BEYOND-THE-STANDARD-MODEL PHYSICS WITH HADRONS AND NUCLEI

Jordy de Vries
University of Amsterdam & Nikhef
The search for something non-Standard...

13.6 billion years

Theoretical puzzles

\[ \frac{m_{\text{Higgs}}}{m_{\text{Planck}}} \sim 10^{-16} \]

\[ \frac{m_e}{m_t} \sim 10^{-6} \]

\[ \bar{\theta}_{CP} < 10^{-10} \]
The search for something non-Standard...

Energy

Reach ~ Collider Energy
LHC, FCC, CEPC, ....

Probe indirect BSM effects with known (sometimes no) SM background

Examples: Flavor, g-2, EDMs, $0\nu\beta\beta$, proton decay
Also: colliders if BSM scale too high!

Reach ~ experimental and theoretical accuracy
Theoretical precision often involves QCD

Many examples

- Proton decay & n-nbar oscillations
- Neutrinoless double beta decay
- Mu-to-e conversion
- Dark Matter direct detection
- Axion searches
- Electric dipole moments
- Parity-violating e-p scattering (Qweak)
- Precision beta-decay experiments
- Muon g - 2
- Lepton-flavor universality in B decays
- .................

How to interpret and compare experiments in search for BSM physics?

How can hadronic and nuclear community contribute here?
Theoretical precision often involves QCD

Many examples

- Proton decay & n-nbar oscillations
- **Neutrinoless double beta decay**
- Mu-to-e conversion
- Dark Matter direct detection
- Axion searches
- **Electric dipole moments**
- Parity-violating e-p scattering (Qweak)
- Precision beta-decay experiments
- Muon g - 2
- Lepton-flavor universality in B decays
- .................

BSM physics

Hadrons

Nuclei

How to interpret and compare experiments in search for BSM physics?

How can hadronic and nuclear community contribute here?

2 examples with a lot of overlap
A general Standard-Model-EFT framework

Energy

$\Lambda$

$E_{\text{Exp}} \ll \Lambda$

Effects of heavy BSM fields capture by local effective operators

Most relevant SMEFT operators at dimension five (n=1) and six (n=2)
Two low-energy searches for BSM physics

I) Neutrinoless double beta decay
   Dim-5

II) Electric dipole moments
    Dim-6
Neutrino masses in SM-EFT

- Neutrinos are formally massless in the SM → but neutrino oscillations ....
- Easy fix: Insert gauge-singlet right-handed neutrino $\nu_R$

$$\mathcal{L} = -y_\nu \bar{L} \tilde{H} \nu_R - M_R \nu_R^T C \nu_R$$

- Integrate out heavy right-handed neutrinos

$$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$$

Neutrino Majorana mass

- Obtain the single dimension-5 SMEFT operator

$$\mathcal{L}_5 = c_5 \frac{v^2}{\Lambda} \nu^T C \nu$$  \hspace{1cm} Weinberg '79

- Violates an accidental SM symmetry: Lepton Number
- Implies neutrino are Majorana states → connection to leptogenesis
Low-energy probes of LNV

- How to determine that neutrinos are Majorana states?
- Most promising way: look at `neutrinoless' processes
  
  \[ K^- \rightarrow \pi^+ + e^- + e^- \quad pp \rightarrow e^+ + e^+ + \text{jets} \]

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

- Most sensitive probe right now
  
  \[ \tau^{136\text{Xe}} > 1.1 \cdot 10^{26} \text{ year} \]
Low-energy probes of LNV

- How to determine that neutrinos are Majorana states?
- Most promising way: look at ‘neutrinoless’ processes

\[ K^- \rightarrow \pi^+ + e^- + e^- \quad pp \rightarrow e^+ + e^+ + \text{jets} \]

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

- Most sensitive probe right now \( \tau(^{136}\text{Xe}) > 1.1 \cdot 10^{26} \text{ year} \)

- Exchange of light Majorana Neutrinos:
  \[ \Gamma \sim 1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta} \]
  \[ m_{\beta\beta} = \sum_i U_{ei}^2 m_i \]

‘Band’ due to hadronic/nuclear uncertainties

Next-generation discovery possible if inverted hierarchy or \( m_{\text{lightest}} > 0.05 \text{ eV} \)

Or if there is a different LNV mechanism!
Towards reliable theoretical predictions

- Assuming ‘standard’ mechanism: uncertainties from **hadronic & nuclear theory**

\[ \Gamma \sim |M_{0\nu}|^2 (m_{\beta\beta})^2 \]

- Goals: reduce uncertainty using **chiral EFT + lattice + ab initio calculations**

1. **Chiral EFT**: strong nuclear force and electroweak currents
2. **Lattice**: Compute low-energy constants (hadronic matrix elements)
3. **Ab initio**: Nuclear structure and nuclear transition amplitudes
Leading-order transition currents

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Leads to ‘long-range’ $nn \rightarrow pp + ee$

\[ V_\nu \sim \frac{m_{\beta\beta}}{q^2} \]

\[ q \sim k_F \sim m_\pi \]

\[ V_\nu = (2G_F^2m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{q^2} \left[ (1 + 2g_A^2) + \frac{g_A^2m_\pi^4}{(q^2 + m_\pi^2)} \right] \otimes \bar{e}_L e^c_L \]

- No unknown hadronic input! Only unknown is $m_{\beta\beta}$
Leading-order transition currents

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Leads to ‘long-range’ \( nn \rightarrow pp + ee \)

\[
V_\nu \sim \frac{m_{\beta\beta}}{q^2} \quad q \sim k_F \sim m_\pi
\]

\[
V_\nu = (2G_F^2m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{q^2} \left[ (1 + 2g_A^2) + \frac{g_A^2m_\pi^4}{(q^2 + m_\pi^2)} \right] \otimes \bar{e}_L e^c_L
\]

- No unknown hadronic input! Only unknown is \( m_{\beta\beta} \)

- **Story changes once we consider initial- and final-state interactions**
- Nucleon-nucleon scattering states generated from leading-order potential

\[
V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{q^2 + m_\pi^2}
\]
Leading-order transition currents

- Iterate strong potential to all orders to get wave function
- Integrals lead to divergences that are absorbed into $C_0$
- Nucleon-nucleon phase shifts are renormalized (regulator independent)
- Insert long-distance neutrino exchange into scattering states

\[ V_{\text{strong}} = C_0 - \frac{g_A^2}{4f^2} \frac{m^2_{\pi}}{q^2 + m^2_{\pi}} \]

Insert long-distance neutrino exchange into scattering states

\[ \sim (1 + 2g_A^2) \left( \frac{m_N C_0}{4\pi} \right)^2 \left( \frac{1}{\epsilon} + \log \frac{\mu^2}{p^2} \right) \]

New divergences

Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL ’18
Leading-order transition currents

- Iterate strong potential to all orders to get wave function
- Integrals lead to divergences that are absorbed into $C_0$
- Nucleon-nucleon phase shifts are renormalized (regulator independent)
- Insert long-distance neutrino exchange into scattering states

$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f^2} \frac{m_{\pi}^2}{q^2 + m_{\pi}^2}$$

$$\sim (1 + 2g_A^2) \left( \frac{m_N C_0}{4\pi} \right)^2 \left( \frac{1}{\epsilon} + \log \frac{\mu^2}{p^2} \right)$$

New divergences

- Logarithmic regulator dependence!
- Requires a counter term: a short-range $nn \rightarrow pp + ee$ operator

Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL ‘18
A new leading-order contribution

\[ n \rightarrow p \rightarrow e \rightarrow n \rightarrow p \]

'Long-range' neutrino-exchange included in all calculations

\[ n \rightarrow n \rightarrow p \rightarrow p \sim g_{\nu} \]

'Short-distance' neutrino exchange required by renormalization of amplitude

- **Short-distance piece depends on unknown QCD matrix element** \( g_{\nu} \)
- Crucial input for nuclear calculations of neutrinoless double beta decay
- How to determine the value of this matrix element?
A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process

- Isospin-breaking nucleon-nucleon scattering data determines $C_1 + C_2$
- Electromagnetism conserves parity $(L + R)$ coupling and $g_\nu \sim C_1$ only
- Large-$N_c$ arguments indicate $C_1 + C_2 \gg C_1 - C_2$

- We assume $g_\nu \sim (C_1 + C_2)/2$, what happens to neutrinoless double beta decay?

Richardson, Schindler, Pastore, Springer '21
Impact on nuclear matrix elements

- Use chiral potentials to generate wave functions
- Extract $g_\nu \sim (C_1 + C_2)/2$ from same potential

### Nuclear matrix elements

<table>
<thead>
<tr>
<th></th>
<th>Long Range</th>
<th>Short Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{Be} \rightarrow ^{12}\text{C} + e^- + e^-$</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Short-distance effects are sizable and change matrix elements by $O(1)$

- **Caveat-1** Based on $g_\nu \sim (C_1 + C_2)/2$ relation
- **Caveat-2** No calculations yet for heavier nuclei

---

**Ab Initio** Treatment of Collective Correlations and the Neutrinoless Double Beta Decay of $^{48}\text{Ca}$

J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodriguez, and H. Hergert


**Ab Initio** Neutrinoless Double-Beta Decay Matrix Elements for $^{76}\text{Ge}$, and $^{82}\text{Se}$

A. Belle, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt

Can we help with Caveat 1?

- Input for nuclear calculations is the effective neutrino potential

\[
\begin{array}{c}
\text{n} \rightarrow \text{p} \\
\text{p} \quad \text{e} \\
\text{e} \\
\text{n} \rightarrow \text{p}
\end{array}
\]

- The value of \(g_\nu\) can be obtained from the total \(\text{nn} \rightarrow \text{pp}\) amplitude

**Ideally lattice QCD**

Tremendous progress for the ‘toy-problem’

\[
\pi^- + \pi^- \rightarrow e^- + e^-
\]

Formalism for lattice calculations being developed

Tuo et al. ‘19; Detmold, Murphy ‘20

Davoudi, Kadam PRL ‘21 Briceno et al ‘19 ‘20
An analytic approach

- The $nn \rightarrow pp + ee$ amplitude can be represented as an integral expression

$$A_\nu \sim G_F^2 \int \frac{d^4 k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2} \int d^4 x e^{ik \cdot x} \langle pp | T\{J^\mu_W(x)J^\nu_W(0)\} | nn \rangle$$

$J^\mu_W = \text{weak current (V-A)}$

- Can represent the `red box' in regions of the virtual neutrino momentum $k$
An analytic approach

- The nn → pp + ee amplitude can be represented as an integral expression

\[ A_\nu \sim G_F^2 \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2} \int d^4x e^{ik \cdot x} \langle pp | T\{J_\mu^W(x)J_\nu^W(0)\} | nn \rangle \]

- At small virtual momentum: NLO chiral EFT

- Intermediate momentum: (model-dependent) resonance contributions to nucleon form factors and to NN scattering

- Large momentum: Perturbative QCD + Operator Product Expansion

Small dependence on local 4-quark matrix elements
The total amplitude

- The result of this exercise is an expression for total nn → pp + ee amplitude
- Ab initio nuclear calculations can fit the short-distance $g_\nu$ in their regulator scheme

\[ |A_\nu(|p|, |p'|)| = -0.019(1) \text{ MeV}^{-2} \]

Example: in dimensional regularization in MS-bar scheme

\[ g_\nu(\mu = m_\pi) = (1.3 \pm 0.1 \pm 0.2 \pm 0.5) \]

- This matching can be done for any scheme suitable for nuclear calculations
- Same strategy was used to ‘predict’ EM corrections to nucleon-nucleon scattering

\[ a_{CIB} = \frac{a_{nn} + a_{pp} - 2a_{np}}{2} = (15 \pm 5) \text{ fm} \quad a_{CIB}^{\text{data}} = (10.4 \pm 0.2) \text{ fm} \]

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL ‘21
The total amplitude

- The result of this exercise is an expression for total $nn \rightarrow pp + ee$ amplitude
- Ab initio nuclear calculations can fit the short-distance $g_D$ in their regulator scheme

- To be done: determine impact on heavier nuclei
- Ab initio nuclear community is implementing short-distance contribution
- **Unclear yet whether it will increase or decrease the total nuclear matrix element**!
Two low-energy searches for BSM physics

I) Neutrinoless double beta decay

II) Electric dipole moments
A brief intro to EDMs

- Electric Dipole Moments (EDMs) are probes of CP violation

\[ H = \mu \sigma \cdot B + d \sigma \cdot E \]

\[ H = \mu \sigma \cdot B - d \sigma \cdot E \]
A brief intro to EDMs

- Electric Dipole Moments (EDMs) are probes of CP violation

\[ H = \mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E} \]

- EDMs are induced by the SM weak interaction only at 3 loop-level (electron EDM at 4-loop)

- SM prediction essentially out of reach right now
A brief intro to EDMs

- Electric Dipole Moments (EDMs) are probes of CP violation

\[ H = \mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E} \]

- EDMs are induced by the SM weak interaction only at 3 loop-level (electron EDM at 4-loop)

If \( \theta \approx 1 \)
- SM prediction essentially out of reach right now
- EDMs can still arise from the QCD theta term

\[ \mathcal{L}_\theta \sim \bar{\theta} e^{\mu \nu \alpha \beta} G^a_{\mu \nu} G^a_{\alpha \beta} \]

- Strong CP problem: \( \theta < 0.0000000001 \)
CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)

- Many BSM models induce new CP violation

---

**Example 1:** Bino-Higgsino loop contribution to the electron EDM

**CP-odd dipoles**

\[
\begin{align*}
\sim & \frac{1}{\Lambda^2} \frac{\alpha_{em}}{\pi} \sin \phi_{CP}
\end{align*}
\]

**Left-right symmetric models**

\[
\begin{align*}
\sim & \frac{1}{\Lambda^2} \sin \phi_{CP}
\end{align*}
\]
**CP violation in SM-EFT**

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

\[ \mathcal{L}_\theta \sim \bar{\theta} e^{\mu \nu \alpha \beta} G_{\mu \nu}^a G_{\alpha \beta}^a \]

- Induce electric dipole moments of leptons, hadrons, nuclei, atoms, molecules
CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

\[ \mathcal{L}_\theta \sim \bar{\theta} e^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} \]

- Use chiral perturbation theory to obtain CP-violating hadronic Lagrangian

\[ \pi^0, \pm \quad n, p \quad \bar{g}_0 \]
\[ \pi^0 \quad n, p \quad \bar{g}_1 \]
\[ \bar{g}_{0,1} \quad \pi^0, \pm \quad n, p \quad \text{CP-odd nuclear force} \]

JdV et al '12
Bsaisou et al '14
CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

\[
\mathcal{L}_\theta \sim \bar{\theta} \epsilon^{\mu \nu \alpha \beta} G^a_{\mu \nu} G^a_{\alpha \beta}
\]

- Use chiral perturbation theory to obtain CP-violating hadronic Lagrangian

- Nucleon EDMs \( d_{n,p} \)

- Loop suppression: nuclear EDMs dominated by **CP-odd nuclear force** (exceptions exist)
Nuclear CP violation

Problem I: Calculate nuclear EDMs in terms of CP-odd interactions

Easiest example: the deuteron
\[ d_D = d_n + d_p + (0.18 \pm 0.02) \bar{g}_1 \text{ e fm} \]

EDMs of light ions measureable in storage-ring experiments

\[ \vec{\Omega} = \frac{q}{m} \left[ a \vec{B} + \left( \frac{1}{v^2} - a \right) \vec{v} \times \vec{E} \right] + 2d \left( \vec{E} + \vec{v} \times \vec{B} \right) \]

- Similar expressions for heavier nuclei, but sizeable nuclear uncertainties
- Effort from nuclear structure community to improve this. E.g. Engel et al' PRL 18
Example: QCD theta term

**Problem II:** Calculate CP-odd LECs $\tilde{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

\[ \mathcal{L}_{QCD} = \mathcal{L}_{\text{kin}} - \bar{m}q - \epsilon \bar{m}q\tau^3q + m_\star \bar{q}i\gamma^5 q \]

SU$_A$(2) rotation

\[ m_\star = \frac{m_u m_d}{m_u + m_d} \]
Example: QCD theta term

- **Problem II:** Calculate CP-odd LECs $\tilde{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

$$\mathcal{L}_{QCD} = \mathcal{L}_{kin} - \bar{m}q - \epsilon \bar{m}q \tau^3 q$$

$$\mathcal{L}_{\chi+m} = \mathcal{L}_{\chi} - \frac{m^2_\pi}{2} \pi^2 - \delta m_N \bar{N} \tau^3 N$$

SU$_A$(2) rotation

$$+ m_\star \bar{q}i \gamma^5 q$$

$$+ \bar{g}_0 \bar{N} \tau \cdot \pi N$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

Crewther et al ‘79
CP-odd matrix elements

- Problem II: Calculate CP-odd LECs $\bar{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

\[
\mathcal{L}_{QCD} = \mathcal{L}_{\text{kin}} - \bar{m}q - \epsilon \bar{m}q \tau^3 q
\]
\[
\mathcal{L}_{\chi^m} = \mathcal{L}_{\chi} - \frac{m^2_\pi}{2} \pi^2 - \delta m_N \bar{N} \tau^3 N
\]

SU$_A$(2) rotation

\[
m_* = \frac{m_u m_d}{m_u + m_d}
\]

\[
\bar{g}_0 \bar{N} \tau \cdot \pi N
\]

Nucleon mass splitting
(strong part, no EM)

\[
\bar{g}_0 = -\frac{\delta m_N}{2 f_\pi} \frac{1 - \epsilon^2}{2 \epsilon} \bar{\theta} = (15.5 \pm 2.5) \cdot 10^{-3} \bar{\theta}
\]

$\delta m_N$ from lattice-QCD

e.g. Borsanyi et al '14

CP-odd pion-nucleon

Crewther et al '79

JdV et al '15
Higher-dimensional operators

- **Problem II:** Calculate CP-odd LECs $\bar{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

$$\mathcal{L}_{CEDM} = \bar{d}_q q \sigma^{\mu\nu} i \gamma^5 \lambda^a q G^a_{\mu\nu}$$

$\bar{g}_0 \bar{N} \tau \cdot \pi N + \bar{g}_1 \bar{N} N \pi^0$

- Values CP-odd pion-nucleon couplings not well understood

$$\bar{g}_0 = (5 \pm 10)(\bar{d}_u + \bar{d}_d) \text{ fm}^{-1}$$
Higher-dimensional operators

- **Problem II**: Calculate CP-odd LECs $\tilde{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

\[ \mathcal{L}_{CEDM} = \tilde{d}_q \bar{q} \sigma^{\mu \nu} i \gamma^5 \lambda^a q G_{\mu \nu} \quad \longleftrightarrow \quad \mathcal{L}_{CMDM} = \tilde{c}_q \bar{q} \sigma^{\mu \nu} \tau^3 \lambda^a q G_{\mu \nu} \]

- Values CP-odd pion-nucleon couplings not well understood

\[ \tilde{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d) \text{fm}^{-1} \]

- CPV couplings related to corrections to hadronic spectrum

\[ \tilde{g}_0 = \frac{\tilde{d}_u + \tilde{d}_d}{2} \left( \sigma_3^3 + \ldots \right) \quad \sigma_3^3 = \frac{-1}{2m_N} \langle N | \bar{q} \sigma^{\mu \nu} \tau^3 \lambda^a q G_{\mu \nu} | N \rangle \]

• Relations valid up to next-to-next-to-leading-order chiral corrections
• Original motivation: study modified sigma terms on the lattice
A connection to spin physics

Relating Hadronic $CP$ Violation to Higher-Twist Distributions
Chien-Yeh Seng
Phys. Rev. Lett. 122, 072001 – Published 22 February 2019

- Generalization of connection between nucleon tensor charge and transversity distribution

$$\tilde{g}_0 = \frac{\tilde{d}_u + \tilde{d}_d}{2} (\sigma^3_C + \ldots)$$

$$\sigma^3_C = \frac{-1}{2m_N} \langle N | \bar{q} \sigma^{\mu\nu} \tau^3 \lambda^a q G^a_{\mu\nu} | N \rangle$$

- Connection twist-3 distribution functions:

$$e^q(x) \sim \int d\lambda e^{i\lambda x} \langle P | \bar{q}(0)[0,\lambda n] q(\lambda n) | P \rangle$$

Modified sigma term linked to third Mellin moment of $e^q$ distribution

- At time of paper, little experimental input on $e^q(x)$. SIDIS @ CLAS ( ep → e$\pi^+$X)

- Can this be improved at the EIC? **Could be very beneficial for EDM studies**!

- Further developments in Hatta ’20, ’21 and Weiss ’21 for Weinberg operator and nucleon EDMs
Concluding remarks

- Very rich experimental program exploring BSM physics at low energies
- Low-energy searches very complementary and competitive with HEP experiments
- Interpretation of experiments involves hadronic and nuclear physics
- Interplay between EFTs, lattice-QCD, nuclear structure, spin physics