T-odd Correlations in Beta Decay: Theory

An Overview

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"Theoretical issues and experimental opportunities in searches for time reversal invariance violation using neutrons"

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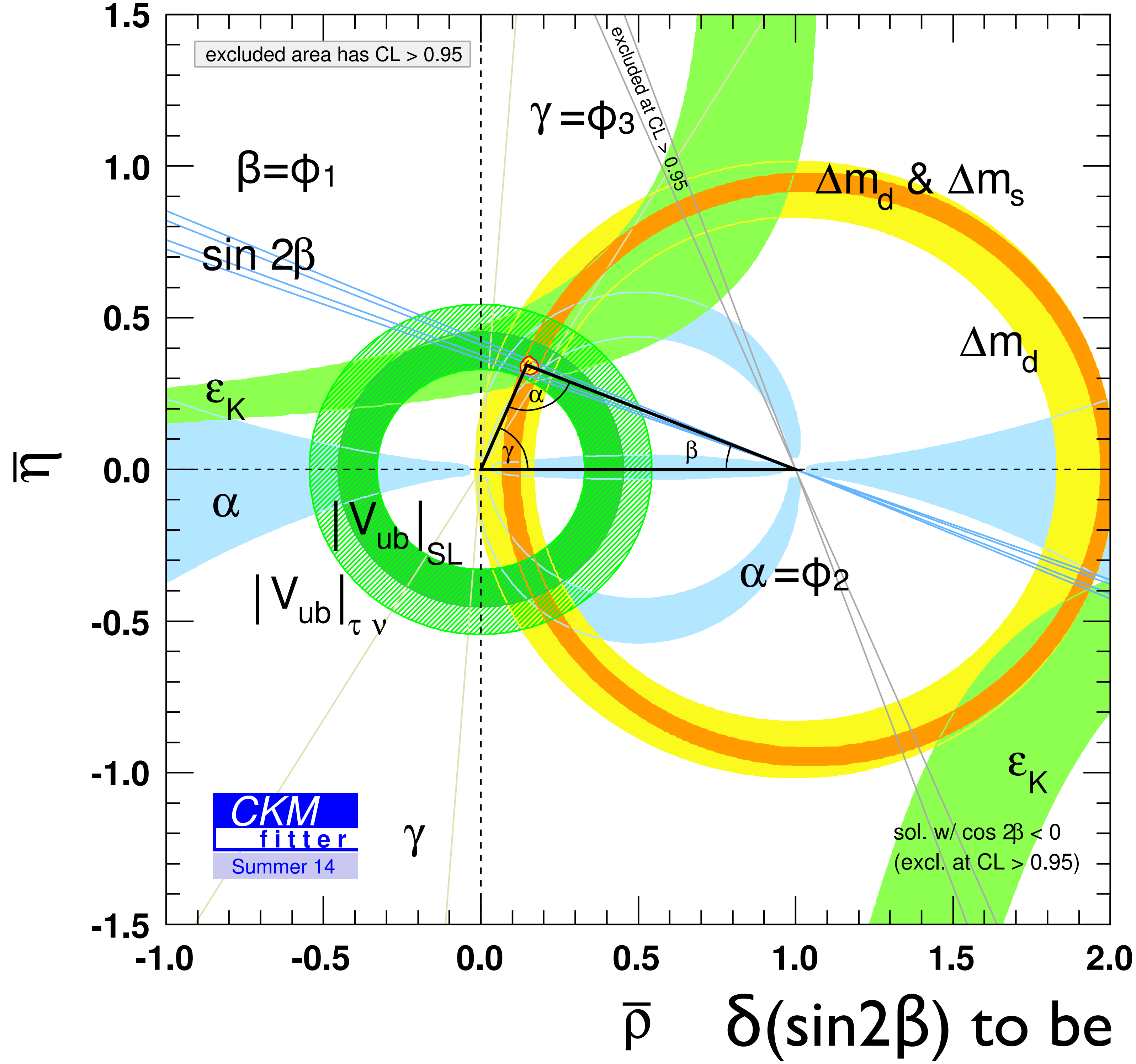
Beyond the CKM Paradigm?

The CKM matrix describes the flavor and CP violation observed in charged-current processes



[CKM Fitter: Charles et al., 1501.05013]

N.B. lattice QCD plays a key role!

Global fit glosses over whether $S(\phi K_S) \neq S(\psi K_S)$, etc.

[Golob, Trabelsi, & Urquijo (Belle II), 2015]

$\delta(\sin 2\beta)$ to be reduced ~10x at Belle II!

Some T-odd Observables

"D versus d"

A permanent electric dipole moment $\vec{d} \propto \vec{S}$

$$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

Maxwell Equations… **MDM: P even, T even**
EDM: P odd, T odd

→ under CPT, CP is also broken

In contrast, a "T-odd" decay correlation can only be **motion-reversal odd**: it can be mimicked by FSI….

In β decay these are controlled by electromagnetism & can be computed

T-odd Decay Correlations

In neutron β decay, triple product correlations are spin dependent. Major experimental efforts have recently been concluded.

D term [Mumm et al., 2011; Chupp et al., 2012]

D probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$ and is T-odd, P-even.

$D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$ (best ever!)
D_{FSI} is well-known (N^3LO) and some $10\times$ smaller. [Callan and Treiman, 1967; Ando et al., 2009]
D limits the phase of C_A/C_V...

R term [Kozela et al., 2009; Kozela et al., 2012]

Here the transverse components of the electron polarization are measured.

R probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \hat{\boldsymbol{\sigma}})$ and is T-odd, P-odd.
N probes $\boldsymbol{J} \cdot \hat{\boldsymbol{\sigma}}$ and gives a non-zero check.

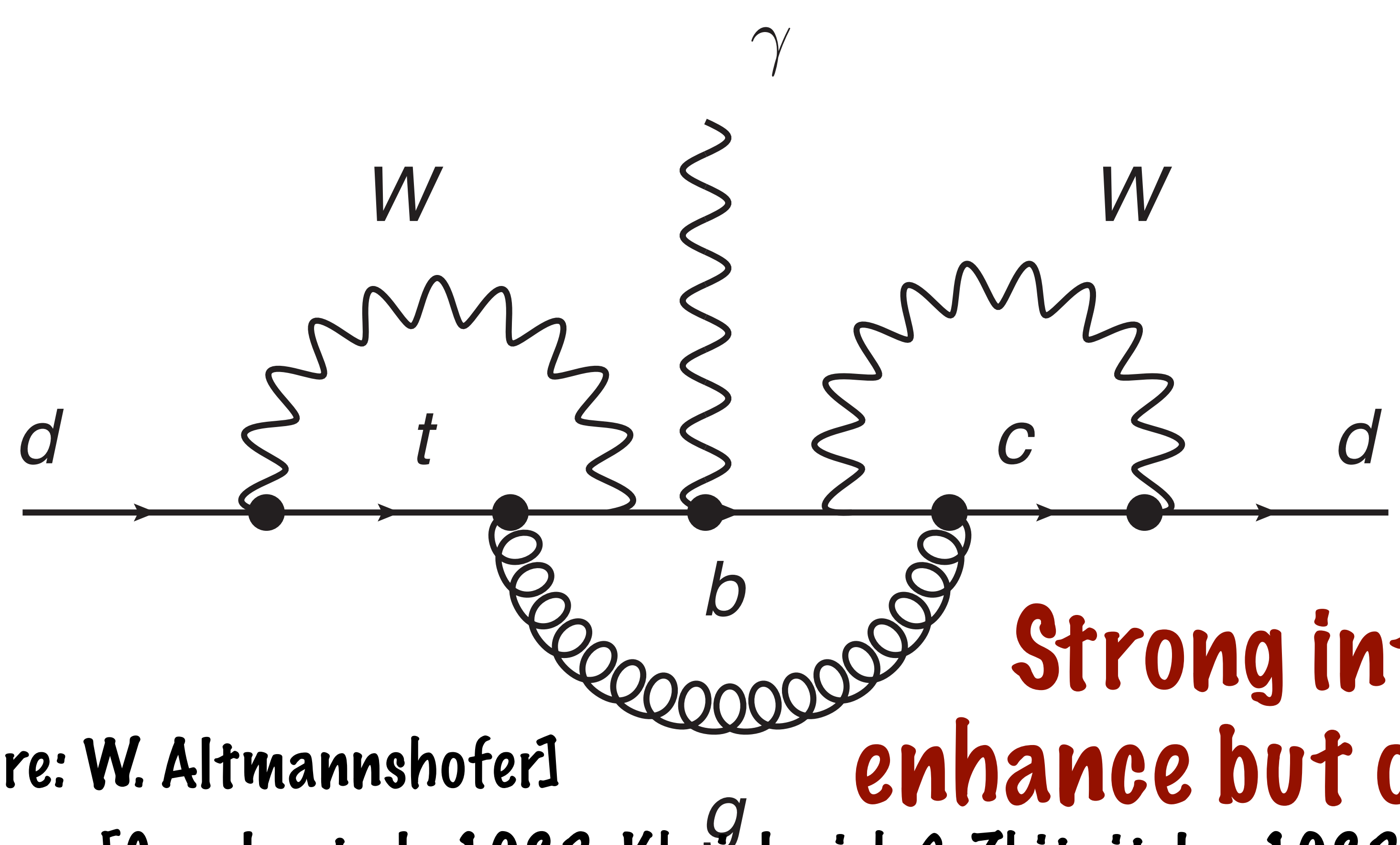
$R = 0.004 \pm 0.012(\text{stat}) \pm 0.005(\text{sys})$
R limits the imaginary parts of scalar, tensor interactions...

In contrast, in radiative β-decay one can form a T-odd correlation from momenta alone, $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$, so that the spin does not enter.

EDMs for New Sources of CPV

The contribution from the CKM matrix first appears in three-loop order!

The EDM is flavor diagonal, so that…
at one-loop order no "Im V…" piece survives
at two-loop order the "Im V…" piece vanishes [Shabalin, 1978]
at three-loop order the gluon-mediated terms dominate [Khriplovich, 1986]



[figure: W. Altmannshofer]

$|d_d| \sim 10^{-34}$ e-cm

[Czarnecki & Krause, 1997]

Inaccessibly small!

Strong interaction effects can enhance but only by $10^{2\ \mathrm{or}\ 3}$ in neutron

[Gavela et al., 1982: Khriplovich & Zhitnitsky, 1982; Mannel & Uraltsev, 2012;... Seng, 2015]

Today

What kinds of new physics models can generate a "T-odd" decay correlation and not an appreciable EDM (nor a signature at a high energy collider?)

To what extent are the two sorts of measurements complementary?

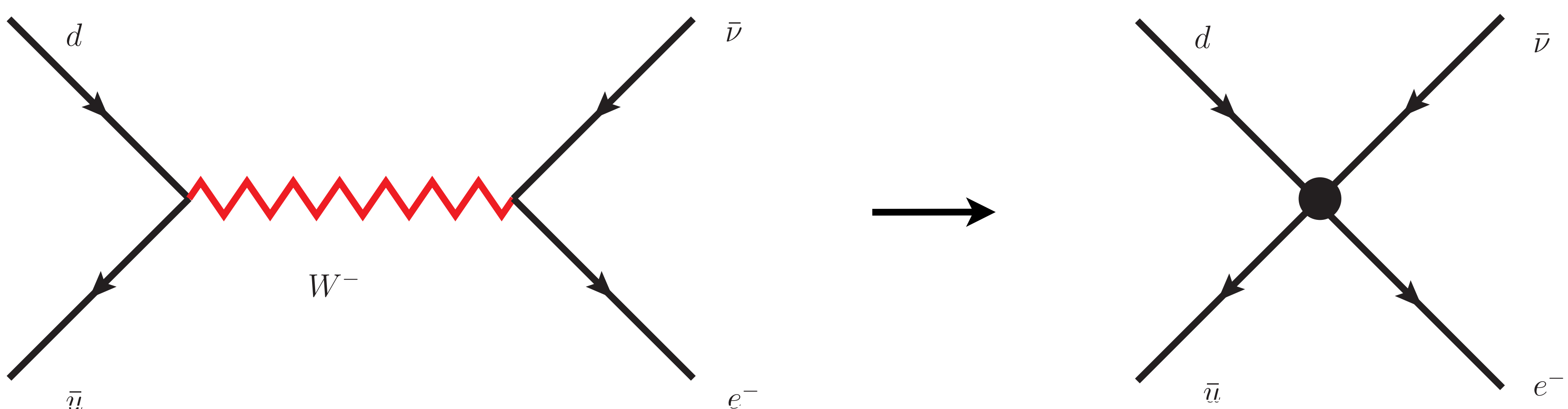
How well can the FSI that generate the T-odd correlations be calculated? Can new physics modify these predictions, too?

A Common Thinking

New physics can (only) appear at high energy

In this case, increasing the precision of a low-energy measurement translates into ever higher energy reach

E.g., enter the charged weak current of the SM…



[dim 6 operator]

$$G_F \sim g^2/M_W^2$$

implying probes for new physics via tests of lepton flavor universality or of the V-A law or ….

Analysis Framework

!!

Suppose new physics enters at energies beyond a scale Λ

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimension D>4

Symmetries guide their construction [Weinberg, 1979]

We impose $SU(2)_L \times U(1)$ gauge invariance on the operator basis (flavor physics constraints)

New physics can enter as (i) new operators or as (ii) modifications of c_i for operators in the SM

cf. non-V-A tests with tests of CKM unitarity

New High Energy or Low Energy Physics (or Neither)?

Much discussion of nature of new physics at E > Λ, i.e., of low energy consequences of $\Lambda_{CPV} >> \Lambda_{SUSY}$, etc.

Yet new physics at E < Λ could also be appreciable, nor need it require a particular energy scale to appear

E.g., the following term can appear within QCD

$$\mathcal{L}_\theta = \frac{g^2}{32\pi^2}\theta_{\rm QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

as can a similar term from the quark masses, so that

$$\theta_{\rm QCD} \Longrightarrow \bar{\theta} = \theta_{\rm QCD} + \theta_{\rm Yukawa}$$

But the experimental limit on d_n implies $\bar{\theta} < 10^{-10}$

E.g., also enter the right-handed ν, or the axion a….

Theoretical Framework

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\rm SM} + \frac{1}{v^2} \sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

Radiative correction*!

$$\begin{aligned}
\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \Big(1 + \delta_\beta\Big)\ \bar{e}\gamma_\mu (1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\
+ & \quad \epsilon_L\ \bar{e}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1-\gamma_5) d + \tilde{\epsilon}_L\ \ \bar{e}\gamma_\mu (1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\
+ & \quad \epsilon_R\ \ \bar{e}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1+\gamma_5) d\ +\ \tilde{\epsilon}_R\ \ \bar{e}\gamma_\mu (1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1+\gamma_5) d \\
+ & \quad \epsilon_S\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d\ +\ \tilde{\epsilon}_S\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- & \quad \epsilon_P\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ & \quad \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d\ +\ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5) d \\
+ & \quad \text{h.c.}\ .
\end{aligned}$$

*[Sirlin, 1974, 1978, 1982; Marciano & Sirlin, 1986, 2006; Czarnecki, Marciano, & Sirlin, 2004]

Note right-handed neutrinos appear explicitly

QCD (hadron matrix elements) also play a key role!

Are new particles invisible or merely feeble at low energies?

New Low or High Energy Physics?

How can these possibilities be distinguished?

[Le Dall, Pospelov, and Ritz, 2015]

Consider the ν mass: it can come from...

- a dimension-five operator (Weinberg)

N.B. not "UV complete" — new high E BSM is required!

→ $|B - L|$ violating!

- introducing a right-handed neutrino and using the Higgs mechanism

This in itself is UV complete.

But which mechanism operates?

Or do both?

But only the one with B-L violation allows 0 ν ββ decay

High or Low Energy New Physics?

The muon g-2 anomaly

$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{\mathrm{th}} = (287 \pm 80) \times 10^{-11}$$

[Jegerlehner and Nyffeler, 2009]

$$\vec{\mu}_\mu = \frac{e}{2m_\mu}(1 + a_\mu)\vec{\sigma}$$

[Czarnecki and Marciano, 2001]

could arise for either high or low E BSM

[Fayet, 2001; Gninenko & Krasnikov, 2001; Pospelov, 2009]

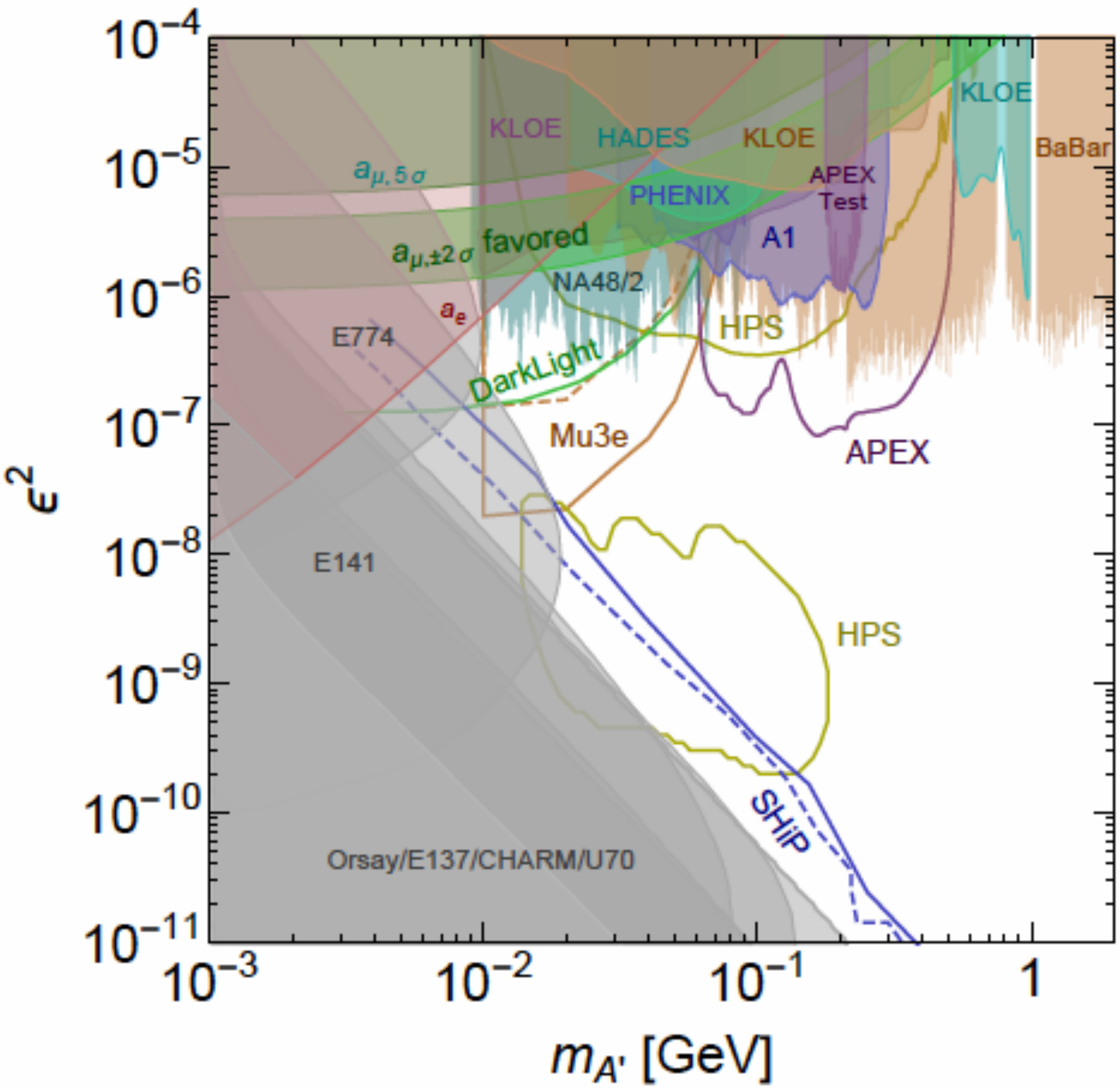
Models with new weak scale physics can also be tested at the LHC [Freitas et al., 2014]

A' mixing models with no invisible decays have now been ruled out [BaBar, 2014 & NA48/2, 2015]

Dark Photon Decays to Visibles (Only)

Exclude a "dark" explanation of the muon g-2 anomaly

[Pospelov, 2009]



But this may only speak to our assumptions…

Gauge Theories of the Hidden Sector

Minimal ($U(1)_X$) Extensions of the SM

Consider the dark photon... (with kinetic mixing)

$$\mathcal{L}_{A'} = \frac{\varepsilon}{2} F^{Y\,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^{\mu} A'_{\mu}$$

Diagonalization and field definition yields

$$A^\mu \longrightarrow A^\mu - \varepsilon A'^\mu \text{ but } Z - A' \text{ mixing } \mathcal{O}(\varepsilon m_{A'}^2 / M_Z^2)$$

{Bjorken, Essig, Schuster, and Toro, 2009...}

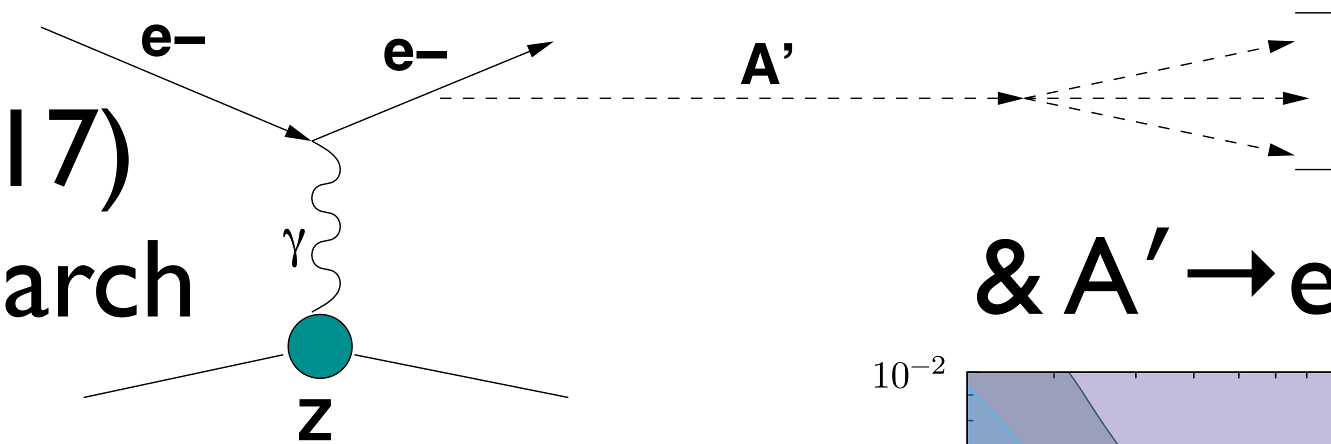
Thus the A′ couples to SM fermions.

In $U(1)_X$ extensions there are new currents, too, with new patterns of X-fermion couplings

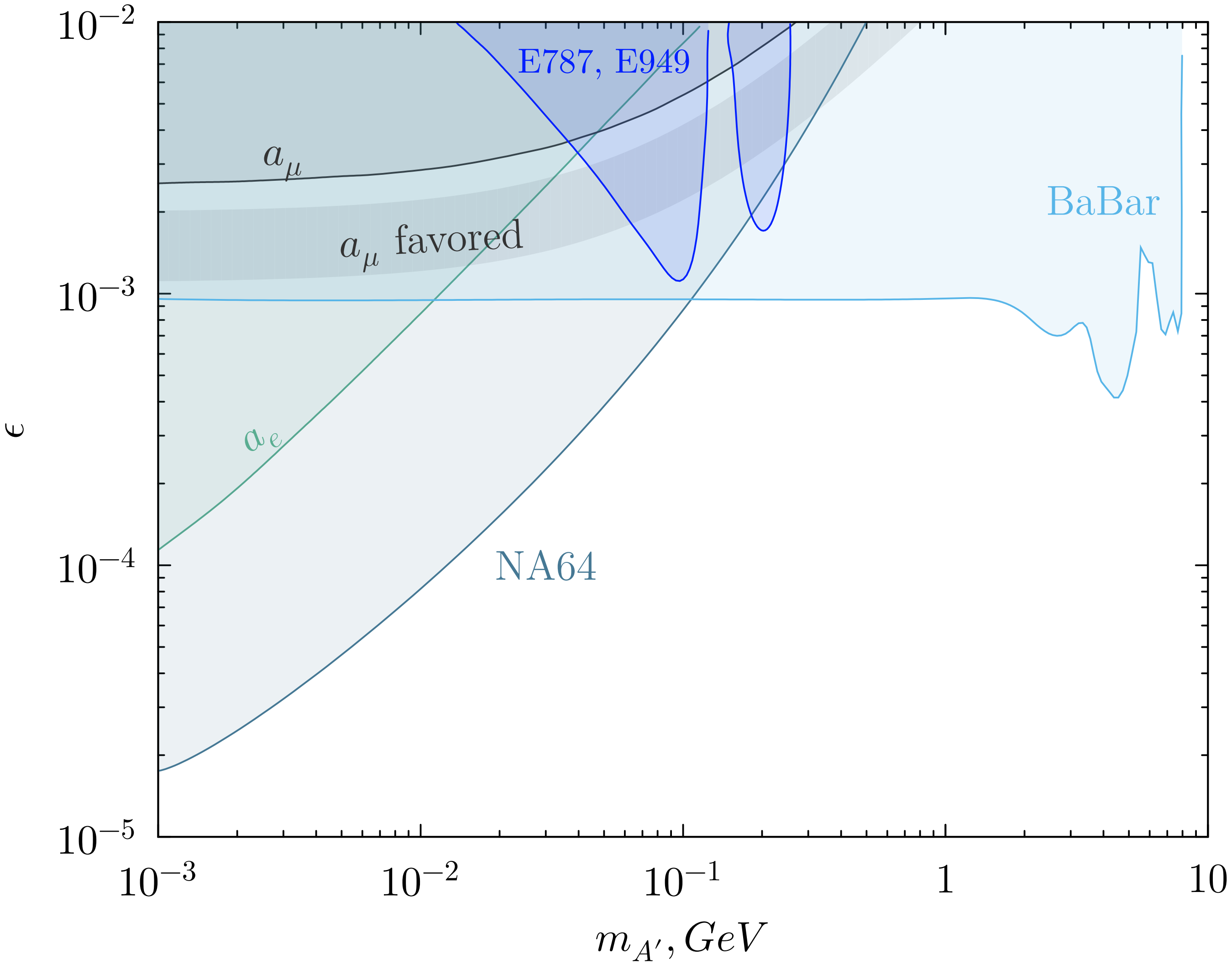
Opportunities in Neutron β Decay?

Dark bremsstrahlung could impact the β spectrum....

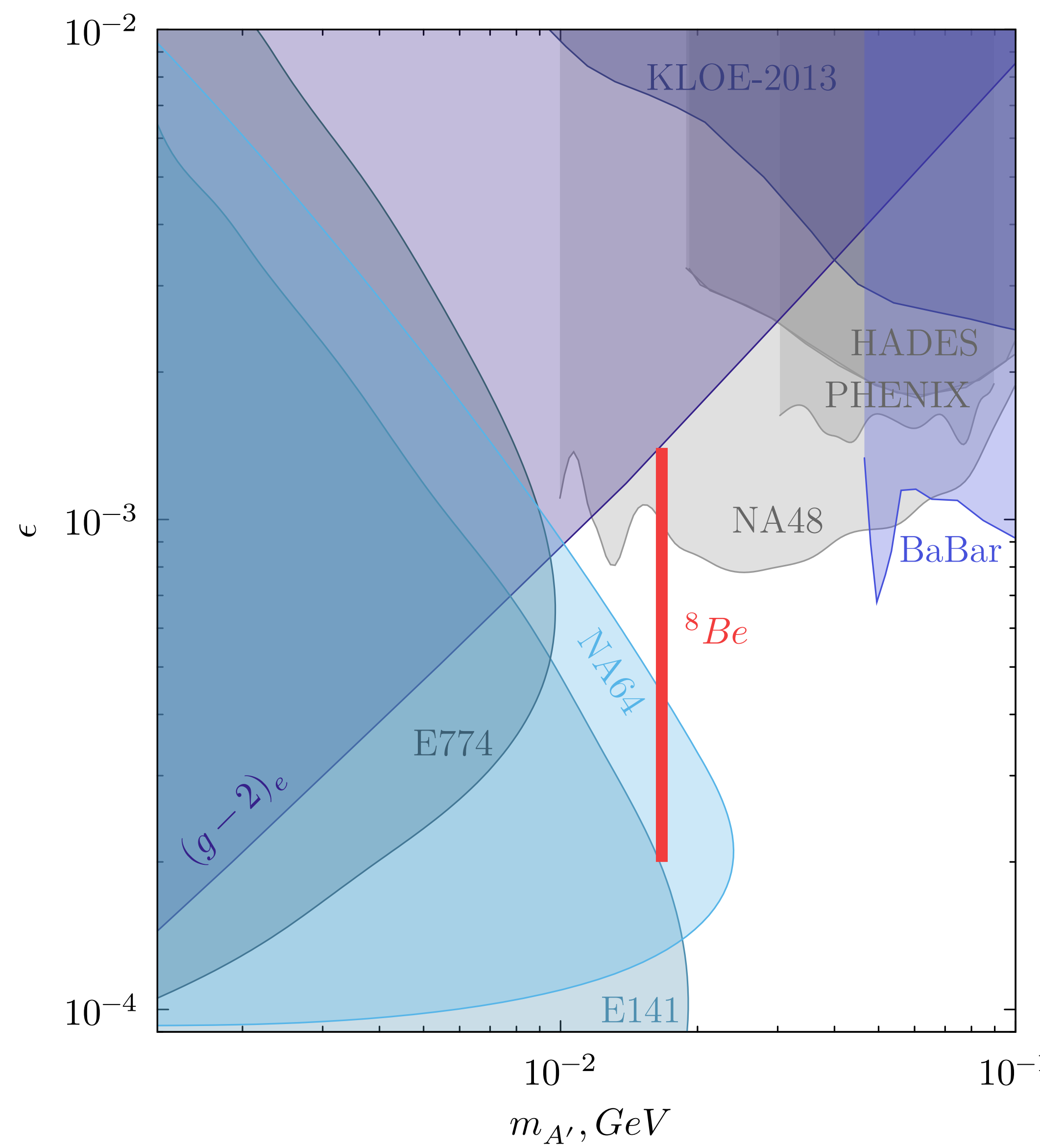
cf. NA64 (2017)
"invisibles" search



Br meas!



& $A' \to e^+e^-$: (2018)



New Low or High Energy Physics?

How can these possibilities be distinguished?

[Le Dall, Pospelov, and Ritz, 2015]

Consider the EDM...

- There are many dim-6 sources in SM EFT
- "dark V" contribution to e EDM is negligibly small (e EDM "UV sensitive")
- n EDM could be saturated by θ term

There are other perspectives....

Model Dependent Connections

New physics which contributes to a^V_{LR} can also generate an EDM, so that EDM constraints limit D as well. Namely,

[Ng and Tulin, 2012]

$$\mathcal{L}_{\dim 6} = \frac{c}{\Lambda^2} \bar{u}_R \gamma^\mu d_R i H^T \epsilon D_\mu H + h.c.$$

[Buchmuller and Wyler, 1986]

couples W to a right-handed current; after integrating out the W (quark level match ($n_f = 5$)), this yields (setting $V_{ud} = 1$)

$$\mathcal{L}_{\dim 6} = -\frac{c}{\Lambda^2} (\bar{u}_R \gamma^\mu d_R \bar{e}_L \gamma_\mu \nu_{eL} + \bar{u}_R \gamma^\mu d_R \bar{d}_L \gamma_\mu u_L) + h.c.$$

Thus Im(c) contributes to a^V_{LR} (D) and $\mathcal{O}_{LR}$ (d).

$$\begin{aligned} \mathcal{O}_{LR} &\equiv i(\bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{d}_L \gamma_\mu u_L \bar{u}_R \gamma^\mu d_R) \\ &\propto -\bar{u} u \bar{d} \gamma_5 d + \bar{u} \gamma_5 u \bar{d} d \end{aligned}$$

Thus $\mathrm{Im}(c) \propto C_{ud} + C_{du}$

Finally with $|d_n| < 2.9 \times 10^{-26}$ e-cm [Baker et al., 2006] one finds $|D_n/\kappa| < 3 \times 10^{-7}$.

[Ng and Tulin, 2012]

Final-State Interactions

Consider, too, role of IR new physics

We first compute $\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}$ and then the asymmetry. We work in $\mathcal{O}(\alpha)$ and in **leading recoil order**. [SG and He, 2012]

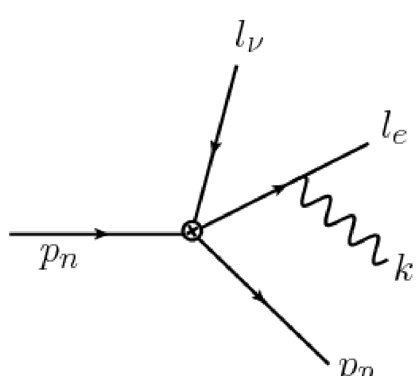
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}} \equiv \frac{1}{2} \sum_{\mathrm{spins}} |\mathcal{M}|^2_{\mathrm{T-odd}} = \frac{1}{2} \sum_{\mathrm{spins}} (2\mathrm{Re}(\mathcal{M}_{\mathrm{tree}} i \mathrm{Im} \mathcal{M}^*_{\mathrm{loop}}))$$

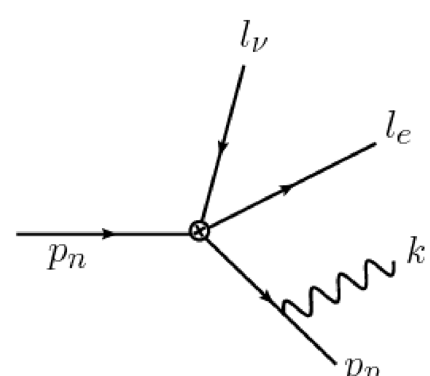
Note "Cutkosky cuts" [Cutkosky, 1960]

$$\mathrm{Im}(\mathcal{M}_{\mathrm{loop}}) = \frac{1}{8\pi^2} \sum_n \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}^*_{in} = \frac{1}{8\pi^2} \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}_{ni}$$

There are many cancellations. At tree level



(01)



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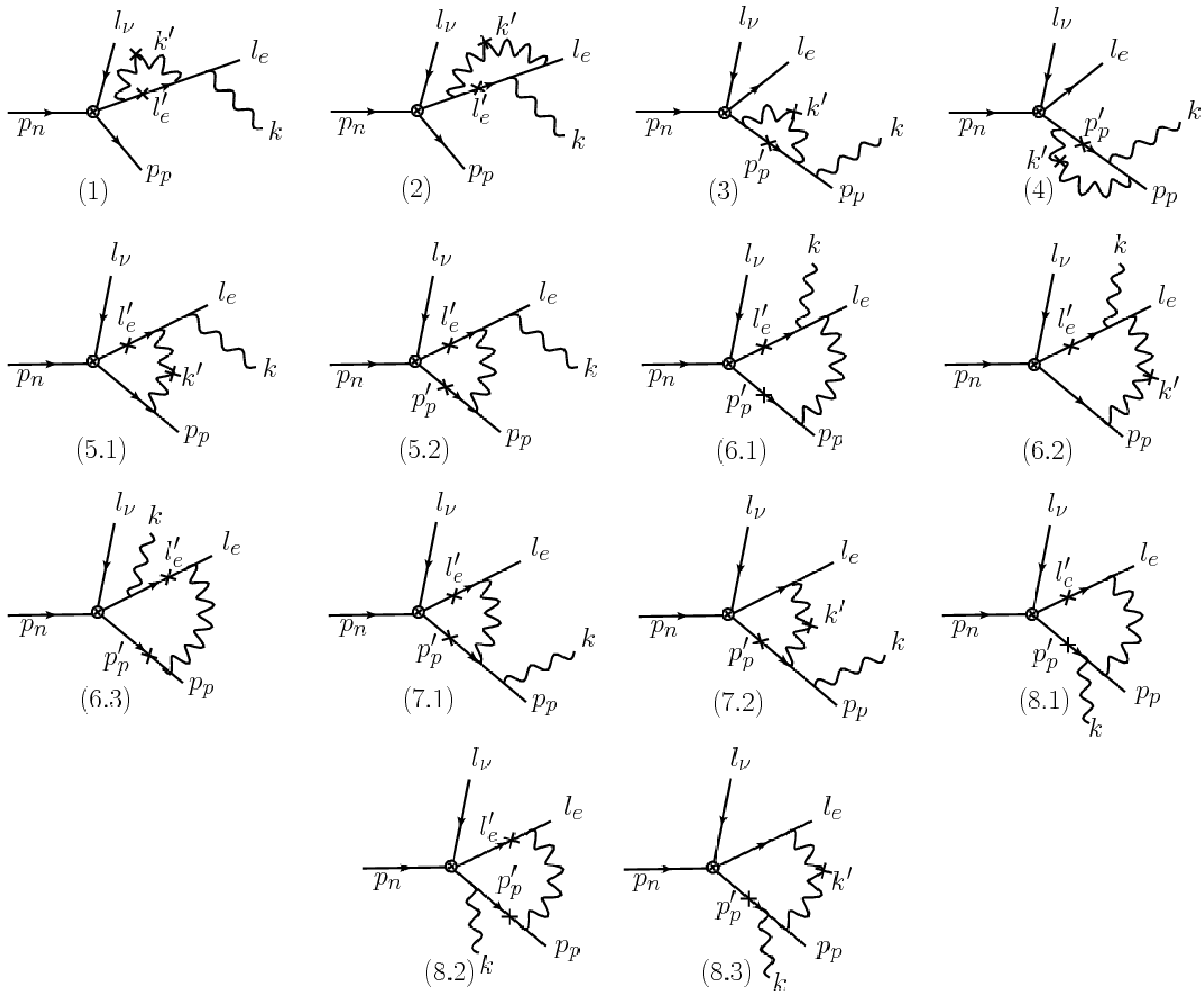

l_ν
l_e
l'_e
k
k'
p_n
p_p
p'_p
(1)
(2)
(3)
(4)
(5.1)
(5.2)
(6.1)
(6.2)
(6.3)
(7.1)
(7.2)
(8.1)
(8.2)
(8.3)

The interference with the tree level amplitude can yield zero. Namely, for the $\gamma - p$ family

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[3.01 + 3.02 + 4.01 + 4.02 + 7.2.01 + 7.2.02 + 8.3.01 + 8.3.02] = 0 + \mathcal{O}(M)\,,$$

The $e - p - \gamma$ family includes

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[7.1.01 + 7.1.02 + 8.1.01 + 8.1.02] = 0 + \mathcal{O}(M)\,,$$

For the $e - p$ family $a_{8.2}^{\mathrm{div}} \sim J_{8.2}^{\mathrm{div}} \sim (l_e \cdot k) J_{6.3}^{\mathrm{div}}/(M\omega)$ and $a_{6.3}^{\mathrm{div}} \sim f_{6.3}^{\mathrm{div}} \sim J_{6.3}^{\mathrm{div}}$:

$$\begin{aligned}&\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}\,[6.3.01 + 6.3.02 + 8.2.01 + 8.2.02] \\ &= -\alpha^2 g_V^2 G_F^2 \xi 64 M^3 (1-\lambda^2) \left(\frac{2m_e^2}{l_e \cdot k} k_{6.3} - \frac{2E_e}{\omega} k_{6.3} - \frac{2E_e}{\omega} a_{6.3} - \frac{2M}{\omega} i_{6.3} \right. \\ &- \frac{M}{\omega} c_{6.3} - \frac{m_e^2}{l_e \cdot k} f_{6.3} + \frac{2m_e^2}{l_e \cdot k} a_{6.3} - \frac{m_e^2}{l_e \cdot k} J_{6.3} + \frac{2ME_e}{l_e \cdot k} a_{8.2} + \frac{2ME_e}{l_e \cdot k} i_{6.3} \\ &\left. - \frac{2ME_e}{l_e \cdot k} h_{6.3} + \frac{M^2}{l_e \cdot k} c_{8.2} - \frac{M^2}{l_e \cdot k} e_{6.3} \right).\end{aligned}$$

The infrared divergence cancels in $\mathcal{O}(M^2)$.

The asymmetry computed from the "$e - p$" and "$e - p - \gamma$" cuts dominate the numerical results.
For the neutron...

$\omega_{\rm min}$(MeV)	$A_\xi{}^{\rm SM}$
0.01	1.76×10^{-5}
0.05	3.86×10^{-5}
0.1	6.07×10^{-5}
0.2	9.94×10^{-5}
0.3	1.31×10^{-4}
0.4	1.54×10^{-4}
0.5	1.70×10^{-4}
0.6	1.81×10^{-4}
0.7	1.89×10^{-4}

The nuclear radiative β-decay calculation can readily be reduced to "neutron" form.
Let's look at this explicitly for ^{19}Ne β-decay.
There are many more graphs, but they all cancel in leading recoil order.

Note new (CP conserving!) IR physics can contribute in O(ε^2)….

New CP-Violating Interactions?

What sort of interaction gives rise to a $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$ correlation at low energy?

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ makes the baryon vector current anomalous and gives rise to "Chern-Simons" contact interactions (containing $\varepsilon^{\mu\nu\rho\sigma}$) at low energy.

[Harvey, Hill, and Hill (2007, 2008)]

In a chiral Lagrangian with nucleons, pions, and a complete set of electroweak gauge fields, the requisite terms appear at N^{2}LO in the chiral expansion. Namely, [Hill (2010)]

$$\mathcal{L}^{(3)} = \ldots + \frac{c_5}{M^2} \bar{N} i \varepsilon^{\mu\nu\rho\sigma} \gamma_\sigma \tau^a \mathrm{Tr}(\{A_\mu, [iD_\nu, iD_\rho]\}) N + \ldots$$

Thus the weak vector current can mediate parity violation on its own.

Our correlation probes the Im part of the interference with the leading vector amplitude. Existing constraints are poor.

Note EMIT II limits Im $g_V < 7 \cdot 10^{-4}$ (68%CL).
First row CKM unitarity yields Im $g_V < 2 \cdot 10^{-2}$ (68%CL).

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay interference with the $V - A$ terms yields to leading recoil and radiative order

$$|\mathcal{M}|^2 = 512M^2 \frac{e^2 G_F^2}{2} \mathrm{Im}\,(c_5\, g_v) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \ldots$$

The pseudo-T-odd interference term is finite as $\omega \to 0$.

Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$ we partition phase space into regions of definite sign:

$$\mathcal{A} \equiv \frac{(\Gamma_{\xi>0} - \Gamma_{\xi<0})}{(\Gamma_{\xi>0} + \Gamma_{\xi<0})}$$

To leading recoil order, where ω^{min} is lowest detectable photon energy,

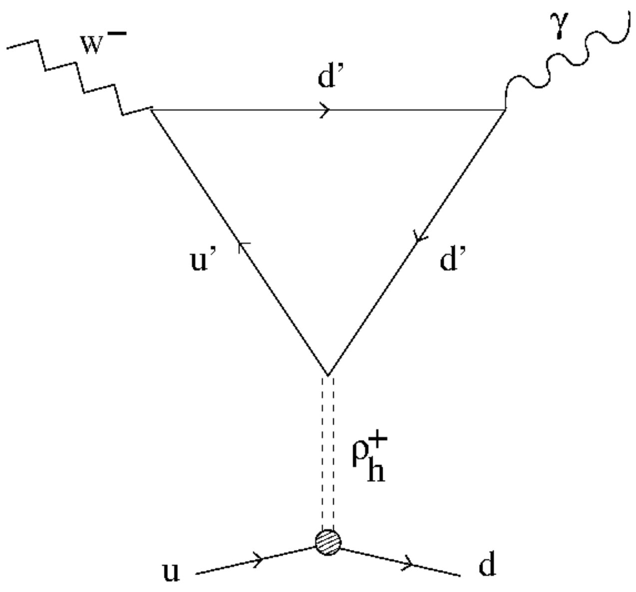
$$\mathcal{A}(\omega^{\mathrm{min}} = 0.01\,\mathrm{MeV}) = -1.2 \cdot 10^{-2} \mathrm{Im}\,\frac{c_5 g_v}{M^2} (\mathrm{MeV}^{-2})\,,$$

$$\mathrm{Br}(\omega^{\mathrm{min}} = 0.01\,\mathrm{MeV}) = 3.5 \cdot 10^{-3} \text{ and}$$

$$\mathcal{A}(\omega^{\mathrm{min}} = 0.3\,\mathrm{MeV}) = -1.0 \cdot 10^{-1} \mathrm{Im}\,\frac{c_5 g_v}{M^2} (\mathrm{MeV}^{-2})\,, \mathrm{Br}(\omega^{\mathrm{min}} = 0.3\,\mathrm{MeV}) = 8.6 \cdot 10^{-5}$$

The LEC c_5 need not be real in theories beyond the SM.

To illustrate, hidden-sector fermionic matter can appear via



and interfere with SM contributions to yield $\mathrm{Im}(c_5\, g_v)$.

The notion of new matter with QCD-like interactions is not new. Note, e.g., "quirks" [Okun (1980); Kang and Luty (2008)] "dark quarks" [Blennow et al. (2011)].

Here we imagine the matter to be light and weakly coupled. We probe CP phases associated with hidden-sector interactions.

Direct constraints (and $H \to \gamma\gamma$) can be evaded via light masses and/or small mixing angles.

Summary

Weakly coupled physics at low energies
is its own frontier!

Neutron experiments, even if devoted to other "primary" missions, can play an important role

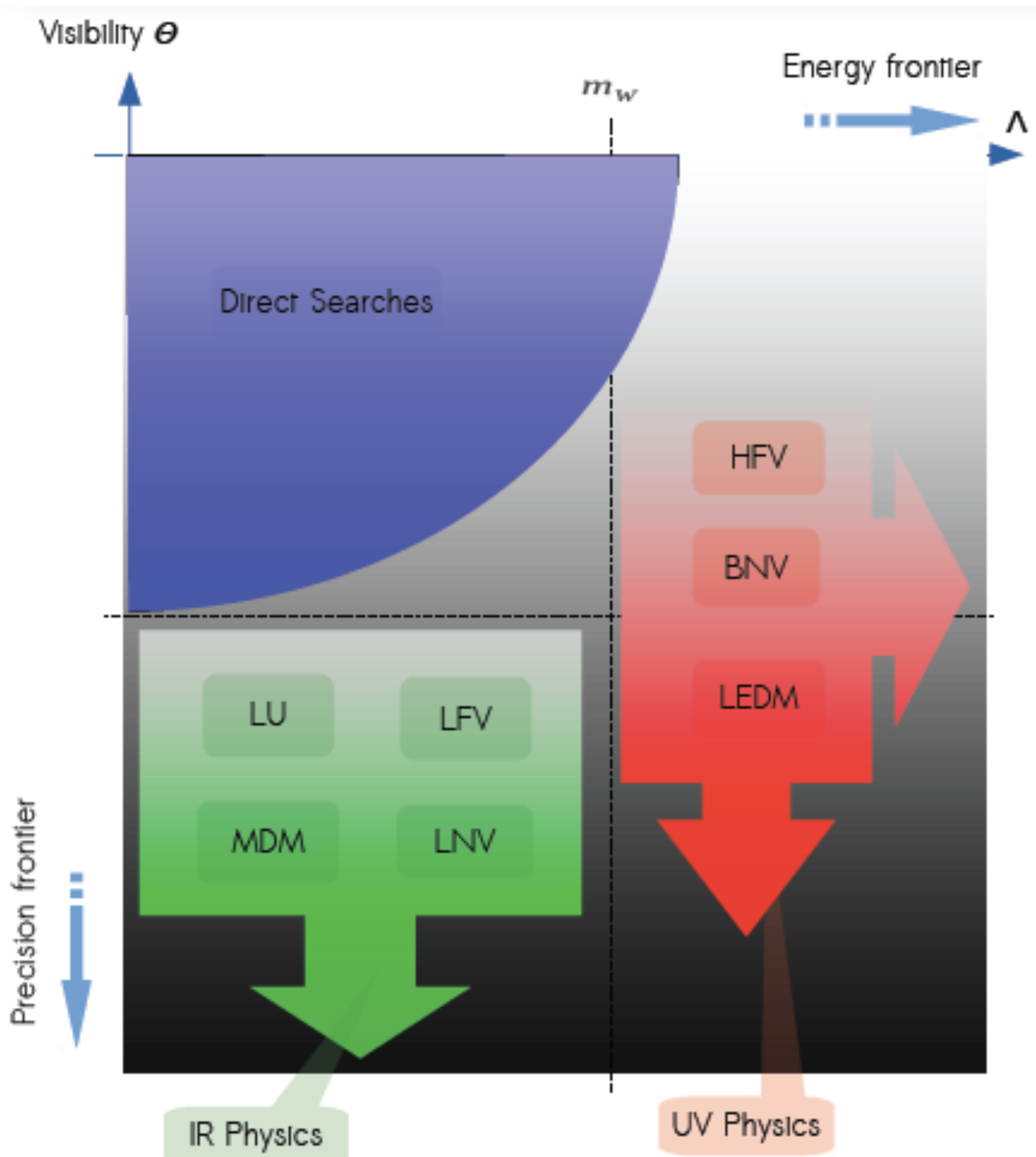
Dedicated efforts to detect new long range forces (& using neutrons) are also ongoing

T-odd correlations can also used to limit light, weakly coupled physics

Backup Slides

EDMs: Broader Impacts

Low or high energy physics?



The discovery of the electron EDM at anticipated sensitivity would reveal weak scale new physics

[Le Dall, Pospelov, and Ritz, 2015]

The limits anticipated in next generation EDM experiments give decisive tests of EWB in popular models

[Cirigliano et al., 2010; Chao and Ramsey-Musolf, 2014]

Gauge Theories of the Hidden Sector

There are many possible vector portals
- but only some are "anomaly free"

Typical to consider Abelian groups as $F^{\mu\nu}$ is gauge invariant

- $U(1)_Y$ or $U(1)_{em}$: enter the dark photon and A-A′ mixing [Holdom, 1986…]
- $U(1)_Y$ with an extended Higgs sector : now mixing with both the photon and Z occurs – enter the Z_d
  [Davoudiasl, Lee, Marciano, 2014]
- $U(1)_B$ but not anomaly free [Nelson & Tetradis, 1989; Tulin, 2014; Dobrescu & Frugiuele, 2014…]
- $U(1)_{\mu-\tau}$ [Altsmannshofer, Gori, Pospelov, & Yavin, 2014]

Model for the Be-8 IPC anomaly

There's no unique choice, but here's one:

[Feng, Fornal, Galon, SG, Smolinsky, Tait, Tanedo, 2016]

- Gauge the $U(1)_{B-L}$ global symmetry of the SM
- This is anomaly-free with the addition of 3 sterile neutrinos
- Generically the B-L boson mixes with the photon:

$$\varepsilon_u : \quad \frac{2}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad\qquad \varepsilon_\nu : \quad -\varepsilon_{B-L}$$

$$\varepsilon_d : \quad -\frac{1}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad\qquad \varepsilon_e : \quad -\varepsilon - \varepsilon_{B-L} \ ,$$

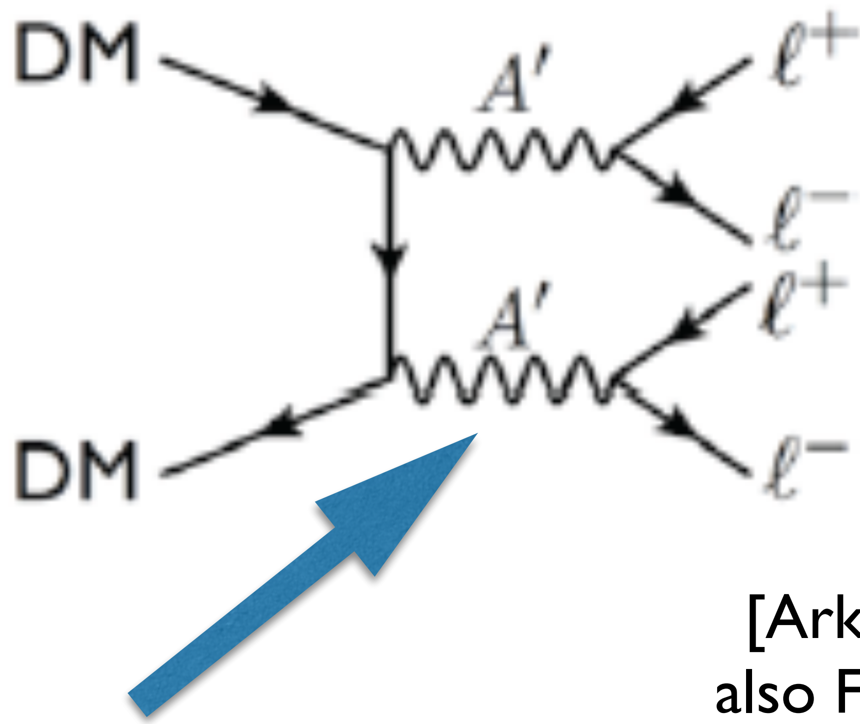
- For $\varepsilon + \varepsilon_{B-L} \approx 0$, we get both $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e << \varepsilon_{u,d}$!
- The neutrino X-charge is too large. This problem is mitigated if X is heavier, then ε_{B-L} can be smaller. It can be remedied in different ways – e.g., by mixing with X-charged sterile neutrinos.

Other model possibilities are being developed….

Hunting Hidden Forces

"Early" e^+ and e^- excesses in the gamma-ray sky from dark matter annihilation

N.B. Fermi LAT results (& others), 2008-9



Could explain size of excesses if new GeV-scale gauge bosons exist

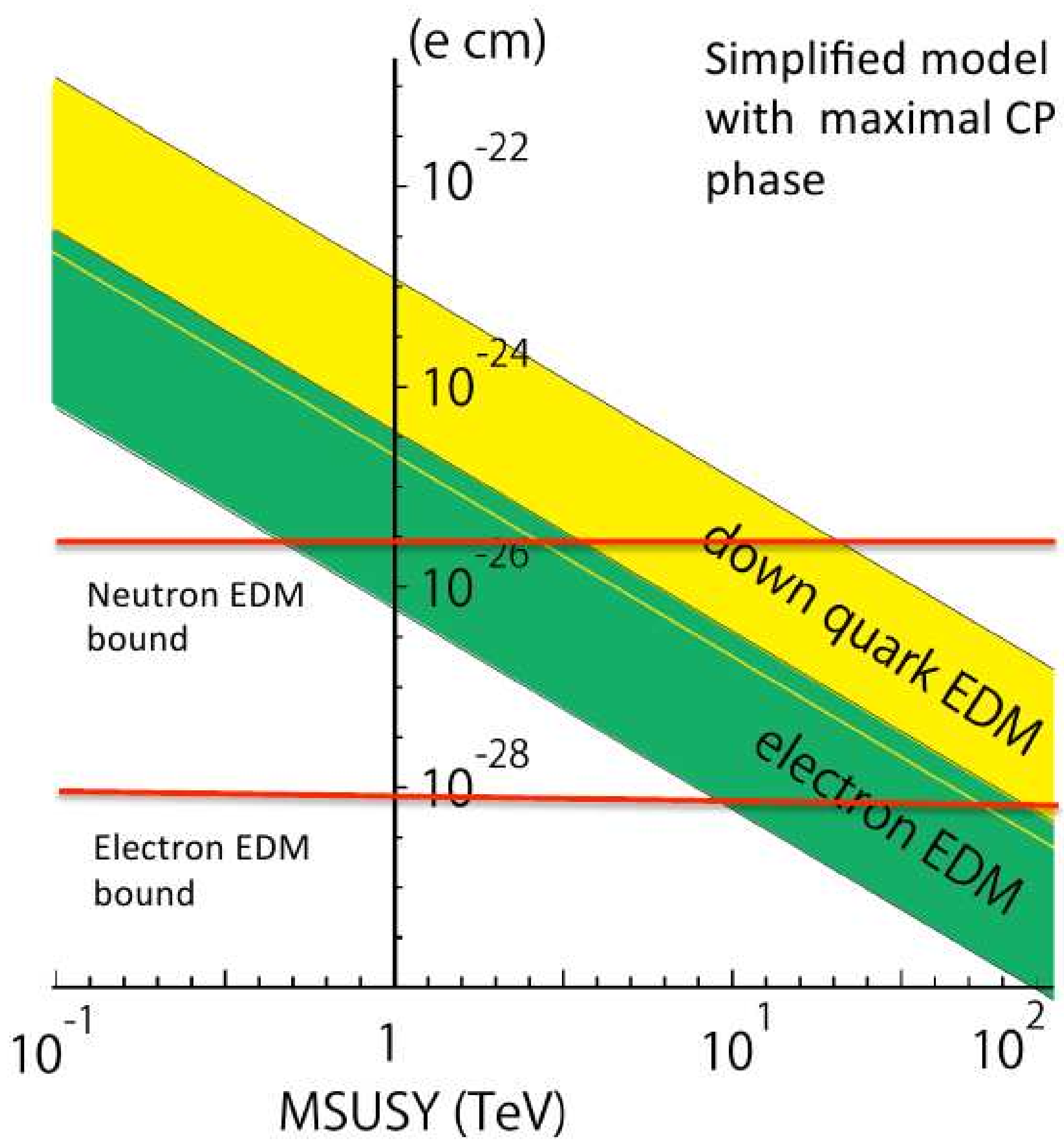
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009;
also Fox & Poppitz, 2009,…Pospelov 2009 (μ g-2)]

new gauge boson is a "portal" to a hidden sector

Plausible conventional explanations now exist, but the possibility was opened nonetheless….

EDMs & the SUSY CP Problem

Models with O(1) CP phases & weak scale supersymmetry



(Hisano @ Moriond EW 2014)

[Figure: W. Altmannshofer]

An EDM can now appear at one loop!

EDM bounds push super partner masses far above the TeV scale!

Different models can make the pertinent CP phases effectively small...

LHC results now suggest "decoupling" is a partial answer

Lepton EDMs in the SM

The contribution from the CKM matrix first appears in four-loop order!

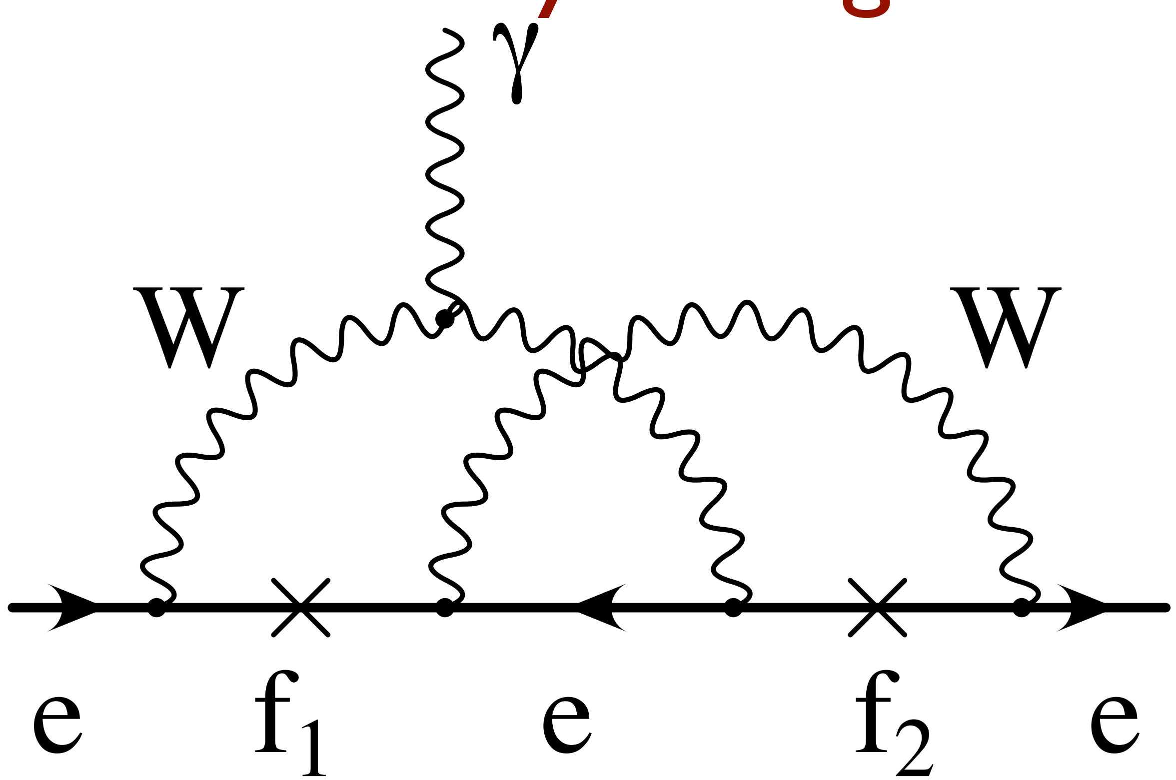
cf. d_e^{eff} *from CPV e-N*
[Pospelov & Ritz, 2013]

$d_e \sim 10^{-44}$ e-cm [Khriplovich & Pospelov, 1991]

Majorana neutrinos can enhance a lepton EDM

[Ng & Ng, 1996]

but not nearly enough to make it "visible"



For "fine tuned" parameters

$d_e \lesssim 10^{-33}$ e-cm

[Archambault, Czarnecki, & Pospelov, 2004]

Look to CPV in ν oscillations to probe leptogenesis!

CP violation in the SM

Observed effects appear through quark mixing under the weak interaction

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \quad ; \quad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) has hierarchical mixing

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

[Wolfenstein, 1983]

The CKM Matrix is a unitary 3x3 matrix with 4 parameters in the Standard Model

What is also possible but **not seen** is CP violation from QCD — because the n EDM has not been observed!

Operator Mass Dimension Memo

Predictive power in QFT demands than D cannot be > 4

The action $\mathcal{S}$

$$\mathcal{S} = \int d^4x \mathcal{L}$$

To make S dimensionless, we must have dim[$\mathcal{L}$] = 4.

Recall $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $m\bar{\psi}\psi$

Thus $F_{\mu\nu}F^{\mu\nu}$ dim[A^μ]=1 also dim[ψ]=3/2

$$\dim[\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}] = 5$$

Note in chiral basis

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \quad \psi_{\substack{L \\ R}} \equiv \frac{1}{2}(1 \mp \gamma_5)$$

$$\bar{\psi}\gamma^\mu\psi = (\bar{\psi}_L\gamma^\mu\psi_L + \bar{\psi}_R\gamma^\mu\psi_R)$$

EDMs & Sensitivity to New Physics

The electric and magnetic moments change chirality

$$\bar{\psi}\sigma^{\mu\nu}\psi = (\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\psi_L)$$

$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi = (\bar{\psi}_L\sigma^{\mu\nu}\gamma_5\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\gamma_5\psi_L)$$

By dimensional analysis we infer the scaling

"New Physics Scale"

$$d_f \sim e\frac{\alpha}{4\pi}\frac{m_f}{\Lambda^2}\sin\phi_{\rm CP}$$

$$d_{d\,\rm quark} \sim 10^{-3}e\frac{m_d(\rm MeV)}{\Lambda(\rm TeV)^2} \sim 10^{-25}\frac{1}{\Lambda(\rm TeV)^2}e-\rm cm$$

Note ILL limit on neutron EDM:

$d_n < 3\times10^{-26}$ e-cm @ 90%CL [Pendlebury et al., 2015]

EDM experiments have TeV scale sensitivity