Flavourful Inert Doublet Dark Matter

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Flavour Puzzle

- Lepton Flavour Universality is sacred in the SM.
- Why then are anomalous results reported in the semi-leptonic B-decays? Hints of New Physics?
  - $R(K), R(K^*)$: $\frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}e^+e^-)}\left(b \to s\ell^+\ell^- \text{ where, } \ell = e, \mu\right)$

Obs.	q^2 bin	Expt.	SM	Significance
$R(K)$	$[1.1,\ 6]$ GeV^2	$0.846^{+0.060+0.016}_{-0.054-0.014}$	$1.0004^{+0.0008}_{-0.0007}$	2.5σ
$R(K^*)$	$[0.045,\ 1.1]$GeV^2	0.660 ± 0.12	$0.920^{+0.007}_{-0.006}$	2.3σ
	$[1.1,\ 6]$GeV^2	$0.69^{+0.11}_{-0.07} \pm 0.05$	$0.996^{+0.002}_{-0.002}$	2.4σ

  - $R(D), R(D^*)$: $\frac{\mathcal{B}(B\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B\to D^{(*)}\ell\bar{\nu}_\ell)}\left(b \to c\ell\nu_\ell\right)$

Obs.	Expt.	SM	Sig.	Combined Sig.
$R(D)$	$0.340 \pm 0.027 \pm 0.013$	0.299 ± 0.003	1.4σ	3.1σ
$R(D^*)$	$0.295 \pm 0.011 \pm 0.008$	0.258 ± 0.005	2.5σ	

A few others...

- Anomalous Magnetic Moments :

$$a_\ell = \frac{g-2}{2}$$

$$\Delta a_\mu = a_\mu^{expt} - a_\mu^{SM} = 27.9(7.9) \times 10^{-10}\ (3.7\sigma)$$

$$\Delta a_e = a_e^{expt} - a_e^{SM} = -8.7(3.6) \times 10^{-13}\ (\text{Negative } 2.4\sigma)$$

- KOTO Anomaly : $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\text{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9} \to$ 3 signal events!

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Question : Can a dark sector address them together?

Inert Higgs Doublet Model (IHDM)

- The **Inert Higgs Doublet Model** is the simplest higgs portal extension of the SM where the lightest neutral scalar is the stable dark matter candidate.
- This model was first proposed by Ernest Ma in 1977 (Phys. Rev., D18:2574, 1978.).

The two doublets can be written as :

$$H_1 = \begin{pmatrix} \phi^+ \\ v + (h + i\chi)/\sqrt{2} \end{pmatrix}, \; H_2 = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

and the scalar potential is given by

$$\begin{aligned} V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\ + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + h.c.] \end{aligned}$$

Inert Higgs Doublet Model

- H_2 is odd under a discrete $\mathbb{Z}_2$ symmetry. So the lightest neutral component (H^0/A^0) becomes a stable DM candidate.
- The IHDM satisfies the correct relic abundance only in the following DM mass ranges :
  - **Low Mass** (50 GeV $< m_{H^0} <$ 90 GeV)
    - The dominant annihilation channel is the SM higgs(h) mediated self-annihilation process(s-channel) into $b\bar{b}$ or $\tau^+\tau^-$
  - **High Mass** ($m_{H^0} >$ 500 GeV)
    - Correct relic abundance is achieved if and only if the masses of H^0, A^0 and $H^\pm$ are almost degenerate[PHYSICAL REVIEW D 92, 015002].
    - All annihilation channels (both s and t/u channels) are open and annihilation cross-sections are large.
    - Cancellation between direct quartic coupling diagrams (i.e annihilation to vector boson final states) and t/u channel diagrams are required to bring down the annihilation cross-section to the desired level.
    - Also now, there are extra co-annihilation channels.

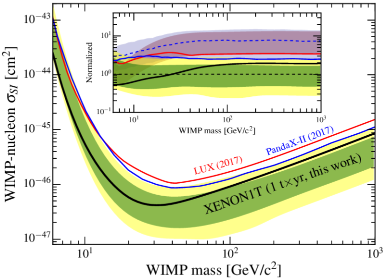
Extended IHDM

$$\mathscr{L}_{\text{int}} = (\lambda^E)_{ij} \; \bar{L}_i H_2 E_{Rj} \; + \; (\lambda^D)_{ij} \; \bar{Q}_{Li} H_2 D_{Rj} + h.c.$$

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
H_2	1	2	1/2	-1
$D_{L,R}$	3	1	-1/3	-1
$E_{L,R}$	1	1	-1	-1

With this framework we aim to simultaneously explain :

- Dark Matter relic abundance ($\Omega h^2 = 0.12 \pm 0.001$ by Planck), abiding by the direct detection constraints.
- $R(K), R(K^*)$ anomaly
- Muon $(g-2)$ anomaly

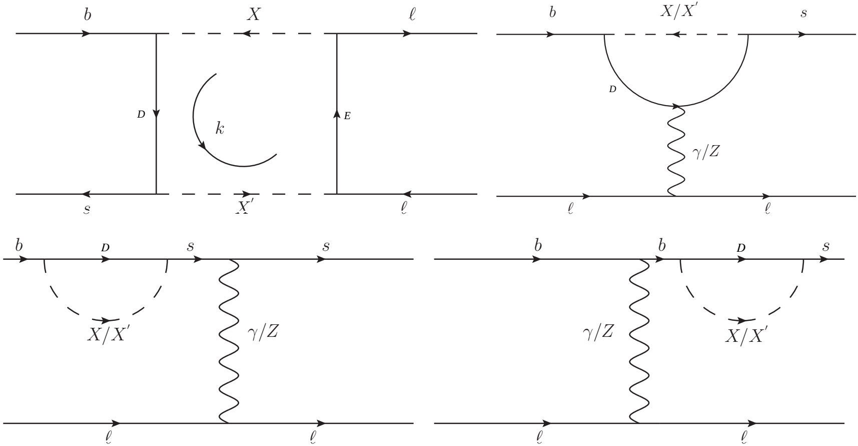


In collaboration with Soumitra Nandi, Debasish Borah, Basabendu Barman

Model Contributions

Contribution to $b \to s\ell\ell$ process : C_9 & C_{10} only!

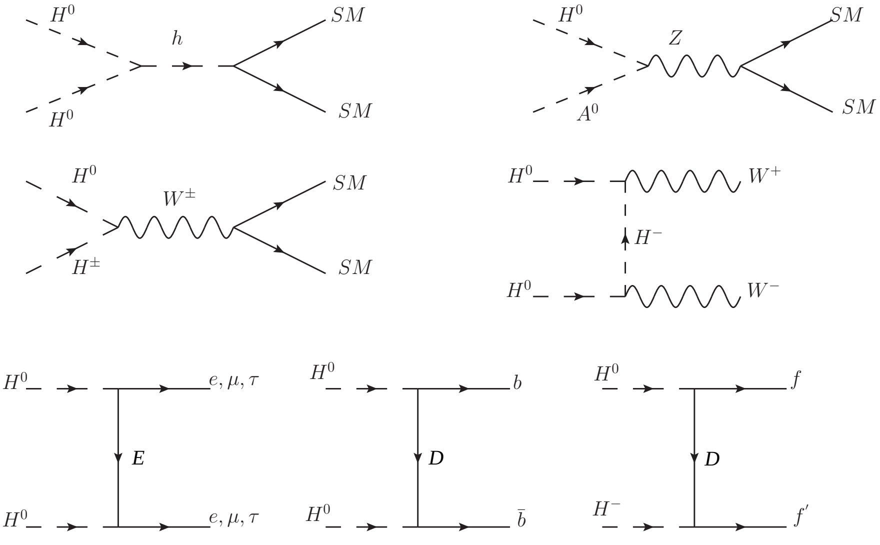
Effective operators : $\mathcal{O}_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$ & $\mathcal{O}_{10} \propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$



where $X/X^{'}$ can either be H^0 or A^0.

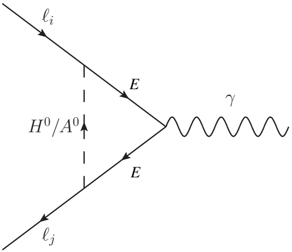
Model Contributions

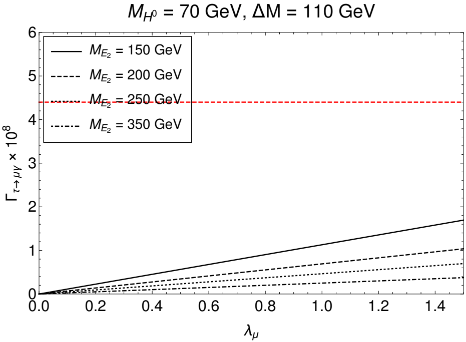
Contribution to relic : Annihilation diagrams :



Let's Set the Stage!

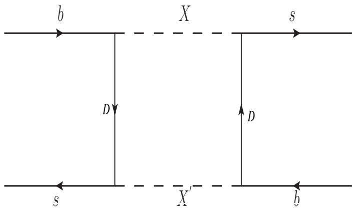
- For simplicity, we assumed $\lambda_{ij} << \lambda_{ii}$, where $(i, j = 1, 2, 3)$
- In order to ensure LUV, we further assumed $\lambda_e(\lambda^E_{11}) << \lambda_\mu(\lambda^E_{22})$ in lepton sector



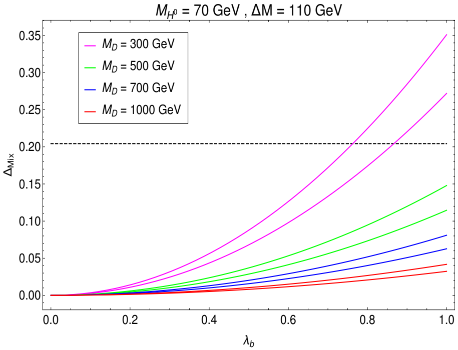


Let's Set the Stage!

- The choice $\lambda_s(\lambda_{23}^D) << \lambda_b(\lambda_{33}^D)$ helps overcome current constraints on $B_s - \bar{B}_s$ mixing, $\mathcal{B}(B \to X_s\gamma)$ etc.



Here, $\Delta_{\text{Mix}} = \frac{(\Delta M_{B_s})_{NP}}{(\Delta M_{B_s})_{SM}}$



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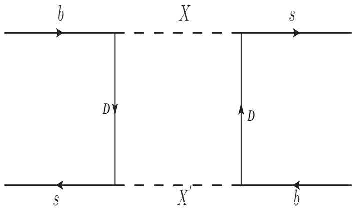

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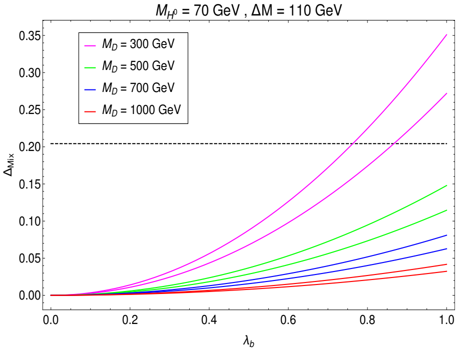
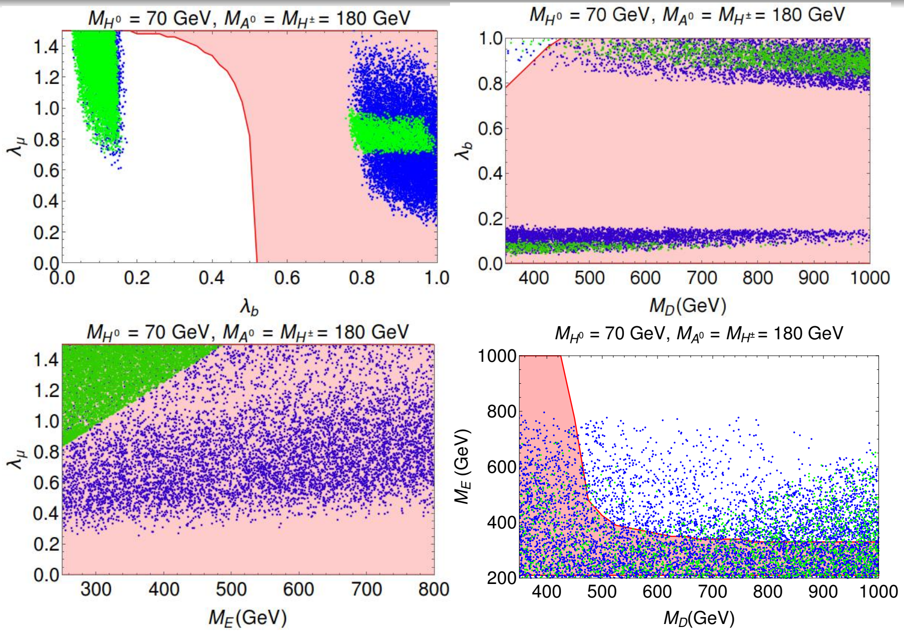


We thus fix the following parameters for the entire analysis :

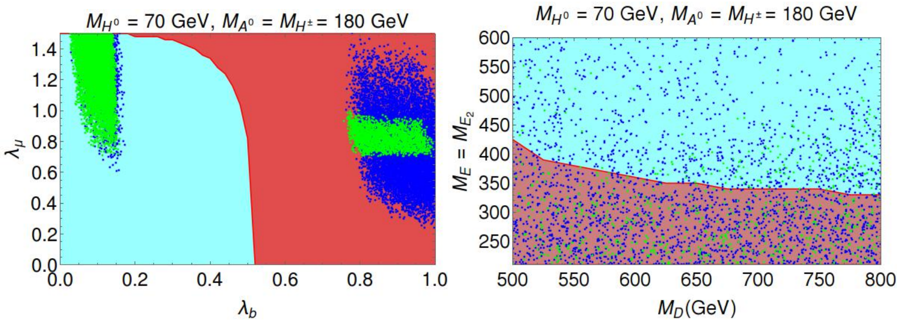
- $\lambda_d = 10^{-3}, \lambda_s = 10^{-2}, \lambda_e = 10^{-3}, 1.0 \leq \lambda_\tau \leq 1.5$
- $M_{D_1} = M_{D_2} = M_{D_3} = M_D$
- $M_{E_1} = M_{E_2} = M_{E_3} = M_E$

Results : Low Mass DM



Results : Low Mass DM

If we relax the mass degeneracy → More Parameter Space!



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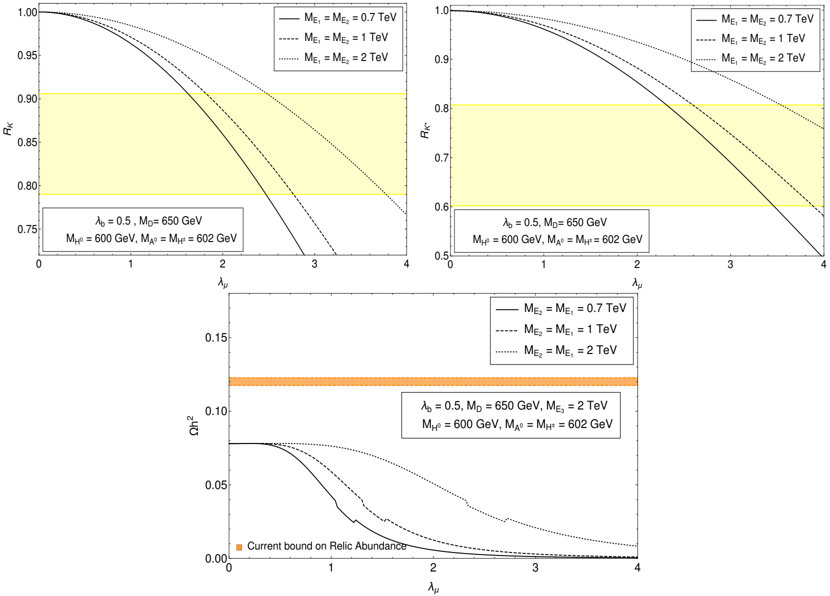

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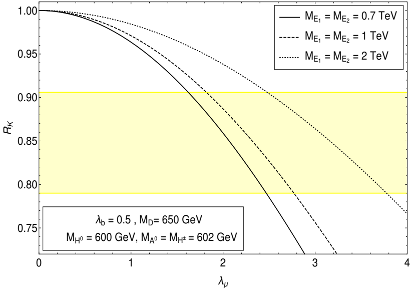
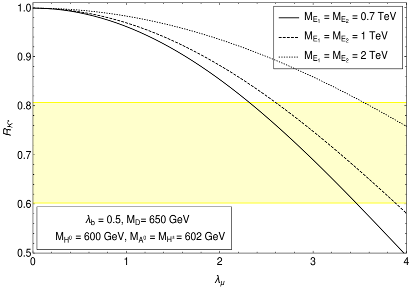
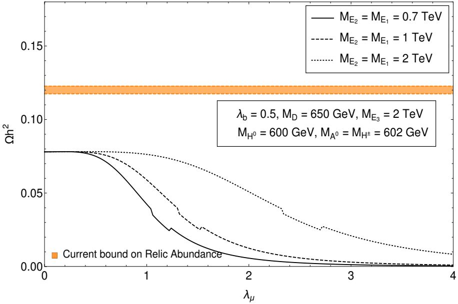






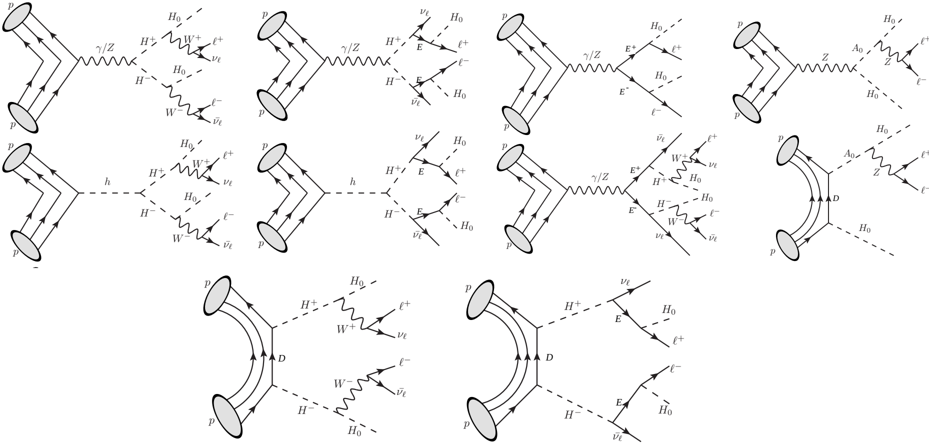
NO SOLUTION!

Searches @ LHC : Benchmark Points

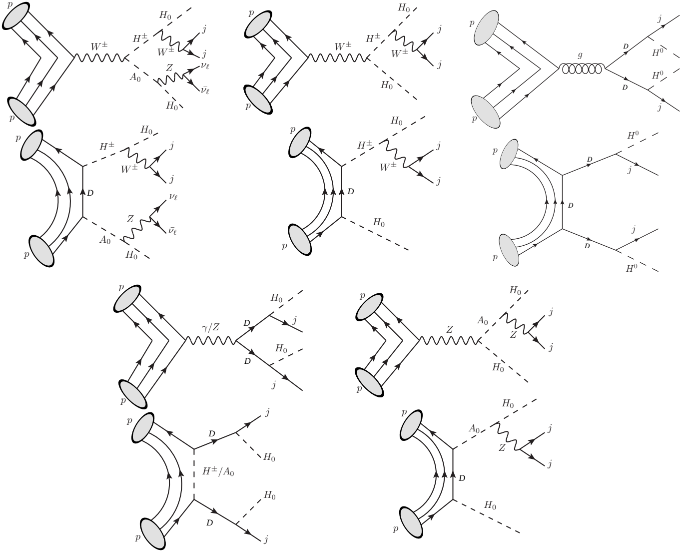
BP	M_D (GeV)	λ_b	M_{E_2} (GeV)	λ_μ	M_{E_3} (GeV)	λ_τ
1.	500	0.8	150	0.5	350	1.5
2.	750	0.8	250	0.7	250	1.2
3.	750	0.8	200	0.7	350	1.5
4.	850	0.8	250	0.7	250	1.2
5.	900	0.8	350	0.8	350	1.5
6.	800	0.1	350	1.5	350	1.5
7.	800	0.1	180	1.5	500	1.5

Searches @ LHC : Final States

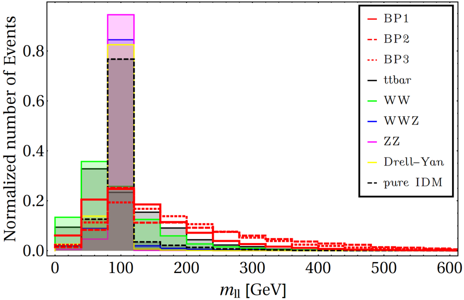
1. Final state : Dilepton + $\not{E}_T$

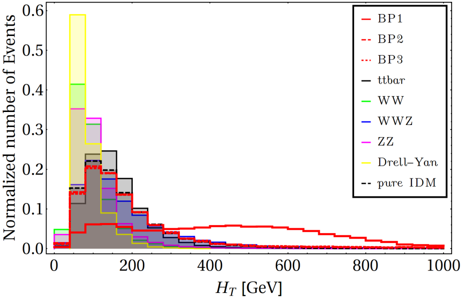


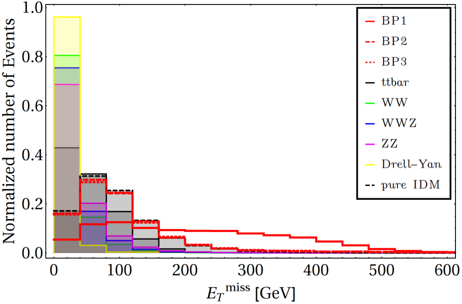
2. Final state : Dijet + $\not{E}_T$



Searches @ LHC : Distributions

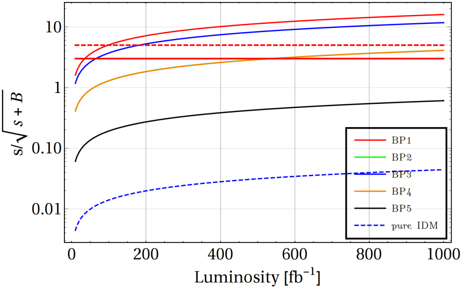


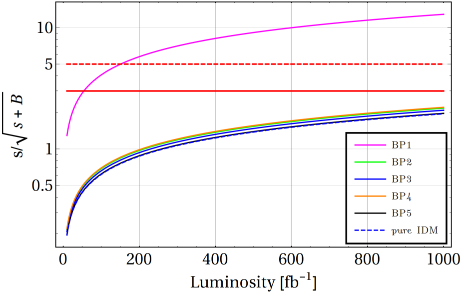




Searches @ LHC : Signal Significance

- Final Cut on dilepton final state events : $M_{\ell\ell} > 200$ GeV and $H_T > 280$ GeV
- Significance bin for dijet final state: 240 GeV $\leq \not{E}_T \leq$ 280 GeV
- Huge excess in BP1 observed.
- LHC has not seen any excess in these channels BP1 in danger!![1]
- Low mass VL fermions ruled out!





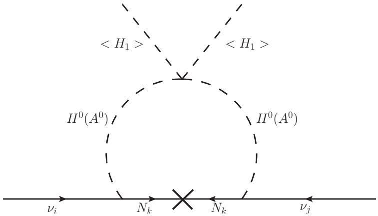
[1] *JHEP, 05:025, 2018*

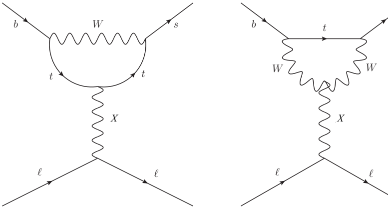
Other Extensions involving IHD

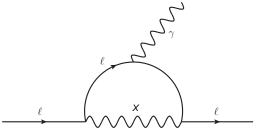
- $SM \times U(1)_X$ is very popular extension $\rightarrow$ Eg : $U(1)_{B-L}, U(1)_{L_\mu - L_\tau}$ etc.
- In presence of RHN and Inert Higgs doublet:
  - Neutrino Mass via one-loop scotogenic mechanism
  - Leptogenesis
- Recently we studied the low scale $U(1)_X$ origin of flavour anomalies, DM and neutrino mass $\rightarrow$ 2007.13778

$$\mathcal{L}_{\rm int}^{\rm NP} = i \sum_{i=1}^{3} n_i \, g_X (\bar{\ell}_i^L \gamma^\mu \ell_i^L + \bar{e}_i^R \gamma^\mu e_i^R) X_\mu + \frac{\epsilon}{4} B_{\mu\nu} X^{\mu\nu}$$

- $U(1)_X$ charges n_i are constrained from low energy data : LUV observables in $b \rightarrow s\ell\ell$ decays and Δa_μ
- We focus in the region $M_X > 2m_\mu$

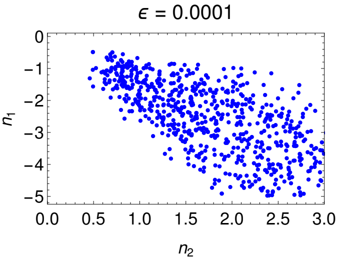


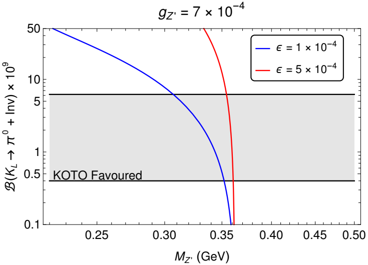


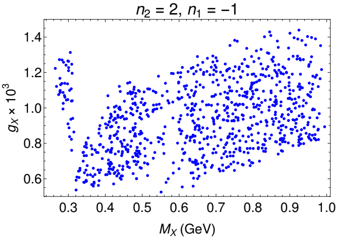


$SM \times U(1)_X$

- $(n_1, n_2, n_3) = (-1, 2, -1)$ is found to be a good solution!
- Anomaly cancellation requires additional chiral fermions $\rightarrow$ 3 RHNs with charges : $(n'_1, n'_2, n'_3) = (-1, 2, -1)$
- All RHNs are odd under $\mathbb{Z}_2$.
- Lightest RHN is considered to be the DM.
- Inert doublet for ν-mass generation.



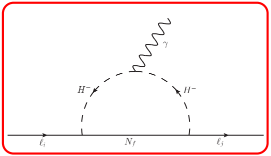


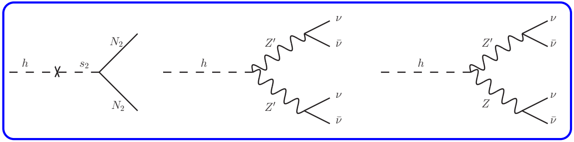


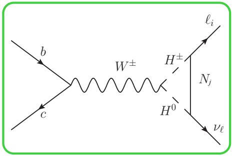
$$-\mathcal{L}_Y \supset \sum Y^{\ell}_{ij} \bar{L}_i H_1 e_{jR} + \sum Y_{ij} \bar{L}_i \tilde{H}_2 N_j + Y_{22} \bar{L}_2 \tilde{H}_2 N_2$$

$SM \times U(1)_X$

- Additional Phenomenology :
  - Lepton Flavour Violation
  - Electron Magnetic Moment
  - R(D), R(D*)
  - Higgs Invisible and LFV decays







- **Summary :**
  - It is interesting to study BSM scenarios which also have plausible explanations to lepton flavour universality violation.
  - We are able to simultaneously address recent results in rare decays and dark sector as well as study the collider prospects for the future LHC runs.
  - In this talk I consider extensions of SM with Inert Doublet Higgs. But, for a similar model without inert Higgs, read our article 2007.13778.

THANK YOU!

- Most recent update by ATLAS :

$$R(\tau/\mu) = \frac{BR(W \to \tau\nu_\tau)}{BR(W \to \mu\nu_\mu)} = 0.992 \pm 0.013$$

- NP correction of $W\tau\nu_\tau$ vertex in our model is $\sim 2\%$