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

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

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: $m_{A'}$, ε

- **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: $m_{A'}$, ε , m_χ , α_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_{χ} , Q_{χ}/ε ,

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: θ , 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: λ , θ , 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 Majorara 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

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

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 , $g_{a\gamma\gamma}=f_\gamma^{-1}$
- **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

$B \to K\, l^+\, l^-$

$B \to D\, l\, \nu$

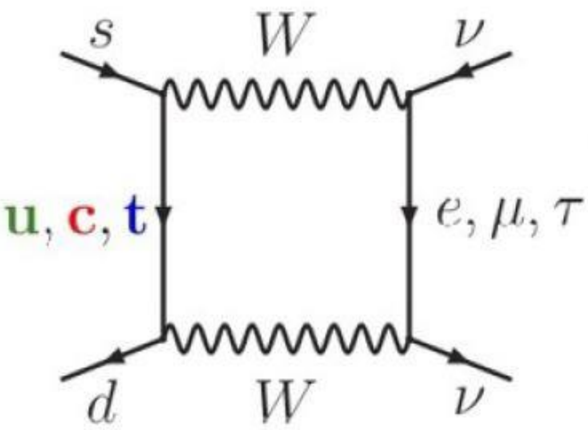
Still some debate about size of QCD uncertainties

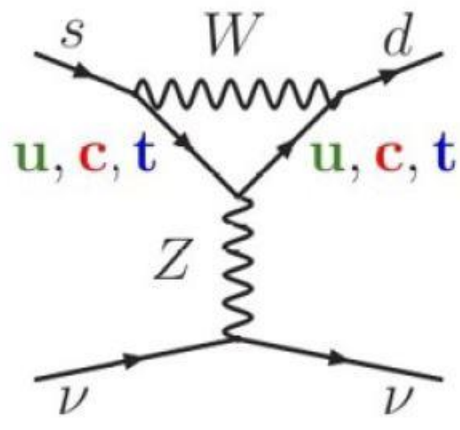
Challenges for theorists:

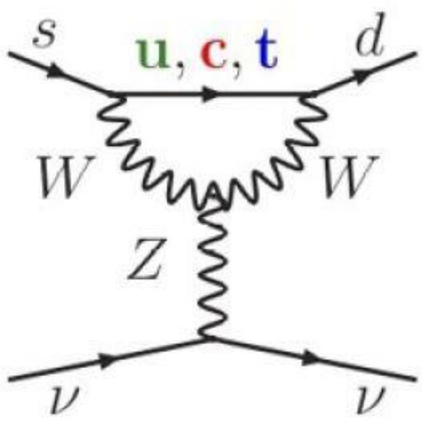
Anomalies only in semi-leptonic decays

No anomalies in; semileptonic K and π decays, purely leptonic τ decays, electroweak precision observables

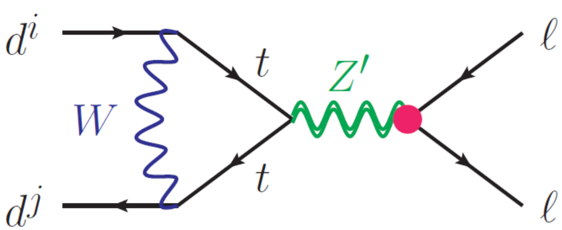
BSM - Lepton Flavour Violation



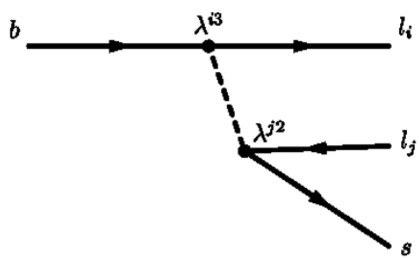




Possible solutions introduce new four fermion operators e.g.



- Z’
- Leptoquarks



Alternative approach using EFT (but still have to make assumptions about gauge structure)

LFV and K decays

In most explanations:

NA62: $K^+ \to \pi^+ \nu \bar{\nu}$

KLEVER: $K_L \to \pi^0 \nu \bar{\nu}$

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