Searching for New Physics: the Fundamental Symmetry Experiments

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Outline

• The quest for new physics: Energy and Precision / Intensity frontiers

• The role of nuclear science experiments at the Precision / Intensity frontier — a theory overview

• Selected topics:
  • rare / forbidden processes: $0
\nu\beta\beta$ decay, EDMs
  • precision measurements: $\beta$ decays
The quest for new physics
New physics: why?

- The SM is remarkably successful, but it’s probably not the whole story.

No Baryonic Matter, no Dark Matter, no Dark Energy, no Neutrino Mass

What stabilizes $G_{\text{Fermi}}/G_{\text{Newton}}$ against radiative corrections?

Do forces unify at high $E$? What is the origin of families?

…
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What stabilizes $G_{\text{Fermi}}/G_{\text{Newton}}$ against radiative corrections?

Do forces unify at high $E$? What is the origin of families?

…

Addressing these puzzles likely requires new degrees of freedom.
Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

$\approx 250$ GeV
New physics: where?

- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

- Two approaches
New physics: where?

- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

- Two approaches

Often requires use of powerful particle accelerators (hence also “Intensity Frontier”)
• Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Heavy mediators: precision tests
- Neutrino properties
- Dark sectors
- ...

• Two approaches, both needed to reconstruct BSM dynamics: structure, symmetries, and parameters of $\mathcal{L}_{BSM}$
Nuclear Science Fundamental Symmetry experiments play a prominent role at the Precision Frontier.

- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Heavy mediators: precision tests
- Neutrino properties
- Dark sectors
- ...

Where is the new physics? Is it Heavy? Is it Light & weakly coupled?
News from the energy frontier

The Large Hadron Collider

• Run 1: pp \( @ \sqrt{s} = 7-8 \text{ TeV} \)
• Run 2: pp \( @ \sqrt{s} = 13 \text{ TeV} \)
Integrated luminosity \( \sim 150 \text{ fb}^{-1} \)

• Major discovery: Higgs boson with \( m_h = 125 \text{ GeV} \)

• So far negative results from \textit{direct} searches for TeV-scale new dynamics

• Few-\( \sigma \) “anomalies” in semi-leptonic B-meson decays (LHCb) [this is really intensity frontier!]
News from the energy frontier

- Simplest scenarios of new physics pushed to TeV scale and beyond

- High hopes for the High Luminosity / High Energy LHC upgrade (3000 fb$^{-1}$ over next two decades)
Precision frontier searches — a theory overview
Three classes of new physics probes

1. Searches for rare or forbidden processes that probe approximate or exact symmetries of the SM: proton decay, n-nbar oscillations, $0\nu\beta\beta$, EDMs, $\mu \rightarrow e$, quark flavor violation, …
Three classes of new physics probes

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2. Precision measurements of SM-allowed processes: \( \beta \)-decays (neutron, nuclei), PVES, muon properties (lifetime, g-2), …
The precision frontier

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   - μ→e, quark flavor violation, …

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3. Searches / characterization of light and weakly coupled particles:
   - active vs, sterile vs, dark photon, dark Higgs, axion, …
The precision frontier

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To efficiently analyze the impact of precision frontier searches, one would like a fairly general theory framework, encompassing many underlying models.
Heavy new particles affect low-energy physics through local operators suppressed by inverse powers of heavy scale.

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots
\]

[ \Lambda \leftrightarrow M_{\text{Heavy}} ]

\[ C_i \ [g_{\text{BSM}}, \frac{M_a}{M_b}] \]

For any observable \( O \),
\[ \delta O_{\text{BSM}} / O_{\text{SM}} \sim (\text{VEW}/\Lambda)^n \ n=2,4,\ldots \]

Can make “apples-to-apples” model-independent sensitivity comparisons with collider probes.

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**Theory framework**

- **IR new physics**: “portals” (vector, neutrino, Higgs, axion)

- **UV new physics**: EFT

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- **Precision Frontier**
  - (indirect access to UV d.o.f)
  - (direct access to light d.o.f.)
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\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O^{(6)} + \cdots \]

[ \Lambda \leftrightarrow M_{\text{Heavy}} ]

At lower energy, to connect to hadronic / nuclear observables, use tools such as chiral EFT, lattice QCD, dispersion relations, quantum many body methods.

• IR new physics: “portals” (vector, neutrino, Higgs, axion)

• UV new physics: EFT

See talk by S. Reddy
Impact of precision frontier searches

• Discovery potential
  • new ways to look for cracks in the SM

• Diagnosing power
  • Multiple EDM searches → underlying sources of CPV
  • $0\nu\beta\beta$, mass scale, oscillations, LFV ($\mu \rightarrow e, \ldots$) → neutrino mass model
  • …

• Connection to big open questions
  • e.g. unique sensitivity to symmetry breaking required by Sakharov conditions for baryogenesis (B, L, CP);
  • …
Connection to big questions

- Nuclear Science Fundamental Symmetries experiments cluster around open questions — often probing dynamics otherwise inaccessible.
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Neutrinoless double beta decay and Lepton Number Violation

See talk by J. Klein
Neutrinoless double beta decay ($0\nu\beta\beta$)

$$(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$$

Lepton number changes by two units: $\Delta L = 2$

- B-L conserved in SM $\rightarrow$ new physics, with far-reaching implications
- Demonstrate that neutrinos are their own antiparticles
- Establish a key ingredient to generate the baryon asymmetry via leptogenesis

Fukugita-Yanagida 1987
Shechter-Valle 1982
$0\nu\beta\beta$ physics reach

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27-28} \text{ yr}$) will probe at unprecedented levels LNV from a variety of mechanisms.
• Ton-scale 0νββ searches ($T_{1/2} > 10^{27-28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms.
• Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27-28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms?

$0\nu\beta\beta$ physics reach

![Diagram showing various mechanisms for $0\nu\beta\beta$ transitions.]

- "Standard Mechanism" (high-scale see-saw)
- Left-Right SM
- RPV SUSY

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• Ton-scale 0νββ searches ($T_{1/2} > 10^{27-28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms
High-scale seesaw: discovery potential

- In this case $0\nu\beta\beta$ is a direct probe of $\nu$ mass matrix: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

\[
\langle m_{\beta\beta} \rangle^2 = \left| \sum U_{e i} m_{\nu i} \right|^2
\]

Dark bands: unknown phases
Light bands: uncertainty from oscillation parameters (90% CL)

Assume range for nuclear matrix elements from different many-body methods

Discovery possible for inverted spectrum or $m_{\text{lightest}} > 50$ meV

Plot by K. Heeger
High-scale seesaw: diagnosing power

- Interplay with other $\nu$ mass probes can test high-scale seesaw and possibly unravel new sources of LNV or physics beyond $\Lambda CDM + m_\nu$.

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \quad \text{(0v}\beta\beta \text{ decay)}$$

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \quad \text{(Tritium } \beta \text{ decay)}$$

$$\Sigma = \sum_i m_i \quad \text{(Cosmology)}$$
High-scale seesaw: diagnosing power

- Interplay with other $\nu$ mass probes can test high-scale seesaw and possibly unravel new sources of LNV or physics beyond "$\Lambda CDM + m_\nu$"

\[
m_{\beta\beta} = \left| \sum_i U^2_{ei} m_i \right|
\]

$0\nu\beta\beta$ decay

\[
m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}
\]

Tritium $\beta$ decay

\[
\Sigma = \sum_i m_i
\]

Cosmology

Ton scale

Project8

KATRIN

Cosmology (95% CL limit)

Capozzi et al, 1601.07777

Planck 1807.06209
High-scale seesaw: theory developments

• Steps towards controllable uncertainties in matrix elements:
  • Use chiral EFT as guiding principle
  • Use first-principles results in light nuclei as a benchmark
  • “Ab initio” nuclear structure calculations with QCD-rooted potentials for $^{48}\text{Ca}$ and $^{76}\text{Ge}$

Coordinated effort through DOE-funded DBD Nuclear Theory Topical Collaboration (PI Jon Engel)
http://c51.lbl.gov/~0nubb/webhome/
Leading order $nn \to pp$ transition operator for nuclear structure calculations should be
New insights from EFT

- Renormalization of $nn \rightarrow ppee$ amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

\[ C \sim 4\pi/(mNQ) \]

$Q$ is soft scale $\sim k_F$

UV divergence $\sim 1/(Q^2) \log(\mu)$

V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001
New insights from EFT

- Renormalization of $nn \rightarrow ppee$ amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

\[ \tilde{C} \sim \frac{4\pi}{\left(m_N Q\right)} \]

$Q$ is soft scale $\sim k_F$

Strong short-range interaction

UV divergence $\sim 1/(Q^2) \log(\mu)$ reabsorbed by $g_\nu$

- Coupling flows to $g_\nu \sim 1/Q^2 \sim 1/k_F^2$, same order as tree-level $\nu$ exchange

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New insights from EFT

- Renormalization of $nn \rightarrow ppee$ amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

Previously missed short-range coupling $g_\nu$ encodes the physics of “high momentum” $\nu_M$ exchange ($q \gg k_F$)
New insights from EFT

- Renormalization of $nn \rightarrow ppee$ amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

Expect significant impact of (unknown) $g_\nu$ on $m_{\beta\beta}$ phenomenology

Several approaches to estimate $g_\nu$
(symmetry relation to $I=2$ EM couplings\textsuperscript{**}, dispersive, lattice QCD)

Work is underway on various fronts

V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001
LNV from multi-TeV scale dynamics

- TeV sources of LNV may lead to sizable contributions to NLDBD 
  *not directly related to the exchange of light neutrinos*
LNV from multi-TeV scale dynamics

- TeV sources of LNV may lead to sizable contributions to NLDBD not directly related to the exchange of light neutrinos

- LHC can compete with $0\nu\beta\beta$ in certain (limited) parameter space

Peng, Ramsey-Musolf, Winslow, 1508.0444
LNV from multi-TeV scale dynamics

- TeV sources of LNV may lead to sizable contributions to NLDBD not directly related to the exchange of light neutrinos

- LHC can compete with $0\nu\beta\beta$ in certain (limited) parameter space

- New contributions can interfere with $m_{\beta\beta}$ or add incoherently, significantly affecting the interpretation of experimental results

Peng, Ramsey-Musolf, Winslow, 1508.0444

Simplified model ~ RPV-SUSY

$A_{0\nu\beta\beta} \sim (g_{\text{eff}})^4 / (M_{\text{eff}})^5$
LNV from multi-TeV scale dynamics

- Leptoquark example: *dim-7 operator can interfere with dim-5* \((m_{\beta\beta})\)

\[
\frac{m_{\beta\beta}^{(\text{eff})}}{g_A^2 M_\nu} = \left( \frac{G_{1/2}}{G_{01}} \right)^{-1/2}
\]

- Inverted Hierarchy
- Normal Hierarchy

\[\Lambda = 600 \text{ TeV}\]

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390
LNV from multi-TeV scale dynamics

- Left-right symmetric model: **dim-9 contribution can be dominant in NH**

Illustrative LHC-safe \((pp \rightarrow ee \ jj)\) parameters

\[
\begin{align*}
  m_{WR} &= 4.5 \text{ TeV} \\
  m_{\nu_R} &= O(10 \text{ TeV}) \\
  U_R &= U_{PMNS}
\end{align*}
\]

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02789
$0\nu\beta\beta$ physics reach — summary

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27-28}$ yr) have significant discovery potential — and yes, even “if it’s normal hierarchy”! (This is because we don’t know the scale $\Lambda$ associated with LNV)

- **Model diagnosing**: in combination with osc., direct mass meas., cosmology & LHC, can probe source of LNV

- Exciting prospects to improve theory uncertainties thanks to synergy of EFT, lattice QCD, and nuclear structure
Electric Dipole Moments

- Essentially free of SM background (from CKM CP-violation)
- Probe new sources of CPV for baryogenesis (SM CPV is insufficient)
Broad sensitivity to new physics

- Strongest constraints of CPV Higgs couplings
- One of few observables probing PeV scale SUSY
- Strong constraints on baryogenesis models

Dzuba, Flambaum, Samsonov, Stadnik, 1805.01234
Abel et al., 1708.06367
LeDall, Pospelov, Ritz 1505.01865
Mantry, Pitschmann, Ramsey-Musolf 1401.7339
…
EDMs and CPV Higgs couplings

- Leading \((1/\Lambda^2)\) CP-violating BSM interactions involving the Higgs:

\[
\begin{align*}
H-q_L-q_R & : \text{pseudo-scalar} \\
& \text{Yukawa couplings} \\
H-q_L-q_R-V & : \text{dipole} \\
& V = g, W^a, B \\
H-H-V-\tilde{V} & \\
& F_{\mu\nu} \tilde{F}^{\mu\nu} \sim E \cdot B
\end{align*}
\]
EDMs and CPV Higgs couplings

- Leading $(1/\Lambda^2)$ CP-violating BSM interactions involving the Higgs:

  \begin{align*}
  \text{H-q}_L-q_R: & \quad \text{pseudo-scalar} \\
  \text{Yukawa couplings} \end{align*}

- Affect Higgs production / decay at the LHC and EDMs, e.g.:
EDMs and CPV Higgs couplings

- Leading \((1/\Lambda^2)\) CP-violating BSM interactions involving the Higgs:

  \[
  H-{q_L}-{q_R}: \text{pseudo-scalar Yukawa couplings}
  \]

  \[
  H-{q_L}-{q_R}-{V}: \text{dipole} \quad V = g, W^a, B
  \]

  \[
  H-H-V-\tilde{\nu} \quad F_{\mu\nu} \tilde{F}_{\mu\nu} \sim E \cdot B
  \]

- EDMs provides the strongest constraints in most cases

- Sensitivity @ \(5 \times 10^{-27}\) e cm with mildly improved matrix elements will make nEDM the strongest probe for all couplings involving quarks and gluons
EDMs in high-scale SUSY models

- “Split-SUSY”: retain gauge coupling unification and DM candidate


EDMs among a handful of observables capable of probing such high scales

Same CPV phase controls $d_e, d_n [d_q]$

Barr-Zee diagram
Studying the ratio $d_n/d_e$ with precise matrix elements ($LQCD$) → stringent upper bound $d_n < 4.1 \times 10^{-29}$ e cm

Split-SUSY can be falsified by current EDM searches

Example of model diagnosing enabled by multiple measurements (e,n) and controlled theoretical uncertainty
EDMs and weak scale baryogenesis

For a review see: Morrissey & Ramsey-Musolf 1206.2942

• B violation
• C & CP violation
• Departure from thermal equilibrium

Sakharov 1967
EDMs and weak scale baryogenesis

Requirements on BSM scenarios:
- 1st order phase transition (testable at LHC & future colliders)
- New CPV (EDMs often provide strongest constraint)

Rich literature: (N)MSSM, Higgs portal (scalar extensions), flavored baryogenesis,…

For a review see: Morrissey & Ramsey-Musolf 1206.2942

Sakharov 1967
EDMs and weak scale baryogenesis

- NMSSM: CPV couplings appearing in the gaugino-higgsino mixing contribute to both BAU and EDM

- In simplest case (with only one CP-violating coupling), successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches

[Diagram showing CP violation and EDM relationship]

Compatible with baryon asymmetry

Next generation neutron EDM

Li, Profumo, Ramsey-Musolf
0811.1987
EDMs and weak scale baryogenesis

- NMSSM: CPV couplings appearing in the gaugino-higgsino mixing contribute to both BAU and EDMs and weak scale baryogenesis.

- In simplest case (with only one CP-violating coupling), successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches.

CAVEAT: current uncertainties in
1) hadronic matrix elements;
2) early universe calculations;
may shift these lines and alter the conclusions.

VC, C. Lee, S. Tulin, 1106/0747

Next generation neutron EDM

Compatible with baryon asymmetry

Li, Profumo, Ramsey-Musolf
0811.1987
Precision measurements
• Beta decays and parity-violating electron scattering have played a central role in establishing the Standard Model.

• Today, with precision approaching the 0.1% level (together with the muon g-2 at the <ppm level!) they probe quantum effects in the Standard Model at unprecedented levels.

• “Broad band” sensitivity to new physics, both heavy and light.

Representative diagrams for muon g-2.
Beta decays: SM and beyond

- In the SM, $W$ exchange $\Rightarrow$ $V$-$A$ currents, universality

\[ G_F \sim g^2 V_{ij}/M_W^2 \sim V_{ij}/v^2 \]
Beta decays: SM and beyond

- In the SM, $W$ exchange ⇒ $V$-$A$ currents, universality

\[ G_F \sim g^2 V_{ij} / M^2 w^2 \sim V_{ij} / v^2 \]

\[ E \ll \Lambda \]

\[ \epsilon_{\Gamma} \sim \tilde{\epsilon}_{\Gamma} \sim (v / \Lambda)^2 \]

\[ \mathcal{L}_{\text{SM}} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_{\Gamma} \left[ \epsilon_{\Gamma} \bar{\ell} \Gamma \nu_L \cdot \bar{u} \Gamma d + \tilde{\epsilon}_{\Gamma} \bar{\ell} \Gamma \nu_R \cdot \bar{u} \Gamma d \right] \]

Ten effective couplings \[ \Gamma = L, R, S, P, T \]
How do we probe the $\varepsilon_\alpha$?

For comprehensive review, see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

1. Differential decay distribution

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

$\alpha(\mathbf{g}_A), \; \mathbf{A}(\mathbf{g}_A), \; \mathbf{B}(\mathbf{g}_A, \mathbf{g}_\alpha \varepsilon_\alpha), \ldots$

isolated via suitable experimental asymmetries

Nucleon charges from LQCD

CalLat 1805.12030
Bhattacharya et al 1806.09006
How do we probe the $\epsilon_\alpha$?

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1. Differential decay distribution

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

isolated via suitable experimental asymmetries

2. Total decay rates

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

CKM Unitarity Test

$$|\overline{V}_{ud}|^2 + |\overline{V}_{us}|^2 + |\overline{V}_{ub}|^2 = 1 + \Delta_{\text{CKM}}(\epsilon_i)$$

Nucleon charges from LQCD

CallLat 1805.12030
Bhattacharya et al 1806.09006
CKM unitarity test

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

Extraction dominated by $0^+ \to 0^+$ nuclear transitions

Extraction dominated by $K$ decays:
$K \to \pi\nu\bar{e}$ \& $K \to \mu\nu$ vs $\pi \to \mu\nu$ ($V_{us}/V_{ud}$)

Hardy-Towner 1411.5987
CKM 2016

FLAVIANET report 1005.2323 and refs therein
Lattice QCD input from FLAG 1607.00299 and refs therein
+ MILC 2018 1809.02827
CKM unitarity test

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

- \( \Delta_{CKM} = -(4 \pm 5) \times 10^{-4} \sim 1\sigma \)
- \( \Delta_{CKM} = -(12 \pm 6) \times 10^{-4} \sim 2\sigma \)

Hint of \( \epsilon_L + \epsilon_R \neq 0 \)
or SM theory input?

Worth a closer look:
at the level of the best EW precision tests,
probing scale \( \Lambda \sim 10\text{ TeV} \)
CKM unitarity test

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

\[ \Delta_{\text{CKM}} = -(14 \pm 4) \times 10^{-4} \approx 3.5\sigma \]

\[ \Delta_{\text{CKM}} = -(22 \pm 5) \times 10^{-4} \approx 4.5\sigma \]

With new radiative correction from Seng-Gorcheitn-Patel-Ramsey-Musolf [1807.10197]
CKM unitarity test

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

\( \Delta_{\text{CKM}} = -(14 \pm 4) \times 10^{-4} \sim 3.5\sigma \)

\( \Delta_{\text{CKM}} = -(22 \pm 5) \times 10^{-4} \sim 4.5\sigma \)

\( V_{us} \) from \( K \rightarrow \mu\nu \)

\( V_{us} \) from \( K \rightarrow \pi\nu \nu \)

With new radiative correction from Seng-Gorchtein-Patel-RamseyMusolf

[1807.10197]

With radiative correction from Czarnecki-Marciano-Sirlin

[1907.06737] one gets \( 2(3) \sigma \)

Something to watch closely in the future. Neutron decay can be the arbiter!
Impact of neutron measurements

- Independent extraction of $V_{ud} @ 0.02\%$ requires:

\[
\tilde{V}_{ud} = \left[ \frac{4908.6(1.9) \text{ s}}{\tau_n (1 + 3 \bar{g}_A^2)} \right]^{1/2}
\]

\[
\begin{align*}
\delta\tau_n &\sim 0.35 \text{ s} \\
\delta\tau_n/\tau_n &\sim 0.04 \% \\
\delta g_A/g_A &\sim 0.15\% \rightarrow 0.03\% \\
(\delta a/a, \delta A/A &\sim 0.14\%)
\end{align*}
\]

UCNt @ LANL $[\tau_n \sim 877.7(7)(3)\text{s}]$ is almost there, will reach $\delta\tau_n \sim 0.2 \text{ s}$ 1707.01817

$\delta A/A < 0.2\%$ can be reached by PERC, UCNA+ $\delta a/a \sim 0.1\%$ at Nab

Czarnecki, Marciano, Sirlin 1802.01804
Sensitivity to $\varepsilon_L$ and $\varepsilon_R$: $\beta$ vs collider

- Due to SU(2) gauge invariance:

- Vertex corrections inducing $\varepsilon_{L,R}$ involve the Higgs field!

- $\varepsilon_L$ also corrects $Zqq$ vertex

$$O_{\varphi\varphi} = i(\varphi^T \epsilon_D \varphi)(\bar{u}\gamma^\mu d)$$

$$O^{(3)}_{\varphi q} = i(\varphi^T D^\mu \sigma^a \varphi)(\bar{q}\gamma_{\mu} \sigma^a q)$$

Due to SU(2) gauge invariance:
Sensitivity to $\varepsilon_L$ and $\varepsilon_R$: $\beta$ vs collider

90%CL, assumes only two operators at high scale

Neutron decay:
$\lambda = g_A (1 - 2 \varepsilon_R)$

Constraint on $\varepsilon_R$ uses
$g_A = 1.271(13)$
(CalLat 1805.12030)

$\Delta_{\text{CKM}} \propto \varepsilon_L + \varepsilon_R$

$\delta \Gamma_{(\pi \to \mu \nu)} \propto \varepsilon_L - \varepsilon_R$
($f_{\pi}$ from LQCD)
Sensitivity to $\varepsilon_L$ and $\varepsilon_R$: $\beta$ vs collider

90%CL, assumes only two operators at high scale

Associated Higgs production at LHC

Neutron decay:
$\lambda = g_A (1 - 2 \varepsilon_R)$

Constraint on $\varepsilon_R$ uses
$g_A = 1.271(13)$
(CalLat 1805.12030)

- $\beta$ decays quite competitive with collider (probing $\Lambda_{L,R} > 10$ TeV)
- Caveat: going beyond a 2-coupling analysis relaxes some of these constraints (but not the one on $\varepsilon_R$ from $\lambda$!)
- $\beta$ decays provide *independent competitive constraints* in a global analysis
Sensitivity to $\varepsilon_S$ and $\varepsilon_T$: $\beta$ vs collider

Current low-E data: dominated by $0^+ \rightarrow 0^+, \tau(n), A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijs, 1803.08732

LHC: $pp \rightarrow e\nu + X$

Bhattacharya et al 1806.09006

$\varepsilon_{S,T} @ \mu = 2$ GeV (MS-bar)

LHC 36fb$^{-1}$ @ 13 TeV
Sensitivity to $\varepsilon_S$ and $\varepsilon_T$: $\beta$ vs collider

FUTURE

$\varepsilon_{S,T} @ \mu = 2 \text{ GeV (MS-bar)}$

Current low-E data: dominated by $0^+ \to 0^+, \tau(n), A(n)$

Prospective beta decay measurements competitive with strong LHC constraints, probing $\Lambda_{S,T} \sim 5-10 \text{ TeV}$

$\text{Bhattacharya et al} 1806.09006$

$\text{Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732}$

$d\Gamma \sim \Gamma_0 (1 + b m_e / E_e)$

LHC 36fb$^{-1}$

@ 13 TeV

$b (n) @ 0.001$

$b (^{6}\text{He}) @ 0.001$
Concluding comments

- Energy and Precision frontiers are exploring uncharted territory in our search for BSM physics.

- Vibrant Nuclear Science portfolio probes BSM dynamics related to open questions about our universe.
Concluding comments

• Current / planned nuclear science experiments provide competitive probes of dark sectors and new physics up to $\Lambda \gg \text{TeV}$

• Win-win situation:

  • Should new physics appear at the LHC, Nuclear Science probes will play a key role in understanding the symmetries of BSM dynamics and disentangle models

  • Should new physics NOT appear at the LHC, the precision frontier will be for a while the only laboratory tool to explore new physics
Thank you!

A drawing by
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