Impact of $b \to c$ measurements on $\Lambda_b \to p\tau\bar{\nu}$ decay in U_1 leptoquark model.

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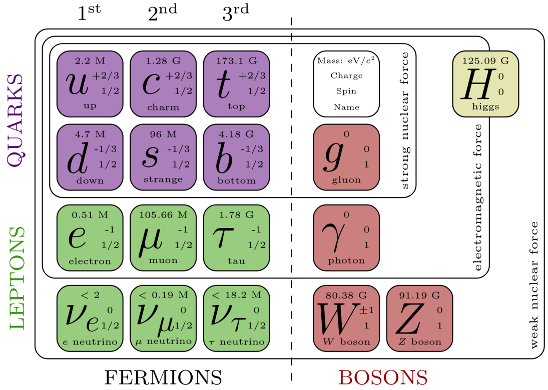
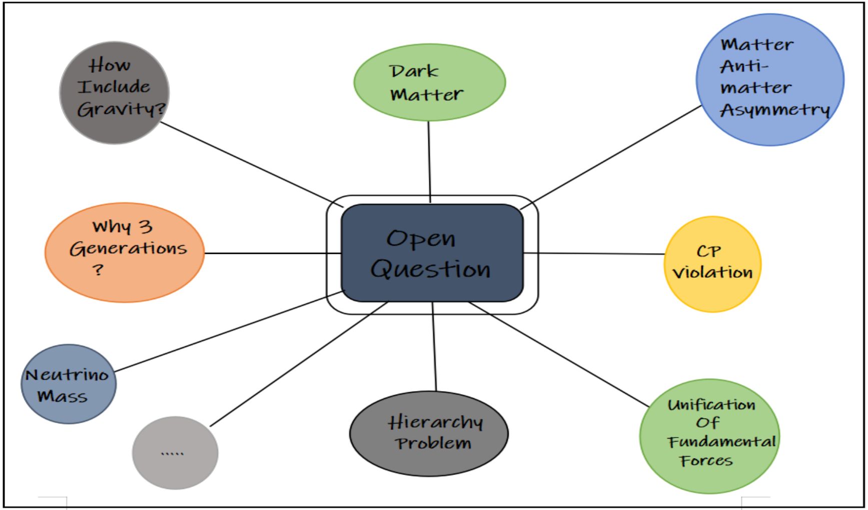
Outline

Introduction



The Standard Model is Structurally Complete - But....

Standard Model



Lepton Flavour Universality Violation

Lepton Flavour Universality Violation

- In semileptonic B-decays , R_K and R_{K^*} $\Rightarrow$ neutral current $b \to s$ transition and R_D and R_{D^*} $\Rightarrow$ charged current $b \to c$ transition have deviation from SM prediction.

$b \to s$ sector

$$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}, \ (\mathbf{3.1}\sigma)$$

$R_K{}^{[1.1,6]} = 0.846^{+0.060}_{-0.054} \pm 0.016$, LHCb

$$R_{K^*} = \frac{Br(B \to K^*\mu\mu)}{Br(B \to K^*ee)} \ (\mathbf{2.5}\sigma),$$

$R_{K^*}{}^{[0.045,1.1]} = 0.660^{+0.110}_{-0.070} \pm 0.024,$

$R_{K^*}{}^{[1.1,6]} = 0.685^{+0.113}_{-0.069} \pm 0.047$ LHCb

$b \to c$ sector

$$R_D = \frac{Br(B \to D\tau\nu_\tau)}{Br(B \to Dl\nu_l)},$$

$R_D^{SM} = 0.298 \pm 0.004$, $R_D = 0.339 \pm 0.026 \pm 0.014$ HFLAV

$$R_{D^*} = \frac{Br(B \to D^*\tau\nu_\tau)}{Br(B \to D^*l\nu_l)}$$

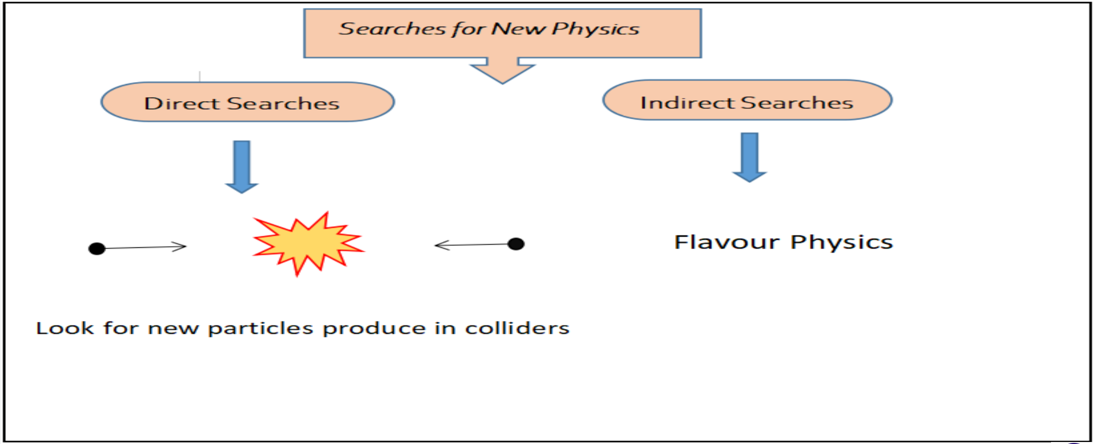
$R_D - R_{D^*} \approx \mathbf{3.2}\sigma$

$R_D^{*SM} = 0.254 \pm 0.005$, $R_{D^*} = 0.295 \pm 0.010 \pm 0.010$ HFLAV

These deviations are smoking gun signature for New Physics beyond SM.

Searches for New Physics

How can we search for the **NEW PHYSICS** ?



Effective Field Theory

The effective Hamiltonian for the transition goverened by $b \to q\, l\, \nu$ (q = c,u)is given by:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{qb} \left[(1 + C_{V_L}) O_{V_L} + C_{V_R} O_{V_R} + C_{S_L} O_{S_L} + C_{S_R} O_{S_R} + C_T O_T \right] ,$$

where the operators are:

$$\begin{aligned}
O_{V_L} &= (\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu) \\
O_{V_R} &= (\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)\,, \\
O_{S_R} &= (\bar{c} P_R b)\,(\bar{\tau} P_L \nu)\,, \\
O_{S_L} &= (\bar{c} P_L b)\,(\bar{\tau} P_L \nu)\,, \\
O_T &= (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)\,.
\end{aligned}$$

In context of U_1 leptoquark, we explore the correlation between observables in $b \to c$ sector and $b \to u$ sector.

Interaction between U_1 and SM quark and leptons :

$$H_{eff}^{U_1} = h_{ij}^{L} \bar{Q}^i \gamma_\mu U_1^\mu P_L L^j + h_{ij}^{R} \bar{d}_R^i \gamma_\mu U_1^\mu P_R l_R^j + h.c.,$$

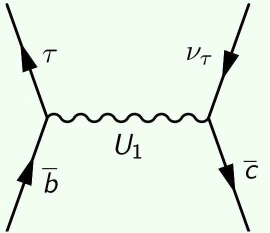
$$h^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & h_{23}^L \\ 0 & 0 & h_{33}^L \end{pmatrix}, \qquad h^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h_{33}^R \end{pmatrix}$$

Asumming mixing in the up-type quark sector :

$$H_{\rm eff} = \Big[\left(V_{us} h_L^{23} + V_{ub} h_{33}^L \right) \bar{u} \gamma_\mu \nu_L + \left(V_{cb} h_L^{33} + V_{cs} h_{23}^L \right) \bar{c} \gamma_\mu \nu_L + h_L^{23} \bar{s}_L \gamma_\mu \tau_L + h_L^{33} \bar{b}_L \gamma_\mu \tau_L + h_R^{33} \bar{b}_R \gamma_\mu \tau_R \Big] U_1^\mu.$$

- Only O_{V_L} and O_{S_R} contribute to $b \to c\tau\nu^-$ and $b \to u\tau\nu^-$ processes.

U_1 LQ NP contribution to b $\to c$ transition :

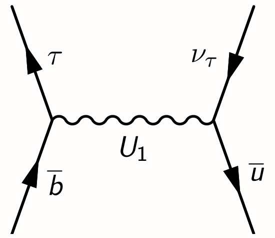


The relevant WCs for $b \to c\tau\bar{\nu}$ decay :

$$C_{V_L}^{b\to c} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{\left(V_{cb}h_{33}^L + V_{cs}h_{23}^L\right) h_{33}^L}{M_{U_1}^2},$$

$$C_{S_R}^{b\to c} = -\frac{1}{\sqrt{2}G_F V_{cb}} \frac{\left(V_{cb}h_{33}^L + V_{cs}h_{23}^L\right) h_{33}^R}{M_{U_1}^2}.$$

U_1 LQ NP contribution to b $\to$ u transition :



The WCs for $b \to u\tau\bar{\nu}$ decay :

$$C_{V_L}^{b\to u} = \frac{1}{2\sqrt{2}G_F V_{ub}} \frac{\left(V_{ub}h^L_{33} + V_{us}h^L_{23}\right) h^L_{33}}{M^2_{U_1}},$$

$$C_{S_R}^{b\to u} = -\frac{1}{\sqrt{2}G_F V_{ub}} \frac{\left(V_{ub}h^L_{33} + V_{us}h^L_{23}\right) h^R_{33}}{M^2_{U_1}}.$$

Observable in $b \to c$ sector :

- The flavor ratios R_D, R_{D^*} and $R(\Lambda_c)$,
- τ and D^* longitudinal polarization fraction in $B \to D^* \tau \bar{\nu}$ decays,
- Branching ratio of $B_c \to \tau \bar{\nu}$.

$$\chi^2(C_i^{eff}) = \sum_{m,n=R_D,R_{D^*}} \left(O^{th}(C_i) - O^{exp}\right)_m \left(V^{exp} + V^{SM}\right)^{-1}_{mn} \left(O^{th}(C_i) - O^{exp}\right)_n + \frac{(R^{th}_{\Lambda_c}(C_i) - R^{exp}_{\Lambda_c})^2}{\sigma^2_{R_{\Lambda_c}}} + \frac{(P_\tau^{D^*\, th}(C_i) - P_\tau^{D^*\, exp})^2}{\sigma^2_{P_\tau}} + \frac{(f_L^{D^*\, th}(C_i) - f_L^{D^*\, exp})^2}{\sigma^2_{f_L}}$$

Fit results and Predictions

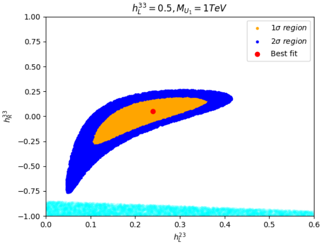
Fit results

Best fit value of NP couplings for three scenarios are given as:

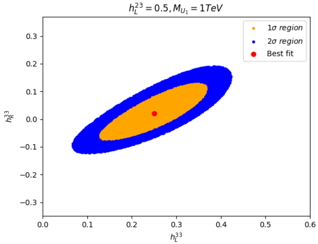
	Best fit value(s)	$\chi^2_{\rm min}$
SM	$C_i = 0$	26.06
$S1$	$h^L_{23} = 0.23 \pm 0.08,\ h^R_{33} = 0.04 \pm 0.12$	6.64
$S2$	$h^L_{33} = 0.25 \pm 0.08,\ h^R_{33} = 0.02 \pm 0.07$	6.64
$S3$	$h^L_{33} = 0.16 \pm 0.03,\ h^L_{23} = 1.22 \pm 0.05$	9.17

Fit is significantly improved over SM in S1, S2, S3 scenarios which is evident from the χ^2_{min} values.

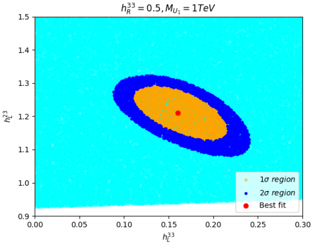
- The 1σ and 2σ allowed regions of the new physics couplings :



S1



S2



S3

For S_3 scenario complete region of NP parameter space is excluded from the constraints $B(B_c \to \tau\bar{\nu}) < 30\%$(The region with cyan color).

Observables in $\Lambda_b \to p l \bar{\nu}$

The differential branching ratio and LFU ratio is defined as

$$\frac{d\mathcal{B}(\Lambda_b \to p l \bar{\nu})}{dq^2} = \tau_{\Lambda_b} \frac{d\Gamma}{dq^2} \qquad R_p(q^2) = \frac{\frac{d\Gamma(\Lambda_b \to p \tau \bar{\nu})}{dq^2}}{\frac{d\Gamma(\Lambda_b \to p \mu \bar{\nu})}{dq^2}}$$

Longitudinal polarization of final state baryon and tau is defined as

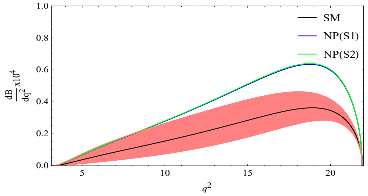
$$P_p^L = \frac{\frac{d\Gamma^{\lambda_p=1/2}}{dq^2} - \frac{d\Gamma^{\lambda_p=-1/2}}{dq^2}}{\frac{d\Gamma^{\lambda_p=1/2}}{dq^2} + \frac{d\Gamma^{\lambda_p=-1/2}}{dq^2}}, \quad P_\tau^L = \frac{\frac{d\Gamma^{\lambda_\tau=1/2}}{dq^2} - \frac{d\Gamma^{\lambda_\tau=-1/2}}{dq^2}}{\frac{d\Gamma^{\lambda_\tau=1/2}}{dq^2} + \frac{d\Gamma^{\lambda_\tau=-1/2}}{dq^2}}$$

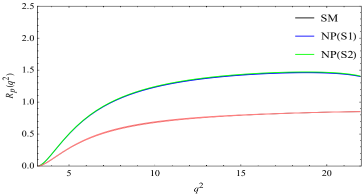
The lepton forward-backward asymmetry is:

$$A_{FB} = \frac{\int_0^1 \left(\frac{d^2\Gamma}{dq^2\, d\cos\theta}\right) d\cos\theta - \int_{-1}^0 \left(\frac{d^2\Gamma}{dq^2\, d\cos\theta}\right) d\cos\theta}{\int_0^1 \left(\frac{d^2\Gamma}{dq^2\, d\cos\theta}\right) d\cos\theta + \int_{-1}^0 \left(\frac{d^2\Gamma}{dq^2\, d\cos\theta}\right) d\cos\theta}$$

Predictions in $\Lambda_b \to p l \bar{\nu}$ decay

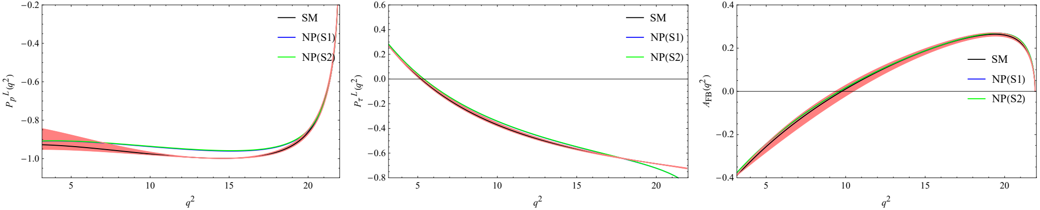
- We predict observables in $\Lambda_b \to p l \bar{\nu}$ decay for benchmark scenarios $NP(S_1)$ and $NP(S_2)$ which correspond to the maximum deviation from the SM predictions.





- The data available of $b \to c$ sector allows two times enhancement in DBR and R_p.

Predictions in $\Lambda_b \to p l \bar{\nu}$ decay



The observables lepton forward-backward asymmetry A_{FB}, longitudinal tau polarization P_τ^L and longitudinal polarization of final state Baryon P_p^L are consistent with SM.

Conclusions

- We have studied new physics effect in $\Lambda_b \to p l \bar{\nu}$ decay in U_1 LQ model.
- The new physics couplings in $b \to u \tau \bar{\nu}$ transition can be expressed in terms of couplings in $b \to c \tau \bar{\nu}$ decay along with a suitable combinations of elements of the CKM matrix.
- One expects a strong correlations between these two sectors.
- The new physics parameter space is constrained by the measurements in $b \to c \tau \bar{\nu}$.
- For S_3 scenario ($h^R_{33} = 0.5, h^L_{33}$, h^L_{23} varying.) complete region of NP parameter space is excluded from the constraints $B(B_c \to \tau \bar{\nu}) < 30\%$.
- The data available of $b \to c$ sector allows two times enhancement in DBR and R_p and other observables A_{FB}, P^L_τ, P^L_p are consistent with SM.

Thank You

Backup slides go here

$$\frac{d^2\Gamma(\Lambda_b \to p l \bar{\nu})}{dq^2\, d\cos\theta_l} = N\Big(1 - \frac{m_l^2}{q^2}\Big)^2 \Big[A + \frac{m_l^2}{q^2} B + 2\, C + \frac{4 m_l}{\sqrt{q^2}} D\Big], \tag{1}$$

where

$$A = 2\sin^2\theta_l\Big(H^2_{\frac{1}{2},0} + H^2_{-\frac{1}{2},0}\Big) + \Big(1 - \cos\theta_l\Big)^2 H^2_{\frac{1}{2},1} + \Big(1 + \cos\theta_l\Big)^2 H^2_{-\frac{1}{2},-1}, \tag{2}$$

$$B = 2\cos^2\theta_l\Big(H^2_{\frac{1}{2},0} + H^2_{-\frac{1}{2},0}\Big) + \sin^2\theta_l\Big(H^2_{\frac{1}{2},1} + H^2_{-\frac{1}{2},-1}\Big) + 2\Big(H^2_{\frac{1}{2},t} + H^2_{-\frac{1}{2},t}\Big) - 4\cos\theta_l\Big(H_{\frac{1}{2},t}H_{\frac{1}{2},0} + H_{-\frac{1}{2},t}H_{-\frac{1}{2},0}\Big) \tag{3}$$

$$C = \Big(H^{SP}_{\frac{1}{2},0}\Big)^2 + \Big(H^{SP}_{-\frac{1}{2},0}\Big)^2, \tag{4}$$

$$D = -\cos\theta_l\Big(H_{\frac{1}{2},0}H^{SP}_{\frac{1}{2},0} + H_{-\frac{1}{2},0}H^{SP}_{-\frac{1}{2},0}\Big) + \Big(H_{\frac{1}{2},t}H^{SP}_{\frac{1}{2},0} + H_{-\frac{1}{2},t}H^{SP}_{-\frac{1}{2},0}\Big). \tag{5}$$

The q^2 dependence of the helicity form factors in the lattice QCD calculations are defined as:

$$f_i(q^2) = \frac{1}{1 - q^2/(m^f_{pole})^2}[a^f_0 + a^f_1 z(q^2)]\,, \tag{6}$$

where $i = +, \perp, 0$ and the expansion parameter is defined as

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}\,. \tag{7}$$

Here $t_+ = (m_{B_1} + m_{B_2})^2$ and $t_0 = (m_{B_1} - m_{B_2})^2$.