SLAC Summer Institute 2018
Standard Model at 50: Successes and Challenges
July 30 - Aug 10 2018

Challenging the Standard Model with nuclei, atoms, and molecules -2

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Plan of the lectures

- Introduction:
  - Nuclei / atoms / molecules as probes of the Standard Model (exact or approximate) symmetries and what may lie beyond

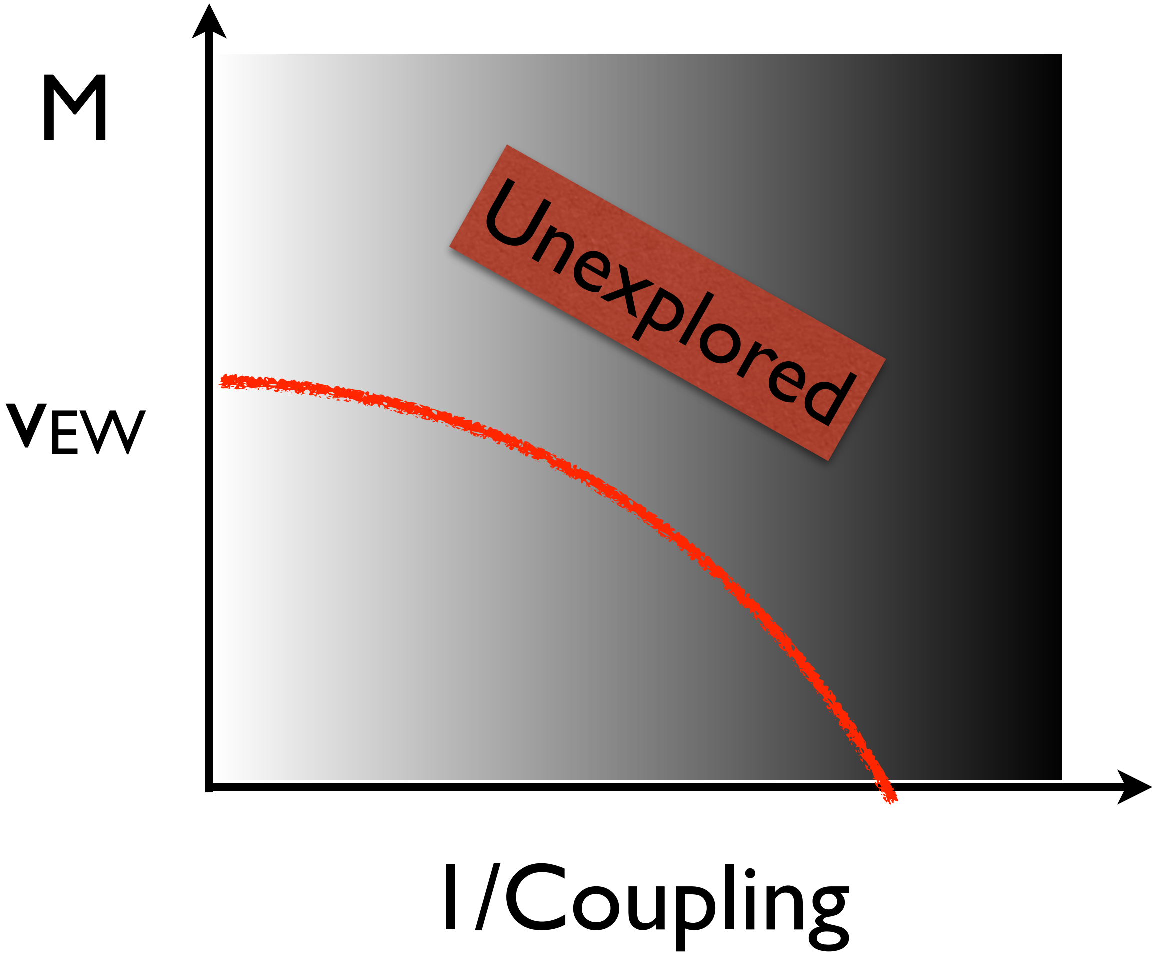
- Selected topics:
  - Nuclear beta decays: gauge coupling universality
  - Neutrinoless double beta decay: B-L violation and nature of ν's
  - Permanent Electric Dipole Moments: CP violation

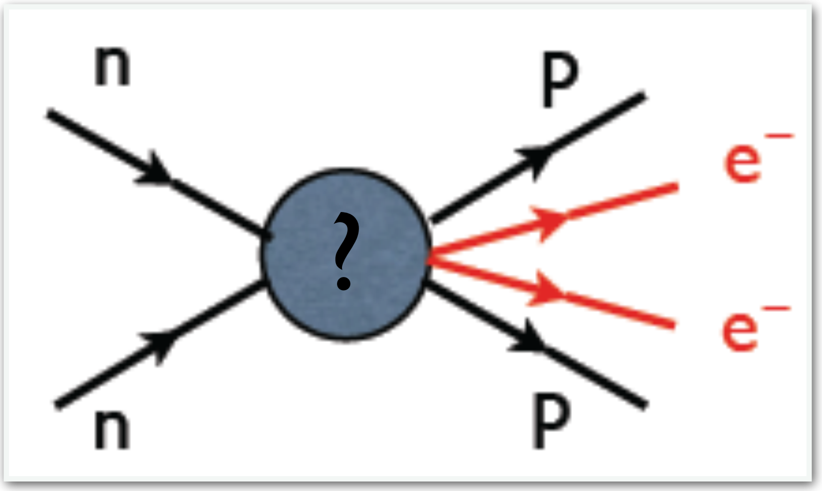
Neutrinoless double beta decay: B-L violation and nature of ν's

Experimental aspects discussed in Krishna Kumar's lecture

0νββ and Lepton Number Violation

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms





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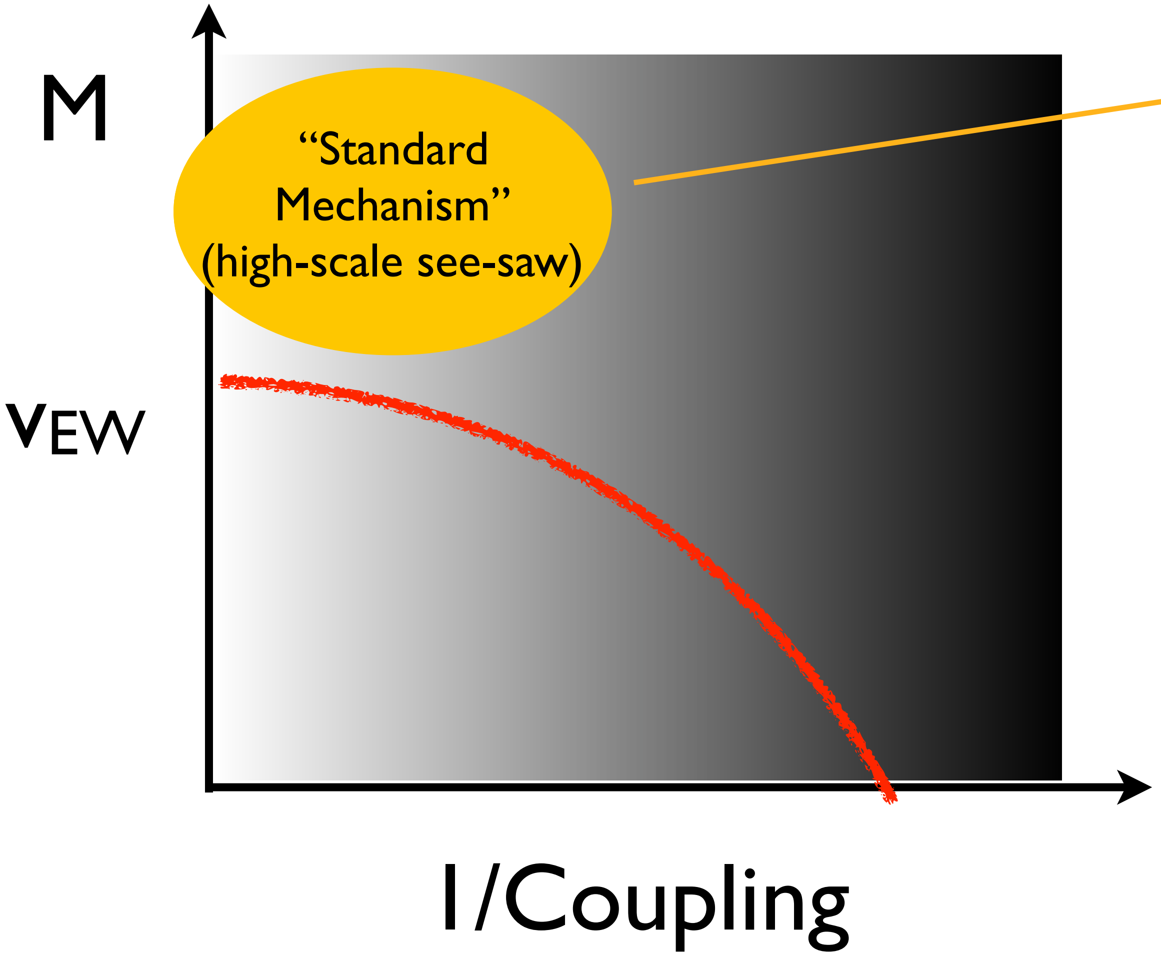
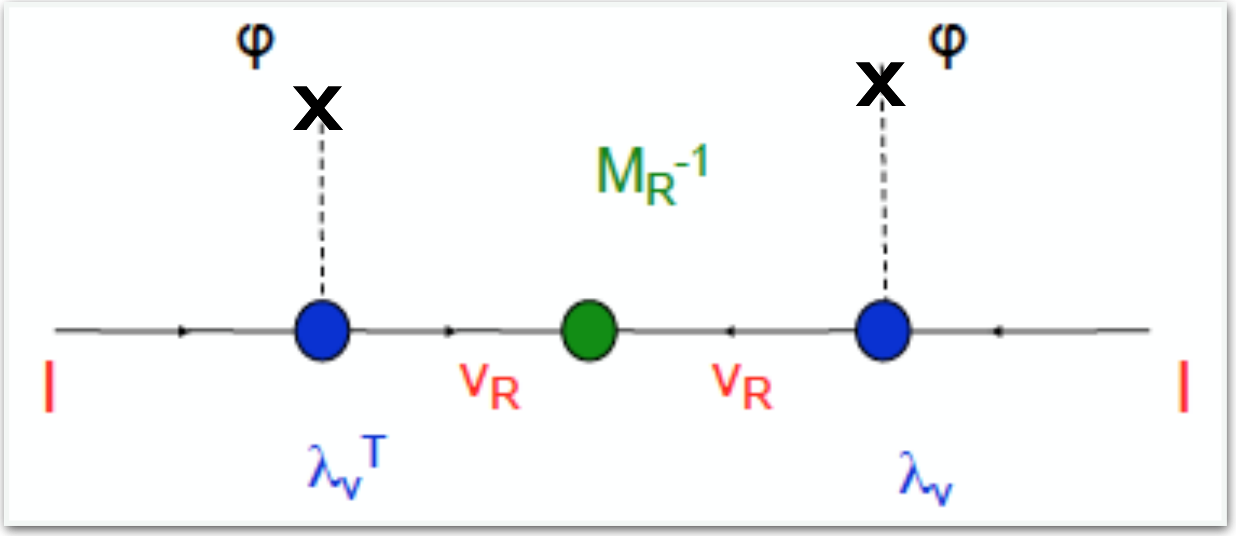


LNV dynamics at M >> TeV:
it leaves as *only* low-energy footprint
3 light Majorana neutrinos

Example: 3 heavy R-handed neutrinos

This generates Weinberg's dim5 operator



$$m_\nu \sim (v_{EW})^2 \lambda_\nu^T M_R^{-1} \lambda_\nu$$

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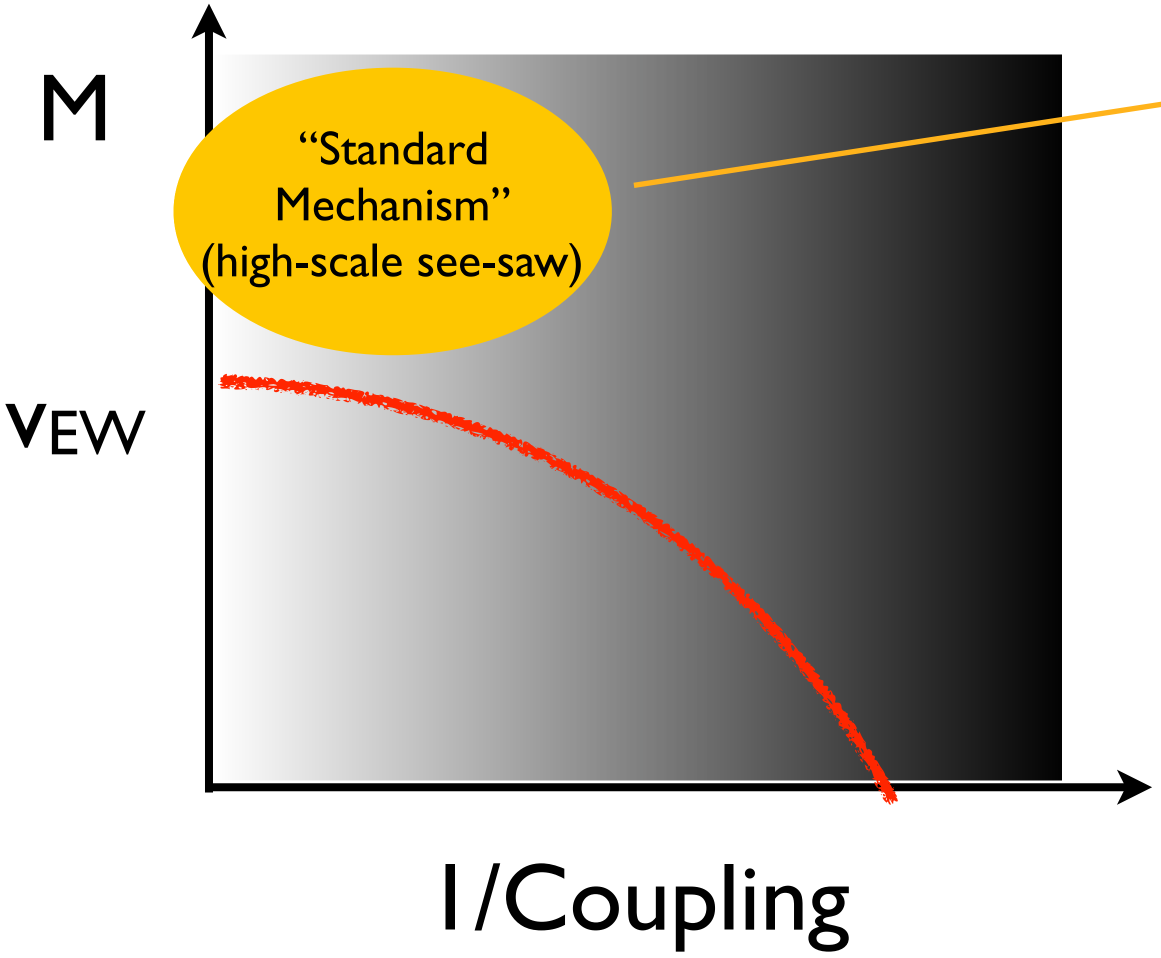

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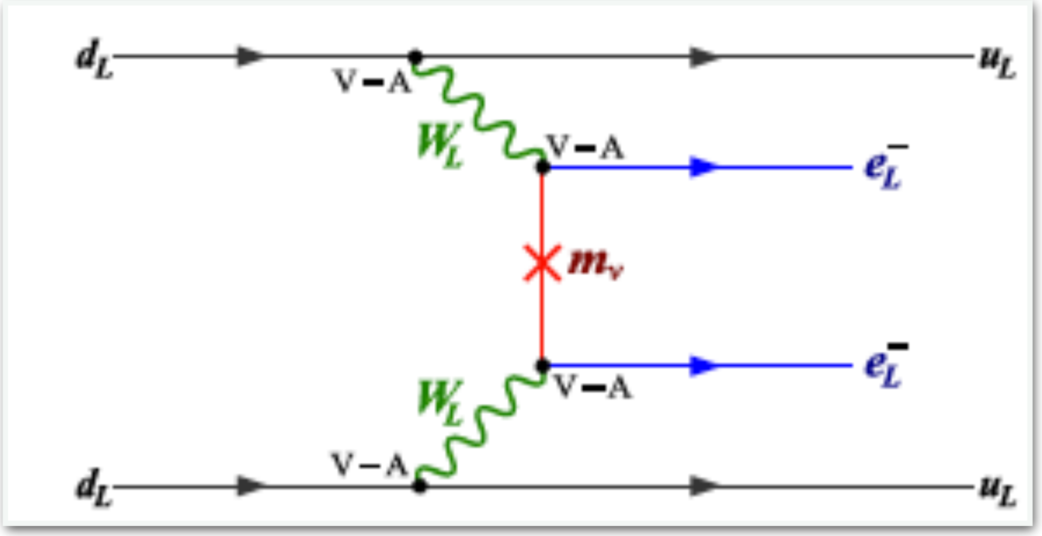

Amplitude proportional to

$$m_{\beta\beta} = \sum U_{ei}^2 m_i$$

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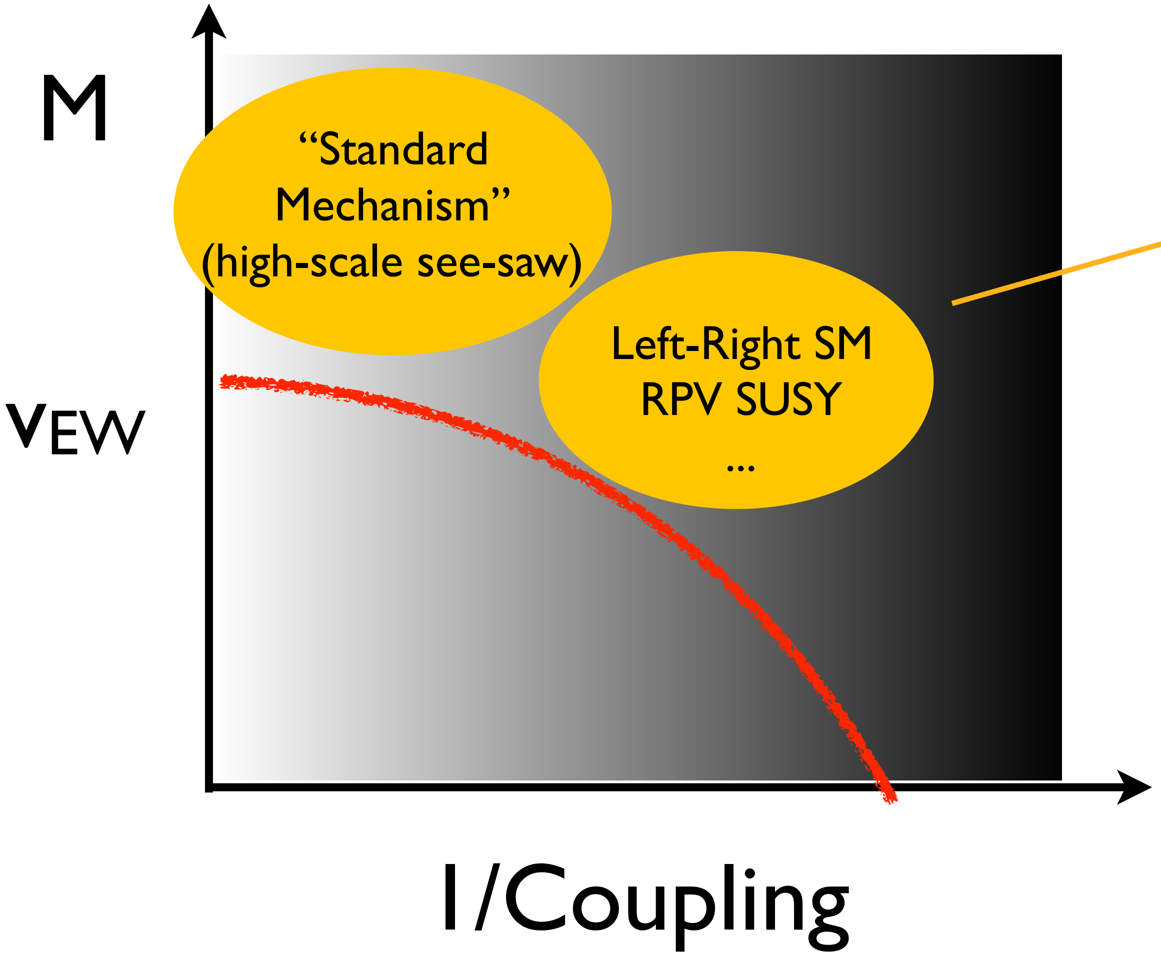
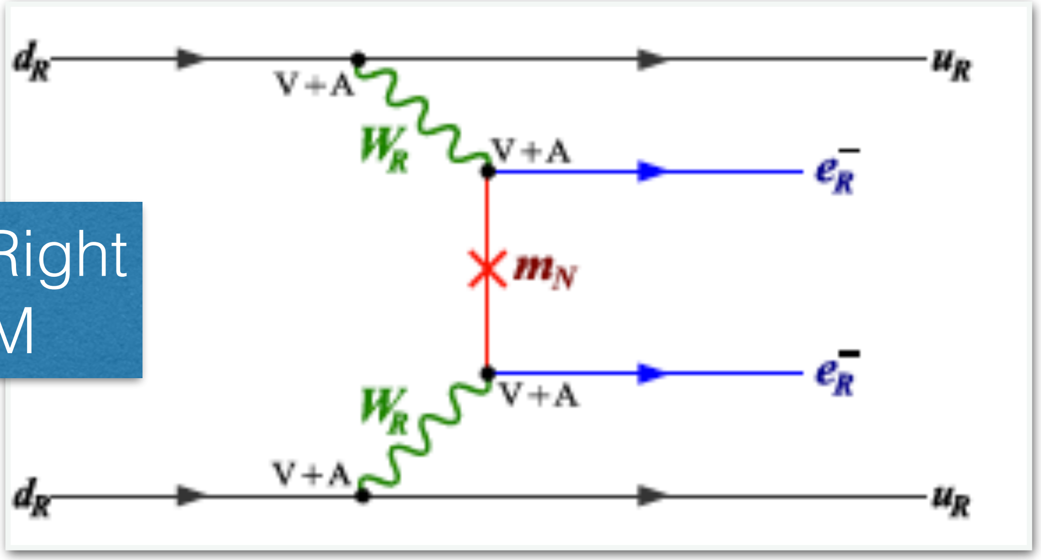


LNV dynamics at M ~ TeV:
1) new contribution to 0νββ not related to light neutrino mass;
2) pp → eejj at the LHC

Left-Right SM



This generates dim9 operators
(dim7 also possible)

0νββ and Lepton Number Violation

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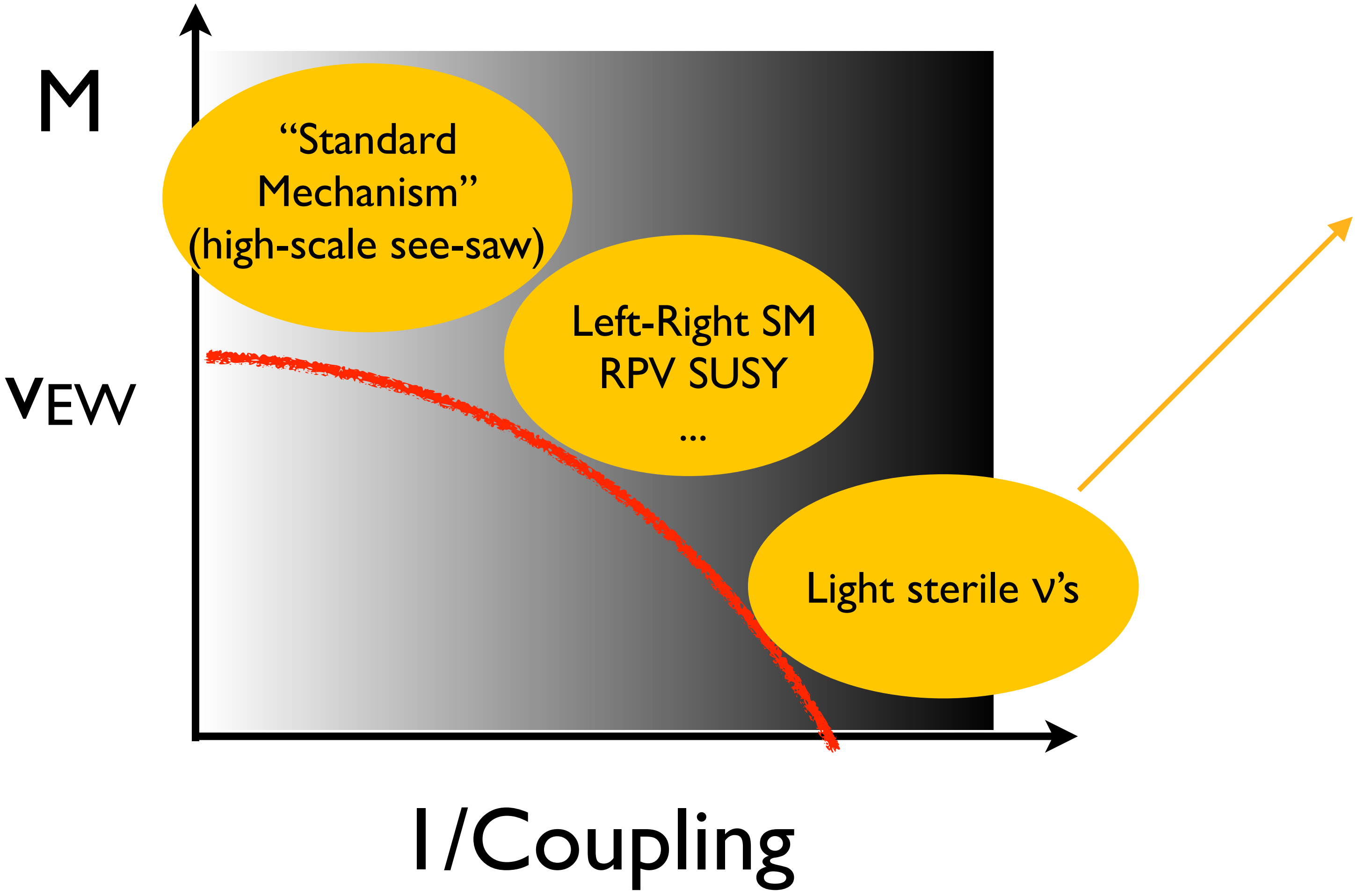
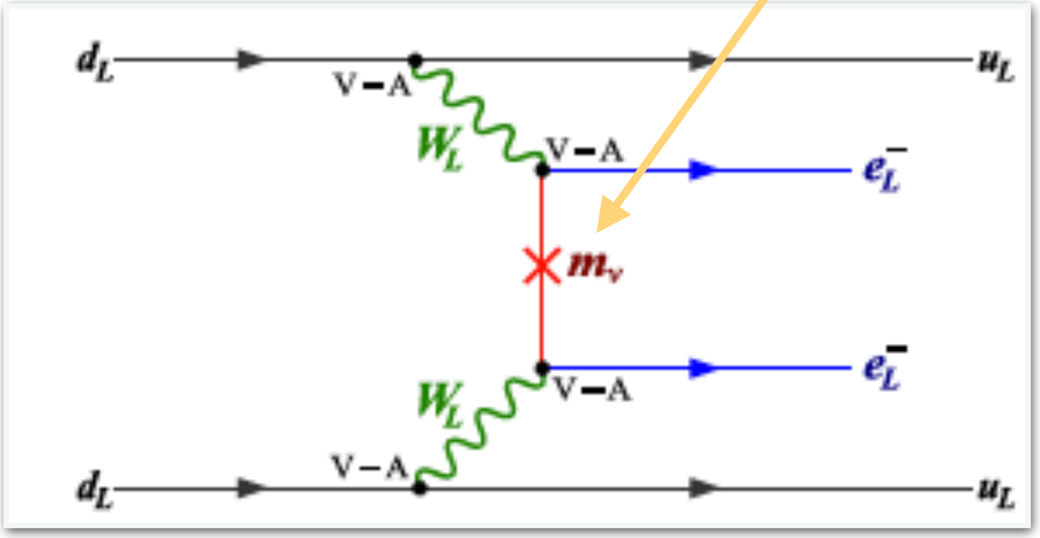


Additional light Majorana states (e.g. induced by singlet ν_R's with M_R: eV → GeV)



The hadronic / nuclear physics is the same as for dim5 operators

0νββ and Lepton Number Violation

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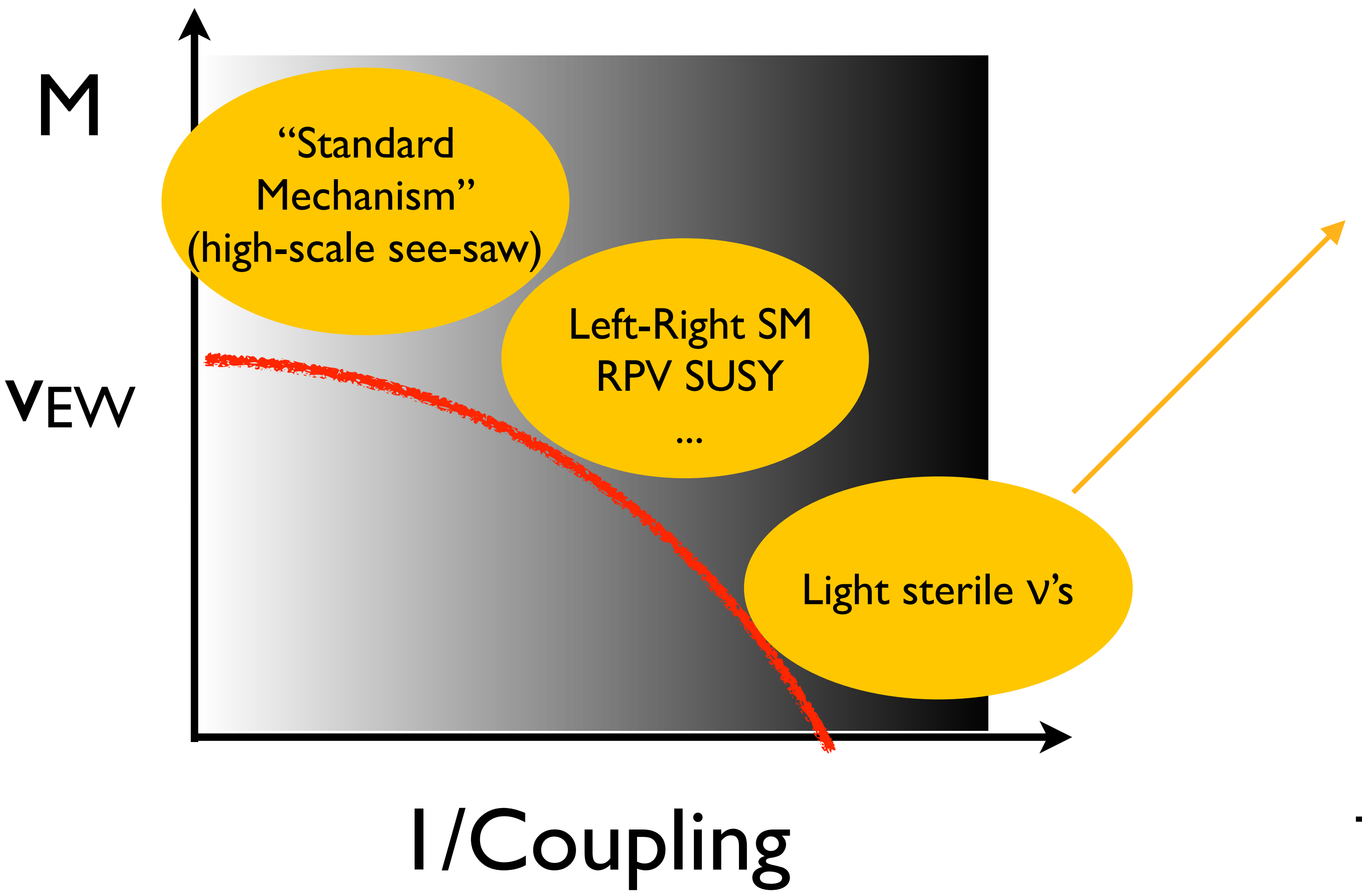
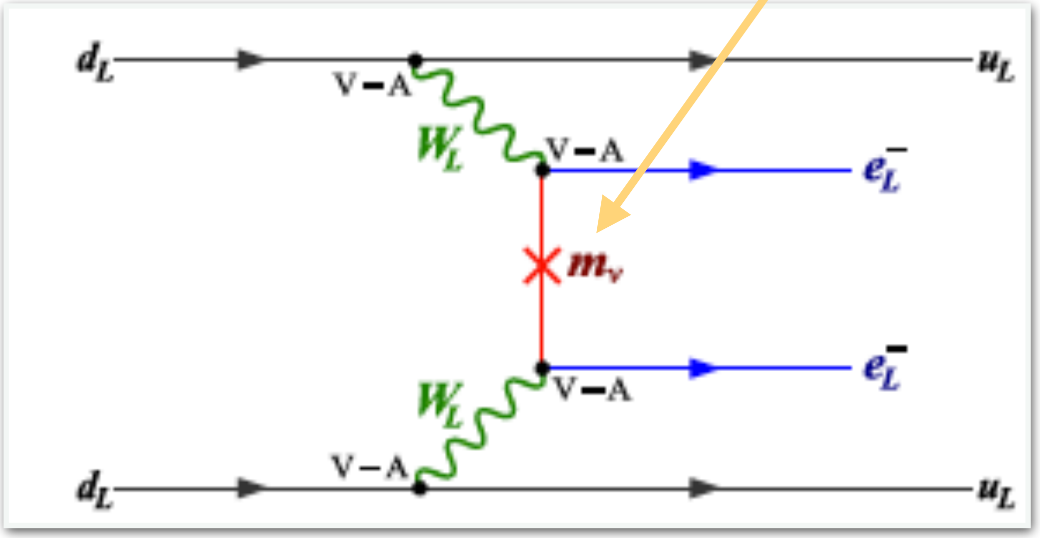


"Standard Mechanism" (high-scale see-saw)

Left-Right SM
RPV SUSY
…

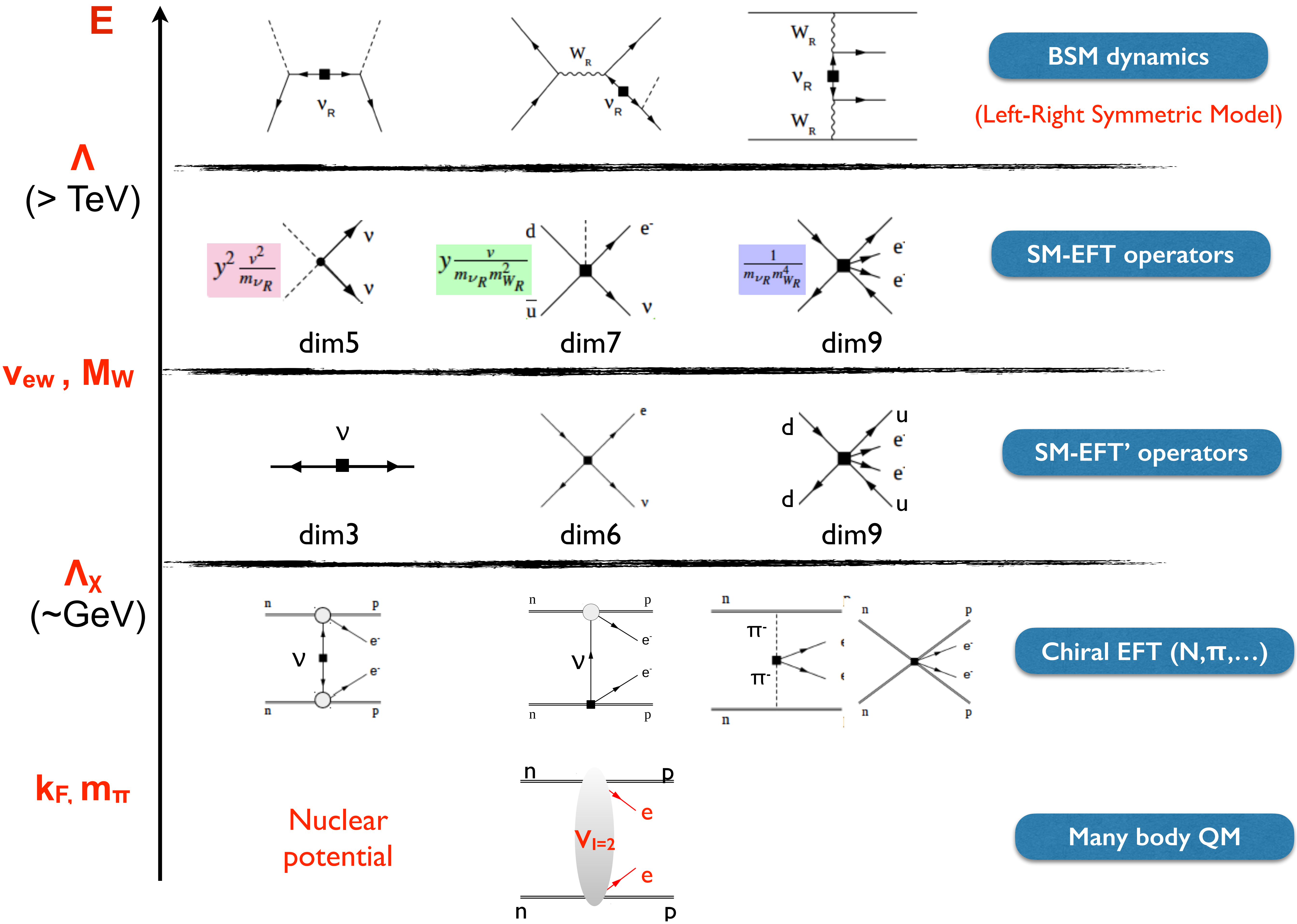
Light sterile ν's

Additional light Majorana states (e.g. induced by singlet ν_R's with M_R: eV → GeV)



The hadronic / nuclear physics is the same as for dim5 operators

Impact of 0νββ searches most efficiently analyzed in EFT framework



BSM dynamics

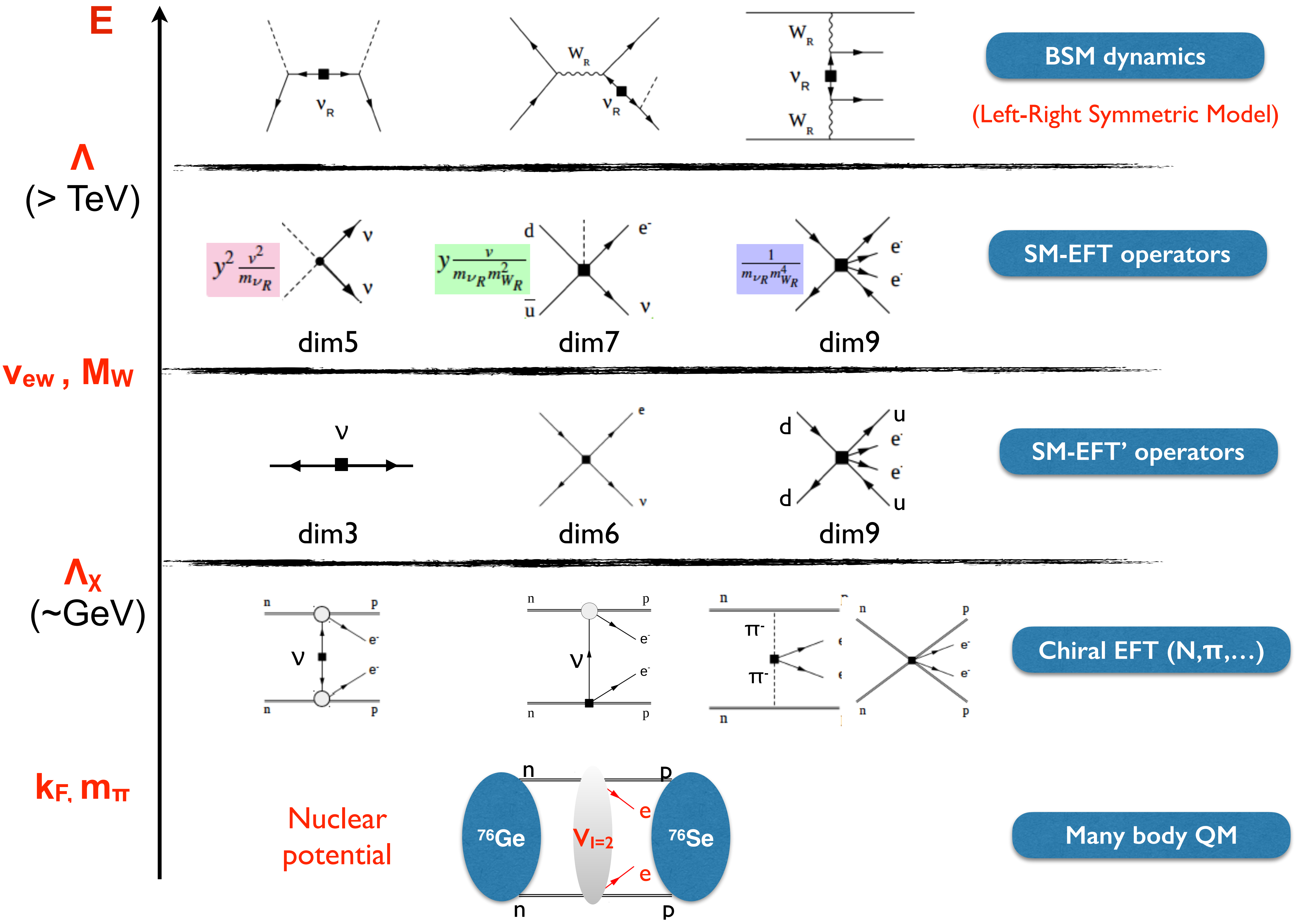
(Left-Right Symmetric Model)

SM-EFT operators

SM-EFT' operators

Chiral EFT (N,π,…)

Many body QM



E

Λ (> TeV)

v_{ew} , M_W

Λ_χ (~GeV)

$k_{F,}$ m_π

BSM dynamics

(Left-Right Symmetric Model)

$y^2 \frac{v^2}{m_{\nu R}}$

$y \frac{v}{m_{\nu R} m_{W R}^2}$

$\frac{1}{m_{\nu R} m_{W R}^4}$

dim5 dim7 dim9

SM-EFT operators

dim3 dim6 dim9

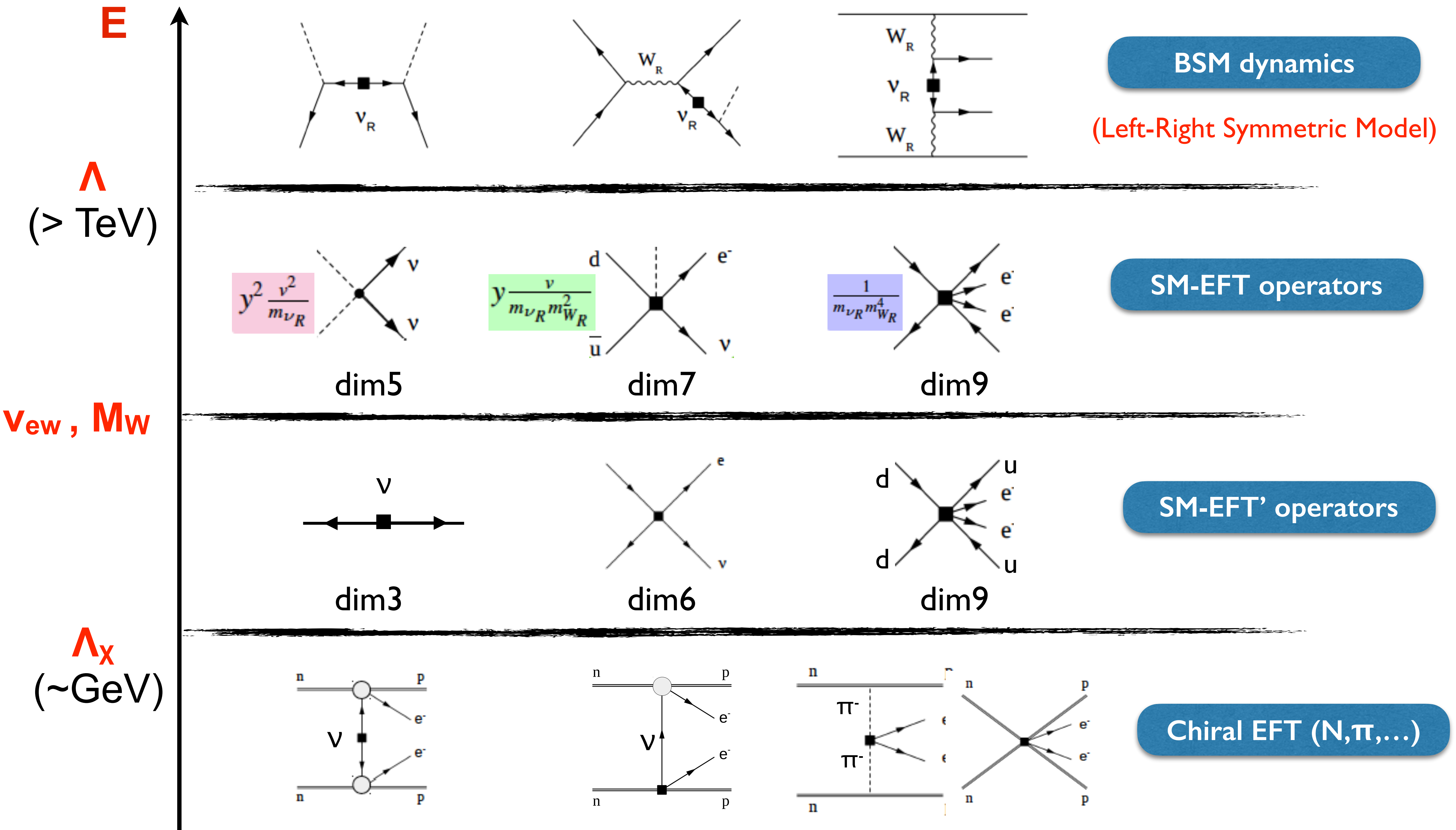
SM-EFT’ operators

Chiral EFT (N,π,…)

Nuclear potential

^{76}Ge $V_{I=2}$ ^{76}Se

Many body QM



BSM dynamics

(Left-Right Symmetric Model)

SM-EFT operators

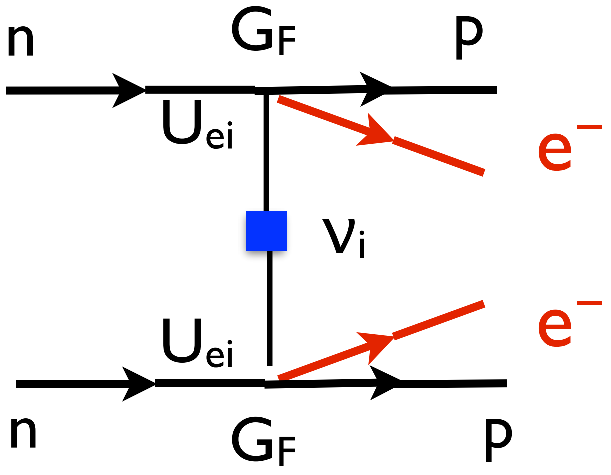
SM-EFT’ operators

Chiral EFT (N,π,…)

$$\boxed{V_{I=2} = m_{\beta\beta} V_\nu + \frac{m_\pi^2}{v} (c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN}) + \ldots}$$

Many body QM

0νββ from light ν$_M$ exchange



Decay amplitude

$$\boxed{A \propto m_{\beta\beta} \langle f | \sum_{a,b} V_\nu^{(a,b)} | i \rangle}$$

$m_{\beta\beta} = \sum U_{ei}^2 m_i$

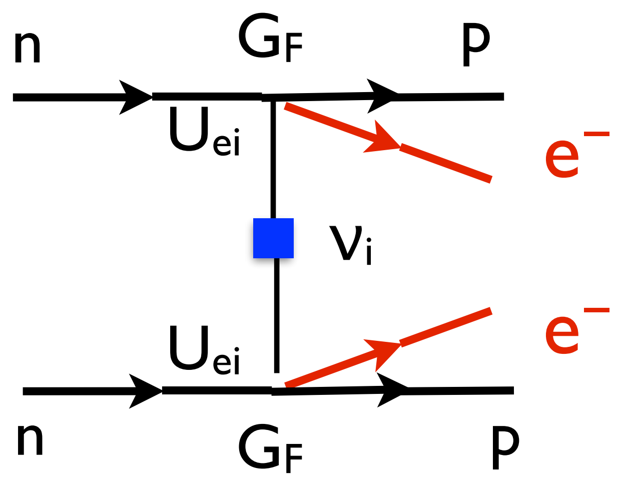
Transition operator (traditional non-EFT-based analyses)

$$V_\nu^{(a,b)} = \tau^{+,a}\tau^{+,b} \frac{1}{\mathbf{q}^2} \left(J_V^{(a)}(\mathbf{q}) J_V^{(b)}(-\mathbf{q}) + J_A^{(a)}(\mathbf{q}) J_A^{(b)}(-\mathbf{q}) \right)$$

$J_V \sim 1$

$J_A \sim g_A \, \sigma$

0νββ from light ν_M exchange



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$J_V \sim 1$

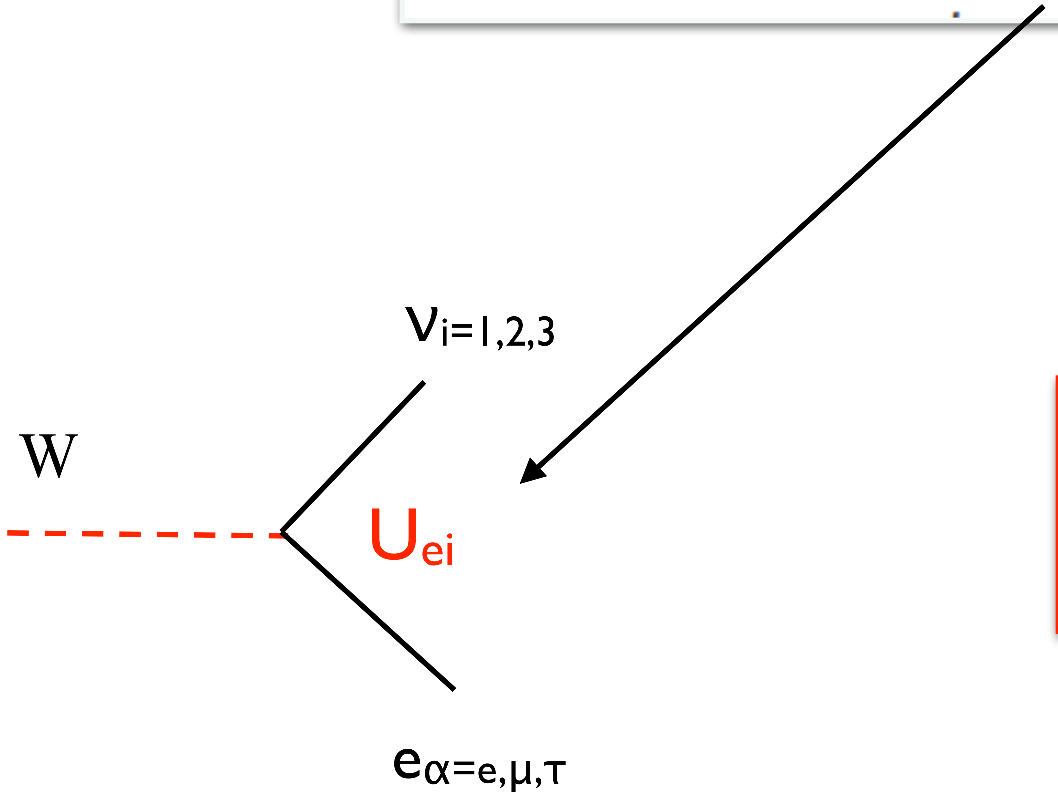
$J_A \sim g_A\, \sigma$

In this case 0νββ is a *direct* probe of ν mass and mixing: $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

$m_{\beta\beta}$ phenomenology

- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$



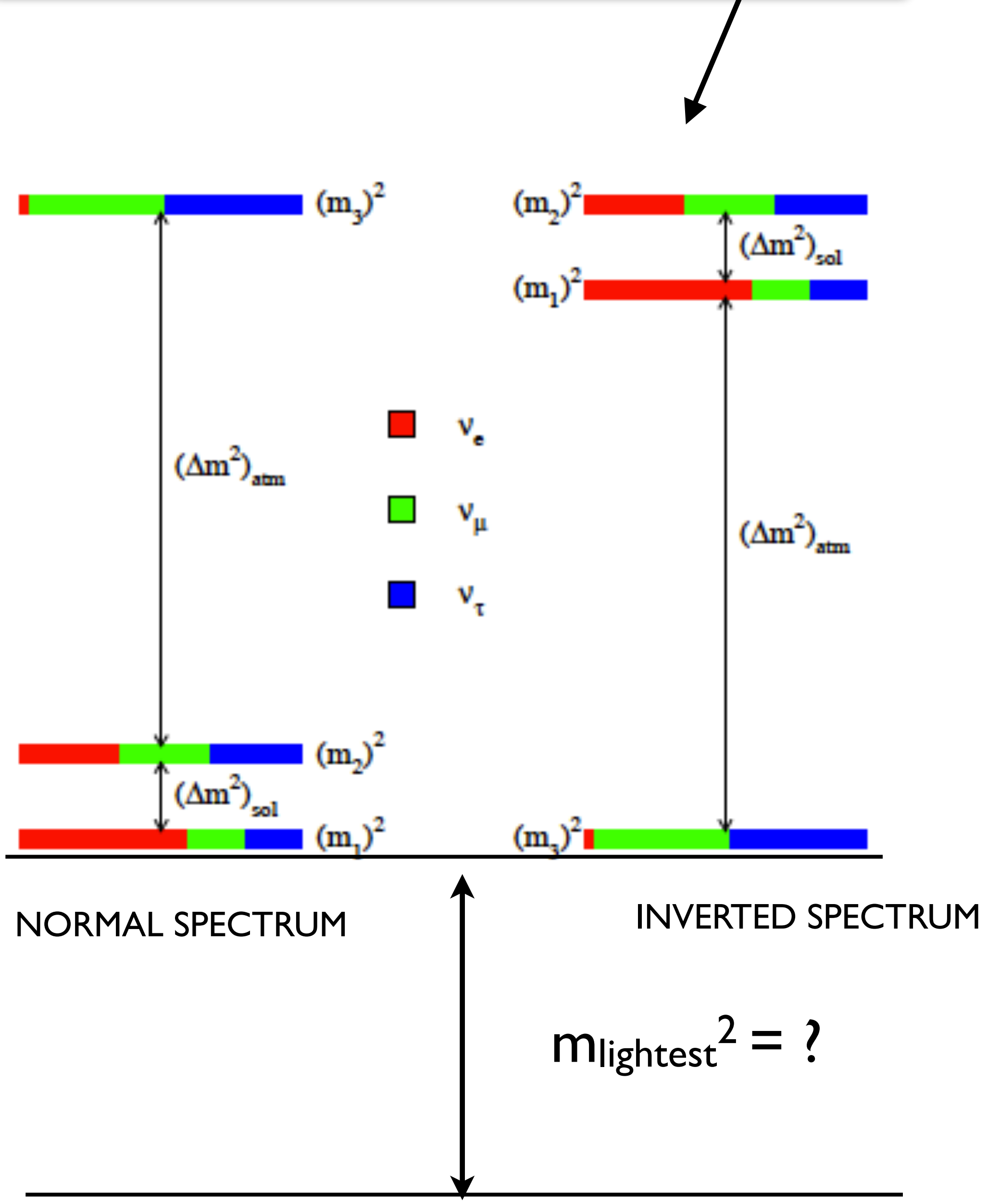
$$\frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \nu_L^i$$

Unitary mixing in CC vertex:
3 angles (known), 1+2 phases (unknown)

mββ phenomenology

- Strong correlation of 0νββ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



Mass ordering still not fixed by oscillation data

mββ phenomenology

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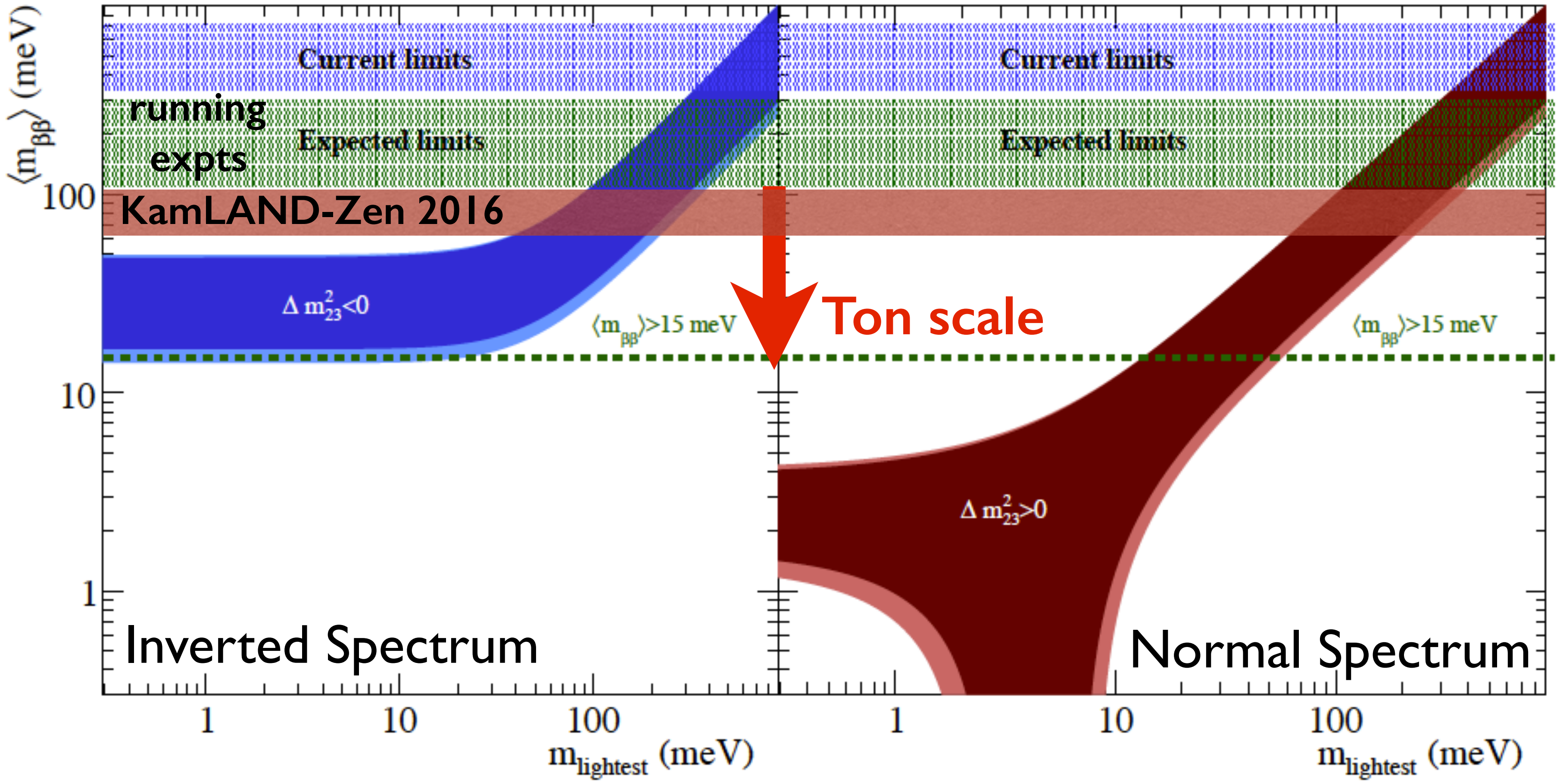

Dark bands:
unknown phases

Light bands:
uncertainty from
oscillation
parameters(90% CL)

$m_{\beta\beta}$ phenomenology

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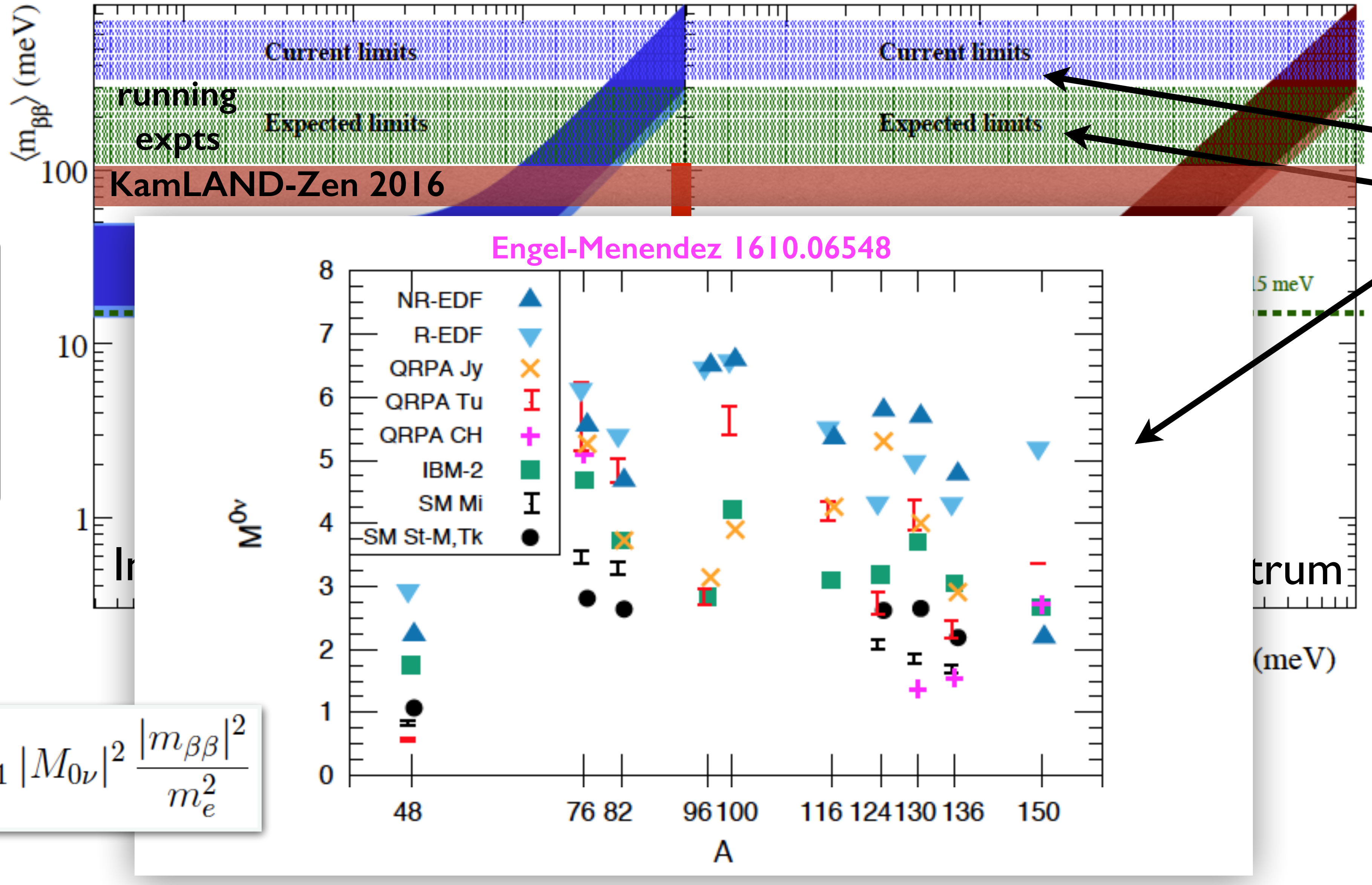

Assume range for nuclear matrix elements from different many-body methods

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, G_{01}\, |M_{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

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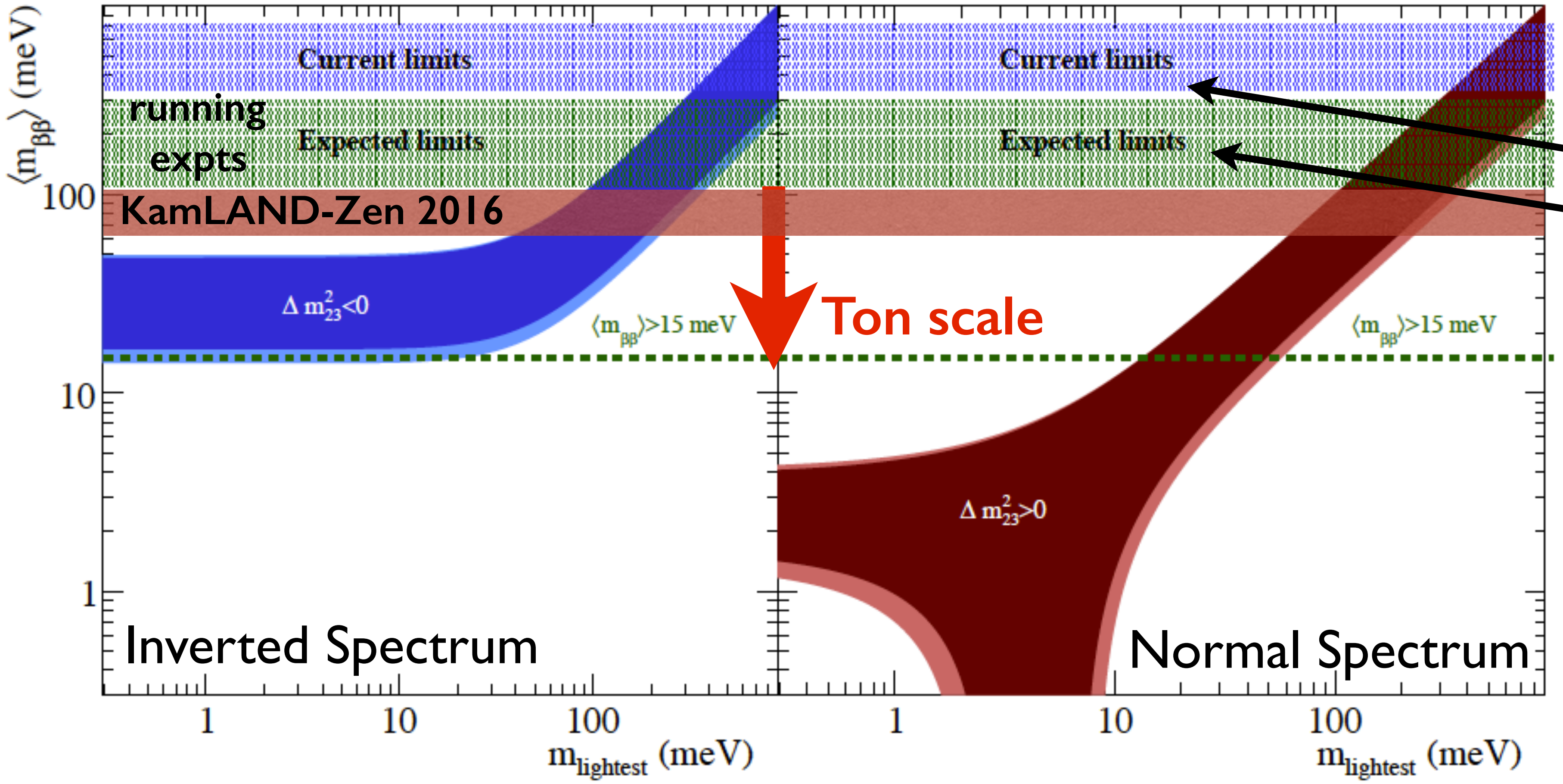


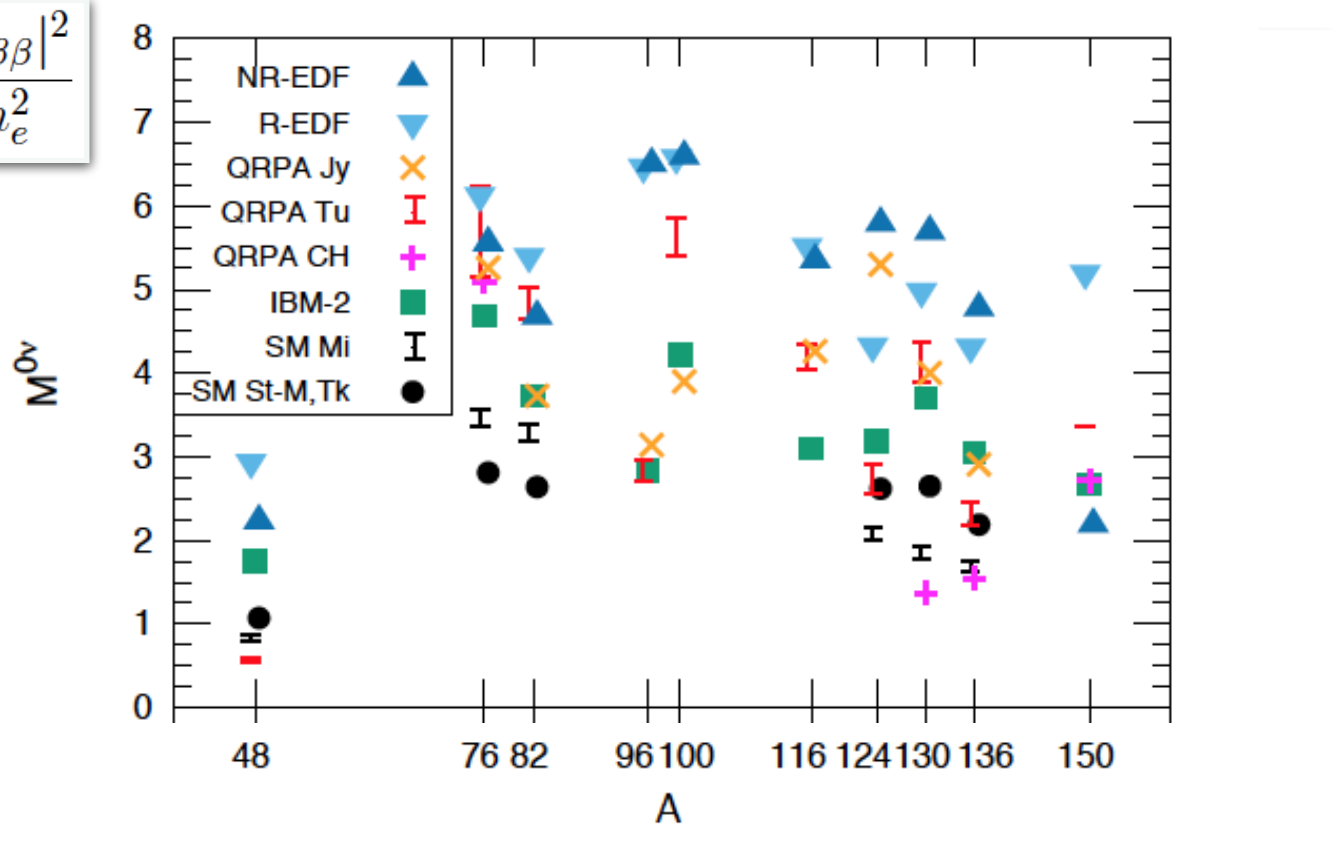
Assume range for nuclear matrix elements from different many-body methods

- Assuming current range for matrix elements, discovery *possible* for inverted spectrum or m_{lightest} > 50 meV

Room for improvement?

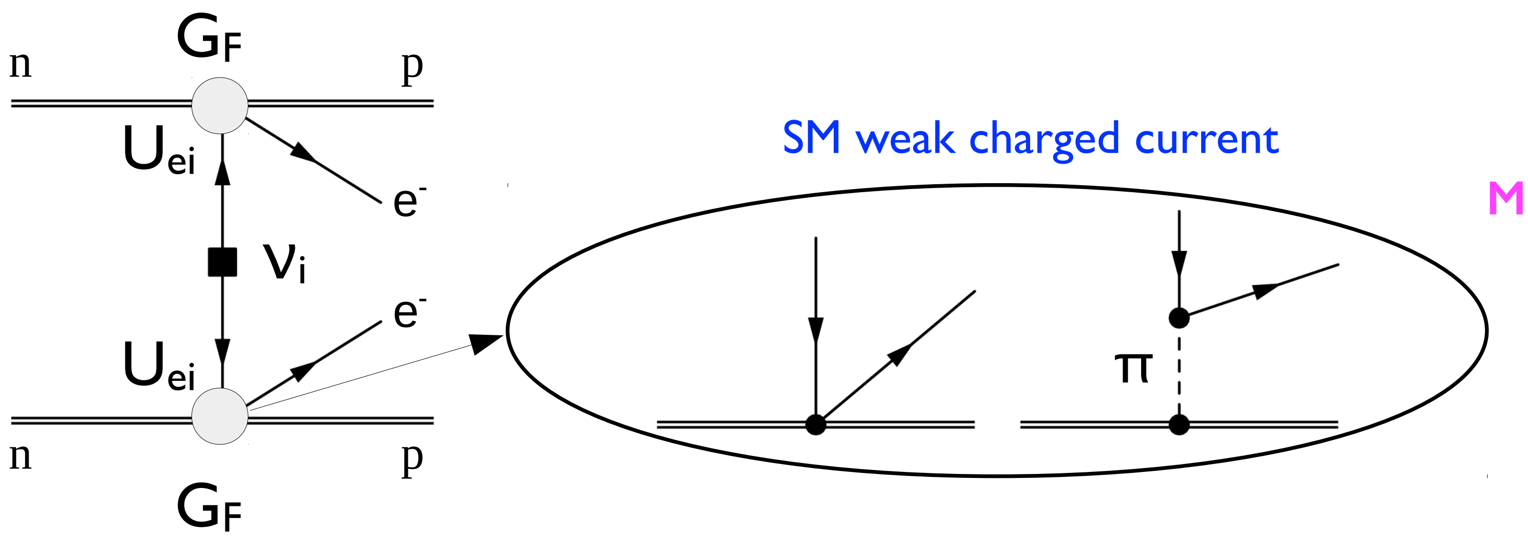
Engel-Menendez 1610.06548

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4\, G_{01}\, |M_{0\nu}|^2\, \frac{|m_{\beta\beta}|^2}{m_e^2}$$



- Steps towards controllable uncertainties in matrix elements:
  - Use chiral EFT as guiding principle
  - Use exact results in light nuclei as a benchmark
  - “Ab initio” nuclear structure in sight for ^{48}Ca, with QCD-rooted chiral potentials

Light ν_M exchange in chiral EFT

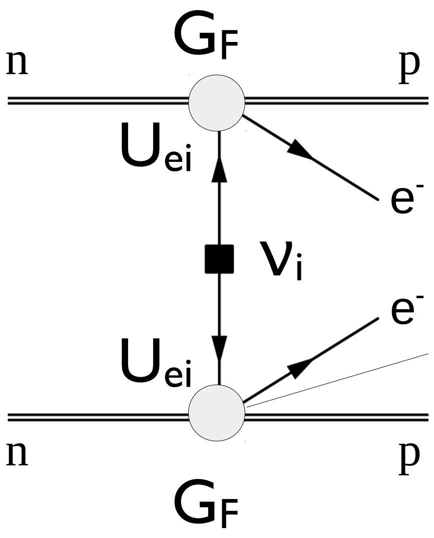


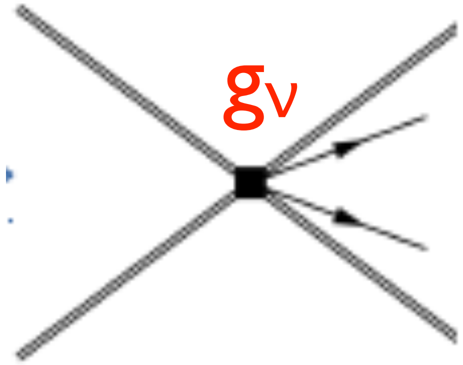
VC, W. Dekens,
M. Graesser, E. Mereghetti,
S. Pastore, J. de Vries,
U. van Kolck
1802.10097

- Leading order contribution in Q/Λ_χ $(Q \sim k_F \sim m_\pi)$: tree-level ν_M exchange

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \boxed{\frac{1}{\mathbf{q}^2}} \left\{ 1 - g_A^2 \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q}\, \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q}\, \frac{2m_\pi^2 + \mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right] \right\}$$

Light ν_M exchange in chiral EFT





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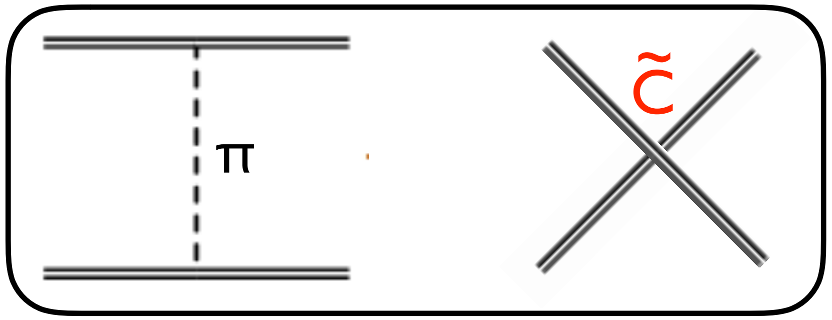
- Renormalization of nn→ppee amplitude in presence of LO strong potential requires a leading order counterterm $g_\nu \sim 1/F_\pi^2 \sim 1/k_F^2$

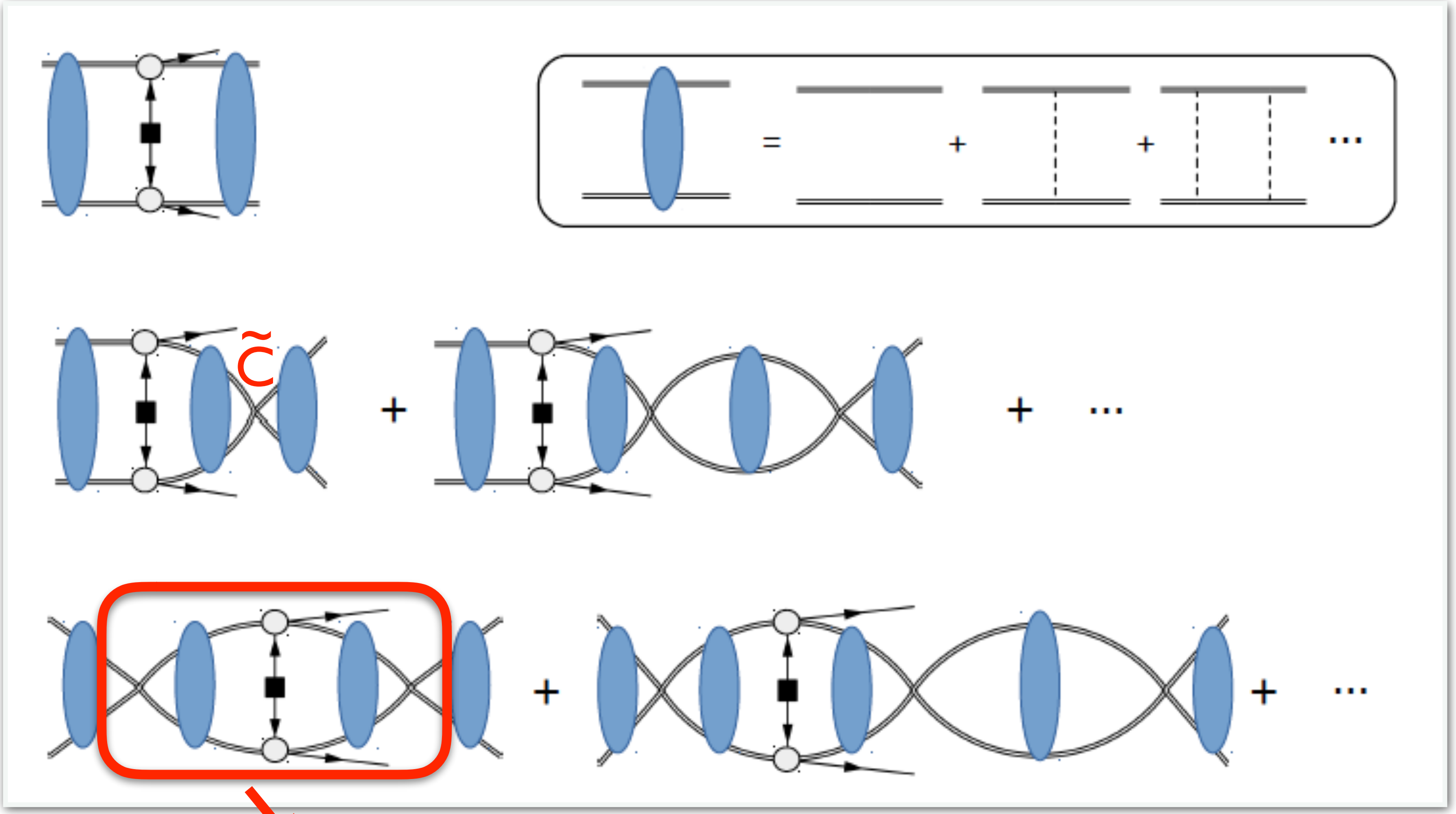
$$V_{\nu,CT}^{(a,b)} = -2\, g_\nu\; \tau^{(a)+}\tau^{(b)+}$$

Scaling of contact term in 0νββ

- nn→ppee amplitude with LO strong potential



Weinberg 1991



$\tilde{C} \sim$ 1/F_π^2 from fit to a_{NN}

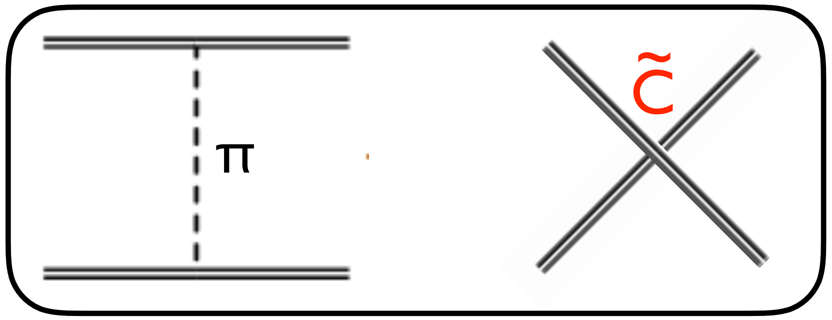
UV divergence

$$\sim \boxed{\frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2}\left(\frac{1}{4-d}+\log\mu^2\right)$$

$\sim$ 1/F_π^2

Scaling of contact term in 0νββ

- nn→ppee amplitude with LO strong potential



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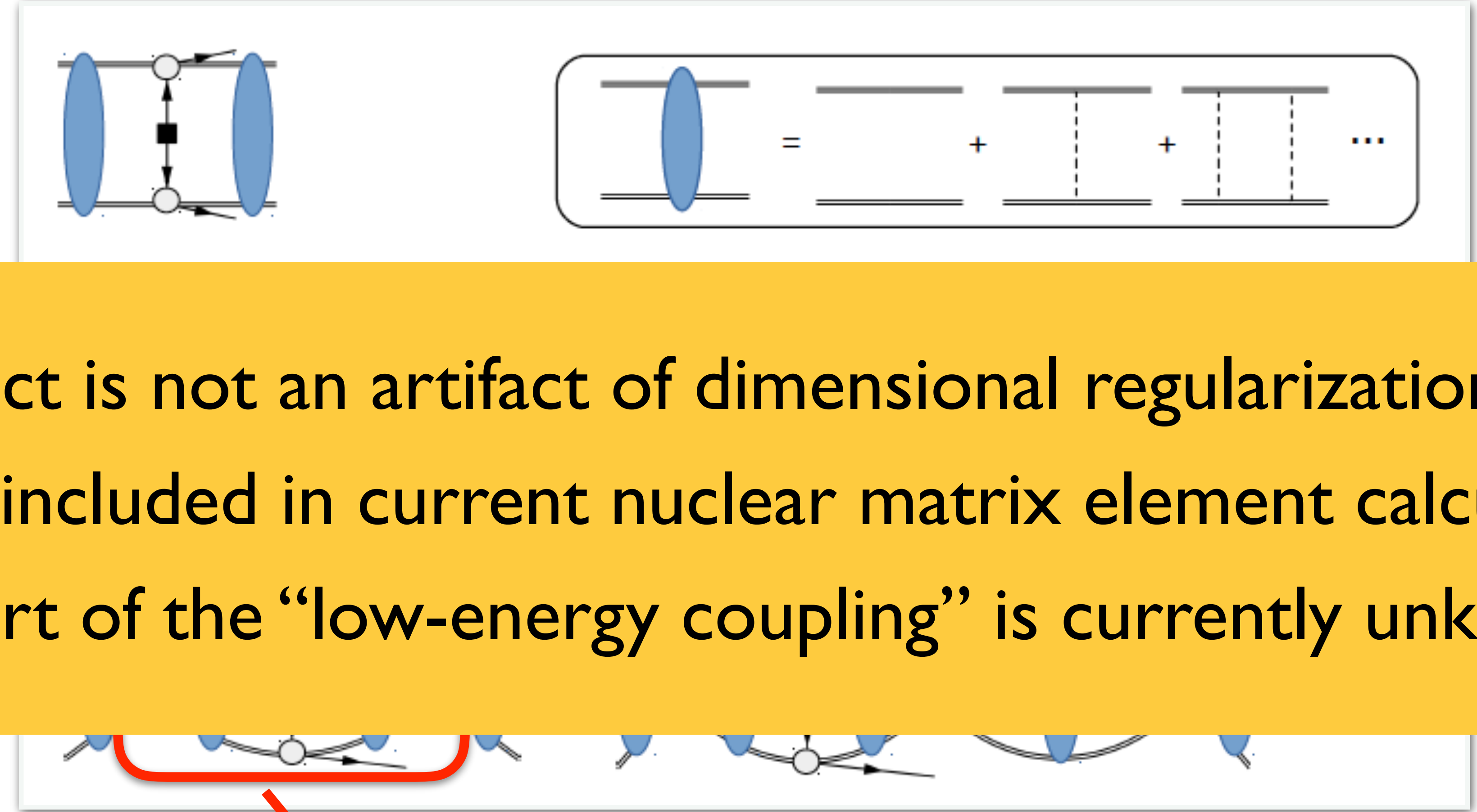

$\tilde{C}$ ~ $1/F_\pi^2$ from fit to a_{NN}

- This effect is not an artifact of dimensional regularization
- It is not included in current nuclear matrix element calculations
- Finite part of the “low-energy coupling” is currently unknown

UV divergence

$$\boxed{\sim \frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2}\left(\frac{1}{4-d}+\log\mu^2\right)$$

~ $1/F_\pi^2$

Estimating finite part of g_ν

1) Match χEFT & lattice QCD calculation of hadronic amplitude nn→pp

$$S_{\rm eff}^{\Delta L=2} = \frac{i8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, T\Big(\bar{u}_L \gamma_\mu d_L(x)\, \bar{u}_L \gamma_\mu d_L(y)\Big) g^{\mu\nu}$$

Scalar massless propagator
(remnant of ν propagator)

Estimating finite part of g_ν

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Scalar massless propagator
(remnant of ν propagator)

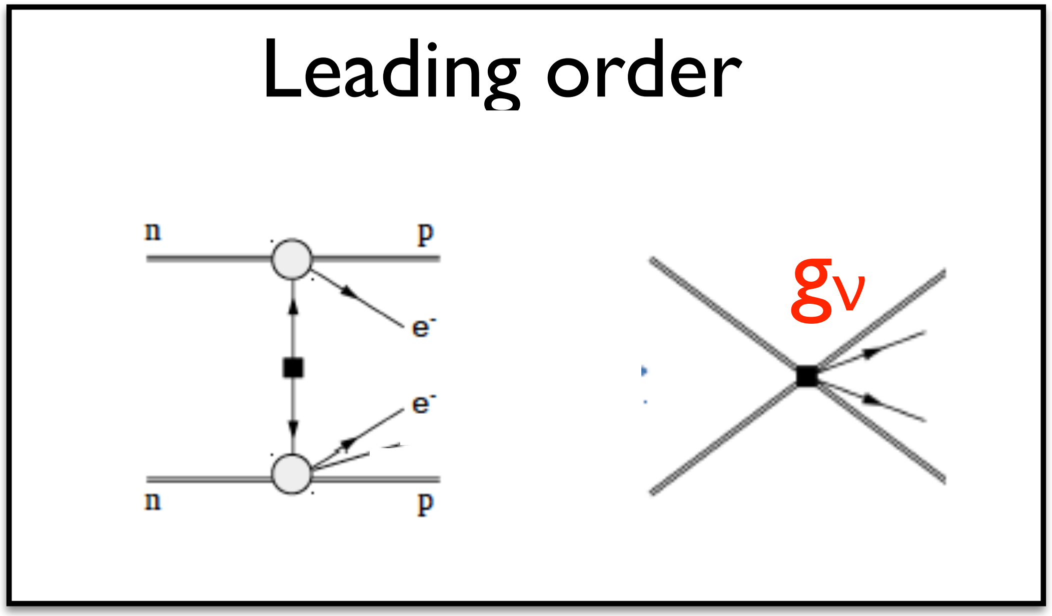
$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2) Chiral symmetry relates g_ν to one of two I=2 EM LECs

- Only one combination of the EM constants fixed by NN scattering
- Using this as rough estimate of g_ν get O(50%) shift of the matrix element in light nuclei
- Strong motivation to pursue lattice QCD calculation

Anatomy of 0νββ amplitude

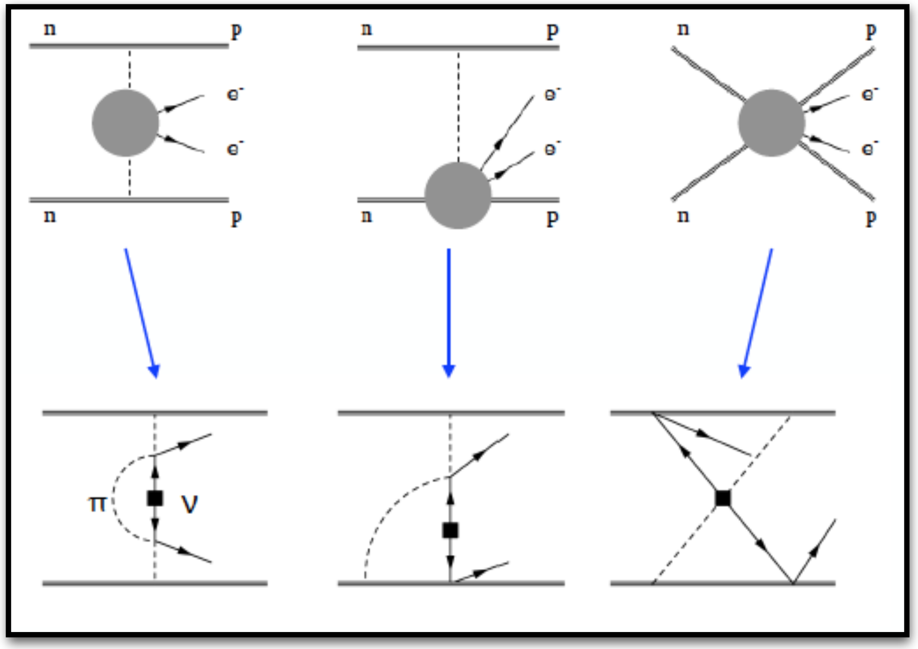
Expansion parameter Q/Λ_χ
with $Q \sim k_F \sim m_\pi$ and $\Lambda_\chi \sim M_n$



VC, W. Dekens,, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck 1802.10097

$V_{I=2}$

N2LO



VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

Related to matrix elements and excitation energies needed to predict 2νββ decay

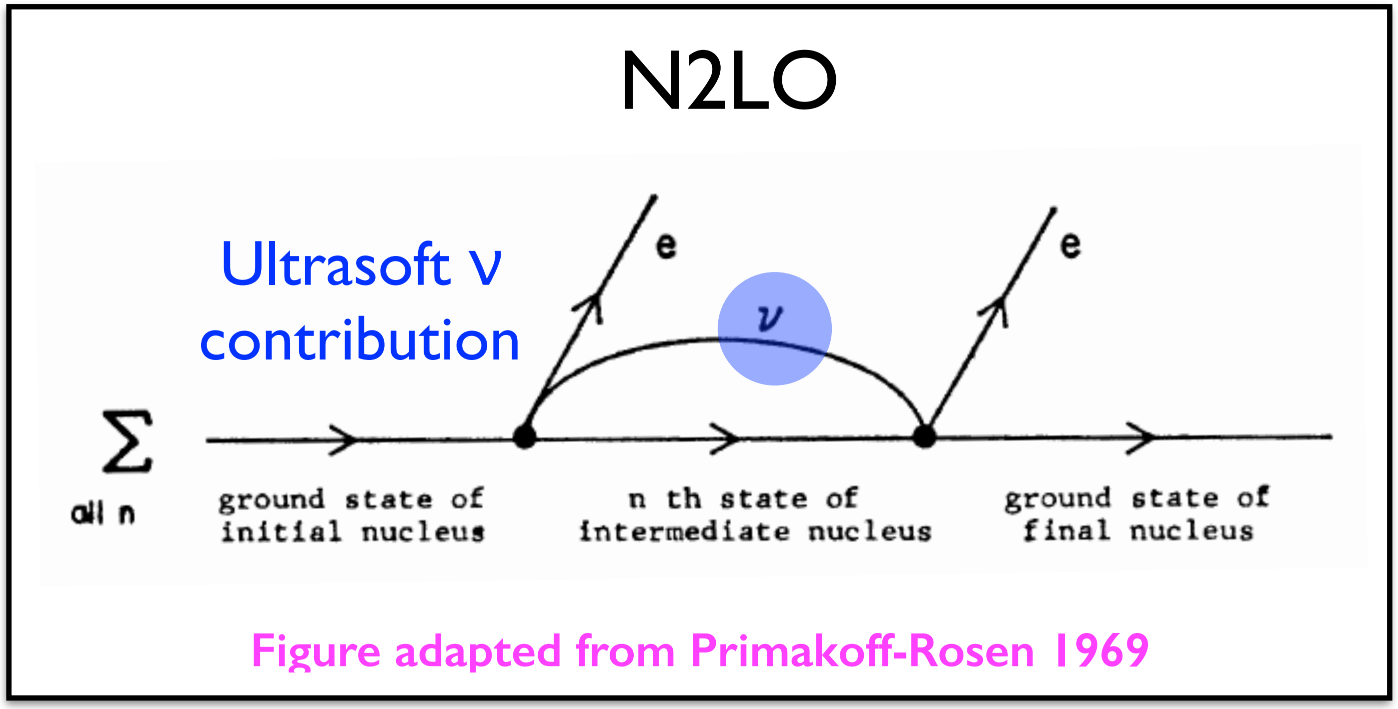
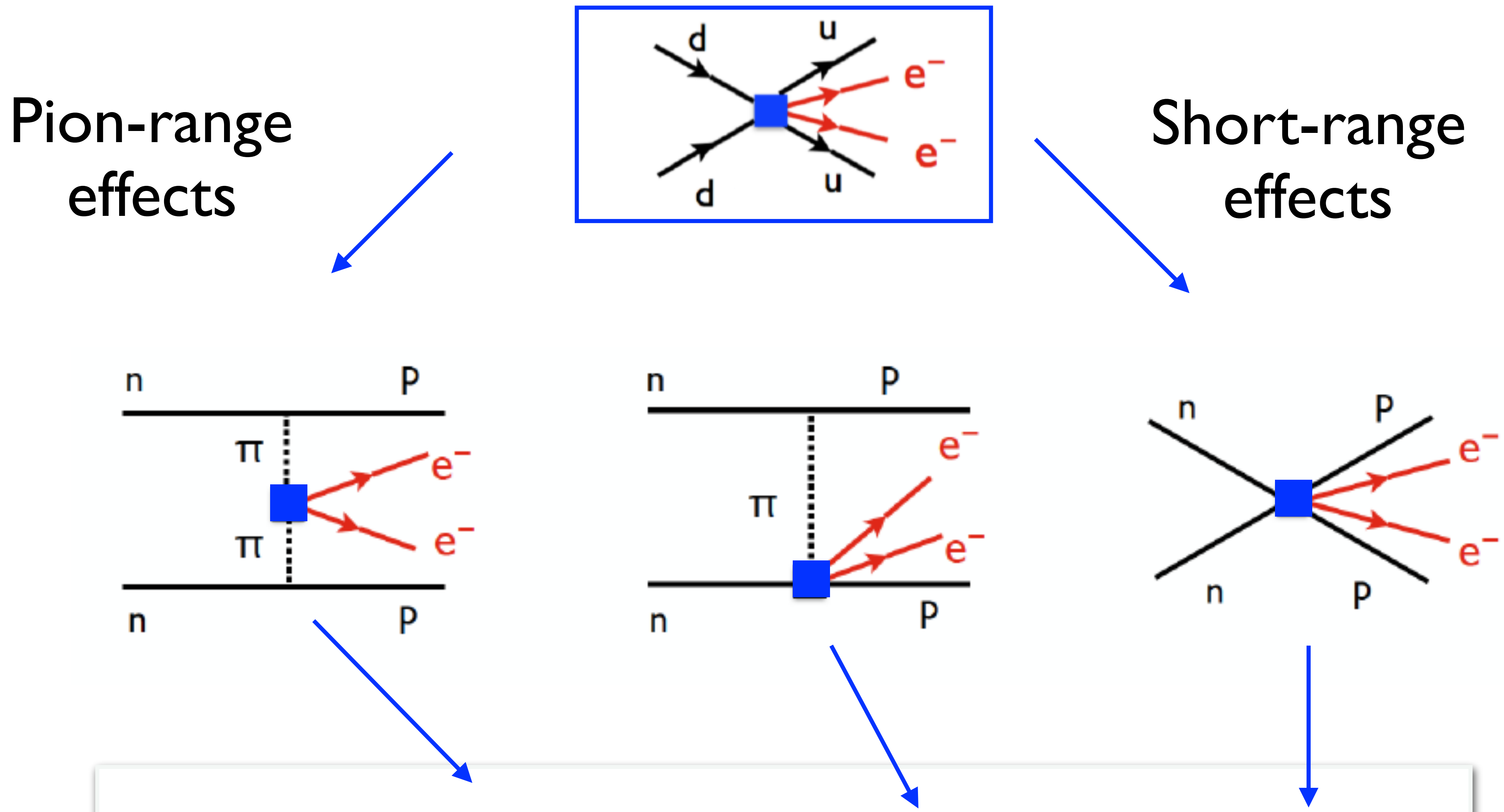


Figure adapted from Primakoff-Rosen 1969

0νββ from $\mathcal{L}^{(9)}_{\Delta L=2}$



Pion-range effects

Short-range effects

$$V_{I=2} \supset \left(c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN} \right)$$

Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

c_α ~ short-distance coupling (model-dep.) × hadronic matrix element

0νββ from $\mathcal{L}^{(9)}_{\Delta L=2}$

- Example: scalar operators

VC, W. Dekens, M. Graesser, E. Mereghetti, J. de Vries 1806.02780

$$\mathcal{O}_1 = \bar{u}_L\gamma^\mu d_L\,\bar{u}_L\,\gamma_\mu d_L$$

$$\mathcal{O}_2 = \bar{u}_L d_R\,\bar{u}_L\,d_R, \qquad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta\,\bar{u}_L^\beta\,d_R^\alpha$$

$$\mathcal{O}_4 = \bar{u}_L\gamma^\mu d_L\,\bar{u}_R\,\gamma_\mu d_R, \qquad \mathcal{O}_5 = \bar{u}_L^\alpha\gamma^\mu d_L^\beta\,\bar{u}_R^\beta\,\gamma_\mu d_R^\alpha$$

- Hadronic realization depends on O_i's chiral properties

$$\mathcal{L}_{NN} = \left(g_1^{NN}C_{1L}^{(9)} + g_2^{NN}C_{2L}^{(9)} + g_3^{NN}C_{3L}^{(9)} + g_4^{NN}C_{4L}^{(9)} + g_5^{NN}C_{5L}^{(9)}\right)(\bar{p}n)\,(\bar{p}n)\,\frac{\bar{e}_L C\bar{e}_L^T}{v^5}$$

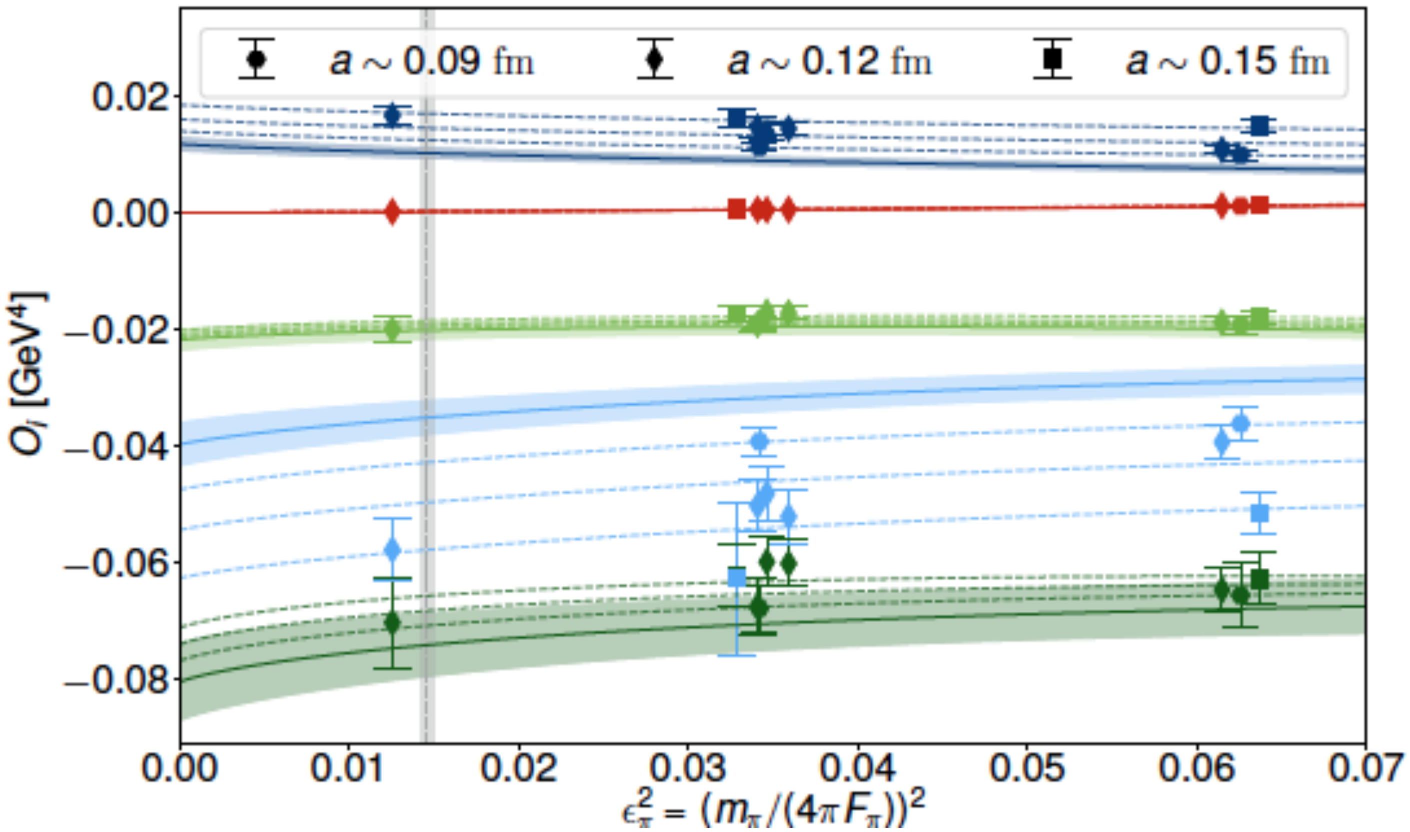
$$\mathcal{L}_\pi = \frac{F_0^2}{2}\left[\frac{5}{3}g_1^{\pi\pi}C_{1L}^{(9)}\,\partial_\mu\pi^-\partial^\mu\pi^- + \left(g_4^{\pi\pi}C_{4L}^{(9)} + g_5^{\pi\pi}C_{5L}^{(9)} - g_2^{\pi\pi}C_{2L}^{(9)} - g_3^{\pi\pi}C_{3L}^{(9)}\right)\pi^-\pi^-\right]$$
$$\times\frac{\bar{e}_L C\bar{e}_L^T}{v^5} + (L\leftrightarrow R) + \dots$$

$$g_1^{\pi\pi} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{\pi\pi} \sim \mathcal{O}(\Lambda_\chi^2) \qquad\qquad g_1^{NN} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{NN} \sim \mathcal{O}\left(\frac{\Lambda_\chi^2}{F_\pi^2}\right)$$

Pion matrix elements from LQCD

Nicholson et al., 1805/02634

$\langle \pi^+ | O_i | \pi^- \rangle$



MS-bar at μ=2GeV

$g_1^{\pi\pi} = +0.4$

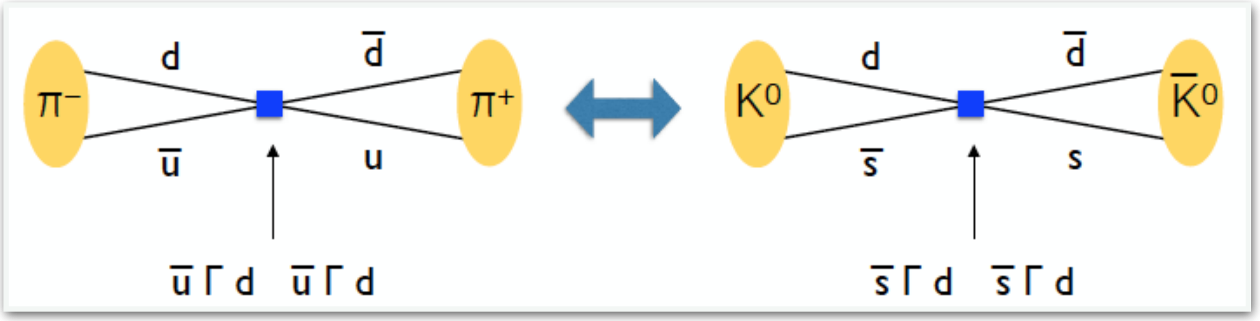
$g_2^{\pi\pi} = -(1.8\,\mathrm{GeV})^2$

$g_3^{\pi\pi} = +(1.0\,\mathrm{GeV})^2$

$g_4^{\pi\pi} = -(1.7\,\mathrm{GeV})^2$

$g_5^{\pi\pi} = -(3.6\,\mathrm{GeV})^2$

- Quite consistent with result obtained from kaon m.e. via chiral SU(3)

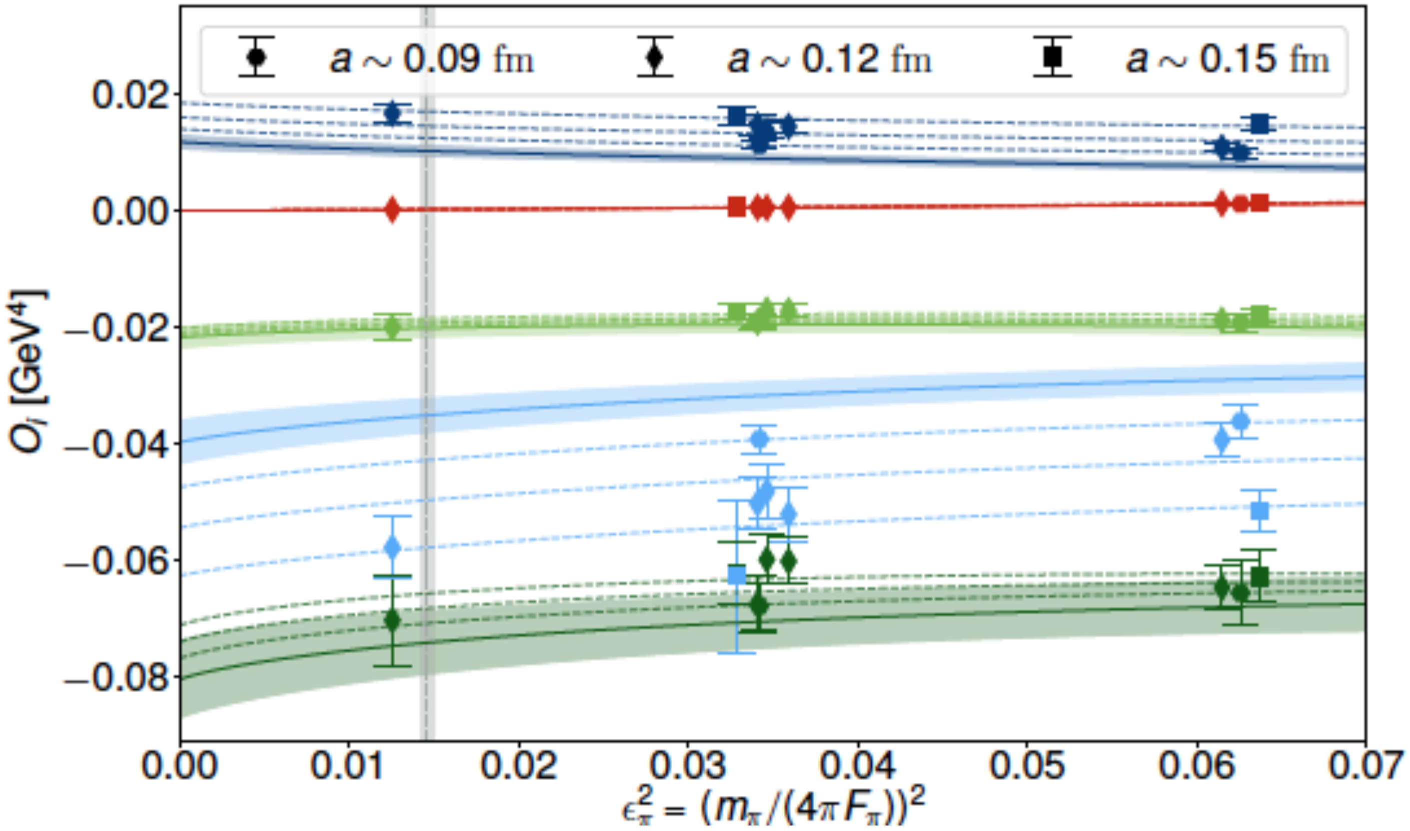


VC , W. Dekens, M. Graesser,
E. Mereghetti 1701.01443

Pion matrix elements from LQCD

Nicholson et al., 1805/02634

$<\pi^+|O_i|\pi^->$



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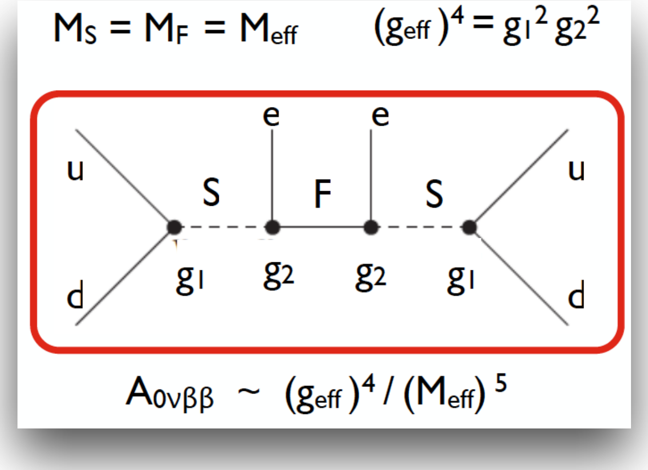
$g_5^{\pi\pi} = -(3.6\,\mathrm{GeV})^2$

- Result is < 1/2 x “vacuum insertion approximation”, commonly used in literature!
- $<pp|O_i|nn>$ ($<p\pi^+|O_i|n>$) not yet known from LQCD (only factorization model)
- In some instances, using “wrong hadronization” (e.g. no pion range) leads to factor >10 change in sensitivity to short-distance couplings

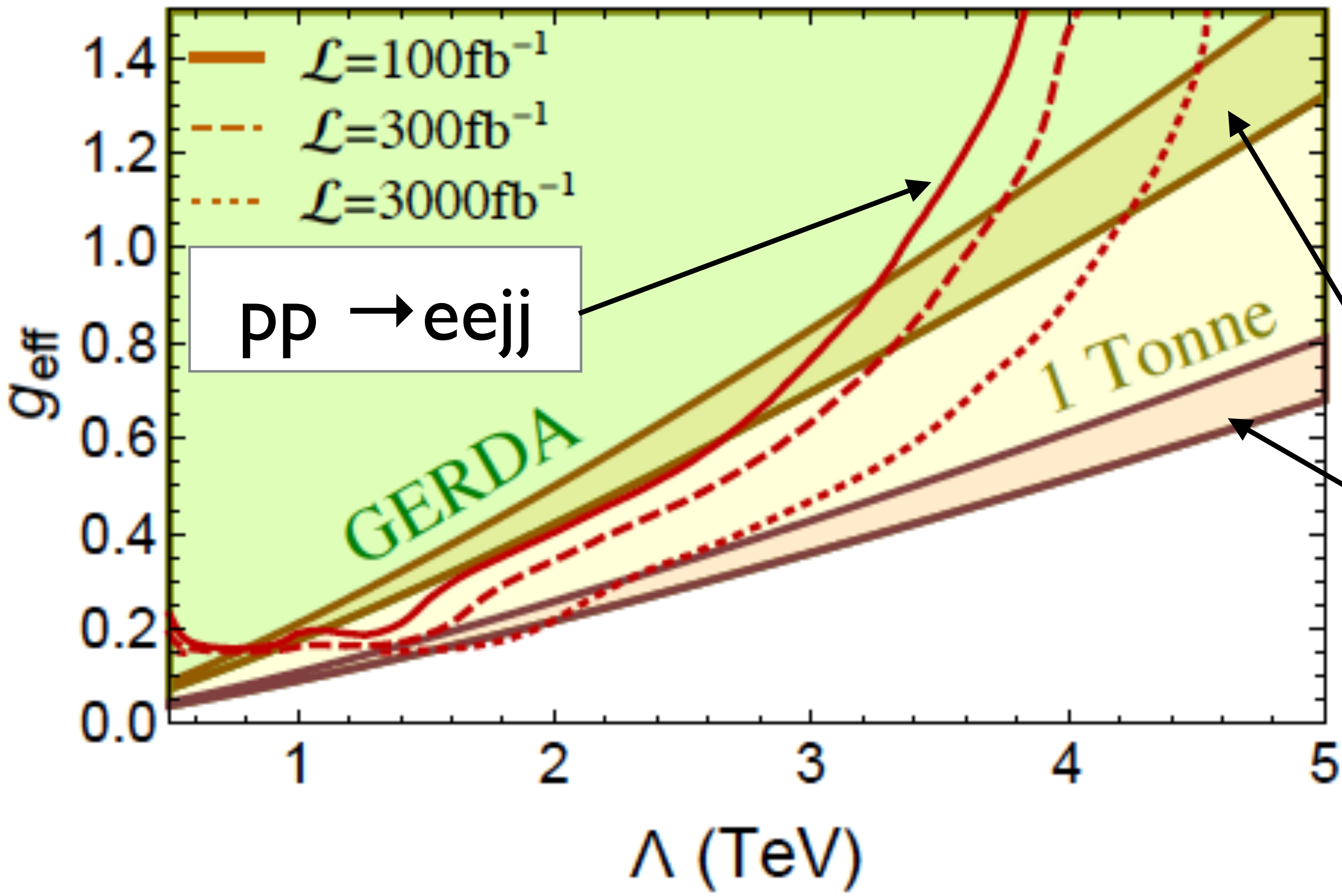
Impact on phenomenology

- Dim-9 ops ($O_{2,3}$) from TeV-scale simplified model ~ RPV-SUSY


$M_S = M_F = M_{eff}$ $(g_{eff})^4 = g_1^2 g_2^2$

$A_{0\nu\beta\beta} \sim (g_{eff})^4 / (M_{eff})^5$

Peng, Ramsey-Musolf, Winslow, 1508.0444



Sensitivity study:
$0\nu\beta\beta$ vs LHC
(current and future)

Plot assumes 30% uncertainty in the nuclear & hadronic matrix elements and VIA for ππ matrix element *(> 2 x lattice result)*

Electric Dipole Moments

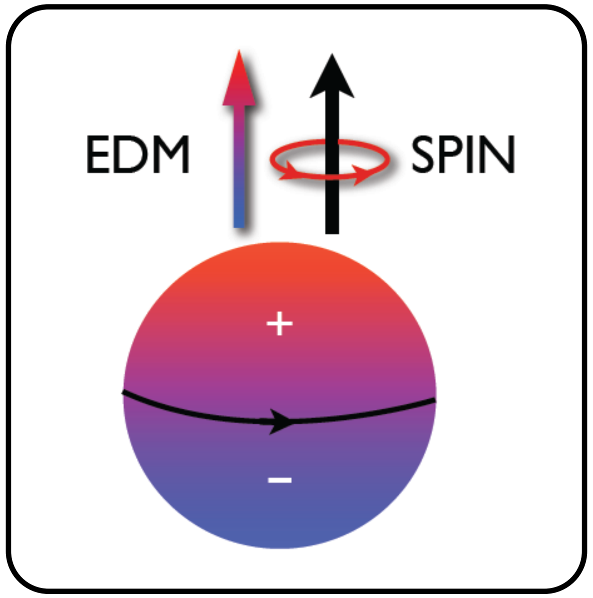
Chupp, Fierlinger, Ramsey-Musolf, Singh, 1710.02504

Electric dipole moments

- EDMs of *non-degenerate* systems violate P and T: $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$

Classical picture →

Quantum level:
Wigner-Eckart theorem



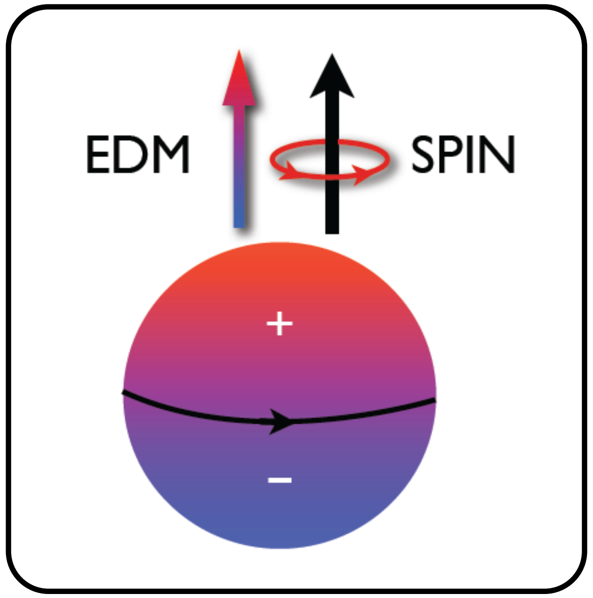
$$\vec{d} = \sum_i q_i\,\vec{r}_i$$

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

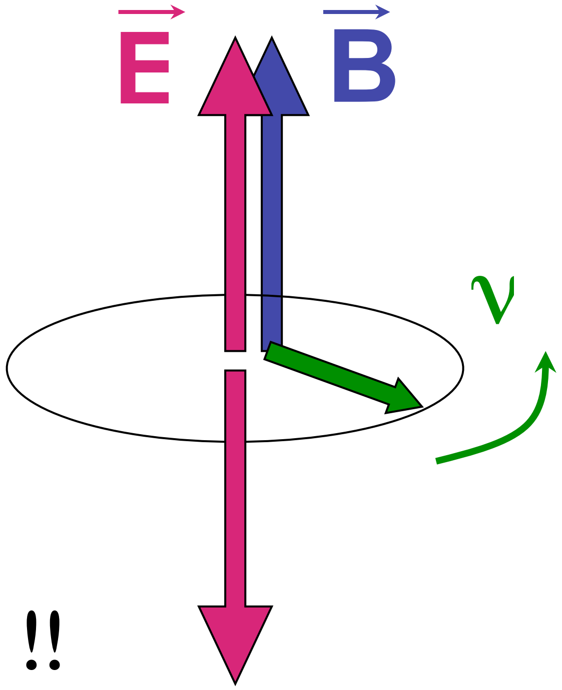
CPT invariance ⇒ nonzero EDMs signal CP violation

Electric dipole moments

- EDMs of *non-degenerate* systems violate P and T: $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$



- Measurement: look for linear shift in precession frequency due to external E field



$$\nu = (2\mu B \pm 2dE)/h$$

Current 90%CL neutron bound $d_n < 3 \times 10^{-13}$ e cm !!

Baker et al., PRL 97 131801 (2006)

Electric dipole moments

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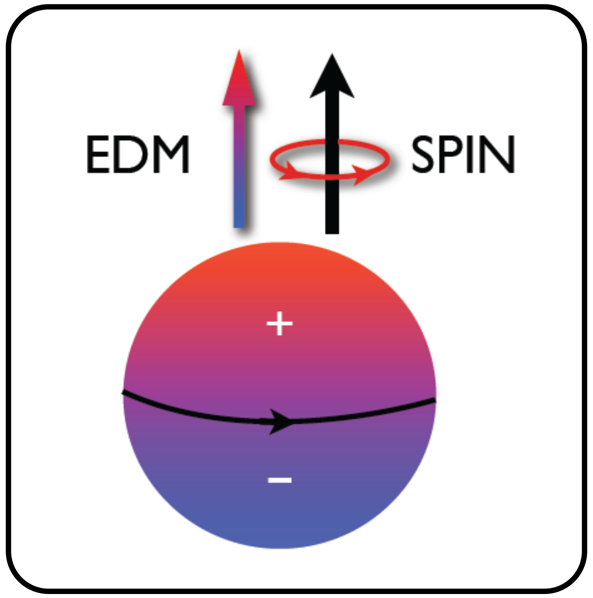

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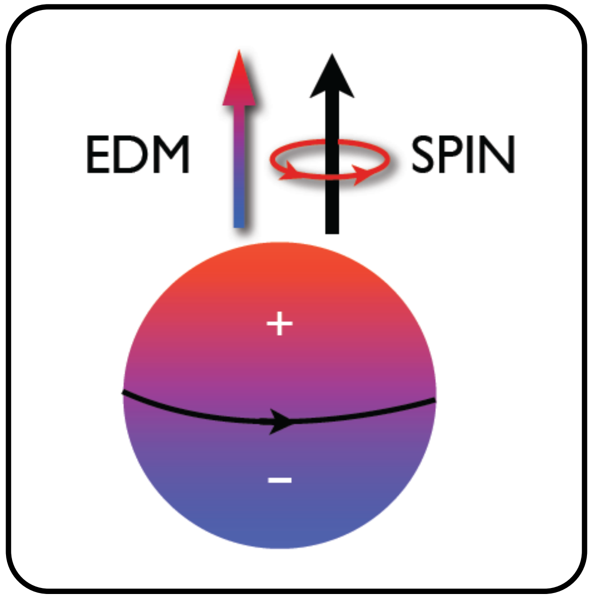
Baker et al., PRL 97 131801 (2006)

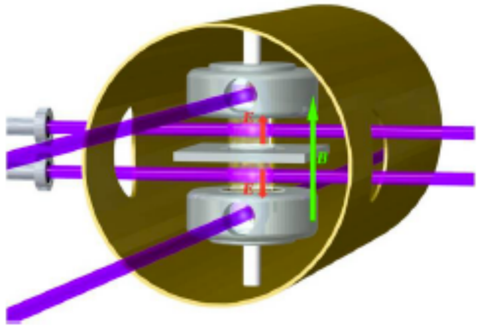
Neutron = Earth

Charge separation = human hair

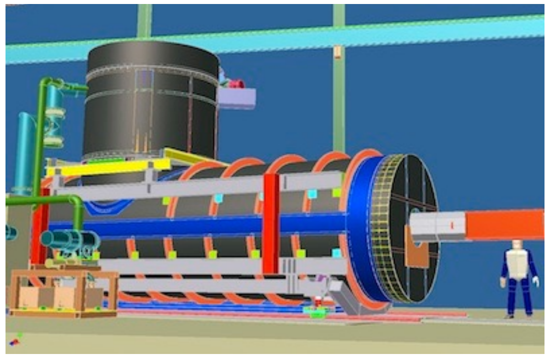
Electric dipole moments

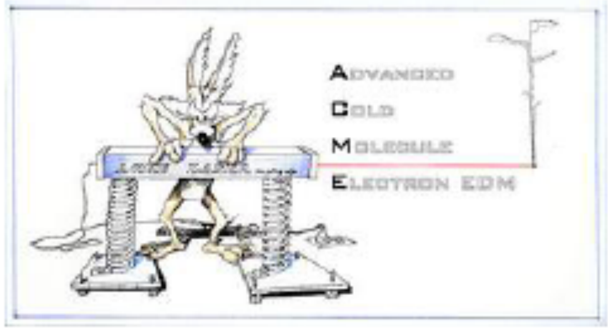
- EDMs of *non-degenerate* systems violate P and T: $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$





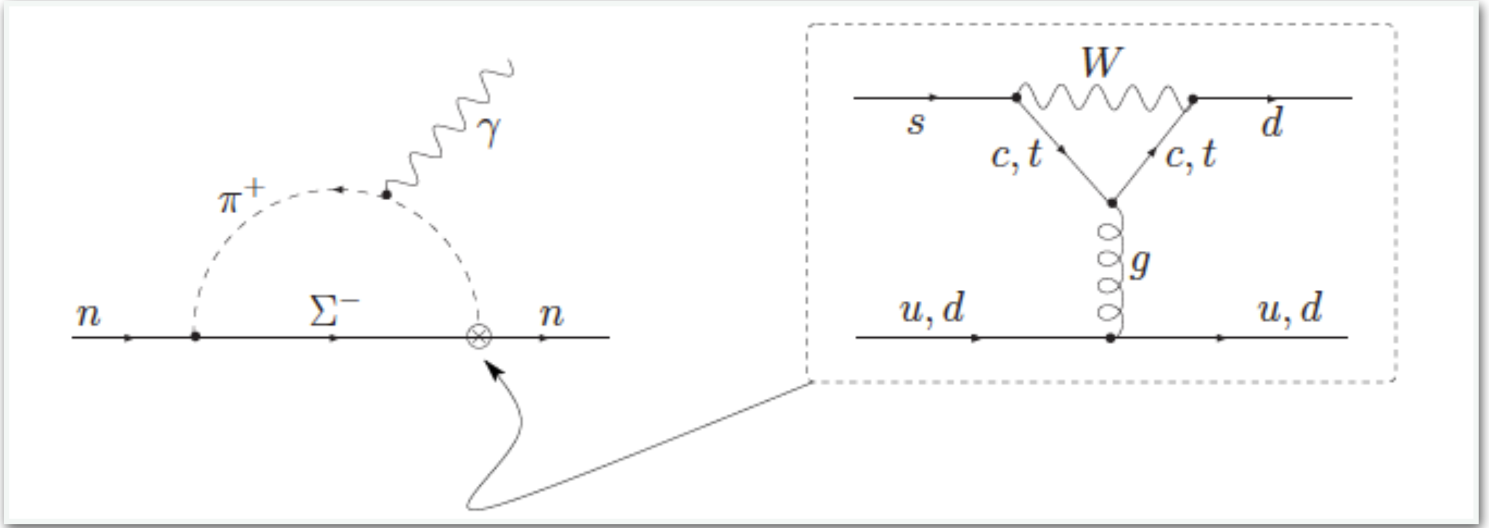
- Ongoing and planned searches in several systems, probing different sources of T (CP) violation
    - ★ n, p
    - ★ Light nuclei: d, t, h
    - ★ Atoms: diamagnetic (^{129}Xe, ^{199}Hg, ^{225}Ra, ...);
      paramagnetic (^{205}Tl, ...)
    - ★ Molecules: YbF, ThO, ...





EDMs in the Standard Model?

- Weak interactions (CPV in u_i-d_j-W vertex): highly suppressed



Dominant "long-distance" contribution to nEDM

$d_n \sim 10^{-31}$ e cm

Pospelov-Ritz hep-ph/0504231
C.Y. Seng 1411.1476

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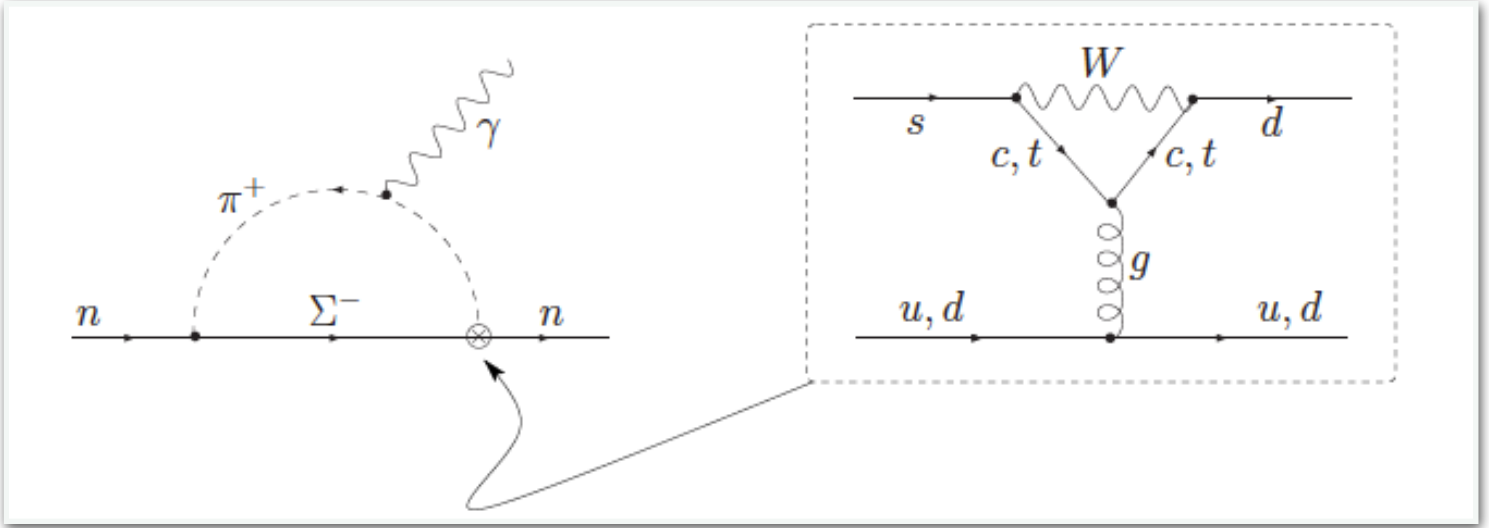

Dominant "long-distance" contribution to nEDM

$d_n \sim 10^{-31}$ e cm

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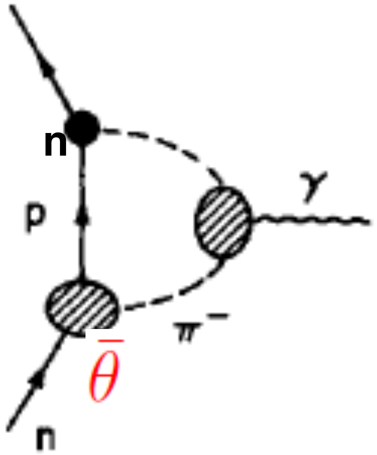
- Strong interactions (complex quark mass $m_* \bar{\theta}$): potentially large but…



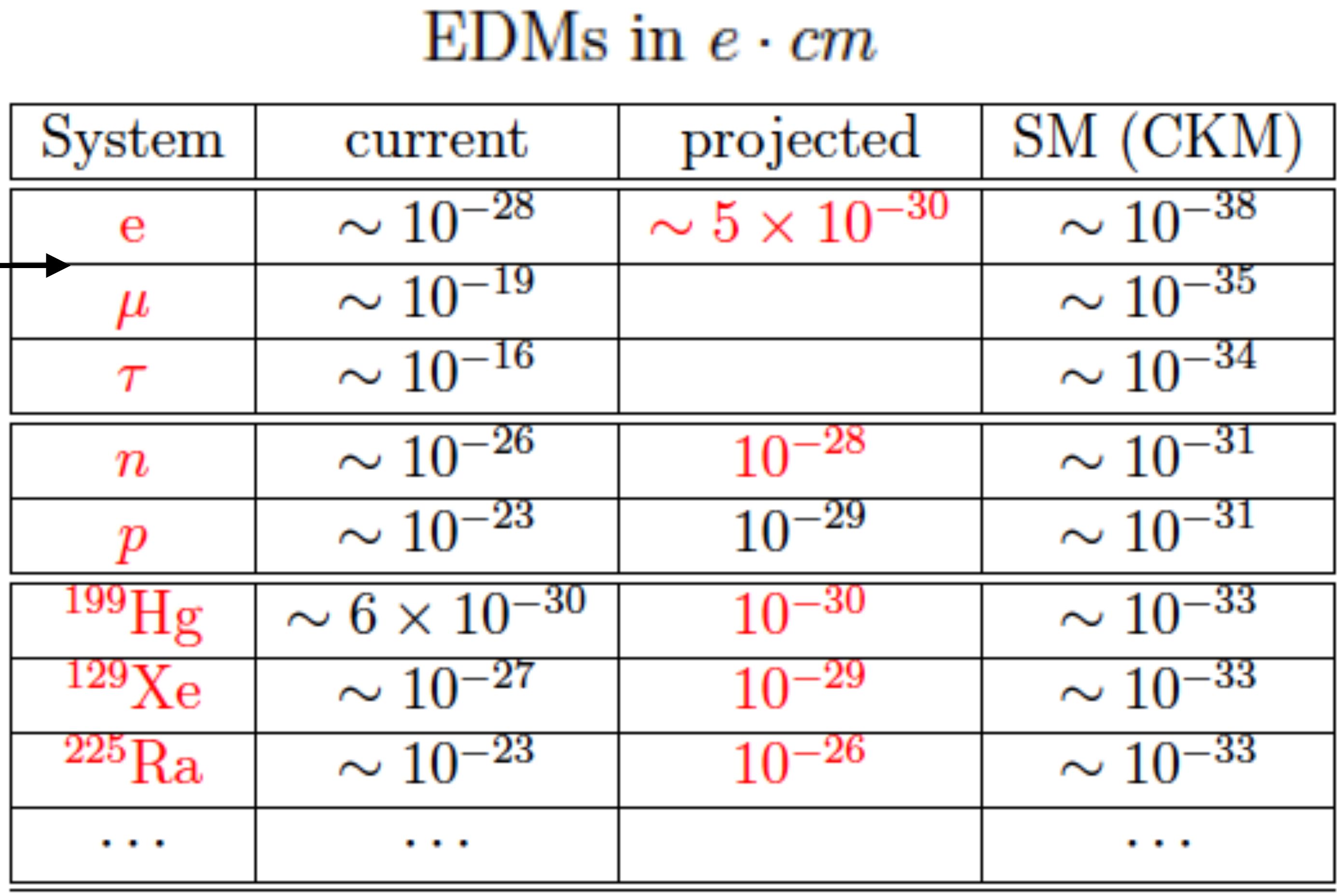
$$d_n \sim \frac{m_*}{\Lambda^2_{\rm had}} e\bar{\theta} \sim 10^{-17}\,\bar{\theta}\,e\mathrm{cm} \rightarrow |\bar{\theta}| < 10^{-9}$$

$$m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$

Motivated mechanisms to dynamically relax $\bar{\theta}$ to zero

EDMs as probes of new physics

- Essentially free of SM “background” (CKM)*



EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	$\sim 5 \times 10^{-30}$	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29}	$\sim 10^{-31}$
^{199}Hg	$\sim 6 \times 10^{-30}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
$\cdots$	$\cdots$		$\cdots$

Th0 →

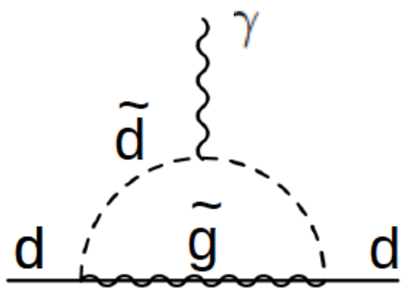
* Observation would signal new physics or a tiny QCD θ-term (< 10^{-10}). Multiple measurements can disentangle the two effects

For a recent review: Chupp, Fierlinger, Ramsey-Musolf, Singh, 1710.02504

EDMs as probes of new physics

- Essentially free of SM “background” (CKM)*

- Probe high-scales, up to Λ~10^2-3 TeV



$$\boxed{\frac{\alpha_s}{4\pi}\frac{v^2}{M^2_{SUSY}} \times \phi_{CP} \times 10^{-22}\, e\,\mathrm{cm}}$$

- Probe key ingredient for bayrogenesis (CPV in SM is insufficient)

EDMs in $e \cdot cm$

Th0 →

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e	$\sim 10^{-28}$	$\sim 5 \times 10^{-30}$	$\sim 10^{-38}$
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...	...		...

* Observation would signal new physics or a tiny QCD θ-term (< 10^{-10}). Multiple measurements can disentangle the two effects

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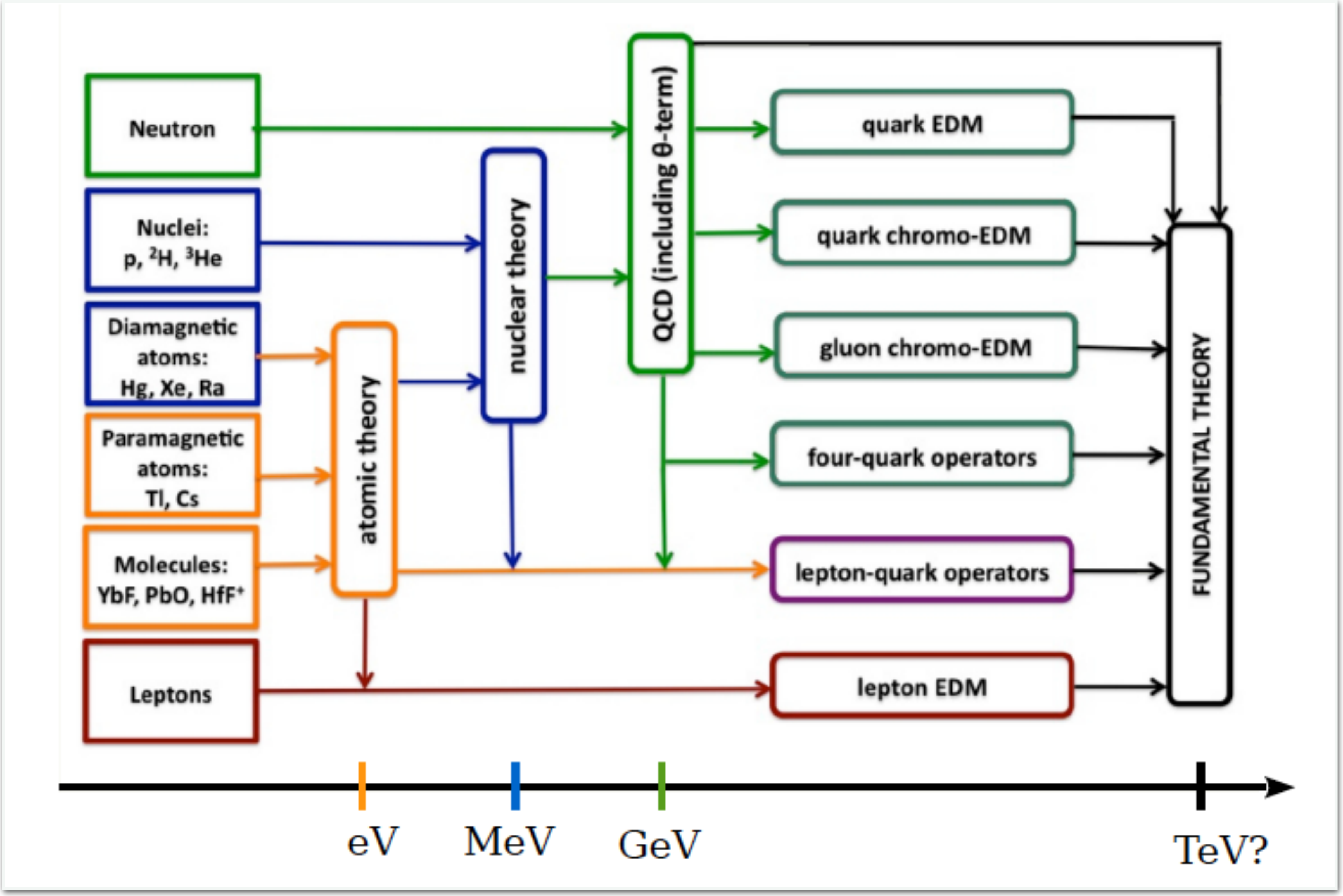
The EDM inverse problem



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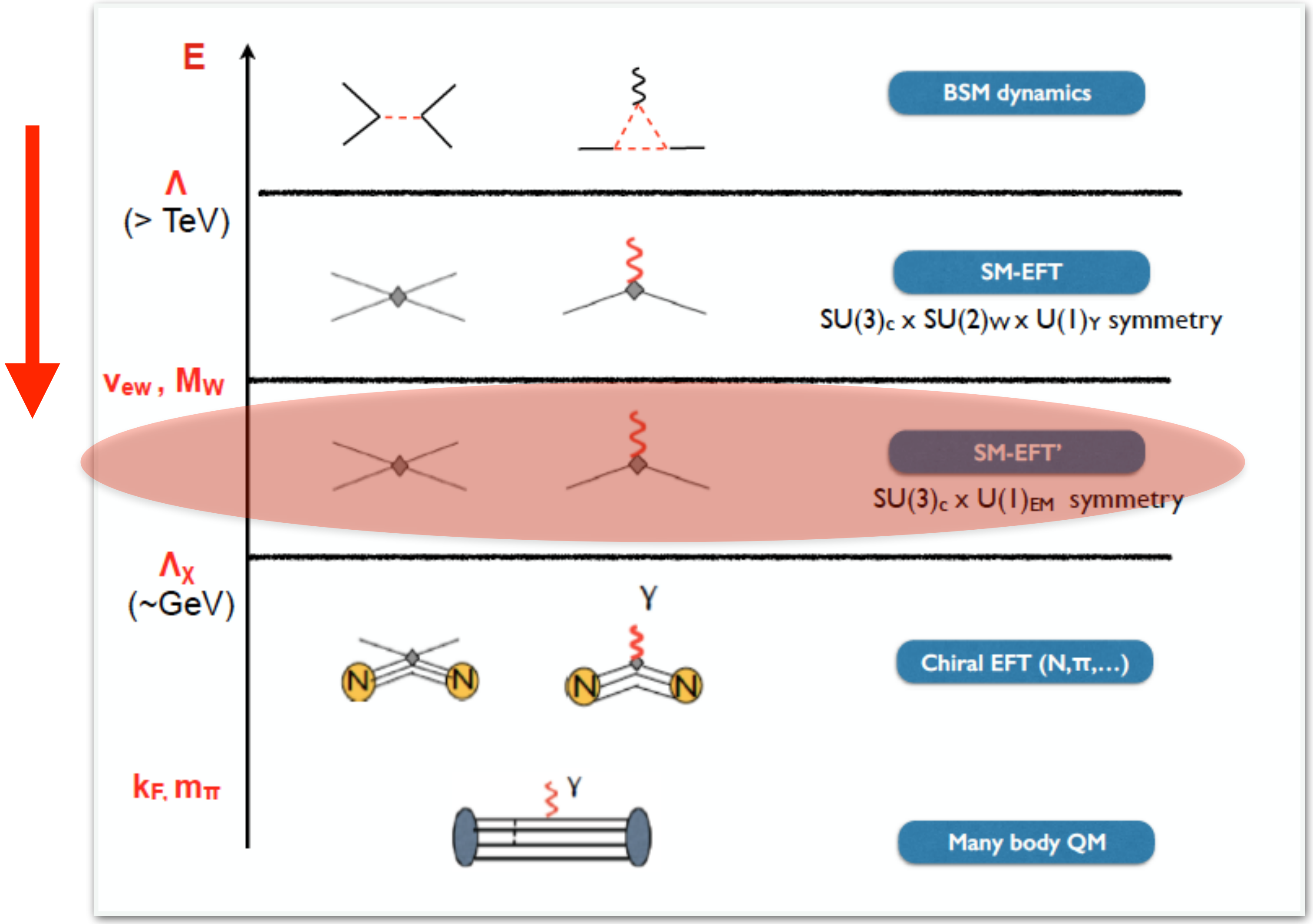
CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading dim=6 operators



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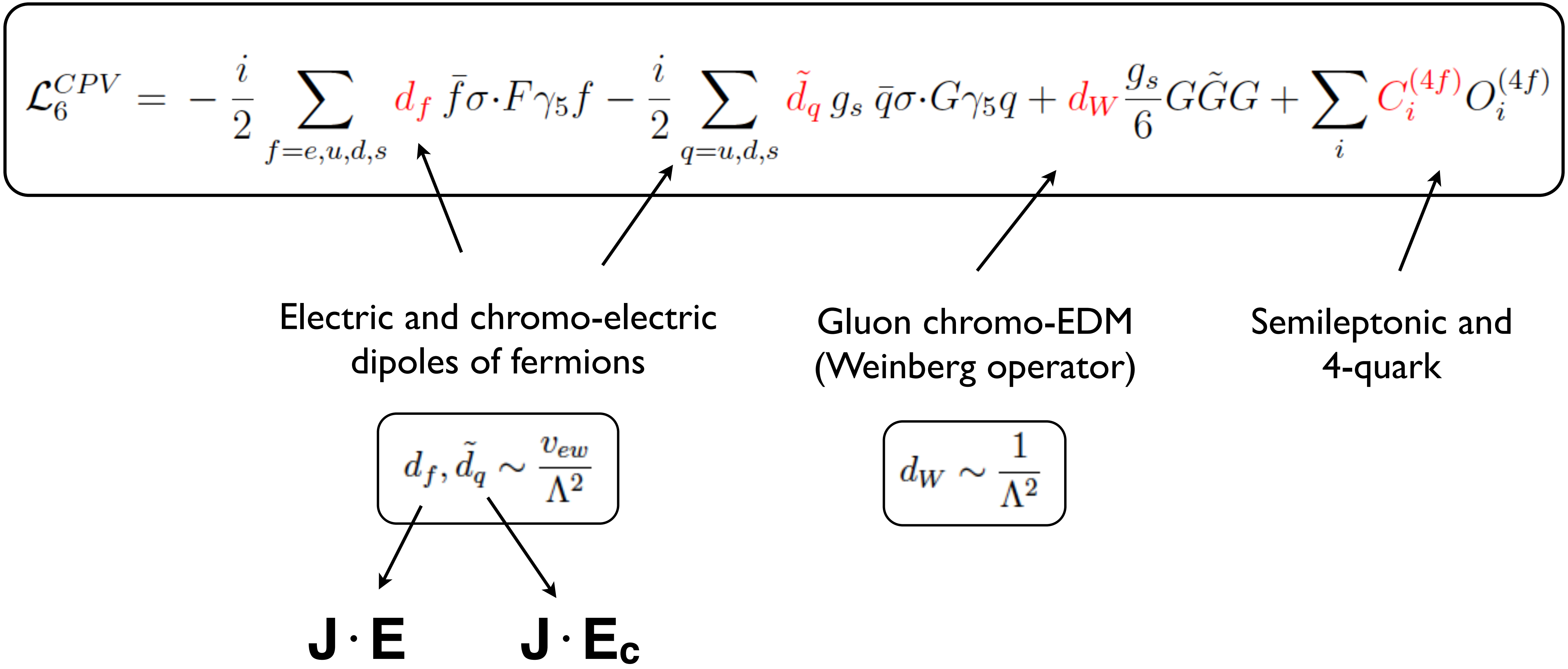


$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\,\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\,g_s\,\bar{q}\sigma\cdot G\gamma_5 q + d_W\frac{g_s}{6}G\tilde{G}G + \sum_i C_i^{(4f)}O_i^{(4f)}$$

Electric and chromo-electric dipoles of fermions

Gluon chromo-EDM (Weinberg operator)

Semileptonic and 4-quark

$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

$$d_W \sim \frac{1}{\Lambda^2}$$

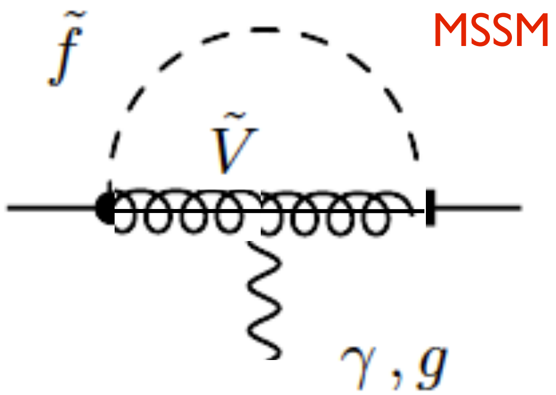
$\mathbf{J}\cdot\mathbf{E}$ $\mathbf{J}\cdot\mathbf{E}_c$

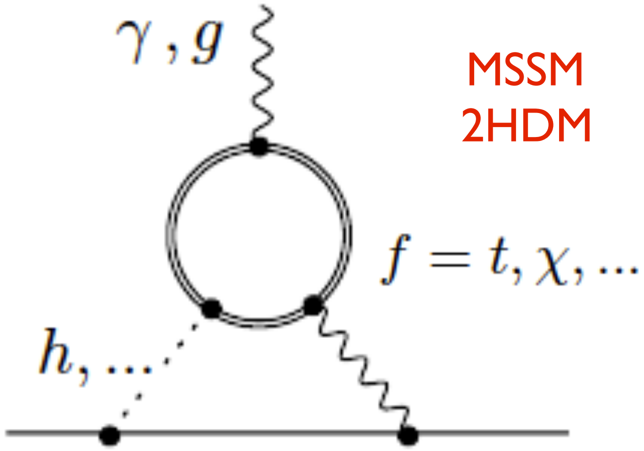
CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading dim=6 operators

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\,\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\, g_s\,\bar{q}\sigma\cdot G\gamma_5 q + d_W\frac{g_s}{6}G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

- Generated by a variety of BSM scenarios





→ Quark EDM and chromo-EDM

CPV at the quark-gluon level

- CPV at hadronic scale, induced by leading dim=6 operators

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\,\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\,g_s\,\bar{q}\sigma\cdot G\gamma_5 q + d_W\frac{g_s}{6}G\tilde{G}G + \sum_i C_i^{(4f)}O_i^{(4f)}$$

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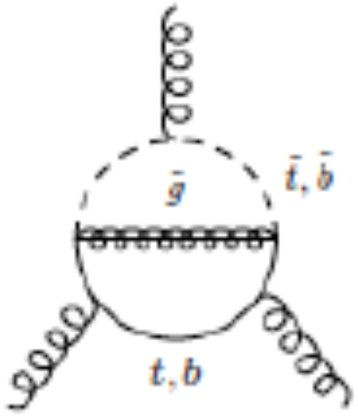
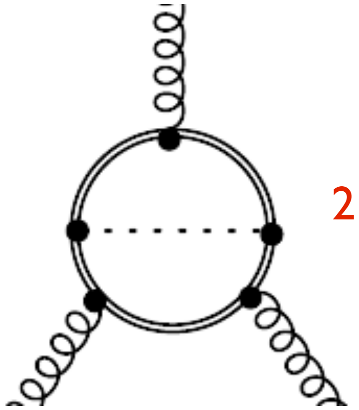


MSSM



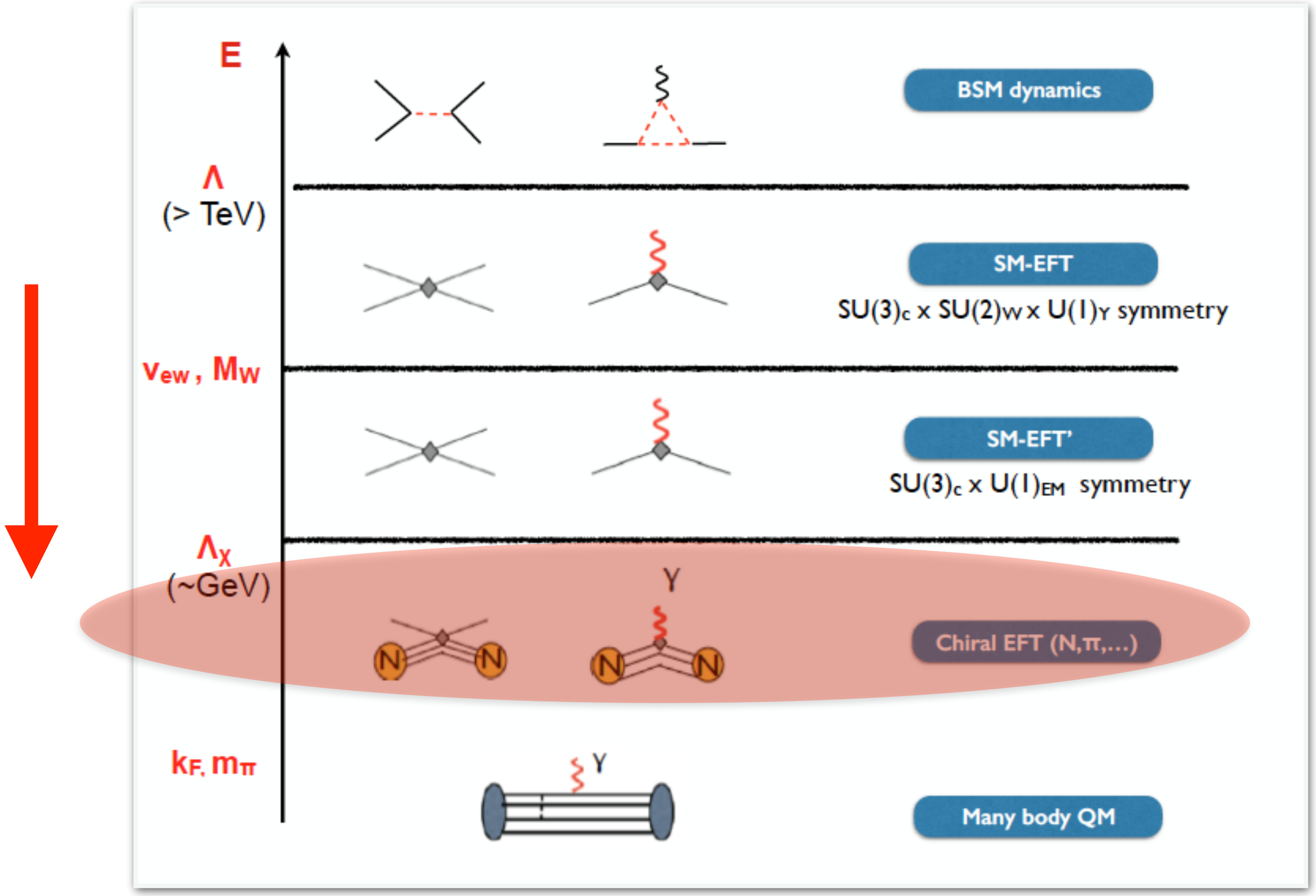
2HDM

→

Weinberg operator

CPV at the hadronic level

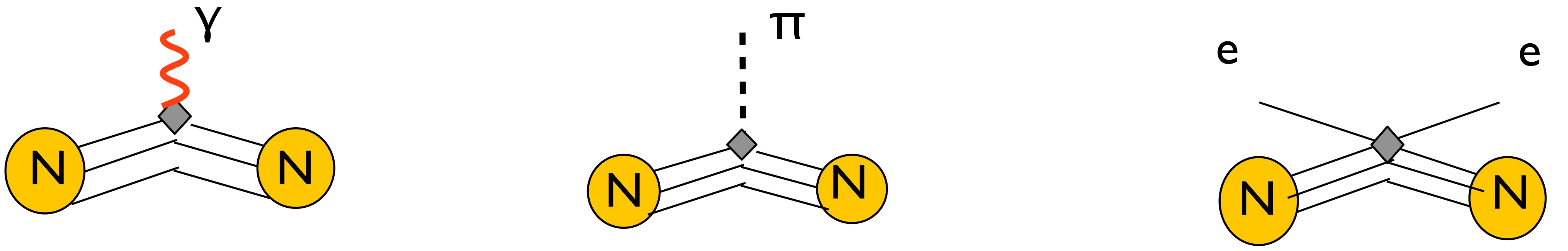
- Leading pion-nucleon CPV interactions characterized by few LECs



CPV at the hadronic level

- Leading pion-nucleon CPV interactions characterized by few LECs

$$\tilde{\mathcal{L}}_{\mathrm{CPV}} = -\frac{i}{2}\sum_{i=n,p,e} d_i\,\bar{\psi}_i\,\sigma\cdot F\gamma_5\,\psi_i - \bar{N}\left[\bar{g}_0\,\vec{\tau}\cdot\vec{\pi} + \bar{g}_1\,\pi^0\right]N + \ldots$$



Electron and Nucleon EDMs

T-odd P-odd pion-nucleon couplings

Short-range 4N and 2N2e coupling

$d_N[d_q]$ known with 10% uncertainty (lattice QCD)

Other $d_N[c_\alpha]$ $\quad \bar{g}_{0,1}[c_\alpha]$ $\quad \ldots$ O(100%) uncertainty

CPV at the hadronic level

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Lattice QCD calculation: Bhattacharya et al 1506.04196

$$\begin{aligned} d_n &= -(0.22\pm0.03)d_u + (0.74\pm0.07)d_d + (0.0077\pm0.01)d_s \\ &\quad -(0.55\pm0.28)e\tilde{d}_u - (1.1\pm0.55)e\tilde{d}_d \pm (50\pm40)\,\mathrm{MeV}\,e\,d_W \end{aligned}$$

μ=1 GeV

Pospelov-Ritz hep-ph/0504231 and refs therein

QCD Sum Rules (50% guesstimate)

QCD Sum Rules + NDA (~100%)

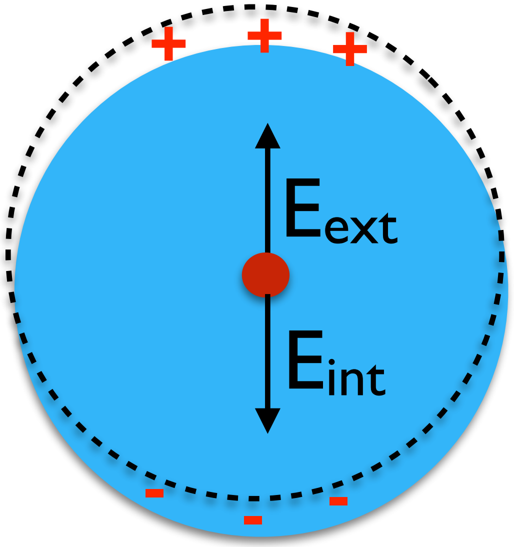
$$\bar{g}_0 = (5\pm10)(\tilde{d}_u+\tilde{d}_d)\,\mathrm{fm}^{-1}\ , \qquad \bar{g}_1 = (20^{+40}_{-10})(\tilde{d}_u-\tilde{d}_d)\,\mathrm{fm}^{-1}$$

Pospelov-Ritz hep-ph/0504231 and refs therein

Towards lattice QCD calculation: Walker-Loud and Mereghetti

CP Violation at atomic level

- Need to work against Schiff's theorem: no atomic EDM due to d_e, d_{nucl} (charged constituents rearrange to screen applied E_{ext})



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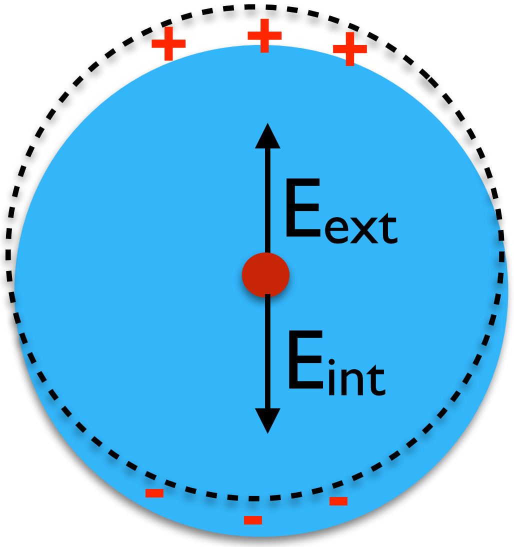
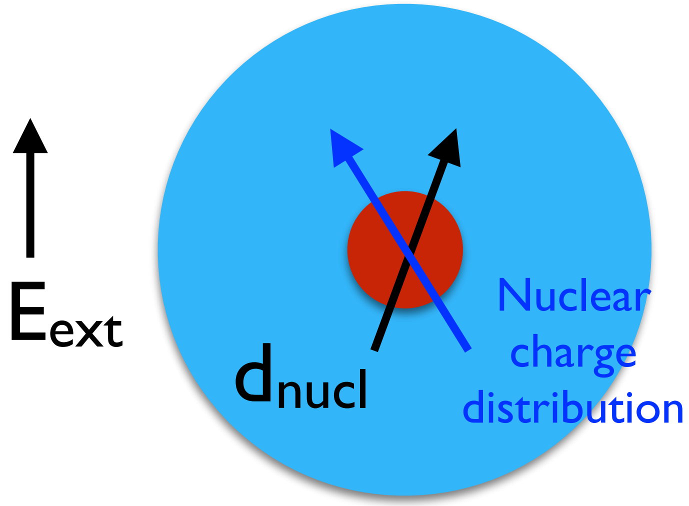


- Need to work against Schiff's theorem: no atomic EDM due to d_e, d_{nucl} (charged constituents rearrange to screen applied E_{ext})

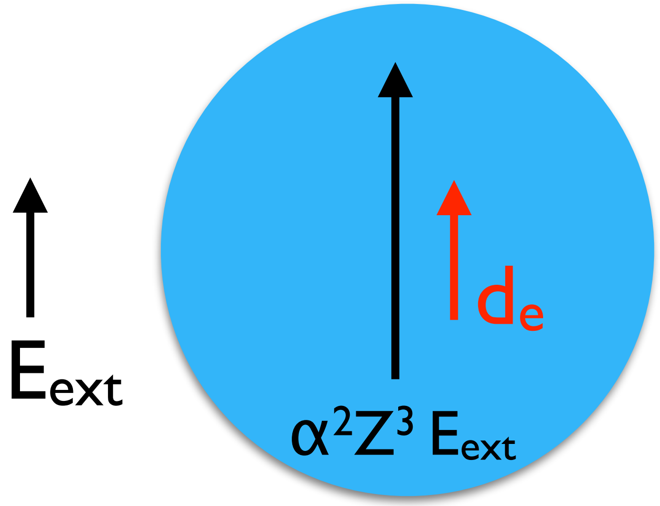
- Evading Schiff screening: finite size effects in diamagnetic atoms make $d_A[d_{nucl}] \neq 0$. Suppression $d_A \sim Z^2 (R_N/R_A)^2 d_{nucl}$

Schiff 1963



- Evading Schiff screening: relativistic effects in paramagnetic atoms (and molecules) make $d_A[d_e] \neq 0$. Enhancement $d_A \sim \alpha^2 Z^3 d_e$

Sandars 1965



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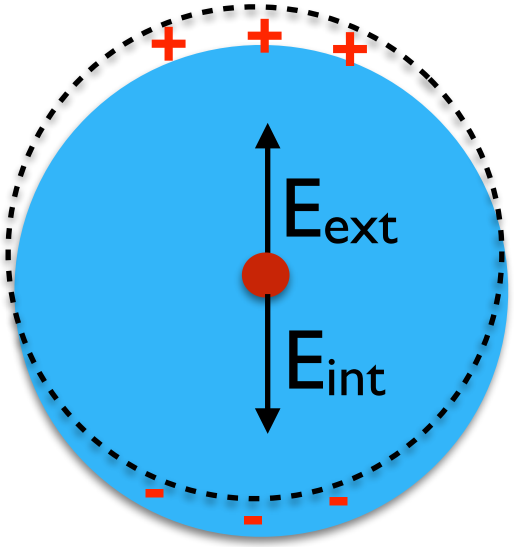
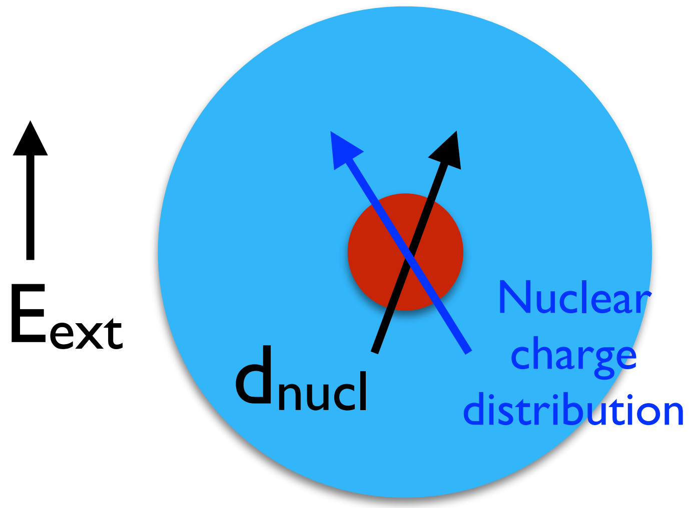


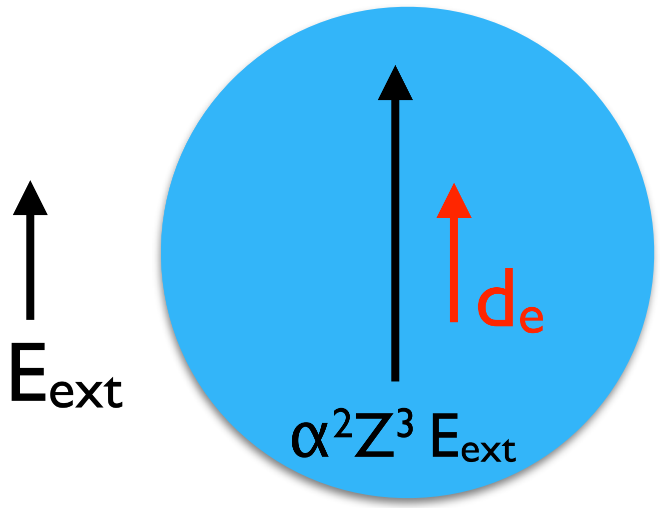
- Evading Schiff screening: finite size effects in diamagnetic atoms make $d_A[d_{nucl}] \neq 0$.

O(few 100%) uncertainties



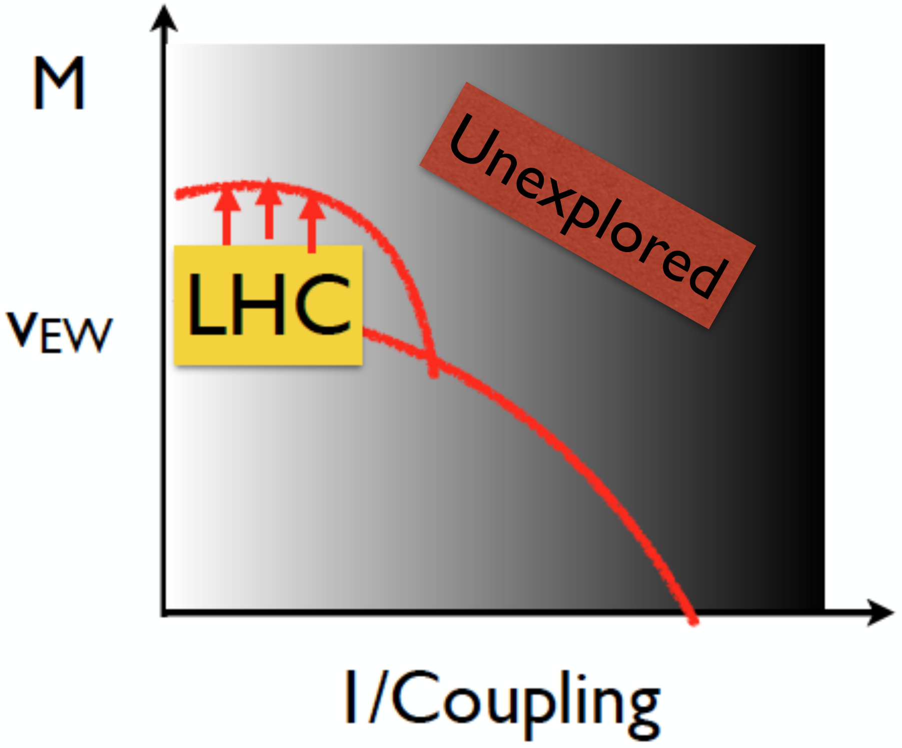
- Evading Schiff screening: relativistic effects in paramagnetic atoms (and molecules) make

O(10%) uncertainties



EDMs in the LHC era

- LHC output so far:
    - Higgs boson @ 125 GeV
    - Everything else is quite heavier (or very light)

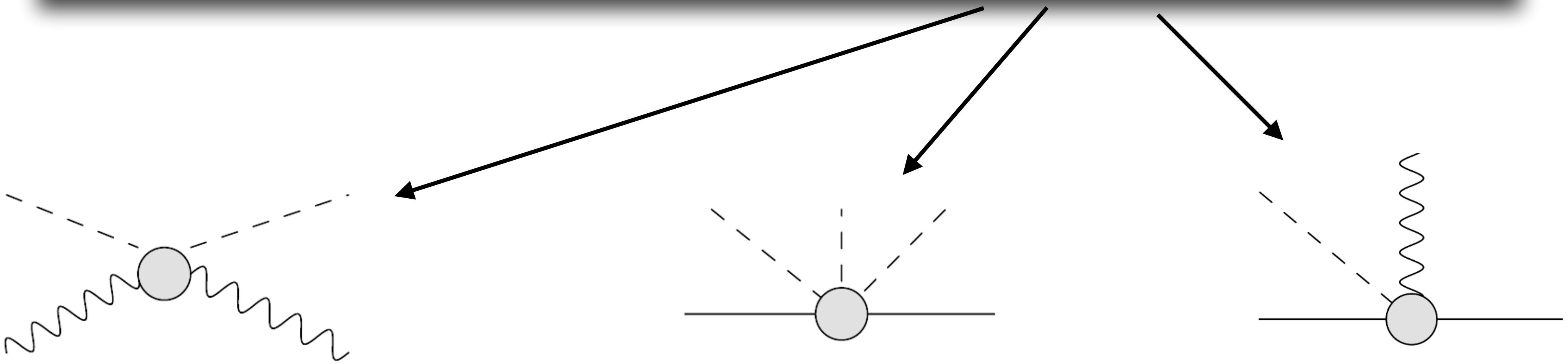


- *EDMs more relevant than ever:*
    - Strong constraints of non-standard CPV Higgs couplings
    - One of few observables probing PeV scale supersymmetry

EDMs and CPV Higgs couplings

- Several dim-6 operators in the SM-EFT involve CPV Higgs interactions

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$



H-H-V-$\tilde{V}$

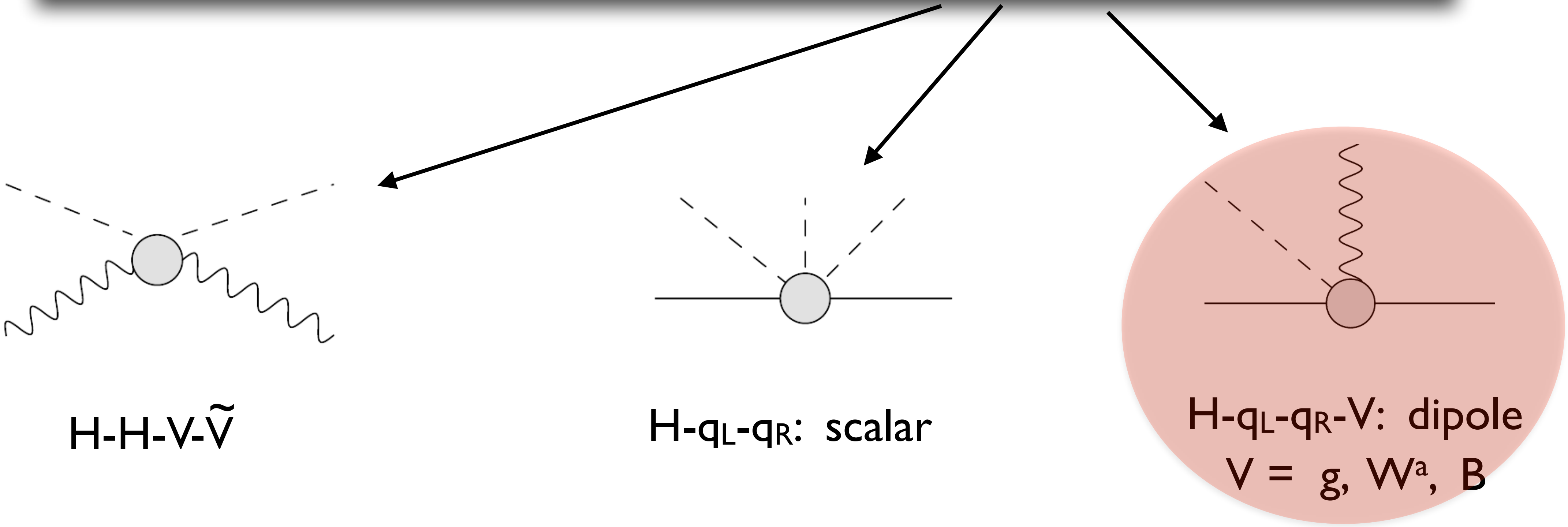
H-q_L-q_R: scalar

H-q_L-q_R-V: dipole
V = g, W^a, B

EDMs and CPV Higgs couplings

- Several dim-6 operators in the SM-EFT involve CPV Higgs interactions

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$



H-H-V-$\tilde{V}$

H-q_L-q_R: scalar

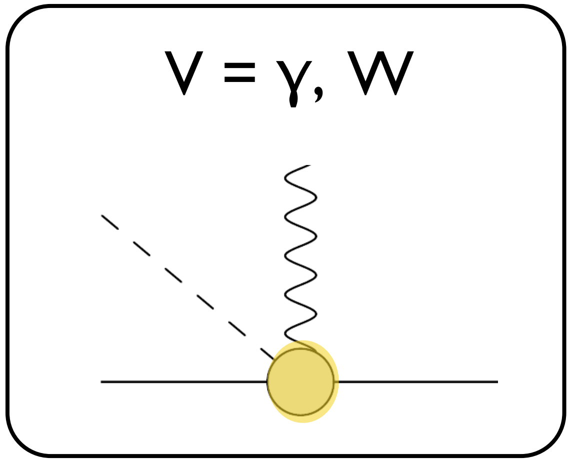
H-q_L-q_R-V: dipole
V = g, W^a, B

Rich literature. Here discuss only case of top quark EW dipoles

Higgs-top couplings

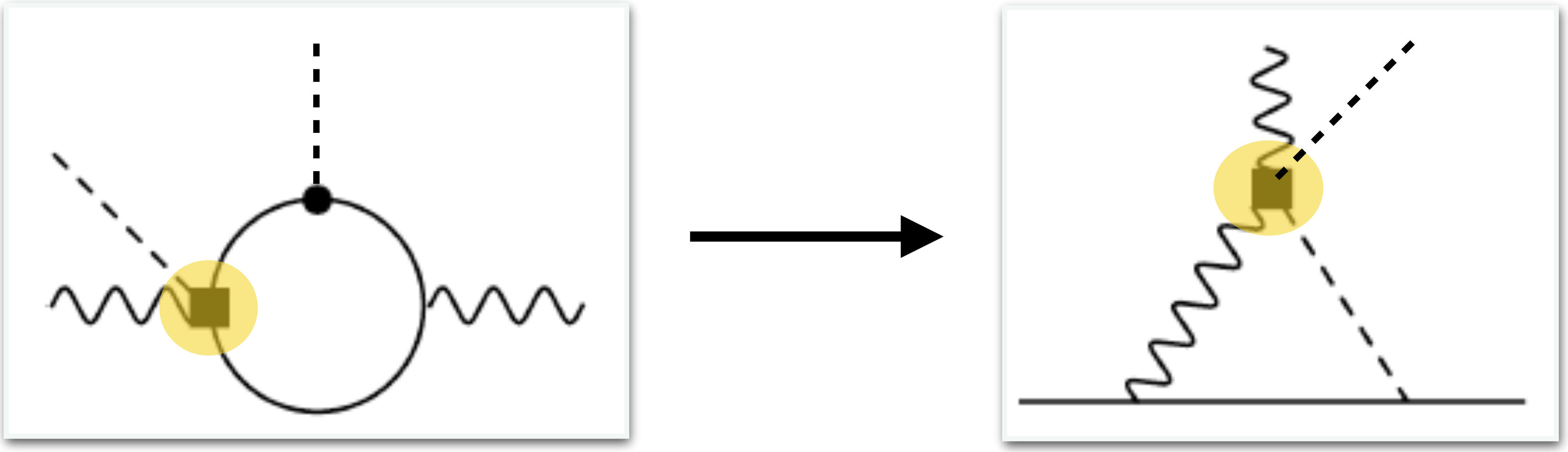
- Top quark particularly interesting: strongest coupling to Higgs; largest deviations from SM in several BSM scenarios; LHC is a top factory

C_γ, C_{Wt}



H-t_L-t_R-V: EW top dipoles

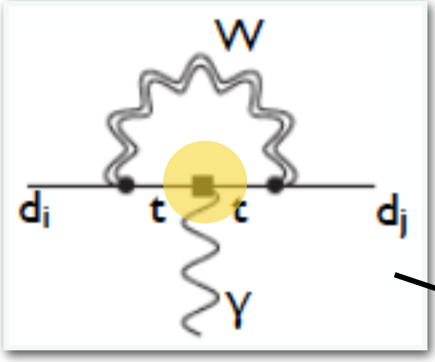
- C_γ, C_{Wt} affect eEDM and qEDMs via two-step mixing



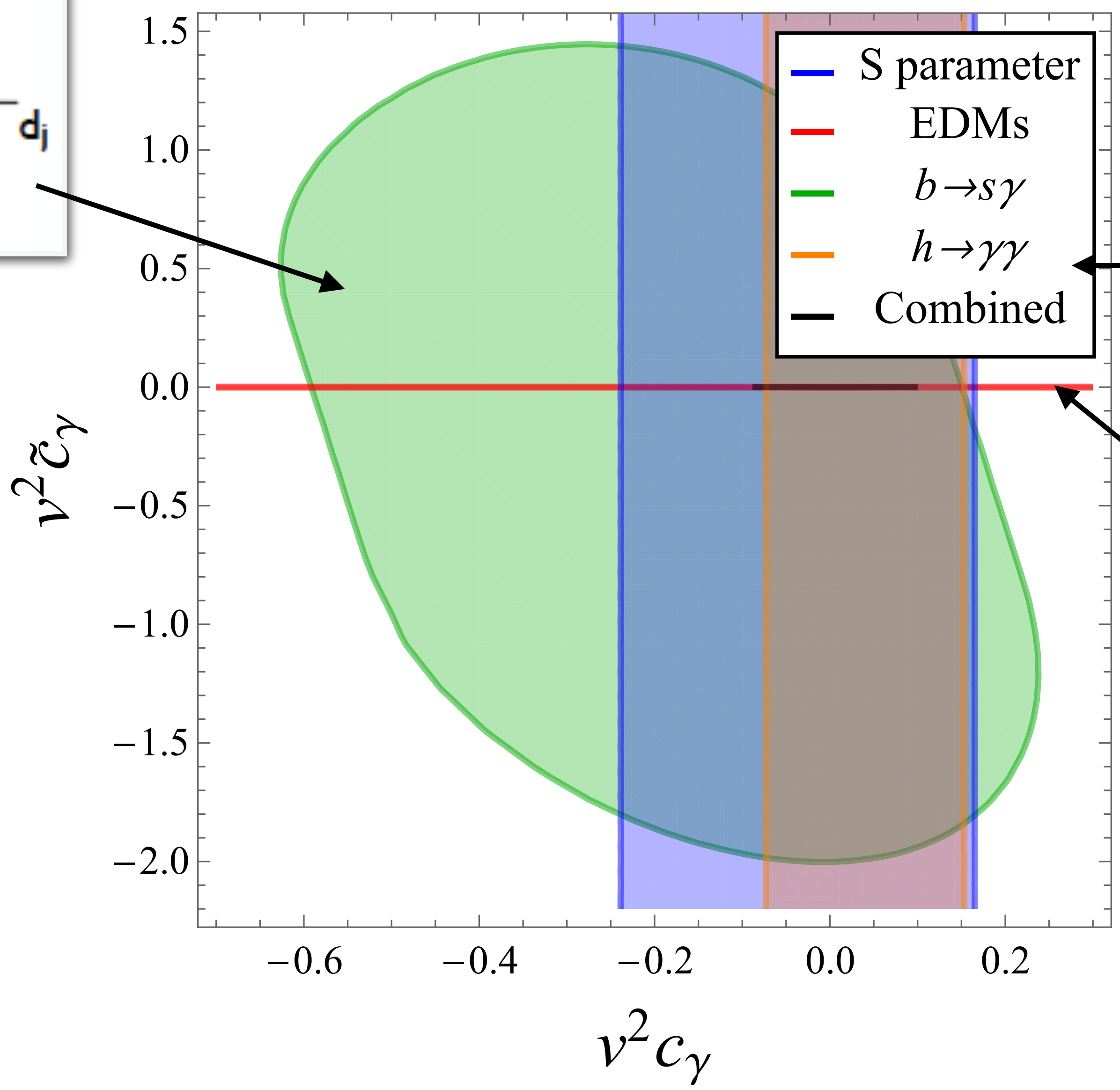
VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049
Fuyuto and Ramsey-Musolf 1706.08548

Higgs-top couplings

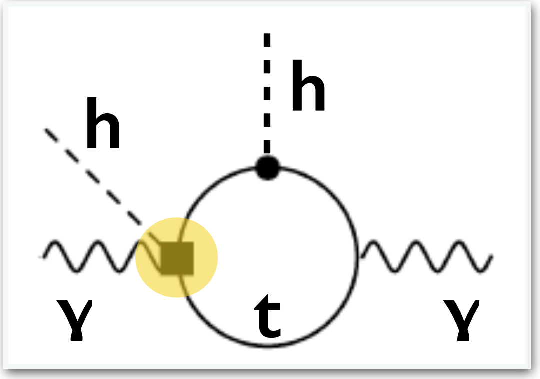
- EDM vs flavor and collider constraints

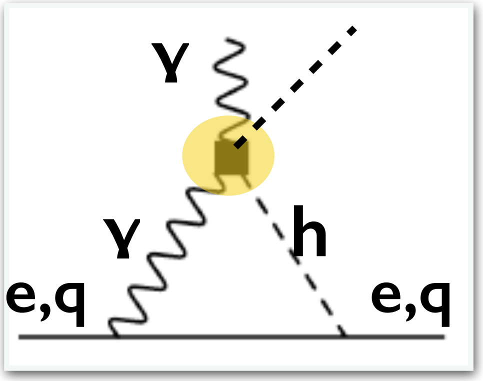


Top EDM
$d_t = eQ_t m_t \tilde{c}_\gamma$



Top MDM $\mu_t = eQ_t m_t c_\gamma$





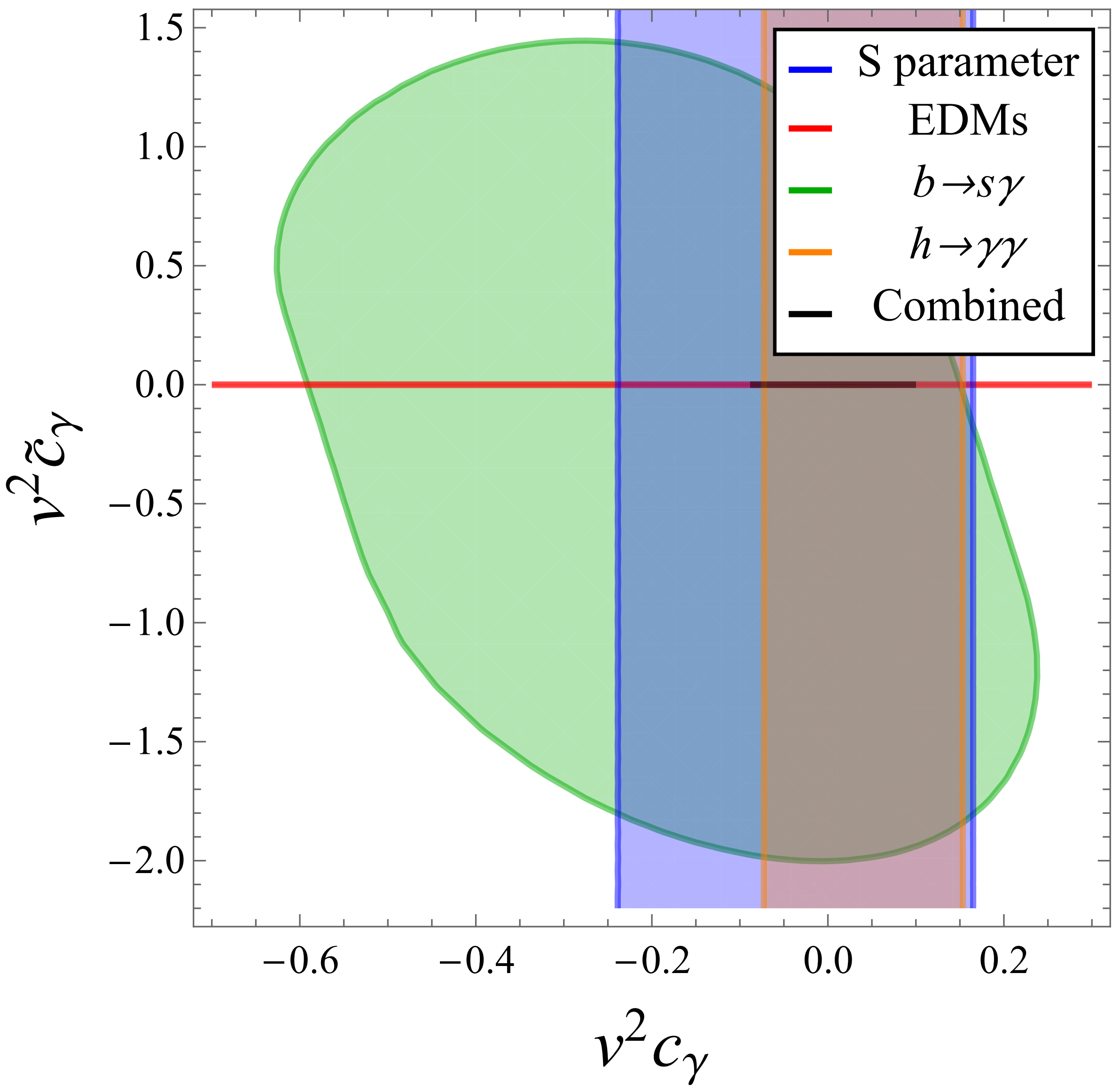
VC, W. Dekens, J. de Vries, E. Mereghetti
1603.03049

Higgs-top couplings

- EDM vs flavor and collider constraints

Top EDM

$d_t = eQ_t m_t \tilde{c}_\gamma$



Top MDM $\mu_t = eQ_t m_t c_\gamma$

Bound on top EDM improved by three orders of magnitude: $|d_t| < 5 \times 10^{-20}$ e cm

Dominated by eEDM

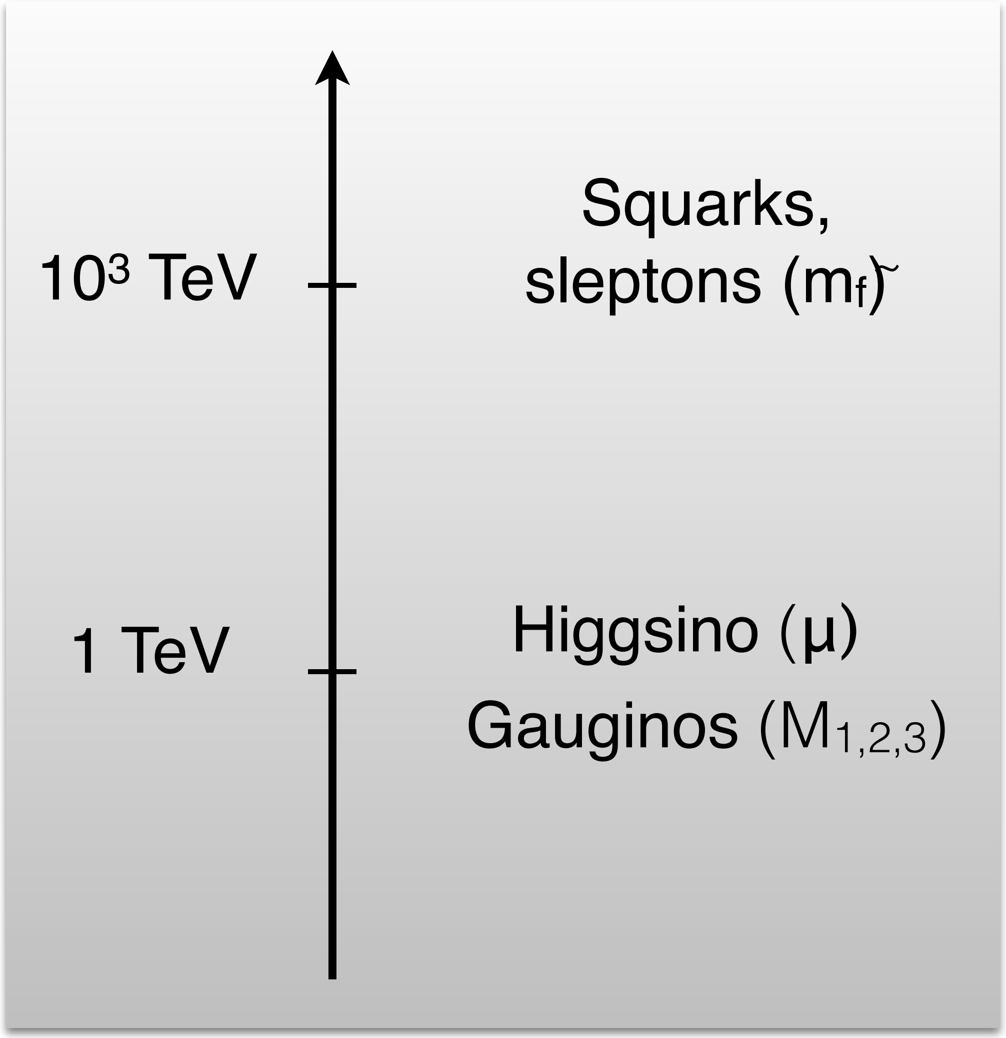
1000x stronger than direct LHC sensitivity (pp → jet t γ) **[Fael-Gehrmann 13, Bouzas-Larios 13]**

VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049

EDMs in high-scale SUSY (I)

- Higgs mass + absence of other signals point to heavy super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, Altmannshofer-Harnik-Zupan 1308.3653, …



10^3 TeV

Squarks, sleptons ($m_{\tilde{f}}$)

1 TeV

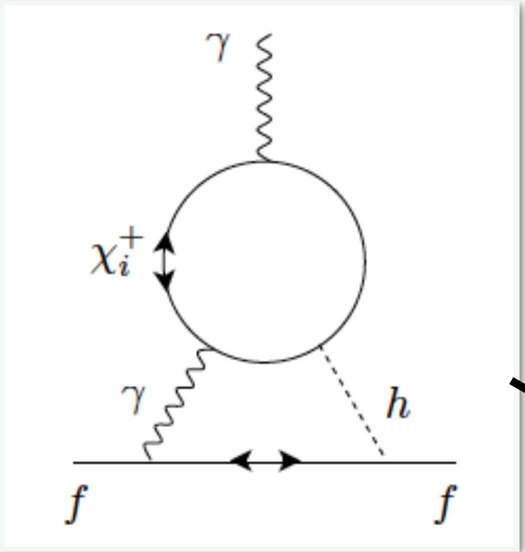
Higgsino (μ)

Gauginos ($M_{1,2,3}$)

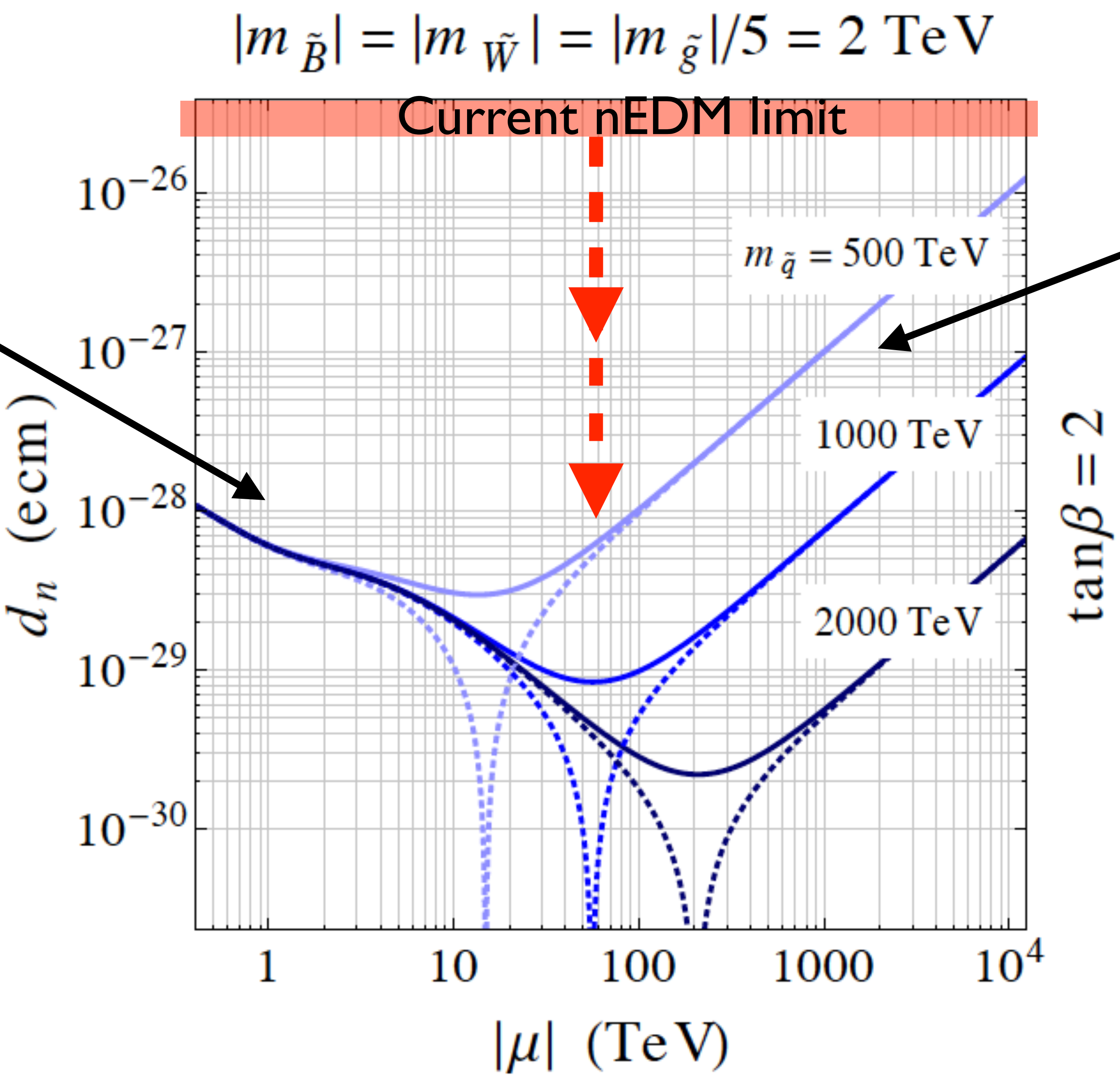
EDMs among a handful of observables capable of probing such high scales

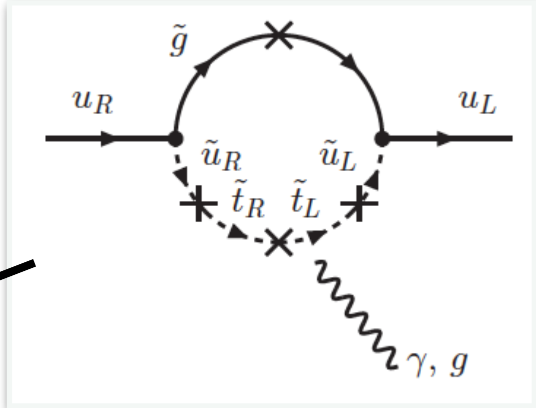
EDMs in high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



$$d_q \sim \frac{\alpha\,\alpha_w}{(4\pi)^2}\,\frac{m_q}{\mu M_2}\,\sin\phi_2$$



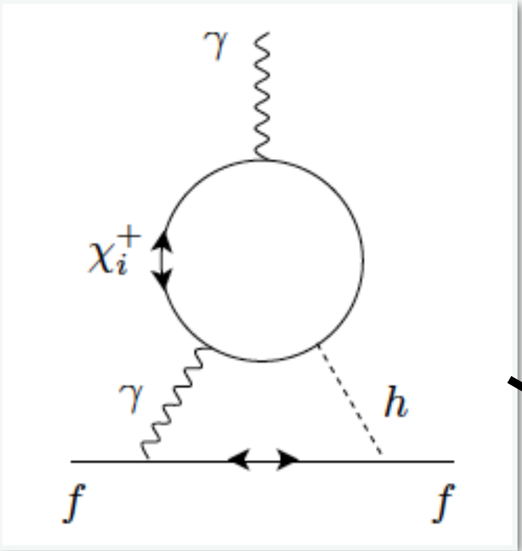


$$\tilde{d}_u \sim \frac{\alpha_s}{4\pi}\,\frac{m_t}{m_{\tilde{q}}^2}\,\frac{\mu M_3}{m_{\tilde{q}}^2}\,\delta^L_{ut}\delta^R_{tu}\,\sin\phi_u$$

Maximal CPV phases.
Squark mixings fixed at 0.3

EDMs in high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



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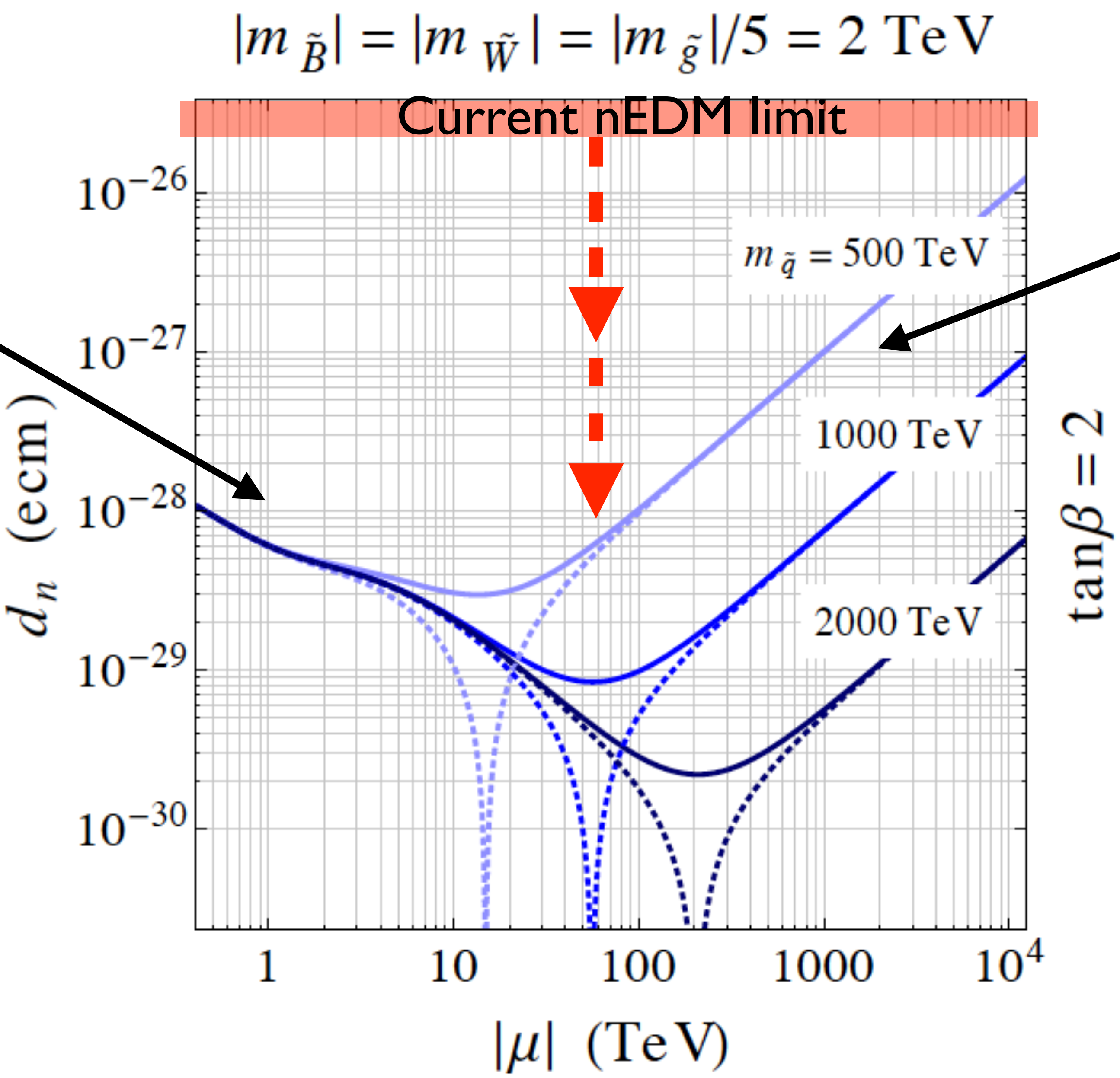
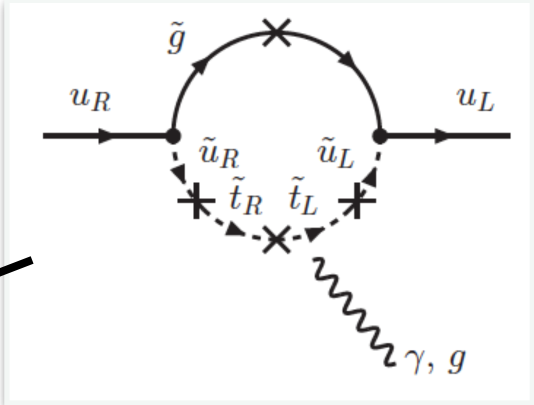




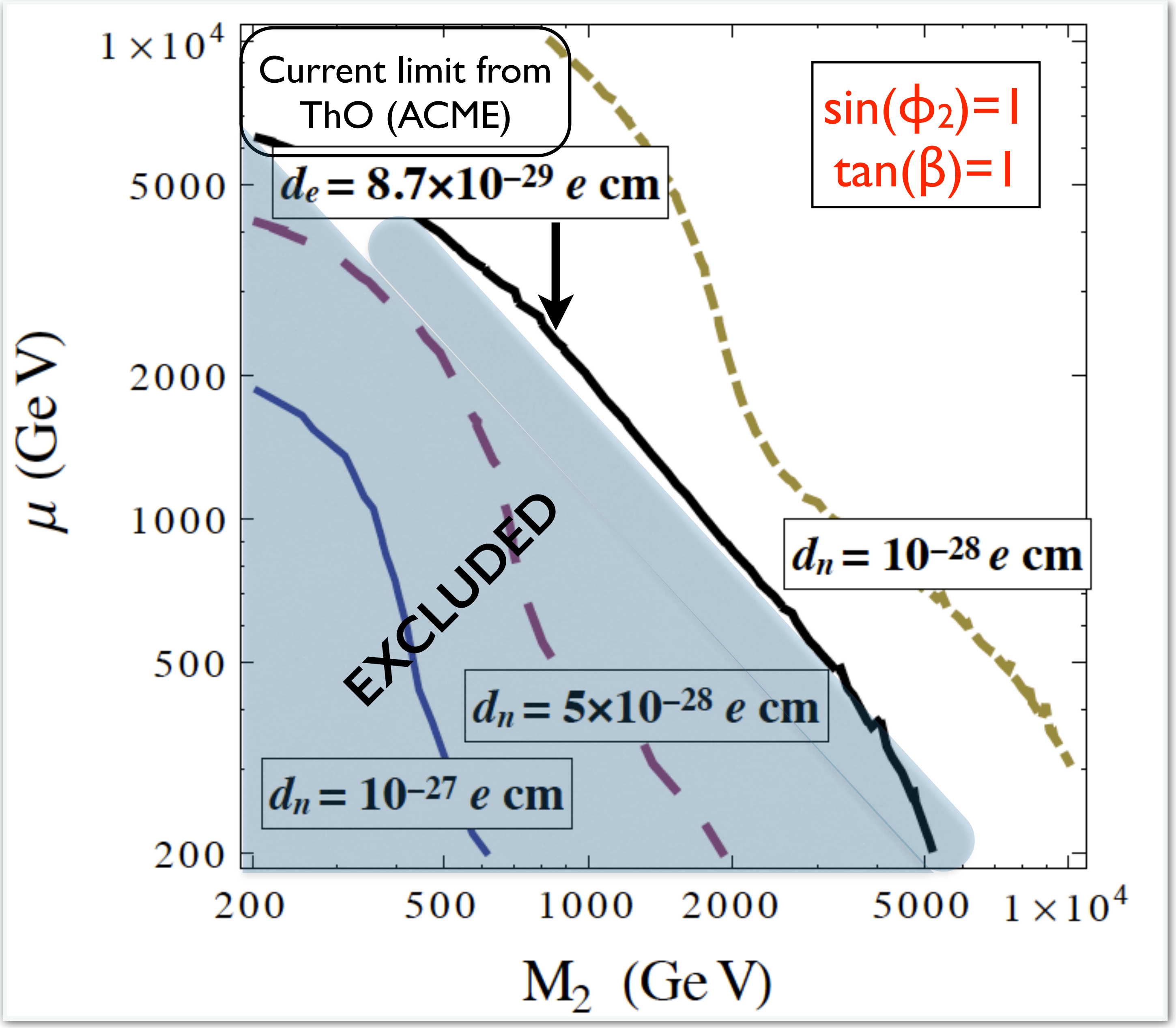
$$\tilde d_u \sim \frac{\alpha_s}{4\pi}\,\frac{m_t}{m_{\tilde q}^2}\,\frac{\mu M_3}{m_{\tilde q}^2}\,\delta^L_{ut}\delta^R_{tu}\,\sin\phi_u$$

Maximal CPV phases.
Squark mixings fixed at 0.3

For $|\mu| < 10$ TeV, $m_{\tilde q} \sim 1000$ TeV, same CPV phase controls d_e, d_n → correlation?

EDMs in high-scale SUSY (3)

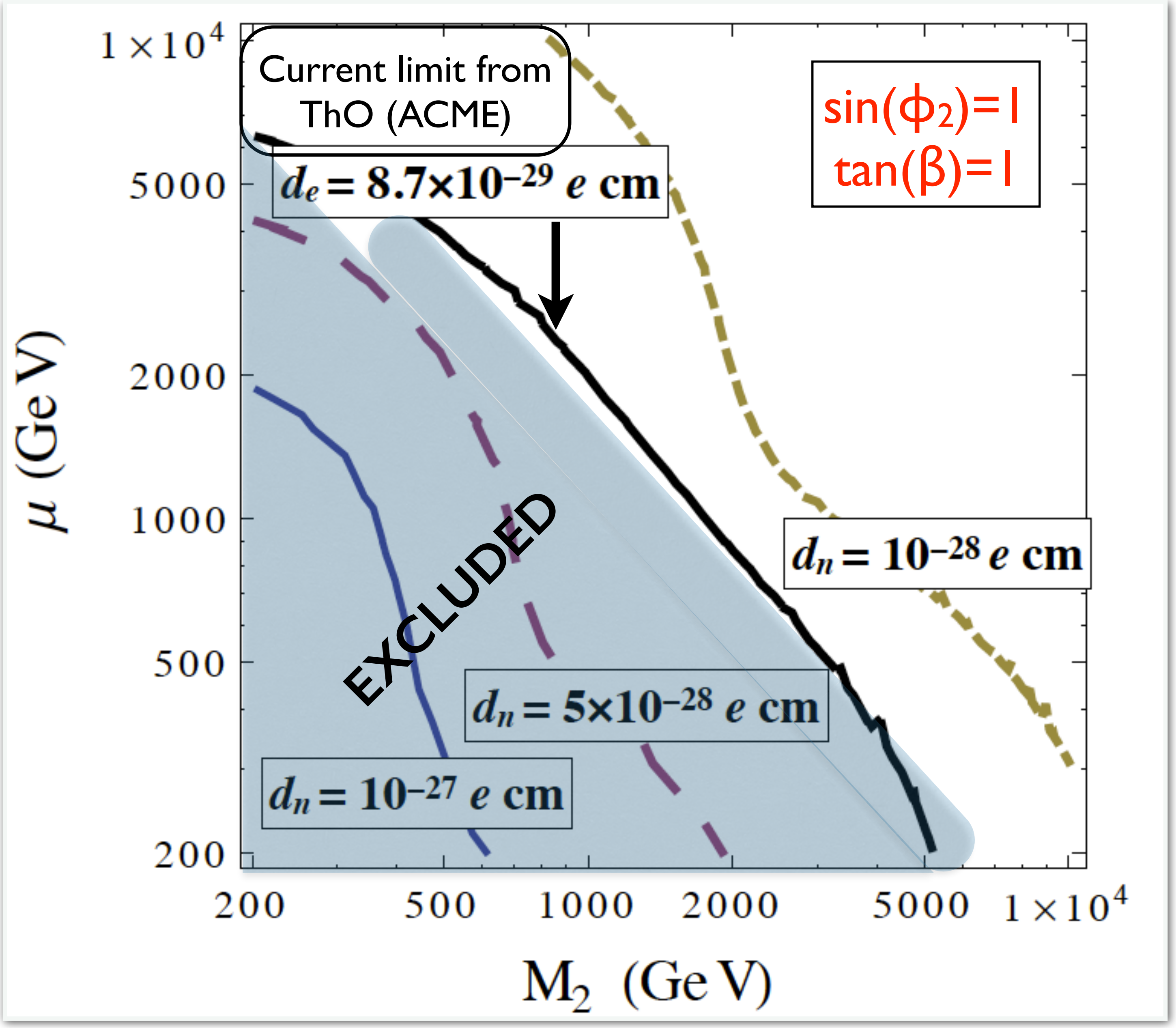
Bhattacharya, VC, Gupta, Lin, Yoon 1506.04196



- Both d_e and d_n within reach of current searches for M_2, μ < 10 TeV

EDMs in high-scale SUSY (3)

Bhattacharya, VC, Gupta, Lin, Yoon 1506.04196



- Both d_e and d_n within reach of current searches for M_2, μ < 10 TeV
- Studying the ratio d_n / d_e *with precise matrix elements (LQCD)* → stringent upper bound $d_n < 4 \times 10^{-28}$ e cm
- Split-SUSY can be falsified by current nEDM searches

Example of model diagnosing enabled by multiple measurements (e,n) and controlled theoretical uncertainty

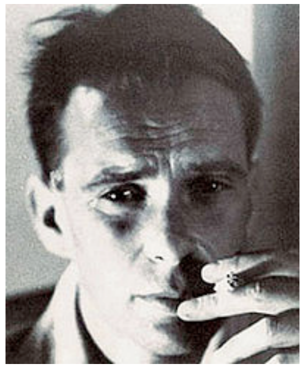
Summary

- Nuclei played a central role in the making of the Standard Model ("V-A was the key", S. Weinberg)

- Nowadays, nuclei, atoms, molecules allow us to push the SM limits
  - Probing the structure of both CC and NC weak interactions
  - Searching for processes that break global ($L_{e,\mu\tau}$, L) or discrete (CP) symmetries (sensitive to very high mass scale)

- Significant theoretical challenges associated with the interpretation of a positive or null signals!
  - Improvable by systematic use of chiral EFT and lattice QCD

Thank you!



A drawing by
Bruno Touschek

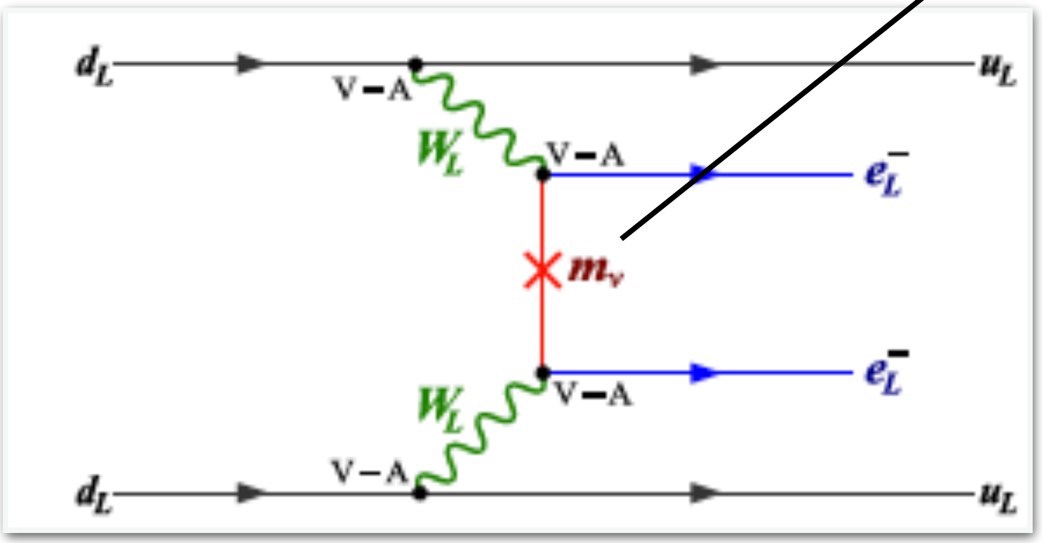
Backup material

Backup material — NLDBD

Low-scale LNV

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass

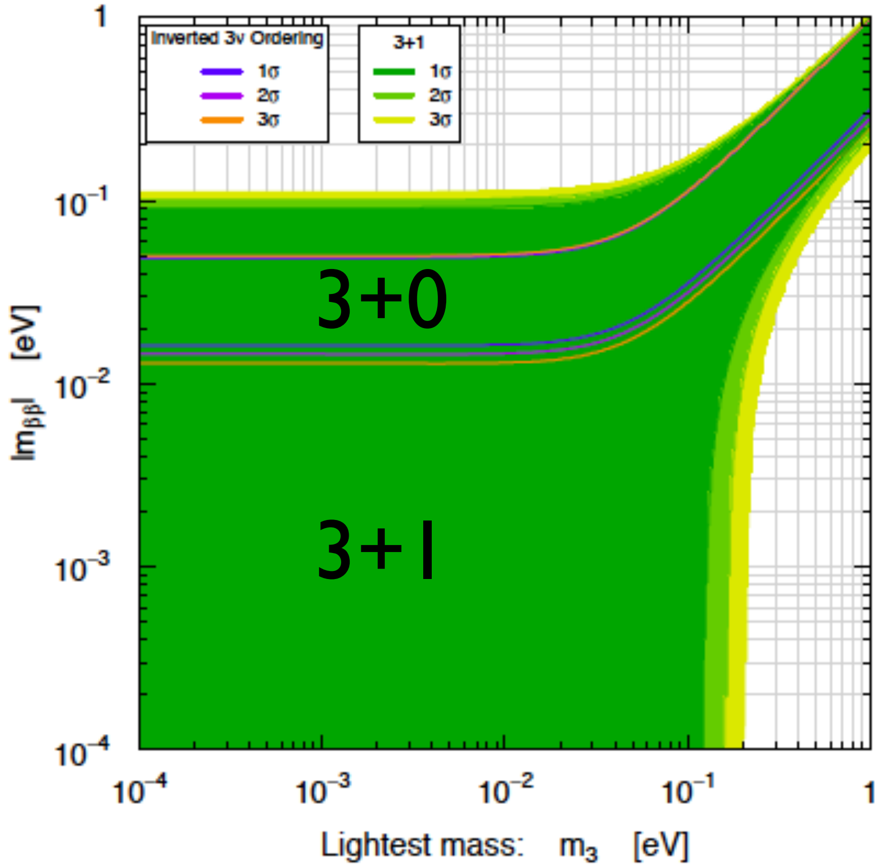
$$m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 \, e^{2i\Phi} \, m_4$$



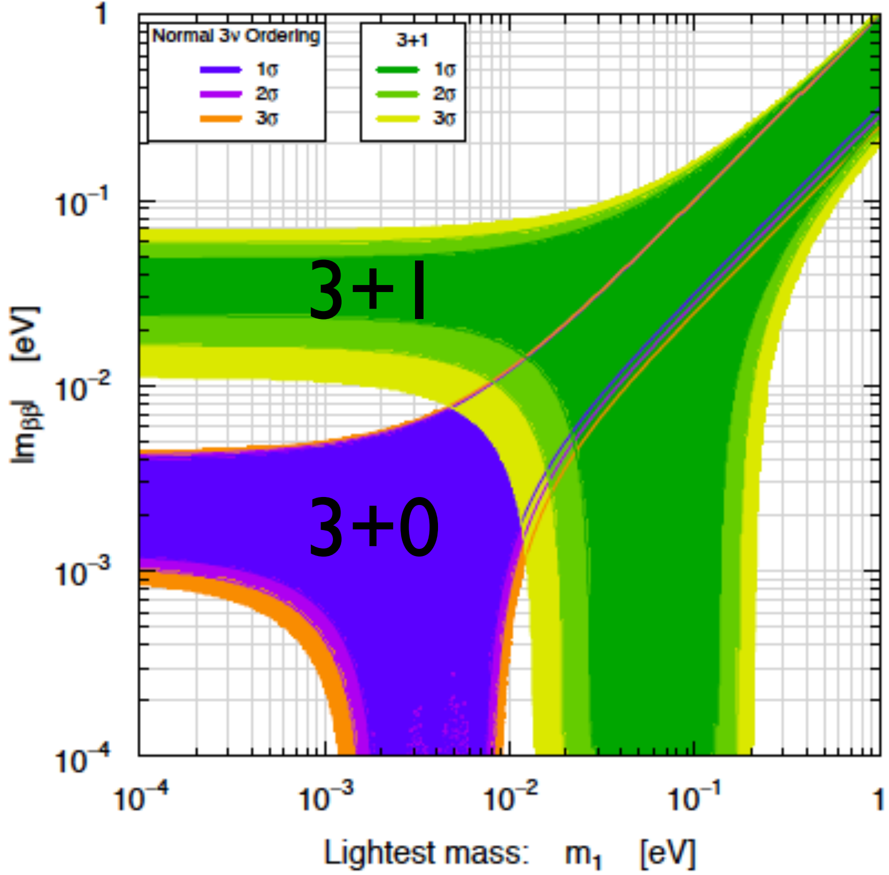
Low-scale LNV

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass $m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2\, e^{2i\Phi}\, m_4$

Inverted Spectrum



Normal Spectrum



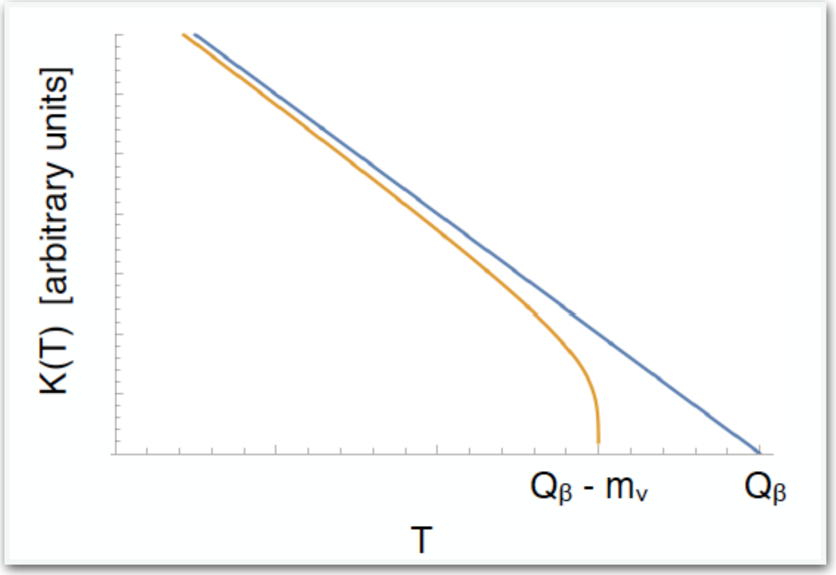
Giunti-Zavanin
1505.00978

Usual phenomenology turned around !

$m_{\beta\beta}$ vs other mass probes

- Correlation with other mass probes will contribute to the interpretation of positive or null result

Electron spectrum endpoint



Tritium beta decay →

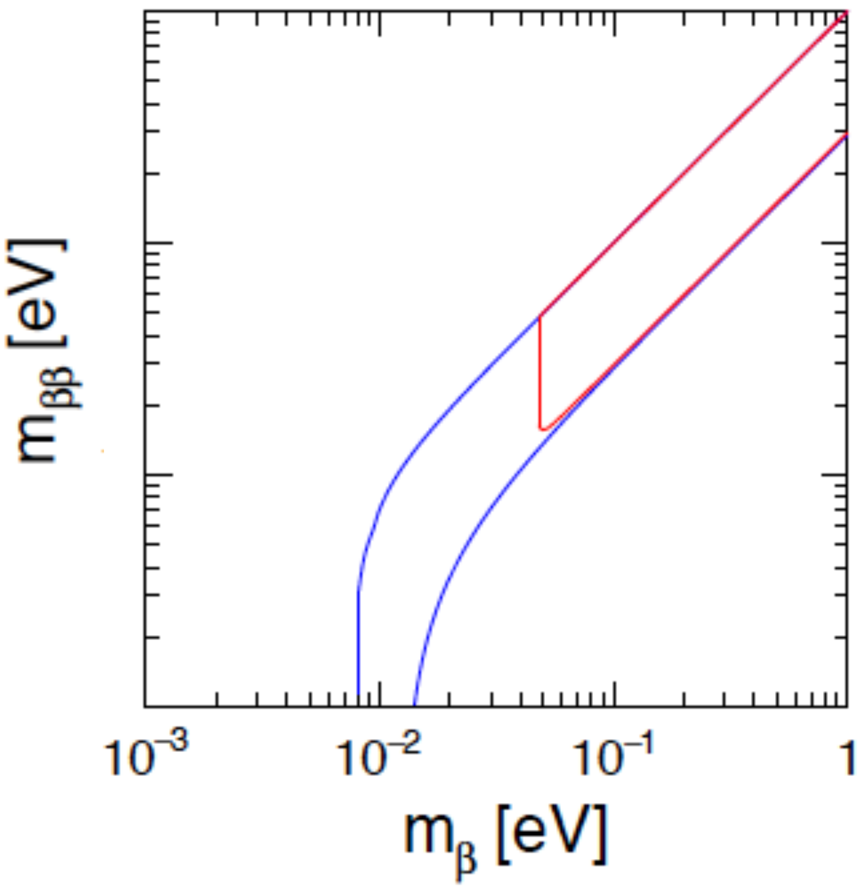
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Cosmology →

$$\Sigma = \sum_i m_i$$

mββ vs other mass probes

- Correlation with other mass probes will contribute to the interpretation of positive or null result



Capozzi et al, 1601.07777

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

$m_{\beta\beta}$ vs other mass probes

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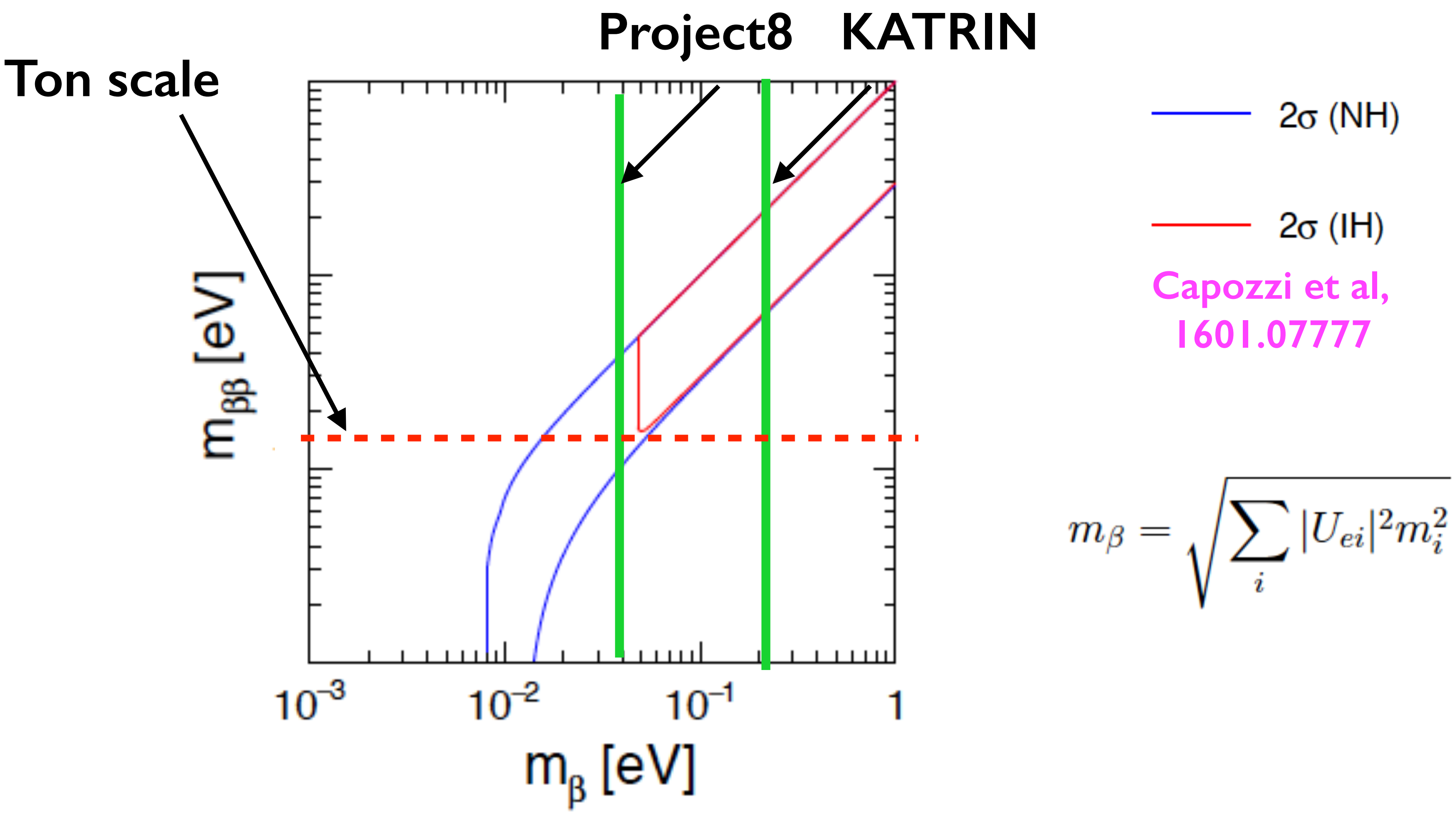


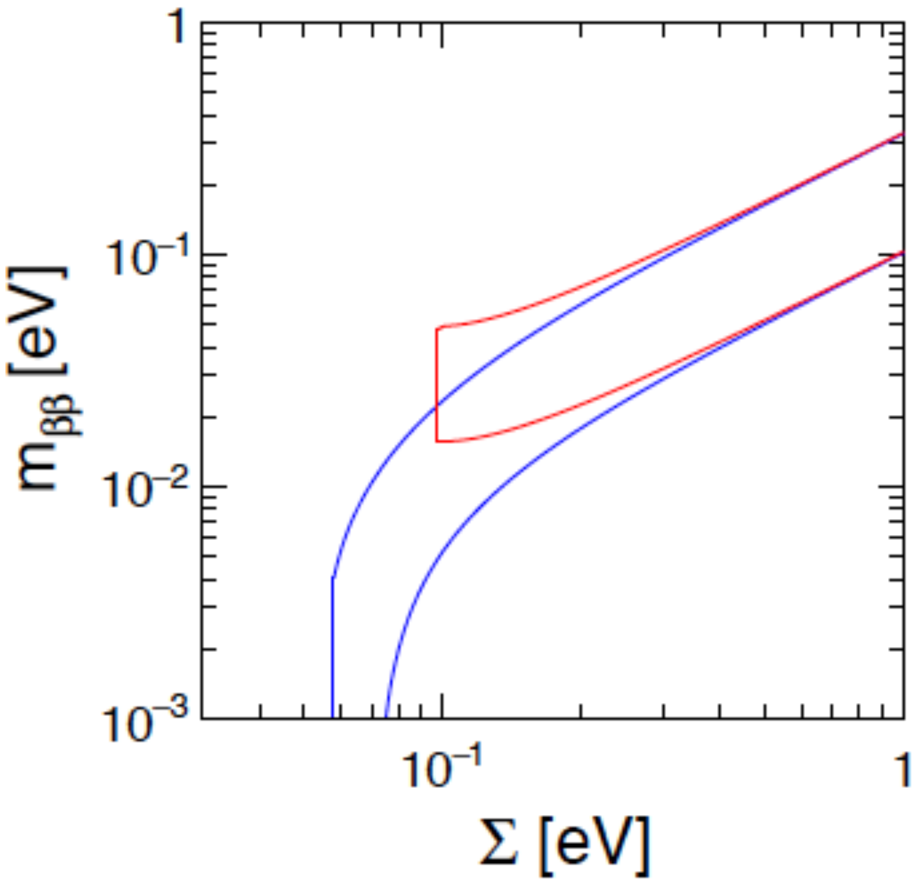
Capozzi et al, 1601.07777

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

- Positive result in KATRIN, Project8 would imply $0\nu\beta\beta$ within reach

mββ vs other mass probes

- Correlation with other mass probes will contribute to the interpretation of positive or null result



Capozzi et al, 1601.07777

$$\Sigma = \sum_i m_i$$

mββ vs other mass probes

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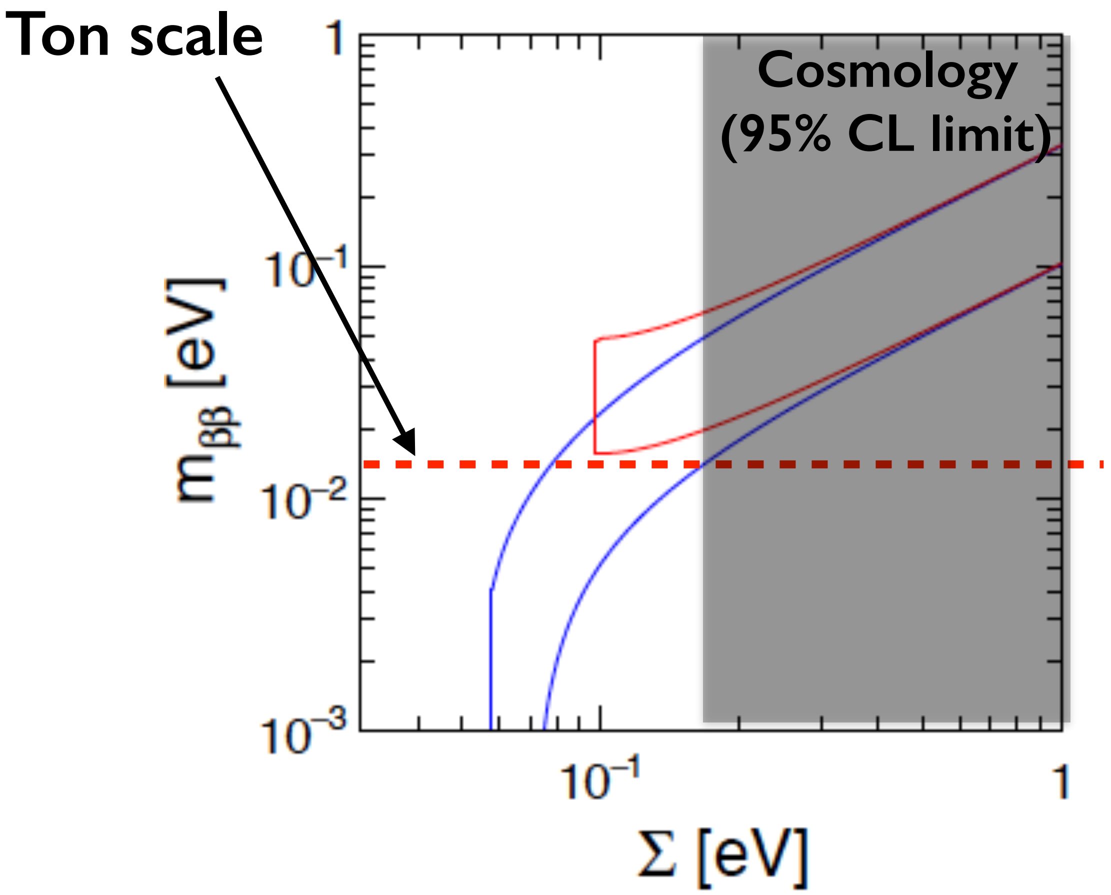


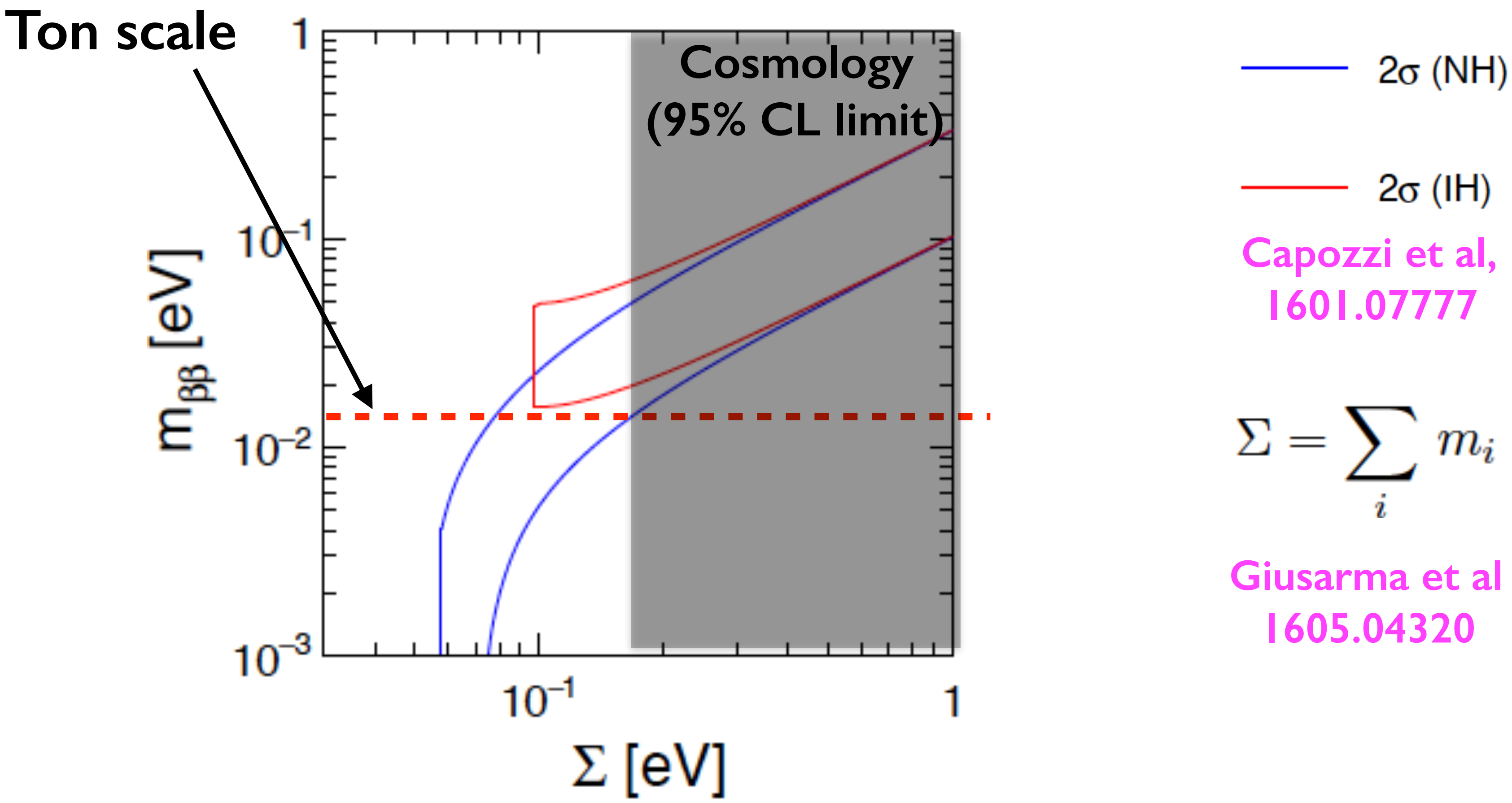
Capozzi et al, 1601.07777

$$\Sigma = \sum_i m_i$$

Giusarma et al 1605.04320

$m_{\beta\beta}$ vs other mass probes

- Correlation with other mass probes will contribute to the interpretation of positive or null result



Capozzi et al,
1601.07777

$$\Sigma = \sum_i m_i$$

Giusarma et al
1605.04320

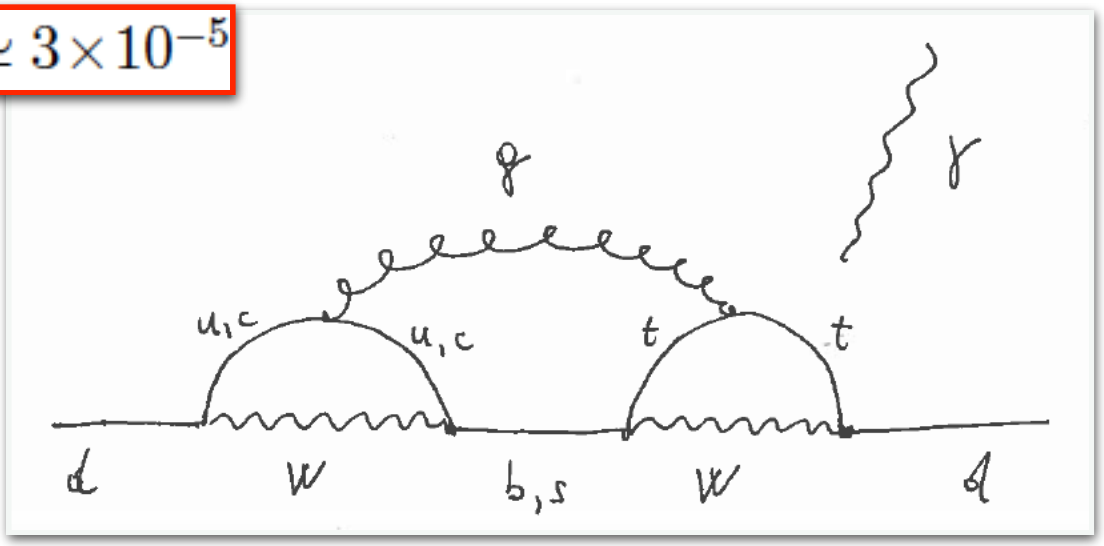
- Interplay with cosmic frontier: expose new physics in cosmology (is "ΛCDM + m_ν" the full story?) or in $0\nu\beta\beta$ (new sources of LNV?)
- Assuming we know correct range for nuclear matrix elements

Backup material — EDMs

EDMs in the SM: CKM phase

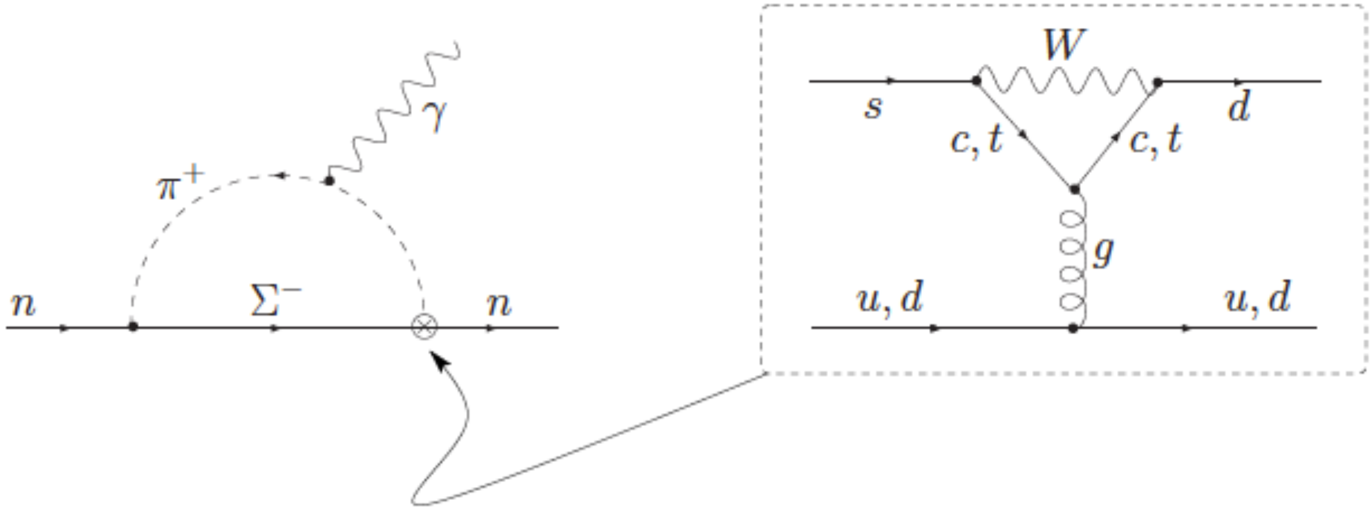
- Highly suppressed "short-distance" contributions start at 3 loops

$$J_{CP} = \mathrm{Im}(V_{tb}V_{td}^{*}V_{cd}V_{cb}^{*}) \simeq 3\times10^{-5}$$



$d_q \sim 10^{-34}$ e cm

- Dominant "long-distance" contribution to nEDM still fairly small



$d_n \sim$ 1-6 10^{-32} e cm

Chien-Yeah Seng
1411.1476 [hep-ph]

Pospelov-Ritz
hep-ph/0504231

EDMs in the SM: QCD

Baluni 1979 Crewther, Di Vecchia, Veneziano, Witten 1979

$$\mathcal{L}_{\rm CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} \;\rightarrow\; -m_*\,\bar{\theta}\sum_{q=u,d,s}\bar{q}\,i\gamma_5 q$$

~ $\mathbf{E_c \cdot B_c}$

$$\bar{\theta} = \theta - \mathrm{ArgDet}(\mathcal{M}_q) \qquad m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$

–

EDMs in the SM: QCD

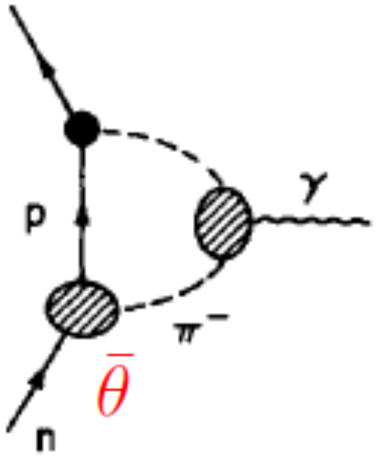
Baluni 1979 Crewther, Di Vecchia, Veneziano, Witten 1979

$$\boxed{\mathcal{L}_{\rm CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} \;\rightarrow\; -m_*\,\bar{\theta}\sum_{q=u,d,s}\bar{q}\,i\gamma_5 q}$$

$\sim \mathbf{E_c \cdot B_c}$

$$\bar{\theta} = \theta - \mathrm{ArgDet}(\mathcal{M}_q) \qquad m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$

- Leading contribution to neutron EDM via chiral loop

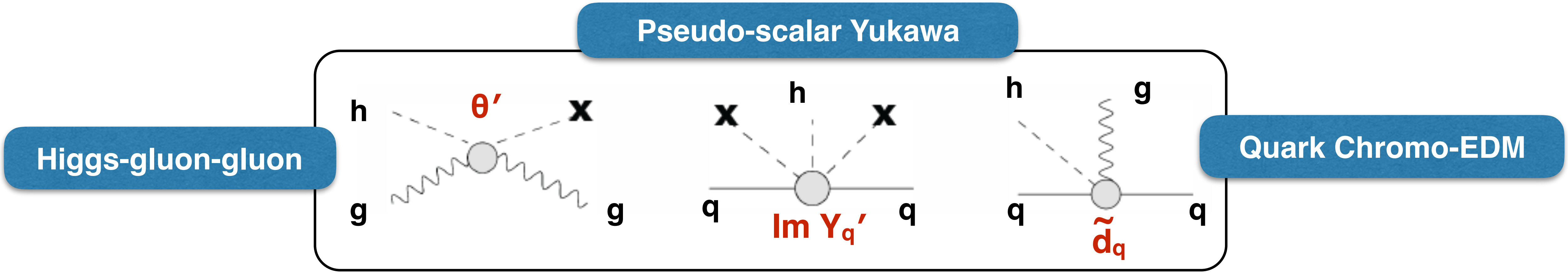


$$\boxed{d_n \;\sim\; \frac{m_*}{\Lambda_{\rm had}^2}\,e\,\bar{\theta} \;\sim\; 10^{-17}\,\bar{\theta}\,e{\rm cm}} \;\rightarrow\; |\bar{\theta}| < 10^{-9}$$

Motivated mechanism that relax dynamically $\bar{\theta}$ to zero (e.g. axions)

CPV Higgs couplings (I)

- Leading interactions with q,g strongly constrained by gauge invariance



$$\theta', \mathrm{Im} Y_q' \sim \frac{1}{\Lambda^2} \qquad \tilde{d}_q \sim \frac{v}{\Lambda^2}$$

- Affect Higgs production and decay at LHC *and* EDMs (n, ^{199}Hg, e)

Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

CPV Higgs couplings (I)

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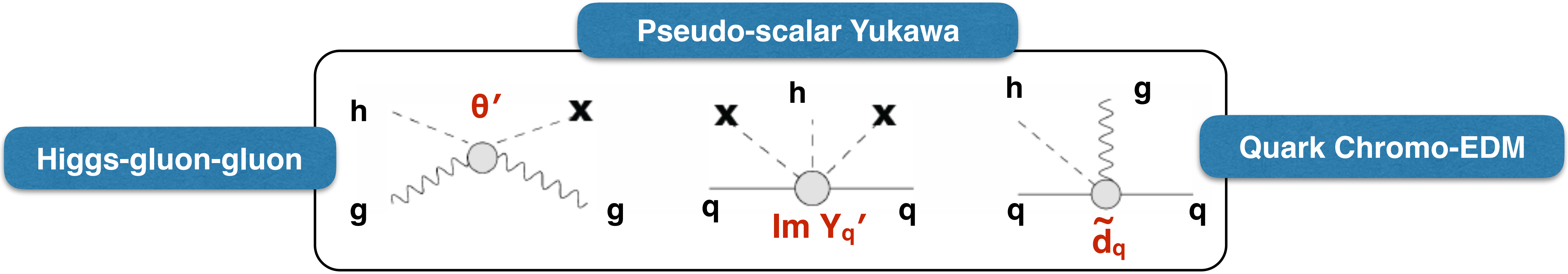
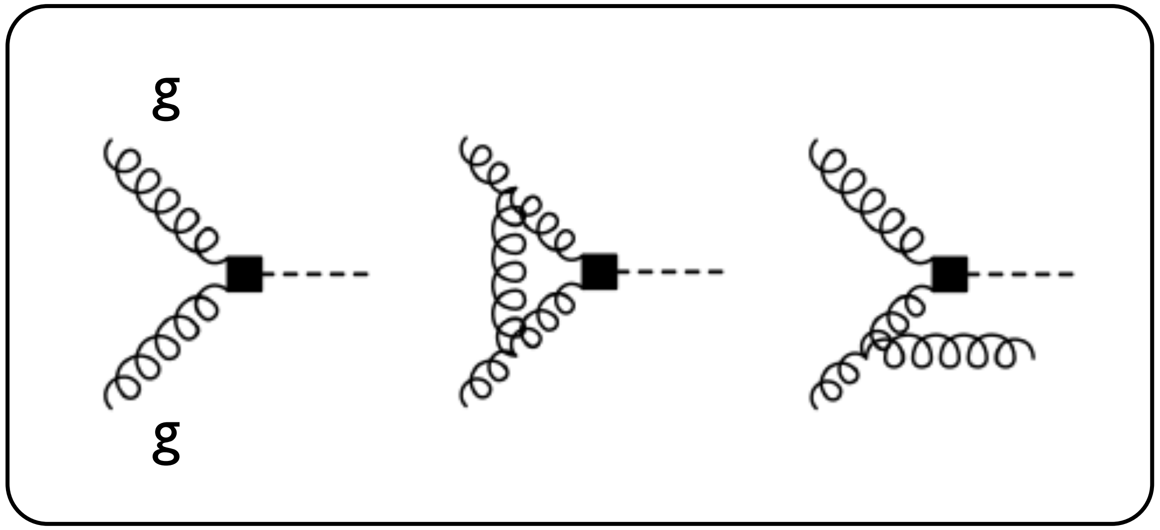

Pseudo-scalar Yukawa

Higgs-gluon-gluon

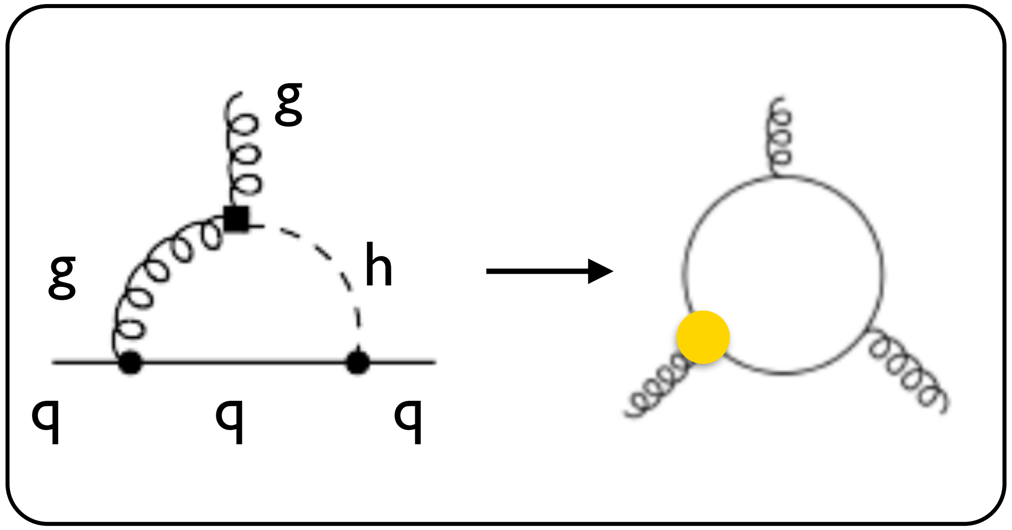
Quark Chromo-EDM

- Signatures of various operators: Higgs-gluon-gluon (θ′)

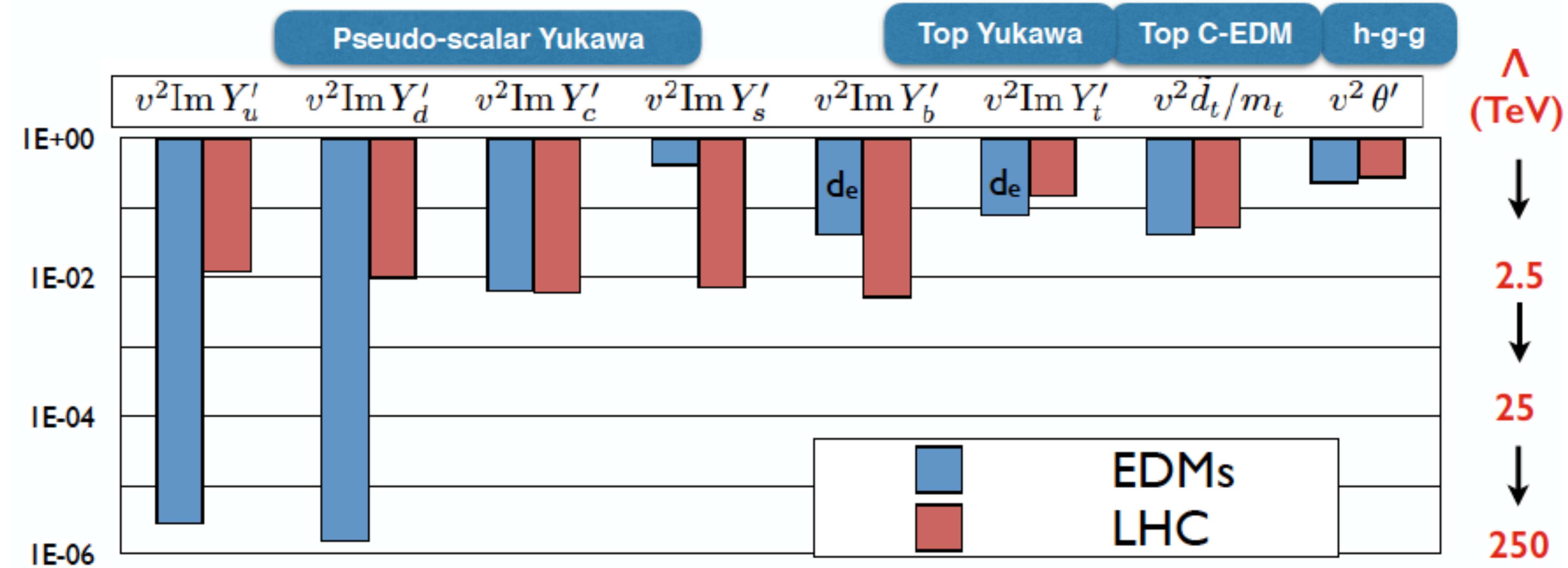
LHC: Higgs production via gluon fusion



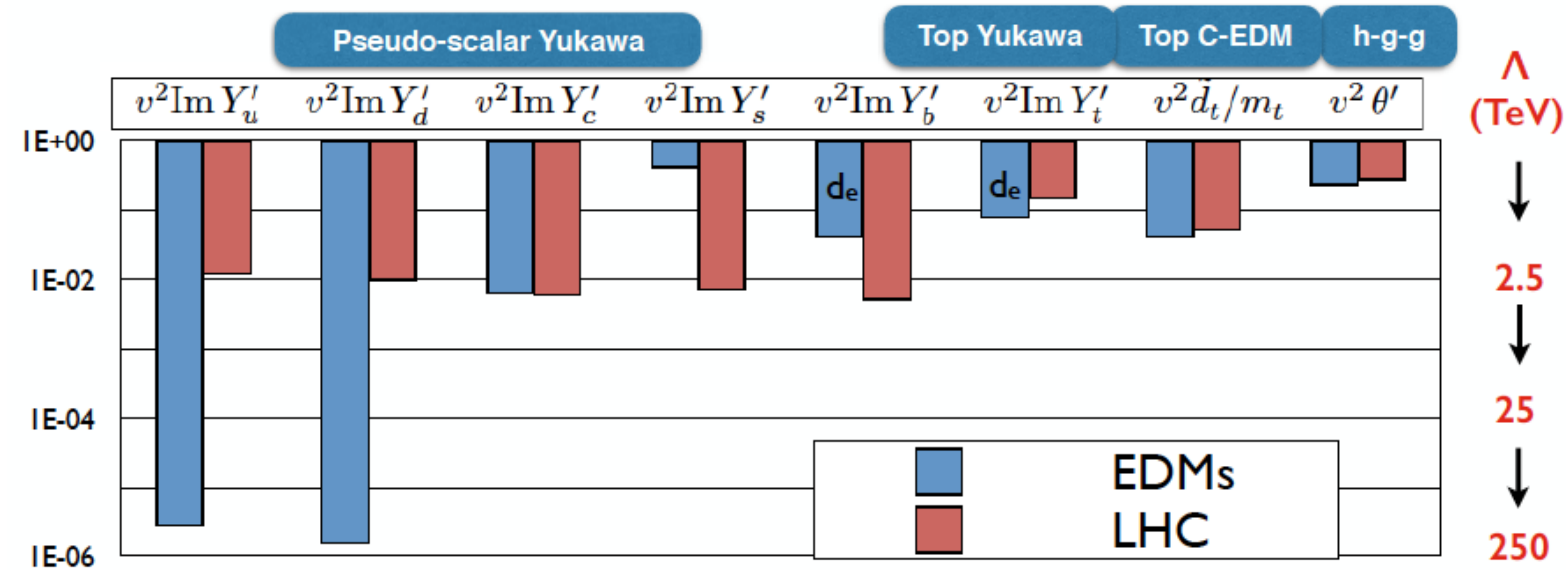
Low Energy: quark (C)EDM + Weinberg



CPV Higgs couplings (2)

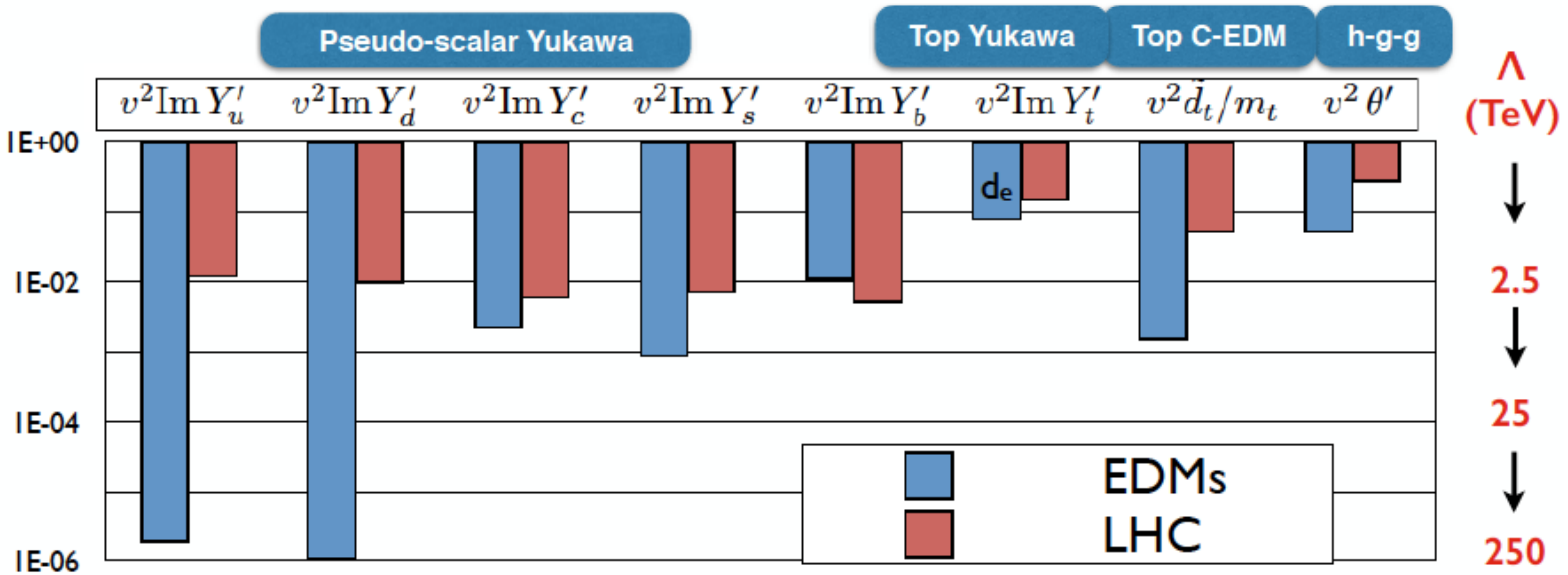


CPV Higgs couplings (2)



- Neutron EDM is teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

CPV Higgs couplings (2)



- Much stronger impact of nEDM with reduced uncertainties

$d_{n,p}[\tilde{d}_{u,d}]$ $d_{n,p}[d_s]$ $d_{n,p}[d_W]$

25% 50%

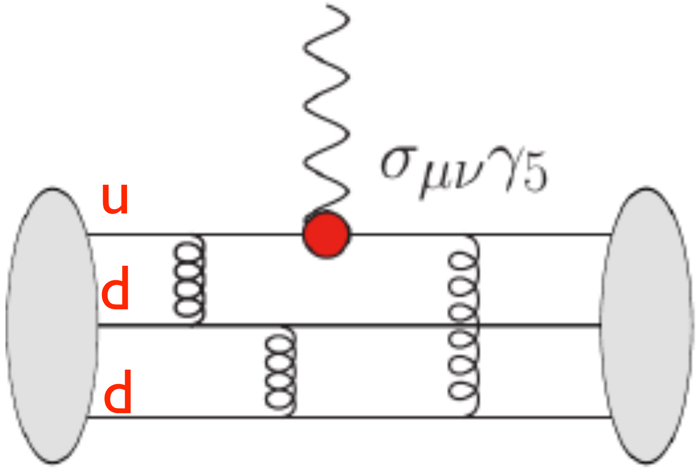
Target for Lattice QCD
in the 5-year time scale

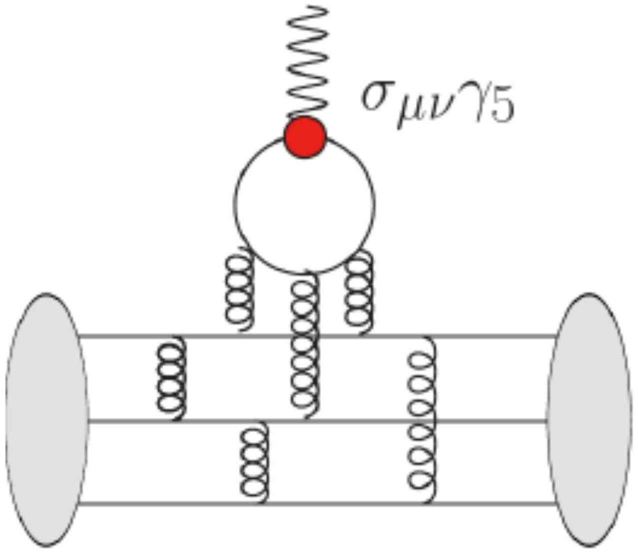
- Experiment at 5 x 10^{-27} e cm and improved matrix elements will make nEDM the strongest probe for all couplings

Neutron EDM from quark EDM

- Quarks couple directly to photon (in a CP-odd way)

$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q}\sigma_{\mu\nu}\gamma_5 q \, F^{\mu\nu}$$





Neutron EDM from quark EDM

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$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F^{\mu\nu}$$

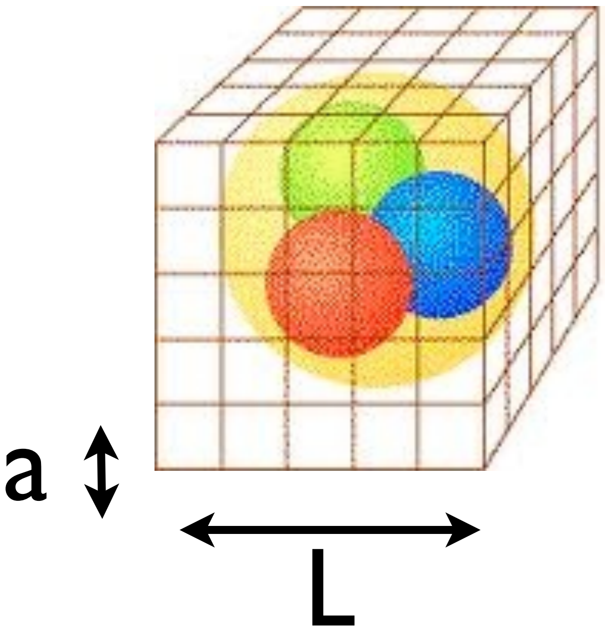
- Problem “factorizes”: need so-called tensor charge of the neutron

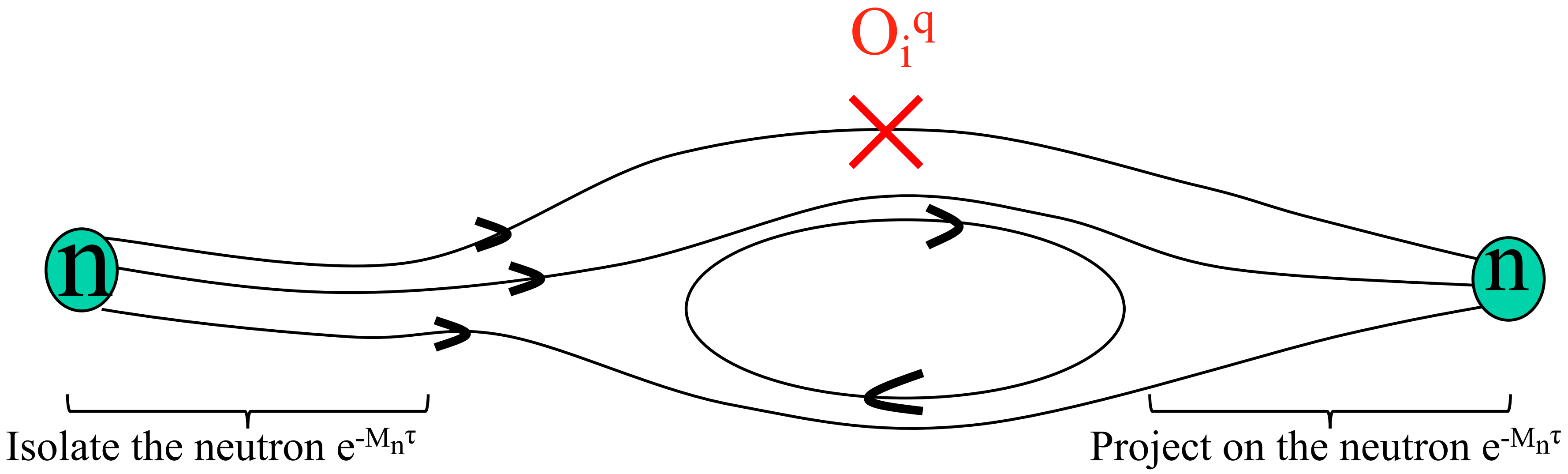
$$\boxed{d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}}$$

$$\langle N | \, \bar{q} \sigma_{\mu\nu} q \, | N \rangle \equiv g_T^{(N,q)} \; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

Neutron EDM from quark EDM

- Discretize space-time into a finite Euclidean lattice (a,V) → perform Monte Carlo integration of the path integral





- Do it on many little universes with different m_q, a, V

Neutron EDM from quark EDM

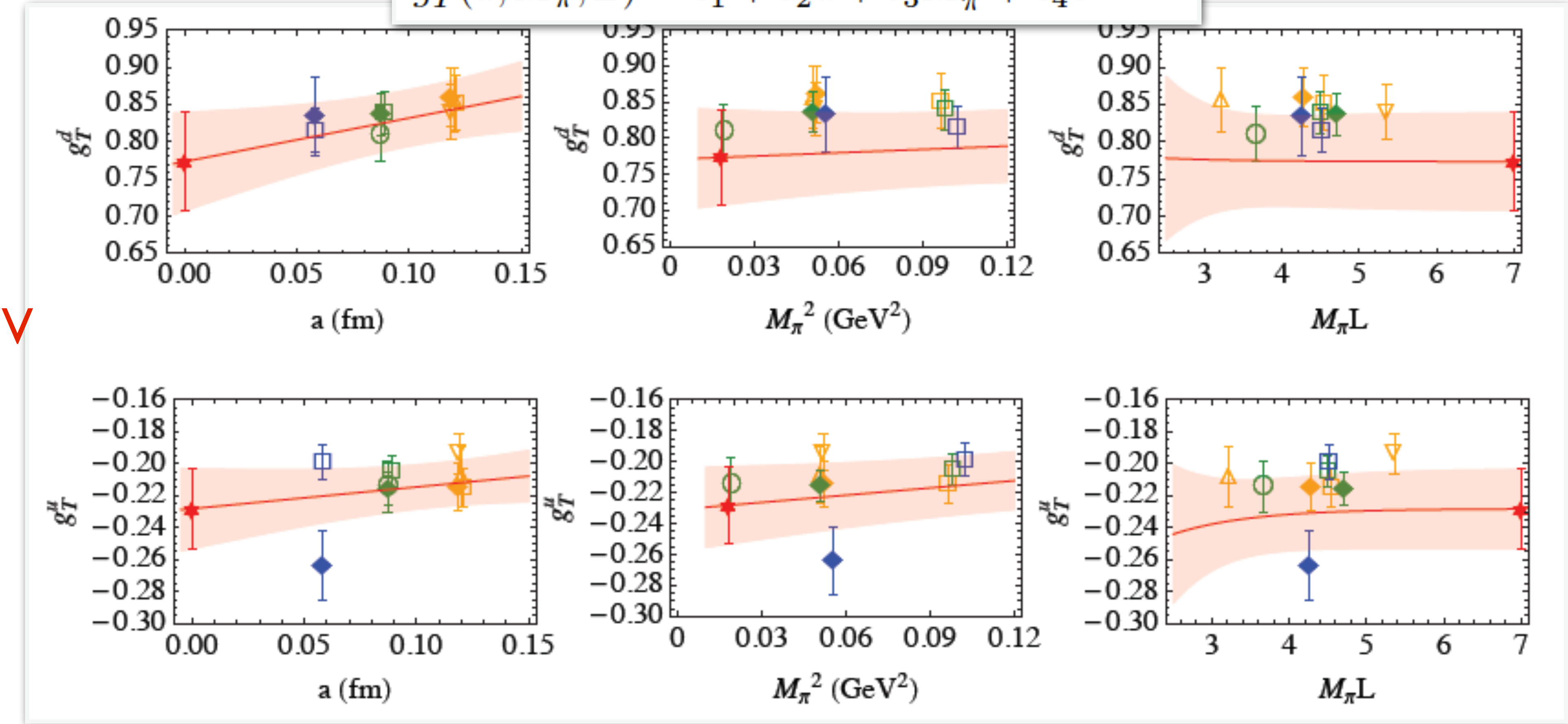
$g_T^{(n,u)} = -0.23(3)$

$g_T^{(n,d)} = 0.77(7)$

$g_T^{(s)} = 0.008(9)$

$g_T(a, M_\pi, L) = c_1 + c_2 a + c_3 M_\pi^2 + c_4 e^{-M_\pi L}$

$\overline{\text{MS}}$ @ 2 GeV

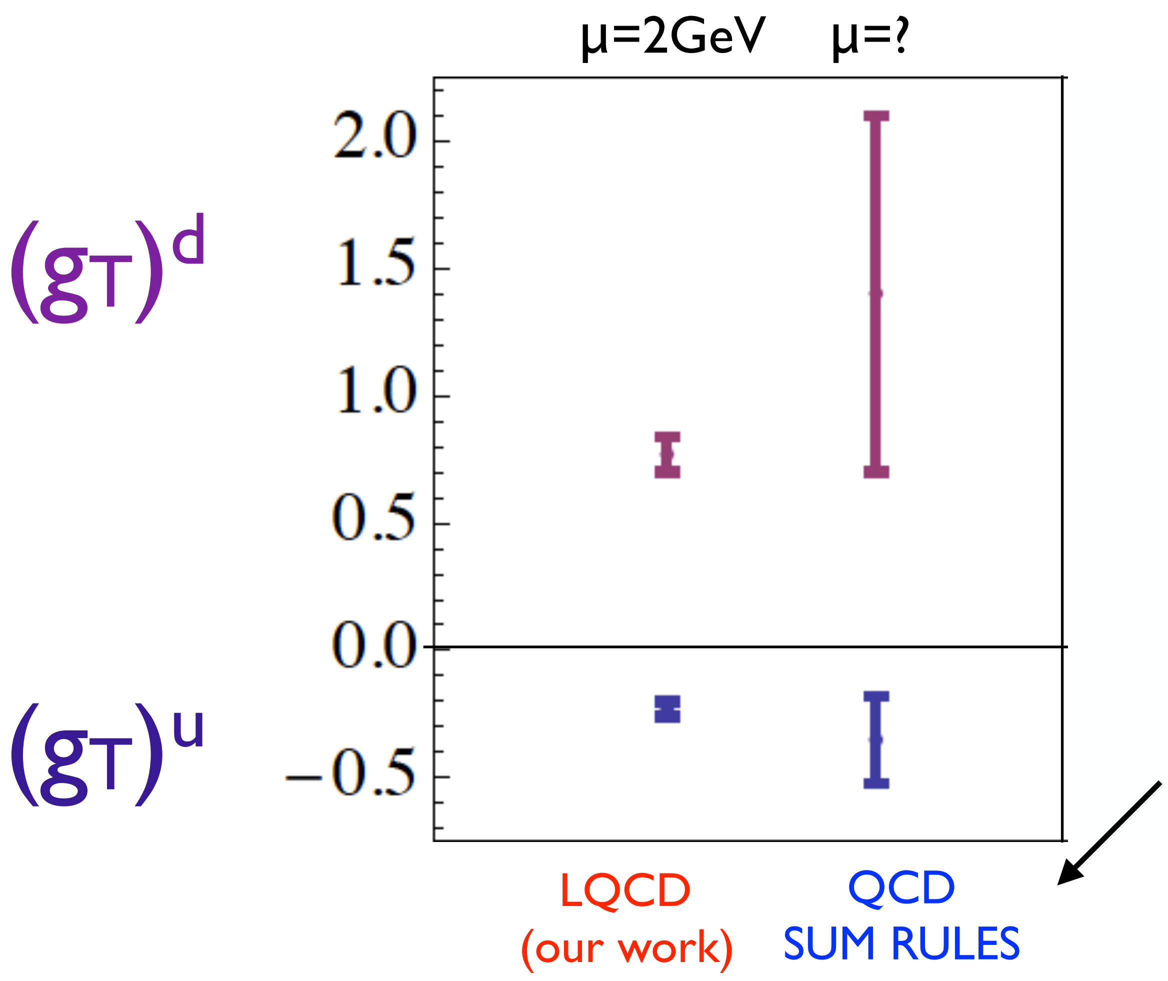


Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

O(10%) error including all systematics: excited states, continuum, quark masses, volume

Neutron EDM from quark EDM

- Impact of Lattice results:



Widely used in BSM studies of neutron EDM (Pospelov-Ritz hep-ph/0504231)

Smaller (50% → 10%) & controlled error; scale/scheme dependence.
Smaller central values of g_T's $\Rightarrow$ d_n "less sensitive" to new physics in d_q

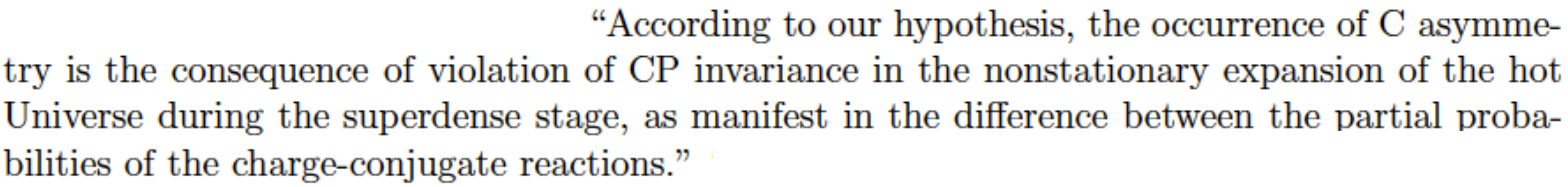
Ongoing efforts by LANL, BNL, LBL groups to tackle other operators

Conditions for Baryogenesis

"...The Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons [...] implies a non-zero baryon charge (baryon asymmetry).

Sakharov '67

We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe, by making use of the effects of CP invariance violation. To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law."



"According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

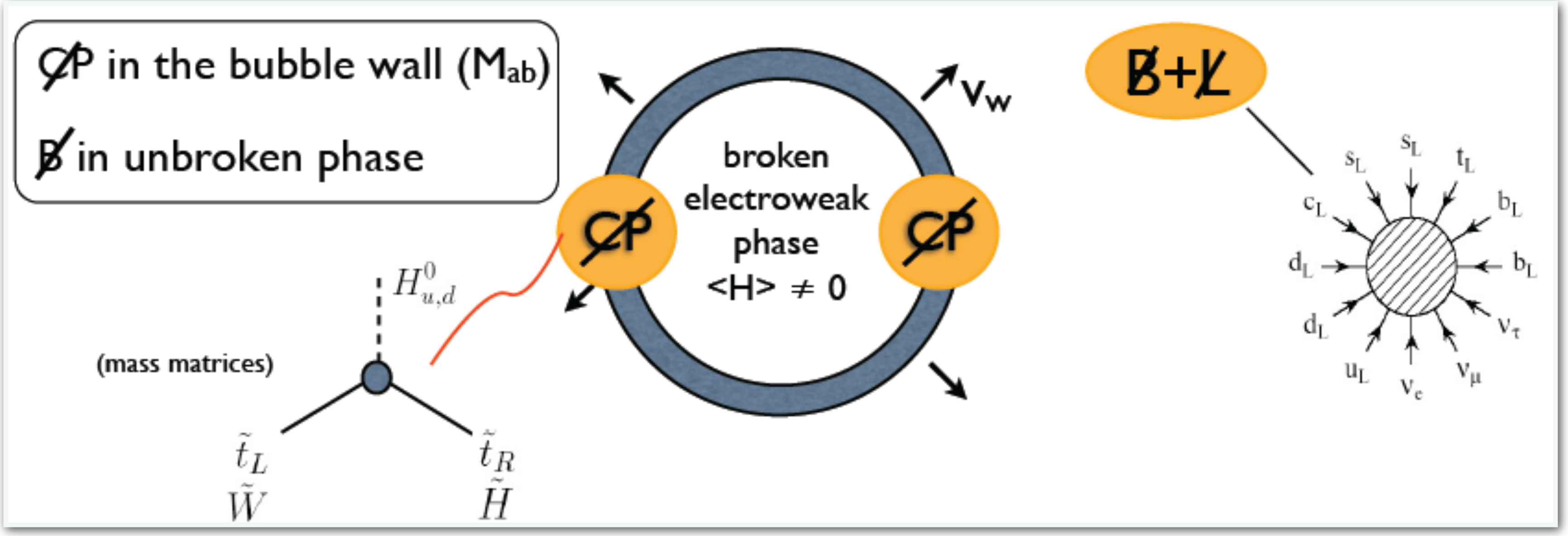
Conditions for Baryogenesis (recap)

- The dynamical generation of net baryon number during cosmic evolution requires the concurrence of three conditions:

Sakharov '67

1. B (baryon number) violation
   - To depart from initial B=0
2. C and CP violation $\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})$
   - To distinguish baryon and anti-baryon production
3. Departure from thermal equilibrium (or CPT violation)
   - <B(t)>=<B(0)>=0 in equilibrium (and assuming CPT invariance)

EDMs and EW baryogenesis (1)



For a review see: Morrissey & Ramsey-Musolf 1206.2942

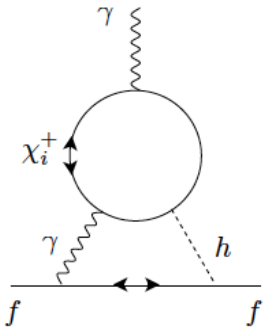
- Requirements on BSM scenarios:
  - 1st order phase transition: new particles, testable at LHC
  - New CPV: EDMs often provide strongest constraint.

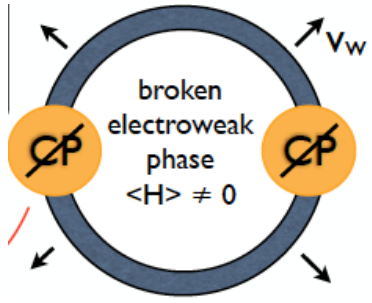
- Rich literature: (N)MSSM, Higgs portal (scalar extensions), flavored baryogenesis,…

See M. Ramsey-Musolf talk at APS April Meeting 2018

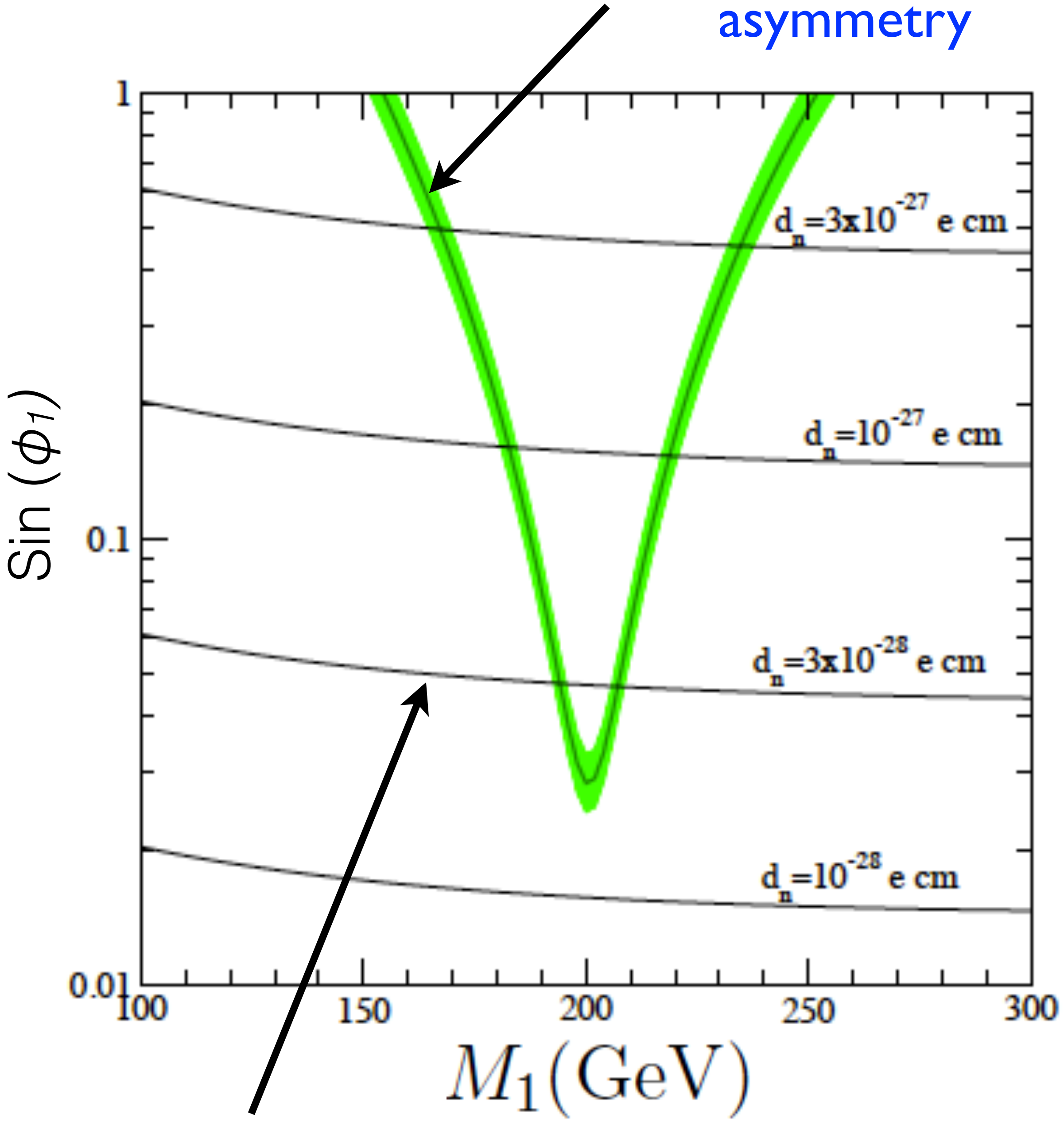
EDMs and EW baryogenesis (2)

- In Supersymmetry, 1st order phase transition disfavored by LHC in minimal model (MSSM), need singlet extension (NMSSM)
- CPV phases appearing in the gaugino-higgsino mixing contribute to both BAU and EDM





- In *scenario with universal phases* $\varphi_1=\varphi_2$, successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches



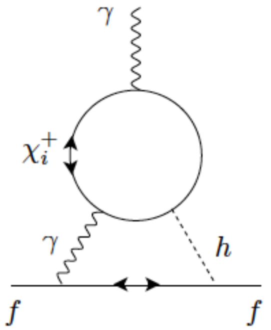
Compatible with baryon asymmetry

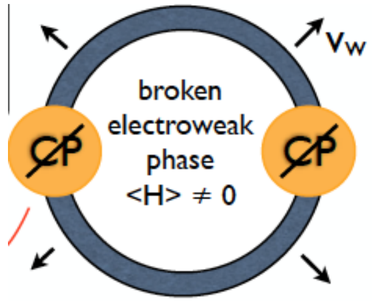
Next generation neutron EDM

Li, Profumo, Ramsey-Musolf 0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589

EDMs and EW baryogenesis (2)

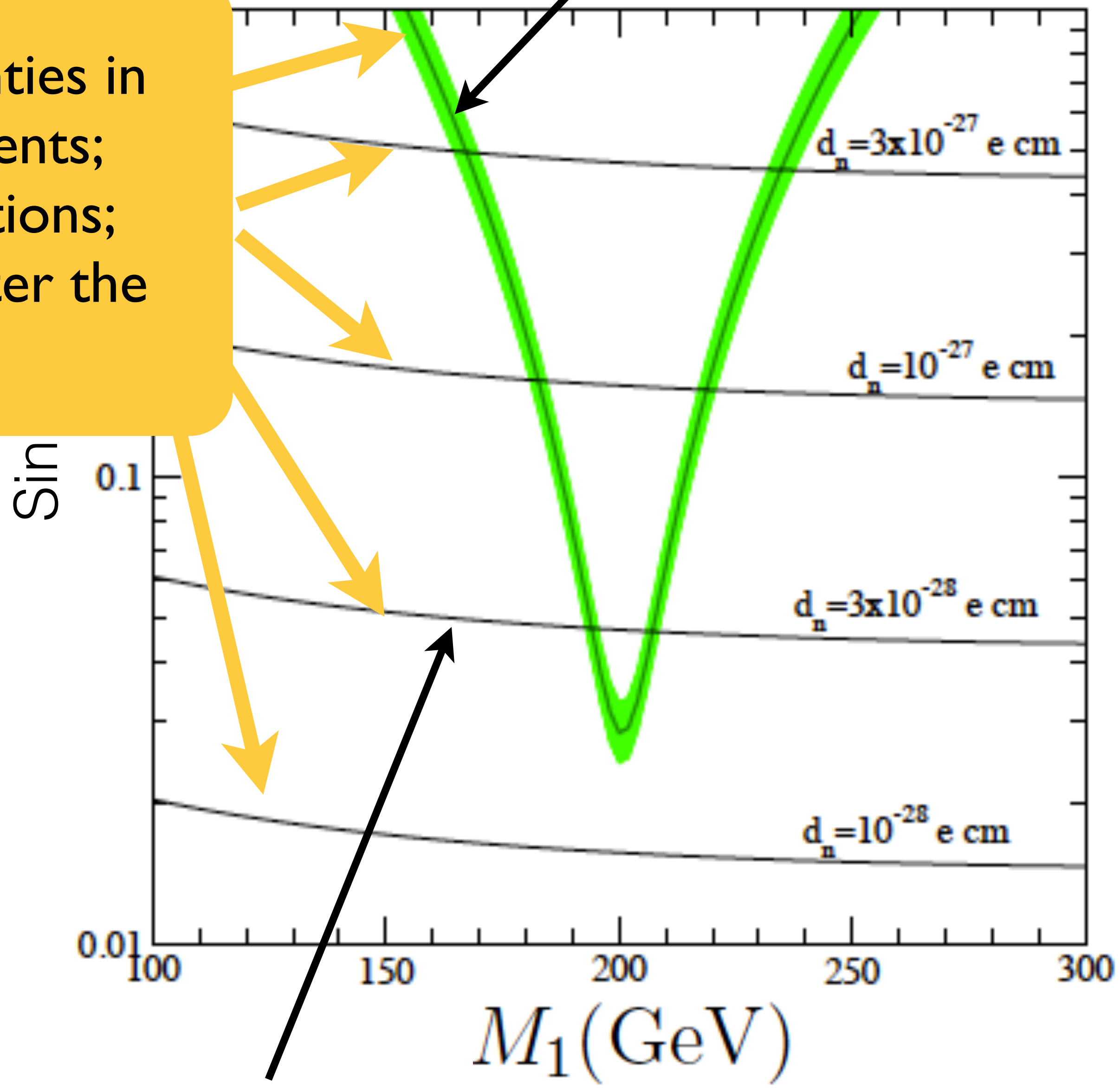
- In Supersymmetry, 1st order phase transition disfavored by LHC in mini need singlet
- CPV phases gaugino-higg contribute to both BAU and EDM





- In *scenario with universal phases* $\varphi_1=\varphi_2$, successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches

CAVEAT: current uncertainties in
1) hadronic matrix elements;
2) early universe calculations;
may shift these lines and alter the conclusions



Compatible with baryon asymmetry

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