Revisiting Higgs Physics in presence of a Light Radion

Soumya Sadhukhan

Vivekananda Centre for Research, RKM Residential College (Autonomous)
&
Indian Association of Cultivation of Sciences, Kolkata, India

HPNP2025, Osaka University

June 10, 2025

Background: Light Radion (+ Higgs Mixing)

- Absence of new physics at the TeV scale: new physics exists only at energies higher than the TeV scale. Lighter New Physics ?
  - Super-TeV new physics requires some fine tuning and scope of their search is limited $\Rightarrow$ Introduce new physics around sub-100 GeV scale.
  - LHC probe of lighter spectrum is not efficient due to enormous QCD background $\Rightarrow$ Good to consider innovative model building around 100 GeV scale.
  - Recent LHC results show mild excesses ($< 3\sigma$) in lighter mass range, many in $\gamma\gamma$ channel $\Rightarrow$ Better to look for something with distinct $\gamma\gamma$ coupling.

Can Radion be the light new particle of interest?

Radion is the scalar mode arising from the metric fluctuation of the warped extra dimensional models like the Randall Sundrum model.

- Radion-Higgs mixing case is interesting:
  - Radion mass can be light. It has enhanced gg coupling, can modify Higgs rate through mixing.
  - Trace anomaly contribution is present there in $\gamma\gamma$ channel: can be important compared to other channels.

Radion in Randall Sundrum (RS) model

- Minimal Randall-Sundrum (RS) model, an extra warped dimension of radius r_c is compactified: Gravity peaks at brane at $x_4 = 0$ (Planck brane). SM fields are confined to the $x_4 = r_c\pi$ (visible brane).
- Solving Einstein's equations, the metric has form Randall,Sundrum, 1999

$$ds^2 = e^{-2k|x_4|}\eta_{\mu\nu}dx^\mu dx^\nu - dx_4^2 \quad \text{with}, k = \sqrt{\frac{-\Lambda}{24M_5^3}}, |x_4| = r_c\theta$$

- r_c is considered as the vev of a modulus field $F(x)$ that quantifies the fluctuation about the radius: Goldberger, Wise, 1999

$$ds^2 = e^{-2k|\theta|F(x)}g_{\mu\nu}dx^\mu dx^\nu - F^2(x)d\theta^2$$

- With this metric, 4D effective action reduces to

$$\mathcal{S} = \frac{2M_5^3}{k}\int d^4x\sqrt{-g}\left[1 - \frac{k\,\Phi^2}{24\,M_5^3}\right]R + \frac{1}{2}\int d^4x\sqrt{-g}\partial_\mu\Phi\partial^\mu\Phi$$

for the radion field $\Phi = \sqrt{\frac{24\,M_5^3}{k}}\,e^{-k\,\pi F(x)}$.

- A mechanism is needed to fix r_c uniquely to the desired value: Goldberger-Wise mechanism.

Radion Interaction to SM fields

- Radion interaction with matter on the visible brane:

$$\mathcal{L}_{int} = \frac{\varphi}{\langle \Phi \rangle} T^{\mu}_{\mu} \equiv \frac{\varphi}{\Lambda_{\varphi}} T^{\mu}_{\mu},$$

$\Lambda_{\varphi} \equiv \langle \Phi \rangle$. $T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta \mathcal{S}_{matter}}{\delta g^{\mu\nu}}$ is the gauge invariant tree-level energy-momentum tensor with the form:

$$T^{\mu}_{\mu} = \sum_{f} m_f \bar{f} f - \partial_{\mu} h \partial^{\mu} h + 2 m_h^2 h^2 - 2 m_W^2 W^{+\mu} W^{-}_{\mu} - m_Z^2 Z^{\mu} Z_{\mu}$$

- The trace anomaly appears because of breaking of the scale invariance of massless fields by the running of respective gauge coupling constants.
- Massless gauge boson radion interaction:

$$\mathcal{L}^{gauge}_{int} = \sum_{i} \frac{\beta(e_i)}{2 e_i^3} F^{\mu\nu i} F^{i}_{\mu\nu} \frac{\varphi}{\Lambda_{\varphi}}$$

where $\beta(e_i)$ is the beta function for gauge coupling e_i.
- The Radion-Higgs mixing is induced through the following term Giudice; Csaki

$$\mathcal{L}_{mix.} = -\xi \sqrt{-g_i} R(g_i) H^{\dagger} H.$$

Radion Higgs Mixing

- The Higgs and radion sector becomes, with $\gamma \equiv v/\Lambda_\varphi$,

$$\mathcal{L} = \frac{1}{2}\partial^\mu h\,\partial_\mu h - \frac{1}{2}m_h^2 h^2 + \frac{(1+6\gamma^2\xi)}{2}\partial^\mu\varphi\,\partial_\mu\varphi - \frac{1}{2}m_\varphi^2\varphi^2 - 6\gamma\xi\,\partial^\mu\varphi\,\partial_\mu h.$$

- The mass eigenstates h_m, r_m can be combined through overall mixing:

$$\begin{aligned} h &= \left(\cos\theta - \frac{6\xi\gamma}{Z}\sin\theta\right)h_m + \left(\sin\theta + \frac{6\xi\gamma}{Z}\cos\theta\right)\varphi_m, \\ \varphi &= -\frac{\sin\theta}{Z}h_m + \frac{\cos\theta}{Z}\varphi_m \end{aligned}$$

where mixing angle θ is given as $\tan 2\theta = \frac{12\gamma\xi Z m_h^2}{m_\varphi^2 - m_h^2(Z^2 - 36\gamma^2\xi^2)}$

- The physical mass are given by:

$$\begin{aligned} m_{\varphi_m}^2 &= \frac{1}{2Z^2}\left(\Xi - \sqrt{\Xi^2 - 4Z^2 m_\varphi^2 m_h^2}\right) \\ m_{h_m}^2 &= \frac{1}{2Z^2}\left(\Xi + \sqrt{\Xi^2 - 4Z^2 m_\varphi^2 m_h^2}\right) \end{aligned}$$

with $\Xi = m_\varphi^2 + (1+6\gamma^2\xi)m_h^2$.

Higgs and Radion Couplings

Coupling	Value
$c_{\varphi\bar{f}f}$	$\frac{-m_f}{v}\left(s_\theta+\frac{6\xi\gamma c_\theta}{Z}+\frac{\gamma c_\theta}{Z}\right)$
$c_{\varphi\gamma\gamma}$	$\frac{-1}{v}\left[\left(s_\theta+\frac{6\xi\gamma c_\theta}{Z}+\frac{\gamma c_\theta}{Z}\right)\left(F_1(\tau_W)+\frac{4}{3}F_{1/2}(\tau_t)\right)-\gamma(b_2+b_Y)\frac{c_\theta}{Z}\right]$
$c_{\varphi gg}$	$\frac{-1}{v}\left[\left(s_\theta+\frac{6\xi\gamma c_\theta}{Z}+\frac{\gamma c_\theta}{Z}\right)\frac{F_{1/2}(\tau_t)}{2}-\gamma b_3\frac{c_\theta}{Z}\right]$
$c_{\varphi W^+W^-}$	$\frac{2m_W^2}{v}\left(s_\theta+\frac{6\xi\gamma c_\theta}{Z}+\frac{\gamma c_\theta}{Z}\right)$
$c_{\varphi ZZ}$	$\frac{m_Z^2}{v}\left(s_\theta+\frac{6\xi\gamma c_\theta}{Z}+\frac{\gamma c_\theta}{Z}\right)$
$c_{h\bar{f}f}$	$-\frac{m_f}{v}\left(c_\theta-s_\theta\frac{6\xi\gamma}{Z}-s_\theta\frac{\gamma}{Z}\right)$
$c_{h\gamma\gamma}$	$\frac{-1}{v}\left[\left(c_\theta-s_\theta\frac{6\xi\gamma}{Z}-s_\theta\frac{\gamma}{Z}\right)\left(F_1(\tau_W)+\frac{4}{3}F_{1/2}(\tau_t)\right)+\gamma(b_2+b_Y)\frac{s_\theta}{Z}\right]$
c_{hgg}	$\frac{-1}{v}\left[\left(c_\theta-s_\theta\frac{6\xi\gamma}{Z}-s_\theta\frac{\gamma}{Z}\right)\frac{F_{1/2}(\tau_t)}{2}+\gamma b_3\frac{s_\theta}{Z}\right]$
$c_{hW^+W^-}$	$\frac{2m_W^2}{v}\left(c_\theta-s_\theta\frac{6\xi\gamma}{Z}-s_\theta\frac{\gamma}{Z}\right)$
c_{hZZ}	$\frac{m_Z^2}{v}\left(c_\theta-s_\theta\frac{6\xi\gamma}{Z}-s_\theta\frac{\gamma}{Z}\right)$

$b_3=7, b_2=19/6, b_Y=-41/6$

Free parameters of the model

- Higgs radion mixing parameter (ξ)
- Radion vacuum expectation value (Λ_φ)
- Radion mass (m_φ)

Constraints

- Theoretical Constraints, EWPT
- LEP, LHC Exclusion bound (HiggsBounds-4)
- Higgs Signal Measurements (HiggsSignals)

LHC Phenomenology

- Light (Higgs mixed) Radion: $\gamma\gamma$ Excess
- 95 GeV Radion (Higgs mixed)

Theoretical (+ Other) Constraints

- Scalar masses:
  - For the Higgs and radion masses to be real:

$$\left(m_{\varphi_m}^2 + m_{h_m}^2\right)^2 > \frac{4(1+6\gamma^2\xi)m_{\varphi_m}^2 m_{h_m}^2}{Z^2}$$

  - Mixing angle is real to keep the radion kinetic term positive. This translates to:

$$\frac{1}{12}\left(1-\sqrt{1+\frac{4}{\gamma^2}}\right) \leq \xi \leq \frac{1}{12}\left(1+\sqrt{1+\frac{4}{\gamma^2}}\right)$$

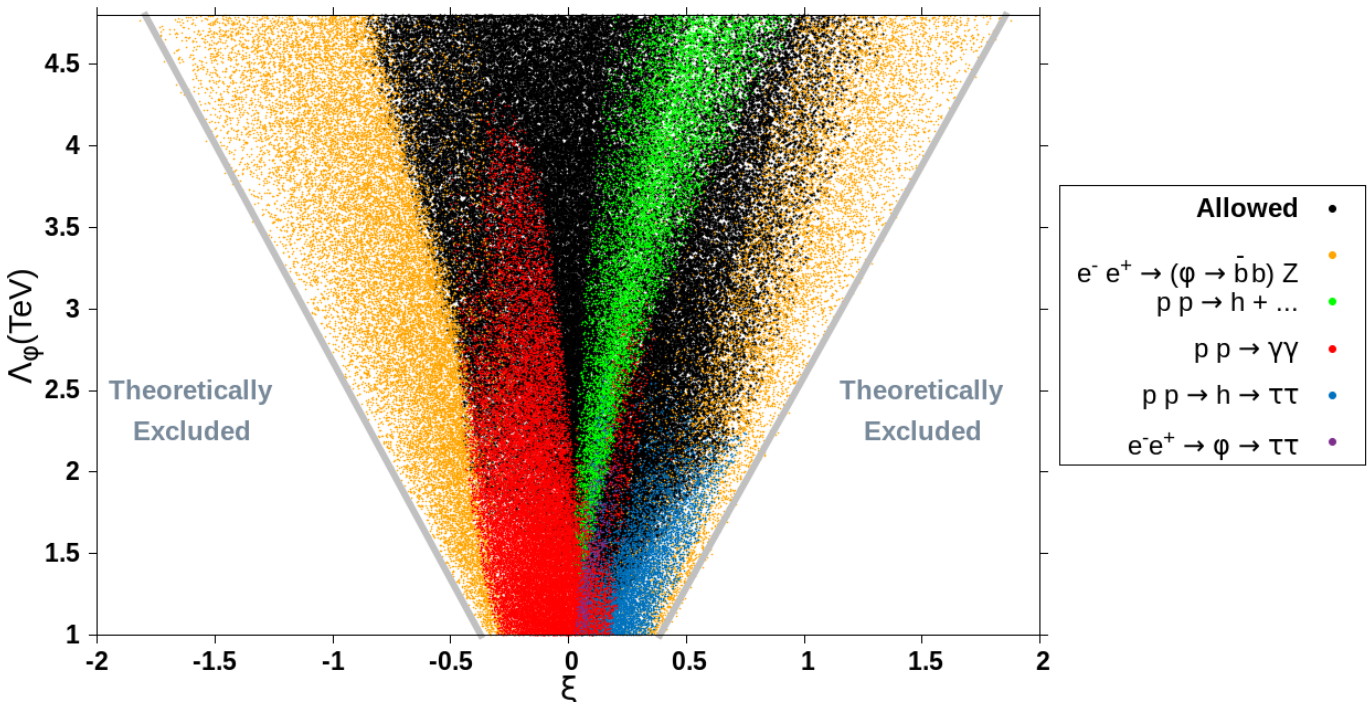
- Unitarity
  - The contribution of a light radion with $\Lambda_\varphi \sim$(1-5) TeV to the amplitudes of gauge boson scattering is subleading. High energy behaviour is mainly decided by the SM higgs boson.

- Constraints coming from Electroweak precision test (EWPT) due to presence of a radion were taken into account. Gunion et al, 2004

LHC LEP Exclusion

• Limits from the non observation of Higgs like resonances at LEP, Tevatron and LHC are imposed. This is done using the model implementation in HiggsBounds package. Exclusion in extended scalar sectors: Heinemeyer et al

• Theoretical and exclusion limits from collider search of Higgslike scalar constrain the parameter space:



Key Points: LEP, LHC Exclusion

- LEP $e^- e^+ \to Zjj/b\bar{b}$ search: puts the most stringent bound.
  - Lightness of $m_\varphi < m_h$ + enhanced coupling of the φ to gluon, $e^- e^+ \to Z\varphi$ contributes significantly to $e^- e^+ \to Zjj/b\bar{b}$.
  - The points at higher ξ (both +ve and -ve) for any Λ_φ get curtailed.
- LHC $\sigma(p\,p \to h)$ search also restricts significant part.
  - LHC SM Higgs-like scalar search before the Higgs discovery put the upper limits through restricting $\sigma(p\,p \to h)$ close to the SM values.
  - Here the Higgs-like particle has enhanced gluon couplings in $\xi > 0$ range, leading to enhanced gluon fusion production: even small medium positive ξ part ruled out.
- LHC $pp \to \gamma\gamma$ search constrains some -ve ξ part:
  - Due to the non-minimal contribution of new radion mediated process $pp \to \varphi \to \gamma\gamma$, the $pp \to \gamma\gamma$ increases.
  - Even with reduced gluon fusion production for -ve ξ, diphoton channels then can rule out those parts of the parameter space.

Higgs Signal Measurement

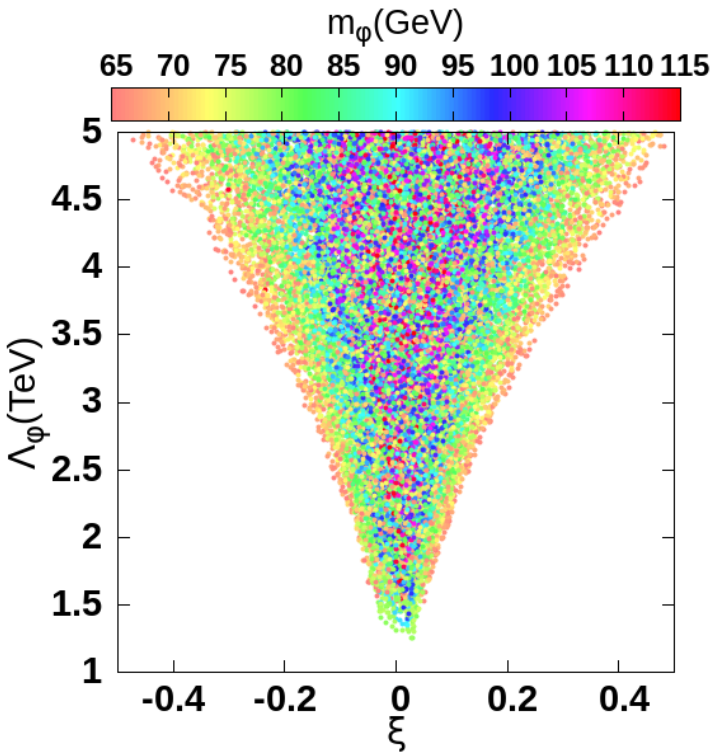
- Higgs Signal: The constraints on the Higgs signal are given in terms of μ parameters obtained from the LHC data,

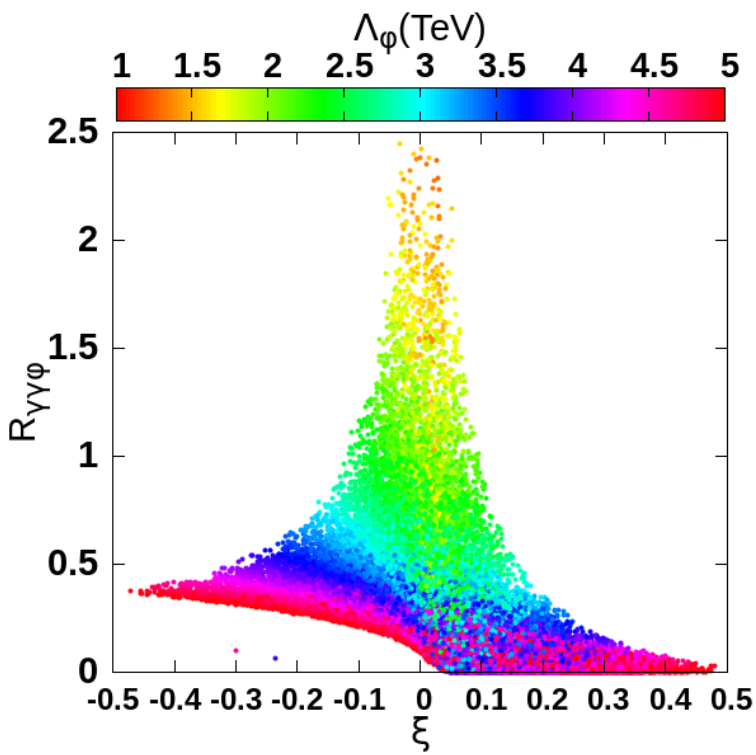
	CMS & ATLAS Combined	CMS, 13 TeV, 2023
$\mu_{\gamma\gamma}$	$1.16^{+0.19}_{-0.18}$	$1.13^{+0.09}_{-0.09}$
μ_{bb}	$0.70^{+0.29}_{-0.27}$	$1.05^{+0.22}_{-0.21}$
$\mu_{\tau\tau}$	$1.11^{+0.24}_{-0.22}$	$0.85^{+0.10}_{-0.10}$
μ_{ZZ}	$1.29^{+0.26}_{-0.23}$	$0.97^{+0.12}_{-0.11}$
μ_{WW}	$1.09^{+0.18}_{-0.16}$	$0.97^{+0.09}_{-0.09}$

- 2 σ range of the μ parameters are taken to find out allowed parameter space.
- Radion Signal: The relative radion signal strength is defined as:

$$R_{\gamma\gamma\varphi} = \frac{\sigma(pp \to \varphi) \times \mathrm{BR}(\varphi \to \gamma\gamma)}{[\sigma(pp \to h) \times \mathrm{BR}(h \to \gamma\gamma)]_{SM}} \approx \frac{\Gamma(\phi \to gg)}{\Gamma(h \to gg)_{SM}} \times \frac{\mathrm{BR}(\varphi \to \gamma\gamma)}{\mathrm{BR}(h \to \gamma\gamma)_{SM}}$$

Higgs Signal Constraints





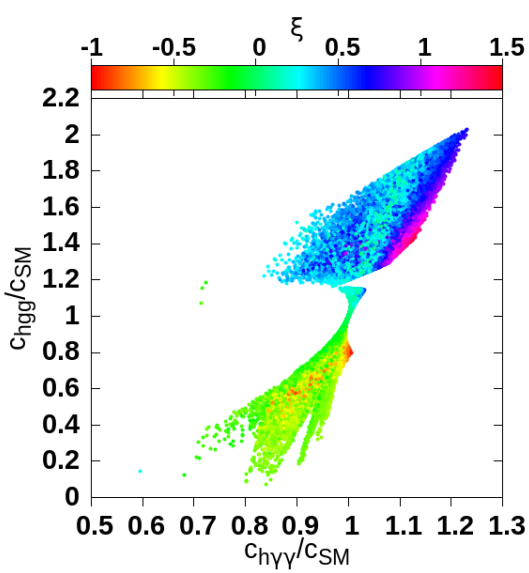
• The parameter space allowed from the exclusion limits significantly reduced: for $\Lambda_\varphi < 5$ TeV, mixing parameter is restricted as $-0.5 < \xi < 0.5$.

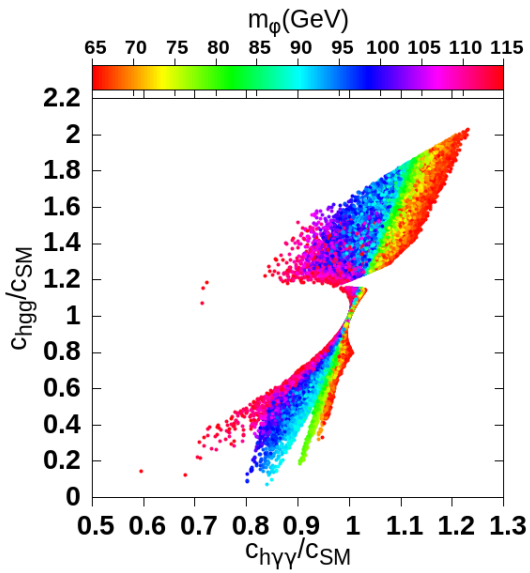
SM Higgs vs Radion Mixed Higgs: χ^2 test

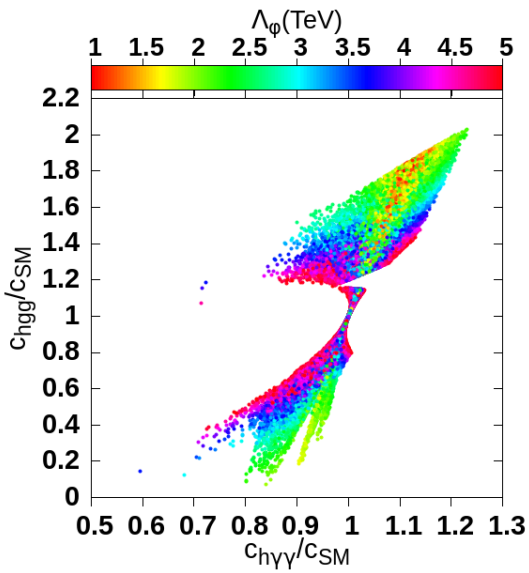
- The χ^2 test is performed to compare the mixed radion-Higgs scenario with the SM.
- With $\chi^2_{\varphi h}$ computed for radion-mixed Higgs,

$$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{\varphi h},$$

and $\Delta\chi^2 > 0$ fits the LHC observations better than the SM Higgs.

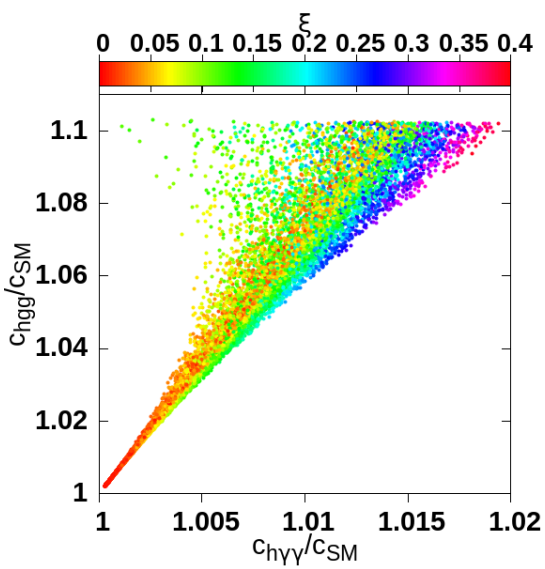


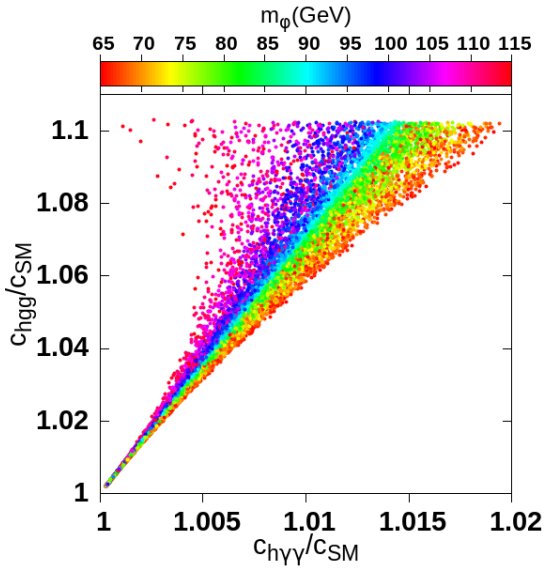


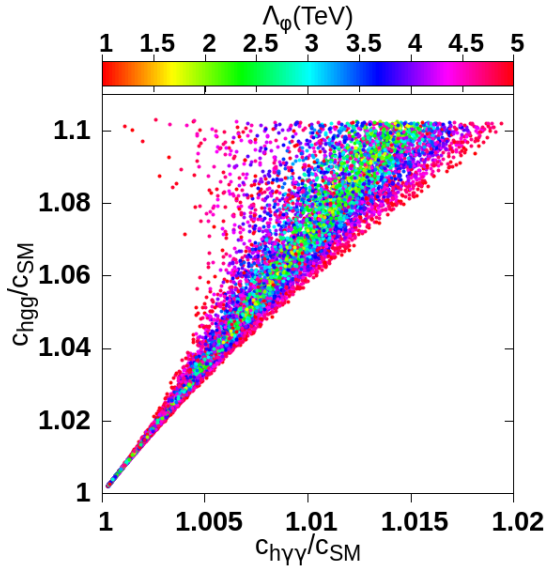


- In general, $c_{h\gamma\gamma}$ is more restricted than c_{hgg}: QCD trace anomaly contributions are dominant compared to that from the weak (QED) sector.

Radion Mixed Higgs: 125 GeV Scalar



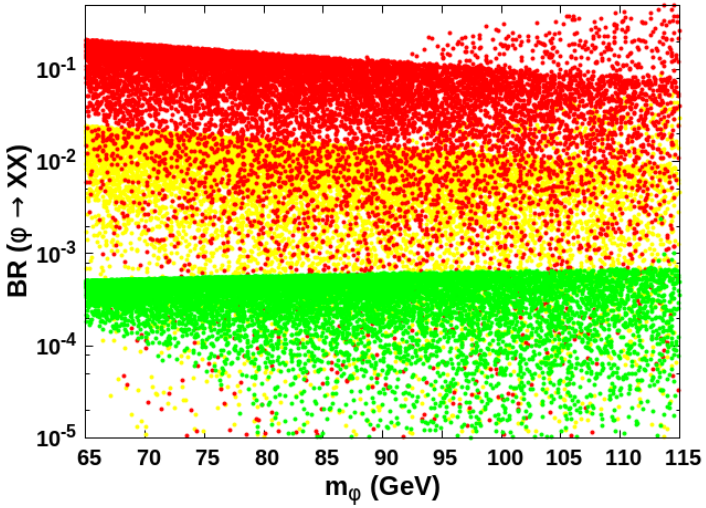




- Only the parts of parameter space with $\xi > 0$ fit better to the LHC data compared to the SM Higgs.
- This correlation is more prominent for $\Delta\chi^2 > 0$: it restricts the $c_{h\gamma\gamma}$ close to the SM values while allowing a 10% increase for c_{hgg}/c_{SM} values.
- A slight increase of gg fusion production rate: push the μ parameters towards larger values, fitting the data better than the SM.

Light Higgs mixed Radion: $\gamma\gamma$ Signal

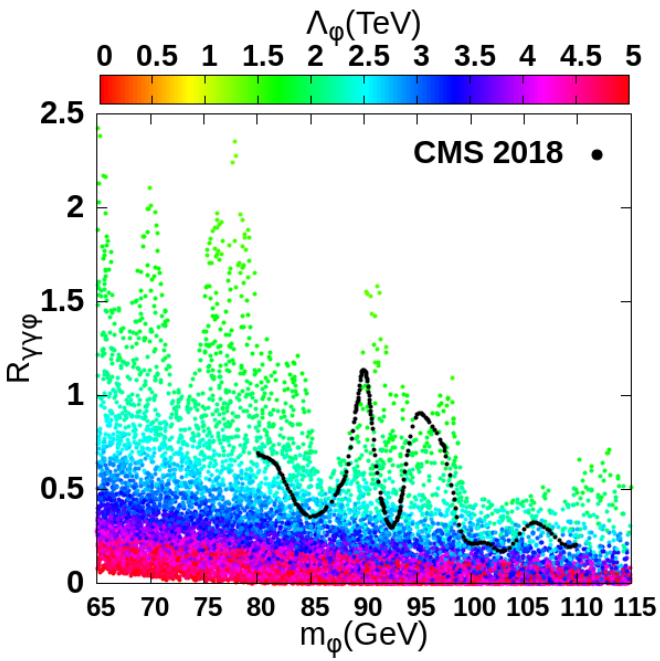
- For a generic light radion, we probe the radion mass $65 - 115$ GeV.

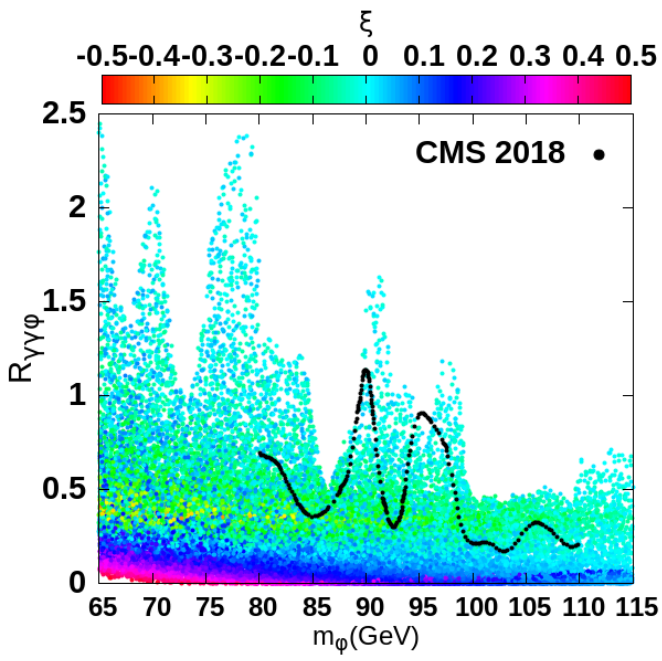


Red: bb channel, Yellow: $\tau\tau$ channel, Green: $\gamma\gamma$ channel

- This enhancement leads to a significant increase in $\varphi \to g\,g$ branching ratio (BR): reduces the radion BR into other final states.
- The drop in BR ($\varphi \to \gamma\,\gamma$) is minimal compared to the other channels: It remains a significant mode to radion search at colliders.
- Similar to the SM Higgs, radion is dominantly produced in the gluon fusion mode: due to enhanced $c_{\varphi gg}$.
- For $\Delta\chi^2 > 0$ points, the enhancement of radion cross section is significantly curtailed to limit itself to at most twice of the SM values, for significant part of the parameter space.

Light Higgs mixed Radion: $\gamma\gamma$ Signal

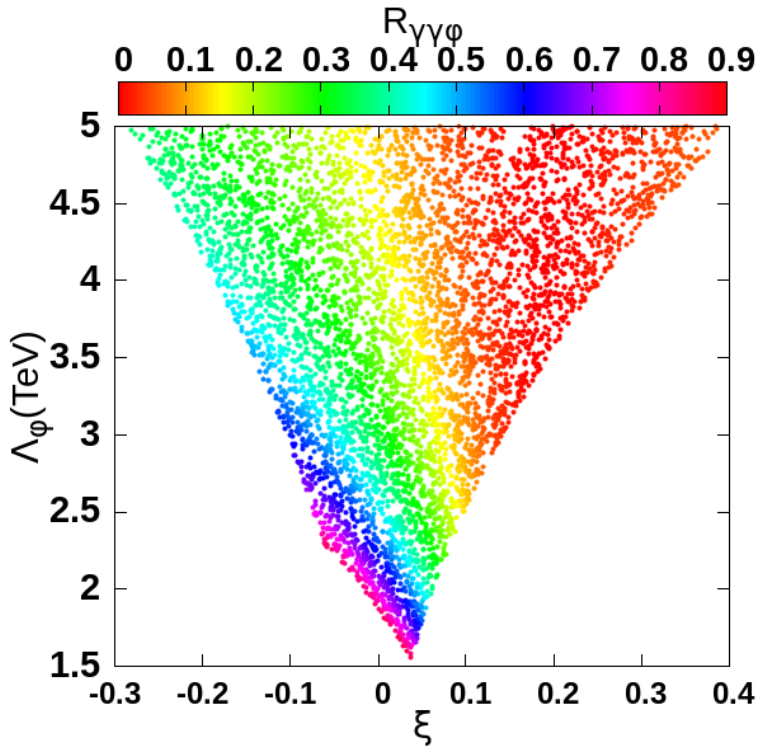


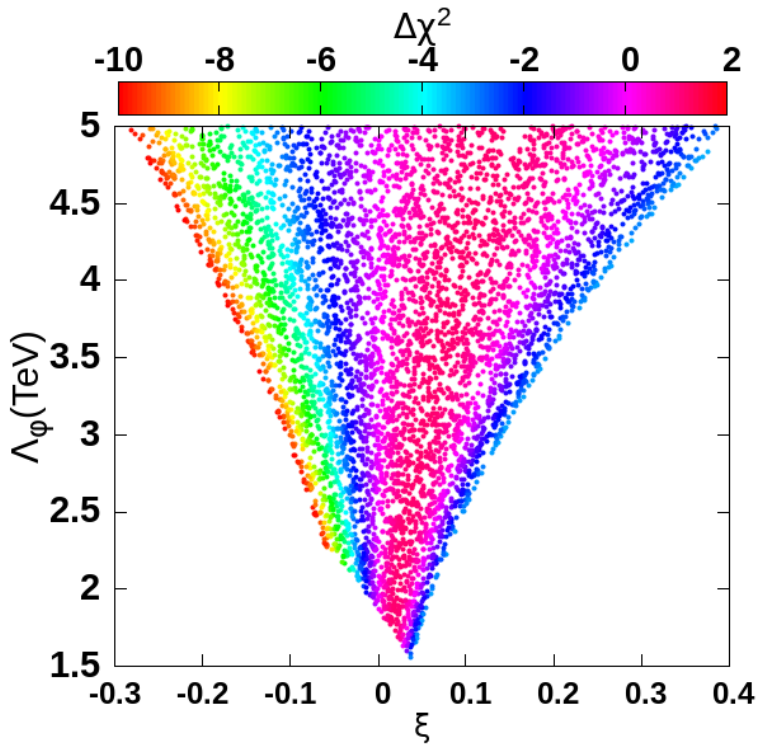


- Smaller $R_{\gamma\gamma\varphi}$ favored, consistent with LHC light scalar search: roughly corresponds to $\Lambda_\varphi > 2.5$ TeV.
- Points with smaller positive ξ and smaller Λ_φ produce excesses in the $\gamma\gamma$ channel for different radion masses: an indication of excess around $m_\varphi \sim 95$ GeV, already hinted in CMS observation.
- The radion-Higgs mixing predicts towards a hint of radion diphoton rate enhancement at other masses like $m_\varphi \sim 70, 77, 90$ GeV as well.

Higgs mixed Radion: 95 GeV Excess

- Radion mass is fixed at $m_\varphi = 95$ GeV. Allowed parameter space:





- $-0.25 \leq \xi \leq 0.35$ and $1.5 \leq \Lambda_\varphi \leq 5$ (TeV) satisfies all the theoretical and experimental constraints.
- With $\Delta\chi^2 > 0$ condition, only a small strip near positive ξ remain allowed.
- The exact signal strength ($R_{\gamma\gamma\varphi} = 0.7$) is achieved by fixing $\xi \sim 0.01$, $\Lambda_\varphi \sim 2$ TeV.

Summary & Outlook

- The Higgs and new scalar search exclusion results from LEP, Tevatron and LHC: $e^+e^- \to Zh/\varphi, h/\varphi \to bb/jj$ most constraining, with $pp \to \gamma\gamma$ and $pp \to h + X$ being the next ones.
- With $\xi > 0$, along with modified gluon fusion production rate, Higgs-like scalar with a tinge of radion is a more favorable candidate than the SM Higgs to be the observed 125 GeV scalar.
- It is phenomenologically viable for the Higgs mixed radion to be a light sub-125 GeV BSM scalar to produce a diphoton signal at the LHC.
- It is worthwhile to explore different BSM scenarios with a 125 GeV scalar that explains the LHC Higgs data better than the SM Higgs, along with explaining other issues not resolved in the SM.
- This work (published in PRD with Divya Sachdeva) contains the analysis upto 2020. Most updated analysis taking into account the most recent data, need of the hour.

Thank You