Welcome workshop : 11/24/2020

Model building in Pati-Salam models

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IBS-CTPU

Research interests

phenomenology of beyond the Standard Model [SM]

- supersymmetry
  - for gauge hierarchy, LSP dark matter, gauge coupling unification
  - LHC/DM/Higgs physics where wino is heavier than gluino
- vector-like particle (4^{th} family quark/lepton)
  - as a mediator for Dark Matter [DM] annihilation
  - explain anomalies in $(g-2)_\mu$, $b \to s\ell\ell$
- flavor structure
  - “flavon” for Froggatt-Nielsen mech. stabilized with Higgs
  - analyze moduli/anomaly mediation in 10D SYM with magnetic flux

Pati-Salam unification


http://timesofahmad.blogspot.com/

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(4)_C \times SU(2)_L \times SU(2)_R = G_{PS}$$

$$(4,2,1) \to (3,2)_{\frac{1}{6}} + (1,2)_{\frac{1}{2}}$$

$$(\overline{4},1,2) \to (\overline{3},1)_{\frac{2}{3}} + (\overline{3},1)_{-\frac{1}{3}} + (1,1)_{-1} + (1,1)_0$$

$$Q_L = (q_L \quad \ell_L) = \begin{pmatrix} u_L & \nu_L \\ d_L & e_L \end{pmatrix}$$

$$Q_R^c = \begin{pmatrix} u_R^c & \nu_R^c \\ d_R^c & e_R^c \end{pmatrix}$$

quarks and leptons are unified into two multiplets

Pati-Salam unification

- $G_{\rm PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$
  - hypercharge is quantized: $Y = \frac{1}{2}(B-L) + T_{3R}$
  - no dangerous gauge/Higgs boson triplets
  - may be realized in an orbifold Grand Unification Theory [GUT]

- Coupling unifications $\quad Q_L = (q_L \quad \ell_L), \quad Q_R^c = \begin{pmatrix} u_R^c & \nu_R^c \\ d_R^c & e_R^c \end{pmatrix}$

$$\mathcal{L} \supset y_{ij}\, Q_{L\,i}\, \mathcal{H}\, Q_{R\,j}^c \qquad \mathcal{H} = \begin{pmatrix} H_u \\ H_d \end{pmatrix}$$

  - Yukawa couplings are unified wo/ PS breaking
  - better fit to quark/lepton mass/mixing than $SO(10)$ GUT 1703.09309, S.Raby et.al
  - orbifold GUT may require gauge coupling unification

Objectives

1. explain baryon asymmetry in PS
    - thermal leptogenesis
    - lepto-axiogenesis
    - else ?
2. TeV-scale leptoquark from PS
    - light leptoquark consistent with Yukawa structure
    - relation to flavor observables, particularly B anomalies

Leptogenesis

- baryon asymmetry

  our world is made of matter, but not of anti-matter

  Sakharov condition
  - baryon number violation
  - C/CP violation
  - out of equilibrium

- asymmetry from Majorana neutrino

$$Y_\nu\, \bar{\ell}\, H_u \nu_R^c + \frac{1}{2} M_R \nu_R^c \nu_R^c \rightarrow m_\nu \sim v_H^2\, Y_\nu\, M_R^{-1} Y_\nu^T$$ see-saw mech.

  - Majorana mass violates lepton number
  - lepton number is converted to baryon number via EW sphaleron

Thermal leptogenesis in PS

Yukawa unification predicts $Y_\nu \sim Y_u$

$$\rightarrow \quad m_\nu \sim v_H^2\, Y_\nu\, M_R^{-1} Y_\nu^T \sim v_H^2\, Y_u\, M_R^{-1} Y_u^T$$

- ✓ Y_u is hierarchical, c.f. $(m_u, m_c, m_t) \sim (10^{-3}, 1, 100)$ GeV
- ✓ mixing in Dirac Yukawa may be small for CKM matrix

e.g. 0507045, R.Dermisek, S.Raby

small ν mass diff.

large ν mixing

$\rightarrow$

- hierarchical Majorana mass $\sim (10^9, 10^{11}, 10^{14})$ GeV
- N_1 has sizable coupling with τ via "top" Yukawa
- too strong wash-out for N_1

$\rightarrow$ leptogenesis via N_1 looks difficult

sol.1) production via N_2 into (e, μ) direction (?)

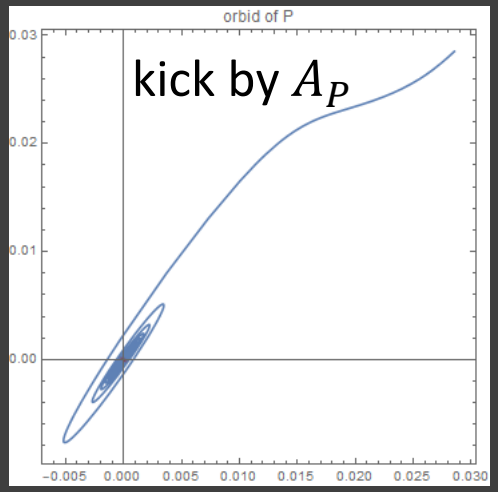
sol.2) other mechanism

Lepto-axiogenesis

R.T.Co, K.Harigaya et.al, 1910.02080, 2006.05687

- asymmetry from Peccei-Quinn [PQ] field dynamics

$$V_P = m_P^2|P|^2 + \frac{|P|^{2n-2}}{\Lambda^{2n-6}} + \left(A_P \frac{P^n}{\Lambda^{n-3}} + h.c.\right)$$



PQ number is generated via kick by A-term

*similarly to Affleck-Dine mech.

- Conversion of asymmetry

PQ number → lepton/Higgs number → B-L number

Yukawa sphaleron

Weinberg op. $(\ell H)^2/\Lambda$

Axion quality in PS model

JK, S.Raby 2009.04582

- Axion quality

  $U(1)_{PQ}$ is anomalous global symmetry to solve strong CP problem

  → may be broken by higher-order effects, e.g. gravitational int.

$$V_{PQV} \supset A_P \frac{P^n}{\Lambda^{n-3}} \rightarrow \Delta\theta_{QCD} \sim 10^{63-8n}$$ when $A_P, f_P, \Lambda \sim 10^5, 10^{10}, 10^{18}$ GeV

→ $n \gtrsim 10$ is necessary for axion "quality"

- SUSY Pati-Salam with non-anomalous $Z_R^4 \times Z_N$ symmetry
  - anomalous $U(1)_{PQ}$ arises accidentally
  - R-parity can be violated sizably if there are two PQ fields
  - A-term $A_P P^n$ $(n \geq 10)$ is allowed by discrete sym. → axiogenesis

Objectives

1. explain baryon asymmetry in PS

    - thermal leptogenesis
    - lepto-axiogenesis
    - else ?

2. **<u>TeV-scale leptoquark from PS</u>**

    - light leptoquark consistent with Yukawa structure
    - relation to flavor observables, particularly B anomalies

Light vector leptoquark in PS

- gauge boson of $SU(4)_C$

$$V_\mu^{PS} = \begin{pmatrix} G_\mu & X_\mu \\ X_\mu^\dagger & V_\mu^{B-L} \end{pmatrix}$$

G_μ : gluon

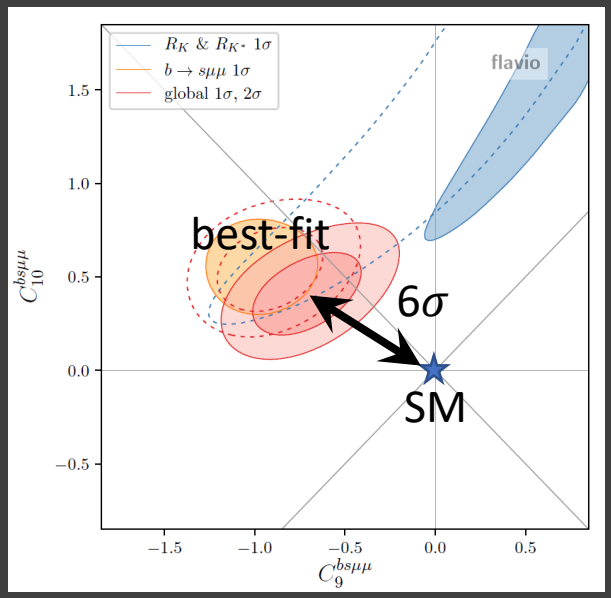
V_μ^{B-L}: B-L gauge boson

X_μ : leptoquark, $\sim SU(4)_C/SU(3)_C$

- relation to anomalies
  - anomaly reported in $b \to s\mu\mu, c\tau\nu$
  - TeV-scale leptoquark is a solution

However…

limit on leptoquark in "minimal" model is at PeV by $K_L \to \mu e$



1903.10434 J. Aebischer et.al

TeV scale leptoquark in PS

JK et.al, in preparation

$K_L \to \mu e$ can, in principle, be avoided by introducing vector-like fermions

1709.00692, L.Calibbi et.al

We show explicitly that the following texture of mass matrices,

$$M_e^{9\times 9} \sim \begin{pmatrix} 0_{3\times 3} & m_e & 0_{3\times 3} \\ m_d & 0_{3\times 3} & M_{\ell_L} \\ m_{\ell_R} & 0_{3\times 3} & 0_{3\times 3} \end{pmatrix} \qquad M_d^{9\times 9} \sim \begin{pmatrix} 0_{3\times 3} & m_e & m_{Q_L} \\ m_d & 0_{3\times 3} & 0_{3\times 3} \\ 0_{3\times 3} & M_{Q_R} & 0_{3\times 3} \end{pmatrix}$$

- is consistent with Pati-Salam Yukawa matrix unification
- forbids $K_L \to \mu e$ transition, since m_e, m_d is in different block
- TeV scale leptoquark is realized

➢ on-going works

- quantify how precisely the texture should be hold
- flavor violation via scalar, particularly Higgs doublets

Summary

- Research interests
  - searching for beyond the Standard Model
  - model building with SUSY, vector-like fermion, DM, additional symmetry
  - LHC, flavor, DM phenomenology
  - looking for new ideas, perhaps in astrophysics/string phenomenology
- Pati-Salam model
  - phenomenology under Yukawa matrix unification
  - trying to explain baryon asymmetry via leptogenesis/axiogenesis
  - building a model for TeV scale Pati-Salam breaking for light leptoquark

backup

Thermal leptogenesis in PS

- Majorana mass from PS breaking

*other options: $SU(2)$ triplets

$$SQ^c N + \frac{1}{2} M_N NN \qquad Q_R^c = \begin{pmatrix} u_R^c & \nu_R^c \\ d_R^c & e_R^c \end{pmatrix} : (\overline{4}, 1, 2),\ \text{S: } (4,1,2),\ \text{N: } (1,1,1)$$

$$\begin{pmatrix} \langle S \rangle = v_S \neq 0 \\ \text{integrate out } N \end{pmatrix} \rightarrow \frac{1}{2} M_R \nu_R^c \nu_R^c \qquad M_R \sim \frac{v_S^2}{M_N}$$

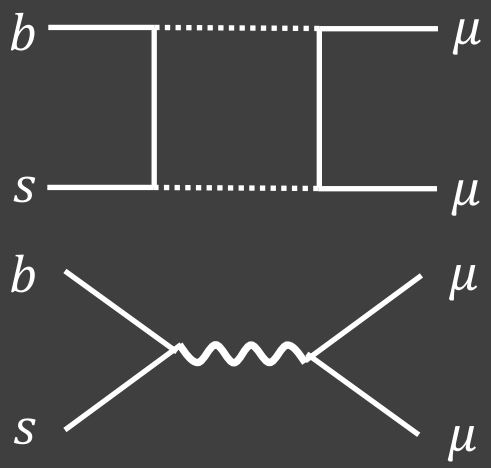
Research interests

phenomenology of beyond the Standard Model [SM]

- LHC

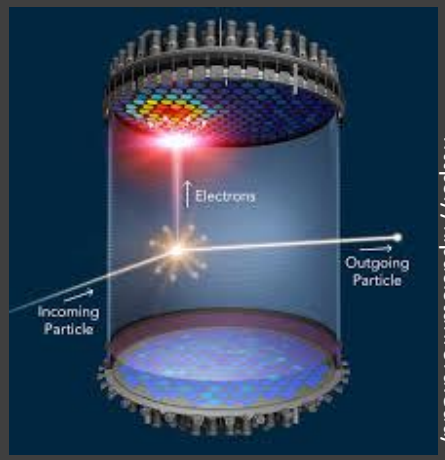
- direct production at TeV scale
- searches for sparticles/vector-like fermion/dark matter

- Flavor violation



- searches for (rare) flavor violating process
- explain anomaly in $b \to s\ell\ell$
- relation to dark matter

- DM search



https://kipac.stanford.edu/

- signals of dark matter via (in)direct detection