Hunting Traces of TeV-Scale Physics in Low-Energy Processes

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Hall C Summer Workshop 2007

UNIVERSITY OF KENTUCKY

Orientation

Collider experiments probe new physics directly. Precision, low-energy measurements probe new physics indirectly, i.e., through the failure of robust Standard Model predictions.

Some Basic Questions

- How do we know there is a "Beyond"?
- Why do we think there is new physics at the TeV scale?
- Why do we think we can probe TeV-scale physics in precision, low-energy experiments?
- Are indirect searches for new TeV-scale physics rendered obsolete by the LHC?

How do we know there is a "Beyond"?

There is much theoretical "evidence" that the Standard Model is incomplete — *it leaves many questions unanswered.*
Here are a few.

- It does not explain dark matter, dark energy
- It does not explain the number of generations nor the large range of fermion masses
- It does not explain the weak mass scale (the "hierarchy" problem)
- It cannot explain the baryon asymmetry of the Universe

Most notably, the Standard Model only explains 5% of the known Universe.
There is much observational evidence for dark matter.
Note, too, recent direct evidence from the "bullet" cluster:

[Clowe et al., astro-ph/0608407]

How do we know there is a "Beyond"?

We have, moreover, direct empirical evidence from terrestrial experiments for physics beyond the Standard Model.

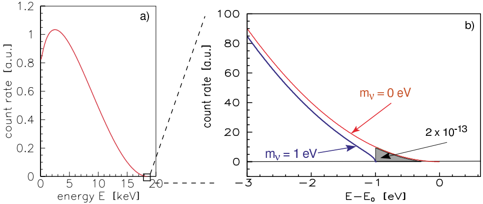
Empirical evidence for neutrino oscillations allows us to conclude $\Delta m^2 \equiv m_i^2 - m_j^2 \neq 0$ with surety.

That is, neutrinos have mass.

We see then that the particle content of the Standard Model is incomplete: there is a ν_R, which is "sterile" under Standard Model interactions.

This is not to say that the effects of neutrino mass are large.

Distortions in the shape of the electron energy spectrum in ^{3}H β-decay near its endpoint bound m_ν^2. [KATRIN, loi]



The Emergence of Physics Beyond the Standard Model

Why do we think there is new physics at $\sim$ 1 TeV?

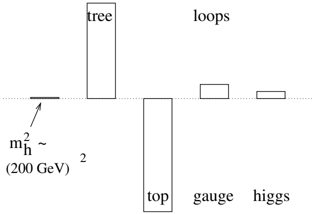
[Schmaltz, hep-ph/0210415]

Suppose we assume the Standard Model is valid for scales $E \leq \Lambda$, where $\Lambda \sim \mathcal{O}(1\text{TeV})$.

At one-loop level, we find large corrections to the tree-level Higgs mass m_{tree}.

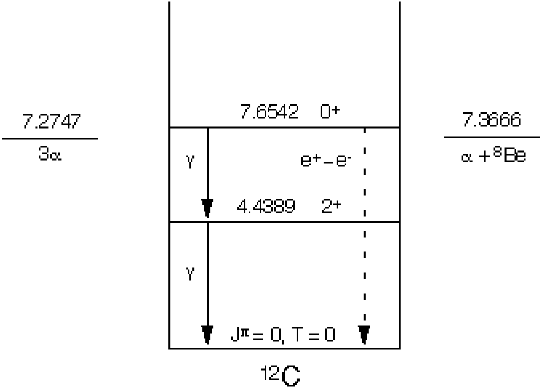
All contributions must sum to $m_H^2 \sim (200\text{GeV})^2$, but each one $\sim \Lambda^2$!

At $\Lambda = 10$ TeV, m_{tree} must be tuned to one part in 100!



New physics at the TeV scale can enter to make the cancellations “natural.”

“Fine-Tuning” does exist in Nature



[Hoyle, 1953; Cook, Fowler, Lauritsen, Lauritsen, 1957]

Can we probe TeV-scale physics at low energies?

Yes. Let's illustrate this in a toy model.

Consider the Gerasimov-Drell-Hearn sum rule:

[Gerasimov, 1966; Drell and Hearn, 1966.]

$$\frac{2\pi\alpha\kappa_i^2}{M^2} = \frac{1}{\pi}\int_{\omega_{\rm th}}^{\infty} \frac{\Delta\sigma_i}{\omega}\, d\omega \equiv \frac{1}{\pi}\int_{\omega_{\rm th}}^{\infty} \frac{(\sigma_{{\rm P}i}(\omega) - \sigma_{{\rm A}i}(\omega))}{\omega}\, d\omega$$

The photon and nucleon spins are aligned parallel (P) or anti-parallel (A).

A *linearized* sum rule also exists:

[Holstein, Pascalutsa, and Vanderhaeghen, 2005.]

$$\frac{4\pi\alpha\delta\kappa_i}{M^2} = \frac{1}{\pi}\int_{\omega_{\rm th}}^{\infty} \frac{\Delta\tilde{\sigma}_i}{\omega}\, d\omega$$

where $\Delta\tilde{\sigma} \equiv \partial\Delta\sigma/\partial\kappa_{0i}|_{\kappa_{0p}=\kappa_{0n}=0}$. We can compute the contribution to κ_i from

$$\mathcal{L}_{\pi NN} = \frac{g}{2M}\bar{\psi}\gamma^\mu\gamma^5\tau^a\psi\partial_\mu\pi^a$$

We thus determine the loop contribution to κ_i from a "pion" produced at some inelastic threshold ω_{New} in $\gamma - p$ scattering.

Can we probe TeV-scale physics at low energies?

As $\mu \equiv M_\pi / M \to \infty$ this yields

$$\delta\kappa_p = \frac{g^2}{(4\pi)^2}(5 - 4\ln\mu)\frac{1}{\mu^2} + \mathcal{O}(\mu^{-4})$$
$$\delta\kappa_n = \frac{g^2}{(4\pi)^2}2(3 - 4\ln\mu)\frac{1}{\mu^2} + \mathcal{O}(\mu^{-4})$$

Thus if we choose $M_\pi \sim 1$ TeV, $\mu \sim 10^3$, with $g^2/4\pi = 13.5$,

$$\delta\kappa_p = -2.4 \cdot 10^{-5} \qquad \kappa_p^{\rm exp} = 1.792847351(28)$$
$$\delta\kappa_n = -5.3 \cdot 10^{-5} \qquad \kappa_n^{\rm exp} = -1.9130427(5)$$

The effects of putative TeV-scale physics on the anom. mag. moments are appreciable.

The empirical anomalous magnetic moments are already sufficiently well-known to be impacted by TeV-scale physics, though these effects are obscured by non-perturbative QCD effects.

A challenge to lattice QCD!

How do we probe new physics in low-energy experiments?

We control non-perturbative QCD effects by exploiting the symmetries of the Standard Model. Some possibilities:

1. Nuclear, neutron, pion, kaon β-decay

Search for non-$V - A$ interactions. Tests of CKM unitarity.

2. The effective weak charge of an electron, proton, nucleus

Test the “running” of $\sin^2(\theta_W(Q))$ away from the Z^0-pole.

3. Neutron, Atom, Molecular Electric Dipole Moments

The Standard Model produces *negligibly small* EDMs. A measureably non-zero EDM connotes the presence of physics beyond the Standard Model.

Beyond “V-A” in Neutron β-Decay

The search for non-V-A interactions continues...

$$\mathcal{H}_{int} = (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu) + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu)$$
$$-(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu) + (\bar{\psi}_p \gamma_5 \gamma_\mu \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu)$$
$$+\frac{1}{2}(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma^{\lambda\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma^{\lambda\mu} \gamma_5 \psi_\nu) + h.c.$$

[Lee and Yang, 1956; note also Gamow and Teller, 1936]

C'_X denote parity-nonconserving interactions.

In polarized neutron (nuclear) β-decay one more correlation appears: b

$$d^3\Gamma = \frac{1}{(2\pi)^5} \xi E_e |\boldsymbol{p}_e| (E_e^{\max} - E_e)^2 \times$$
$$[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{P} \cdot (A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu})] dE_e d\Omega_e d\Omega_\nu$$

[Jackson, Treiman, and Wyld, Phys. Rev. 106, 517 (1957)]

Note, e.g.,

$$b\xi = \pm 2\mathrm{Re}[C_S C_V^* + C'_S C'^*_V + 3(C_T C_A^* + C'_T C'^*_A)]$$

If the electron polarization is also detected, more correlations enter.

Limits from Nuclear β-Decay

Recent limits on b come from nuclear β-decay:

- $b = +0.0001 \pm 0.0026$ ($|C_S/C_V| \leq 0.0013$)
  from survey of $0^+ \rightarrow 0^+$ transitions in nuclei
  [Towner and Hardy, PRL 94, 092502 (2005)]

- $\tilde{a} \equiv a/(1 + bm_e/\langle E_e \rangle) = 0.9981 \pm 0.0030 \pm 0.0037$
  from $0^+ \rightarrow 0^+$ pure Fermi decay of ^{38m}K
  [A. Gorelov et al., PRL 94, 142501 (2005)]

Both limits are consistent with the Standard Model.
Tests to this precision do not rely on the knowledge of nuclear structure in any way.
Ingredients: CVC hypothesis ($g_V = (1 + \mathcal{O}(\alpha))V_{ud}$), recoil expansion ($\mathcal{O}(E)/M \ll 1$).
It is possible to test the CVC hypothesis (and more) in neutron β-decay through comparison of the a and A correlation coefficients. [SG, Chi Zhang, 2001]

The Cabibbo-Kobayashi-Maskawa (CKM) Matrix

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

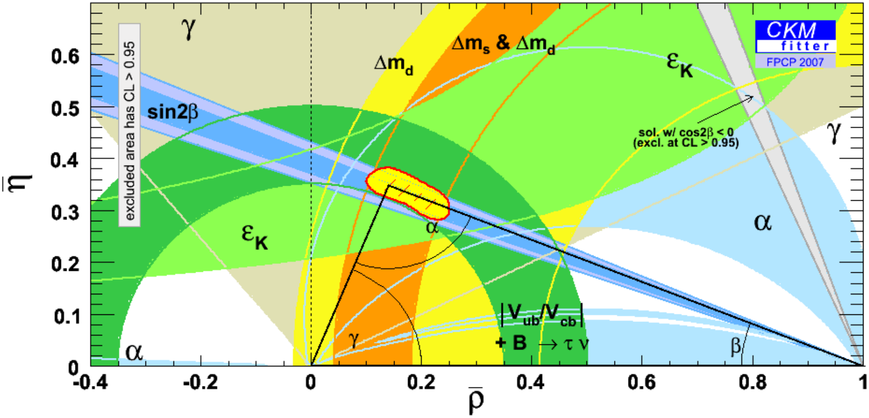
In the Wolfenstein parametrization (1983)

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

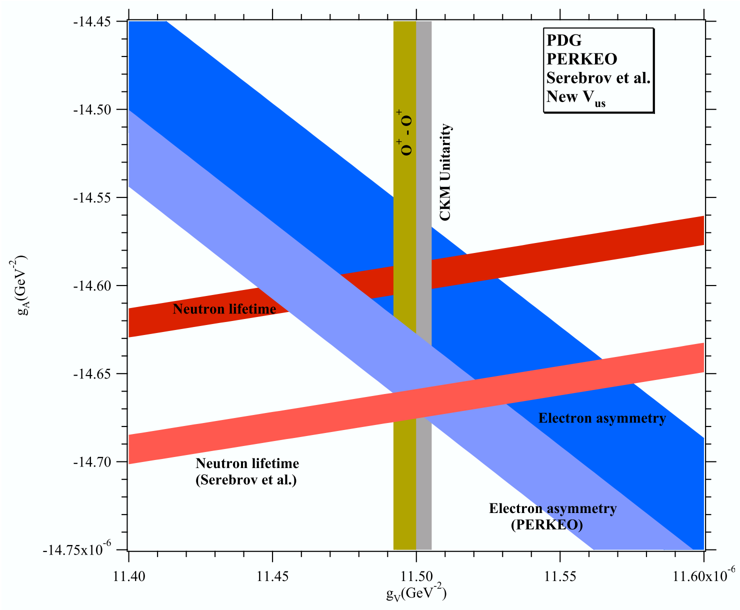
where $\lambda \equiv |V_{us}| \simeq 0.22$ and is thus “small”. A, ρ, η are real.

- There are three “generations” of particles.
  Thus, the CKM matrix is unitary [$V^\dagger_{\rm CKM} V_{\rm CKM} = 1$]
- The unitarity of the CKM matrix and the structure of the weak currents implies that four parameters capture the CKM matrix.
- A real, orthogonal 3×3 matrix contains three parameters. The fourth parameter (η) must make $V_{\rm CKM}$ complex.
- All CP-violating phenomena are encoded in η.

Testing CKM Unitarity – "the" Unitarity Triangle

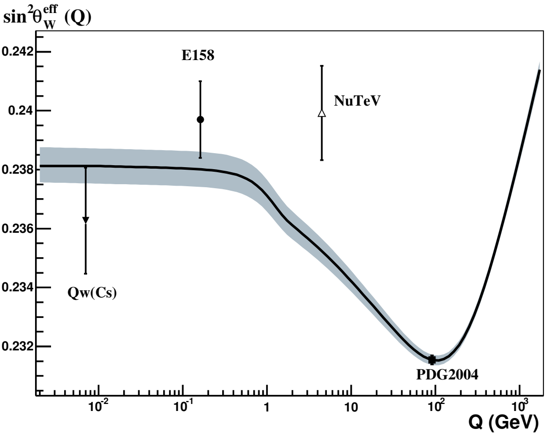


[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – June, 2007 update]


PDG
PERKEO
Serebrov et al.
New V_{us}
0^+ - 0^+
CKM Unitarity
Neutron lifetime
Neutron lifetime
(Serebrov et al.)
Electron asymmetry
Electron asymmetry
(PERKEO)
$g_A(\mathrm{GeV}^{-2})$
$g_V(\mathrm{GeV}^{-2})$
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
11.40
11.45
11.50
11.55
11.60x10^{-6}

[J. Nico (NIST)]

The Effective Weak Charge



[E158, Anthony et al, PRL 95 (2005) 081601]

[Theory: Czarnecki and Marciano, 1996, 2000; Erler and Ramsey-Musolf, 2005]

Future experimental studies should yield much sharper tests.

The Electric Dipole Moment - A Primer

The electric dipole moment d of a particle with spin S is defined via
$\mathcal{H} = -d\frac{\mathbf{S}}{S} \cdot \mathbf{E}$

$d \neq 0$ violates both T and P.

E. M. Purcell and N. F. Ramsey, “On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei,” Phys. Rev. 78, 807 (1950):

> The argument against electric dipoles, in another form, raises the question of parity.... But there is no compelling reason for excluding this possibility....

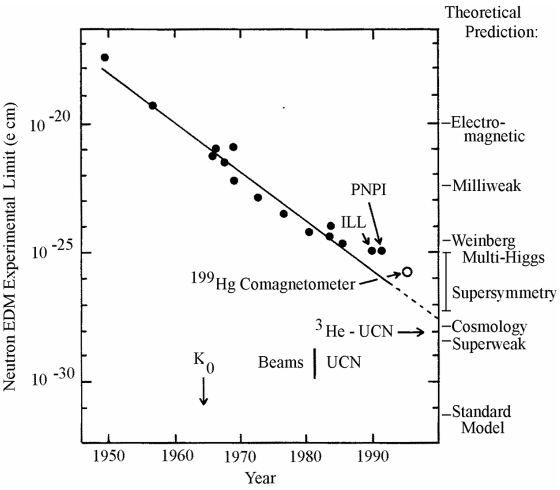
Context: Dirac (1949) – A magnetic monopole violates P, T.

A experimental strategy for d:

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

Limit set by neutron density, observation time, and the strength of the applied electric field.

Neutron EDM Timeline – The “Model Killer”



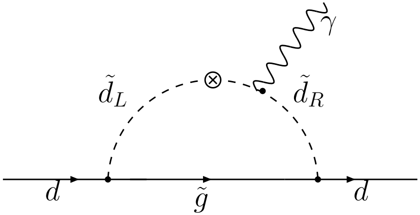
[S. Lamoreaux (Yale)]

Electric Dipole Moments

EDM measurements exist on neutrons, paramagnetic atoms (^{205}Tl: "d_e"), and diamagnetic atoms.

Supersymmetric models naturally "overproduce" electric dipole moments – picking parameters at random invariably lead to EDMs at odds with experiment, the "SUSY CP problem".

[Pospelov and Ritz, 2005]

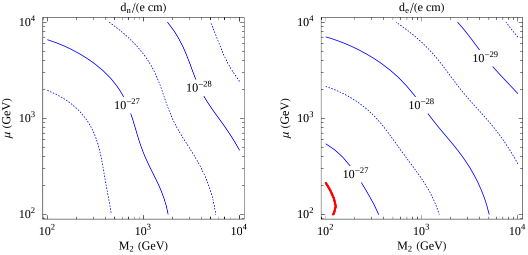


Can resolve by making scalars heavy or CP-violating parameters small.

Electric Dipole Moments

Models with “split” supersymmetry (heavy scalars!) can still produce significant EDMs at two-loop order:

[Giudice and Romanino, 2006]



The red shows current limit on d_e.

Both d_e and d_n are expected to improve.

$|d_n| \leq 3 \cdot 10^{-26}$ e-cm [Baker et al.,ILL, hep-ex/0602020] to 10^{-28} e-cm [LANL/SNS EDM expt]

$|d_e| \leq 1.6 \cdot 10^{-27}$ e-cm [Regan, Commins, Schmidt, DeMille, PRL 88, 071805 (2002)]

to $10^{-29\,(31)}$ e-cm [DeMille]

Electric Dipole Moments

Estimates of hadronic electric dipole moments depend on the hadron's non-perturbative structure.

For example, in the SM (CKM mechanism of CP violation), long-distance effects (π-loop) give for the neutron

$d_n^{\mathrm{KM}} \simeq 10^{-32}$e-cm [Gavela et al., PLB 1982; Khriplovich & Zhitnitsky, PLB 1982]

whereas a LL computation in three-loops yields

$d_d^{\mathrm{KM}} \simeq 10^{-34}$e-cm. [Czarnecki & Krause, PRL 1997]

cf. QCD sum rules w/ dim ≤ 5 CP-violating ops. give d_n to $\sim 50\%$

[Pospelov & Ritz, PRL 1999]

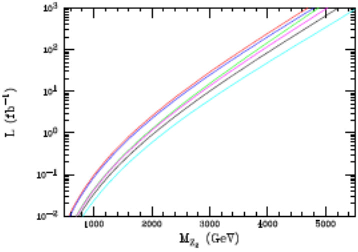
Evaluating d_n and d_p is also important to interpreting the ^2H EDM.

[Lebedev et al., PRD 2004]

The quality of the nucleon matrix element computations needed to extract bounds on fundamental Lagrangian parameters can be tested by confronting the empirical anomalous moments. [Brodsky, SG, Hwang, 2006]

The Lesson of the Z'. Note 5σ discovery reach:

The LHC should accumulate $10 fb^{-1}$ in *L each year*.



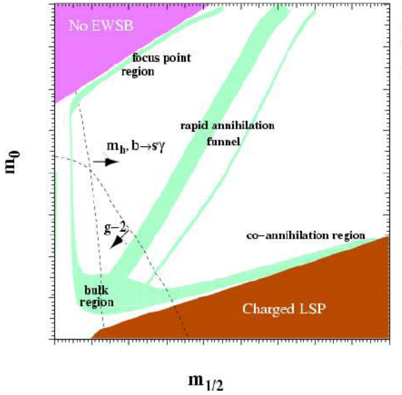
[T. Rizzo (SLAC), TASI 06]

The LHC should quickly find a Z' of a few TeV in mass — and eventually determine its spin.

But is it *really* a Z'? For that, determining its complings to SM fermions are essential... and low-energy experiments can play a crucial role.

Complementarity

In supersymmetric models with restricted parameter space (note the "CMSSM"), the constraints of the superpartner masses from cosmological and low-energy data are severe. Caveat Emptor!



[M. Schmitt (Northwestern), SSI 2007, after J. Feng, astro-ph/0511043 and refs. therein]

Major ticks are separated by 100 GeV.

Outlook

We look forward to an era of discovery!