Theory Overview

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Outline:
Overview of PBC BSM physics
Benchmark portal models
Lepton flavour violation
Evidence for BSM Physics

Strong experimental evidence

Neutrino Oscillations
Abundance of matter, lack of anti-matter
Galactic Dynamics
CMB

Fine tuning /naturalness
No evidence of strong CP violation
Higgs mass fine tuning
Benchmark models - Portals
Portals

\[ \mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}} \]

Operator of standard model fields

Operator of dark sector fields

In the absence of a symmetry assume that lowest order operators will be most important
Vector Portals

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} = \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B_{\mu\nu} \]

- Kinetic mixing parameter
- Field strength of new U(1) gauge field
- Hypercharge field strength

\[ \mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'_\mu}^2 (A'_{\mu})^2 + |(\partial_{\mu} + ig_D A'_{\mu})\chi|^2 + ... \]

- Dark photon mass
- Possible new matter field
Vector Portal Benchmark Models

• **BC1.** Minimal Dark Photon Model
  Only one new field.
  Dark Matter assumed to be elsewhere
  Dark Photons decay back to SM states
  Parameters: $m_{A'}$, $\varepsilon$

• **BC2.** Light Dark Matter Coupled to Dark Photon
  Minimally coupled WIMP dark matter
  Preferred values of dark coupling $\alpha_D = g_D^2/(4\pi)$ s.t.
  decay of dark photon is primarily into dark fermion states
  Parameters: $m_{A'}$, $\varepsilon$, $m_\chi$, $\alpha_D$
Vector Portal Benchmark Models

• **BC3. Millicharged Particles**

  Zero dark photon mass
  Dark fermions get a small effective U(1) charge;
  \[ |Q_\chi| = |\varepsilon g_D e| \]
  Parameters: \( m_\chi, Q_\chi / \varepsilon \),
Scalar Portals

Only allowed 3 and 4 dimension operators interact with the Higgs

\[ \mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H \]

Higgs portal couplings

Dark sector may include dark (matter) fermion

\[ \mathcal{L}_{\text{DS}} = S \bar{\chi} \chi + \ldots \]

After EW symmetry breaking, mixing of scalar with the Higgs. When this is small

\[ \theta = \frac{\mu v}{m_h^2 - m_S^2} \]
Scalar Portal Benchmark Models

• **BC4.** Higgs Mixed Scalar
  No dimension four interaction
  Parameters: $\theta$, $m_S$

• **BC5.** Higgs Mixed Scalar – Large Pair-Production
  Dimension four interaction dominates scalar production
  If, eg $\lambda \sim 5 \times 10^{-4}$, model avoids LHC direct searches
  Parameters: $\lambda$, $\theta$, $m_S$
Neutrino Portals aka Heavy Neutral Leptons

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I} (\bar{L}_\alpha H) N_I$$

SM Lepton doublets

Heavy neutral lepton(s)

Dark sector Lagrangian can include both Dirac and Majorana mass terms for the HNLs

After EW symmetry breaking find mixing between neutrinos determined by matrix $U$

Assume $U$ controls both production and decay
Neutrino Portal Benchmark Models

• **BC6.** \( U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1 \)
  
  Inverted hierarchy

  Parameters: \( m_N, |U_e|^2 \)

• **BC7.** \( U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8 \)
  
  Normal hierarchy

  Parameters: \( m_N, |U_\mu|^2 \)

• **BC8.** \( U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3 \)
  
  Normal hierarchy

  Parameters: \( m_N, |U_\tau|^2 \)
Axion Portals – Pseudoscalar portals

Includes QCD axions, and axion-like particles

\[ \mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4 f_\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{a}{4 f_G} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_{\alpha} l_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_{\beta} \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta \]

- Photon coupling
- Gluon coupling
- Lepton coupling
- Quark coupling

Dark sector Lagrangian may contain new states required for UV completion
Axion Portal Benchmark Models

• **BC9.** Photon Dominance
  Dominant coupling to photons
  Parameters: $m_a, g_{\gamma \gamma} = f_{\gamma}^{-1}$

• **BC10.** Fermion dominance
  Dominant coupling to fermions
  For simplicity assume $f_q = f_l$
  Parameters: $m_a, f_l^{-1}, f_q^{-1}$

• **BC11.** Gluon dominance
  Dominant coupling to gluons
  Requires fine tuning of axion mass
  Parameters: $m_a, f_G^{-1}$
Lepton Flavour Universality

Hints (~3σ) of violation of Lepton Flavour Universality in semi-leptonic $b$ decays

\[ B \rightarrow K l^+ l^- \]
\[ B \rightarrow D l \nu \]

Still some debate about size of QCD uncertainties

**Challenges for theorists:**

Anomalies only in semi-leptonic decays

No anomalies in; semileptonic $K$ and $\pi$ decays, purely leptonic $\tau$ decays, electroweak precision observables
BSM - Lepton Flavour Violation

Possible solutions introduce new four fermion operators e.g.

- $Z'$
- Leptoquarks

Alternative approach using EFT (but still have to make assumptions about gauge structure)
LFV and K decays

In most explanations:

NA62: \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

KLEVER: \( K_L \rightarrow \pi^0 \nu \bar{\nu} \)

Can be sensitive to the new physics, although in a model dependent way

\( K_L \) decay is CP violating, \( K^+ \) is not, and so two channels give complementary information
Summary

Compelling evidence for BSM physics

A wide range of possibilities for what this could be (and large parameter spaces)

11 benchmark models for low energy experiments: vector, scalar, neutrino and axion portals

Possibility to test LFV with rare K decays