SLAC Summer Institute 2016
August 24-25 2016

Intensity Frontier-Collider Complementarity (2)

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Los Alamos NATIONAL LABORATORY EST. 1943

Plan of the lectures

- Introduction: energy-intensity complementarity in broad brush
- Mini-Review of flavor and CP in the Standard Model: Intensity Frontier's traditional bread and butter
- Probing new physics at the Intensity Frontier: landscape in the LHC era
- "Zoom in" on selected Intensity Frontier probes
    - Quark Flavor Violation (highlights from K physics)
    - Lepton Number Violation
    - Electric Dipole Moments and CP violation

Today ↙

Quark FCNCs
(rare K decays)

Flavor physics beyond the SM

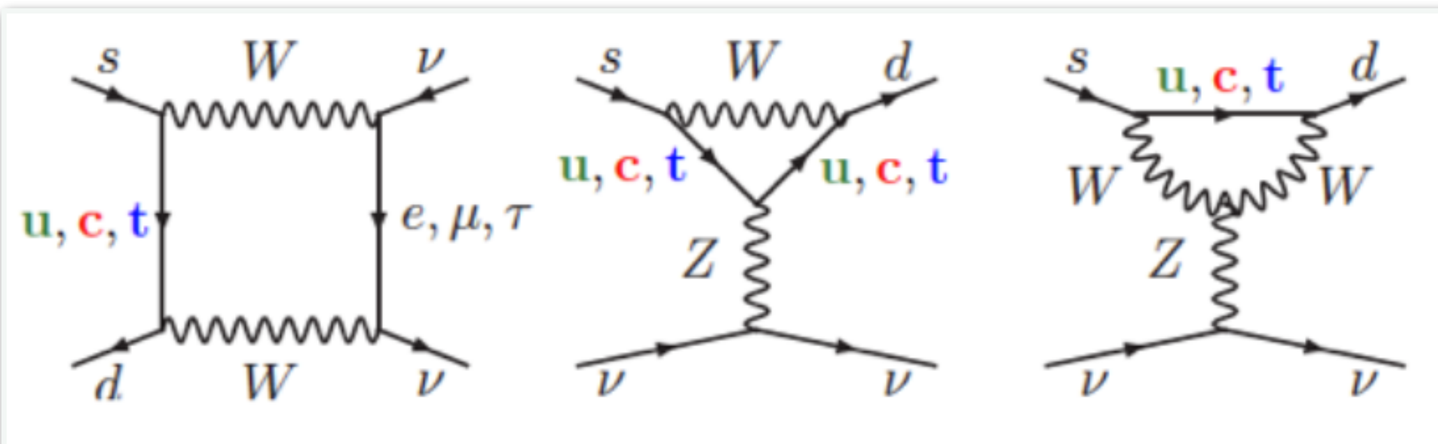
- In the SM, $U(3)^5$ symmetry broken only by Y_U and Y_D

- BSM, new sources of $U(3)^5$ flavor-symmetry breaking are possible

- A major goal of flavor physics in the LHC era is to explore the flavor structure of BSM scenarios (that hopefully will emerge at the LHC)

Special role of rare K decays

- $K \to \pi\nu\nu$: one of cleanest probes of new flavor-breaking structures



- Quadratic GIM suppresses light-quark (long-distance) contribution
- Predicted with high precision: (matrix element from $K \to \pi e \nu$)
- Strong suppression from λ^5 CKM factor (enhanced sensitivity to BSM)

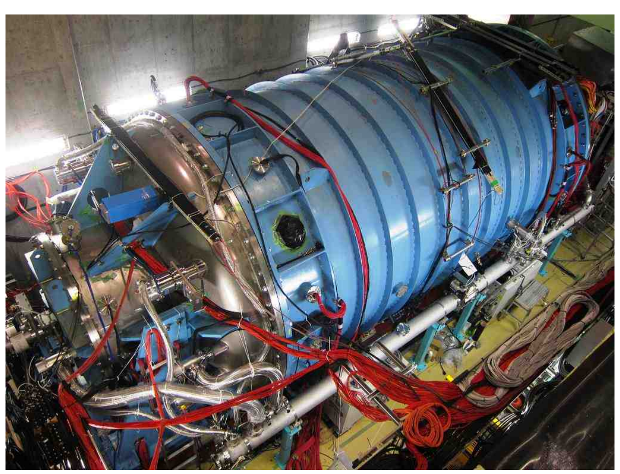
$$A(s \to d) \sim \frac{g^2}{(4\pi v)^2} y_t^2 V_{ts} V_{td}^* + \frac{\delta_{sd}}{\Lambda^2}$$

λ^5 suppression in the SM

- Theory + Experiment status and prospects

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	~10% at NA62 ~5% at ORKA ~2% at *Project X*
$\mathcal{B}(K^0_L \to \pi^0 \nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO ~5% at *Project X*

1311.1076 and refs therein: 1st error parametric, 2nd intrinsic



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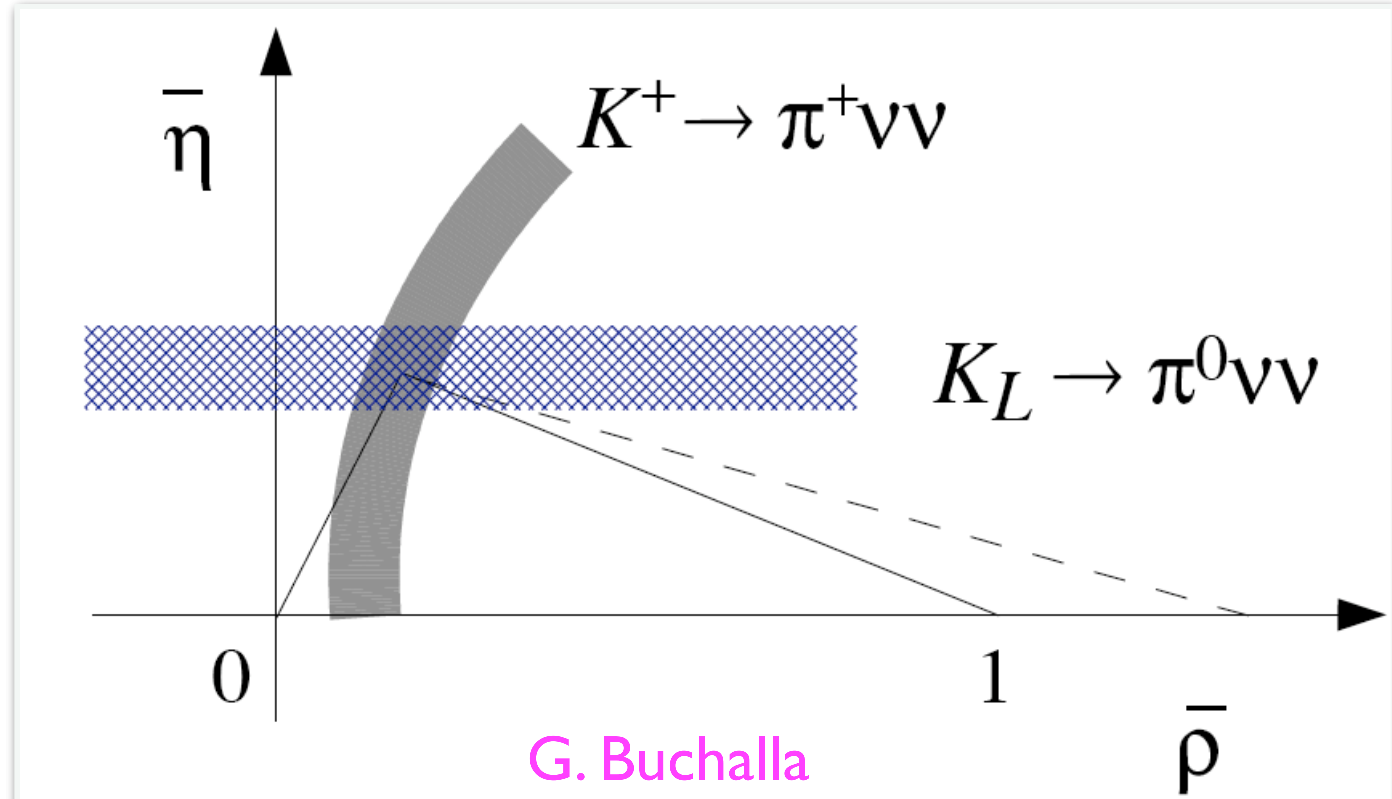
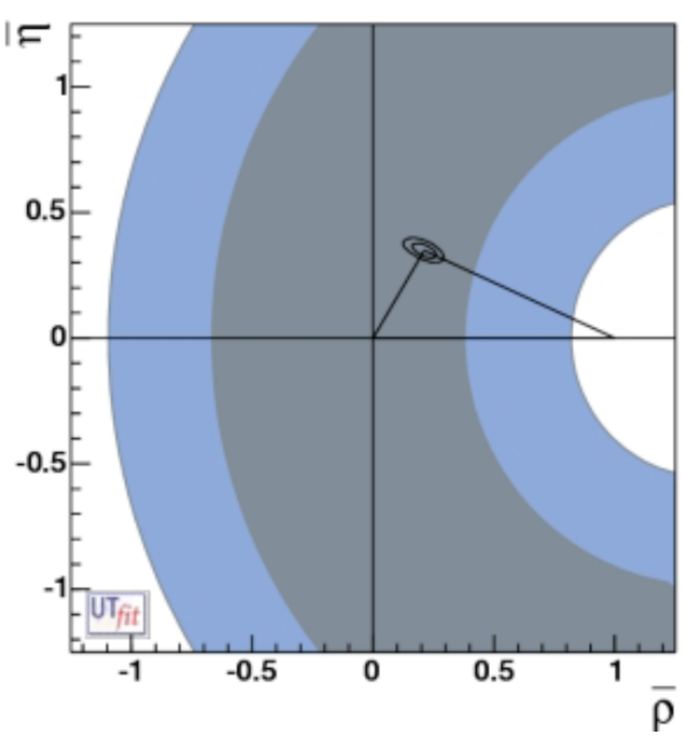
- O(10%) exp. precision (SM BR) $\Rightarrow$
  - $\Lambda \sim 300$ TeV (generic flavor structure)
  - $\Lambda \sim 10$ TeV (MFV structure, λ^5 suppression)

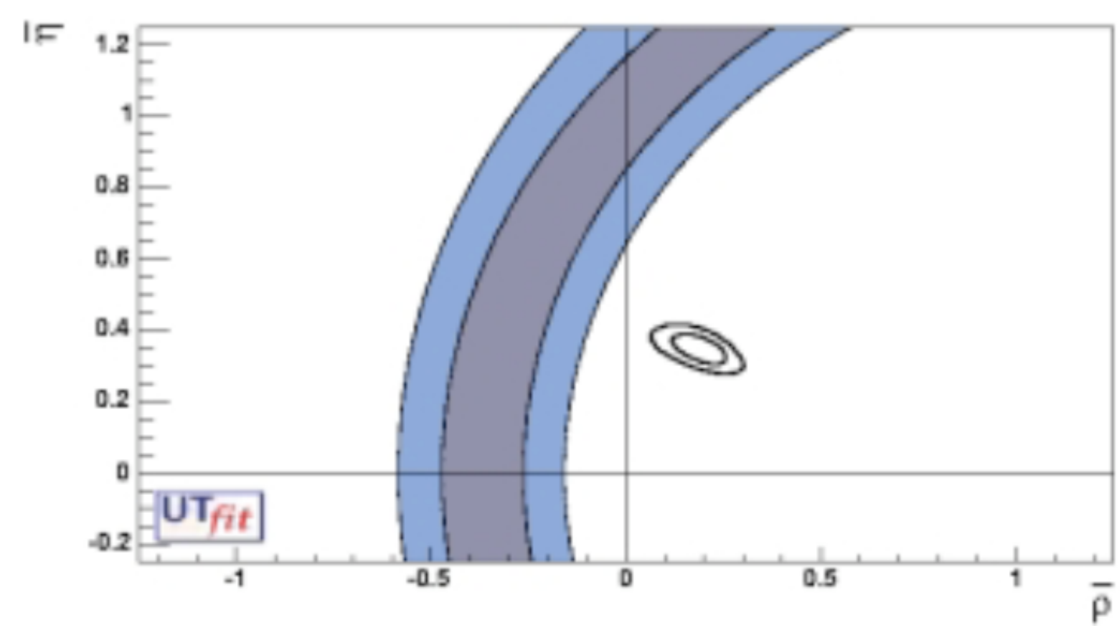
The Kaon Unitarity Triangle

- Can get unitarity triangle from K decays only
- New physics may affect K and B differently





Same central value with 10% uncertainty and 1/2 theory error



EFT approach: Kaon matrix

- In this framework, can study both
  - “Discovery potential” of rare decays: given the constraints from other observables, how large of a deviation from the SM can one expect?
  - “Diagnosing power”: correlations among observables

EFT approach: Kaon matrix

Uli Haisch,
S. Jaeger

$$\mathcal{L}_{\rm eff} = \sum_i C_i Q_i$$

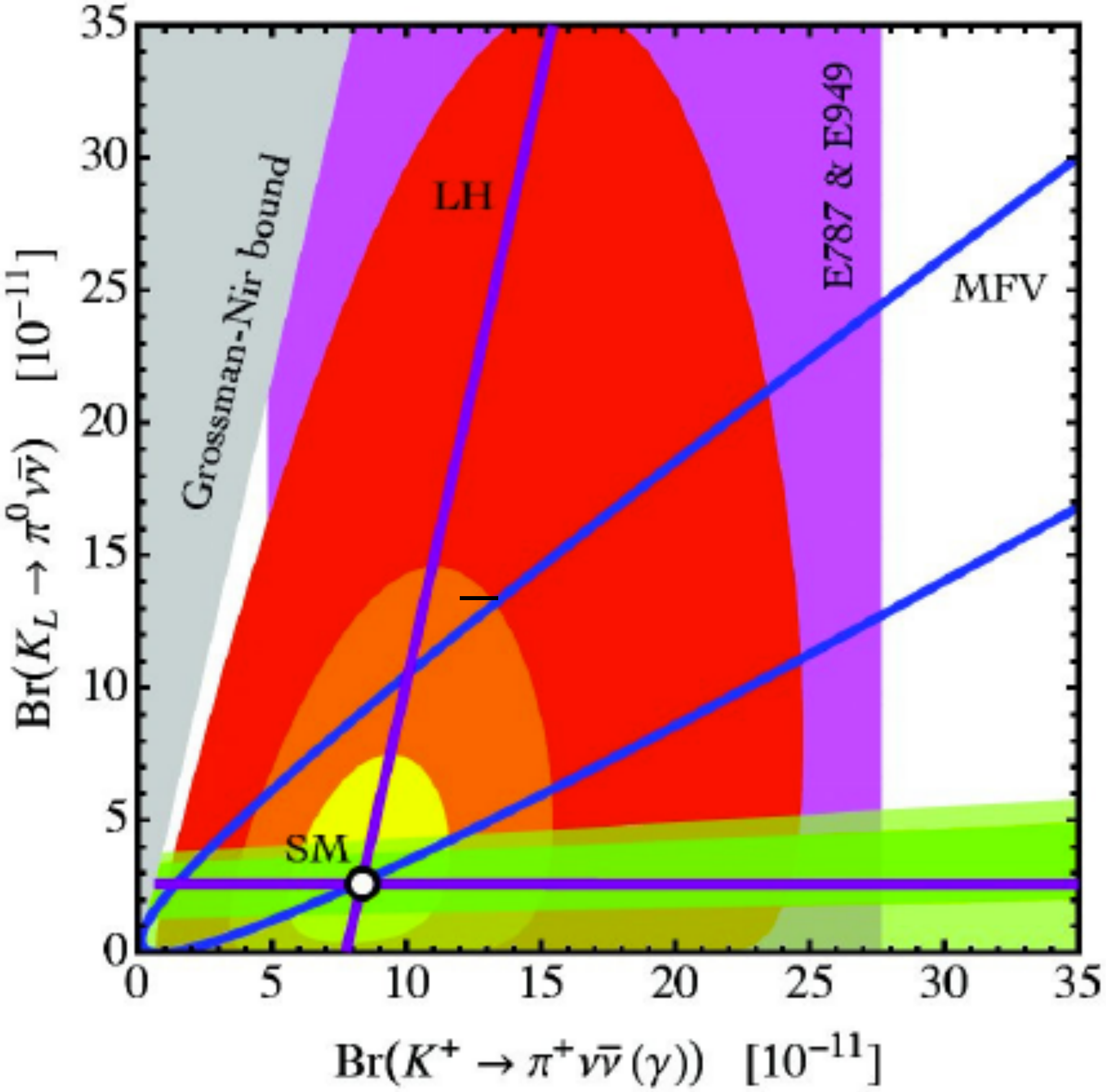
Operator		$K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 l^+ l^-$	$K_L \to l^+ l^-$	$K^+ \to l^+ \nu$	$P_T(K^+ \to \pi^0 \mu^+ \nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K
$Q_{lq}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—
$Q_{lq}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\bar L_L \gamma^\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	—	—
Q_{qe}	$(\bar D_L \gamma_\mu S_L)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	hs	✓	✓	—	—
Q_{ld}	$(\bar d_R \gamma_\mu s_R)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—
Q_{ed}	$(\bar d_R \gamma_\mu s_R)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	—	—	—	—	—
$Q_{lq}^{t\dagger}$	$(\bar u_R S_L)(\bar l_R L_L)$	—	—	—	—	✓	✓	✓	—	—
$(Q_{lq}^{t})^\dagger$	$(\bar u_R \sigma_{\mu\nu} S_L)(\bar l_R \sigma^{\mu\nu} L_L)$	—	—	—	—	—	?	?	—	—
Q_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	—	—	✓	✓	—	—	—	—	—
$Q_{qde}^\dagger$	$(\bar D_L s_R)(\bar l_R L_L)$	—	—	✓	✓	✓	✓	✓	—	—
$Q_{\phi q}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)
$Q_{\phi q}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\phi^\dagger D^\mu \sigma^i \phi)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)
$Q_{\phi d}$	$(\bar d_R \gamma_\mu s_R)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)

- K→ πνν sensitive to 6 operators
- 3 essentially unconstrained: can induce large deviations
- 3 “Z penguins”: constraints from ε‘?

Correlations in K decays

Uli Haisch,
S. Jaeger

- If Z-penguins dominate (MSSM, RS, ...)



$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar{d}_L \gamma_\mu s_L Z^\mu + \widetilde{C}_{\rm NP}\, \bar{d}_R \gamma_\mu s_R Z^\mu$$

- $|C_{\rm NP}| \leq 0.5\, |\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq 2\, |\lambda_t C_{\rm SM}|$

$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

- $C_{\rm NP} \propto \lambda_t C_{\rm SM}$

- $\epsilon'/\epsilon \in [0.5, 2]\, (\epsilon'/\epsilon)_{\rm SM}$
- $\epsilon'/\epsilon \in [0.2, 5]\, (\epsilon'/\epsilon)_{\rm SM}$

- 50% deviations from SM BR still possible in $K_L \to \pi^0 \nu\nu$. Should influence ultimate experimental sensitivity

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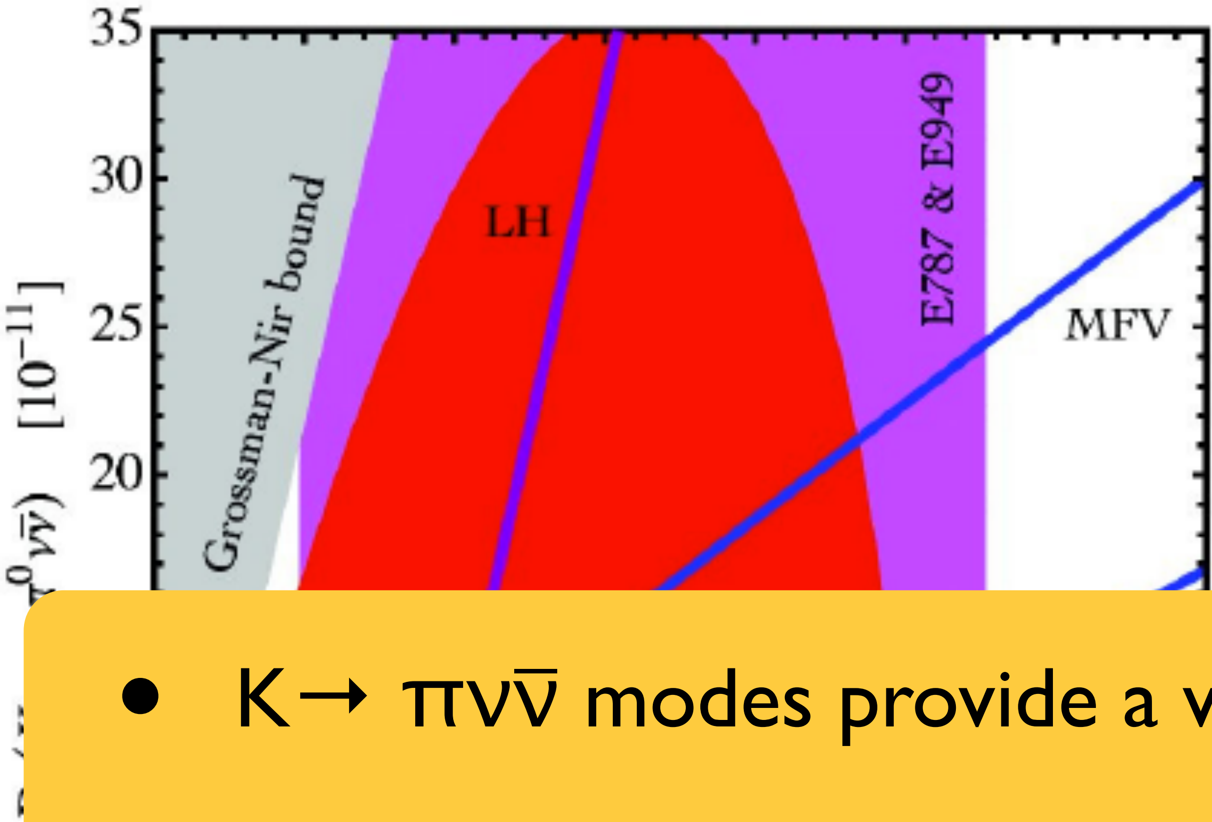

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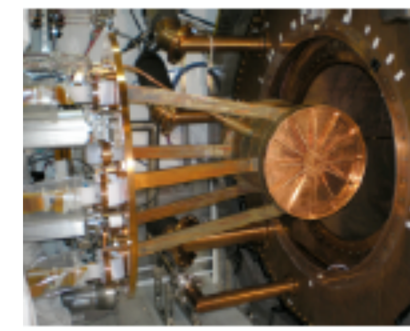
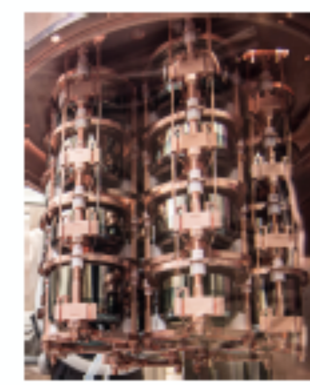
- $|C_{\rm NP}| \le 2\,|\lambda_t C_{\rm SM}|$

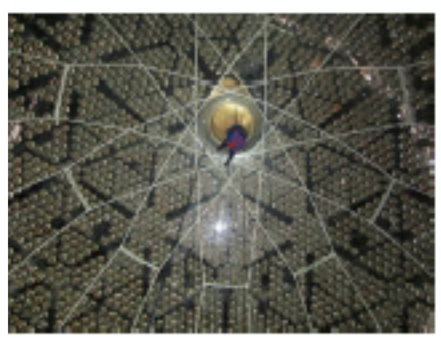
- $K \to \pi\nu\bar{\nu}$ modes provide a win-win opportunity
  - Sizable (non λ^5 suppressed) BSM effect is possible
  - Even if BSM is small (MFV, Z-penguin, …), can still detect it due to “clean” SM prediction

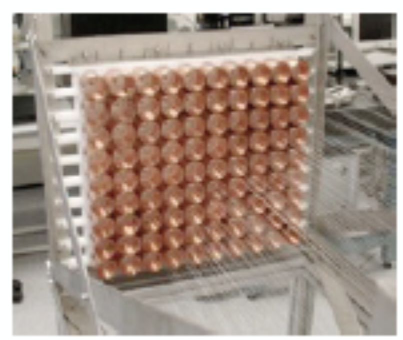
- 50% deviations from SM BR still possible in $K_L \to \pi^0\nu\nu$. Should influence ultimate experimental sensitivity

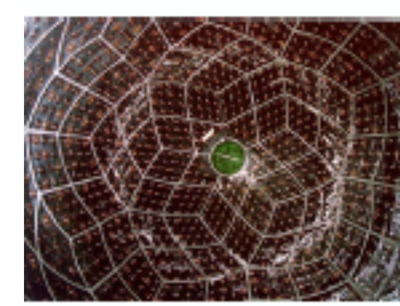
Lepton Number Violation
$(0\nu\beta\beta)$





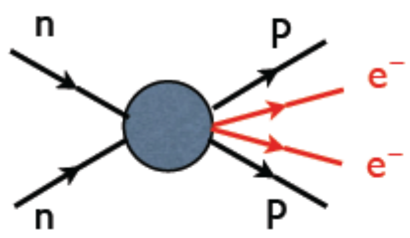




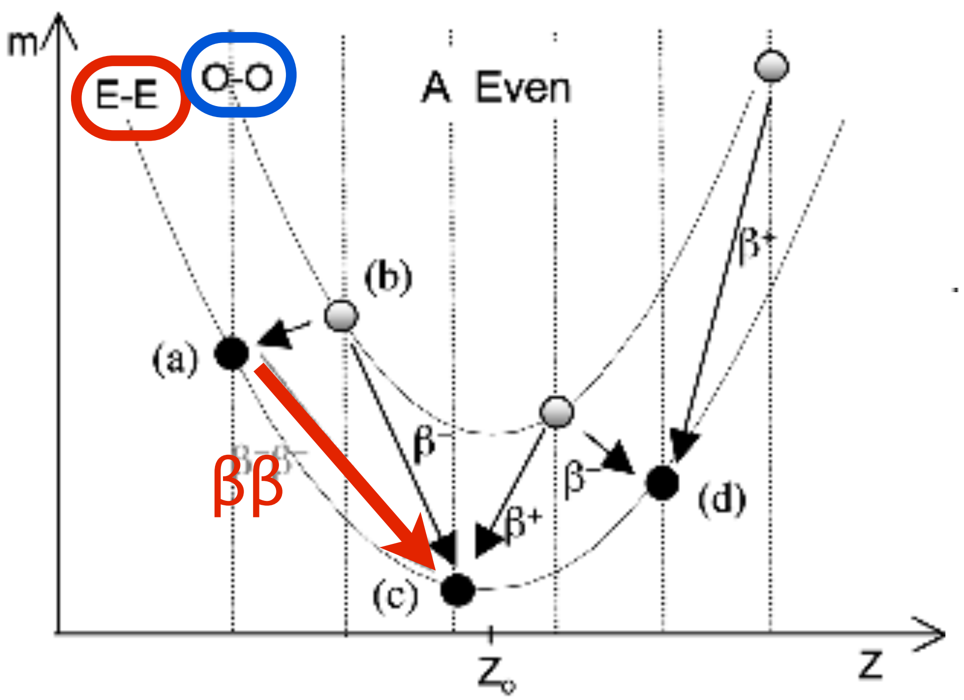


LNV: neutrinoless double beta decay

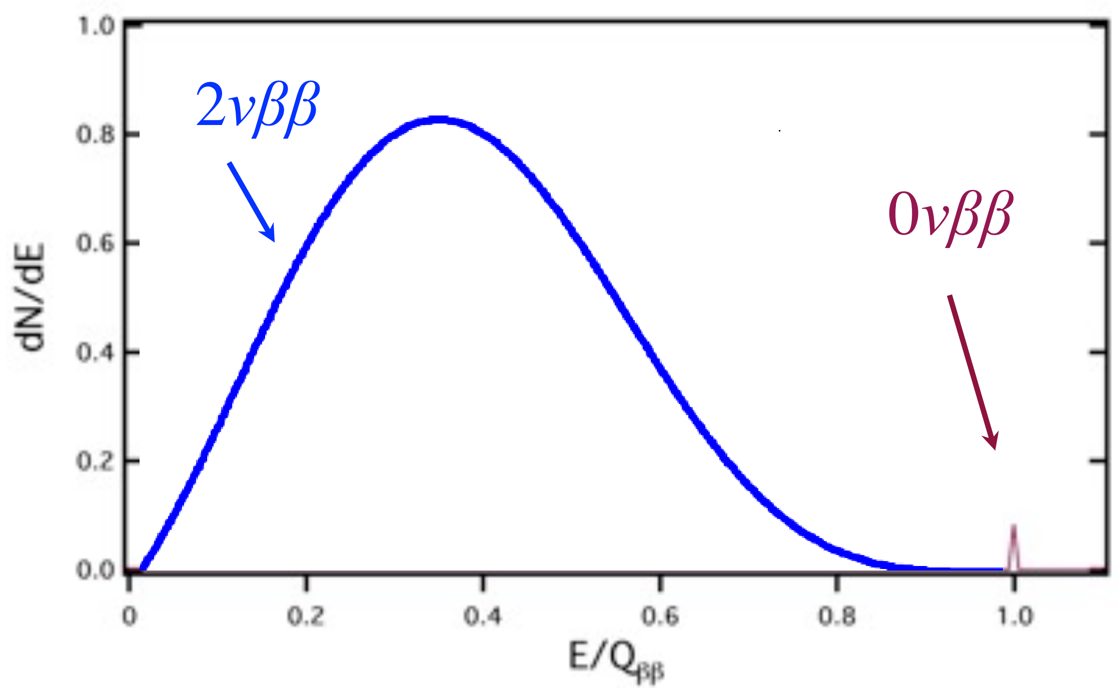
$$(N, Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



Lepton number changes by two units: ΔL=2



**Enabled by nuclear physics energetics



Unique laboratory** to study lepton number violation (LNV)

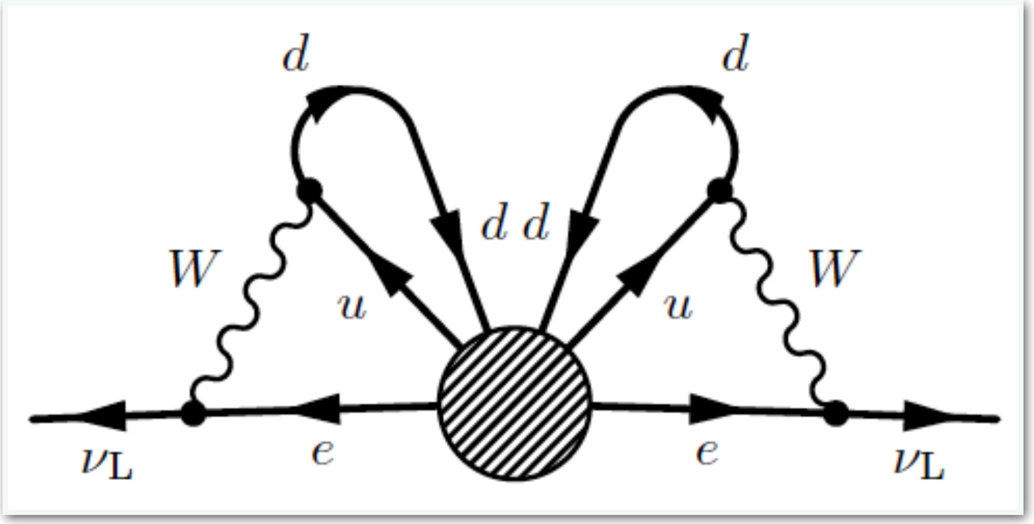
Experimentally very challenging (Q ~ few MeV)

Why is it a big deal?

- B-L conserved in the Standard Model $\Rightarrow$ Observation of NLDBD would be direct evidence of new physics, with far-reaching implications

- Demonstrate that neutrinos are Majorana fermions (i.e. their own antiparticles: $\nu = \nu^c$)

- Shed light on the mechanism of neutrino mass generation



Schechter-Valle 1980

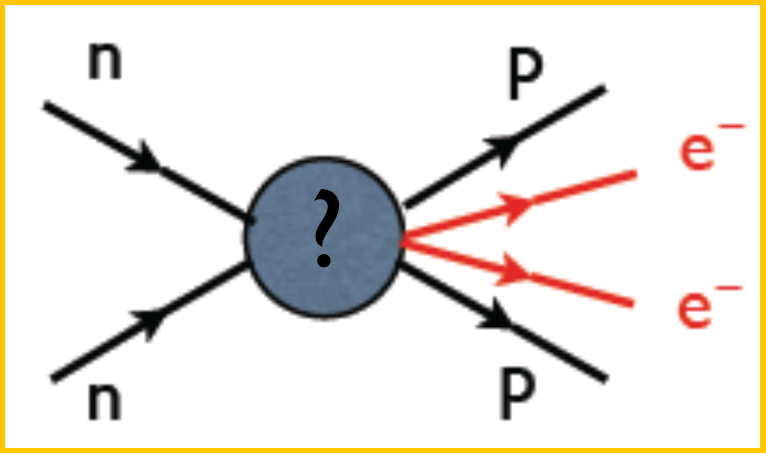
- Probe the basic ingredient (LNV) needed to generate the cosmic baryon asymmetry via "leptogenesis"

Why is it a big deal?

- B-L conserved in the Standard Model ⇒ Observation of NLDBD would be direct evidence of new physics, with far-reaching implications

- The proposed ton-scale experiments will probe LNV violation at the level of $T_{1/2} \sim 10^{27}$yr (100x improvement)

- To assess the discovery potential, need to take a look inside the blob



Looking into the blob

(Classifying sources of LNV: organize discussion by scales)

Looking into the blob

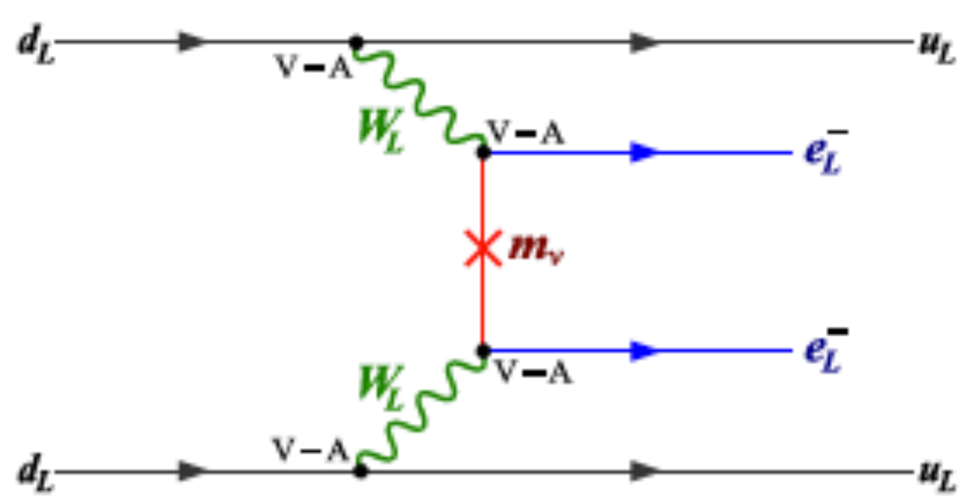
(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

Low energy footprints encoded in the leading dim-5 operator

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

This is a Majorana mass term for ν's: NLDBD mediated by light ν exchange



Looking into the blob

(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

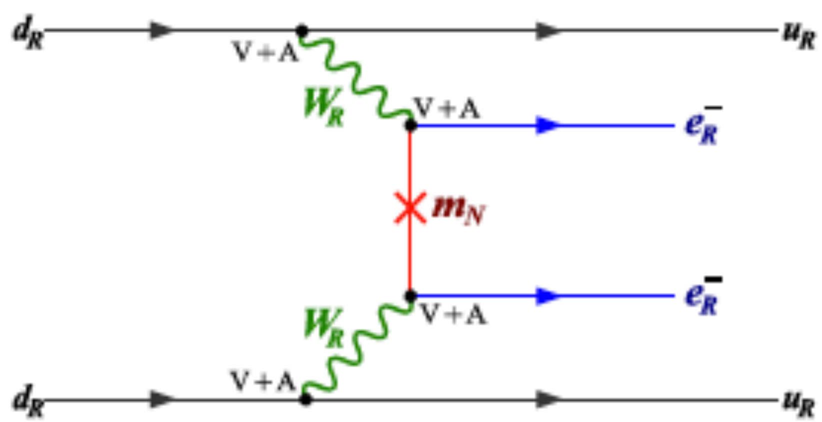
$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\, H\, H$$

- LNV dynamics at lower scale (Λ~TeV)

Higher dimensional operators become important

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

Arise in well-motivated models:
Left-Right Symmetric Model,
RPV-SUSY, ...



Looking into the blob

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- LNV dynamics at very high scale (Λ>> TeV)

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

- LNV dynamics at lower scale (Λ~TeV)

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

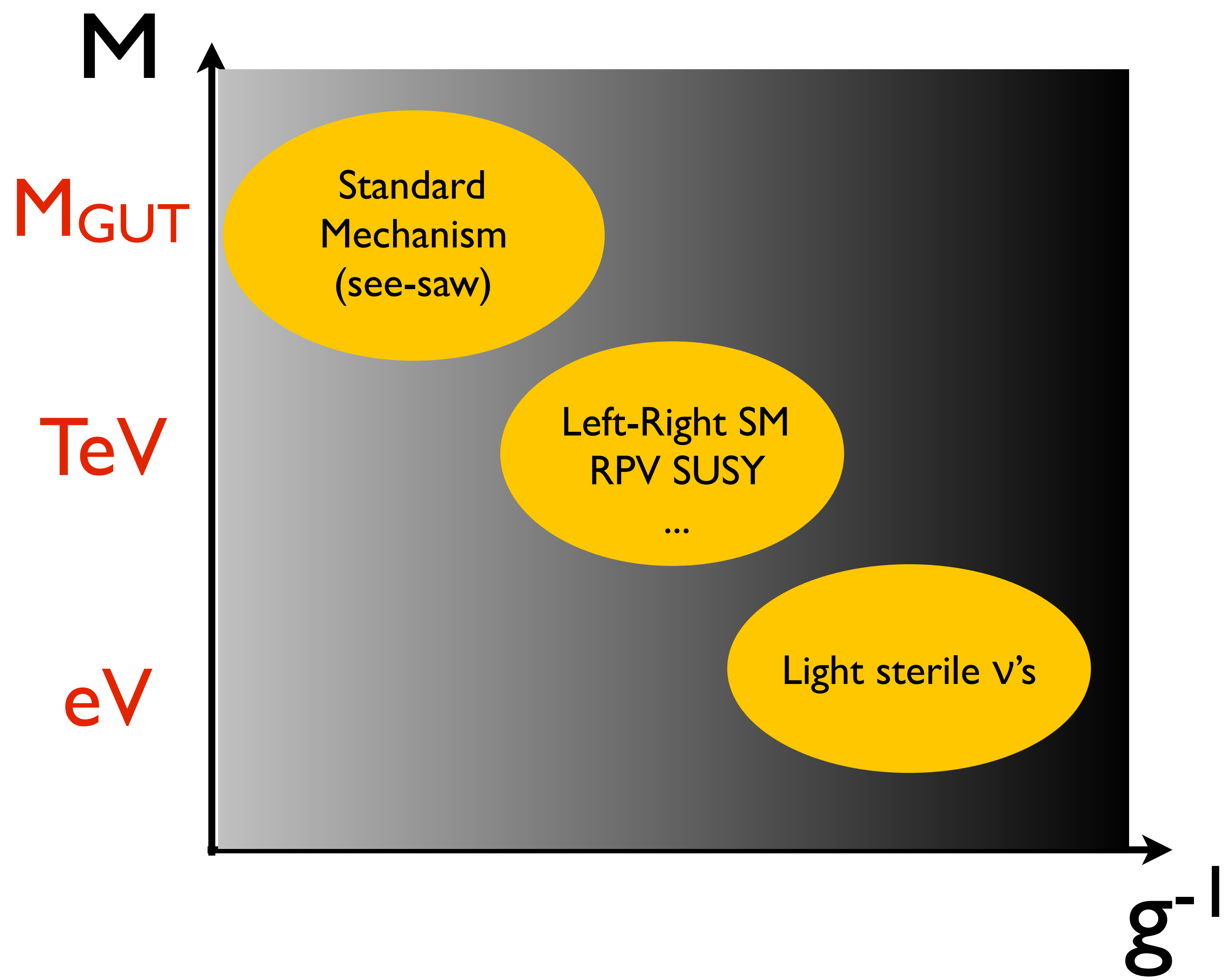
- LNV dynamics at very low energy (e.g. low-scale seesaw)

$$-\frac{1}{2}M_R\,\overline{\nu_R^c}\nu_R\;+\;Y_\nu\,\bar{\ell}\nu_R\,H$$

Affects NLDBD in significant ways, depending on mass scale M_R: eV → 100 GeV

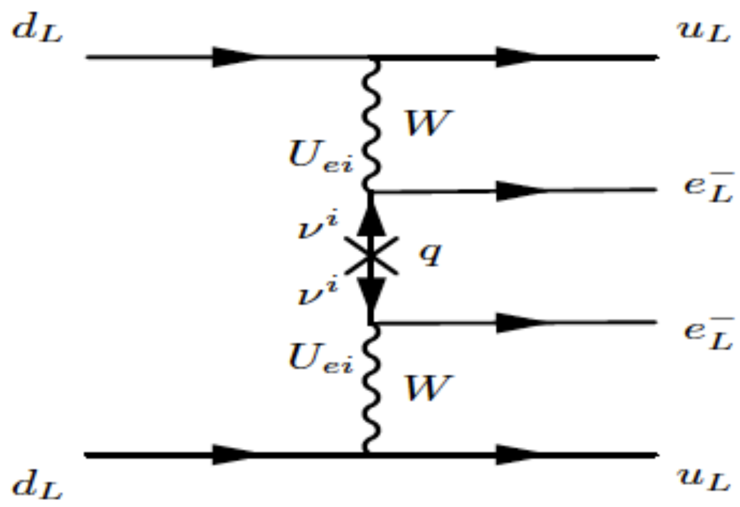
Looking into the blob

- In summary: ton-scale $0\nu\beta\beta$ probes LNV from a variety of mechanisms, involving different scales (M) and coupling strengths (g)



- In each case, next-generation searches have significant discovery potential

The "Standard" Mechanism

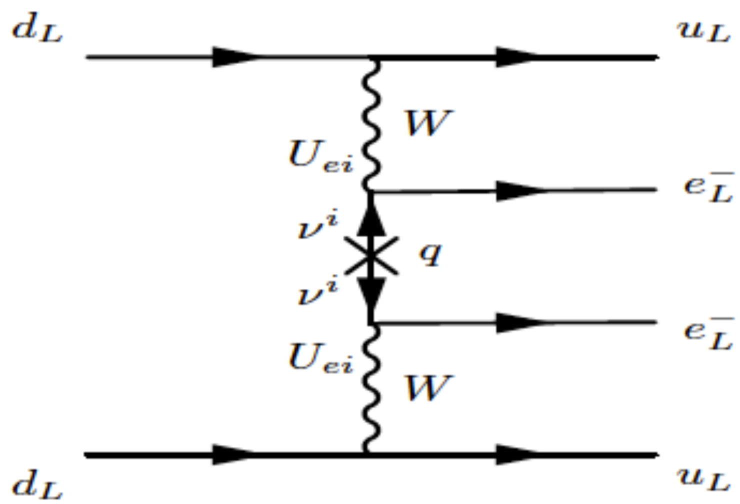


$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} g_A^4 \left| M^{(0\nu)} \right|^2 \langle m_{\beta\beta} \rangle^2$$

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

$$\langle m_{\beta\beta} \rangle^2 \ = \ |\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3|^2$$

The "Standard" Mechanism



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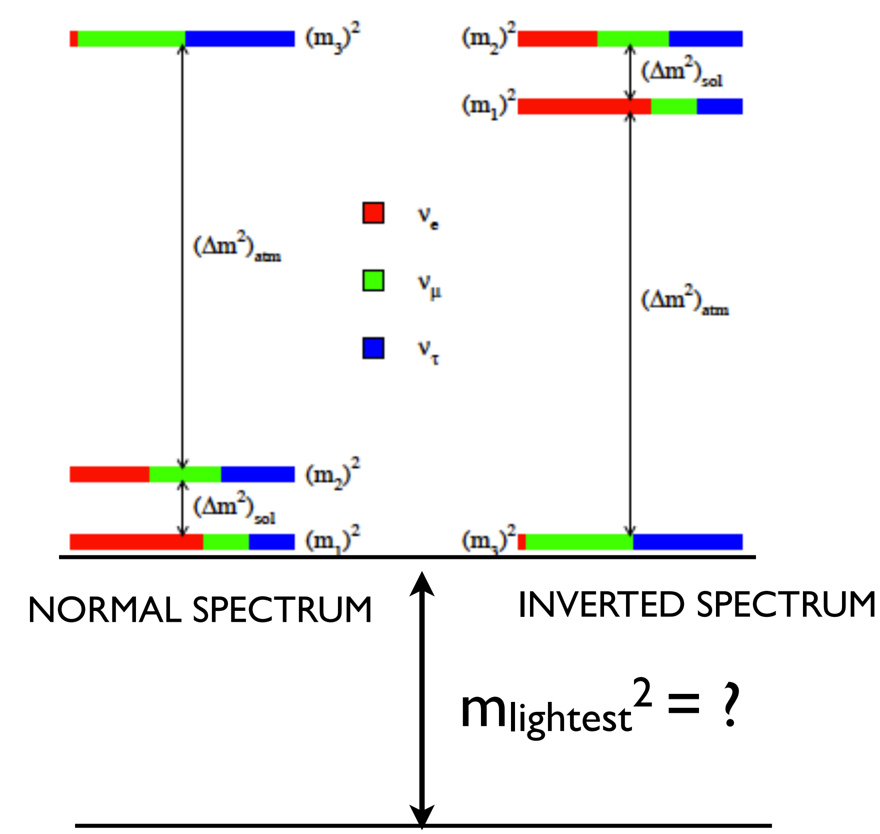
- We have only partial knowledge of parameters controlling $m_{\beta\beta}$, which nevertheless provides important guidance:
    - We know mixing angles and mass splittings
    - We don't know the *ordering* and *absolute scale* of the spectrum
    - We don't know the phases δ_{CP} and $\lambda_{2,3}$

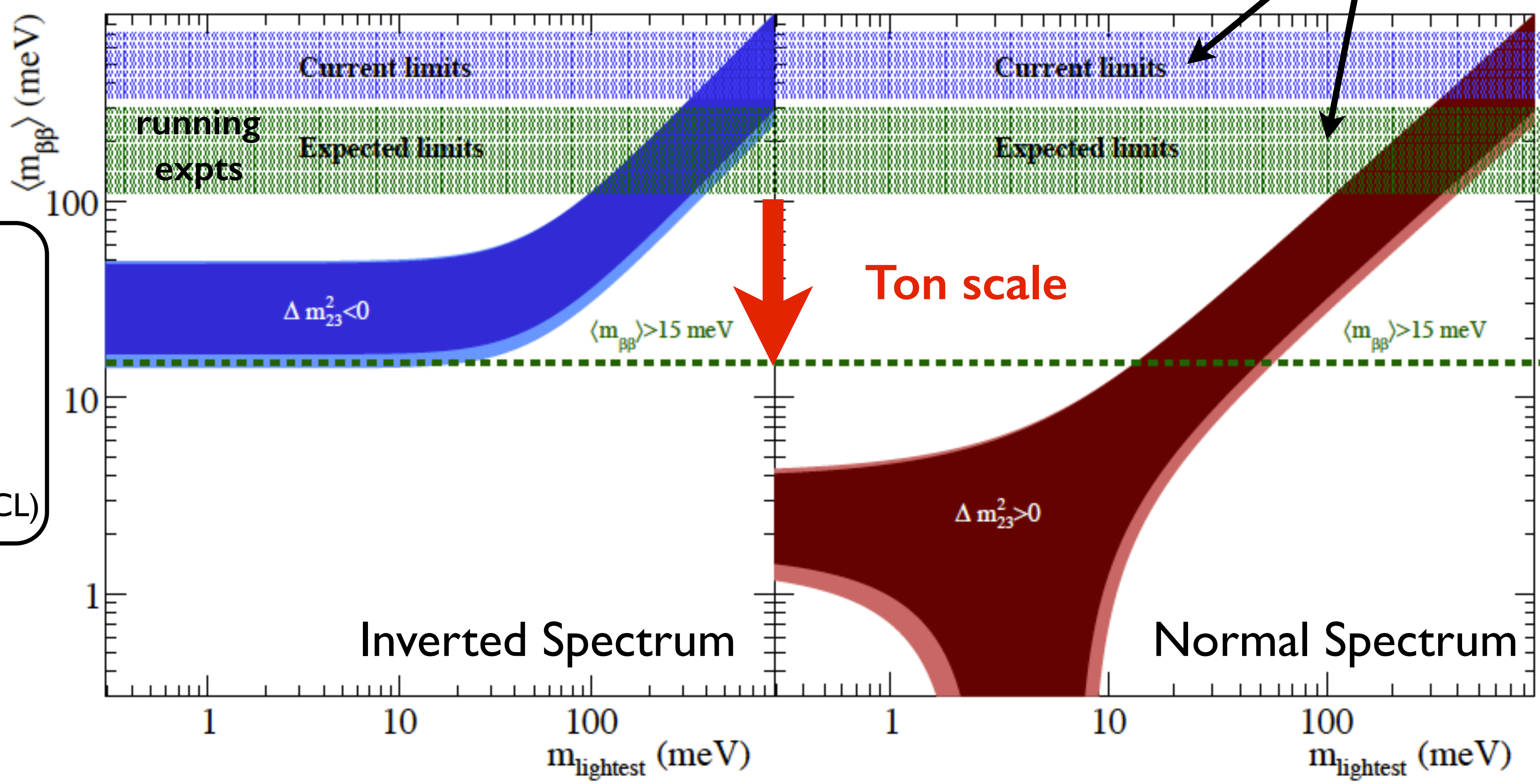


The "Standard" Mechanism

Assume most "pessimistic" values for nuclear matrix elements

Dark bands: unknown phases

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



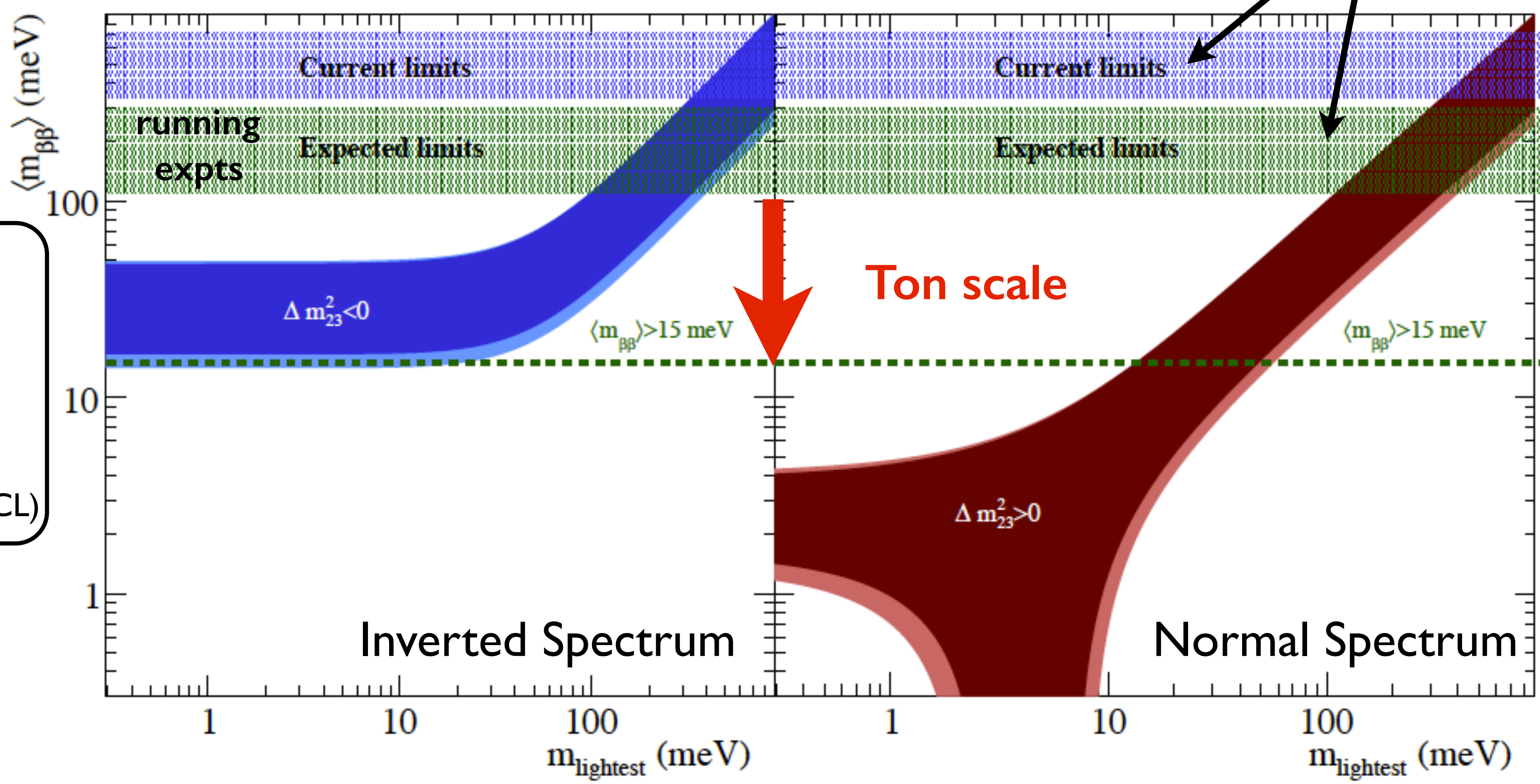
- Ton-scale experiment will make a discovery if spectrum has
  1. inverted ordering *or*
  2. $m_{lightest}$ > 50 meV (irrespective of ordering)

The "Standard" Mechanism

Assume most "pessimistic" values for nuclear matrix elements

Dark bands: unknown phases

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



- Other probes of the same coupling? LNV meson decays

$BR_{exp} < 5\times10^{-10}$

$$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) \sim 10^{-33} \left(\frac{\langle m_{ee}\rangle}{\mathrm{eV}}\right)^2$$

Avogadro's number makes $0\nu\beta\beta$ the winner

TeV-scale LNV

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

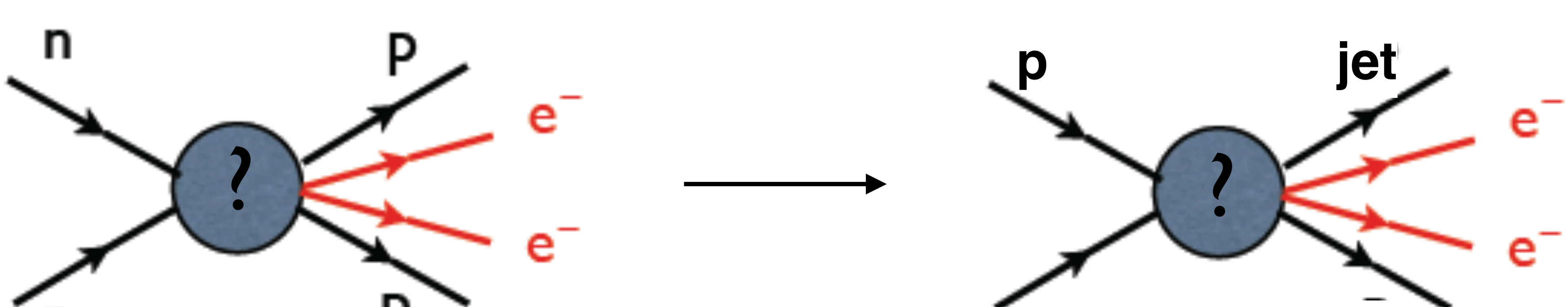
- Rough estimate → similar size for $m_{\beta\beta}$~eV and Λ~ TeV

$$A_\nu \sim \frac{G_F^2\, m_{\beta\beta}}{p^2}$$

$p \sim 100\ \mathrm{MeV}$

$$A_H \sim \frac{G_F^2 M_W^4}{\Lambda^5}$$

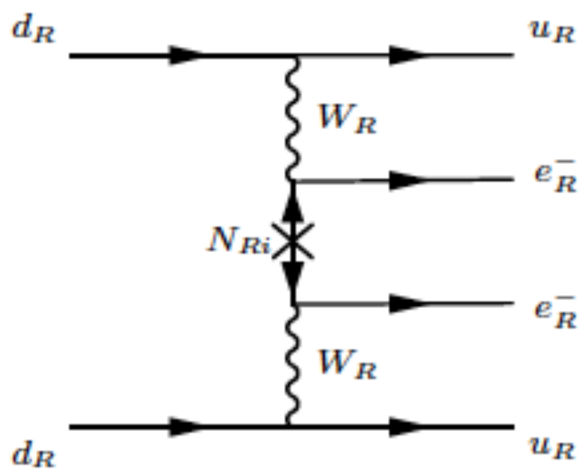
- Both mechanisms can produce 0νββ signal at current sensitivity. TeV-scale mechanism can be probed at the LHC, too! (pp →eejj)

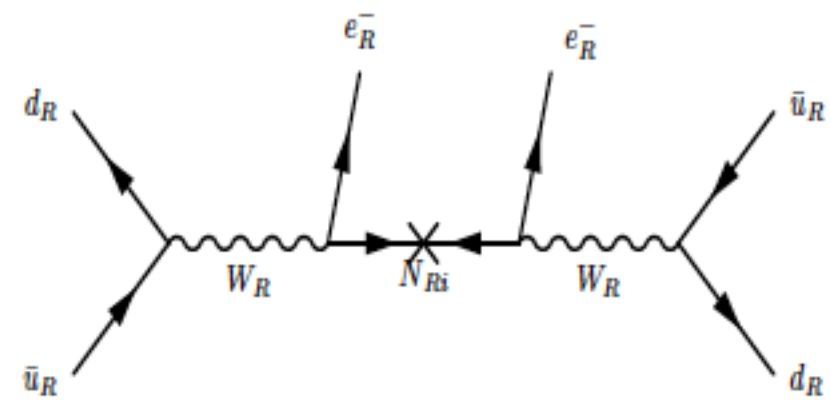


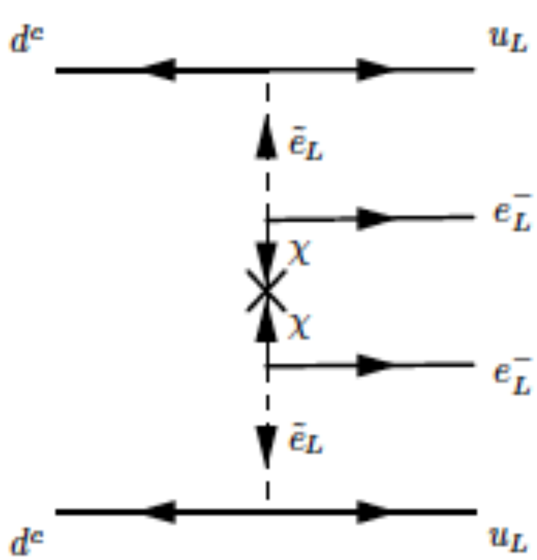
TeV-scale LNV

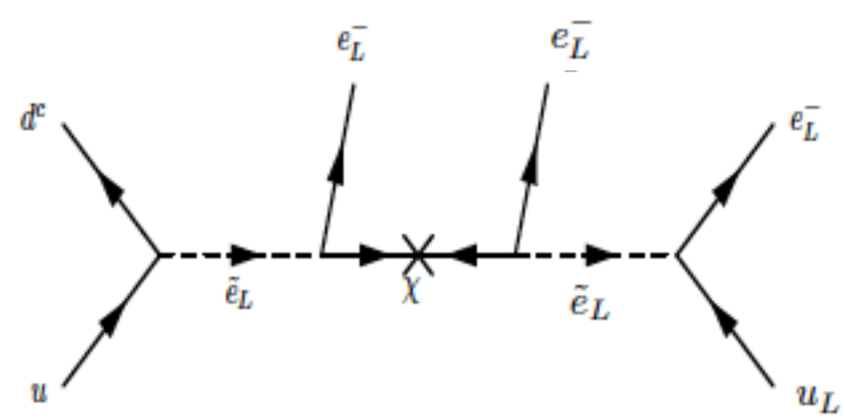
- TeV sources of LNV may lead to significant contributions to NLDBD *not directly related to the exchange of light neutrinos*

- Arise in a variety of models, e.g. Left-Right symmetry, RPV SUSY









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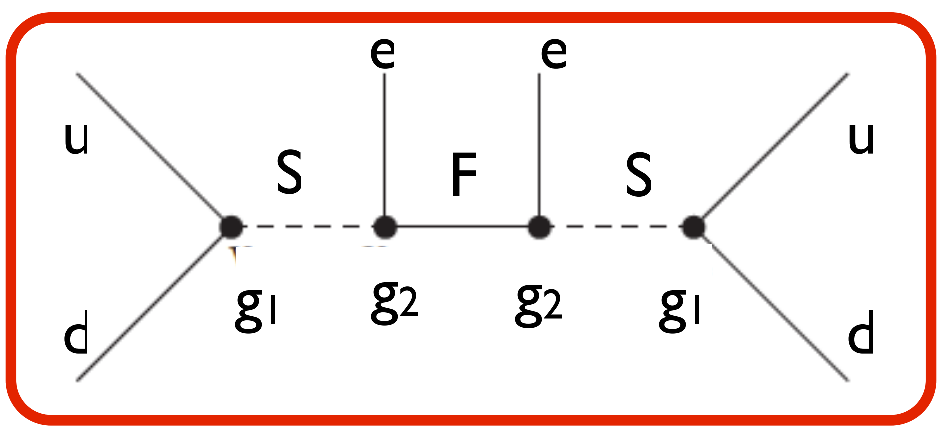
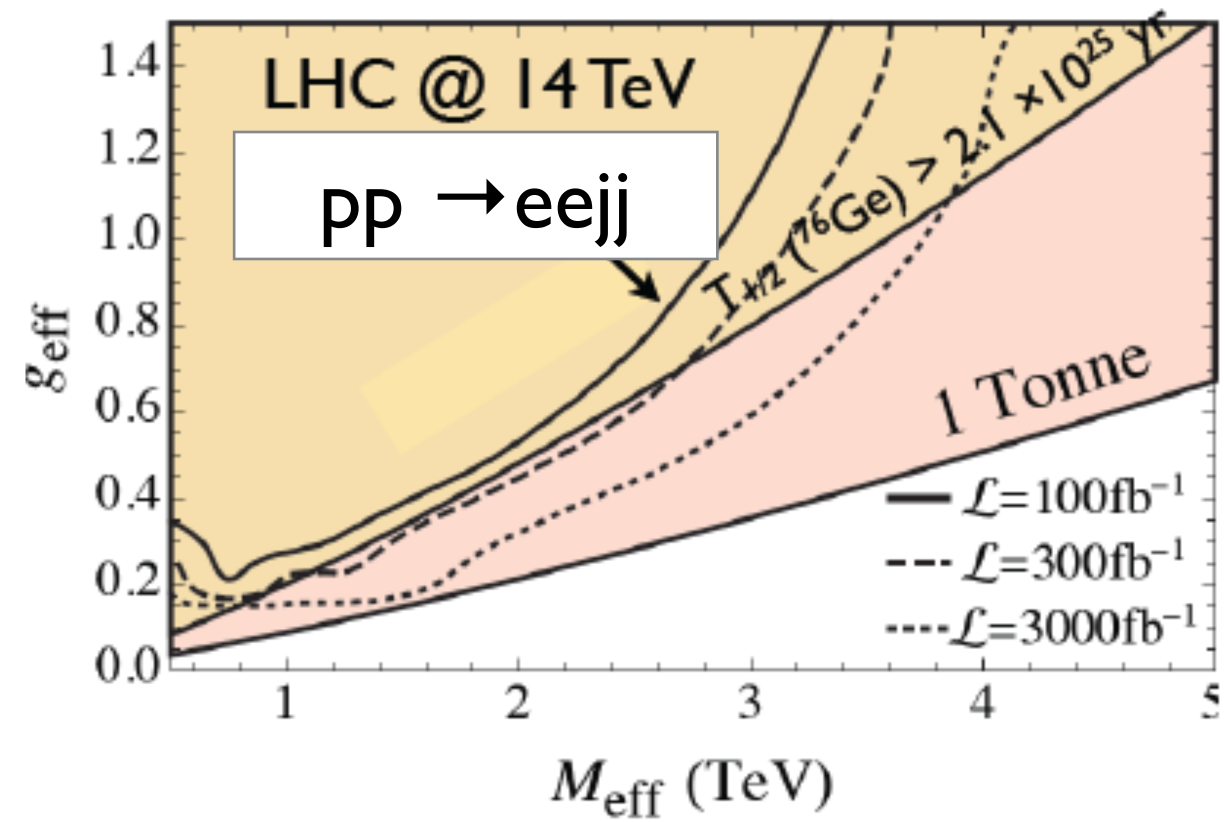
Simplified model ~ RPV-SUSY

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



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

Peng, Ramsey-Musolf, Winslow, 2015



Illustrates competition of Ton-scale NLDBD and LHC

TeV-scale LNV

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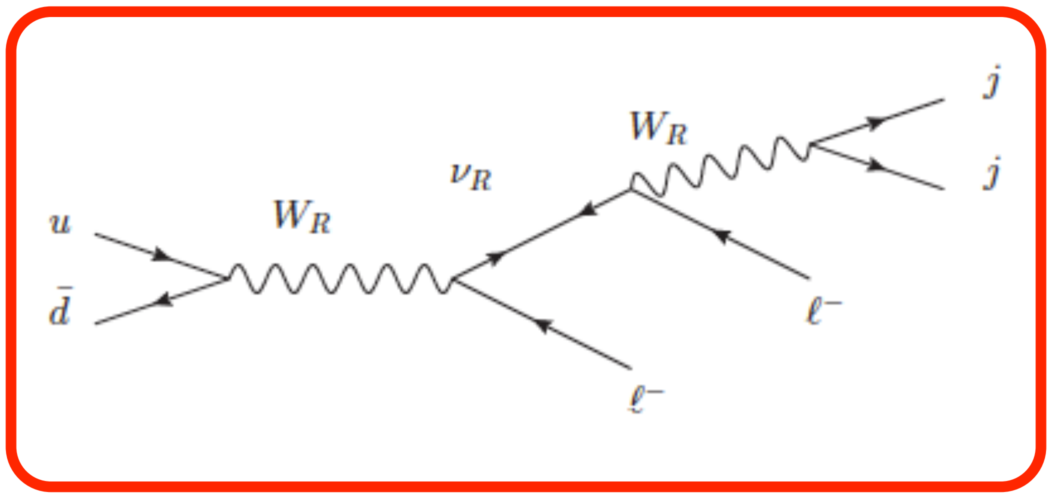
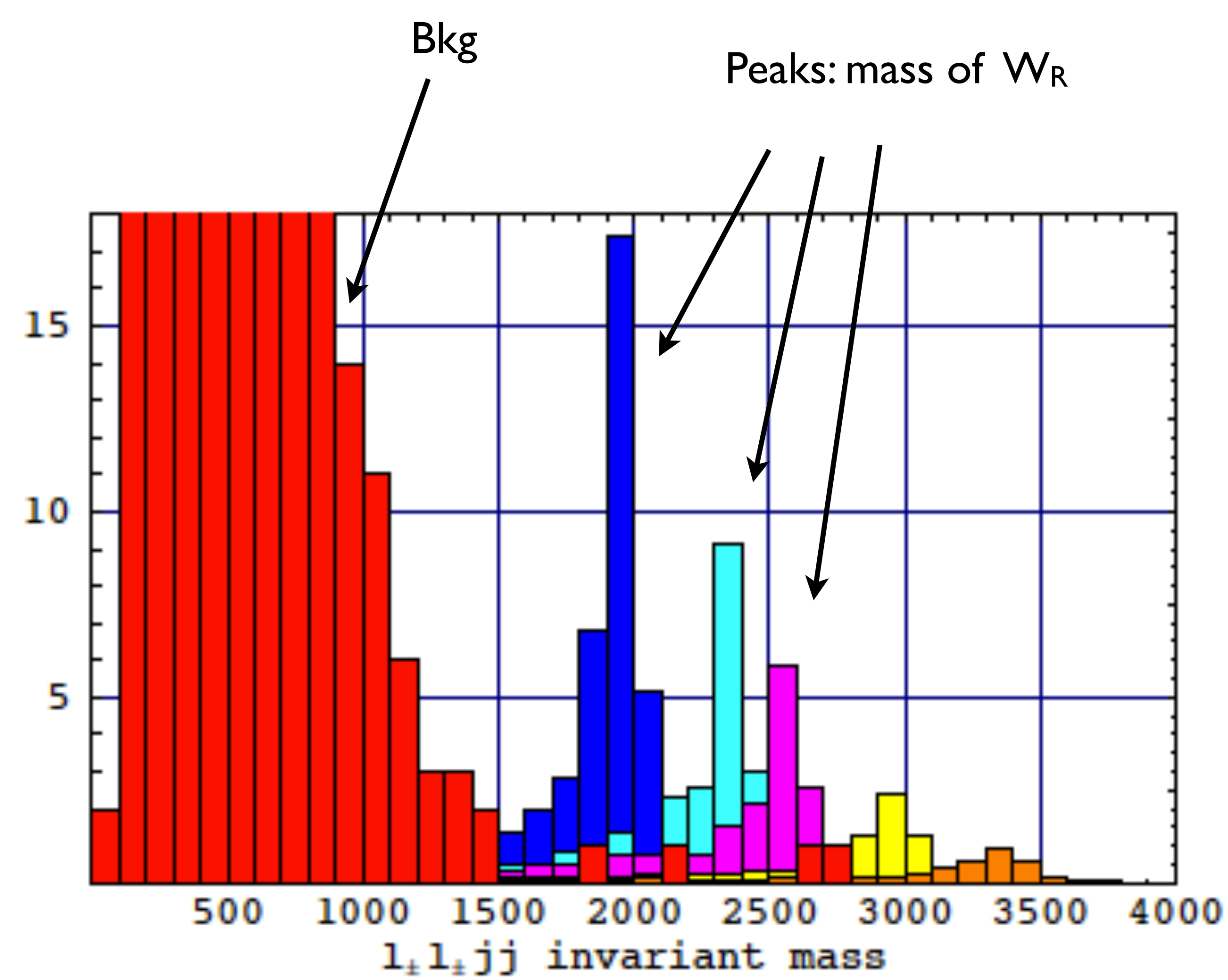
Left-Right symmetric model



L=8 fb^{-1}, s$^{1/2}$ = 14 TeV



- Sensitivity up to W_R mass ~ 6 TeV with L = 300 fb^{-1}

Maiezza, Nemevsek, Nesti, Senjianovic, 2010

TeV-scale LNV

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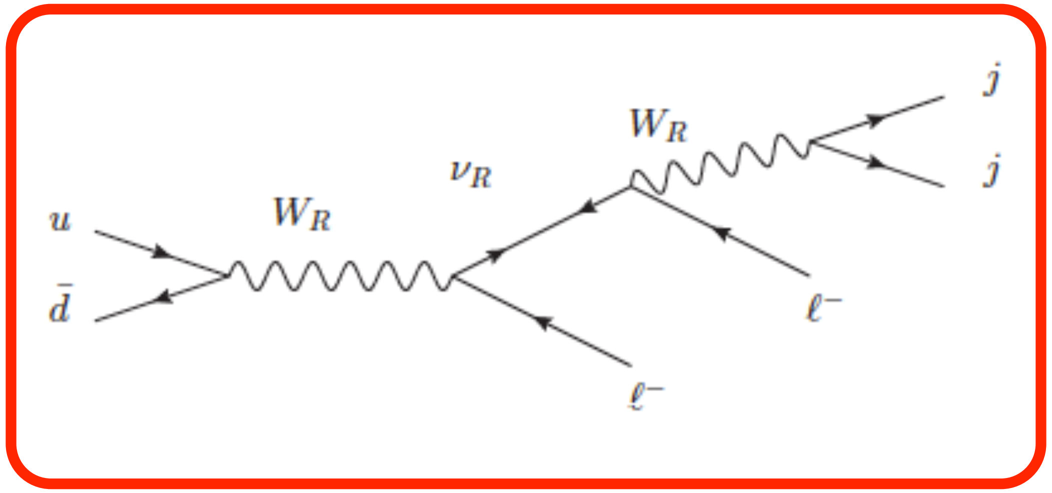
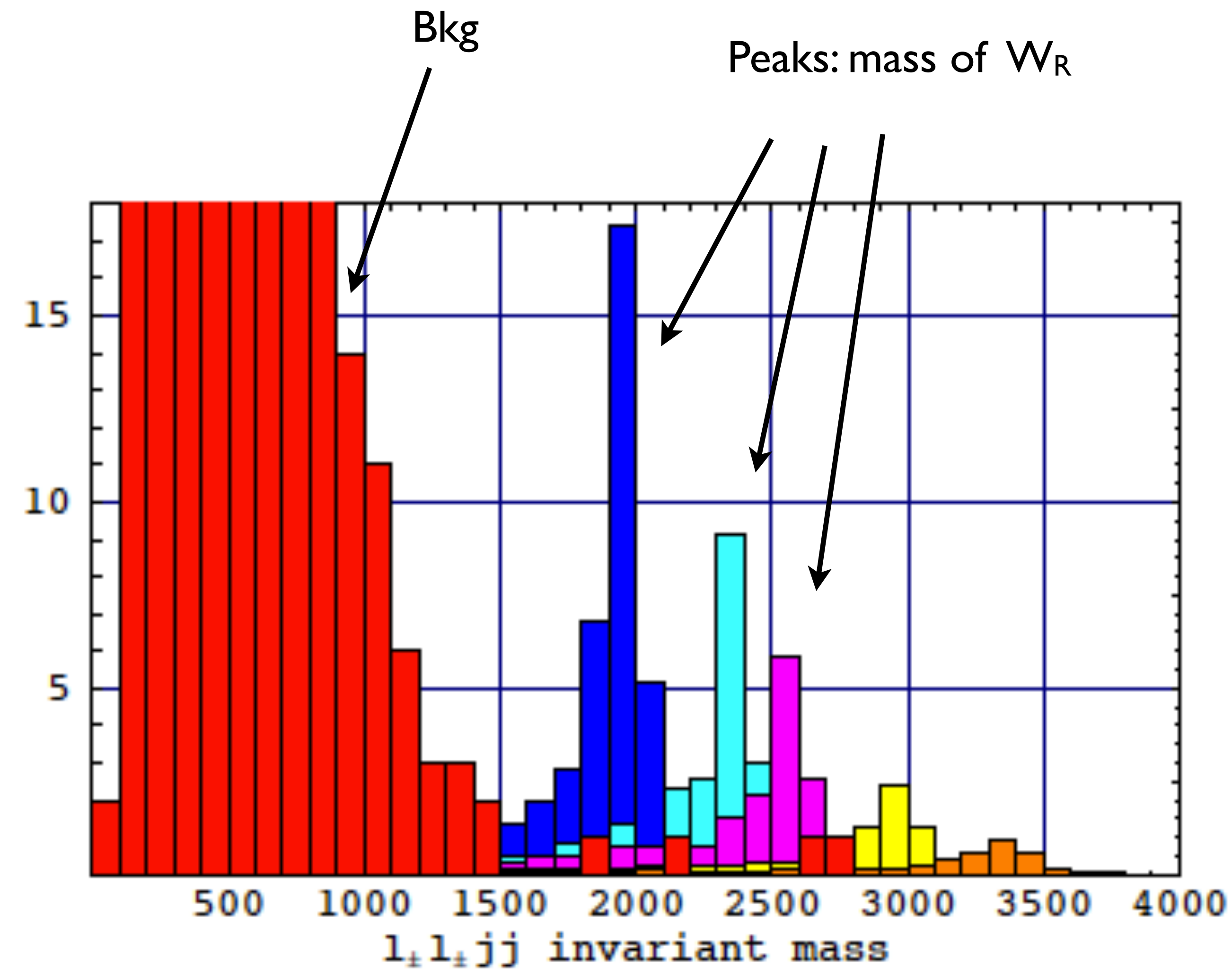


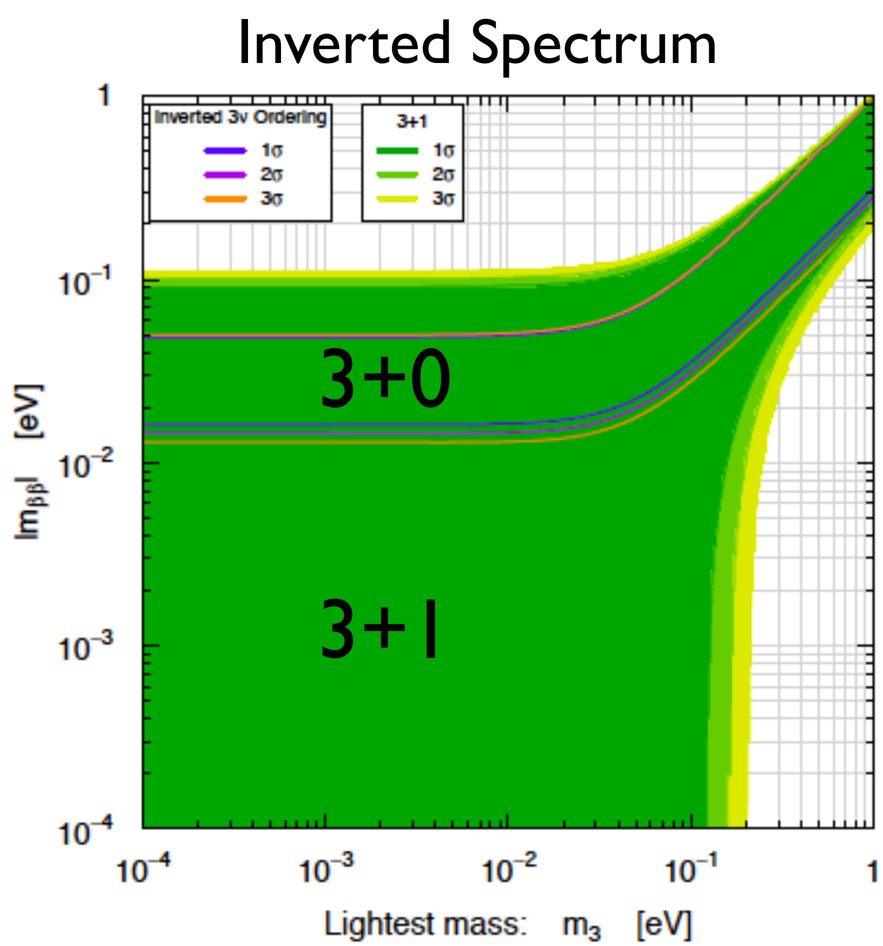
L=8 fb^{-1}, s$^{1/2}$ = 14 TeV

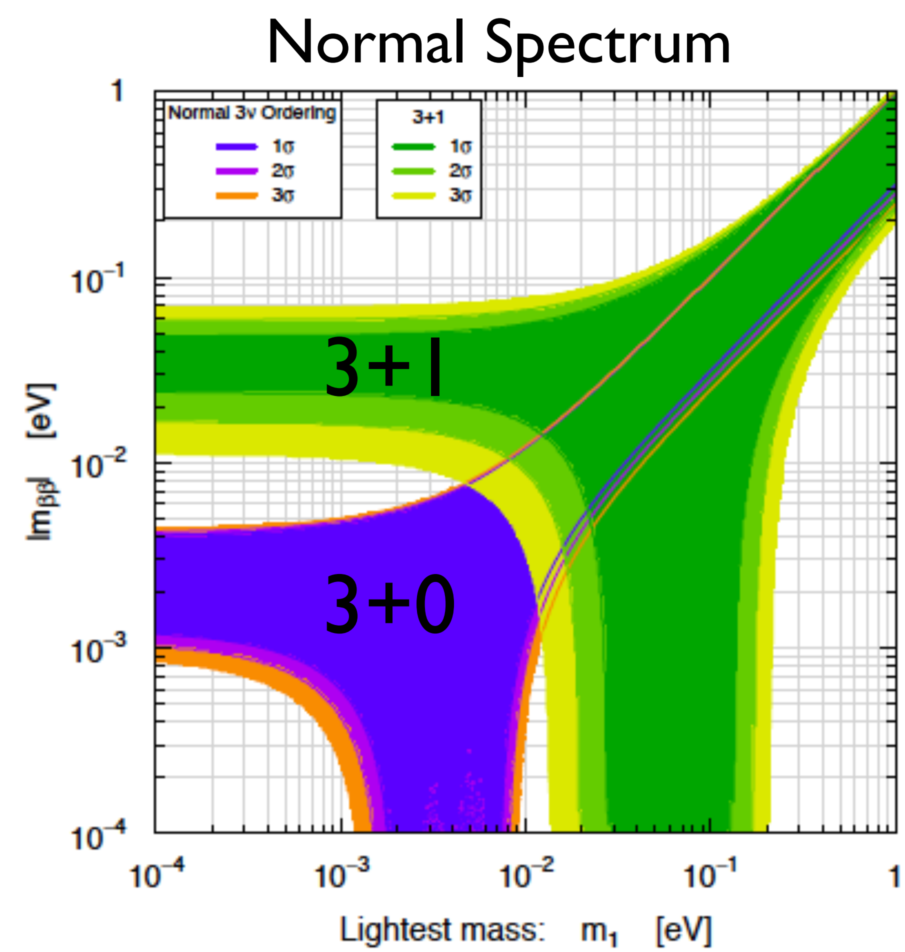


In case of positive NLDBD signal, interplay with LHC will be important to pin down LNV mechanism

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





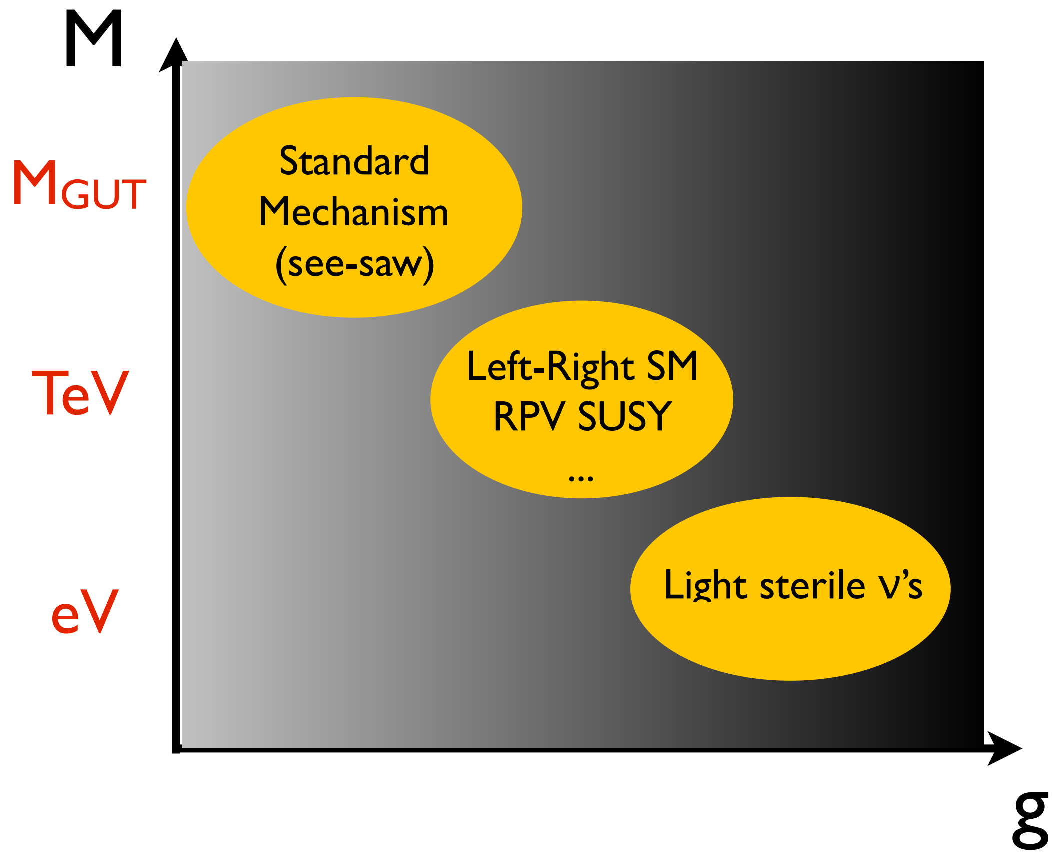
Giunti-Zavanin 2015

Usual phenomenology turned around!!

Summary on NLDBD

- NLDBD is the most powerful kmowm probe of Lepton Number Violation, sensitive to new physics over a vast range of scales, with far reaching implications

  - Demonstrate Majorana nature of neutrino
  - Probe new mass mechanism
  - Probe ingredient for leptogenesis

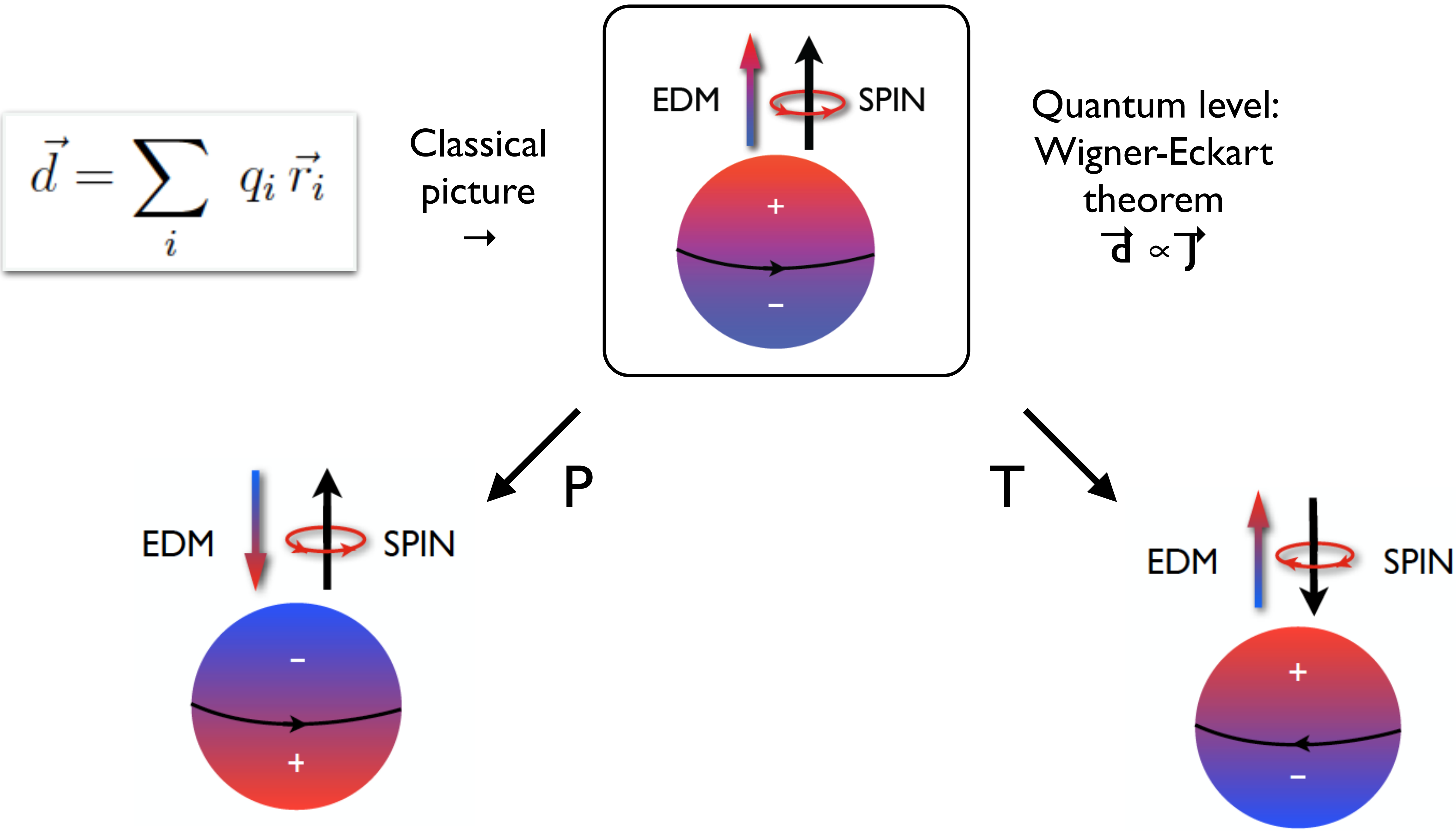


- In case of discovery, pinning down the mechanism will require multiple measurements (e.g. different nuclei, single electron spectrum, angular distribution) and interplay with LHC

EDMs and new sources of CP-violation

EDMs and symmetry breaking

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

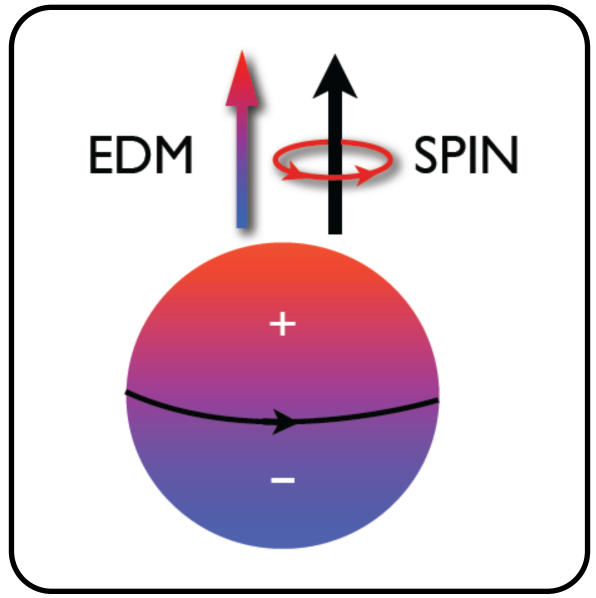


EDMs and symmetry breaking

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

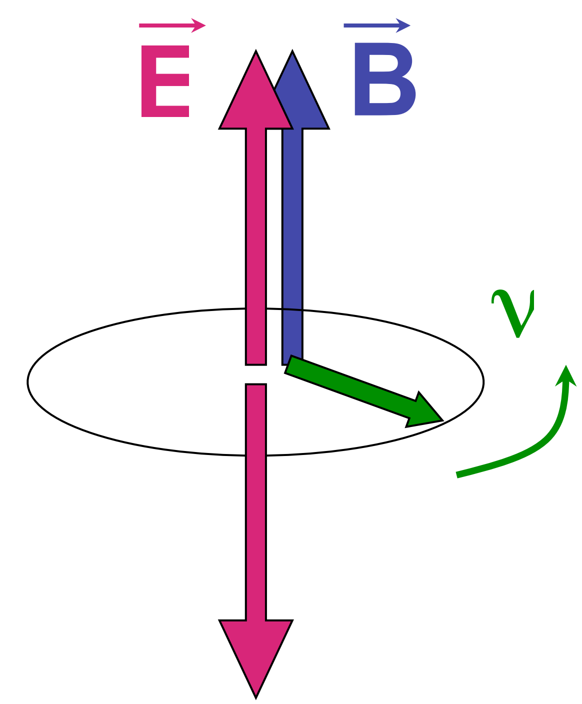
$$\vec{d} = \sum_i q_i\,\vec{r}_i$$

Classical picture →



Quantum level: Wigner-Eckart theorem $\vec{d} \propto \vec{J}$

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

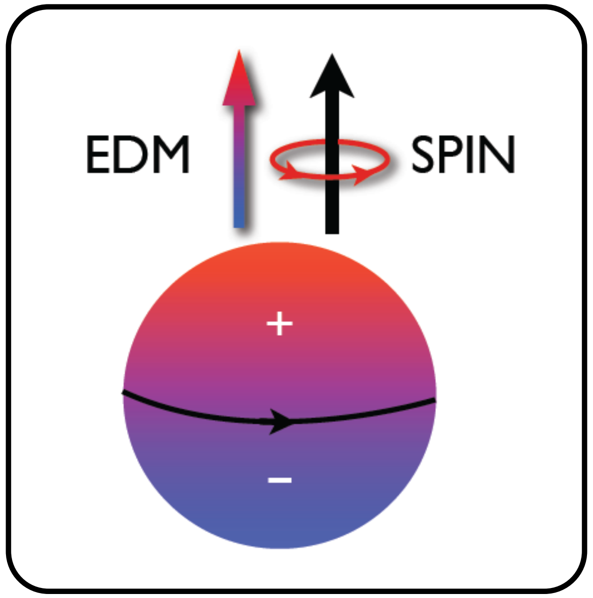


$$\nu = (2\mu B \pm 2dE)/h$$

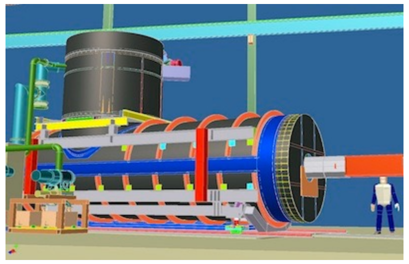
Sensitivity to $d_n \sim 10^{-13}$ e fm !!

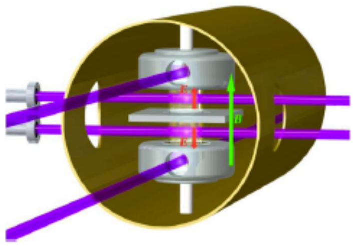
EDMs and symmetry breaking

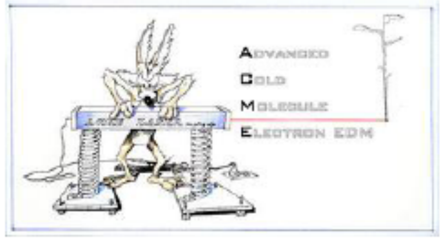
- EDMs of non-degenerate systems violate P and T (CP): $\mathcal{H} \sim d\,\vec{J} \cdot \vec{E}$



- Ongoing and planned searches in several systems



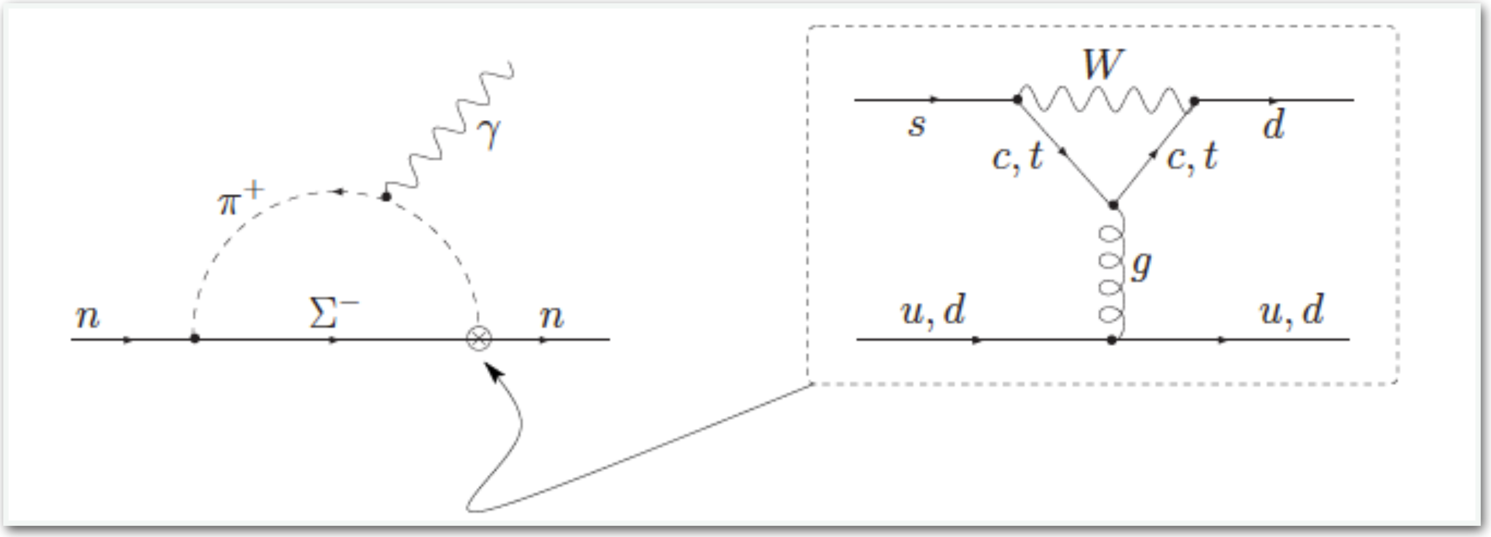




★ n, p
★ Light nuclei: d, t, h
★ Atoms: diamagnetic (^{129}Xe, ^{199}Hg, ^{225}Ra, ...);
paramagnetic (^{205}Tl, ...)
★ Molecules: YbF, ThO, ...

EDMs in the Standard Model?

- CKM: dominant "long-distance" contribution to nEDM fairly small



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

See Pospelov-Ritz 2005 review

EDMs in the Standard Model?

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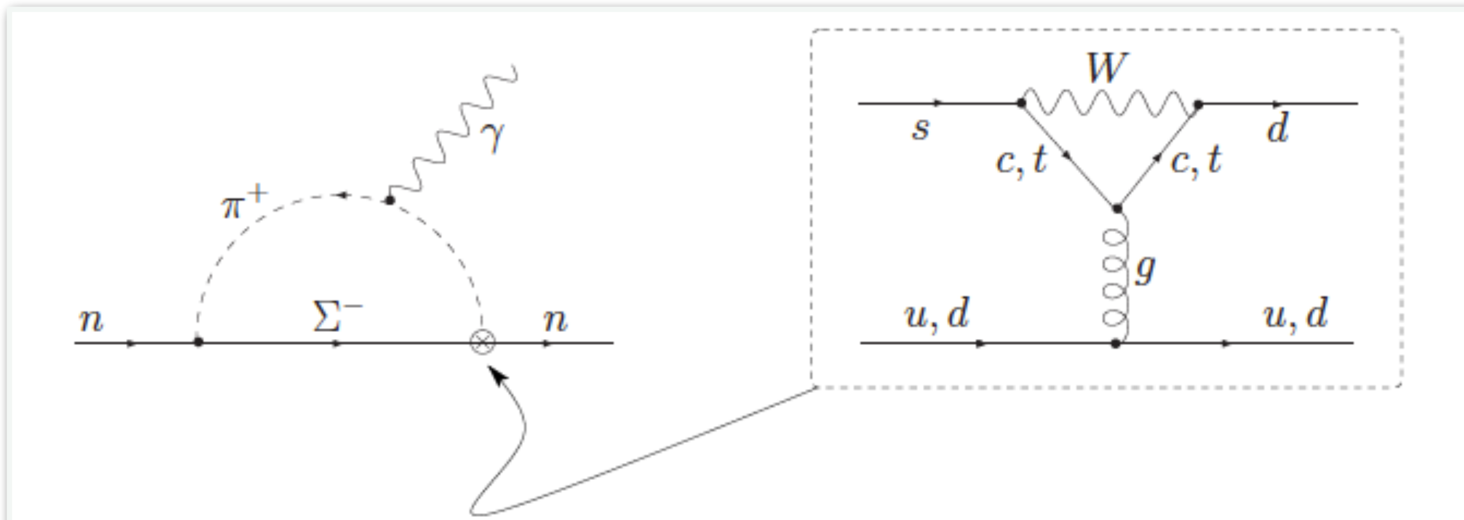


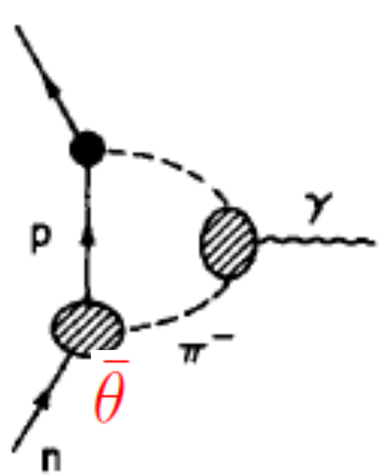
$d_n \sim 10^{-31}$ e cm

See Pospelov-Ritz 2005 review

- QCD

$$\mathcal{L}_{\rm CPV} = -m_* \, \bar\theta \sum_{q=u,d,s} \bar q i \gamma_5 q$$

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



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

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

Crewther, Di Vecchia, Veneziano, Witten 1979

EDMs and new physics

- Essentially free of SM "background" (CKM)*
- Probe high-scales, up to $\Lambda \sim 10^{2\text{-}3}$ TeV

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

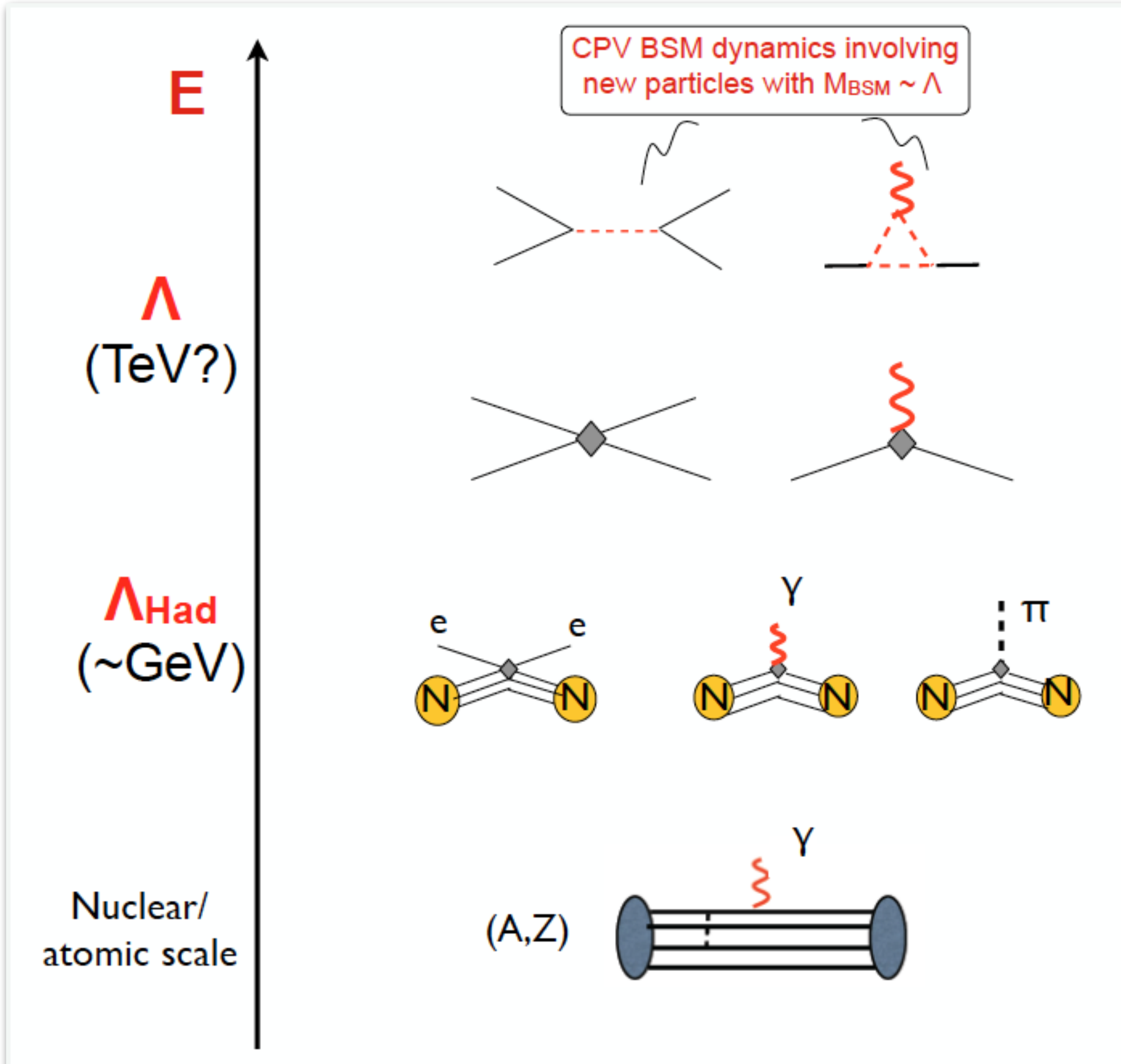
- Probe key ingredient for bayrogenesis (CPV in SM is insufficient)

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}	$\sim 10^{-33}$
...	...		...

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

Connecting EDMs to BSM CPV



- It's a multi-scale problem: need RG evolution of effective couplings (at the quark-gluon level) and hadronic / nuclear / molecular calculations of matrix elements

CPV at the quark-gluon level

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

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

Electric and chromo-electric dipoles of fermions

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

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

Gluon chromo-EDM (Weinberg operator)

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

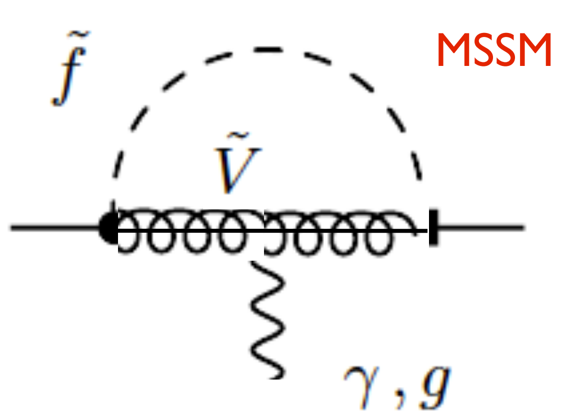
Semileptonic and 4-quark

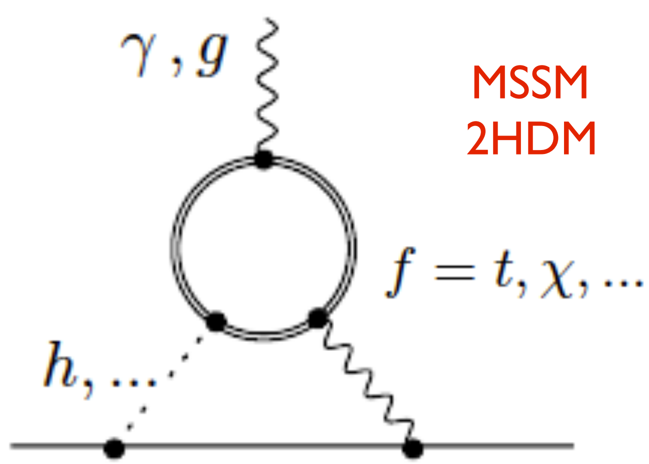
CPV at the quark-gluon level

- 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

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

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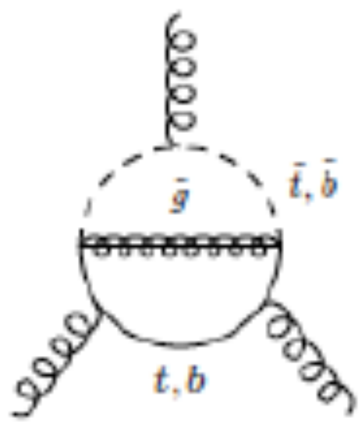
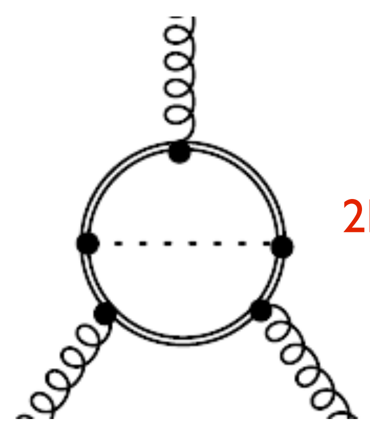


MSSM



2HDM → Weinberg operator

CPV at the quark-gluon level

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

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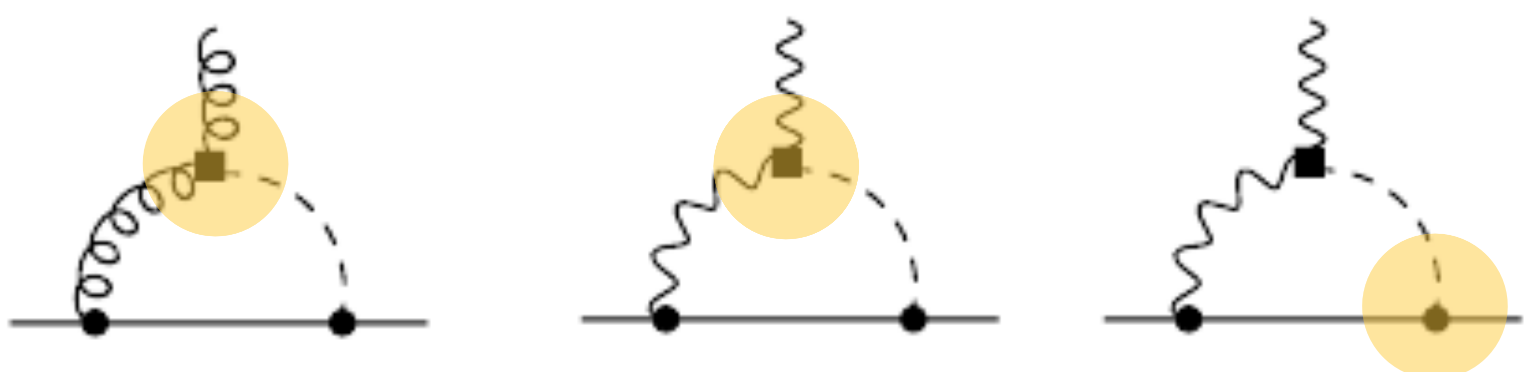


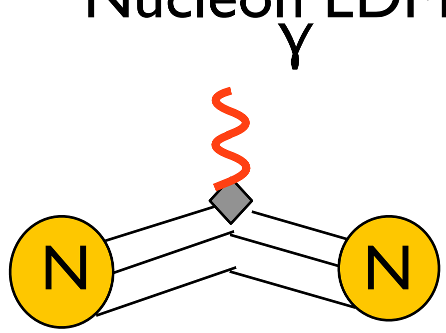
Operator mixing and threshold corrections →
EDM sensitivity to non-standard Higgs couplings (hVV, ...), heavy quark CPV, ...

CPV at the hadronic level

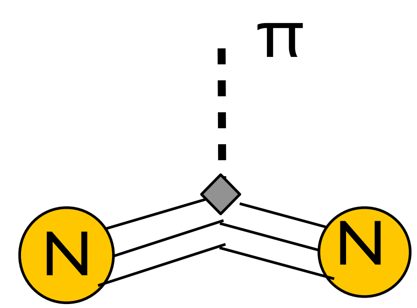
- Leading pion-nucleon CPV interactions characterized by few LECs

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

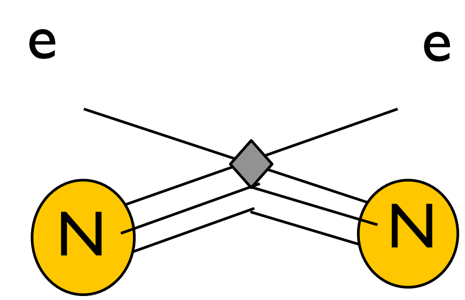
Electron and Nucleon EDMs



T-odd P-odd pion-nucleon couplings



Short-range 4N and 2N2e coupling



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

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

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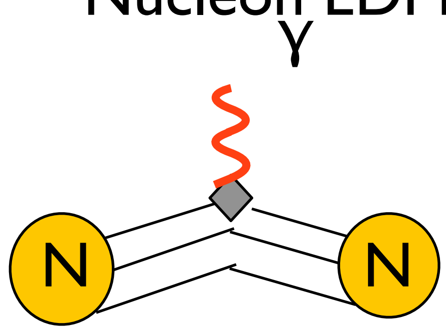
Electron and Nucleon EDMs



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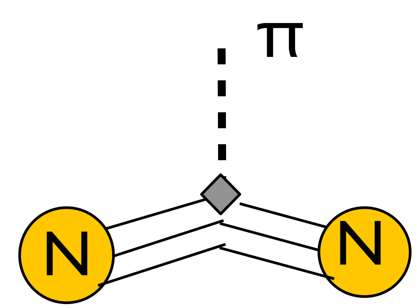

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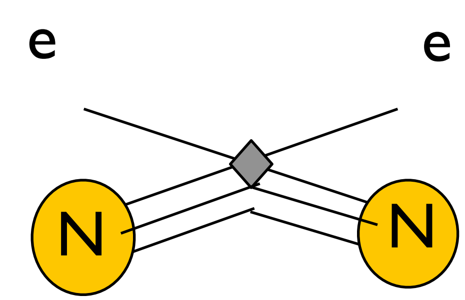
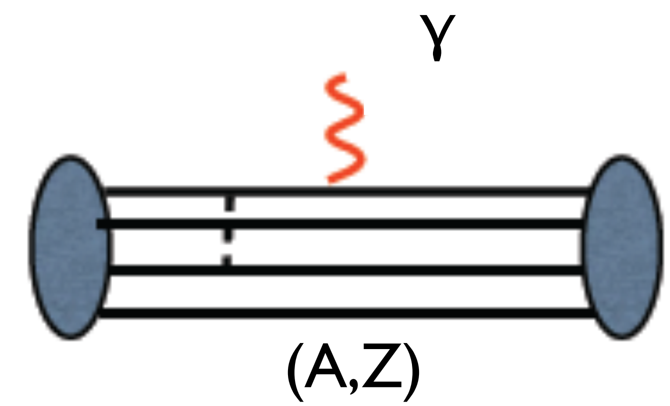


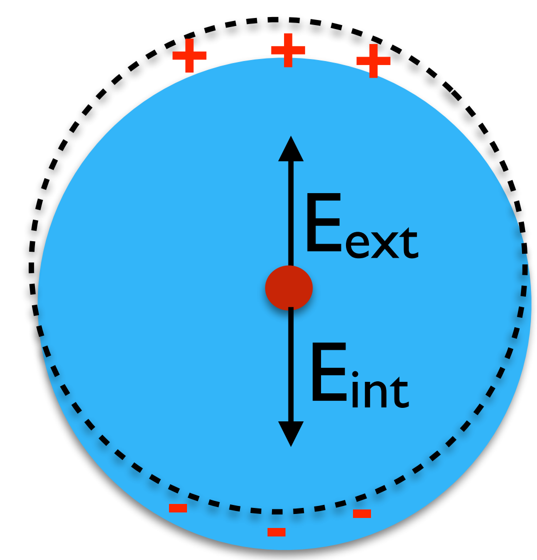
$$d_n = -(0.22\pm0.03)d_u + (0.74\pm0.07)d_d + (0.0077\pm0.01)d_s$$
$$-(0.55\pm0.28)e\tilde{d}_u - (1.1\pm0.55)e\tilde{d}_d \pm (50\pm40)\,\mathrm{MeV}\,e\,d_W$$

μ=1 GeV

CPV at the atomic level

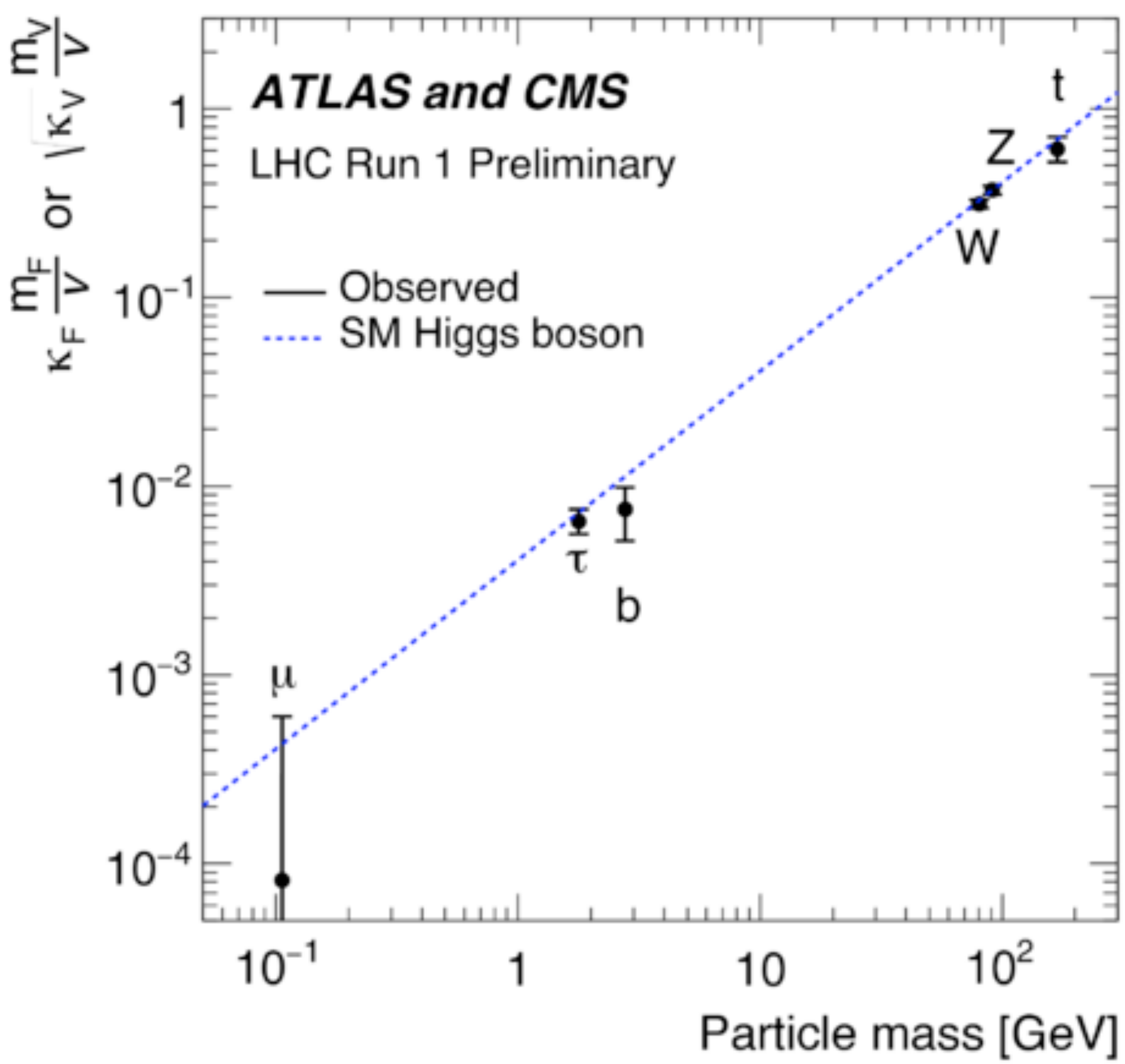
- CPV at the atomic level: need to work against Schiff's theorem
    - No atomic EDM due to d_e, d_{nucl} (charged constituents rearrange to screen the externally applied E_{ext})
- Evaded by finite-size and relativistic effects
- Uncertainties: O(10%) in paramagnetic systems; O(few 100%) in diamagnetic systems





EDMs and Higgs couplings

- So far, Higgs properties are compatible with SM expectations



- Couplings to W, Z, γ,g and t, b, τ known at 20-30% level
- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2 & important goal for low energy experiments
- EDMs play an important role in pinning down non-standard CP-violating Higgs couplings

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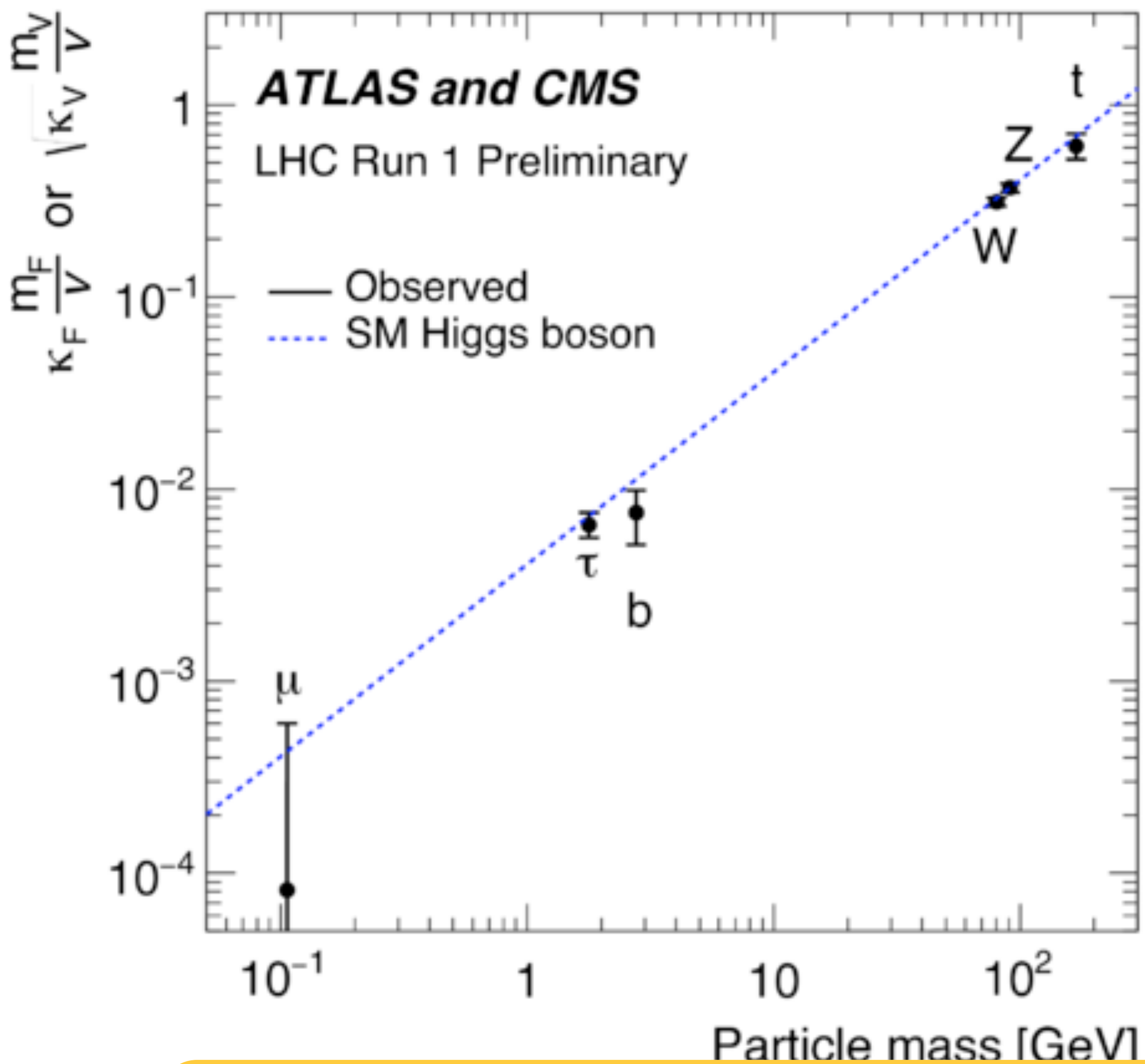

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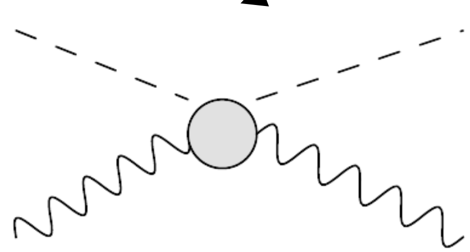
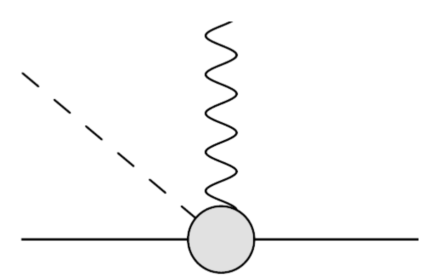
If Λ_{BSM} > TeV, EFT approach applicable to EDMs *and* colliders

- A number of dim-6 operators in the SM-EFT involve CPV Higgs interactions

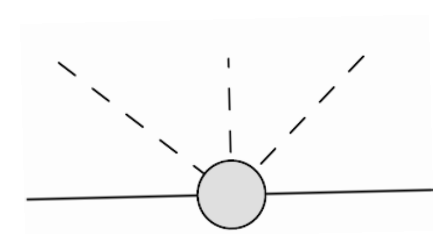
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$



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



H-$\mathrm{q_L}$-$\mathrm{q_R}$-V: dipole



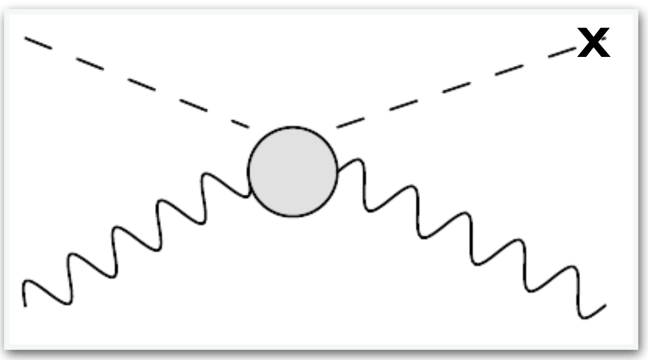
H-$\mathrm{q_L}$-$\mathrm{q_R}$: scalar

V = g, $\mathrm{W^a}$, B

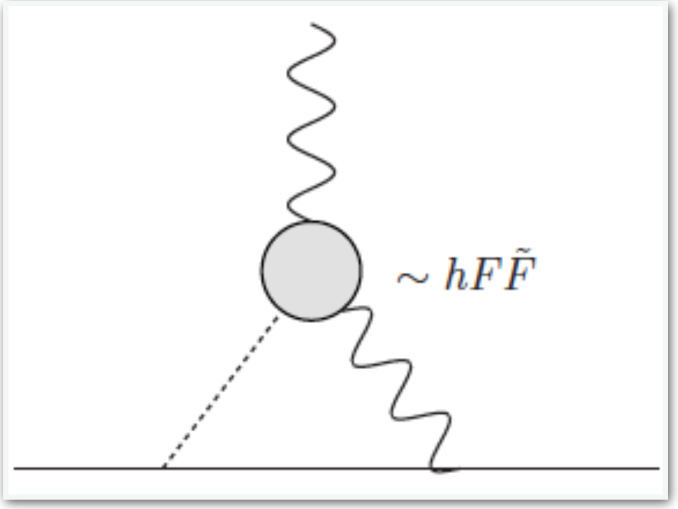
Higgs coupling to photons

- Leading (dim-6) CPV operator affects both Higgs decay and EDMs

$$\mathcal{L} \supset c_{\gamma\gamma}\, v\, h\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$c_{\gamma\gamma} \equiv \frac{1}{\Lambda^2_{\gamma\gamma}}$$



- eEDM $\Rightarrow \Lambda_{\gamma\gamma} > 100$ TeV and hence $\Gamma(h\to\gamma\gamma)/\Gamma(h\to\gamma\gamma)_{SM} - 1 \approx 10^{-5}$

McKeen-Pospelov-Ritz 1208.4597 + ACME new limit

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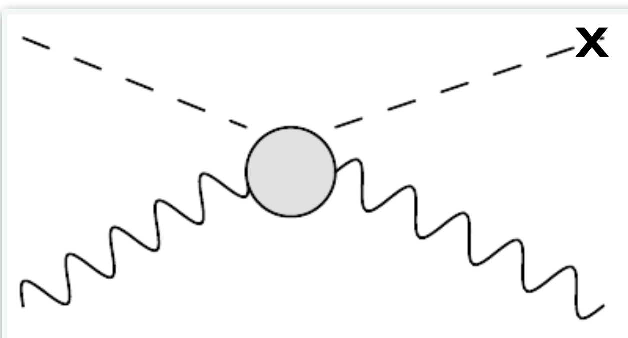

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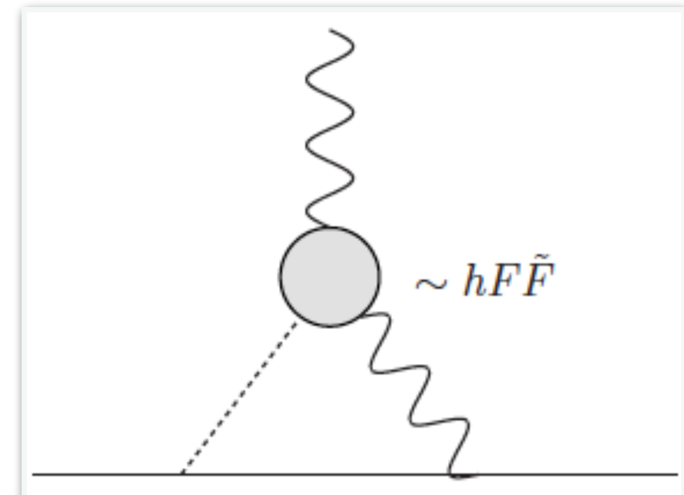


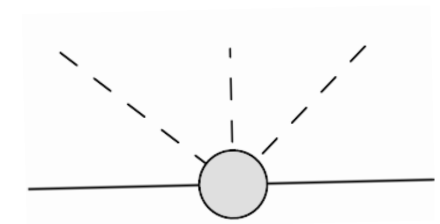
- eEDM $\Rightarrow \Lambda_{\gamma\gamma} > 100$ TeV and hence $\Gamma(h\to\gamma\gamma)/\Gamma(h\to\gamma\gamma)_{SM} - 1 \approx 10^{-5}$
- Bound evaded by more elaborate model-building, involving for example (i) contribution to $d_e(\Lambda)$ that cancels effect of running; (ii) degenerate scalar sector (EFT not applicable)

McKeen-Pospelov-Ritz 1208.4597 + ACME new limit

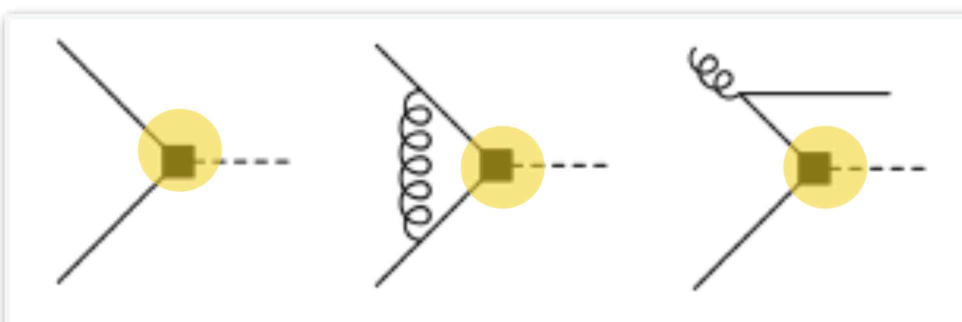
Yukawa couplings to quarks

- Pseudo-scalar Yukawa coupling (e.g. from dim-6 operator)

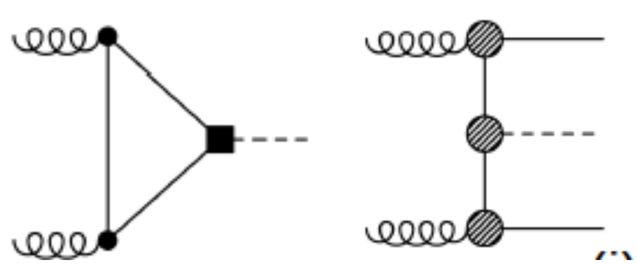
$$\mathcal{L}_6^{CPV} \supset \quad v^2 \mathrm{Im}\, Y'_q \; \bar{q} i \gamma_5 q \; h$$



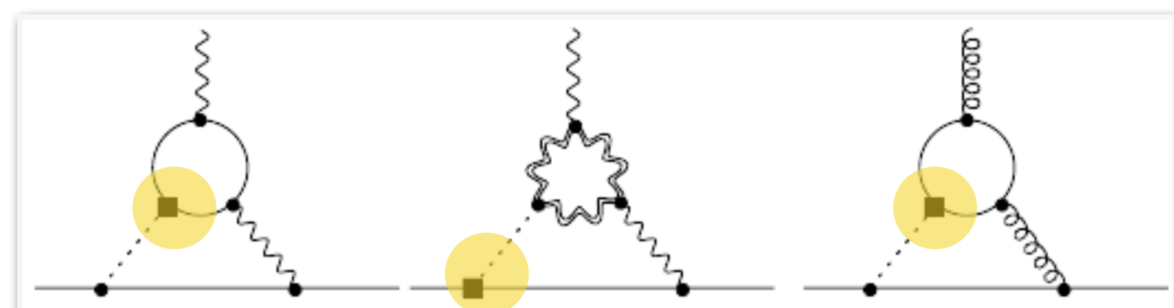
LHC: Higgs production

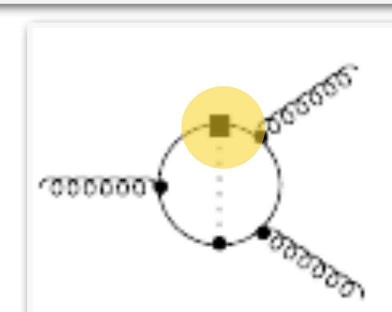


Top quark:



Low Energy: quark (C)EDM, Weinberg, *and* d_e

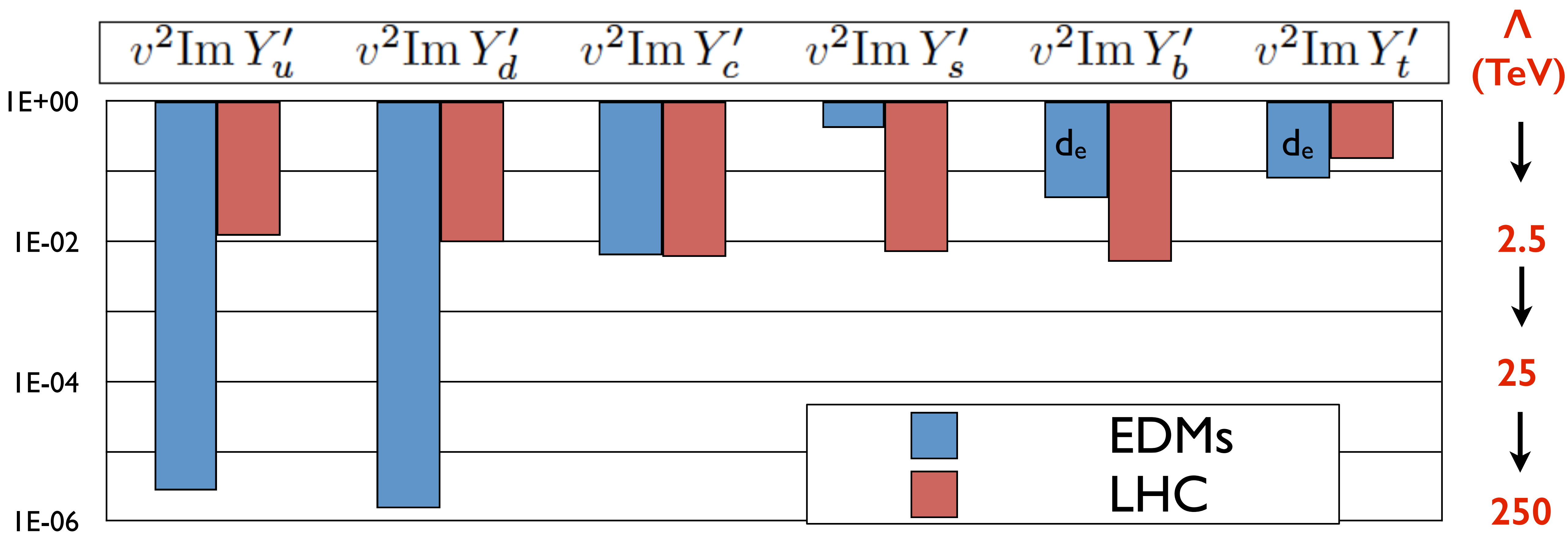




Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385 — third generation Yukawas

Yukawa couplings to quarks

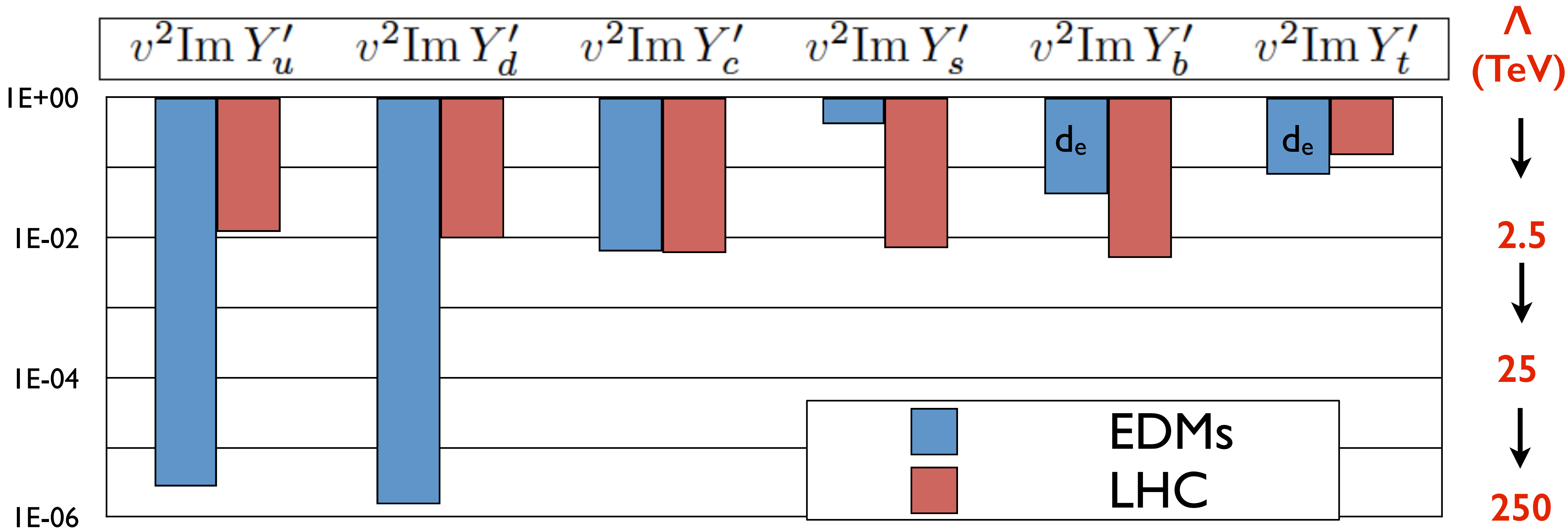


- Pseudo-scalar Yukawas in units of SM Yukawa m_q/v:

$$\mathcal{L} = \frac{m_q}{v} \, \tilde{\kappa}_q \, \bar{q} i \gamma_5 q \, h$$

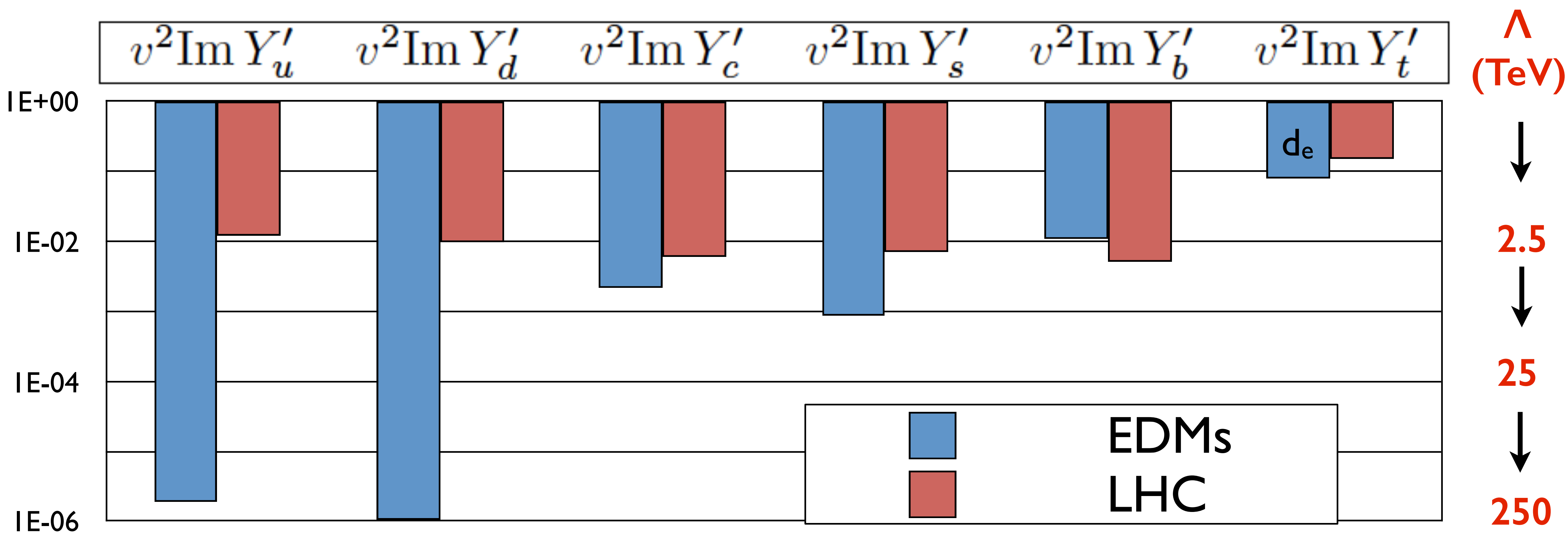
$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

Yukawa couplings to quarks



- Best bounds come from combination of EDMs (neutron and electron) and LHC
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

Yukawa couplings to quarks



- Much stronger impact of n and ^{199}Hg EDM with reduced uncertainties

$$d_{n,p}[\tilde{d}_{u,d}] \quad d_{n,p}[d_s] \quad d_{n,p}[d_W] \quad \bar{g}_{0,1}[\tilde{d}_{u,d}] \quad S_A[\bar{g}_{0,1}]$$

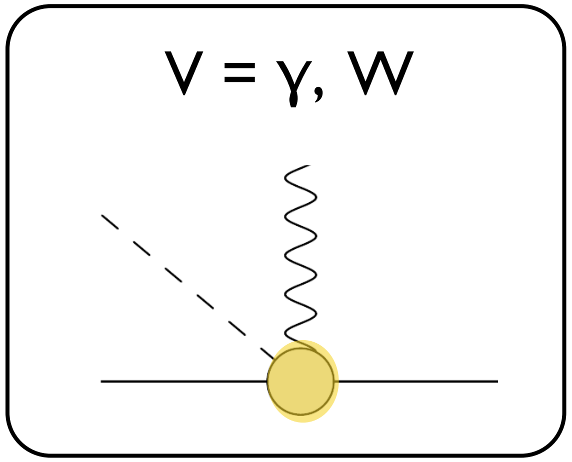
25% 50%

- Challenging but realistic target for LQCD and nuclear structure

Higgs coupling to top and EW bosons

- Top quark particularly interesting, has strongest coupling to Higgs: enhanced new physics effects?

C_γ, C_{Wt}



H-t_L-t_R-V: EW top dipoles

- Impact of EDMs on electroweak dipoles (γ,W) of the top was overlooked

$$\mathcal{L}_6^{\rm CPV} \supset (c_\gamma + i\tilde{c}_\gamma)\, O_\gamma \ + \ {\rm h.c.}$$

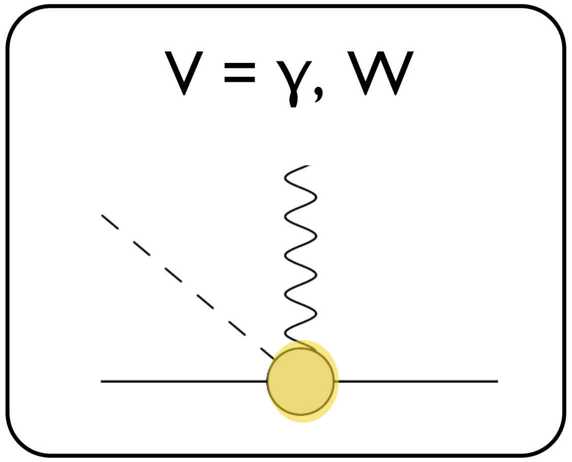
$$O_\gamma \ = \ -\frac{eQ_t}{2} m_t\, \bar{t}_L \sigma_{\mu\nu} \left(F^{\mu\nu} - t_W Z^{\mu\nu}\right) t_R \left(1 + \frac{h}{v}\right)$$

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

Higgs coupling to top and EW bosons

- Top quark particularly interesting, has strongest coupling to Higgs: enhanced new physics effects?

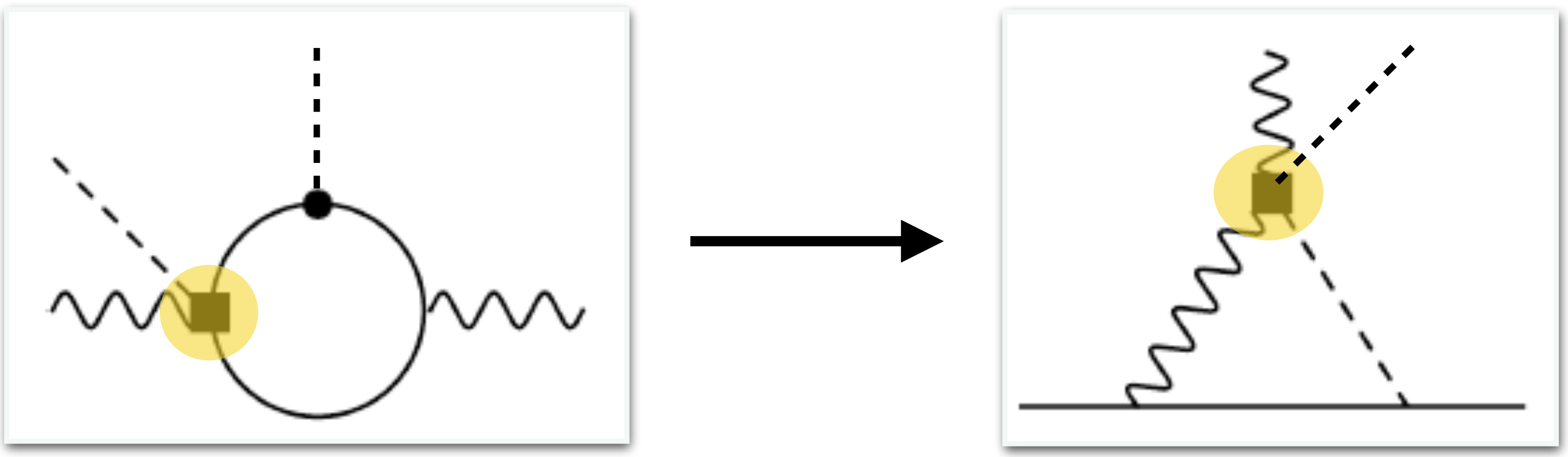
C_γ, C_{Wt}



H-t_L-t_R-V: EW top dipoles

- Impact of EDMs on electroweak dipoles (γ,W) of the top was overlooked

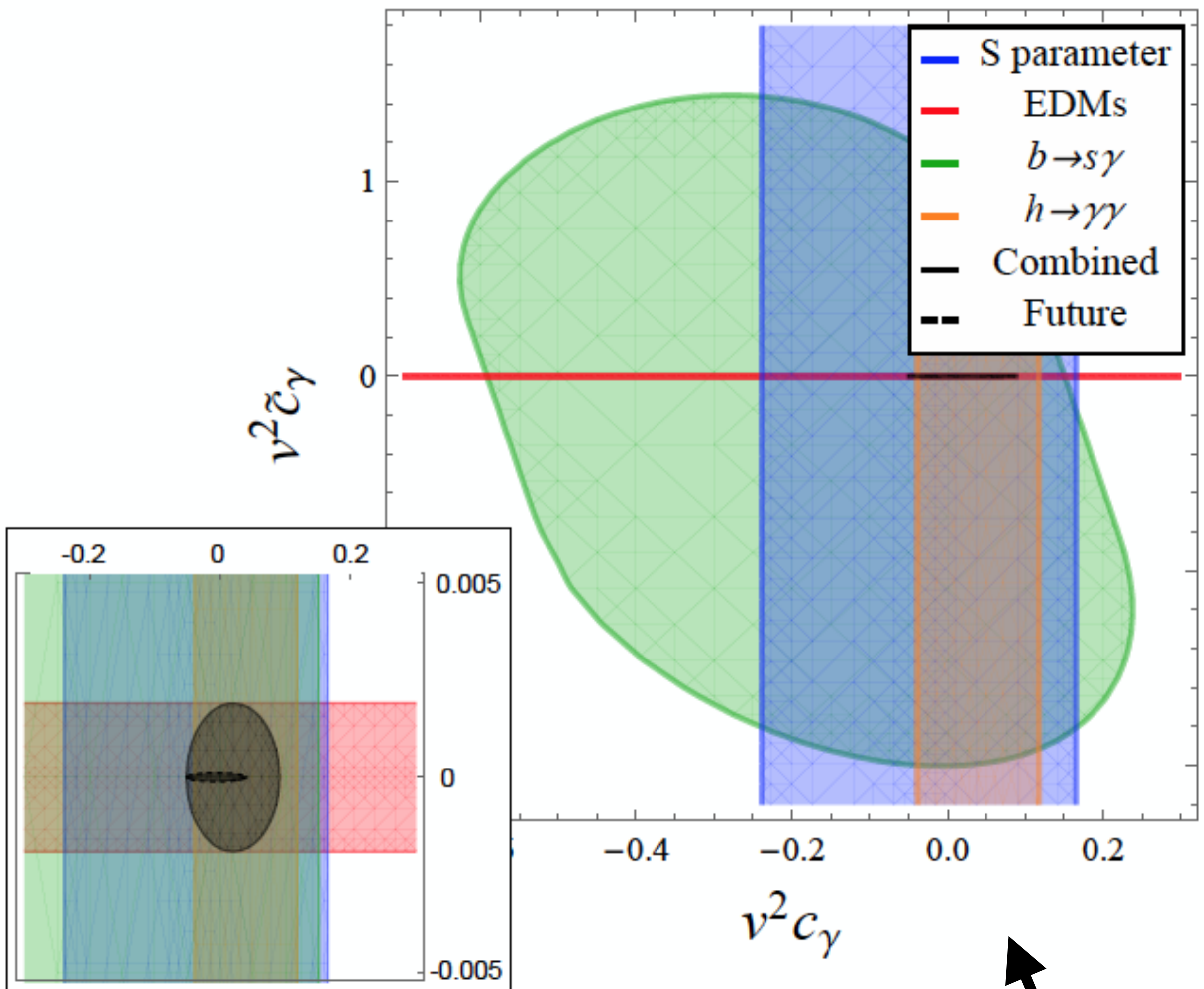
- C_γ, C_{Wt} affect eEDM and qEDMs via two-step mixing

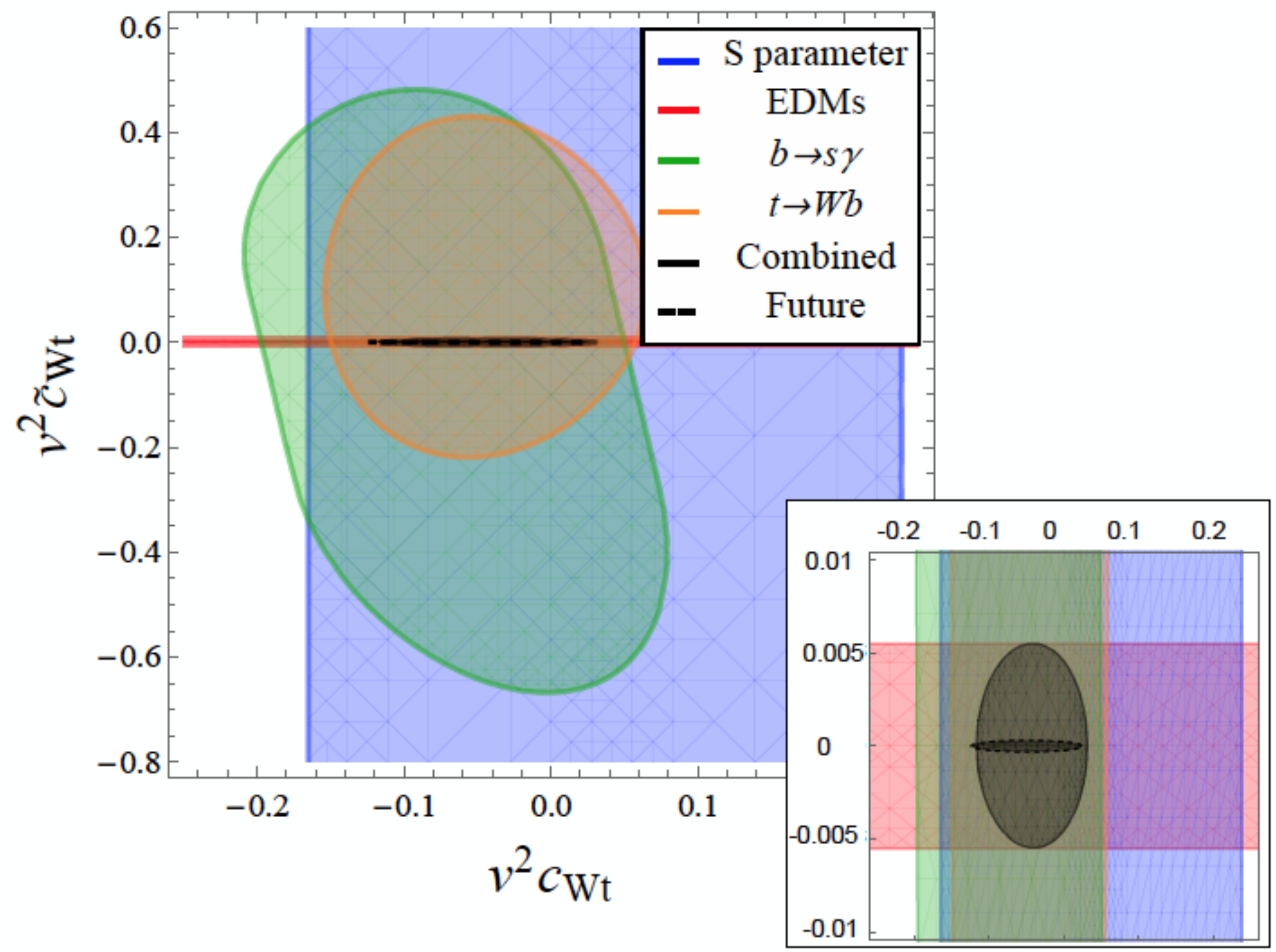


VC, W. Dekens, J. de Vries, E. Mereghetti 1603.03049

- Strong constraints on CP-Violating top EW dipoles, dominated by eEDM

C_γ $\quad$ $C_\alpha = c_\alpha + i\,\tilde{c}_\alpha$ $\quad$ C_{Wt}

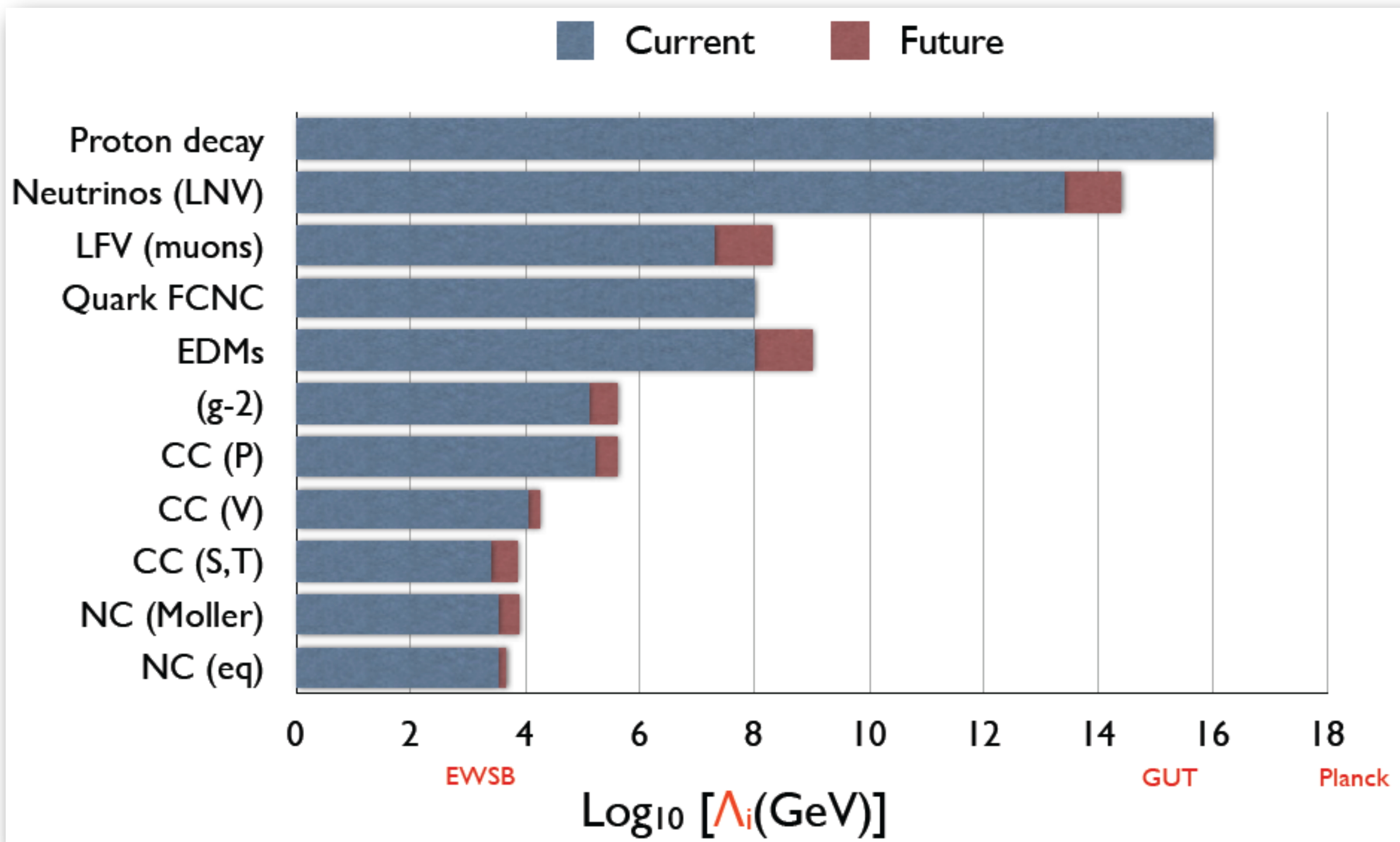




Bound on top-EDM improved by three orders of magnitude:
$|d_t| < 5\times10^{-20}$ e cm

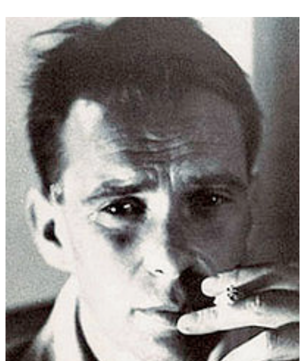
Conclusions

- Intensity Frontier experiments probe mass scale and symmetries of Standard Model extensions to unprecedented levels
- Broad and vibrant experimental program, with very high reach in effective scale



Hope to get discoveries soon!

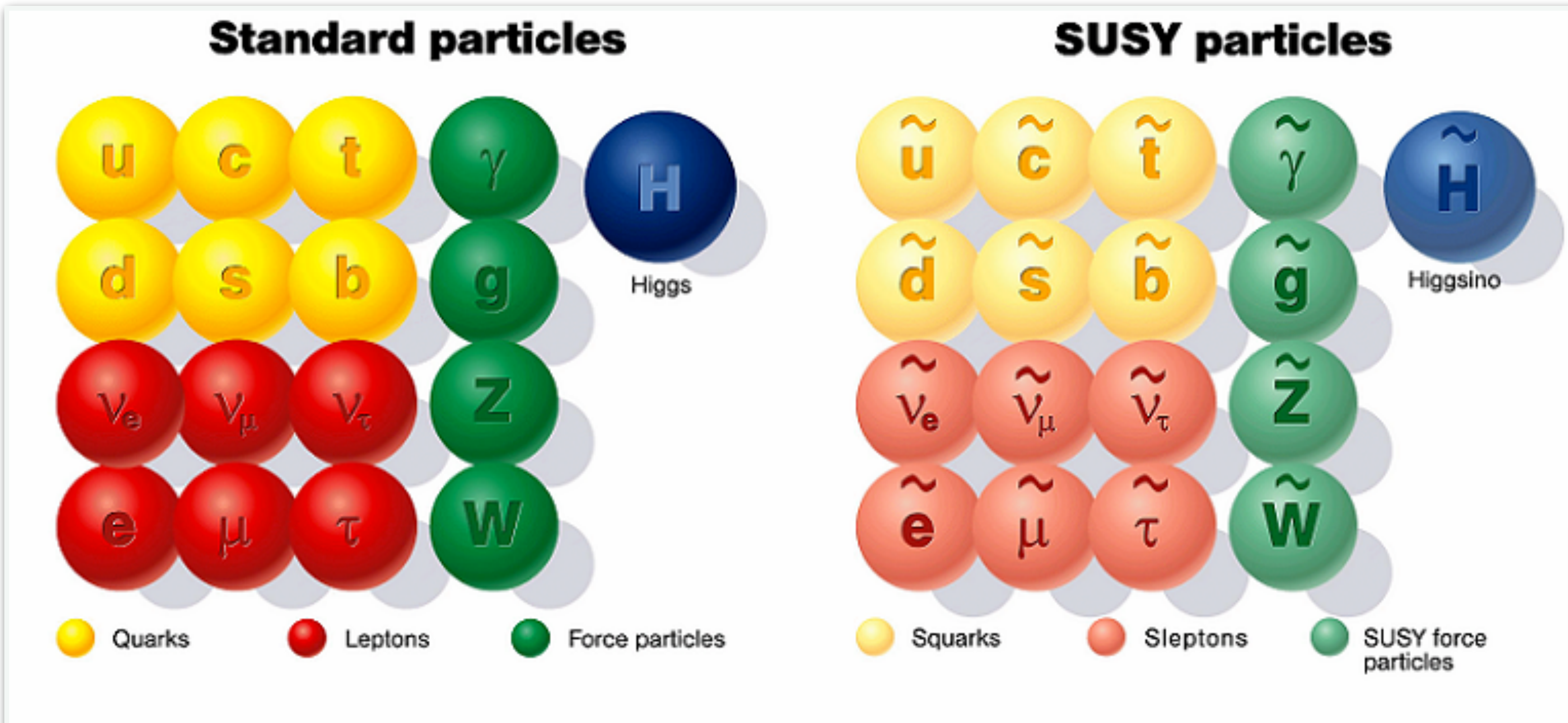
Thank you!



A drawing by
Bruno Touschek

Backup

Probing high-scale SUSY

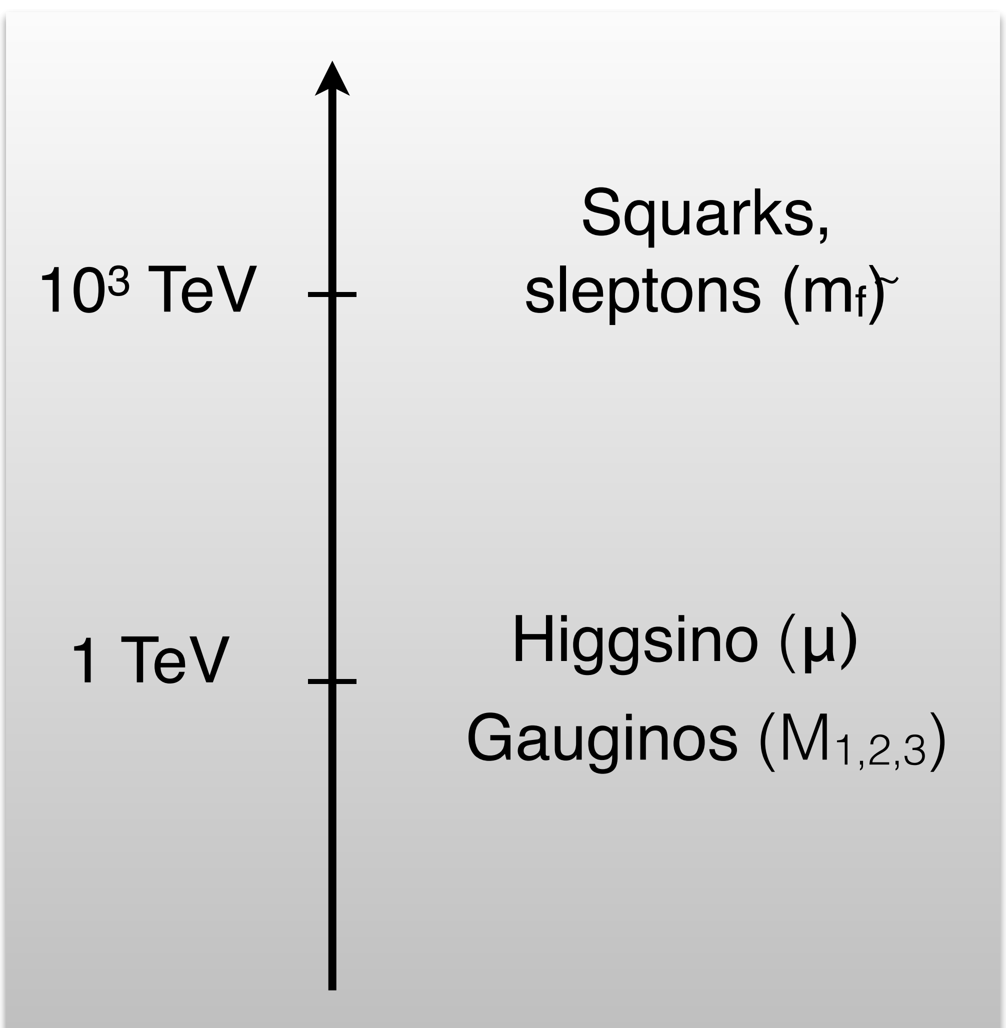


- Absence of direct signals and the observation of Higgs at 125 GeV put strong constraints on the spectrum of SUSY particles

Probing high-scale SUSY

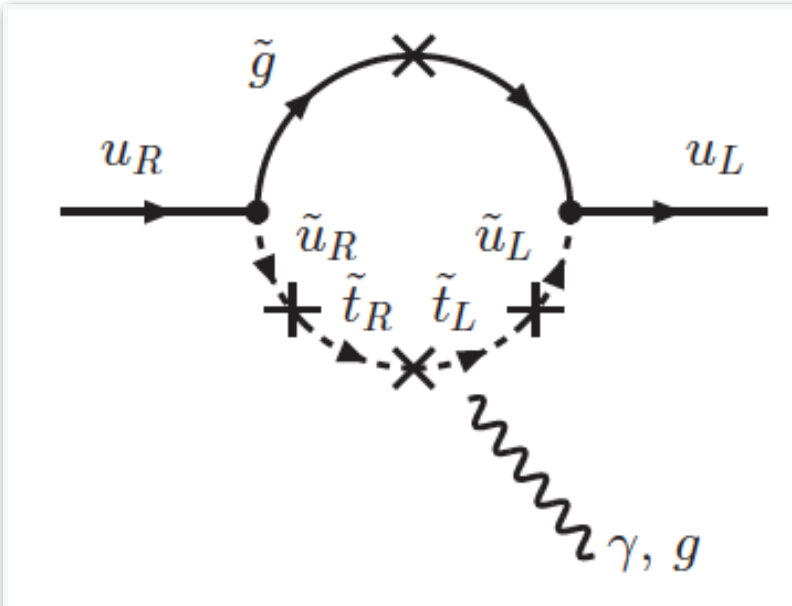
- Higgs mass at ~125 GeV points to PeV-scale super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

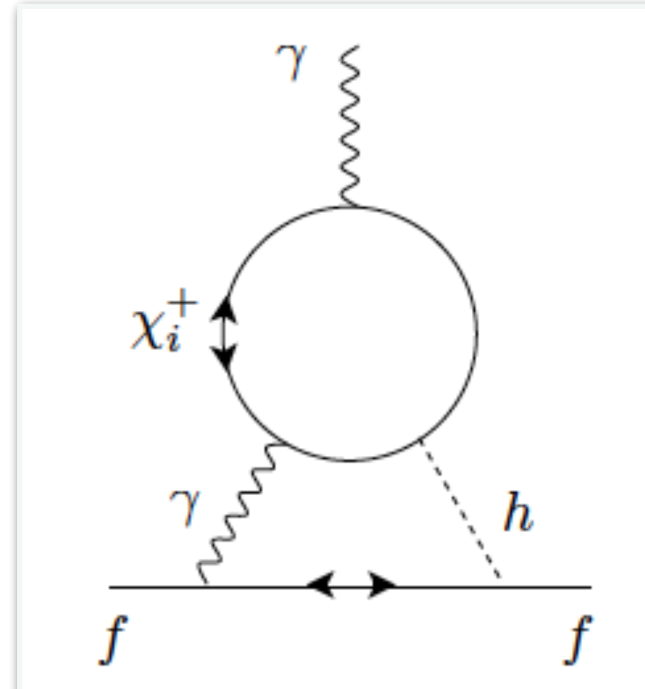
Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, …



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

EDMs in split SUSY (I)





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

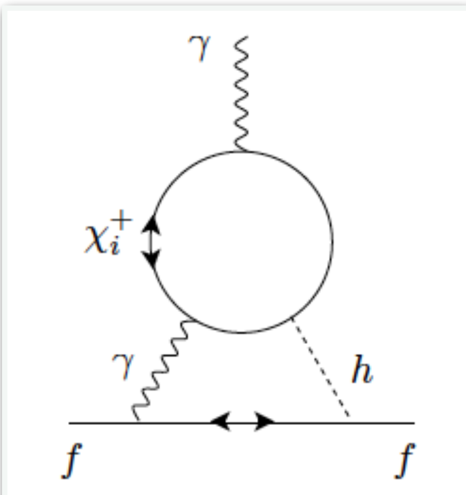
$$d_q \sim \frac{\alpha\,\alpha_w}{(4\pi)^2} \frac{m_q}{\mu M_2} \sin\phi_2$$

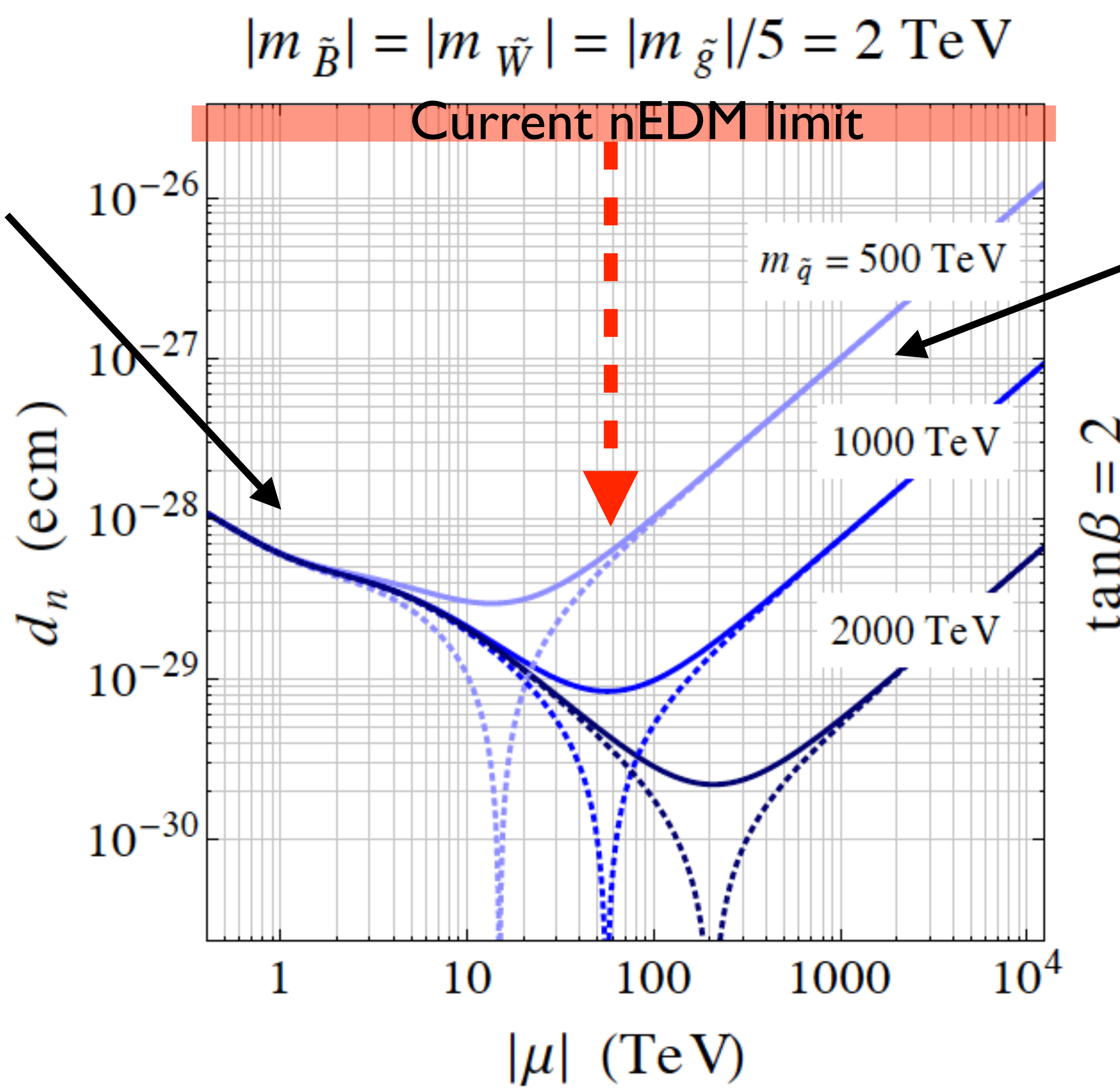
Quark EDMs and chromo-EDMs

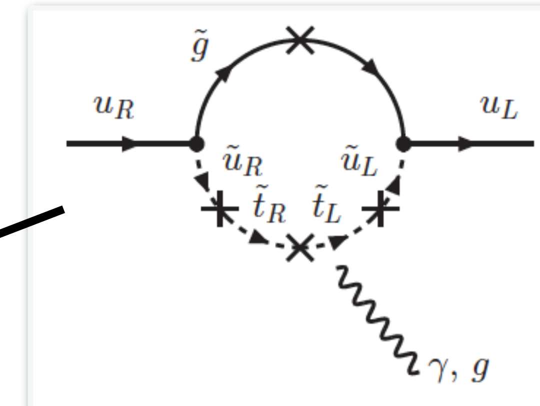
Only fermion EDMs

Relative importance controlled by Higgsino mass parameter |μ|

EDMs in split SUSY (1)







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Maximal CPV phases.
Squark mixings fixed at 0.3

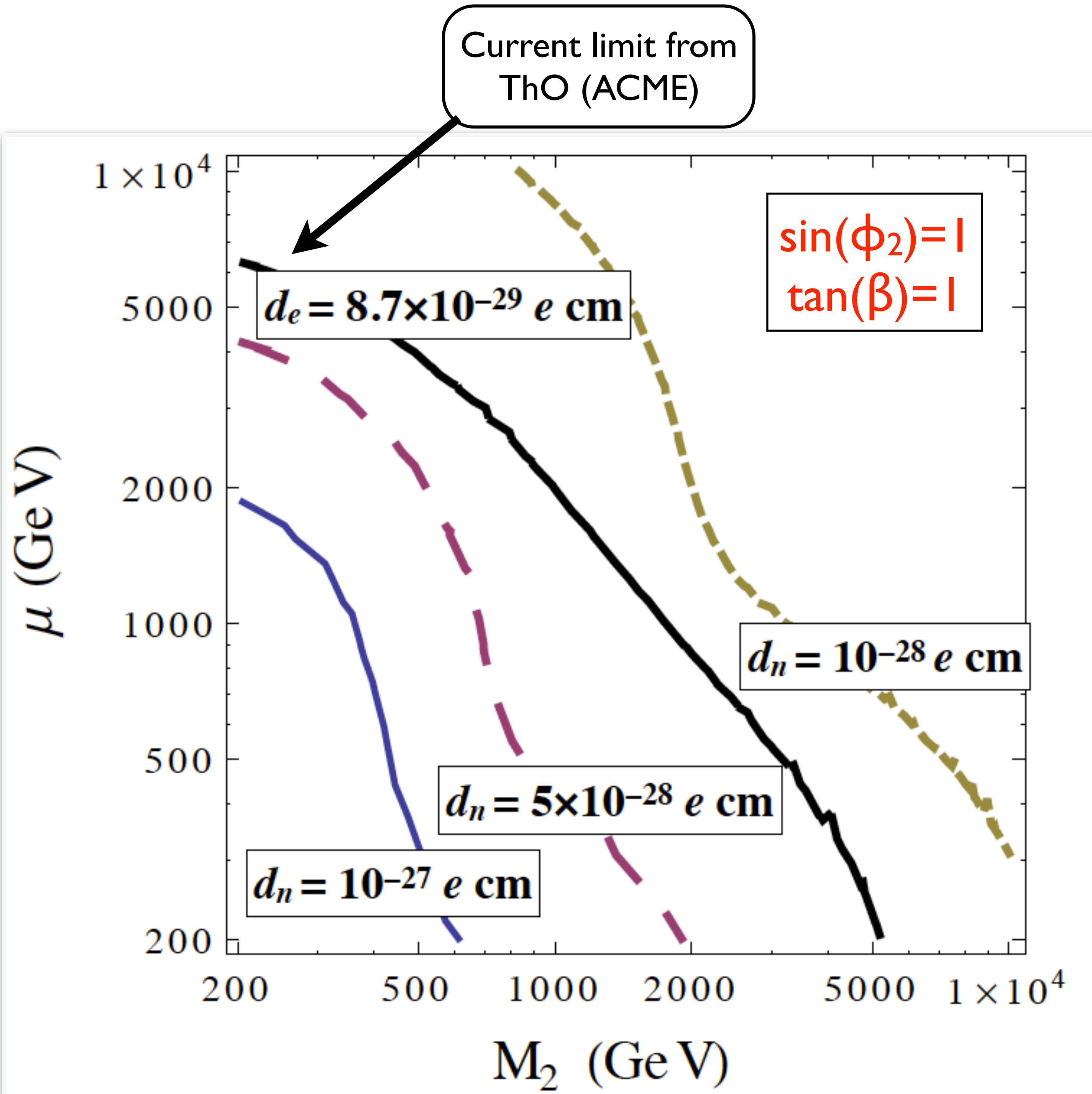
Altmannshofer-Harnik-Zupan
1308.3653

For $|\mu| < 10$ TeV, $m_{\tilde{q}} > 1000$ TeV, same CPV phase controls d_e, d_n .

Distinctive correlations?

EDMs in split SUSY (2)

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* → stringent upper bound $d_n < 4 \times 10^{-28}$ e cm

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

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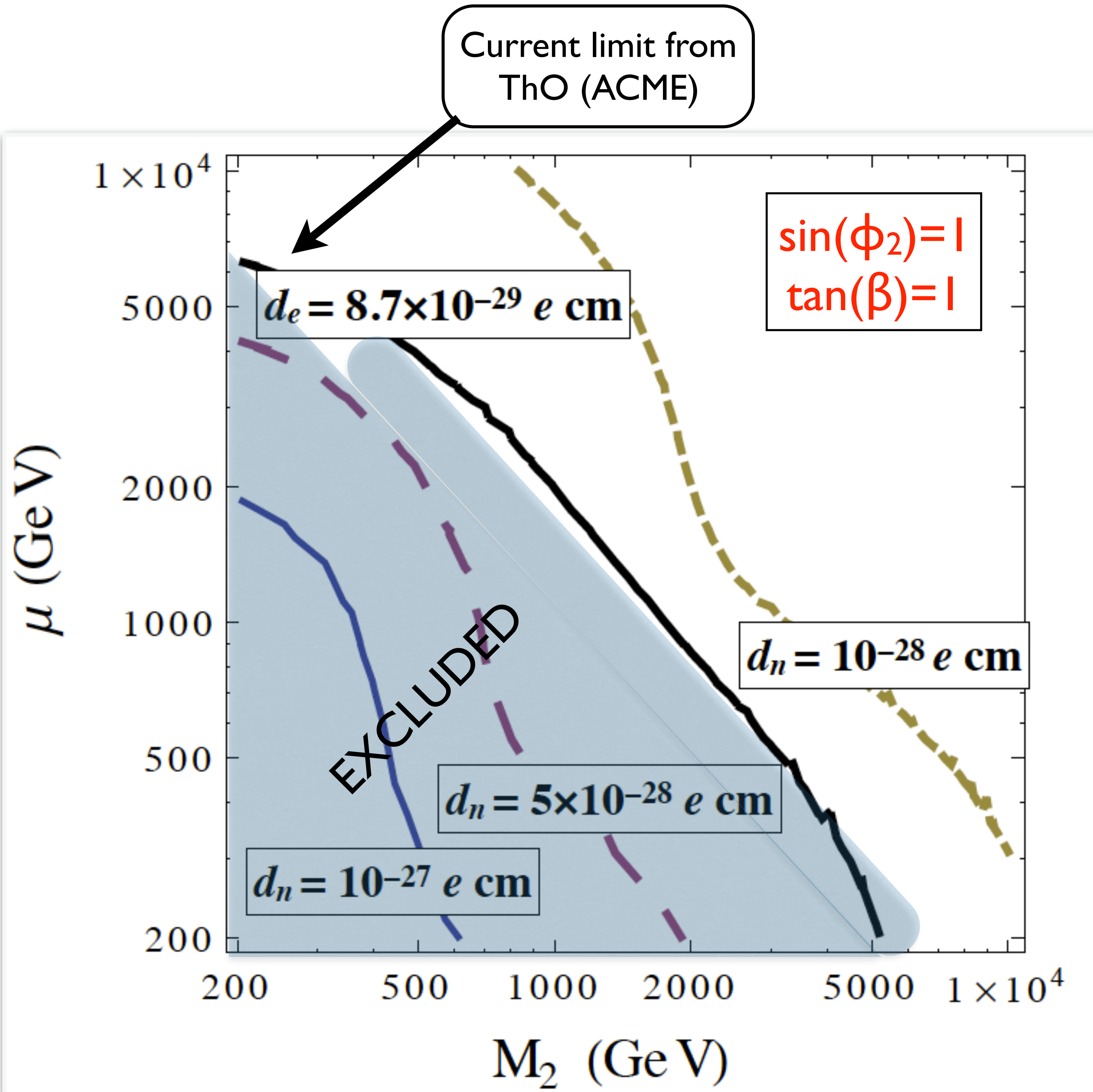

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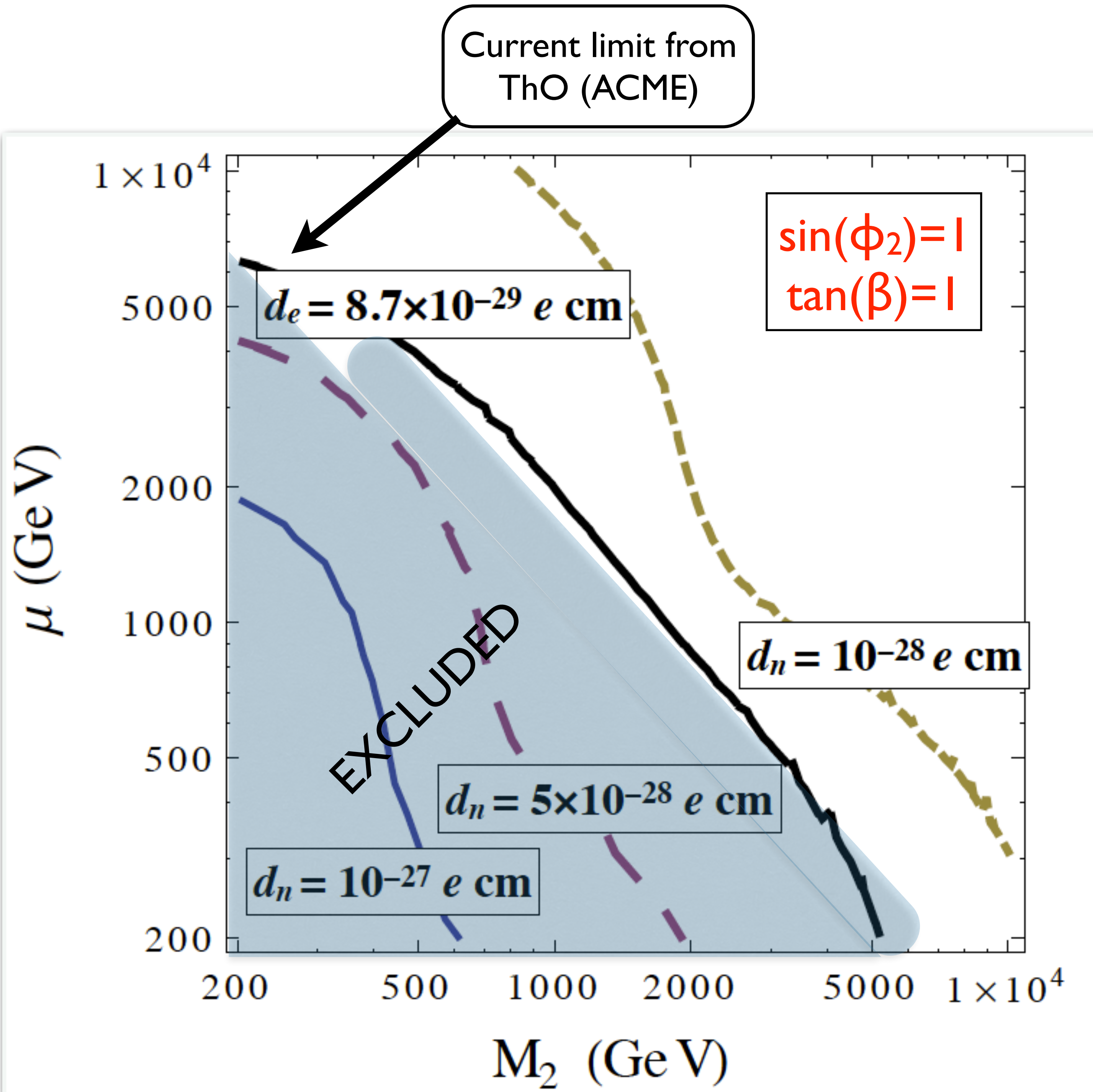


- Studying the ratio d_n / d_e *with precise matrix elements* → stringent upper bound $d_n < 4 \times 10^{-28}$ e cm
- Can be falsified by current nEDM searches
- Illustration of "improved matrix elements → enhanced model-discriminating power"

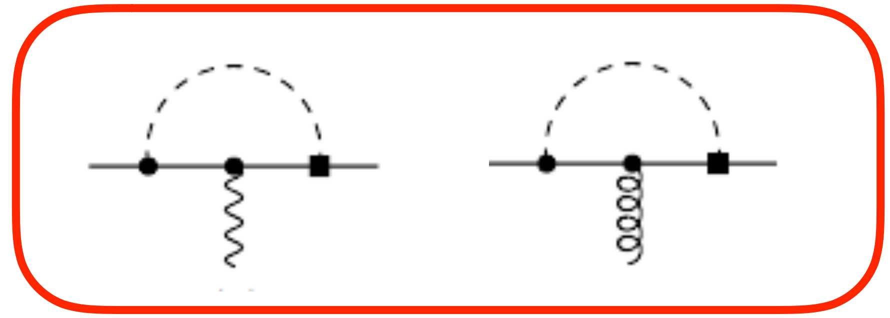
Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

Footprints of CPV Yukawas (C_Y)

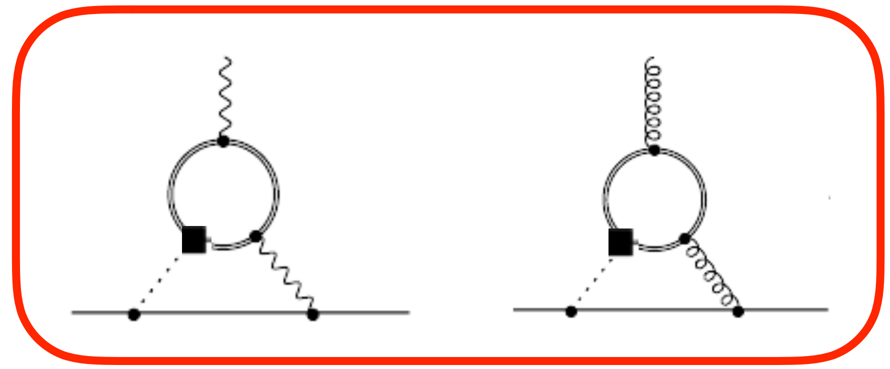
- No mixing, only finite terms

Weinberg 89, Dicus 90, Barr-Zee 90 …

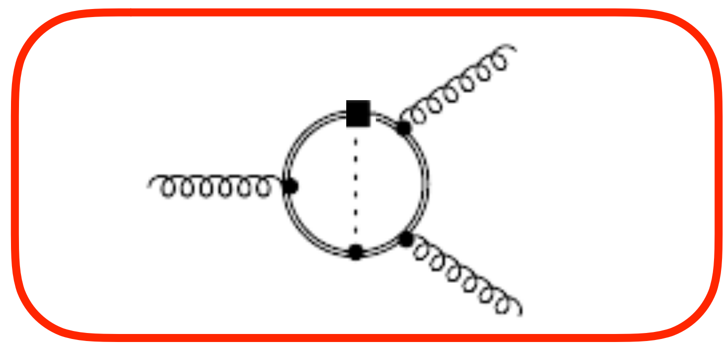
  - $C_Y \rightarrow C_\gamma$, C_g



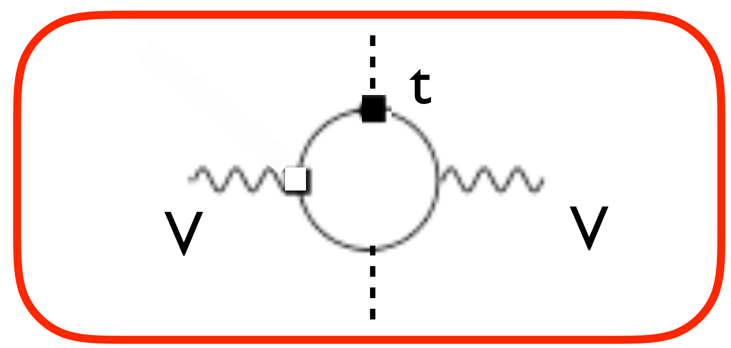
  - $C_Y \rightarrow C_g^{(u,d,s)}$, $C_\gamma^{(u,d,s,e)}$
    - Connects to *all* EDMs
    - Strongest constraint through eEDM



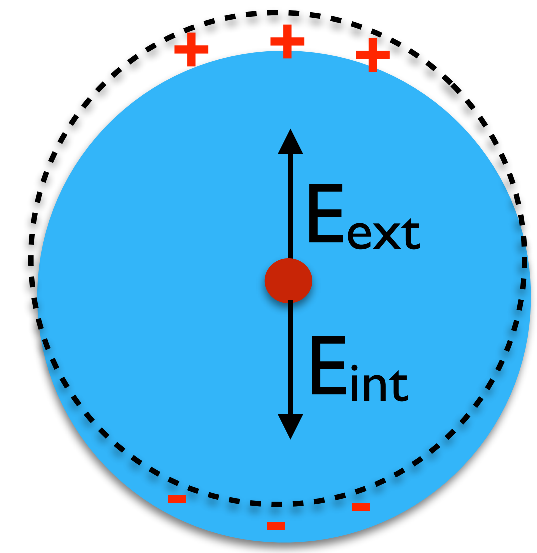
  - $C_Y \rightarrow C_{ggg}$
    - Connects to hadronic EDMs



  - $C_Y \rightarrow C_{VVhh}$, C_{gghh}
    - Connects to Higgs production / decay



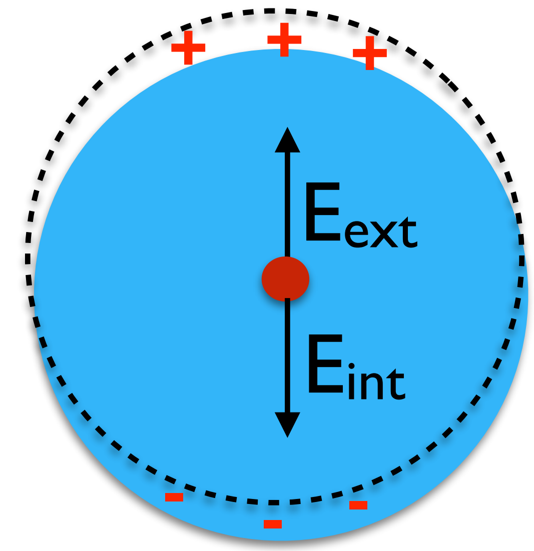
CPV at the atomic level



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

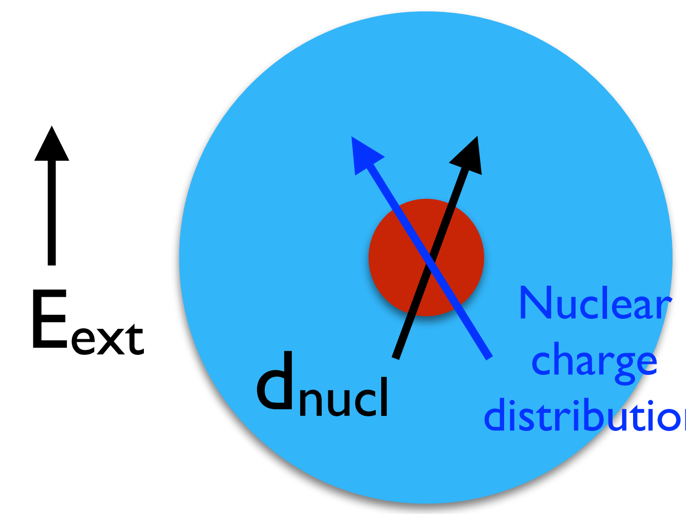
CPV at the atomic level

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



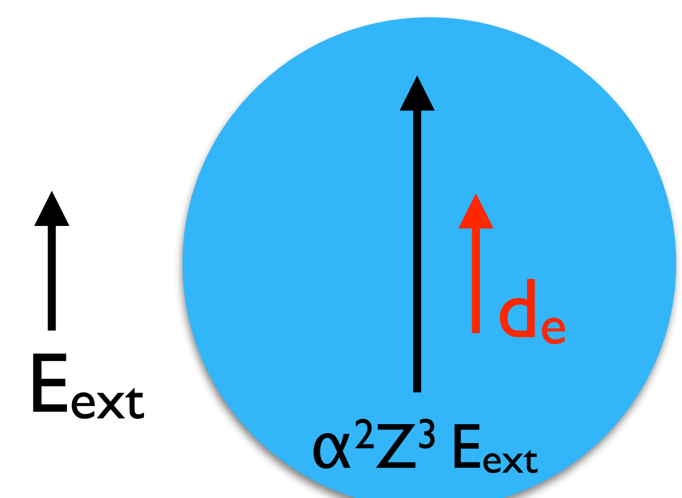
- Evading Schiff screening: finite size effects in diamagnetic atoms make $d_A[d_{nucl}] \neq 0$. Suppression $d_A \sim Z^2 \, (R_N/R_A)^2 \, d_{nucl}$

  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



Correlations in K decays

Uli Haisch,
S. Jaeger

- If Z-penguins dominate (MSSM, RS, ...)

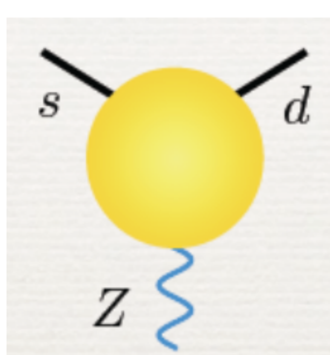
$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar{d}_L \gamma_\mu s_L Z^\mu + \widetilde{C}_{\rm NP}\, \bar{d}_R \gamma_\mu s_R Z^\mu$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im} X)^2,$$
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) \propto |X|^2,$$

$$X = X_{\rm SM} + \frac{1}{\lambda^5}\left(C_{\rm NP} + \widetilde{C}_{\rm NP}\right),$$

$$\frac{\varepsilon_K'}{\varepsilon_K} \propto -\mathrm{Im}\Big[\lambda_t\,(-1.4 + 13.8 R_6 - 6.6 R_8) + (1.5 + 0.1 R_6 - 13.3 R_8)\left(C_{\rm NP} - \widetilde{C}_{\rm NP}\right)\Big]$$

Impact on CP-violation in K→ ππ decays



$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \epsilon + \epsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \epsilon - 2\epsilon'$$

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1 - 6\,\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

Branching ratios in the SM

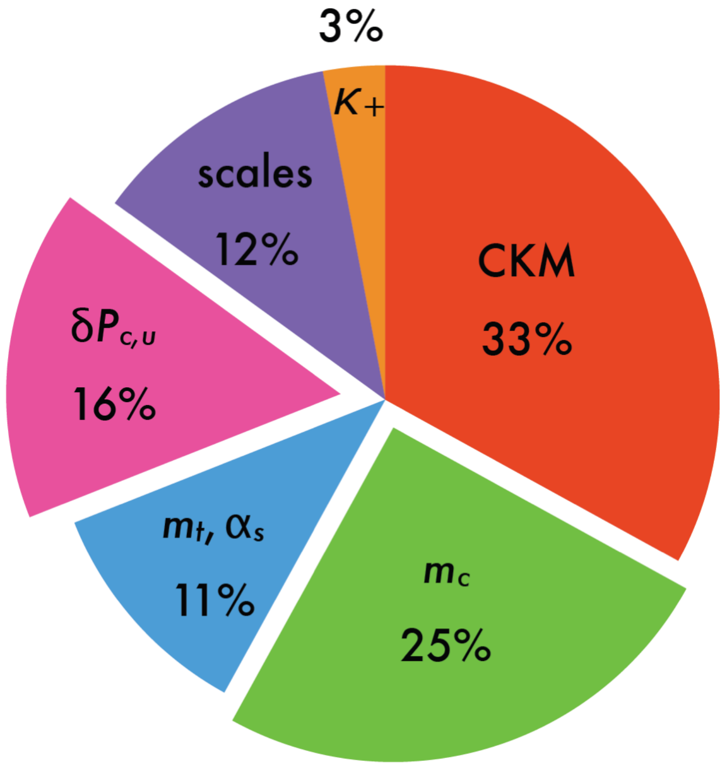
$$\lambda_c = V_{cs}^* V_{cd} \qquad \lambda_t = V_{ts}^* V_{td}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = \kappa_+ \left[\left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_{\rm SM} \right)^2 + \left(\frac{{\rm Re}\lambda_t}{\lambda^5} X_{\rm SM} + \frac{{\rm Re}\lambda_c}{\lambda} \left(P_c + \delta P_{c,u}\right) \right)^2 \right]$$

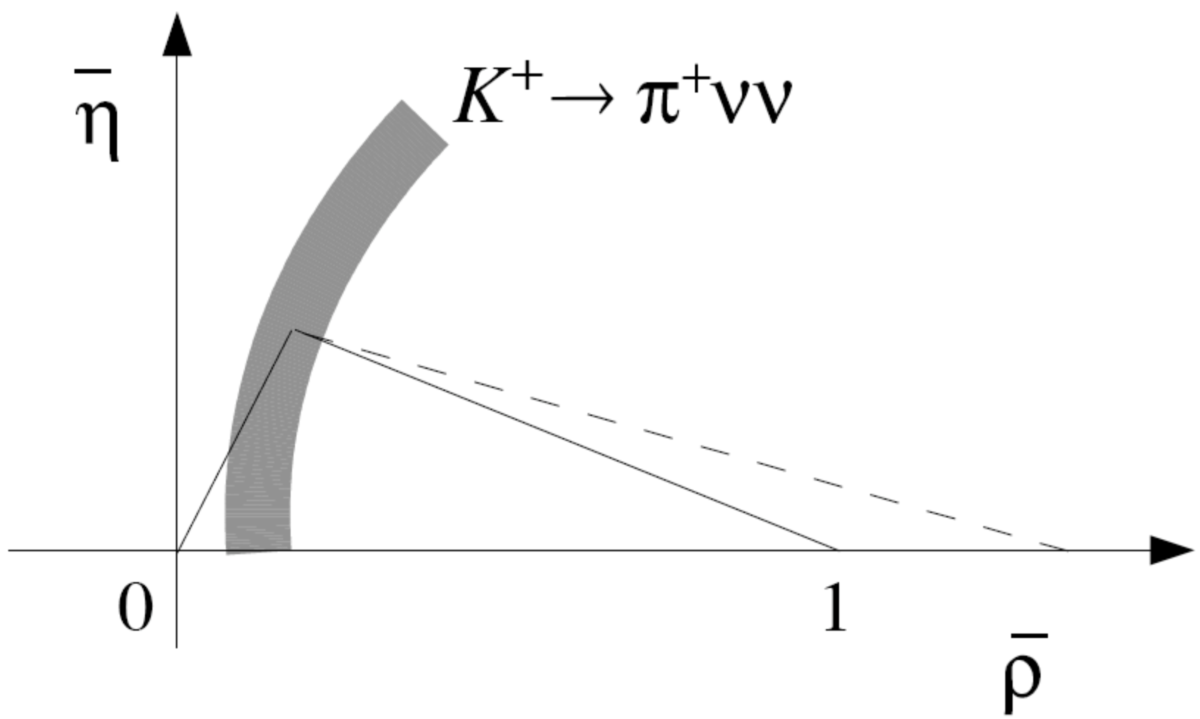
$$\downarrow$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \cdot 10^{-11}$$

12%, divided as follows



Haisch, KAON 07



- Neutral mode:

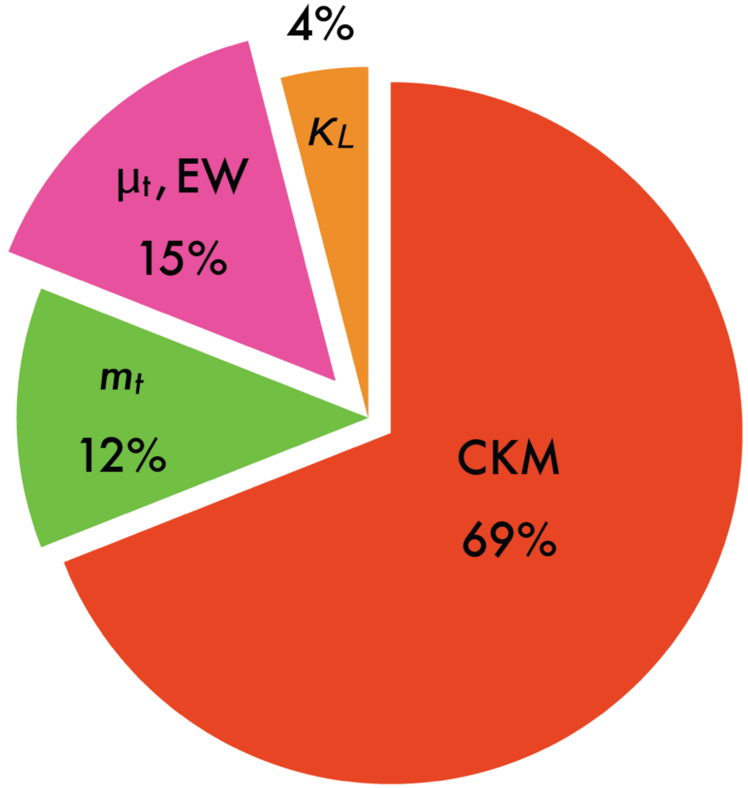
$$\lambda_t = V_{ts}^* V_{td}$$

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})_{\rm SM} = \kappa_L \left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_{\rm SM} \right)^2$$

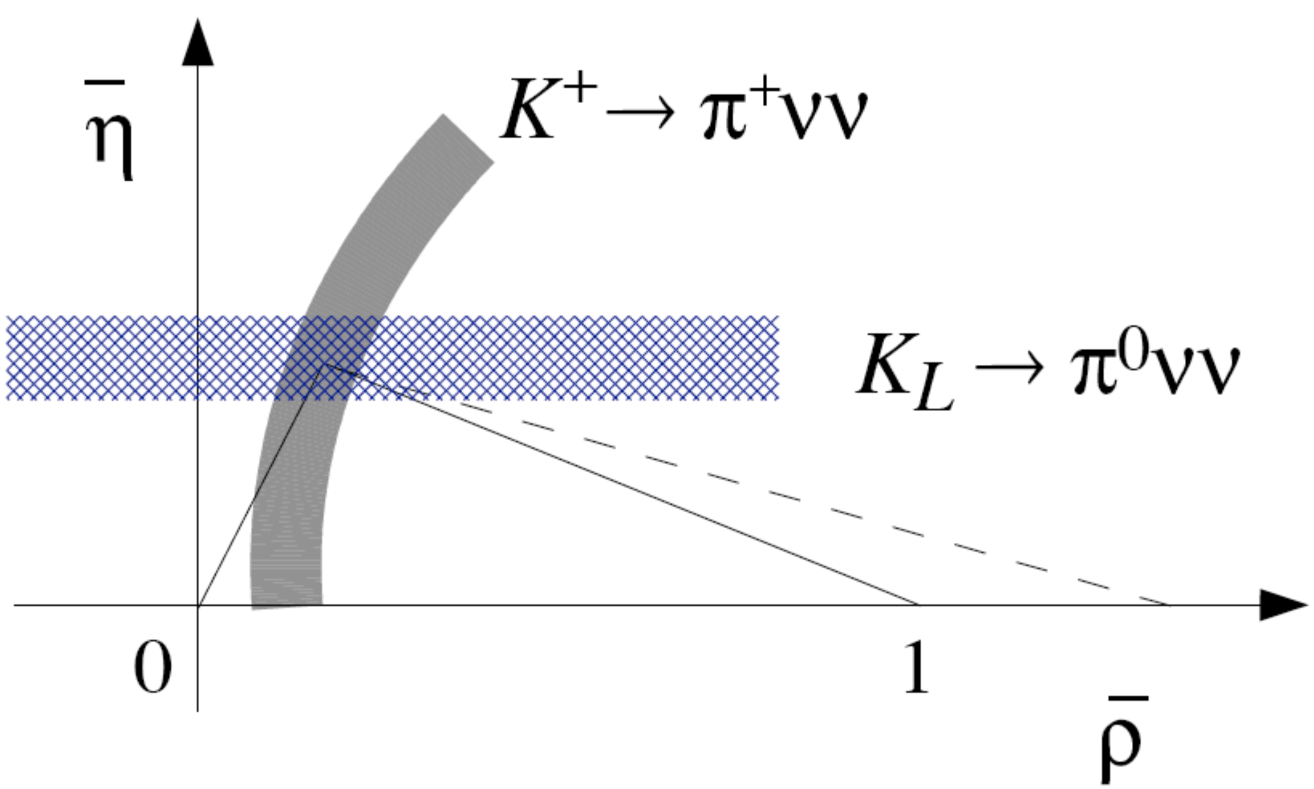
↓

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})_{\rm SM} = (2.7 \pm 0.4) \cdot 10^{-11}$$

<u>15%, divided as follows</u>

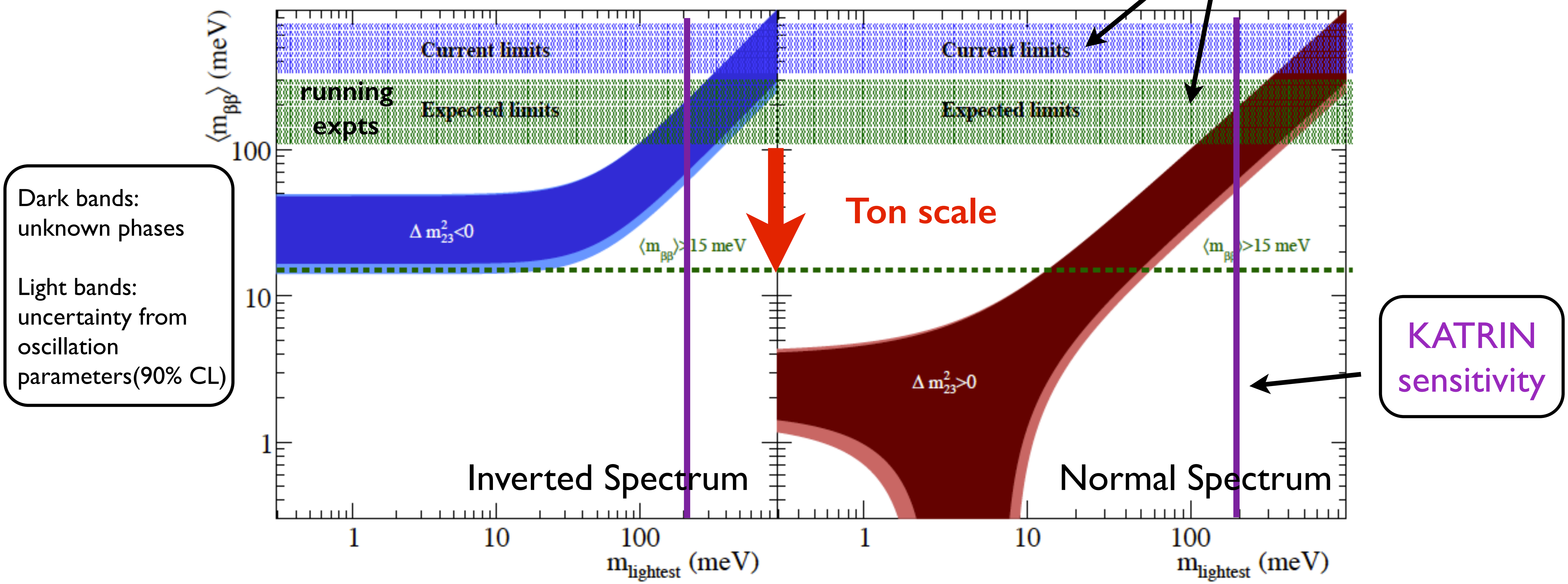


Haisch, KAON 07



- Benchmark sensitivity for standard mechanism

Assume most "pessimistic" values for nuclear matrix elements



Complementary probes:

In the next 5-10 years, expect input on mass ordering (oscillations) and absolute scale from tritium beta decay (<u>m_β: 2 → 0.2 eV</u>) and cosmology (within ΛCDM <u>$\Sigma_i m_i$: 230 → ~50 meV</u>). Combination of probes will:

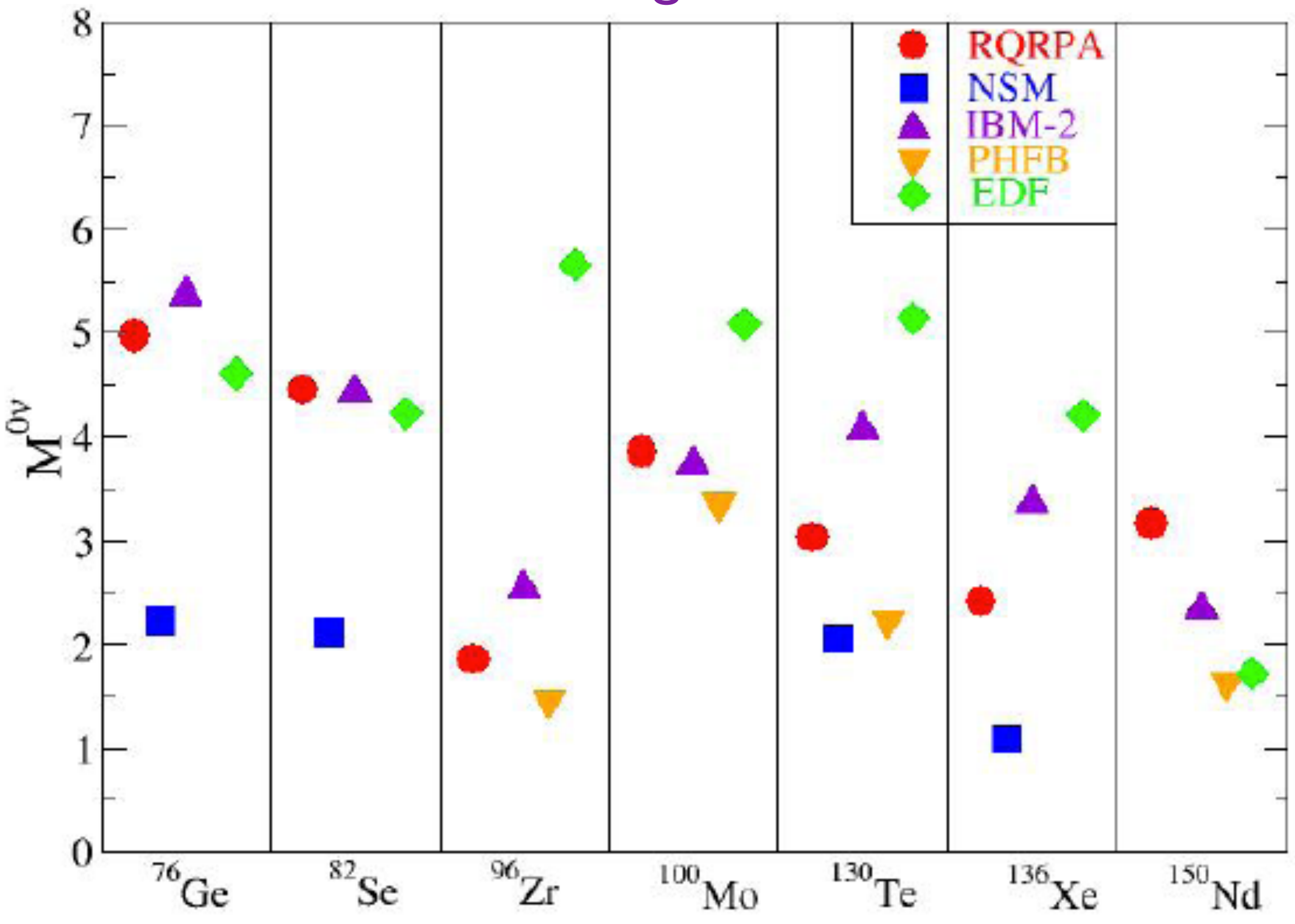
- Contribute to the interpretation of positive or null NLDBD results
- Expose potential new physics (e.g., is "ΛCDM + m_ν" the full story?)

0νββ and nuclear structure

- Connecting experimental rates to parameters of LNV interactions ($m_{\beta\beta}$, ...) requires mechanism-dependent nuclear matrix elements

- Available model results differ by factors of 2-3
- Discovery goals set by taking "pessimistic" matrix elements
- Improvement is highly desirable: the matrix elements are essential for interpretation

P. Vogel 2014



Matrix elements for "standard mechanism"