Neutrino Helicity at 50:

A Celebration of the Goldhaber-Grodzins-Sunyar Experiment

May 2, 2008 at Brookhaven National Laboratory

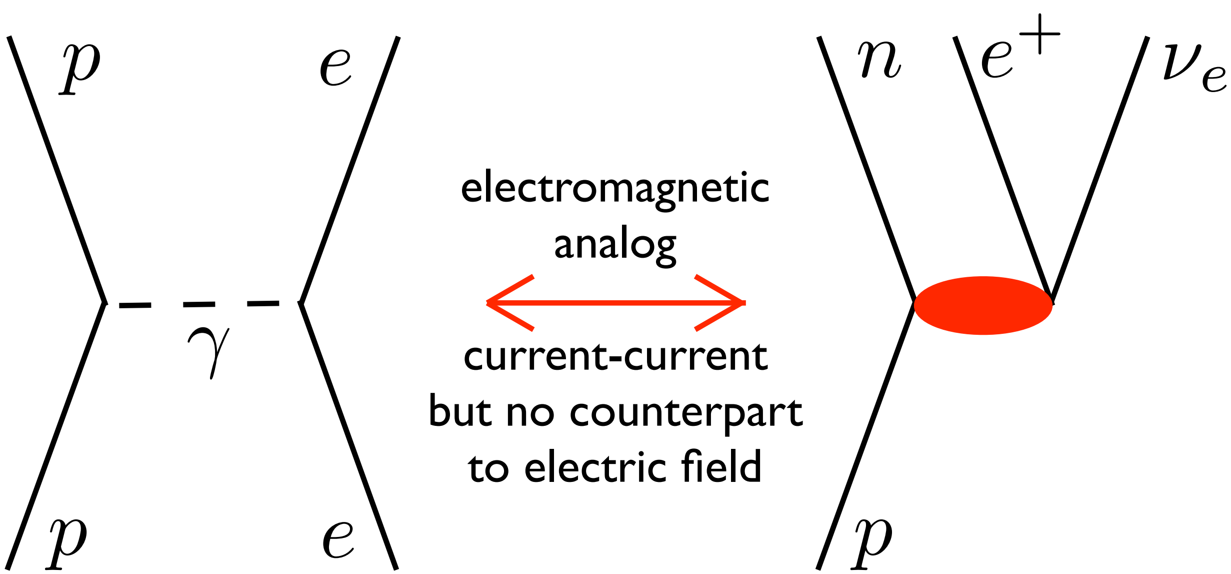
Theory Perspective:
The GGS Experiment and the Neutrino

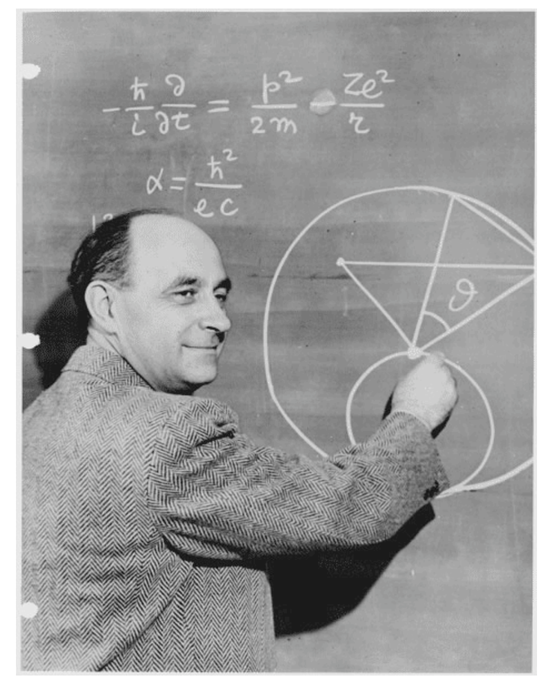
- neutrino helicity and mass
- neutrino moments and interactions

- Pauli's 1930 conjecture that an unobserved neutral, spin-1/2 "neutrino" accounted for the apparent absence of energy conservation in decay -- neutrino viewed as a nuclear constituent

- Chadwick's 1932 discovery of the neutron

- prompted Fermi to propose

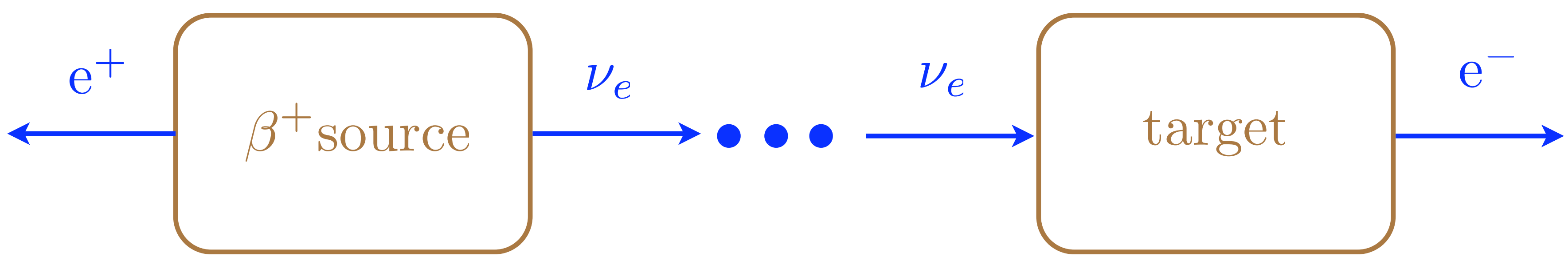




- remarkable conjecture: correct effective theory for the low-energy weak interaction apart from one detail, parity violation

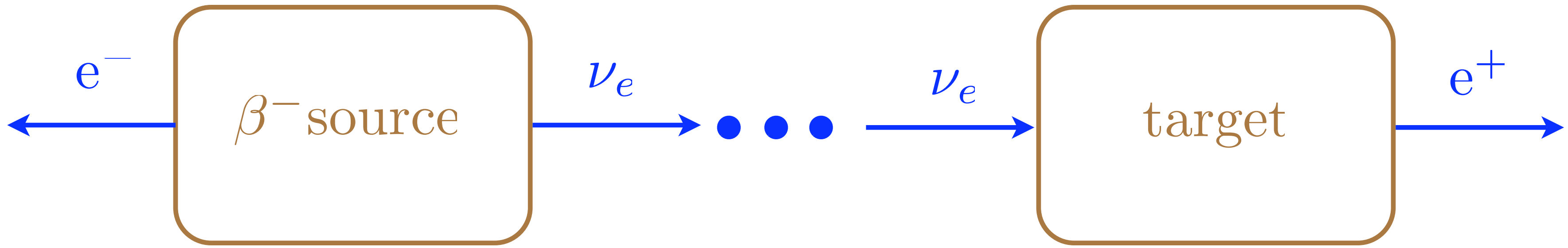
- produced neutrino has no charge or other distinguishing additive quantum number, raising the question -- are the neutrinos produced in β^- and β^+ decay the same?

so we do an experiment:



this defines the ν_e which is then found to produce: e^-

and a second one:



this defines the $\bar{\nu}_e$ which is then found to produce: e^+

- with these definitions of the ν_e and ν_e , they appear operationally distinct, producing different final states

- introduce a "charge" to distinguish the neutrino states and to define the allowed reactions, l_e , which we require to be additively conserved

$$\sum_{in} l_e = \sum_{out} l_e$$

$lepton$	l_e
e^-	$+1$
e^+	-1
ν_e	$+1$
$\bar{\nu}_e$	-1

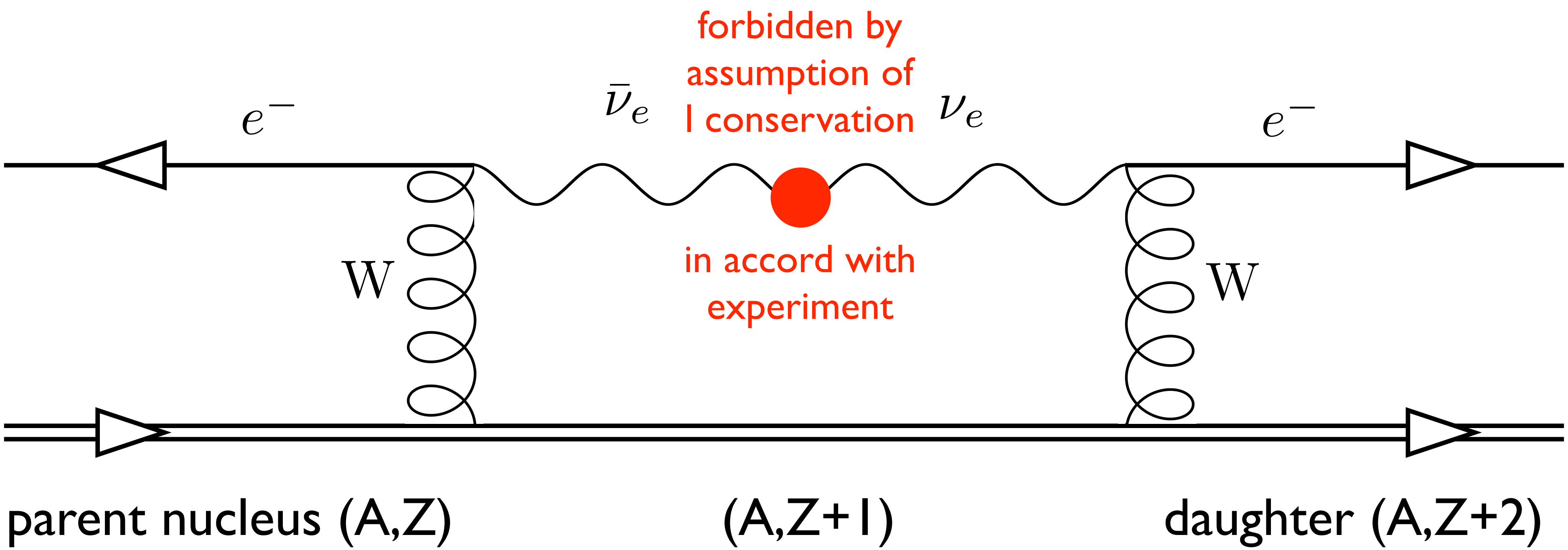
- historically connected with the development of the Cl solar neutrino detector: after Pontecorvo's suggestion, Alvarez did a carefully background study for this detector for a potential reactor experiment, but did not pursue a measurement

- Davis's BNL program included a Savannah River experiment in which reactor anti-neutrinos

$$^{37}\mathrm{Cl} + \bar{\nu}_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

failed to produce Ar, indicating that the ν_e and $\bar{\nu}_e$ are distinct at $\sim 5\%$, a prejudice embedded in the standard model

These experiments are done virtually in neutrinoless $\beta\beta$ decay (Wilkerson)



- only SM fermion where this question of identity under particle-antiparticle conjugation arises: other fermions carry charges

- the arguments make an assumption about neutrino helicity that has important consequences for descriptions of neutrino mass

Circa 1957

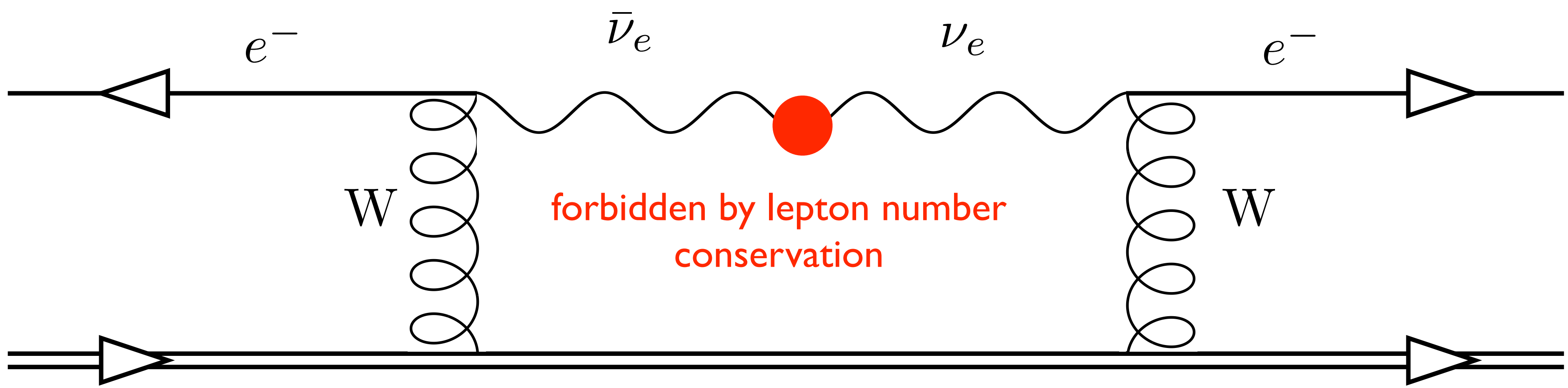
- parity was used early in the 1920s to classify atomic wave functions and atomic transitions: in 1927 Wigner showed that "Laporte's rule" was a consequence of the mirror symmetry of the electromagnetic force

- in 1956 Lee and Yang considered the tau-theta puzzle, the apparent existence of a pair of equal-mass mesons, one of which has negative parity and decays into three pions, the other with positive parity and decaying into two pions: observed that the experimental support for parity conservation was limited to the strong and E&M interactions

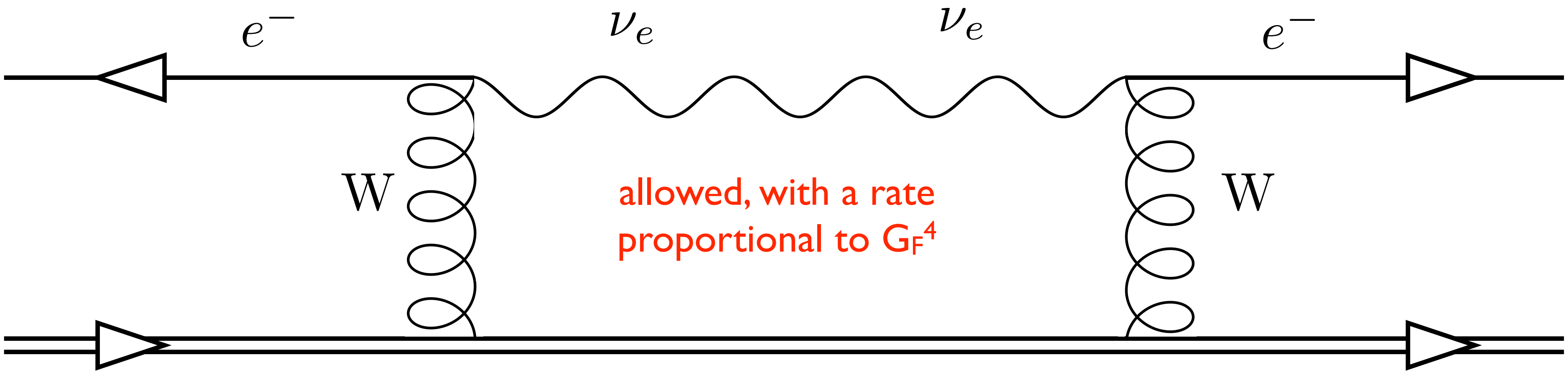
- parity violation demonstrated by
  - ◇ Wu, Ambler, Hayward, Hoppes, and Hudson: observed the angular asymmetry of the βs from the decay of polarized ^{60}Co
  - ◇ Garwin, Lederman, and Weinrich: established large μ polarization in π β-decay from the angular distribution of μ-decay electrons

- elegant GGS experiment showing β-decay νs are left-handed (Grodzins)

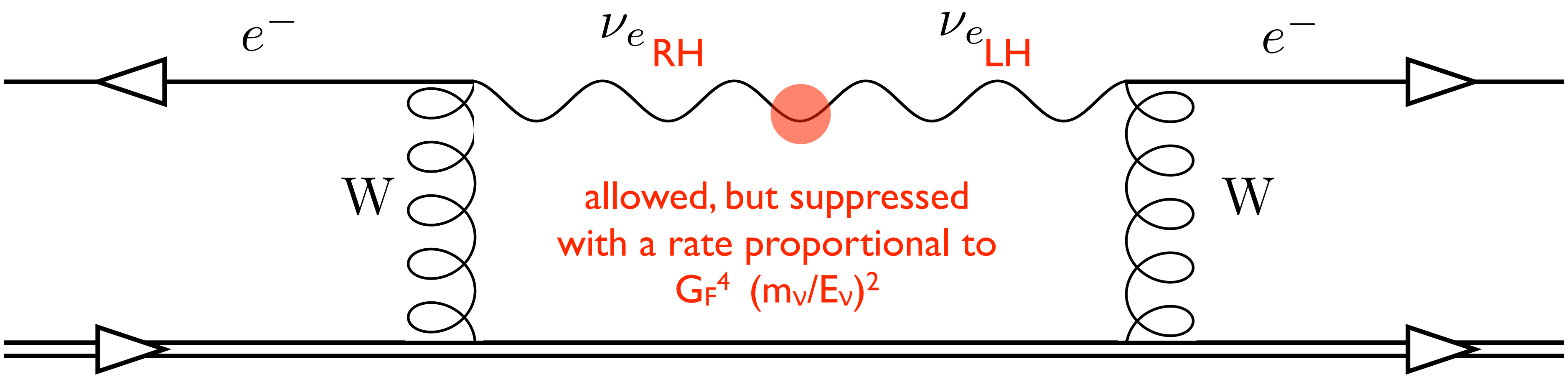
If the weak interaction produces left-handed νs and right-handed ν̅s, let's re-examine



Remove the restriction of an additively conserved lepton number



and account for suppressed rates by the nearly exact handedness

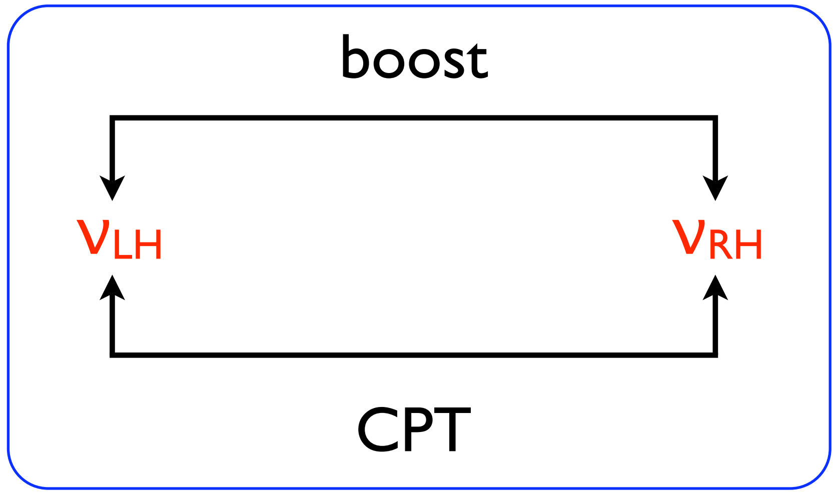


the γ_5-invariance is not exact if the ν has a mass as the "RH-ed" ν state with then contain a small piece of LH-ed helicity proportional to m_ν/E_ν where $E_\nu \sim 1/R_{nuclear}$

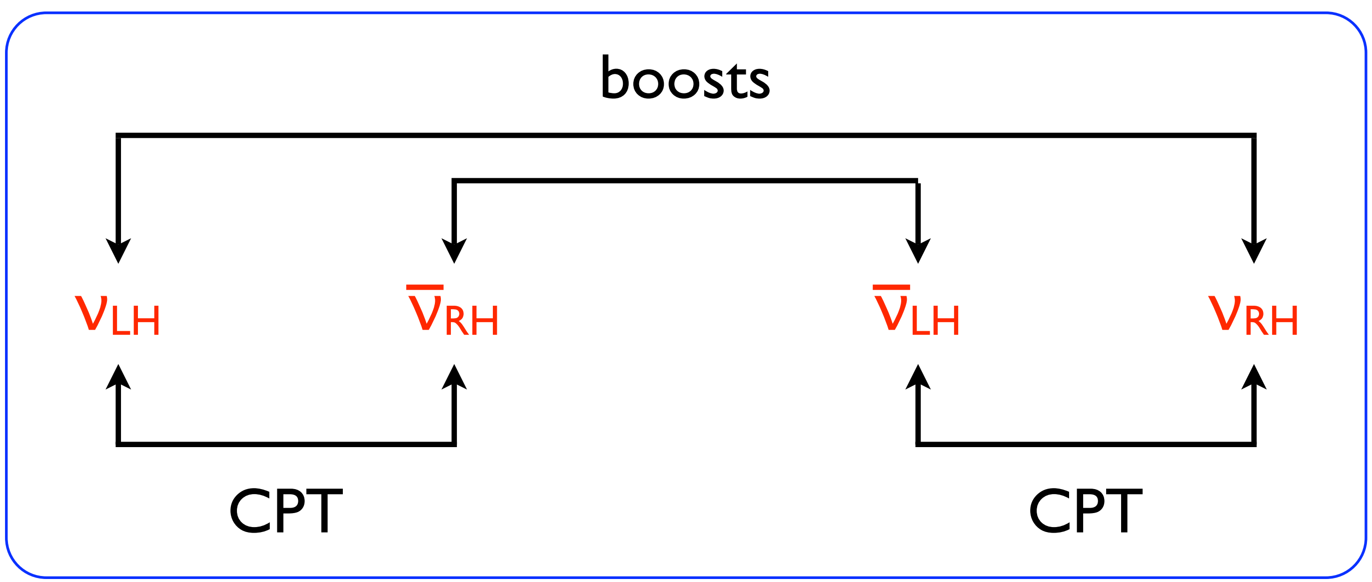
more important, we have found that, because of PNC, there is no need for an additively conserved quantum number constraining descriptions of the neutrino, unlike the case for other SM fermions

Massive neutrino descriptions

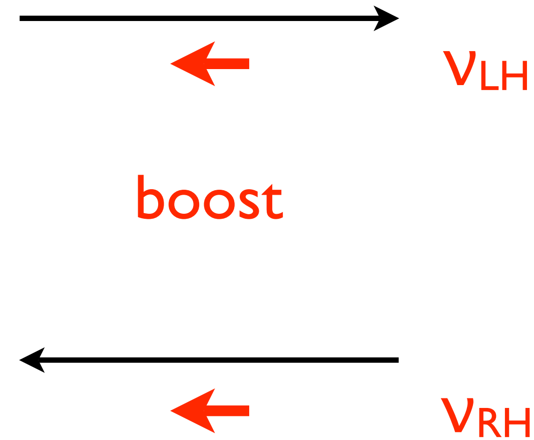
Majorana:



Dirac:



Lorentz invariance



or some linear combinations of the two

Let's see the mass consequences: start with the Dirac eq., project out

$$\psi_{R/L} = \frac{1}{2}(1 \pm \gamma_5)\psi] \qquad C\ \psi_{R/L}\ C^{-1} = \psi^c_{R/L}$$

Allow for flavor mixing

$$L_m(x) \sim m_D \bar{\psi}(x)\psi(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) \qquad \Psi_L \equiv \begin{pmatrix} \Psi^e_L \\ \Psi^\mu_L \\ \Psi^\tau_L \end{pmatrix}$$

To give the mass 4n by 4n matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & & M_D^T \\ 0 & 0 & M_D & \\ & M_D^\dagger & 0 & 0 \\ M_D^* & & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

Observe that the handedness allows an additional generalization

$$L_m(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) + (\bar{\Psi}^c_L(x) M_L \Psi_L(x) + \bar{\Psi}^c_R(x) M_R \Psi_R(x) + h.c.)$$

to give the more general matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

which has a number of interesting properties

- the eigenvectors are two-component Majorana spinors: 2n of these

- the introduction of M_L, M_R breaks the global invariance $\Psi \rightarrow e^{i\alpha}\Psi$ associated with a conserved lepton number

- the removal of M_L, M_R makes the eigenvalues pairwise degenerate: two two-component spinors of opposite CP can be patched together to form one four-component Dirac spinor -- so one gets n of these

- the mass that appears in double beta decay is $\sum_{i=1}^{2n} U_{ei}^2 \lambda_i m_i$, where λ_i is the ith's neutrino CP eigenvalue and U_{ei}^2 the coupling probability to the electron: this vanishes when $M_L, M_R \to 0$

- the MSM has no RHed neutrino field; M_L can be constructed, but does not appear in the MSM because it is not renormalizable

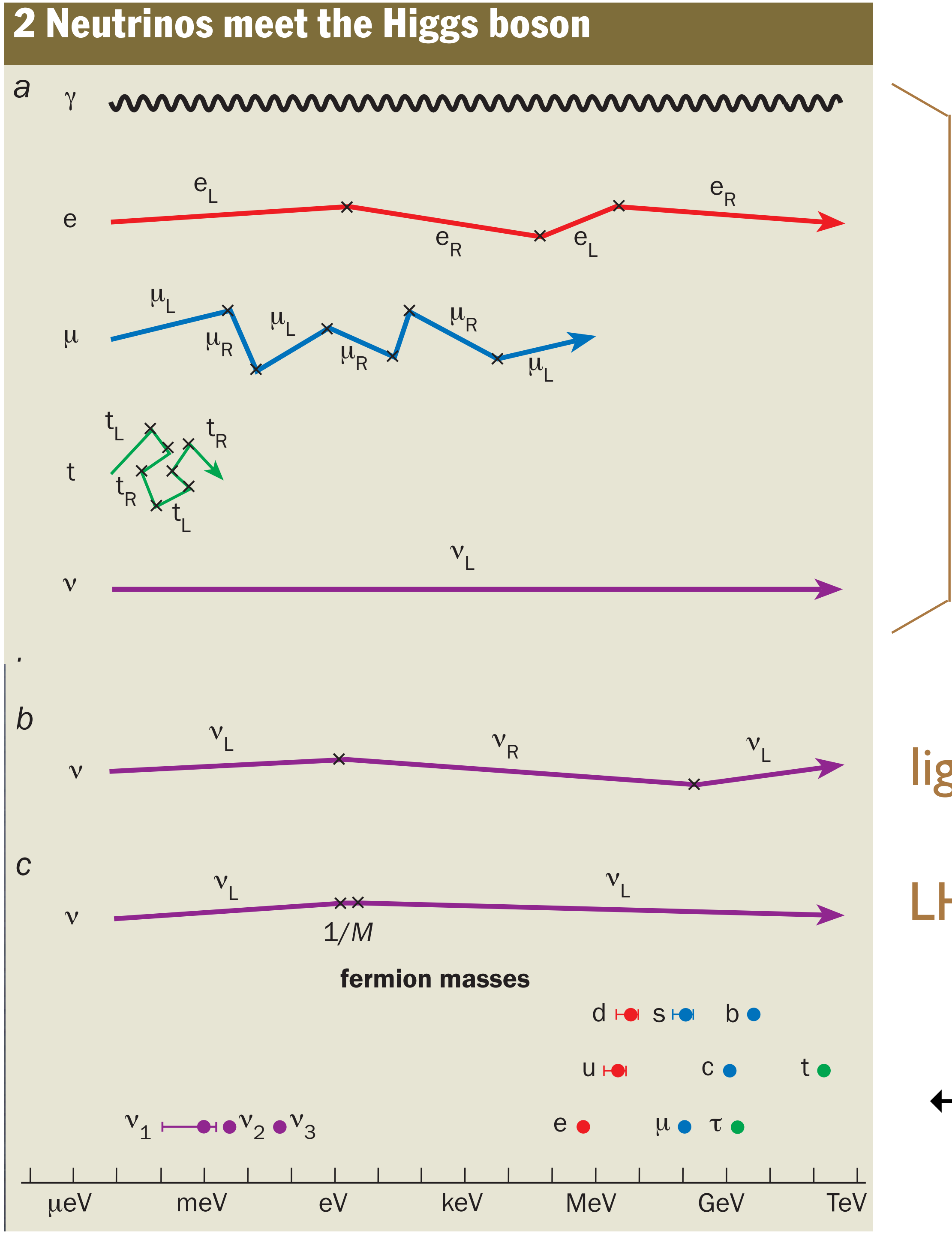
$$M_L \sim \frac{\langle \phi \rangle^2}{M_{new}}$$

  it is the only such dimension-five operator in the SM, and thus a likely source of the new physics that would show the MSM is breaking down

- ββ decay constrains the LHed Majorana mass to be below about an eV

- removal of M_D yields two sets of n decoupled LHed/RHed Majorana νs

Murayama's ν mass cartoon



standard model masses

light Dirac neutrino

LHed Majorana neutrino

← the anomalous ν mass scale

The ν's handedness allows a more general mass ⇒ explanation ν mass scale

- give the ν an M_D typical of other SM fermions

- take $M_L \sim 0$, in accord with $\beta\beta$ decay

- assume $M_R >> M_D$ as we have not found new RHed physics at low E

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \Rightarrow \; m_\nu^{\text{light}} \sim m_D \left(\frac{m_D}{m_R}\right)$$

- take $m_\nu \sim \sqrt{m^2{}_{23}} \sim 0.05$ eV and $m_D \sim m_{top} \sim 180$ GeV

$$\Rightarrow m_R \sim 0.3 \times 10^{15} \text{ GeV}$$

this is a novel mass generation mechanism, not shared by other SM fermions; ν mass may originate from physics near the GUT scale

Neutrino electromagnetic interactions: expected for massive νs

- potential nonzero moments for a spin-1/2 fermion include
  - ◇ charge form factor (charge distribution) C0
  - ◇ magnetic moment M1
  - ◇ anapole moment (P odd, T even) E1
  - ◇ electric dipole moment (P odd, T odd) C1

$$\bar{U}(p')(F_1(q^2)\gamma^\mu - i\frac{F_2(q^2)}{2M}\sigma^{\mu\nu}q_\nu + \frac{a(q^2)}{M^2}(\not{q}q^\mu - q^2\gamma^\mu)\gamma_5 - i\frac{d(q^2)}{M}\sigma^{\mu\nu}q_\nu\gamma_5)U(p)$$

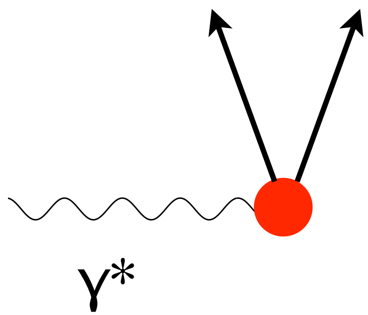
- Dirac neutrinos can exhibit all of these

- one C-even moment arises for Majorana νs, which requires PNC, the anapole moment -- generates an axial contact interaction for virtual photons: could this be exploited to settle the Dirac/Majorana question?

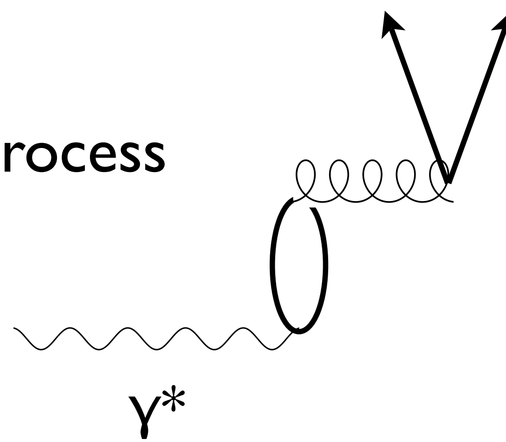
- none measured + the "practical Dirac-Majorana confusion theorem"

- best current limits come from red-giant burning $\gamma^* \to \nu\bar{\nu}$

where the triple-α ignition of the degenerate He core is delayed by anomalous cooling



vs SM process



$$\Rightarrow \mu \leq 3 \times 10^{-12} \mu_b$$

(and still some 8 orders of magnitude below the most naive estimates of μ for an eV-scale ν)

- but transition moments allowed for both

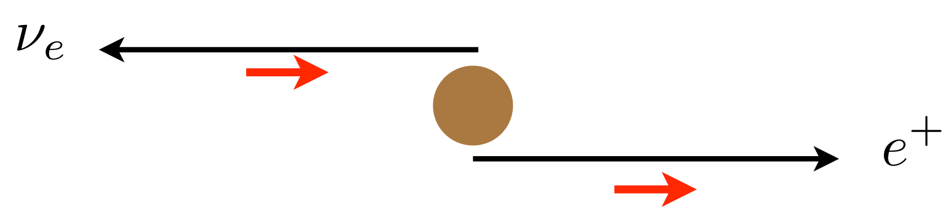
- neutrino magnetic moments are much discussed in solar ν physics because magnetic shifts can compensate for vacuum mass differences between ν flavors: “spin-flavor” oscillations of Lim and Marciano, Ahkmedov -- potential source of solar-cycle dependence

Non-V-A weak interactions a la GGS -- a example from the Northwest

- the LHed neutrino found in the GGS experiment was consistent with a V-A interaction and maximal PNC -- the aspect of the weak interaction that Fermi could not anticipate

- determining whether small admixtures of exotic interactions alter the SM's exact V-A structure is an important motivation for precise tests of β decay, in the style of GGS

- high-Q-value $0^+ \to 0^+$ (Fermi) β decay a nice laboratory



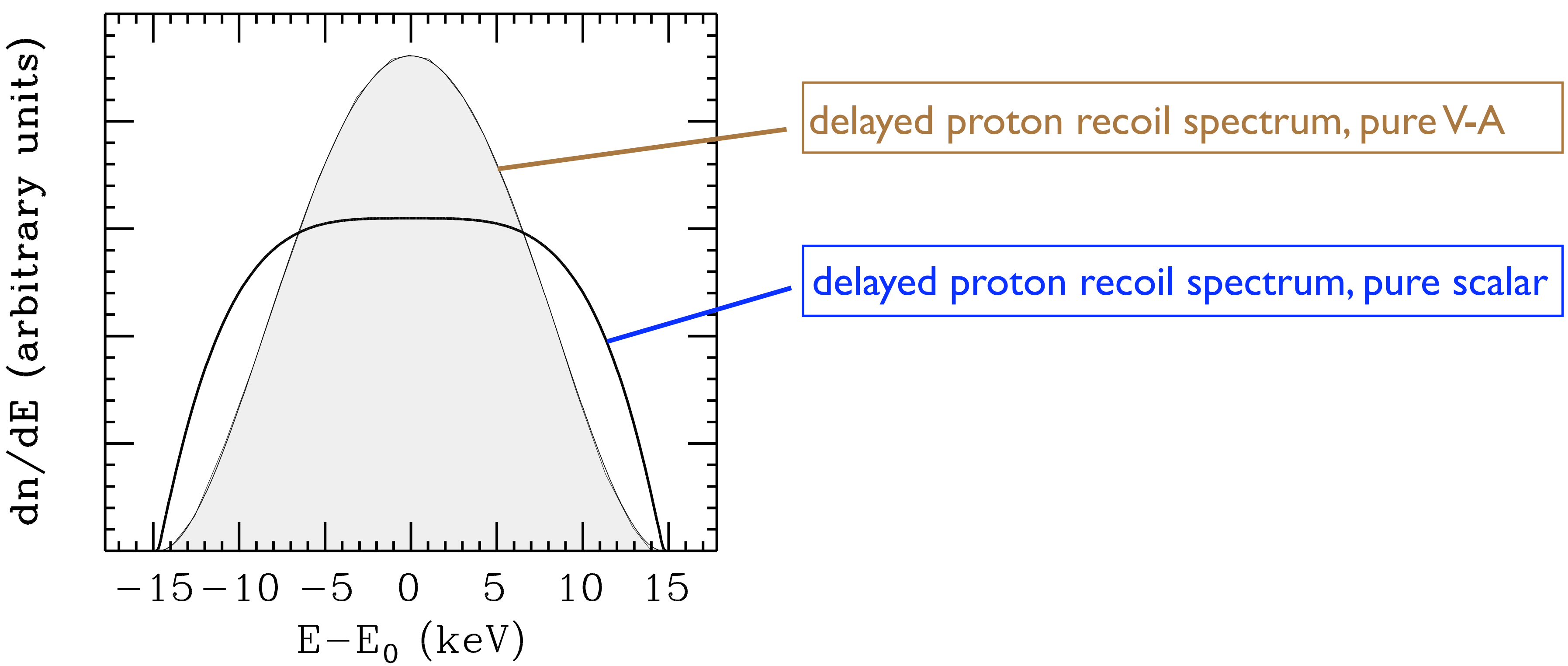
back-to-back decay forbidden for V-A because of unbalanced angular momentum

for probing new, non-SM exchanges (leptoquark, charged Higgs,...)

$$H_\beta = (\bar{\psi}_n \gamma_\mu \psi_p)(\bar{\psi}_\nu C_V \gamma_\mu (1-\gamma_5)\psi_e) + (\bar{\psi}_n \psi_p)(\bar{\psi}_\nu (C_S + C'_S \gamma_5)\psi_e)$$

- such scalar interactions produce leptons with identical chiralities, preventing their omission in the *same* direction: recoil momentum of daughter nucleus then tests whether such contributions are present

- this momentum can be measured best in systems whether the daughter nucleus decays quickly to light particles (e.g., delayed protons) whose distribution can be accurately measured: idea behind the ^{32}Ar β-delayed proton measurements of Adelberger et al. at Isolde

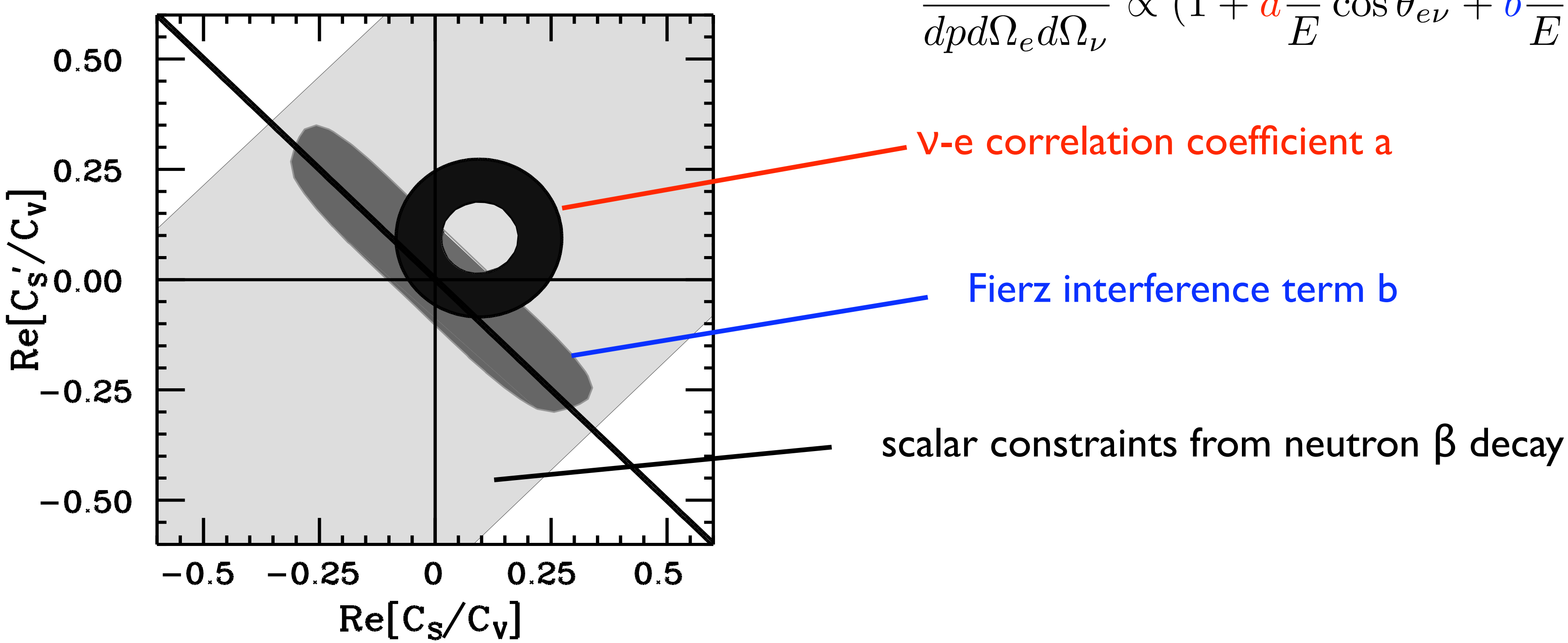


- yielded a 1% limit on the ν-e correlation coefficient

$$a \equiv \frac{2 - |C_S|^2 - |C_S'|^2 + 2Z\alpha m/p \, \mathrm{Im}[C_S + C_S']}{2 + |C_S|^2 + |C_S'|^2}$$

$$= 0.9989 \pm 0.0052(stat) \pm 0.0036(syst)$$

$$\frac{d^3\omega}{dp d\Omega_e d\Omega_\nu} \propto (1 + a\frac{p}{E}\cos\theta_{e\nu} + b\frac{m}{E})$$



Summary: What we know we don't know about the neutrino

- GGS showed the neutrino is left-handed, consistent with V-A: we suspect beyond-the-SM effects may alter this result, but we do not know their level

- we know the neutrino has a mass, but the ambiguity in $\beta\beta$ decay between helicity suppression and exact conservation of lepton number prevents us from determining what kind(s) of mass

- we know the freedom available in describing ν masses provides an elegant explanation for the ν mass scale -- but we do not know whether nature uses the seesaw mechanism, or whether the seesaw scale suggested by δm_{23} is an important hint about GUTs

- we know Dirac and Majorana νs can exhibit distinct E&M moments -- but in practical situations no consequential differences will arise, and the likely scale of these interactions is well beyond our present reach

- we have recently learned a great deal about νs from their oscillations -- mass splittings, two large mixing angles, and consequently the possibility of significant CP violation -- but we do not know the origin/significance of curiosities like $\theta_{23} \sim 45°$

and, of course, there is what we don't know we don't know

Congratulations to the pioneers of a field still going strong after 50 years!