New Perspectives on Fundamental Symmetry Tests with Quarks

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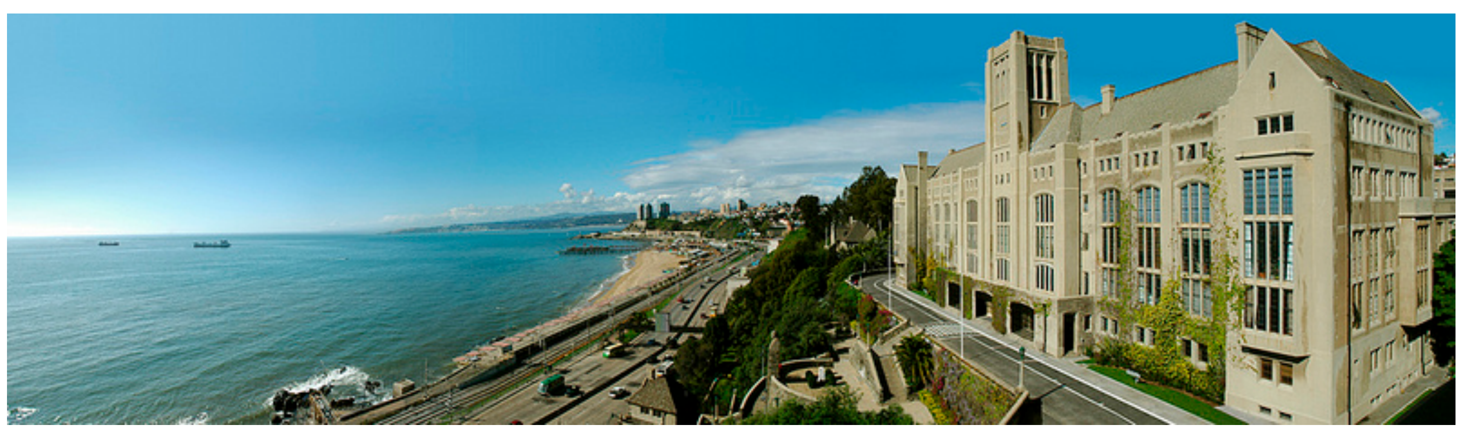


Context

The LHC has discovered a Higgs (like) boson but no other new particles - yet.

{N.B. This discovery required new methods for loops and many legs in perturbative QCD [Note Bern, Dixon, Kosower,....]}

Observational cosmology tells us, however, that only some 4% of the energy density of the Universe is in known stuff (baryons)...

Dark matter speaks to possible **hidden sector** particles, interactions, symmetries

How can we discover such new dynamics?

Context

Here: the discovery prospects of low energy, precision measurements...

Answering questions that the Standard Model does not may require new theoretical paradigms

Emerging experimental anomalies can guide "bottom-up" constructions.

A diverse set of low-energy experiments is possible.

QCD plays a key role in their interpretation!

For a more comprehensive discussion, see
N. Brambilla, S. Eidelman, P. Foka, SG, A. Kronfeld et al., Eur. Phys. J. C 74 (2014) 2981 (arXiv: 1404. 3723) --- and esp. Ch. 5: SG, H.-W. Lin, F. Llanes-Estrada, W. M. Snow, X. Garcia i Tormo, & A. Kronfeld

Two Paths to Discovery

via low energy, precision measurements

→ Make "null" tests of the breaking of SM symmetries

Enter tests of B-L, CP (*), ...

***e.g., EDMs, $A_{\rm CP}$ in charm (Dalitz plot), T-odd decay correlations**

→ Confront nonzero quantities which can be computed precisely (or assessed) within the SM

Enter PVES, muon g-2, beta decay correlations, ...

All probe new degrees of freedom, both visible and possibly "hidden"

More Motivation for BSM searches:

The Puzzle of the Missing Antimatter

Confronting the observed 2H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

But estimates of the baryon excess in the Standard Model are much too small, [Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

$$\eta < 10^{-26} \quad \text{(sic: 125 GeV Higgs)}$$

Why? The operative CP violation in the SM (CKM) is special: it appears only if SU(3) flavor is also broken....

Interconnections

A baryon asymmetry (BAU) could be generated in different ways, and various discovery experiments can give hints

- The discovery of a EDM would speak to new CP phases (enter electroweak baryogenesis)
- The discovery of $0\nu\,\beta\beta$ decay would tell us that neutrinos are Majorana (enter leptogenesis)
- The discovery of $n\bar{n}$ oscillations would tell us that neutrons are Majorana (enter leptogenesis)
- The discovery of a DM asymmetry would tell us that DM carries "baryon" number (enter "darko"genesis)

In some models the generation of DM and the cosmic baryon excess are tied....

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

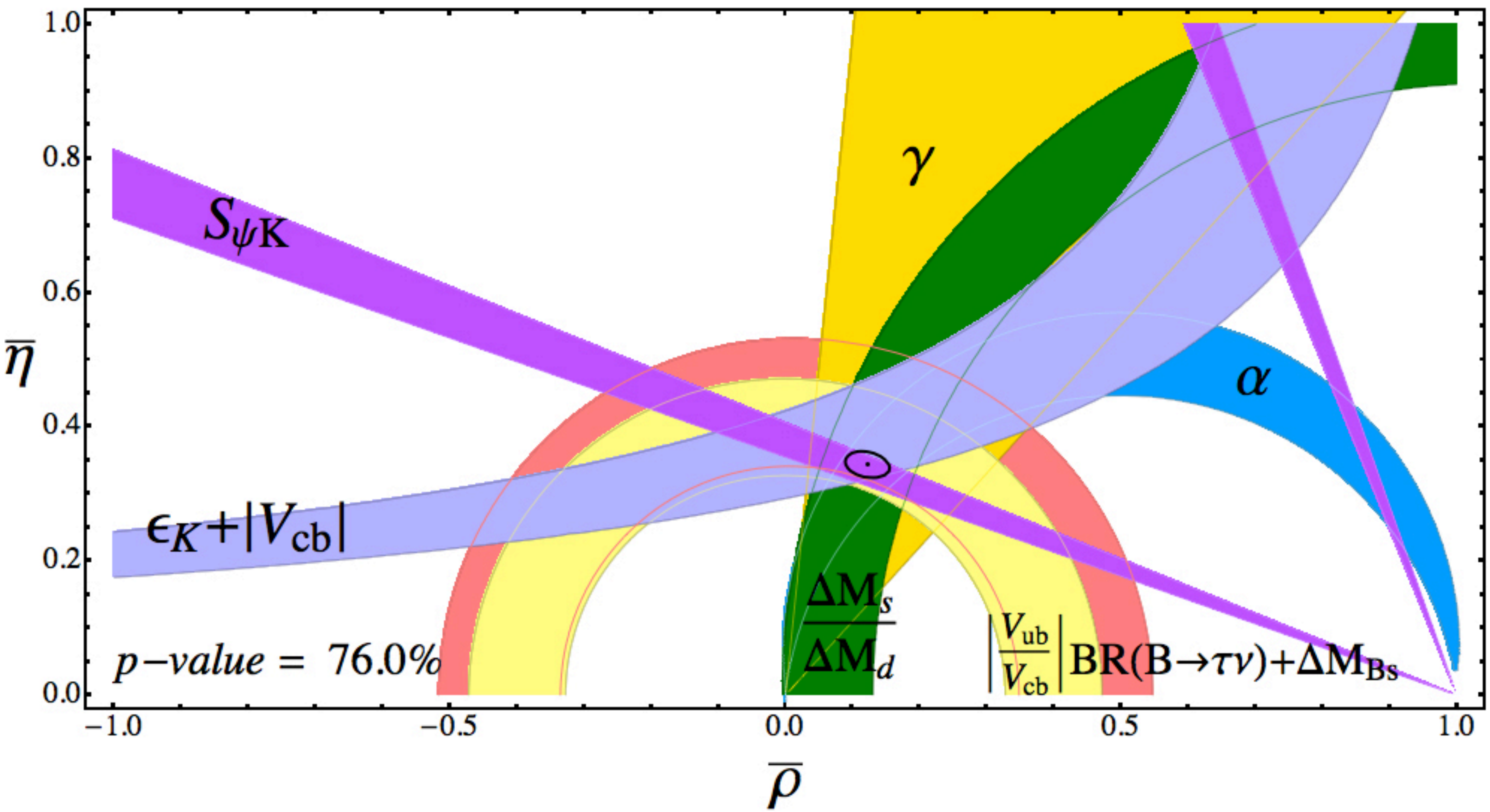
Symmetries guide their construction [Weinberg]

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

Analysis Framework

Flavor physics studies tells us that flavor and CP violation in CC processes are CKM-like ("Minimal Flavor Violation")



[2013 update (th+exp) of Laiho, Lunghi, van de Water, arXiv: 0910.2928]

Lattice QCD plays a key role

Low-energy BSM experiments

Null results are crucial: they constrain Λ !

E.g., from dimensional analysis:
the EDM d_f of a fermion f of mass m_f

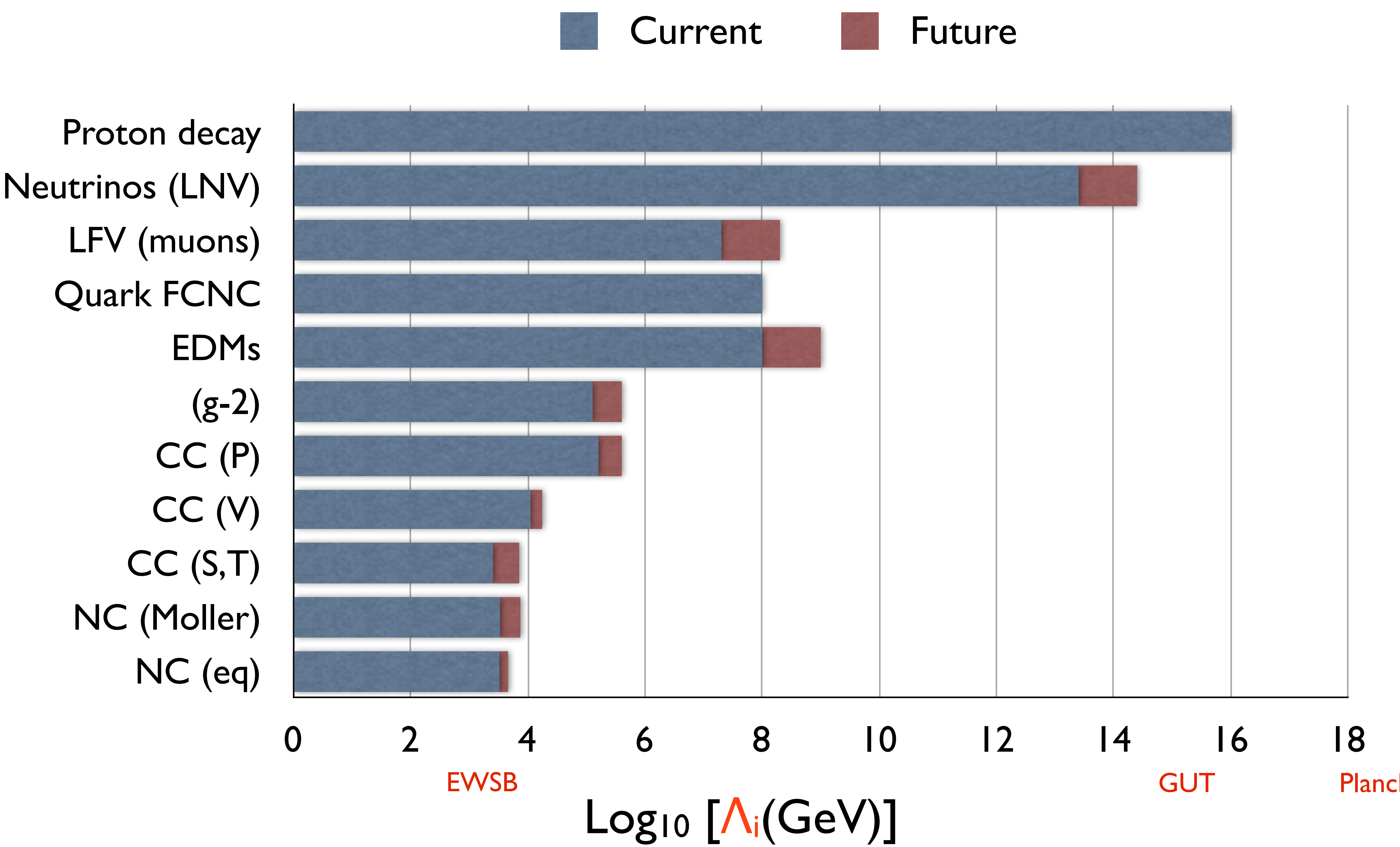
$$d_f \sim e \sin \phi_{\mathrm{CP}} m_f / \Lambda^2$$ [de Rujula et al., 1991]

With $\sin \phi_{\mathrm{CP}} \sim 1$, $m_f \sim 10$ MeV, and $|d_n^{\mathrm{expt}}| < 2.9 \times 10^{-26}$ e-cm [Baker et al., 2006]
$\log_{10}[\Lambda(\mathrm{GeV})] \sim 5$. With a loop factor of $\alpha/4\pi \sim 10^{-3}$, $\Lambda \sim 3\,\mathrm{TeV}$.

Estimates can vary considerably.

Many Low-Energy Experiments

Estimated physics reach from dimensional analysis (careful!)

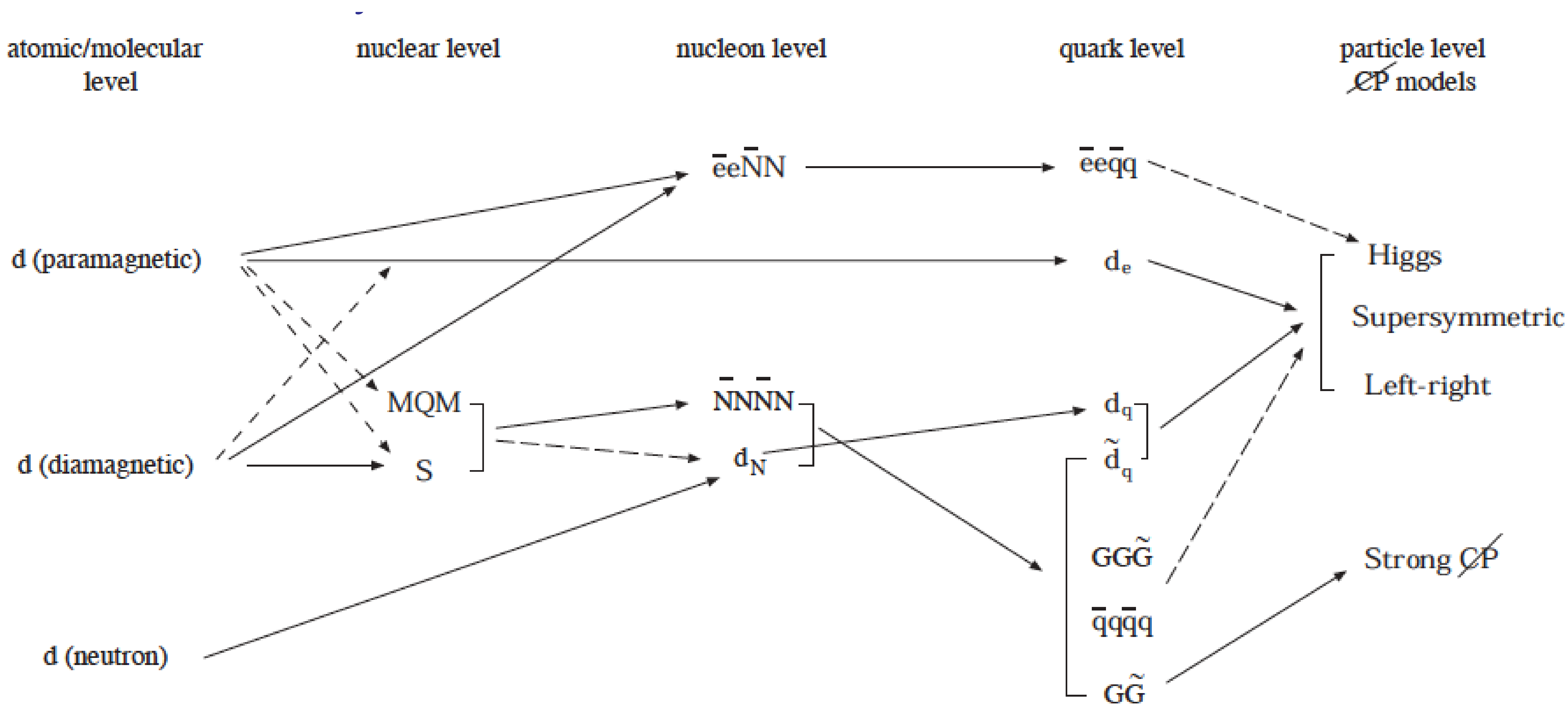


[Cirigliano & Ramsey-Musolf, arXiv:1304.0017]

Low-Energy BSM Searches

Naturally involve multiple energy scales

Example: Heavy Atom EDMs



[Ginges and Flambaum, 2004]

In many systems non-relativistic potential models are employed

QCD and New Physics

To interpret "null" tests and connect observables with minimal assumptions must accommodate

- many "UV sources" [model independent?]
- the construction of EFTs at multiple scales [with QCD evolution and operator matching]
- the computation of non-perturbative matrix elements in (lattice) QCD
- fits for low-energy constants & embedding of theory errors in those fits

Additional QCD matrix elements can enter through electroweak radiative corrections

Some Recent & Incipient Progress

- **permanent electric dipole moments (EDMs):** EDMs break T and P and would reveal physics BSM; many candidate systems exist.
  (i) footprints of various BSM models [Dekens et al., 2014]
  (ii) LEC fits [Yamanaka et al., 2014; Chupp & Ramsey-Musolf, 2014]
  (iii) lattice QCD evolving beyond n matrix elements for $\theta_{\rm QCD}$

  [H.-w. Lin, talk here at QNP; "set-up" for dim-5 calculations,

  Bhattacharaya et al., 2015] - many lattice calcs in progress!

- **T-odd beta decay correlations:**
  EDM connections [Ng & Tulin, 2011; Seng et al., 2014; Dekens & Vos, 2015] & not [SG & Daheng He, 2012, 2013]

Some Recent & Incipient Progress

- **proton radius puzzle:** the ultra-precise $\mu - H$ result disagrees with electronic r_p measurements
  [CODATA 10: Mohr, Taylor, Newell, arXiv:1203.5425;
  new review: Carlson, arXiv:1502.05314;

  new mu-He results (CREMA) anticipated and new, planned expts: MUSE, PRad]

$$[\mu - H] : r_p = 0.84087(39)\,\mathrm{fm}$$

$$[\mathrm{CODATA\ 10(el.)}] : r_p = 0.8775(51)\,\mathrm{fm}$$

$$\Longrightarrow \delta r_P = -0.03663 \pm 0.00549\,\mathrm{fm}\ (!)$$

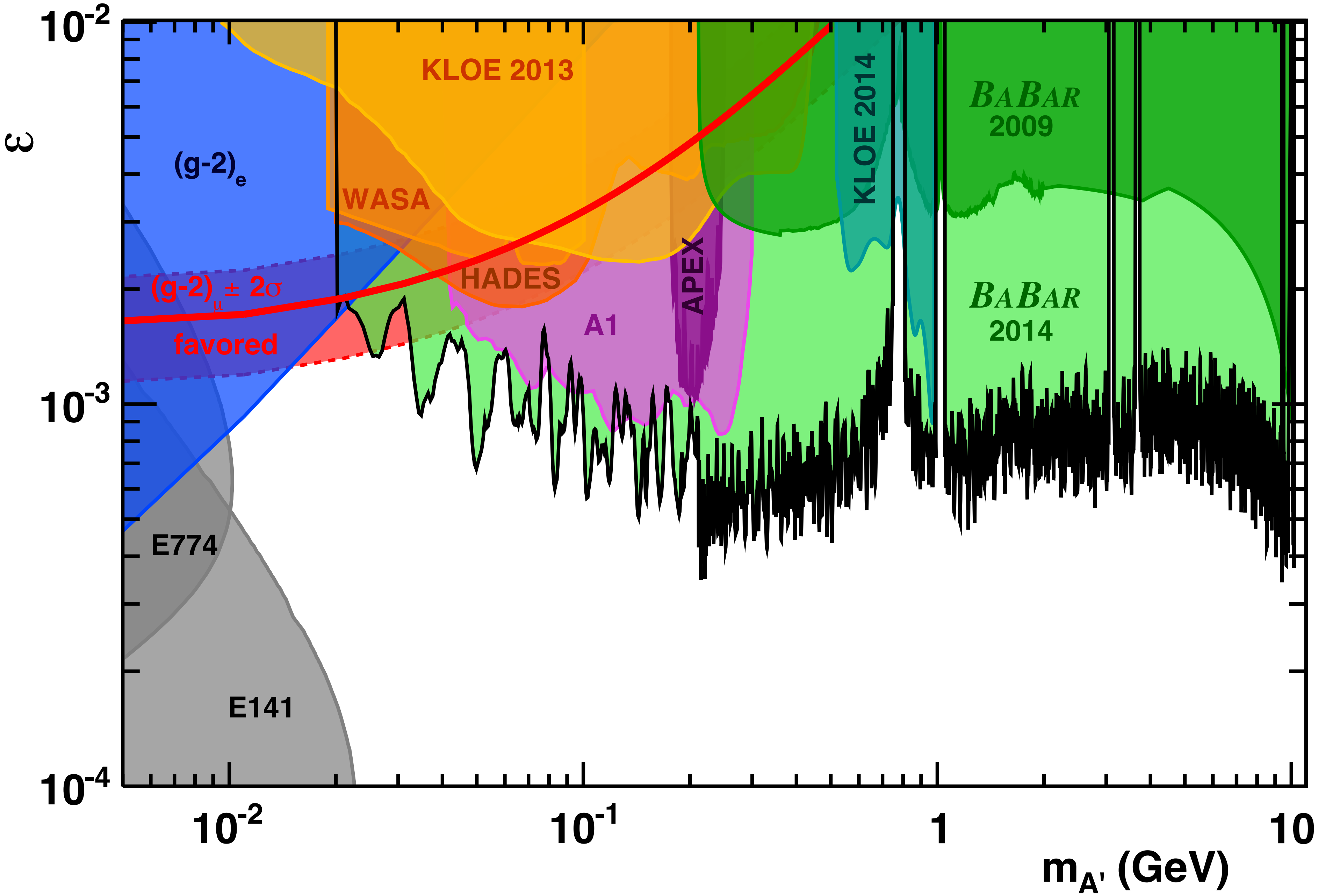
$$[e - H] : r_p = 0.8758(77)\,\mathrm{fm}$$

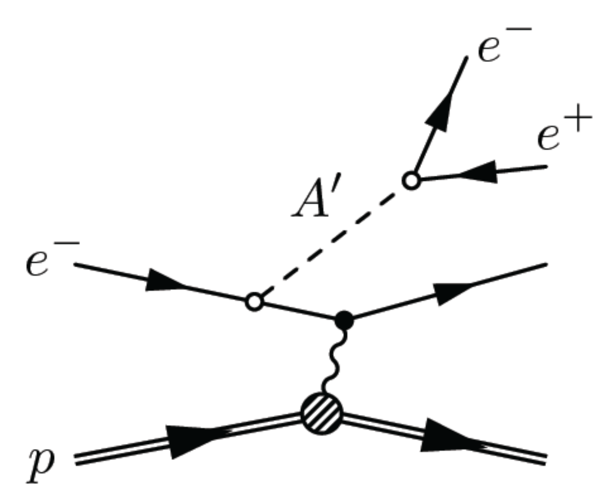
- **muon g-2:** assessments of hadronic effects in $\mathcal{O}(\alpha^4)$
  [Kutz et al., 2014; Colangelo et al., 2014] (about a 2 ppm discrepancy!)
  $\delta((g-2)/2) = 28.5 \pm 6.3_{\mathrm{expt}} \pm 4.9_{\mathrm{SM}}$
- **New limits on light, hidden sectors (dark photons):**
  [BaBar, 2014 (arXiv: 1406.2980); PHENIX, 2014 (arXiv:1409.0851)]
  constrain the "g-2 window" [Pospelov, 2009]

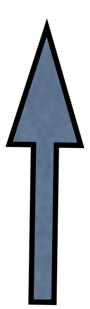
Some Recent & Incipient Progress

Hidden Sector Forces? Enter the Dark Photon A′

[Bjorken, Essig, Schuster, Toro, 2009; Batell, Pospelov, Ritz, 2009;....]







mixing parameter

[BaBar, arXiv:1406.2980 - & more to come from JLab, Mainz, ...]

Some Recent & Incipient Progress

- **non-V-A currents in beta decay:**

  (i) EFT+ lattice QCD to sharpen limits

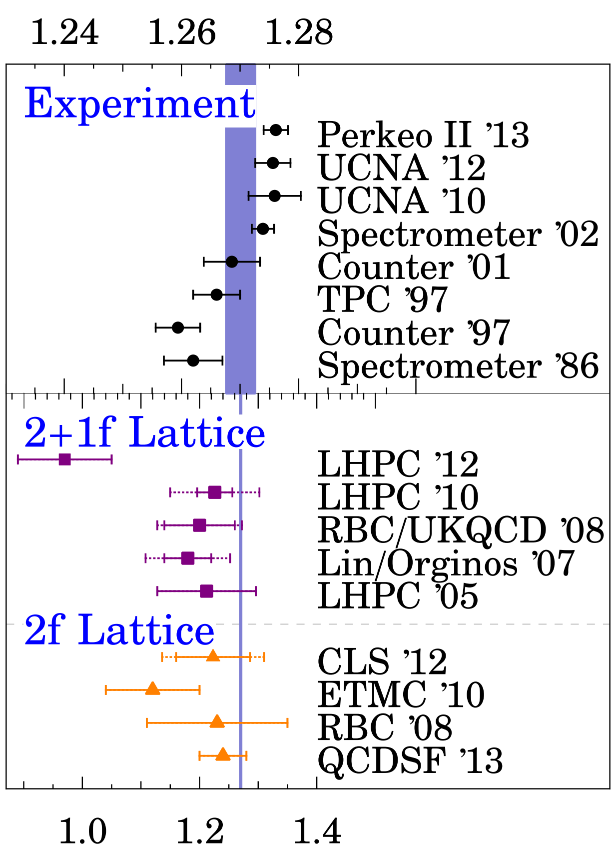
  [Cirigliano et al., 2010; Bhattacharya et al., 2011, 2013; Gonzalez-Alonso & Carmalich, 2013]

  (ii) maximum-likelihood fits incl. theory errors

  [SG & Plaster, 2013 - after "CKMFitter", Charles et al., 2005]

  (iii) progress on lattice g_A!

  [H.-w. Lin, talk here at QNP; E. Shintani, talk here at QNP]



g_A/g_V [Bhattacharya et al., arXiv:1306.5435]

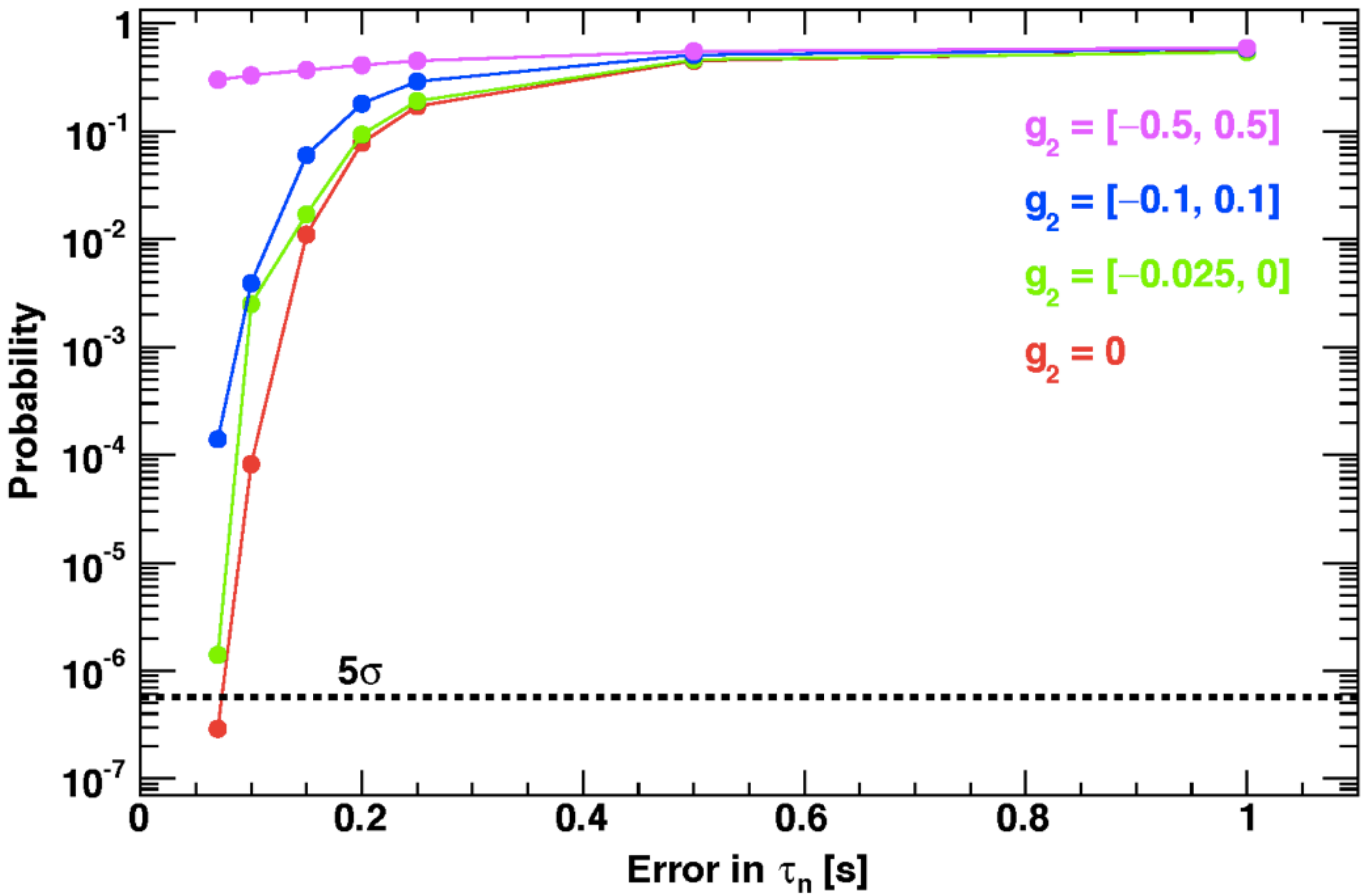
In beta-decay we must fit for SM and BSM physics simultaneously

BSM small enough that "second class" terms matter

[SG & Plaster, 2013]

Resolving the limits of the V-A Law

[SG & Plaster, 2013 & 2014]



Need sharper determinations of the SCC terms!

- A Challenge for Lattice QCD? -

QCD Prospects

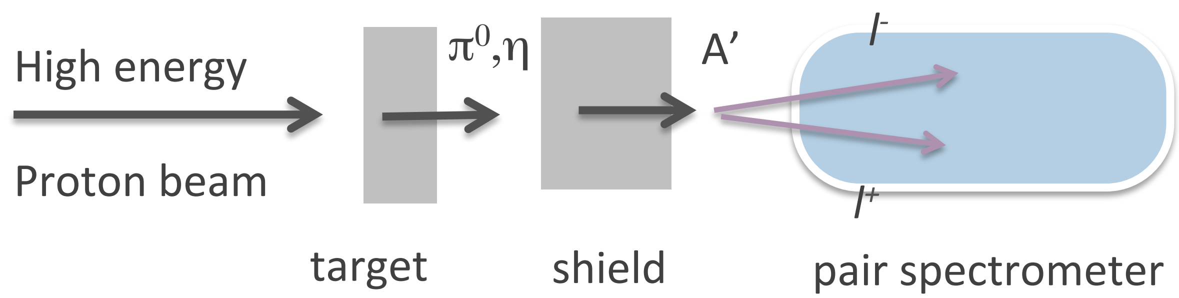
QCD can also open new windows on new physics

i) Weakly coupled non-Abelian hidden sectors?

Visible and hidden sectors can mix in different ways; what of a non-Abelian [gluon] portal?

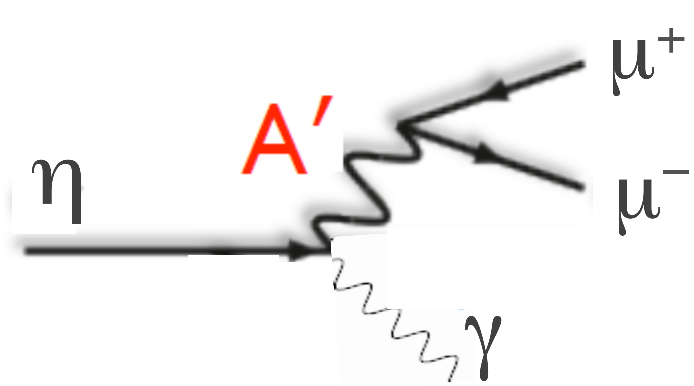
[Batell, Pospelov, Ritz, 2009; Baumgart et al., 2009; SG & He, 2013; Tulin, 2014]

Can probe via "shining through walls" as part of Seaquest/E906 FNAL (R. Holt, priv. comm.) [SG & Holt, in prep.]



$$A' \to \rho'$$

$$\mu^+\mu^- \to \pi^+\pi^-$$

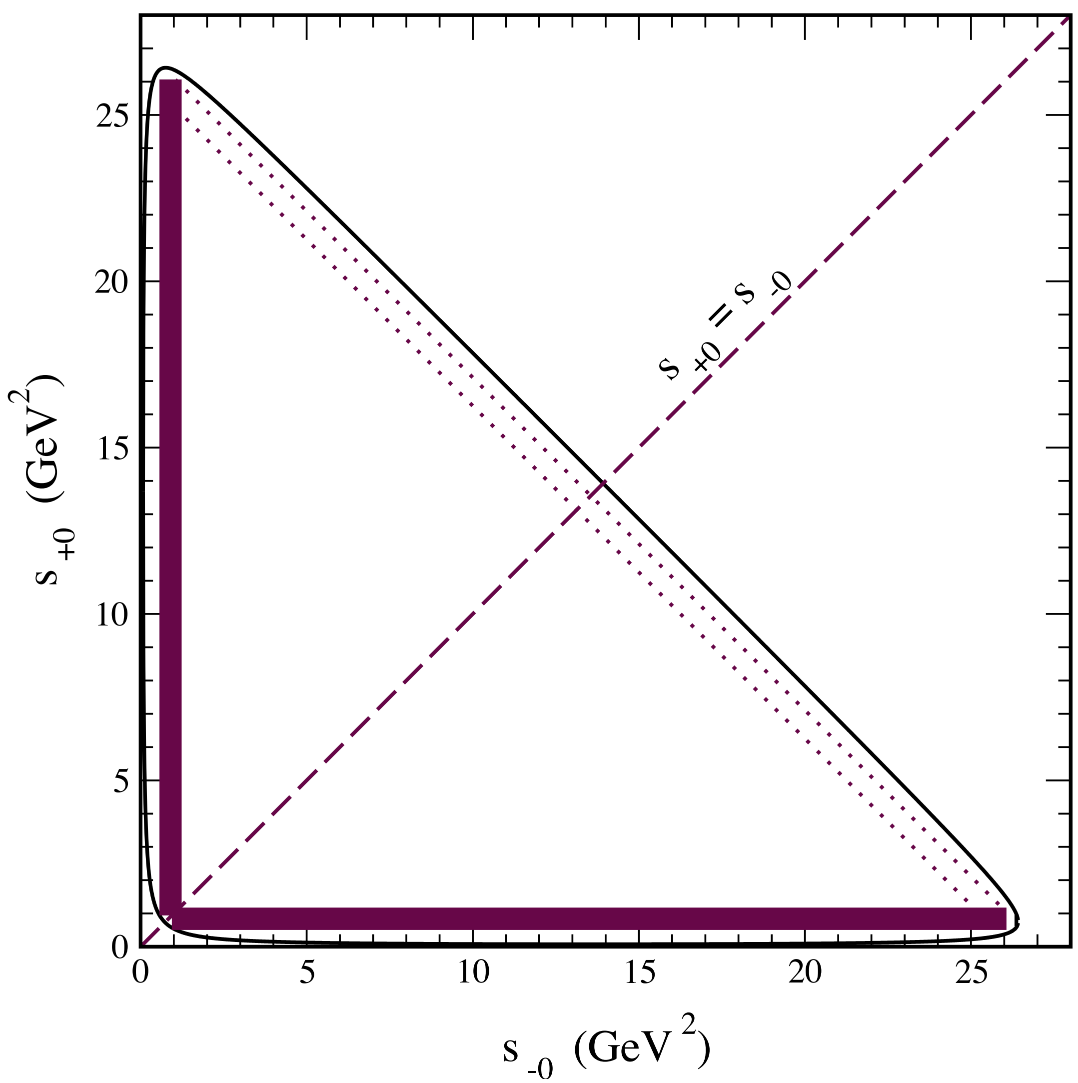


QCD Prospects

QCD can also open new windows on new physics

ii) Dalitz Studies of CPV in $\eta\,(\eta') \to \pi^+\pi^-\pi^0$ via the breaking of mirror symmetry

[SG, 2003; SG & Tandean, 2004; SG, acfi, 2014]



C-odd, P-even

This can be generated by $s-p$ interference of $\left|[\pi^+(\boldsymbol{p})\,\pi^-(-\boldsymbol{p})]_l\,\pi^0(\boldsymbol{p}')_l\right\rangle$ final states of 0^- meson decay.
It is linear in a CP-violating parameter.
This contribution **cannot** be generated by $\bar{\theta}_{\rm QCD}$!
"C violation" [Lee and Wolfenstein, 1965; Lee, 1965, Nauenberg, 1965; Bernstein, Feinberg, and Lee, 1965]

C-even, P-odd

This can be generated by the interference of amplitudes which distinguish $\left|[\pi^-(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_l\,\pi^+(\boldsymbol{p}')_l\right\rangle$ from $\left|[\pi^+(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_l\,\pi^-(\boldsymbol{p}')_l\right\rangle$ as in, e.g., $B \to \rho^+\pi^-$ vs. $B \to \rho^-\pi^+$. "CP-enantiomers" [SG, 2003]
This possibility is not accessible in $\eta \to \pi^+\pi^-\pi^0$ decay (but in η' decay, yes). Thus a "left-right" asymmetry in $\eta \to \pi^+\pi^-\pi^0$ decay tests C-invariance, too.

QCD Prospects

QCD can also open new windows on new physics

iii) $n - \bar{n}$ oscillations:

The quark analogue of $0\nu\,\beta\beta$ decay

Usual thought: magnetic field mitigation necessary to observe an effect

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

$$P_{n\to\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2}\left[1 - \cos(2\mu_n B t)\right]$$

[Marshak & Mohapatra, 1980]

But there are four physical degrees of freedom in a magnetic field, and CPT guarantees that two states are degenerate - and a different conclusion!

→

Employ a 4x4 effective Hamiltonian framework! Transverse magnetic fields play a crucial role!

[SG & Jafari, 2014]

On neutron-antineutron oscillations

The Role of Spin

Employ the basis

$$|n+\rangle, |\bar{n}+\rangle, |n-\rangle, |\bar{n}-\rangle$$

$$\mathcal{H} = \begin{pmatrix} M+\omega_0 & \delta & \omega_1 & 0 \\ \delta & M-\omega_0 & 0 & -\omega_1 \\ \omega_1 & 0 & M-\omega_0 & -\delta \\ 0 & -\omega_1 & -\delta & M+\omega_0 \end{pmatrix} .$$

$\mathbf{B}_0$ defines the quantization axis and $\omega_0 \equiv -\mu_n B_0\,;\, \omega_1 \equiv -\mu_n B_1$

with δ the usual $n - \bar{n}$ mixing matrix element.

If a transverse field ($\mathbf{B}_1$) ! is applied at t=0:

$$\mathcal{P}_{n\to\bar{n}}(t) = \delta^2 \left[\frac{\omega_1^2 t^2}{\omega_0^2+\omega_1^2} + \frac{\omega_0^2}{(\omega_0^2+\omega_1^2)^2}\sin^2(t\sqrt{\omega_0^2+\omega_1^2}) + \frac{\omega_0^2\omega_1^2 t}{(\omega_0^2+\omega_1^2)^{5/2}}\left(1-\sin\left(2t\sqrt{\omega_0^2+\omega_1^2}\right)\right)\right] + \mathcal{O}(\delta^3)\,,$$

The transition probability is O(1) in magnetic fields!

Summary

The control of non-perturbative QCD is important to many new physics searches.

If new physics exists beyond some high scale, an EFT framework links low-energy precision observables with QCD and new physics

QCD (with light quarks) also admits new sorts of BSM searches that probe
(i) new, light, weakly coupled sectors
(ii) new sources of (C and) CP violation
(iii) new possibilities for B-L violation

See Brambilla et al., arXiv:1404.3723, EPJC 74 (2014) 2981 for a comprehensive review of these topics -- and much more!

Backup Slides

Resolving the limits of the V-A Law

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi$$

$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

$$\lambda \equiv \frac{g_A}{g_V}$$

$$\Xi = 1 + 3\lambda^2 + (g_S\epsilon_S)^2 + 3(4g_T\epsilon_T)^2 \,,$$

$$a = a_1 + a_2 \beta \cos\theta_{e\nu}$$

$$a_0 = \frac{(1-\lambda^2) - (g_S\epsilon_S)^2 + (4g_T\epsilon_T)^2}{(1+3\lambda^2) + (g_S\epsilon_S)^2 + 3(4g_T\epsilon_T)^2} \,,$$

$$a_1 = a_0 + f(g_A, f_2, g_2, f_3, E_e)$$

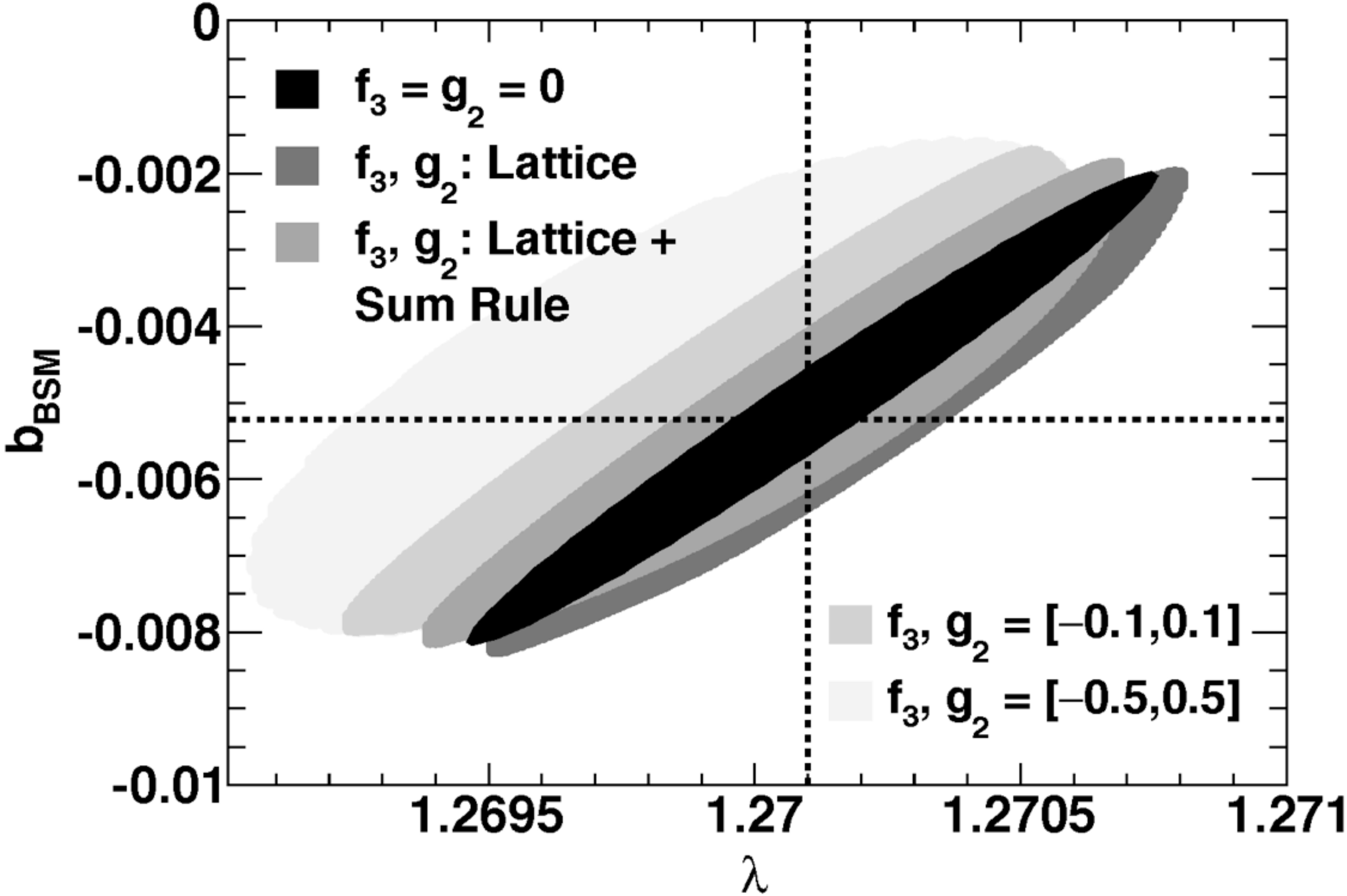
$$b_{\rm BSM} = \frac{2(g_S\epsilon_S) - 6\lambda(4g_T\epsilon_T)}{(1+3\lambda^2) + (g_S\epsilon_S)^2 + 3(4g_T\epsilon_T)^2} \,,$$

$$a_2 = \frac{3(\lambda^2 - 1)}{(1+3\lambda^2)} \frac{E_e}{M}$$

$$a_{\rm exp} \equiv \frac{N(\cos\theta_{e\nu} > 0) - N(\cos\theta_{e\nu} < 0)}{N(\cos\theta_{e\nu} > 0) + N(\cos\theta_{e\nu} < 0)} = \frac{1}{2}\beta \frac{a_1}{1 + b_{\rm BSM}\frac{m_e}{E_e} + \frac{1}{3}a_2\beta^2} \,,$$

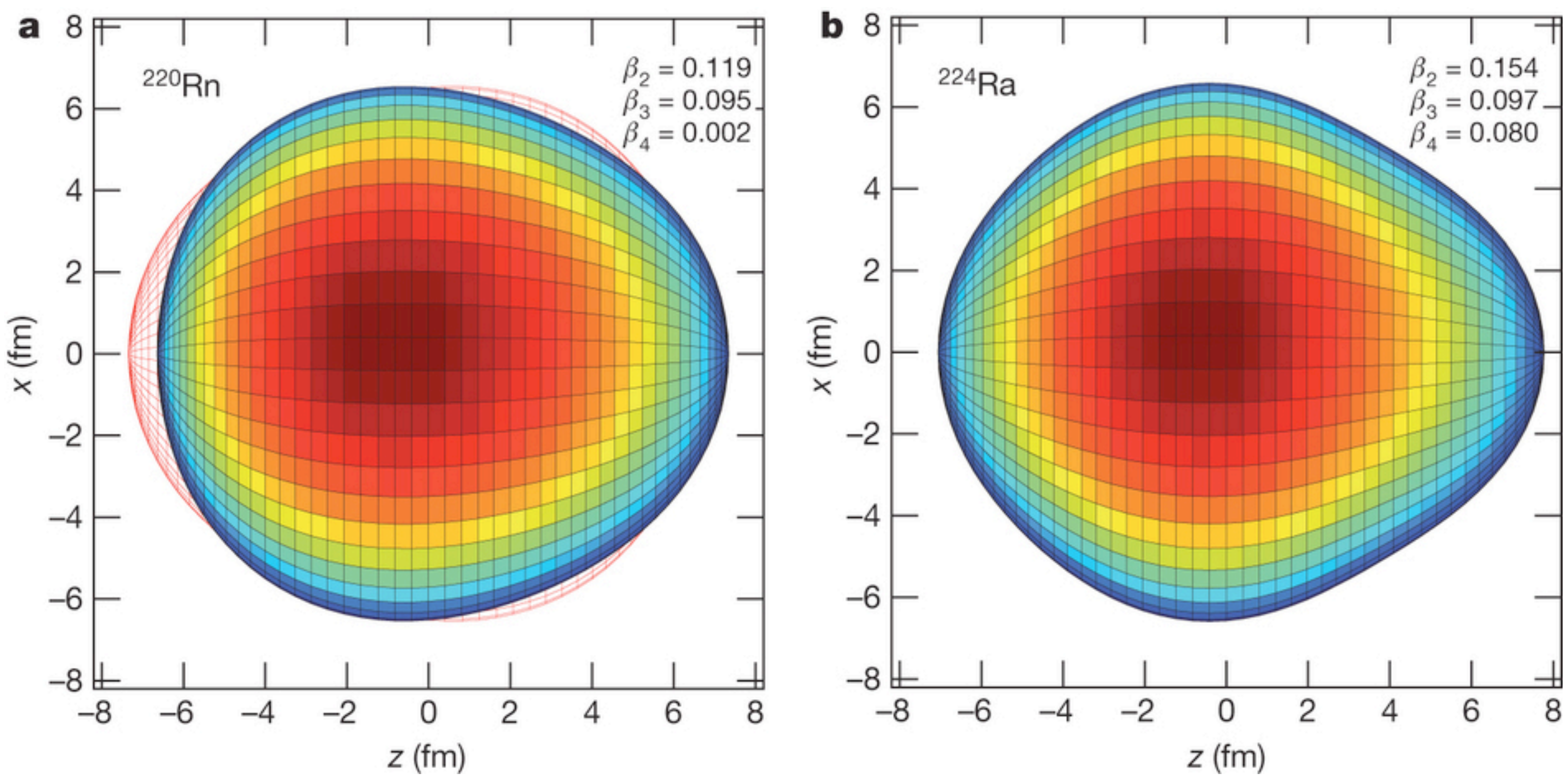
$$A_{\rm exp} \equiv \frac{N(\cos\theta_e > 0) - N(\cos\theta_e < 0)}{N(\cos\theta_e > 0) + N(\cos\theta_e < 0)} = \frac{1}{2}\beta \frac{A}{1 + b_{\rm BSM}\frac{m_e}{E_e}} \,.$$

Maximum Likelihood Fit



Heavy atom EDMs

evade Schiff's theorem through large Z, finite nuclear size, and octupole deformation



[Gaffney et al., Nature (2013)]

Permanent deformation makes the nucleus more "rigid" and the Schiff moment computation more robust and 1000x bigger than ^{199}Hg (existing best atomic EDM limit)

A great opportunity for rare isotope facilities!

Triple Product Momentum Correlations

In radiative beta-decay one can form a T-odd correlation from momenta alone

This is a pseudo-T-odd observable, so that it can be mimicked by FSI, but these are computable up to recoil order terms [SG, Daheng He, 2012]

The interaction which generates it comes from the gauging of the WZW term under SM electroweak gauge invariance [Harvey, Hill, Hill, 2007, 2008]

A direct measurement which constrain the phase of this interaction from physics BSM, possibly from "strong" hidden sector interactions [SG, Daheng He, 2013]