Precision β-Decay Studies in the LHC Era

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY 40506

gardner@pa.uky.edu

International Workshop on “UCN Sources and Experiments,”
TRIUMF, September 13-14, 2007

UNIVERSITY OF KENTUCKY

Orientation

The Standard Model, successful though it may be, leaves many questions unanswered.
Yet the only compelling evidence we have for physics beyond the SM from terrestrial experiments is that neutrinos have mass.

Some Basic Questions, circa 2007

- How well has the Standard Model been tested?
- How well should we have to test it to find “new physics”?
- Does the specific nature of the new physics we know constrain what we don’t know? Really?
- Does the LHC make the low energy searches for new physics moot?

Tests exist in different sectors...

1. Precision Electroweak.

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

June 12, 2007 11:05

2. Precision QED (& QCD).

G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom, *New Determination of the Fine Structure Constant from the Electron g Value and QED*, PRL **97**, 030802 (2006).

Quantum electrodynamics (QED) predicts a relationship between the dimensionless magnetic moment of the electron (g) and the fine structure constant (α). A new measurement of g using a one-electron quantum cyclotron, together with a QED calculation involving 891 eighth-order Feynman diagrams, determine α^{-1}=137.035 999 710 (96) [0.70 ppb]....

3. Precision Flavor Physics.

Enter the CKM matrix...

The Cabibbo-Kobayashi-Maskawa (CKM) Matrix

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

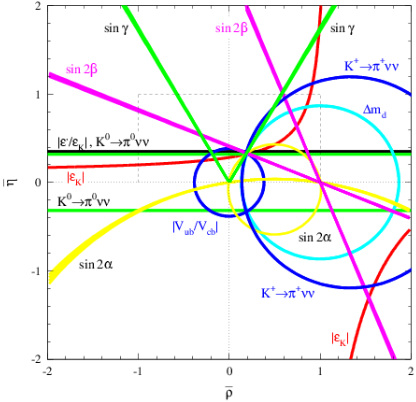
In the Wolfenstein parametrization (1983)

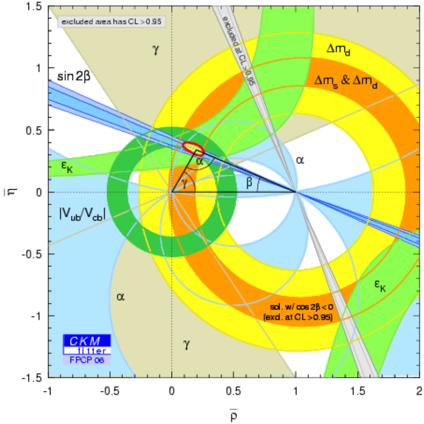
$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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 [$V_{\text{CKM}}^\dagger V_{\text{CKM}} = 1$]
- 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_{CKM} complex.
- All CP-violating phenomena are encoded in η.

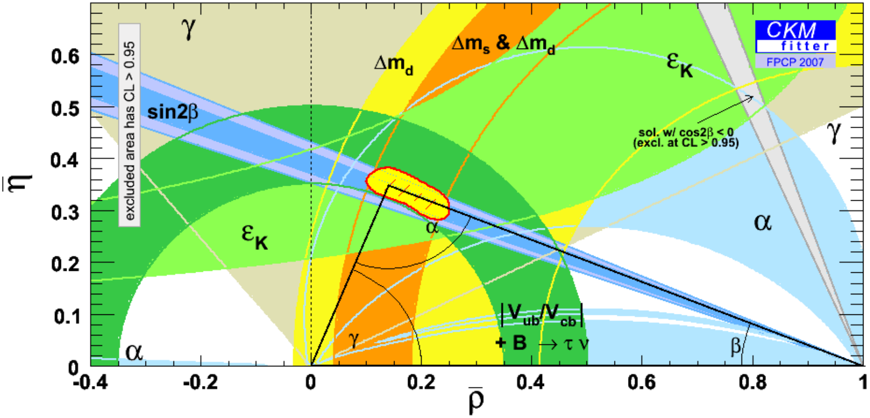
Testing CKM Unitarity – "the" Unitarity Triangle





[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – April, 2006 update]

Testing CKM Unitarity – "the" Unitarity Triangle



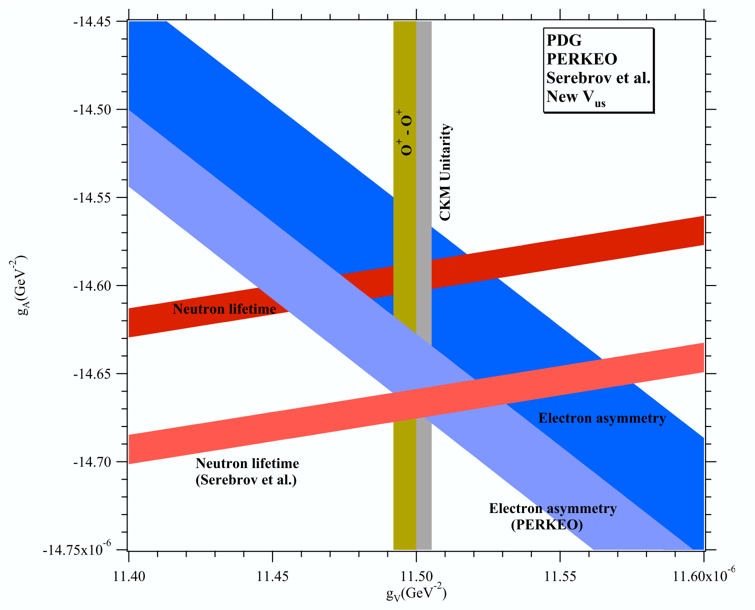
[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – June, 2007 update]

Testing the CKM Paradigm

Observable	central ± C.L. ≡ 1σ	± C.L. ≡ 2σ	± C.L. ≡ 3σ
$\|V_{ud}\|$	$0.97383^{+0.00024}_{-0.00023}$	$^{+0.00047}_{-0.00047}$	$^{+0.00071}_{-0.00071}$
$\|V_{us}\|$	$0.2272^{+0.0010}_{-0.0010}$	$^{+0.0020}_{-0.0020}$	$^{+0.0030}_{-0.0030}$
$\|V_{ub}\|$ $[10^{-3}]$	$3.82^{+0.15}_{-0.15}$	$^{+0.31}_{-0.29}$	$^{+0.49}_{-0.44}$
$\|V_{ub}\|$ $[10^{-3}]$ (meas. not in fit)	$3.64^{+0.19}_{-0.18}$	$^{+0.39}_{-0.36}$	$^{+0.60}_{-0.55}$
$\|V_{cd}\|$	$0.22712^{+0.00099}_{-0.00103}$	$^{+0.00199}_{-0.00205}$	$^{+0.00300}_{-0.00307}$
$\|V_{cs}\|$	$0.97297^{+0.00024}_{-0.00023}$	$^{+0.00048}_{-0.00047}$	$^{+0.00071}_{-0.00071}$
$\|V_{cb}\|$ $[10^{-3}]$	$41.79^{+0.63}_{-0.63}$	$^{+1.26}_{-1.27}$	$^{+1.89}_{-1.90}$
$\|V_{cb}\|$ $[10^{-3}]$ (meas. not in fit)	$44.9^{+1.2}_{-2.8}$	$^{+2.4}_{-5.7}$	$^{+3.8}_{-7.7}$
$\|V_{td}\|$ $[10^{-3}]$	$8.28^{+0.33}_{-0.29}$	$^{+0.92}_{-0.57}$	$^{+1.38}_{-0.86}$
$\|V_{ts}\|$ $[10^{-3}]$	$41.13^{+0.63}_{-0.62}$	$^{+1.25}_{-1.24}$	$^{+1.87}_{-1.86}$
$\|V_{tb}\|$	$0.999119^{+0.000026}_{-0.000027}$	$^{+0.000052}_{-0.000054}$	$^{+0.000078}_{-0.000082}$
$\|V_{td}/V_{ts}\|$	$0.2011^{+0.0081}_{-0.0065}$	$^{+0.0230}_{-0.0127}$	$^{+0.0345}_{-0.0195}$
$\|V_{ud}V_{ub}^*\|$ $[10^{-3}]$	$3.72^{+0.15}_{-0.14}$	$^{+0.30}_{-0.29}$	$^{+0.48}_{-0.43}$
$\arg[V_{ud}V_{ub}^*]$ (deg)	$59.8^{+4.9}_{-4.0}$	$^{+13.9}_{-7.8}$	$^{+20.9}_{-12.1}$
$\arg[-V_{ts}V_{tb}^*]$ (deg)	$1.043^{+0.061}_{-0.057}$	$^{+0.151}_{-0.114}$	$^{+0.238}_{-0.176}$
$\|V_{cd}V_{cb}^*\|$ $[10^{-3}]$	$9.49^{+0.15}_{-0.15}$	$^{+0.30}_{-0.30}$	$^{+0.45}_{-0.45}$
$\arg[-V_{cd}V_{cb}^*]$ (deg)	$0.0339^{+0.0021}_{-0.0020}$	$^{+0.0050}_{-0.0040}$	$^{+0.0077}_{-0.0060}$
$\|V_{td}V_{tb}^*\|$ $[10^{-3}]$	$8.27^{+0.33}_{-0.29}$	$^{+0.93}_{-0.57}$	$^{+1.38}_{-0.85}$
$\arg[V_{td}V_{tb}^*]$ (deg)	$-22.84^{+1.00}_{-0.99}$	$^{+1.98}_{-2.02}$	$^{+2.93}_{-3.21}$
$\sin\theta_{12}$	$0.2272^{+0.0010}_{-0.0010}$	$^{+0.0020}_{-0.0020}$	$^{+0.0030}_{-0.0030}$
$\sin\theta_{13}$ $[10^{-3}]$	$3.82^{+0.15}_{-0.15}$	$^{+0.31}_{-0.30}$	$^{+0.49}_{-0.44}$
$\sin\theta_{23}$ $[10^{-3}]$	$41.78^{+0.63}_{-0.63}$	$^{+1.26}_{-1.26}$	$^{+1.90}_{-1.89}$

Table 3: *Numerical results of the global CKM fit (II) [51]. The errors correspond to one, two and three standard deviations, respectively.*

[F. Wilczek, "Anticipating a New Golden Age," arXiv:0708.4235v2 and refs therein.]


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

[J. Nico (NIST)]

Testing CKM Unitarity

Using the global fits...

The first row of the CKM matrix yields the most precise test of CKM unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992 \pm 0.0011$$

whereas

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1.001 \pm 0.005$$
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.968 \pm 0.181$$

N.B. the W leptonic width and the V_{ud} unitarity test (1^{st} row) yields

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.003 \pm 0.027$$

cf. $\alpha + \beta + \gamma = 184^{+20}_{-15}{}^\circ$.

["The CKM Quark-Mixing Matrix," PDG, 2006.]

Tests to this precision require precise computations of SM radiative corrections...

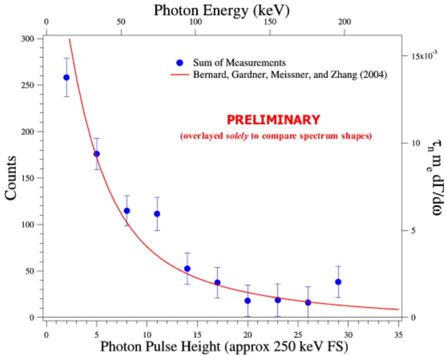
$$g_v = V_{ud}(1 + \Delta\hat{r}_\beta - \Delta\hat{r}_\mu)$$

The precision of the current unitarity tests probes the reliability of these computations to the sub-1% level.

Testing SM radiative corrections

SM radiative corrections relate the vector weak coupling constant g_V of the nucleon to V_{ud}.

The decay $n \to p e^- \bar{\nu}_e \gamma$ has finally been observed.



For $\omega \in [0.015\,\text{MeV}, 0.340\,\text{MeV}]$ we find a Br of $2.85 \cdot 10^{-3}$, cf. with the expt'l result of $3.13 \pm 0.34 \cdot 10^{-3}$. [Nico et al. (NIST), Nature, 2006]

The $\mathcal{O}(1/M)$ terms contribute $\mathcal{O}(0.04\%)$ to the Br.

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 $0^+ \to 0^+$ 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 $0^+ \to 0^+$ 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, Zhang, PRL 2001]

Global Fits to Neutron and Nuclear β-Decay Data

A seven-parameter (real couplings) global fit yields

[Severijns, Beck, Naviliat-Cuncic, RMP, 2006]

$$-1.40 < C_A/C_V < -1.17$$
$$0.87 < C'_V/C_V < 1.17$$
$$0.86 < C'_A/C_A < 1.16$$
$$-0.065 < C_S/C_V < 0.070$$
$$-0.067 < C'_S/C_V < 0.066$$
$$-0.076 < C_T/C_A < 0.090$$
$$-0.078 < C'_T/C_A < 0.089$$

At 95.5% CL one encloses the SM, namely $C_S = C'_S = C_T = C'_T = 0$ and $C'_V/C_V = C'_A/C_A = 1$.

How large do we expect new physics effects to be?

Let's look at the C_s term in $\mathcal{H}_{int}$ in a quark basis e.g.:

$$C_S \bar{\psi}_p \psi_n \bar{\psi}_e \psi_\nu \rightarrow C_S^q \bar{\psi}_u \psi_d \bar{\psi}_e \psi_\nu$$

This is a dimension-6 operator, so that we'd expect

$$C_S^q \sim \frac{\alpha}{4\pi} \left(\frac{M_W}{M_{\rm new}} \right)^2 \sim 10^{-3} \quad \text{if} \quad M_W \sim M_{\rm new}$$

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

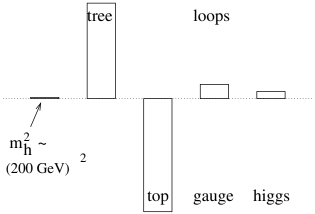
[Schmaltz, hep-ph/0210415]

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}.

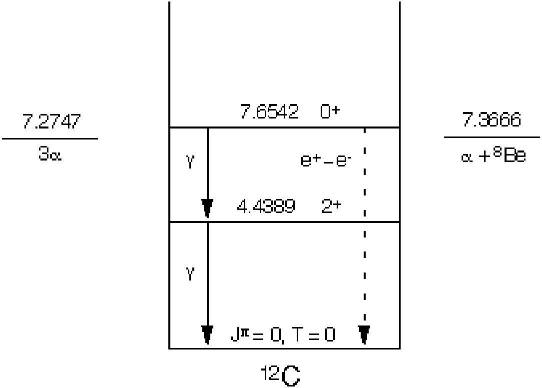
All contributions must sum to $m_H^2 \sim (200\text{GeV})^2$, but each one $\sim \Lambda^2$!

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]

The New Physics We Know...

We do have 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.

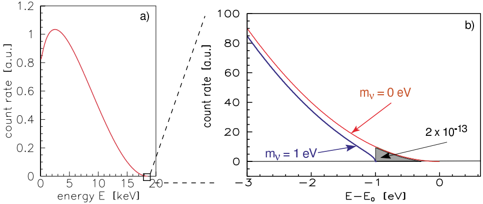
That is, neutrinos have mass.

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

Note $m(\nu_e) \leq 2.3$ eV/c^2 at 95% CL from ^{3}H β-decay [Ch. Kraus et al., EPJ C40 (2005) 447.] and $\sum_\nu m(\nu) < 0.66$ eV/c^2 at 95% CL from 3-year WMAP data set and others (ΛCDM Model).

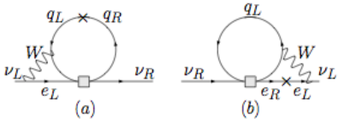
[D.N. Spergel et al. (WMAP), Astrophys. J. Suppl. 170 (2007) 377.]

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



ν *Mass Constraints on* β*-Decay?*

The ν mass involves chirality-changing interactions, e.g.,



which can appear in other observables, such as the magnetic moment. Using "naturalness" bounds in an EFT framework yields for a Dirac neutrino,

$$\mu_\nu \lesssim 3 \cdot 10^{-15} \mu_B \left(\frac{m_\nu}{1\,\mathrm{eV}}\right) \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^2$$

[N.F. Bell et al., PRL **95** (2005) 151802.]

Such relationships can be evaded, typically by imposing a symmetry which makes m_ν "unnaturally" small. [Volshin, SJNP 1988; Georgi and Randall, PLB 1990; Grimus and Neufeld, NPB 1991; Babu and Mohapatra, PRL 1990; Barr, Freire, and Zee, PRL 1990.]

Similar ideas can be used to bound scalar and tensor interactions in β decay from chirality-changing operators.

[Ito and Prezeau, PRL 2005.]

ν *Mass Constraints on* β*-Decay?*

Using CMB ν mass bounds, yields, e.g.,

$$|C_S/C_V| \lesssim 5 \cdot 10^{-3}\,;\ |C_T/C_A| \lesssim 1.2 \cdot 10^{-2}$$

[Ito and Prezeau, PRL 2005.]

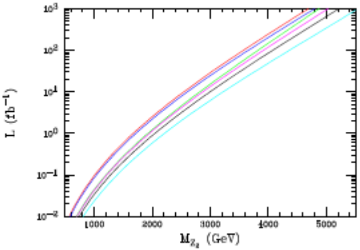
However, effective scalar and tensor couplings can be generated in other ways, note, e.g., and can be *much* larger.

[Profumo, Ramsey-Musolf, Tulin, 2006]

ν mass constraints aren't show-stoppers!

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

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



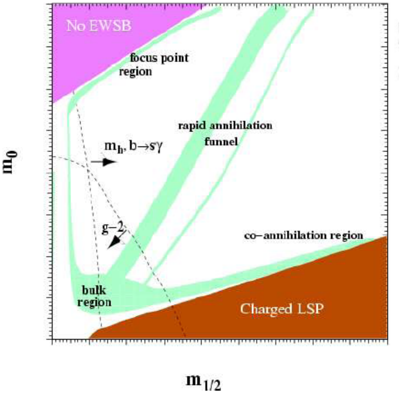
[T. Rizzo (SLAC), TASI 06]

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!