National Nuclear Physics Summer School
MIT, Cambridge, MA
July 18-29 2016

Fundamental Symmetries - 3

Vincenzo Cirigliano
Los Alamos National Laboratory

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EST. 1943

Flow of the lectures

- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries

1.5 lectures

- Beyond the SM: an effective theory perspective and overview
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (PVES); muon g-2, ..
  - Symmetry tests: CP (T) violation and EDMs; Lepton Flavor and Lepton Number violation

1.5 lectures

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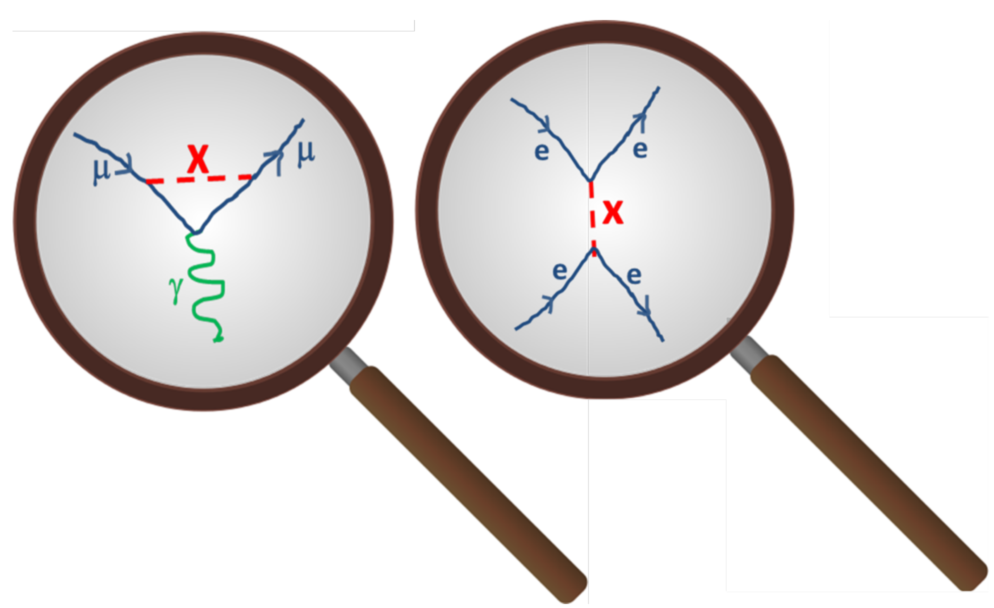
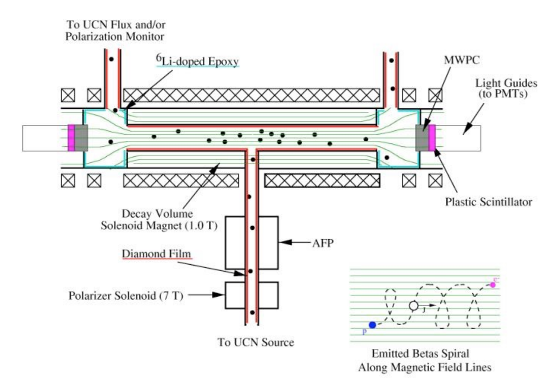
1.5 lectures

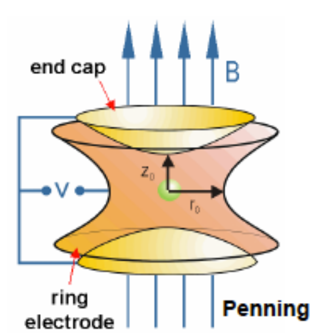
Today

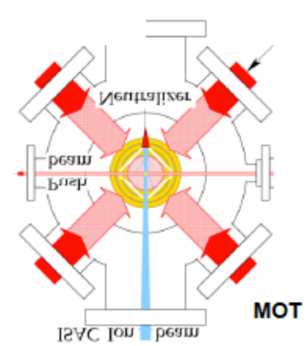
Precision measurements as probes of new physics

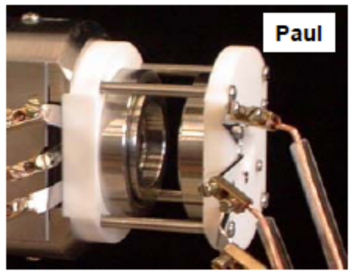


Charged Current (continued)









Summary of low energy constraints

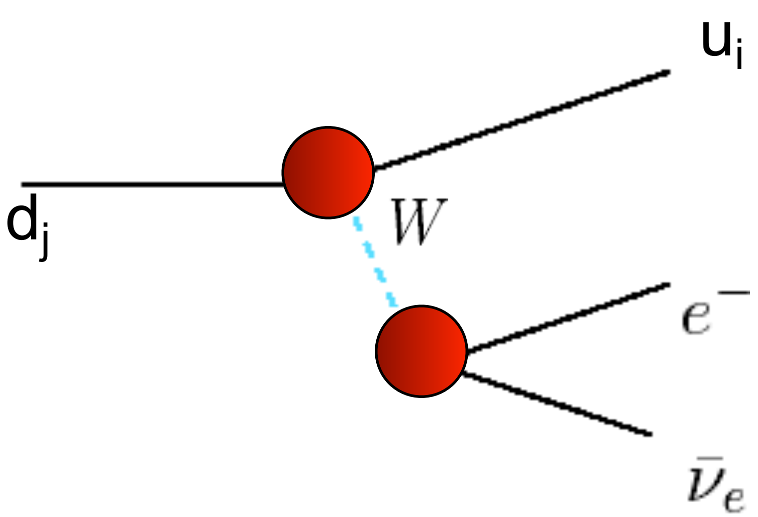
- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)
- Focus on probes that depend on the ε's *linearly*

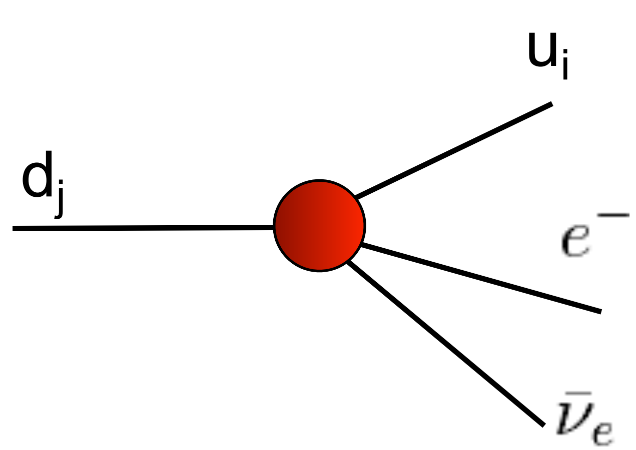
$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \ldots}$$

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	$\Delta_{\rm CKM}$	$\sim 0.05\%$	$< 0.05\%$ *
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$	
$\epsilon_P, \quad \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$	$\sim 0.05\%$	
$\mathrm{Re}(\epsilon_S)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}]$	$\sim 0.5\%$	$< 0.3\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$	
$\mathrm{Re}(\epsilon_T)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}], \quad \pi \to e\nu\gamma$	$\sim 0.1\%$	$< 0.03\%$
$\mathrm{Im}(\epsilon_T)$	$R_{^8Li}$	$\sim 0.2\%$	$\sim 0.05\%$
$\tilde{\epsilon}_{\alpha \neq P}$	a, b, B, A	$\sim 5 - 10\%$	

High energy constraints

- The new physics that contributes to ε_α affects other observables!
- Relative strength of constraints depends on the specific model
- Model-independent statements possible in "heavy BSM" limit: M_{BSM} > TeV → new physics looks point-like at the weak scale





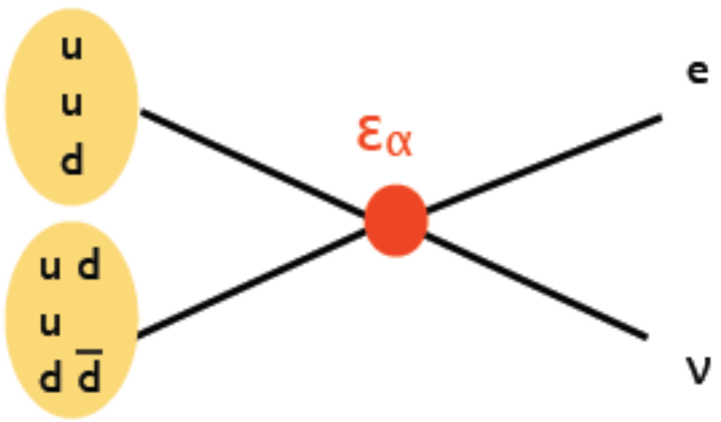
Vertex corrections strongly constrained by Z-pole observables (Δ_{CKM} is at the same level)

Four-fermion interactions "poorly" constrained: σ_{had} at LEP would allow Δ_{CKM} ~0.01 and non V-A structures at ε_i ~ 5%. What about LHC?

VC, Gonzalez-Alonso, Jenkins 0908.1754

LHC constraints

- Heavy BSM limit: all ϵ_α couplings contribute to the process
  $p\,p \to e\,\nu + X$



T. Bhattacharya, VC, et al, 1110.6448

VC, Gonzalez-Alonso, Graesser, 1210.4553

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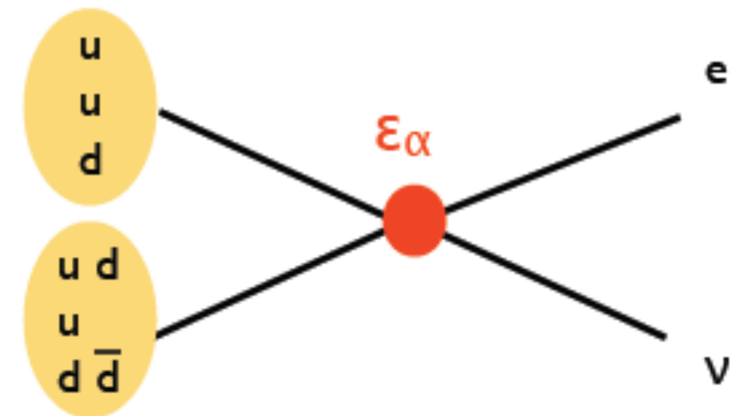
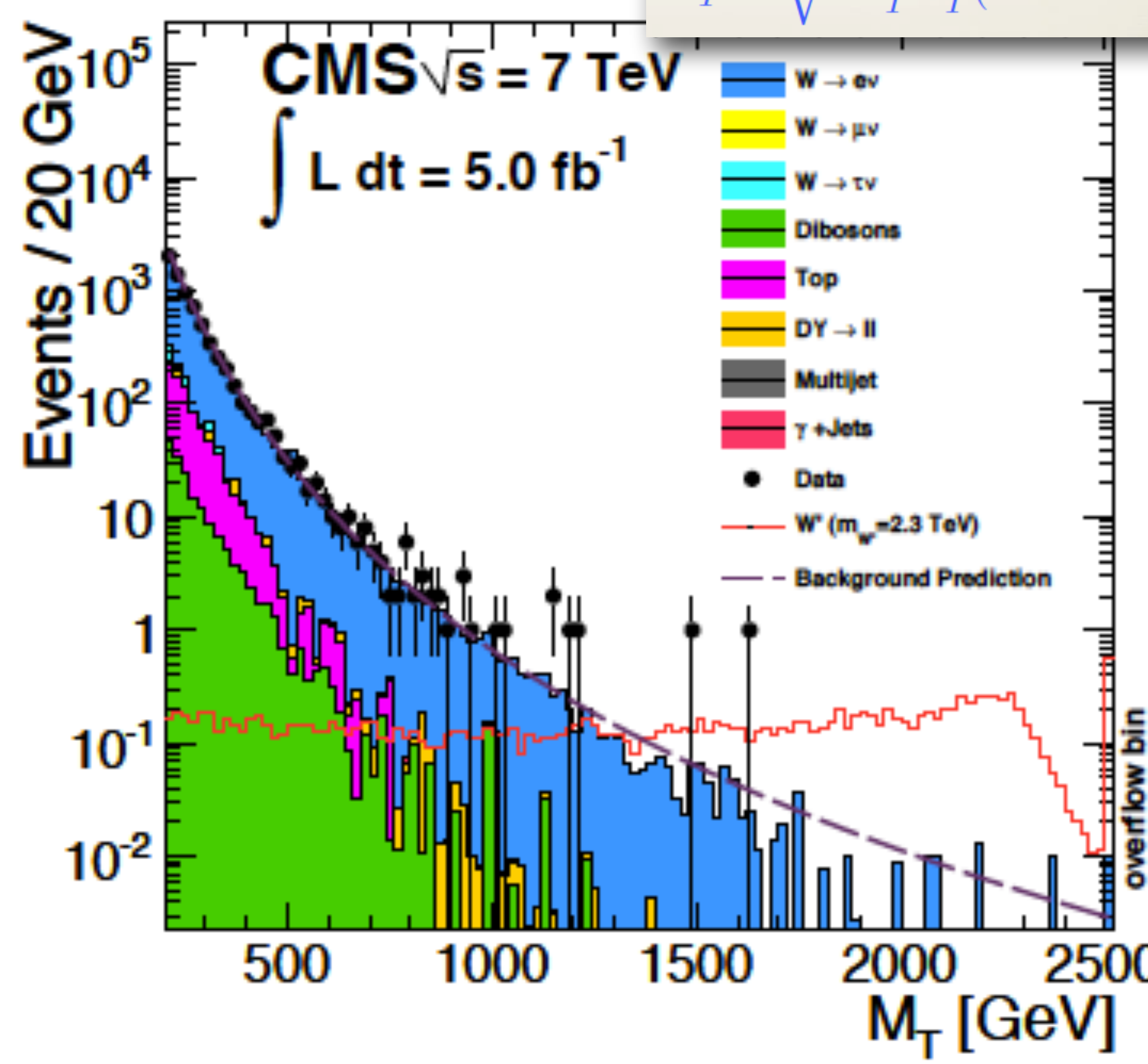


$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$



- No excess events at high m_T
  $\Rightarrow$ bounds on ε_α

- Current bounds at the level of 0.3%-1%, depending on the operator

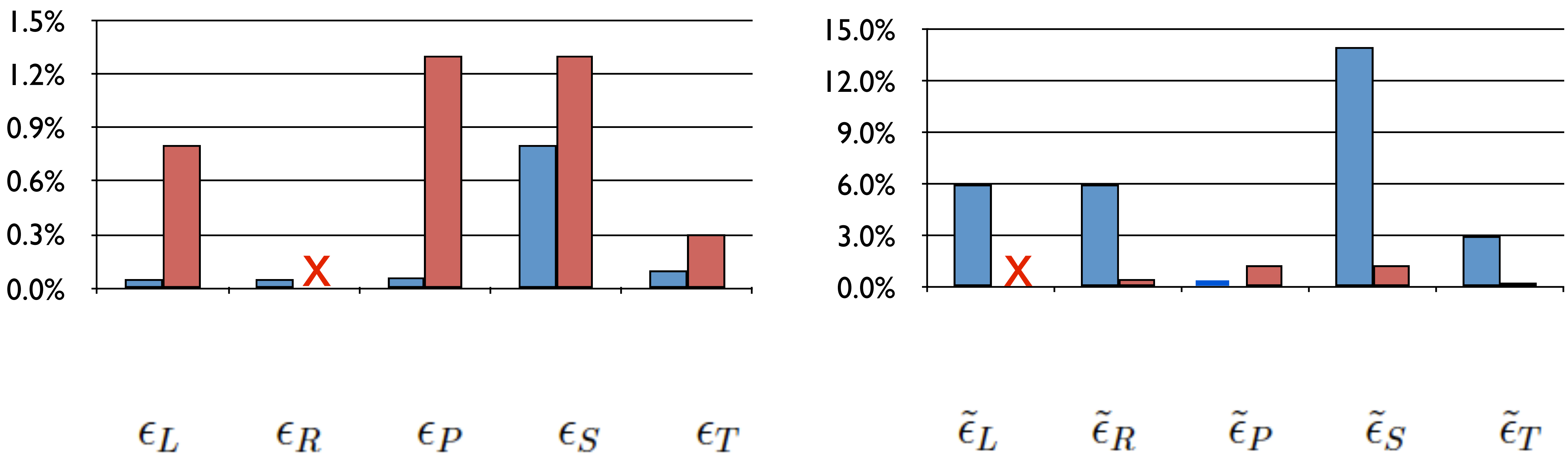
T. Bhattacharya, VC, et al, 1110.6448
VC, Gonzalez-Alonso, Graesser, 1210.4553

β decays vs LHC reach

LHC:
$\sqrt{s}$ = 7 TeV
L = 5 fb^{-1}

β decays | LHC

All ε's in $\overline{\text{MS}}$ @ μ = 2 GeV



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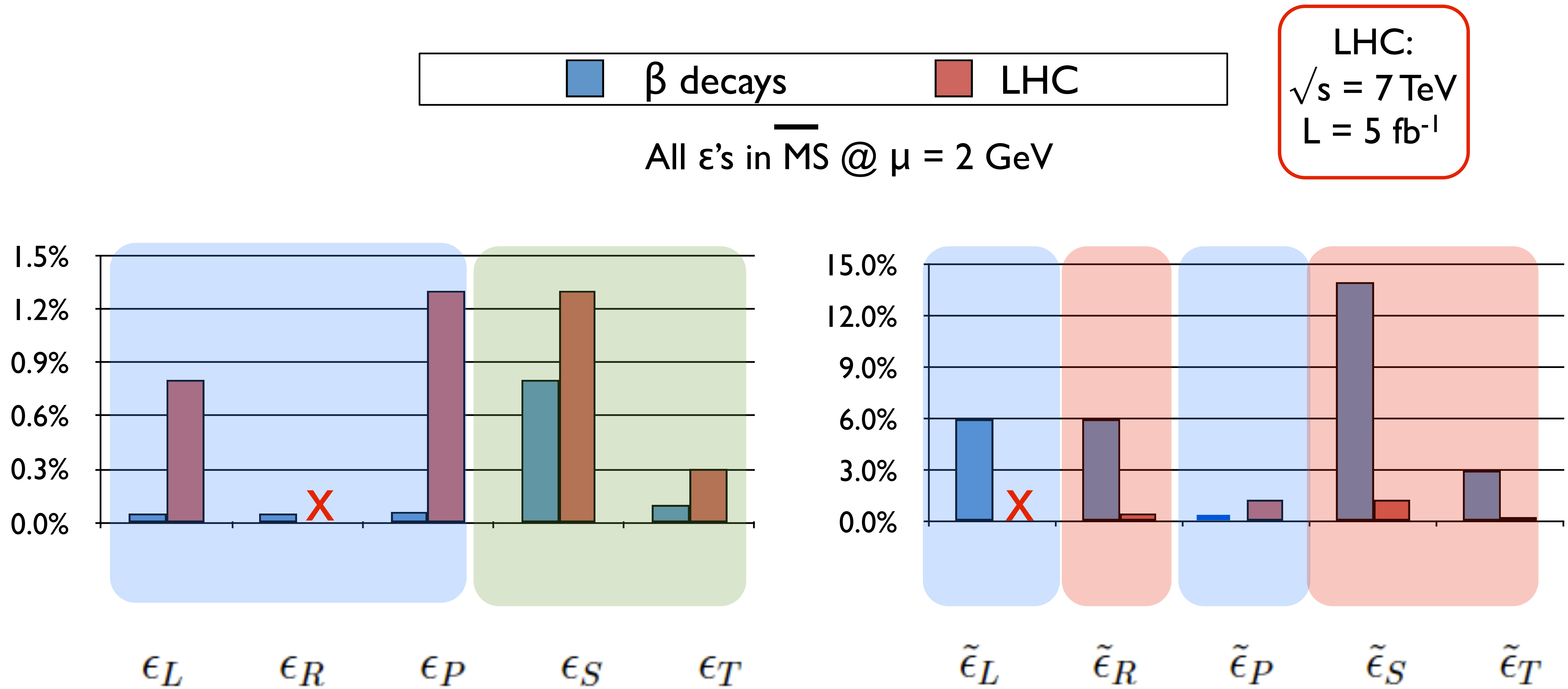
β decays vs LHC reach



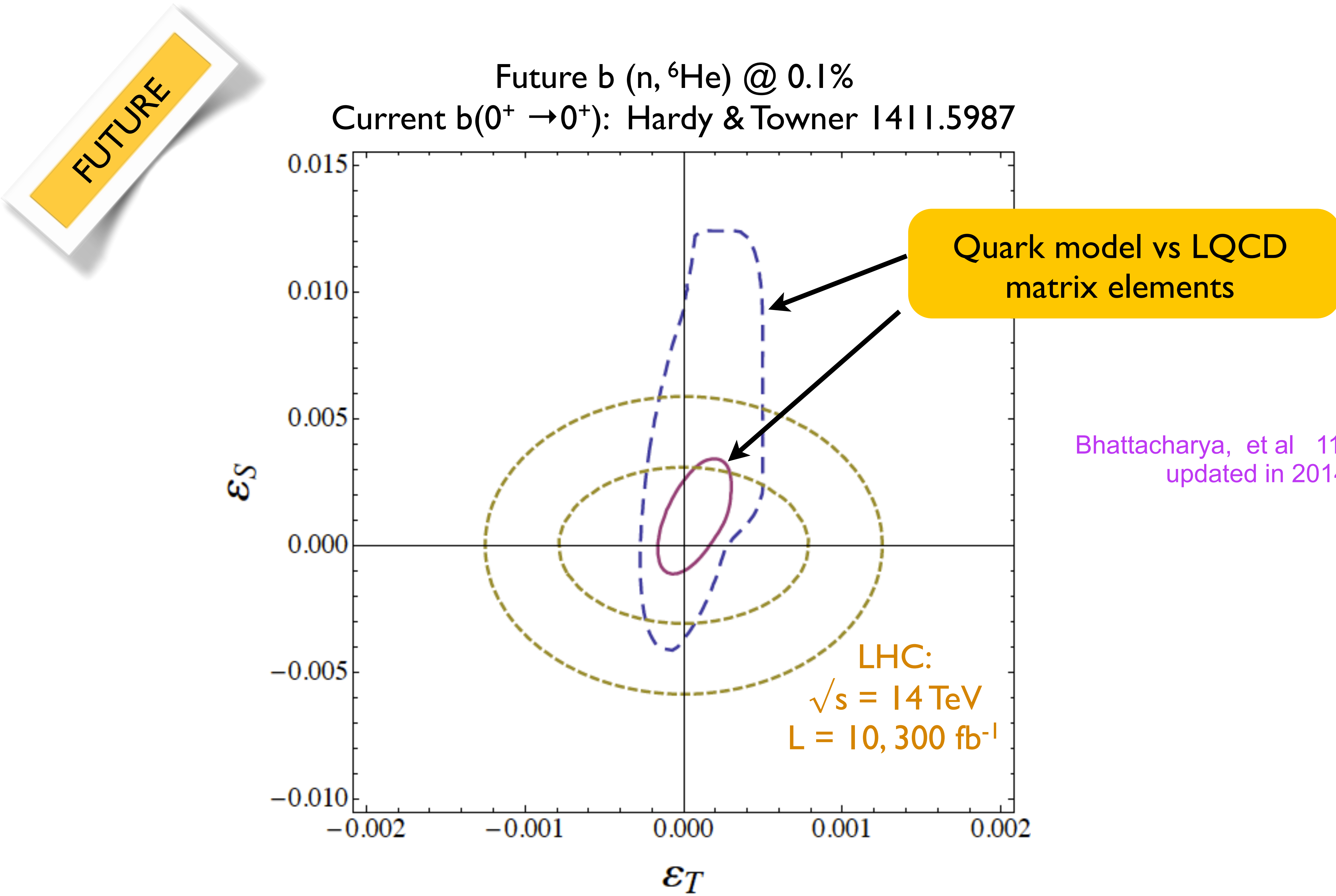
Unmatched low-energy sensitivity and future reach

LHC limits close to low-energy. Interesting interplay in the future

LHC reach already stronger than low-energy

VC, Gonzalez-Alonso, Graesser, 1210.4553

- Scalar and tensor operators: β-decays can probe deeper than the LHC!



Bhattacharya, et al 1110.6448, updated in 2014

Connection to models

- A given model → set overall size and pattern of ε_α couplings
- Beta decays can play very useful diagnosing role. Qualitative picture:

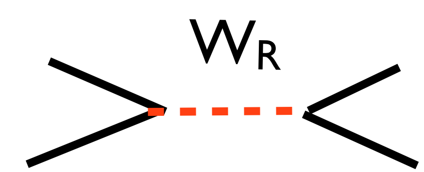
	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓

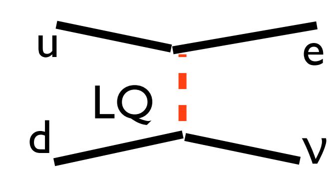
YOUR FAVORITE MODEL ... ...

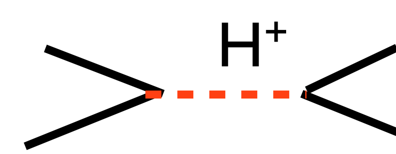
Can be made quantitative

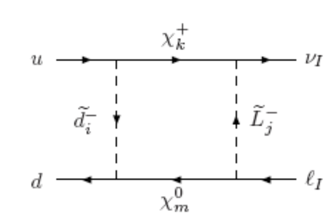
Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035

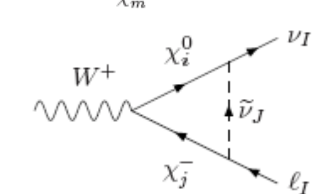
Profumo, Ramsey-Musolf, Tulin hep-ph/0608064







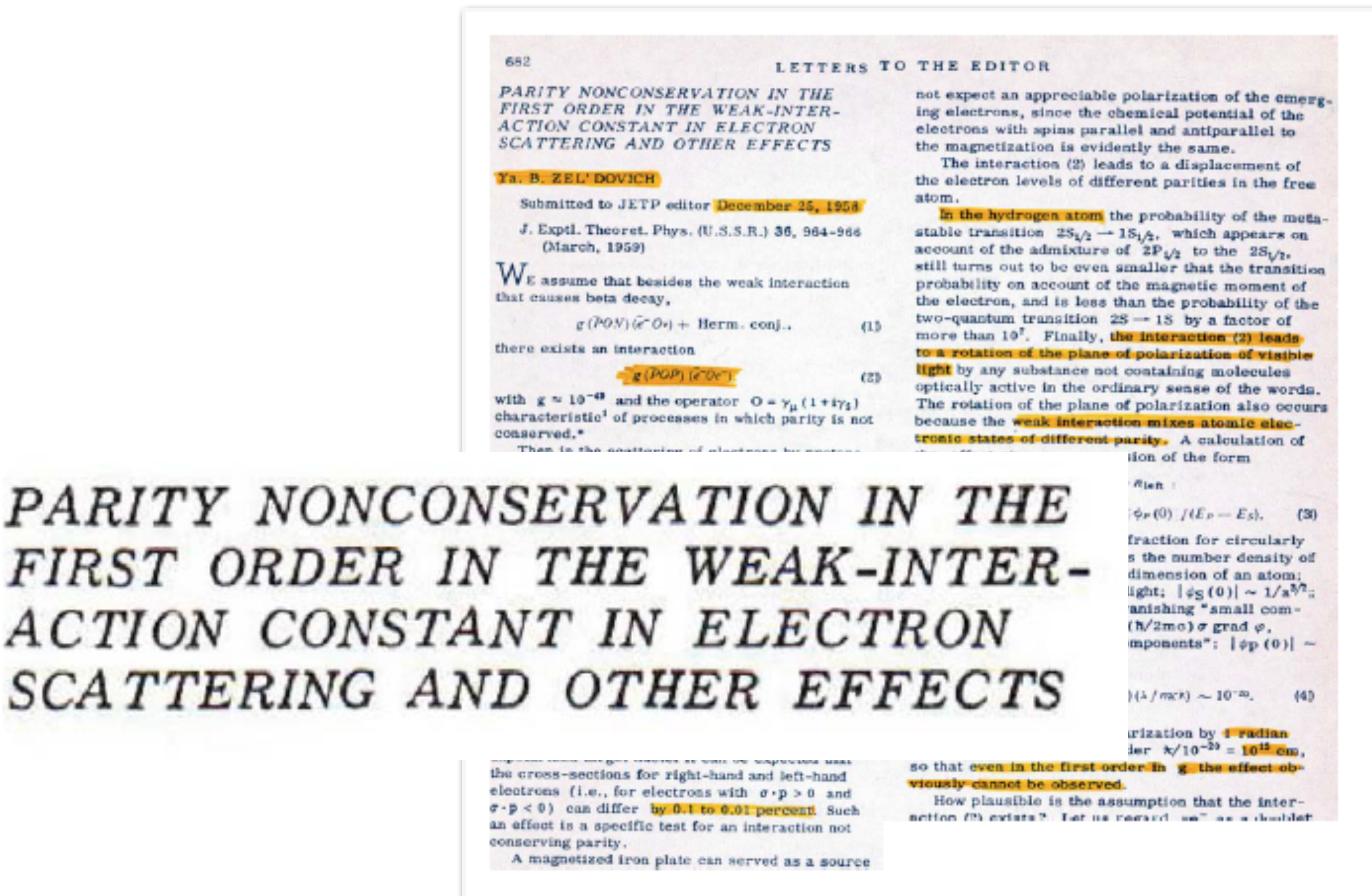




Neutral Current

Neutral analogue of V-A CC interaction?

- Speculation by Zel'dovic before the incorporation within the SU(2)xU(1) model of electroweak interactions



682 LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL'DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964-966 (March, 1959)

We assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.}, \quad (1)$$

there exists an interaction

$$g(\bar{P}OP)(\bar{e}^- Oe^-) \quad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

...

the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

A magnetized iron plate can served as a source

...

not expect an appreciable polarization of the emerging electrons, since the chemical potential of the electrons with spins parallel and antiparallel to the magnetization is evidently the same.

The interaction (2) leads to a displacement of the electron levels of different parities in the free atom.

In the hydrogen atom the probability of the metastable transition $2S_{1/2} \to 1S_{1/2}$, which appears on account of the admixture of $2P_{1/2}$ to the $2S_{1/2}$, still turns out to be even smaller that the transition probability on account of the magnetic moment of the electron, and is less than the probability of the two-quantum transition $2S \to 1S$ by a factor of more than 10^7. Finally, the interaction (2) leads to a rotation of the plane of polarization of visible light by any substance not containing molecules optically active in the ordinary sense of the words. The rotation of the plane of polarization also occurs because the weak interaction mixes atomic electronic states of different parity. A calculation of ... ion of the form

... $\psi_P(0) / (E_P - E_S)$. (3)

... fraction for circularly ... s the number density of ... dimension of an atom; ... light; $|\psi_S(0)| \sim 1/a^{3/2}$; ... anishing "small com- ... $(\hbar/2mc)\sigma$ grad φ, ... mponents": $|\psi_P(0)| \sim$

... $(\hbar/mc)$ ... $\sim 10^{-20}$. (4)

... rization by 1 radian ... der $\lambda/10^{-20} = 10^{15}$ cm, so that even in the first order in g the effect obviously cannot be observed.

How plausible is the assumption that the inter- action (2) exists? Let us regard ...

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

1958

↓

Discovery of neutral currents in $\nu_\mu e \to \nu_\mu e$ would be made in 1973

Krishna Kumar

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

WE assume that besides the weak interaction that causes beta decay,

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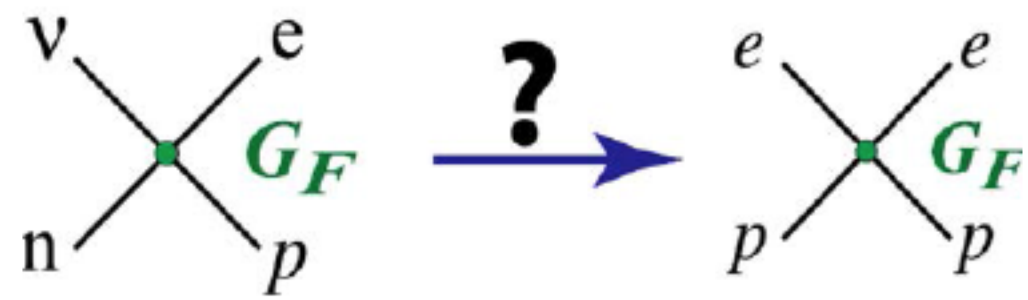
Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot \mathbf{p} > 0$ and $\sigma \cdot \mathbf{p} < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.



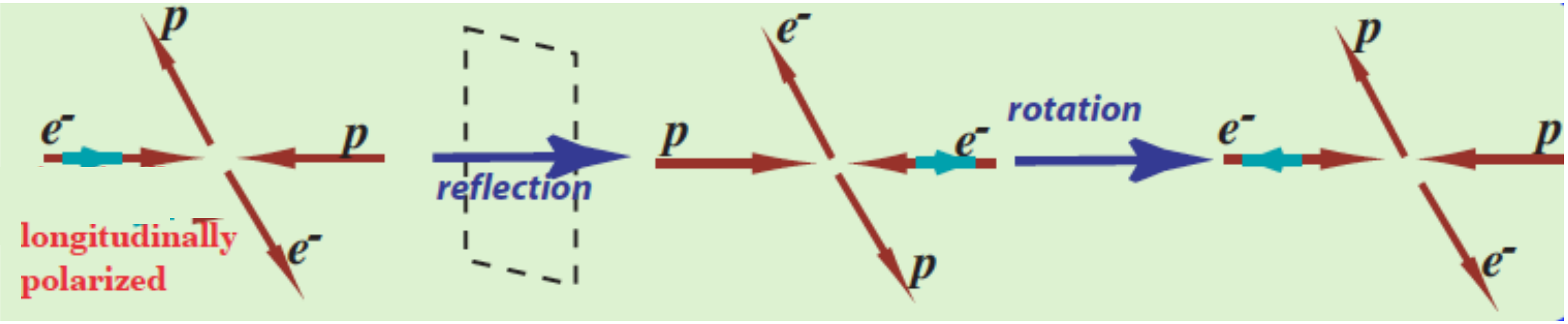
$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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

Parity violating

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

- A_{PV} violates parity:



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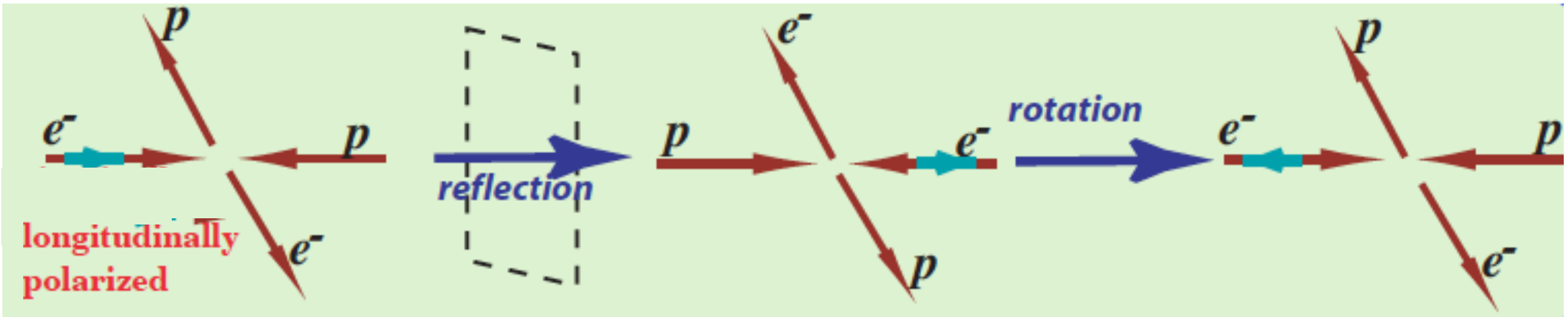
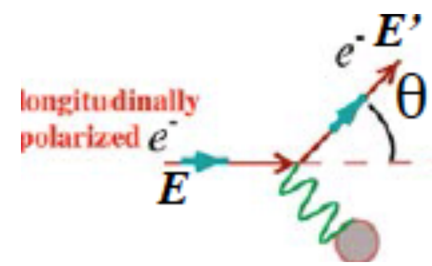
- A_{PV} violates parity:



- Expected size of the effect:

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity non-conservation effects can be of the order of 0.1 to 0.01 percent.



4-momentum transfer

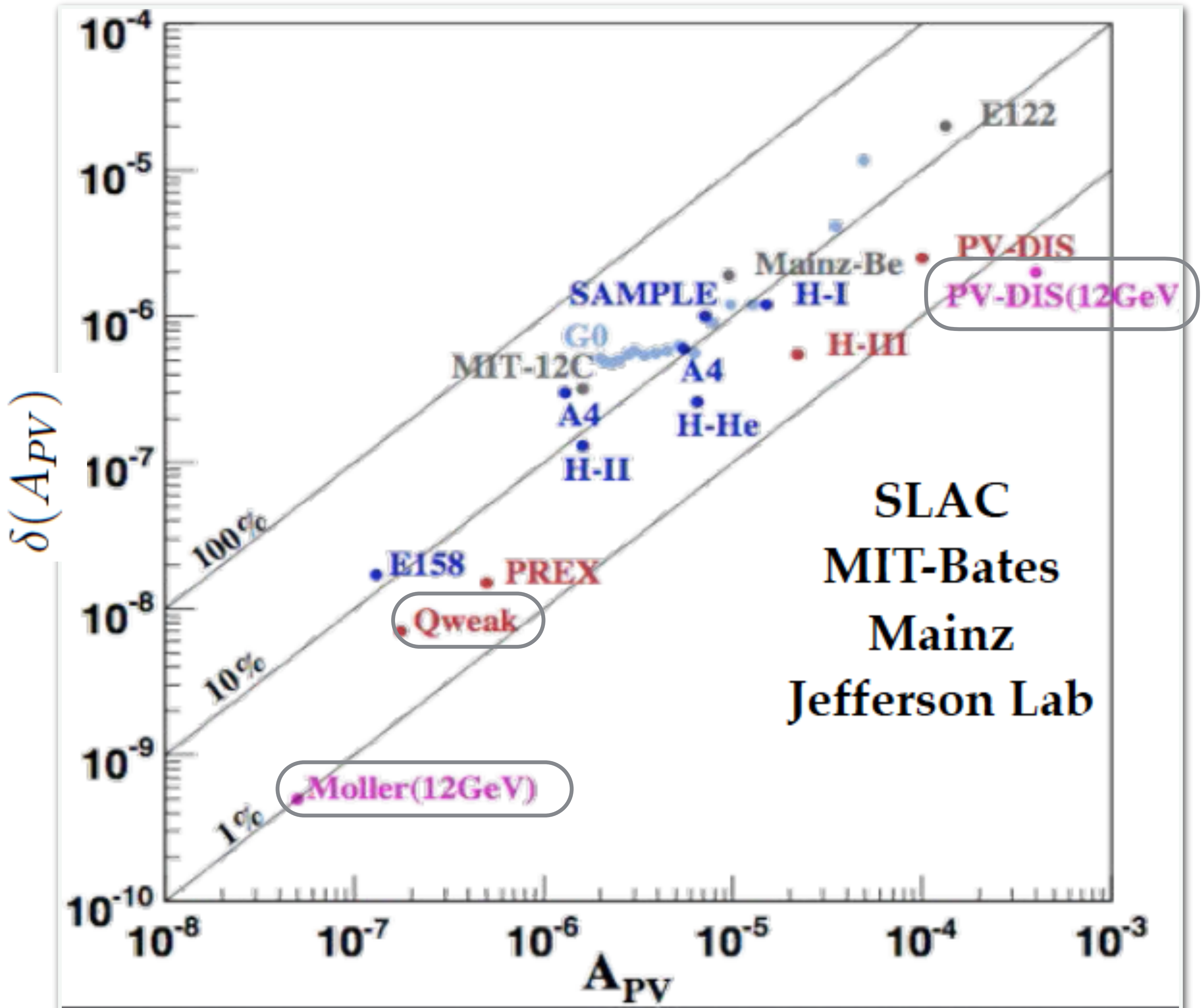
$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

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

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

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

- Neutral currents predicted in the Standard Model

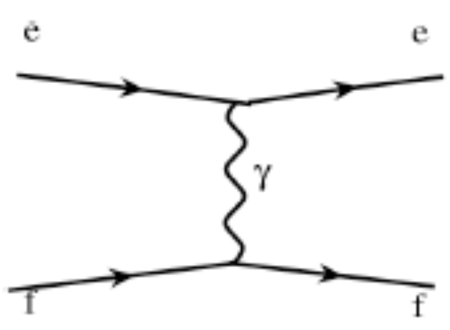
$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta}\; Z^\mu\; \bar{\psi}_f \left(g_V^{(f)}\gamma_\mu - g_A^{(f)}\gamma_\mu\gamma_5\right)\psi_f$$

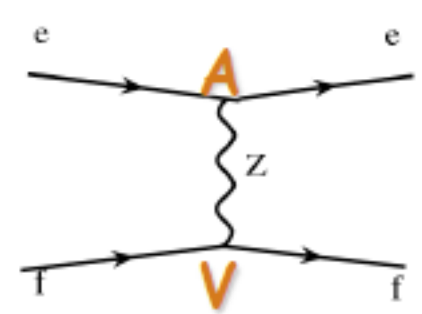
$$\theta = \arctan\frac{g'}{g}$$

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

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

Weak charge of the fermion





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

- Through g_V, A_{PV} provides a handle on weak mixing angle

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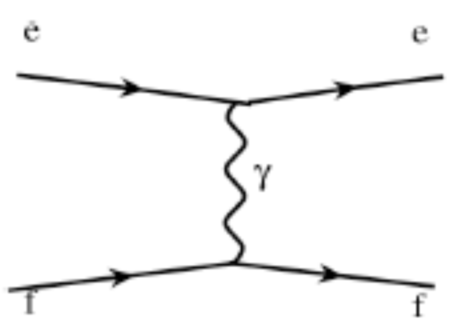

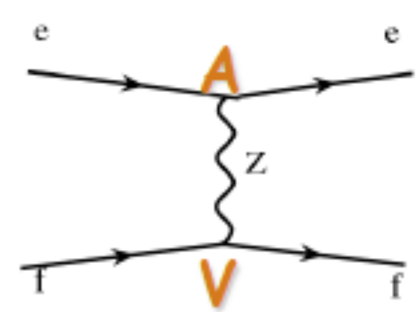

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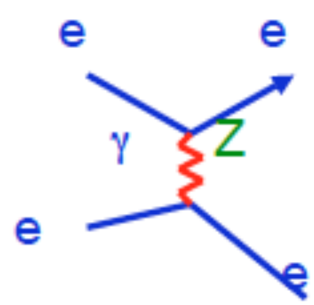
$$Q_W = 1 - 4\sin^2\theta_W$$

For electron and proton

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

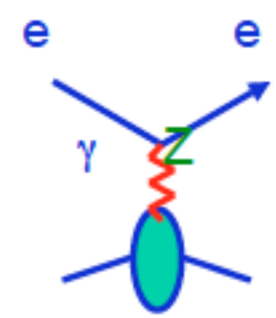
Processes

Møller Scattering



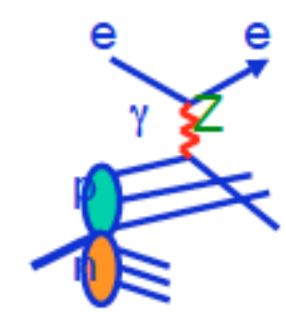
- Purely Leptonic

Q-Weak (JLab)



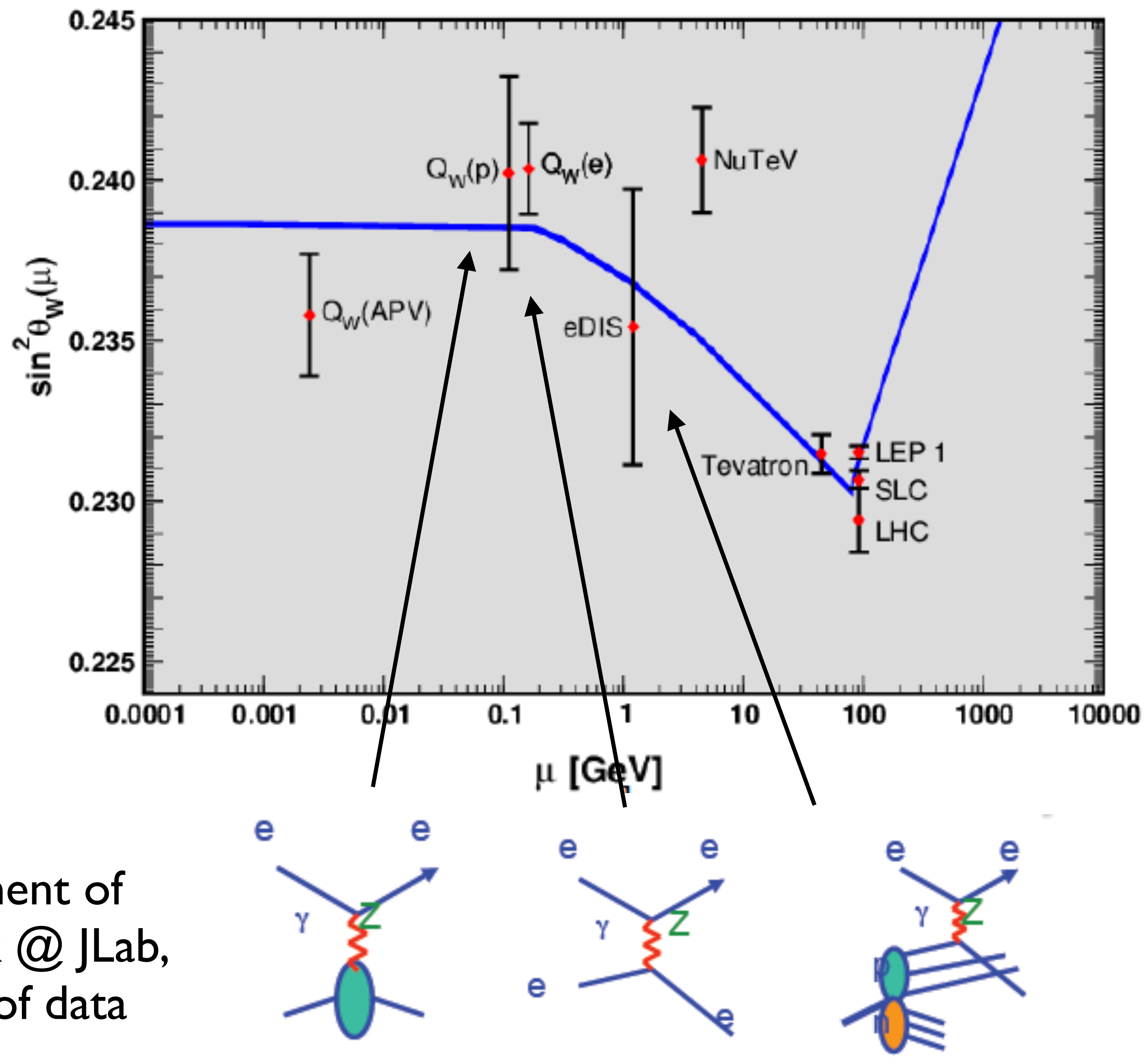
- Coherent quarks in p

DIS-Parity



Impact of PVES on θ_W

J. Erler



First measurement of $Q_W(p)$ by Qweak @ JLab, using only 4 % of data

Impact of PVES on θ_W

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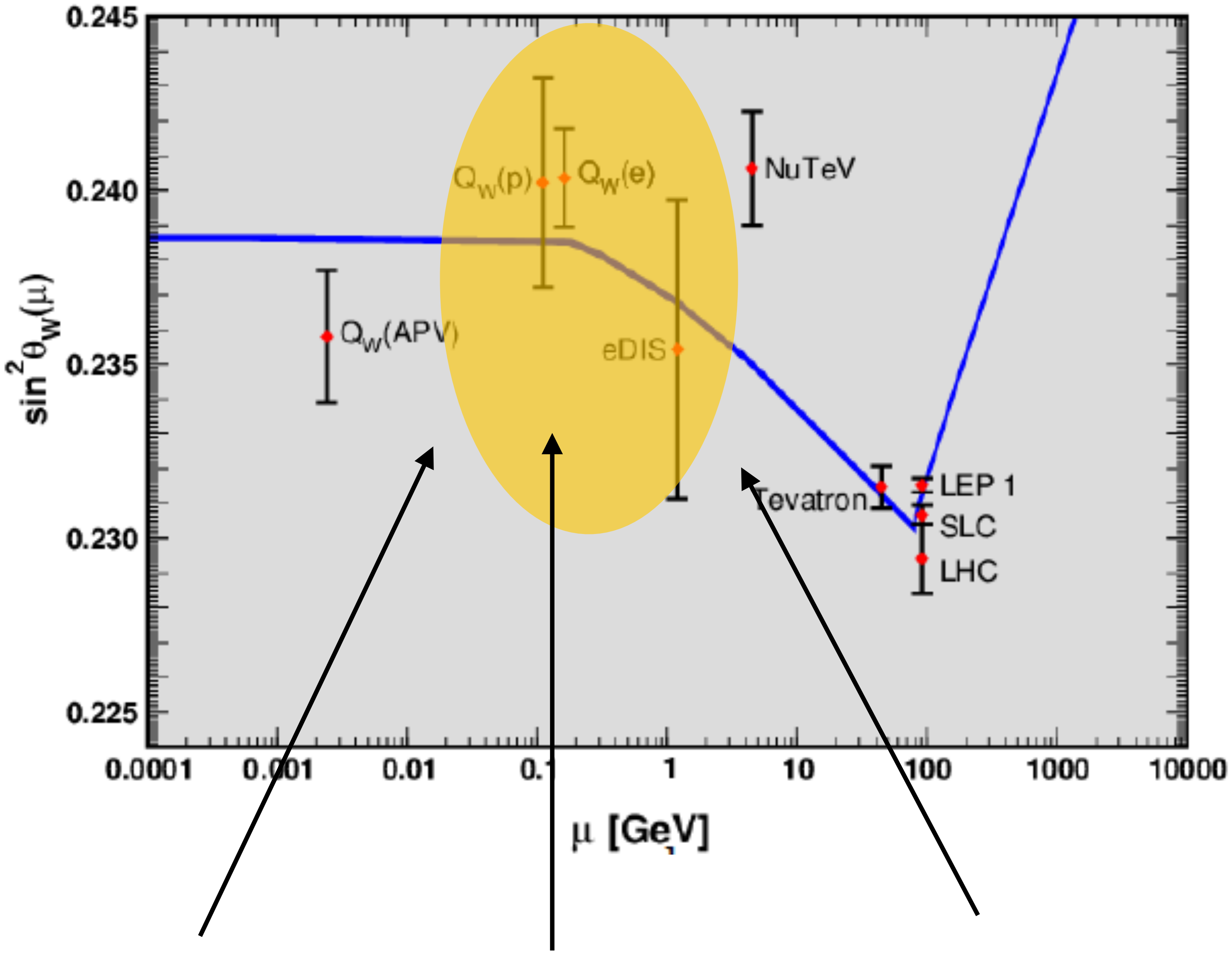


Qweak will improve $Q_W(p)$ by factor of 3

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

SoLID@JLab will improve eDIS by factor of ~3

Impact on new physics

BSM $$\mathcal{L}_{eq} = \sum_{i,j=L,R} \frac{g_{ij}^2}{\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{q}_j \gamma^\mu q_j$$ + purely leptonic (Moller)

Sensitivities to new physics

- $\Lambda_{new} \simeq [\sqrt{2}\, G_F\, \Delta Q_W]^{-1/2} = 246.22\ \text{GeV} / \sqrt{\Delta Q_W}$
  - $\Lambda_{new} \simeq$ 3.4 TeV (Q_W^e from E158)
  - $\Lambda_{new} \simeq$ 4.6 TeV (Q_W^p from Qweak)
  - $\Lambda_{new} \simeq$ 2.5 TeV (C_{ij} from SoLID)
  - $\Lambda_{new} \simeq$ 7.5 TeV (Q_W^e from MOLLER)
  - $\Lambda_{new} \simeq$ 6.3 TeV (Q_W^p from P2@Mainz)
  - $\Lambda_{new} \simeq$ 3.7 TeV (g_R^2 from NuTeV)
  - $\Lambda_{new} \simeq$ 5.2 TeV (Q_W^n from APV in Cs)

J. Erler

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

Muon “g-2”

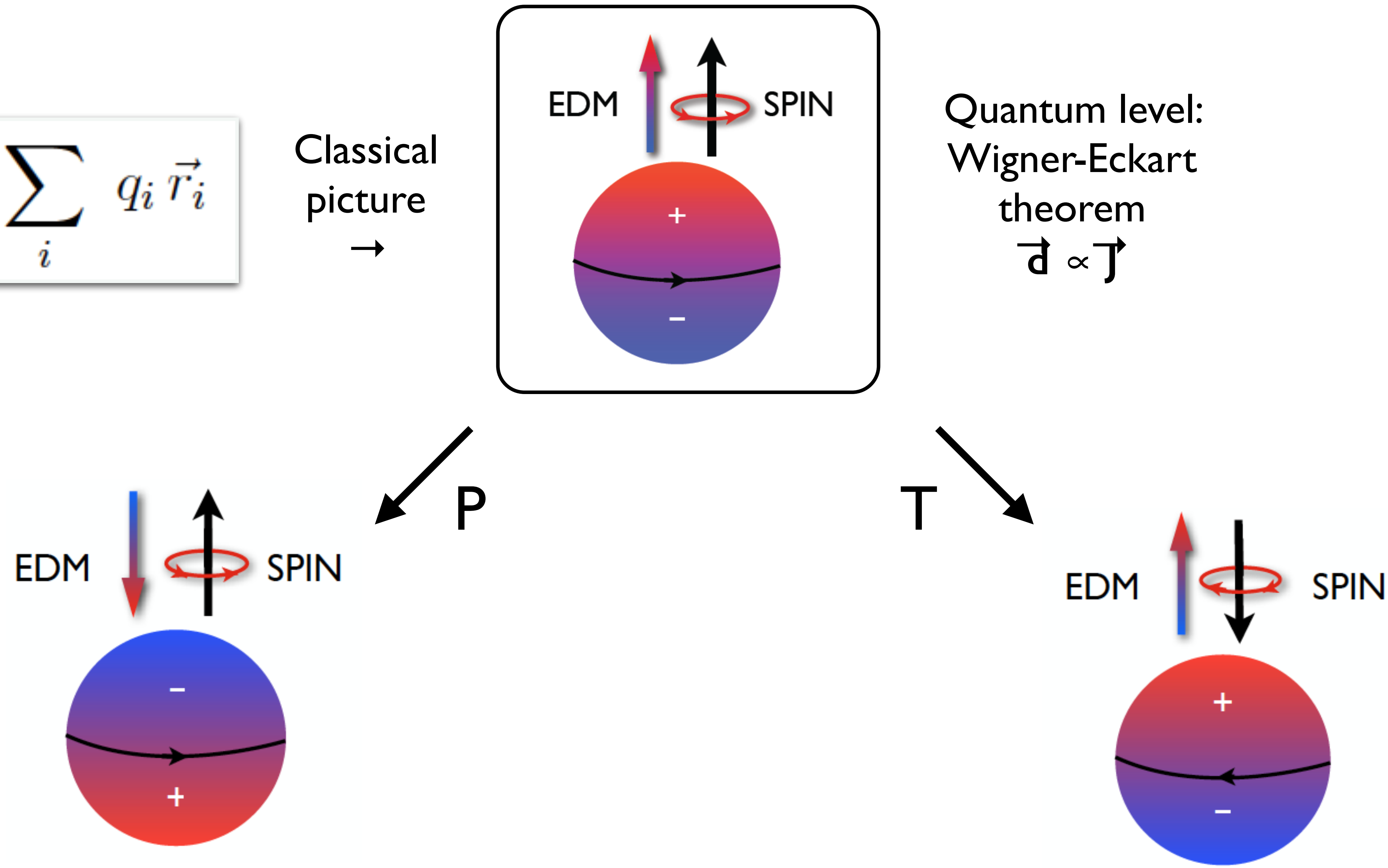
Symmetry tests

EDMs and T (CP) violation beyond the Standard Model

EDMs and symmetry breaking

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

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



EDMs and symmetry breaking

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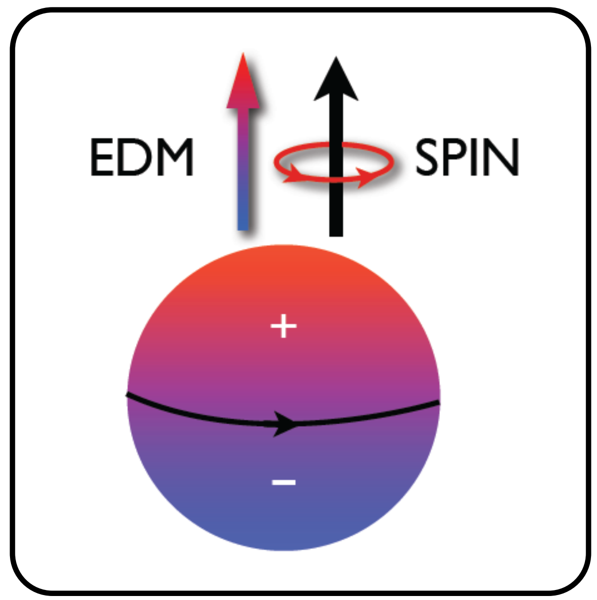
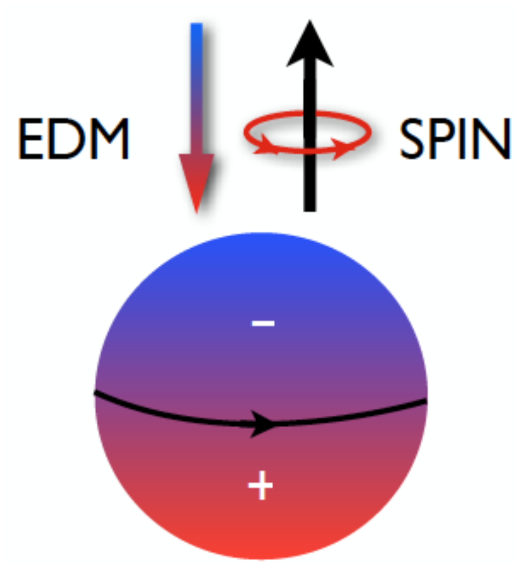
Classical picture →



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

P



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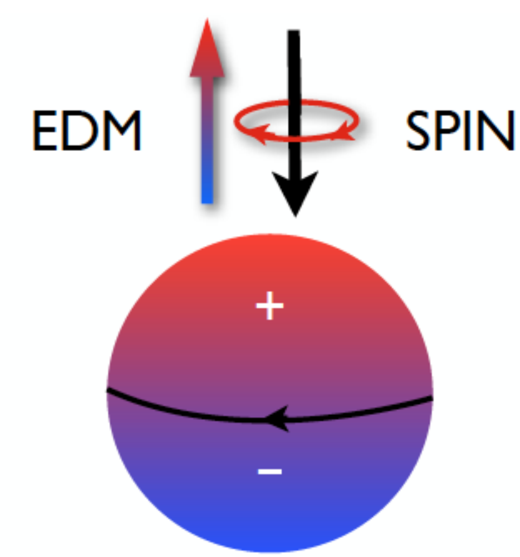
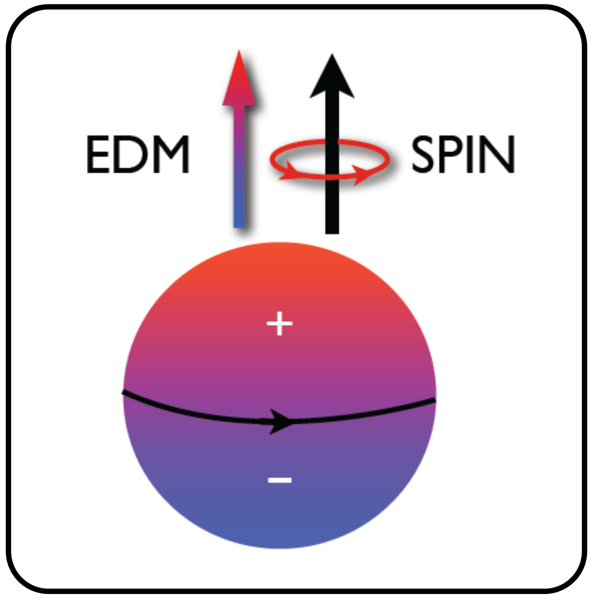
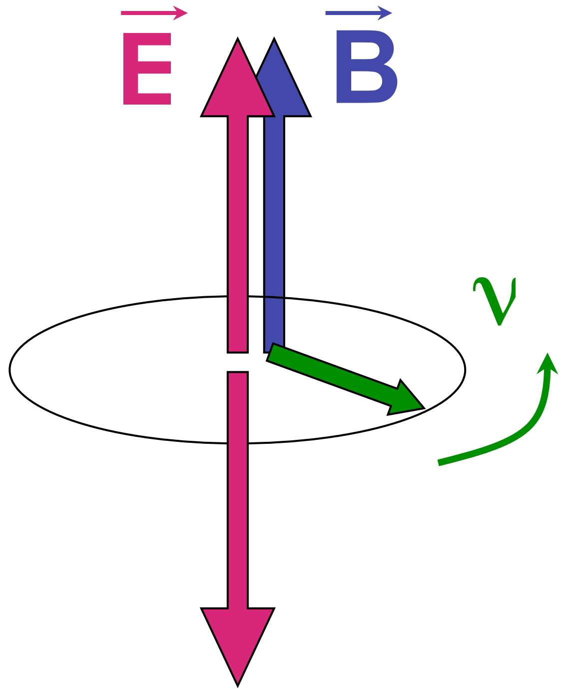


EDMs and symmetry breaking

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



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

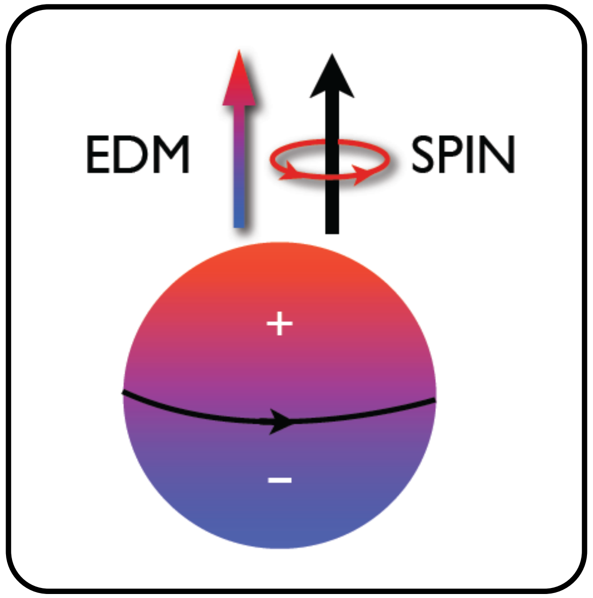


$$\nu = (2\mu B \pm 2dE)/h$$

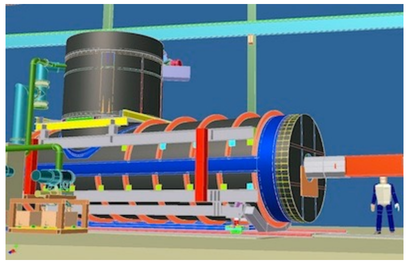
Sensitivity to $d_n \sim 10^{-13}$ e fm !!

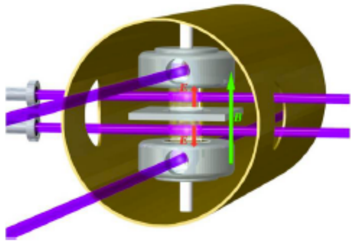
EDMs and symmetry breaking

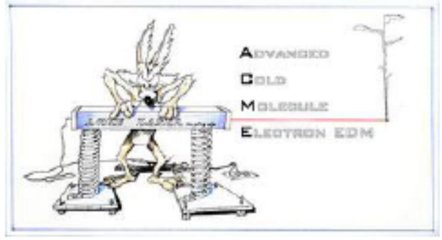
- EDMs of non-degenerate systems violate P and T (CP): $\mathcal{H} \sim d\,\vec{J} \cdot \vec{E}$



- Ongoing and planned searches in several systems





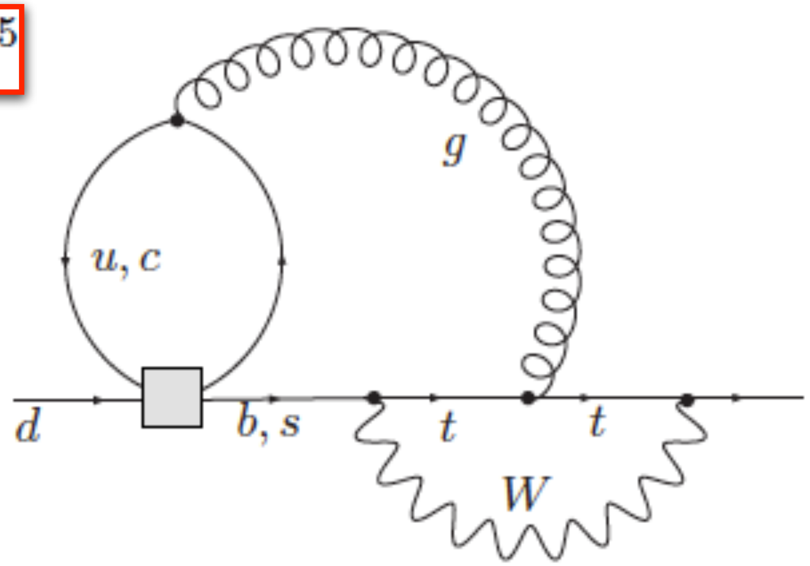


  - ★ n, p
  - ★ Light nuclei: d, t, h
  - ★ Atoms: diamagnetic (^{129}Xe, ^{199}Hg, ^{225}Ra, ...);
    paramagnetic (^{205}Tl, ...)
  - ★ Molecules: YbF, ThO, ...

EDMs in the SM: CKM

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

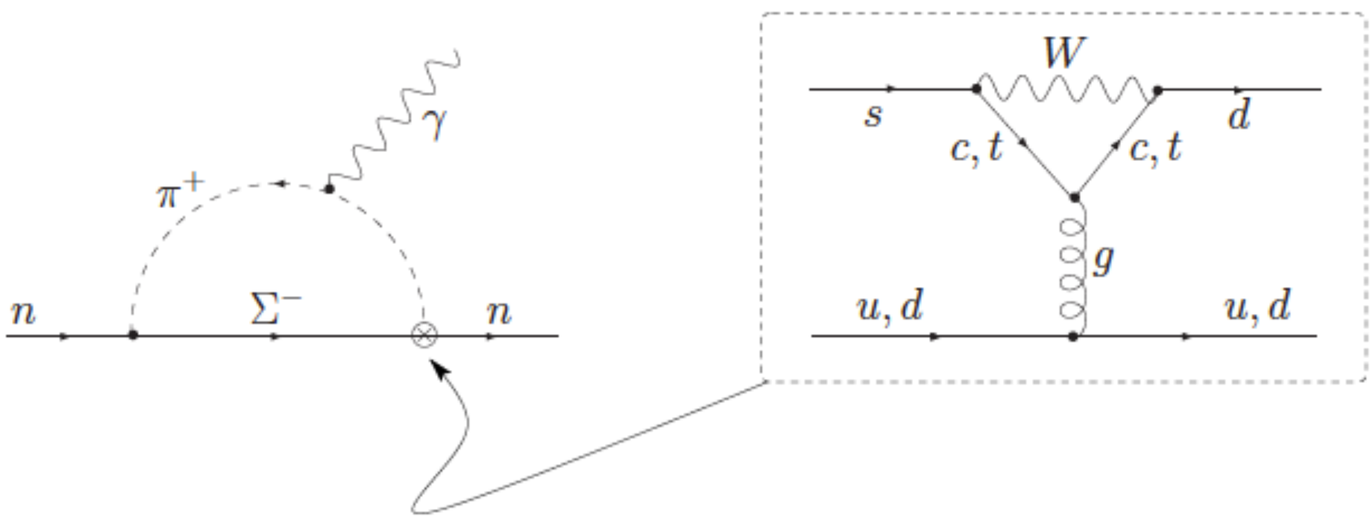
$$J_{CP} = \mathrm{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*) \simeq 3\times 10^{-5}$$



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

$d_e \sim 10^{-38}$ 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]

EDMs in the SM: QCD

Baluni 1979 Crewther, Di Vecchia, Veneziano, Witten 1979

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

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

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

EDMs in the SM: QCD

Baluni 1979 Crewther, Di Vecchia, Veneziano, Witten 1979

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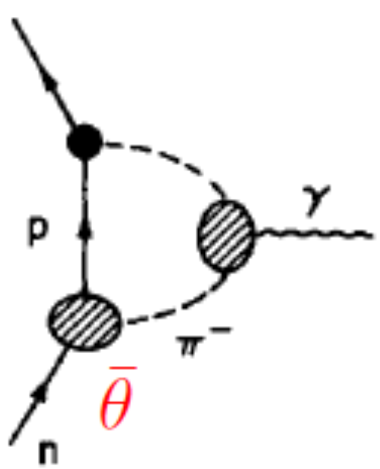
$\sim \mathbf{E_c \cdot B_c}$

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

- Leading contribution to neutron EDM via chiral loop



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

Teaching us something deep about CPV.
Motivated scenarios that relax dynamically θ to zero (e.g. axions)

EDMs and new physics

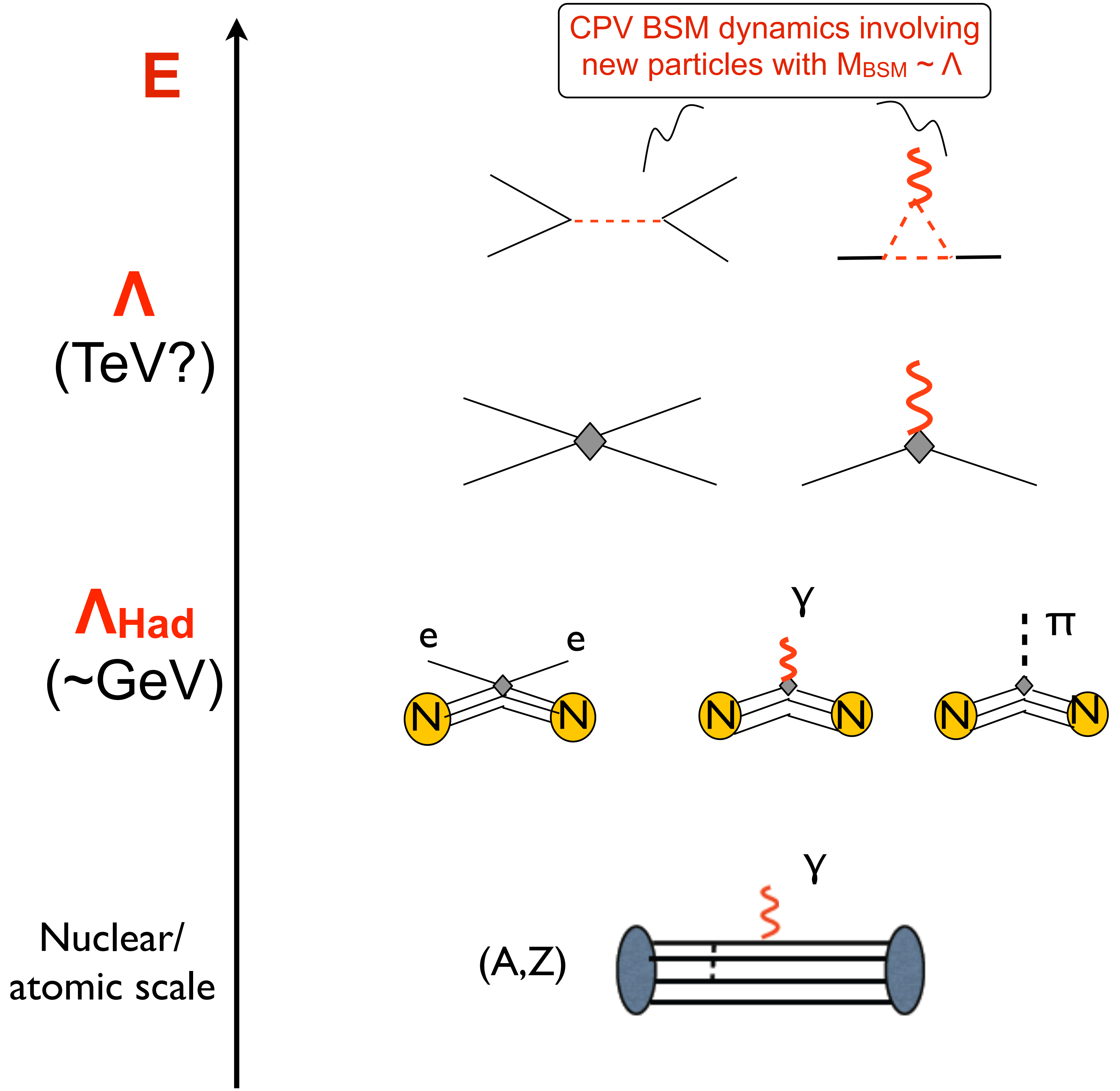
- Essentially free of SM "background" (CKM)*
- Probe high-scales, up to $\Lambda \sim 1000$ TeV
- Probe key ingredient for bayrogenesis (CPV in SM is insufficient)

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



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

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

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

Gluon chromo-EDM (Weinberg operator)

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

Semileptonic and 4-quark

CPV at the quark-gluon level

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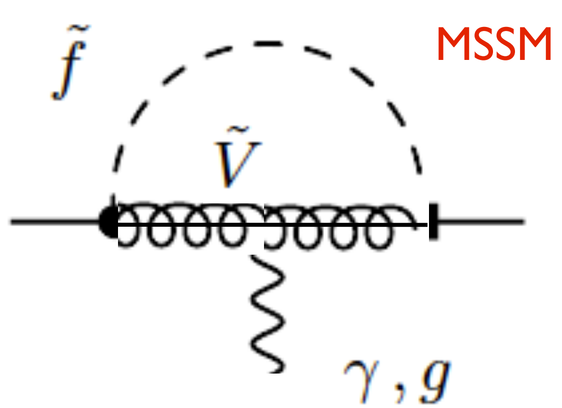
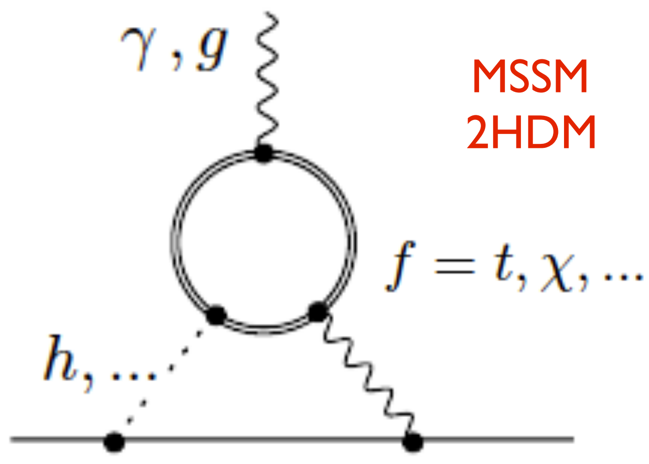
$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\,\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\, g_s\,\bar{q}\sigma\cdot G\gamma_5 q + d_W\frac{g_s}{6}G\tilde{G}G + \sum_i C_i^{(4f)}O_i^{(4f)}$$

- 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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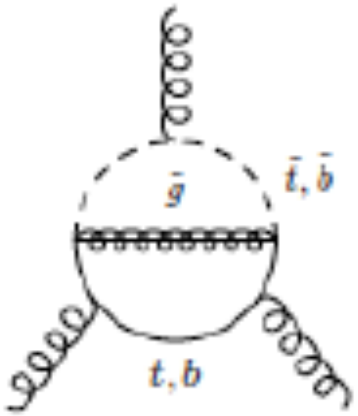
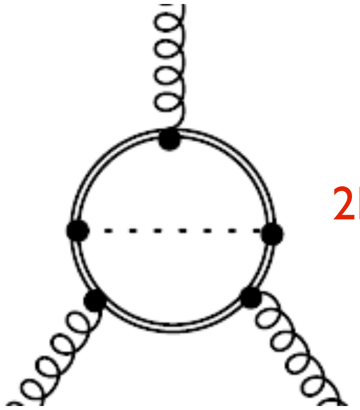


MSSM



2HDM → Weinberg operator

CPV at the quark-gluon level

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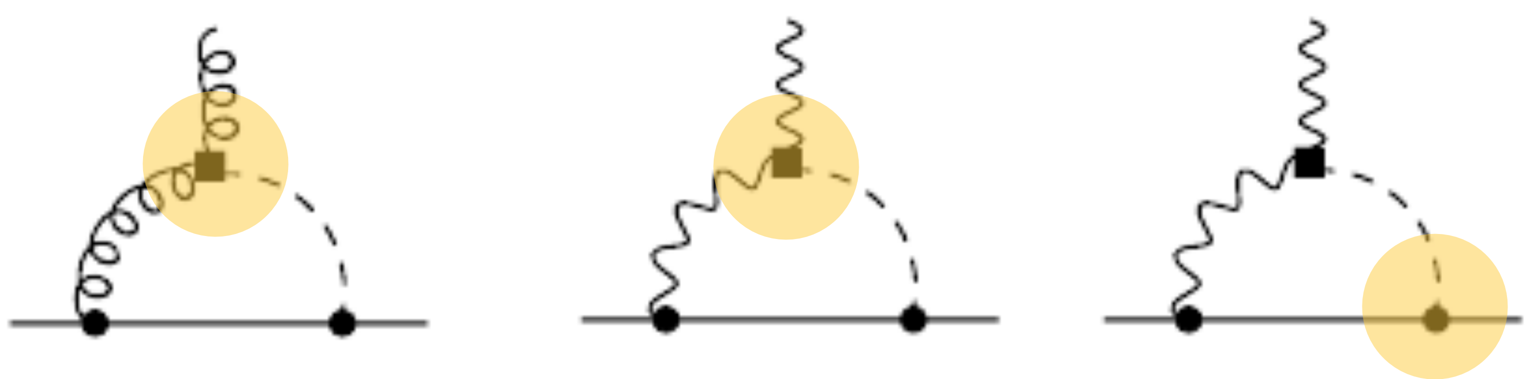
- Generated by a variety of BSM scenarios



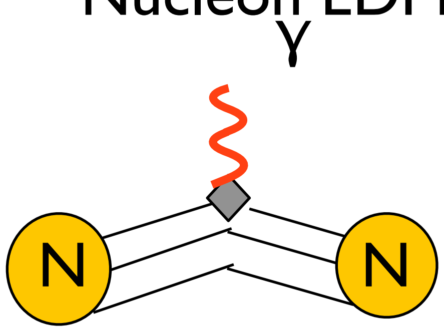
Non-standard Higgs couplings (hVV, ...), heavy quark CPV, ...

CPV at the hadronic level

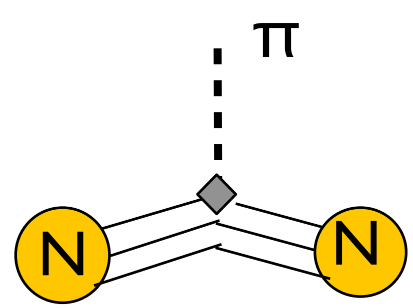
- Leading pion-nucleon CPV interactions characterized by few LECs

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

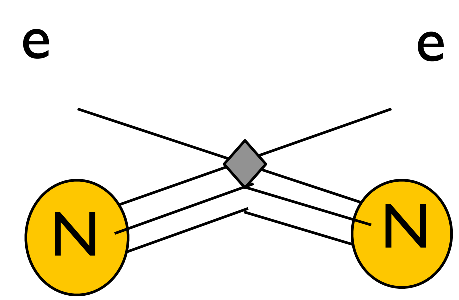
Electron and Nucleon EDMs



T-odd P-odd pion-nucleon couplings



Short-range 4N and 2N2e coupling



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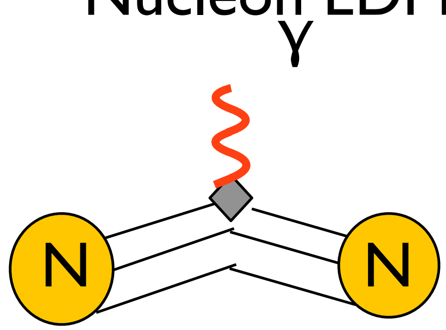
Electron and Nucleon EDMs



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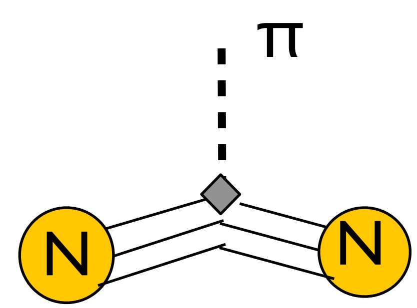

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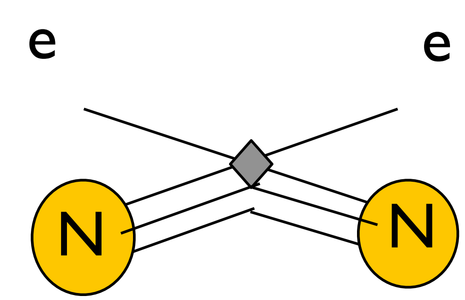
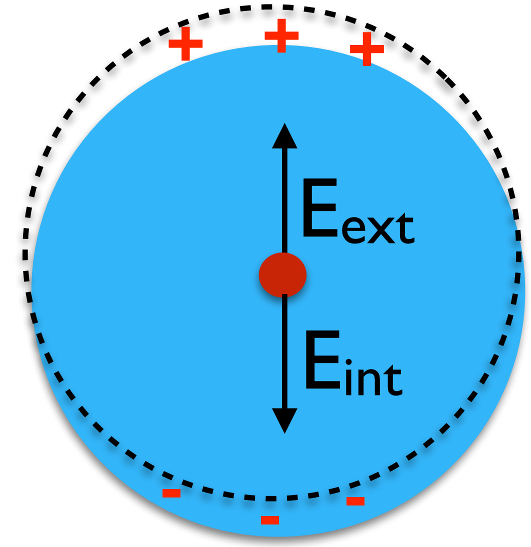


$d_N[d_q]$ known with 10% uncertainty (lattice QCD)

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

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})



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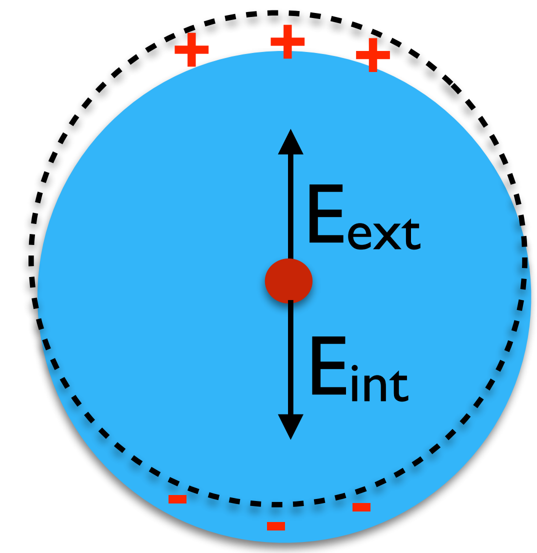
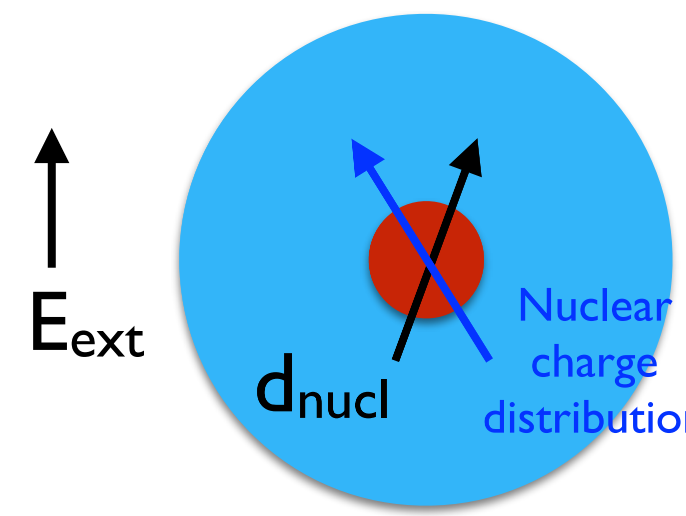


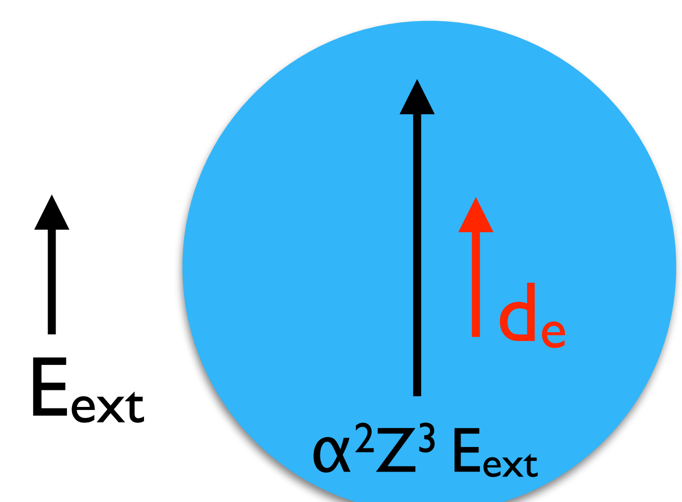
- Evading Schiff screening: finite size effects in diamagnetic atoms make $d_A[d_{nucl}] \neq 0$. Suppression $d_A \sim Z^2 (R_N/R_A)^2 d_{nucl}$

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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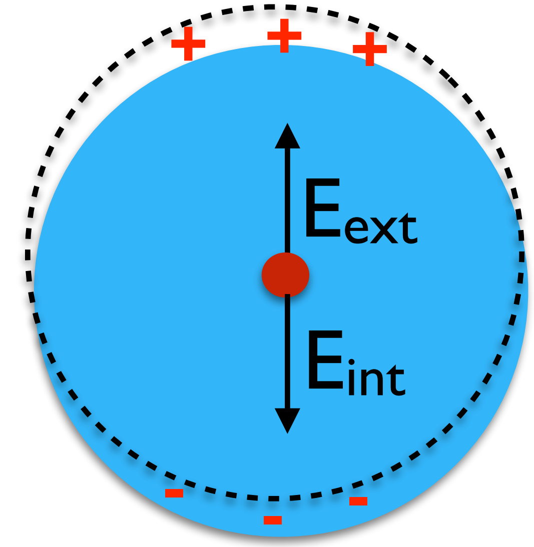

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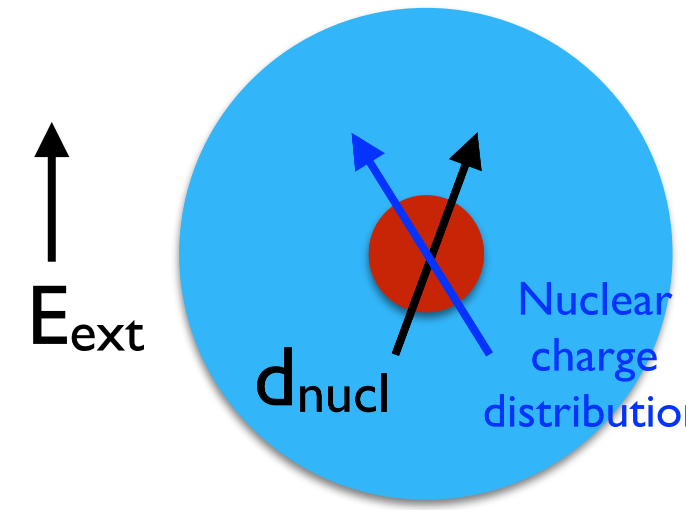
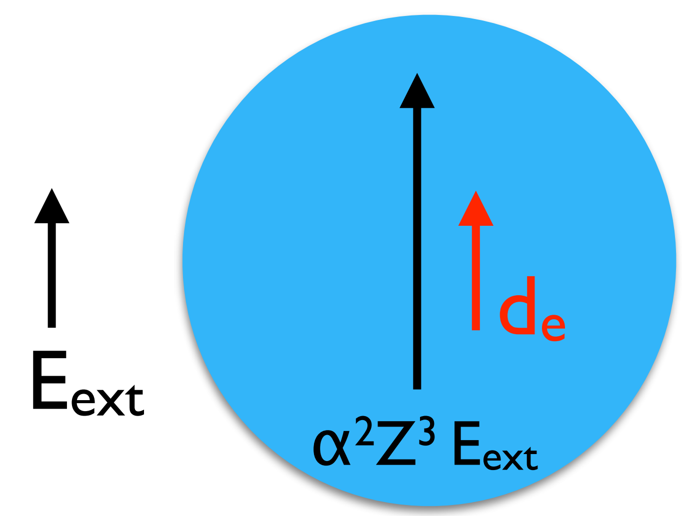
O(few 100%) uncertainties

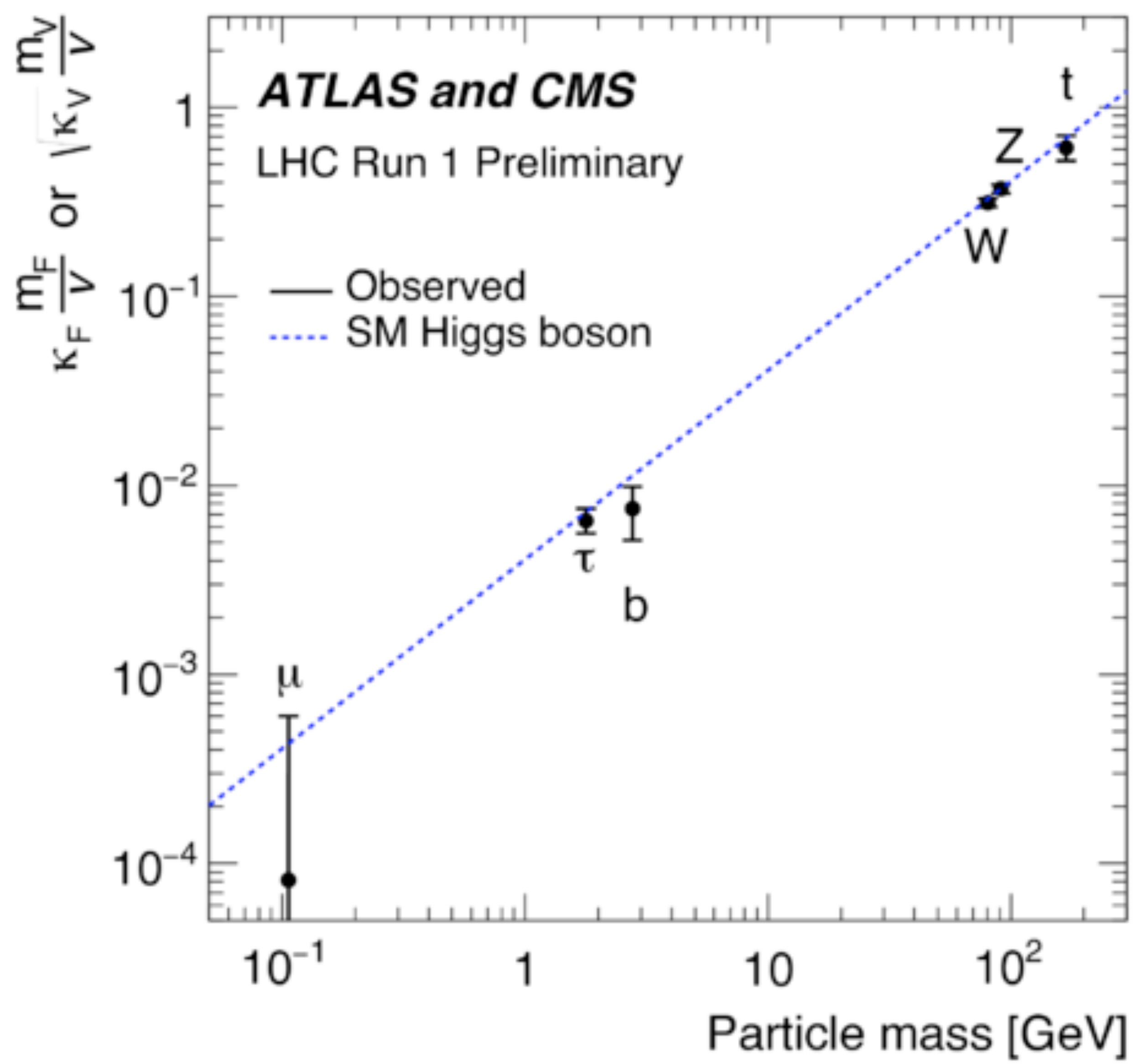


- Evading Schiff screening: relativistic effects in paramagnetic atoms (and molecules) make $d_A[d_e] \neq 0$. Enhancement $d_A \sim \alpha^2 Z^3 d_e$

O(10%) uncertainties



EDMs and CPV Higgs couplings

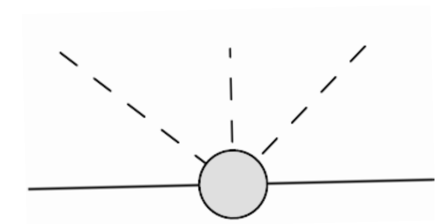


- EDMs play an important role in pinning down <u>non-standard</u> CP-violating Higgs couplings
- Very competitive with LHC

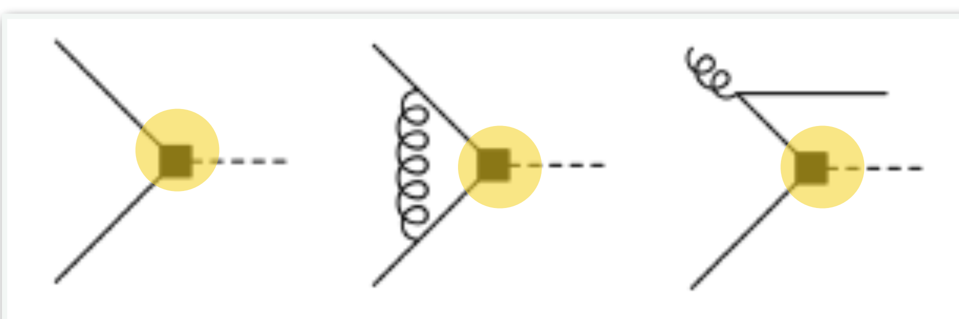
Yukawa couplings to quarks

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

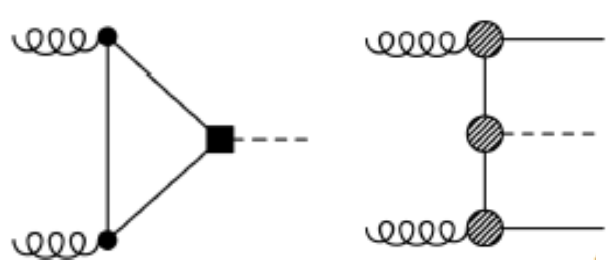
$$\mathcal{L}_6^{CPV} \supset v^2 \mathrm{Im}\, Y_q' \, \bar{q} i \gamma_5 q \; h$$



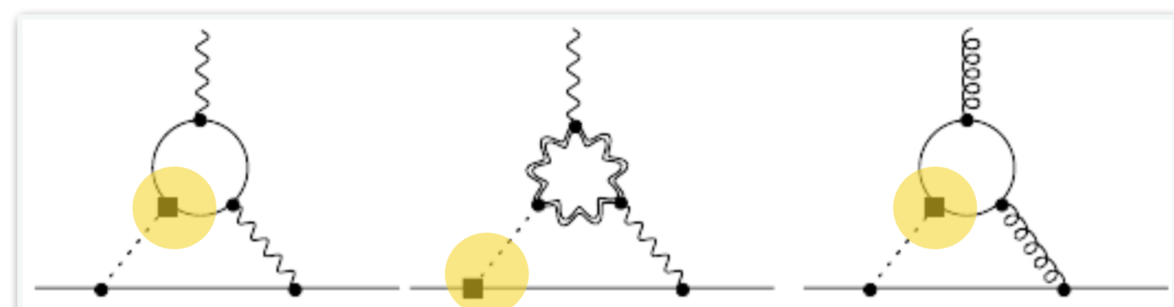
LHC: Higgs production

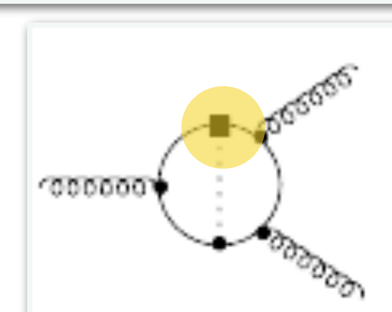


Top quark:



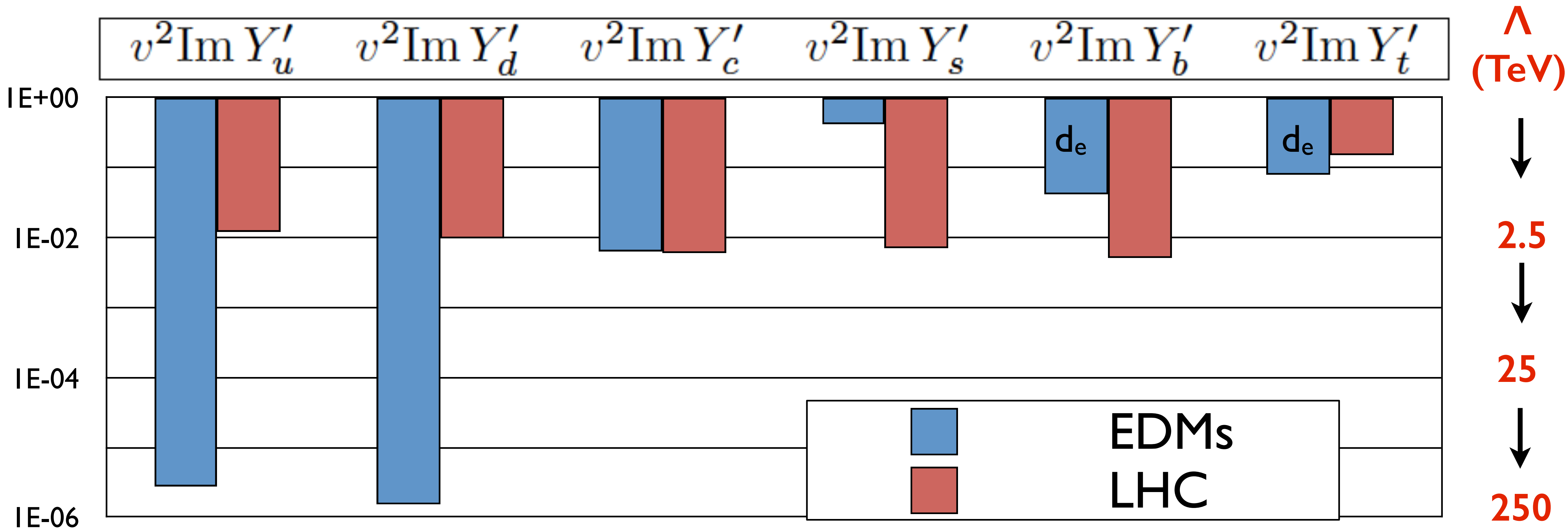
Low Energy: quark (C)EDM, Weinberg, *and* d_e





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

Yukawa couplings to quarks

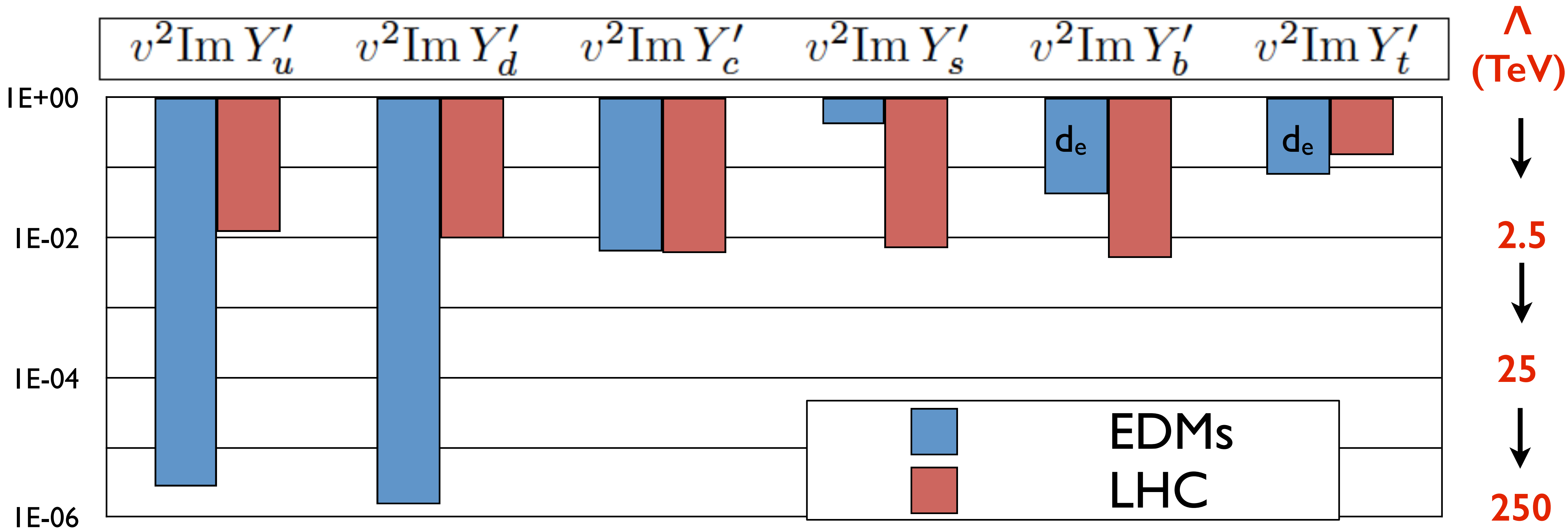


- Pseudo-scalar Yukawas in units of SM Yukawa m_q/v:

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

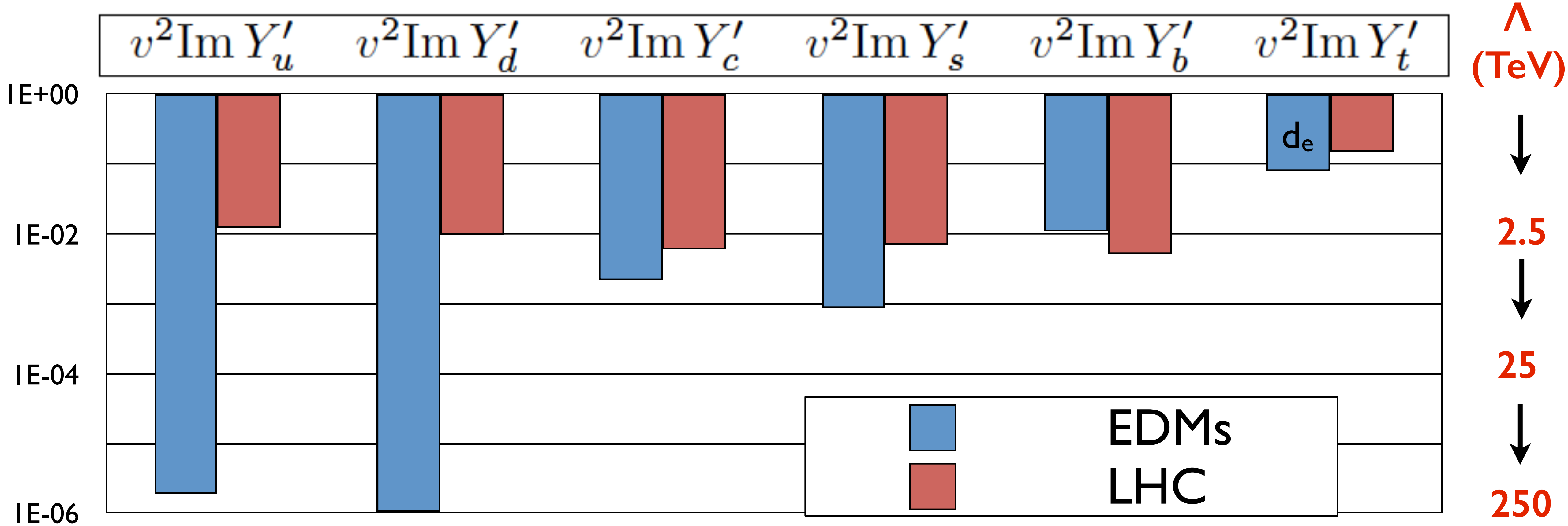
$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

Yukawa couplings to quarks



- Complementarity: 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



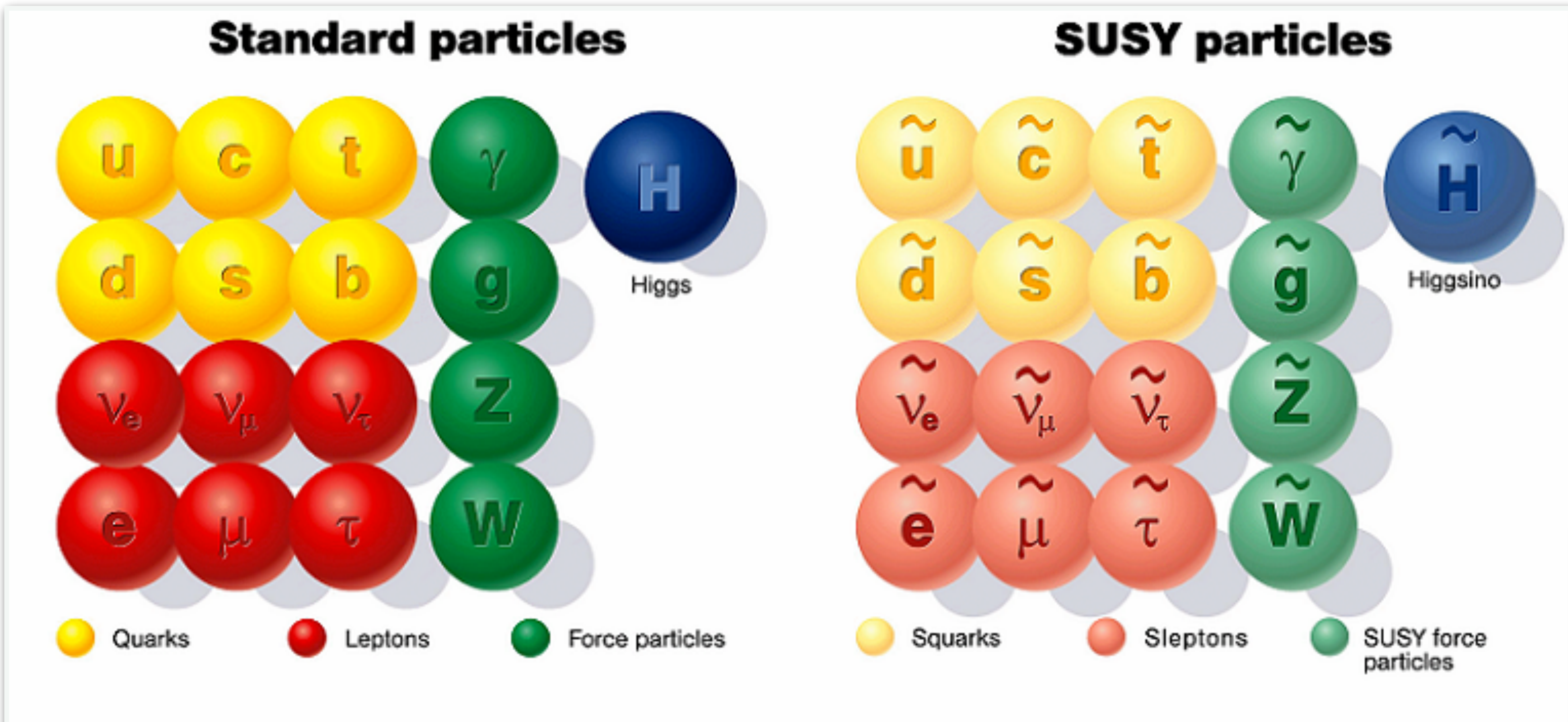
- Much stronger impact of n and ^{199}Hg EDM with reduced uncertainties

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

25%   50%

- Challenging but realistic target for LQCD and nuclear structure

Probing high-scale SUSY

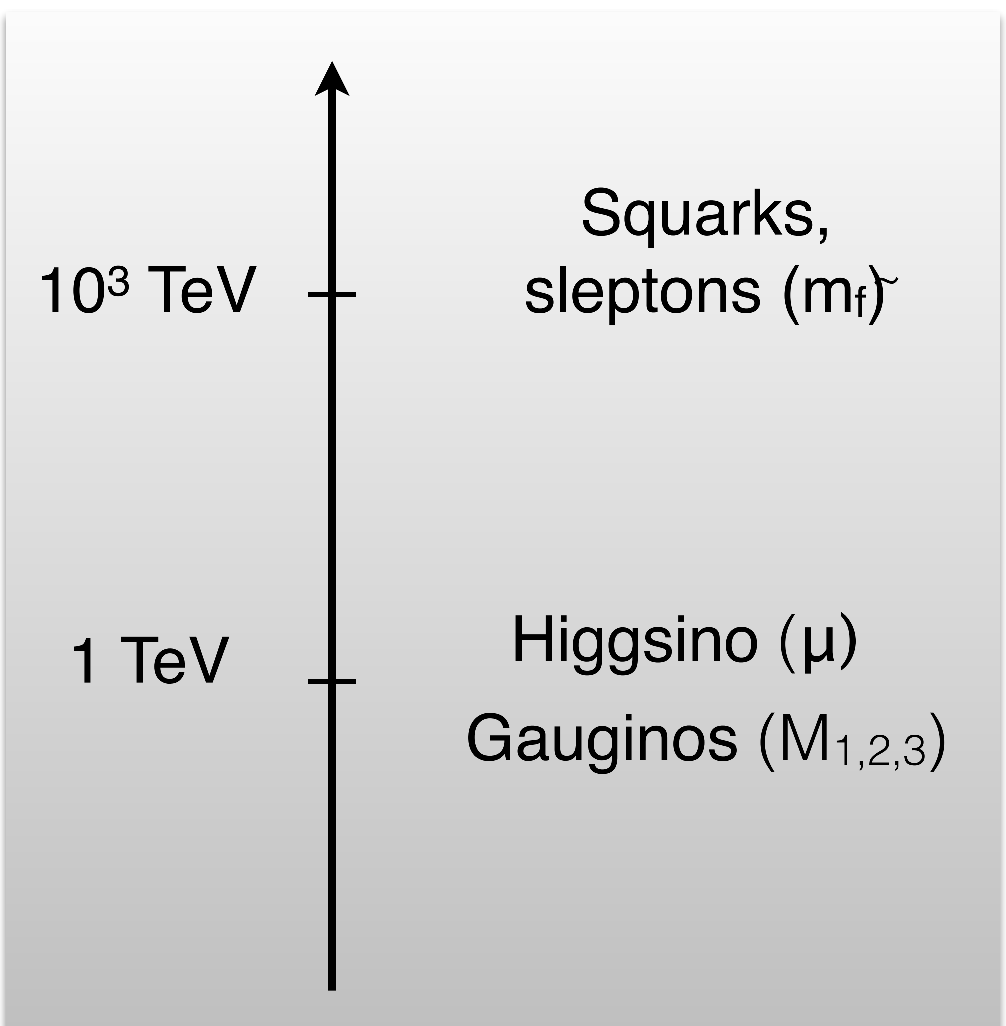


- Absence of direct signals and the observation of Higgs at 125 GeV put strong constraints on the spectrum of SUSY particles

Probing high-scale SUSY

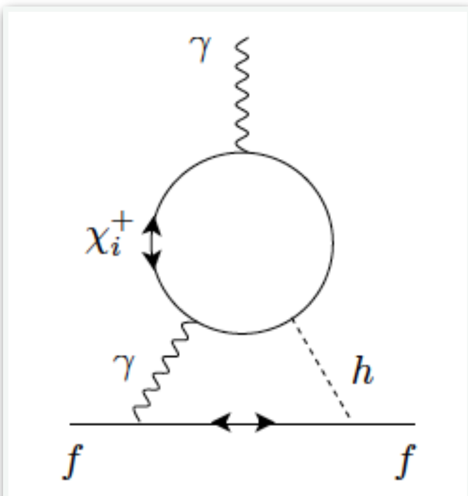
- Higgs mass at ~125 GeV points to PeV-scale super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

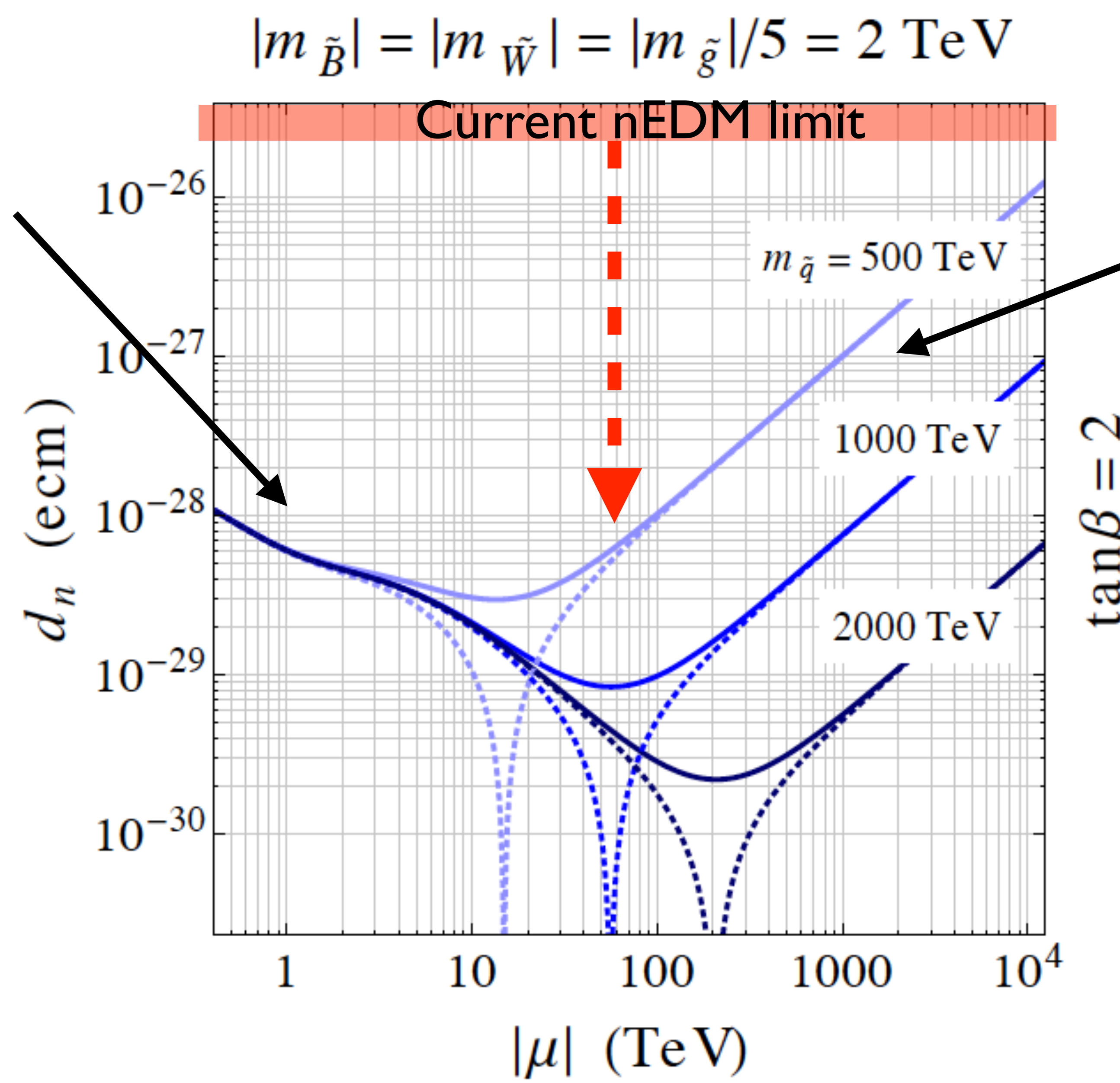
Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004,
Arkani-Hamed et al 2012, …

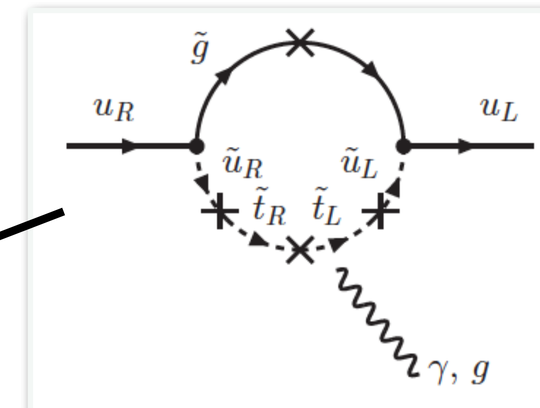


EDMs among a handful of observables capable of probing such high scales!

EDMs in split SUSY (1)







Maximal CPV phases.
Squark mixings fixed at 0.3

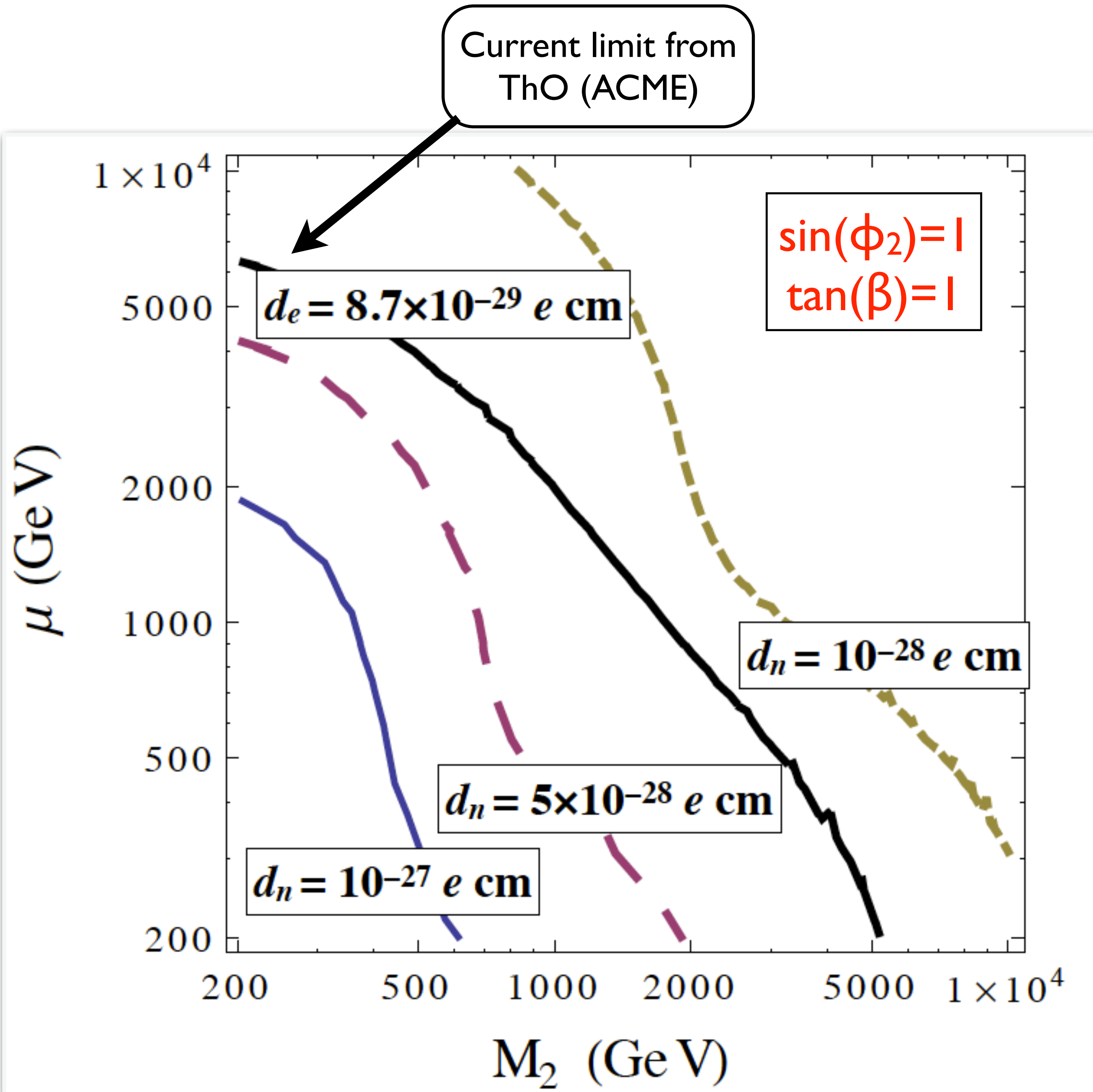
Altmannshofer-Harnik-Zupan 1308.3653

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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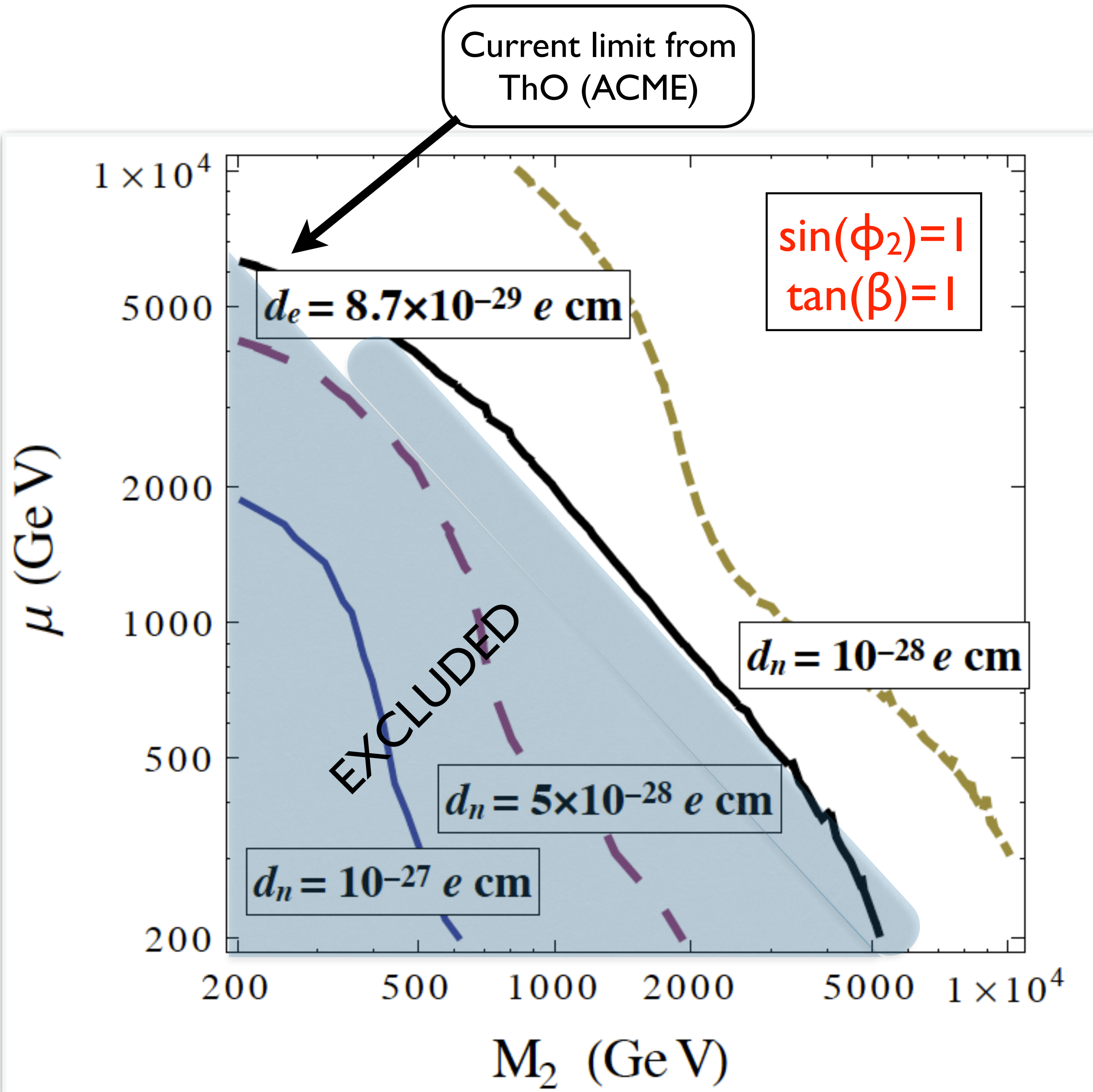

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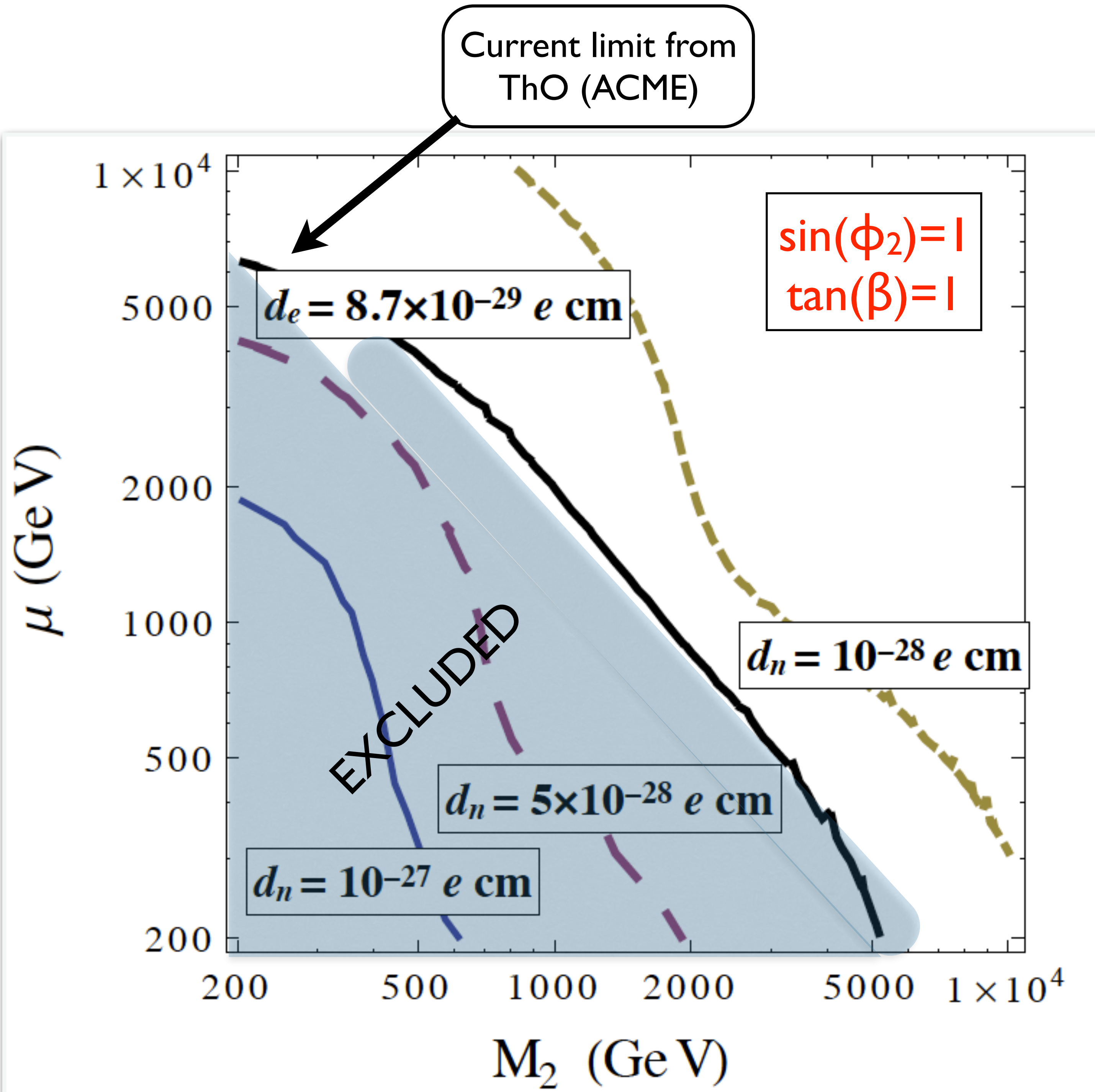
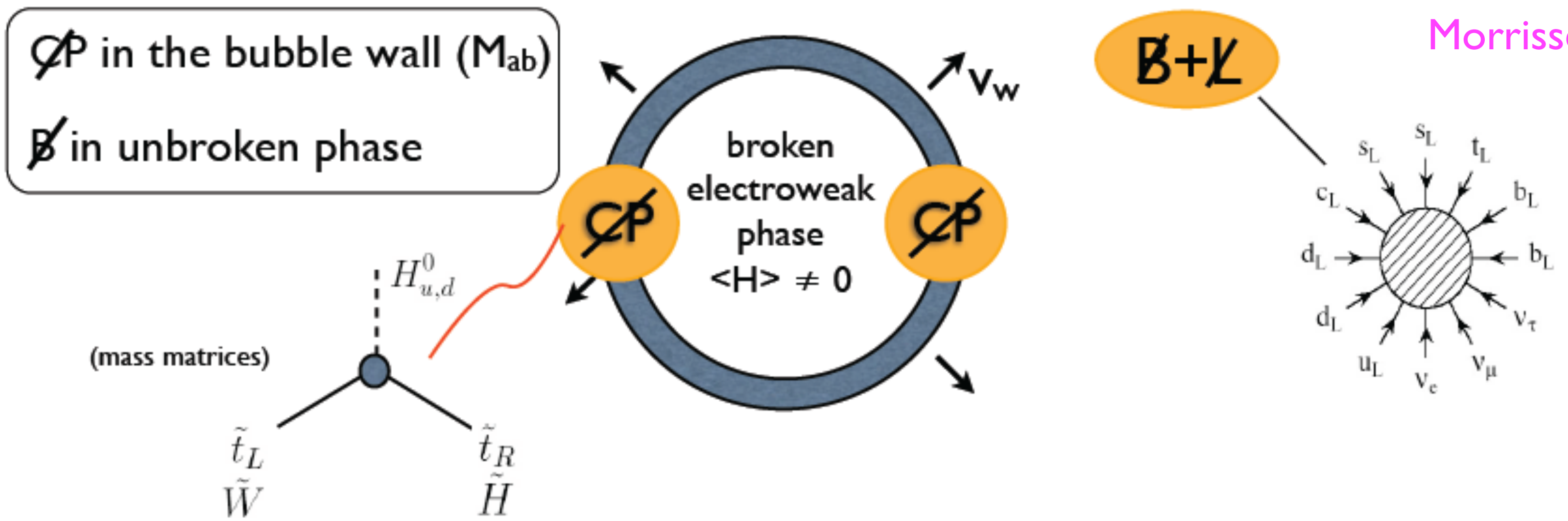


- Studying the ratio d_n/d_e *with precise matrix elements* → stringent upper bound $d_n < 4 \times 10^{-28}$ e cm
- Can be falsified by current nEDM searches
- Illustration of "improved matrix elements → enhanced model-discriminating power"

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

Supersymmetric EW baryogenesis?



For a review:
Morrissey & Ramsey-Musolf
1206.2942

- MSSM: no first order phase transition
- Singlet extensions (NMSSM): first order phase transition viable

Supersymmetric EW baryogenesis?

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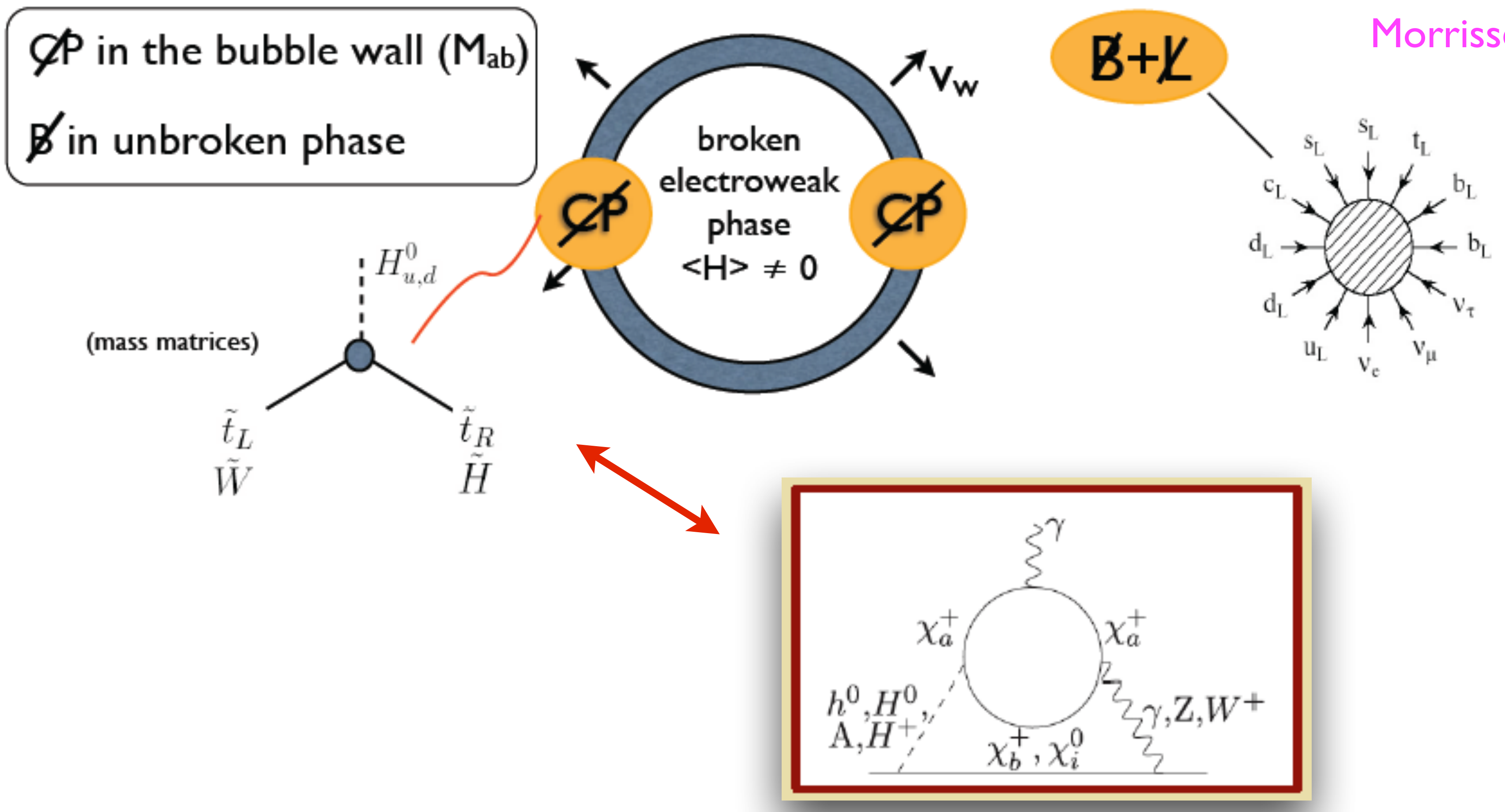
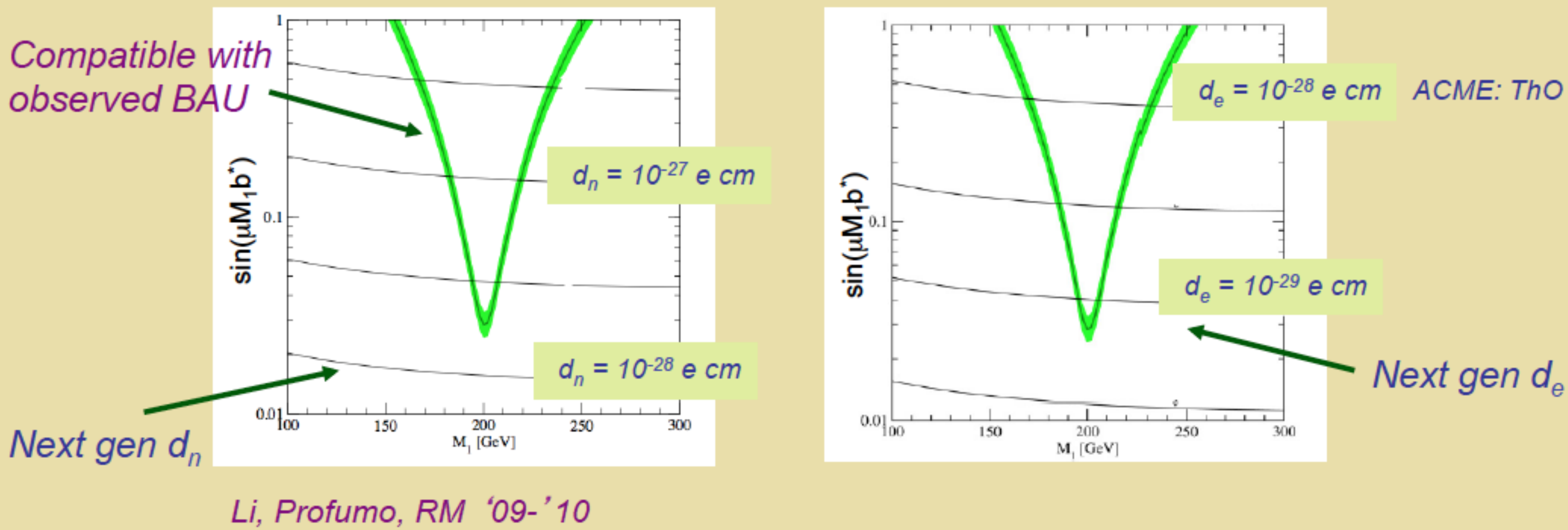


- MSSM: no first order phase transition
- Singlet extensions (NMSSM): first order phase transition viable
- CPV phases appearing in the gaugino-higgsino mixing contribute to both baryogenesis and EDM: correlation?

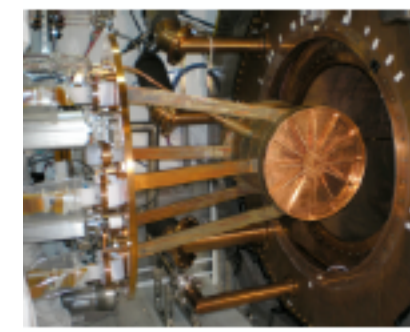
EDMs and Baryogenesis: NMSSM

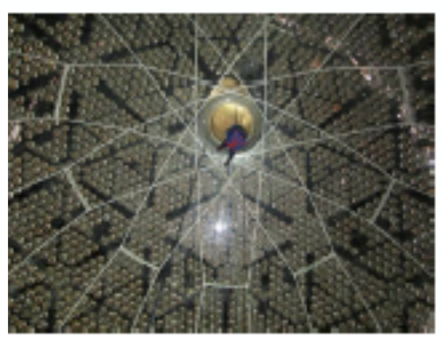
M. Ramsey-Musolf

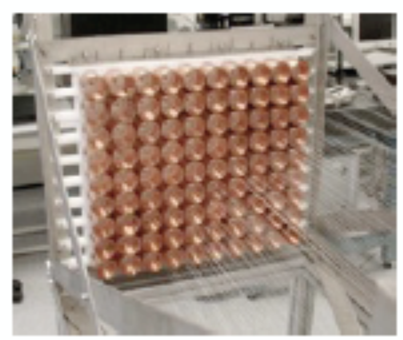


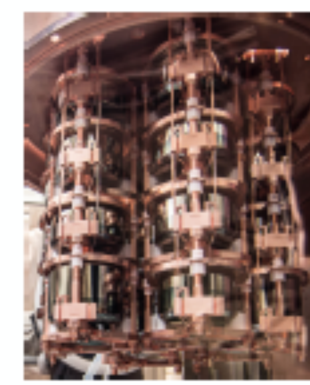
- In this model, successful baryogenesis implies a "guaranteed signal" for EDM, within reach of planned experiments
- Unfortunately, this is not a generic feature (model dependent)

0νββ and Lepton Number Violation







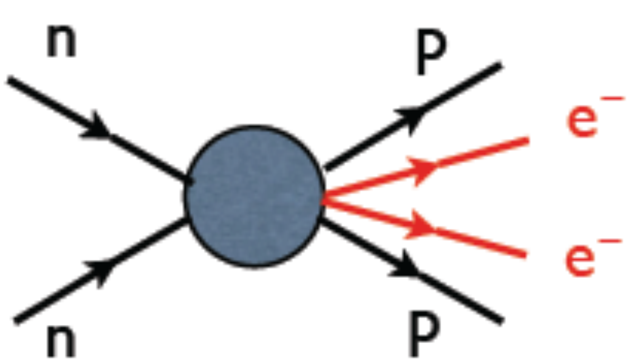


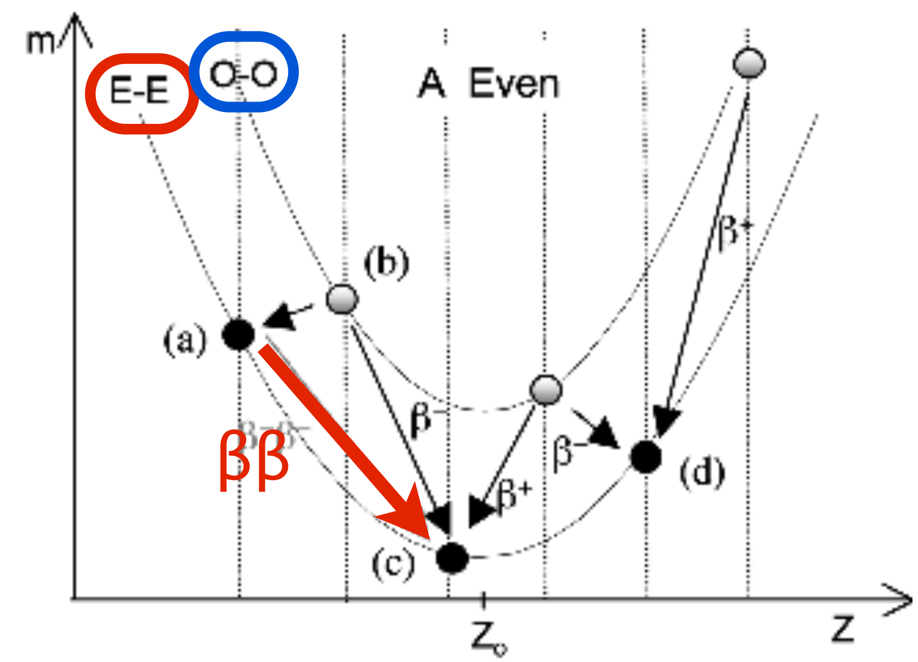
For a detailed discussion see Lindley Winslow's lectures

Neutrinoless double beta decay

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

Lepton number changes by two units: ΔL=2



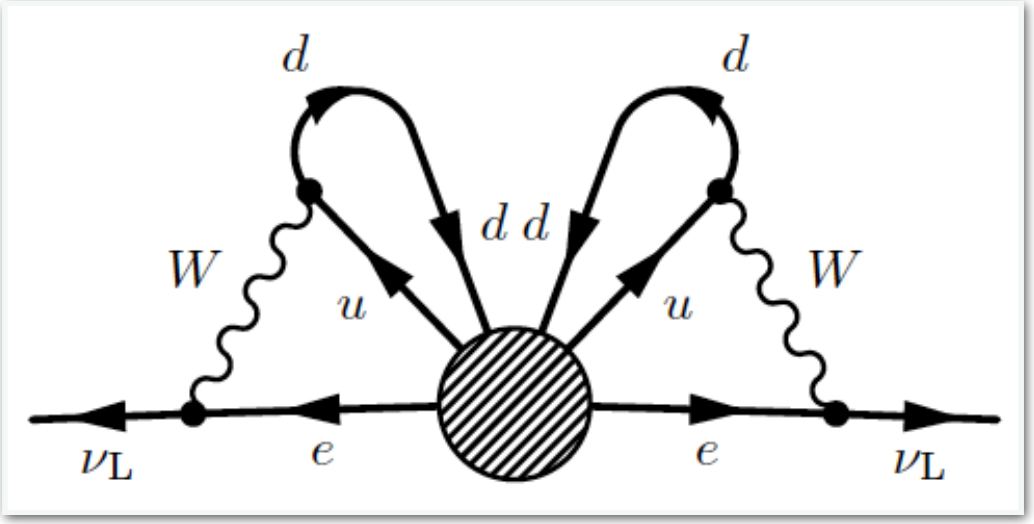


*Enabled by nuclear physics energetics

Unique laboratory* to study lepton number violation (LNV)

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



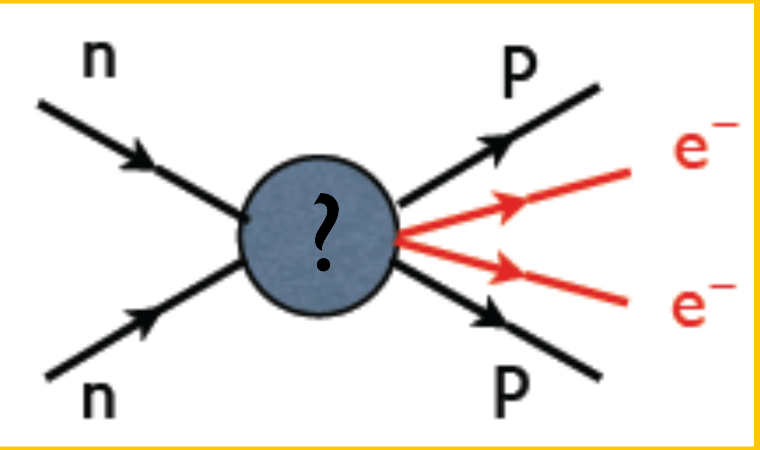
- Demonstrate that neutrinos are Majorana fermions (i.e. their own antiparticles!)
- Shed light on the mechanism of neutrino mass generation
- Probe the basic ingredient (LNV) needed to generate the cosmic baryon asymmetry via "leptogenesis"

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): a discovery would have major impact on our understanding of fundamental interactions

- 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

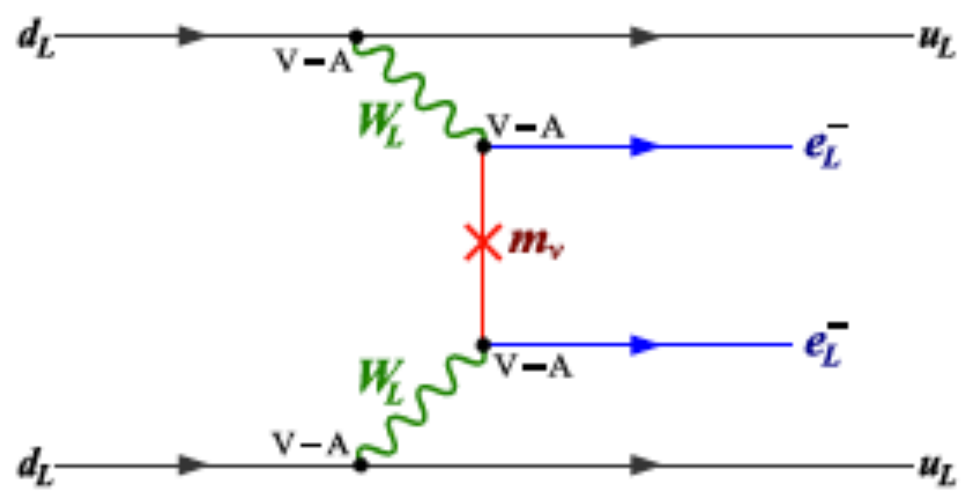
(Classifying sources of LNV: organize discussion by scales)

- 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)

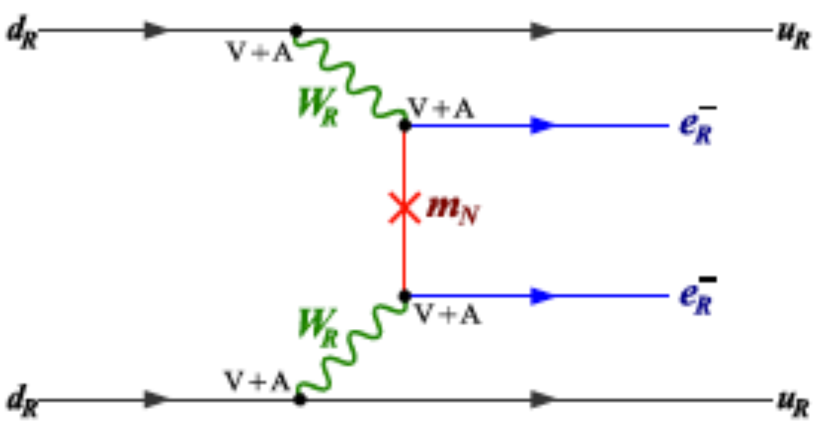
$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

- LNV dynamics at lower scale (Λ~TeV)

Higher dimensional operators become relevant

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

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



Looking into the blob

(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)

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

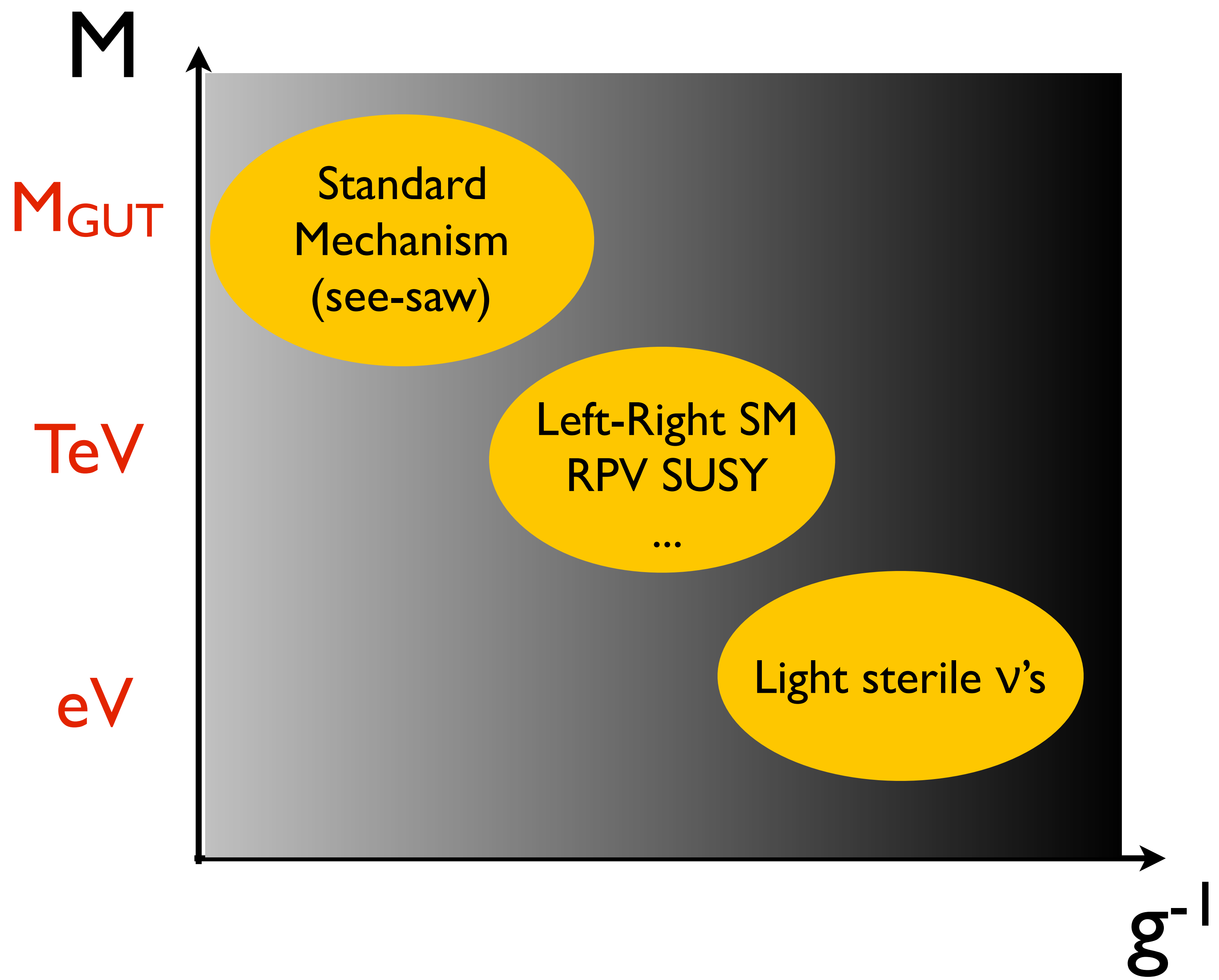
- LNV dynamics at very low energy (e.g. low-scale seesaw)

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

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 variety mechanisms, involving different scales (M) and coupling strengths (g)

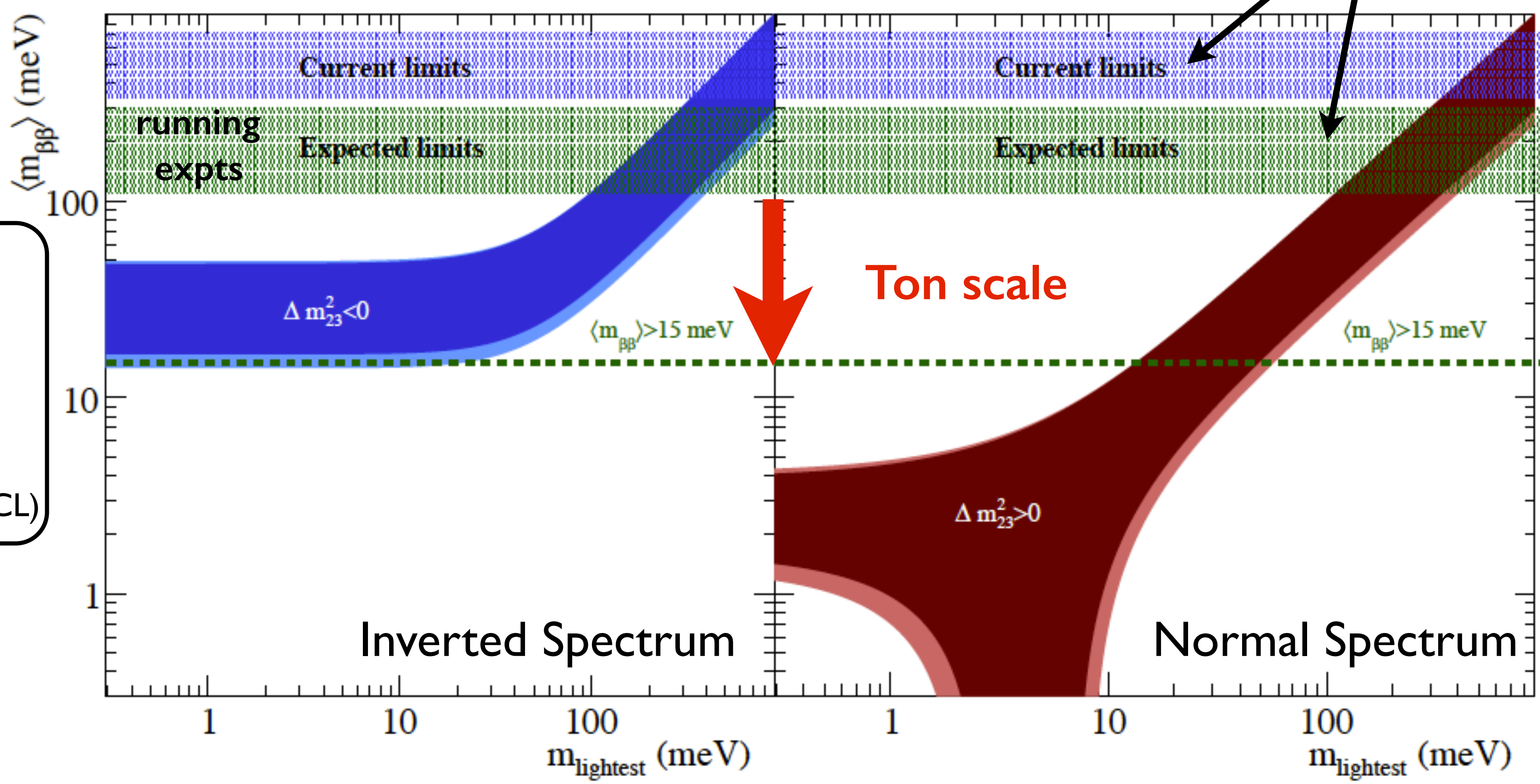


Standard mechanism

Assume most “pessimistic” values for nuclear matrix elements

Dark bands: unknown phases

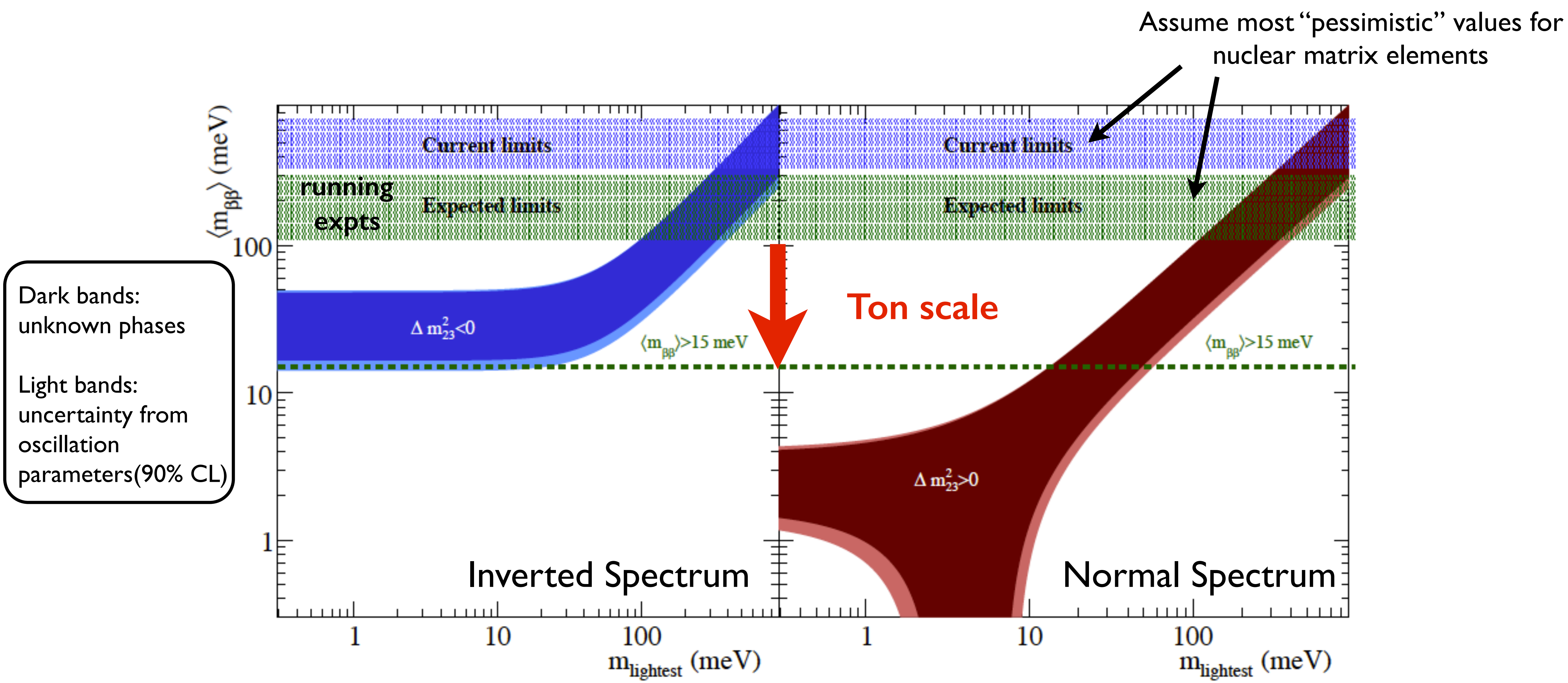
Light bands: uncertainty from oscillation parameters(90% CL)



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

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

Standard mechanism



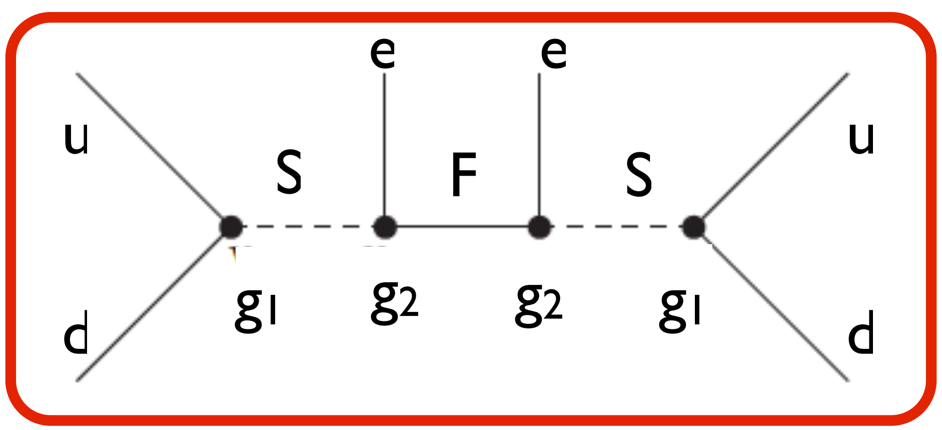
- Ton-scale experiment will make a discovery if spectrum has
  1. inverted ordering *or*
  2. $m_{lightest}$ > 50 meV (irrespective of ordering)

TeV-scale LNV

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

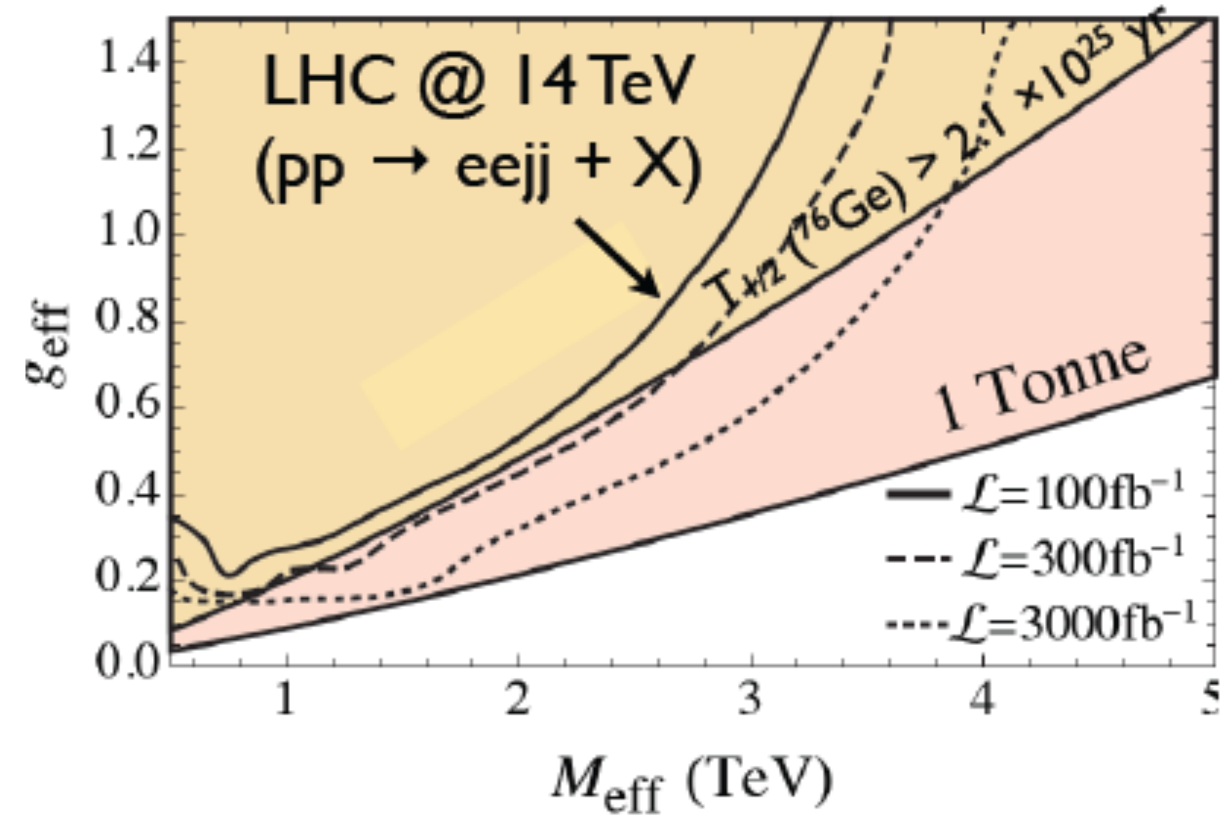
Simplified model ~ RPV-SUSY

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



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

Peng, Ramsey-Musolf, Winslow, 2015



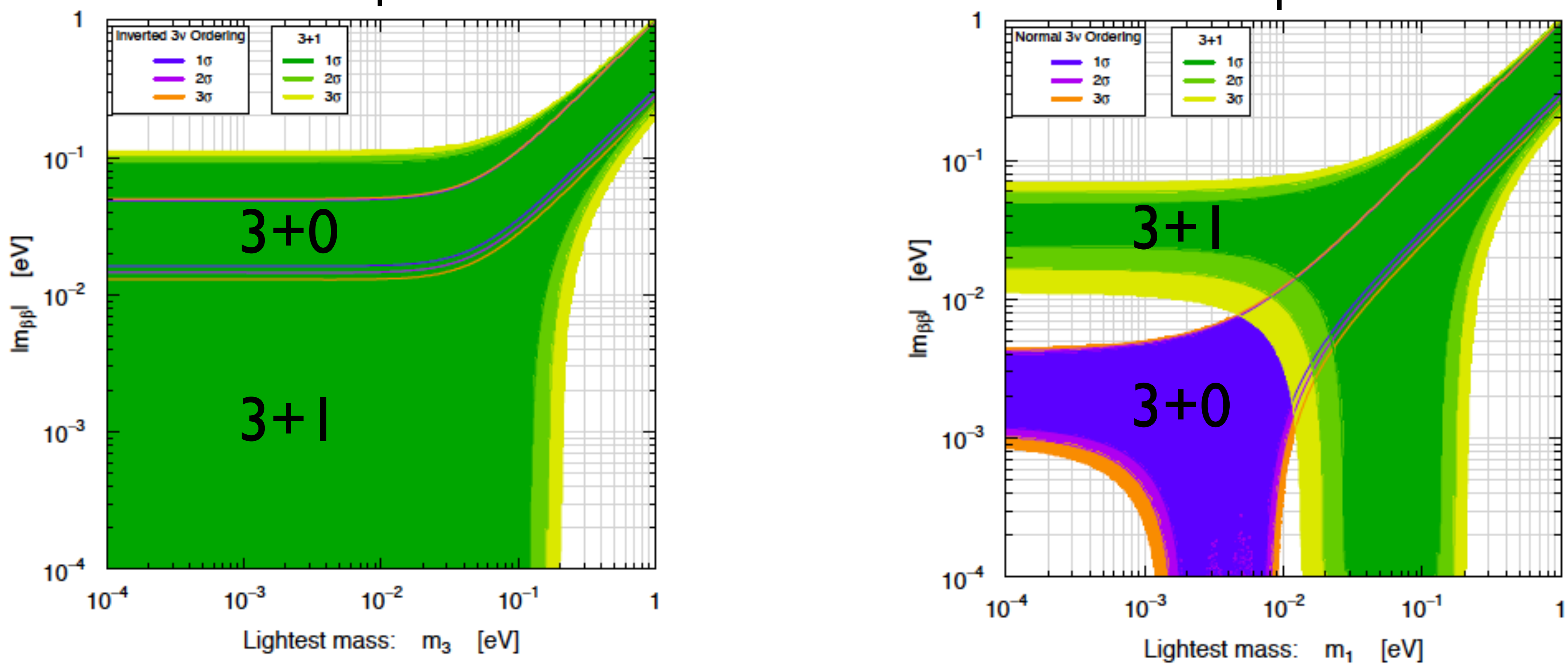
Ton-scale NLDBD significantly extends mass reach (multi TeV) and covers LHC-inaccessible regions

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



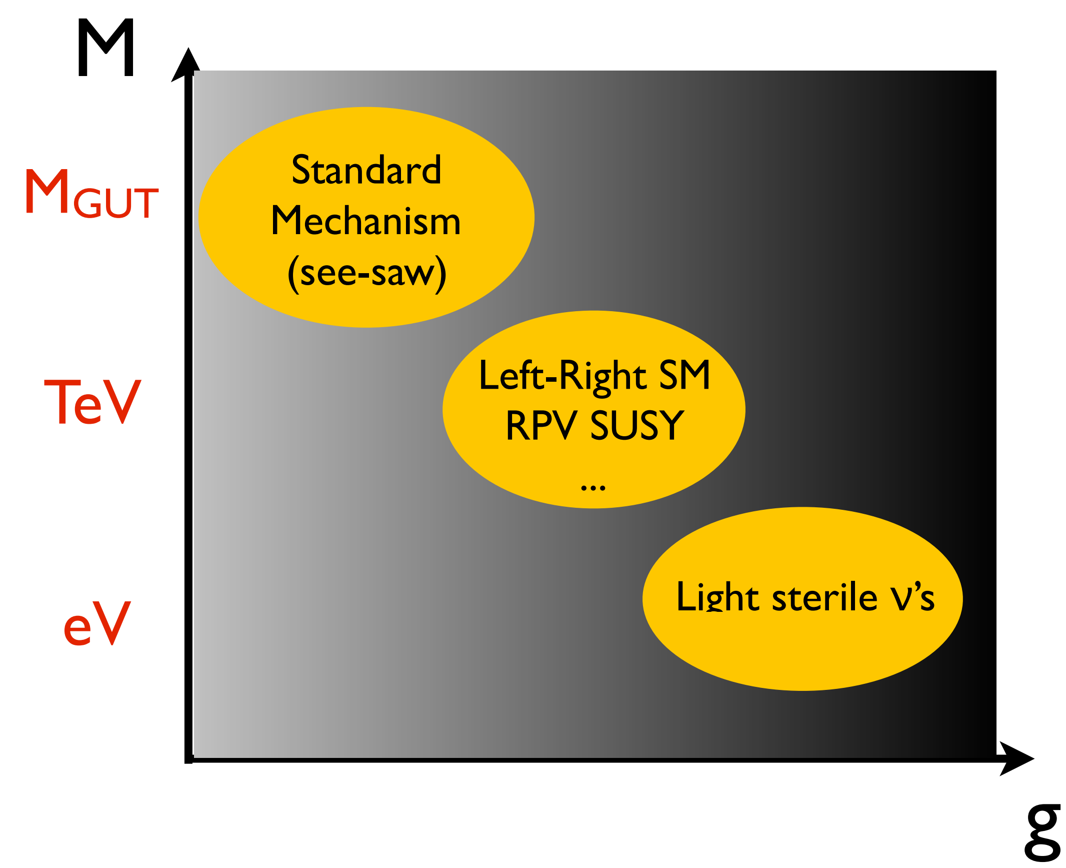
Giunti-Zavanin 2015

Usual phenomenology turned around!!

Summary on NLDBD

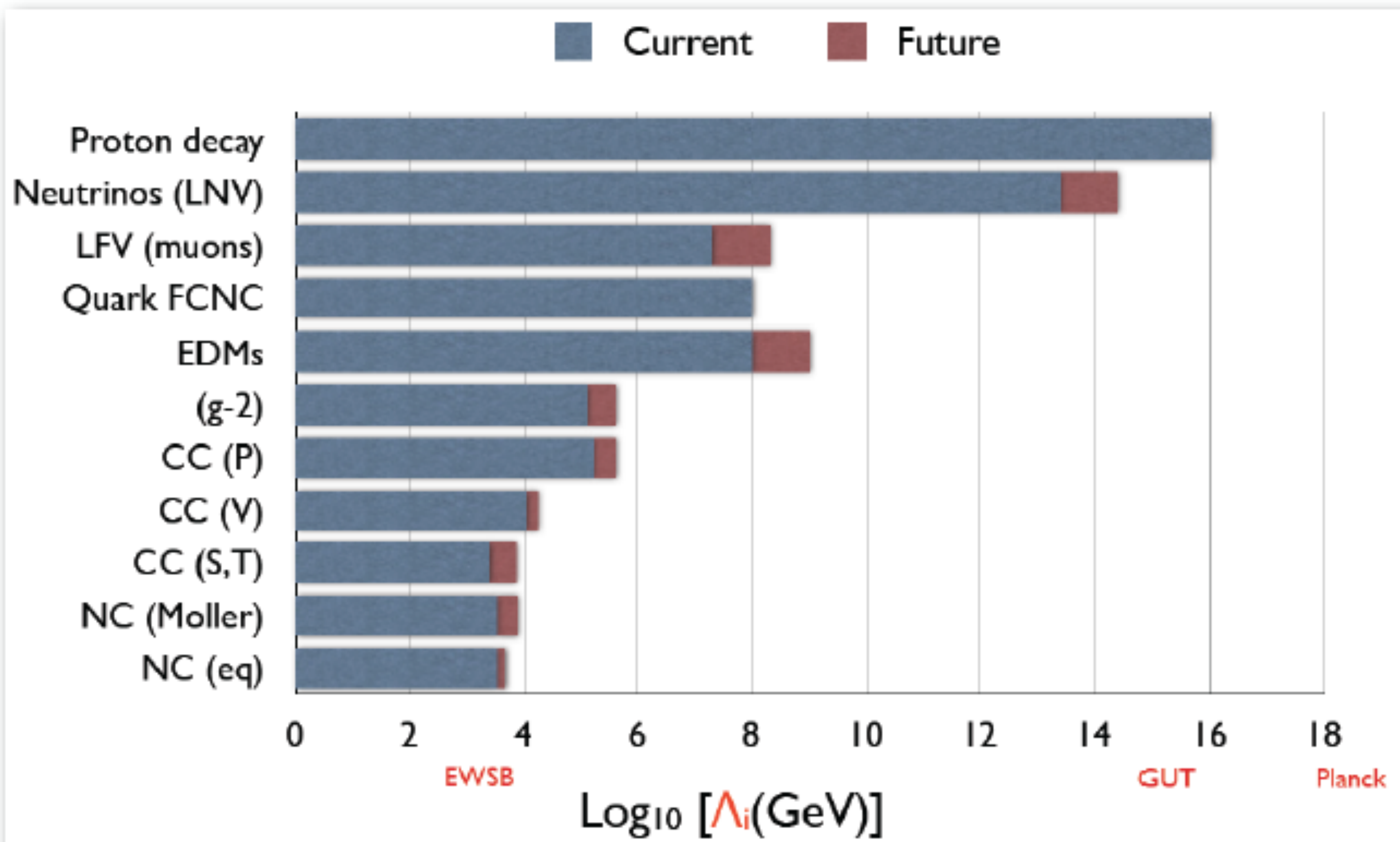
- NLDBD is the most powerful and comprehensive probe of Lepton Number Violation, sensitive to new physics over a vast range of scales, with far reaching implications

- Demonstrate Majorana nature of neutrino
- Probe new mass mechanism
- Cosmic baryon asymmetry

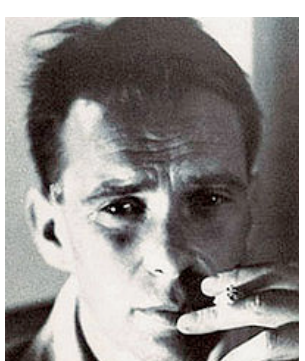


Conclusion

- Through the precision frontier Nuclear Physics plays a key role in the search for the "new Standard Model" and its symmetries
- Broad and vibrant experimental program, hope to get discoveries soon



Thank you!



A drawing by
Bruno Touschek

Backup

See-saw and leptogenesis

See-saw mechanism for m_ν

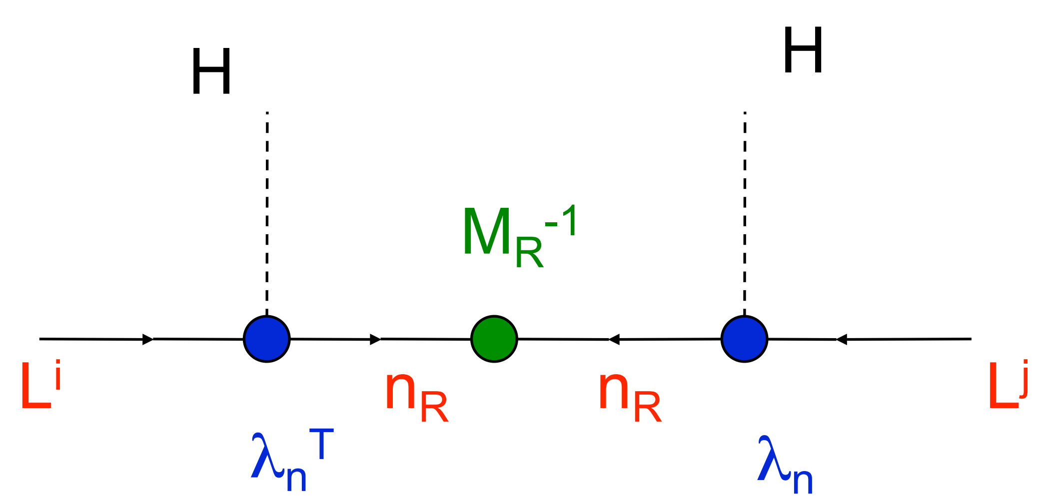
Type I for illustration

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

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

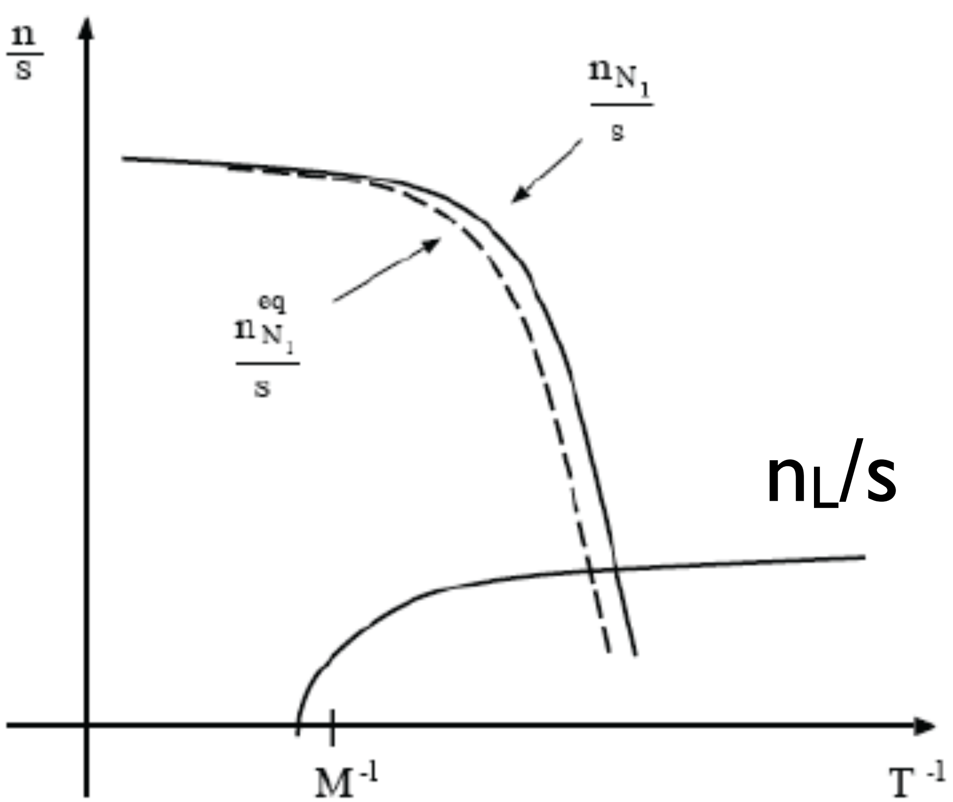
See-saw mechanism for m_ν

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

M_R : L violation
λ_ν : CP and L_i violation

1) C̸P and L̸ 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

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

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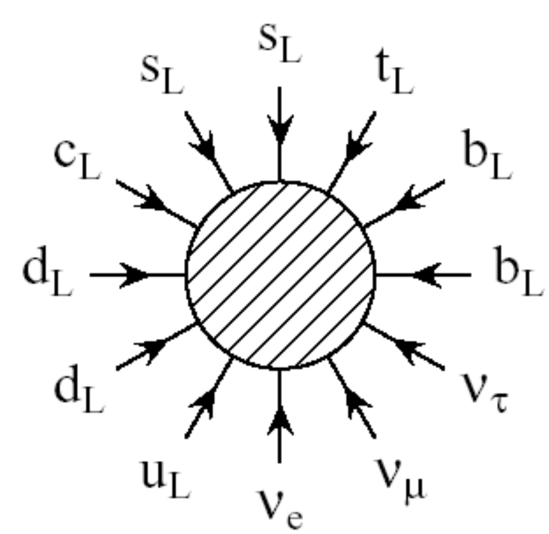
2) EW sphalerons $\Rightarrow n_B = - k\, n_L$

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



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

If CP & L_i violation is communicated to particles with mass Λ~TeV

Observable LFV

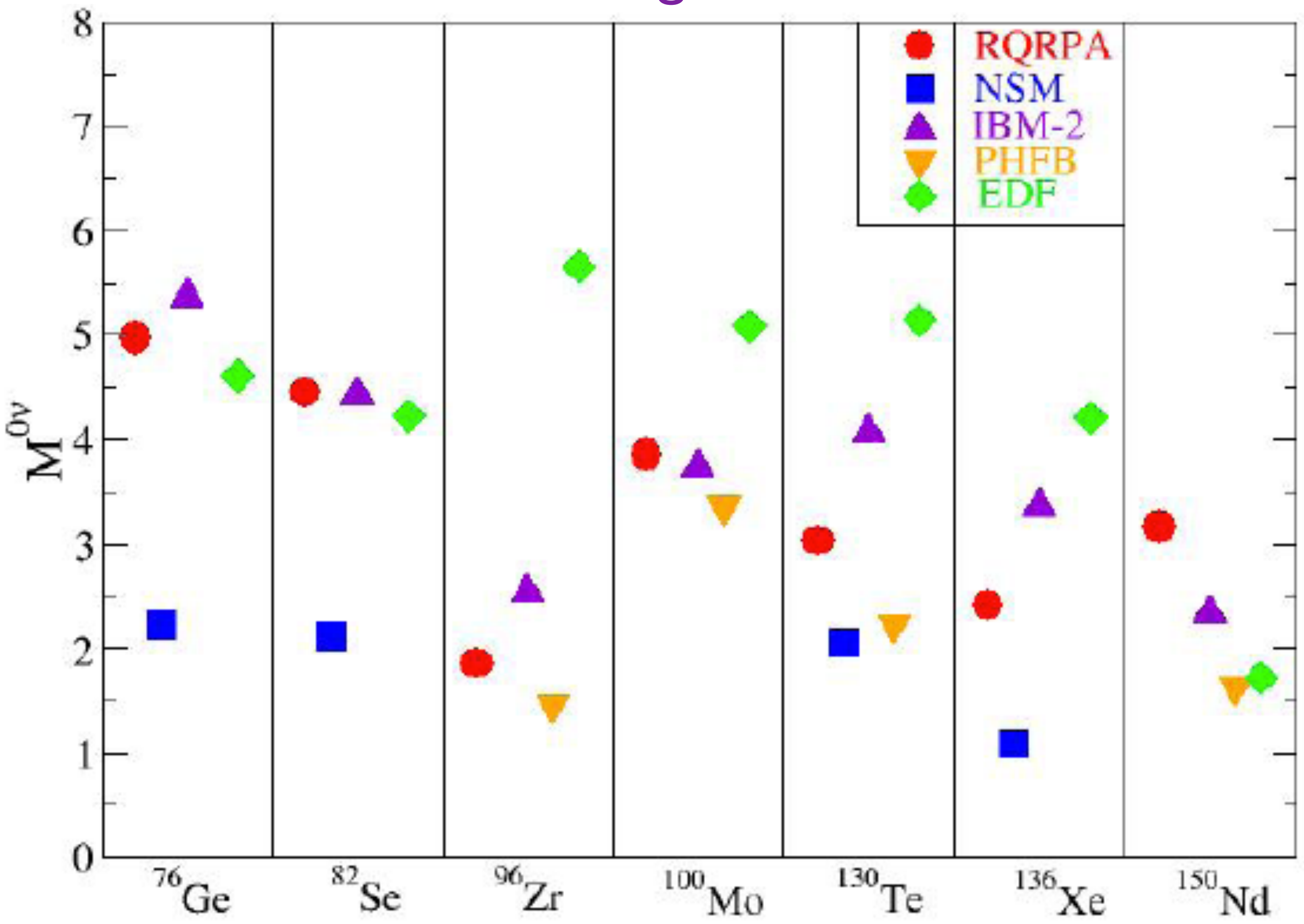
Observable lepton EDMs

The role of 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"

CPV at the hadronic level

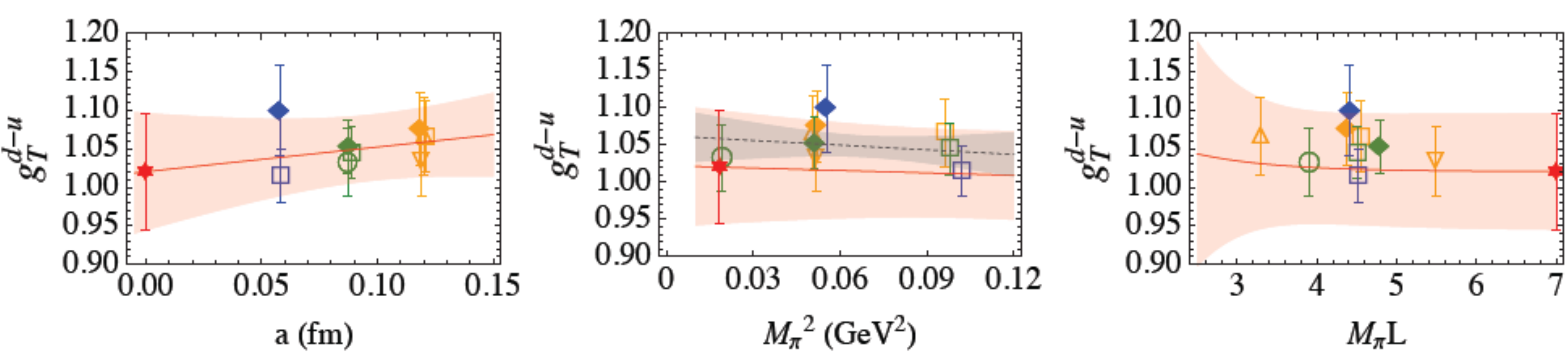
- Leading pion-nucleon CPV interactions characterized by few LECs

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

- Matching with lattice QCD (for quark EDM): 10% uncertainties

μ=1 GeV

$$d_n = -(0.22\pm0.03)d_u + (0.74\pm0.07)d_d + (0.0077\pm0.01)d_s$$



Lattice QCD calculation: Bhattacharya et al PRL 115 (2015) 212002 [1506.04196], PRD 92 (2015) 114026 [1506.06411]

CPV at the hadronic level

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

- Matching with QCD sum rules: 50% → 200% uncertainties

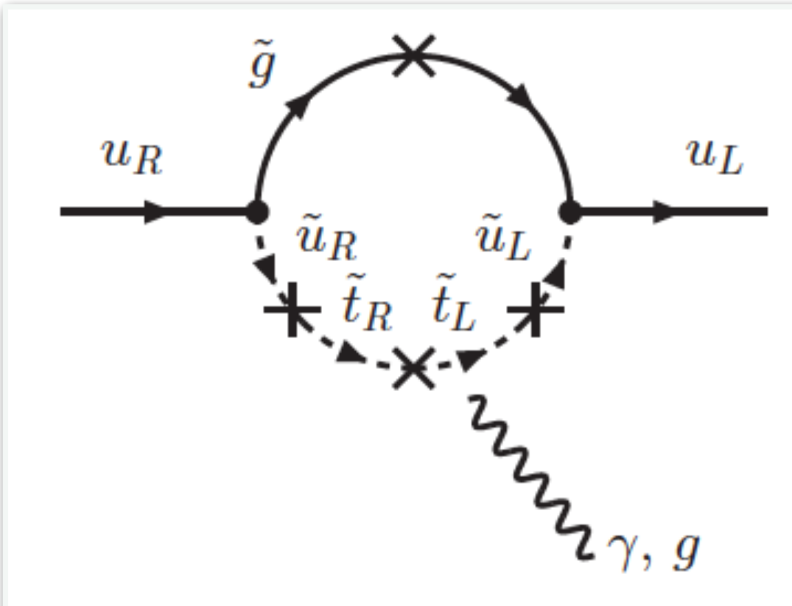
μ=1 GeV

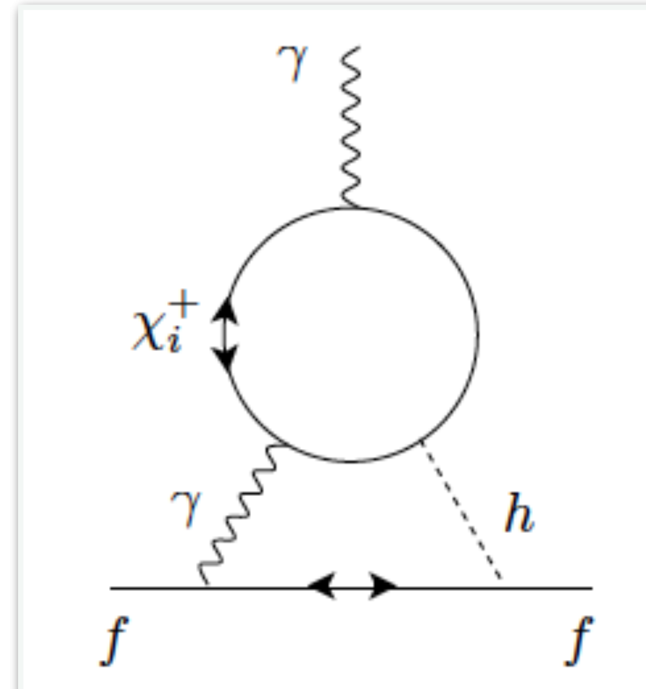
$$d_n = -(0.22 \pm 0.03) d_u + (0.74 \pm 0.07) d_d + (0.0077 \pm 0.01) d_s$$
$$-(0.55 \pm 0.28) e \tilde{d}_u - (1.1 \pm 0.55) e \tilde{d}_d \pm (50 \pm 40) e \, d_W$$

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

Pospelov-Ritz hep-ph/0504231 and refs therein

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 $|\mu|$

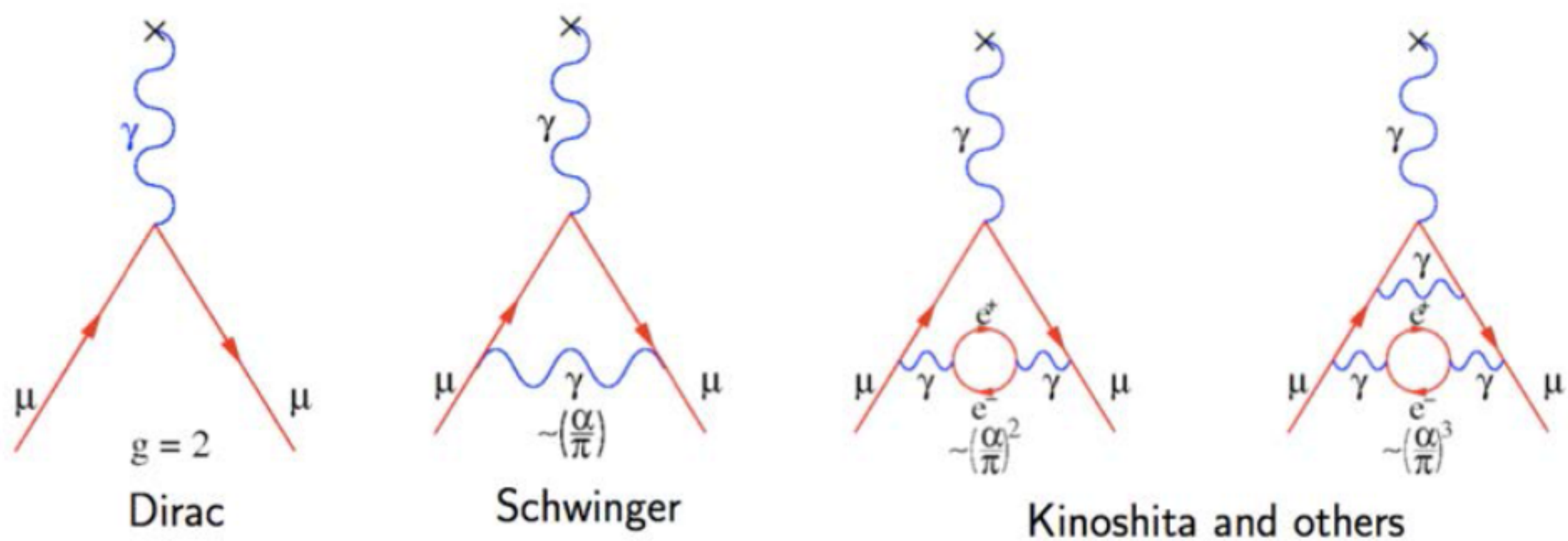
Muon “g-2”

D. Kawall

Lepton magnetic moments

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}, \qquad \vec{s} = \frac{\hbar}{2}\vec{\sigma}$$

- Dirac predicts g=2 in 1928
- 1947: Measurements find $g_e \neq 2$
- Schwinger calculated $g_e = 2(1 + a_e) \quad a_e = \frac{(g_e - 2)}{2} = \frac{\alpha}{2\pi} \approx 0.00116$



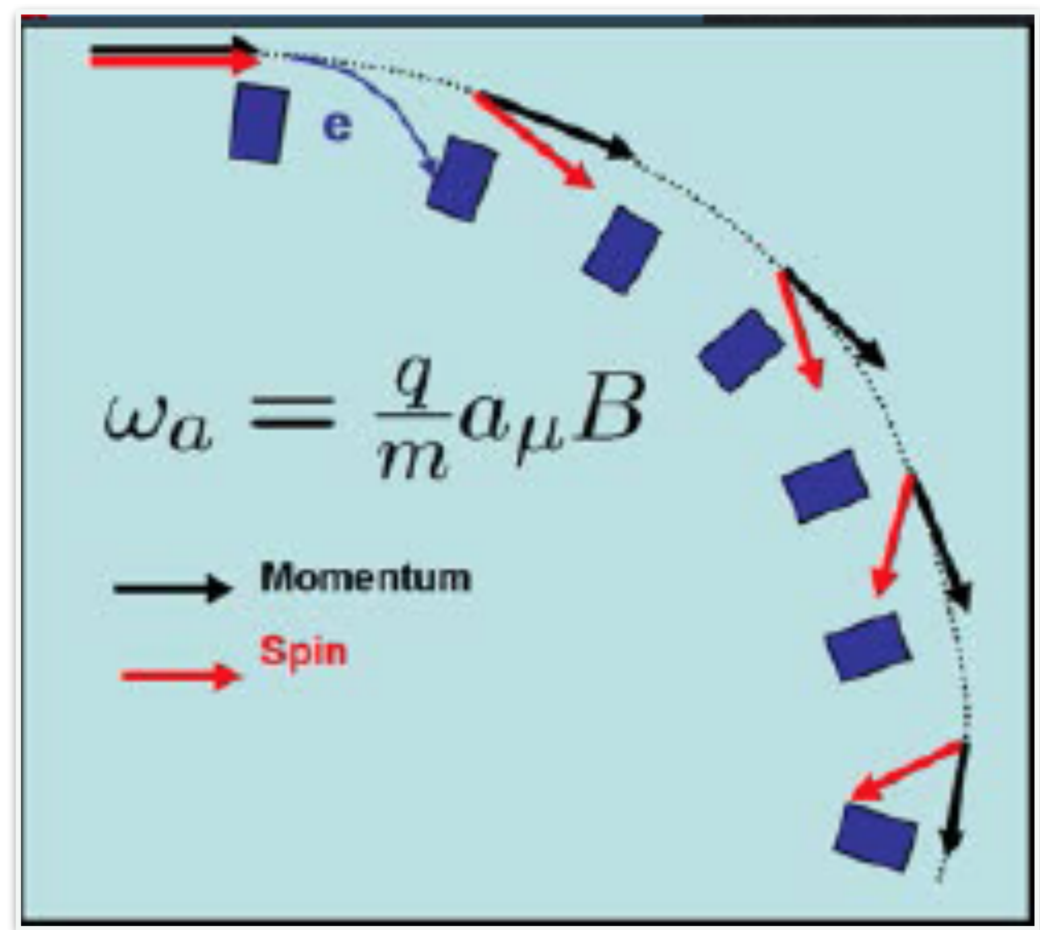
Great success of QED

D. Hertzog

- Current experimental precision: $\Delta g_e = 5.2\times 10^{-13}$ and $\Delta g_\mu = 1.2\times 10^{-9}$
    - g_e used to determine the electromagnetic coupling
    - g_μ used to challenge the SM!

- How is g_μ (a_μ) measured?
    - Exploit the fact that momentum and spin do not precess in the same way in a B field
    - Relative frequency ω_a proportional to (g-2)*B

$$\omega_C = \frac{eB}{mc\gamma}$$



$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

D. Hertzog

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  - g_e used to determine the electromagnetic coupling
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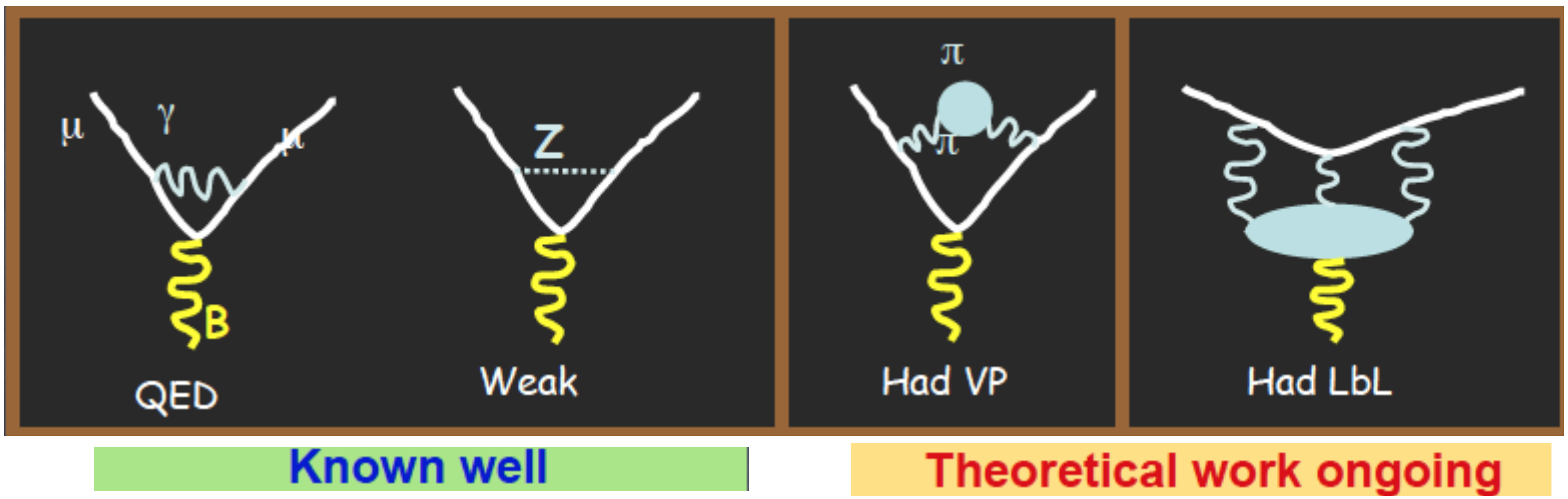
- At this level of precision, g_μ (a_μ) depends on loops from all Standard Model particles that couple to the muon



Known to 5 loops!
Kinoshita et al 2012

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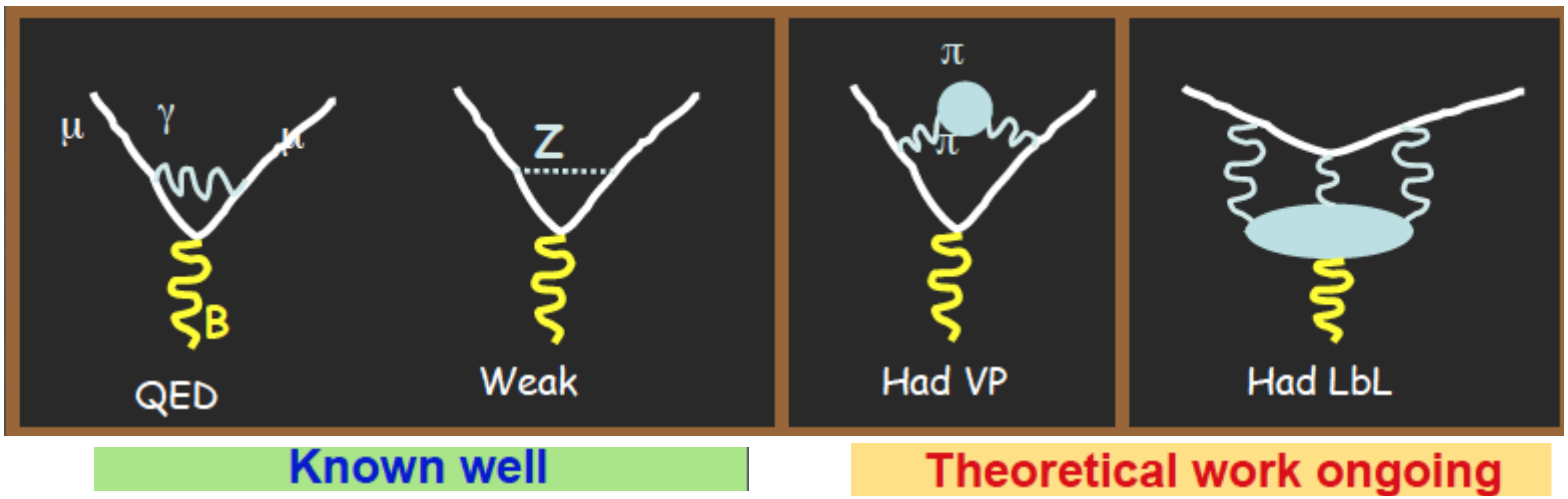

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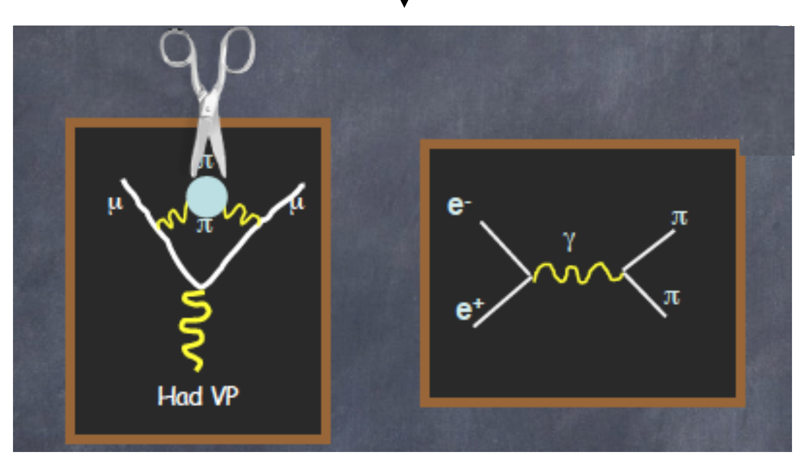

g-2 contribution linked to cross-section $e^+e^- \rightarrow$ hadrons

D. Hertzog

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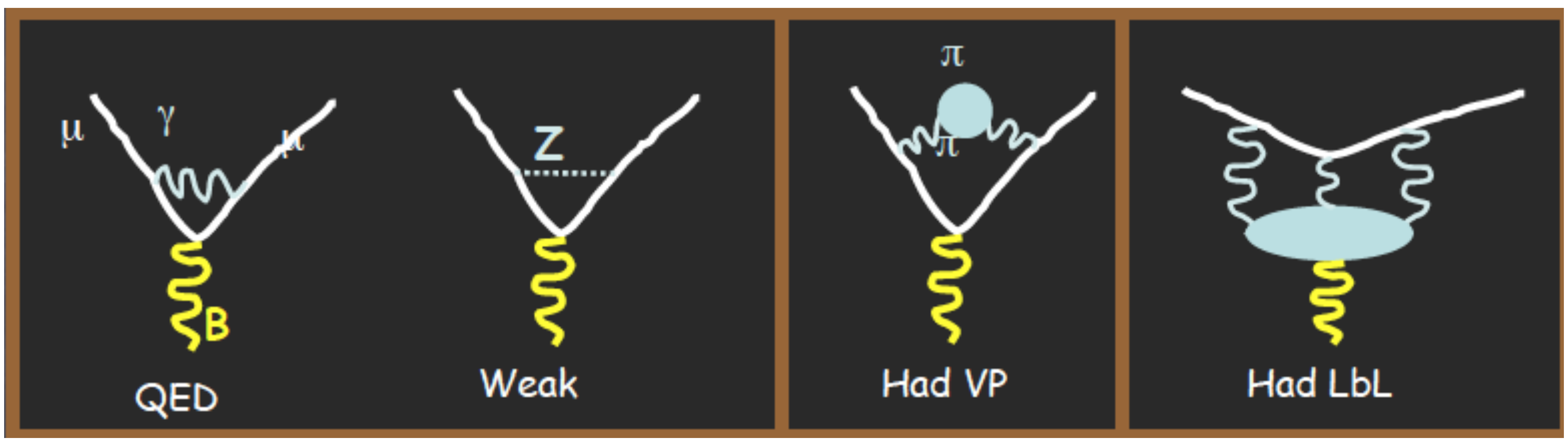
  - g_e used to determine the electromagnetic coupling
  - g_μ used to challenge the SM!

- At this level of precision, g_μ (a_μ) depends on loops from all Standard Model particles that couple to the muon



Known well

Theoretical work ongoing

- Anatomy:

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

D. Hertzog

Where are we?

- Hint of new physics

$$a_\mu = (g_\mu - 2)/2$$

$$a_\mu(\text{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$
$$a_\mu(\text{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

BNL E821 (2006)

$$\Rightarrow \Delta a_\mu = 287(80) \times 10^{-11}$$

3.6σ discrepancy

Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

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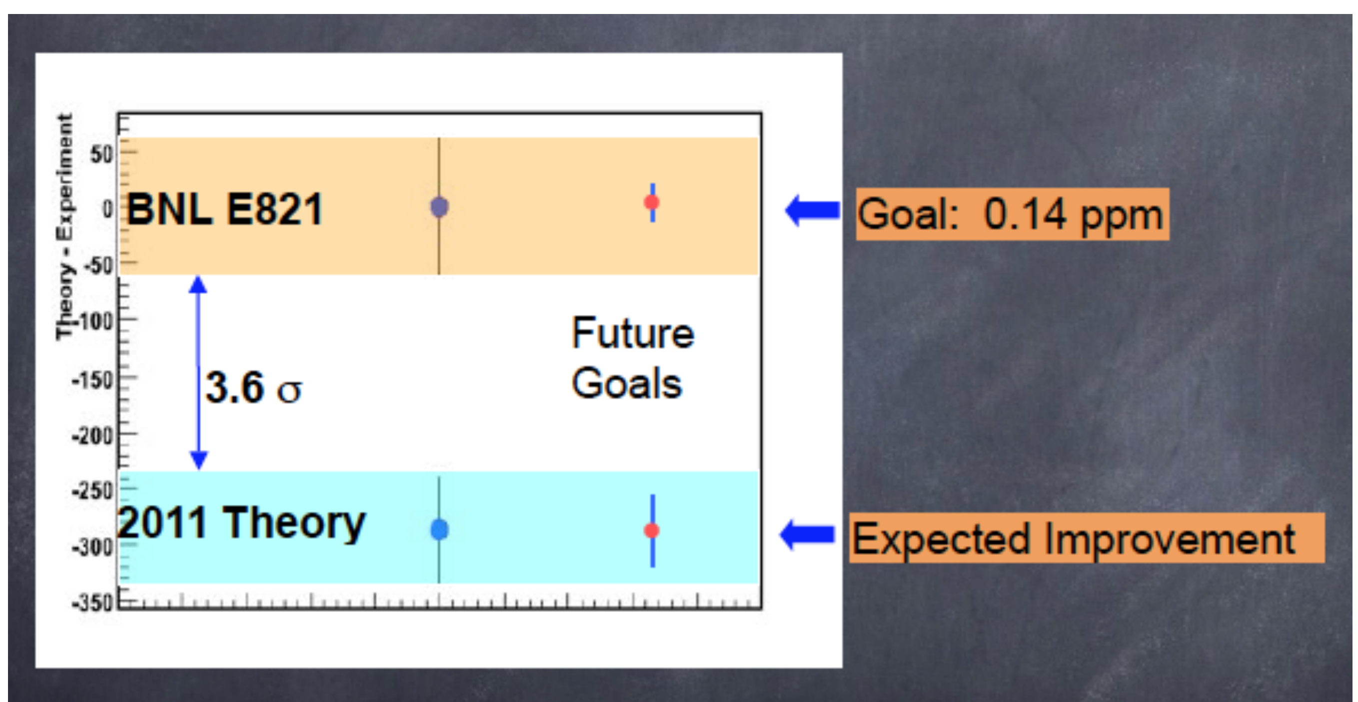

New g-2 at Fermilab will improve uncertainty factor of 4

D. Hertzog

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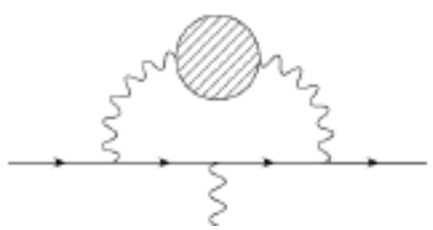
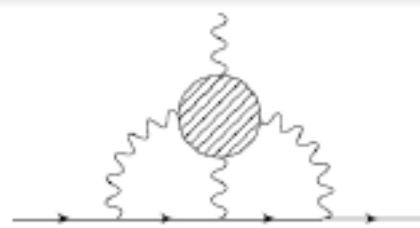




Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

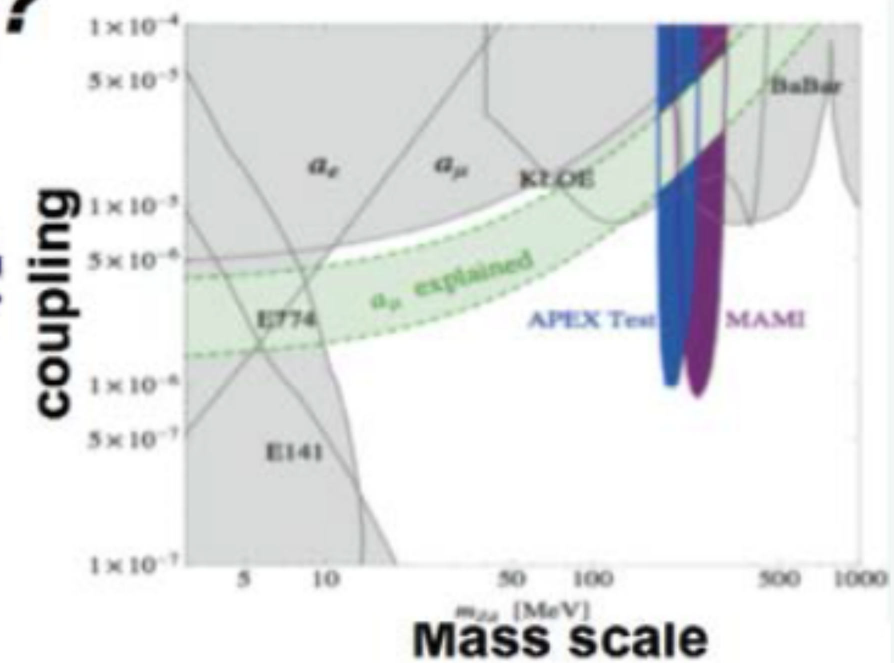
- Probe BSM mag. dipole operators $\mathcal{L} \xrightarrow{\text{EWSB}} y_\mu \frac{v}{\Lambda^2}\, \bar{\mu}\, \sigma^{\alpha\beta}\, \mu\, F_{\alpha\beta}$

- 3.6σ discrepancy $\Rightarrow \Lambda/\sqrt{y_\mu} \sim 140$ TeV $\quad (\Lambda \sim 3.5$ TeV$)$

D. Hertzog

Impact on models

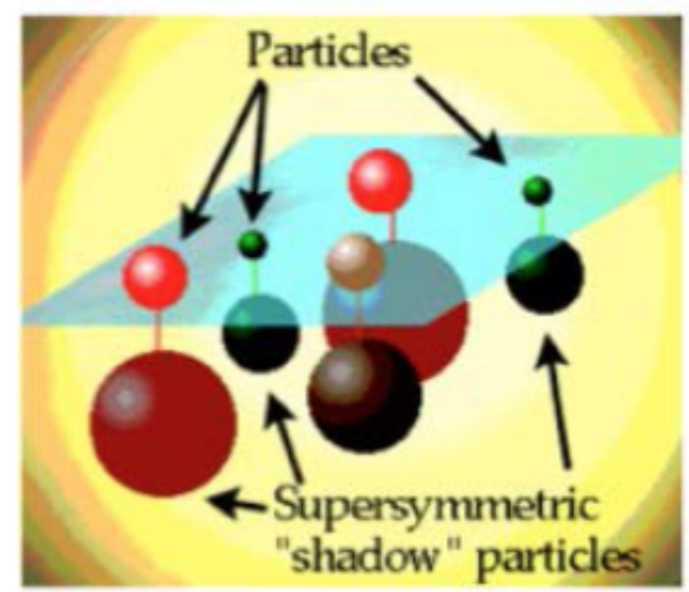
New physics enters through *loops. What might the g-2 signal imply?*



- **Dark Photons**
  - **light new vector particles V kinetically mixed with the photon**
- **Supersymmetry**

$$a_\mu^{SUSY} \approx 130\times10^{-11}\left(\frac{100\,\mathrm{GeV}}{M_{SUSY}}\right)^2 \tan\beta\,\mathrm{sign}(\mu)$$

Difficult to measure at the LHC



- **The Uninvented**
  - **Perhaps the most important of all**

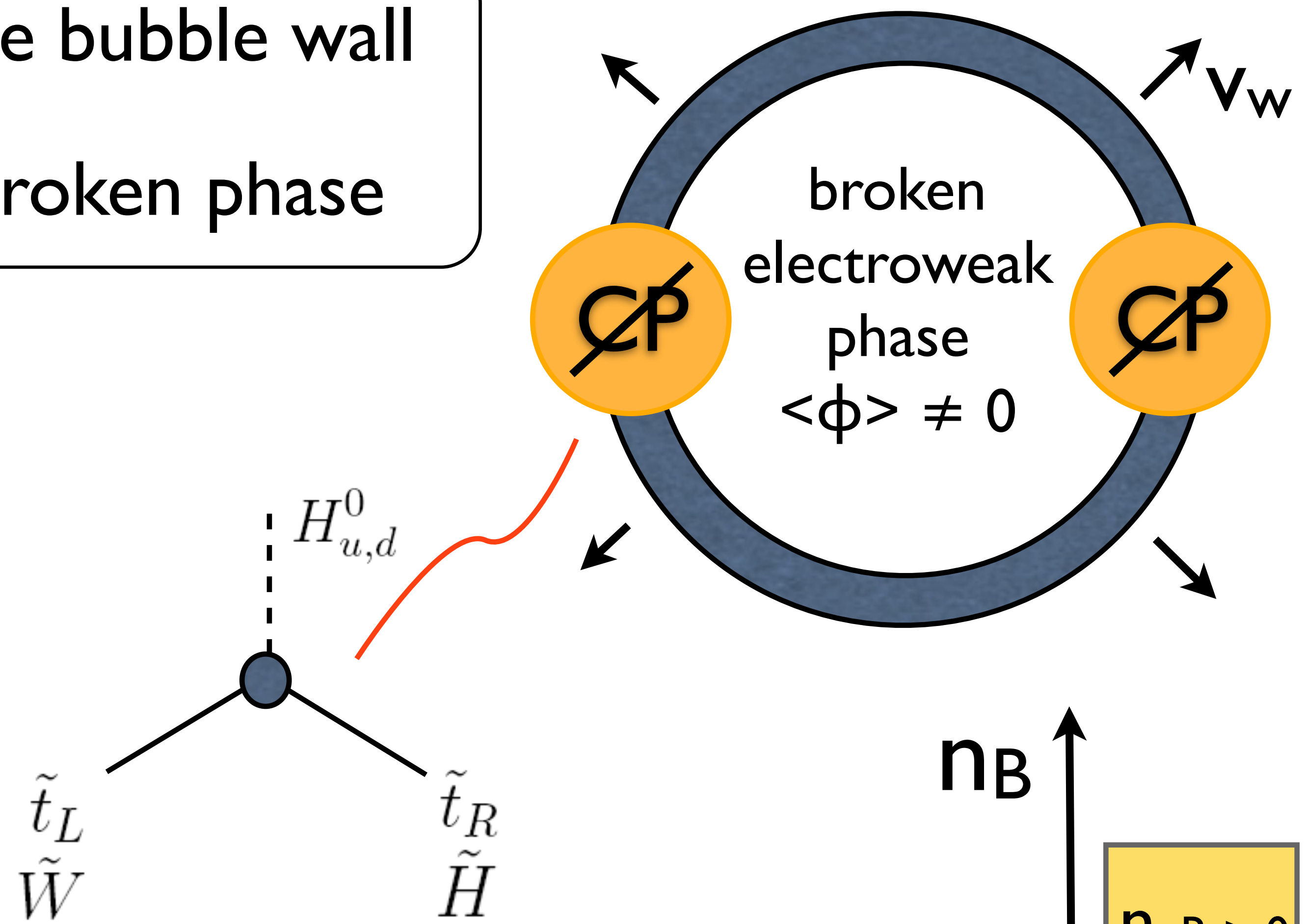
Weak scale baryogenesis mechanism

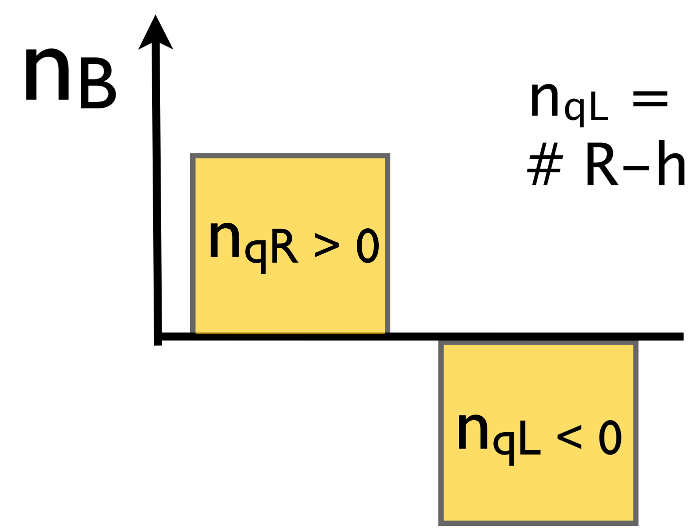
How does it work?

Kuzmin-Rubakov-Shaposhnikov
Cohen-Kaplan-Nelson
....

$\not{CP}$ in the bubble wall

$\not{B}$ in unbroken phase





n_{qL} = # L–handed quarks – # R–handed antiquarks

1) Bubbles of broken electroweak phase nucleate and expand

2) *Charge asymmetries (i) develop through CPV interactions with Higgs;*
(ii) diffuse in unbroken phase and get converted into L-handed fermionic charge (n_L)

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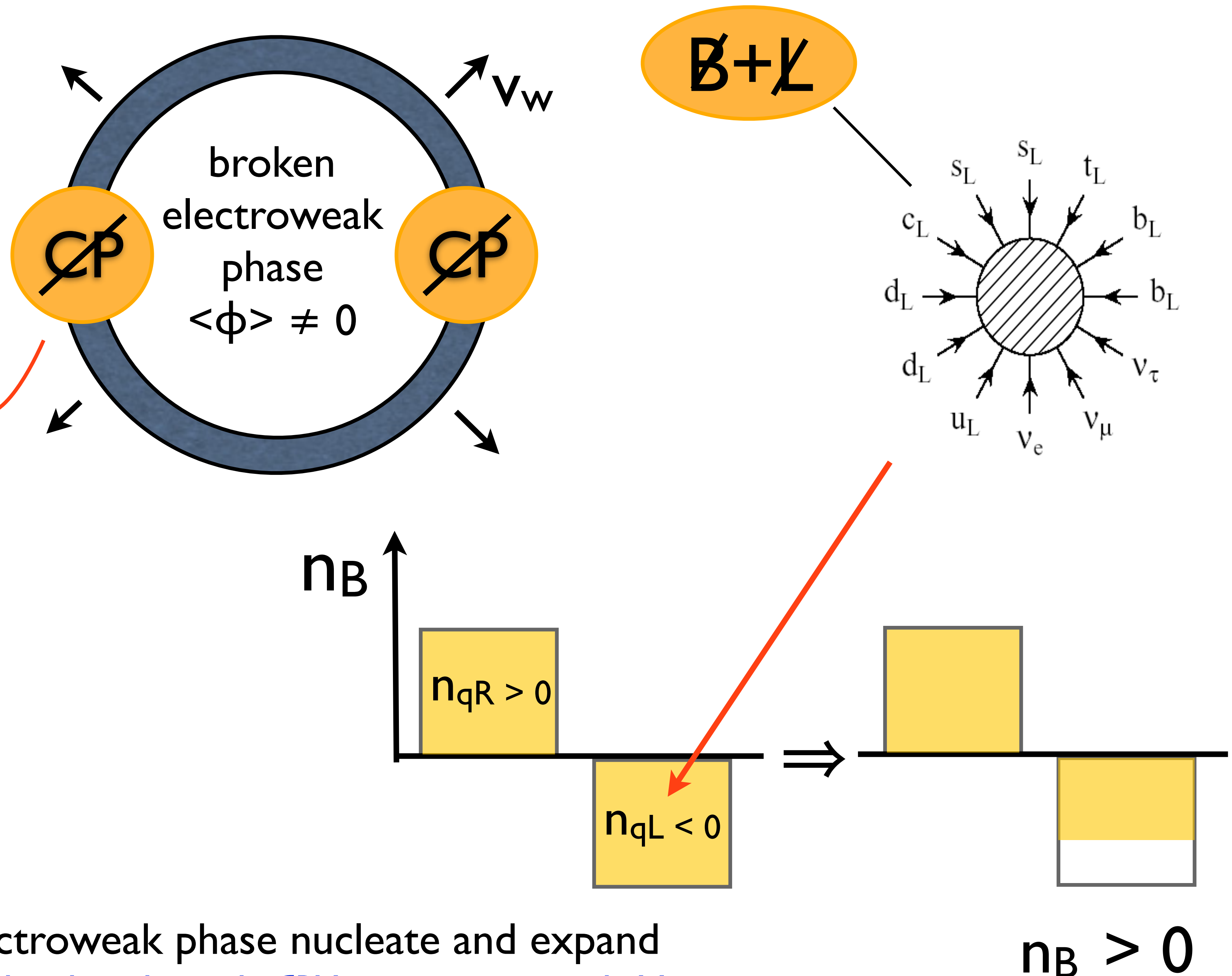

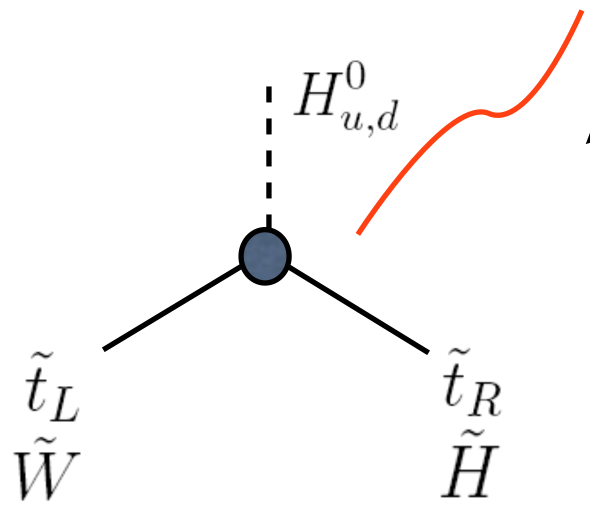

1) Bubbles of broken electroweak phase nucleate and expand

2) *Charge asymmetries (i) develop through CPV interactions with Higgs;*
(ii) diffuse in unbroken phase and get converted into L-handed fermionic charge (n_L)

3) Sphalerons convert excess of n_L into net baryon number

4) Baryon asymmetry is captured by expanding bubble wall and "freezes in"