Fundamental Symmetries - 5

Vincenzo Cirigliano
Los Alamos National Laboratory
Plan of the lectures

• Review symmetry and symmetry breaking

• Introduce the Standard Model and its symmetries

• Beyond the SM:
  • hints from current discrepancies?
  • effective theory perspective

• Discuss a number of “worked examples”
  • Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  • Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.
Neutral Current
Parity violating electron scattering

- Speculation by Zel’dovich (1958) before the SM: neutral analogue of V-A charged current interaction?

![Diagram of electron scattering](image)

- In electron proton scattering, the weak and EM amplitudes interfere.

\[
\sigma \propto |A_{EM} + A_{weak}|^2 \\
\sim |A_{EM}|^2 + 2A_{EM}A_{weak}^* + \ldots
\]

Parity violating

- Expect asymmetry in scattering of L and R polarized electrons!

\[
A_{PV} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2}
\]
• $A_{PV}$ violates parity:
• $A_{PV}$ violates parity:

\[ A_{PV} = \frac{\sigma - \sigma}{\sigma + \sigma} \sim \frac{A_{\text{weak}}}{A_{\text{EM}}} \sim \frac{G_F Q^2}{4 \pi \alpha} \]

\[ A_{PV} \sim 10^{-4} \cdot Q^2 (\text{GeV}^2) \]

Tiny asymmetries!
• Through 4 decades of technical progress, parity-violating electron scattering (PVES) has become a precision tool.
\( A_{PV} \) in the Standard Model

- Recall neutral current in the Standard Model

\[ \mathcal{L}_{\text{int}} = -\frac{g}{2\cos\theta} Z^\mu \bar{\psi}_f \left( g_V^{(f)} \gamma^\mu - g_A^{(f)} \gamma^\mu \gamma_5 \right) \psi_f \]

\[ \theta = \arctan \frac{g'}{g} \]
\[ e = g \sin\theta. \]

\[ g_V^{(f)} = T_3^{(f)} - 2 \sin^2 \theta Q^{(f)} \]
\[ g_A^{(f)} = T_3^{(f)} \]

Weak charge of the fermion

- Precision tool: low \( q^2 \) measurements of \( \sin(\theta_W) \) + sensitivity to BSM

\[ A_{PV} \approx \frac{\sigma_{\downarrow \downarrow} - \sigma_{\downarrow \uparrow}}{\sigma_{\downarrow \downarrow} + \sigma_{\downarrow \uparrow}} \sim \frac{A_{\text{weak}}}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha} \left( g_A e g_V^T + \beta g_V e g_A^T \right) \]
\[ A_{PV} \text{ in the Standard Model} \]

- Recall neutral current in the Standard Model

\[
\mathcal{L}_{\text{int}} = -\frac{g}{2 \cos \theta} \bar{Z}^{\mu} Z^{\mu} \bar{f} \left( g_{V}^{(f)} \gamma_{\mu} - g_{A}^{(f)} \gamma_{\mu} \gamma_{5} \right) f
\]

\[
g_{V}^{(f)} = T_{3}^{(f)} - 2 \sin^{2} \theta \quad Q_{W}^{(f)} = 2 g_{V}^{(f)}
\]

\[
g_{A}^{(f)} = T_{3}^{(f)}
\]

For electron and proton

\[
Q_{W} = 1 - 4 \sin^{2} \theta_{W}
\]

\[
\frac{\delta(Q_{W})}{Q_{W}} \sim 10\% \Rightarrow \frac{\delta(\sin^{2} \theta_{W})}{\sin^{2} \theta_{W}} \sim 0.5\%
\]
Processes

Møller Scattering

Q-Weak (JLab)

DIS-Parity
Recent result by Q-Weak

At forward angles and small $Q^2$, $A_{PV}$ accesses the weak charge

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \frac{Q^2 - 0}{\sigma_R} \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [Q^p_W + Q^2 B(Q^2, \theta)]$$

$B(Q^2, \theta)$ is a form-factor term. About 30% correction to $A_{PV}$ for Qweak. Well determined by existing PVES data.

Qweak of the Proton

$A_{PV} = -226.5 \pm 7.3 \text{(stat)} \pm 5.8 \text{(syst)} \text{ ppb at } Q^2 = 0.0249 \text{(GeV/c)}^2$

- All nuclear PVES data up to $Q^2 \sim 0.7 \text{ GeV}^2$
- (hydrogen, deuterium, helium)
- 5 parameters ($C_{1u}$, $C_{1d}$, isovector axial FF, $\rho_s$, $\mu_s$)
- Fit and data shown corrected to forward angle limit

Standard Model:

$Q^p_W = 0.0708 \pm 0.0003$

Qweak + PVES data base:

$Q^p_W = 0.0719 \pm 0.0045$

K. Paschke talk at CIPANP 2018
Impact of PVES on $\theta_W$

*Qweak 2017 + PVES data base:*
\[
\sin^2\theta_W = 0.2382 \pm 0.0011
\]

SM prediction: relating EW measurements at $Q \sim 100$ GeV to low-energy

Marciano, Erler, Ramsey-Musolf
Impact of PVES on $\theta_W$

MESA-P2 will improve $Q_w(p)$ by factor ~3.3

MOLLER@JLab will improve $Q_w(e)$ by factor of 5

SoLID@JLab will improve eDIS by factor of ~3

Best Collider $\delta(sin^2\theta_W)$:
- $A_t(SLD)$: 0.00026
- $A_t(LEP)$: 0.00029

Future projections, similar time scale
- Final Tevatron: ~ 0.00046
- LHC 14 TeV, 300 fb$^{-1}$: ~ 0.00036
- Note: pdf uncertainties
- MOLLER: ~ 0.00028
- Mainz P2: ~ 0.00032
Impact of PVES on new physics

- Sensitivity to heavy new physics parameterized by local operators

\[ \Lambda \sim 5 \rightarrow 8 \text{ TeV (Q-Weak)} \]
\[ \Lambda \sim 6 \text{ TeV (SoLID)} \]
\[ \Lambda \sim 11 \text{ TeV (MOLLER)} \]

\[ \Lambda_{LHC} \sim 5-10 \text{ TeV (di-lepton searches)} \]

J. Erler et al.
1401.6199

Best contact-interaction reach for leptonic operators, at low OR high-energy
Impact of PVES on new physics

• Q-Weak result provides constraint on linear combination of $C_{1u}, C_{1d}$

$$Q^p_W = -2(2C_{1u} + C_{1d})$$

• Agreement with Standard Model + APV constrains the size (mass scale) of possible new physics contribution
Impact of PVES on new physics

- Sensitivity to dark sector: $U(1)_d$ dark boson $Z_d$ can mix with $\gamma$ and $Z$

\[
L_{\text{dark } Z} = -\left( \varepsilon e J_{em}^\mu + \varepsilon_Z \frac{g}{2 \cos \theta_W} J_{NC}^\mu \right) Z_{d \mu}
\]

Davoudsial-Lee-Marciano 1402.3620
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• Introduce the Standard Model and its symmetries

• Beyond the SM:
  • hints from current discrepancies?
  • effective theory perspective

• Discuss a number of “worked examples”
  • Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  • Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.
EDMs and T (CP) violation beyond the Standard Model
EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T:
  \[ H \sim d \vec{J} \cdot \vec{E} \]
  \[ \vec{d} = \sum_i q_i \vec{r}_i \]
  \[ \vec{d} = d \vec{J} \]

Classical picture \rightarrow Quantum level: Wigner-Eckart theorem
EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T: $\mathcal{H} \sim d \vec{J} \cdot \vec{E}$

  Classical picture $\rightarrow$
  Quantum level: Wigner-Eckart theorem

- CPT invariance $\Rightarrow$ nonzero EDMs signal CP violation

\[ \vec{d} = \sum_i q_i \vec{r}_i \]

\[ \vec{d} = d \vec{j} \]
EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T: $\mathcal{H} \sim d \mathbf{J} \cdot \mathbf{E}$

- Measurement: look for linear shift in energy (change in precession frequency) due to external E field

\[ \nu = \frac{(2\mu B \pm 2dE)}{h} \]
EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T: $\mathcal{H} \sim d \vec{J} \cdot \vec{E}$

- Measurement: look for linear shift in energy (change in precession frequency) due to external E field

\[ \nu = \frac{(2\mu B \pm 2dE)}{\hbar} \]

Current neutron sensitivity $d_n \sim 10^{-13}$ e fm !!
EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T: $\mathcal{H} \sim d \vec{J} \cdot \vec{E}$

- Ongoing and planned searches in several systems, probing different sources of T (CP) violation
  - n, p
  - Light nuclei: d, t, h
  - Atoms: diamagnetic ($^{129}$Xe, $^{199}$Hg, $^{225}$Ra, ...); paramagnetic ($^{205}$Tl, ...)
  - Molecules: YbF, ThO, ...
EDMs and new physics

1. Essentially free of SM “background” (CKM) $^1$

<table>
<thead>
<tr>
<th>System</th>
<th>current $\sim 10^{-28}$</th>
<th>projected $10^{-29}$</th>
<th>SM (CKM) $\sim 10^{-38}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$\sim 10^{-19}$</td>
<td>$10^{-16}$</td>
<td>$\sim 10^{-35}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\sim 10^{-16}$</td>
<td></td>
<td>$\sim 10^{-34}$</td>
</tr>
<tr>
<td>$n$</td>
<td>$\sim 10^{-23}$</td>
<td>$10^{-29}$ **</td>
<td>$\sim 10^{-31}$</td>
</tr>
<tr>
<td>$p$</td>
<td>$\sim 10^{-26}$</td>
<td></td>
<td>$\sim 10^{-31}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$\sim 10^{-29}$</td>
<td>$10^{-30}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$\sim 10^{-27}$</td>
<td>$10^{-29}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>$^{225}$Ra</td>
<td>$\sim 10^{-23}$</td>
<td>$10^{-26}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
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</tr>
</tbody>
</table>

$^1$ Observation would signal new physics or a tiny QCD $\theta$-term ($< 10^{-10}$). Multiple measurements can disentangle the two effects.
EDMs and new physics

1. Essentially free of SM “background” (CKM) \(*^1\)

2. Sensitive to high scale BSM physics (\(\Lambda \sim 10-100 \text{ TeV}\))

\[
d_n \propto \frac{m_q}{\Lambda^2} e \phi_{CP}
\]

3. Probe key ingredient of baryogenesis

- B violation
- C and CP violation
- Departure from equilibrium

New particles with mass \(\sim \Lambda\)

Sakharov ‘67

broken electroweak phase \(<H> \neq 0\)
Connecting EDMs to new physics

Dynamics involving particles with \( M_{BSM} > \Lambda \)

Describe dynamics below the scale \( M_{BSM} \sim \Lambda \gg v = G_F^{1/2} \) in terms of \( L_{eff} \)

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

Non-perturbative matrix elements
Connecting EDMs to new physics

- At $E \sim \text{GeV}$, leading BSM effects encoded in handful of dim-6 operators

\[
\mathcal{L}_{6}^{\text{CPV}} = -\frac{i}{2} \sum_{f=e,u,d,s} d_{f} \bar{f} \sigma \cdot F \gamma_{5} f - \frac{i}{2} \sum_{q=u,d,s} \bar{d}_{q} g_{s} \bar{q} \sigma \cdot G \gamma_{5} q + d_{W} \frac{g_{s}}{6} G \tilde{G} G + \sum_{i} C_{i}^{(4f)} O_{i}^{(4f)}
\]

- Electric and chromo-electric dipoles of fermions: $J \cdot E$

- Gluon chromo-EDM (Weinberg operator): $J \cdot E_{c}$

- Semileptonic and 4-quark: $d_{W} \sim \frac{1}{\Lambda^{2}}$

\[
d_{f}, \bar{d}_{q} \sim \frac{v_{ew}}{\Lambda^{2}}\]
Connecting EDMs to new physics

- At $E \sim \text{GeV}$, leading BSM effects encoded in handful of dim-6 operators

$$\mathcal{L}_{6}^{\text{CPV}} = -\frac{i}{2} \sum_{f=e,u,d,s} d_f \bar{f} \sigma \cdot F \gamma_5 f - \frac{i}{2} \sum_{q=u,d,s} \tilde{d}_q g_s \bar{q} \sigma \cdot G \gamma_5 q + d_W \frac{g_s}{6} \tilde{G} \tilde{G} G + \sum_{i} C_i^{(4f)} O_i^{(4f)}$$

- Hadronic / nuclear matrix elements not very well known. Can be improved in lattice QCD. Example of neutron EDM:

QCD Sum Rules (50% guesstimate) QCD Sum Rules + NDA ($\sim$100%)

Pospelov-Ritz hep-ph/0504231 and refs therein
EDMs in the LHC era

• LHC output so far:
  • Higgs boson @ 125 GeV
  • Everything else is quite heavier (or very light)

• **EDMs more relevant than ever:**
  • Strongest constraints of non-standard CPV Higgs couplings
  • One of few observables probing PeV scale supersymmetry
  • Non trivial constraints on baryogenesis models
  • Sensitivity to axion-like dark matter

Abel et al., 1708.06367
EDMs and CPV Higgs couplings (1)

- Leading interactions with $q, g$ strongly constrained by gauge invariance
EDMs and CPV Higgs couplings (1)

- Leading interactions with $q, g$ strongly constrained by gauge invariance

\[ \mathcal{L}^{CPV}_6 = -\nu \theta' \frac{\alpha_s}{8\pi} h G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + v^2 \text{Im} Y'_{q'} \bar{q} i\gamma_5 q h - \frac{i}{2} \tilde{d}_q g_s \bar{q} \sigma \cdot G \gamma_5 q \left(1 + \frac{h}{v}\right) + O(h^2) \]
EDMs and CPV Higgs couplings (1)

- Leading interactions with $q, g$ strongly constrained by gauge invariance

- Affect Higgs production and decay at LHC and EDMs ($n$, $^{199}$Hg, e), e.g.

  LHC: Higgs production via gluon fusion

  Low Energy: quark (C)EDM + Weinberg
EDMs and CPV Higgs couplings (2)
Neutron EDM is teaching us something about the Higgs!

Future: factor of 2 at LHC; EDM constraints scale linearly

Experiment at $5 \times 10^{-27}$ e cm and improved (25-50%) matrix elements will make nEDM the strongest probe for all couplings.
EDMs and high-scale SUSY (I)

- Higgs mass + absence of other signals point to heavy super-partners

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

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

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004
EDMs and high-scale SUSY (2)

\[ d_q \sim \frac{\alpha \alpha_w m_q}{(4\pi)^2} \frac{\mu M_2}{m_q} \sin \phi_2 \]
For $|\mu| < 10$ TeV, $m_\tilde{q} \sim 1000$ TeV, same CPV phase controls $d_e, d_n \rightarrow$ correlation?
EDMs and high-scale SUSY (3)

- Both $d_e$ and $d_n$ within reach of current searches for $M_2$, $\mu < 10$ TeV
EDMs and high-scale SUSY (3)

- Both $d_e$ and $d_n$ within reach of current searches for $M_2$, $\mu < 10$ TeV
- Studying the ratio $d_n/d_e$ with precise matrix elements $\rightarrow$ upper bound $d_n < 4 \times 10^{-28}$ e cm
- Split-SUSY can be falsified by current nEDM searches

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

Bhattacharya, VC, Gupta, Lin, Yoon
$0\nu\beta\beta$ and Lepton Number Violation
0νββ and Lepton Number Violation

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

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

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

Shechter-Valle 1982
Fukugita-Yanagida 1987
0νββ and Lepton Number Violation

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

LNV dynamics at $M >> \text{TeV}$: it leaves as only low-energy footprint 3 light Majorana neutrino

$m_\nu \sim \frac{v_{EW}^2}{M_R}$
$0\nu\beta\beta$ and Lepton Number Violation

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

LNV dynamics at $M \sim$ TeV:
1) new contribution to $0\nu\beta\beta$ not related to light neutrino mass;
2) $pp \rightarrow eejj$ at the LHC
$0\nu\beta\beta$ and Lepton Number Violation

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

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

Integrate out heavy particles

\[ \mathcal{L}_{\text{eff}} = \frac{C_5}{\Lambda} O_5 + \sum_i \frac{C_7}{\Lambda^3} O_7^i + \sum_i \frac{C_9}{\Lambda^5} O_9^i \]

"Standard Model EFT"

\[ \mathcal{L}_{\pi,N} = \sum_i \tilde{C}_i (C_i) \tilde{O}_i \]

Chiral EFT

\[ T_{1/2} [ \tilde{C}_i [C_i] ] \sim (m_W/\Lambda)^A (\Lambda_X/m_W)^B (k_F/\Lambda_X)^C \]

For general analysis see VC, W. Dekens, M. Graesser, E. Mereghetti, J. de Vries 1806.02780

Chain of EFT +

lattice QCD & many-body methods

theoretical uncertainties
High-scale seesaw

- Strong correlation of $0\nu\beta\beta$ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

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

NORMAL SPECTRUM

INVERTED SPECTRUM

$m_{\text{lightest}}^2 = ?$
Strong correlation of $0\nu\beta\beta$ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta} \rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$

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

Assume most “pessimistic” values for nuclear matrix elements

- Discovery possible for inverted spectrum OR $m_{\text{lightest}} > 50$ meV
TeV scale LNV

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

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

Sensitivity study: $0\nu\beta\beta$ vs LHC (current and future)

Illustrates competition of Ton-scale NLDBD and LHC
Low-scale LNV

- Low scale seesaw: intriguing example with one light sterile $\nu_R$ with mass ($\sim$eV) and mixing ($\sim$0.1) to fit short baseline anomalies
- Extra contribution to effective mass

\[ m_{\beta\beta} = m_{\beta\beta}\big|_{\text{active}} + |U_{e4}|^2 e^{2i\Phi} m_4 \]

Usual phenomenology turned around!
Summary

• The precision / intensity frontier plays a key role in the search for the “new Standard Model” and its symmetries
• Broad and vibrant experimental program
• Probes very high scales
Summary

• The precision / intensity frontier plays a key role in the search for the “new Standard Model” and its symmetries
• Broad and vibrant experimental program
• Connects to big open questions
Thank you!

A drawing by Bruno Touschek
Additional material
\[ \frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q) \left(1 + RC\right) \rightarrow ft \left(1 + RC\right) = \frac{2984.48(5) \text{ s}}{|V_{ud}|^2} \]

\[ (1 + RC) = (1 - \delta_C) (1 + \delta_R) (1 + \Delta_C) \]

Coulomb distortion of wave-functions

\[ \langle f | \tau_+ | i \rangle = \sqrt{2} \left(1 - \frac{\delta_C}{2}\right) \]

Nucleus-dependent rad. corr.

(Z, E_{\text{max}}, \text{nuclear structure})

\[ \delta_C \sim 0.5\% \]

\[ \delta_R \sim 1.5\% \]

Towner-Hardy
Ormand-Brown

Nucleus-independent short distance rad. corr.

\[ \Delta_R \sim 2.4\% \]

Marciano-Sirlin ‘06

\[ \nu \rightarrow e^{-} \]

\[ W \rightarrow Q^2 \gamma \]

\[ n \rightarrow p \]

Sirlin-Zucchini ‘86
Jaus-Rasche ‘87

\[ V_{ud} \text{ from } 0^+ \rightarrow 0^+ \text{ nuclear } \beta \text{ decays} \]
$V_{ud}$ from $0^+ \rightarrow 0^+$ nuclear $\beta$ decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q) \left( 1 + RC \right) \longrightarrow ft \left( 1 + RC \right) = \frac{2984.48(5) s}{|V_{ud}|^2}$$

$V_{ud} = 0.97417 (21)$
CKM unitarity: input

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

\[ \langle \pi | V_\mu | K \rangle \propto f_+(0)(p_K + p_\pi)_\mu + \ldots \]

\[ V_\mu = \bar{s}\gamma_\mu u \]

\[ \langle 0 | A_\mu | K \rangle \propto F_K(p_K)_\mu \]

\[ A_\mu = \bar{s}\gamma_\mu \gamma_5 u \]
CKM unitarity: input

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

- New LQCD calculations have led to smaller $V_{us}$ from $K \rightarrow \pi\nu\nu$

\[
\begin{align*}
    f_+^{K\rightarrow\pi(0)} &= 0.959(5) \quad \rightarrow \quad 0.970(3)
    \\
    F_K/F_{\pi} &= 1.1960(25) \quad \text{[stable]}
\end{align*}
\]

\[
\begin{align*}
    V_{us} &= 0.2254(13) \quad \rightarrow \quad 0.2231(9)
    \\
    V_{us} / V_{ud} &= 0.2313(7)
\end{align*}
\]

$V_{us}$

CKM unitarity (from $V_{ud}$)

FLAG 2016

New LQCD calculations have led to smaller $V_{us}$ from $K \rightarrow \pi\nu\nu$
EDMs in the Standard Model?

- Weak interactions (CPV in $u_i$-$d_j$-$W$ vertex): highly suppressed

  \[ d_n \sim 10^{-31} \text{ e cm} \]

  Pospelov-Ritz
  hep-ph/0504231

- Strong interactions (complex quark mass $m_\ast \bar{\Theta}$): potentially large but...

  \[ d_n \sim \frac{m_\ast}{\Lambda_{\text{had}}^2} e \bar{\Theta} \sim 10^{-17} \bar{\Theta} \text{ e cm} \]

  \[ \rightarrow |\bar{\Theta}| < 10^{-9} \]

  \[ d_n < 3 \times 10^{-26} \text{ e cm} \]

  Motivated mechanisms to dynamically relax $\bar{\Theta}$ to zero
nEDM and axion-like dark matter

First laboratory constraint on the coupling of axion DM to gluons

Ample room for improvement in next. gen. nEDM

Abel et al., 1708.06367
EDMs and EW baryogenesis (1)

For a review see: Morrissey & Ramsey-Musolf 1206.2942

• Requirements on BSM scenarios:
  • 1\textsuperscript{st} order phase transition: new particles, testable at LHC
  • New CPV: EDMs often provide strongest constraint.

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

See M. Ramsey-Musolf talk at APS April Meeting 2018
EDMs and EW baryogenesis (2)

- In Supersymmetry, 1st order phase transition disfavored by LHC in minimal model (MSSM), need singlet extension (NMSSM)

- CPV phases appearing in the gaugino-higgsino mixing contribute to both BAU and EDM

- In scenario with universal phases $\phi_1 = \phi_2$, successful baryogenesis implies a “guaranteed signal” for next generation EDMs searches

Compatible with baryon asymmetry

Next generation neutron EDM

Li, Profumo, Ramsey-Musolf
0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589
EDMs and EW baryogenesis (2)

- In Supersymmetry, 1st order phase transition disfavored by LHC in minimal model (MSSM), need singlet extension (NMSSM).
- CPV phases appearing in the gaugino-higgsino mixing contribute to both BAU and EDM.
- In scenario with universal phases $\varphi_1=\varphi_2$, 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.

Next generation neutron EDM

Compatible with baryon asymmetry

Li, Profumo, Ramsey-Musolf
0811.1987
VC, Li, Profumo, Ramsey-Musolf,
0910.4589
Neutrinoless double beta decay

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

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

*Enabled by nuclear physics energetics

Unique laboratory to study lepton number violation (LNV)
Status of nuclear matrix elements

Engel-Menendez 1610.06548
See-saw and leptogenesis

See-saw mechanism for $m_\nu$

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^{T_i} C \nu_R^{j} - \lambda_{ij} \bar{\nu}_R^i (H_u^T L_L^j) + \text{h.c.}$$

Heavy $\nu_R$

$M_R$: L violation
$\lambda_\nu$: CP and $L_i$ violation

$\sim v_{ew}^2 \lambda_n^T M_R^{-1} \lambda_n$

Type I for illustration
See-saw and leptogenesis

See-saw mechanism for $m_\nu$

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^{T_i} C \nu_R^{j} - \lambda_{ij} \bar{\nu}_R^i (H^+_c L_L^j) + h.c.$$

$M_R$ : L violation
$\lambda_{ij}$ : CP and L violation

1) $C$P and $L$ out-of-equilibrium decays of $N_i$ ($T \sim M_R$) $\Rightarrow n_L$

$$\Gamma(N_i \rightarrow l_k H^*) \neq \Gamma(N_i \rightarrow \bar{l}_k H)$$
See-saw and leptogenesis

\[ \mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^T C \nu_R^j - \lambda_{ij}^{\nu} \bar{\nu}_R^i (H_c^\dagger L_L^j) + \text{h.c.} \]

- \( M_R \): L violation
- \( \lambda_{\nu} \): CP and L\(_i\) violation

1) \( \not\exists \) CP and \( \not\exists \) out-of-equilibrium decays of \( N_i \) (\( T \sim M_R \)) \( \Rightarrow n_L \)

\[ \Gamma(N_i \to l_k H^*) \neq \Gamma(N_i \to \bar{l}_k H) \]

2) EW sphalerons \( \Rightarrow n_B = -k n_L \)

\[ \eta_B \equiv \frac{n_B}{n_\gamma} \neq 0 \]
See-saw and leptogenesis

\[ \mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^T \nu_R - \lambda_{ij} \bar{\nu}_R (H^*_c L^*_L) + \text{h.c.} \]

1) CP and L out-of-equilibrium decays of $N_i (T \sim M_R) \Rightarrow n_L$

\[ \Gamma(N_i \rightarrow l_k H^*) \neq \Gamma(N_i \rightarrow \bar{l}_k H) \]

2) EW sphalerons $\Rightarrow n_B = -k n_L$

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If CP & L_i violation is communicated to particles with mass $\Lambda \sim \text{TeV}$

- Observable LFV
- Observable lepton EDMs