HUGS 2018
Jefferson Lab, Newport News, VA
May 29- June 15 2018

Fundamental Symmetries - 5

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Los Alamos National Laboratory

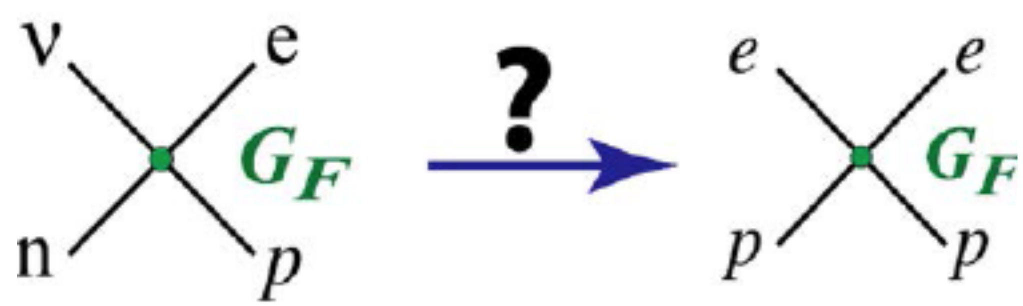
Plan of the lectures

- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries
- Beyond the SM:
  - hints from current discrepancies?
  - effective theory perspective
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  - Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.

Neutral Current

Parity violating electron scattering

- Speculation by Zel'dovich (1958) before the SM: neutral analogue of V-A charged current interaction?



We now know that such interaction exists, mediated by the Z boson

- In electron proton scattering, the weak and EM amplitudes interfere

$$\sigma \propto |A_{EM} + A_{weak}|^2$$

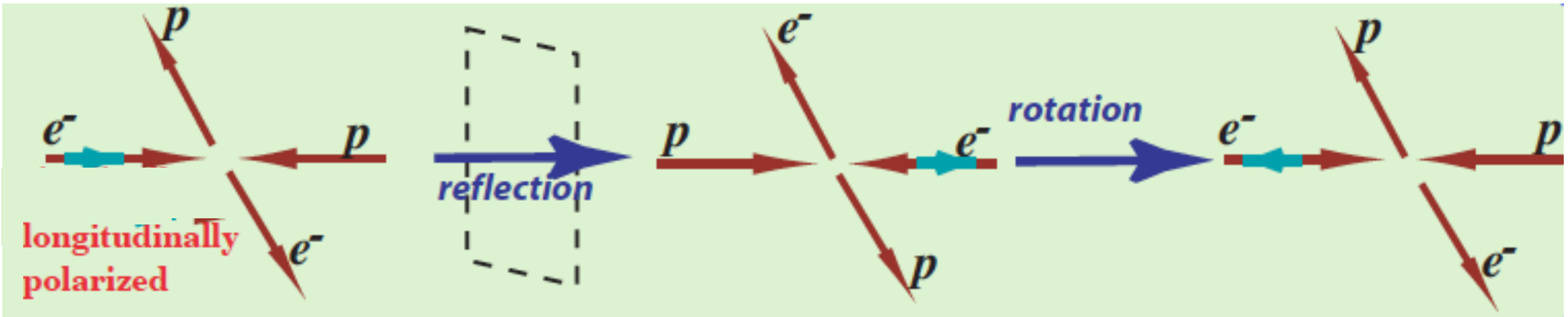
$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

Parity violating

- Expect asymmetry in scattering of L and R polarized electrons!

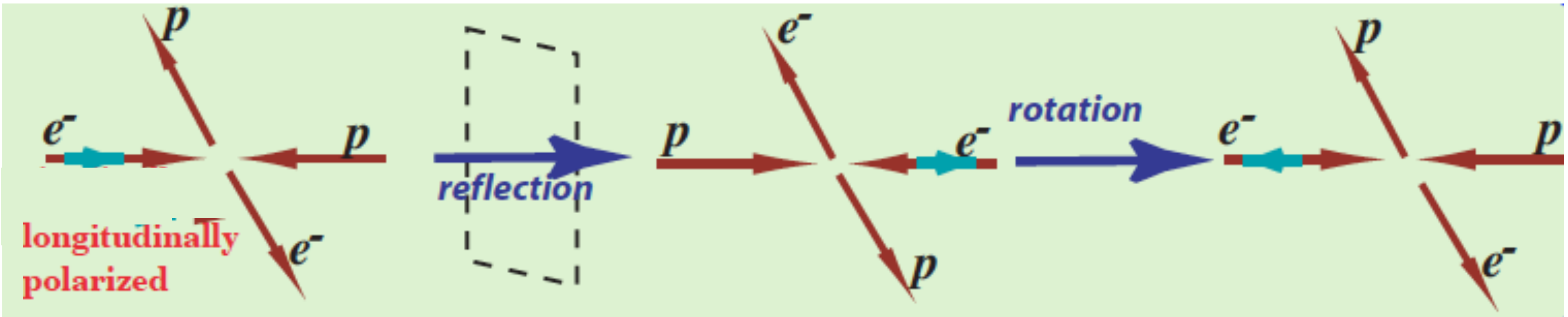
$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

- A_{PV} violates parity:

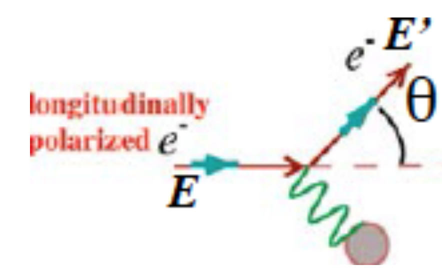


Krishna Kumar

- A_{PV} violates parity:



- Estimate size of the effect:



$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

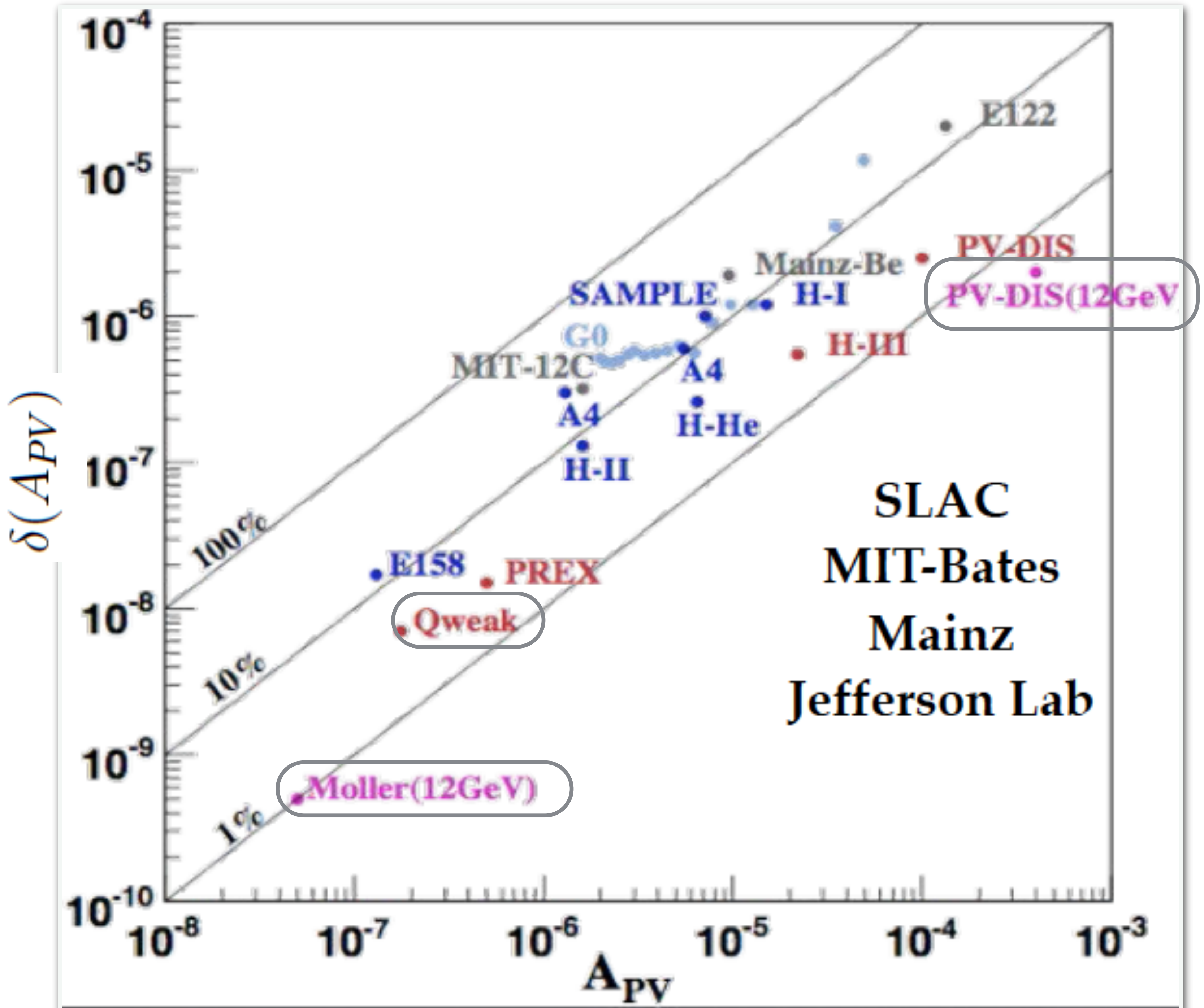
$$A_{PV} \sim 10^{-4} \cdot Q^2 (\mathrm{GeV}^2)$$

4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Tiny asymmetries!

- Through 4 decades of technical progress, parity-violating electron scattering (PVES) has become a precision tool



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A_{PV} in the Standard Model

- Recall neutral current in the Standard Model

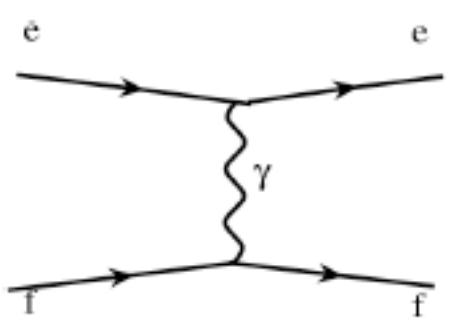
$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta}\; Z^\mu\; \bar{\psi}_f \left(g_V^{(f)}\gamma_\mu - g_A^{(f)}\gamma_\mu\gamma_5\right)\psi_f$$

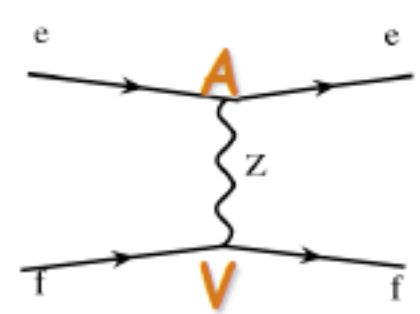
$$\theta = \arctan\frac{g'}{g}$$

$$e = g\sin\theta,$$

$$g_V^{(f)} = T_3^{(f)} - 2\sin^2\theta\, Q^{(f)} \qquad g_A^{(f)} = T_3^{(f)} \qquad Q_W^{(f)} = 2\, g_V^{(f)}$$

Weak charge of the fermion





$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha}\,(g_A^e g_V^T + \beta\, g_V^e g_A^T)$$

- Precision tool: low q^2 measurements of $\mathrm{Sin}(\theta_W)$ + sensitivity to BSM

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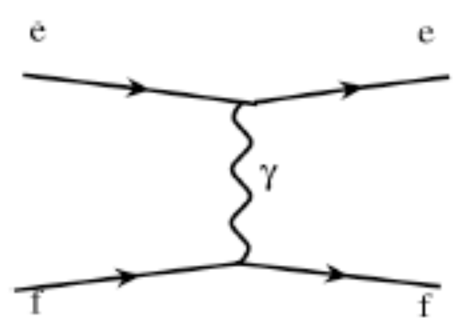

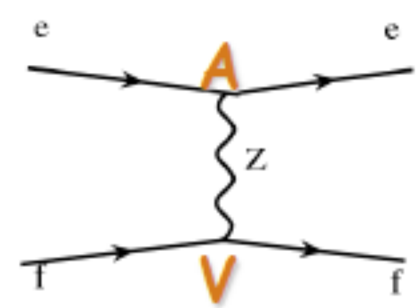

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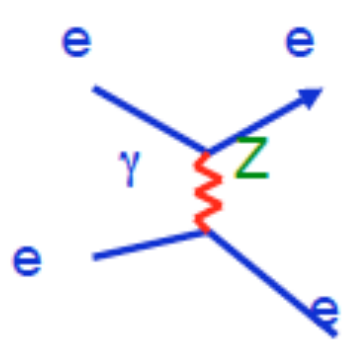
$$Q_W = 1 - 4\sin^2\theta_W$$

For electron and proton

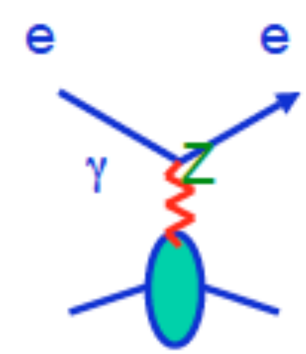
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

Processes

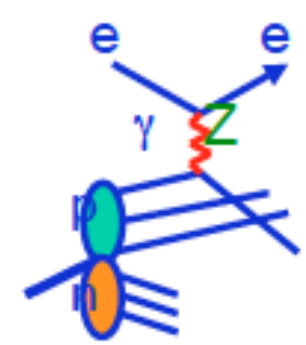
Møller Scattering



Q-Weak (JLab)



DIS-Parity



Recent result by Q-Weak

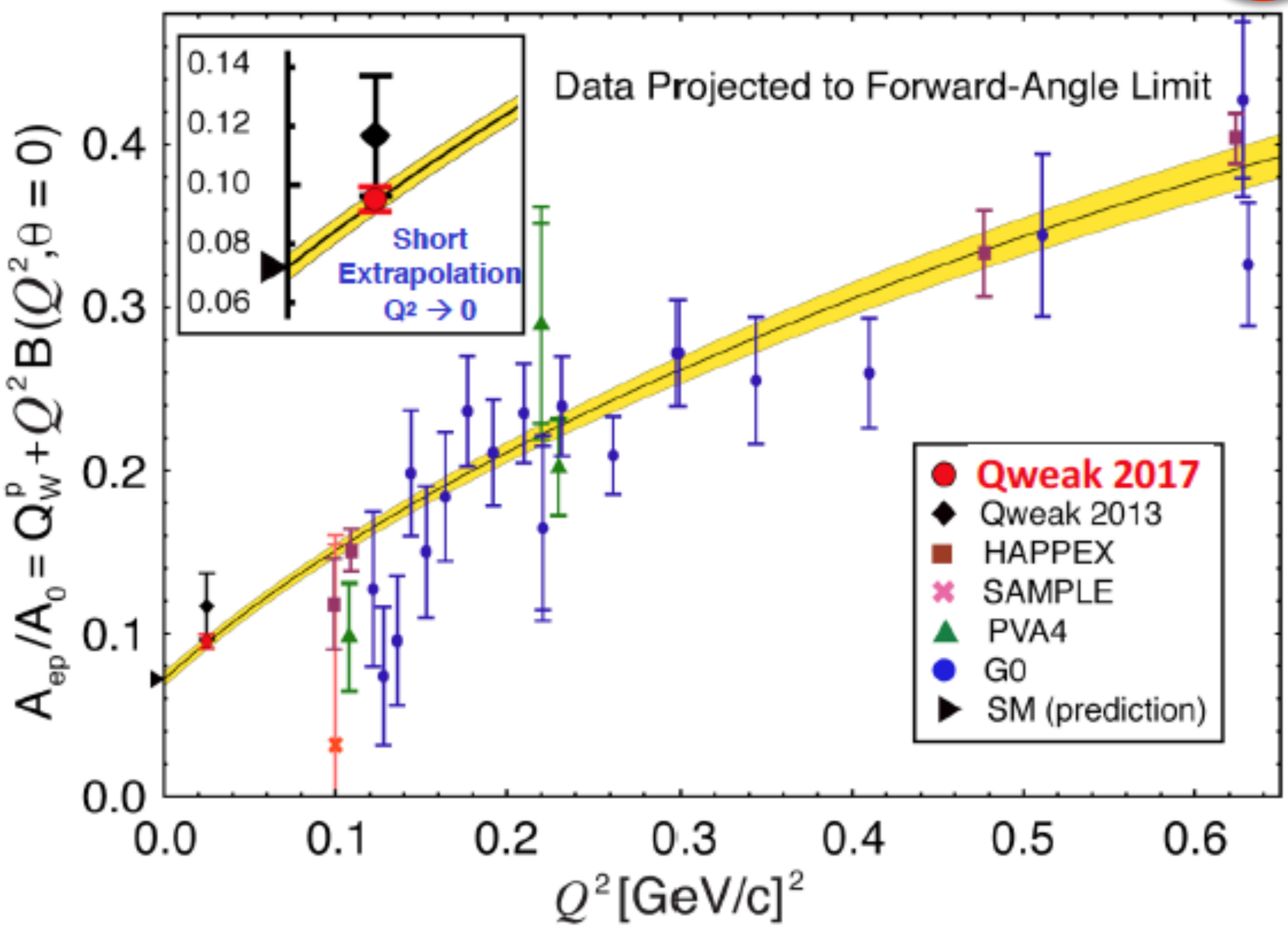
At forward angles and small Q^2, A_{PV} accesses the weak charge

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \xrightarrow[\theta \to 0]{Q^2 \to 0} -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 B(Q^2, \theta)\right]$$

$B(Q^2,\theta)$ is a form-factor term. About 30% correction to A_{PV} for Qweak. Well determined by existing PVES data.

Qweak of the Proton

$$A_{PV} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at } Q^2 = 0.0249(\text{GeV/c})^2$$



- All nuclear PVES data up to $Q^2 \sim 0.7$ GeV^2 (hydrogen, deuterium, helium)
- 5 parameters (C_{1u}, C_{1d}, isovector axial FF, ρ_s, μ_s)
- Fit and data shown corrected to forward angle limi

Standard Model:

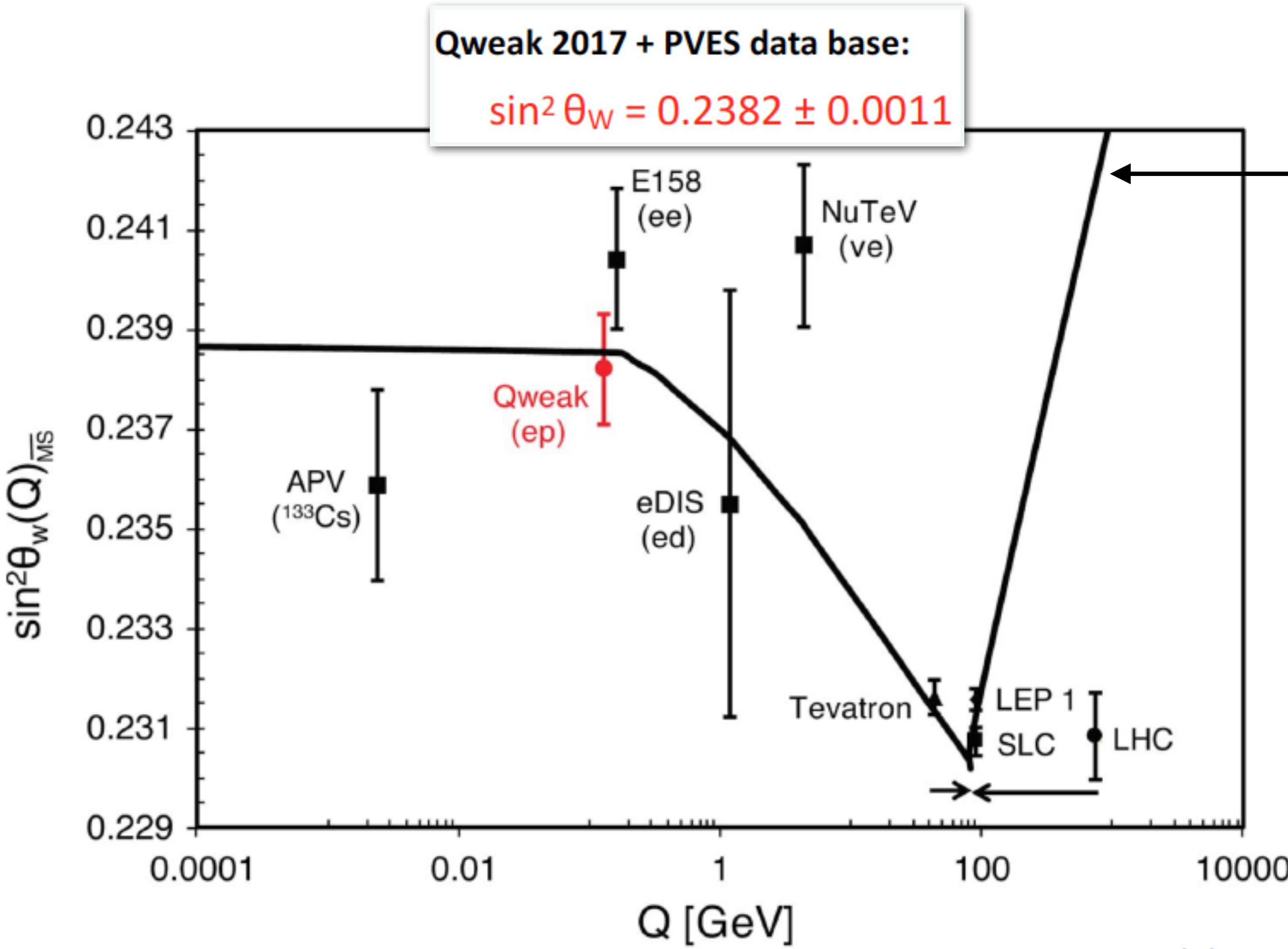
$$Q_W^p = 0.0708 \pm 0.0003$$

Qweak + PVES data base:

$$Q_W^p = 0.0719 \pm 0.0045$$

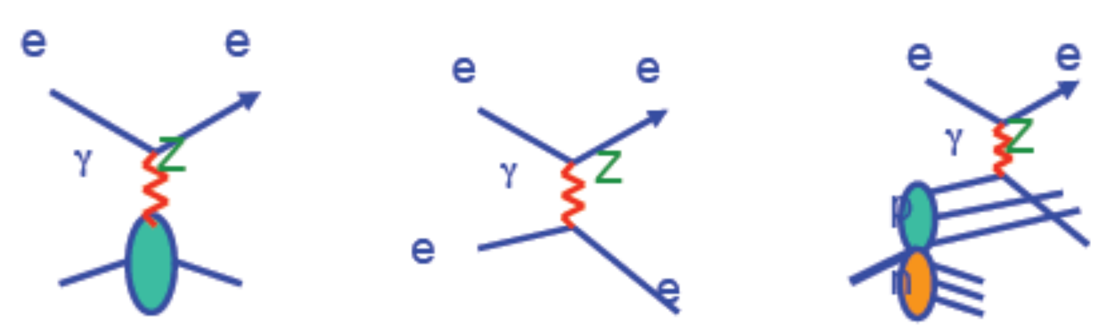
K. Paschke talk at CIPANP 2018

Impact of PVES on θ_W



SM prediction: relating EW measurements at Q~100 GeV to low-energy

Marciano, Erler, Ramsey-Musolf



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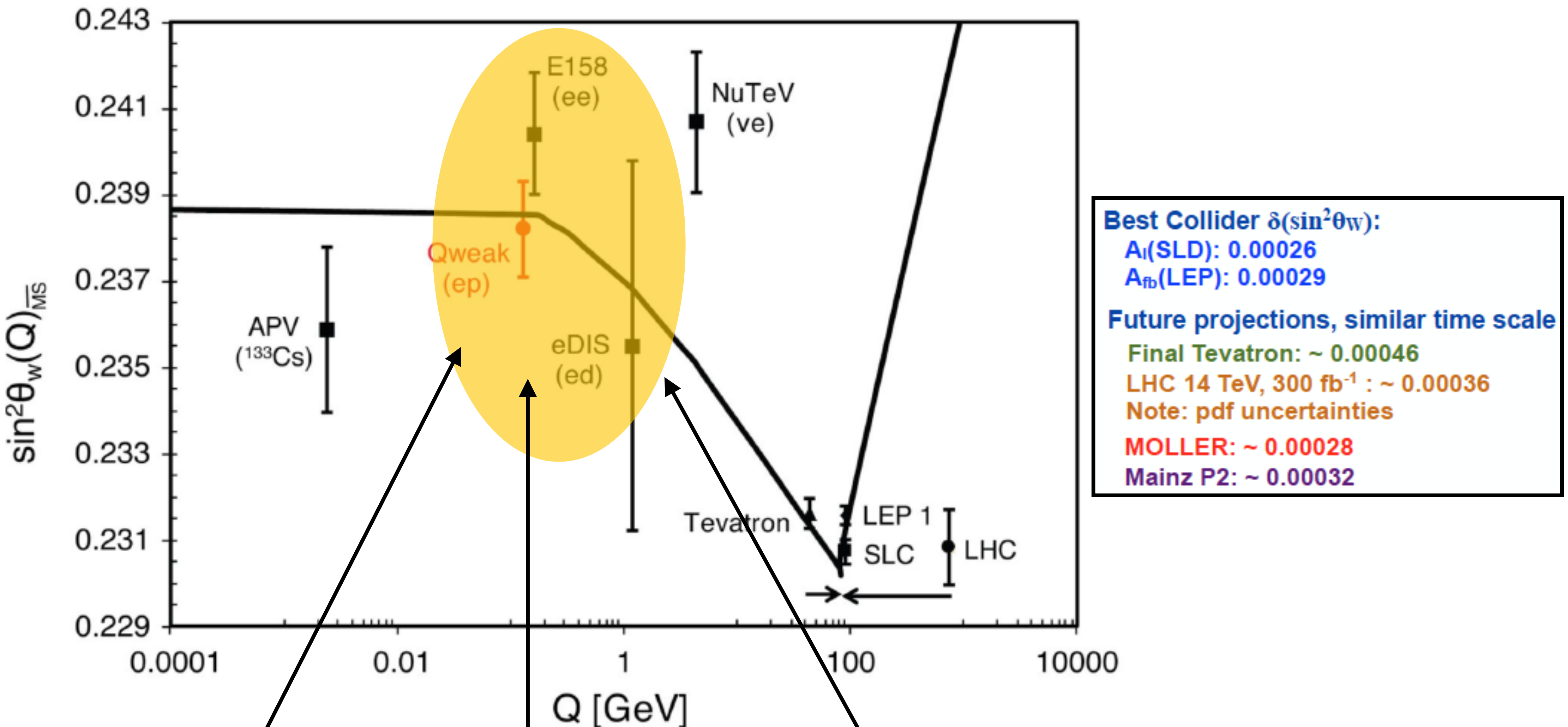


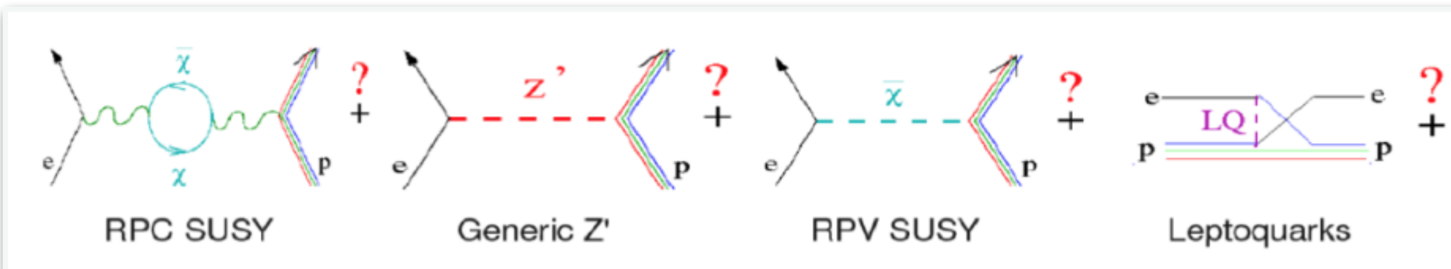
MESA-P2 will improve $Q_W(p)$ by factor ~3.3

MOLLER@JLab will improve $Q_W(e)$ by factor of 5

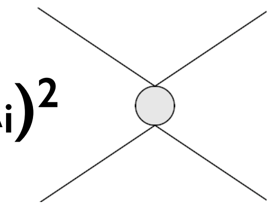
SoLID@JLab will improve eDIS by factor of ~3

Impact of PVES on new physics

- Sensitivity to heavy new physics parameterized by local operators



→ $1/(\Lambda_i)^2$



$\Lambda \sim 5 \rightarrow 8$ TeV (Q-Weak)
$\Lambda \sim 6$ TeV (SoLID)
$\Lambda \sim 11$ TeV (MOLLER)

J. Erler et al. 1401.6199

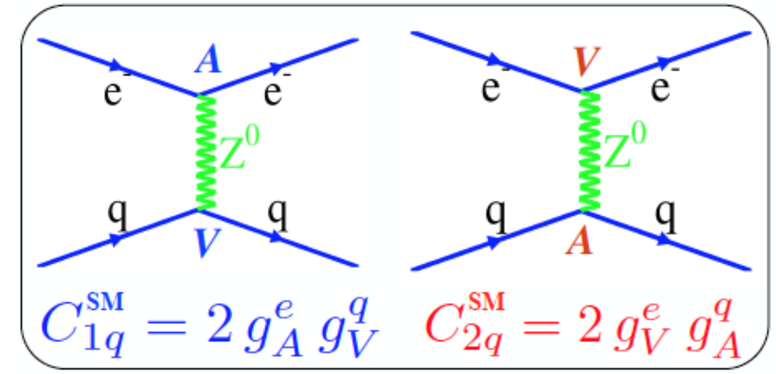
Best contact-interaction reach for leptonic operators, at low OR high-energy

$\Lambda_{LHC} \sim$ 5-10 TeV (di-lepton searches)

Impact of PVES on new physics

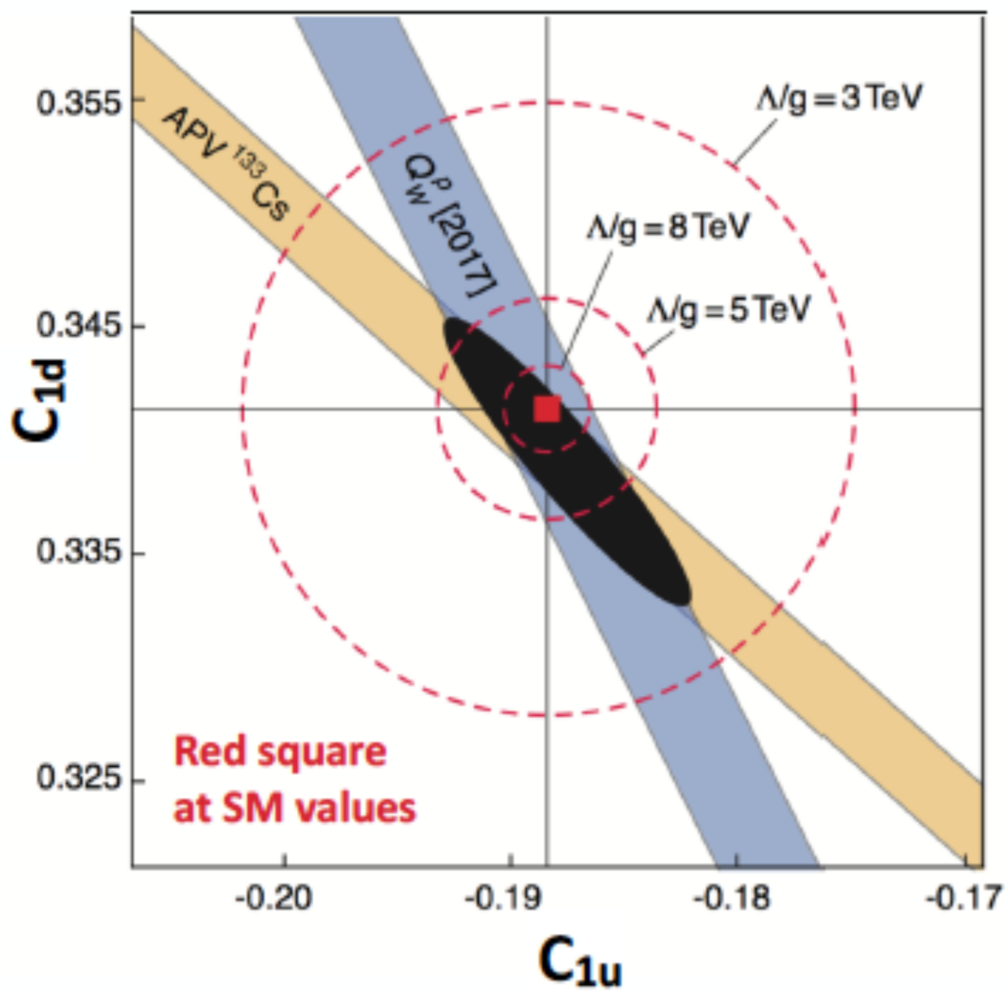
- Q-Weak result provides constraint on linear combination of C_{1u}, C_{1d}

Effective electron-quark couplings



$$Q_W^p = -2(2C_{1u} + C_{1d})$$

New Physics Ruled Out
@95% CL Below Mass Scale of Λ/g



- Agreement with Standard Model + APV constrains the size (mass scale) of possible new physics contribution

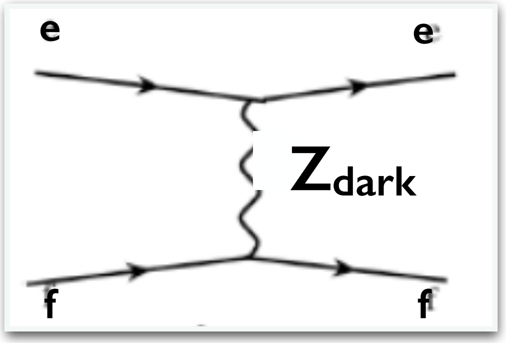
$$\mathcal{L}_{NP}^{PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

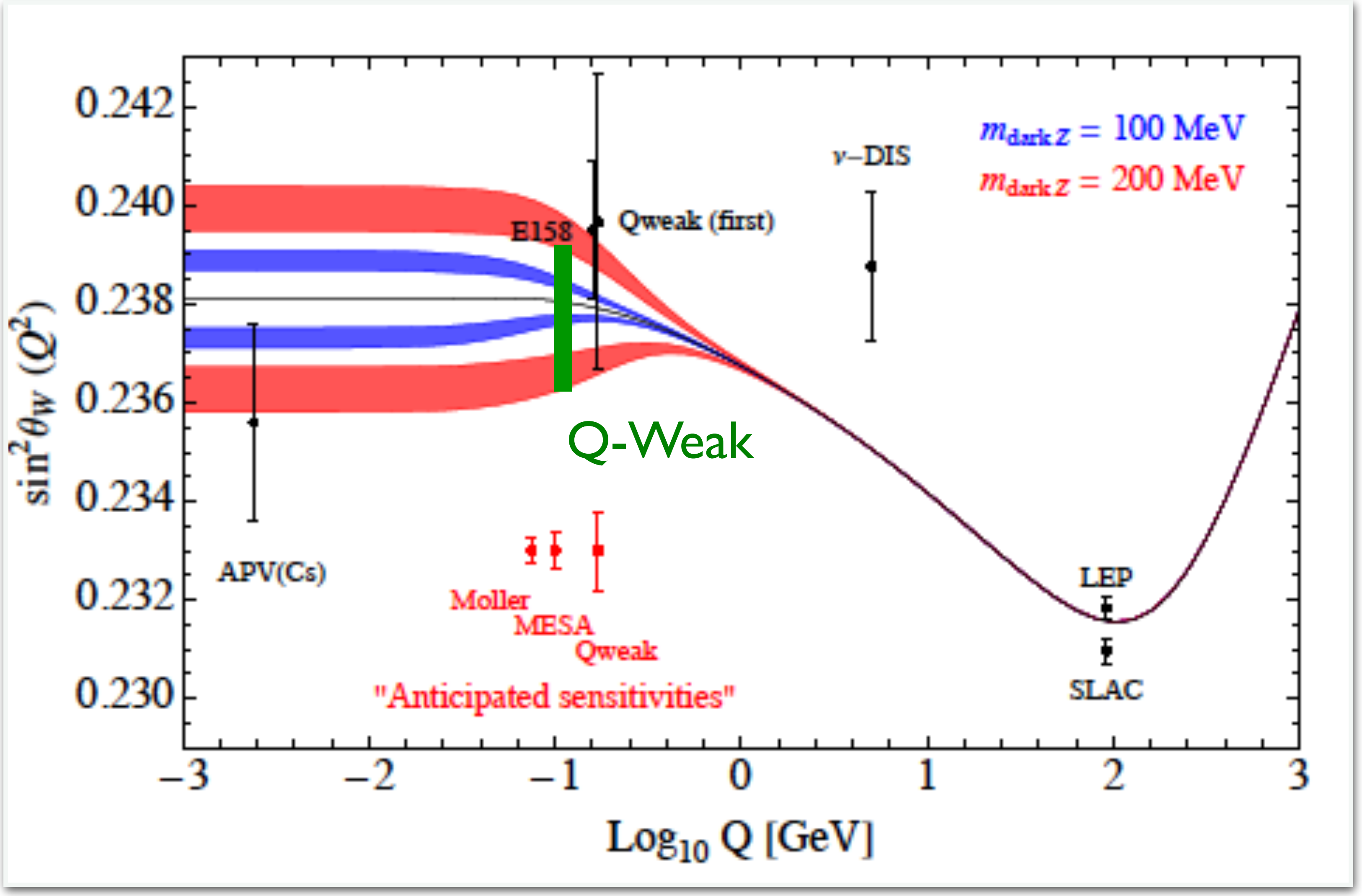
Impact of PVES on new physics

- Sensitivity to dark sector: $U(1)_d$ dark boson Z_d can mix with γ and Z

Davoudsial-Lee-Marciano 1402.3620

$$\mathcal{L}_{\text{dark }Z} = -\left(\varepsilon e J^\mu_{em} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^\mu_{NC}\right) Z_{d\mu}$$





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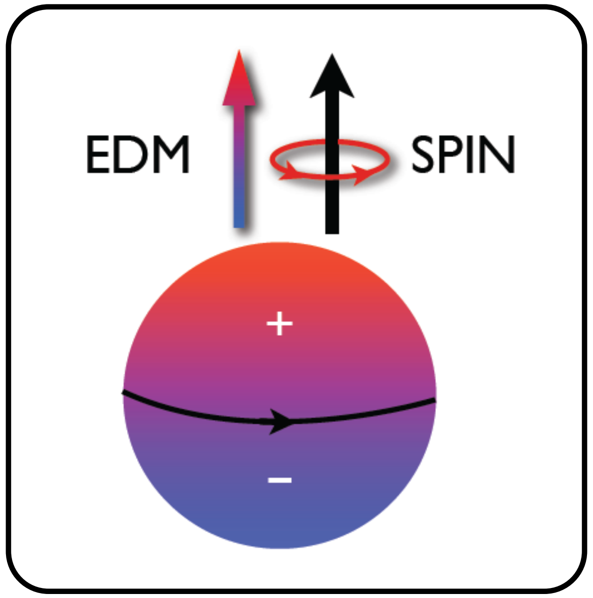
EDMs and T (CP) violation beyond the Standard Model

EDMs and symmetry breaking

- 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



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

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

EDMs and symmetry breaking

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Classical picture →

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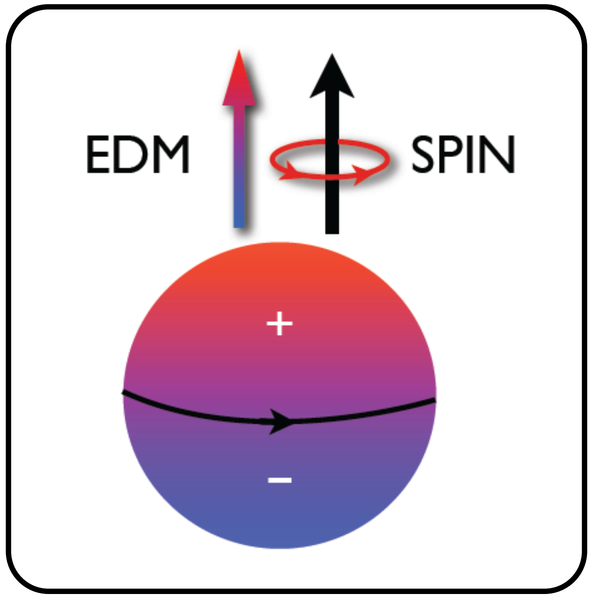


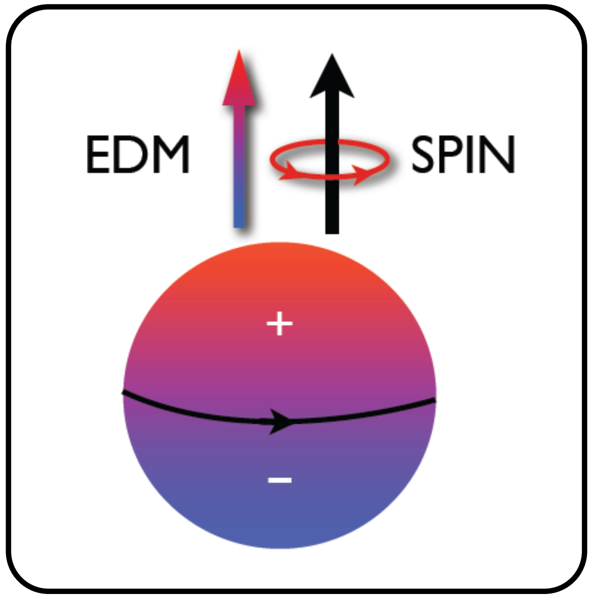
$$\vec{d} = \sum_i q_i\, \vec{r}_i$$

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

- CPT invariance ⇒ nonzero EDMs signal CP violation

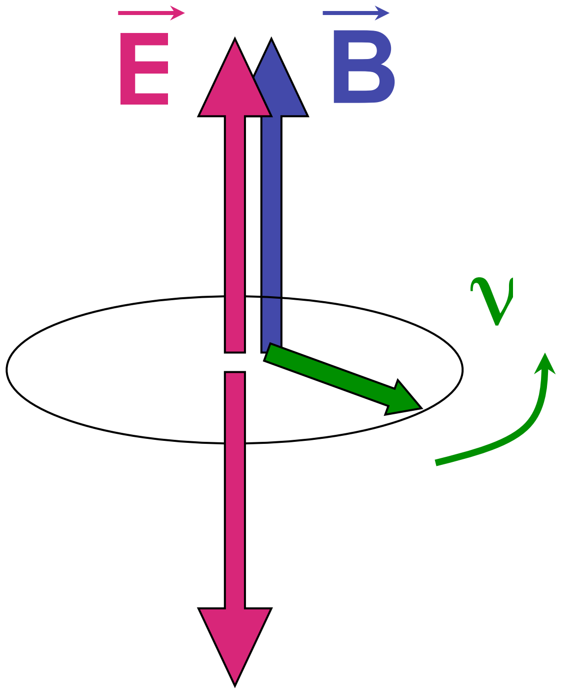
EDMs and symmetry breaking

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



- Measurement: look for linear shift in energy (change in precession frequency) due to external E field

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



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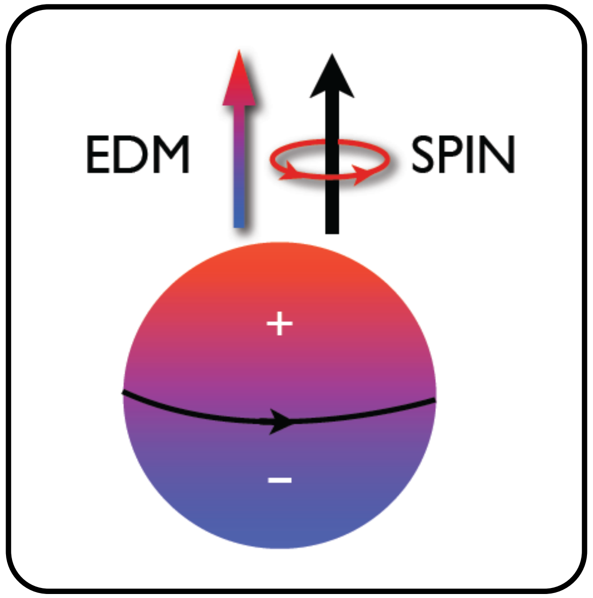


Neutron = Earth

Charge separation = human hair

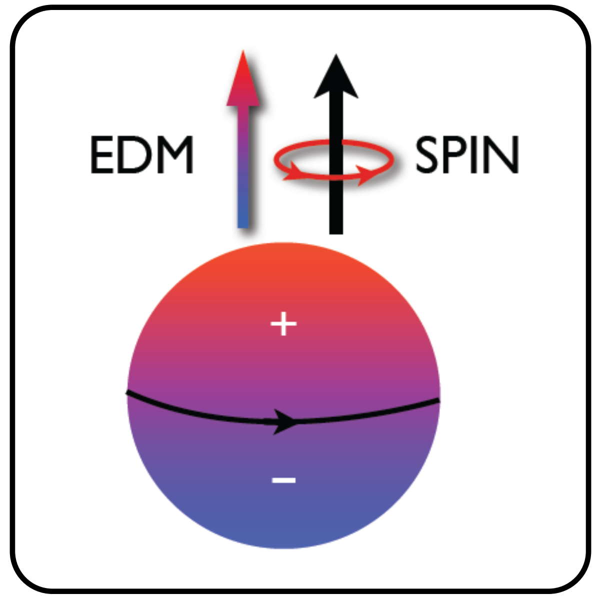
- Measurement: look for linear shift in energy (change in precession frequency) due to external E field

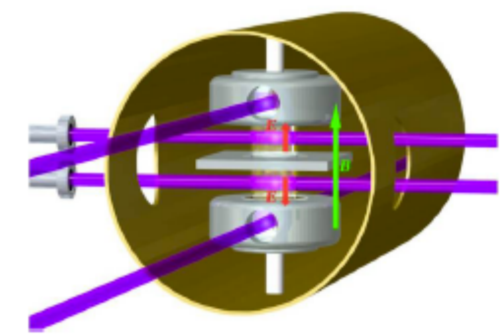
$$\nu = (2\mu B \pm 2dE)/h$$

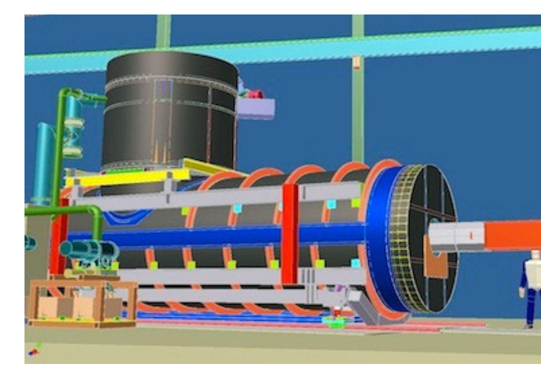
Current neutron sensitivity $d_n \sim 10^{-13}$ e fm !!

EDMs and symmetry breaking

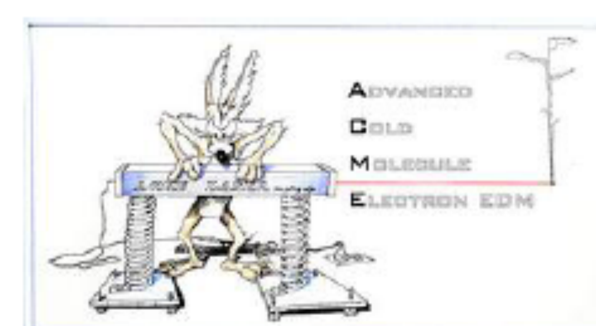
- EDMs of non-degenerate systems violate P and T: $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$







- 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 and new physics

1. Essentially free of SM "background" (CKM) *[1]

EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
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	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

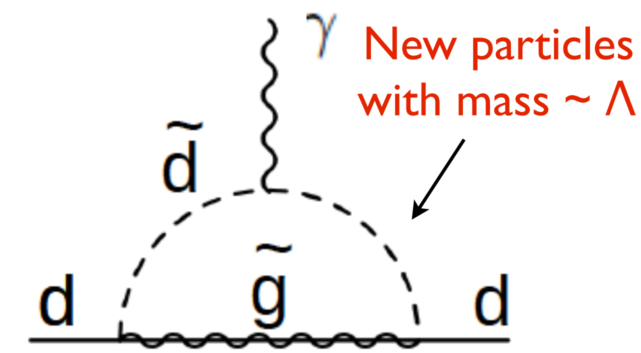
*[1] Observation would signal new physics or a tiny QCD θ-term ($< 10^{-10}$).
Multiple measurements can disentangle the two effects.

EDMs and new physics

1. Essentially free of SM "background" (CKM) *1

2. Sensitive to high scale BSM physics (Λ~10-100 TeV)

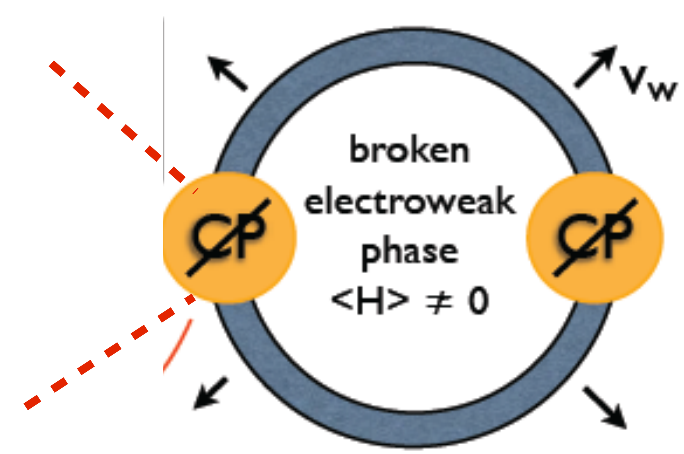
$$d_n \propto \frac{m_q}{\Lambda^2} e\, \phi_{CP}$$



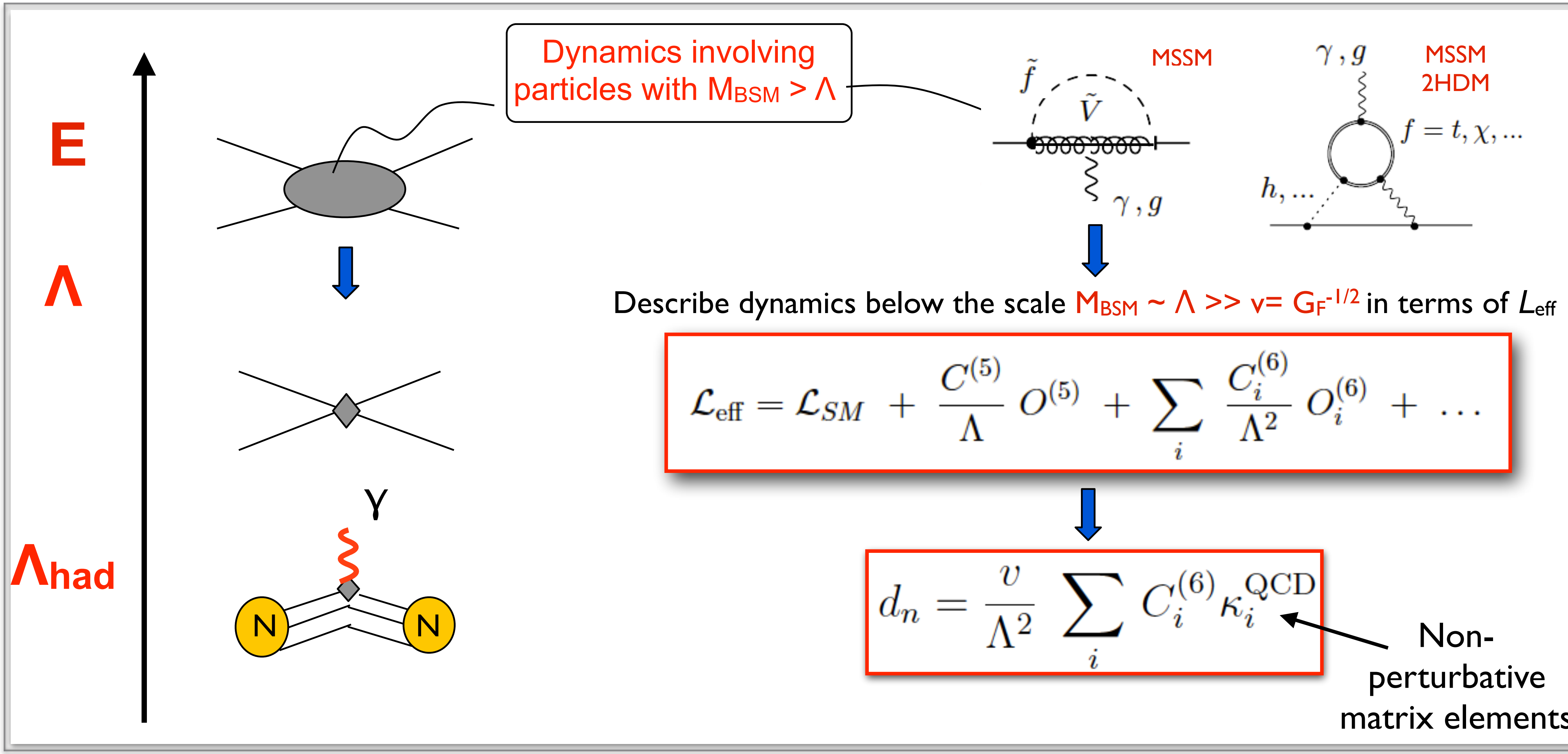
3. Probe key ingredient of baryogenesis

Sakharov '67

- B violation
- C and CP violation
- Departure from equilibrium*



Connecting EDMs to new physics



Connecting EDMs to new physics

- At E ~GeV, leading BSM effects encoded in handful of dim-6 operators

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

Electric and chromo-electric dipoles of fermions

Gluon chromo-EDM (Weinberg operator)

Semileptonic and 4-quark

J·E **J·E$_c$**

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

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

Connecting EDMs to new physics

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- Hadronic / nuclear matrix elements not very well known.
  Can be improved in lattice QCD. Example of neutron EDM:

nEDM fro qEDM in lattice QCD: Bhattacharya et al, PRL 115 (2015) 212002 [1506.04196]

μ=2GeV

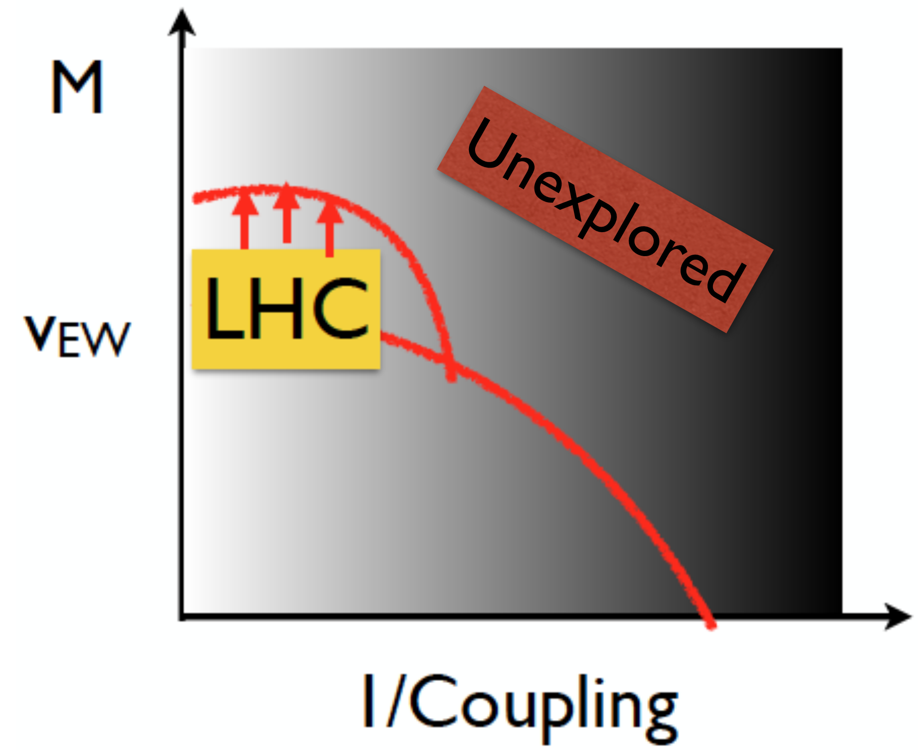
$$\begin{aligned} d_n \;=\; & -(0.22\pm0.03)d_u + (0.74\pm0.07)d_d + (0.0077\pm0.01)d_s \\ & -(0.55\pm0.28)e\tilde{d}_u - (1.1\pm0.55)e\tilde{d}_d \pm (50\pm40)\,\mathrm{MeV}\,e\,d_W \end{aligned}$$

QCD Sum Rules (50% guesstimate) QCD Sum Rules + NDA (~100%)

Pospelov-Ritz hep-ph/0504231 and refs therein

EDMs in the LHC era

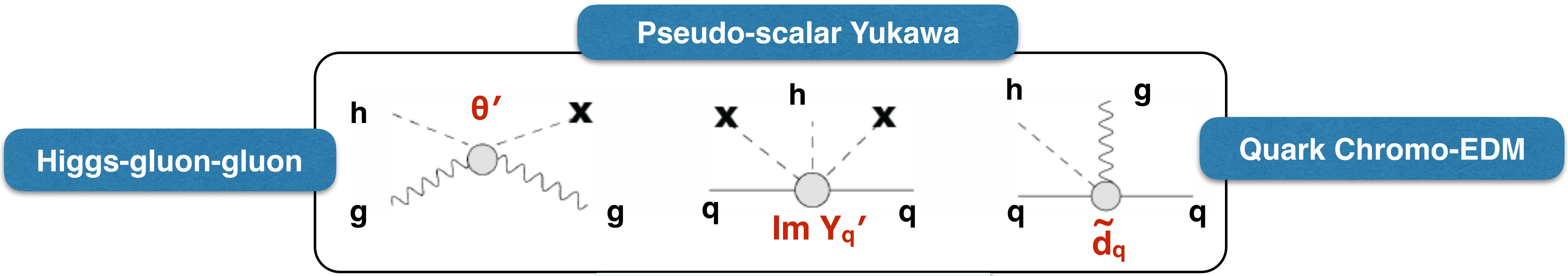
- LHC output so far:
  - Higgs boson @ 125 GeV
  - Everything else is quite heavier (or very light)



- *EDMs more relevant than ever:*
  - Strongest constraints of non-standard CPV Higgs couplings
  - One of few observables probing PeV scale supersymmetry
  - Non trivial constraints on baryogenesis models
  - Sensitivity to axion-like dark matter   Abel et al., 1708.06367

EDMs and CPV Higgs couplings (1)

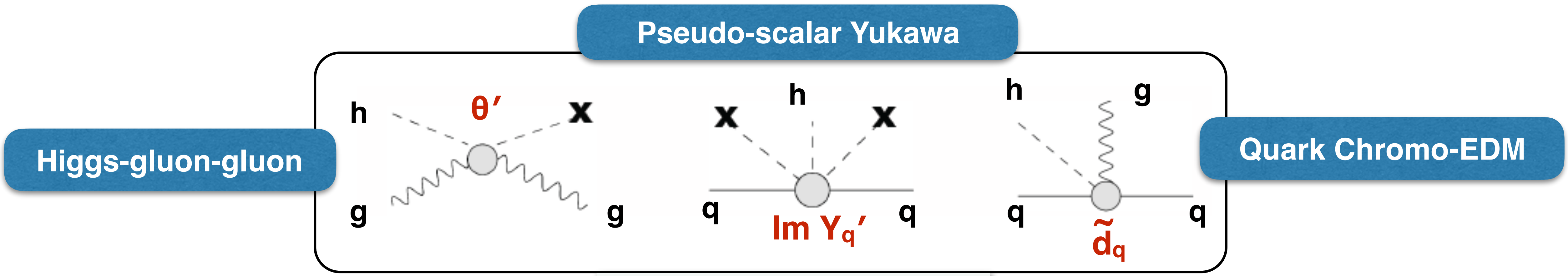
- Leading interactions with q,g strongly constrained by gauge invariance



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

EDMs and CPV Higgs couplings (I)

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



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

$$\mathcal{L}_6^{CPV} = -v\theta' \frac{\alpha_s}{8\pi}\, h G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + v^2 \mathrm{Im}\, Y_q' \, \bar{q} i \gamma_5 q \, h - \frac{i}{2} \tilde{d}_q \, g_s \, \bar{q} \sigma \cdot G \gamma_5 q \left(1 + \frac{h}{v}\right) + O(h^2)$$

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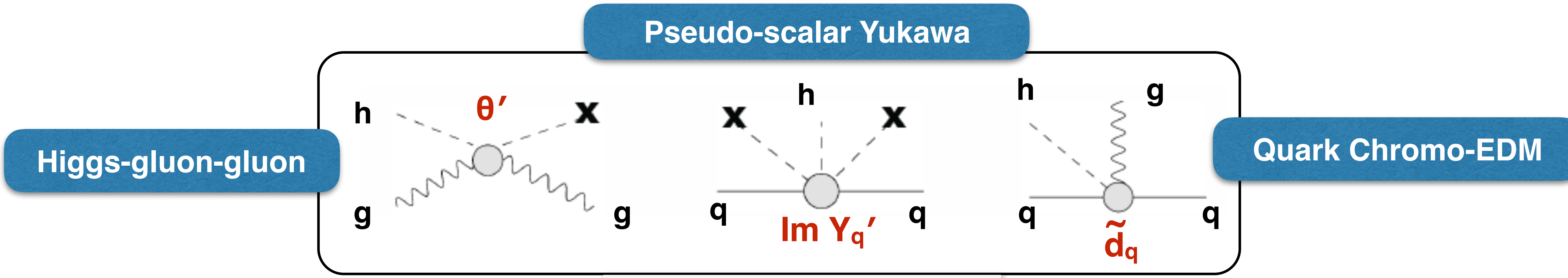
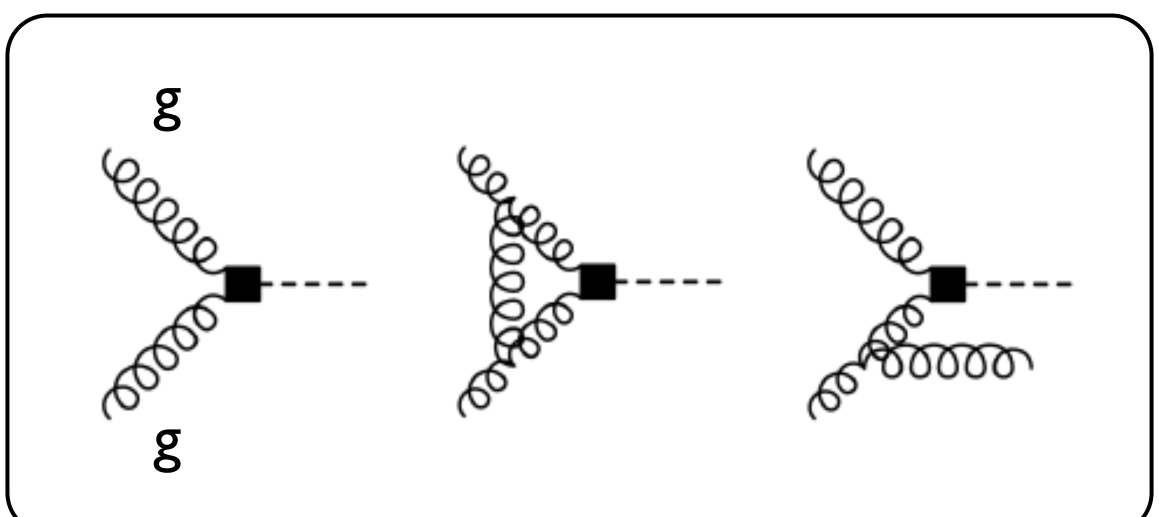
- Leading interactions with q,g strongly constrained by gauge invariance



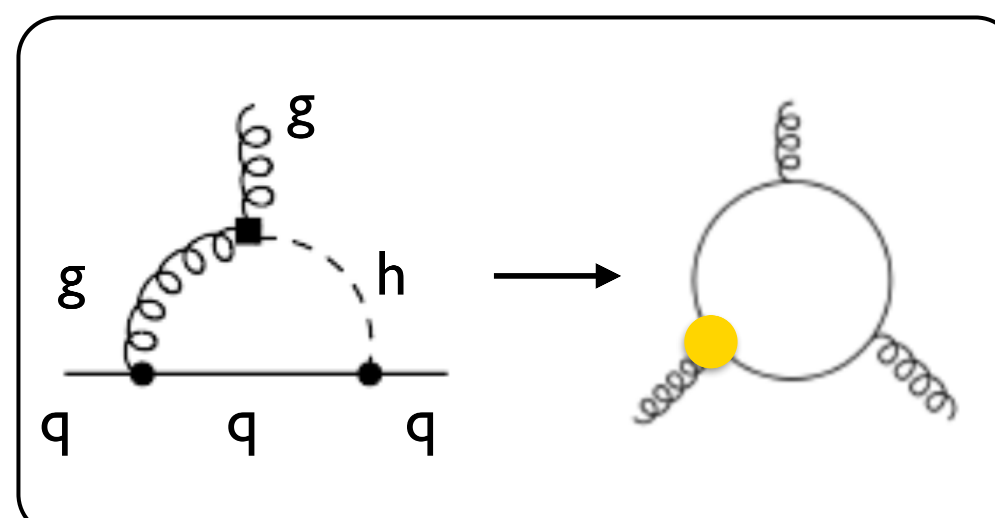
$$\theta', \mathrm{Im}Y_q' \sim \frac{1}{\Lambda^2} \qquad \tilde{d}_q \sim \frac{v}{\Lambda^2}$$

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

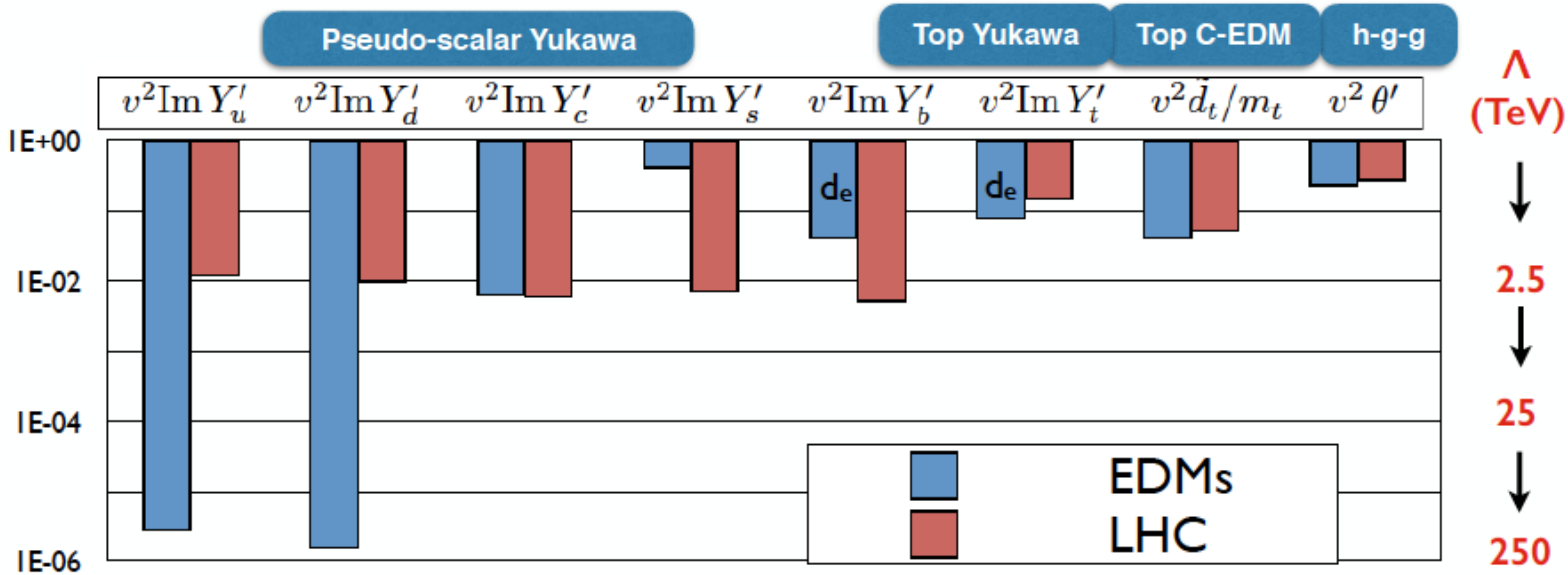
LHC: Higgs production via gluon fusion



Low Energy: quark (C)EDM + Weinberg

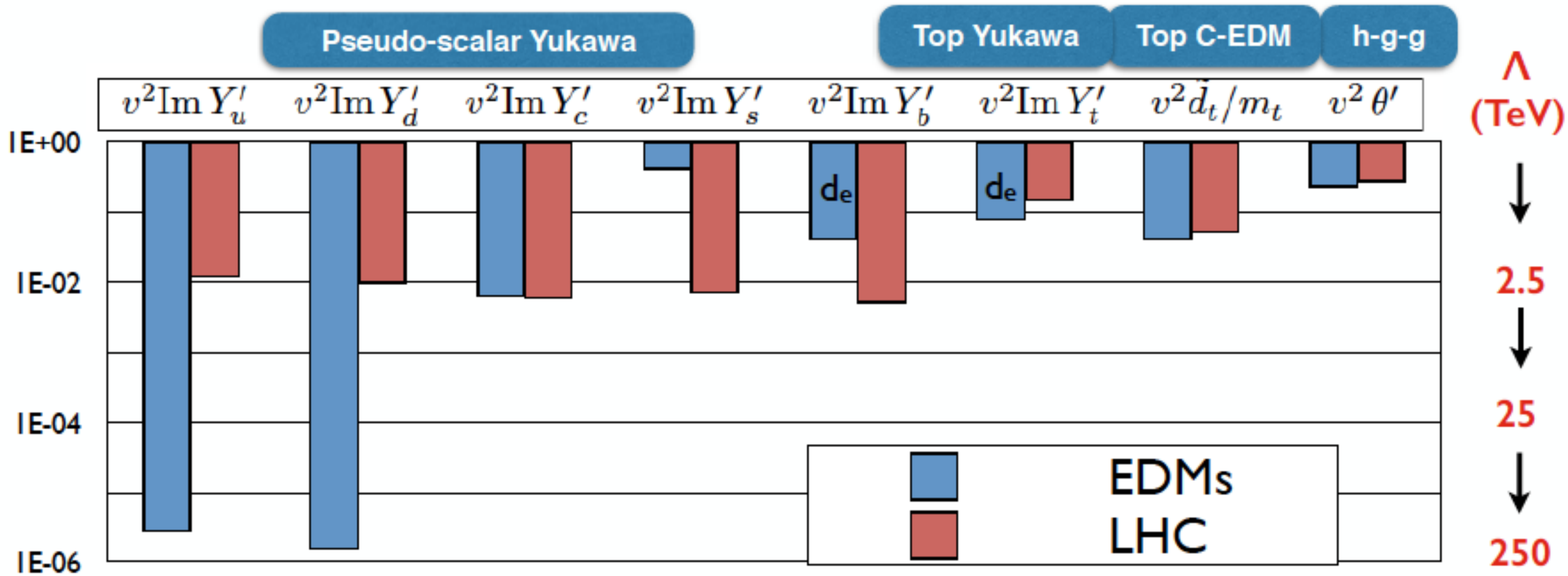


EDMs and CPV Higgs couplings (2)



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

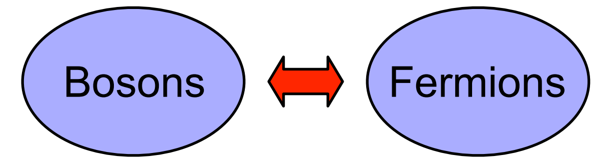
EDMs and CPV Higgs couplings (2)



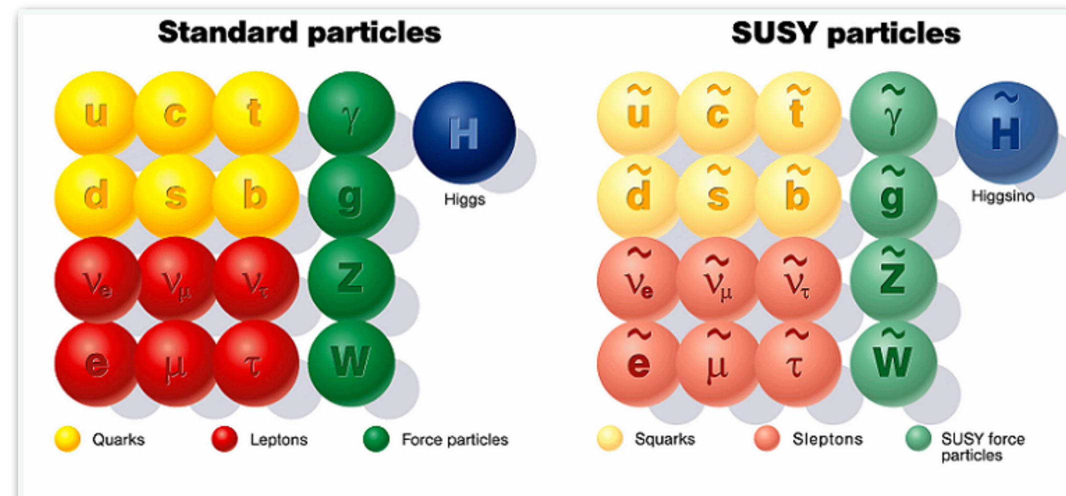
Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

- Neutron EDM is teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Experiment at 5 x 10^{-27} e cm and improved (25-50%) matrix elements will make nEDM the strongest probe for all couplings

EDMs and high-scale SUSY (1)



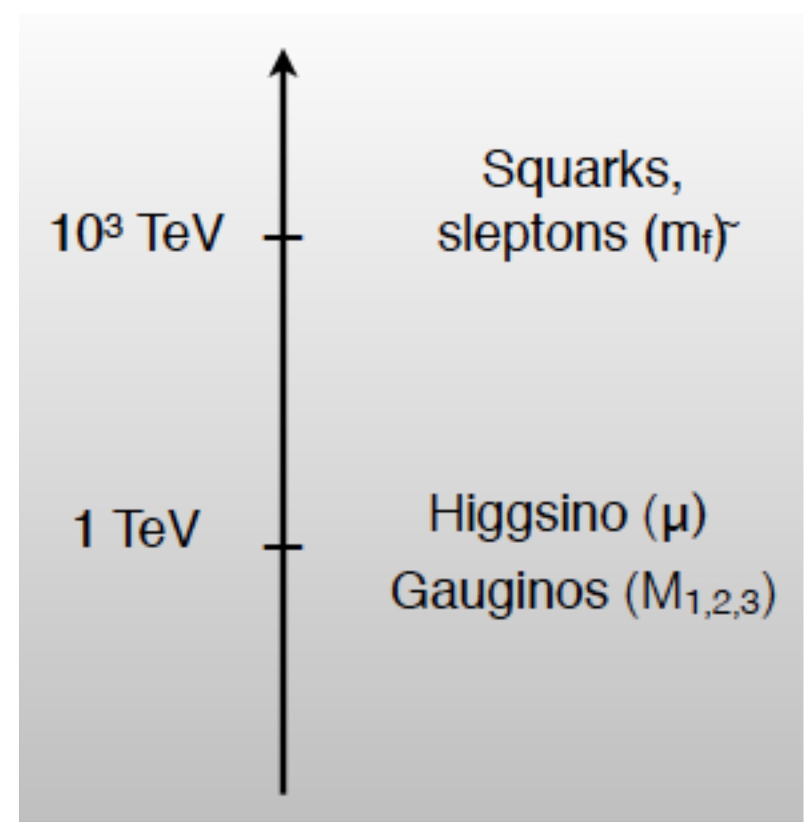
- Higgs mass + absence of other signals point to heavy super-partners



- "Split-SUSY": retain gauge coupling unification and DM candidate

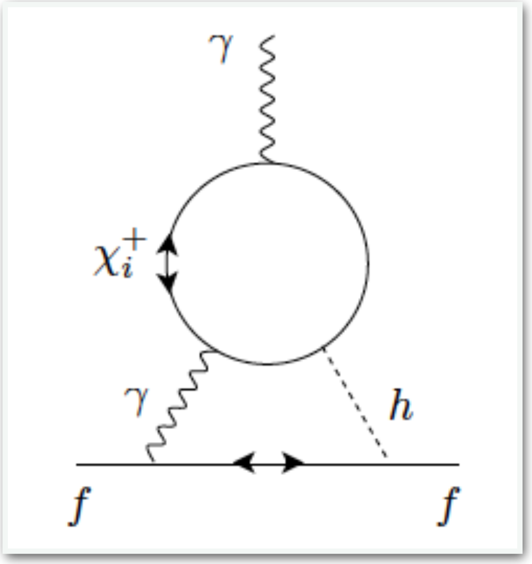
EDMs among a handful of observables capable of probing such high scales

Arkani-Hamed, Dimopoulos 2004,
Giudice, Romanino 2004

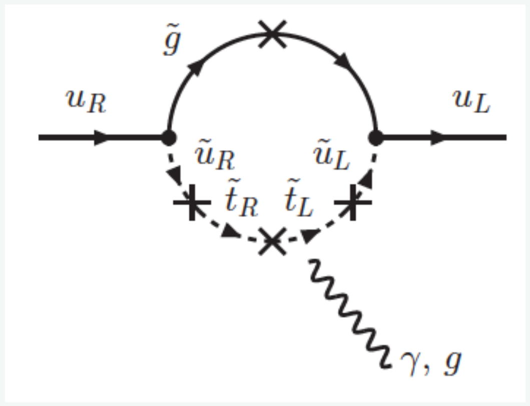


EDMs and high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



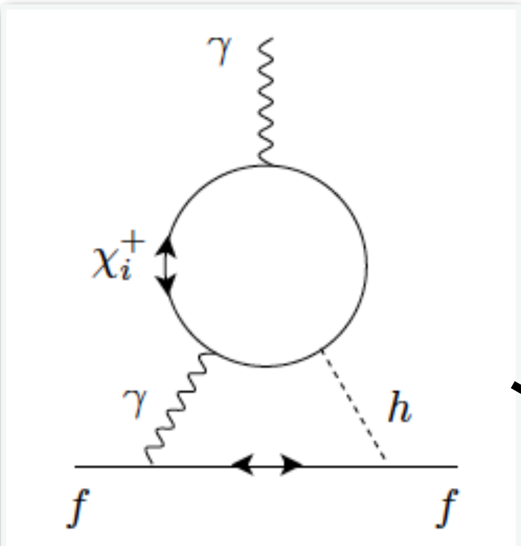
$$d_q \sim \frac{\alpha\,\alpha_w}{(4\pi)^2}\,\frac{m_q}{\mu M_2}\,\sin\phi_2$$



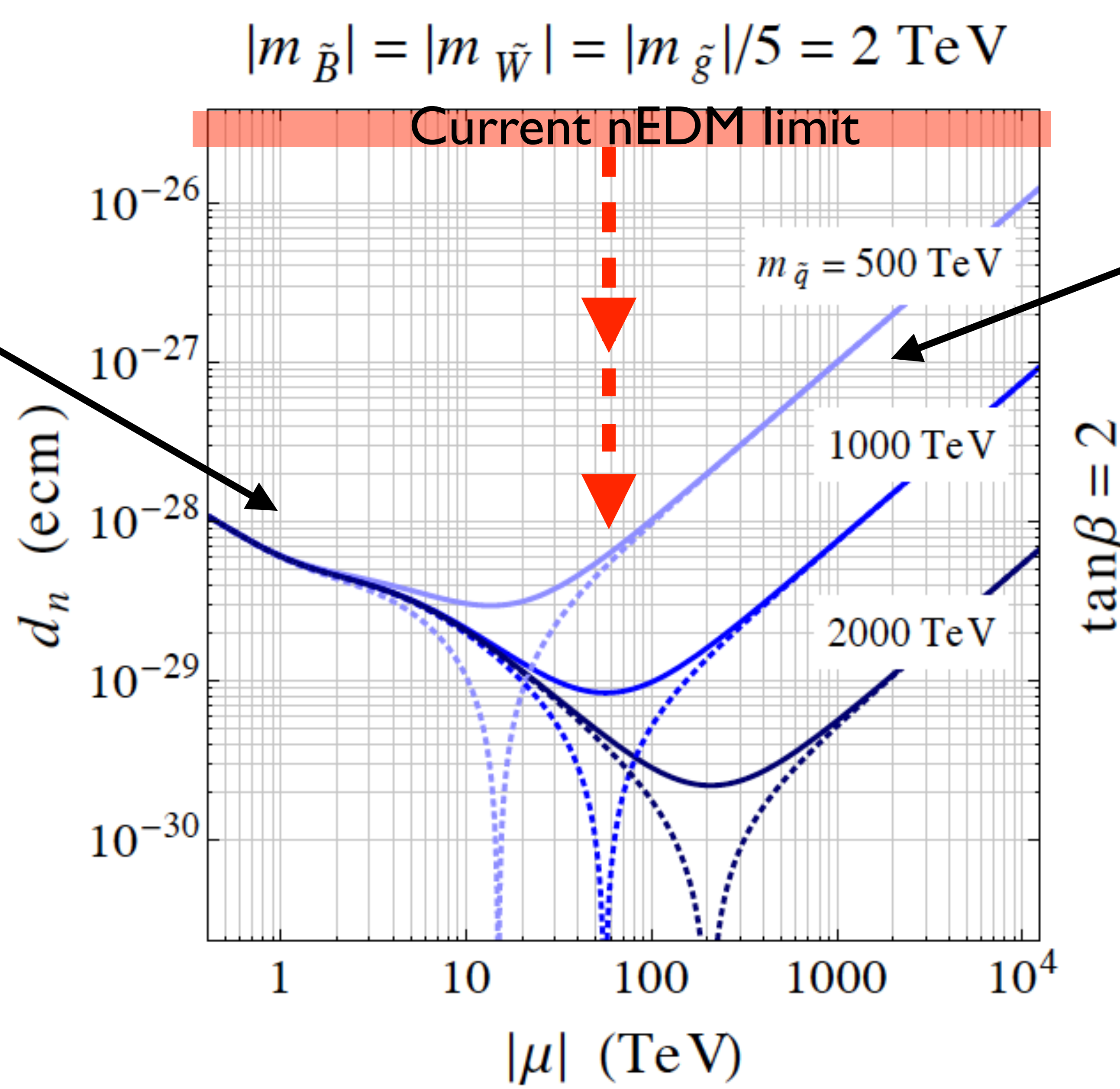
$$\tilde{d}_u \sim \frac{\alpha_s}{4\pi}\,\frac{m_t}{m_{\tilde{q}}^2}\,\frac{\mu M_3}{m_{\tilde{q}}^2}\,\delta_{ut}^L\delta_{tu}^R\,\sin\phi_u$$

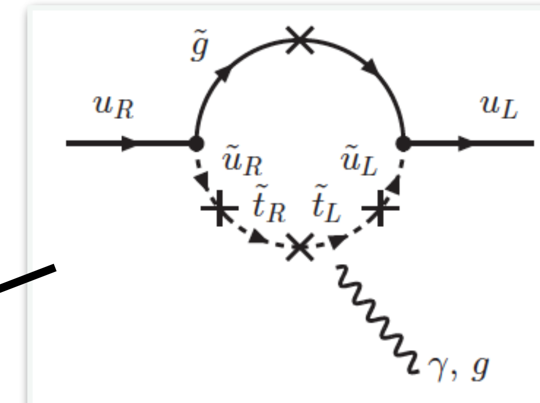
EDMs and high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



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



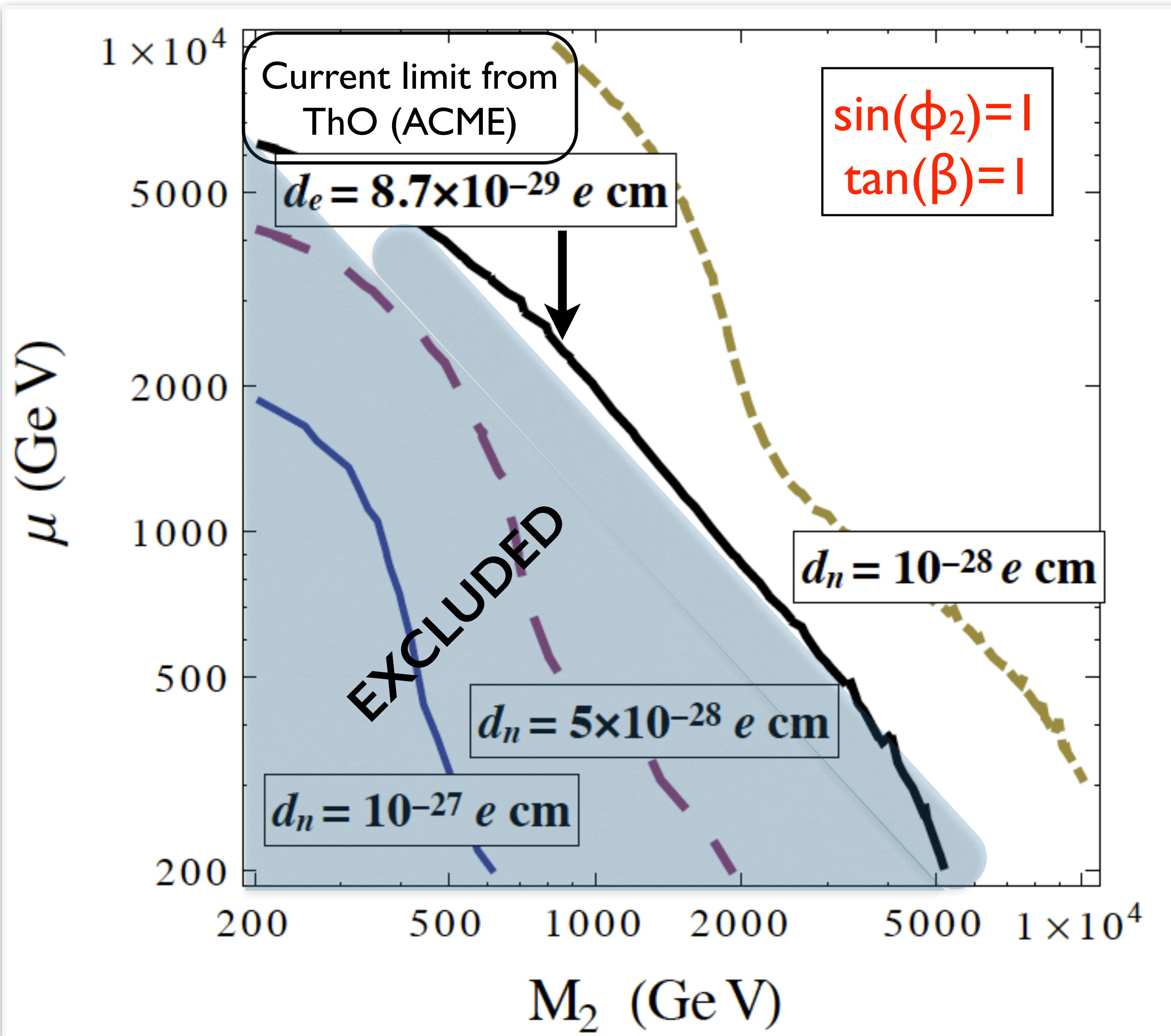


$$\tilde{d}_u \sim \frac{\alpha_s}{4\pi}\,\frac{m_t}{m_{\tilde{q}}^2}\,\frac{\mu M_3}{m_{\tilde{q}}^2}\,\delta^L_{ut}\delta^R_{tu}\,\sin\phi_u$$

Maximal CPV phases.
Squark mixings fixed at 0.3

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

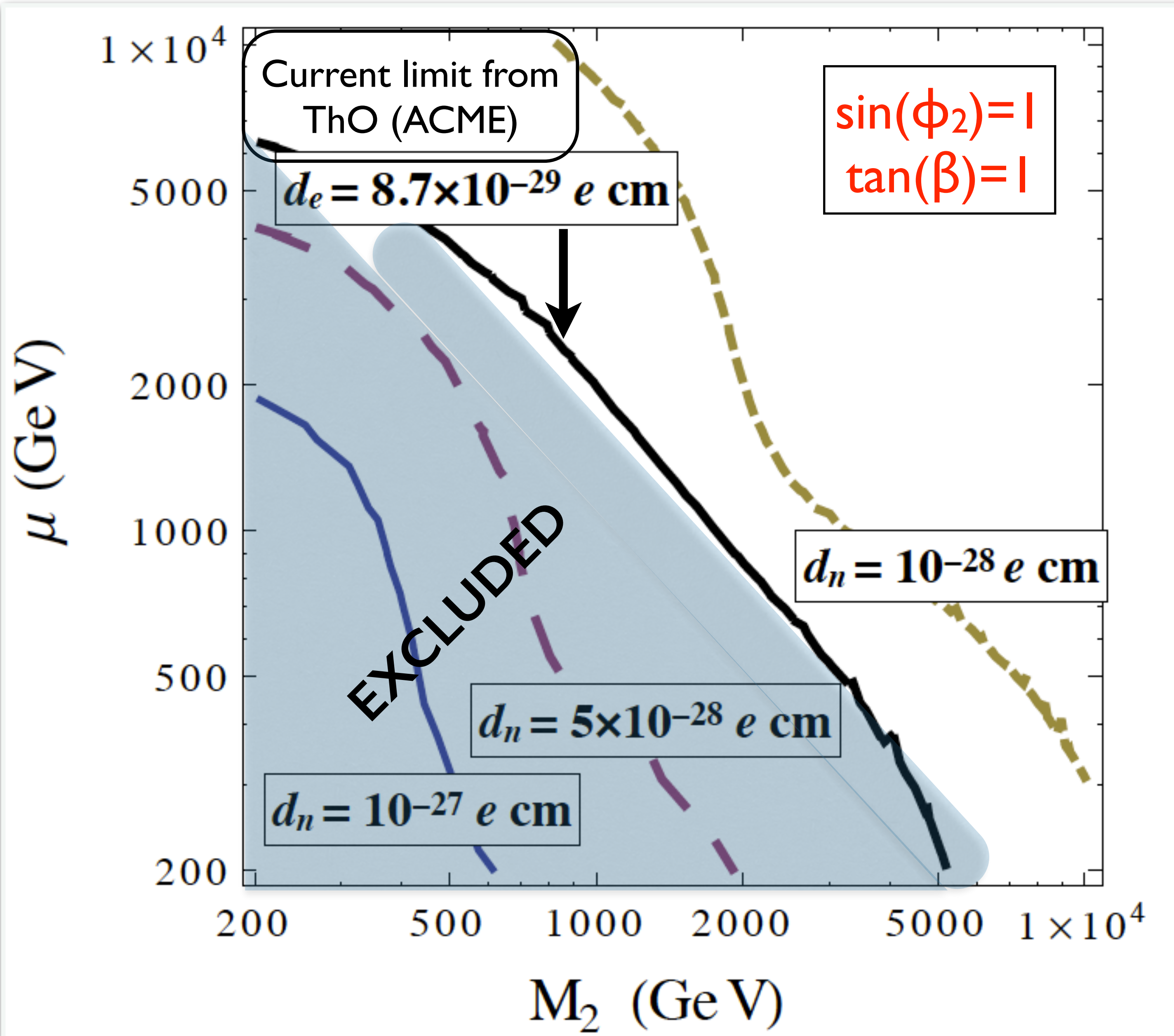
EDMs and high-scale SUSY (3)



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

Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

EDMs and high-scale SUSY (3)



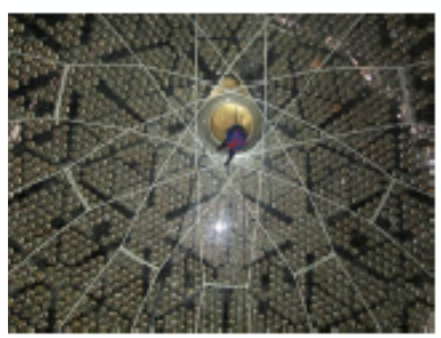
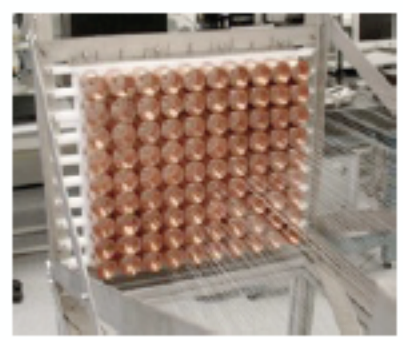
- Both d_e and d_n within reach of current searches for M_2, μ < 10 TeV
- Studying the ratio d_n/d_e *with precise matrix elements* → upper bound $d_n < 4\times10^{-28}$ e cm
- Split-SUSY can be falsified by current nEDM searches

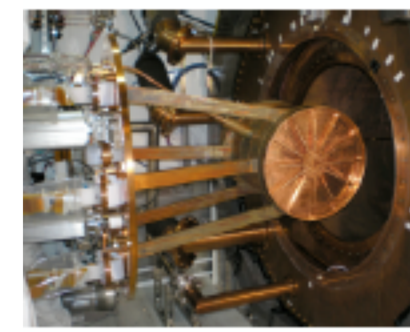
Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

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

0νββ and Lepton Number Violation

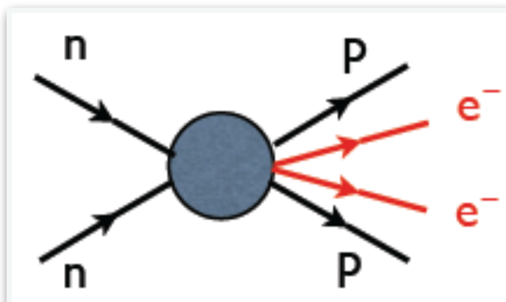


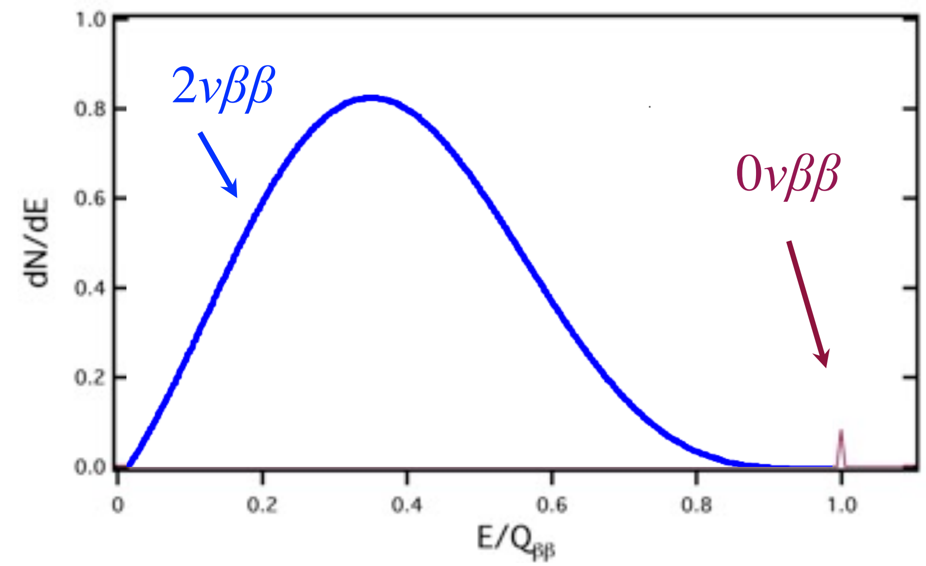


0νββ and Lepton Number Violation

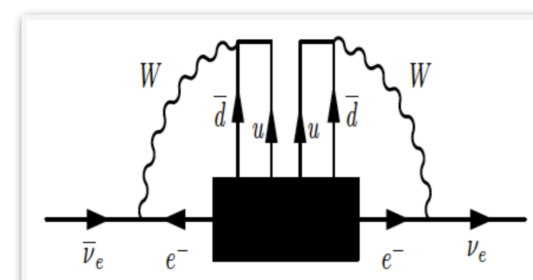
$$(N, Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



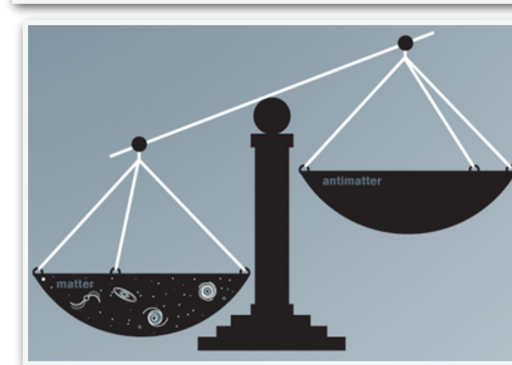
Lepton number changes by two units: ΔL=2



- B-L conserved in SM → new physics, with far-reaching implications
  - Demonstrate that neutrinos are their own antiparticles
  - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



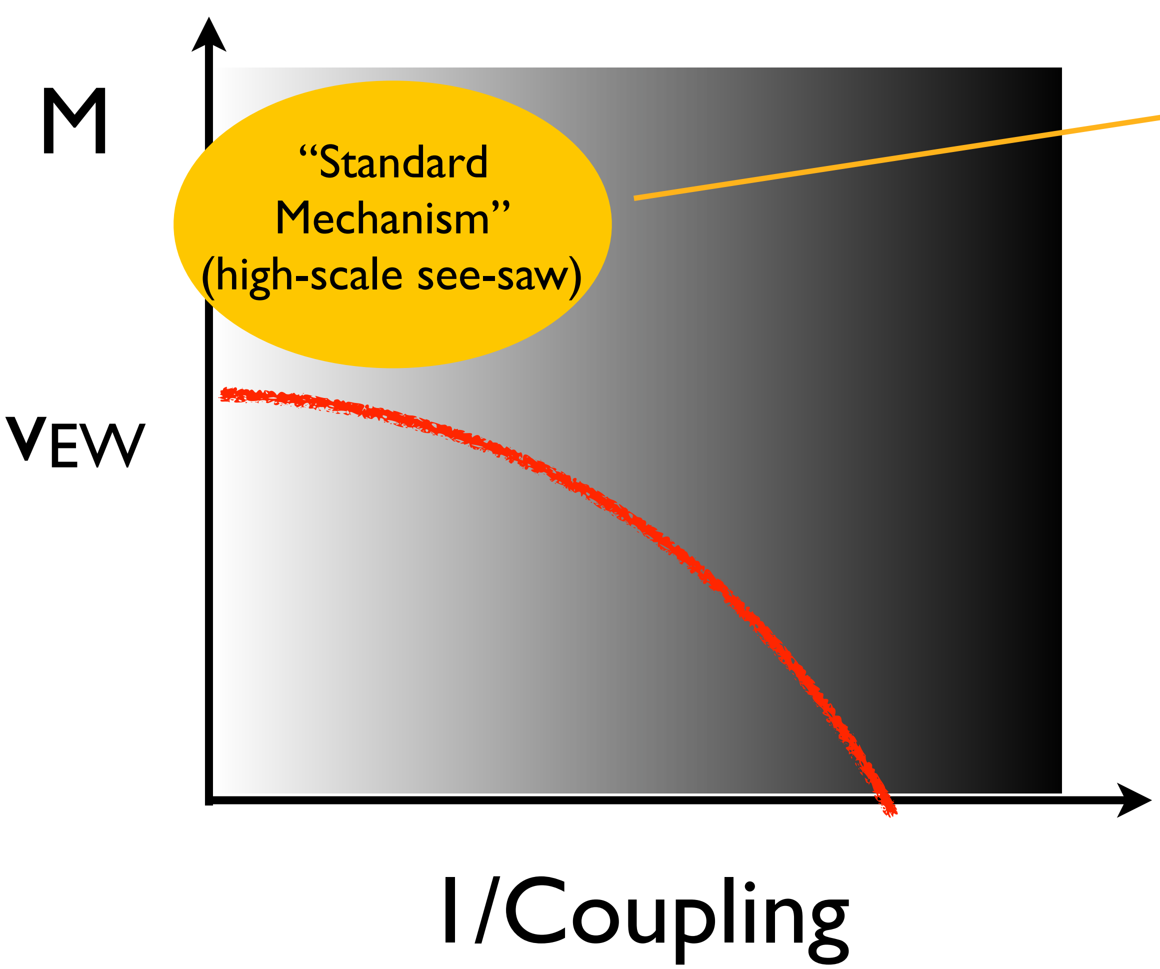
Shechter-Valle 1982



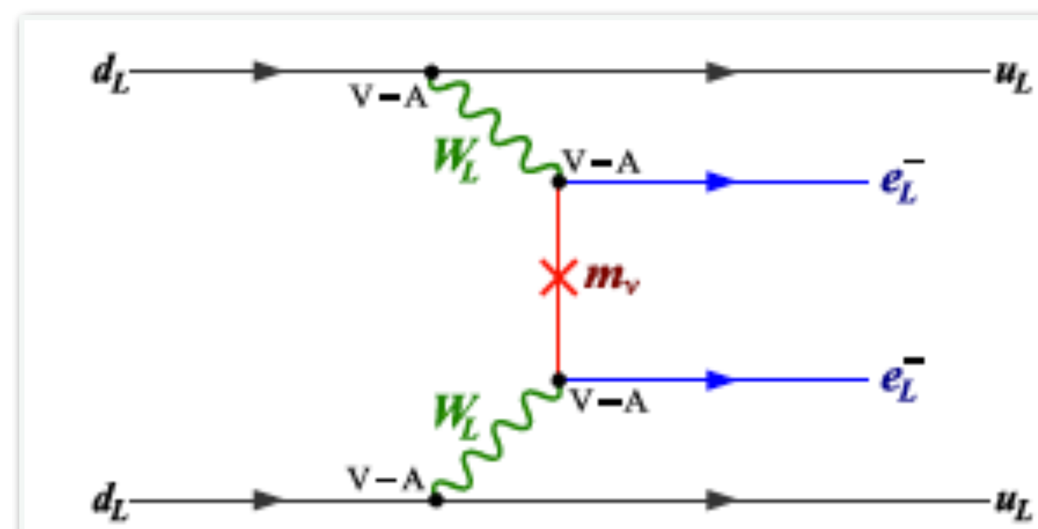
Fukujgita-Yanagida 1987

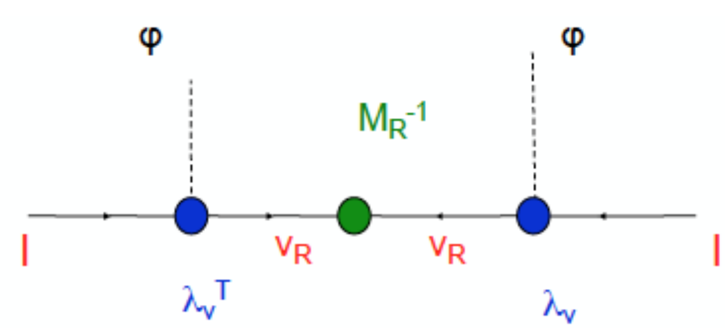
0νββ and Lepton Number Violation

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



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

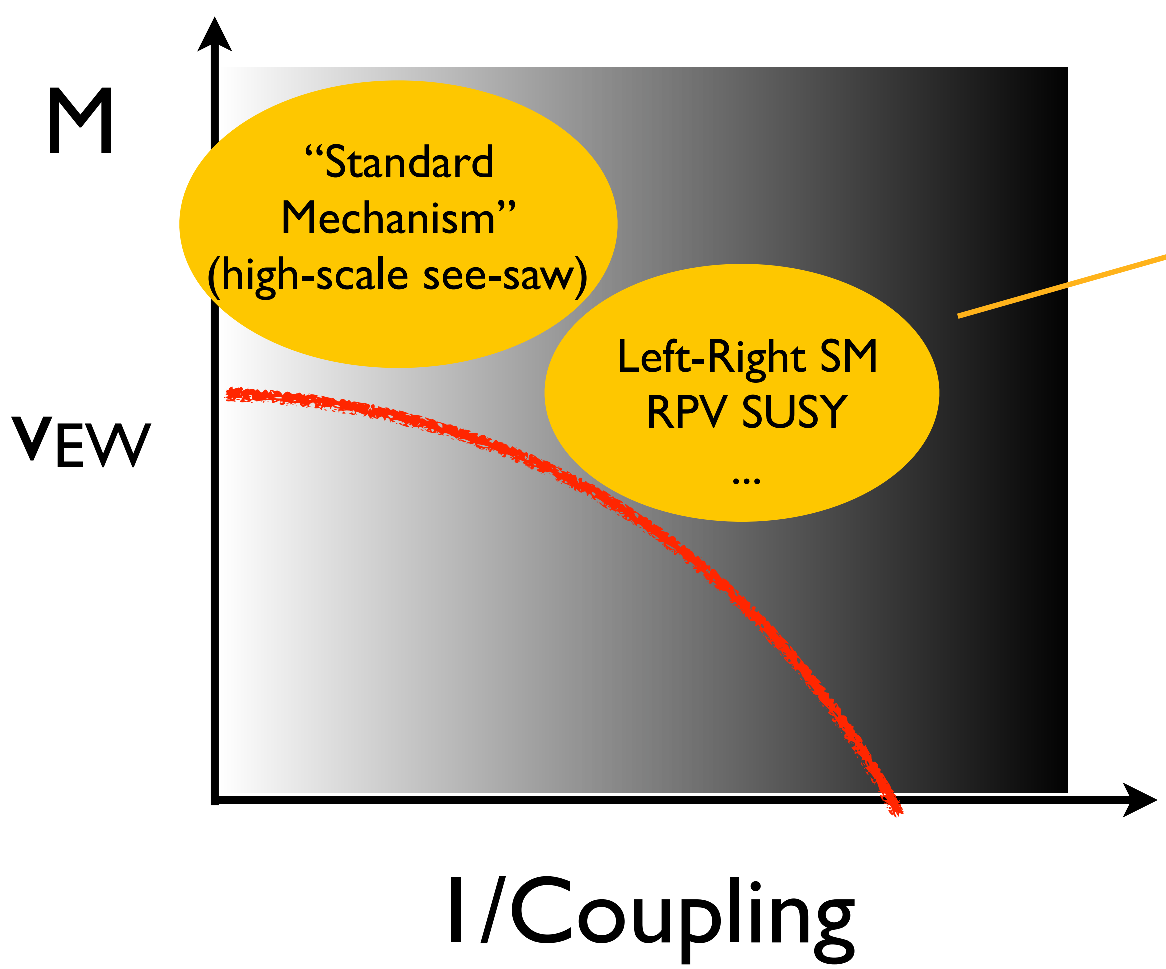




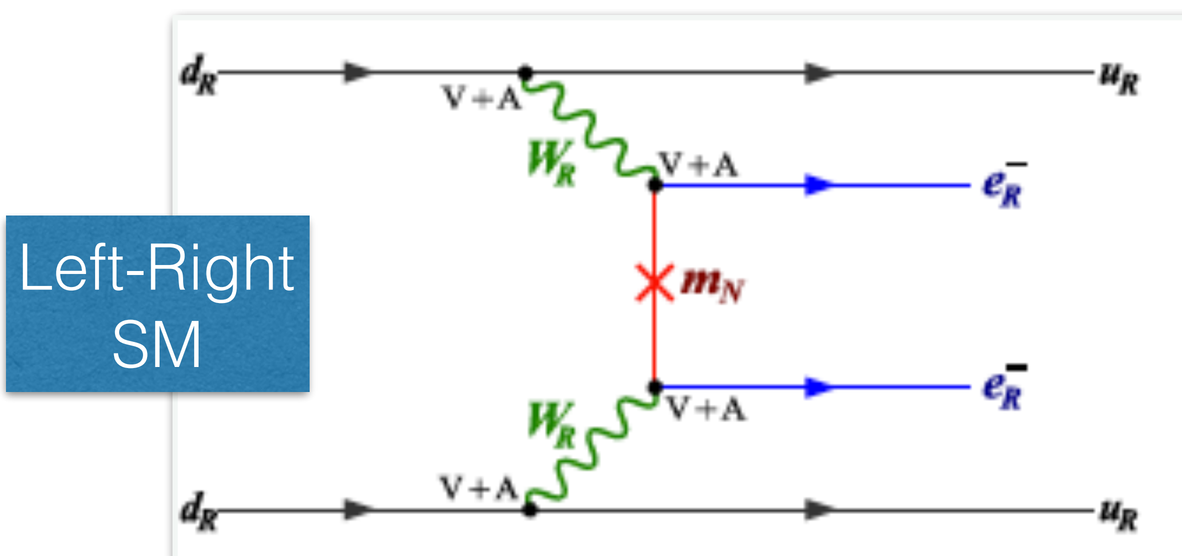
$$m_\nu \sim \frac{v_{EW}^2}{M_R}$$

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



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



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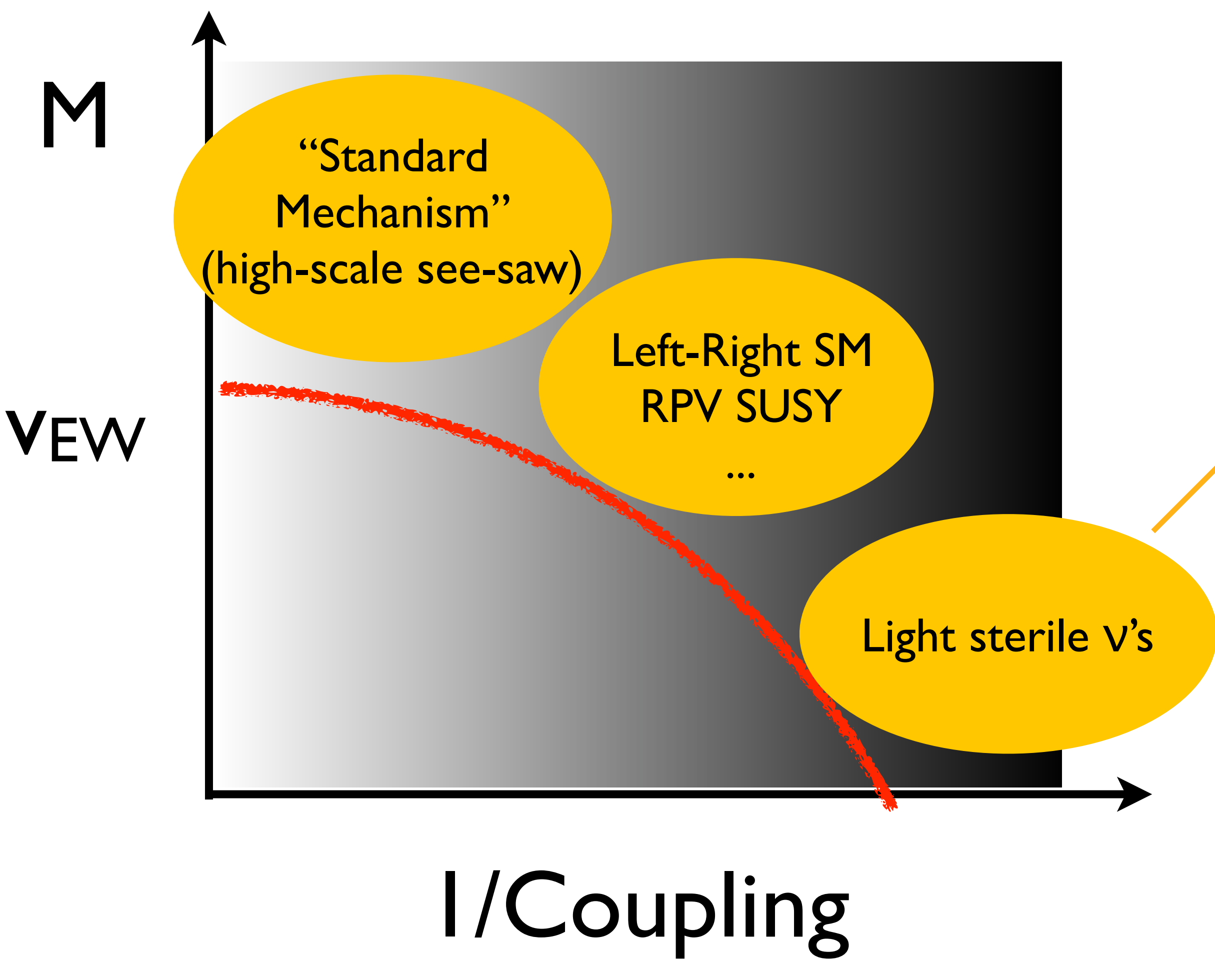
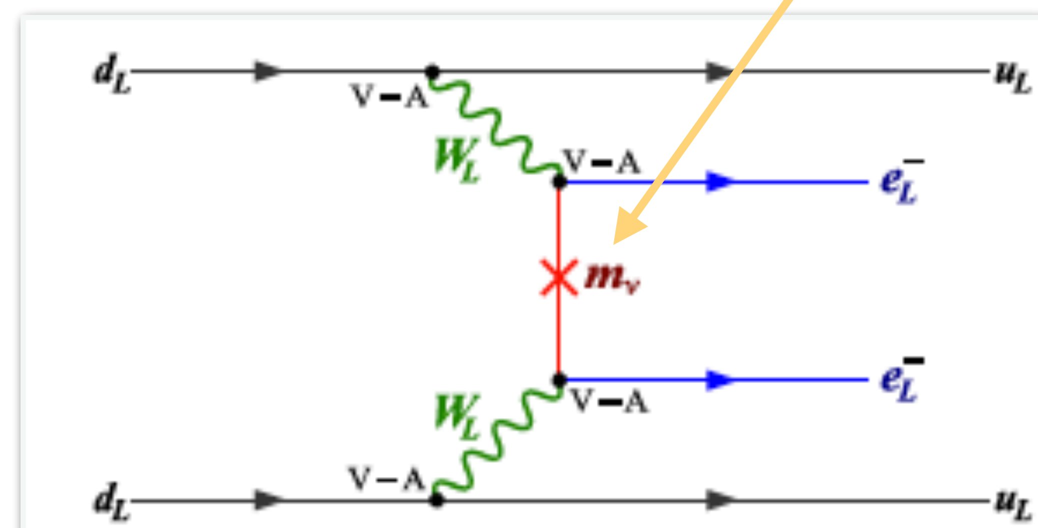


LNV dynamics at M_R : eV → GeV: additional light Majorana states



Connecting 0νββ to new physics

E

Λ
(> TeV)

Quarks

Λ_χ
(~GeV)

Nucleons, pions

Nuclei

$\mathcal{L}_{\rm BSM}$

Integrate out heavy particles

$$\mathcal{L}_{\rm eff} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

"Standard Model EFT"

Hadronic matrix elements

$$\mathcal{L}_{\pi,N} = \sum_i \tilde{C}_i(C_i)\, \tilde{O}_i$$

Chiral EFT

Nuclear matrix elements

$T_{1/2}[\, \tilde{C}_i\, [C_j]]$

For general analysis see VC, W. Dekens, M. Graesser, E. Mereghetti, J. de Vries 1806.02780

Chain of EFT +

lattice QCD & many-body methods

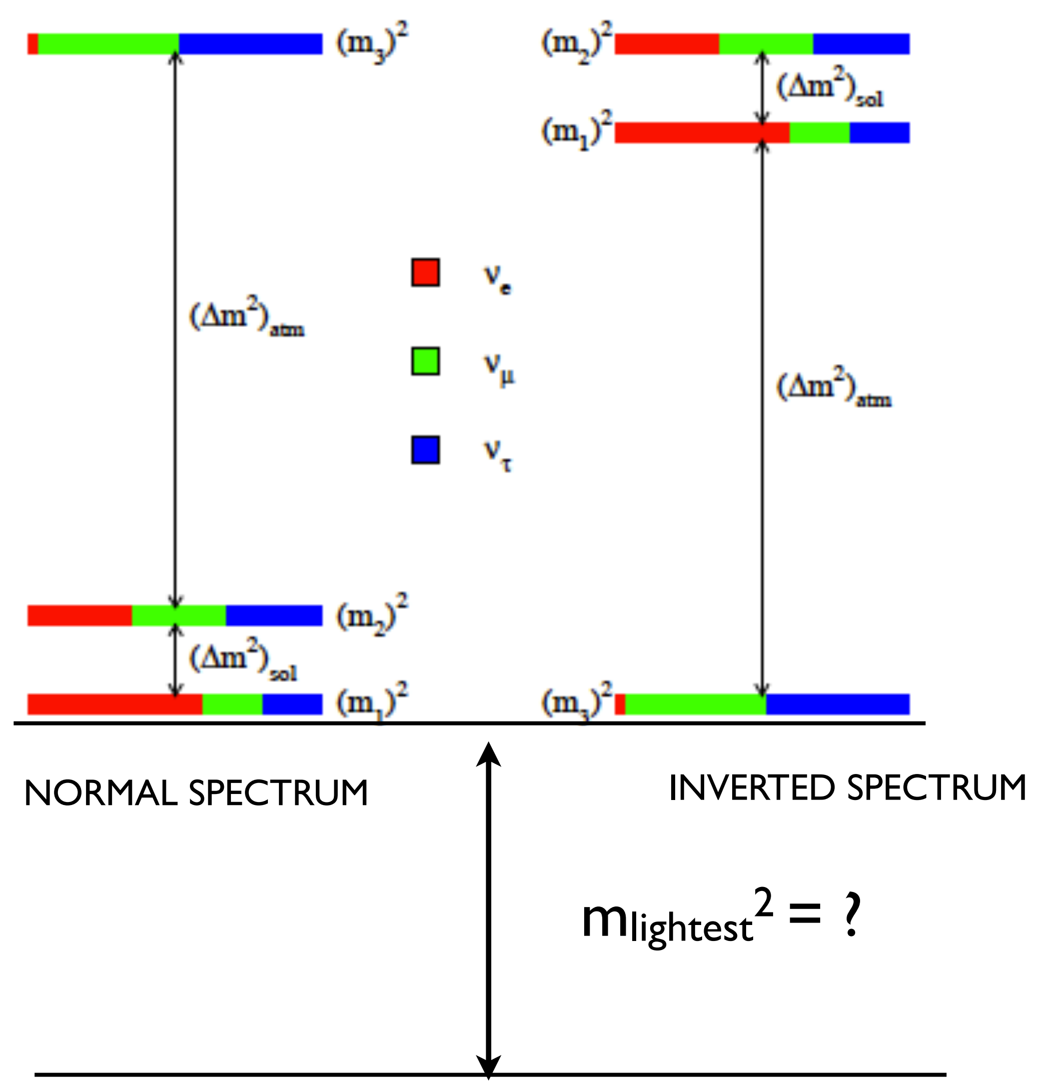
theoretical uncertainties

$$T_{1/2}[\, \tilde{C}_i\, [C_j]\,] \sim (m_W/\Lambda)^A\ (\Lambda_\chi/m_W)^B\ (k_F/\Lambda_\chi)^C$$

High-scale seesaw

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

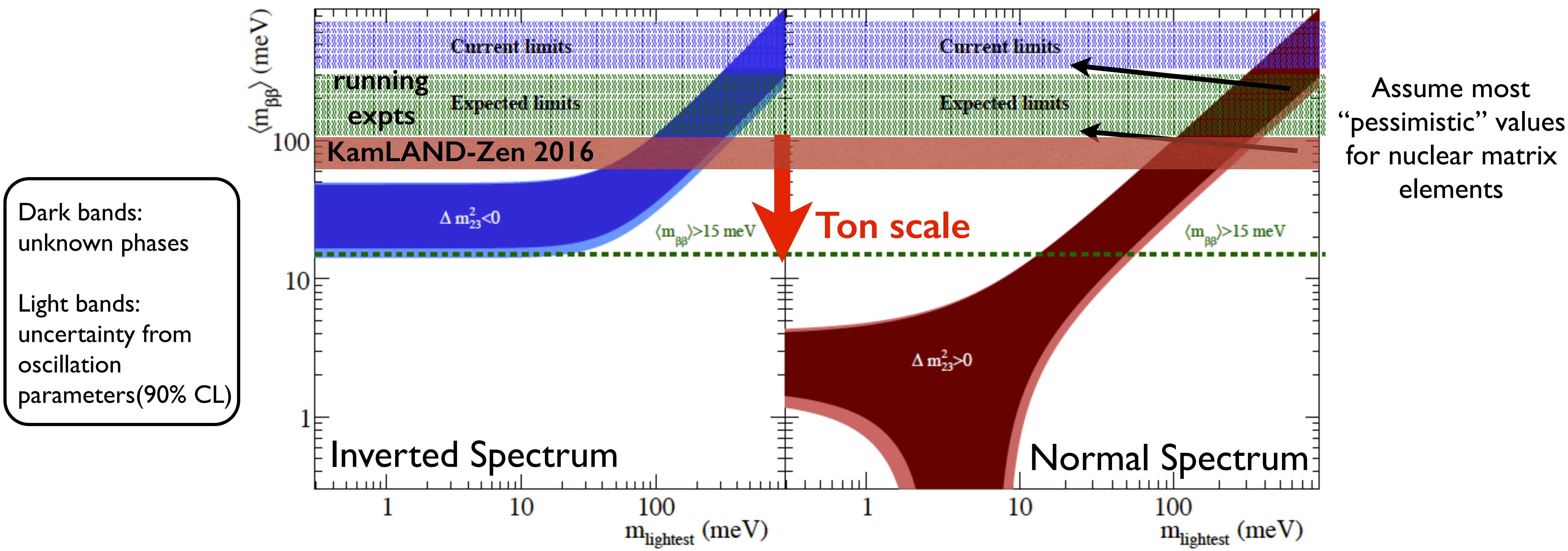
$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$



High-scale seesaw

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

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

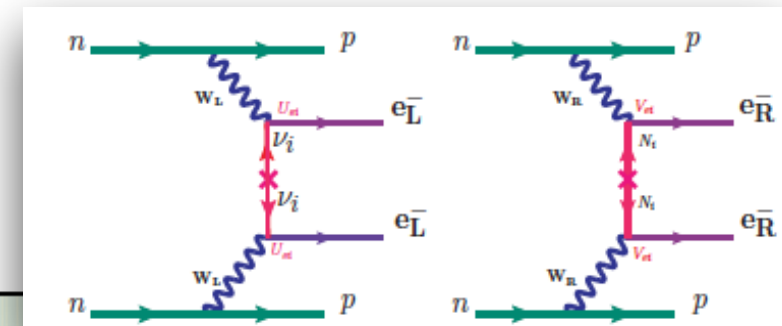


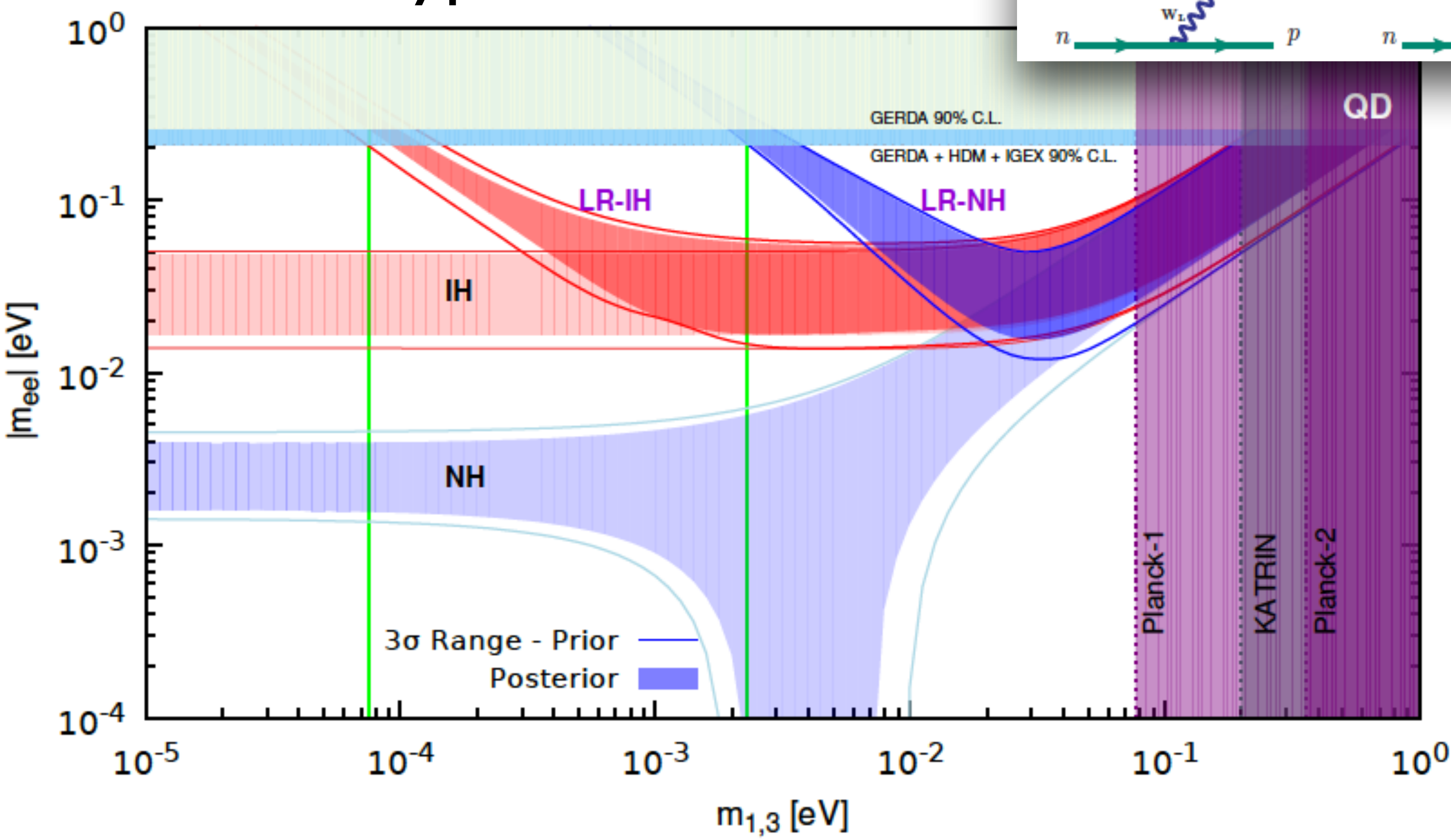
- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

TeV scale LNV

- TeV sources of LNV may lead to significant contributions to NLDBD *not directly related to the exchange of light neutrinos*

Left-Right Symmetric Model
with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

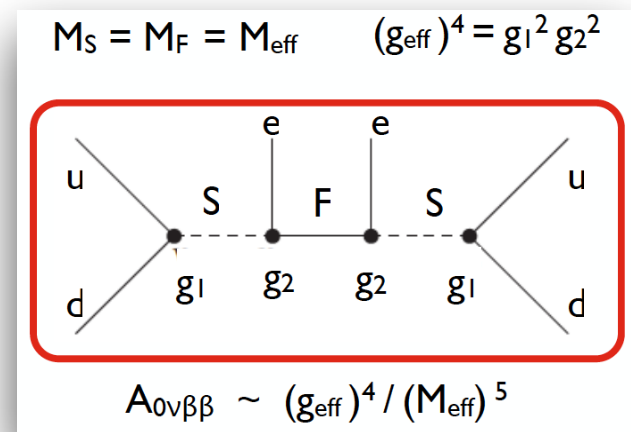
$$M_i = \frac{m_i}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_i}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

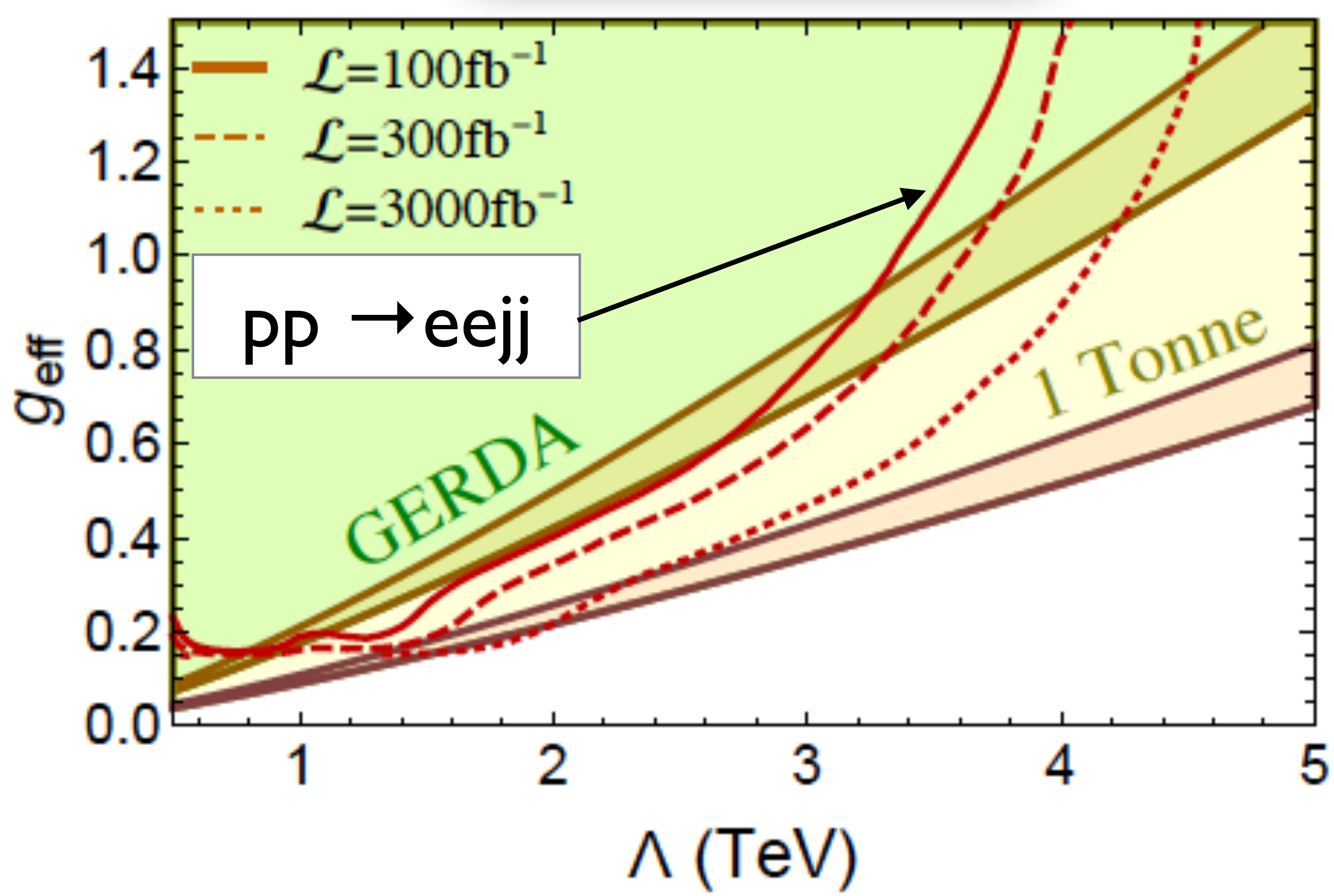
Ge-Lindner-Patra 1508.07286

TeV scale LNV

- TeV sources of LNV may lead to significant contributions to NLDBD *not directly related to the exchange of light neutrinos*



Peng, Ramsey-Musolf, Winslow, 1508.0444



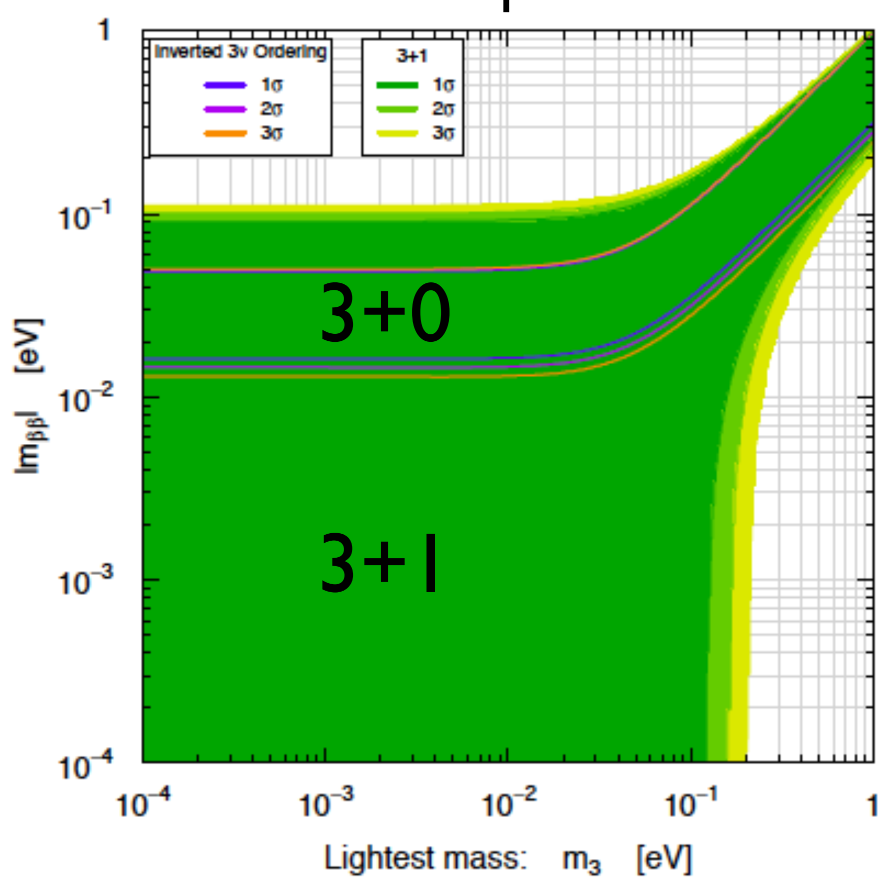
Sensitivity study: $0\nu\beta\beta$ vs LHC (current and future)

Illustrates competition of Ton-scale NLDBD and LHC

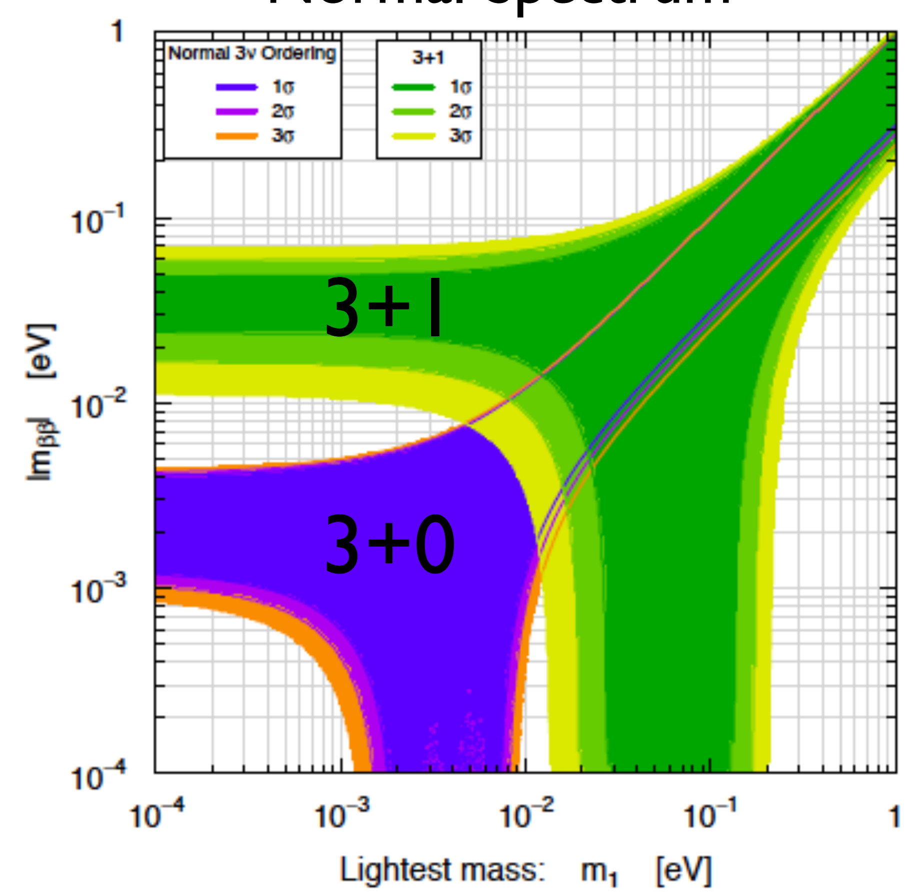
Low-scale LNV

- 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

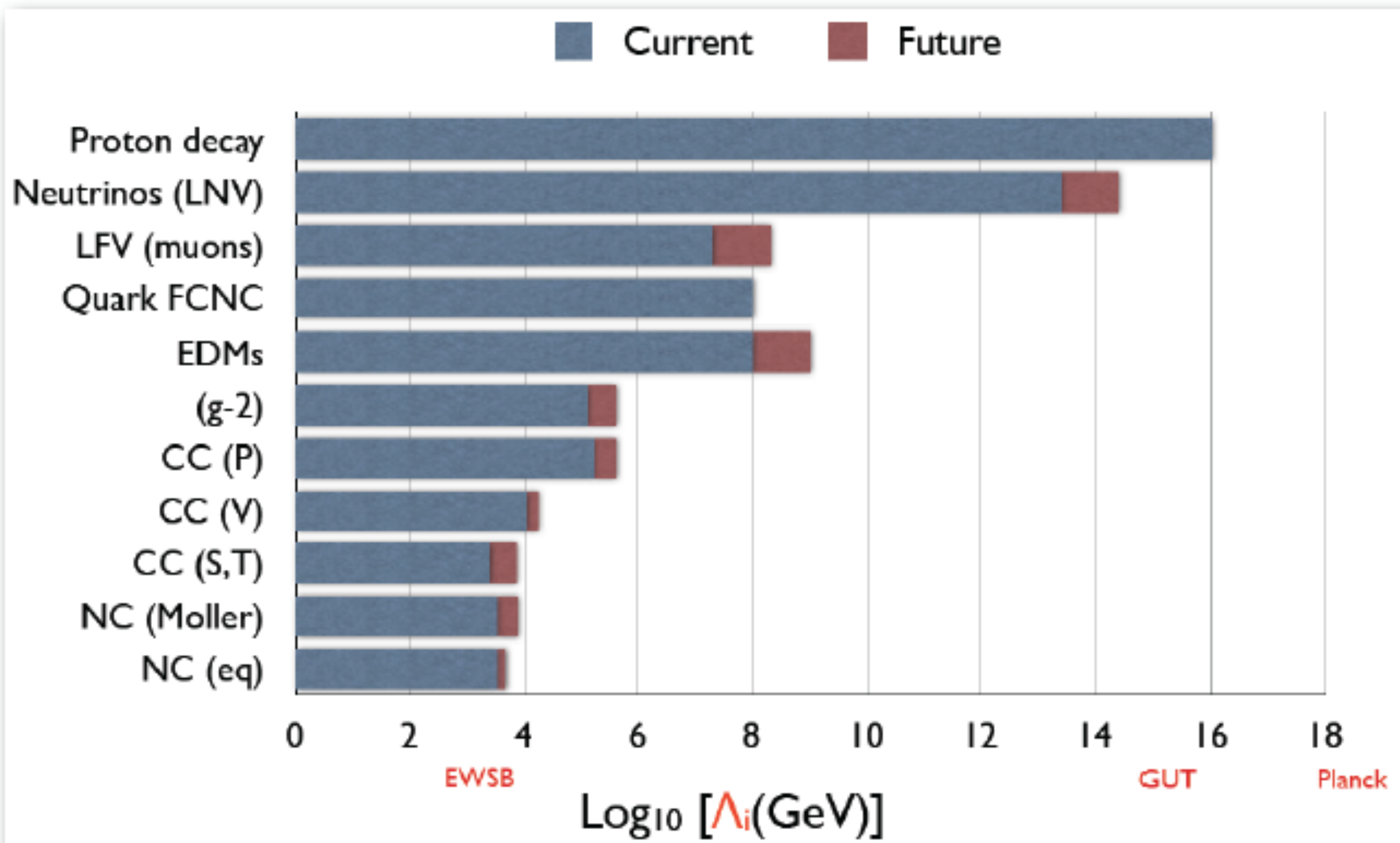


Giunti-Zavanin
1505.00978

Usual phenomenology turned around !

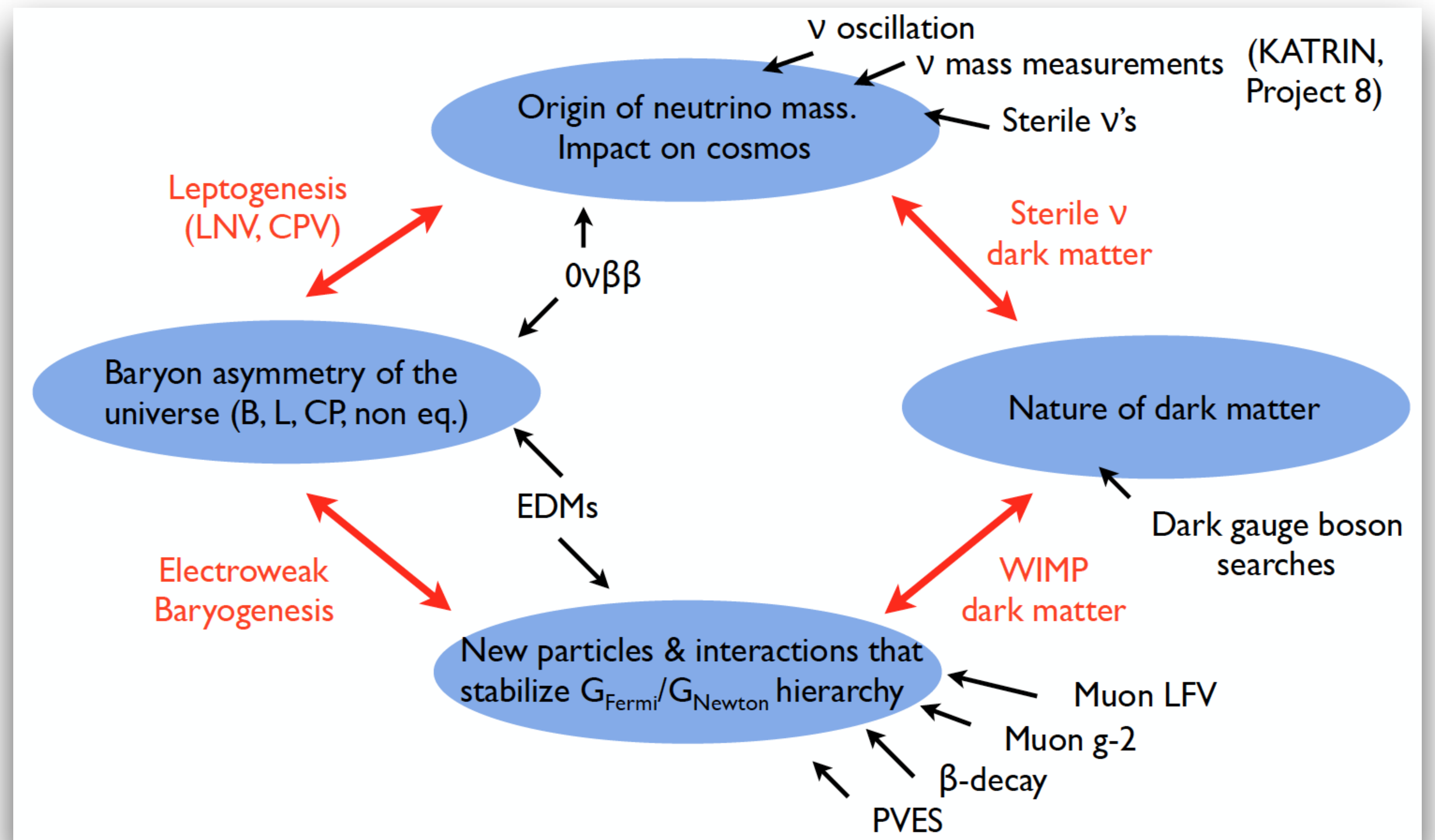
Summary

- The precision / intensity frontier plays a key role in the search for the "new Standard Model" and its symmetries
- Broad and vibrant experimental program
- Probes very high scales

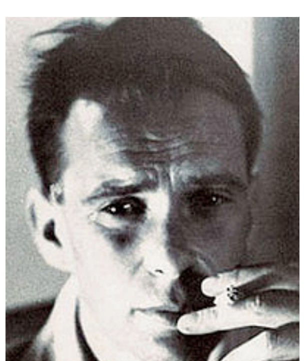


Summary

- The precision / intensity frontier plays a key role in the search for the "new Standard Model" and its symmetries
- Broad and vibrant experimental program
- Connects to big open questions



Thank you!



A drawing by
Bruno Touschek

Additional material

V_{ud} from $0^+ \rightarrow 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\,(1 + RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

$$(1 + RC) = (1 - \delta_C)\,(1 + \delta_R)\,(1 + \Delta_C)$$

$$\langle f | \tau_+ | i \rangle = \sqrt{2}\,(1 - \delta_C/2)$$

Coulomb distortion of wave-functions

$$\delta_C \sim 0.5\%$$

Towner-Hardy
Ormand-Brown

Nucleus-dependent rad. corr.
(Z, E max ,nuclear structure)

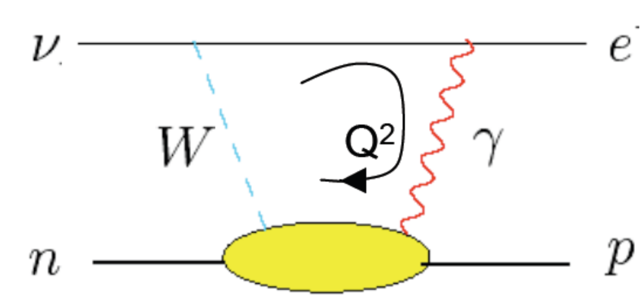
$$\delta_R \sim 1.5\%$$

Sirlin-Zucchini '86
Jaus-Rasche '87

Nucleus-independent short distance rad. corr.

$$\Delta_R \sim 2.4\%$$

Marciano-Sirlin '06



V_{ud} from $0^+ \rightarrow 0^+$ nuclear β decays

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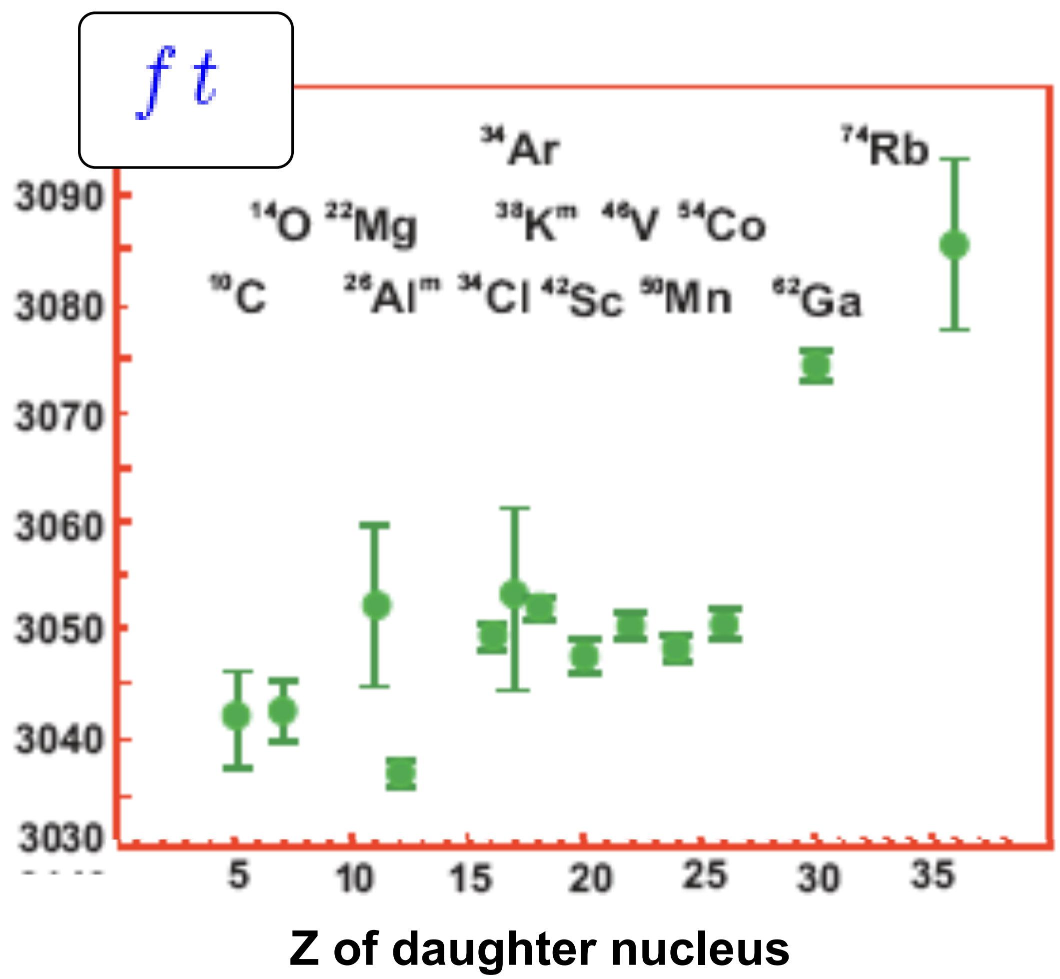
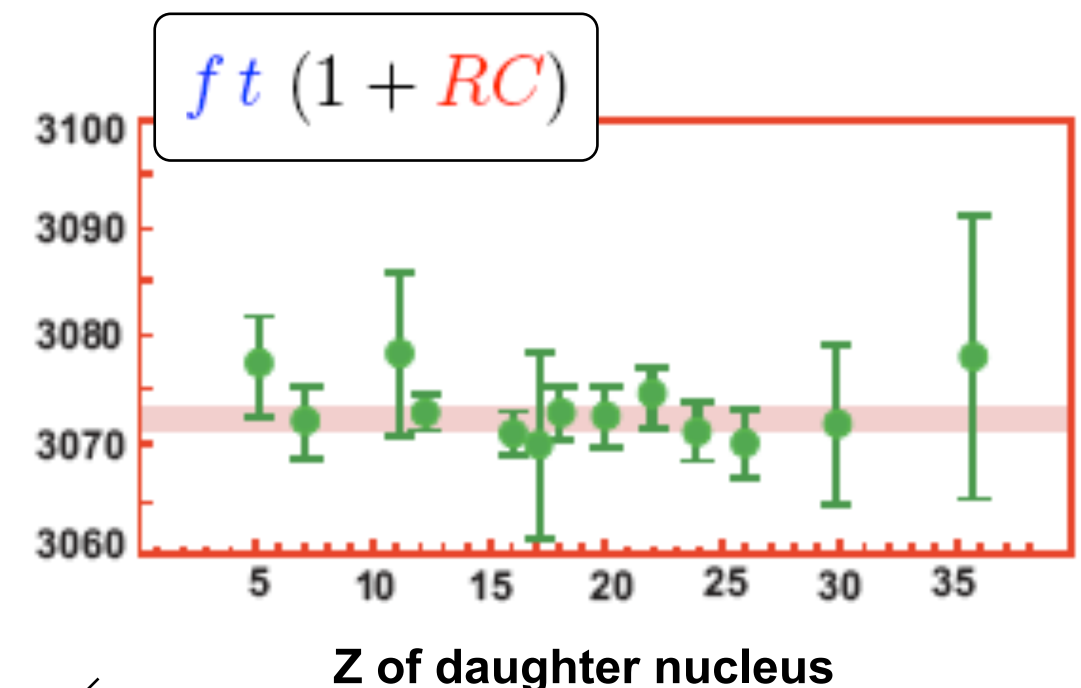
Towner-Hardy, Sirlin-Zucchini, Marciano-Sirlin



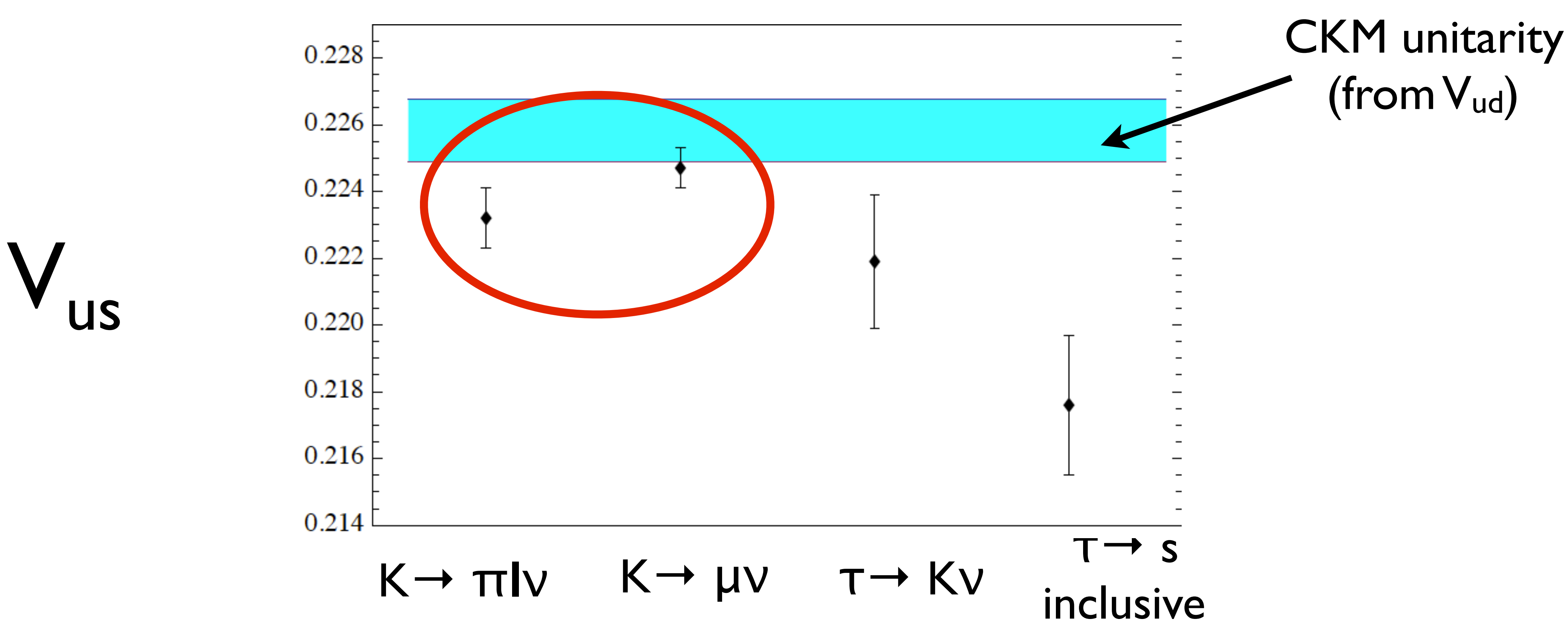


$$V_{ud} = 0.97417\ (21)$$

Townwer-Hardy 2014

CKM unitarity: input

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



$$\langle \pi | V_\mu | K \rangle \propto f_+(0)(p_K + p_\pi)_\mu + \ldots$$

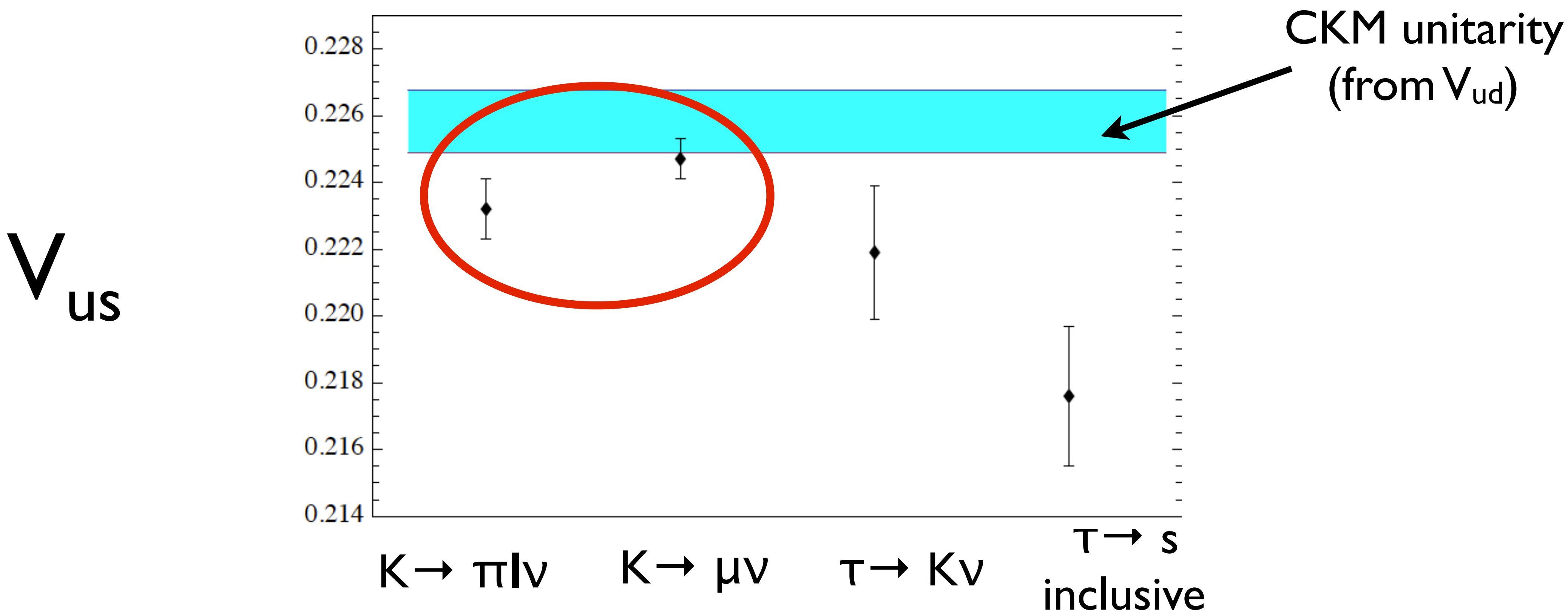
$$V_\mu = \bar{s}\gamma_\mu u$$

$$\langle 0 | A_\mu | K \rangle \propto F_K (p_K)_\mu$$

$$A_\mu = \bar{s}\gamma_\mu\gamma_5 u$$

CKM unitarity: input

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



- New LQCD calculations have led to smaller V_{us} from K→ πlν

$f_+^{K\to\pi}(0) = 0.959(5) \rightarrow 0.970(3)$

$F_K/F_\pi = 1.1960(25)$ [stable]

$m_\pi \rightarrow m_\pi^{phys}$, $a \rightarrow 0$, dynamical charm

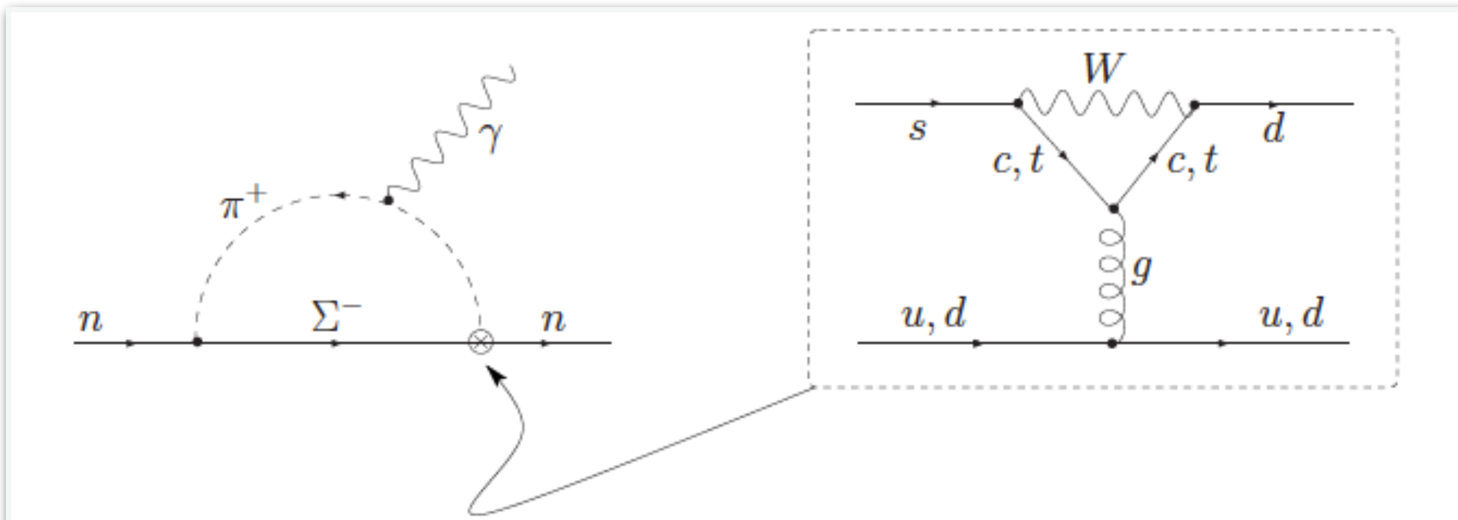
$V_{us} = 0.2254(13) \rightarrow 0.2231(9)$

$V_{us} / V_{ud} = 0.2313(7)$

FLAG 2016

EDMs in the Standard Model?

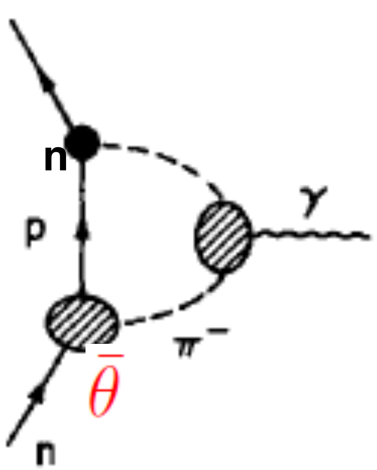
- Weak interactions (CPV in u_i-d_j-W vertex): highly suppressed



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

Pospelov-Ritz
hep-ph/0504231

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



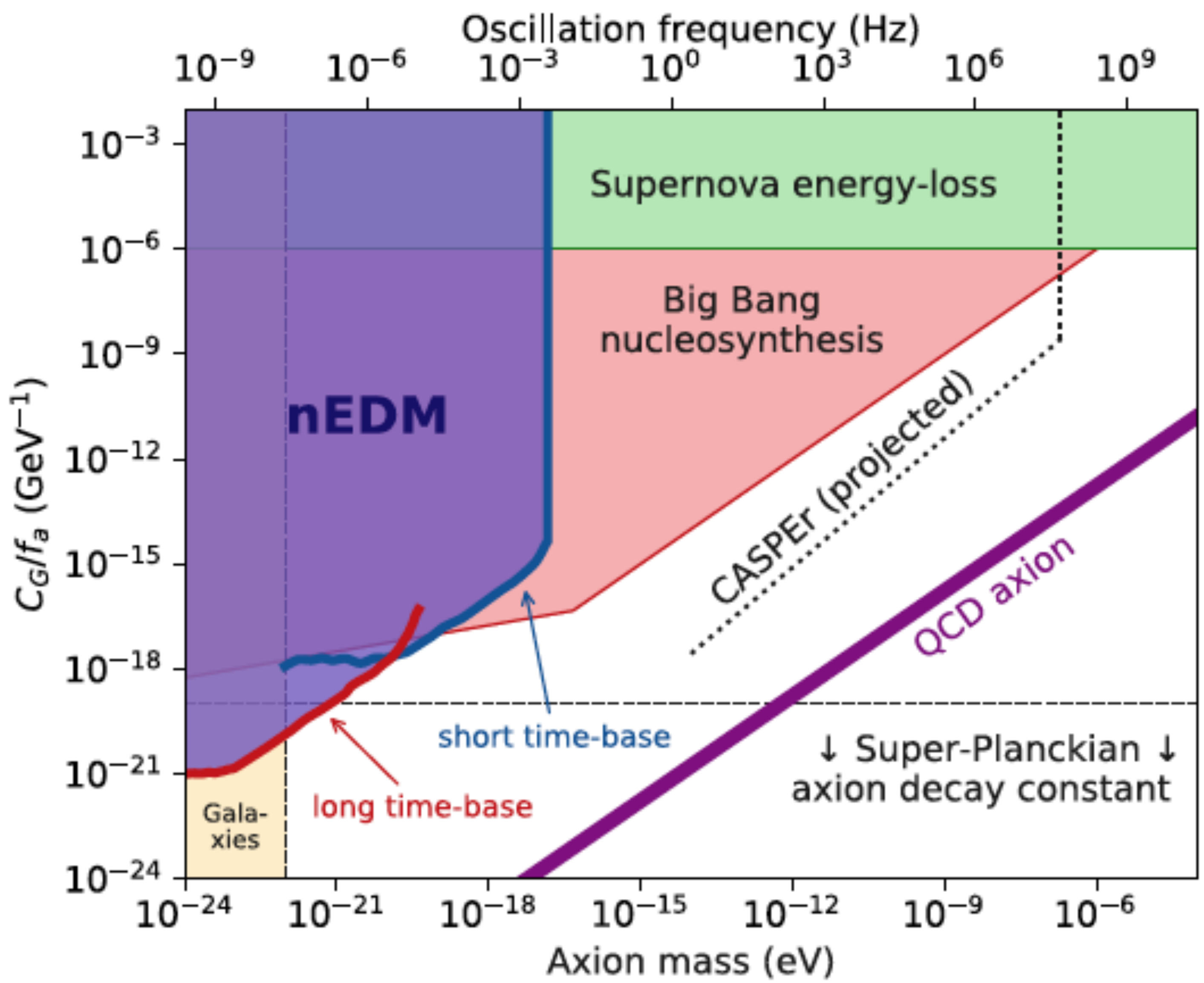
$$d_n \sim \frac{m_*}{\Lambda^2_{\rm had}} e\,\bar{\theta} \sim 10^{-17}\,\bar{\theta}\,e{\rm cm} \rightarrow |\bar{\theta}| < 10^{-9}$$

$d_n < 3\ 10^{-26}$ e cm

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

nEDM and axion-like dark matter

$$\mathcal{L}_{\rm int} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^b_{\mu\nu}\tilde{G}^{b\mu\nu}$$

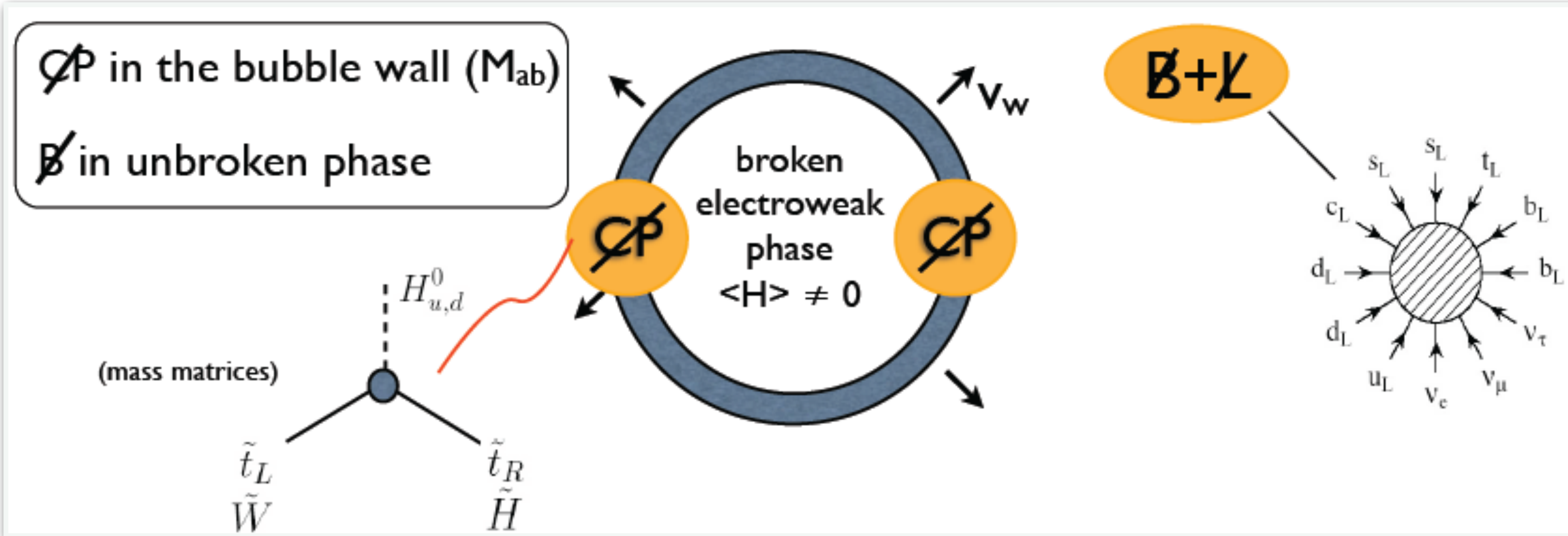


First laboratory constraint on the coupling of axion DM to gluons

Ample room for improvement in next. gen. nEDM

Abel et al., 1708.06367

EDMs and EW baryogenesis (1)



For a review see: Morrissey & Ramsey-Musolf 1206.2942

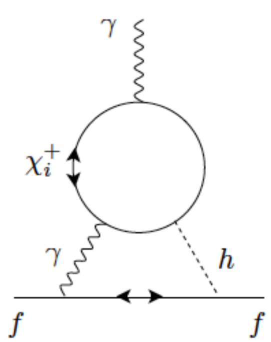
- Requirements on BSM scenarios:
  - 1st order phase transition: new particles, testable at LHC
  - New CPV: EDMs often provide strongest constraint.

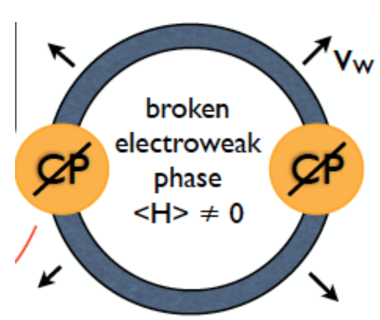
- Rich literature: (N)MSSM, Higgs portal (scalar extensions), flavored baryogenesis,…

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

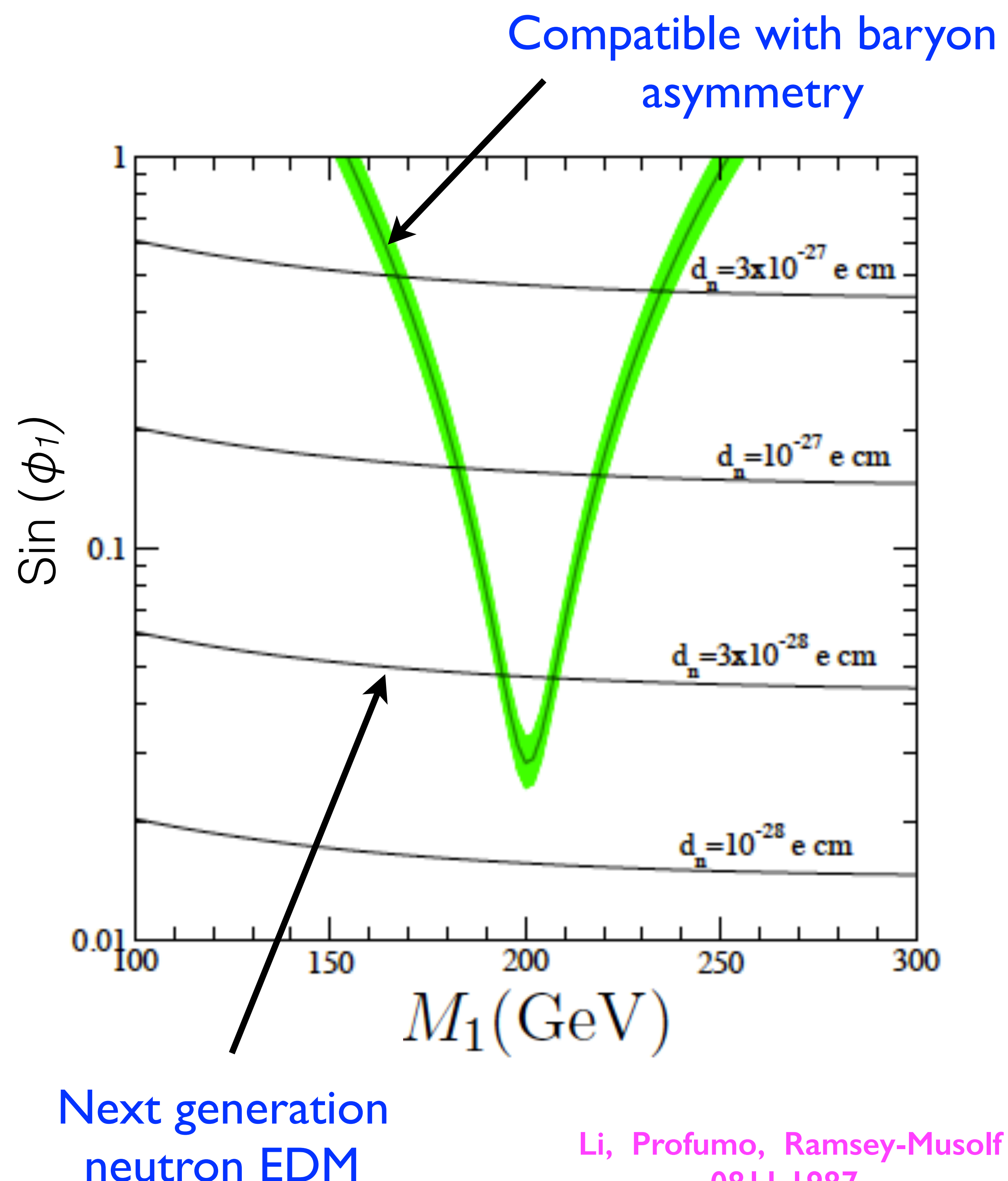
EDMs and EW baryogenesis (2)

- 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

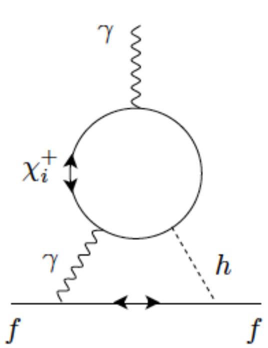


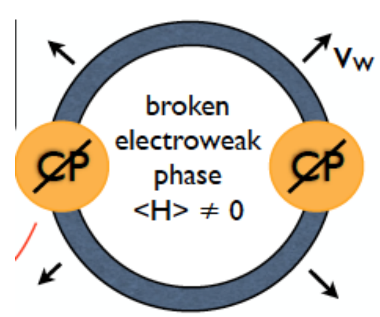
Li, Profumo, Ramsey-Musolf 0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589

EDMs and EW baryogenesis (2)

- In Supersymmetry, 1st order phase transition disfavored by LHC in mini[...] need singlet[...]

- CPV phases [...] gaugino-higg[...] contribute to [...]

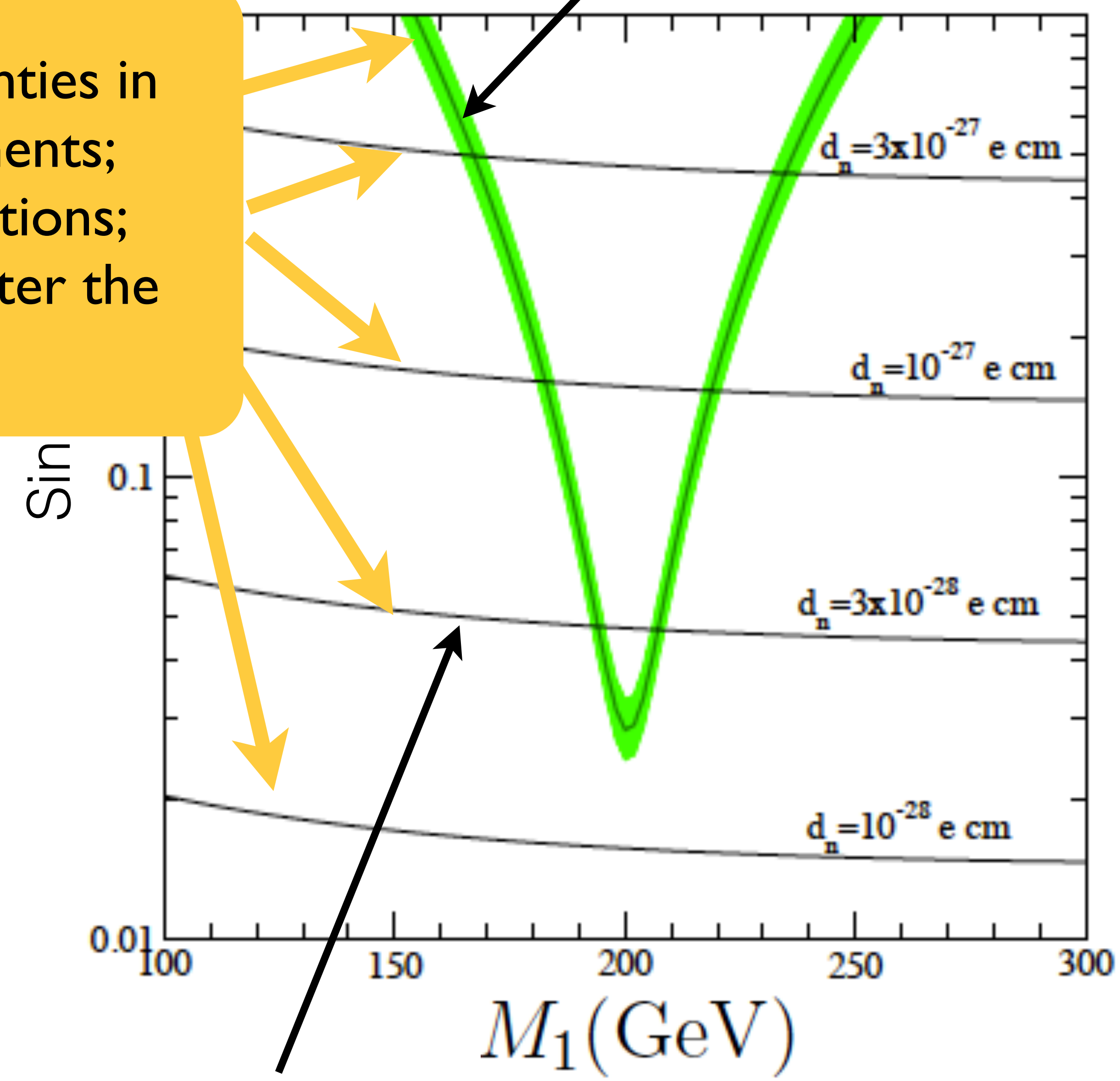




- In *scenario with universal phases* $\varphi_1=\varphi_2$, successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches

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

Compatible with baryon asymmetry



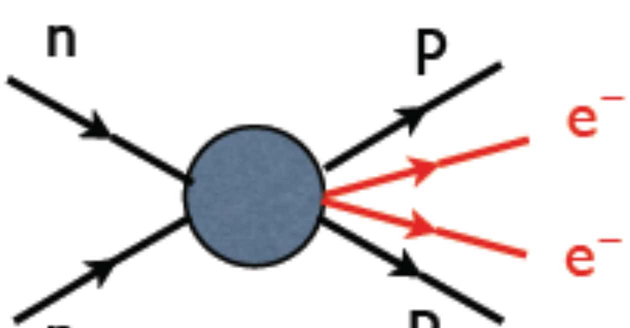
Next generation neutron EDM

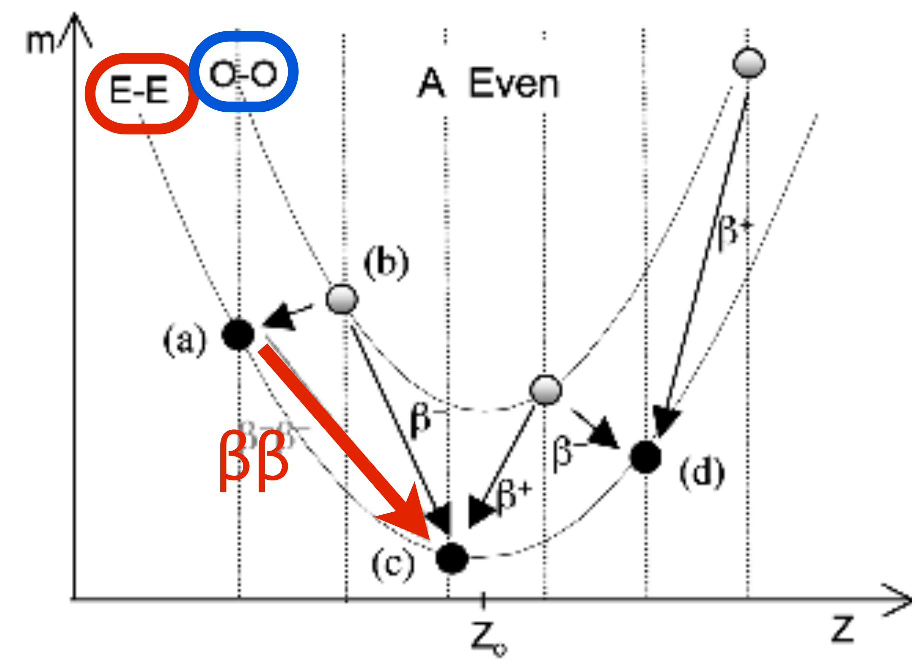
Li, Profumo, Ramsey-Musolf 0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589

Neutrinoless double beta decay

$$(N, Z) \rightarrow (N-2, Z+2) + e^{-} + e^{-}$$

Lepton number changes by two units: $\Delta L=2$



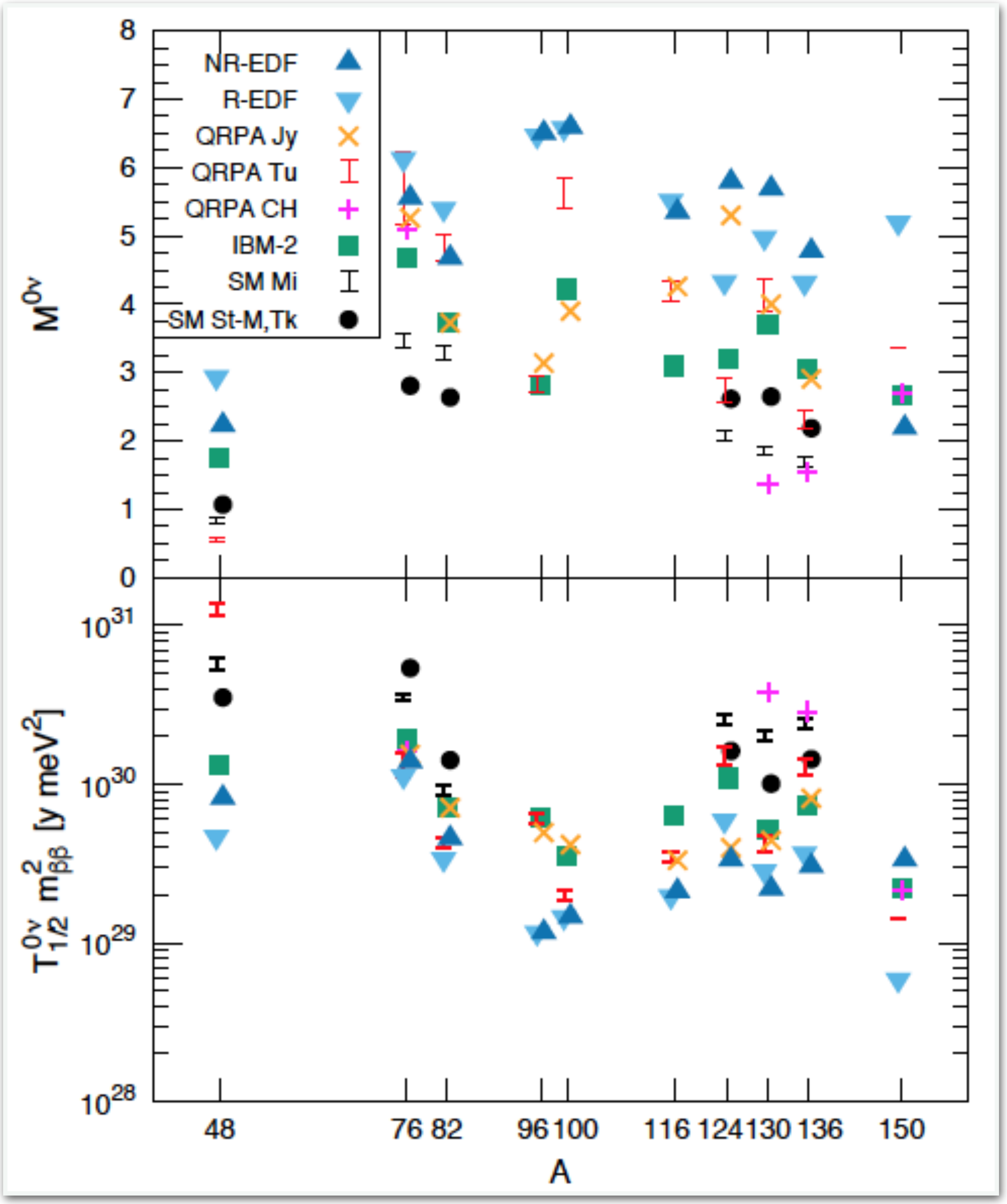


*Enabled by nuclear physics energetics

Unique laboratory to study lepton number violation (LNV)

Status of nuclear matrix elements

Engel-Menendez 1610.06548



See-saw and leptogenesis

See-saw mechanism for m_ν

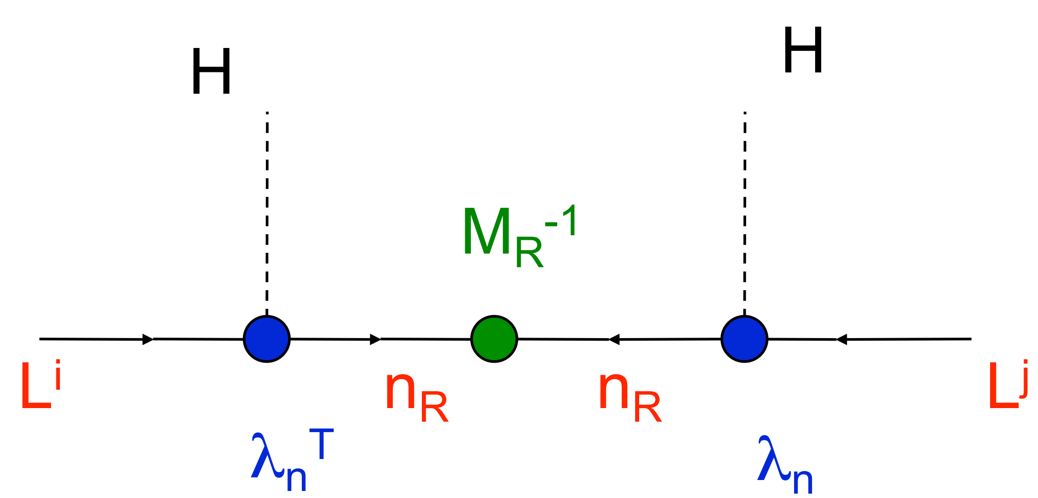
Type I for illustration

$$\mathcal{L} \supset \frac{1}{2}(M_R)_{ij}\, \nu_R^{Ti}\, C\, \nu_R^j \; - \; \lambda_\nu^{ij}\, \bar{\nu}_R^i\, (H_c^\dagger\, L_L^j) + \text{h.c.}$$

Heavy ν_R

M_R : L violation

λ_ν : CP and L_i violation



$m_n \sim v_{ew}^2\ \lambda_n^T M_R^{-1} \lambda_n$

See-saw and leptogenesis

See-saw mechanism for m_ν

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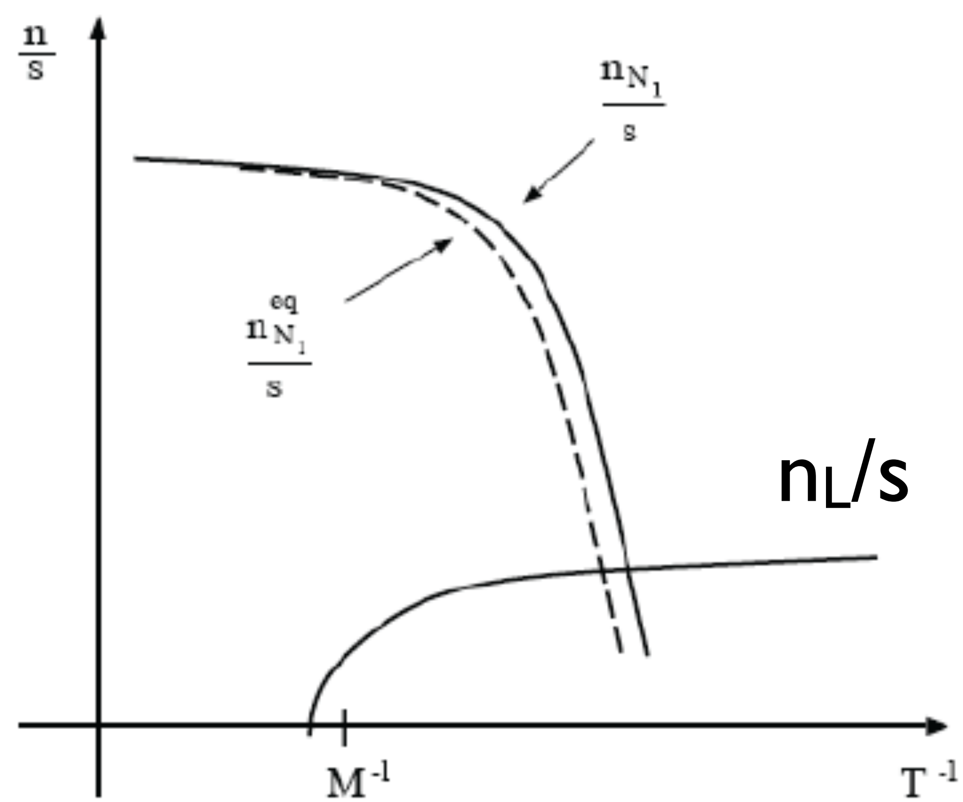
M_R : L violation
λ_ν : CP and L_i violation

1) $\not{CP}$ and $\not{L}$ out-of-equilibrium decays of N_i ($T \sim M_R$) $\Rightarrow n_L$

$$\Gamma(N_i \to l_k\, H^*) \neq \Gamma(N_i \to \bar{l}_k\, H)$$



See-saw and leptogenesis

See-saw mechanism for m_ν

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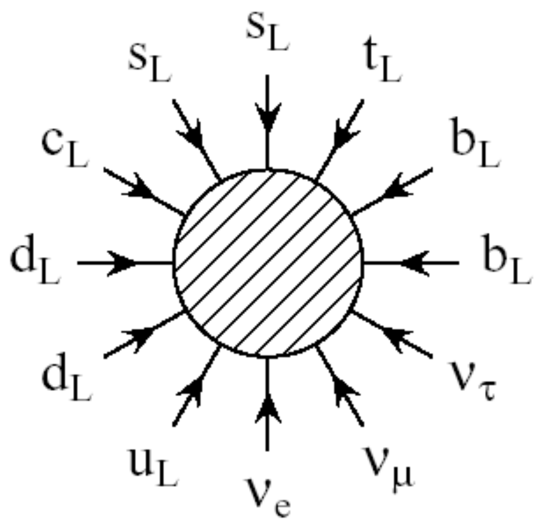
2) EW sphalerons $\Rightarrow n_B = -k\, n_L$

$$\eta_B \equiv \frac{n_B}{n_\gamma} \neq 0$$



See-saw and leptogenesis

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If CP & L_i violation is communicated to particles with mass $\Lambda \sim$ TeV

Observable LFV

Observable lepton EDMs