Mass

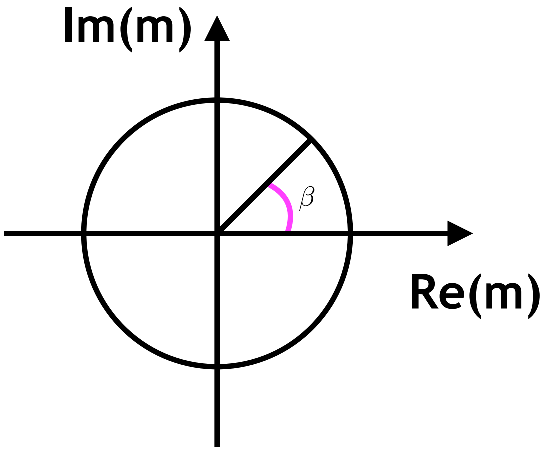
$$-m\bar{\psi}_R\psi_L + \text{h.c.}$$

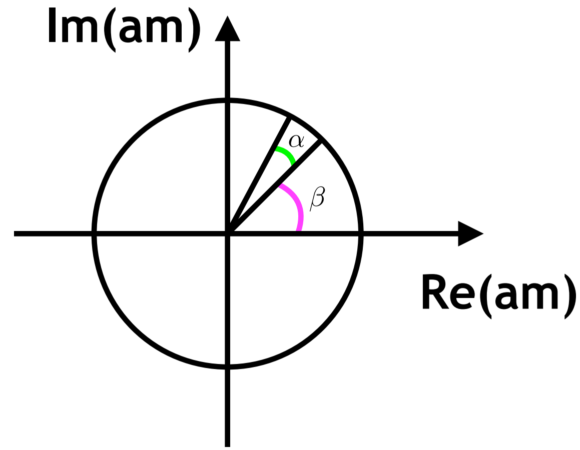
$m \leftarrow e^{i\beta}$

Dipole moment

$$am\bar{\psi}_R\sigma^{\mu\nu}F_{\mu\nu}\psi_L + \text{h.c.}$$

$a \leftarrow e^{i\alpha}$, $m \leftarrow e^{i\beta}$





β is arbitrary, unphysical

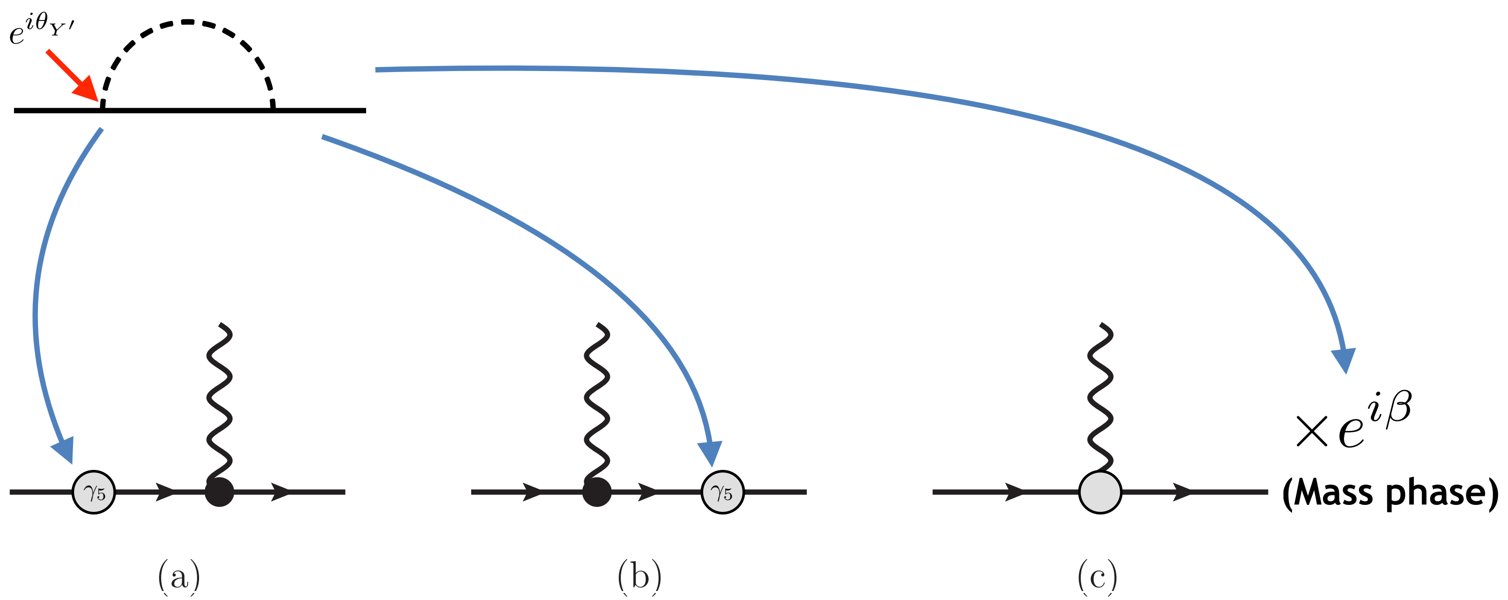
Chiral phase of CP-odd mass only contributes to β, unphysical

α (relative phase between mass and dipole) is chiral invariant, physical

Irreducible EDM contribute to α, physical

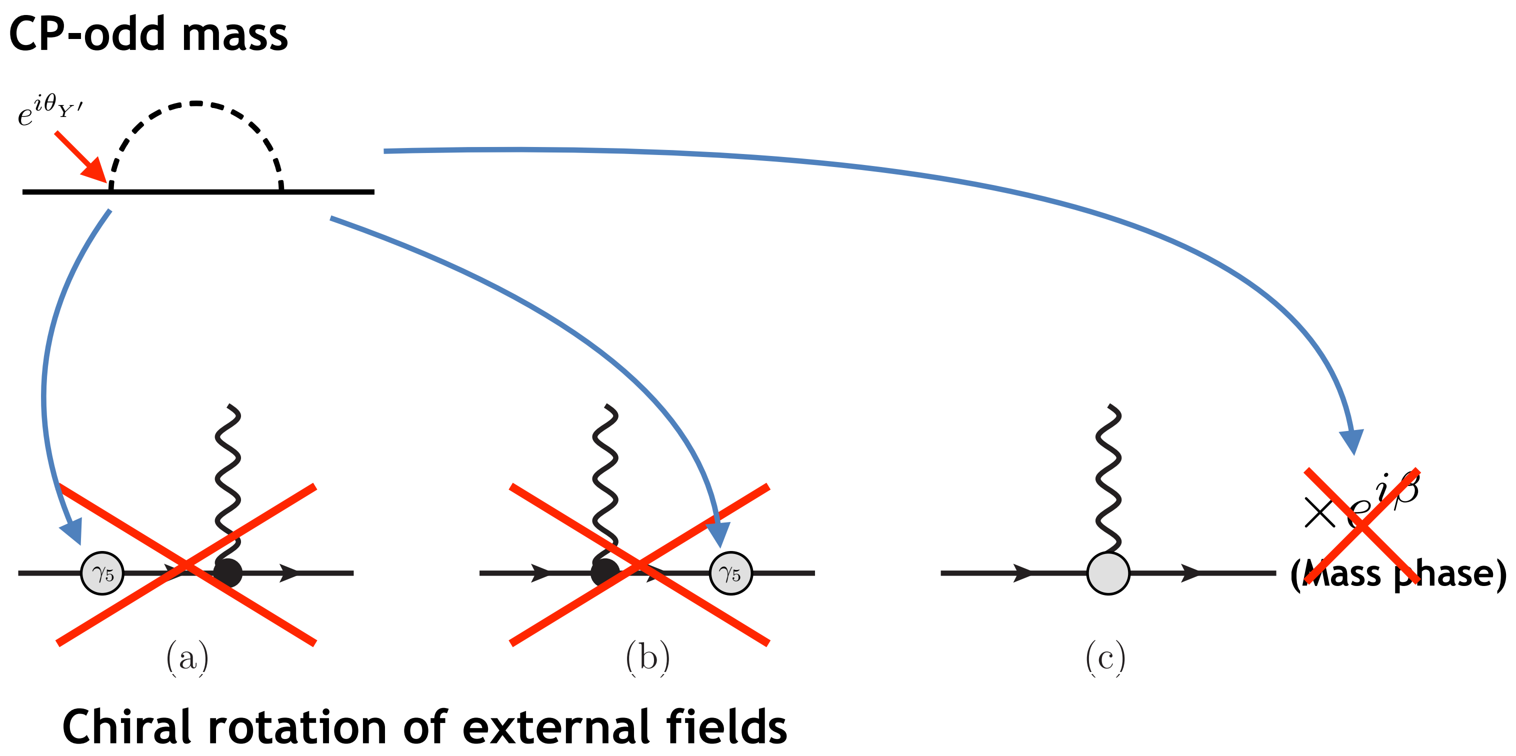
Diagrammatically

CP-odd mass

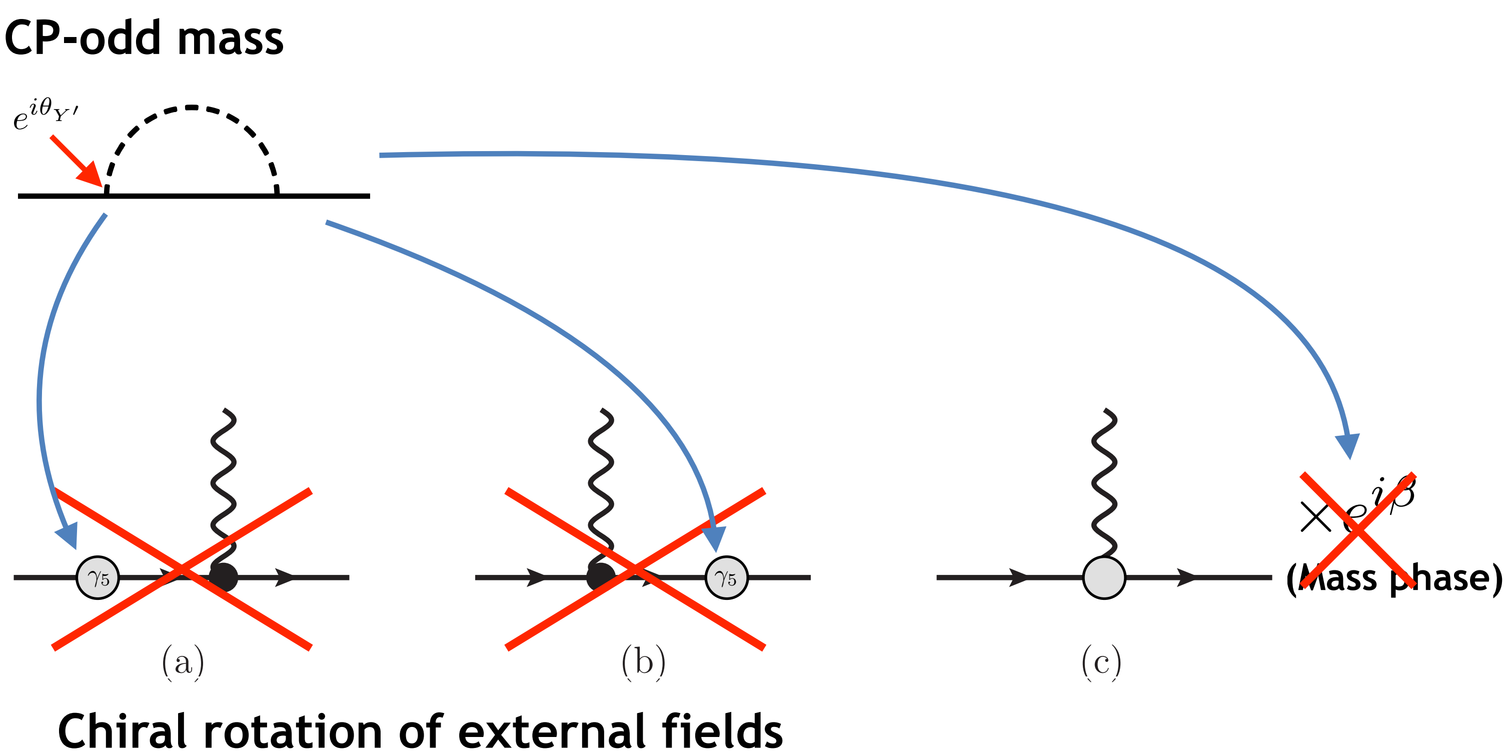


Chiral rotation of external fields

Diagrammatically



Diagrammatically



- CP phases of mass terms cancel
- Only irreducible diagrams are physical

A new theory MUST violate CP

We saw in previous examples that complex phases of coupling constants which cannot be absorbed in fields generate CP violation

In the SM, all CP phases have already been fixed

➡ If we add new particles and interactions in the SM, CP is broken!

(we call this "NATURALNESS")

There is no reason for BSM couplings to have the same (aligned) complex phases as SM interactions, unless there is some physics behind

➡ We can look for new physics BSM by experimentally probing CP violation !

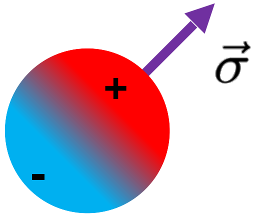
➡ EDM !!

Electric dipole moment

Electric dipole moment (EDM)

Permanent polarization of internal charge of a particle.

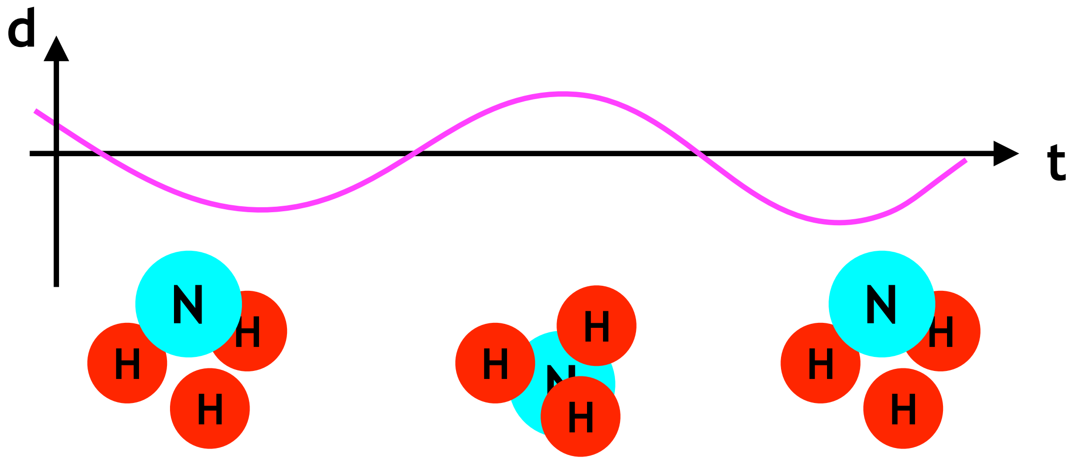
$$\vec{d}_\psi = \sum_i \langle\psi|Q_i e\vec{r}_i|\psi\rangle$$



(The unit of EDM is e cm :
effective distance of internal charge displacement)

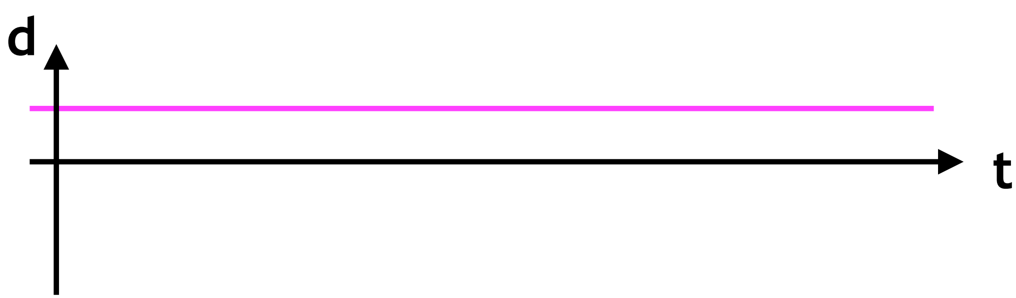
- **Direction:** $\vec{d} \propto \vec{\sigma}$
- **Interaction:** $H_{\mathrm{EDM}} = -d\,\langle\vec{\sigma}\rangle \cdot \vec{E}$
- **Transformation properties:**
  - **Under parity tr.:** $\begin{cases} \vec{E} \xrightarrow{\mathrm{P}} -\vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{P}} \vec{\sigma} \end{cases}$ → H_{EDM} is P-odd
  - **Under time reversal:** $\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$ → H_{EDM} is CP-odd !

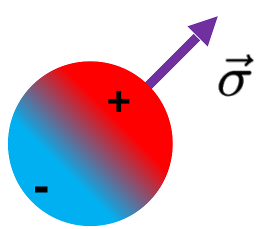
Polar molecules (example of ammonia)



EDM oscillates
⇒ Average is zero!

Particles with CP violating EDM

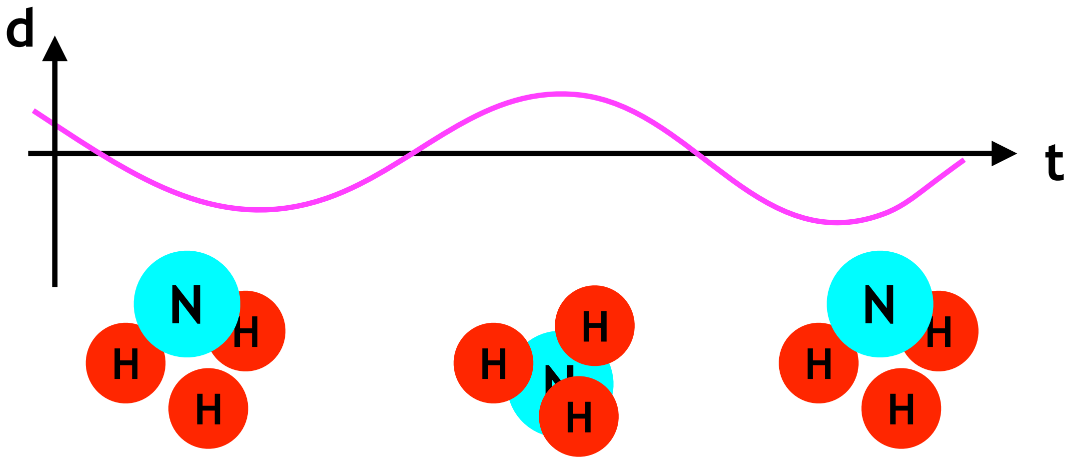




Permanent polarization

EDM of polar molecules

Polar molecules (example of ammonia)



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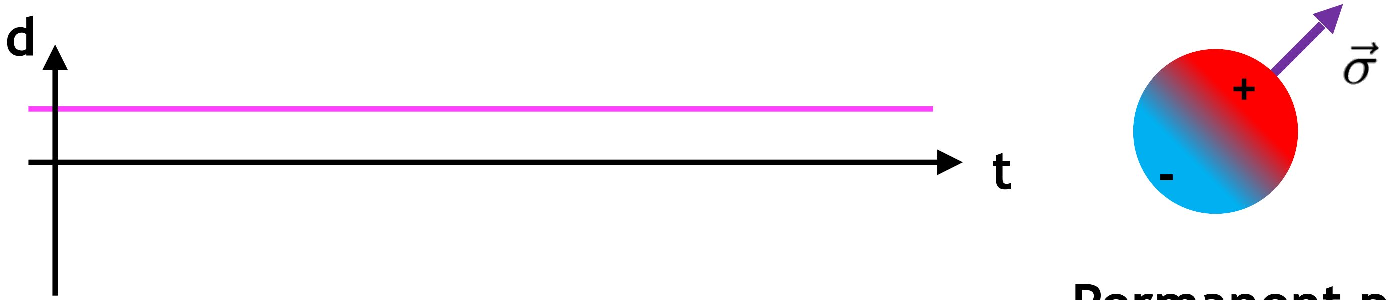
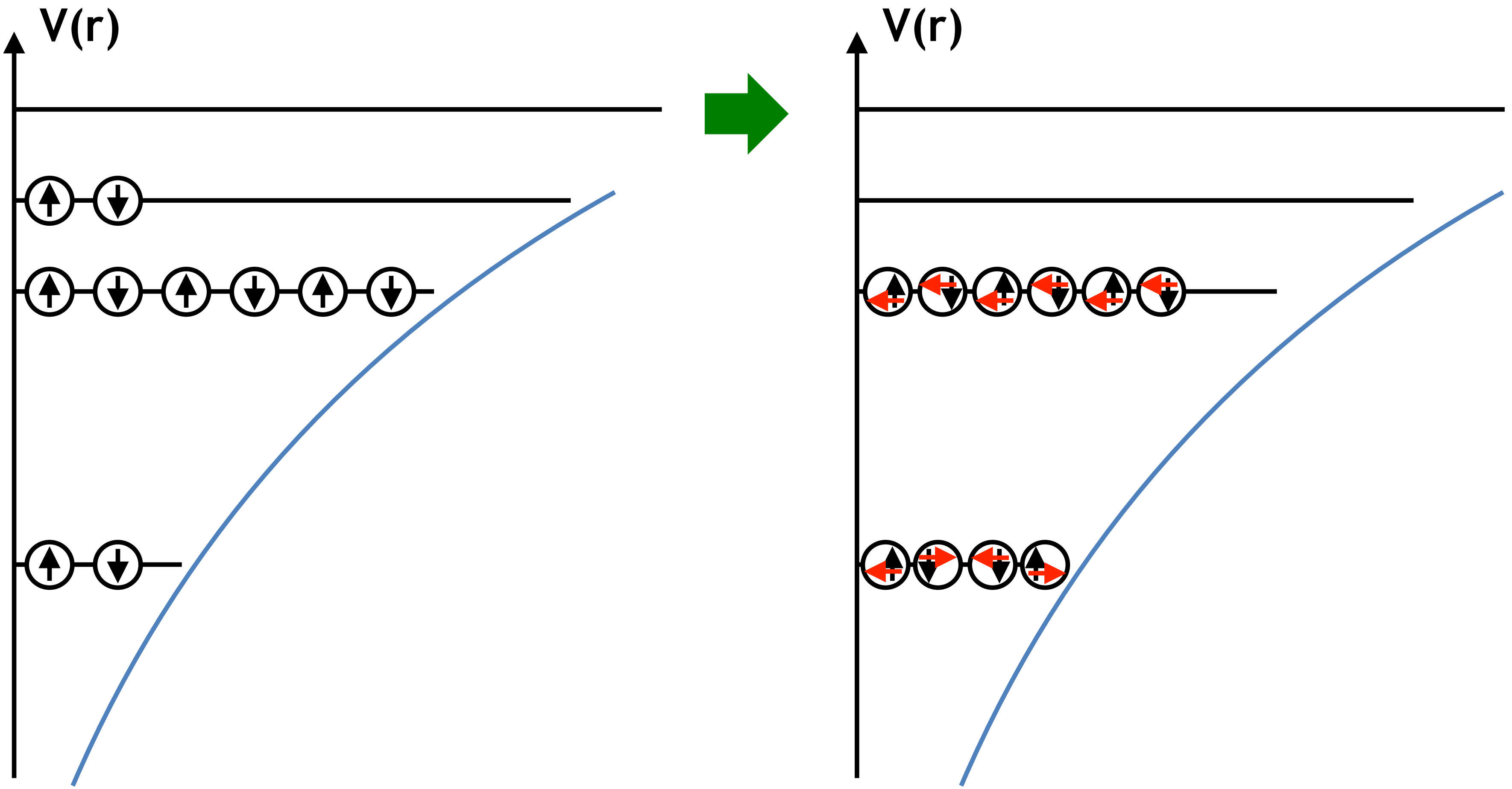


Permanent polarization

Important property : why proportional to spin?

If not, there would be additional quantum numbers for EDM

We would have more degeneracy in atomic electrons of same orbit



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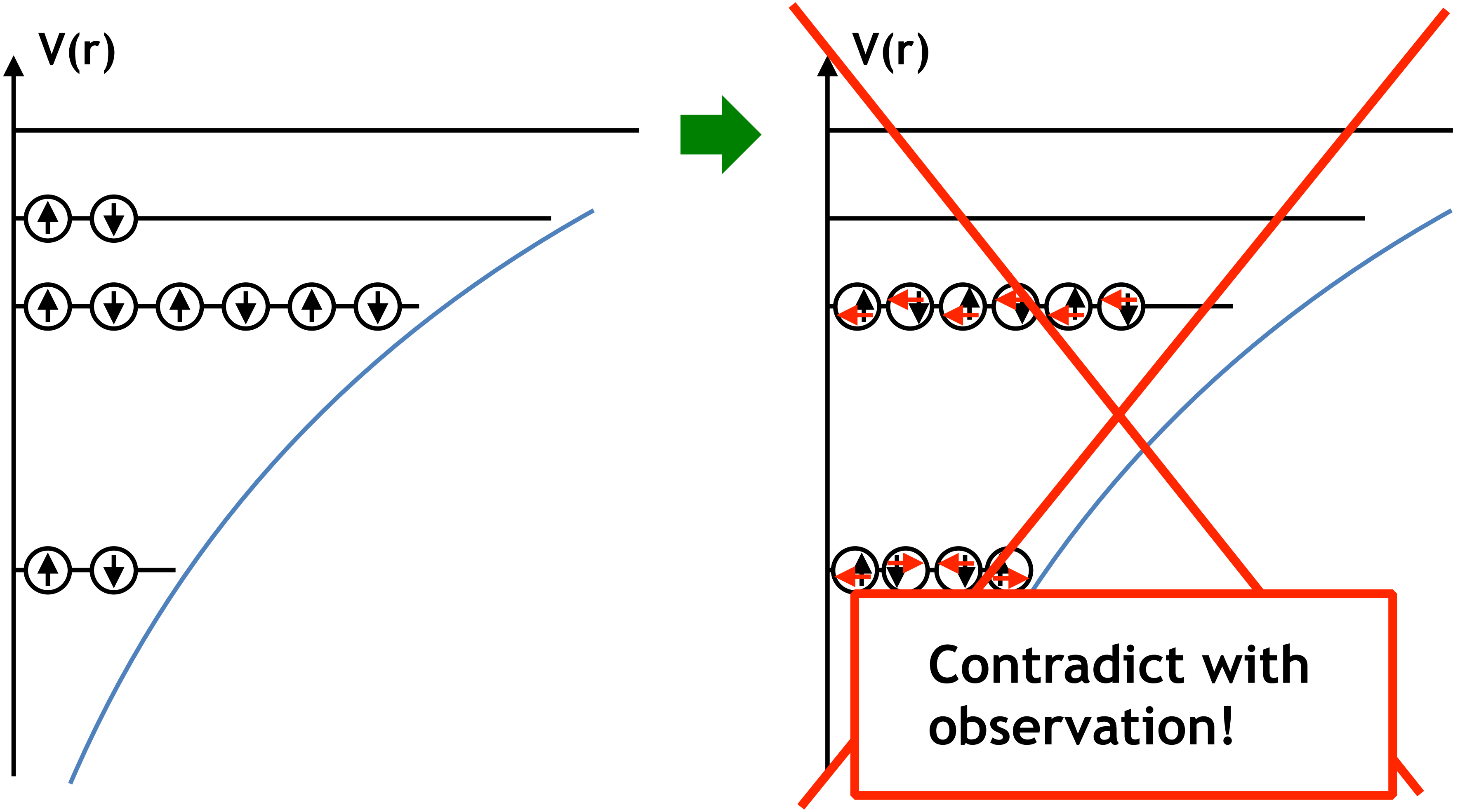
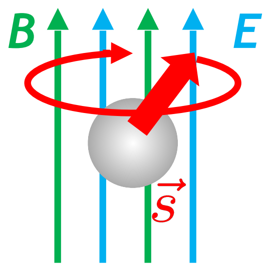


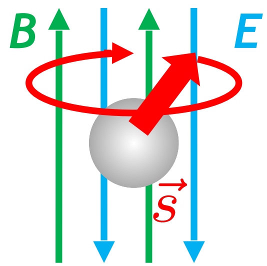
Experimental principle of EDM measurement (neutral sys.)

EDM and magnetic moment parallel to particle spin: $\vec{d}, \vec{\mu} \propto \vec{\sigma}$

➡ **Difference of spin precession frequency with parallel & opposite B and E in the presence of EDM!!**



$$\omega_{\uparrow\uparrow} = 2(\mu B + dE)/\hbar$$



$$\omega_{\uparrow\downarrow} = 2(\mu B - dE)/\hbar$$

Measured EDM:

$$d = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

Required Skills:

- Particle density
- Polarization of particles
- Long coherence time
- Strong electric field
- …

Current EDM experimental data

EDM experimental data provide very strong constraints.

- **Electron EDM (HfF^+ ion experiment):**

$$|d_e| < 4.1 \times 10^{-30}\ e\ cm$$

T. S. Roussy et al., Science **381** (2023) 46.

- **Neutron EDM:**

$$|d_n| < 1.8 \times 10^{-26}\ e\ cm$$

C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020).

- **^{199}Hg EDM:**

$$|d_{Hg}| < 7.4 \times 10^{-30}\ e\ cm$$

B. Graner et al., Phys. Rev. Lett. **116**, 161601 (2016).

All EDM data are consistent with zero : strong constraint on BSM !

Future EDM experiments

There are many EDM experimental projects, may be realized in near future?

- Electron EDM (using solids):

  $d_e \sim 10^{-35}$ e cm ??

- Muon EDM (prospect of J-PARC?):

  $d_\mu \sim 10^{-25}$ e cm

- ^{210}Fr, ^{225}Ra, ^{129}Xe EDM:

  $d_{Fr} \sim 10^{-27}$ e cm $\quad$ $d_{Ra} \sim 10^{-28}$ e cm $\quad$ $d_{Xe} \sim 10^{-33}$ e cm

- Proton, light nuclear EDMs (using storage rings):

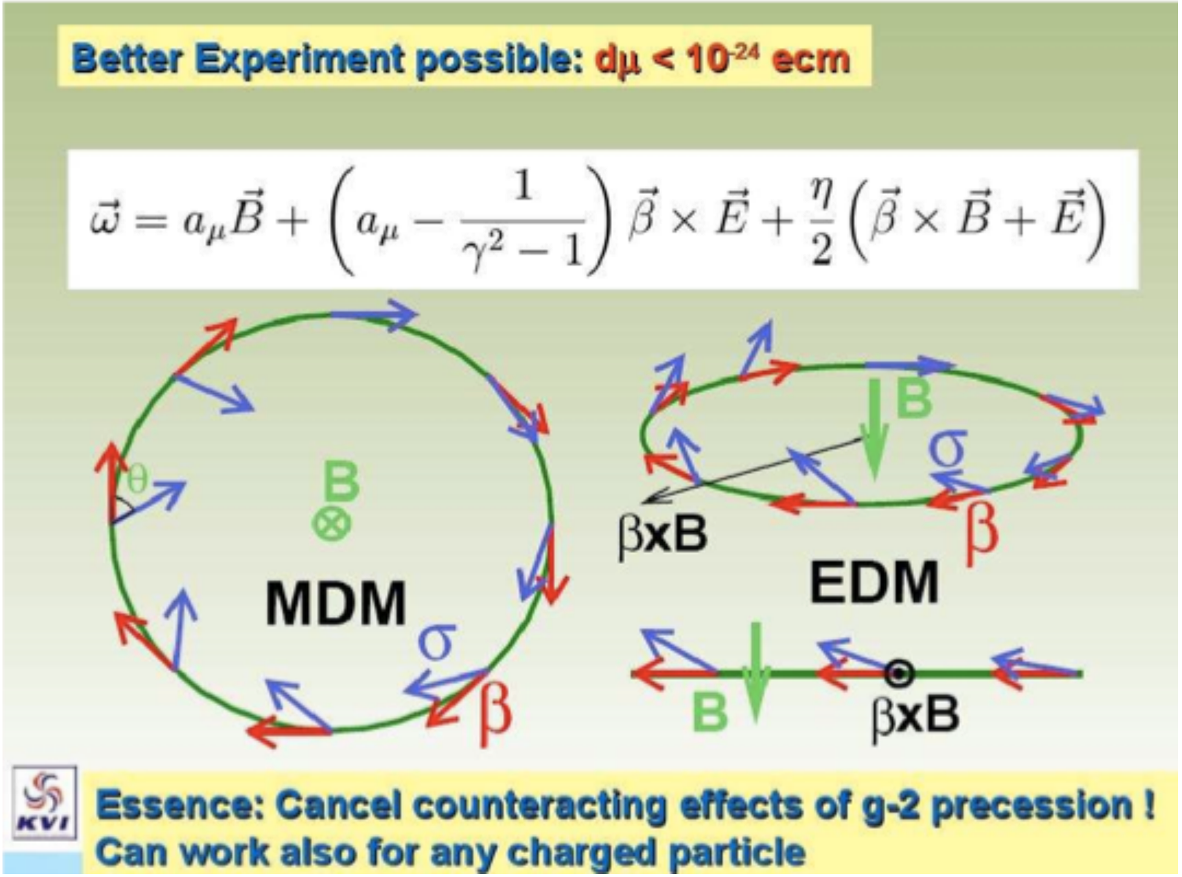
  $d_{p,A} \sim 10^{-29}$ e cm

Interesting because they will (certainly) be measured before the next generation of collider experiments

Measuring EDM of charged particles using storage rings

EDM of charged particles is accurately measurable!

EDMs of proton, light nuclei



Prospect:

$O(10^{-29})$ e cm!!

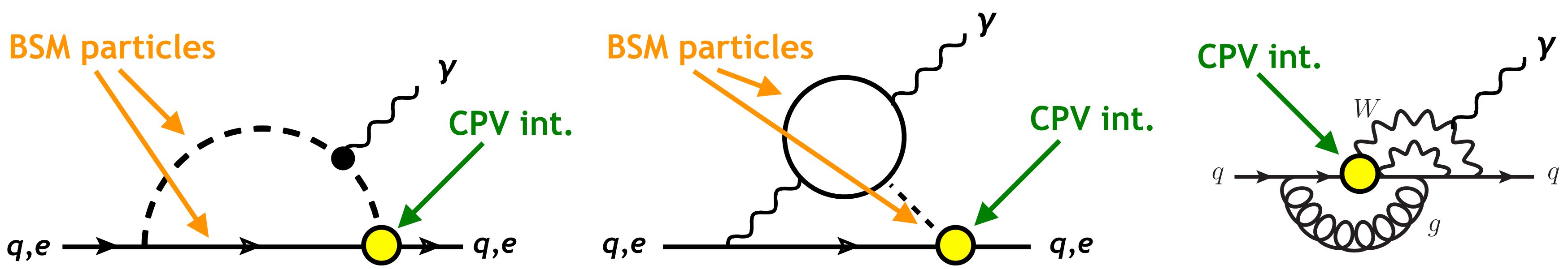
EDM from physics beyond Standard model

EDM operator in relativistic field theory: dimension five-5 operator

$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \xrightarrow{\text{Nonrela. lim.}} \quad -d_\psi \sigma \cdot \mathbf{E}$$

EDM is generated by CP violating interactions.

Can be calculated using Feynman diagrams:



1-loop diagram (e.g. SUSY)

2-loop diagram (e.g. 2-Higgs models)

3-loop diagram (Standard model)

EDM very small in SM, but generated at low loop in BSM

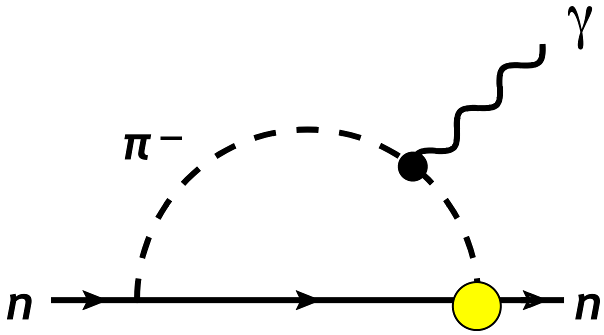
➡ EDM is a very good probe of BSM new physics!

EDM as a sensitive probe of BSM physics

Naïve estimation of neutron EDM:

- New physics couplings, CP phases = O(1) (naturalness)
- Contribute from one-loop graph
- New physics scales as $1/M_{NP}^2$

$$d_n \sim \frac{m_N e}{(4\pi)^2 M_{NP}^2} \sim \frac{10^{-22} e\,\mathrm{cm}}{(M_{NP}/\mathrm{TeV})^2}$$



Experimental data: $|d_n| < 1.8 \times 10^{-26}$ e cm

C. Abel *et al.*, Phys. Rev. Lett. **124**, 081803 (2020).

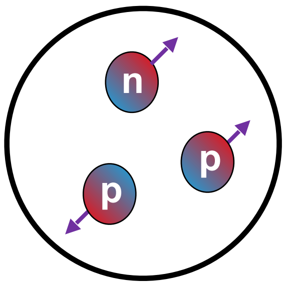
⇒ Current exp data of Neutron EDM can probe M_{NP} ~ 100TeV!

➡ **EDM is more sensitive than LHC!**

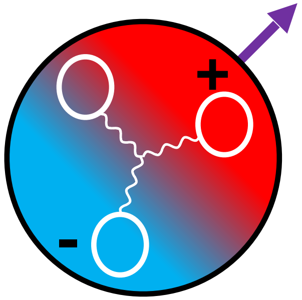
EDM of composite systems

EDM is often measured in composite systems (neutron, atoms, molecules, nuclei)

EDM is not only generated by the EDM of the components, but also by CP violating many-body interactions.

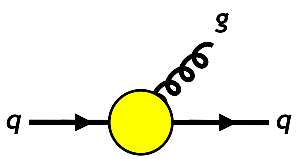


EDM of constituents

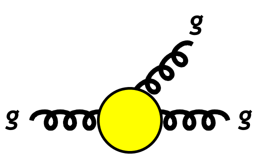


CP-odd many-body interaction

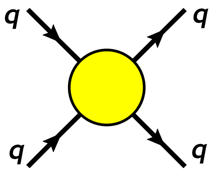
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



P, CP-odd 4-quark interaction

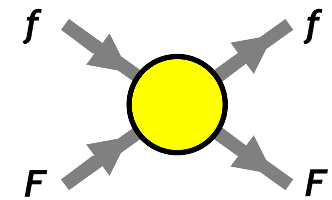
Effect of CPV many-body interaction may be enhanced/suppressed!

EDM (polarization) from CP-odd many-body interactions

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

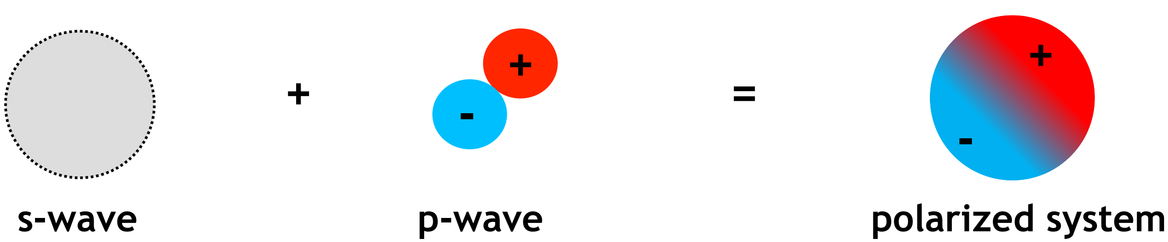
$$H = \begin{pmatrix} H_{even} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{even} \end{pmatrix}$$



P, CP-odd
4-fermion int.

P, CP-even
interactions

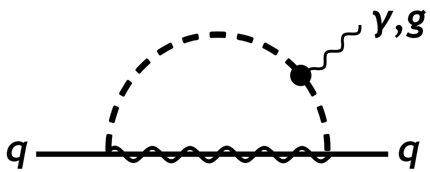
CP-odd 4-fermion interactions mixes opposite parity states



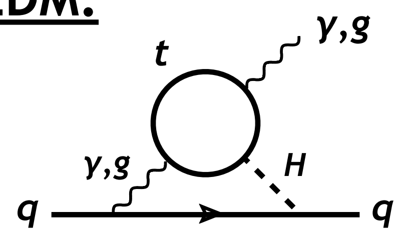
Parity mixing ⇒ Polarized ground state!

Elementary level CP violation from BSM physics (SMEFT)

- **Fermion EDM, quark chromo-EDM:**



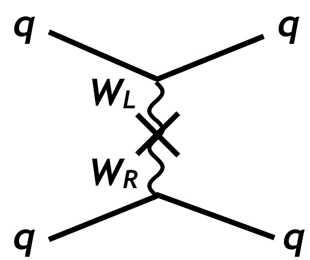
SUSY: 1-loop

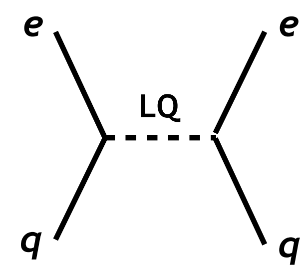


2-Higgs doublet: 2-loop

- **CP-odd 4-fermion interaction:**

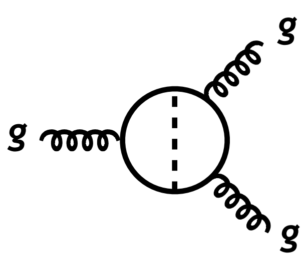
Tree level:
* Left-right symmetric model
* Scalar exchange (e.g. Higgs)
* Leptoquarks





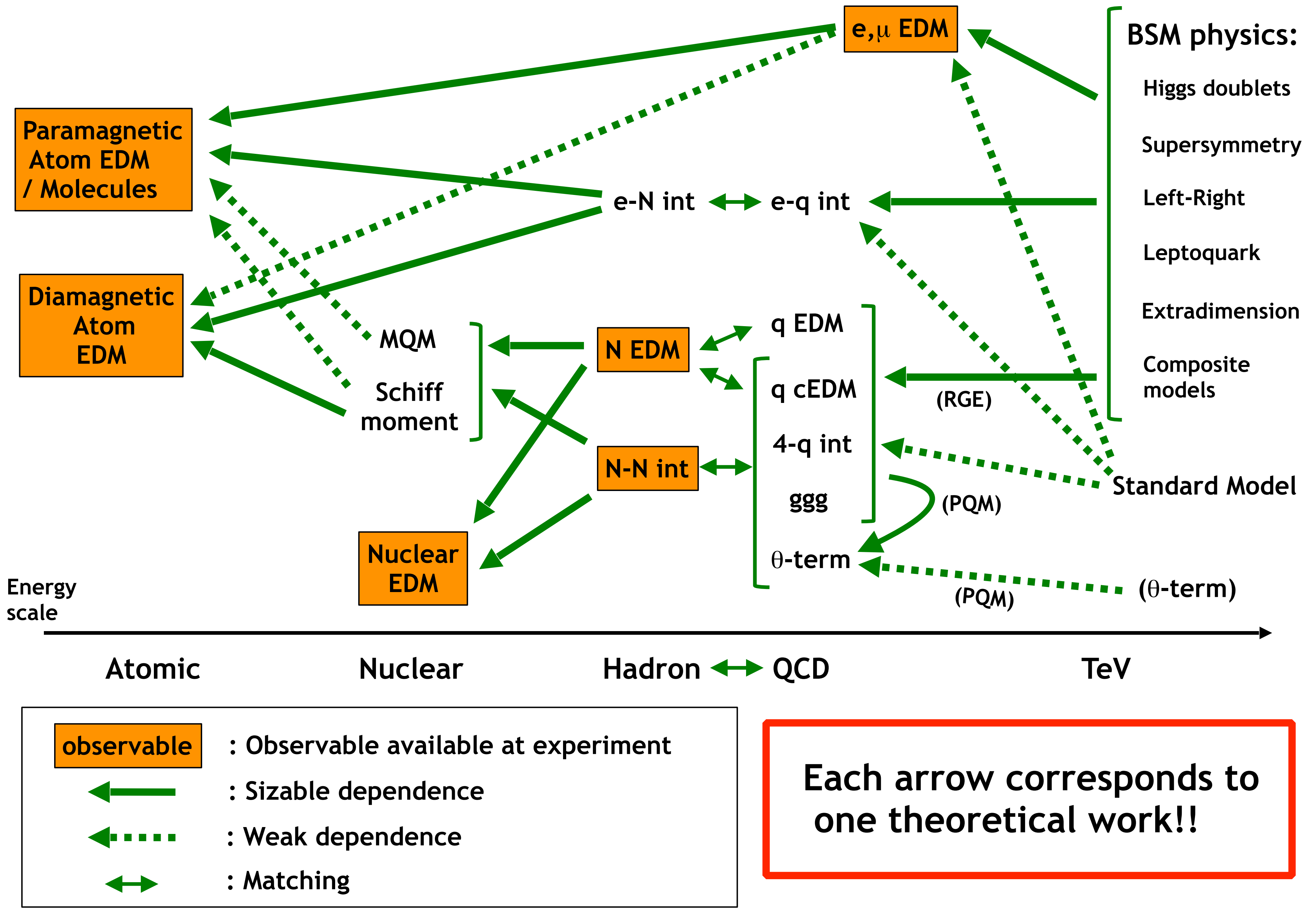
- **Weinberg operator:**

2-loop diagram:
* 2-Higgs doublet model
* Vectorlike quark model



All these processes scale as $1/M_{BSM}^2$

EDM from elementary level CP violation



Each arrow corresponds to one theoretical work!!

What is better in EDM experiments

Elementary level CPV is unknown but small

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Unknown CP violating couplings beyond the standard model

$$d_A = K_e d_e + K_u d_u + K_d d_d + \ldots$$

Depends on the structure of the system!

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Depends on the structure of the system!

$\Rightarrow$ Linear coefficients depends only on the structure of the system, not in BSM

To derive them, we need QCD, nuclear and atomic level calculations

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⇒ Large coefficients means high sensitivity ⇒ Experimentally interesting!

Let us see known mechanisms of enhancement / suppression

Hadron level CP violation

Hadron level CP violation

Hadronic CP violation has large uncertainty due to QCD nonperturbative physics

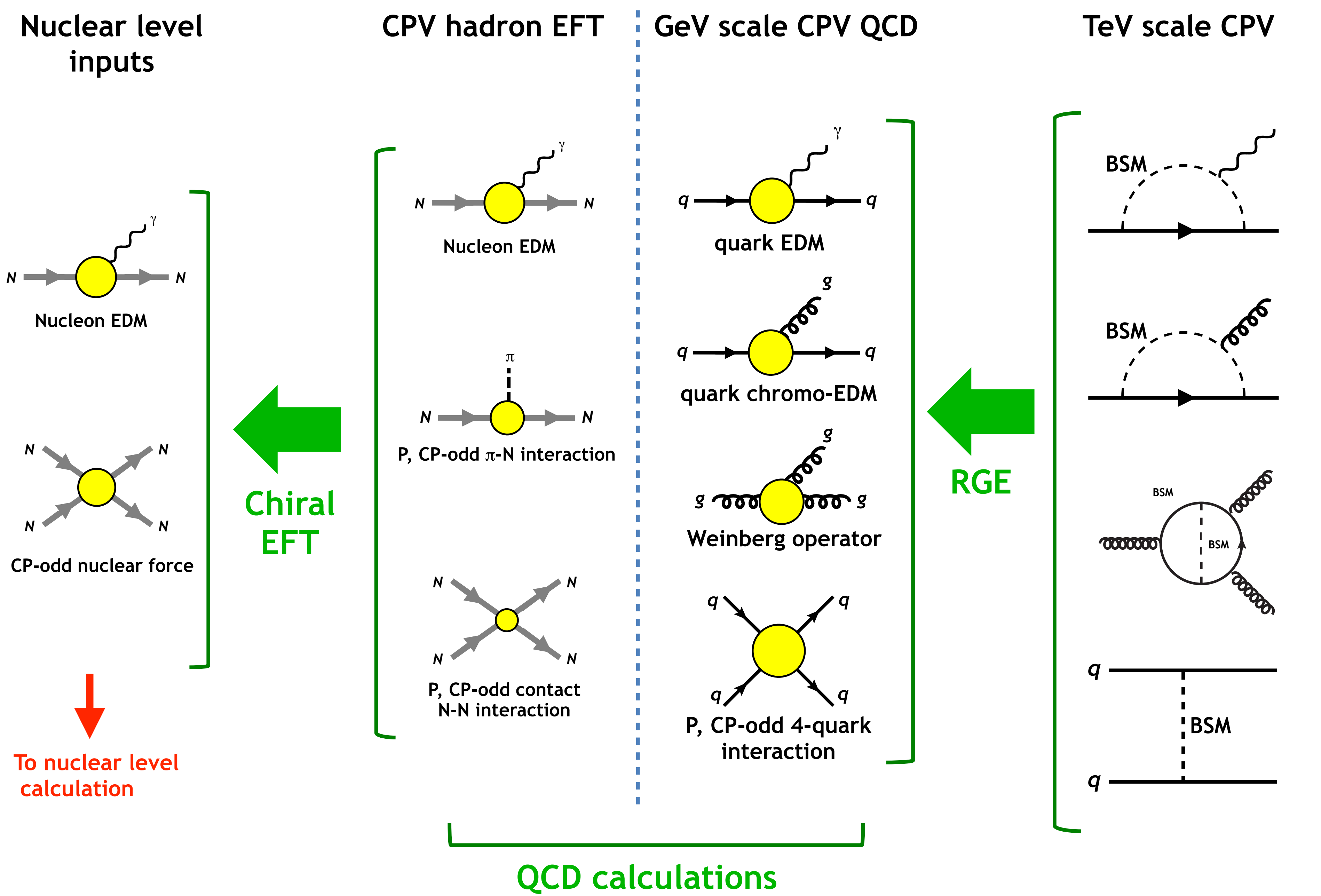
But recently, there were significant progress in the quantification

(We now know much more than 5 years ago!)

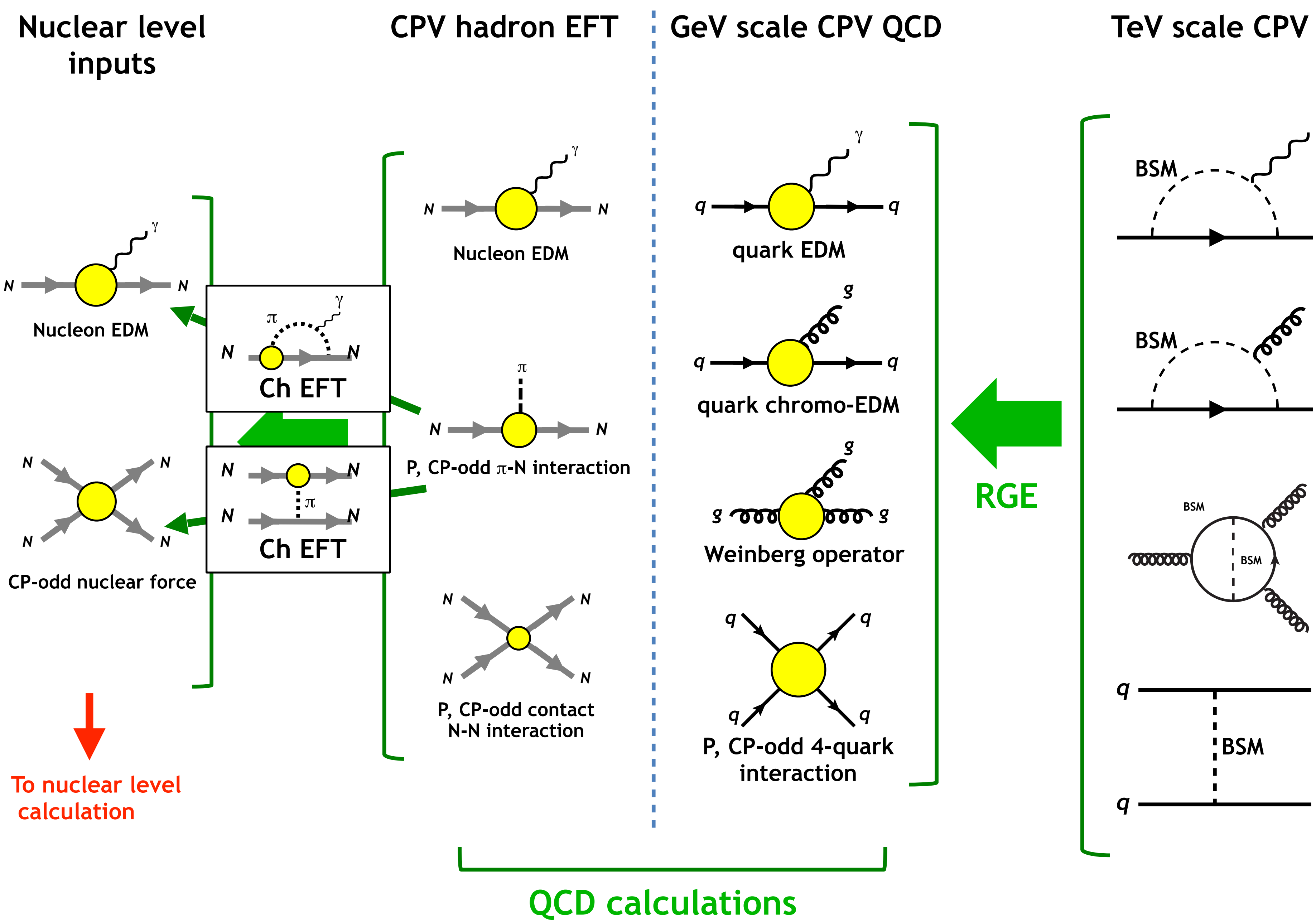
In particular, the leading hadronic contribution has recently been identified

In this section, we review the hadronic CPV contributing to EDMs

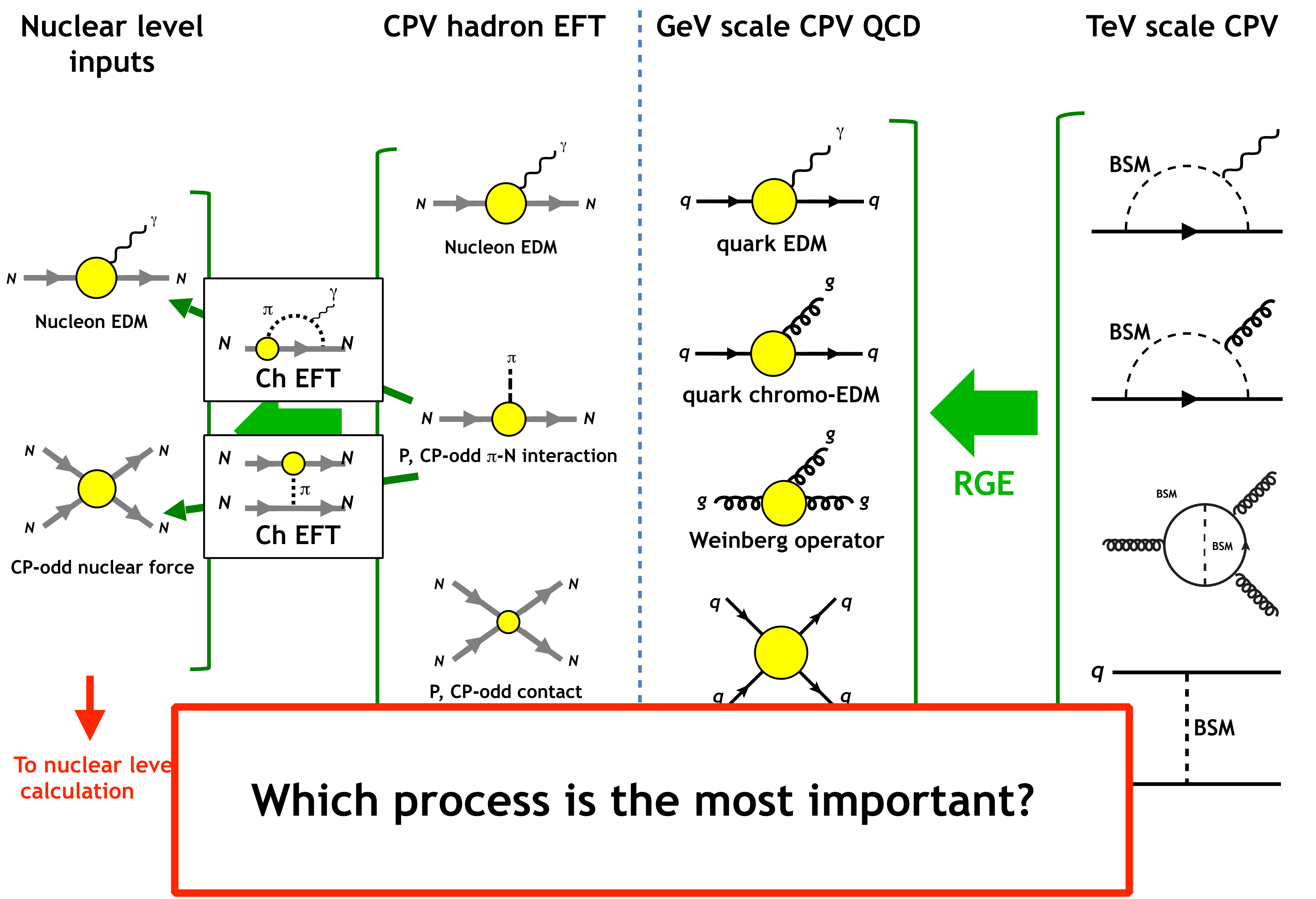
Hadronic CP violation: from TeV to hadron level



Hadronic CP violation: from TeV to hadron level



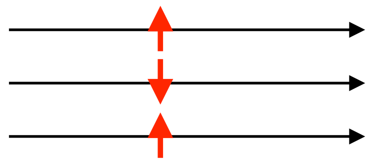
Hadronic CP violation: from TeV to hadron level



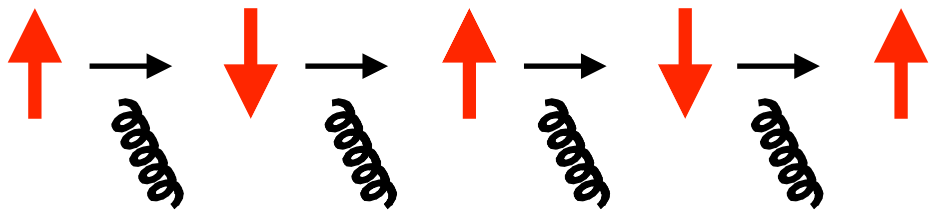
Which process is the most important?

Rough tendency: scalar and spin

- Spin (tensor, axial charges) : suppression

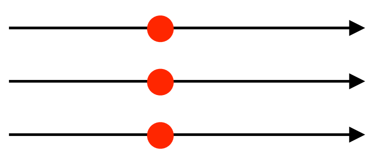


Pairing of spin in many-fermion system
⇒ No enhancement of spin

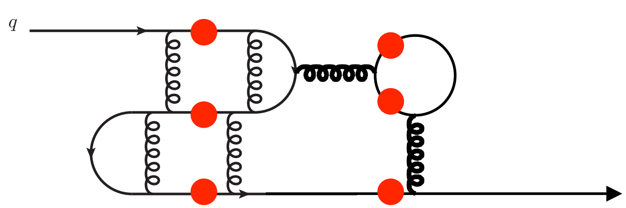


Quark EDM is a superposition of spin flipping states after gluon emissions/absorptions
⇒ Suppressed

- Scalar density : enhancement



Scalar density is coherent : enhanced!



Relativistic effect : Z graph, loops

Scalar densities of particles and antiparticles have same sign
⇒ Large with Z-graphs (relativistic)
⇒ Enhanced!

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D **88**, 074036 (2013);
NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

Renormalization group evolution of CPV QCD operators

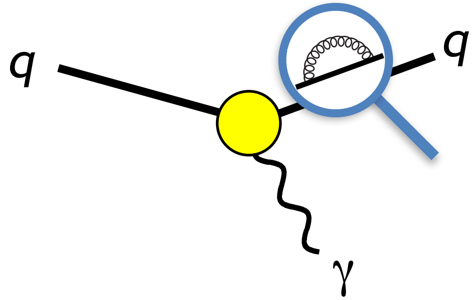
Change of energy scale modifies the coupling constants, mixes operators

Significant change for quark/gluon operators due to QCD

Renormalization group equation:

$$\frac{d}{d\ln\mu}\mathbf{C}(\mu) = \hat{\gamma}^T(\alpha_s)\mathbf{C}(\mu)$$

C : Wilson coefficients of CPV operators



Anomalous dimension matrix:

$$\hat{\gamma}^{(0)} = \begin{pmatrix} 8C_F & 0 & 0 \\ 8C_F & 16C_F - 4n_c & 0 \\ 0 & 2n_c & n_c + 2n_f + \beta_0 \end{pmatrix}$$

Degrassi et al., JHEP **0511** (2005) 044
Yang et al., Phys. Lett. B **713** (2012) 473
Dekens et al. JHEP**1305**(2013)149

- **Renormalization = resummation of perturbative QCD corrections**
- **Large uncertainty due to nonperturbative effect below μ = 1 GeV**

⇒ We have to stop (perturbative) RG evolution and calculate the hadronic processes with nonperturbative methods

Renormalization group evolution of CPV QCD operators

- **Scalar density:**

$\bar{q}q$ → $2\ \bar{q}q$

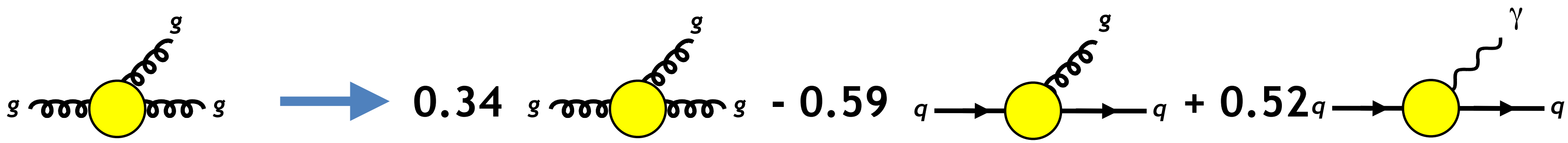
μ = 1 TeV → μ = 1 GeV

- **Quark EDM:**

d_q → $0.8\ d_q$

μ = 1 TeV → μ = 1 GeV

- **Weinberg operator:**



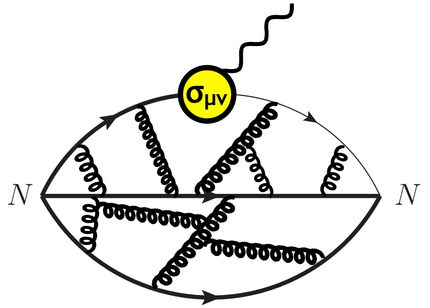
μ = 1 TeV → μ = 1 GeV

Roughly, scalar increases and spin decreases when scale goes down

Quark EDM contribution to nucleon EDM : tensor charge

Quark EDM contribution to nucleon EDM is given by

the tensor charge $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$

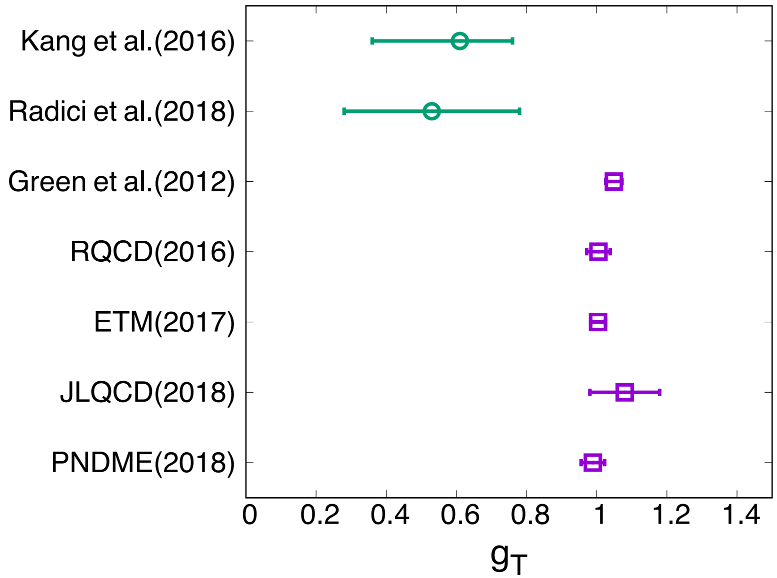


⇒ Lattice QCD results available

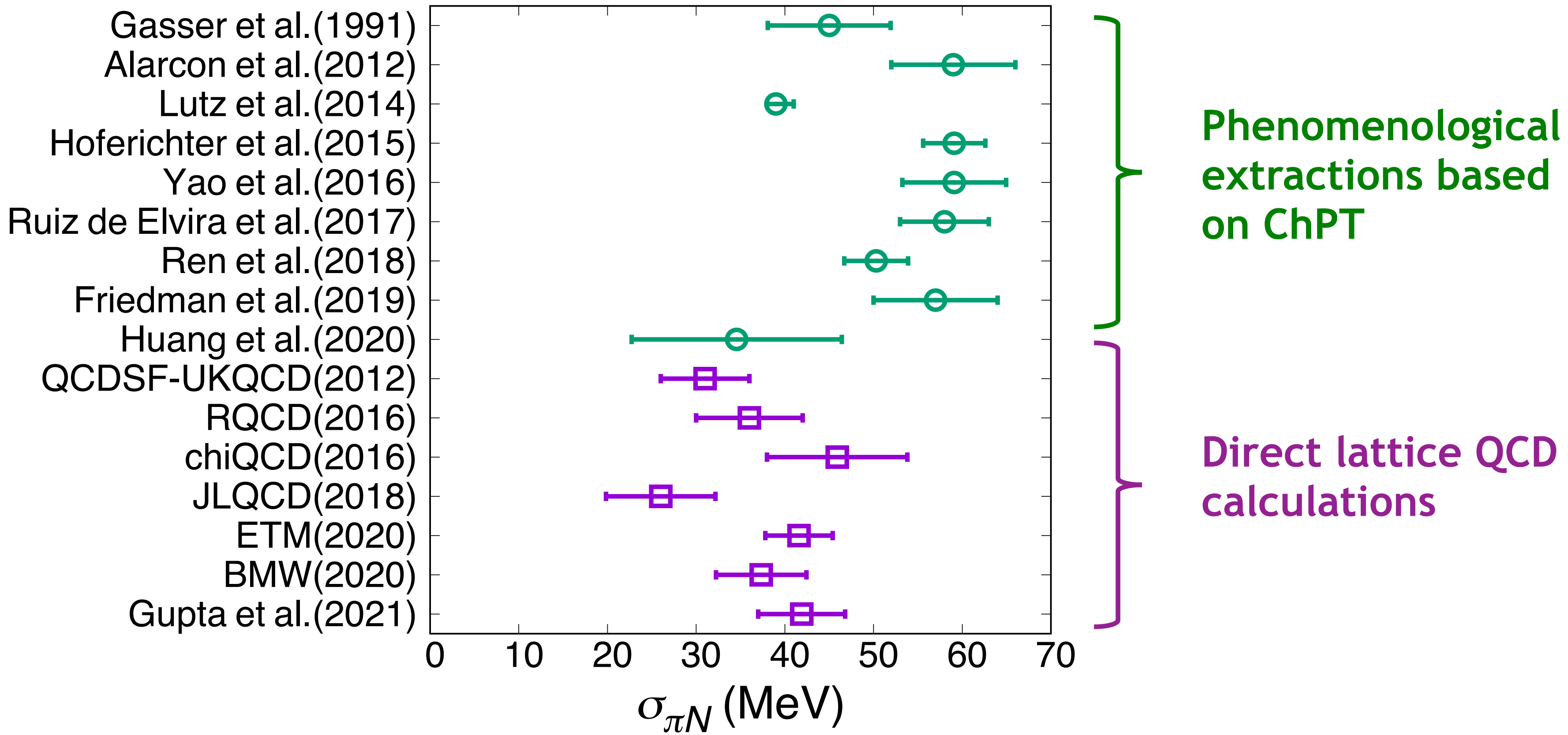
⇒ Accurate up to 10% error

(Little disagreement with pQCD)

⇒ No particular enhancement



Present status of the calculations of πN sigma-term

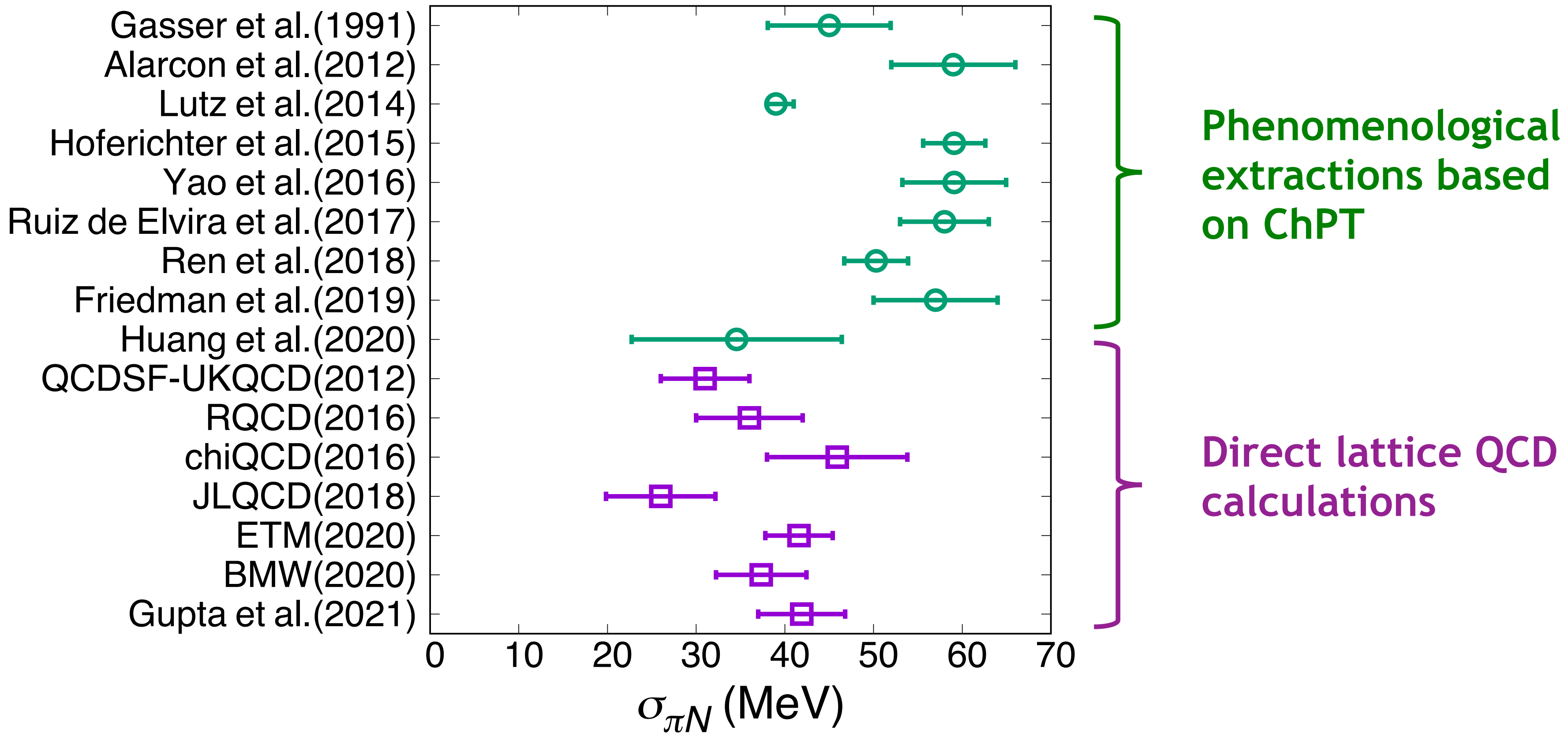


Extractions of $\sigma_{\pi N} \equiv \frac{m_u + m_d}{2} \langle N|\bar{u}u + \bar{d}d|N\rangle$

suggests $\langle N|\bar{u}u + \bar{d}d|N\rangle \sim 10$

⇒ Enhancement of EDM if $\sigma_{\pi N}$ contributes

Present status of the calculations of πN sigma-term



Phenomenological extractions : $\sigma_{\pi N} \sim 60$ MeV

Lattice QCD calculations : $\sigma_{\pi N} \sim 30$ MeV

⇒ Visible disagreement

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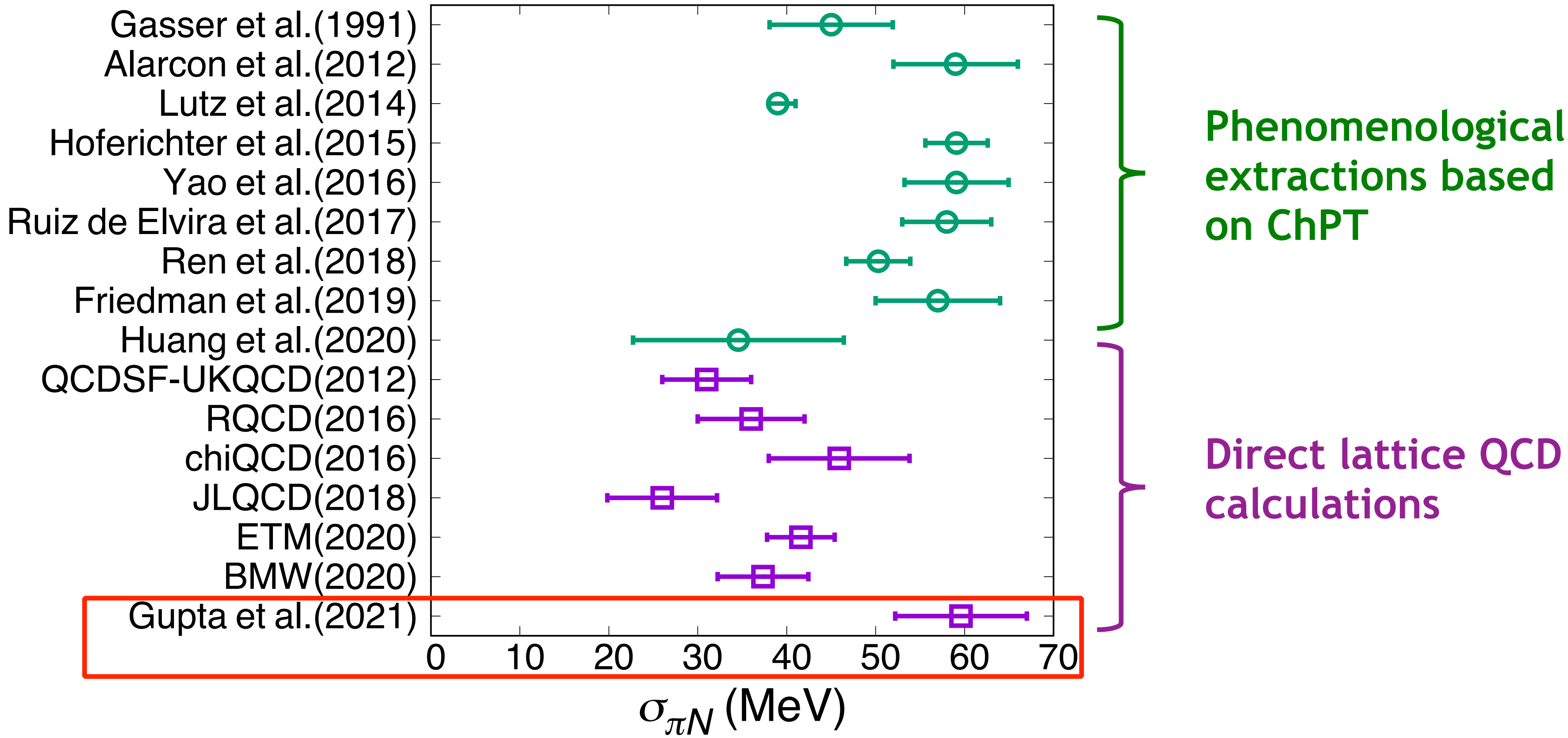

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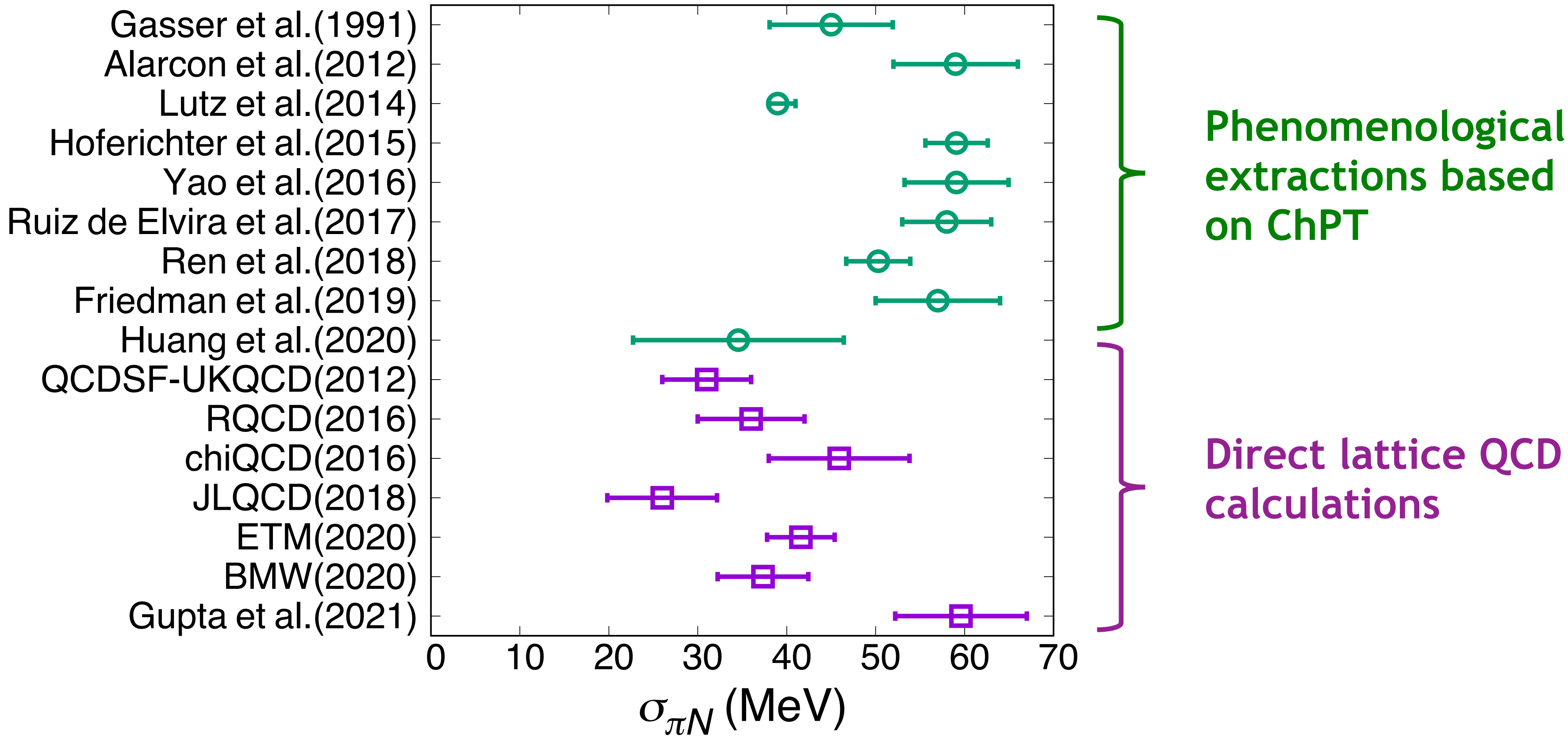
Lattice QCD calculations : $\sigma_{\pi N} \sim 30$ MeV

⇒ Visible disagreement

⇒ Gupta et al. are suggesting some potential resolution??

Present status of the calculations of πN sigma-term



Phenomenological extractions : $\sigma_{\pi N} \sim 60$ MeV

Lattice QCD calculations : $\sigma_{\pi N} \sim 30$ MeV

⇒ Visible disagreement

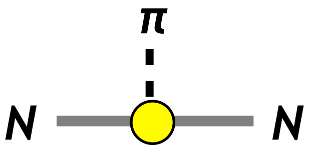
Homework:

We have to resolve this problem for quantifying EDMs

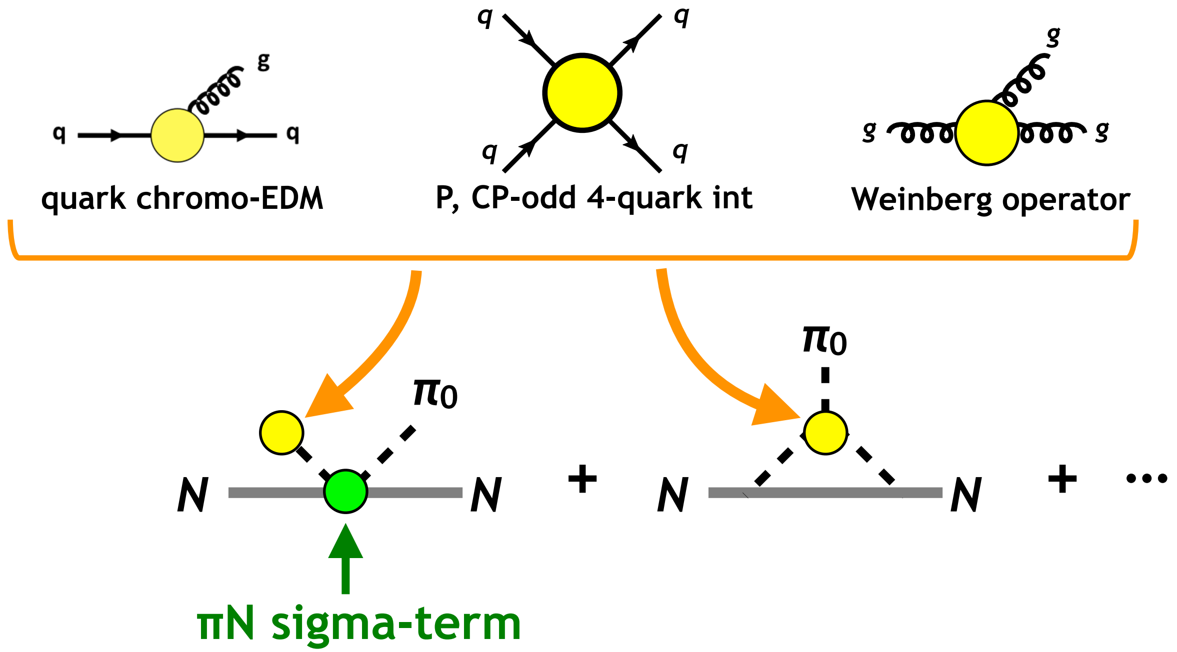
Chiral EFT analysis of CP-odd pion-nucleon interaction

CP-odd pion-nucleon (πNN) interaction

$$\mathcal{L}_{\pi NN} = \bar{g}^{(0)}_{\pi NN}\pi_a \bar{N}\tau_a N + \bar{g}^{(1)}_{\pi NN}\pi_0 \bar{N}N$$



Lattice QCD calculation is difficult, but we can quantify with chiral EFT :



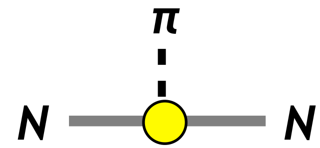
⇒ $\bar{g}^{(1)}$ is enhanced by sigma term, x10 ! NLO is also sizable!

⇒ CP-odd N-N interaction is enhanced, nuclear EDM is important!

Chiral EFT analysis of CP-odd pion-nucleon interaction

CP-odd pion-nucleon (πNN) interaction

$$\mathcal{L}_{\pi NN} = \bar{g}^{(0)}_{\pi NN} \pi_a \bar{N} \tau_a N + \bar{g}^{(1)}_{\pi NN} \pi_0 \bar{N} N$$



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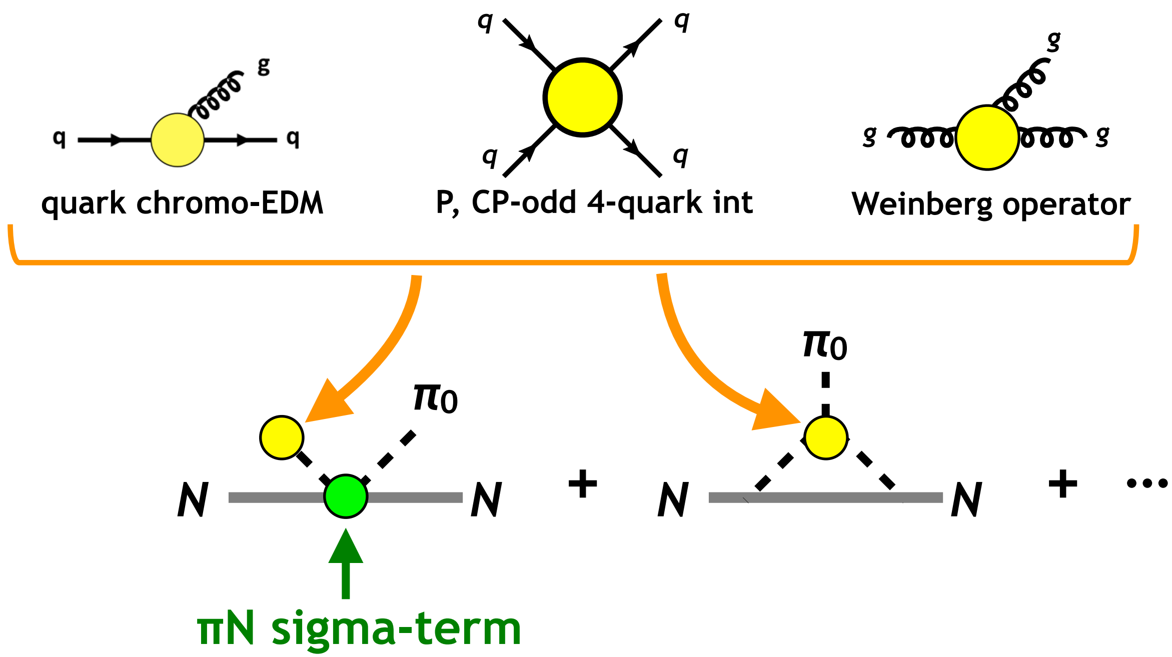
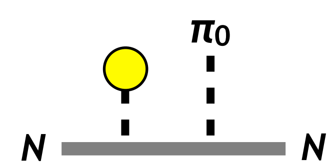


Be careful!



does not contribute due to chiral sym.

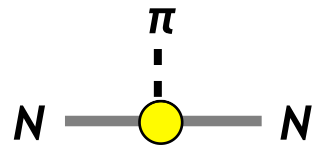
⇒ $\bar{g}^{(1)}$ is enhanced by sigma term, x10 ! **NLO is also sizable!**

⇒ CP-odd N-N interaction is enhanced, nuclear EDM is important!

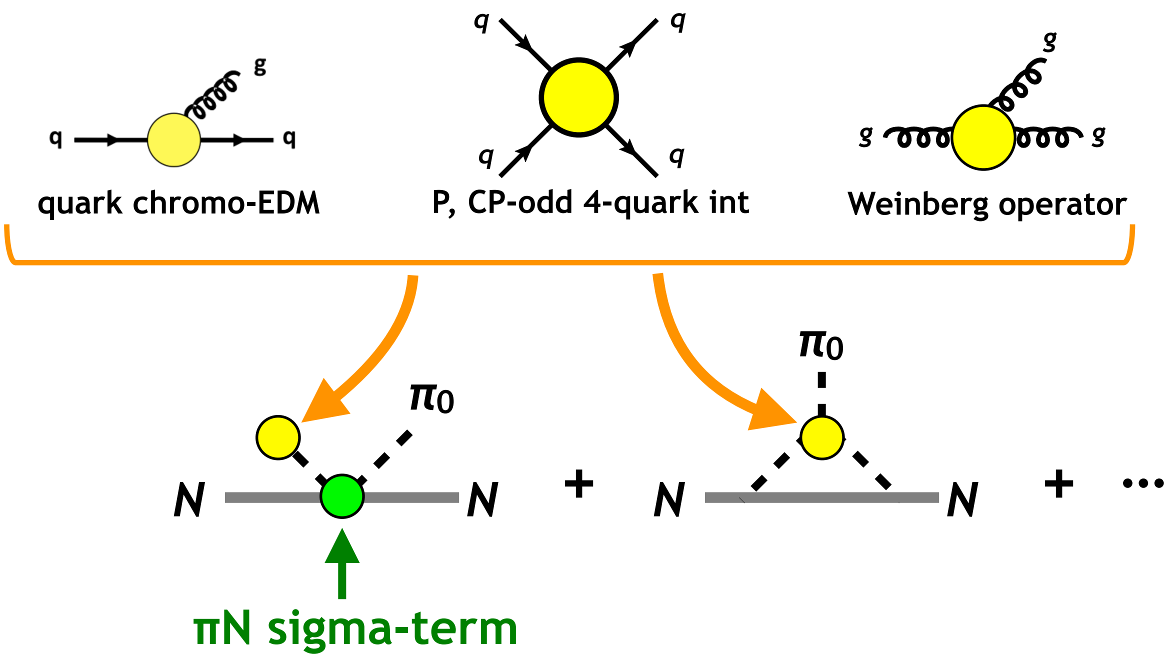
Chiral EFT analysis of CP-odd pion-nucleon interaction

CP-odd pion-nucleon (πNN) interaction

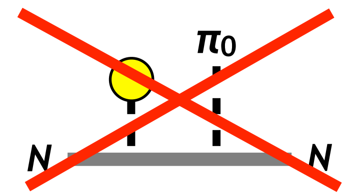
$$\mathcal{L}_{\pi NN} = \bar{g}^{(0)}_{\pi NN} \pi_a \bar{N} \tau_a N + \bar{g}^{(1)}_{\pi NN} \pi_0 \bar{N} N$$



Lattice QCD calculation is difficult, but we can quantify with chiral EFT :



Be careful!



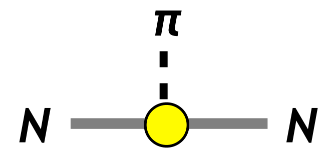
does not contribute due to chiral sym.

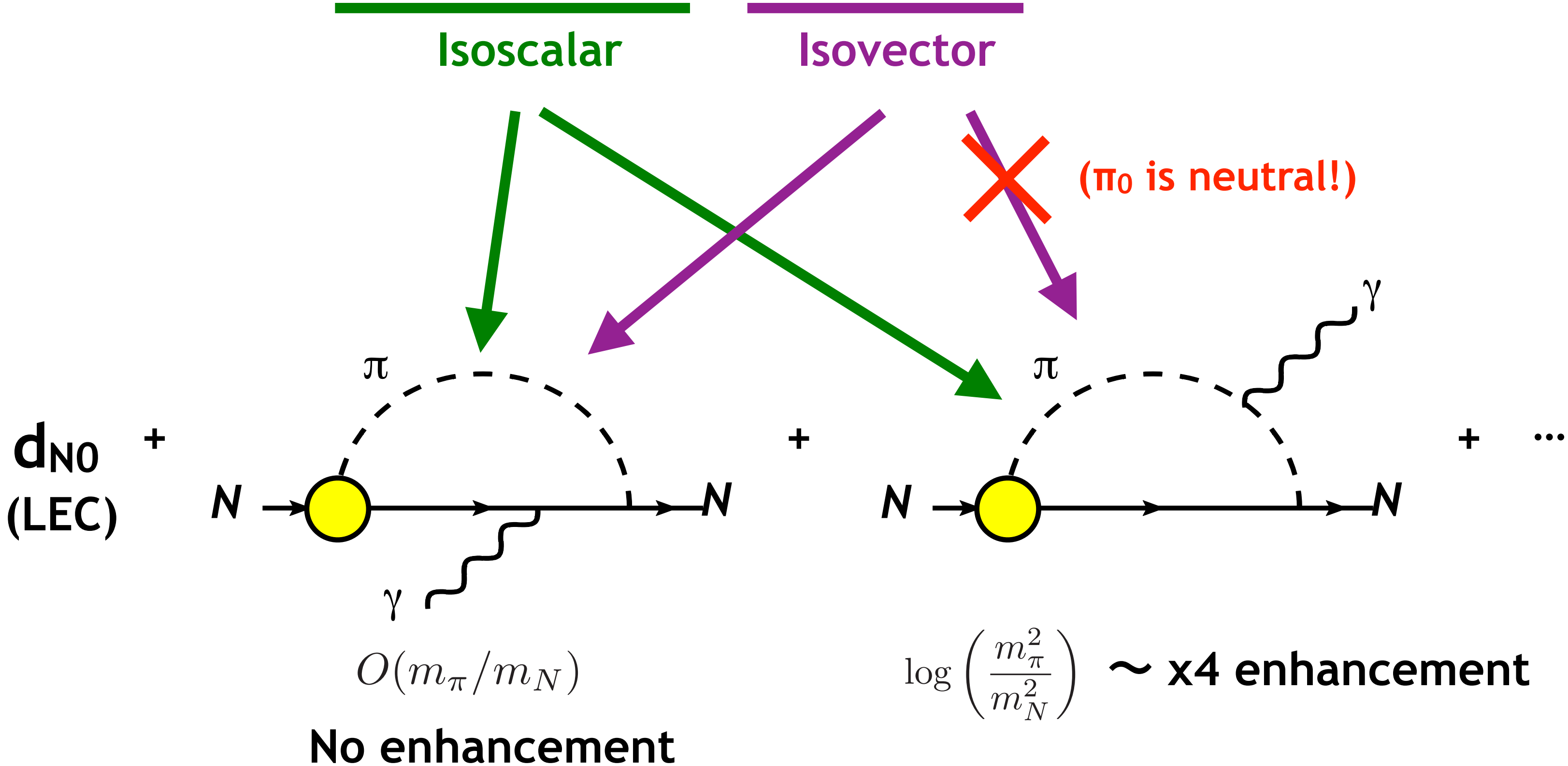
⇒ $\bar{g}^{(1)}$ is enhanced by sigma term, x10 !   NLO is also sizable!

⇒ CP-odd N-N interaction is enhanced, nuclear EDM is important!

Chiral EFT analysis of nucleon EDM

$$\mathcal{L}_{\pi NN} = \bar{g}^{(0)}_{\pi NN}\pi_a \bar{N}\tau_a N + \bar{g}^{(1)}_{\pi NN}\pi_0 \bar{N}N$$



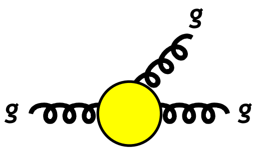


⇒ Only $\bar{g}^{(0)}$ is important, but no notable enhancement

Weinberg operator

$$\mathcal{L}_w = \frac{1}{3!} w f^{abc} \epsilon^{\alpha\beta\gamma\delta} G^a_{\mu\alpha} G^b_{\beta\gamma} G^{\mu,c}_\delta$$

(= gluon chromo-EDM)



Induced in many candidates of BSM physics

- **2-Higgs doublet model**

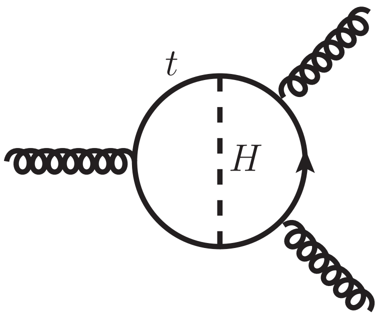
  S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).

- **Minimal supersymmetric standard model**

  J. Dai *et al.*, Phys. Lett. B **237**, 216 (1990).

- **Vectorlike quark model**

  K. Choi *et al.*, Phys. Lett. B **760**, 666 (2016).



Typical 2-loop diagram

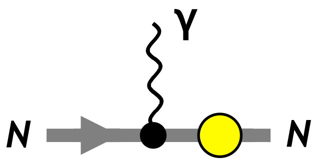
Chiral EFT cannot be used for WO, more difficult to quantify

However, quantification of WO contribution progressed recently

Errata of Weinberg operator evaluations

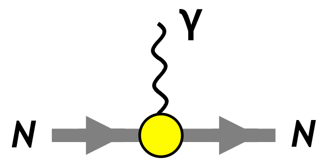
Nucleon EDM:

(Scale : μ = 1 TeV)



Chiral rotation of g-2

D. Demir et al., PRD **67**, 015007 (2003);
U. Haisch *et al*., JHEP **1911** (2019) 154.

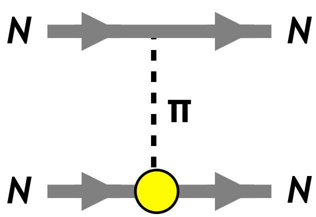


Contact

NY et al.,
PRD **103**, 035023 (2021).

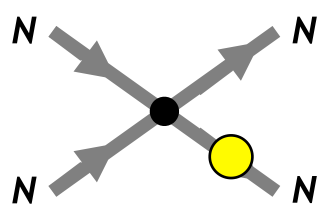
$$d_n \approx 7\, w\, e\, \mathrm{MeV}$$

CP-odd nuclear force:

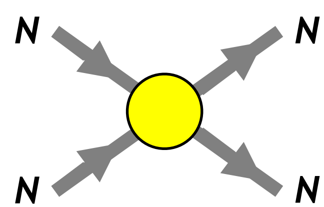


π-exchange

N. Osamura et al.,
JHEP **2206** (2022) 072.



Chiral rotation
of CP-even NN



Contact

NY et al.,
PRD **106**, 075021 (2022)

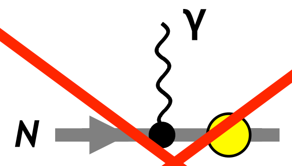
$$d_{\mathrm{He}} \sim 0.2\, w\, e\, \mathrm{MeV}$$

(Valence nucleon EDM effect not included)

Errata of Weinberg operator evaluations

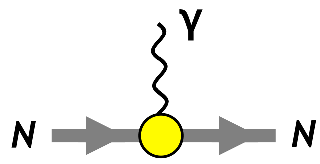
Nucleon EDM:

(Scale : μ = 1 TeV)



~~Chiral rotation of g-2~~

~~D. Demir et al., PRD **67**, 015007 (2003);~~
~~U. Haisch *et al*., JHEP **1911** (2019) 154.~~



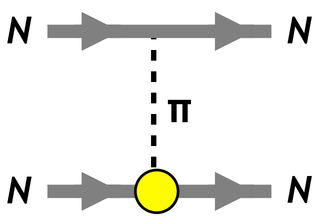
Contact

NY et al.,
PRD **103**, 035023 (2021).

~~$d_n \approx 7\, w\, e\, \mathrm{MeV}$~~

$$d_n^{(\mathrm{irr})} \approx -2\, w\, e\, \mathrm{MeV}$$

CP-odd nuclear force:



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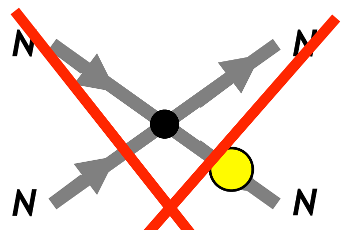
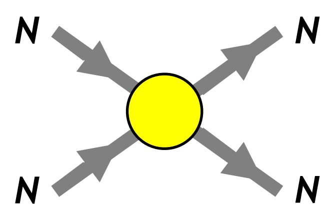
N. Osamura et al.,
JHEP **2206** (2022) 072.



~~Chiral rotation of CP-even NN~~



Contact

NY et al.,
PRD **106**, 075021 (2022)

~~$d_{\mathrm{He}} \approx 0.2\, w\, e\, \mathrm{MeV}$~~

$$d_{\mathrm{He}}^{(\mathrm{irr})} \sim -0.5\, w\, e\, \mathrm{MeV}$$

(Valence nucleon EDM effect not included)

Eventual leading contribution of Weinberg operator

Weinberg operator also generates chromo-EDM via RGE

For nuclear CP-odd moments, things may change
since EDM generated by WO is now small

Let us compare the direct and RGE (cEDM) contributions:

$$d_{\rm Hg}^{(\rm irr)} \approx 7 \times 10^{-4}\, w(\mu = 1\,{\rm TeV})\, e\,{\rm MeV}$$

$$\Uparrow$$

$$d_{\rm Hg}^{(\rm RGE)} \approx -9 \times 10^{-3}\, w(\mu = 1\,{\rm TeV})\, e\,{\rm MeV}$$

➡ Weinberg operator contributes to atomic/ nuclear EDMs via chromo-EDM !

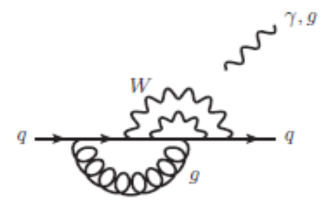
Enhancement of SM (CKM) contributions

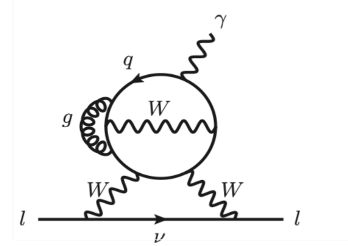
Leading CP violation from Jarlskog invariant

$$J = \mathrm{Im}[V_{ts}^{*}V_{td}V_{us}V_{ud}^{*}] = -\mathrm{Im}[V_{cs}^{*}V_{cd}V_{us}V_{ud}^{*}]$$
$$= (3.06 \pm 0.21)\times 10^{-5} \text{ (PDG value)}$$

C. Jarlskog, PRL **55**, 1039 (1985).

Short distance process:





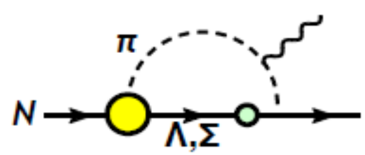
EDM in the Standard model starts from
* 3-loop diagram for quark ~ 10^{-35}e cm
* 4-loop diagram for electron ~ 10^{-48}e cm

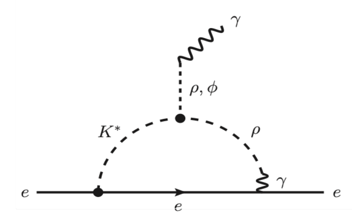
⇒ Very small due to GIM mechanism with quark mass factors

A. Czarnecki et al., PRL **78**, 4339 (1997)
M. Pospelov et al., PRD **89**, 056006 (2014)

Long distance (hadron level) process:

Generated by two distinct hadron level |ΔS|=1 interactions
* Electron EDM ~ 10^{-39}e cm
* Neutron EDM ~ 10^{-32}e cm
* Deuteron EDM ~ 10^{-31}e cm





⇒ No strong GIM cancelation, much larger EDM

C.-Y. Seng, PRC **91**, 025502 (2015)
NY and E. Hiyama, JHEP **1602** (2016) 067
Y. Yamaguchi and NY, PRL **125**, 241802 (2020)

Some enhancement, but still well below experimental sensitivity

Summary of hadronic CPV

No notable enhancement for quark EDM

Weinberg operator suppressed by RGE and
hadron matrix elements

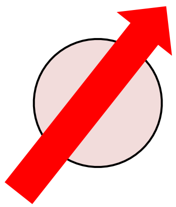
➡ **Chromo-EDM contribution is the most enhanced!**

(Some 4-quark interactions may also be enhanced,
but model specific, like left-right sym. models)

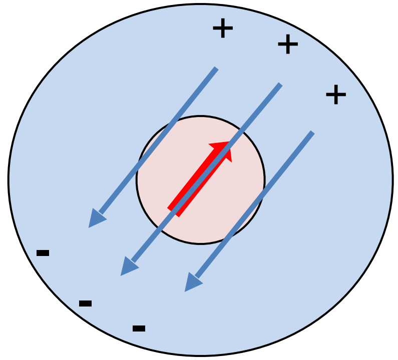
Nuclear and atomic level many-body physics of EDM

Atomic EDM and Schiff's screening

In atoms, EDM of nonrelativistic constituents suffers Schiff's screening



EDM of bare constituent



Atomic EDM :
screening via rearrangement

Typically, looses sensitivity by α_{QED}^2 ~ 10^{-4}

Leading processes avoiding Schiff's screening :

- Relativistic effect of constituents (e^- in heavy atoms,molecules)
- CP-odd electron-nucleon interaction
- Schiff moment (finite size effect of nuclear EDM)

L. I. Schiff, Phys. Rev. **132**, 2194 (1963).

- Oscillating EDM of constituents (interaction with axion dark matter?)

V. Flambaum et al., Phys. Rev. D **100**, 111301 (2019).

Relativistic electron EDM enhancement in atoms/molecules

Atomic EDM induced by electron EDM:

$$d_A = \sum_n \frac{\langle \Psi_0 | -e \sum_i^Z z_i | \Psi_n \rangle \langle \Psi_n | d_e \sum_j^Z (1 - \gamma_{0j}) \boldsymbol{\sigma}_j \cdot \mathbf{E}_j | \Psi_0 \rangle}{E_n - E_0} \equiv K_e d_e$$

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965); Phys. Lett. **22**, 290 (1966).

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Dipole operator

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965); Phys. Lett. **22**, 290 (1966).

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1st order perturbation by eEDM interaction

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965); Phys. Lett. **22**, 290 (1966).

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(Relativisitic effect, not canceled by Schiff's screening)

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⇒ O(100) enhancement for heavy atoms/molecules

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965); Phys. Lett. **22**, 290 (1966).

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E.g. **Tl : K_e = -585** Porsev et al., PRL **108**, 173001 (2012).

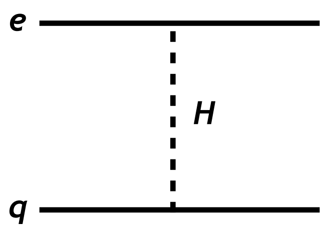
Fr : K_e = 800 Shitara et al., JHEP 2102 (2021) 124

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965); Phys. Lett. **22**, 290 (1966).

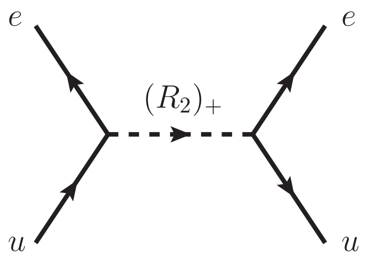
CP-odd electron-nucleon (e-N) interaction : the best ?

Generated by BSM particle exchange between electrons and quarks

Examples:



CPV Higgs exchange



Leptoquark

3 structures

$$H_{eN} = \frac{G_F}{\sqrt{2}} \sum_{N=p,n} \left[C_N^{SP} \bar{N} N \, \bar{e} i \gamma_5 e + C_N^{PS} \bar{N} i \gamma_5 N \, \bar{e} e - \frac{1}{2} C_N^T \epsilon^{\mu\nu\rho\sigma} \bar{N} \sigma_{\mu\nu} N \, \bar{e} \sigma_{\rho\sigma} e \right]$$

S-Ps type e-N interaction is important :

⇒ Tree level effect

⇒ Enhanced by relativistic atomic/molecular effect (like eEDM)

⇒ Enhanced by πN sigma-term

The leading CPV contribution in all EDM physics?

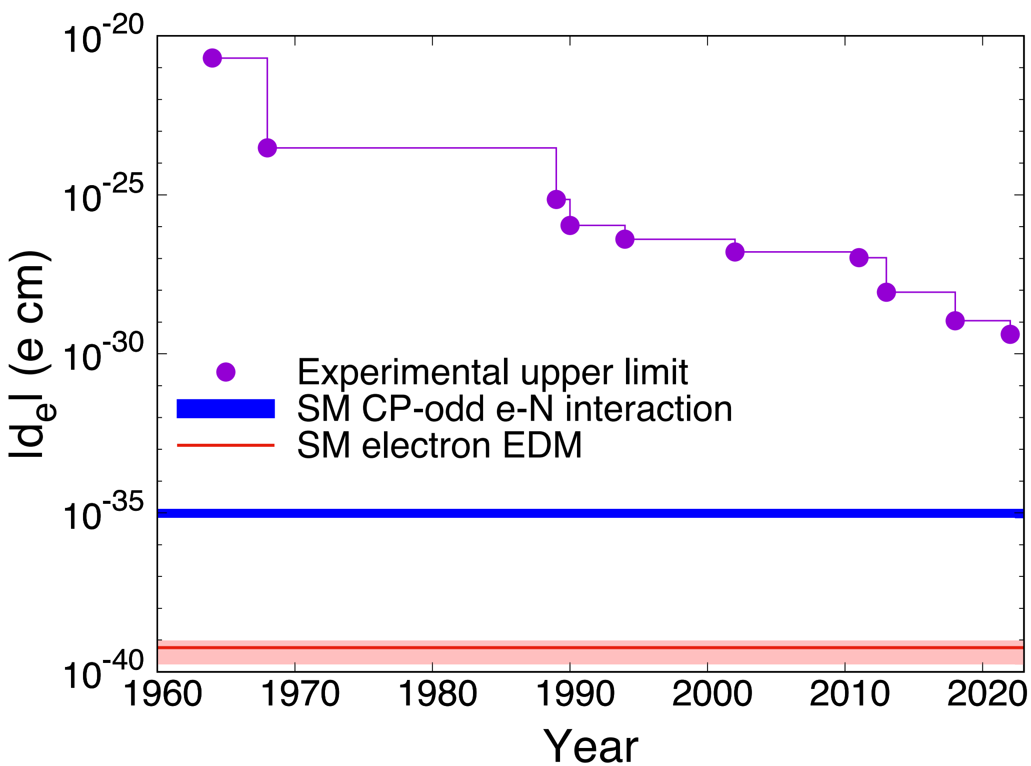
CP-odd electron-nucleon (e-N) interaction : the best ?

Generated by BSM particle exchange between electrons and quarks

Examp

An example is the SM contribution:

CPV e-N "EDM equivalent" is much larger than d_e



3 struct

H_{eN} … $\bar{e}\sigma_{\rho\sigma}e\Big]$

S-Ps t

⇒ Tr

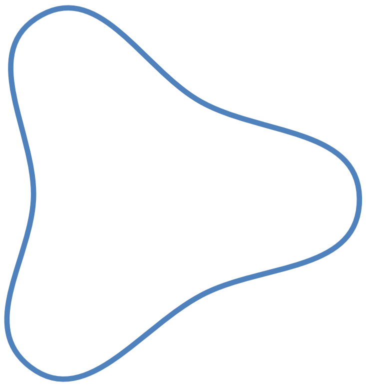
⇒ Er … **M)**

⇒ Enhanced by πN sigma-term

The leading CPV contribution in all EDM physics?

Octupole deformation : polar molecules

Octupole is this
(3 axes)



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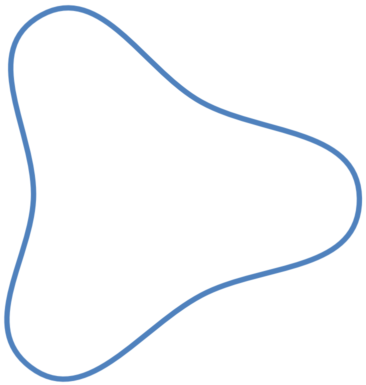
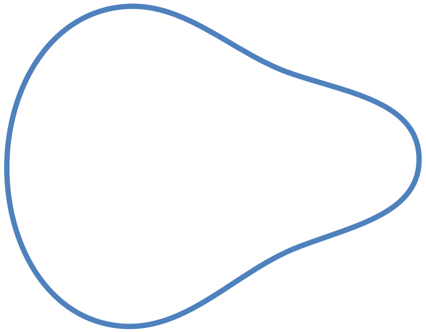


An octupole deformed system looks like this



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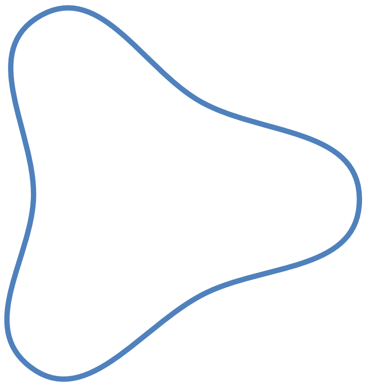

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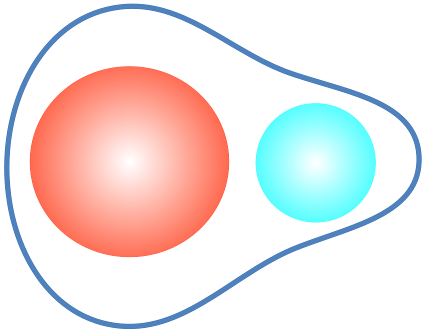

Polar molecule!

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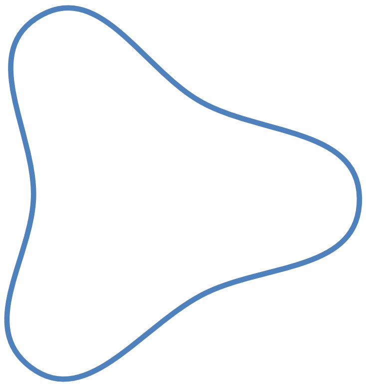

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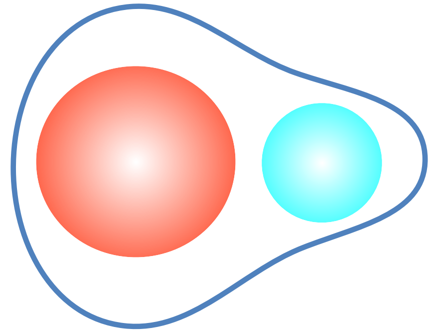
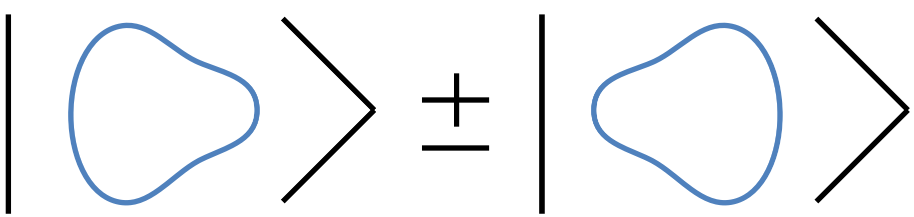


Polar molecule!

Physical state is a (anti)symmetric superposition of polarization



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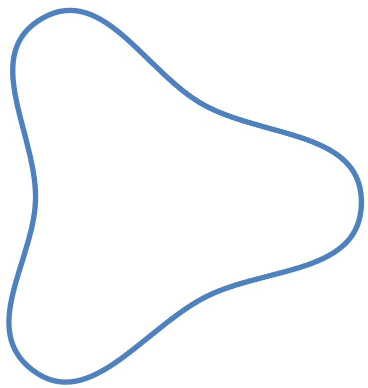

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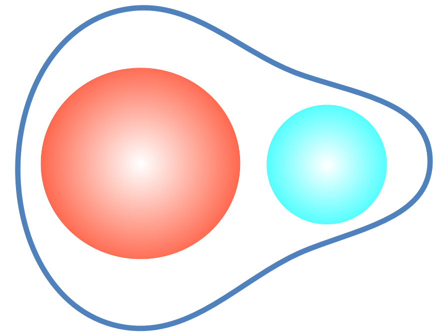

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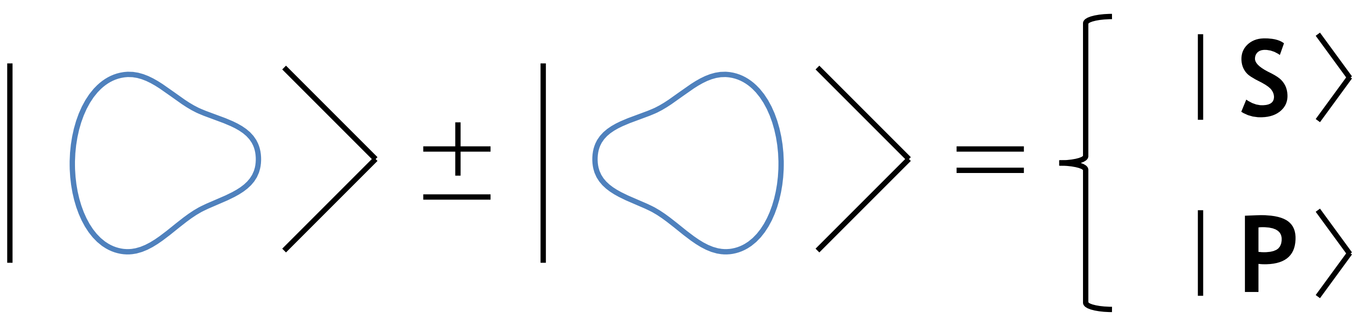
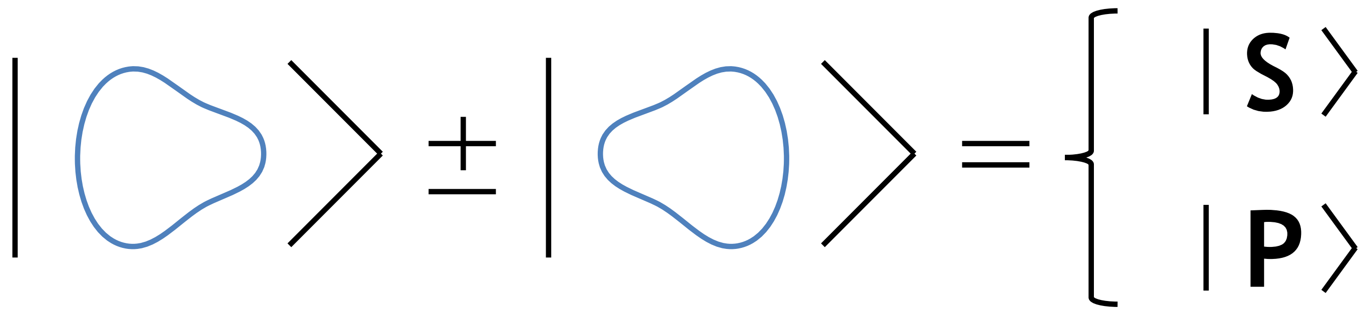


⇒ Opposite parity states (parity doublet)

Enhancement in octupole systems: parity doubling



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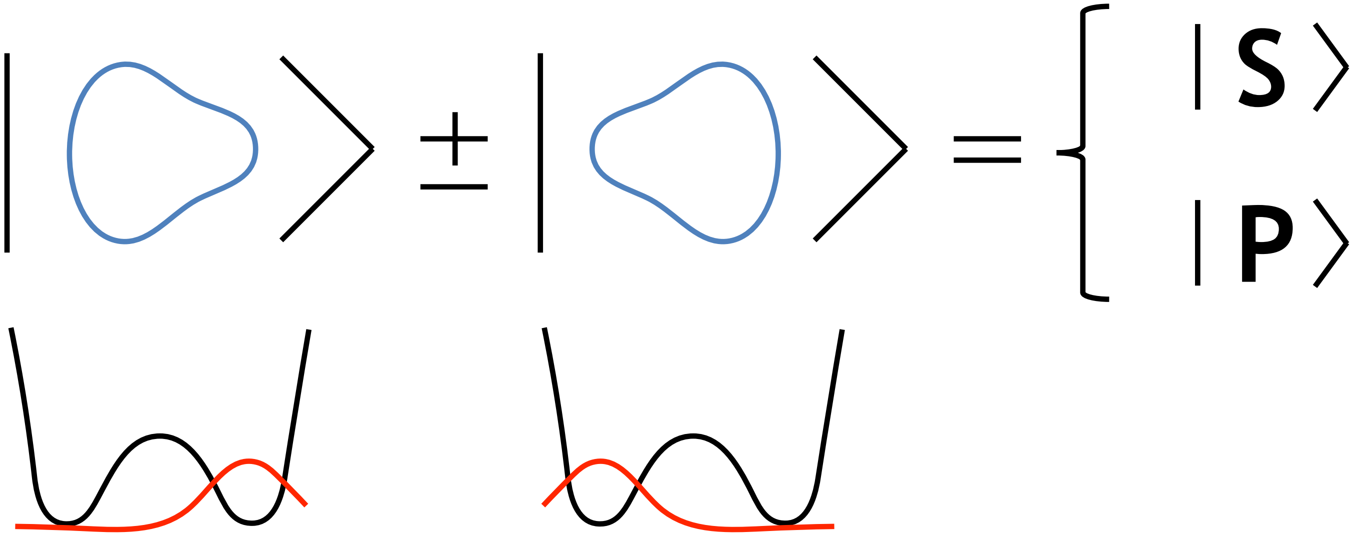
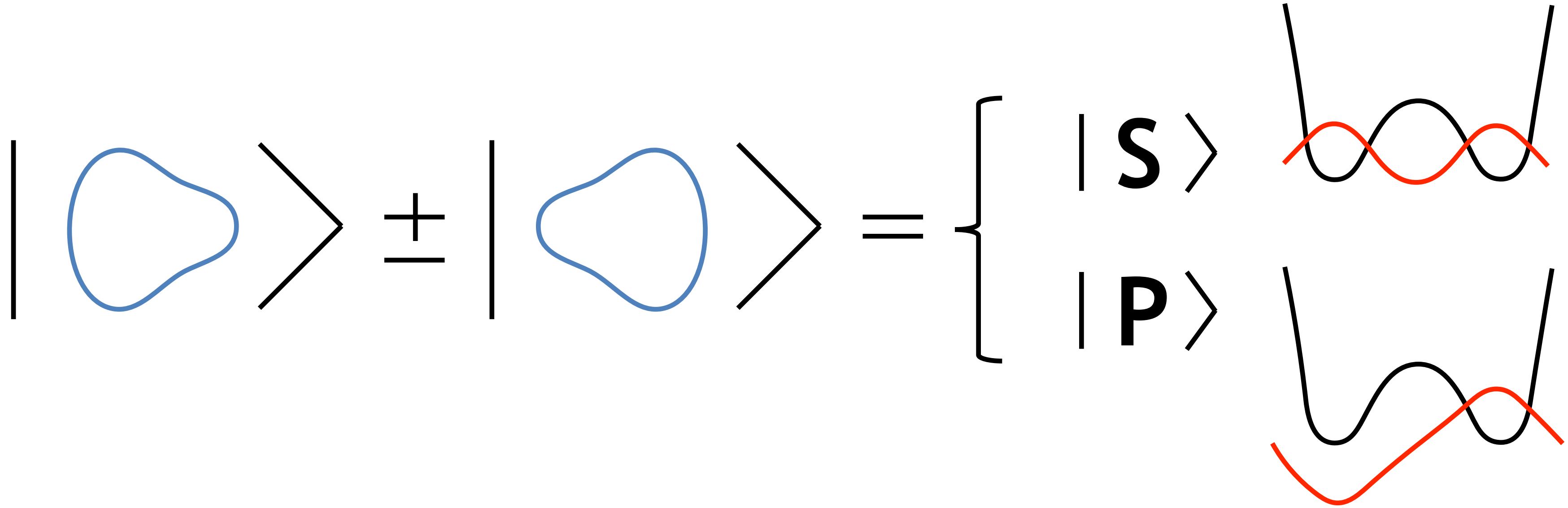


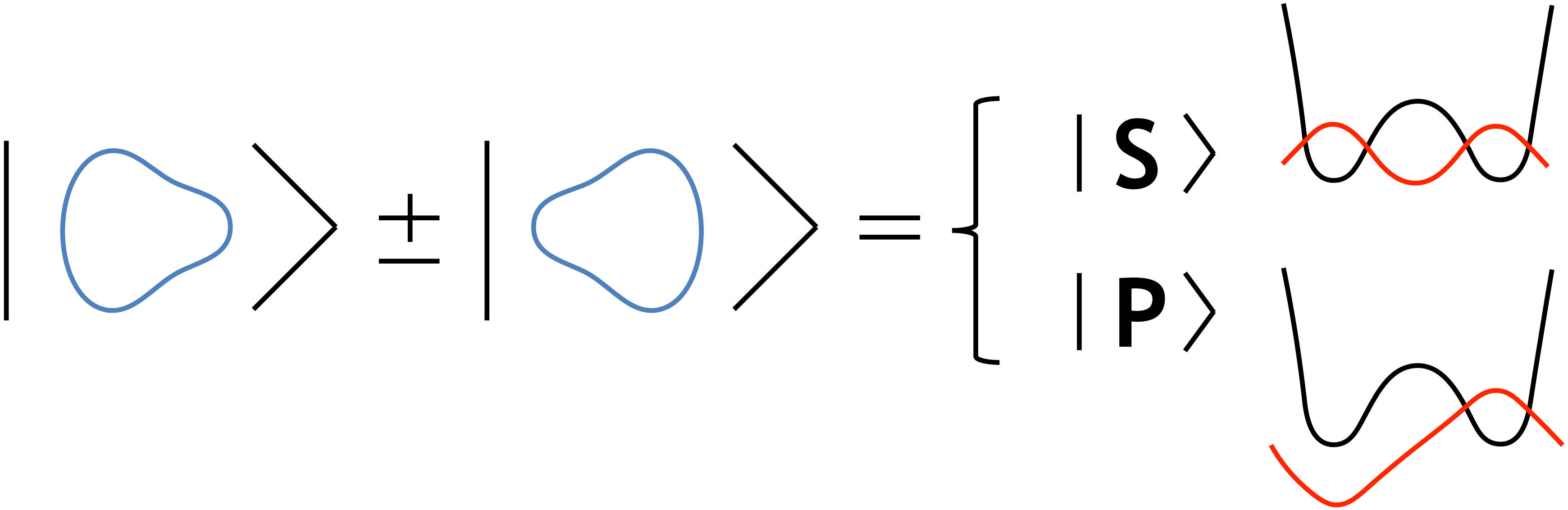
Each orientation corresponds to localized state in double well potential

Enhancement in octupole systems: parity doubling



⇒ **Nearly degenerate** **symmetric (S) and antisymmetric (P) states, very close energy levels between opposite parity**

Enhancement in octupole systems: parity doubling



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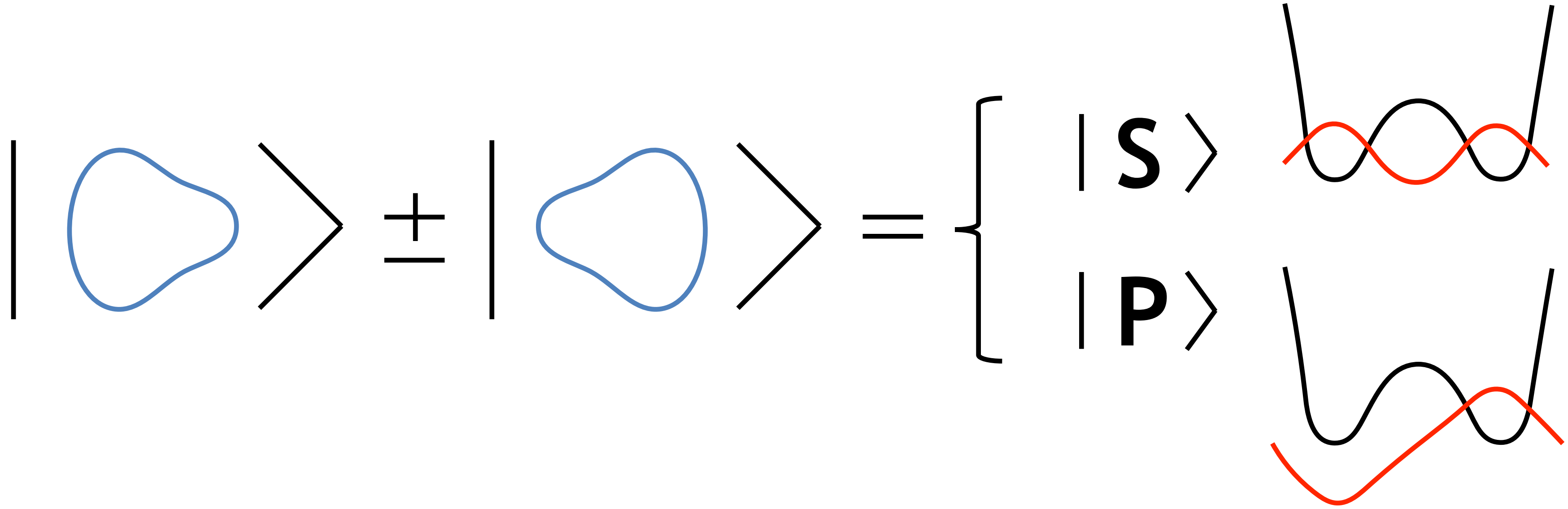
Remember that small energy splitting enhances CP violation

Enhancement in octupole systems: parity doubling



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Octupole deformed systems enhance CP violation by close opposite parity levels (parity doubling)

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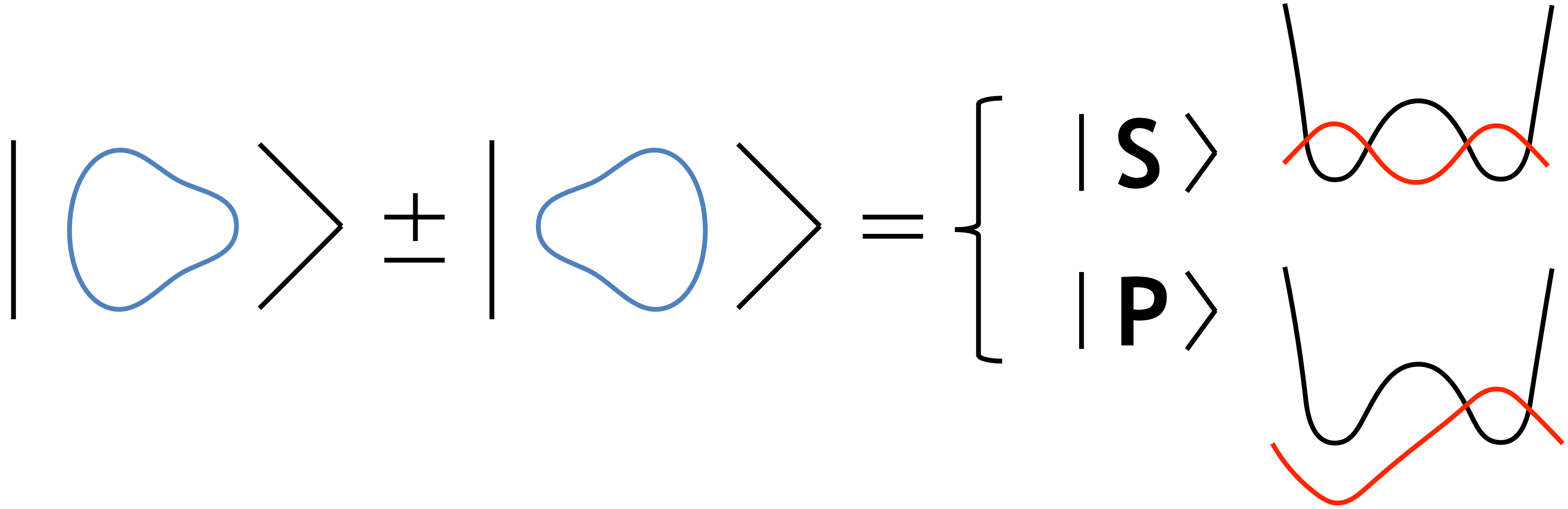

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Octupole deformed systems enhance CP violation by close opposite parity levels (parity doubling)

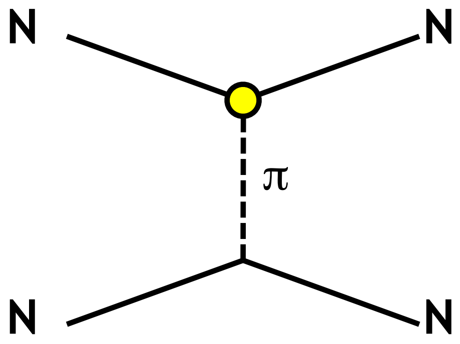
This is why polar molecule/ion experiments are sensitive to electron EDM

Current world record by HfF+ ion exp. : $|d_e| < 4.1 \times 10^{-30}$ e cm

T. S. Roussy et al., Science **381** (2023) 46.

P, CP-odd nuclear force from one pion exchange

P, CP-odd nuclear force : we assume one-pion exchange process



$$\sim \frac{1}{q^2 - m_\pi^2} \bar{N}N \; \bar{N}i\gamma_5 N$$

- P, CP-odd Hamiltonian (3-types):

$$\mathcal{H}_{PT} = -\frac{1}{8\pi m_N}\left[\left(\bar{G}_\pi^{(0)}\tau_a \cdot \tau_b + \bar{G}_\pi^{(2)}(\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z)\right)(\sigma_a - \sigma_b) + \bar{G}_\pi^{(1)}(\tau_b^a \sigma_a - \tau_b^z \sigma_b)\right] \cdot \nabla\left(\frac{e^{-m_\pi r}}{r}\right)$$

Isoscalar ($\bar{G}_\pi^{(0)}$), Isotensor ($\bar{G}_\pi^{(2)}$), Isovector ($\bar{G}_\pi^{(1)}$)

- 4 important properties:
  - Coherence in nuclear scalar density : enhanced in nucleon number
  - One-pion exchange : suppress long distance contribution
  - Spin dependent interaction : closed shell has no EDM
  - Derivative : contribution from the surface

- What is expected:
  - Polarization effect grows in *A* for small nuclei
  - May have additional enhancements with cluster, deformation, …

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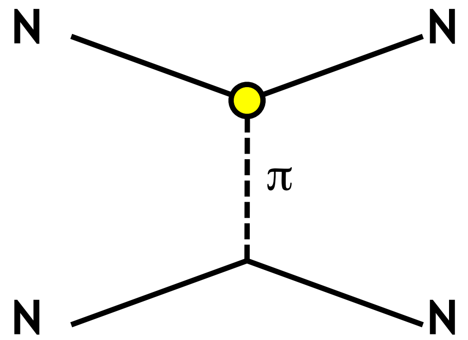

Isocalar CPV NN-int. :

Axion DM, θ-term,…

$i\gamma_5 N$

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Isoscalar Isotensor Isovector

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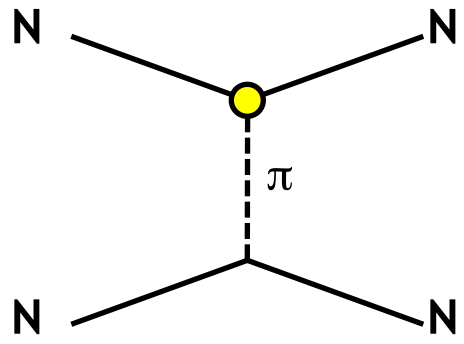

Isocalar CPV NN-int. :
Axion DM, θ-term,…

$i\gamma_5$

Isovector CPV NN-int. :
Higgs, SUSY, …

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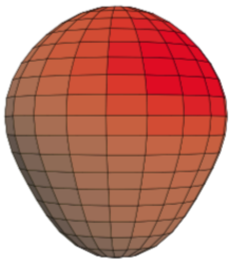
Schiff moment of octupole deformed nuclei: enhancement

Octupole deformation also occurs in heavy nuclei
(^{225}Ra, ^{223}Rn, ^{223}Fr, etc)



⇒ Enhance nuclear Schiff moment
(sensitive to hadronic CP violation)

Comparison with ^{199}Hg:

	a_0(isoscalar)	a_1(isovector)	a_2(isotensor)
^{225}Ra	-1.5 e fm^3	6.0 e fm^3	-4.0 e fm^3
^{199}Hg	0.08 e fm^3	0.08 e fm^3	0.14 e fm^3

J. Dobaczewski and J. Engel, Phys. Rev. Lett. **94**, 232502 (2005)
J. Dobaczewski et al., Phys. Rev. Lett. **121**, 232501 (2018).
(Comparison ^{199}Hg result of Yanase and Shimizu, PRC **102**, 065502 (2020)

➡ Octupole deformation enhances NSM by O(100) times!!

Results of nuclear/atomic EDM calculations

$d_A = a_0 \bar{G}_\pi^{(0)} + a_1 \bar{G}_\pi^{(1)} + a_2 \bar{G}_\pi^{(2)}$	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)	
^{129}Xe atom K. Yanase et al., PRC **102**, 065502 (2020) B. Sahoo et al., PRA **108**, 042811(2023)	-1.2×10^{-6} *e* fm	-1.3×10^{-6} *e* fm	-2.6×10^{-6} *e* fm	atoms
^{199}Hg atom K. Yanase et al., PRC **102**, 065502 (2020) M. Hubert et al., PRA **106**, 022817 (2022)	-1.4×10^{-5} *e* fm	-1.3×10^{-5} *e* fm	-2.6×10^{-5} *e* fm	atoms
^{225}Ra atom Dobaczewski et al., PRL **94**, 232502 (2005) V. S. Prasannaa et al., JPB **53**, 195004 (2020)	0.00093 *e* fm	-0.0037 *e* fm	0.0025 *e* fm	atoms
Neutron Crewther et al. , PLB **88**,123 (1979) Mereghetti et al., PLB **696**, 97 (2011)	0.01 *e* fm	—	− 0.01 *e* fm	
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	—	0.0145 *e* fm	—	nuclei
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm	nuclei
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015) Froese et al., PRC **104**, 025502 (2021)	—	0.022 *e* fm	—	nuclei
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019) Froese et al., PRC **104**, 025502 (2021)	− 0.015 *e* fm	0.016 *e* fm	− 0.026 *e* fm	nuclei
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015) Froese et al., PRC **104**, 025502 (2021)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm	nuclei
^{11}B nucleus NY et al., PRC **100**, 055501 (2019) Froese et al., PRC **104**, 025502 (2021)	− 0.01 *e* fm	0.016 *e* fm	− 0.02 *e* fm	nuclei
^{13}C nucleus NY et al., PRC 95,065503 (2017) Froese et al., PRC **104**, 025502 (2021)	− 0.003 *e* fm	−0.0020 *e* fm	− 0.003 *e* fm	nuclei
^{129}Xe nucleus N. Yoshinaga et al., PRC **89**, 045501 (2014)	7.0×10^{-5} *e* fm	7.4×10^{-5} *e* fm	3.7×10^{-4} *e* fm	nuclei
Simple shell model O. P. Sushkov et al., Sov. JETP **60**, 873 (1984)	O(0.01) *e* fm	0.07 *e* fm	O(0.01) *e* fm	nuclei

Summary of enhancement mechanisms

- Scalar density

  QCD renormalization

  Sigma term

  Nucleon number in nuclei

- Octupole deformation

  Heavy radioactive nuclei

  Paramagnetic dipolar molecules

➡ CPV process gaining all these enhancement is the CP-odd electron-nucleon interaction (S-Ps type)

➡ The most enhanced hadronic CPV process is quark chromo-EDM

Multiple EDM experiments are needed

Measurement of the EDM of the most sensitive system is enough?

⇒ No!!

EDM experimental result of one system is just one equation

$$d_A = K_e d_e + K_u d_u + K_d d_d + \ldots$$

⇒ We cannot determine all unknown variables

Measuring the EDM of several systems is required to disentangle unknown BSM couplings!

$$\begin{cases} d_A = K_e d_e + K_u d_u + K_d d_d + \ldots \\ d_{A'} = K'_e d_e + K'_u d_u + K'_d d_d + \ldots \\ d_{A''} = K''_e d_e + K''_u d_u + K''_d d_d + \ldots \\ \vdots \end{cases}$$

Where is new physics

Hierarchy problem of Higgs

Hierarchy problem arises when an interacting scalar is present in the theory

Self-interaction   Fermion loop (Yukawa interaction)

$\sim \Lambda^2$ (Λ : cutoff)

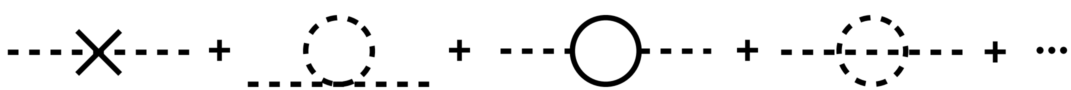
Quadratically divergent!

- **Physical meaning of cutoff :**
  Energy scale at which the theory is replaced by a new theory

- **Implication of quadratic divergence :**

  Let us take $\Lambda = m_{GUT} = 10^{16}$GeV

  Higgs mass :



$= (125\ \text{GeV})^2$

$O(100^2)$ GeV^2 $O(10^{32})$ GeV^2 $O(10^{32})$ GeV^2 $O(10^{32})$ GeV^2

⇒ An extreme fine-tuning!!

This is the most important problem of the standard model!!

Quadratic divergence is unphysical?

In momentum cutoff scheme, quadratic divergence Λ^2 appears

In dimensional regularization, quadratic divergence does not exist !!

➡ Quadratic divergence is scheme-dependent

(depends on how the field is defined)

In theory with elementary scalar field,

we can always absorb quadratic divergence in the definition of mass

$$m^2 + \Lambda^2 \to m_R^2$$ (Mass renormalization)

⇒ Quadratic divergence is unphysical

⇒ No fine-tuning problem, as regards quadratic divergence !!

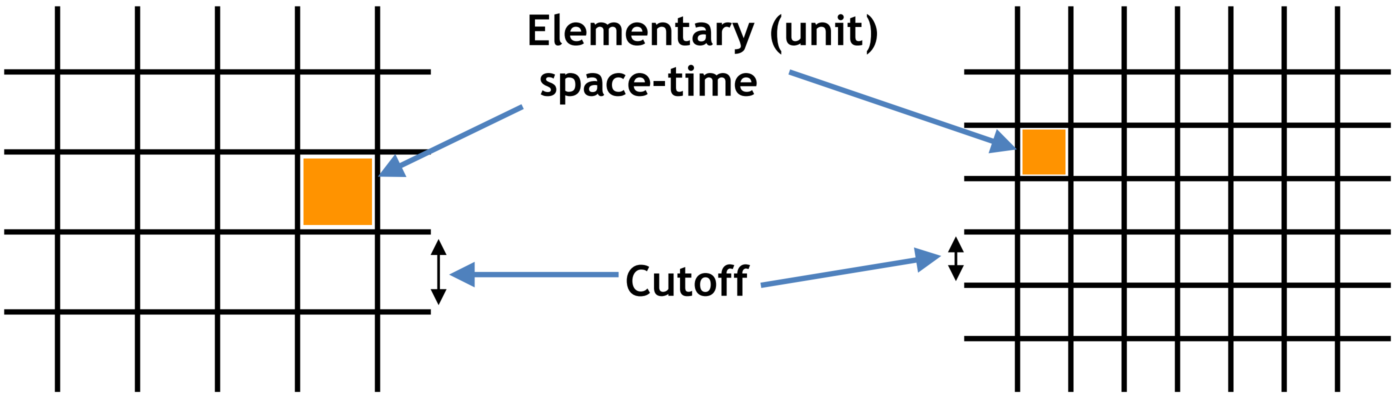
H. Aoki and S. Iso, Phys. Rev. D **86**, 013001 (2012).

Renormalization

Renormalization = how to define a theory with "elementary area"

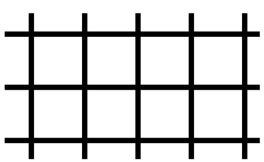
⇒ 2 important features

- **Renormalization scale :** size of the elementary area

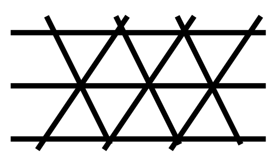


- **Renormalization scheme :** shape of the elementary area

Examples:



Lattice



Triangular lattice

Dimensional regularization
(impossible to draw)

Physical meaning of quadratic divergence

Quadratic divergence can be removed by redefining elementary scalar fields

However, mass correction induced by the interaction with other particles cannot be removed!!

BSM particle loops

$$\delta m_H^2 \sim O(m_{\rm BSM}^2)$$

If the BSM scale is large, serious fine-tuning!

(This is the physical meaning of quadratic divergence)

⇒ We need a BSM physics not far from SM scale, at TeV - PeV

(becomes higher as the coupling to Higgs becomes small)

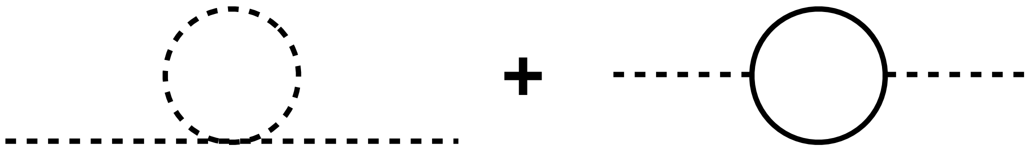
TeV - PeV scale physics again needs another BSM physics not far from its scale

⇒ Tower of BSM physics up to Planck scale

(This is the most “natural” way to conceive particle physics)

Supersymmetry

In SUSY models, quadratic divergences cancel!



$\sim \log \Lambda$

No apparent hierarchy problem from GUT or Planck scale physics!

HOWEVER !!

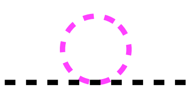
In SUSY, Higgs sector parameters and SUSY breaking scale (and μ) are related!

$$\frac{m_Z^2}{2} \simeq -\mu^2 - m_{H_u}^2$$

⇒ Naturalness : SUSY must be broken just above SM scale

⇒ "Little hierarchy problem"   K. Choi et al., Phys. Lett. B **633**, 355 (2006).

We may avoid by extending SUSY, but cannot avoid threshold corrections…

e.g. stop loop  $\sim m_{\mathrm{SUSY}}^2$ (for m_{SUSY} = TeV, $O(10^{-2})$ fine-tuning)

⇒ SUSY is at TeV!

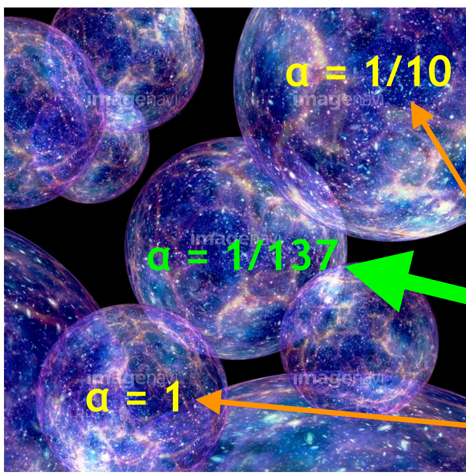
Anthropic principle

We (human beings) were not born if SM does not have current parameters

⇒ We were born BECAUSE parameters are fine-tuned

⇒ Anthropic principle

Anthropic principle is a consequence of multiverse:



<u>Multiverse :</u>
Universes with different fundamental constants

Other universes with other constants have no humans

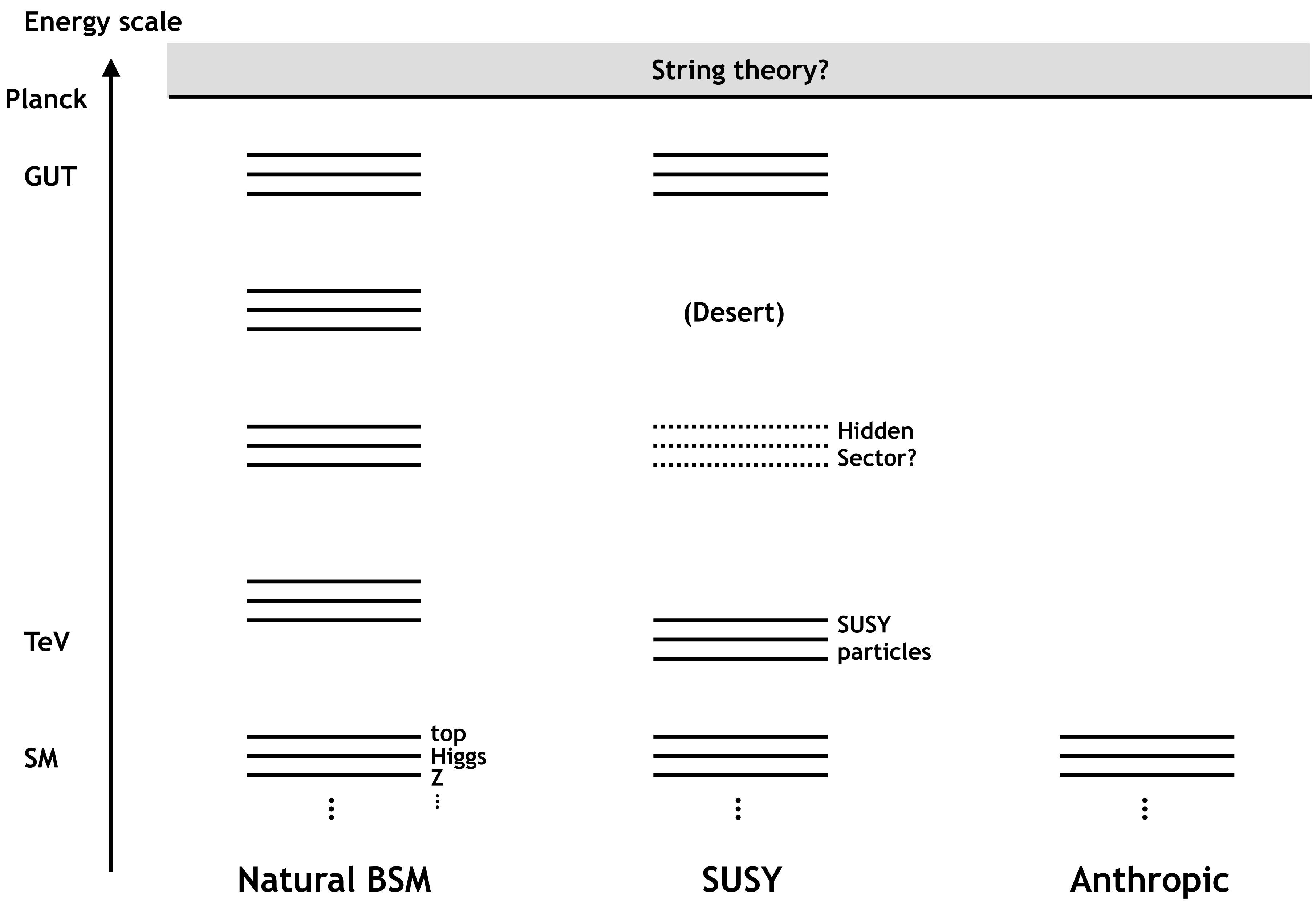
⇒ Fine-tuning is mandatory for humans!

You are born here, you may only observe this!

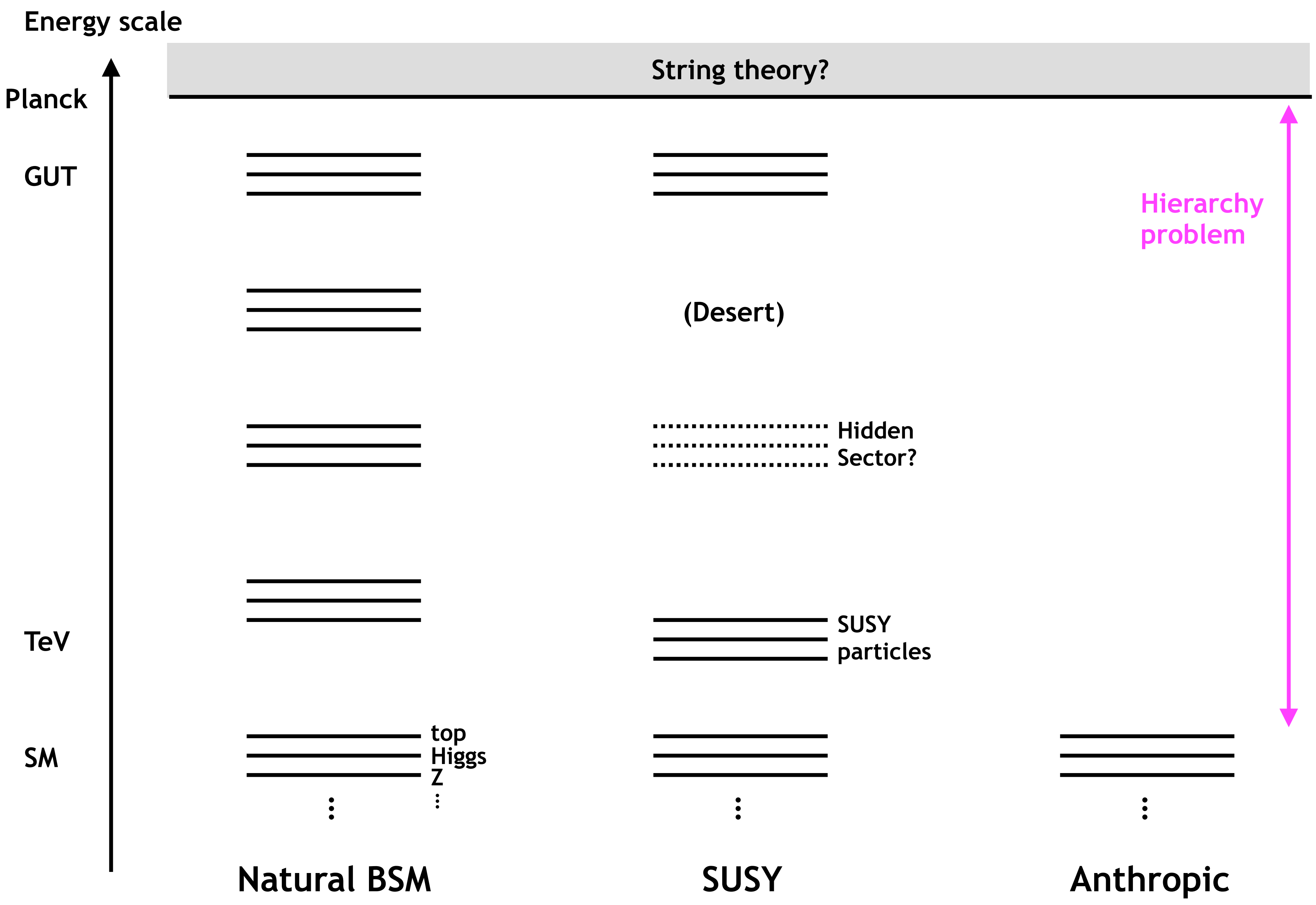
No humans

⇒ No BSM is needed, SM holds up to Planck scale !!

Summary of energy spectra of possible high energy physics



Summary of energy spectra of possible high energy physics



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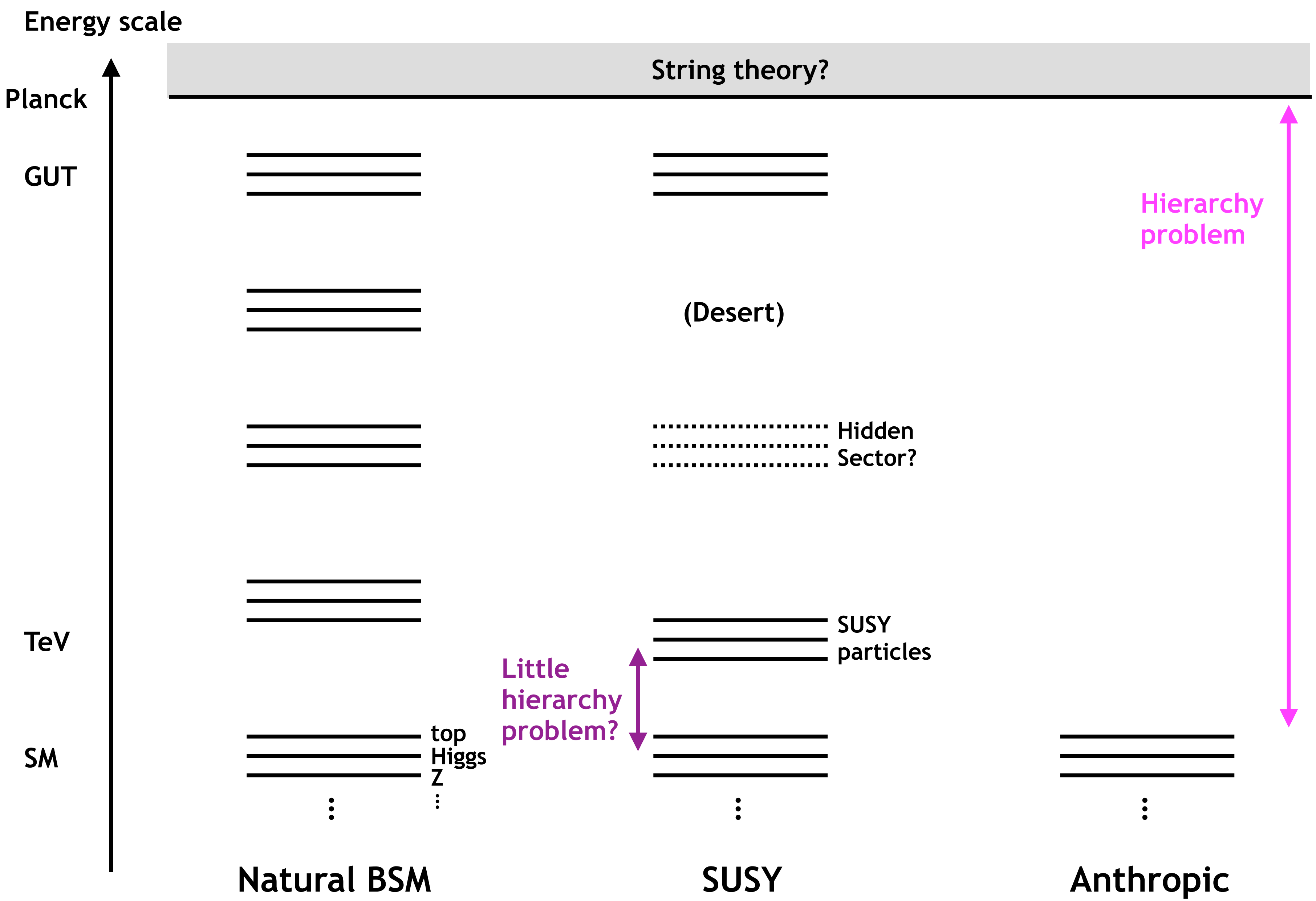


Problems with anthropic principle

- Anthropic principle looks like almighty because

  it is impossible to prove or reject it.

  ⇒ However, we cannot exclude BSM !!

  ⇒ To settle the dispute, we have to inspect TeV and beyond

- Anthropic principle constrains parameters needed for our existence (like m_H , $m_u - m_d$, α_{QED}, etc)

  However, small parameters which do not influence our existence (like EDM, muon g-2) are not constrained

  If parameters are selected randomly, larger EDM, g-2, … are more likely

  ⇒ Small EDM, g-2, etc are unnatural in anthropic principle

  ⇒ "Full" anthropic description seems unlikely

Anthropic principle vs natural theories

The reality seems to be a mixture of natural theories and anthropic events

Example of phenomenon explained by anthropic principle:

- Unlikely to have extraterrestrial “intelligent” lives (no “aliens”)

  Fermi paradox

  Almost zero probability in RNA World hypothesis

  T. Totani, "Emergence of life in an inflationary universe”, Sci. Rep. **10**, 1671 (2020).

- Birth of life in the Earth

  Current abundance and distribution of atoms due to the fine-tuning of isospin splitting between proton and neutron

- In string theory, we have many vacua:
  We expect that some of them effectively generate the SM, and also us

Example of phenomenon explained by natural theories:

- The very busy hadron mass spectrum could be derived from lattice QCD

- Weinberg-Salam theory could unify QED, weak interaction, CKM and Higgs

Motivation of BSM physics

We saw that the full anthropic scenario is disfavored
and that natural BSM (and SUSY) are the most likely
in the “leading order analysis“.

Quadratic divergence strongly suggests BSM close to TeV

Mixing of natural BSM and anthropic is also possible.

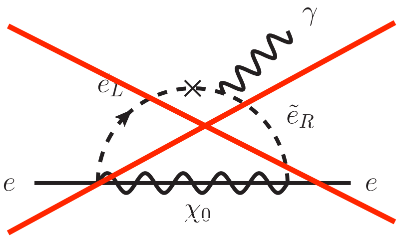
To determine whether BSM or anthropic principle
is working beyond TeV,

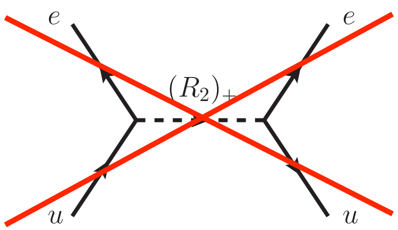
we cannot avoid the study beyond TeV!!

Let us now see recent TeV scale BSM search

EDM suggests PeV?

Simplest TeV scale extensions of SM are excluded by EDMs





One can invent tricky TeV scale BSM models to avoid EDM constraints,
but become less and less natural...

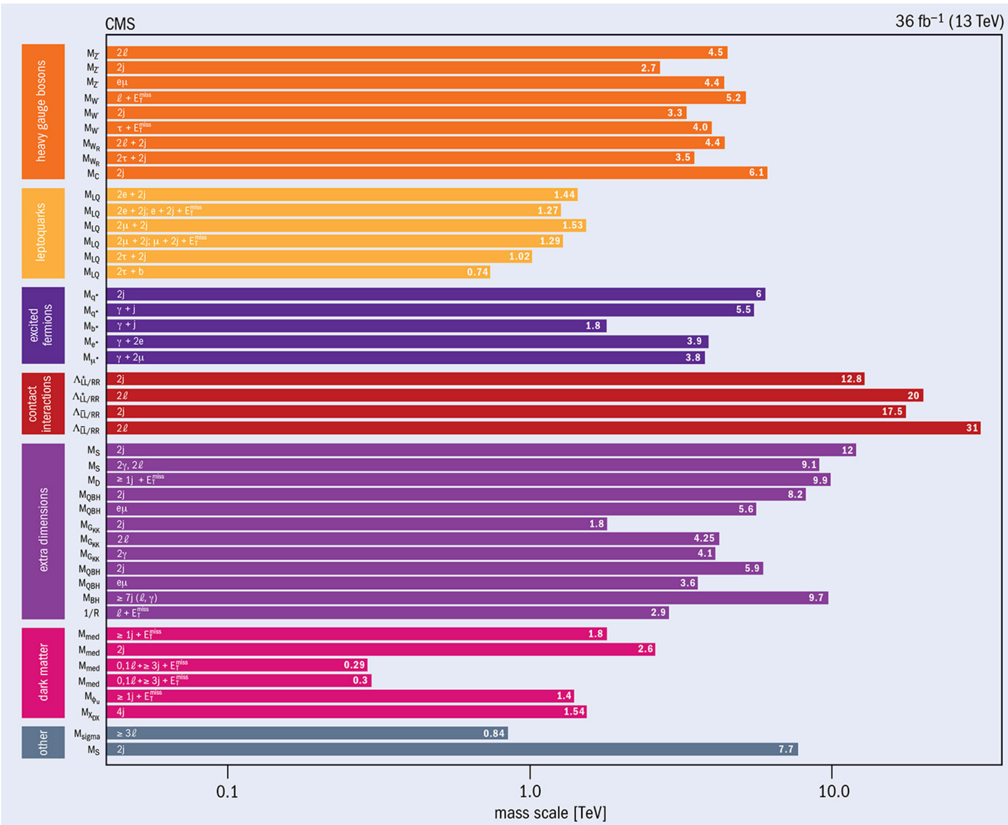
"Leading order prediction" of EDM:

BSM is at PeV scale ??

Let us see the "success" of EDM in relation with recent news

LHC limit on new physics

BSM search in LHC provides us only exclusion (up to TeV), no evidence of BSM particles…

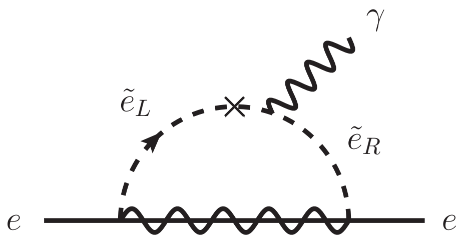


No BSM particles seen up to TeV.

“Naive” SUSY has problems, due to little hierarchy

SUSY CP problem

In SUSY models, fermion EDM is generated at 1-loop level



gaugino

⇒ Very strong constraints on the CP phases of light sfermion

($\theta_{SUSY} < 10^{-(2\text{-}3)}$ for $m_{SUSY} \sim$ TeV)

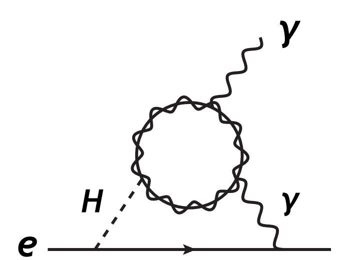
⇒ "Naive" SUSY is rejected, consistent with LHC search

⇒ So-called "SUSY CP problem"

There are ways to avoid SUSY CP problem, such as split-SUSY (very heavy sfermions)

Arkani-Hamed et al., Nucl. Phys. B **709** (2005) 3.

But less and less natural...

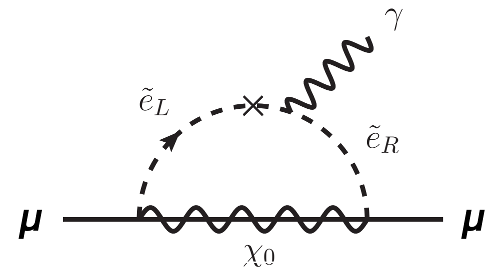


Appears at 2-loop level

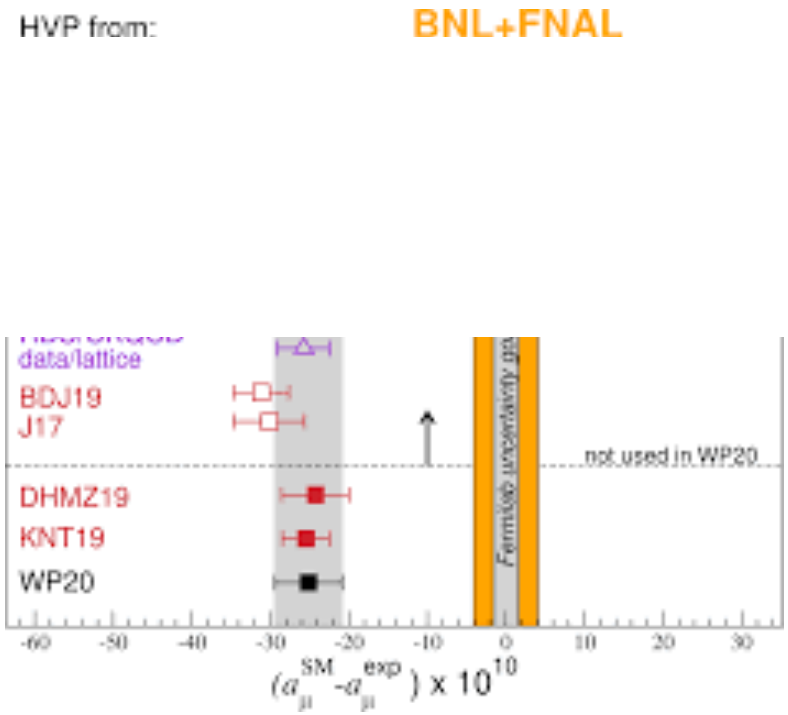
Compare with muon g-2

EDM and g-2 are generated by the same diagrams

(Just a difference of CP phase)



Muon g-2 exp. was so far suggesting deviation from SM (5σ!), TeV BSM



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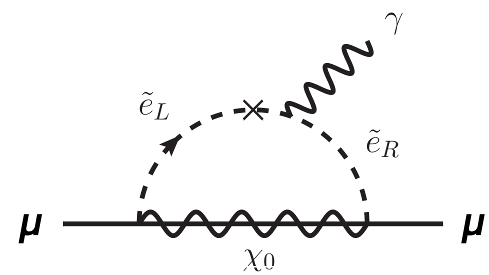

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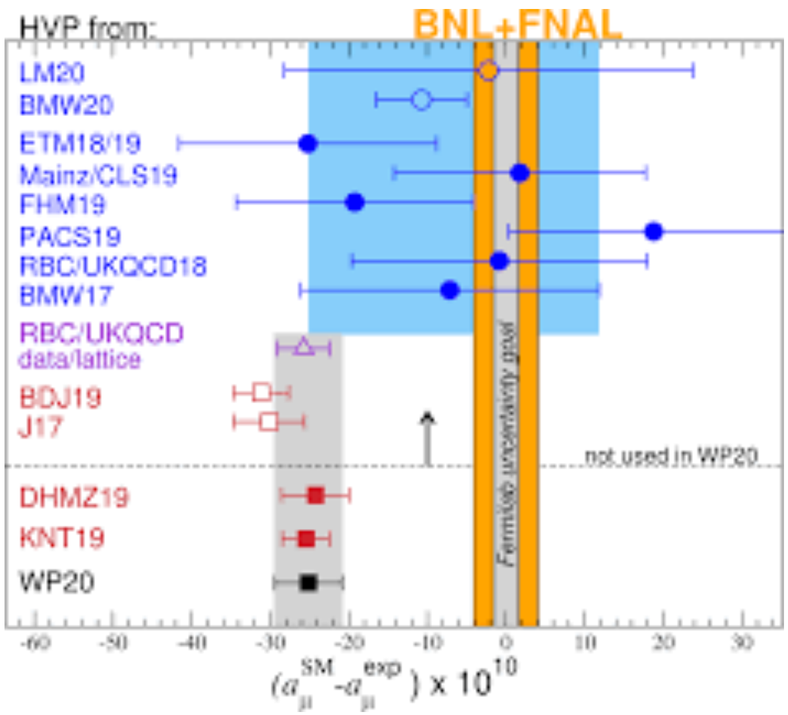
However, recent lattice QCD results show consistency with SM !

= consistent with "no TeV BSM"



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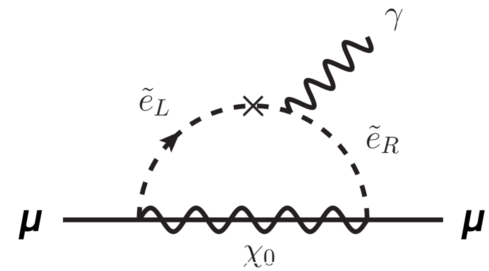

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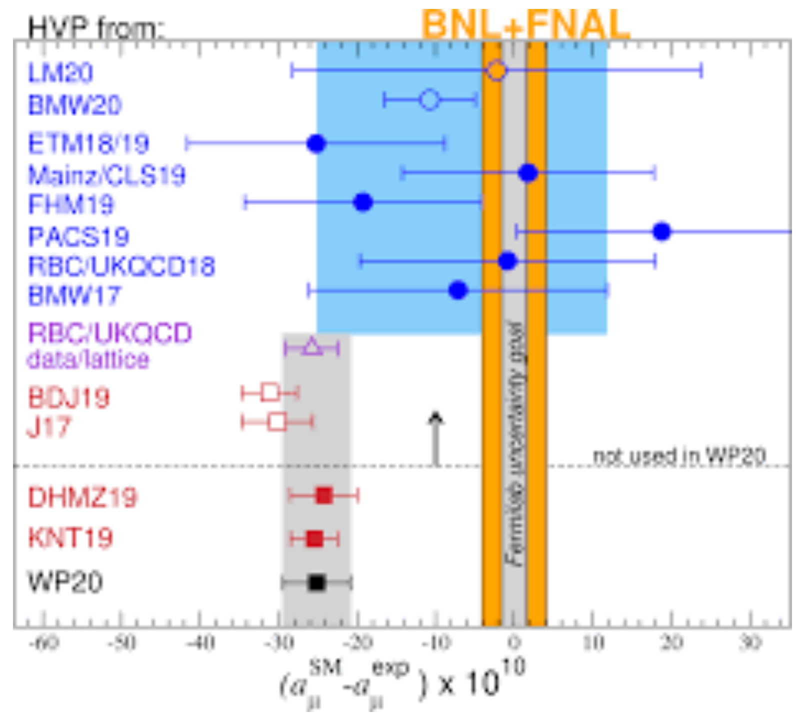

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On the other hand, electron EDM is rejecting TeV scale BSM (with “natural” couplings)

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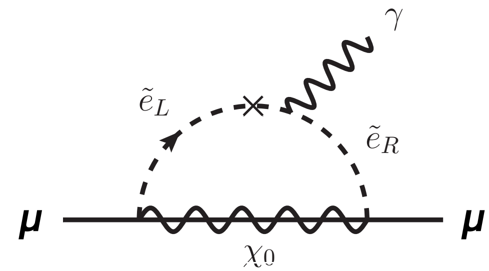

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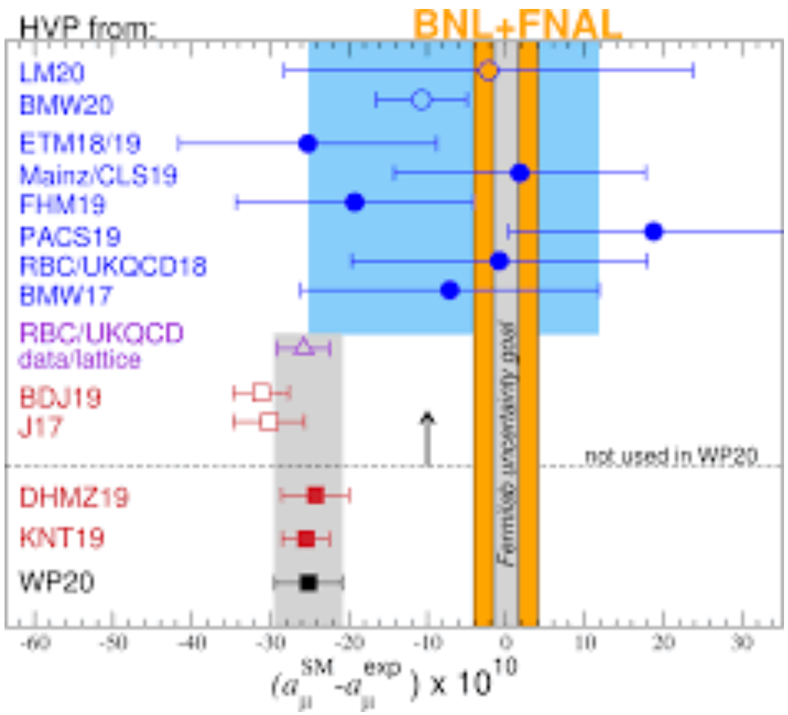


On the other hand, electron EDM is rejecting TeV scale BSM (with "natural" couplings)

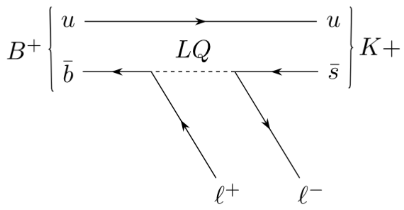
⇒ Consistent !

Compare with R_K

SM predictions of $R_K = \dfrac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)}$, $R_{K*} = \dfrac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$

were so far believed to deviate from LHCb results

TeV leptoquarks were attracting in explaining R_K



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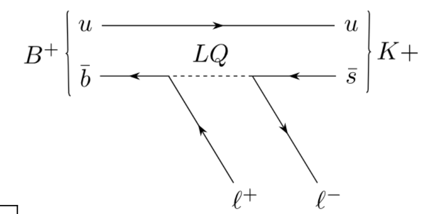
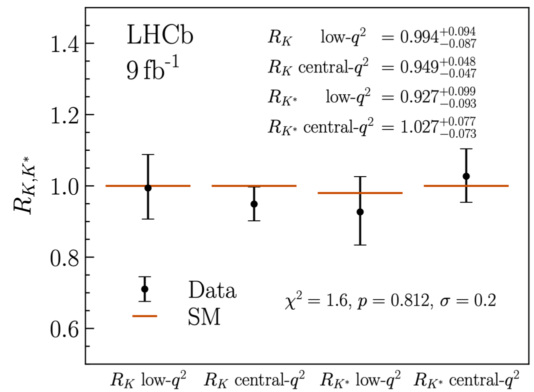


However,…
Recent update consistent with SM…



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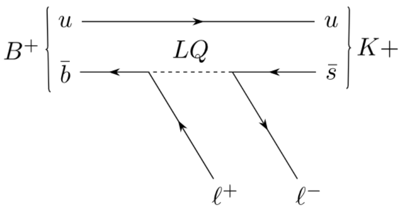

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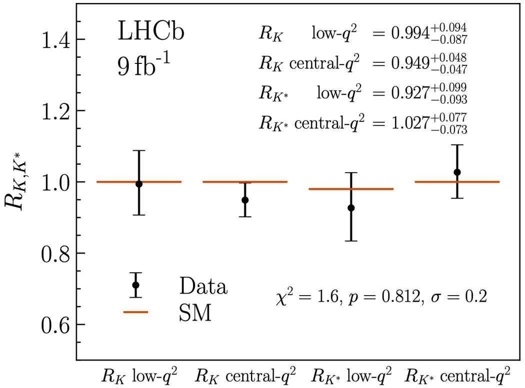
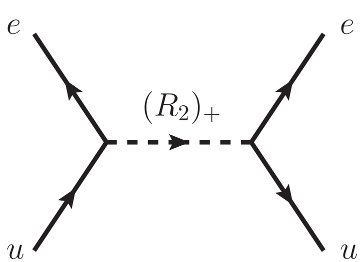


On the other hand, atomic EDM exp.
was already very strongly constraining
leptoquarks (via CPV e-N force)



Herczeg, Phys. Rev. D **68**, 116004 (2003),
Fuyuto et al., Phys. Lett. B **788** (2019) 52,
Yanase et al., Phys. Rev. D **99**, 075021 (2018).

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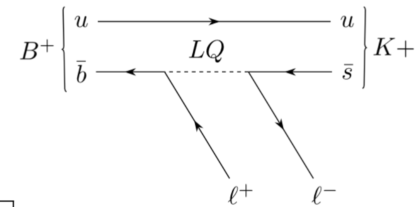
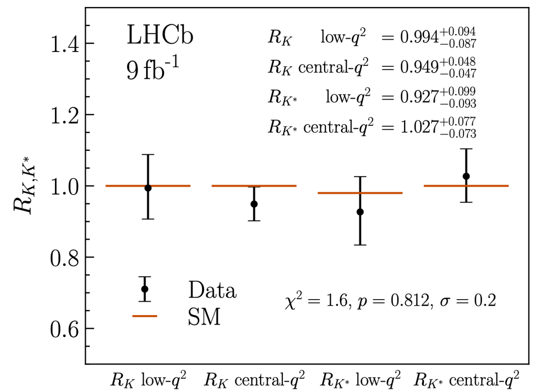


However,...
Recent update
consistent with SM...



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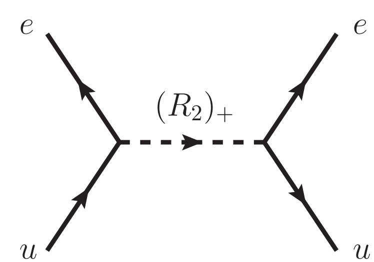


Herczeg, Phys. Rev. D **68**, 116004 (2003),
Fuyuto et al., Phys. Lett. B **788** (2019) 52,
Yanase et al., Phys. Rev. D **99**, 075021 (2018).

$\Rightarrow$ Consistent !

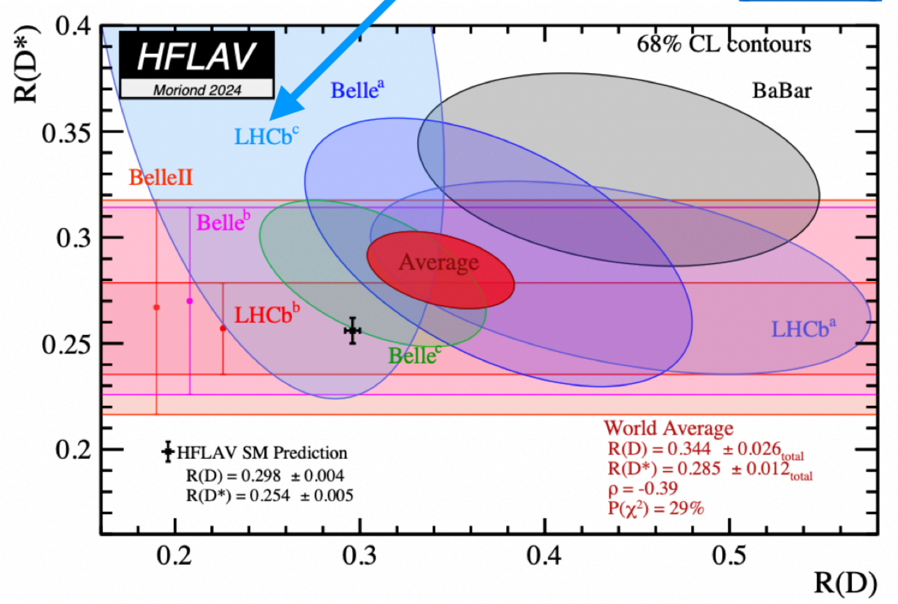
Recent analyses of R_D

$$R_D = \frac{\mathrm{Br}(B \to D\tau\nu)}{\mathrm{Br}(B \to Dl\nu)}$$ and $$R_{D^*} = \frac{\mathrm{Br}(B \to D^*\tau\nu)}{\mathrm{Br}(B \to D^*l\nu)}$$ **still have deviation from SM**

But, ...

This result [LHCb preliminary]

[NEW!] [HFLAV]



Less and less likely for TeV BSM...

New World Average.
Tension with SM at the level of **3.17 σ**.

LHCb Collaboration, talk given at Moriond 2024.

EDMs know everything?

Recent experimental and theoretical "cancellations" of BSM physics are all consistent with the null results of EDM experiments

No TeV BSM!

It looks like EDM knew everything in advance

This is quite explicitly showing the importance of the "diplomatic power" of EDM

⇒ EDM has a high priority in the search for new physics!

(We can inspect first with EDM whether we have BSM of not)

Study of high energy physics (BSM) = EDM

How much do you expect for BSM scale?

Note that we were looking for $\frac{\text{TeV}}{m_H} \sim 10^1$

By the way, $\frac{B_N}{\text{Ry}} \sim 10^5$ $\quad \frac{m_H}{\Lambda_{QCD}} \sim 10^3$

Do not complain even if nothing is discovered at LHC !

Just go to PeV!

From naturalness, new particles and interactions are always CPV

⇒ CPV is a probe of BSM!!

EDM experiments are now progressing, also many new ideas

➡ **Just look for EDM for PeV BSM !**

Next target should be the Higgs sector?

We saw that the Higgs sector has many unnatural points

- Quadratic divergence of Higgs mass :
  BSM must be close

- Too many ad hoc parameters :
  Higgs mass, Yukawa, CKM, charged lepton flavor, neutrino mass

The Higgs sector is full of mystery !!

CP violation of Higgs sector

SM Higgs has no CPV, but its extension may have :

CPV of Higgs sector is a direct probe of BSM!!

Higgs - light fermions interaction (Yukawa) is small

CP violation of Higgs sector

SM Higgs has no CPV, but its extension may have :
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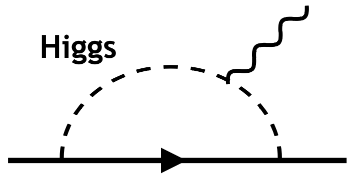

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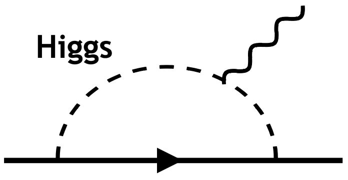

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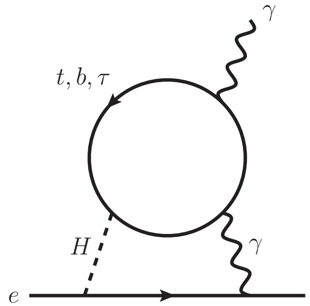
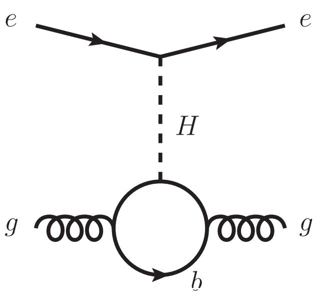
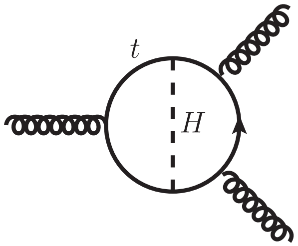


Fermion EDM
(Barr-Zee type diagram)



CP-odd electron-nucleon force
(gluon inside nucleon)



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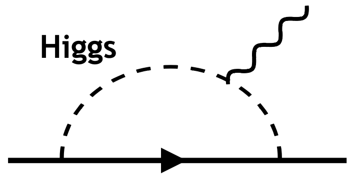

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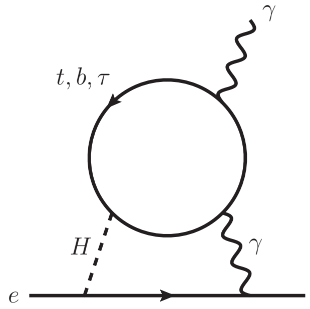

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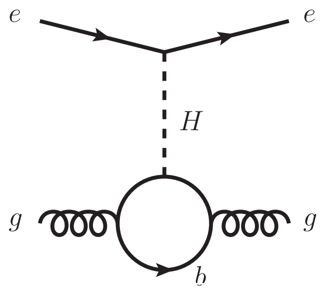

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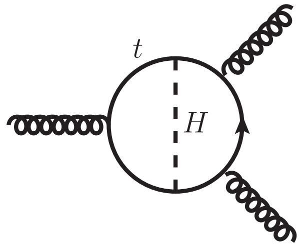

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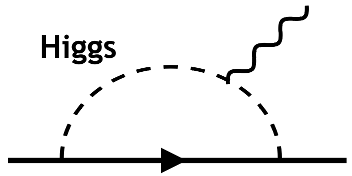

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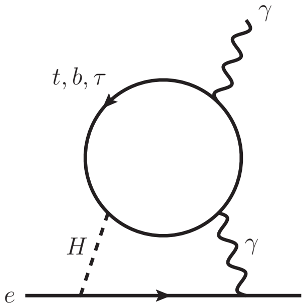

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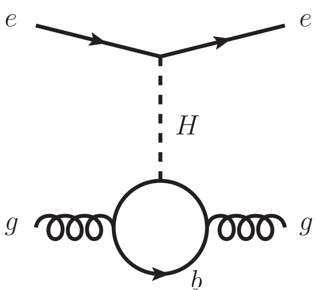

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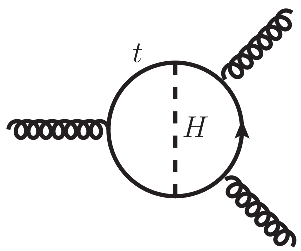

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⇒ The most promising approach to unveil BSM??

Summary

- CP is the genuine symmetry between particles and antiparticles.
- CPV is required to generate baryon number asymmetry.
- CPV is small in SM due to CKM unitarity.
- Naturalness: BSM interaction has always O(1) CP phase.
- EDM is a very sensitive probe of BSM CPV.
- EDM of composite system is sensitive to several microscopic processes, some are enhanced.
- Minimal quantification of EDM of composite systems is achieved, leading CPV contribution was determined.
- Measuring the EDM of several systems is needed to solve the system of equations of BSM parameters.
- EDM rejects TeV scale BSM, consistent with other experimental results.
- EDM should be used as a first inspection of BSM.
- We have to study EDMs for PeV BSM.
- Inspection of Higgs CPV is the most promising?

End