New Physics at the LHC

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In collaboration with
S. Chakdar, K. Ghosh, S. Nandi and S. K. Rai, Phys. Rev. D 88, 095005(2013).
S. Chakdar, K. Ghosh and S. Nandi, arXiv: 1311.2543 [hep-ph].

21st Nov 2013.

Works done so far

- Parallel universe, dark matter and invisible Higgs decays, Shreyashi Chakdar, Kirtiman Ghosh, S. Nandi, arXiv: 1311.2543 [hep-ph], Submitted to Phys.Lett. B

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- Outlook and Future Projects

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- There are also theoretical drawbacks, such as, the Higgs mass being in the Electroweak Scale, Parity Violation, gauge coupling unification, quantization of electric charges, mass hierarchy of the elementary particles and the flavor problem, quantum gravity
- I have worked on models which tries to address some problems of SM such as Parity Violation, Charge quantization, Strong CP problem and not having Dark matter Candidate and test implications of them at LHC

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- iii)Increase the number of spatial dimensions (extra dimensions) and Include gravity into the mix (supergravity and string theory)
- I have worked on models which in broad sense falls into the first category of enlarging the gauge sector and second category of supersymmetry during my PhD till now

Motivation of Left Right Mirror Model

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- One can enlarge the SM into left-right(LR) symmetric structure and by spontaneously breaking mechanism recover the SM.This is the general idea of left right symmetric models ($SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$)(Pati and Salam(1974), Mohapatra and Pati(1975), Senjanovic and Mohaparta(1975)).

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- In this work,we have a LR symmetric mirror model(LRMM) with mirror fermions and mirror Higgs with phenomenology of low lying mirror fermions at the LHC
- The LRMM model solves the strong CP problem,which was shown by Babu and Mohapatra (1989,1990)

- Our gauge symmetry is :$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$ supplemented by a discrete Z_2 symmetry. For every $(u, d)_L$, we have new fermions, $(\hat{u}, \hat{d})_R$.Hence we call it Left-Right Mirror Model

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- Apart from the SM higgs, scalar sector of this model includes a mirror Higgs and a real scalar singlet under both $SU(2)_L$ and $SU(2)_R$
- The right-handed(left-handed) components of mirror-fermions transform as doublet (singlets) under $SU(2)_R$, SM fermions are singlets under $SU(2)_R$,whereas doublets under $SU(2)_L$.Thus gauge anomaly is absent

Fermion Representation of our model for leptons and quarks in the first family

$$l_L^0 = \begin{pmatrix} \nu^0 \\ e^0 \end{pmatrix}_L \sim (1,2,1,-1) \quad , \quad e_R^0 \sim (1,1,1,-2) \quad , \quad \nu_R^0 \sim (1,1,1,0);$$

$$\hat{l}_R^0 = \begin{pmatrix} \hat{\nu}^0 \\ \hat{e}^0 \end{pmatrix}_R \sim (1,1,2,-1) \quad , \quad \hat{e}_L^0 \sim (1,1,1,-2) \quad , \quad \hat{\nu}_L^0 \sim (1,1,1,0);$$

$$Q_L^0 = \begin{pmatrix} u^0 \\ d^0 \end{pmatrix}_L \sim (3,2,1,\frac{1}{3}) \quad , \quad u_R^0 \sim (3,1,1,\frac{4}{3}) \quad , \quad d_R^0 \sim (3,1,1,-\frac{2}{3});$$

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Bracketed entries $\Rightarrow$ transformation properties under $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$. The charge generator : $Q = T_{3L} + T_{3R} + Y'/2$.

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Our Model and the formalism

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- SM fermions as well as right handed singlet neutrino is even under Z_2 and all mirror fermions along with left handed singlet mirror neutrino is odd
- They are used to generate tiny neutrino masses $\simeq 10^{-11}$ GeV with a primary symmetry breaking scale of $\simeq 10^{7}$ GeV

Symmetry breaking and the scalar sector

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\begin{aligned}
V = & - \left(\mu^2\Phi^\dagger\Phi + \hat{\mu^2}\hat{\Phi}^\dagger\hat{\Phi}\right) + \frac{\lambda}{2}\left[\left(\Phi^\dagger\Phi\right)^2 + \left(\hat{\Phi}^\dagger\hat{\Phi}\right)^2\right] \\
& + \lambda_1\left(\Phi^\dagger\Phi\right)\left(\hat{\Phi}^\dagger\hat{\Phi}\right) - \frac{1}{2}\mu_\chi^2\chi^2 + \frac{1}{2}\mu_3\chi^3 \\
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- $\langle\chi\rangle = v_\chi$, breaks the Z_2 symmetry spontaneously and enables us to generate mixing between SM and mirror fermions

Gauge boson masses and mixings

- While mass matrix for the charged gauge bosons is diagonal with masses $M_{W^\pm} = gv/2, M_{\hat{W}^\pm} = g\hat{v}/2$
  mass matrix for the neutral gauge boson sector is not. in the basis $(W^3,\ \hat{W}^3,\ B)$, the neutral gauge boson mass matrix is given by

$$M = \frac{1}{4}\begin{pmatrix} g^2 v^2 & 0 & -gg' v^2 \\ 0 & g^2 \hat{v}^2 & -gg' \hat{v}^2 \\ -gg' v^2 & -gg' \hat{v}^2 & g'^2(v^2 + \hat{v}^2) \end{pmatrix}$$

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- One eigenstate (γ) is identified with the SM photon and the masses of other eigenstates are given by,

$$M_Z^2 = \frac{1}{4}v^2g^2\frac{g^2+2g'^2}{g^2+g'^2}\left[1-\frac{g'^4}{(g^2+g'^2)^2}\epsilon\right],$$

$$M_{\hat{Z}}^2 = \frac{1}{4}\hat{v}^2\left(g^2+g'^2\right)\left[1+\frac{g'^4}{(g^2+g'^2)^2}\epsilon\right],$$

where, $\epsilon = v^2/\hat{v}^2$. Since $\hat{v} >> v$, the $\mathcal{O}(\epsilon^2)$ can be neglected.

Gauge boson masses and mixings

- This mass matrix can be diagonalized by an orthogonal transformation R, which can be expressed in terms of two mixing angle: θ_W and $\hat{\theta}_W$:

$$\cos^2\theta_W = \left(\frac{M_W^2}{M_Z^2}\right)_{\epsilon=0} = \frac{g^2 + g'^2}{g^2 + 2g'^2},$$

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- The couplings of our theory are related to the electric charge (e) by,

$$g = \frac{e}{\sin\theta_W}, \quad g' = \frac{e}{\cos\theta_W \cos\hat{\theta}_W}, \quad \text{which implies,} \quad \frac{1}{e^2} = \frac{2}{g^2} + \frac{1}{g'^2}.$$

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- $\hat{\theta}_W$ is not an independent angle, but is related to θ_W as $\sin\hat{\theta}_W = \tan\theta_W$

Fermion masses and mixings

- Lagrangian invariant under our gauge symmetry as well as the Z_2 symmetry is given by,

$$\mathcal{L} \supset y_d\left(\bar{Q}_L^0 \Phi d_R^0 + \bar{\hat{Q}}_R^0 \hat{\Phi} \hat{d}_L^0\right) + h_d\ \chi \bar{d}_R \hat{d}_L + \mathrm{h.c.}$$

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- The masses and mixing angles are given by:

$$m_f = \frac{y_f v}{\sqrt{2}}, m_{\hat{f}} = \sqrt{\frac{y_f^2 \hat{v}^2 + 2M_{f\hat{f}}^2}{2}};$$

$$\tan 2\theta_R^f = \frac{2\sqrt{2} y_f M_{f\hat{f}} \hat{v}}{y_f^2 \left(v^2 - \hat{v}^2\right) + 2M_{f\hat{f}}^2}, \tan 2\theta_L^f = \frac{2\sqrt{2} y_f M_{f\hat{f}} v}{y_f^2 \left(v^2 - \hat{v}^2\right) - 2M_{f\hat{f}}^2}$$

Neutrino Sector

- The neutrino mass matrix with Dirac mass $(m = f_\nu v/\sqrt{2})$ and $(m' = f_\nu \hat{v}/\sqrt{2})$ and $M_{\nu\hat{\nu}} = h_\nu v_\chi$, Majorana mass (M) in $(\nu_L^0, \nu_R^0, \hat{\nu}_R^0, \hat{\nu}_L^0)$ basis (Assuming $M_{\nu\hat{\nu}} \sim M \sim \hat{v}$):

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- $\hat{v} \sim 10^7$ scale and $M_{f\hat{f}}$ determines the masses of the mirror fermions which for the first family is few hundred GeV to TeV range.

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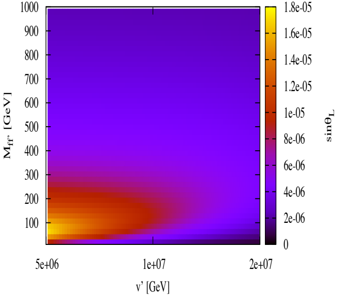
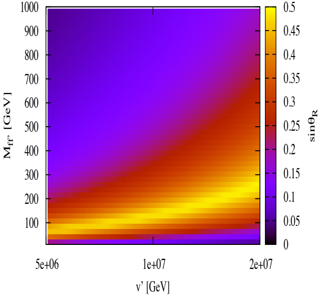
- From study of the charged current interaction,neutral current interaction and interaction Lagrangians of fermions with SM Higgs and mirror Higgs ⇒mirror fermions can decay into a SM fermion and a Z,W or H
- Apart from the known SM parameters and mirror fermion masses, the decay widths of mirror fermions depend on θ_L and θ_R which are determined in terms of two parameters $\hat{v}$ and $M_{f\hat{f}}$

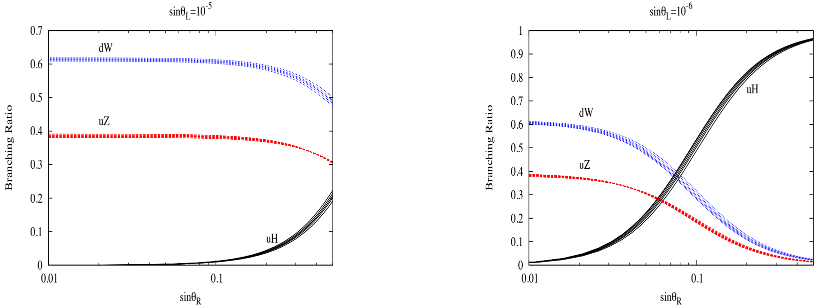
Study of the properties of mirror fermions and bosons

For SM quark in MeV and mirror in TeV: $\sin\theta_L$ is about 10^{-6} whereas $\sin\theta_R$ can be large depending on values of $\hat{v}$ and $M_{f\hat{f}}$

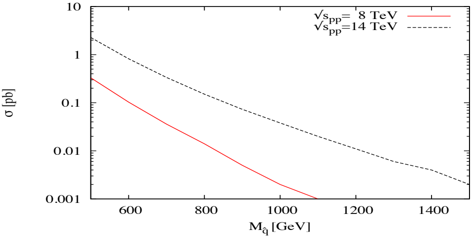




For $\sin\theta_L = 10^{-5}$, $\hat{u}$ decays to SM vector bosons dominatly over Higgs.
Whereas, for $\sin\theta_L = 10^{-6}$, VB decays dominates only for low $\sin\theta_R$



Signature of mirror fermions at the LHC



- Both gluon-gluon (gg) and quark-antiquark ($q\bar{q}$) initial states contribute to the pair production ($\hat{q}\bar{\hat{q}}$) of mirror quarks
- The LO pair production cross-sections of mirror quarks as a function of their masses at 8 TeV and 14 TeV LHC
- $\hat{q} \to qZ,\ q'W$ and qH.Thus pair production of $\hat{q}$ gives rise to a pair of heavy SM bosons with multiple jets in the final state

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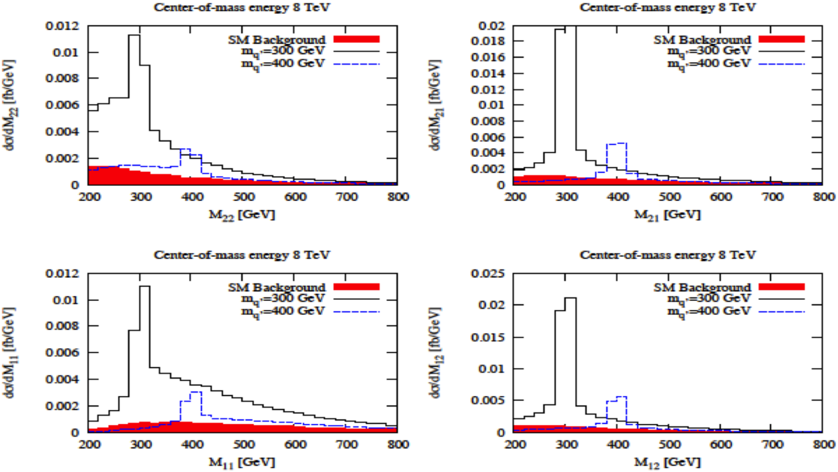
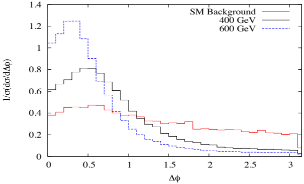
- We consider the reconstruction of mirror quark mass from the invariant mass distribution of qZ pairs in this analysis which is possible for the first two signal topologies only

2 jets+2 Z-bosons signature

- We put $p_T^{j1,j2} > 100$ GeV $p_T^l > 25$ GeV, $-2.5 < \eta < 2.5$, $\Delta R(j_1, j_2) > 0.7$ and $\Delta R(l, j) > 0.4$ Cuts



More Cuts on 2j+Z+W final states:



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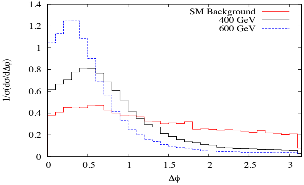

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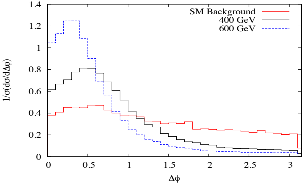

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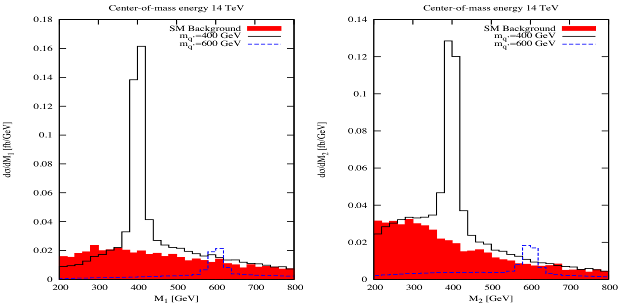
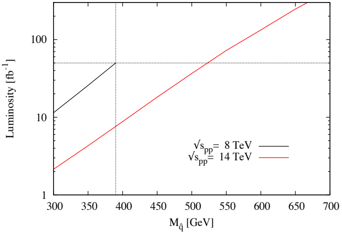
- With other cuts alongwith $\Delta\phi(\vec{p}^{\,l}_T, \vec{Missp}_T) < 1$ cut, 55% background and 14% of signal was reduced at 14 TeV ($m_{\hat{q}} = 600$ GeV)

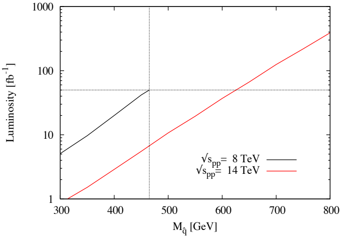
2 jets+Z-boson+W boson signature after $\Delta\phi$ cut



- Jet-Z invariant mass distributions after $\Delta\phi$ cut for the signal ($m_{\hat{q}} = 400 \text{ and } 600$ GeV) and SM background at 14 TeV LHC

Sensitivity at the LHC in 99% CL





- For 2 j+2 Z final states at 8 TeV / (14 TeV) LHC 350 GeV (550 GeV) mirror quark mass can be probed with integrated luminosity 25 fb^{-1} (72 fb^{-1})
- For 2 j+Z+charged lepton+missEt final states at 8 TeV / (14 TeV) LHC 400 GeV (600 GeV) mirror quark mass can be probed with integrated luminosity 20 fb^{-1} (37 fb^{-1})

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- The most striking signal of the model is the existence of resonances in the jet plus Z channel. These resonances $\hat{u}, \hat{d}$ can be reconstructed upto a mass of $\simeq$ 400(600) GeV at the 8 (14)TeV LHC. We are not aware of any other model which predicts such a resonance. Based on this paper, ATLAS has started looking into the jet plus Z and jet plus W channel.

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- In this work,we have studied the invisible decay modes of the Higgs in this situation with phenomenology at the LHC

Model and Formalism

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- We also assume that post-inflationary reheating in the two worlds are different, and the the parallel universe is colder than our universe.(Bertulani et al,2012)This makes it possible to maintain the successful prediction of the big bang nucleosynthesis, though g_* here will be more than $g(T)_{*|T=1MeV} = 10.75$ at the Nucleosynthesis due to extra light degrees of freedoms due to (γ', e' and three ν's)

Fermion Representation

- The fermions belong to the fundamental representations $(4,2,1)+(4,1,2)$. The 4 represent three color of quarks and lepton number as the 4th color (Pati and Salam,1974).The 48(24 Left, 24 Right) Weyl fermions belonging to three generations may be represented by the matrix

$$\begin{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_1 & \begin{pmatrix} u \\ d \end{pmatrix}_2 & \begin{pmatrix} u \\ d \end{pmatrix}_3 & \begin{pmatrix} \nu_e \\ e \end{pmatrix}_4 \\ \begin{pmatrix} c \\ s \end{pmatrix}_1 & \begin{pmatrix} c \\ s \end{pmatrix}_2 & \begin{pmatrix} c \\ s \end{pmatrix}_3 & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_4 \\ \begin{pmatrix} t \\ b \end{pmatrix}_1 & \begin{pmatrix} t \\ b \end{pmatrix}_2 & \begin{pmatrix} t \\ b \end{pmatrix}_3 & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_4 \end{pmatrix}_{L,R} . \qquad (0.1)$$

- We have similar fermion representations for the parallel universe, denoted by primes

Gauge Sector

- The model has 3 gauge coupling constants: g_4 for $SU(4)$ color which we identify with the strong coupling constant of our universe, g_4' for $SU(4)'$ color of the parallel universe, and g for $SU(2)_L$ and $SU(2)_R$ and corresponding electroweak couplings for the parallel universe (We assume $g_L = g_R = g_L' = g_R' = g$).

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- $(1, 3, 1)$ contain the 3 left handed weak gauge bosons, while $(1, 1, 3)$ contain the 3 right handed weak gauge bosons. The parallel universe contain the corresponding parallel gauge bosons

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- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ can be broken to the SM using the Higgs representations $(1, 3, 1) + (1, 1, 3)$ at a scale V_{LR},where $V_{LR} > 2.5\, TeV$

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- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ can be broken to the SM using the Higgs representations $(1, 3, 1) + (1, 1, 3)$ at a scale V_{LR},where $V_{LR} > 2.5\,TeV$
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- $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \to SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \to SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$

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- Thus the mixing terms between the two bi-doublets (one in our universe and one in the parallel universe) $\lambda(H_{VS}^{\dagger}H_{VS})(H_{DS}^{\dagger}H_{DS})$ then leads to mixing between the two light remaining SM like Higgs fields.

Higgs Sector

- The resulting mass terms for the remaining two light Higgs fields can be written as :

$$\mathcal{L}_{Scalar} \supset m_{VS}^2 h_1^2 + m_{DS}^2 h_2^2 + 2\lambda v_{VS} v_{DS} h_1 h_2$$

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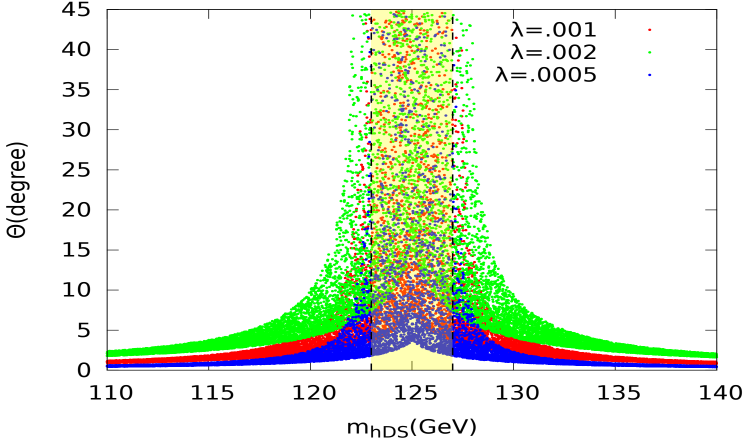
- The masses and the mixing angle of these physical states are given by,

$$\begin{aligned} m^2_{h_1^{(p)},h_2^{(p)}} &= \frac{1}{2}[(m_{VS}^2 + m_{DS}^2) \mp \sqrt{(m_{VS}^2 - m_{DS}^2)^2 + 4\lambda^2 v_{VS}^2 v_{DS}^2}] \\ \tan 2\theta &= \frac{2\lambda\ v_{VS}\ v_{DS}}{m_{DS}^2 - m_{VS}^2}. \end{aligned}$$

where $v_{VS} \simeq v_{DS} \simeq 250 GeV$

Parameter space scan



Phenomenology

- In colliders when producing this light higgs boson, both $h_1^{(p)}$ and $h_2^{(p)}$ states will be produced with respective factors of $cos\theta$ or $sin\theta$. So when decaying they will decay to SM decay modes along with dark sector decay modes. We,in our ordinary world will see this dark sector decay modes as invisible decay modes for the Higgs, the phenomenological implications of which we study here.

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- We study the different constraints on this mixing angle between this two higgs coming from experimental data
- We also take into account Standard Model production cross section and Decay Branching Ratios in different channels to study the parameter space of mixing between two higgs bosons in detail

SM production cross-section, BR's(Th) and Expt value of μ at 8 TeV

Mass of Higgs(GeV)	$\sigma_{ggf}(pb)$	$\sigma_{ttH}(pb)$	$\sigma_{VBF}(pb)$	$\sigma_{Vh}(pb)$
123	20.15	1.608	1.15	0.1366
124	19.83	1.595	1.12	0.1334
126	19.22	1.568	1.06	0.1271
127	18.92	1.552	1.03	0.1241

$BR(H \to WW)$	$BR(H \to ZZ)$	$BR(H \to \gamma\gamma)$	$BR(H \to gg)$	BR($H \to ff$)
0.183	2.18×10^{-2}	2.27×10^{-3}	8.71×10^{-2}	0.687
0.199	2.41×10^{-2}	2.27×10^{-3}	8.65×10^{-2}	0.687
0.231	2.89×10^{-2}	2.28×10^{-3}	8.48×10^{-2}	0.651
0.248	3.15×10^{-2}	2.27×10^{-3}	8.37×10^{-2}	0.633

$\mu = \sigma/\sigma_{SM}$	ATLAS	CMS
$H \to WW \to l\nu l\nu$	1.01 ± 0.31	0.76 ± 0.21
$H \to \gamma\gamma$	$1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$	0.78 ± 0.27

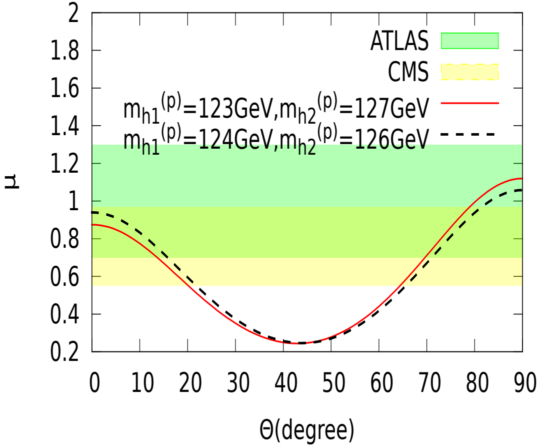

Figure: $H \to WW \to l\nu l\nu$ rate in Present Model as a function of mixing angle θ. The shaded regions correspond to ATLAS and CMS allowed $\mu = \sigma/\sigma_{SM}$ values.

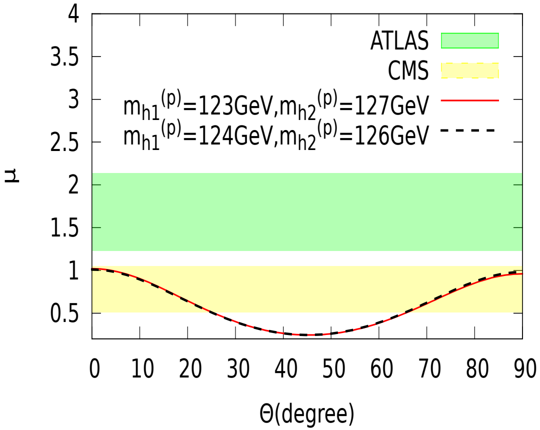

Figure: Higgs decaying into diphoton rate in Present Model as a function of mixing angle θ. The shaded regions again correspond to ATLAS and CMS allowed μ values.

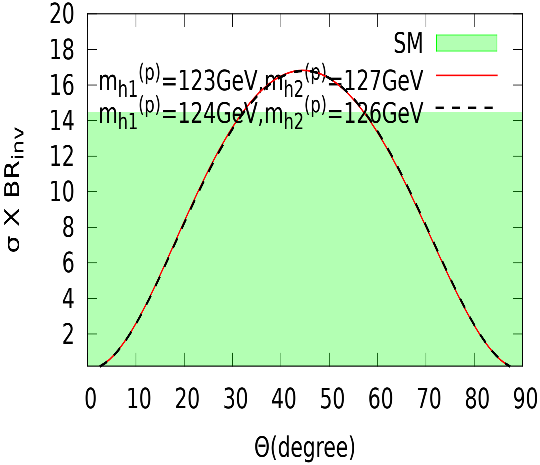

Figure: Decay rate in Present Model as a function of mixing angle θ. The shaded regions correspond to $(\sigma \times BR)_{inv}$ with Higgs ($125 GeV$) produced with a Z boson (ATLAS-CONF-2013-011).

Conclusions

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- The two higgs bosons in both ordinary and parallel world are light and comparable in mass(within 4 GeV) and when produced in LHC cannot be resolved as two separate masses
- This leads to very interesting invisible higgs decay signals which are allowed by the present theoretical and experimental constraints
- We have shown that it can be studied in LHC and definitely looked for in future proposed e+ e- collider like ILC

Outlook

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- I am currently working on a project involving scanning parameter space for mSUGRA for interesting twisted signals
- I am also working on another project of looking for boosted Higgs signal from left-right mirror model at LHC
- Along with the above mentioned, I am also interested in particle cosmology, in identifying the real candidate or candidates for the dark matter and the associated model building and its implications for collider physics.

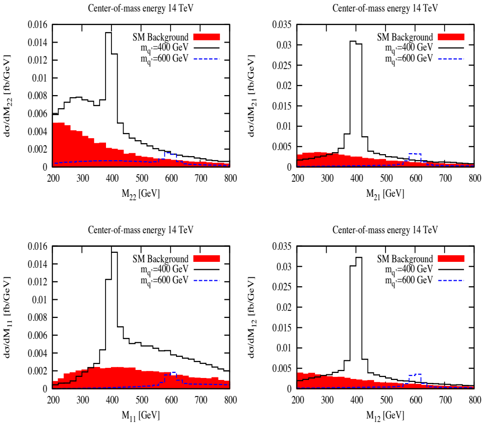
Thank you!

BACKUP: Mixing matrix Expression Gauge sector LRMM

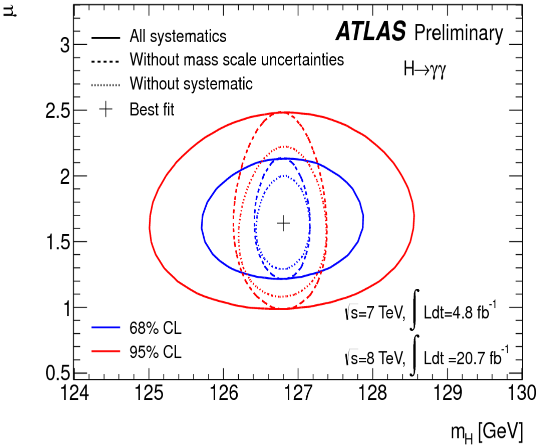
The analytic expression for the mixing matrix R upto $\mathcal{O}(\epsilon)$ is given by,

$$\begin{pmatrix} -\cos\theta_W & -\cos\hat{\theta}_W\sin^2\hat{\theta}_W\epsilon & \sin\theta_W \\ \sin\theta_W\sin\hat{\theta}_W\left[1+\frac{\cos^2\hat{\theta}_W}{\cos^2\theta_W}\epsilon\right] & -\cos\hat{\theta}_W\left[1-\sin^4\hat{\theta}_W\epsilon\right] & \sin\theta_W \\ \sin\theta_W\cos\hat{\theta}_W\left[1-\frac{\sin^2\hat{\theta}_W}{\cos\theta_W}\epsilon\right] & \sin\hat{\theta}_W\left[1+\sin^2\hat{\theta}_W\cos^2\hat{\theta}_W\epsilon\right] & \cos\theta_W\cos\hat{\theta}_W \end{pmatrix}$$

BACKUP: 2 jets+2 Z-bosons signature at 14TeV



BACKUP Higgs mass uncertainty in $H \to \gamma\gamma$ channel



BACKUP: μ and $\sigma \times BR_{invible}$ expression

Here we present the expressions for $\mu = \sigma/\sigma_{SM}$ and total $\sigma \times BR_{invible}$ for present model,

$$\mu = \frac{(\sigma_{h1} cos^4\theta BR_{h1}/(1 + 24BR^{gg}_{h1} sin^2\theta)) + (\sigma_{h2} sin^4\theta BR_{h2}/(1 + 24BR^{gg}_{h2} cos^2\theta))}{\sigma_{SM} * BR}$$

$$\sigma \times BR_{inv} = \frac{\sigma_{h1} cos^2\theta sin^2\theta(BR^{inv}_{h1} + 25BR^{gg}_{h1})}{1 + 24BR^{gg}_{h1} sin^2\theta} + \frac{\sigma_{h2} cos^2\theta sin^2\theta(BR^{inv}_{h2} + 25BR^{gg}_{h2})}{1 + 24BR^{gg}_{h2} cos^2\theta}$$