Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

基本的対称性の理論

久野純治（名大KMI）

国内研究会「日本のスピン物理学の展望」
2021/02/23-24

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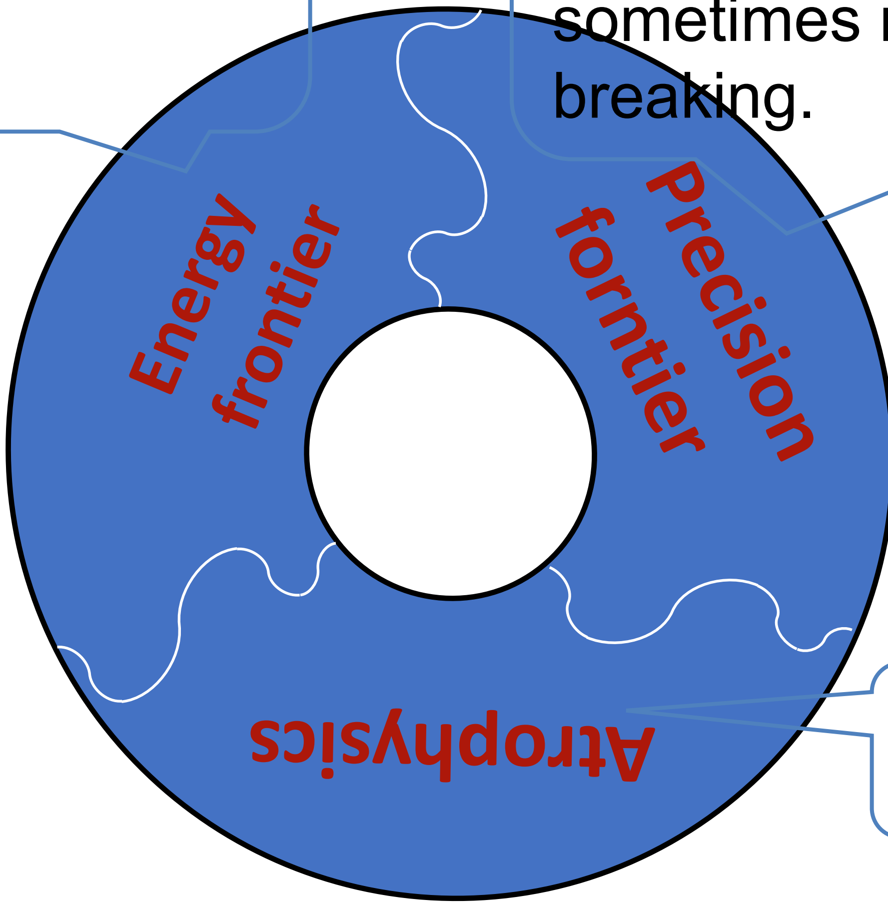
Tools to probe new physics

Direct search for TeV-scale physics
- LHC
- ILC

- High statistical experiment
- High precise theoretical prediction, sometimes related to symmetry breaking.



- Underground exp.
- Cosmology

Searches for symmetry breaking

Global symmetries in SM are not exact in nature.

- **CP violation (CKM in the SM）**

  Electric dipole moments (EDMs)

- **Lepton-flavor violation（neutrino oscillation）**

  Charged lepton flavor-violating decays

- **Lepton and/or baryon number violation (Baryon asymmetry in the universe)**

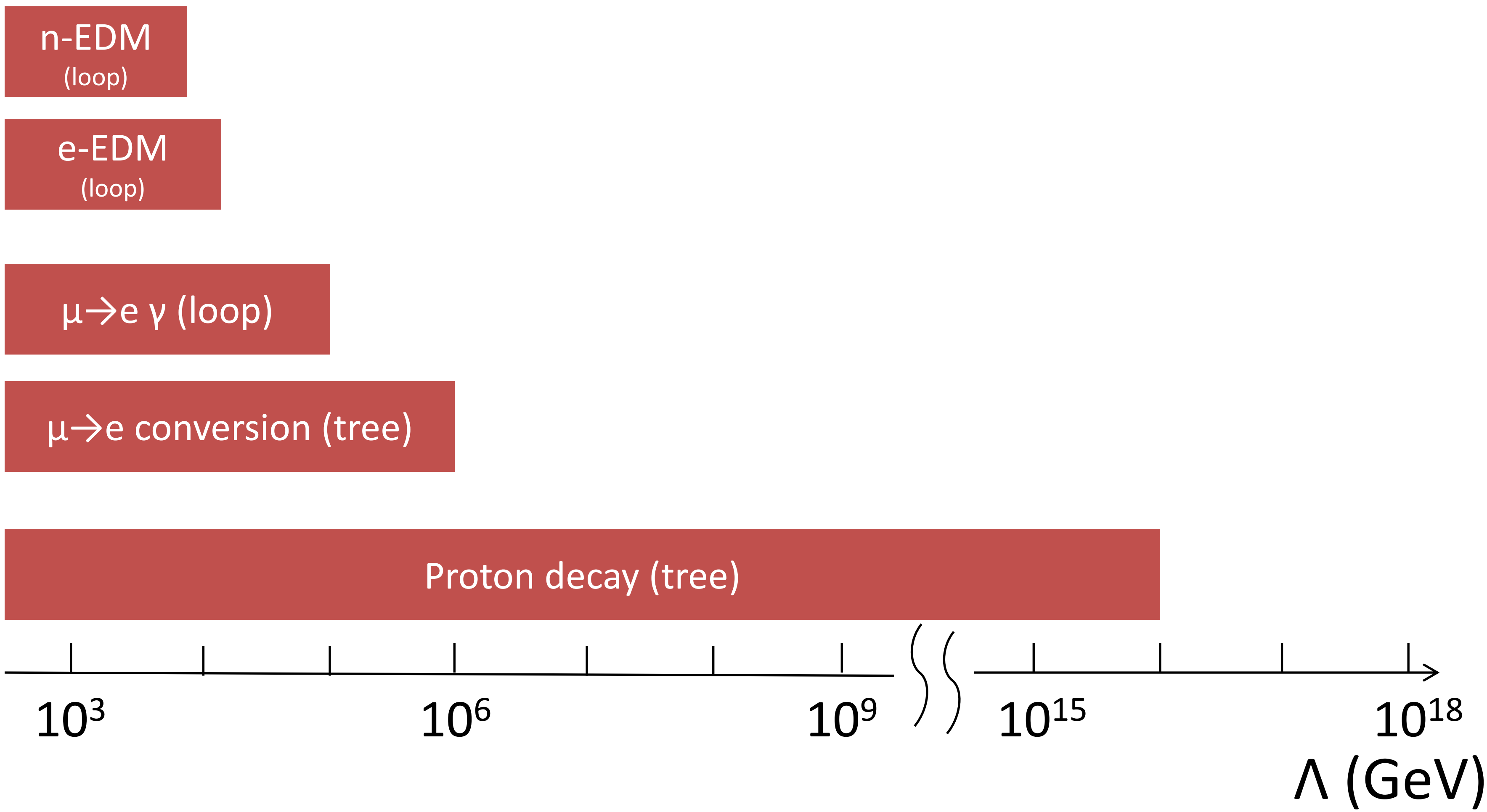
  # Sphaleon process in SM violates B+L conservation.

  $0\nu\beta\beta$decay

  Proton decay

Searches for symmetry breaking

Sensitivities of current experimental bounds on new physics scale (Λ).
Only one loop factors are included for the loop processes.
Small symmetry breaking parameters suppress the sensitivities.



Searches for symmetry breaking

The other fundamental symmetries

- **CPT symmetry**
- **Lorentz symmetry**

Constraints on them are

"Data Tables for Lorentz and CPT Violation"

(V.A.Kostelecky and N.Russell, 0801.0287 [hep-ph])

Neutrinoless ββ decay

Neutrinoless ββ decay

- Lepton number violating (Δ(L) =2) processes

  (A,Z)→(A,Z+2) +2e⁻   (0νββ decay)

- Sensitive to Majorana nature of SM neutrinos.

  Effective operators of Δ(L) =2 in SM

  Dim 5: Weinberg operator (for neutrino masses)

$$\mathcal{L} = \frac{1}{M} LLHH (\to \frac{\langle H \rangle^2}{M} \nu\nu)$$

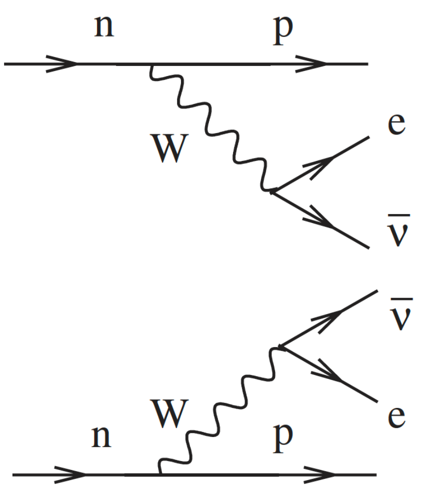
  Dim 7: They might contribute to 0νββ decay.

- Indirect test of seesaw mechanism and leptogenesis

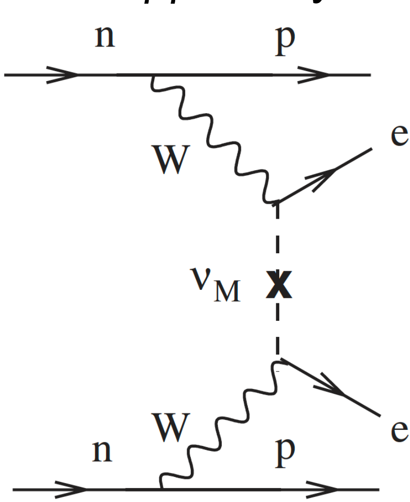
  Minimal seesaw mechanism:

  Introduction of superheavy right-handed neutrinos (SM singlets)

2νββ decay



0νββ decay

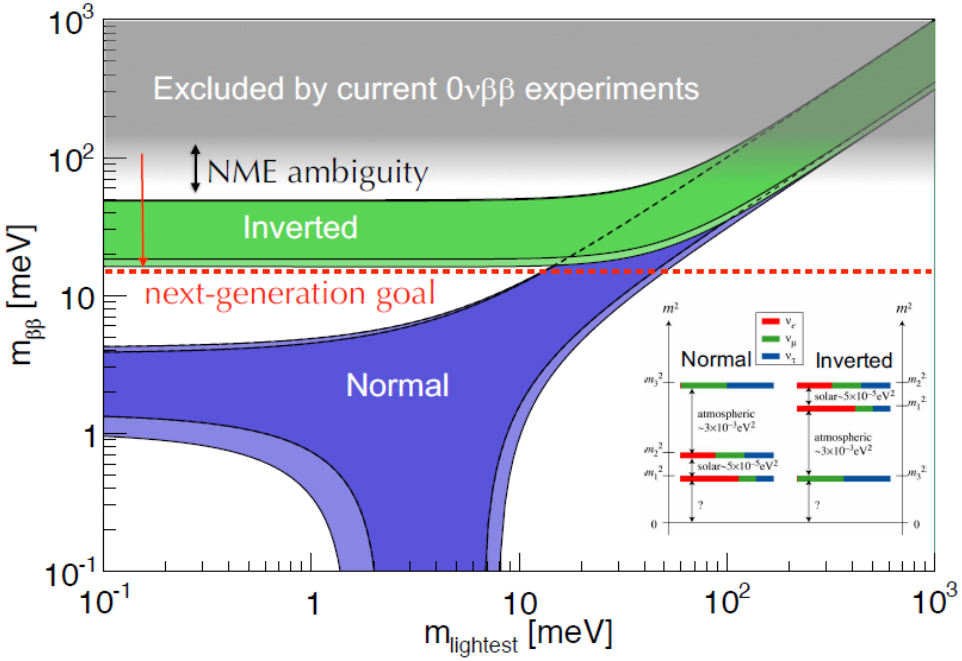


Current limits and future goal

Fukuda-san's slide

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M^{0\nu}_{\text{cont}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



J.Detwiler@nu2020

- To cover IH region, measure $T_{1/2} \geqq 10^{27}$ years
- To reach NH region, need $T_{1/2} \sim 10^{28}$ years measuring

Baryon-number violating nucleon decay

Baryon-number violating nucleon decays

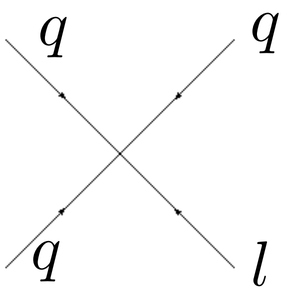
Baryon-number violating nucleon decays are the most sensitive to BSM at extremely high energy scale among rare processes.

- Δ(B+L) =2 nucleon decay

$$p \to e^+\pi^0,\ n \to \bar{\nu}\pi^+,\ \cdots$$

They are induced by D=6 effective operators in SM

Sensitive to GUTs with $M_{\rm GUT} \sim 10^{15-16}{\rm GeV}$.



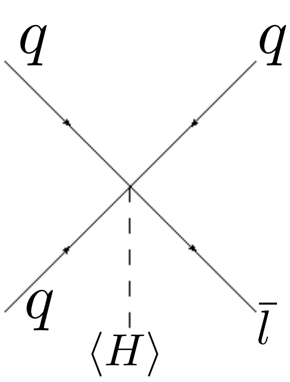
- Δ(B-L)=2 nucleon decay

$$n \to e^-\pi^+,\ \cdots$$

They are induced by D=7 effective operators in SM suppressed by SM Higgs or derivative.

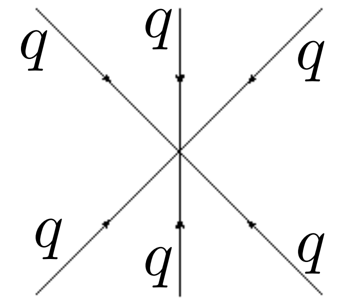
Predicted in SO(10) GUTs with intermediate scale.

They might be linked to baryogenesis.



Baryon-number violating phenomena

- ΔB=2 dinucleon decay



$$pp \to \pi^+\pi^+,\ nn \to \pi^0\pi^0,\ \cdots$$

They are induced by D=9 effective operators in SM.

Predicted in SO(10) GUTs with intermediate scale.

They may be linked to (Majorana) neutrino mass.

Related to n-$\bar{n}$ oscillation.

Lower limit of lifetime for neutrons bound in ^{16}O from SuperKamiokande,

$$\tau_{\rm intra} = 1.9 \times 10^{32} s \times \left(\frac{\tau_{n-\bar{n}}}{2.7 \times 10^8 s} \right)^2$$

while $\tau_{n-\bar{n}} > 8.6 \times 10^7 s$ from free neutron exp.

Proton decay in SUSY SU(5) GUTs

Grand Unified Theories (GUTs)

- Unification of gauge groups

$$SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5),\ SO(10),\ E_6$$

- Unification of quarks and leptons

In $SU(5)$ GUTs

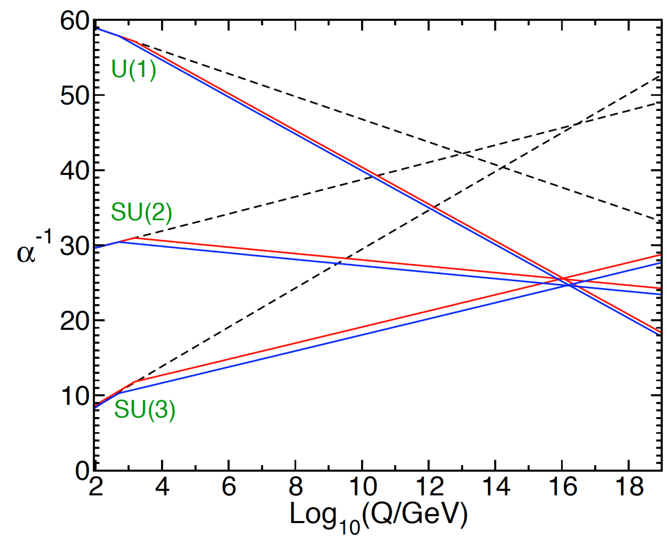
$$\psi(\mathbf{10}) = (u_L, d_L, (u_R)^c, (e_R)^c)$$
$$\phi(\mathbf{5}^\star) = ((d_R)^c, \nu_L, e_L)$$

Electric charge quantization is automatic.

$$|Q_p + Q_e| < 10^{-21}$$

Prediction of GUTs:

- Gauge coupling unification
  tested in SUSY GUTs
- Proton decay

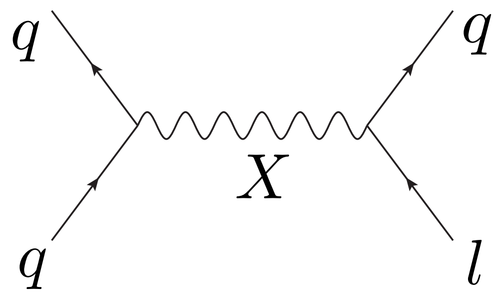


X boson proton decay in SUSY SU(5) GUTs

X bosons are SU(5) partners of SM gauge bosons.

Main decay mode is $p \to e^+\pi^0$.

Effective baryon-number violating ($\not{B}$) operators are D=6.



When MSSM at TeV scale is assumed,

$$\tau_p \simeq 1.2 \times 10^{35}\text{years} \times \left(\frac{M_X}{10^{16}\text{GeV}}\right)^4$$

From experimental bound, $\tau_{p\to e^+\pi^0} > 1.67 \times 10^{34}\text{years}$

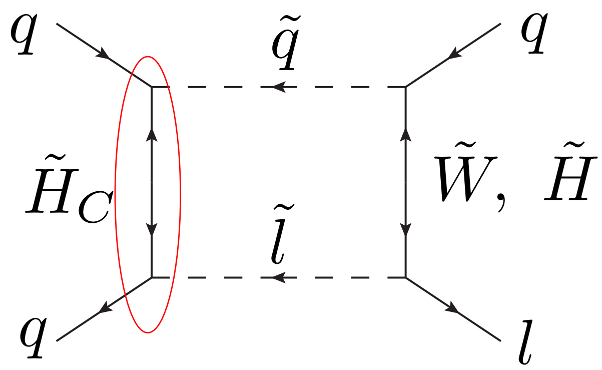
$$M_X > 0.6 \times 10^{16}\text{GeV}$$

SuperKamiokande experiment is approaching close to the GUT scale.

Colored Higgs proton decay in SUSY SU(5) GUTs

Colored Higgses are SU(5) partners of SU(2) doblet Higgses in MSSM.

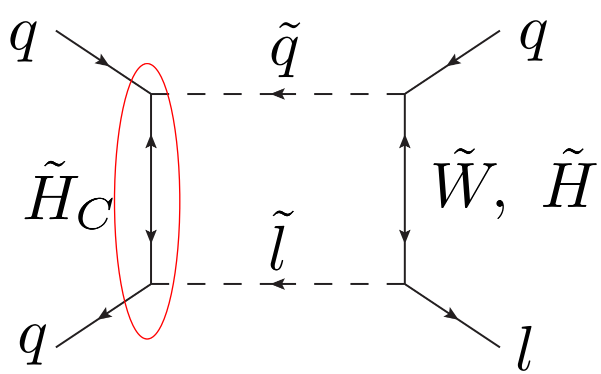
Colored Higgs exchange induces D=5 $\not{B}$ operators, which include squarks or sleptons, and they become D=6 operators with SUSY particle exchange. (Sakai and Yanagida, Winberg, 82)



$$\tau_p \propto M_{H_C}^2 \times M_{SUSY}^2$$

Main decay mode is $p \rightarrow K^+\bar{\nu}$,since it is induced by Yukawa couplings and it also comes nature of D=5 $\not{B}$ operators.

Colored Higgs proton decay in SUSY SU(5) GUTs



Assuming Higgsino exchange dominates over gaugino ones,
$(\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle)$

$$\tau_p \simeq 2 \times 10^{31}\text{years} \times \sin^4 2\beta \left(\frac{M_{H_C}}{10^{16}\text{GeV}}\right)^2 \left(\frac{M_{SUSY}}{\text{TeV}}\right)^2$$

while experimental bound is $\tau_{p\to K^+\nu} > 6.6 \times 10^{33}\text{years}$.

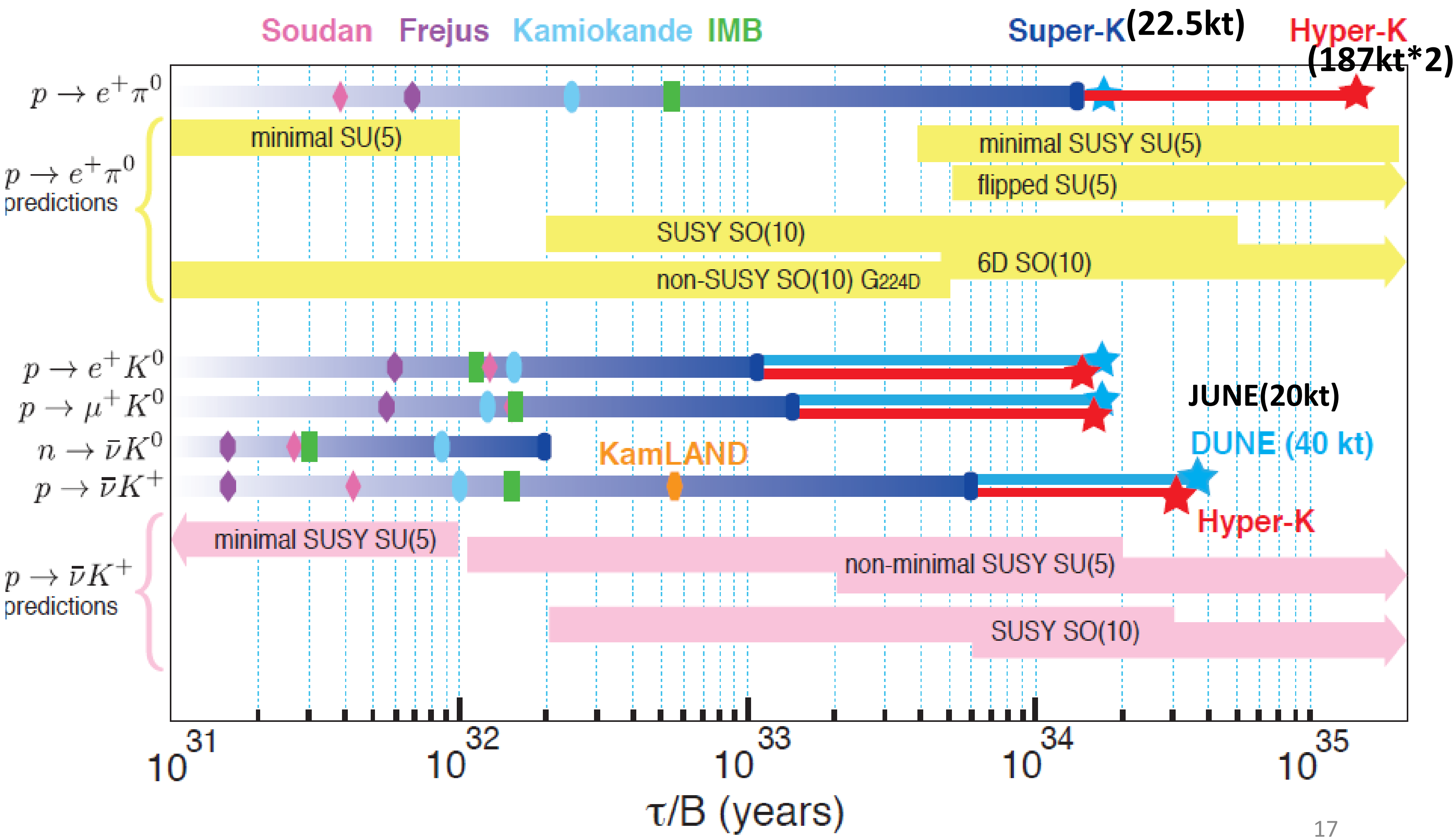
Various models are constructed to suppress the D=5 proton decay,

1) introducing global symmetries, such as Peccei-Quinn symmetry,

2) SUSY particle mass scale is much heavier than O(1) TeV.

Future plan for proton decay searches

Hyper-K, JUNO, and DUNE are future plans for proton decay search.



Lepton-Flavor Violation in Charged Lepton Decay

Shopping list of charged lepton-flavor violation (CLFV)

(Generation of charged lepton is changed in CLFV processes.)

1. $\mu \to e$ transition processes
   - $\mu^+ \to e^+ \gamma$
   - $\mu^+ \to e^+ e^- e^+$
   - $\mu - e$ conversion in nuclei
   - muonium-antimuonium transition: $(\mu^+ e^-) \to (\mu^- e^+)$
   - B/D/K decaying into mu e such as $D^0 \to h^+ h^- \mu e$ $K^+ \to \pi^+ \mu e$

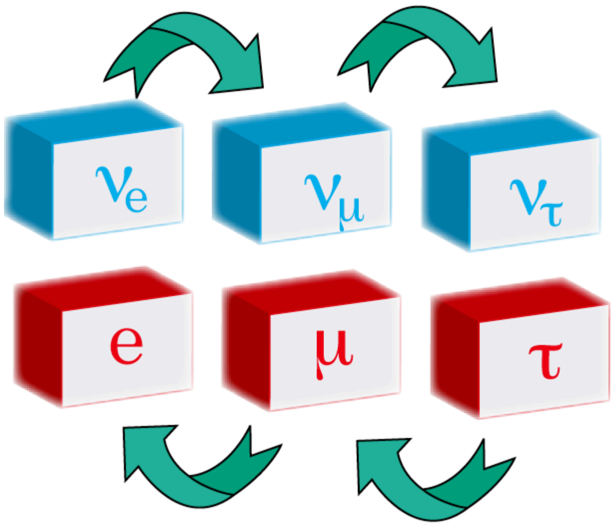
2. $\tau \to \mu/e$ transition processes
   - $\tau \to \mu/e + \gamma$
   - $\tau \to \mu/e + ll$
   - $\tau \to \mu/e + hadrons$
   - $B^0 \to \tau\mu$

Nowadays CLFV decays of heavy particles, such as $H \to \tau\mu$, are available.

In my talk I will mainly concentrate into lepton-flavor violating decay of charged leptons as in my title.

Tiny m_ν does not induce observable effects.

neutrino oscillation



transition among

charged-leptons ??

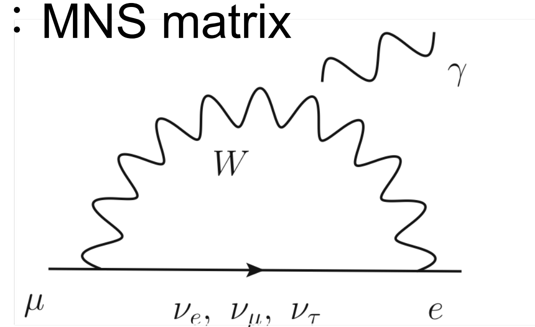
Finite neutrino masses

CLFV processes are suppressed by GIM mechanism.

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{\star}_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m^2_W}\right|^2 < 10^{-54}$$

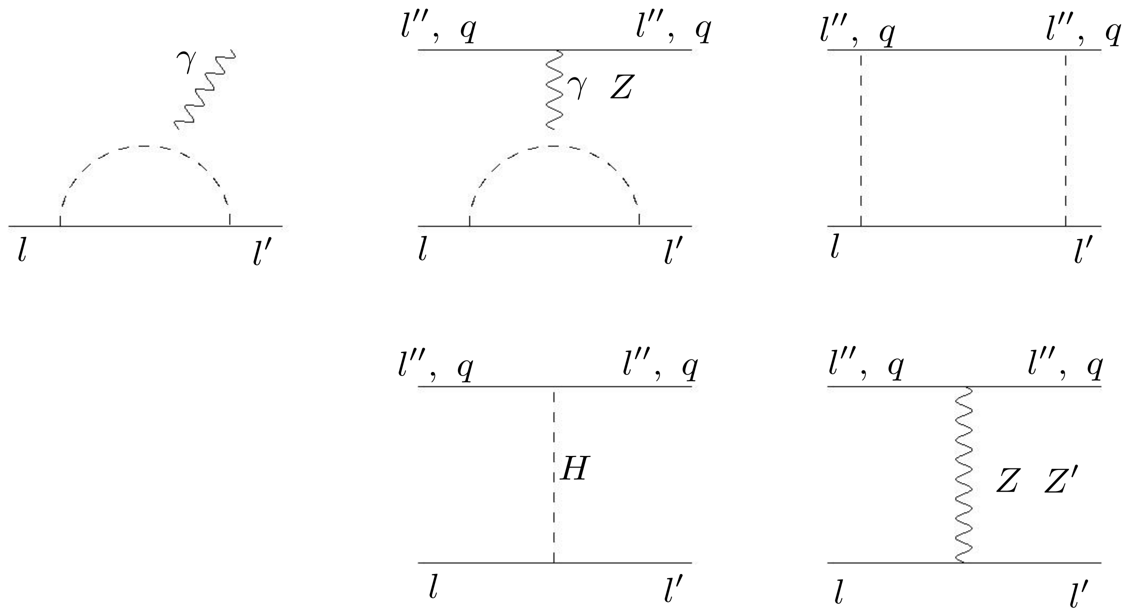
$$\Delta m^2_{i1} \equiv (m^2_{\nu_i} - m^2_{\nu_1})$$

U : MNS matrix



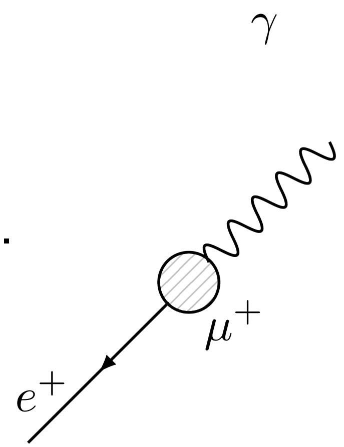
However, lepton flavor may not be conserved in BSM.

Diagrams of CLFV processes



- In WIMP dark matter/naturalness motivated models, such as SUSY SM, Four-Fermi operators come from loop-diagrams.
- In other models, such as extra Higgs, Z', and extra matter models, they are induced at tree level.
- Models are discriminated with pattern of CLFV processes.

MEG and MEG-II experiments ($\mu^+ \to e^+\gamma$)



BGs: accidental BGs and radiative muon decay

Signal: monochromatic, back-to-back, and produced at the same time.

PSI has the most intense DC muon beam up to $10^8 \mu/s$.

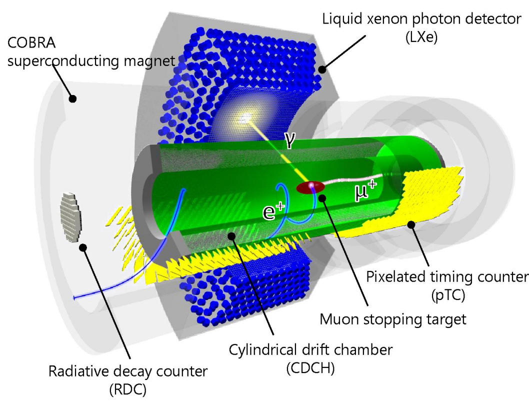
The final result of MEG (2016)

$$\mathrm{BR} < 4.2 \times 10^{-13}\ (90\%\mathrm{C.L.})$$

MEG-II is an upgrade of all sub-detectors.

- First physics run will start in 2020
- Expectation in 3 years run is $\mathrm{BR} \sim 6 \times 10^{-14}$.

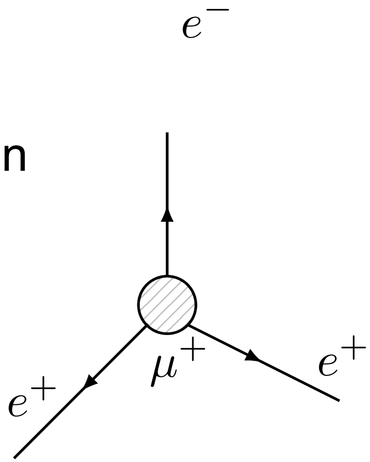
MEG-II experiment



Future experiments: Next target is $BR \sim 10^{15}$. .

Hear Iwamoto-san or see slide of Renga @ CLFV conf.

Mu3e experiment ($\mu^+ \to e^+ e^- e^+$)



BGs: accidental BGs and radiative muon decay with internal conversion

Signal: kinematics, and produced at the same time and same place.

Current bound from SINDUM (1988)

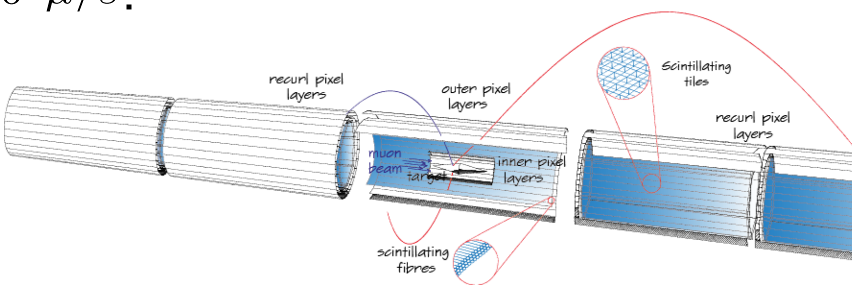
$$BR < 1.0 \times 10^{-12} \ (90\%\text{C.L.})$$

PSI has the most intense DC muon beam up to $10^8 \mu/s$.

Mu2e Phase I detector construction in 2020/21.

Aiming for sensitivity of Mu3e (phase I)

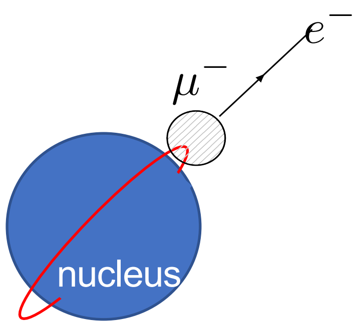
$$BR < 2 \times 10^{-15}$$



Schematic view of Mu3e experiment

"Aiming for sensitivity of phase II is beyond 10^{-16} with $10^9 \mu/s$ (not before 2025, physics up to 2030)." from Schöning@CLFV conf.

COMET and Mu2e experiments (μ-e conversion in nuclei)



Signal of μ-e conversion: monochromatic electron with

$$E = m_\mu - E_{\rm binding} - E_{\rm nuclear\ recoil}$$

BGs: Muon decay in orbit:

Branching ratio drops near the end point (calculated by Czarnecki (16))

Beam related BG

Cosmic ray BG

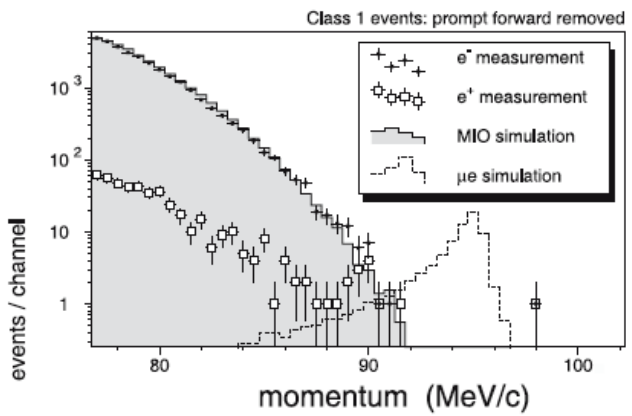
Current bounds (normalized by capture rate)

$$R_{\mu e}(N) \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')}$$

$$R_{\mu e}(\mathrm{Ti}) < 6 \times 10^{-13}$$ (SINDRUM II, 93')

$$R_{\mu e}(\mathrm{Au}) < 7 \times 10^{-13}$$ (SINDRUM II, 00')

(Au case in SINDRUM II)

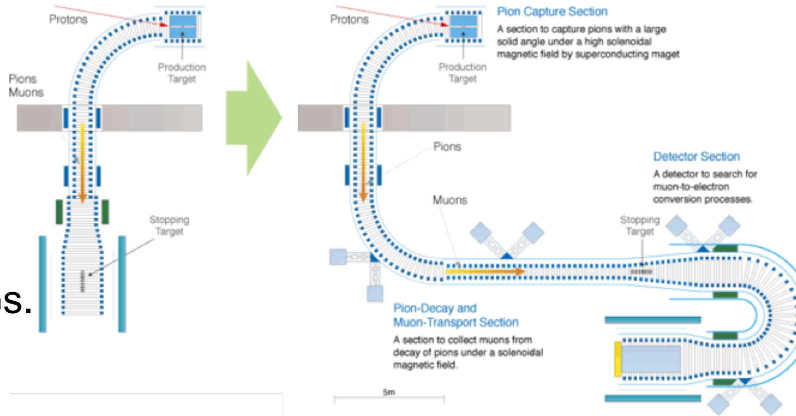


COMET and Mu2e experiment (μ-e conversion in nuclei)

Original idea comes from MELC experiments.

- Thick target with SC solenoidal as capture magnet.
- Long muon beam line with momentum selection
- Light detector to provide precise electron measurement

COMET



COMET@J-Parc

Phase-I: Under construct. Muon beam measured to study BGs.

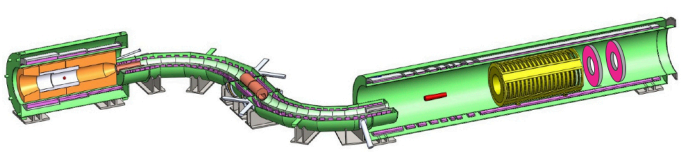
$$R_{\mu e} \sim 3 \times 10^{-15}$$ (S.E.S., 5 months)

Phase-II: Full muon beam line installed.

$$R_{\mu e} \sim 2.6 \times 10^{-17}$$ (S.E.S., 1 year)

"With the same beam power, 10 times better sensitivity ($\mathcal{O}(10^{-18})$) is likely and optimization is on the way. " from Wu Chen@CLFV.

Mu2e

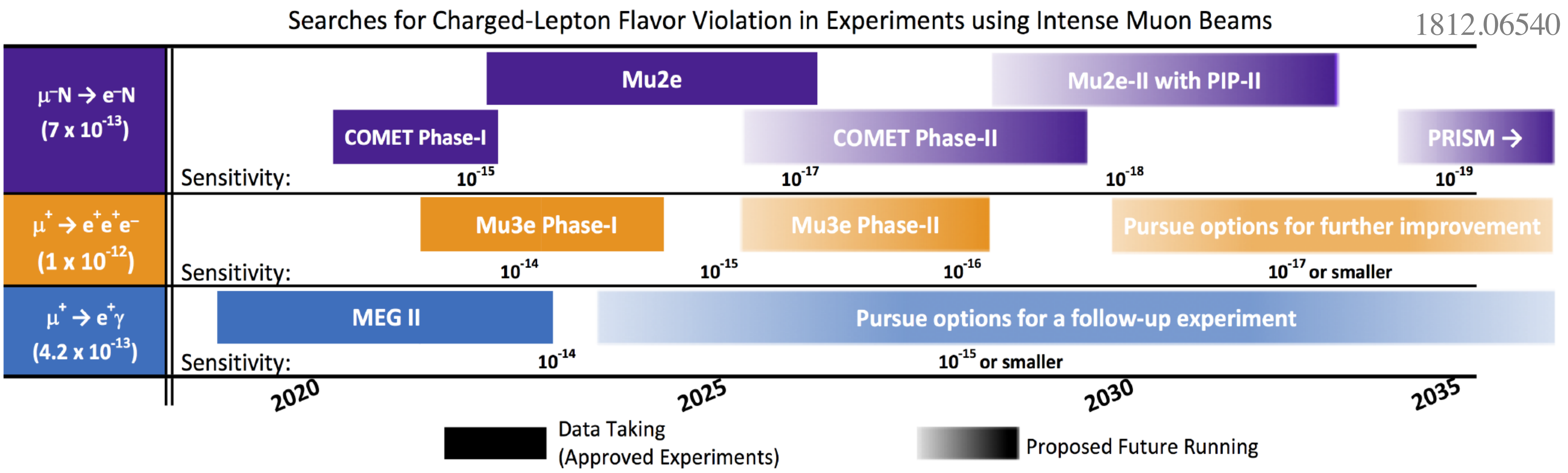


Mu2e@Fermilab (Brendan Kiburg will talk next)

Commissioning expected in 2022.

$$R_{\mu e} \sim 2.5 \times 10^{-17}$$ (S.E.S.)

Schedule of muon LFV searches

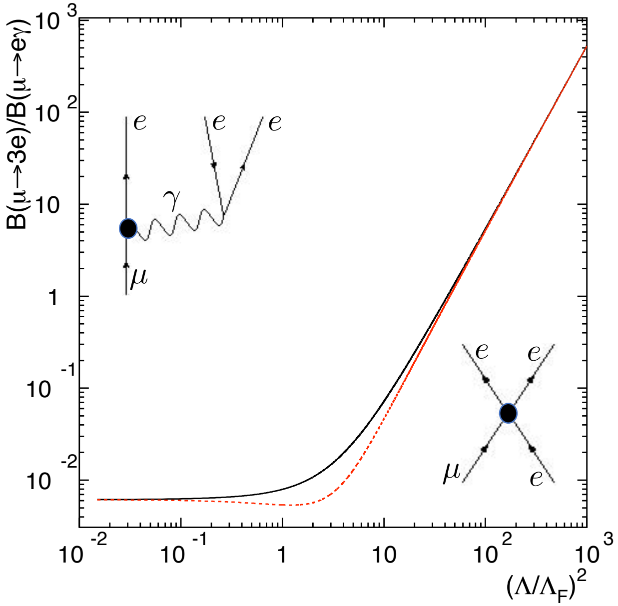


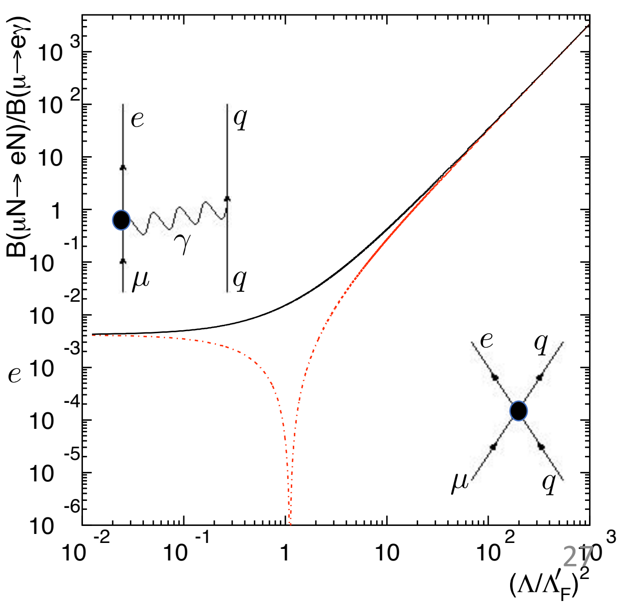
Muon LFV searches will be interesting next decade (2020’s).

Effective operator approach for muon LFV processes

$$\mathcal{L}_{eff} \sim \frac{m_\mu}{\Lambda^2}\bar{e}(\sigma^{\mu\nu}F_{\mu\nu})\mu + \frac{1}{\Lambda_{\rm F}^2}\bar{e}\Gamma_A e\ \bar{e}\Gamma_A\mu + \frac{1}{\Lambda_{\rm F}'^2}\bar{q}\Gamma_A q\ \bar{e}\Gamma_A\mu$$

$\mu \rightarrow e\gamma$ $\mu \rightarrow 3e$ μ-e conversion in nuclei





(ISS Physics Working Group Collaboration,09)

Effective operator approach for muon LFV processes

$$\mathcal{L}_{eff} \sim \frac{m_\mu}{\Lambda^2}\bar{e}(\sigma^{\mu\nu}F_{\mu\nu})\mu + \frac{1}{\Lambda_{\rm F}^2}\bar{e}\Gamma_A e\ \bar{e}\Gamma_A\mu + \frac{1}{\Lambda_{\rm F}^{\prime 2}}\bar{q}\Gamma_A q\ \bar{e}\Gamma_A\mu$$

$\mu \to e\gamma$ $\mu \to 3e$ μ-e conversion in nuclei

When dipole term is dominated, such as in SUSY SM,

$$BR(\mu \to 3e) \simeq 6.1 \times 10^{-3} BR(\mu \to e\gamma)$$

$$R_{\mu e}(\mathrm{Al}) \simeq 3 \times 10^{-3} BR(\mu \to e\gamma)$$

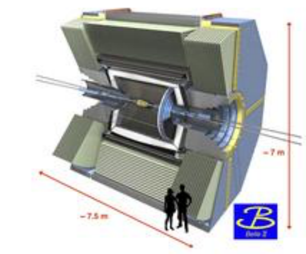
$$R_{\mu e}(\mathrm{Ti}) \simeq 4 \times 10^{-3} BR(\mu \to e\gamma)$$

Muon LFV experiments are competitive and complemental to reach others.

(ISS Physics Working Group Collaboration,09)

Tau LFV searches in Belle II/SuperKEKB

KEKB is upgraded to SuperKEKB (40 times higher luminosity).



$4.6 \times 10^{10}\ \tau^+\tau^-\ (\mathcal{L} = 50ab^{-1})$

- $\tau \to \mu\gamma,\quad e\gamma$

$$e^+e^- \to \tau^+\tau^-$$

↳ $\text{Signal side : } \mu\gamma,\ e\gamma \text{ (full reconstructed)}$

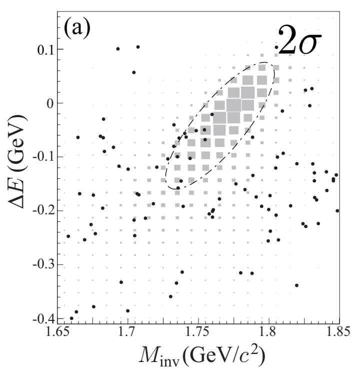
↳ $\text{Tag side : 1 prong + missing } \ (\text{BR} \sim 85\%)$

Main BG: $\tau \to \mu\nu\bar{\nu} + \text{ISR } \gamma$

Belle results: $BR(\tau \to \mu(e)\gamma) < 4.5(1.2) \times 10^{-8}$ (90% C.L.)

BG reduction in Belle II is being discussed. Prospects are O(10^{-9}).

$\tau \to \mu\gamma$@Belle (06)



- $\tau \to l'll,\quad$ such as 3μ

Almost BG free. Belle reached at BR~O(10^{-8}), and prospects of Belle II are O($10^{-(9-10)}$)

μ-e transition in SUSY SM

SUSY-breaking mass terms for sleptons are sources of LFV in SUSY SM.

Origin: 1) Slepton coupling to SUSY breaking sector

2) Radiative correction from LFV int.,

such as in SUSY Seesaw ($10^{12\text{-}15}$GeV)

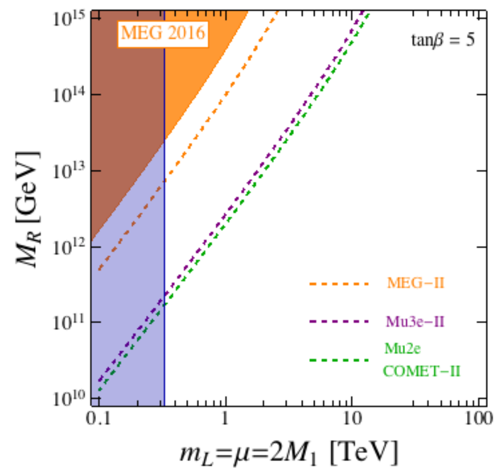
or SUSY GUTs (10^{16}GeV) .

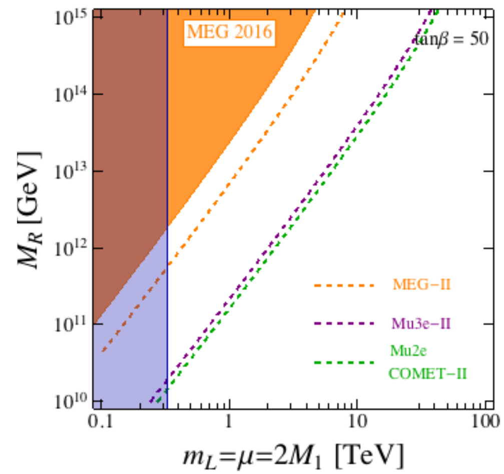
SUSY seesaw:

Neutrino Yukawa coupling (Degenerate RH ν mass,M_R)

$$Y_\nu = \frac{\sqrt{M_R}}{v_u}\sqrt{\hat{m}_\nu}\,U^\dagger \qquad \begin{array}{r l} U & : \text{PMNS matrix} \\ \hat{m}_\nu & : \text{LH } \nu \text{ mass} \end{array}$$

Universal SUSY breaking para. are assumed at GUT scale. Large M_R means larger Yukawa so that large CLFVs are induced.

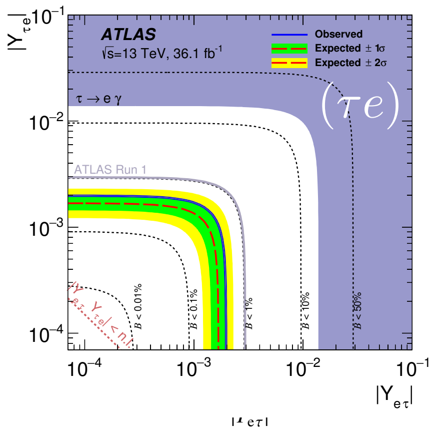


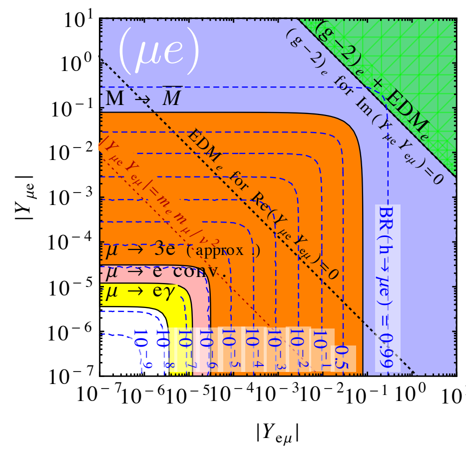


(Calibbi and Signorelli, (17))

LFV Higgs coupling

General flavor violating Higgs coupling: $\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots$





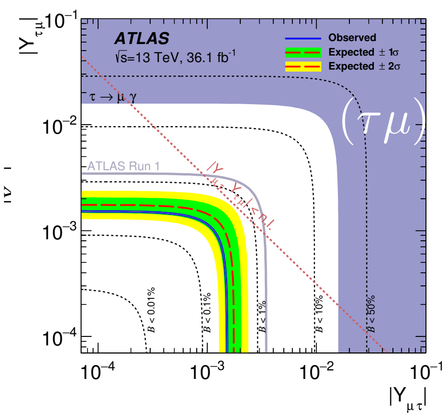
Constraints from LHC is one-order severer than from $\tau \to \mu\gamma$, $\tau \to e\gamma$.

ATLAS (13TeV, 36.1fb^{-1})

$$Br(H \to e\tau) < 0.47\%$$
$$Br(H \to \mu\tau) < 0.28\%$$

(1907.06131)

CMS also have similar results.



It seems difficult for low-energy exp. to improve the bounds now.

This does not deny extra Higgs has LFV Yukawa, though we have to tune models.

EDMs

EDMs sensitive to TeV-scale and beyond

Upper bounds on electron and neutron EDMs:

$|d_e| < 1.1 \times 10^{-29}$ e cm (ACME II, 17) $|d_n| < 1.8 \times 10^{-26}$ e cm (PSI, 20)

Dim. analysis for EDM assuming source of CPV is FC:

$$d_e \sim e\frac{m_e}{M^2} = 10^{-23} ecm \left(\frac{1\mathrm{TeV}}{M}\right)^2$$

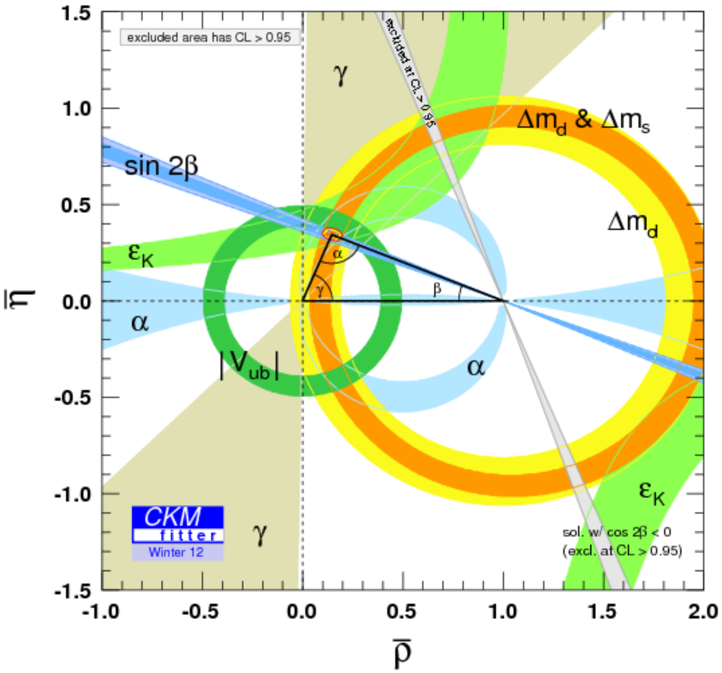
$$d_d \sim e\frac{m_d}{M^2} = 10^{-22} ecm \left(\frac{1\mathrm{TeV}}{M}\right)^2$$

(Renormalizable models give extra suppressions to EDMs by loop factors ($\sim O(10^{-(2-4)})$).)

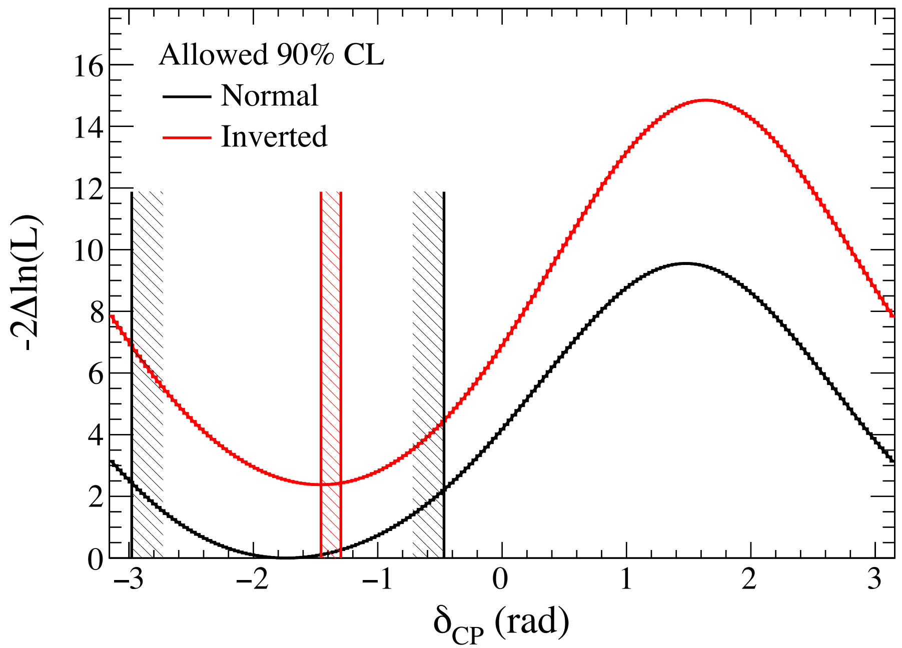
EDM measurements would be important even if LHC finds new physics.

CP phases are naturally O(1) ?

CKM



PMNS



(Flavor-conserving) CP-violating interactions at parton level up to D=6

$$-\mathcal{L} = \frac{g_s^2\bar{\theta}}{32\pi^2}G\tilde{G} + \sum_{f=u,d,s,e} d_f \frac{i}{2}\bar{f}(\sigma\cdot F)\gamma_5 f + \sum_{q=u,d,s} d_f^c \frac{i}{2}\bar{q}(\sigma\cdot G)\gamma_5 q$$

QCD theta term

Quark and lepton EDMs

Quark CEDMs

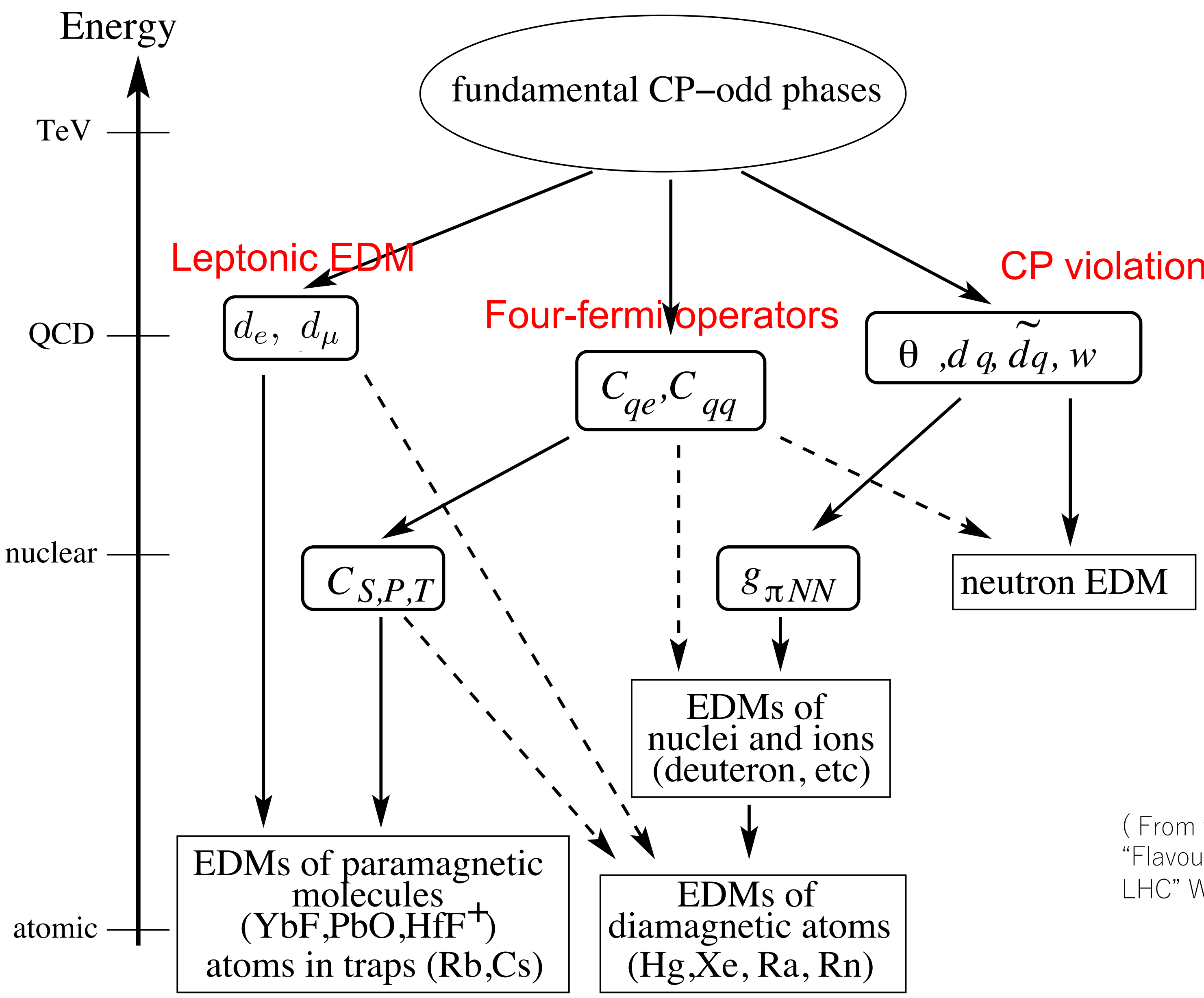
$$+\frac{1}{3}wGG\tilde{G} + \sum_{f,f'=u,d,s,e}(\bar{f}f)(\bar{f}\gamma_5 f)$$

Weinberg op.

4-Fermi

- Wilson coefficients for CP-violating operators depend on CP phases in particle physics models.

Evaluation of EDMs



(From the report of the "Flavour in the era of the LHC" Workshop, 88')

SM prediction

In the SM, origin of CP violation is a phase in Kobayashi-Maskawa matrix (except for QCD theta term). CPV obs. are prpto to Jarlskog (rephasing) invariant:

$$J_{\rm CP} = {\rm Im} V_{cs}^{\star} V_{us} V_{cd} V_{ud}^{\star} \sim 10^{-5}$$

- Quark EDMs

  $d_d \sim 10^{-34}$ e cm (3loops at $O(G_F^2\, \alpha_s)$)

- Neutron EDM

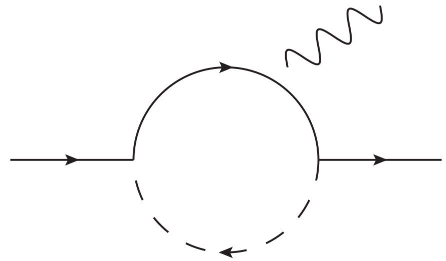
  $d_n \sim 10^{-(31\text{-}32)}$ e cm (long-distance effect at $O(G_F^2)$)

- Electron EDM

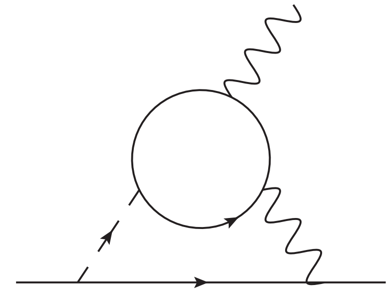
  $d_e \sim 10^{-40}$ e cm (4loops $O(G_F^3\, \alpha_s)$)

Discovery of non-zero EDM means beyond the SM.

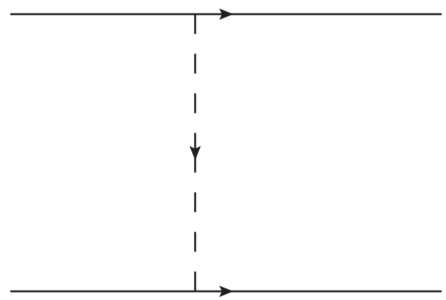
EDMs from BSM



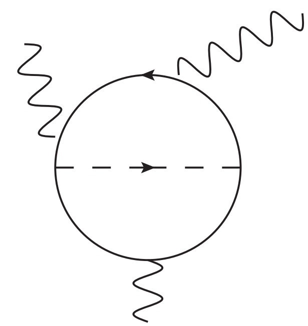
Quark/lepton EDMs



Quark/lepton EDMs
(Barr-Zee diagram)



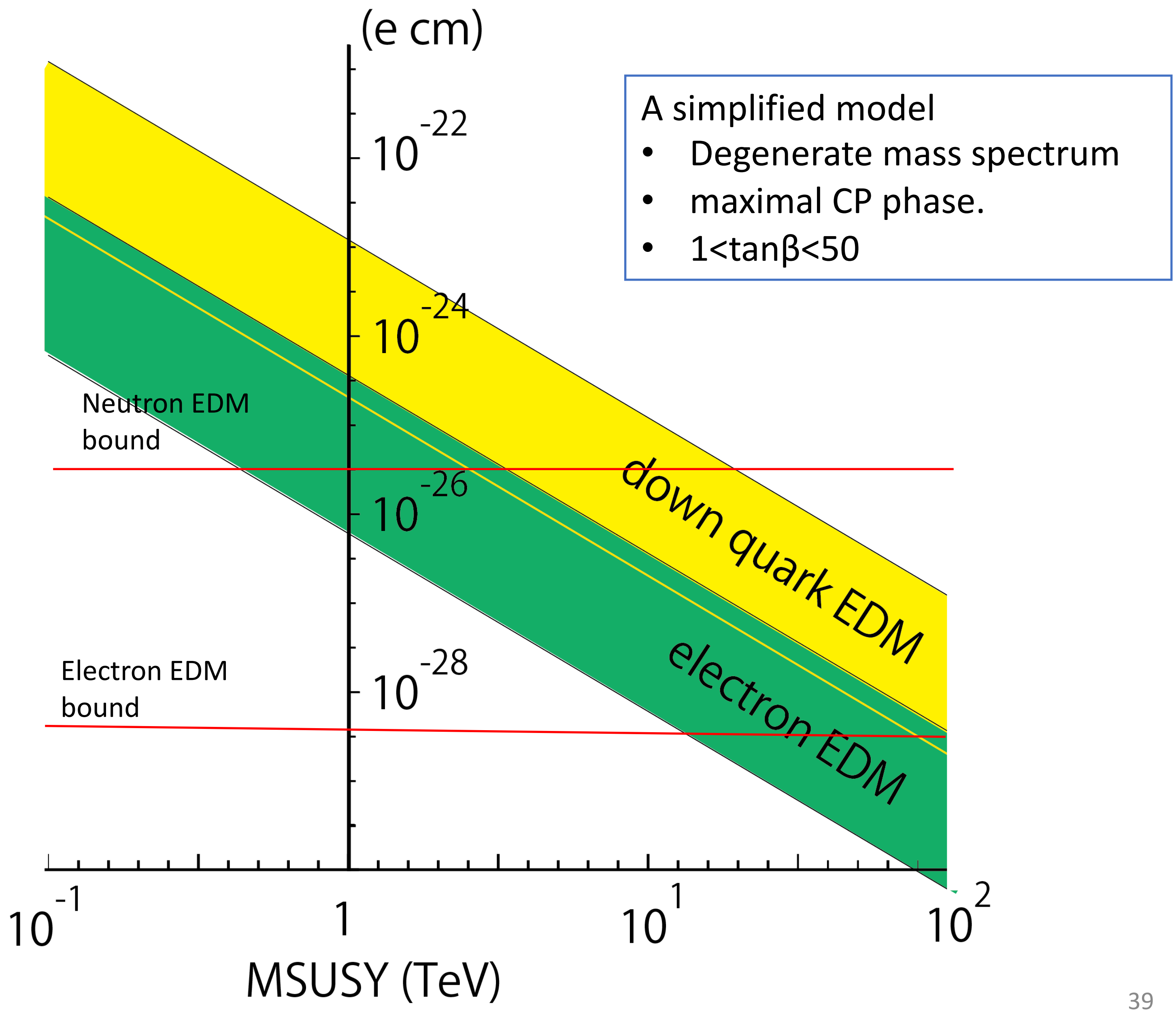
Four-Fermi op.



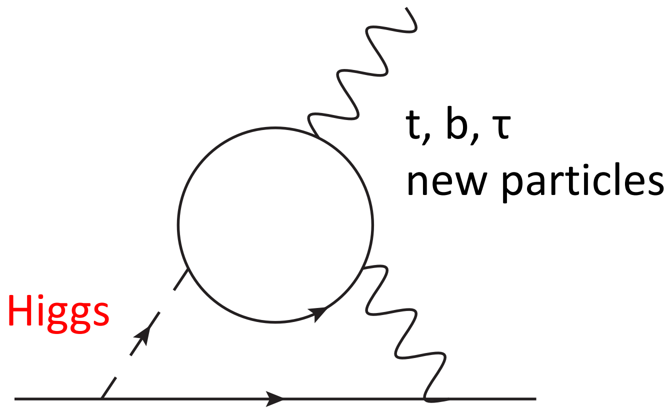
Weinberg op.

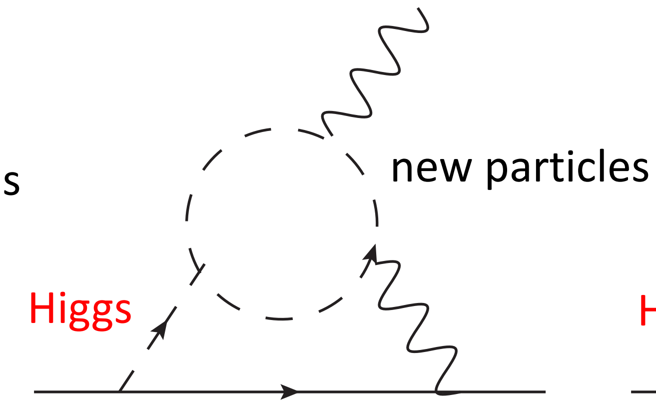
Assuming maximal CP phases, one-loop diagrams for (C) EDMs give strong constraint to new-physics above the TeV scale, and even two-loop diagrams can also constrain new physics around TeV scale.

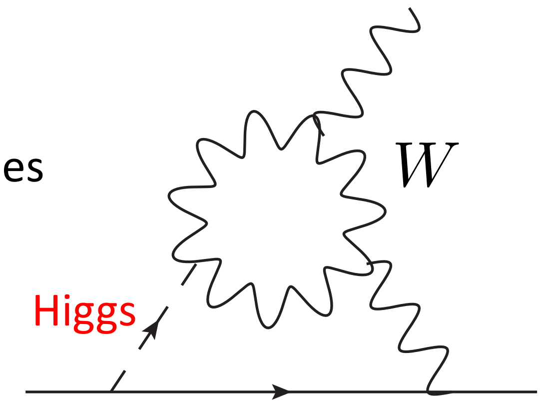
EDMs in Supersymmetric standard model



Higgs-mediated Barr-Zee diagrams

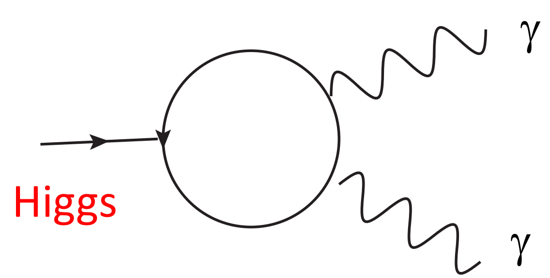






When Higgs boson has CP-violating coupling with SM particles or new particles in BSM, the Barr-Zee diagrams at two-loop level generate (C)EDMs for quarks and leptons.

New (charged) fermions coupled to (discovered) Higgs boson may contribute to both Higgs decay to 2 gammas and also EDMs.

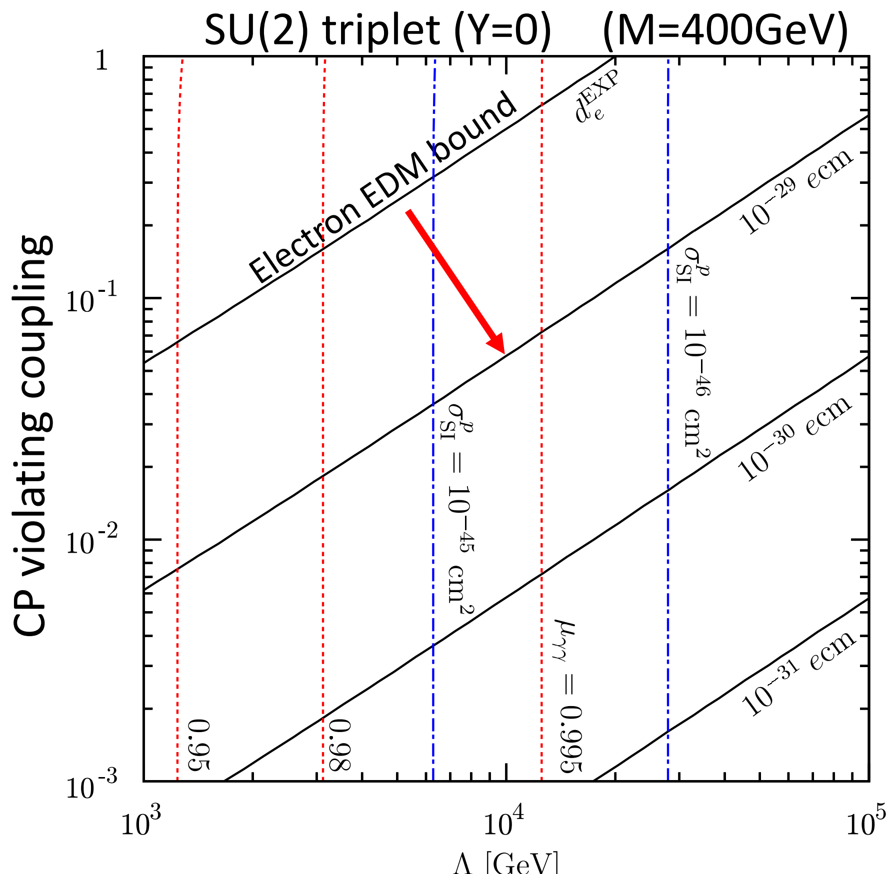


New physics contribution to EDM and h→γγ

SU(2) mutiplet fermions (ψ), whose neutral component is the DM candidate, may have coupling with Higgs boson,

$$\mathcal{L}_H = -\frac{1}{2\Lambda}|H|^2\,\bar{\psi}^c(1+i\gamma_5 f)\psi + h.c..$$

(JH, Kobayashi, Mori, Senaha)



Blue lines: SI Cross section For DM direct Detection
Red lines: Signal strength for h→γγ

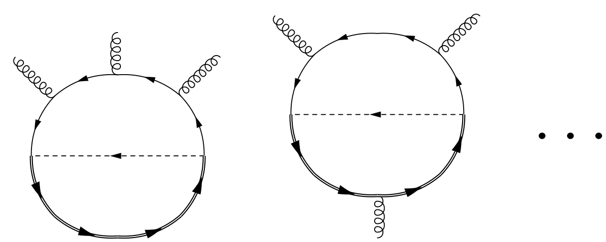
- Gaugino-Higgsino system studied by Giudice and Romanino.
- Recent similar works:
  Fan and Reece.
  McKeen, Pospelov and Ritz.
  …..

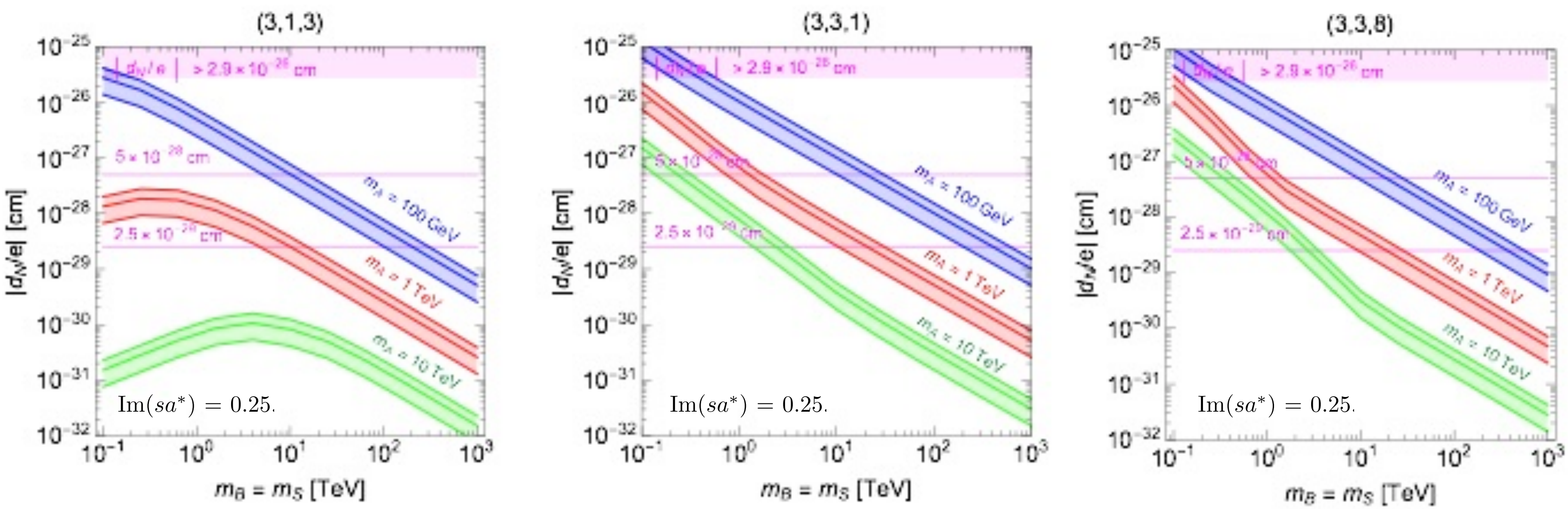
If new colored particle is discovered,

The general fermion-scalar interaction is

$$-\mathcal{L} = \bar{\psi}_B(s_{BAS} + a_{BAS}\gamma_5)\psi_A S + \text{h.c.}$$

And if $\text{Im}[s_{BAS}a^*_{BAS}] \neq 0$, CP is violating. We derive general formula for the Weinberg operator. (Abe, JH, Nagai)





Searches for symmetry breaking are important tools to probe Byond SM.

Global symmetries in SM are not exact in nature.

- **CP violation (CKM in the SM）**

  Electric dipole moments (EDMs)

- **Lepton-flavor violation（neutrino oscillation）**

  Charged lepton flavor-violating decays

- **Lepton and/or baryon number violation (Baryon asymmetry in the universe)**

  # Sphaleon process in SM violates B+L conservation.

  $0\nu\beta\beta$decay

  Proton decay