Probing Supersymmetry/BSM Through Flavor Physics

Shaaban Khalil

Center for Fundamental Physics
Zewail City of Science and Technology

09/08/2016

New Physics Beyond The SM

It is clear that the SM is not a complete theory of Nature:

- **It doesn't include gravity $\Longrightarrow$ it can't be valid at energy scales above $M_{\mathrm{Pl}} \sim 10^{19}$ GeV.**
- **It doesn't allow for neutrino masses $\Longrightarrow$ It can't be valid at energy scales above $M_{\mathrm{seesaw}} \sim 10^{15}$ GeV.**
- **The fine-tuning problem of the Higgs mass and the puzzle of the dark matter suggest that the scale where the SM is replaced with a more fundamental theory is actually much lower, NP $\sim \mathcal{O}(1)$ TeV.**
- **Gauge coupling unification: NP (SUSY) close to EW scale.**

Therefore, the SM is only an effective low energy theory.

Why Flavor?

- In the SM, no Flavor Changing Neutral Current (FCNC) at the tree level and strongly suppressed by small CKM mixing angles at the loop level.
- Tiny CP violation in K and D mesons due to small CKM angles.
- Unobservable LFV & EDM's.
- Flavor & CP violation ideal places to get indirect evidence of NP.
- The charm and top quarks were first "seen" not by producing and observing them as "real" or physical particles but, rather, via their effects in FCNC process in K and B physics respectively.
- So far, most of experimental results on flavor observables are consistent with SM expectations and lead to strong indirect constraints on NP models.
- Increasing the sensitivity of flavor experiments maybe detect an indirect NP signal.

Hadronic Flavor

- **Flavor tests indicate that the CKM flavor patter of the SM represents the main bulk of the flavor structure and CP violation.**
- **Low energy supersymmetry predicts new particles carrying flavour numbers with mass of order TeV that may lead to potentially large FCNC rates.**
- **The FCNC limits put strong constraints on soft SUSY breaking parameters that may give some information on the fundamental theory at high energy.**
- **We will analyze the SUSY contributions to** $B \to D/D^* \tau\nu$

Lepton Flavor Violation

- **The SM possesses an accidental LF symmetry, hence neutrinos are massless.**
- **Many extensions of the SM do not exhibit such symmetries, and therefore, the evidence for non-vanishing neutrino masses provides the first solid hint towards physics beyond the SM.**
- **Although neutrino flavors exhibit large admixtures, LFV, i.e. non-conservation of individual lepton flavor numbers in FCNC transitions among charged leptons, is extremely small.**
- **Thus, the measurements on the LFV processes can provide an indirect signal for the new physics beyond the SM, in particular SUSY models (possible mixing in slepton sector).**
- **Here we will focus on SUSY contributions to** $h \to \tau\mu$

$\bar{B} \to D\tau\nu_\tau$ and $\bar{B} \to D^*\tau\nu_\tau$ puzzle

- It has been recently reported a deviation from the SM expectations in the ratios

$$\mathcal{R}(D) = \frac{\mathrm{BR}(\bar{B} \to D\tau\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to Dl\bar{\nu}_l)}, \quad \mathcal{R}(D^*) = \frac{\mathrm{BR}(\bar{B} \to D^*\tau\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to D^*l\bar{\nu}_l)}, \quad l \text{ refers to either electron or muon}$$

- Belle collaboration measured

$$\mathcal{R}(D)^{\mathrm{Belle}} = 0.375 \pm 0.064, \qquad \mathcal{R}(D^*)^{\mathrm{Belle}} = 0.302 \pm 0.030 \pm 0.011.$$

- The results by BaBar collaboration are

$$\mathcal{R}(D)^{\mathrm{BaBar}} = 0.440 \pm 0.072, \qquad \mathcal{R}(D^*)^{\mathrm{BaBar}} = 0.332 \pm 0.030.$$

- In addition, the LHCb collaboration has found

$$\mathcal{R}(D^*)^{\mathrm{LHCb}} = 0.336 \pm 0.027 \pm 0.030.$$

- The SM predictions for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are

$$\mathcal{R}(D)^{\mathrm{SM}} = 0.305 \pm 0.012, \qquad \mathcal{R}(D^*)^{\mathrm{SM}} = 0.252 \pm 0.004.$$

- The combined results disagree with the SM expectations at the $\sim 3.9\ \sigma$ level ($\sim 1.7\sigma$ for $\mathcal{R}(D)$ and $\sim 3\sigma$ for $\mathcal{R}(D^*)$).

- These deviations, if confirmed, could be important hints for NP.

- **The effective Hamiltonian for $b \to c l \bar{\nu}_l$ is**

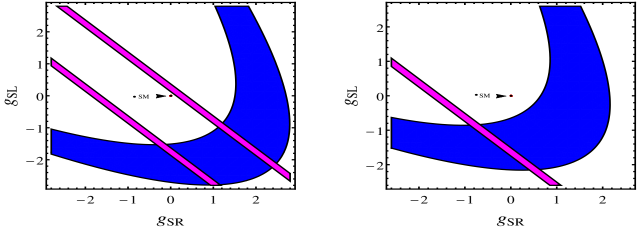
$$\mathcal{H}_{\rm eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big[(1 + g_{VL}) [\bar{c} \gamma_\mu P_L b] [\bar{l} \gamma_\mu P_L \nu_l] + g_{VR} [\bar{c} \gamma_\mu P_R b] [\bar{l} \gamma_\mu P_L \nu_l]$$
$$+ \; g_{SL} [\bar{c} P_L b] [\bar{l} P_L \nu_l] + g_{SR} [\bar{c} P_R b] [\bar{l} P_L \nu_l] + g_T [\bar{c} \sigma^{\mu\nu\tau} P_L b] [\bar{l} \sigma_{\mu\nu} P_L \nu_l] \Big] .$$

- $g_i = \frac{C_i^{\rm SUSY}}{C^{\rm SM}}$ **and The SM Wilson coefficien is given by** $C^{\rm SM} = \frac{4 G_F V_{cb}}{\sqrt{2}}$.

- **since $g_i < 1$, the leading contributions to $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are**

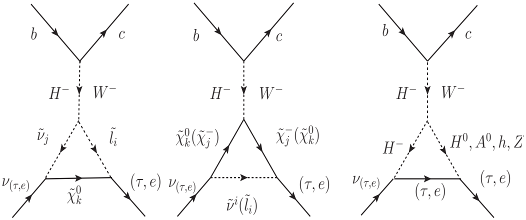
$$\mathcal{R}(D) = \mathcal{R}(D)^{\rm SM} \left(1 + 2{\rm Re}[g_{VL} + g_{VR}] + 1.465 \, {\rm Re}[(g_{SR} + g_{SL})^*] + 1.074 \, {\rm Re}[g_T^*]\right) ,$$
$$\mathcal{R}(D^*) = \mathcal{R}(D^*)^{\rm SM} \left(1 + 2{\rm Re}[g_{VL}] + 0.094 \, {\rm Re}[(g_{SR} - g_{SL})^*] - 4.457 \, {\rm Re}[g_T^*] - 1.748 \, {\rm Re}[g_{VR}^*]\right)$$

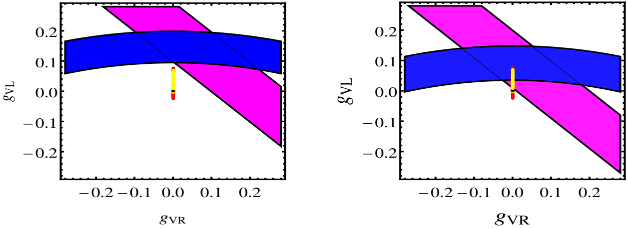
- **In case of a dominant scalar contribution, $\mathcal{R}(D^*)$ cannot be significantly larger than the SM expectation unless $g_{SR} - g_{SL}$ is larger than one (i.e., $C_S^{\rm SUSY} > C^{\rm SM}$), which is not possible.**



- **The allowed regions in the (g_{SL}, g_{SR}) plane by the 1σ experimental results on $\mathcal{R}(D)$ (pink) and $\mathcal{R}(D^*)$ (blue) of BaBar (left) and Belle (right).**

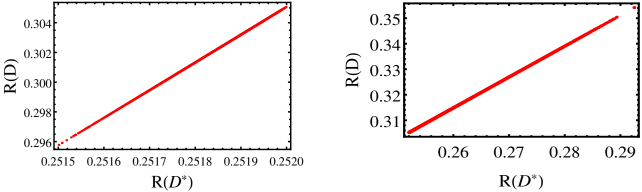
- **Penguins diagrams contributing to $b \to c\tau\nu_\tau$ affecting the leptonic vertex.**





- (g_{VL}, g_{VR}) **plane allowed by the** 1σ **experimental results on** $\mathcal{R}(D)$ **(pink) and** $\mathcal{R}(D^*)$ **(blue) of BaBar (left) and Belle (right). SM (black point) and complete SUSY (red points) predictions (penguin) are also included.**

- **Correlation between** $\mathcal{R}(D)$ **and** $\mathcal{R}(D^*)$ **for the SUSY contributions through tree level (left) and the lepton penguins (right).**



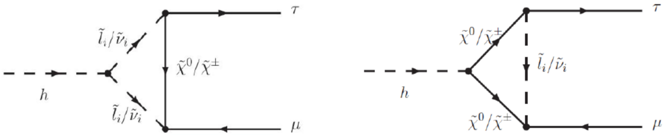
- **MSSM has the potential to explain recent data produced by BaBar and Belle which revealed a rather significant excess above and beyond the best SM predictions available in the observed** $\mathrm{BR}(\bar{B} \to D\tau\bar{\nu}_\tau)$ **and** $\mathrm{BR}(\bar{B} \to D^*\tau\bar{\nu}_\tau)$ **relative to the light lepton cases.**

- **The CMS and ATLAS collaborations reported the first signal of LFV Higgs decay $h \to \tau\mu$. The branching ratio of this decay is found as**

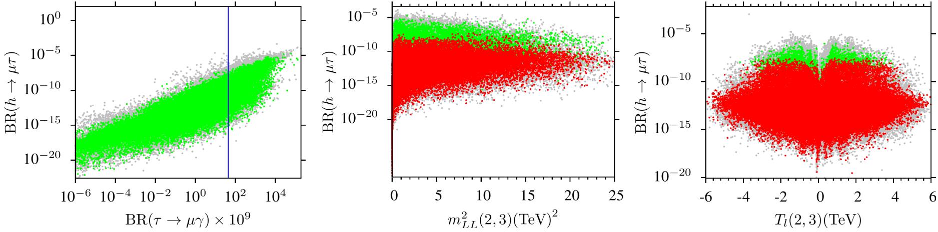
$$BR(h \to \tau\mu) = \left(8.4^{+3.9}_{-3.7}\right) \times 10^{-3} \quad \text{(CMS)},$$
$$BR(h \to \tau\mu) = (7.7 \pm 6.2) \times 10^{-3} \quad \text{(ATLAS)}.$$

- **The SM predicts no tree-level LFV Higgs coupling at the renormalizable level.**

- **In the MSSM framework, a misalignment in the slepton sector with the soft SUSY breaking (SSB) terms can induce LFV processes through the loop processes mediated by charginos or neutralinos.**



- **However, SUSY models with non-zero family mixing in the sleptons also result in enhancement in other LFV processes such as $\mu \to e\gamma$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$.**



- **Correlation between $BR(h \to \tau\mu)$ and $BR(\tau \to \mu\gamma)$. Also the $BR(h \to \tau\mu)$ versus the slepton off-diagonal mass terms $(m^{\tilde{\ell}}_{LL})_{23}$ and T^{ℓ}_{23} in the MSSM with non-diagonal slepton mass matrix.**

- **Gray points are excluded by the LHC constraints, green points satisfy the mass bounds on sparticles and the constraints from the rare B-meson decays.**

- **The vertical line in the left panel indicates the bound on $BR(\tau \to \mu\gamma)$, and the red points in the right panel form a subset of green and they satisfy the bound on $BR(\tau \to \mu\gamma)$.**

- **The maximum value for $BR(h \to \tau\mu)$ is about 10^{-8} without violating the bound on $BR(\tau \to \mu\gamma)$.**

$h \to \tau\mu$ in BLSSM with Inverse Seesaw

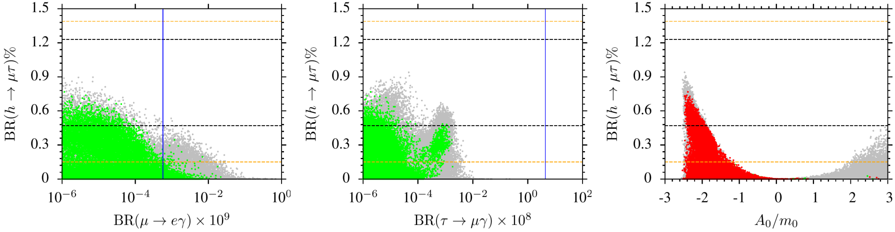
- The solid experimental evidence for neutrino oscillations, pointing towards non-vanishing neutrino masses, is one of the few firm hints for physics beyond the SM.

- BLSSM is the minimal extension of MSSM, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. The particle content of this model is given as follows:

- The Superpotential of the leptonic sector in this model is given by

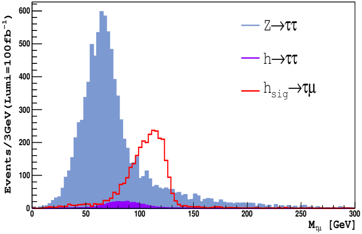
$$W = -\mu_\eta \hat{\chi}_1 \hat{\chi}_2 + \mu \hat{H}_u \hat{H}_d + \mu_S \hat{s}_2 \hat{s}_2 - Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u + Y_s \hat{\nu} \hat{\chi}_1 \hat{s}_2 + Y_\nu \hat{\nu} \hat{l} \hat{H}_u.$$

- In BLSSM-IS, with universal soft SUSY breaking terms, measured values of $BR(h \to \tau\mu)$ are accommodated in a wide region of parameter space without violating LFV constraints.



- Thus, confirming the LFV Higgs decay results will be a clear signal of BLSSM-IS type of models.

- **We consider how likely it is to detect the LFV Higgs boson decay $h \to \tau\mu$ over the relevant SM background.**



- **Number of signal events for LFV $h \to \tau\mu$ decay versus the $\tau - \mu$ invariant mass ($M_{\tau\mu}$) at $\sqrt{s} = 13$ TeV after 100 fb^{-1} luminosity for the solutions with the largest $BR(h \to \tau\mu) \sim 0.77\%$ and $m_{\tilde{\chi}_1^\pm} \sim 800$.**

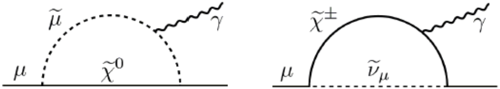
##	parton level cuts	$P_T(l) \geq 30 \& \eta \leq 2.1$	$P_T(j) \geq 35 \& \eta \geq 3.5$	Reject $(j\&MET)$
$Z \to \tau\bar{\tau}$ (bkg)	408913	121249	16055	16055
$Wjj, W \to l\nu$ (bkg)	24582	18160	11745	0.0
$Zjj, Z \to \tau\bar{\tau}$ (bkg)	72694	41838	33678	12
$h \to \tau\bar{\tau}$ (bkg)	3986	2574	848	848
$h \to \tau\bar{\mu}$ (sig)	18062 (7225)	17165 (6866)	5257 (2103)	5257 (2103)
$S/\sqrt{S+B}$	24.9 (10.0)	38.3 (15.7)	20.2 (8.3)	35.3 (15.6)

Muon $g-2$

- **The SM prediction for the $a_\mu = (g-2)_\mu/2$ has a discrepancy with the experimental results:**

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.7 \pm 8) \times 10^{-10}.$$

- **In SUSY, new contributions to muon $g-2$ through chargino and neutralixo exchange.**



- **Within the MSSM, Higgs boson with mass ~ 125 GeV requires rather heavy sparticle spectrum.**

- **Hence it results in a strong tension in simultaneous resolution for both the 125 GeV Higgs boson and the muon $g-2$ problem.**

- **We show that this tension can be alleviated in the BLSSM. In BLSSM, new contribution to the Higgs boson mass in addition to the stop sector of MSSM is obtained.**

- **Also the $g-2$ may receive new contributions due to the extension of the neutralino sector by SM singlet $(B-L)$ Higgsino and B'-ino and also due to the possibility that one of the right-handed sneutrinos is light (due to large mixing between right-handed sneutrinos and right-handed anti-sneutrinos.**

- **The neutralino contributions to a_μ in BLSSM is given by:**

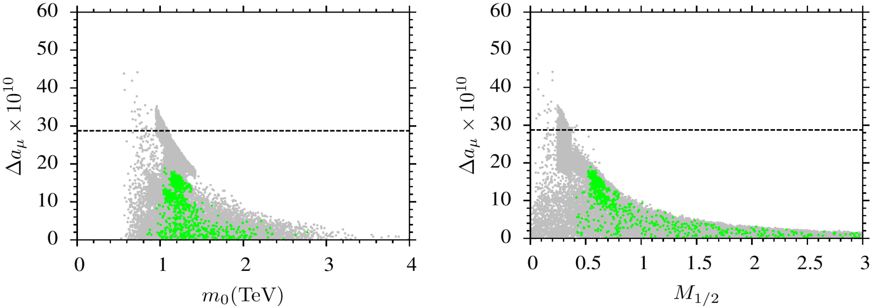
$$
\begin{aligned}
a_\mu^{\chi^0} &= \frac{m_\mu}{16\pi^2}\sum_{m,i}\Bigg\{-\frac{m_\mu}{6m^2_{\tilde{\mu}_m}(1-x_{mi})^4}\left(|N^L_{mi}|^2+|N^R_{mi}|^2\right)\times\left(1-6x_{mi}+3x^2_{mi}+2x^3_{mi}-6x^2_{mi}\ln x_{mi}\right)\\
&+ \frac{m_{\chi^0_i}}{m^2_{\tilde{\mu}_m}(1-x_{mi})^3}N^L_{mi}N^R_{mi}(1-x^2_{mi}+2x_{mi}\ln x_{mi})\Bigg\}\ ,
\end{aligned}
$$

where $x_{mi}=m^2_{\chi^0_i}/m^2_{\tilde{\mu}_m}$, $x_k=m^2_{\chi^\pm_k}/m^2_{\tilde{\nu}}$

$$
\begin{aligned}
N^L_{aij} &= -\frac{i}{2}\left[\sqrt{2}(2g_1+g_{BY})N^*_{a1}(U^*_{\tilde{\mu}}Z^{\mu\,\dagger}_R)_{ij}+\sqrt{2}(2g_{BY}+g_{BL})N^*_{a5}(U^*_{\tilde{\mu}}Z^{\mu\,\dagger}_R)_{ij}+2N^*_{a3}(U_{\tilde{\mu}}Y^T_\mu Z^{\mu\,\dagger}_R)_{ij}\right]\\
N^R_{aij} &= \frac{i}{2}\left[-2N_{a3}(Z^\mu_L Y^\dagger_\mu U^\dagger_{\tilde{\mu}})_{ij}+\sqrt{2}(g_1+g_{BY})N^*_{a1}(Z^\mu_L U^\dagger_{\tilde{m}u})_{ij}+\sqrt{2}g_2N^*_{a2}(Z^\mu_L U^\dagger_{\tilde{m}u})_{ij}+\sqrt{2}(g_{YB}+g_{BL})N^*_{a5}(Z^\mu_L U^\dagger_{\tilde{m}u})_{ij}\right]
\end{aligned}
$$

- **In BLSSM, the Bino contribution has an enhancement by the gauge mixing between $U(1)_Y$ and $U(1)_{B-L}$ characterized by the coupling g_{YB}.**

- **In addition, $B'-ino$ contributes to a_μ through interactions with muon governed by $B-L$ gauge group. Note that N_{a1} can be $\approx N_{a5}$.**



- **$\Delta a_\mu - m_0$ and $\Delta a_\mu - M_{1/2}$ planes. Gray points are compatible with REWSB. Green points satisfy the mass bounds. The dashed line indicates $\Delta a_\mu = 28.7 \times 10^{-10}$.**

- **With universal SSB, heavy gluino constraint leads to heavy sparticle spectrum (about $1-1.5$ TeV), but still muon $g-2$ can be within 2σ uncertainty.**

- **The Bino mass can be as light as about 250 GeV, while $\tilde{Z}'$ can be found even lighter as ~ 190 GeV. Even though these two gauginos form together the lightest neutralinos, they contribute to muon $g-2$ differently.**

Conclusions

- **FCNC play an important role in testing the SM and also probing possible New Physics beyond the SM.**
- **Complementary between direct and indirect searches for New Physics is the essential.**
- **We focus on the appealing possibility that such NP is given by a supersymmetric extension of the SM.**
- **We analyzed the SUSY implications in the flavor violating processes:** $B \to D\tau\nu$ **and** $h \to \tau\nu$**. In addition to the muon** $g-2$**.**
- **So far, measurements have not yielded to a conclusive result of NP.**
- **In near future we anticipate enough data will be gathered, so that we will know which path HEP will go.**

Thank you