Probing TeV Physics through Lattice Neutron-Decay Matrix Elements

Saul D. Cohen (for PNDME Collaboration)
University of Washington
Fermi Theory of Beta Decay

§ Four-fermion interaction explained beta decay before electroweak theory was proposed

ঙ New operators in effective low-energy theories

§ Electroweak theory adds 3 vector bosons

(branch) W and Z bosons directly detected later at CERN

\[ \Lambda \approx m_W \approx 80 \text{ GeV}, \ m_Z \approx 90 \text{ GeV} \]
What You See/How You Look

$\Lambda_{\text{BSM}} \approx \text{TeV}$

$L_{\text{SM}} + L_{\text{BSM}}$

$L_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \hat{O}_i$

$g_S = \langle n | \bar{u}d | p \rangle$

$g_T = \langle n | \bar{u} \sigma_{\mu\nu} d | p \rangle$
Neutron Beta Decay

§ Experiments measure the total neutron decay rate

\[ d\Gamma \propto F(E_e) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A \frac{\vec{a}_n \cdot \vec{p}_e}{E_e} + b \frac{m_e}{E_e} + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\vec{a}_n \cdot \vec{p}_\nu}{E_\nu} + \ldots \right] \]

_within the Standard Model, \( a \) and \( A \) are \( O(10^{-1}) \), \( B_0 \) is \( O(1) \), \( b \) and \( B_1 \) are \( O(10^{-3}) \)
§ Theoretically, $b$ and $B_1$ are related to new interactions: the scalar and tensor

$$H_{\text{eff}} = G_F \left( J_{V-A}^{\text{lept}} \times J_{V-A}^{\text{quark}} + \sum_i \varepsilon_i^{\text{BSM}} \hat{O}_i^{\text{lept}} \times \hat{O}_i^{\text{quark}} \right)$$

$$\hat{O}_S = \bar{u}d \times \bar{e}(1 - \gamma_5)\nu_e \quad \rightarrow \quad g_S = \langle n | \bar{u}d | p \rangle$$

$$\hat{O}_T = \bar{u}\sigma_{\mu\nu}d \times \bar{e}\sigma^{\mu\nu}(1 - \gamma_5)\nu_e \quad \rightarrow \quad g_T = \langle n | \bar{u}\sigma_{\mu\nu}d | p \rangle$$

🛠 $\varepsilon_S$ and $\varepsilon_T$ are related to the masses of the new TeV-scale particles
🛠 … but the unknown coupling constants $g_{S,T}$ are needed
🛠 These are nonperturbative functions of the neutron structure, described by quantum chromodynamics (QCD)
§ Given precision $g_{S,T}$ and $b, B_1$, we can predict possible new particles

$$b = f_b (\varepsilon_{S,T} g_{S,T})$$

$$B_1 = f_B (\varepsilon_{S,T} g_{S,T})$$

UCNs by 2013

Precision LQCD input

$(m_\pi \approx 140 \text{ MeV}, a \to 0)$

\[ \varepsilon_S \text{ and } \varepsilon_T \]

\( \bowtie \) Give the scale of particles mediating new forces

$g_{S,T} = 1$
Current Constraints

Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

Nuclear beta decays
- $0^+ \rightarrow 0^+$ transitions
- $\beta$ asym in Gamow-Teller $^{60}$Co
- polarization ratio between Fermi and GT in $^{114}$In
- positron polarization in polarized $^{107}$In
- $\beta$-$\nu$ correlation parameter $\alpha$

$O_{BSM} = f_0(\varepsilon_{S,T} g_{S,T})$

$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$
§ Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

New UCN Exp. $O_{BSM} = f_0(\varepsilon_{S,T} g_{S,T})$  \[ \varepsilon_{S,T} \propto \Lambda_{S,T}^{-2} \]

LANL UCN neutron decay exp’t

$$d\Gamma \propto F(E_e) \left[ 1 + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\bar{\sigma}_n \hat{p}_\nu}{E_\nu} + \cdots \right]$$

Expect by 2013:

$|B_1 - b|_{BSM} < 10^{-3}$

$|b|_{BSM} < 10^{-3}$

Similar proposal at ORNL by 2015
Crucial Role of Theory

§ Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

New UCN Exp. $O_{BSM} = f_o(\varepsilon_{S,T} g_{S,T})$

Precision LQCD input $(m_\pi \to 140 \text{ MeV}, a \to 0)$

$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

LANL UCN neutron decay exp’t

$d\Gamma \propto F(E_e) \left[ 1 + \left( b \frac{m_e}{E_e} + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\bar{\sigma}_n \vec{p}_\nu}{E_\nu} + \cdots \right) \right]$

Expect by 2013:

$|B_1 - b|_{BSM} < 10^{-3}$

$|b|_{BSM} < 10^{-3}$

Similar proposal at ORNL by 2015
High-Energy Constraints

§ Constraints from high-energy experiments?
LHC current bounds and near-term expectation

Estimated though effective $L$

$$\mathcal{L} = -\frac{\eta_S}{\Lambda_S^2} V_{ud}(\bar{u}d)(\bar{e}P_L\nu_e)$$

$$-\frac{\eta_T}{\Lambda_T^2} V_{ud}(\bar{u}\sigma^{\mu\nu} P_Ld)(\bar{e}\sigma_{\mu\nu} P_L\nu_e)$$

Looking at high transverse mass in $e\nu+X$ channel

Compare with $W$ background

Estimated 90% C.L. constraints on

$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

HWL, 1112.2435; 1109.2542
T. Bhattacharyya et al, 1110.6448
§ Lattice uncertainties:
- Statistical noise
- Unphysical scales $a, L$
- Extrapolation to $M_\pi$

§ Computational costs
- Scaling: $a^{-5\text{--}6}, L^5, M_\pi^{-2\text{--}4}$

§ Most major 2+1-flavor gauge ensembles: $M_\pi < 200$ MeV
- Now including physical pion-mass ensembles

§ Charm dynamics: 2+1+1-flavor gauge ensembles
- MILC (HISQ), ETMC (TMW)

§ Pion-mass extrapolation $M_\pi \rightarrow (M_\pi)_{\text{phys}}$
- (Bonus products: low-energy constants)
§ Difficulties in Euclidean space

§ Exponentially worse signal-to-noise ratios

Consider a baryon correlator \( C = \langle O \rangle = \langle qqq(t) \bar{q} \bar{q} \bar{q}(0) \rangle \)

Variance (noise squared) of \( C \propto \langle O^\dagger O \rangle - \langle O \rangle^2 \)

What you want: \( \pi \)

What you get: \( \pi \)
The Trouble with Nucleons

§ Difficulties in Euclidean space

§ Exponentially worse signal-to-noise ratios

Consider a baryon correlator $C = \langle O \rangle = \langle qqq(t) \bar{q}\bar{q}\bar{q}(0) \rangle$

Variance (noise squared) of $C \propto \langle O^\dagger O \rangle - \langle O \rangle^2$

What you want: 
- $N$
- $N^\dagger$

What you get: 
- $\pi$
- $\pi$

Signal falls exponentially as $e^{-m_N t}$

Noise falls as $e^{-(3/2)m_\pi t}$

Problem worsens with:
- increasing baryon number
- decreasing quark (pion) mass
Statistical Uncertainty

§ Targeted statistical on charges: 2% estimation

☞ Other sources of error: 8% (NPR + continuum extrap. + mixed sys.)
☞ $g_S$ would be most challenging
Systematic Uncertainties

§ Chiral extrapolation suffers biggest systematic uncertainty

☞ Huge obstacle to precision measurement
☞ Issues: validity of XPT over the range of pion masses used, convergence, SU(3) vs. SU(2) flavor, etc.

§ Remaining systematics:
finite-volume effects
☞ Seems pretty well controlled
\( m_\pi L \gtrsim 4 \)

RBC/UKQCD arXiv:1003.3387[hep-lat]

§ Solutions

☞ Include the physical pion mass in the calculation
☞ Extrapolate to the continuum limit (use multiple \( a \))
### Plan

- **MILC HISQ (140-MeV $\pi$ available)**
  - Apr. 1, 2011 (Teragrid 8M SUs)
  - Jul. 1– (USQCD), Dec. (NERSC)
- 10% within 2 years
- $O(1\%)$ in 3–4 years
§ Explore optimal smearing parameters and multiple source-sink separations

§ Analyze the three-point function including excited state
Excited-State Contamination

§ Explore optimal smearing parameters and multiple source-sink separations (0.96—1.44fm)

§ Analyze the three-point function including excited state
§ Our preliminary numbers and world $N_f=2+1$ values

$a = 0.06, 0.09, 0.12$ fm, 220- and 310-MeV pion
§ Our numbers (unrenormalized) and other $N_f=2+1$ values

$a = 0.06, 0.09, 0.12$ fm, 220- and 310-MeV pion
Isovector Scalar Charge

§ Our numbers (unrenormalized) and other $N_f=2+1$ values
§ $g_S$ becomes much noisier at light pion mass

\[ g_{S}^{2+1f} \]

$[\text{HSC anisoCl}(2011)]$
$[\text{Mixed}(2011)]$
$[\text{PNDME}]$
§ Tensor charge: the zeroth moment of transversity

полнение through SIDIS: $g_T(Q^2 = 0.8 \text{ GeV}^2) = 0.77^{+0.18}_{-0.24}$

:absolute estimate 0.8(4)

§ Scalar charge $\langle n|\bar{u}d|p\rangle$ Prior model estimate: $1 \geq g_S \geq 0.25$

\begin{align*}
g_T^{\text{LQCD}} &= 1.05(4) \\
m^2 (\text{GeV}^2) &\quad m^2 (\text{GeV}^2) \\
g_S^{\text{LQCD}} &= 0.79(9)
\end{align*}

HWL, 1112.2435; 1109.2542
The name of the game is precision

§ The precision frontier enables us to probe BSM physics
  ⚫ Opportunities combining both high- (TeV) and low- (GeV) energy

§ Exciting era using LQCD for precision inputs from SM
  ⚫ Increasing computational resources and improved algorithms
  ⚫ Enables exploration of formerly impossible calculations

§ Necessary when experiment is limited
§ Bringing all systematics under control