Parallel Universe, Dark Matter and Invisible Higgs Decays

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:Shreyashi Chakdar, Kirtiman Ghosh and S. Nandi, Phys. Lett. B 732 (2014) 343-348;
:Shreyashi Chakdar, Kirtiman Ghosh and S. Nandi, Work in progress.
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Outline of Talk

- Introduction and Motivation
- Model and Formalism
- Phenomenological Implications
- Conclusions and future work

Introduction and Motivation

- The discovery of the Higgs boson seems to complete the validation of the Standard Model, as all of the predicted particles and interactions have now been observed both qualitatively and quantitatively (within few percent)
- But along with Standard Model's shining achievement , there are several evidences that seem to suggest the presence of new physics.
- These are quatization of electric charges, parity violation at low energy, non-zero neutrino masses, existence of dark matter, absence of strong CP violation, unification of the gauge couplings, hierarchy problem, baryon asymmetry in the Universe
- In this work, we address four of these problems: charge quantization, parity violation at low energy, non-zero neutrino masses, and dark matter in the context of parallel universe and Pati-salam symmetry

Introduction and Motivation

- Theoretical progress towards these questions has been made basically along three direction

- i) Enlarge the SM gauge symmetry to a grand unified symmetry such as $SU(5), SO(10)$. This explains the charge quantization and unification of the couplings, but there is no sign of proton decay so far

- ii) Enlarge the bosonic symmetry to fermi-bose symmetry (supersymmetry). This solves hierarchy problem, agrees with the unification of couplings, and have good candidate for the dark matter. But there is also no sign of superpartners at the LHC yet

- iii)Increase the number of spatial directions (extra dimensions) and Include gravity into the mix (supergravity and string theory), but no sign of Kaluza-Klein excitations so far.

Introduction and Motivation

- The existence of the dark matter with amount about five times the ordinary matter $(\Omega_{DM}/\Omega_b = 4.83 \pm 0.87)$ is now well established experimentally
- There are many dark matter candidates such as the axions , WIMPs(Neutralino(SUSY) ,$B^{(1)}$(Extra dimensions)
- Dark Matter could also be just like the ordinary matter in a parallel universe with $(\alpha_s)_{dark} \simeq$ five times of α_s explaining why the dark matter is $\simeq$ five times the ordinary matter
- The two sectors can interact via the respective Higgs bosons. This will lead to the invisible decays of Higgs boson due to existence of a second light Higgs boson H_{dark} in parallel world, which if in the range of 2 GeV of observed higgs, can not be resolved as a separate mass in LHC
- In this work,we have studied the invisible decay modes of the Higgs in this scenario with phenomenology at the LHC

Model and Formalism

- We assume two universes where the electroweak sector is exactly symmetric, whereas the corresponding couplings in the strong sector are different
- The gauge symmetry is the Pati-Salam, $SU(4)_C \times SU(2)_L \times SU(2)_R$ for our universe, and $SU(4)'_C \times SU(2)'_L \times SU(2)'_R$ for the parallel universe.
- The model explains charge quantization, parity violation at low energy, and and non-zero neutriono masses. Since both universes are described by non-abelian gauge symmetry, the kinetic mixing between the photon (γ) and the parallel photon (γ') is forbidden.
- In our model, stable dark proton and the dark nuclei belonging to the parallel universe constitute the dark matter.
- We also assume that post-inflationary reheating in the two worlds are different, and the the parallel universe is colder than our universe. This keeps the successful prediction of the big bang nucleosynthesis, though g_* here is 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)

Model and the Formalism

- 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.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 ($g_L = g_R, g_L' = g_R'$ by left-right symmetry). We assume that in the EW sector, the couplings of the two universes are same.
- The 21 gauge bosons belong to the adjoint representations $(15, 1, 1)$, $(1, 3, 1)$, $(1, 1, 3)$
- $(15, 1, 1)$ contain the 8 usual colored gluons, 6 lepto-quark gauge bosons $(X, \bar{X})$, and one $(B - L)$ gauge boson
- $(1, 3, 1)$ 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

Model and the Formalism: Symmetry breaking

- Our gauge symmetry is $SU(4)_C \times SU(2)_L \times SU(2)_R$
- $SU(4)$ color symmetry is spontaneously broken to $SU(3)_C \times U(1)_{B-L}$ in the usual Pati-Salam way using the Higgs fields $(15,1,1)$ at a scale V_c,where $V_c > 2300TeV$
- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken to the SM using the Higgs representations $(1,3,1)+(1,1,3)$ at a scale V_{LR},where $V_{LR} > 2.5TeV$
- Finally the remaining symmetry is broken to the $U(1)_{EM}$ at the EW scale using the Higgs bi-doublet $(1,2,2)$ and $(15,2,2)$. Similar Higgs representations are used to break the symmetry in the parallel universe to $U'(1)$
- $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \rightarrow SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \rightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$

Model and the Formalism: Higgs Sector

- A study of the Higgs potential shows that there exist a parameter space where only one neutral Higgs in the bi-doublets remains light and becomes very similar to the SM Higgs in our universe. Similar is true in the parallel universe
- We impose a discrete symmetry in the Higgs sector of the two universes $H_{VIS} \leftrightarrow H_{DARK}$. This makes the vevs of the two sectors, V_{VIS} and V_{DARK} to be the same.
- The mixing terms between the two bi-doublets (one in our universe and one in the parallel universe) $\lambda(H_{VS}^{\dagger}H_{VS})(H_{DS}^{\dagger}H_{DS})$ leads to mixing between the two light remaining SM like Higgs fields.

Model and the Formalism: Higgs Sector

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

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

from which two mass eigenstates and mixing can be calculated

- The two physical light Higgs states are defined as,

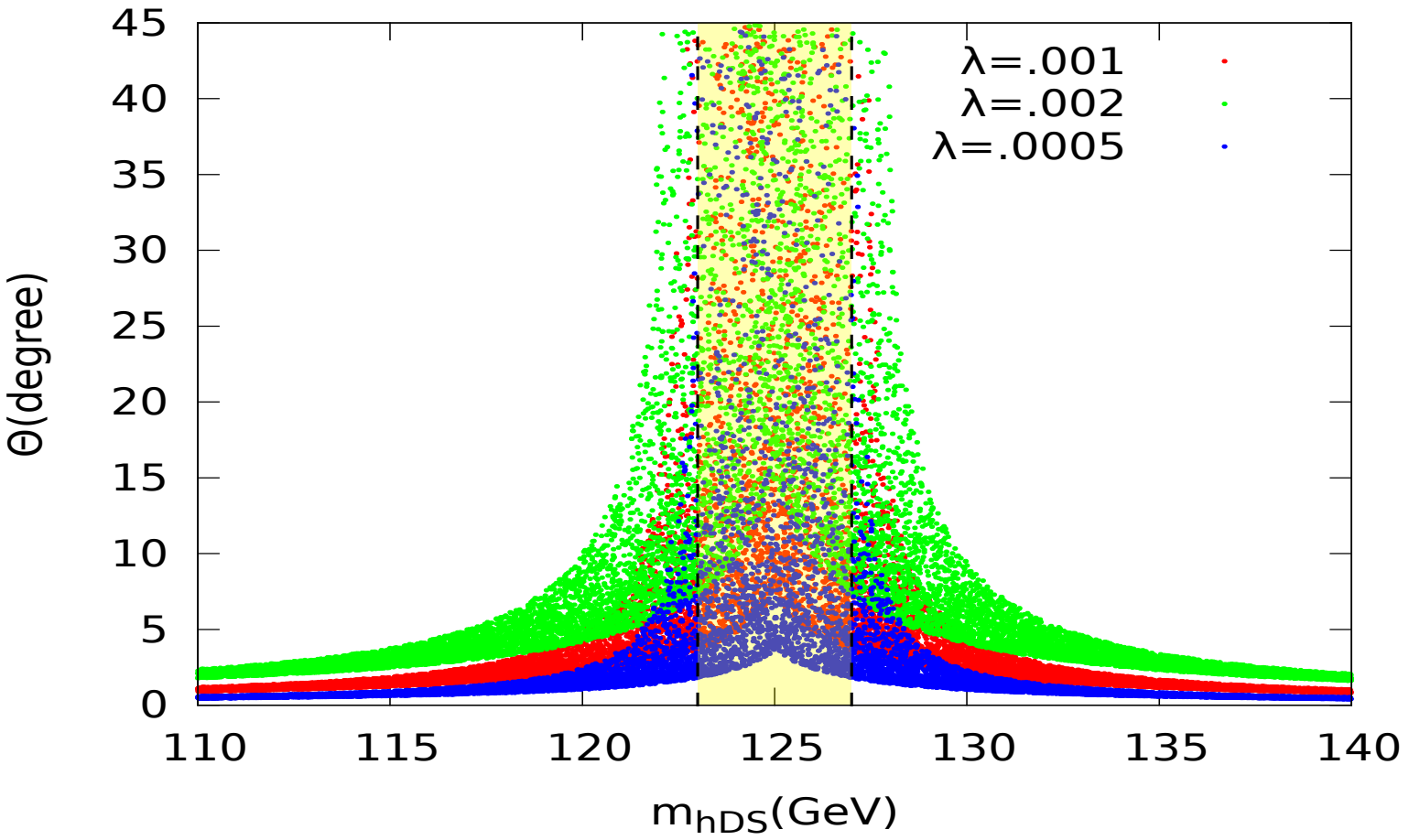
$$\begin{aligned} h_1^{(p)} &= \cos\theta\ h_1 + \sin\theta\ h_2 \\ h_2^{(p)} &= -\sin\theta\ h_1 + \cos\theta\ h_2 \end{aligned}$$

- 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 $v_{VS} = v_{DS} \simeq 250 GeV$

Phenomenology: Parameter space scan with m_{hSM} between $123 - 127$ GeV



Phenomenology: Collider signals

- 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.
- 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

Phenomenology: (Analysis in $\sigma \times$ BR)

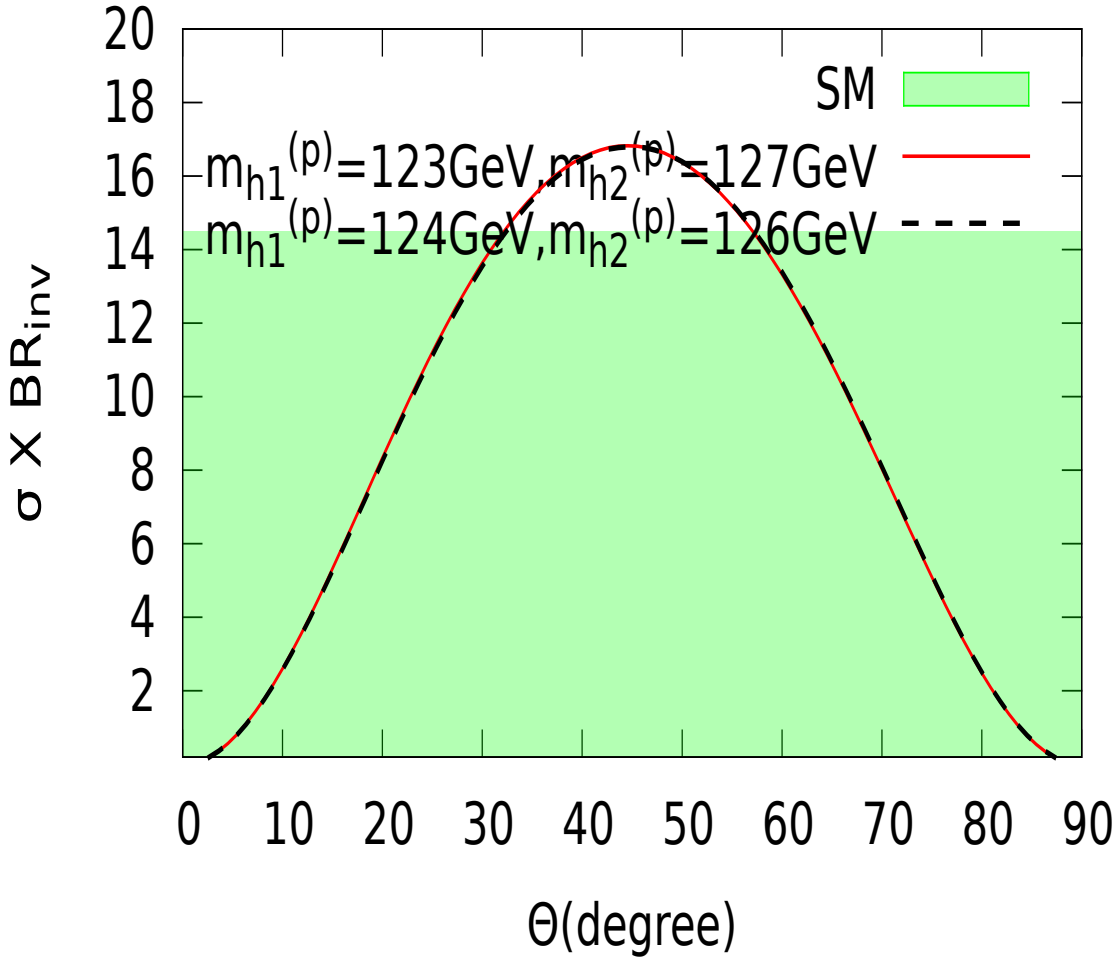


Figure: Production times decay rate in Present Model as a function of mixing angle θ. The shaded regions correspond to the allowed region

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

Phenomenology: (Analysis in $H \to WW \to l\nu l\nu$ channel)

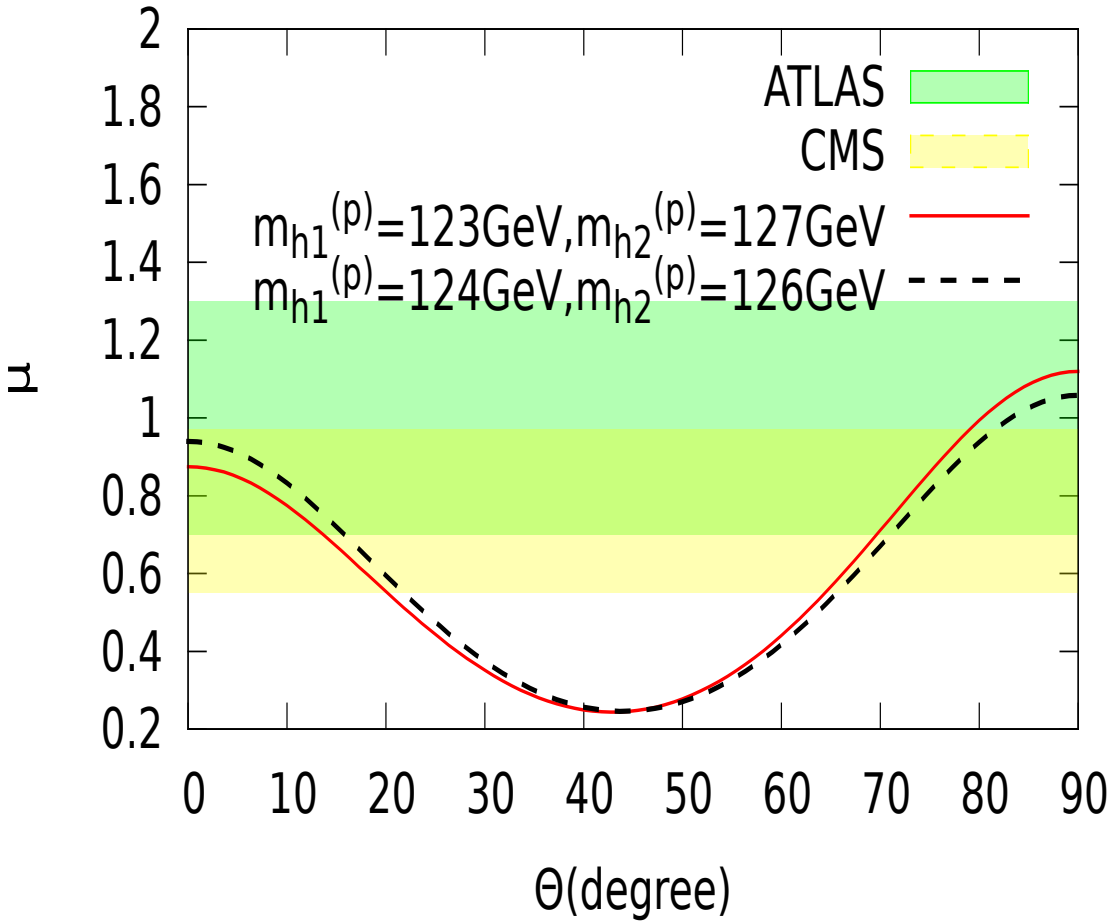


Figure: $H \to WW \to l\nu l\nu$ rate in Present Model as a function of mixing angle θ. The shaded regions correspond to ATLAS and CMS allowed

Phenomenology: (Analysis in $H \to \gamma\gamma$ channel)

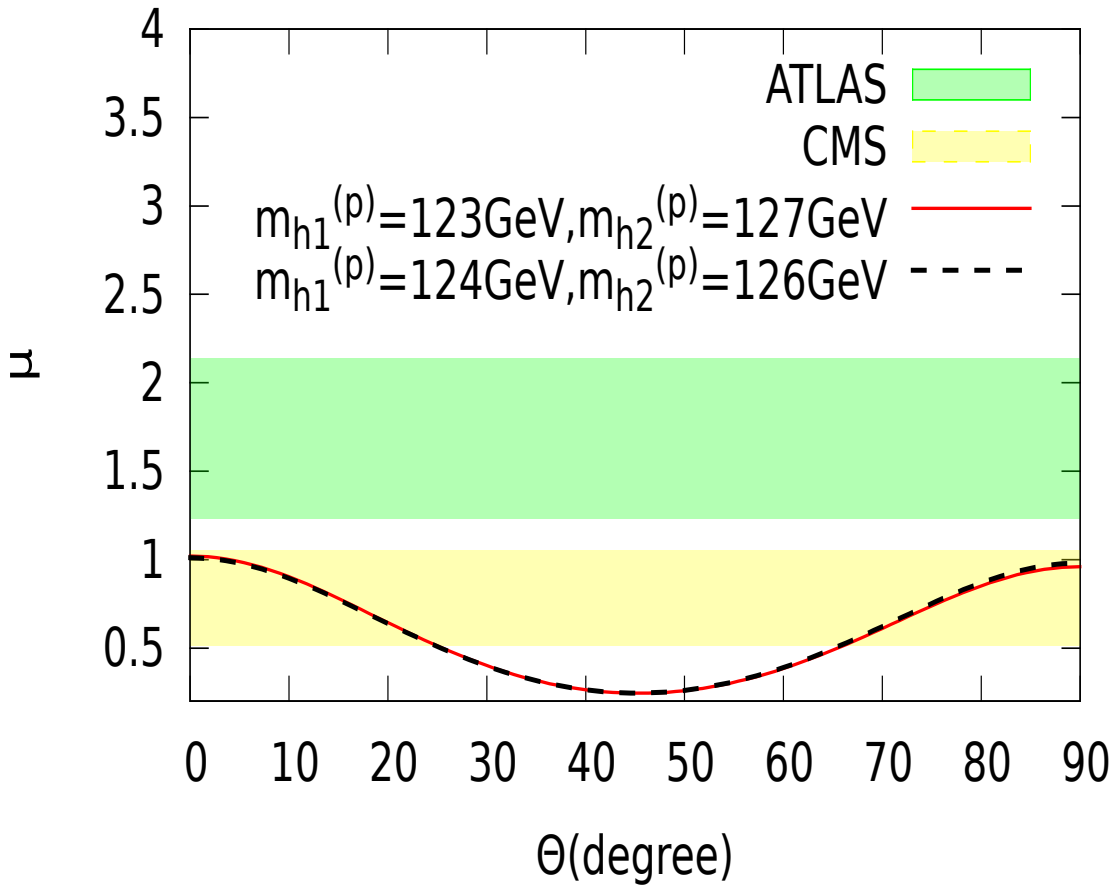


Figure: Higgs decaying into diphoton rate in Present Model as a function of mixing angle θ. The shaded regions again correspond to ATLAS and CMS allowed μ values.

Conclusions

- We presented a model which explains the parity violation at low energy parity, charge quantization, existence of non-zero neutrino masses and solves the dark matter problem
- The model has interesting phenomenological implication for both LHC and ILC.
- The two higgs bosons in both ordinary and parallel world are light and comparable in mass(within 2 GeV) and when produced in LHC cannot be resolved with the current data at the LHC 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.

Work in progress: Testing the model in future ILC and astrophysics

- If the two Higgs masses are split by more than 40 MeV, ILC will be able to see two separate peaks.
- The study of the decay modes of these two Higges will be able to distinguish the model from other models which can have also two low mass Higges.
- If the two Higgs masses are split by less than 40 MeV, then we can study the invisible decay width at the ILC as in LHC now, to test the model.
- Since our model has an exact $U(1)_{DARK}$, it might have an intersting implications for the $gamma$ ray burst.