Beta decays and non-standard interactions in the LHC era

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Unsolved puzzles about our Universe point to the existence of new degrees of freedom and interactions beyond the SM.

Two traditional paths to probe this new physics:

- **High Energy**
  (direct access to new d.o.f)

- **Low Energy, High Precision**
  (indirect access to new d.o.f through virtual effects)

In this talk, take a fresh look at both LE and HE probes of non-standard charged current interactions.
CC interactions and BSM physics

• In the SM, W exchange ⇒ only V-A structure, universality relations

\[ G_F \sim g^2 V_{ij} / M_w^2 \sim 1/v^2 \]
CC interactions and BSM physics

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

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

- BSM: sensitive to tree-level and loop corrections from large class of models $\Rightarrow$ “broad band” probe of new physics

\[ \frac{1}{\Lambda^2} \]
Traditionally, the field is dominated by precision $\beta$ decay probes, with a rich experimental program worldwide.

Current/planned measurements will reach a 0.1%-level,
- tight constraints on BSM contributions interfering with the SM amplitude
- Yet, incoherent BSM contributions (e.g., R-handed neutrino) could be as large as 5 to 10% of the V and A interactions

Severijns, Beck, Naviliat-Cuncic, 2006
• Traditionally, field dominated by precision $\beta$ decay probes, with rich experimental program worldwide

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

\[\downarrow\]

Get improved constraints on nonstandard CC interactions

Assess future prospects

• Yet, incoherent BSM contributions (e.g. R-handed neutrino) could be as large as 5 to 10\% of the V and A interactions

Severijns, Beck, Naviliat-Cuncic, 2006
Outline

• Framework: CC interactions from the TeV scale to hadronic scales

• Low-energy probes: status, prospects

• High-energy probes (LHC): contact interactions and beyond

VC, M. Gonzalez-Alonso, M. Graesser, in progress
VC, M. Graesser, E. Passemard, in progress
Framework
Theoretical Framework

• In absence of an emerging “New Standard Model”, work within an EFT framework: most general approach
  • Assume separation of scales $M_{BSM} \gg M_W$
  • New heavy BSM particles are “integrated out”, and affect the dynamics through local operators of dim > 4
  • If $M_{BSM} \gg \text{TeV}$, one can use this framework to analyze LHC data. Will discuss relaxing this assumption at the end of the talk

• Any model calculation can be cast in the EFT language
Theoretical Framework

Λ (~TeV)

E

BSM dynamics involving new particles with m > Λ

LHC

Λ (~TeV)

M_{W,Z}

SLC, LEP

LANSCE, SNS, ...

Λ_H (~GeV)
Theoretical Framework

- BSM dynamics involving new particles with $m > \Lambda$

- $\mathcal{L}_{\text{BSM}}$

- $\mathcal{L}_{\text{SM}} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}$

- 7+5** SU(2)xU(1)-invariant dim 6 operators contribute to beta decays (4+4 four-fermion & 3+1 vertex correction)

- ** If one includes $\nu_R$ in the low-energy theory
Theoretical Framework

- Below weak scale, $5+5^{**}$ four-fermion (quark + lepton) operators

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

\[ \mathcal{L}_\text{SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)} \]

\[ \mathcal{L}_\text{Fermi} + \sum_{i} \frac{c_i}{\Lambda^2} O_i + \mathcal{L}_{QCD} + \mathcal{L}_{QED} \]
Theoretical Framework

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

\[ E \]

LHC

\[ \Lambda \sim \text{GeV} \]

\[ H = \pi, n, p \]

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

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

\[ \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)} \]

\[ \mathcal{L}_{Fermi} + \sum_{i} \frac{c_i}{\Lambda_i^2} O_i \]

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

Non-perturbative matching

LHC, SLC, LEP, LANSCE, SNS, ...

\[ M_{W,Z} \]

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

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

\[ \varepsilon_i \sim (v/\Lambda)^2 \]
Match to hadronic description

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

- Tools (for both meson and nucleons):
  - symmetries of QCD $\rightarrow$ chiral EFT
  - lattice QCD
Example: $g_{S,T}$ in LQCD

- Hadronic matrix elements ($g_{S,T}$) needed to extract short distance physics ($\varepsilon_{S,T}$) from neutron and nuclear beta decays.

\[
\langle p | \bar{u}d | n \rangle = g_S \bar{u}_p u_n \\
\langle p | \bar{u} \sigma_{\mu\nu} d | n \rangle = g_T \bar{u}_p \sigma_{\mu\nu} u_n
\]

$g_S = 0.8(4)$

$g_T = 1.05(35)$

- First lattice QCD estimates (still large systematics): realistic goal of $\delta g_{S,T}/g_{S,T} = 20\%$ within 2-3 years.

Bhattacharya, VC, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011
Low-energy probes
How do we probe the $\epsilon$'s?

- Low-energy probes fall roughly in two classes:

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

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

Jackson-Treiman-Wyld 1957
How do we probe the $\varepsilon$'s?

- Low-energy probes fall roughly in two classes:

1. Differential decay rates: spectra, angular correlations (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 $(V,A)$ matters!

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

Channel-dependent effective CKM element:

Hadronic matrix element

Radiative corrections (both SD and LD)
Differential probes

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

- **Linear order \( \varepsilon \)’s:** only \( \varepsilon_{S,T} \) survive!
  - \( b \) 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”

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

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

- **Quadratic order in \( \varepsilon \)'s**
  - \( b, b_\nu: \varepsilon_{S,T}^*(\varepsilon_L \pm \varepsilon_R); \quad \tilde{\varepsilon}_{S,T}^*(\tilde{\varepsilon}_L \pm \tilde{\varepsilon}_R) \)
  - \( a: |\varepsilon_S|^2 + |\varepsilon_T|^2 \); \quad |\tilde{\varepsilon}_S|^2 + |\tilde{\varepsilon}_T|^2 \)
  - \( A, B: (\tilde{\varepsilon}_L - \tilde{\varepsilon}_R)^2 \)
- Expect weaker constraints
- Focus on \( \varepsilon_{S,T} \)
Low-energy constraints on $\varepsilon_{S,T}$

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

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

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

- $f_T = 0.24(4)$

Bychkov et al, 2007

Mateu-Portoles 07

Hardy-Towner 2009
Low-energy constraints on $\varepsilon_{S,T}$

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

![Diagram](image)

- $0^+ \rightarrow 0^+$ constraint
  
  
  $-1.0 \times 10^{-3} < g_S \varepsilon_S < 3.2 \times 10^{-3}$

- $\pi \rightarrow e \nu \gamma$ constraint
  
  
  $-1.0 \times 10^{-3} < \varepsilon_T < 1.3 \times 10^{-3}$

- $g_S = g_T = 1$

- $b_{0+} = -(2.2 \pm 4.3) \times 10^{-3}$
Low-energy constraints on $\varepsilon_{S,T}$

- **Current:** $0^+ \rightarrow 0^+$ and $\pi \rightarrow e + \gamma$
- **Future:** neutron $b, b\nu$ @ $10^{-3}$ level (Nab; UCNB,b, abBA, ...)
Low-energy constraints on $\xi_{S,T}$

- **Current:** $0^+ \rightarrow 0^+$ and $\pi \rightarrow e \nu \gamma$
- **Future:** neutron $b, b\nu \ @ 10^{-3}$ level ($Nab; UCNB,b, abBA, ...$)

\[ \Lambda_S = 3.2 \text{ TeV} \]
\[ \Lambda_S = 5 \text{ TeV} \]
\[ \Lambda_T = 7 \text{ TeV} \]
\[ \Lambda_T = 5 \text{ TeV} \]

\[ \epsilon_S = 2 \frac{(v/\Lambda_S)^2}{\Lambda_S} \]
\[ \epsilon_T = (v/\Lambda_T)^2 \]
\[ v = (2\sqrt{2} \ G_F)^{-1/2} \]

$\epsilon_S = \epsilon_T = 1$

\[ b_{0+} = -(2.2 \pm 4.3) \times 10^{-3} \]
Low-energy constraints on $\varepsilon_{S,T}$

- **Current:** $0^+ \rightarrow 0^+$ and $\pi \rightarrow e \nu \gamma$
- **Future:** neutron $b, b_\nu$ @ $10^{-3}$ level (Nab; UCNB,b, abBA, ...)

Quark model estimates:

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

Adler et al, '75
Herczeg '01
Low-energy constraints on $\epsilon_{S,T}$

- **Current:** $0^+ \to 0^+$ and $\pi \to e \nu \gamma$
- **Future:** neutron $b, b_\nu$ @ $10^{-3}$ level (Nab; UCNB,b, abBA, ...)

$Lattice$ $QCD$

$g_S = 0.8 (4)$

$g_T = 1.05(35)$

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

- **Current:** $0^+ \rightarrow 0^+$ and $\pi \rightarrow e \nu \gamma$
- **Future:** neutron $b, b_{\nu} @ 10^{-3}$ level (Nab; UCNB,$b, abBA, ...$)

(90% C.L.)

current lattice results

$\delta g_S/g_S = 10\%$

$\delta g_S/g_S = 20\%$

$\delta g_S/g_S = 50\%$

$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances
Low-energy constraints on $\varepsilon_{S,T}$

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

Messages

- neutron $b$ and $B$ at $10^{-3}$ level will improve current bounds on $\varepsilon_{S,T}$
- Hadronic uncertainties ($g_{S,T}$) strongly dilute significance of bounds
- First lattice results: already great improvement over quark models
- $\delta g_{S,T}/g_{S,T} \sim 20\%$ needed to fully exploit $\sim 10^{-3}$-level measurements

$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances
Low-energy constraints on $\tilde{\varepsilon}_{L,R,S,T}$

- Global fit to beta decay data
  
  $|g_S \tilde{\varepsilon}_S| < 6 \times 10^{-2}$
  
  $|g_T \tilde{\varepsilon}_T| < 2.5 \times 10^{-2}$
  
  $|\tilde{\varepsilon}_L \pm \tilde{\varepsilon}_R| < 7.5 \times 10^{-2}$

- Constraints are relatively weak, as expected

Severijns, Beck, Naviliat-Cuncic, 2006

90% CL
Universality probes

- Master formula for decay rates:

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

\[
|\overline{V}_{ij}|^2 = |V_{ij}|^2 \times \left(1 + \sum_{\alpha} c_{k\alpha}^\alpha \epsilon_{\alpha}\right)
\]

- Precision determination of $\overline{V}_{ij} \Rightarrow$ constraints on the $\epsilon_i$

\[
|\overline{V}_{ud}|^2 + |\overline{V}_{us}|^2 + |\overline{V}_{ub}|^2 - 1 = \Delta(\epsilon_i)
\]
- Status of $V_{ud}$ and $V_{us}$ and Cabibbo universality

Fit result

$V_{ud} = 0.97425 (22)$

$V_{us} = 0.2256 (9)$

$\Delta = (1 \pm 6) \times 10^{-4}$

Error equally shared between $V_{ud}$ and $V_{us}$

$|\varepsilon_L + \varepsilon_R - \varepsilon_L^{(\text{lept})}| < 5 \times 10^{-4}$

90% CL: $(\Lambda_{L,R} > 11 \text{ TeV})$
- Status of $V_{ud}$ and $V_{us}$ and Cabibbo universality

$V_{us} = 0.2256 (9)$

$V_{ud} = 0.97425 (22)$

Error equally shared between $V_{ud}$ and $V_{us}$

$\Delta = (1 \pm 6) \times 10^{-4}$

$|\varepsilon_L + \varepsilon_R - \varepsilon_{L,\text{lept}}| < 5 \times 10^{-4}$

90% CL:

$(\Lambda_{L,R} > 1 \text{ TeV})$

Messages

- Deep probe: current sensitivity well in the TeV region
- Powerful low-energy “boundary condition” for weak-scale models
High-energy probes
LHC (I): contact interactions

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

Moreover, using SU(2) symmetry, $\varepsilon_\alpha$ contribute to

• $p p \rightarrow e^+ e^- + X$

• $p p \rightarrow \nu \bar{\nu} + \text{jet} \quad (\text{“monojet”})$

Missing Transverse Energy
Focus on lepton transverse mass distribution in $pp \rightarrow e \nu + X$
- Focus on lepton transverse mass distribution in $p p \rightarrow e \nu + X$

- $m_T > 1 \text{ TeV}: \ n_{\text{obs}} = 1, n_{\text{bkg}} = 2.2 \pm 1.1 \Rightarrow \text{bound on "signal" BSM events}$

- $n_s < n_{s}\text{up} (n_{\text{obs}}, n_{\text{bkg}}) = 3.0 \quad 90\% \text{ CL}$
• Bounds on the effective couplings:

\[ \sigma_{BSM}(\epsilon_\alpha) \mathcal{L} \xi_{\text{eff}} \equiv n_s < 3.0 \]

\[ m_T > 1 \text{ TeV} \]

\[ \sigma = \sigma_W + \sigma_{BSM}(\epsilon_\alpha) \]

\[ = \sigma_W \left[ (1 + \epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2 \sigma_{WL} \epsilon_L^{(c)} \]

\[ + \sigma_R \left[ |\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] \]

\[ + \sigma_S \left[ |\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right] \]

\[ + \sigma_T \left[ |\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right] \]

Detection efficiency * geometric acceptance
• Bounds on the effective couplings:

$$\sigma_{BSM} (\varepsilon_\alpha) \mathcal{L} \; \varepsilon_{\text{eff}} \equiv n_s < 3.0$$

$$m_T > 1 \text{ TeV}$$

$$\sigma \bigg|_{m_T > m_T^\text{m}} = \sigma_W + \sigma_{BSM} (\varepsilon_\alpha)$$

$$= \sigma_W \left( 1 + \varepsilon_L^{(v)} \right)^2 + |\tilde{\varepsilon}_L|^2 + |\varepsilon_R|^2 \right) - 2 \sigma_{WL} \varepsilon_L^{(c)}$$

$$+ \sigma_R \left( |\tilde{\varepsilon}_R|^2 + |\varepsilon_L^{(c)}|^2 \right)$$

$$+ \sigma_S \left( |\varepsilon_S|^2 + |\tilde{\varepsilon}_S|^2 + |\varepsilon_P|^2 + |\tilde{\varepsilon}_P|^2 \right)$$

$$+ \sigma_T \left( |\varepsilon_T|^2 + |\tilde{\varepsilon}_T|^2 \right)$$

Incoherent contributions (interference $\sim m/E$)

SM + vertex corrections + interference terms

VC, Gonzalez-Alonso, Graesser, in progress
• Bounds on the effective couplings:

\[ \sigma_{BSM}(\varepsilon_\alpha) \mathcal{L} \varepsilon_{\text{eff}} \equiv n_s < 3.0 \]

\[ m_T > 1 \text{ TeV} \]

|\varepsilon_{S,P}|, |\tilde{\varepsilon}_{S,P}| < 1.7 \times 10^{-2}

|\varepsilon_T|, |\tilde{\varepsilon}_T| < 3.4 \times 10^{-3}

|\tilde{\varepsilon}_R| < 6.3 \times 10^{-3}

Already strong bounds on “incoherent” contributions, regardless of neutrino chirality
### $\beta$ decays vs LHC

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- **Unmatched low-energy sensitivity**
- **LHC limits close to low-energy. Interesting interplay in the future**
- **LHC already superior to low-energy! Need $\delta a_{GT}/a_{GT} < 0.05\%$ to match LHC**
Low-energy constraints are currently stronger
$\varepsilon_{S,T}$: $\beta$ decays vs LHC

LHC is catching up rapidly!

~ full dataset at 7 TeV

LHC @ 7 TeV, 10 fb$^{-1}$

LHC @ 7 TeV, 1 fb$^{-1}$

Low-energy current
$(0^+ \rightarrow 0^+ \pi \rightarrow e\nu\gamma)$

(90% C.L.)
$\epsilon_{S,T}$: $\beta$ decays vs LHC

LHC projected limits: based on aggressive $m_T$ cut (to reduce bkg events < 1) and assumption of no observed events
\[ \varepsilon_{S,T} : \beta \text{ decays vs LHC} \]

Messages

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

- b and B at $10^{-4}$ level would give unmatched discovery potential: strong motivation to pursue these experiments
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:

$$A_\beta \sim g_1 g_2 / M^2 \equiv \varepsilon$$

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

- 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 $m_T > 1$ TeV

![Graph](image)

$\sigma$ suppression due to $m < (m_T)_{\text{cut}}$

$\varepsilon_S$

Improvable with lower $(m_T)_{\text{cut}}$

But larger SM bkg

Decoupling regime**
t-channel mediator

- Scalar leptoquark $S_1$ $(3^*,1,1/3)$
- $\varepsilon_T = -1/4$ $\varepsilon_S = -1/4$ $\varepsilon_P$

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

Decoupling regime

$M_{\mathrm{LQ}}$ (TeV)
t-channel mediator

Scalar leptoquark S = (2*, 1, 1/3)

\( \varepsilon_T = -1/4 \quad \varepsilon_S = -1/4 \quad \varepsilon_P ... \)

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

- For TeV-scale mediator mass (m > 1 TeV), LHC bounds on \( \varepsilon \)'s based on contact interactions range from robust (t-channel) to conservative (s-channel)
- For low mass mediators (m < 0.5 TeV), the LHC bounds on \( \varepsilon \)'s quickly deteriorate: limits based on contact interactions are too optimistic

Messages

- For TeV-scale mediator mass (m > 1 TeV), LHC bounds on \( \varepsilon \)'s based on contact interactions range from robust (t-channel) to conservative (s-channel)
- For low mass mediators (m < 0.5 TeV), the LHC bounds on \( \varepsilon \)'s quickly deteriorate: limits based on contact interactions are too optimistic
Summary

- Improved picture of nonstandard CC interactions through combination of low-energy and collider probes**

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** Based on short-distance origin of new interactions
Summary

• Improved picture of nonstandard CC interactions through combination of low-energy and collider probes

• Low-energy:

  • Illustrated the importance of $g_{S,T}$ to obtain bounds on short distance $S,T$ couplings. First lattice QCD estimate

  • Established relevance of $10^{-3}$-level measurements of $b,B$ to probe $\varepsilon_{S,T}$

• Collider:

  • Demonstrated importance of LHC in setting bounds on CC non-standard couplings: it’s catching up fast!

  • Explored dependence of LHC bounds on the mediator mass (tree-level in $s$ and $t$ channels)
Extra Slides
Complementarity: an example

- Scalar resonance in s-channel

\[ \epsilon_S = 2\lambda_S \lambda_l \frac{v^2}{m^2} \]

- Observation of such a scalar resonance implies a lower bound on effective scalar coupling probed at low-energy:

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

\[ \tau = \frac{m^2}{s}, \]
• If LHC can determine scalar nature of the resonance, then predict a “guaranteed signal” for beta decay

• If LHC cannot determine spin of resonance, beta decay searches (positive or negative) provide discriminating input