Beta decays and non-standard interactions in the LHC era

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Introduction
Why “beyond the Standard Model”? 

- The SM is remarkably successful, but has no answer to a number of questions about our universe $\Rightarrow$ new degrees of freedom

Empirical questions

Theoretical questions

Why “beyond the Standard Model”? 

- The SM is remarkably successful, but has no answer to a number of questions about our universe $\Rightarrow$ new degrees of freedom
Two Frontiers

- Two complementary strategies to probe BSM physics:
  - High Energy Frontier (direct access to new d.o.f)
  - Precision Frontier (indirect access to new d.o.f through virtual effects)

$E \gg M_{BSM}$

$E_{exp} \ll M_{BSM}$

$g^{-1}$

+ sensitivity to light weakly coupled particles
Two Frontiers

- Two complementary strategies to probe BSM physics:

- Both frontiers needed to reconstruct the structure, symmetries, and parameters of $\mathcal{L}_{BSM}$ → address the outstanding open questions
In this talk, take a fresh look at non-standard charged current interactions, using both Precision and Energy Frontier probes.

Two Frontiers

- Two complementary strategies to probe BSM physics:

  - High Energy Frontier: (direct access to new d.o.f)
  - Precision Frontier: (indirect access to new d.o.f through virtual effects)

  \[ E \]
  \[ M_{BSM} \]
  \[ E_{exp} \ll M_{BSM} \]
CC interactions and BSM physics

- In the SM, $W$ exchange $\Rightarrow$ only V-A structure, universality relations

\[ G_F \sim \frac{g^2 V_{ij}}{M_w^2} \sim \frac{1}{v^2} \]

Peculiar “V-A” pattern in spectra and decay correlations

Lepton universality

\[ \frac{[G_F]_e}{[G_F]_\mu} = 1 + \Delta_{e/\mu} \]

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM} \]

Cabibbo universality
**CC interactions and BSM physics**

- In the SM, W exchange $\Rightarrow$ only V-A structure, universality relations

\[
\begin{align*}
G_F & \sim g^2 V_{ij} / M_W^2 \sim 1 / v^2 \\
\frac{1}{\Lambda^2} & \sim g^2 V_{ij} / M_W^2 \sim 1 / v^2
\end{align*}
\]

- BSM: sensitive to tree-level and loop corrections from large class of models $\Rightarrow$ “broad band” probe of new physics
• Traditionally, field dominated by precision $\beta$ decay measurements: rich experimental program worldwide, with precision approaching the 0.1%-level or better.

• Here consider multi-scale analysis, with probes ranging from low energy (nuclei, neutron, and pion) to the LHC.
Outline

• EFT approach to Charged Current interactions

• Beta-decay probes (Precision Frontier)

• Collider probes (Energy Frontier)

4) VC, M. Graesser, E. Passemar, in progress

* Precision Neutron Decay Matrix Elements (PNDME) lattice QCD collaboration
Framework
Theoretical Framework

- In absence of an emerging BSM scenario, work within EFT framework
  - Assume separation of scales $M_{BSM} \gg M_W$
  - New heavy BSM particles are “integrated out” and affect low-energy dynamics through local operators of dim $> 4$
  - If $M_{BSM} \sim$ several TeV, one can use this framework to analyze LHC data. Will discuss relaxing this assumption at the end of the talk
- EFT approach can be used to put constraints on any UV model
- EFT approach misses possible correlations among observables
Theoretical Framework

$\Lambda$ ($\sim$TeV) 

LHC

$\Lambda_H$ ($\sim$GeV)

SLC, LEP

$M_{W,Z}$

$\mathcal{L}_{BSM}$

$\mathcal{L}_{SM} + \sum_i \frac{O_i}{\Lambda_i^2} + \ldots$

12 SU(2)$\times$U(1) gauge invariant operators $O_i$ affect CC interactions

BSM dynamics involving new particles with $m > \Lambda$
Theoretical Framework

**Λ (~TeV)**

E

LHC

**Λ_H (~GeV)**

SLC, LEP

M_{W,Z}

LANSCE, SNS, ...

BSM dynamics involving new particles with m > Λ

\[ \mathcal{L}_{BSM} \]

\[ \mathcal{L}_{SM} + \sum_i \frac{O_i}{\Lambda_i^2} + ... \]

\[ \mathcal{L}_{Fermi} + \mathcal{L}_{QCD} + \mathcal{L}_{QED} \]

\[ -\frac{G_F V_{ud}}{\sqrt{2}} \sum_{\Gamma} \epsilon_{\Gamma} \bar{\ell} \Gamma \nu \cdot \bar{u} \Gamma d \]

\[ \epsilon_{\Gamma} = \sum_i c_{\Gamma i} \frac{\nu^2}{\Lambda_i^2} \]

10 4-fermion operators
Theoretical Framework

\[ \Lambda (\sim \text{TeV}) \]

\[ M_{W,Z} \]

\[ \Lambda_H (\sim \text{GeV}) \]

**BSM dynamics involving new particles with \( m > \Lambda \)**

\[ \mathcal{L}_{\text{BSM}} \]

\[ \mathcal{L}_{\text{SM}} + \sum_i \frac{O_i}{\Lambda_i^2} + \ldots \]

**Non-perturbative matching**

\[ \mathcal{L}_{\text{Fermi}} + \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} \]

\[ \frac{G_F V_{ud}}{\sqrt{2}} \sum_i \epsilon_i \bar{\ell} \Gamma \nu \cdot \bar{u} \Gamma d \]

\[ \mathcal{L}_{\pi, N, \ldots} \]
Match to hadronic description (1)

- To disentangle short-distance physics, need hadronic matrix elements of SM (very precisely, $10^{-3}$ level) and BSM operators

- Tools:
  - symmetries of QCD ($\rightarrow$ chiral EFT)
  - lattice QCD
Match to hadronic description (2)

- Need the matrix elements of quark bilinears between nucleons

\[
\langle p(p_p, s')| \bar{u} \Gamma d | n(p_n, s) \rangle = \bar{u}(p_p, s') f_\Gamma(q^2) u(p_n, s)
\]

- Given the small momentum transfer in the decays \( q/m_n \sim 10^{-3} \), can organize matching according to power counting in \( q/m_n \)

- At what order do we stop? Work to 1st order in

\[
\epsilon_\Gamma \sim 10^{-3} \quad q/m_n \sim 10^{-3} \quad \alpha/\pi \sim 10^{-3}
\]

- Include \( O(q/m_n) \) and rad. corr. only for SM operator

- Caveat: this counting neglects “2nd class currents” effects, \( O(10^{-5} \sim q/m_n \times \text{isospin-breaking}) \)

  [Gardner-Plaster arXiv:1305.0014 discuss impact of these effects]
Low-energy probes
Low-scale Lagrangian

\[ \mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \left[ (1 + \delta_{RC} + \epsilon_L) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. \\
+ \left. \epsilon_R \bar{e} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d \right. \\
+ \left. \epsilon_S \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} d \right. \\
- \left. \epsilon_P \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \right. \\
+ \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right] + \text{h.c.} \\
+ \epsilon_i \rightarrow \tilde{\epsilon}_i \ (1 - \gamma_5) \nu_\ell \rightarrow (1 + \gamma_5) \nu_\ell \]
How do we probe the ε’s?

- Low-energy probes fall roughly in two classes:

1. Differential decay rates: spectra, angular correlations (mostly non V-A)

\[ d\Gamma \propto F(E_e) \left\{ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\} \]
How do we probe the $\varepsilon$'s?

• Low-energy probes fall roughly in two classes:

1. Differential decay rates: spectra, angular correlations (mostly non V-A)

\[ d\Gamma \propto F(E_e) \left\{ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\} \]

\[ a(\varepsilon_\alpha), A(\varepsilon_\alpha), B(\varepsilon_\alpha) \] isolated via suitable experimental asymmetries
How do we probe the $\varepsilon$'s?

- Low-energy probes fall roughly in two classes:

  2. Total decay rates: normalization (mostly V,A) matters!

\[
\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\text{had}}|^2 \times (1 + \delta_{\text{RC}}) \times F_{\text{kin}}
\]

Channel-dependent effective CKM element:  
Hadronic matrix element  
Radiative corrections (both SD and LD)

\[
|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\text{CKM}}(\varepsilon_i)
\]
Survey of constraints

\[ \mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \]
\[ \times \left[ \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \left( 1 - (1 - 2 \epsilon_R) \gamma_5 \right) d \right. \]
\[ + \epsilon_S \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} d \]
\[ - \epsilon_P \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \]
\[ + \epsilon_T \bar{\ell} \sigma_{\mu \nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu \nu} (1 - \gamma_5) d \] + h.c.
\[ + \epsilon_i \rightarrow \tilde{\epsilon}_i \]
\[ (1 - \gamma_5) \nu_\ell \rightarrow (1 + \gamma_5) \nu_\ell \]
Survey of constraints

\[ \mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\pi} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \]

- “No interference” between SM amplitude and \( \tilde{\epsilon}_i \) couplings (m\( \nu \)/E\( \nu \))
- Spectra and angular correlations probe \( \tilde{\epsilon}_i \) to \textit{quadratic order}
- Generally weaker bounds (5-10% level)

\[
- \epsilon_P \quad \bar{\ell}(1 - \gamma_5)\nu_\ell \cdot \bar{u}\gamma_5d
\]

\[
+ \epsilon_T \quad \bar{\ell}\sigma_{\mu\nu}(1 - \gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1 - \gamma_5)d \quad \text{h.c.}
\]

\[
+ \epsilon_i \quad \rightarrow \quad \tilde{\epsilon}_i \quad (1 - \gamma_5)\nu_\ell \quad \rightarrow \quad (1 + \gamma_5)\nu_\ell
\]
Survey of constraints

\[ \mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \]

- Affects overall normalization of “semi-leptonic” \( G_F \)
- Strong constraints from Cabibbo universality tests,

\[ \Delta_{CKM} = (1 \pm 6) \times 10^{-4} \]

\[ \epsilon_L + \epsilon_R < 5 \times 10^{-4} \] at 90% CL

\[ \Lambda > 11 \text{ TeV} \]
Survey of constraints

\[ \mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \]
\[ \times \left[ \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \left( 1 - (1 - 2 \epsilon_R) \gamma_5 \right) \right] d \]
\[ + \epsilon_S \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \]
\[ - \epsilon_P \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \]
\[ + \epsilon_T \bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_\nu \left( 1 - \gamma_5 \right) d \] + n.c.

- Affects relative normalization of axial and vector currents
- Neutron and nuclear decays sensitive to \((1 - 2 \epsilon_R)^* g_A\)
- Disentangling \(\epsilon_R\) requires precision lattice calculations of \(g_A\): we are not there (yet)
Survey of constraints

\[ \mathcal{L}_{CC} = - \frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \]

- Strong constraints from \( R_\pi = \Gamma(\pi \to e\nu) / \Gamma(\pi \to \mu\nu) \) (depend on the structure of \((\varepsilon_P)^{ab}\) in lepton flavor space)

\[
\Delta_{e/\mu} = \left( \frac{R_\pi}{(R_\pi)_{SM}} - 1 \right) = (-3 \pm 3) \times 10^{-3}
\]

\[
|\varepsilon_L - \varepsilon_R| < 2.5 \times 10^{-3} \quad \Lambda_{L-R} > 3.5 \text{ TeV}
\]

\[
|\varepsilon_P| < 6 \times 10^{-4} \quad \Lambda_P > 7 \text{ TeV}
\]

@ 90% CL
Survey of constraints

\[ \mathcal{L}_{CC} = - \frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta \tau) \times \left[ \bar{\ell} \gamma_\mu(1 - \gamma_5) \nu_\ell \cdot \bar{u}d + \epsilon_S \bar{\ell}(1 - \gamma_5) \nu_\ell \cdot \bar{u}d \right. \\
+ \left. \epsilon_P \bar{\ell}(1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \right] + \epsilon_T \bar{\ell} \sigma_{\mu\nu}(1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu}(1 - \gamma_5) d \right] + \text{h.c.} \]

- Neutron and nuclear decay correlation coefficients and spectra
- $\pi \to e \nu \gamma$ Dalitz plot (tensor coupling)
Constraints on $\varepsilon_{S,T}$

- Only $\varepsilon_{S,T}$ contribute to decay correlations to linear order $\varepsilon$’s
  - $b$ and $B = B_0 + b_\nu \frac{m_e}{E_e}$ directly sensitive to $\varepsilon_{S,T}$
  - $a$ and $A$ indirectly sensitive to $\varepsilon_{S,T}$ via $b$ in the asymmetry “denominator”

\[
\tilde{a} = \frac{a_{SM}}{1 + b \langle m_e/E_e \rangle} \quad \tilde{A} = \frac{A_{SM}}{1 + b \langle m_e/E_e \rangle}
\]

\[
d\Gamma \propto F(E_e) \left\{ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\}
\]
Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$ and neutron + nuclear decays

- $-1.0 \times 10^{-3} < g_S \varepsilon_S < 3.2 \times 10^{-3}$

- $-2.0 \times 10^{-4} < f_T \varepsilon_T < 2.6 \times 10^{-4}$

- $b_F = 2\gamma g_S \varepsilon_S$

- $f_T = 0.24(4)$
Constraints on $\varepsilon_{S,T}$

- **Current:** $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$ and neutron + nuclear decays

This plot uses $g_S = 0.8 (4)$ from LQCD.

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011
Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$ and neutron + nuclear decays

Based on global analysis of nuclear decays & neutron lifetime + beta asymmetry “A”
Constraints on $\varepsilon_{S,T}$

- **Current:** $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$ and neutron + nuclear decays
- **Future:** neutron $b, B = B_0 + b_{\nu} m_e/E_e @ 10^{-3}; \ ^6\text{He} (b_{GT}) @ 10^{-3}$

Sensitive to different combinations of $\varepsilon_S$ and $\varepsilon_T$

\[
b_{GT} = -(8\gamma/\lambda) g_T \varepsilon_T
\]

\[
b = \frac{2}{1 + 3\lambda^2} \left[ g_S \varepsilon_S - 12\lambda g_T \varepsilon_T \right]
\]

\[
b_{\nu} = \frac{2}{1 + 3\lambda^2} \left[ \lambda g_S \varepsilon_S - 4(1 + 2\lambda) g_T \varepsilon_T \right]
\]
Constraints on $\varepsilon_{S,T}$

- **Current:** $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$
- **Future:** neutron $b, B = B_0 + b_v m_e/E_e @ 10^{-3}$; $^6\text{He} (b_{GT}) @ 10^{-3}$

### Quark models:

- $0.25 < g_S < 1$
- $0.6 < g_T < 2.3$

### Expressions:

- $\varepsilon_S = 2 \left( \frac{v}{\Lambda_S} \right)^2$
- $\varepsilon_T = \left( \frac{v}{\Lambda_T} \right)^2$
- $v = (2\sqrt{2} \ G_F)^{-1/2}$
Constraints on $\epsilon_S, \epsilon_T$

- **Current**: $0^+ \rightarrow 0^+ (b_F)$ and $\pi \rightarrow e \nu \gamma$

- **Future**: neutron $b, B = B_0 + b\nu m_e/E_e \lesssim 10^{-3}$; $^6$He ($b_{GT}$) $\lesssim 10^{-3}$

|$\Lambda_S = 3.2 \text{ TeV}$| $\Lambda_S = 5 \text{ TeV}$

$\epsilon_S = 2 \left( \nu/\Lambda_S \right)^2$

$\epsilon_T = \left( \nu/\Lambda_T \right)^2$

$\nu = (2\sqrt{2} \ G_F)^{-1/2}$

\[ Lattice \ QCD \]

$g_S = 0.8 \ (4)$

$g_T = 1.05(35)$

\[ Bhattacharya, \ Cirigliano, \ Cohen, \ Filipuzzi, \ Gonzalez-Alonso, \ Graesser, \ Gupta, \ Lin, \ 2011 \]
Impact of QCD uncertainties

- Hadronic uncertainties \((g_{S,T})\) strongly dilute significance of bounds
- Future LQCD calculations will improve constraints

\[
\begin{align*}
\delta g_{S,T}/g_{S,T} &\sim 20\% \\
\text{from LQCD needed to fully exploit experimental advances}
\end{align*}
\]
**Summary of low-E constraints**

<table>
<thead>
<tr>
<th></th>
<th>Re((\epsilon_L))</th>
<th>Re((\epsilon_R))</th>
<th>Re((\epsilon_P))</th>
<th>Re((\epsilon_S))</th>
<th>Re((\epsilon_T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta) decays</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\[ \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \times 10^{-2} \]

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</tr>
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<tbody>
<tr>
<td>(\beta) decays</td>
<td>6</td>
<td>6</td>
<td>0.03</td>
<td>14</td>
<td>3.0</td>
</tr>
</tbody>
</table>

\[ \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \times 10^{-2} \]
High-energy probes
Constraints from LEP & SLC

- The weak-scale operators that contribute to the $\epsilon_\alpha$, affect other observables (precision EW + collider)
- Strongest constraints on “L” coupling

$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$$
Constraints from LEP & SLC

• The weak-scale operators that contribute to the $\varepsilon_\alpha$, affect other observables (precision EW + collider)

• Strongest constraints on “L” coupling

$$\varepsilon_L = \varepsilon_L^{(u)} + \varepsilon_L^{(c)}$$

$$|\varepsilon_L|_{vertex} < 5 \times 10^{-4}$$

• Already strong constraints from Z-pole

• CKM is at the same level
Constraints from LEP & SLC

- The weak-scale operators that contribute to the $\varepsilon_\alpha$, affect other observables (precision EW + collider)

- Strongest constraints on “L” coupling

$$\varepsilon_L = \varepsilon_{L}^{(u)} + \varepsilon_{L}^{(e)}$$

- Already strong constraints from Z-pole
- CKM is at the same level

- Constraints from $\sigma_{\text{had}}$ at LEP would allow $\Delta_{\text{CKM}} \sim 0.01$ !
- CKM “wins” by factor of $\sim 10$
LHC (I): contact interactions

• If the new physics originates at scales $\Lambda > \text{TeV}$, then can use EFT framework at LHC energies

• The effective couplings $\varepsilon_\alpha$ contribute to the process $\text{p p} \rightarrow \text{e} \nu + X$

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011
LHC (I): contact interactions

- If the new physics originates at scales $\Lambda > TeV$, then can use EFT framework at LHC energies

- The effective couplings $\varepsilon_\alpha$ contribute to the process $pp \rightarrow e\nu + X$

- No excess events in transverse mass distribution: bounds on $\varepsilon_\alpha$
• Bounds on the effective scalar and tensor couplings:

\[ n_{\text{obs}} (m_T > m_{T,\text{cut}}) = \varepsilon_{\text{eff}} \times \mathcal{L} \times (\sigma_w + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2) \]

- detection efficiency * geometric acceptance
- integrated luminosity
- SM contribution
- BSM contribution
• Bounds on the effective scalar and tensor couplings:

\[ n_{\text{obs}} (m_T > m_{T,\text{cut}}) = \varepsilon_{\text{eff}} \times L \times (\sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2) \]

• BSM effects \( \propto |\varepsilon_{S,T}|^2 \), but (i) \( \sigma_{S,T} \gg \sigma_W \) and (ii) \( \sigma_{S,T} \) and \( \sigma_W \) have different behavior in \( m_T \Rightarrow \) to suppress bkg, use large \( m_{T,\text{cut}} \)

![Graph showing \( \sigma(f \text{b}) \) vs \( m_{T,\text{cut}} \) in TeV](image)
• Bounds on the effective scalar and tensor couplings:

\[ n_{\text{obs}} \left( m_T > m_{T,\text{cut}} \right) = \varepsilon_{\text{eff}} \times \mathcal{L} \times \left( \sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2 \right) \]

- BSM effects \( \propto |\varepsilon_{S,T}|^2 \), but (i) \( \sigma_{S,T} \gg \sigma_W \) and (ii) \( \sigma_{S,T} \) and \( \sigma_W \) have different behavior in \( m_T \Rightarrow \) to suppress bkg, use large \( m_{T,\text{cut}} \)
• Bounds on all the other effective couplings:

\[
\sigma(m_T > \overline{m}_{T,\text{cut}}) = \sigma_W \left[ (1 + \epsilon^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_L|^2 \right] - 2\sigma_{WL} \epsilon^{(c)}_L \left( 1 + \epsilon^{(v)}_L \right) \\
+ \sigma_R \left[ |\tilde{\epsilon}_R|^2 + |\epsilon_L^{(e)}|^2 \right] + \sigma_S \left[ |\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right] \\
+ \sigma_T \left[ |\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right]
\]

\[\sigma \text{ (fb)}\]

\[\sim \frac{s}{v^4}\]

\[\sim \frac{1}{v^2}\]

\[\sim \frac{1}{s}\]

\[m_{T,\text{cut}} \text{ (TeV)}\]

• Strong bounds on S,T,P couplings with LH \(\nu\)'s

• Strong bounds on S,T,P,R couplings with RH \(\nu\)'s

• Less sensitivity to other couplings
Constraints form $pp \rightarrow e^+e^- + X$

- Using SU(2) symmetry, $\varepsilon_\alpha$ contribute to $pp \rightarrow e^+e^- + X$

- The resulting constraints are slightly stronger than $pp \rightarrow e\nu + X$
### β decays vs LHC

All $\varepsilon$'s in $\overline{\text{MS}}$ @ $\mu = 2$ GeV

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<td>$(-0.3, +0.8)$</td>
<td>−</td>
<td>1.3</td>
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<td>0.3</td>
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Unmatched low-energy sensitivity

LHC limits close to low-energy. Interesting interplay in the future

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<tbody>
<tr>
<td>β decays</td>
<td>6</td>
<td>6</td>
<td>0.03</td>
<td>14</td>
<td>3.0</td>
</tr>
<tr>
<td>LHC $(e\nu)$</td>
<td>−</td>
<td>0.5</td>
<td>1.3</td>
<td>1.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

LHC stronger than low-energy! (except for P,L)
• Take a closer look to scalar and tensor couplings

• LHC and b, B at $10^{-3}$ level will compete in setting strongest bounds on $\varepsilon_S$ and $\varepsilon_T$ probing effective scales $\Lambda_{S,T} \sim 7$ TeV

• b and B at $10^{-4}$ level would give unmatched sensitivity
LHC (II): beyond contact

- What if new interactions are not “contact” at LHC energy? How are the $\varepsilon$ bounds affected?

- Explore classes of models generating $\varepsilon_{S,T}$ at tree-level. Low-energy vs LHC amplitude:

$$A_\beta \sim \frac{g_1 g_2}{M^2} \equiv \varepsilon$$

$$A_{LHC} \sim \varepsilon F[\sqrt{s}/M, \sqrt{s}/\Gamma(\varepsilon)]$$

- Study dependence of the $\varepsilon$ bounds on the mediator mass $M$
s-channel mediator

• Scalar resonance in s-channel
• Upper bound on $\varepsilon_S$ based on $m_{T,\text{cut}} = 1$ TeV

![Graph showing $\sigma$ suppression due to $m < m_{T,\text{cut}}$.](image)

$\sigma$ suppression due to $m < m_{T,\text{cut}}$

$\varepsilon_S$

Improvable with lower $m_{T,\text{cut}}$
But larger SM bkg

$\varepsilon_S = \frac{2\lambda_S\lambda_I v^2}{m^2}$

decoupling regime

resonantly enhanced $\sigma$

contact
resonance

$m$ (TeV)

$ \varepsilon_S $
**t-channel mediator**

- Scalar leptoquark $S_0$ (3*,1,1/3)
- $\varepsilon_T = -1/4 \varepsilon_S = -1/4 \varepsilon_P$

$\sigma$ suppression due to $1/(m^2 - t)$ vs $1/m^2$

Decoupling regime
t-channel mediator

Messages

- For mediator mass >1 TeV, LHC bounds on $\varepsilon$'s based on contact interactions are “conservative”: actual bound is stronger for s-channel resonance, comparable for t-channel.

- For low mass mediators (m < 0.5 TeV), the LHC bounds on $\varepsilon$’s quickly deteriorate: limits based on contact interactions are unreliable.
What if LHC sees something?

- If “bump” in m_T is due to a scalar resonance coupling to e + \nu_e

- ...then we a lower bound on \epsilon_S: \beta-decays provide diagnostic power

\[
\sigma \cdot \text{BR} \leq \frac{|V_{ud}|}{12v^2} \frac{\pi}{\sqrt{2N_c}} |\epsilon_S| \tau L(\tau)
\]

\[
L(\tau) = \int_\tau^1 dx f_q(x)f_q'(\tau/x)/x
\]

\[
\tau = m^2/s
\]
What if LHC sees something?

- If “bump” in $m_T$ is due to a **scalar** resonance coupling to $e + \nu_e$

**Diagnostic power**

- Spin of resonance
- Nature of “MET” (is it $\nu_e$?)
- Additional scalars? (suppression of $\varepsilon_S$ through interference)

\[
\sigma \cdot \text{BR} \leq \frac{|V_{ud}|}{12v^2} \frac{\pi}{\sqrt{2}N_c} |\varepsilon_S| \tau L(\tau)
\]

\[
L(\tau) = \int_{\tau}^{1} dx f_q(x) f'_q(\tau/x)/x
\]

\[
\tau = \frac{m^2}{s}
\]

\[\sqrt{s} = 7 \text{ TeV}\]
Conclusions

• Precise ($\leq 0.1\%$) beta decays: “broad band” probe of new physics

• If new physics arises above the TeV scale, EFT approach gives model-independent connection between $\beta$-decays and HEP

• Positive outlook: for operators involving $\nu_L$, beta decays probe effective scales in the multi-TeV range

  • “Nightmare scenario” (mediators not accessible at the LHC): 0.1%-level $\beta$ decays can be more sensitive than LHC

  • “Optimistic scenario”: $\beta$ decays provide diagnostic power to reconstruct TeV-scale dynamics seen at the LHC

$\downarrow$

Either way, relevance of beta decays well in the LHC era