2HDM with Gauged Higgs Fields

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Collaboration with P. Ko, Y. Omura (PLB717, 202)
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2HDM

- Most new physcis scenarios expect an extension of the Higgs sector in the Standard Model.

- 2HDM: one of the simplest extensions to the SM Higgs sector.
  - without any symmetry both Higgs fields interact with SM fermions.

    Flavor-changing neutral currents (FCNCs) appear.

Natural Conservation Law for 2HDM

- Glashow and Weinberg (PRD15, 1977)

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Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 20 August 1976)

We explore the consequences of the assumption that the direct and induced weak neutral currents in an $SU(2)\otimes U(1)$ gauge theory conserve all quark flavors *naturally*, i.e., for all values of the parameters of the theory. This requires that all quarks of a given charge and helicity must have the same values of weak T_3 and $\vec{T}^2$. If all quarks have charge $+2/3$ or $-1/3$ the only acceptable theories are the "standard" and "pure vector" models, or their generalizations to six or more quarks. In addition, there are severe constraints on the couplings of Higgs bosons, which apparently cannot be satisfied in pure vector models. We also consider the possibility that neutral currents conserve strangeness but not charm. A natural seven-quark model of this sort is described. The experimental consequences of charm nonconservation in direct or induced neutral currents are found to be quite dramatic.

order 10^{-3}.) We see that an off-diagonal Higgs coupling of the form $d\to H+S$ would be expected to produce much too large a K_1^0-K_2^0 mass difference. Thus we are led to our third condition.

Condition III. We demand that the coupling of each neutral Higgs meson be such as naturally to conserve all quark flavors: strangeness, charm, etc.

conserve quark flavor. We conclude that Condition III is equivalent to the requirement that *quarks of given charge receive their mass either* (1) *through the couplings of precisely one neutral Higgs meson or* (2) *through an SU(2)-invariant mass term, but not by both mechanisms.* This condition might be evaded in special cases, as for instance through the judicious introduction of discrete symmetries.

Fermions with identical charge couples to only one Higgs doublet: No FCNCs.

2HDM

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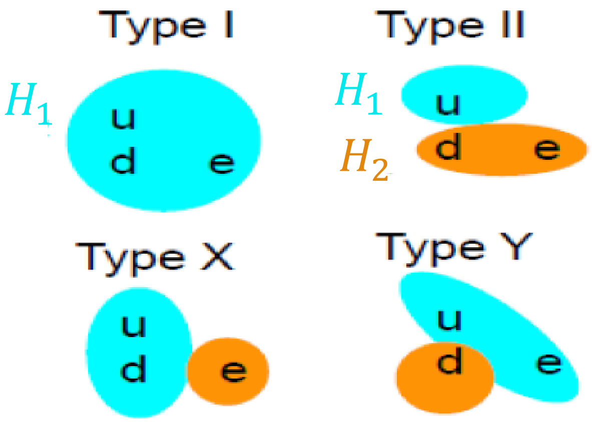
- 2HDM: one of the simplest extensions of the SM Higgs sector.
  - Without any symmetry both Higgs fields interact with SM fermions.

    Flavor-changing neutral currents (FCNCs) appear.

  - A simple way to avoid the FCNC problem is to assign an ad hoc Z_2 symmetry.

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+



Softly Broken Z_2 Symmetry

- Spontaneously broken discrete symmetry can lead to several degenerate ground states.
  - The different ground state regions may be seperated by stable domain walls.

    Okun, Kobzarev, Zeldovich (1974)

- Usually the Z_2 symmetry is assumed to be broken softly by dim-2 operators $H_1^\dagger H_2 + h.c.$.

The softly broken Z_2 symmetric 2HDM potential

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

- What is the origin of the dim-2 terms?

2HDM with Gauged Higgs Fields

- Ko, Omura, and Yu suggested 2HDMs with gauged Higgs fields.

Ko, Omura, Yu, PLB717 (2012)

  - Z_2 Symmetry is replaced by a $U(1)_H$ gauge symmetry.
  - One of Higgs fields is charged under the gauge symmetry.
  - According to the charge assignments to fermions, Type I, II, X, Y models can be realized.
  - The $U(1)_H$ gauge symmetry may have gauge anomaly.
  - Extra fermions are required to cancel the gauge anomaly.
  - In the Type I case, the anomaly cancellation without extra fermions is possible.

Scalar Potential

- The dim-2 and λ_5 terms are forbidden due to the gauge symmetry.

Ko, Omura, Yu, PLB717 (2012)

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

  - The dim-2 terms are related to the mass of the charged Higgs boson.
  - The non-existence of the λ_5 terms implies that the custodial symmetry limit is achieved only when $\lambda_4 = \lambda_5 = 0$.

- The dim-2 terms may be generated by an additional singlet field.

$$-\{\sqrt{2}\mu_\Phi H_1^\dagger H_2 \Phi + H.c.\} \Rightarrow -\mu_\Phi v_\Phi H_1^\dagger H_2 + H.c.$$

  - Then, becomes a 2HD + singlet model.

- Without the dim-2 terms: no pseudoscalar in the model. ⇒ a dark Z model

Scalar Potential in 2HDM + $U(1)_H$

- The scalar potential is

Ko, Omura, Yu, PLB717 (2012)

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

$$+ m_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \tilde{\lambda}_1 (\Phi^\dagger \Phi)(H_1^\dagger H_1) + \tilde{\lambda}_2 (\Phi^\dagger \Phi)(H_2^\dagger H_2) - \{\sqrt{2}\mu_\Phi H_1^\dagger H_2 \Phi + H.c.\}$$

  - only the first line in the dark Z model.

- VEVs

$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_i + i\chi_i^0) \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi + i\chi_\Phi)$$

$$\tan\beta \equiv v_2/v_1 \qquad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

CP-odd states

- CP-odd states

$$M_A^2 = \mu_\Phi \begin{pmatrix} \frac{v_1 v_2}{v_\Phi} & -v_2 & v_1 \\ -v_2 & \frac{v_2 v_\Phi}{v_1} & -v_\Phi \\ v_1 & -v_\Phi & \frac{v_1 v_\Phi}{v_2} \end{pmatrix} \qquad V_A = \begin{pmatrix} 0 & c_\beta & s_\beta \\ c_\delta & s_\beta s_\delta & -c_\beta s_\delta \\ s_\delta & -s_\beta c_\delta & c_\beta c_\delta \end{pmatrix} \rightarrow \begin{pmatrix} \chi_\Phi \\ \chi_1 \\ \chi_2 \end{pmatrix} = V_A^\intercal \begin{pmatrix} G_1^0 \\ G_2^0 \\ A \end{pmatrix}$$

  - Two Goldstone bosons G_1^0 and G_2^0 are eaten by Z and Z' + one pseudoscalar boson.
  - In the dark Z model, two Goldstone bosons are required by two U(1) symmetries and no degree of freedom for pseudoscalar boson remains.

- Charged Higgs boson mass

$$m_{H^\pm}^2 = \left(\frac{\mu_\Phi v_\Phi}{v_1 v_2} - \frac{\lambda_4}{2}\right) v^2$$

  - Without v_Φ, the charged Higgs boson mass is at most 620 GeV.

CP-even states

- 3 CP-even states in the 2HD + singlet model
  - mass matrix

$$M_h^2 = \begin{pmatrix} 2\lambda_\Phi v_\Phi^2 + \mu_\Phi \frac{v_1 v_2}{v_\Phi} & \tilde{\lambda}_1 v_1 v_\Phi - \mu_\Phi v_2 & \tilde{\lambda}_2 v_2 v_\Phi - \mu_\Phi v_1 \\ \tilde{\lambda}_1 v_1 v_\Phi - \mu_\Phi v_2 & 2\lambda_1 v_1^2 + \mu_\Phi \frac{v_\Phi v_2}{v_1} & v_1 v_2(\lambda_3 + \lambda_4) - \mu_\Phi v_\Phi \\ \tilde{\lambda}_2 v_2 v_\Phi - \mu_\Phi v_1 & v_1 v_2(\lambda_3 + \lambda_4) - \mu_\Phi v_\Phi & 2\lambda_2 v_2^2 + \mu_\Phi \frac{v_\Phi v_1}{v_2} \end{pmatrix}$$

  - mixing angles

$$V_h = \begin{pmatrix} c_\psi c_\phi - c_\alpha s_\phi s_\psi & c_\psi s_\phi + c_\alpha c_\phi s_\psi & s_\alpha s_\psi \\ -s_\psi c_\phi - c_\alpha s_\phi c_\psi & -s_\psi s_\phi + c_\alpha c_\phi c_\psi & c_\psi s_\alpha \\ s_\alpha s_\phi & -s_\alpha c_\phi & c_\alpha \end{pmatrix}$$

$$h_i = (V_h)_{ji} S_j$$

$$h_j \equiv (h_\Phi, h_1, h_2)$$

$$S_j \equiv (\tilde{h}, h, H)$$

- 2 CP-even states in the dark Z model.

$$m_{h,H}^2 = \lambda_1 v_1^2 + \lambda_2 v_2^2 \pm \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + (\lambda_3 + \lambda_4)^2 v_1^2 v_2^2}$$

$$\tan 2\alpha = \frac{-(\lambda_3 + \lambda_4)\tan\beta}{\lambda_1 - \lambda_2 \tan^2\beta}$$

$Z - Z'$ Mixing

- Gauge boson mixing in dark Z model

$$\begin{pmatrix} A_X \\ W^3 \\ B \end{pmatrix} = \begin{pmatrix} c_X Z' + s_X Z \\ -s_X c_W Z' + c_X c_W Z + s_W A \\ s_X s_W Z' - c_X s_W Z + c_W A \end{pmatrix}$$

A is a massless state.

  - $Z - Z'$ Mixing

$$\tan 2\theta_X = \frac{-2g_X \sqrt{g^2 + g'^2} v^2 \cos^2\beta}{(g^2 + g'^2)v^2 - g_X^2 v^2 \cos^2\beta}$$

- Similar gauge boson mixing in the 2HD + singlet model

Constraints on Scalar Sector

- Perturbative unitarity

  $|\mathcal{M}| \leq 8\pi$ at high energies

- Bounded from Below

- ρ parameter: $-0.00039 < \Delta\rho < 0.001485$

  $$\Delta\rho_{\mathrm{new}} \approx \Delta\rho_{Z'} + \Delta\rho_H$$

  $\Delta\rho_{Z'}$ = induced by $Z - Z'$ mixing at the tree level

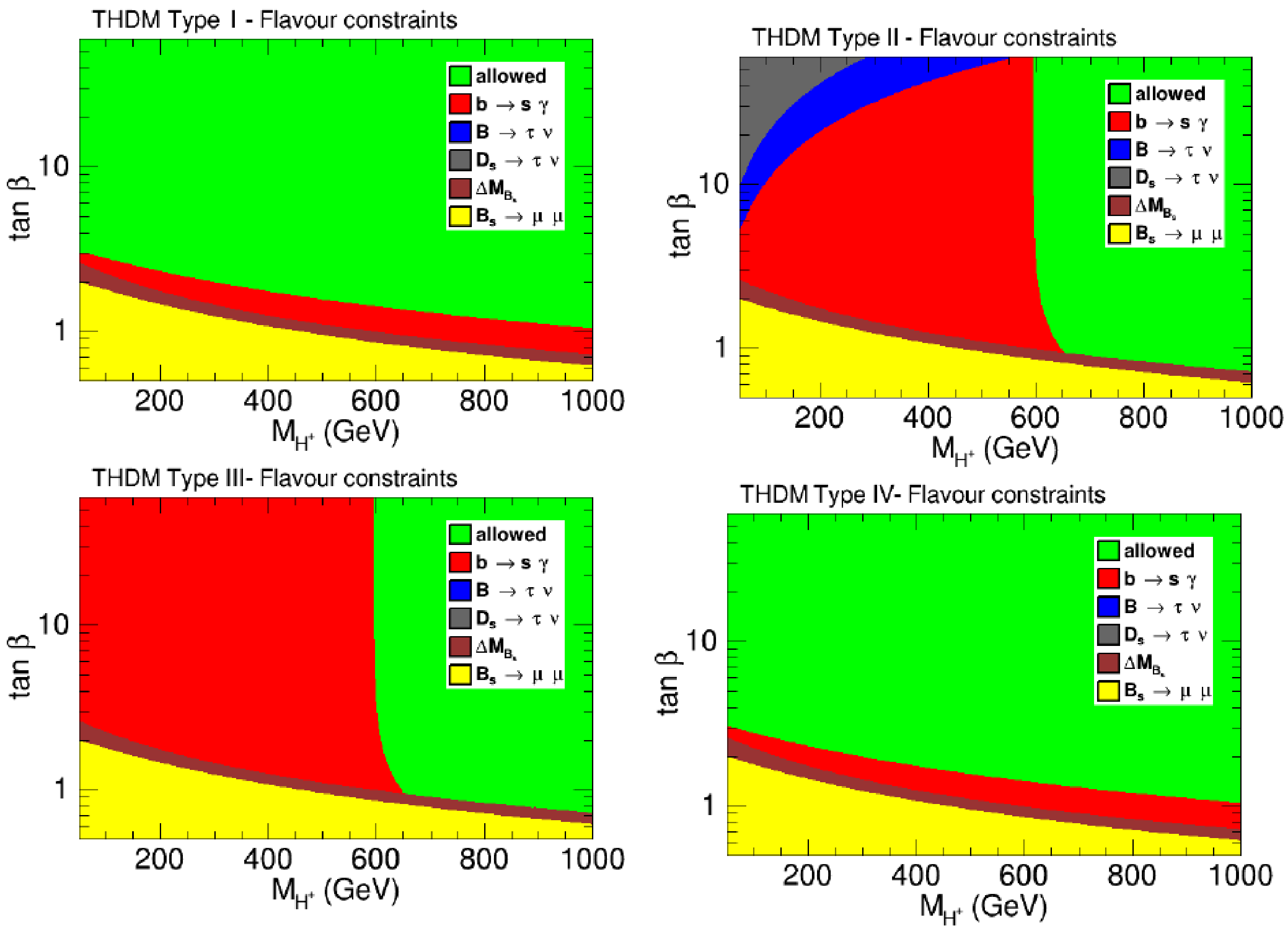
  $\Delta\rho_H$ = induced by scalar loops

- Searches for extra scalar bosons at LHC: HiggsBounds

  no signal so far → 2σ exclusion limit

- Precision measurements of the SM Higgs boson at LHC: HiggsSignals

Constraints from Flavor Physics

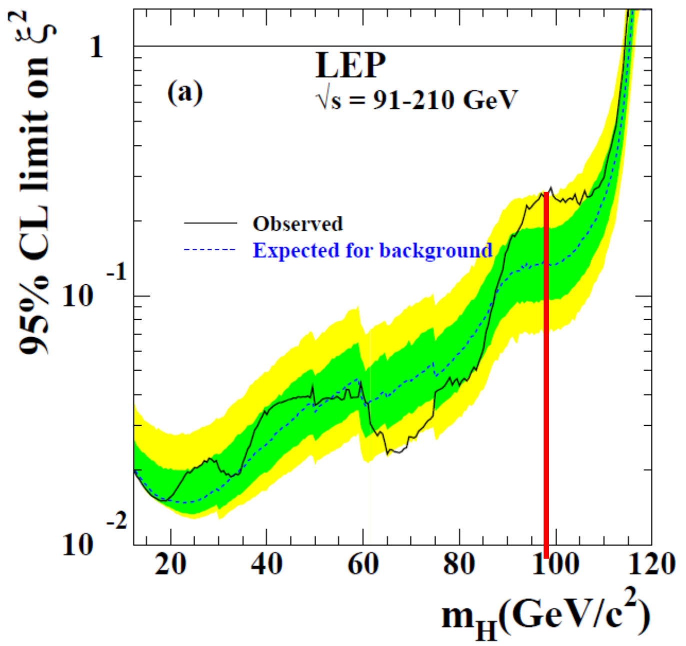


- Depending on the type ot a model, strong bounds on the charged Higgs boson mass.

Arbey et al., arXiv:1706.07414

2HD+singlet model:
Resolution of Resonances at 95 GeV

Resonances at 95 GeV

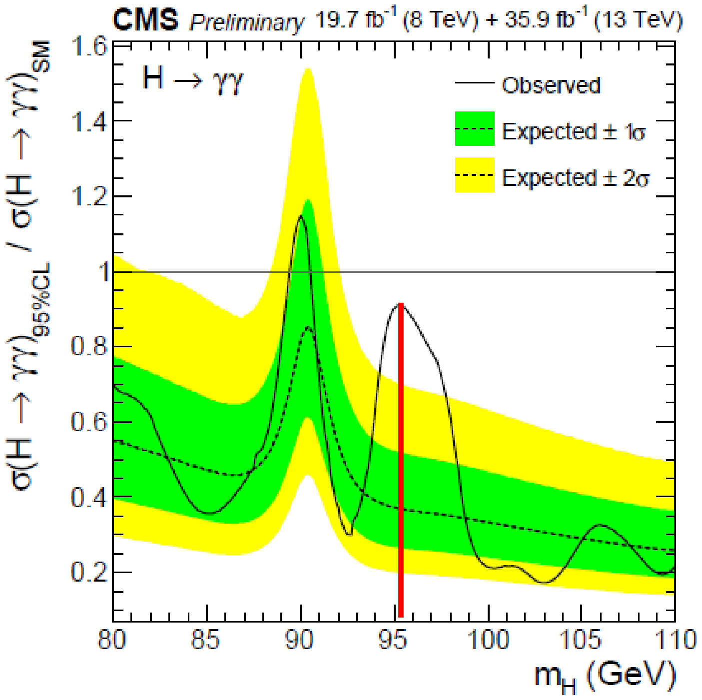


$e^+e^- \to Z\phi \to Zb\bar{b}$

2.3σ local excess

$$\mu_{\text{LEP}} = \frac{\sigma\left(e^+e^- \to Z\phi \to Zb\bar{b}\right)}{\sigma^{\text{SM}}\left(e^+e^- \to ZH \to Zb\bar{b}\right)} = 0.117 \pm 0.057$$

hep-ex/0306033



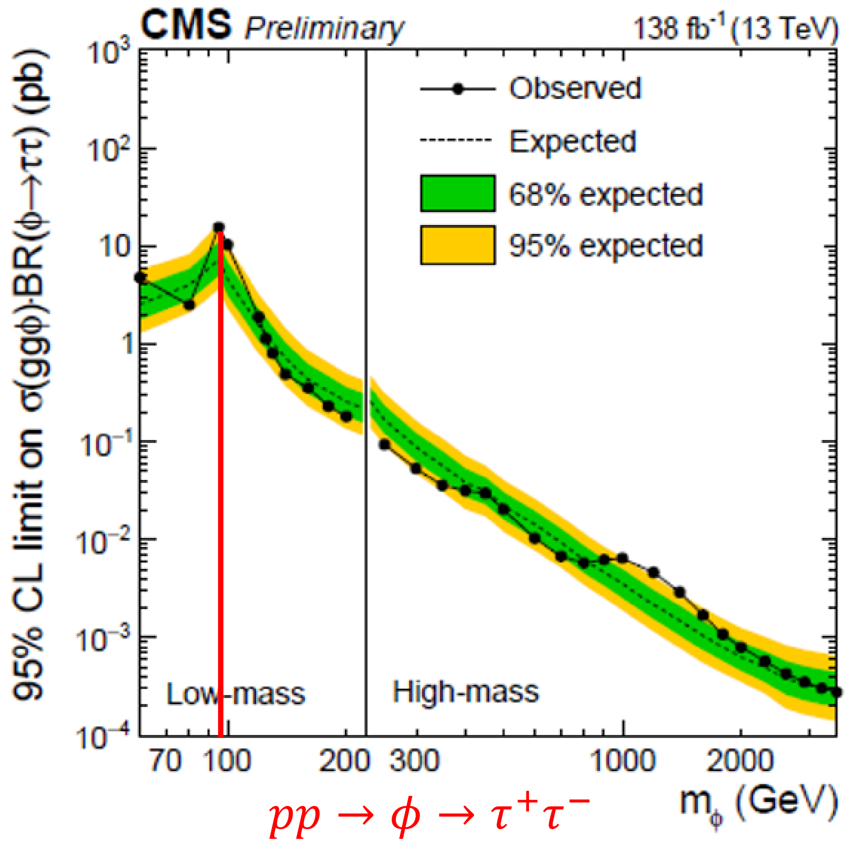
$gg \to \phi \to \gamma\gamma$

3σ local excess

CMS PAS HIG-17-013

ATLAS sees 1.7σ.

$$\mu^{\text{exp}}_{\gamma\gamma} = \mu^{\text{ATLAS+CMS}}_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}\,,$$

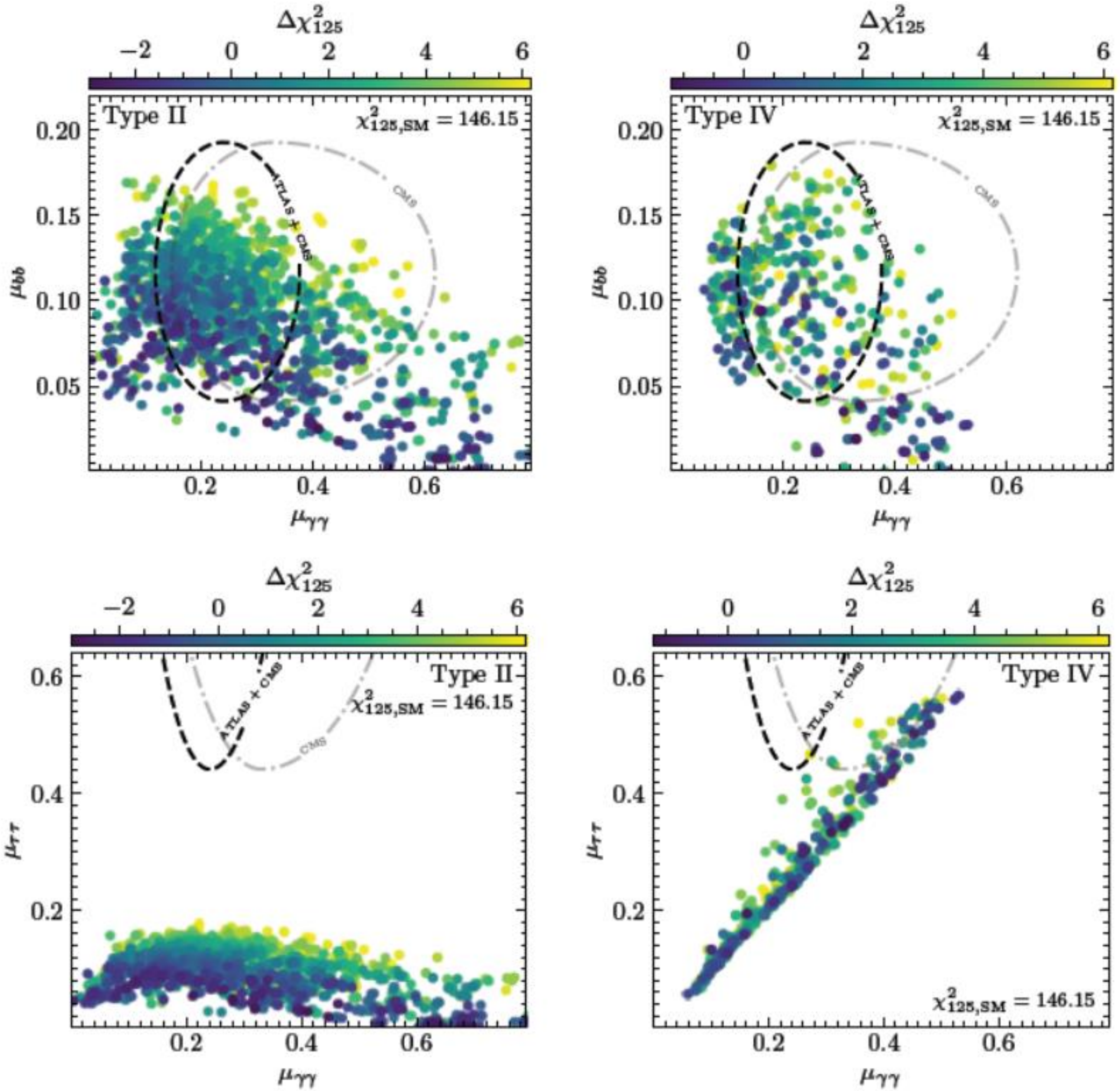


$pp \to \phi \to \tau^+\tau^-$

2.6σ local excess

$$\mu^{\text{exp}}_{\tau\tau} = \frac{\sigma^{\text{exp}}(gg \to \phi \to \tau^+\tau^-)}{\sigma^{\text{SM}}(gg \to H \to \tau^+\tau^-)} = 1.2 \pm 0.5$$

CMS PAS HIG-21-001



Biekötter, Heinemeyer, Weiglein, arXiv:2306.03889

- new scalar boson at 95 GeV?
- Model: S2HDM

  2HD + complex singlet

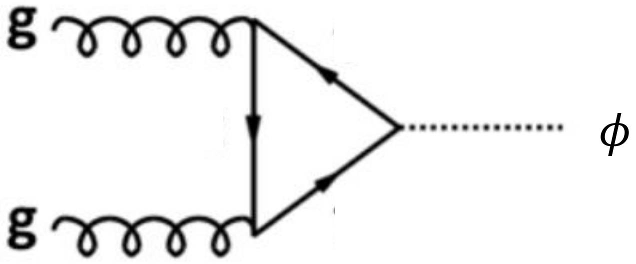
  Z_2 Symmetry

- In the Type II, the di-tau resonance seems to be out of 2σ.
- In the Type IV, the signals are marginal at 1σ.
- The scalar sector in our model is similar to that in the S2HDM.

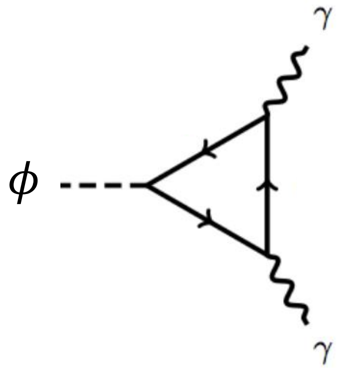
Z_2 vs. $U(1)_H$

1. The Z' boson changes the couplings and decay patterns.

2. The extra fermions may change the production cross section of the scalar boson.

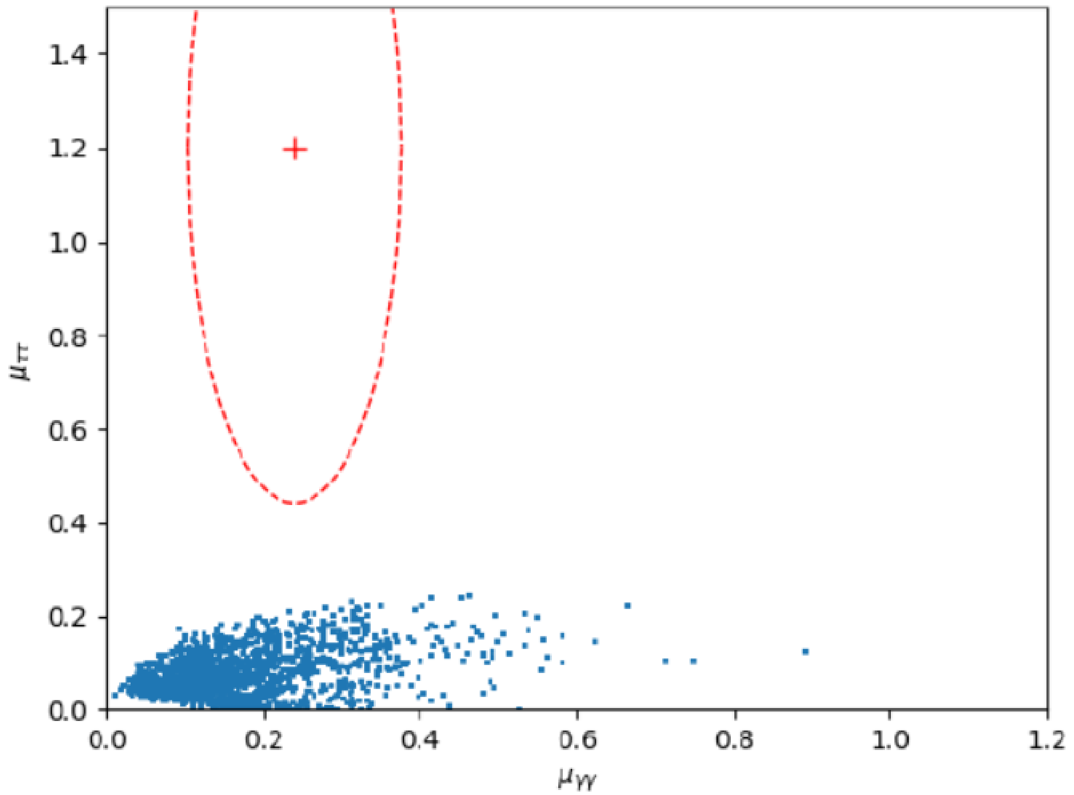


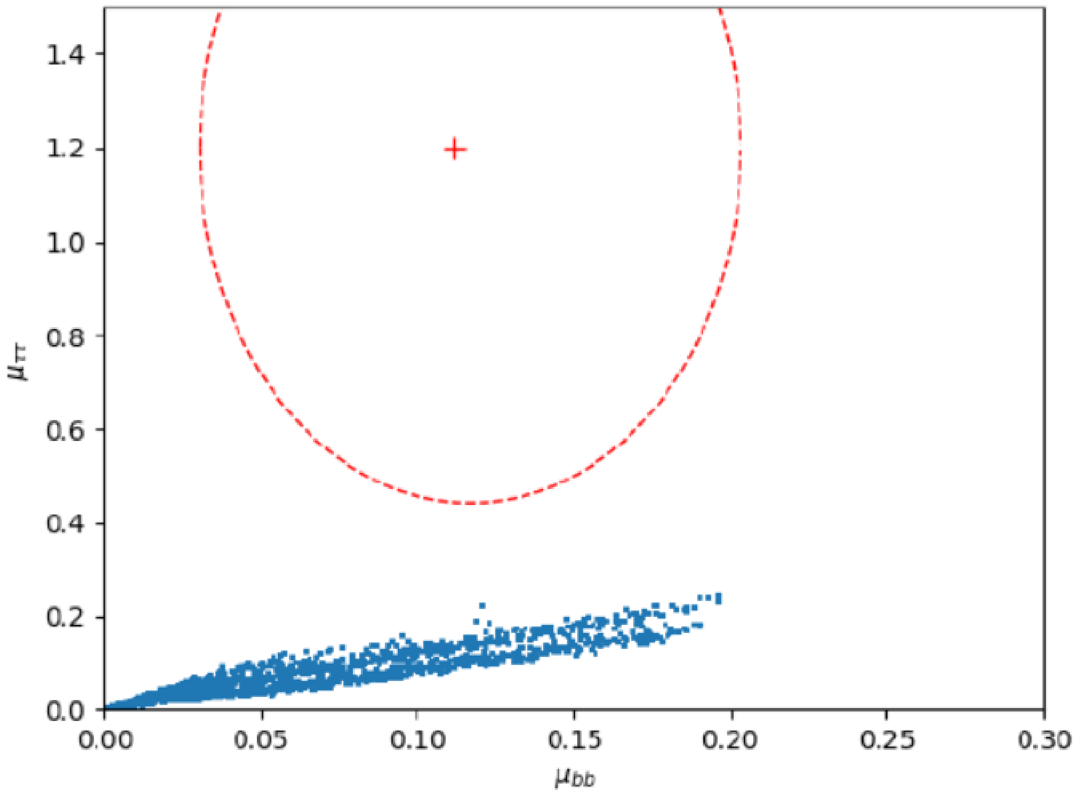
3. The extra fermions may significantly change the branching ratios for the $\gamma\gamma$ decay.



We assume that extra charged lepton and extra quark contributes to the production and decay of ϕ.

Results: Type II





- not preferred within the 1 σ region in the type II model.

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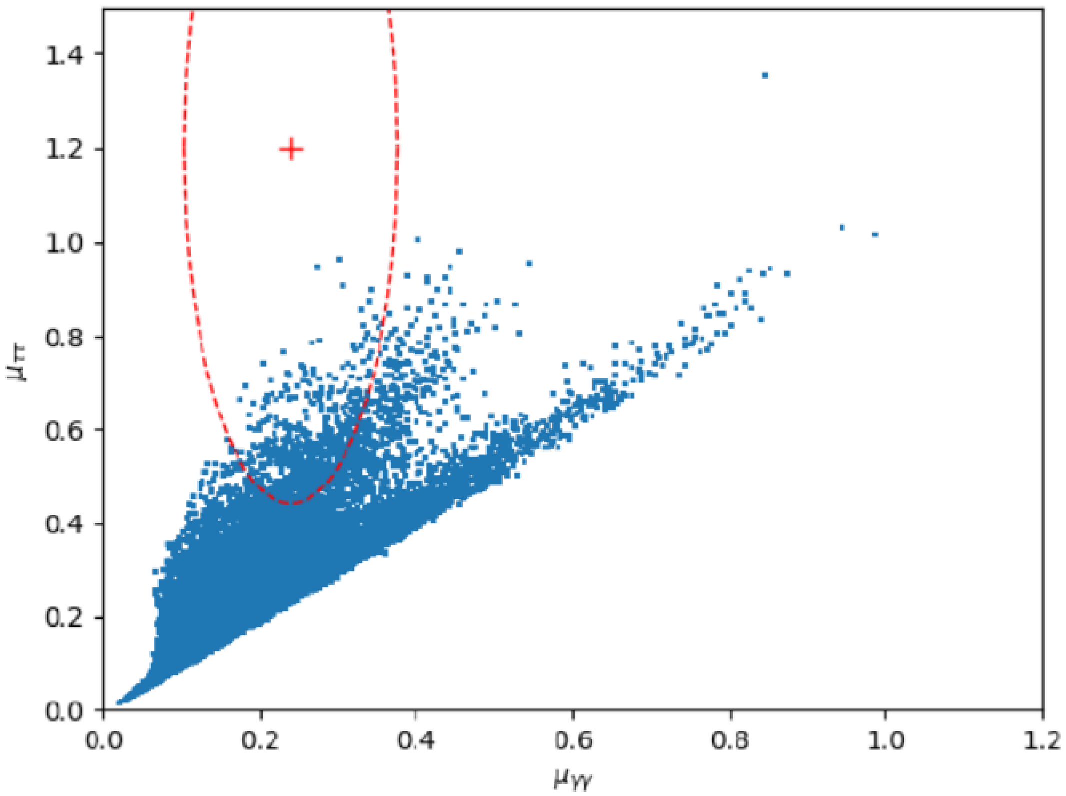
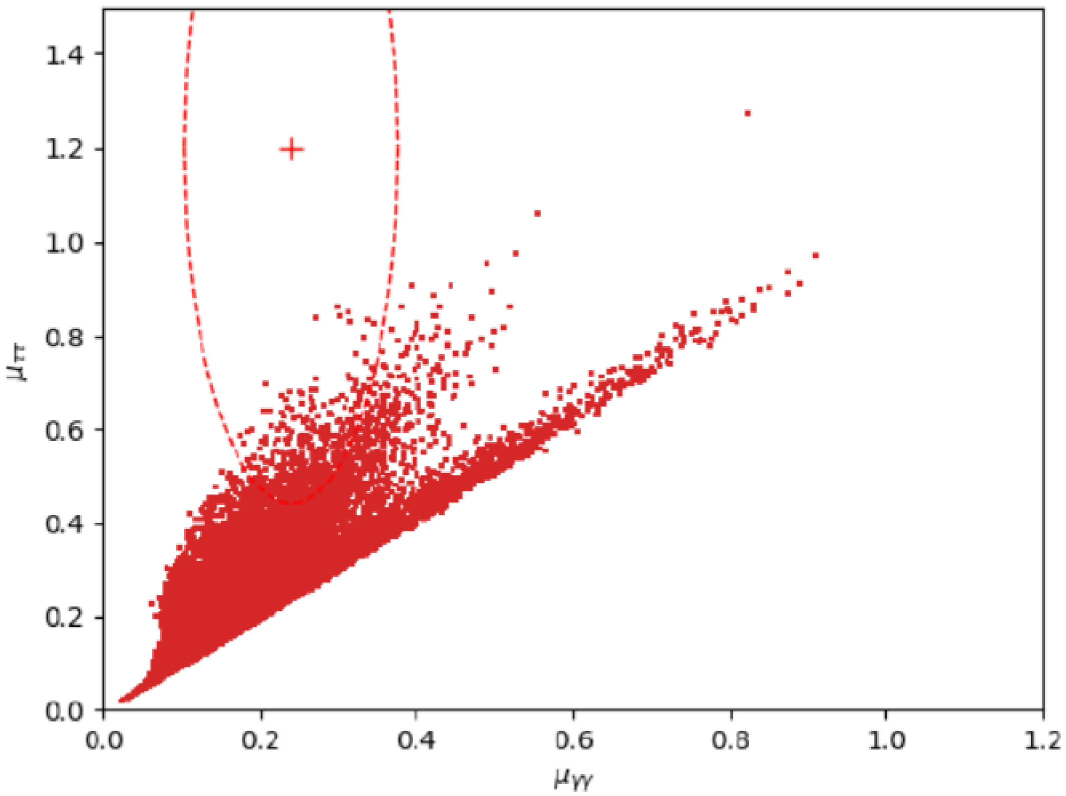
Results: Type IV

Extra fermions included in the loop



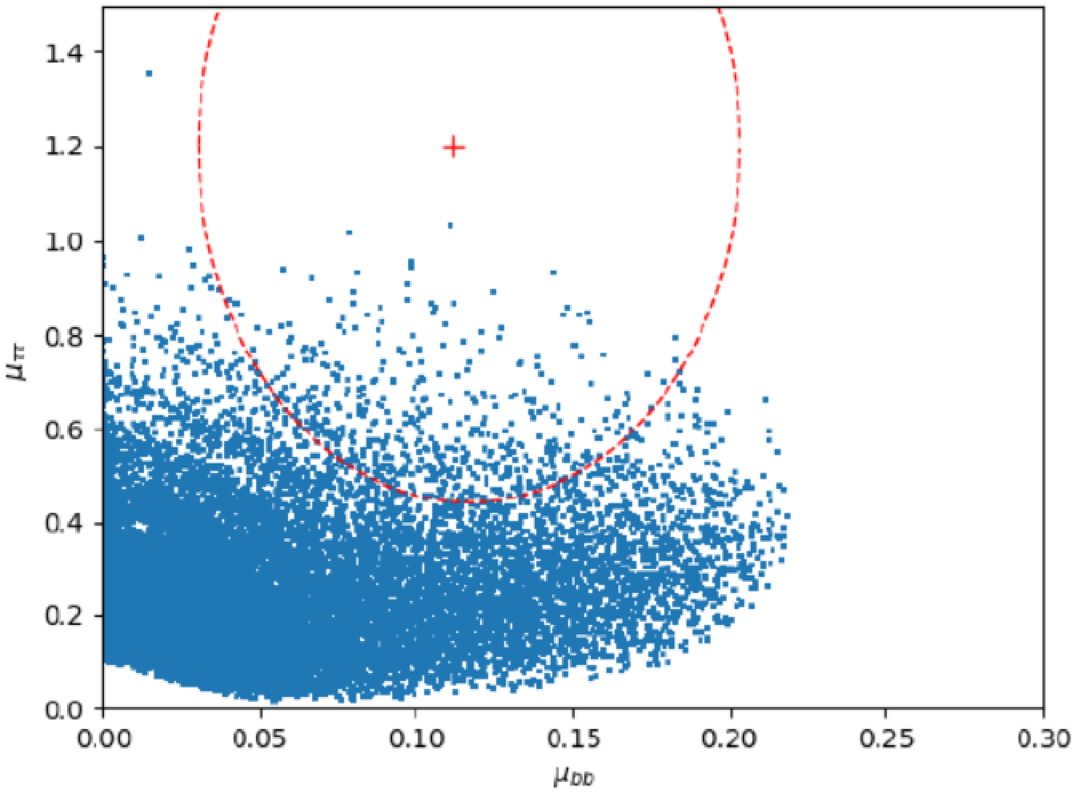
No extra fermions in the loop



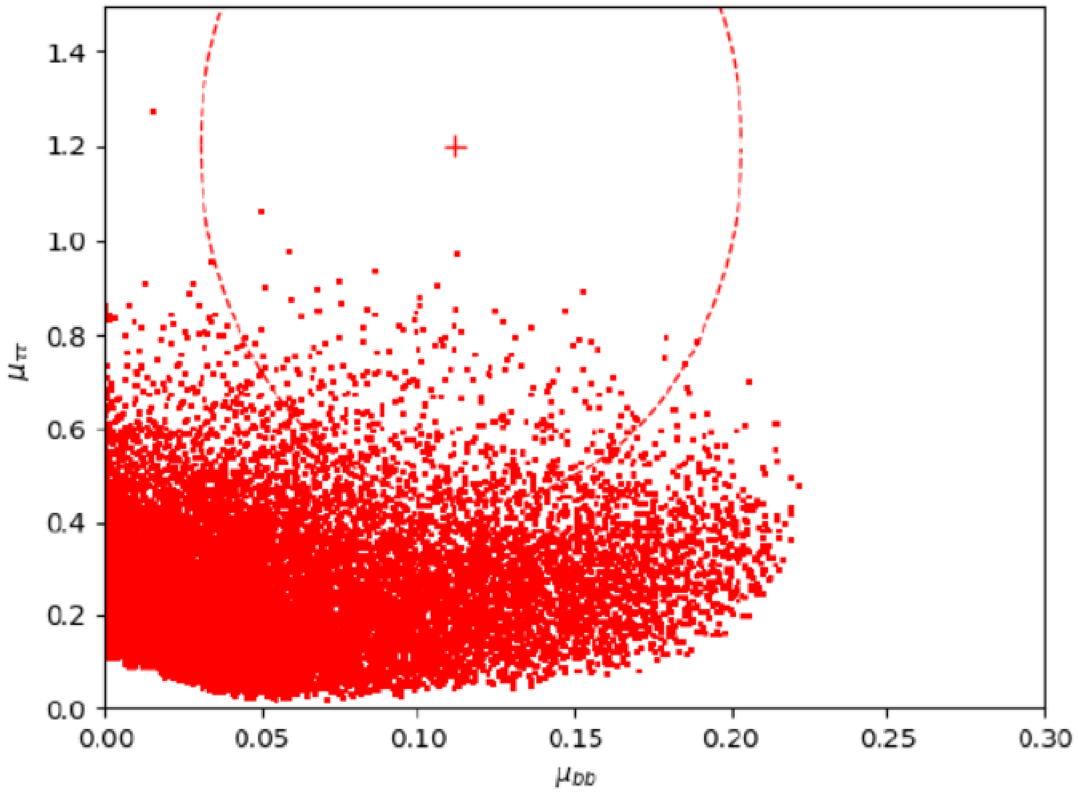
- some points within the 1 σ region in the type IV model.

Results: Type IV

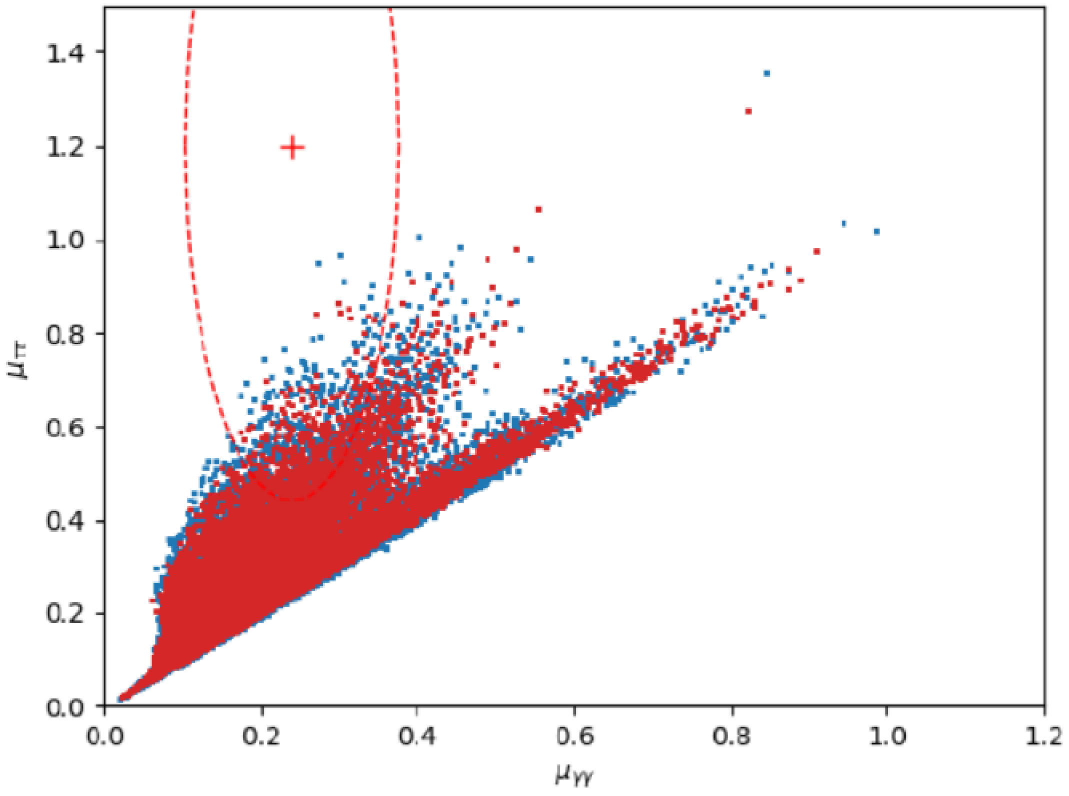
Extra fermions included in the loop



No extra fermions in the loop



Results: Type IV



- The overlapped points have the same parameter set except for the fermions in the loop.

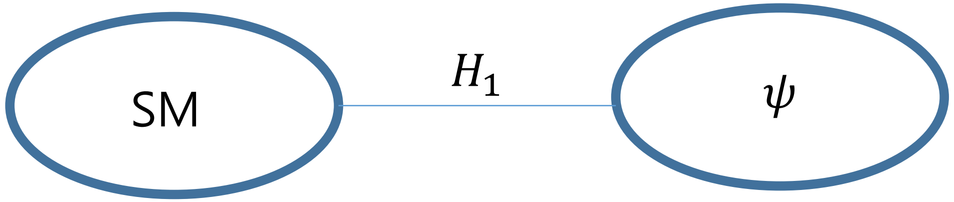
- The blue points (not overlapped) indicate that the parameter set is allowed due to the contribution of extra fermions in the loop.

- The red points (not overlapped) indicate that the parameter set is disallowed if the contribution of extra fermions is included.

Dark Z Model

Dark Z Model

- Gauge group = $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$
- Particle contents: SM fermions + $H_2(1,2,1/2,0)$ + $H_1(1,2,1/2,1/2) + \psi(1,1,1,X)$



  - Due to the $U(1)_X$ charge, H_1 does not couple to the SM fermions.
  - The flavor structure is the same as that in the SM. ⇨ Type I model.

- No new scale in the model.
  - The small Z' mass is preferred.

Dark Z Model

- Scalar potential

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

$$H_i = \begin{pmatrix} H_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix} \qquad \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

  - After EWSB, physical states are $h, H, H^\pm$.
  - The mass of the charged Higgs boson is $m_\pm^2 = -\frac{1}{2}\lambda_4 v^2 \lesssim 620$ GeV.

- Due to the $Z - Z'$ mixing with angle θ_X, the neutral currents are given by

$$\mathcal{L}_{NC} = -eA^\mu \bar{f} Q \gamma_\mu f - c_X Z^\mu \left(g_V \bar{f}\gamma_\mu f + g_A \bar{f}\gamma_\mu\gamma_5 f\right) + s_X Z'^\mu \left(g_V \bar{f}\gamma_\mu f + g_A \bar{f}\gamma_\mu\gamma_5 f\right)$$

  - The Z' couplins to the SM fermions are equal to the SM couplings up to $\sin\theta_X$.

⇨ $Z' =$ Dark Z

Atomic Parity Violation

- The precise measurement of the atomic parity violation constrains the new physics effects in the NC interaction.

  - The weak charge of the nuclei is $Q_W \equiv -2\left(Z g_{AV}^{p} + N g_{AV}^{n}\right)$.

  - The Z' contribution modifies the SM weak charge of the nuclei.

$$Q_W = Q_W^{SM}\left(1 + \frac{m_Z^2}{m_{Z'}^2} s_X^2\right)$$

  - The SM value and experimental results for the Cs atom

$$Q_W^{SM} = -73.16 \pm 0.03 \qquad Q_W^{exp} = -72.82 \pm 0.42$$

  - leads to the constaint on the model

$$\frac{m_Z^2}{m_{Z'}^2} s_X^2 \leq 0.006 \quad \Rightarrow \quad |\sin\theta_X| \lesssim 0.008 \text{ for } m_{Z'} = 10 \text{ GeV}$$

Z Boson Decay

- The Z boson decay width is one of the precise measuments in the SM.
  - The measurement value at LEP and SLD

$$\Gamma_Z = 2.4955 \pm 0.0023 \quad \text{GeV}$$

  - The SM prediction for the decay width

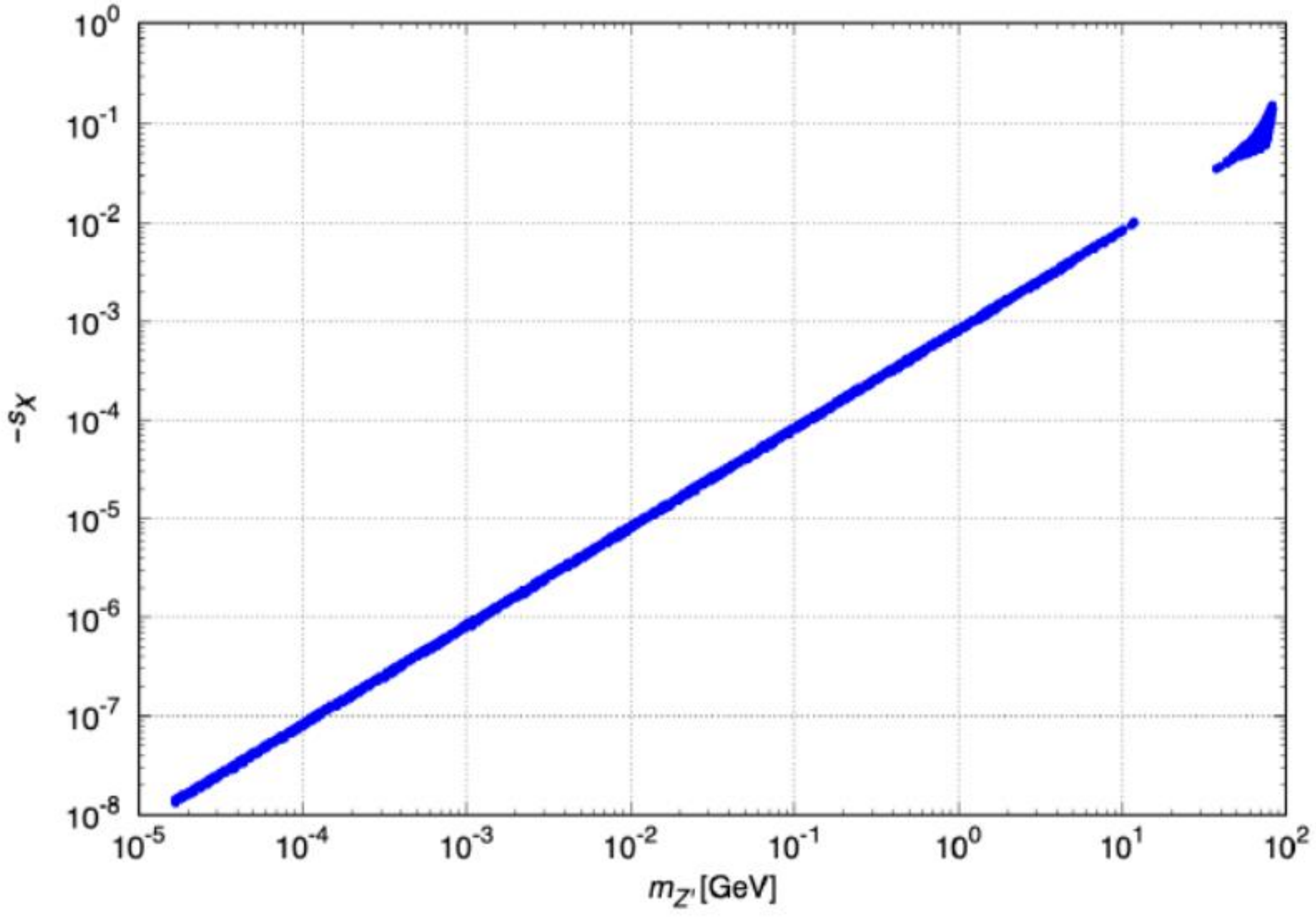
$$\Gamma_Z^{\text{SM}} = 2.4941 \pm 0.0009 \text{ GeV}$$

- If $m_Z > m_{Z'} + m_h$, a new channel $Z \to Z'h$ opens.

$$\Gamma_Z^{\text{New}} = \Gamma_Z^{\text{SM}} + \Gamma(Z \to Z'h)$$

  - Γ_Z^{SM} contains a C_X^2 factor from the $Z - Z'$ mixing but it is close to 1.
  - Thus, $\Gamma(Z \to Z'h)$ should be suppressed sufficiently.

Results



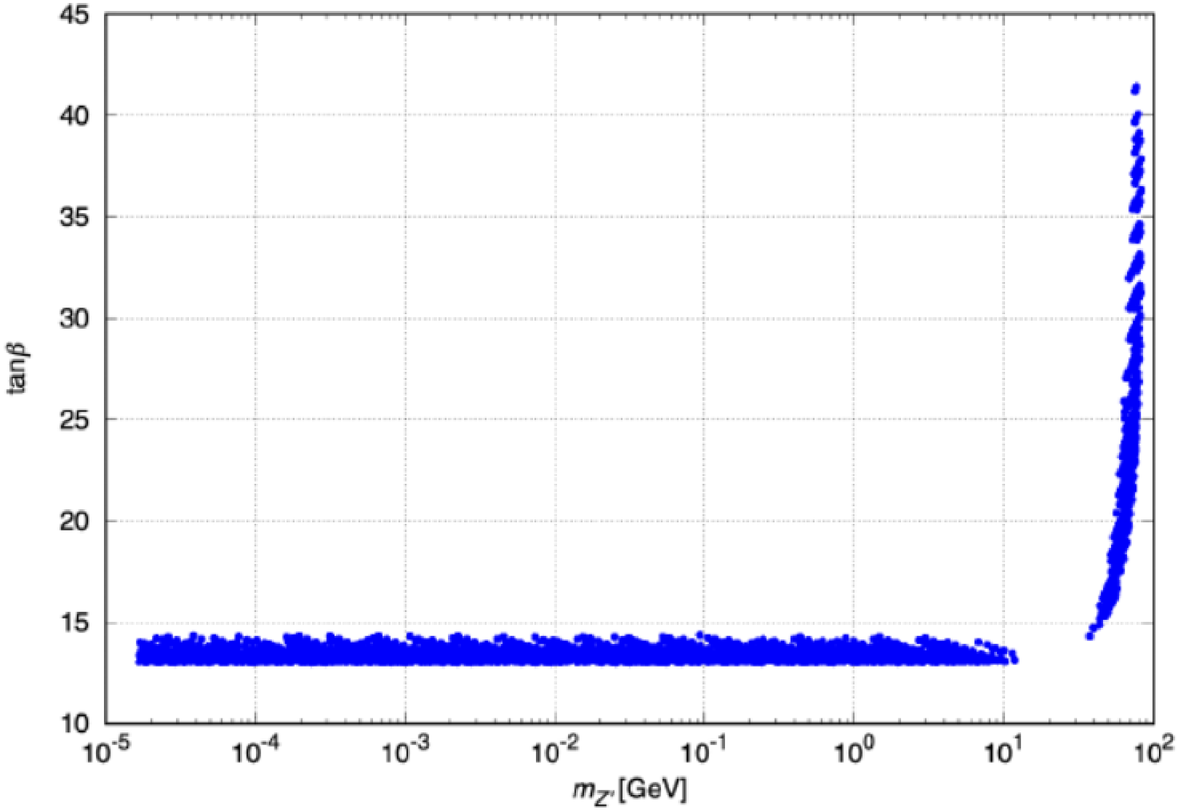
Allowed region for $(m_{Z'}, -\sin\theta_X)$

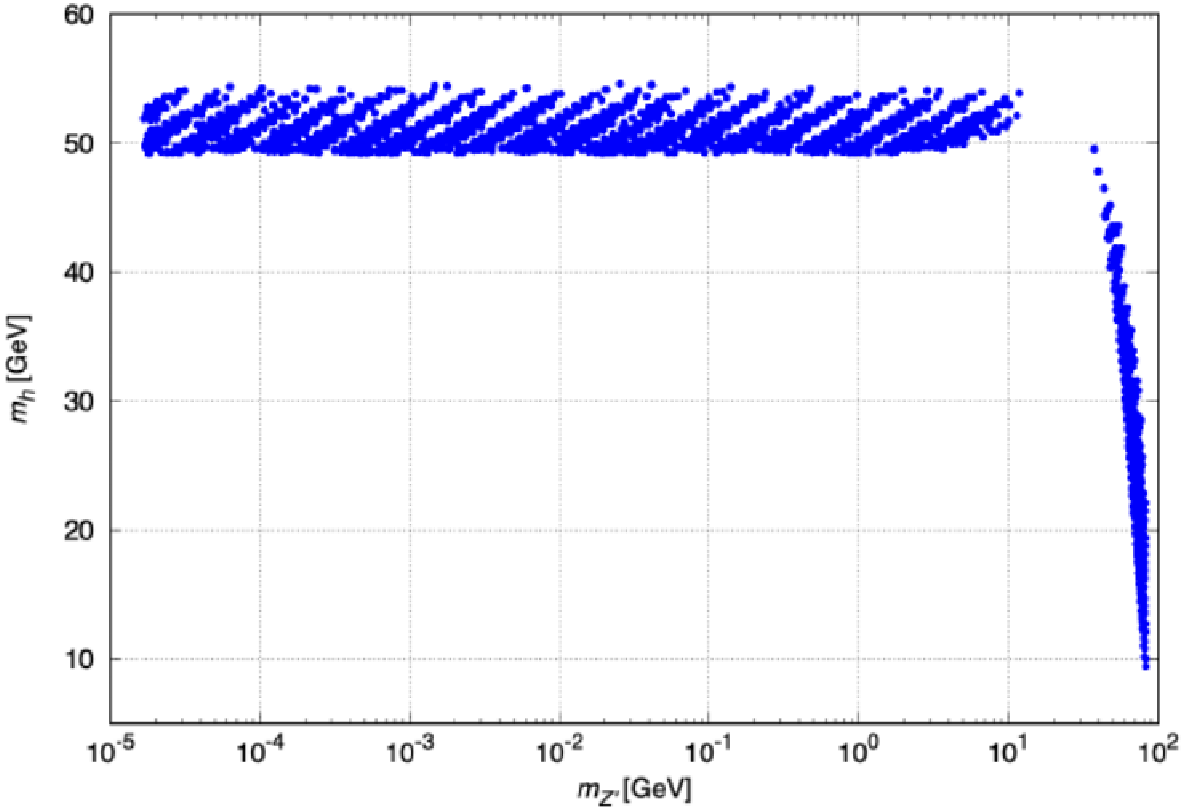
- For $m_{Z'} > 30$ GeV, $\Gamma(Z \to Z'h)$ is kinematically disallowed or suppressed by the kinematic factor $(m_Z - m_{Z'} - m_h)$.

- For $m_{Z'} < 12$ GeV, $\Gamma(Z \to Z'h)$ is suppressed by the mixing angle $\sin\theta_X$ in the $ZZ'h$ coupling.

Jung, Lee, Yu, PRD108, 095002 (2023)

Results





- Show clear separation of parameter sets.
- $\tan\beta$ and m_h are tightly bounded for $m_{Z'} < 12$ GeV.
- Wide range of parameters is allowed for $m_{Z'} > 30$ GeV.

Jung, Lee, Yu, PRD108, 095002

Dark Matter

- The hidden sector Lagrangian

$$\mathcal{L}_{\rm hs} = -\frac{1}{4}F_X^{\mu\nu}F_{X\mu\nu} + \bar{\psi}_X i\gamma^\mu D_\mu \psi_X - m_X \bar{\psi}_X \psi_X \qquad D_\mu = \partial_\mu + i g_X A_\mu^X X$$

  - Due to the $Z - Z'$ mixing, the DM interaction terms with physical gauge bosons are

$$\mathcal{L}_{\rm DM}^{int} = i g_X X \bar{\psi}_X \gamma^\mu \psi_X \left(c_X Z'_\mu + s_X Z_\mu\right)$$

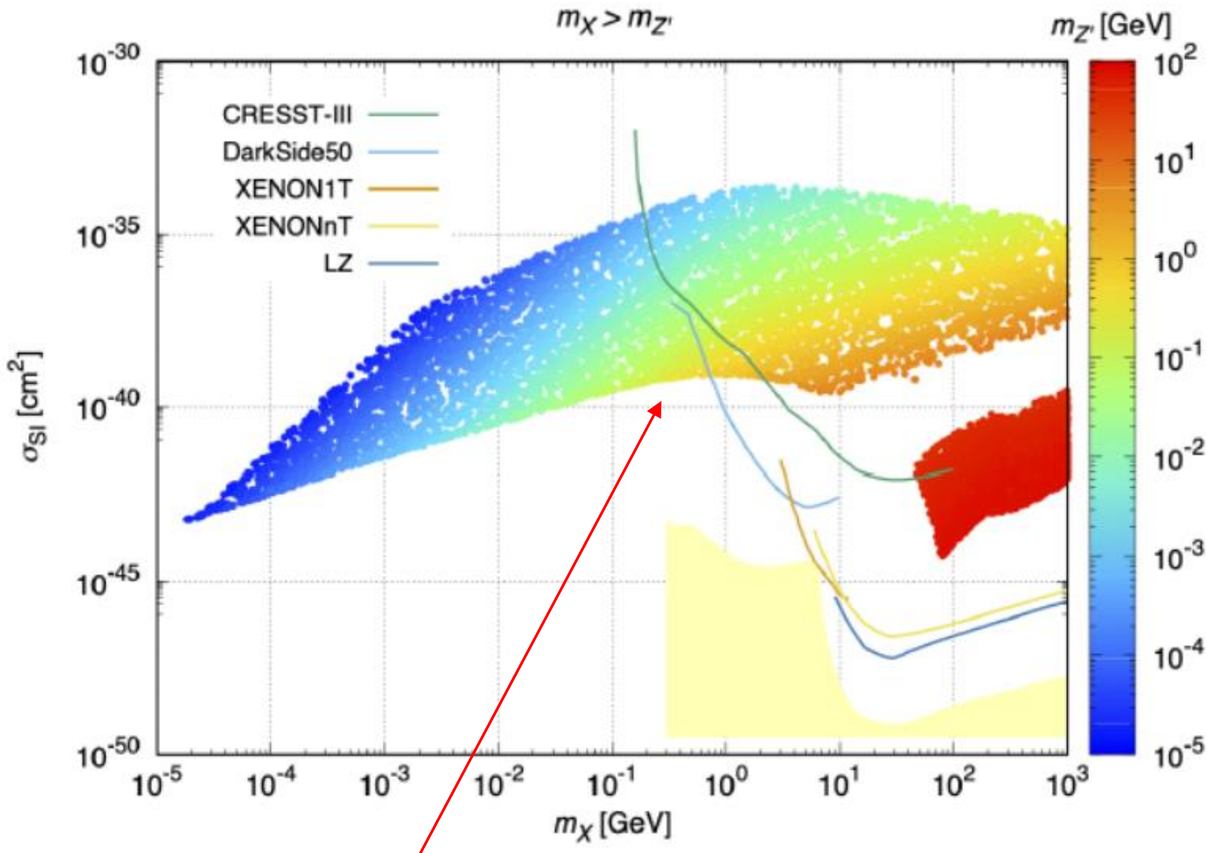
- Make use of MicorOmegas for DM analysis
  - relic density $\Omega_{\rm CDM} h^2 = 0.120 \pm 0.001$

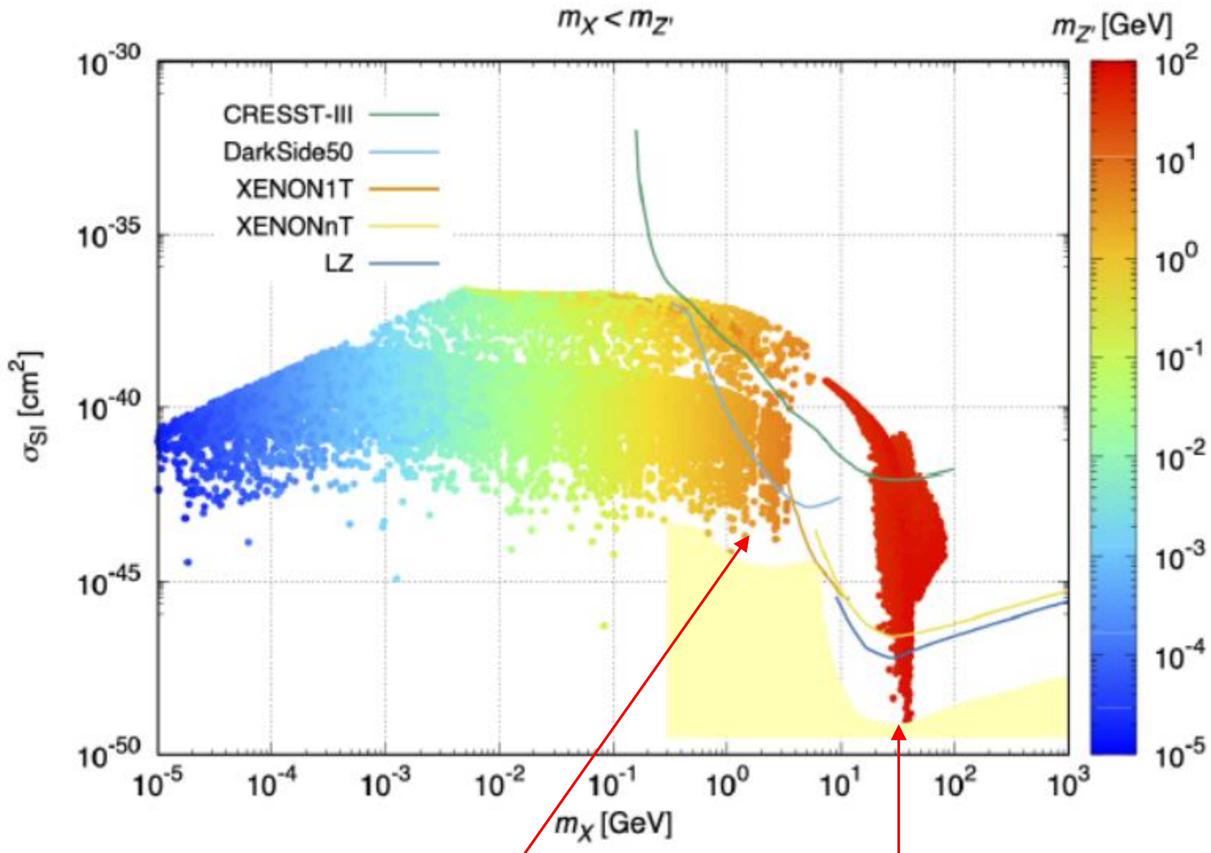
$$\psi_X \bar{\psi}_X \to Z' \to \text{SM particles} \qquad \psi_X \bar{\psi}_X \to Z'Z' \qquad \psi_X \bar{\psi}_X \to Z'h$$

  - the Bullet cluster constraint for DM self interaction $\sigma/m_{DM} \lesssim 1{\rm cm}^2/{\rm g}$

- If $m_Z > 2m_{\psi_{X'}}$ a new channel $Z \to \psi_X \bar{\psi}_X$ is open. (more stringent constraint on the Z decay width)

DM-Nucleon Cross Sections

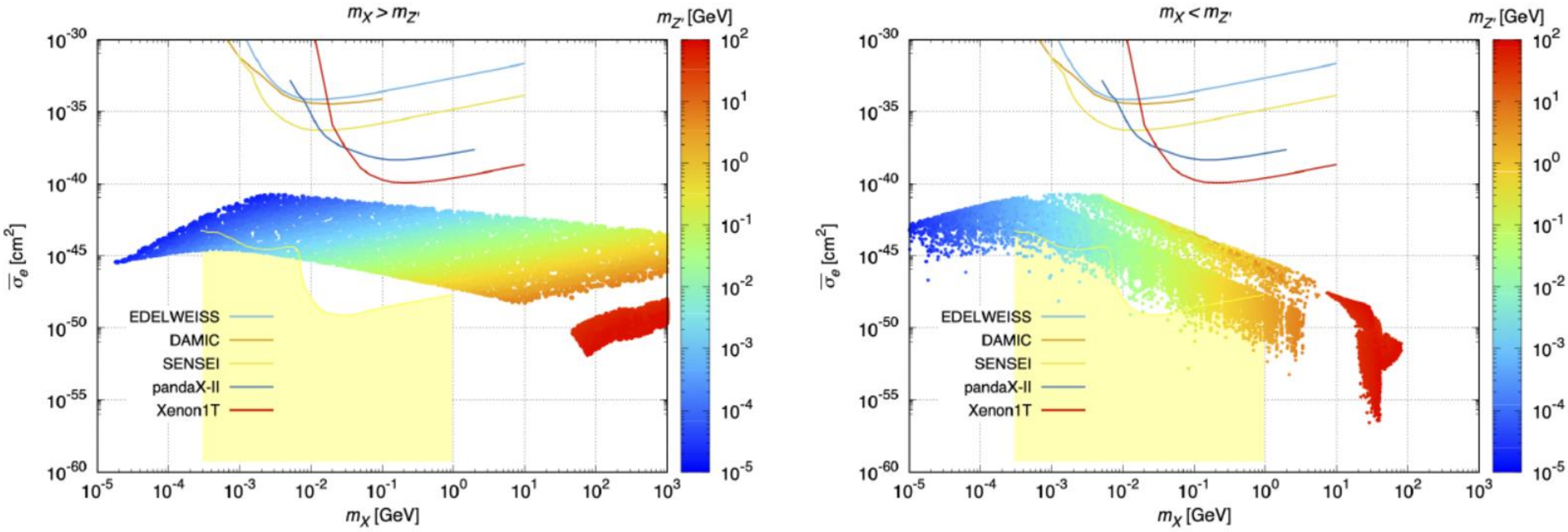




- low mass for Z' less than a few hundred MeV is preferred.
- more constrained $m_{Z'} < 7$ GeV or $43 < m_{Z'} < 83$ GeV

Jung, Lee, Yu, PRD108, 095002

DM-Electron Cross Sections



- The DM-electron cross sections are below current experimental limits.
- to be tested in near future.

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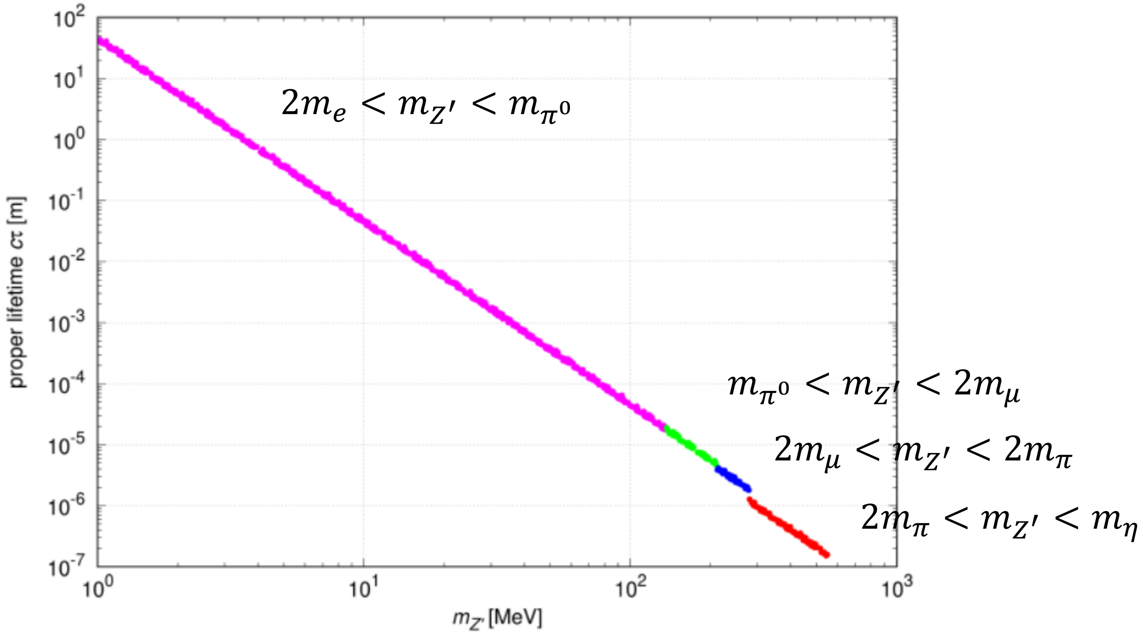
Z' Boson Decay

- If $m_{Z'} > 2m_{\psi_{X'}}$, the dark Z dominantly decays into a dark matter pair. ➡ invisible

- If $m_{Z'} < 2m_{\psi_X}$ and $m_{Z'} < 2m_e$, the dark Z decays into neutrinos only. The decay length is

$$\gamma c\tau = \frac{E_{Z'}}{m_{Z'}} \cdot 3 \times 10^8 \cdot 10^{-5} \sim 3 \times 10^6 \ (\mathrm{m})$$ ➡ escapes detectors.

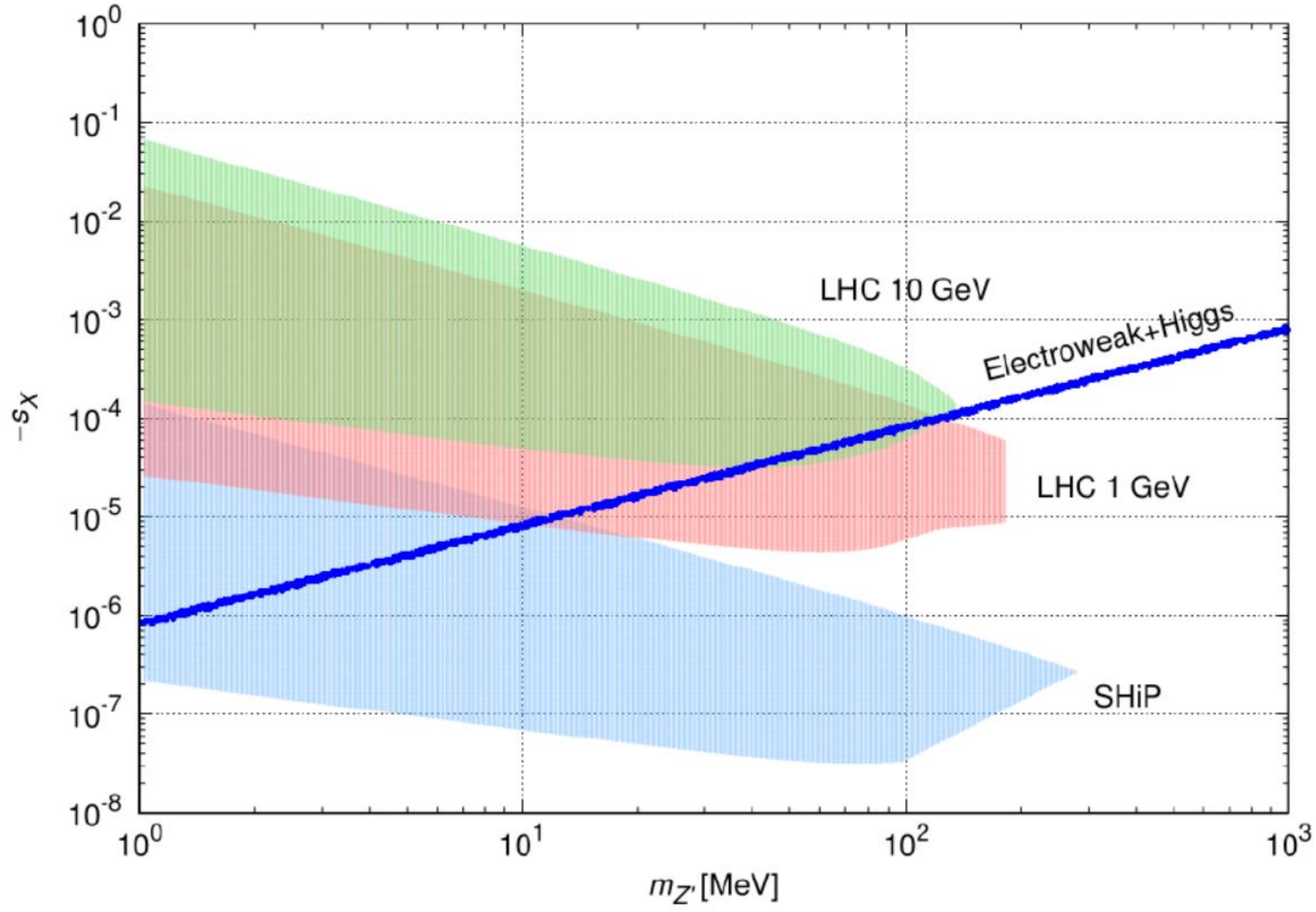
- For $m_{Z'} < 2m_{\psi_X}$ and $m_{Z'} > 2m_e$



- As $m_{Z'}$ increases, new channels for the Z' decay are open.
- Depending on the energy, the Z' can be a long-lived particle.
- could leave the displaced vertex at colliders.

Jung, Lee, Yu, 2311.01962

Sensitivity of LHC and SHiP



- discovery: $N_{\text{events}} > 25$

  for $m_{Z'} \to e^+e^-$

- LHC covers $10 < m_{Z'} < 150$ MeV

- SHiP covers $2m_e < m_{Z'} < 15$ MeV

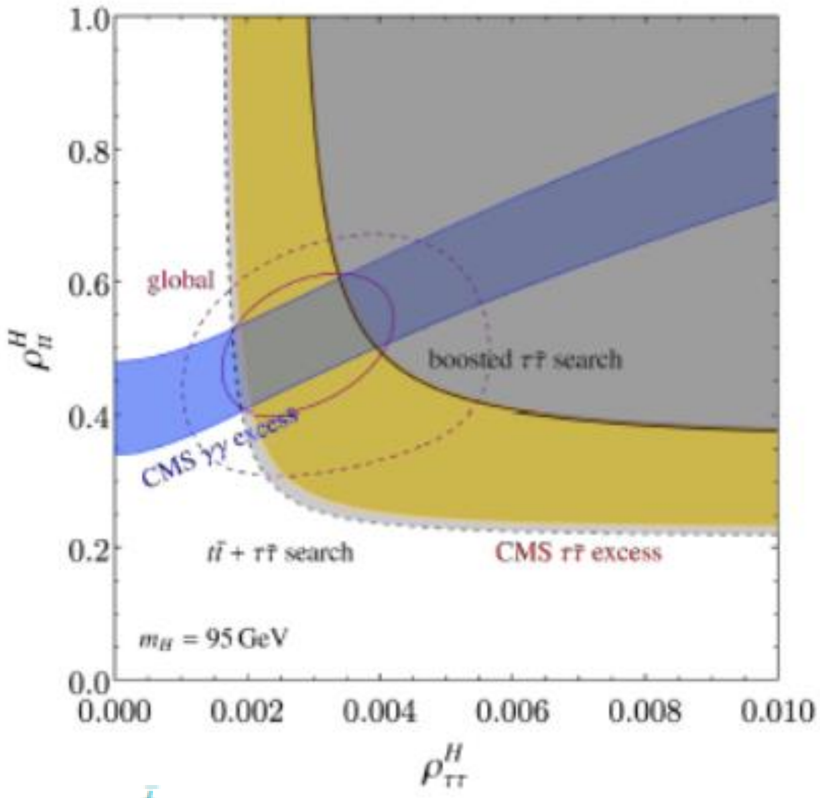
Jung, Lee, Yu, 2311.01962

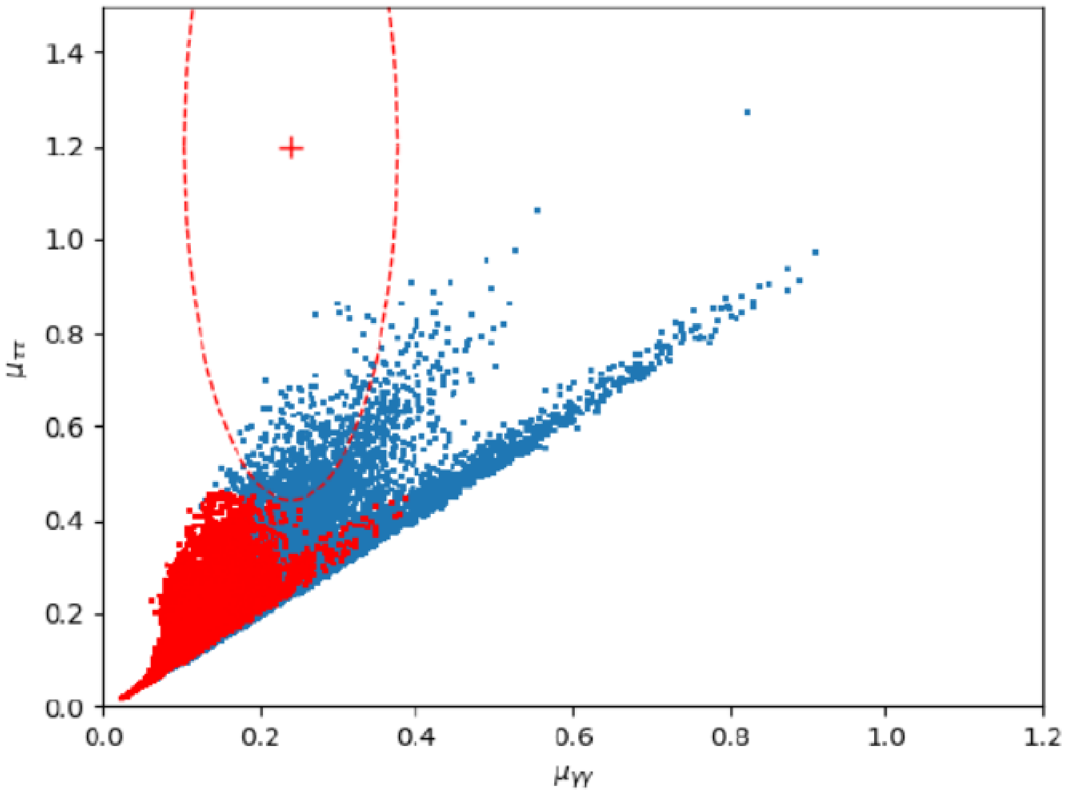
Summary

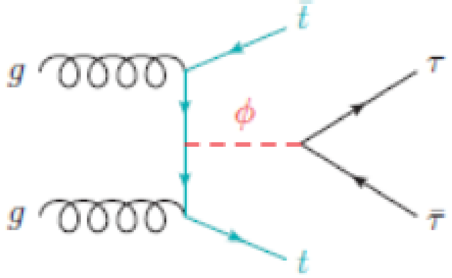
- Gauged Higgs fields provides a resolution of the Higgs mediated FCNC problem.
  - Natural flavor conservation is easily realized.
  - In general the model requires extra fermions for gauge anomaly.
- Dim-2 terms are realized by adding singlet field.
  - may be a resolution of the 95 GeV resonances.
  - Extra fermion contribution in the loop.
- Dark Z model does not contain new scale in the scalar potential.
  - no pesudoscalar boson.
  - Light Z' and fermionic DM are preferred.
  - The displaced vertex could a distinctive signal at colliders.

Backup

$H \to t\bar{t}\tau^+\tau^-$ at ATLAS



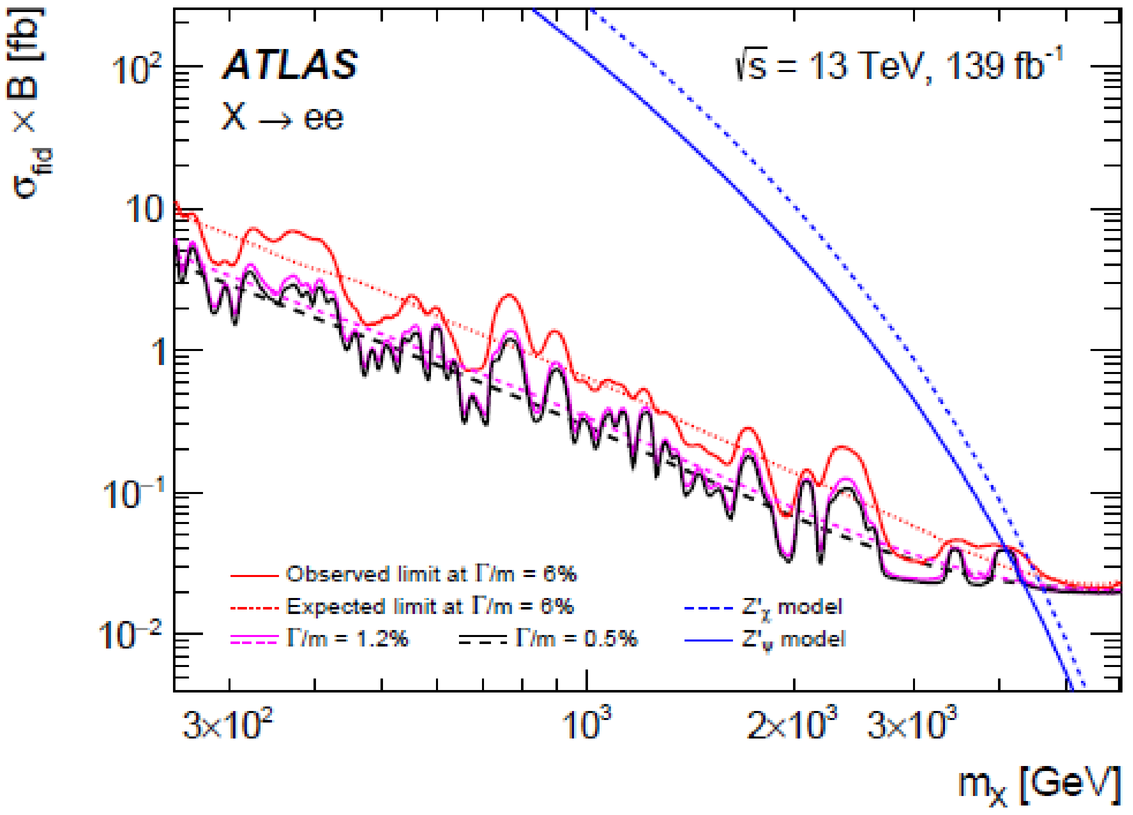


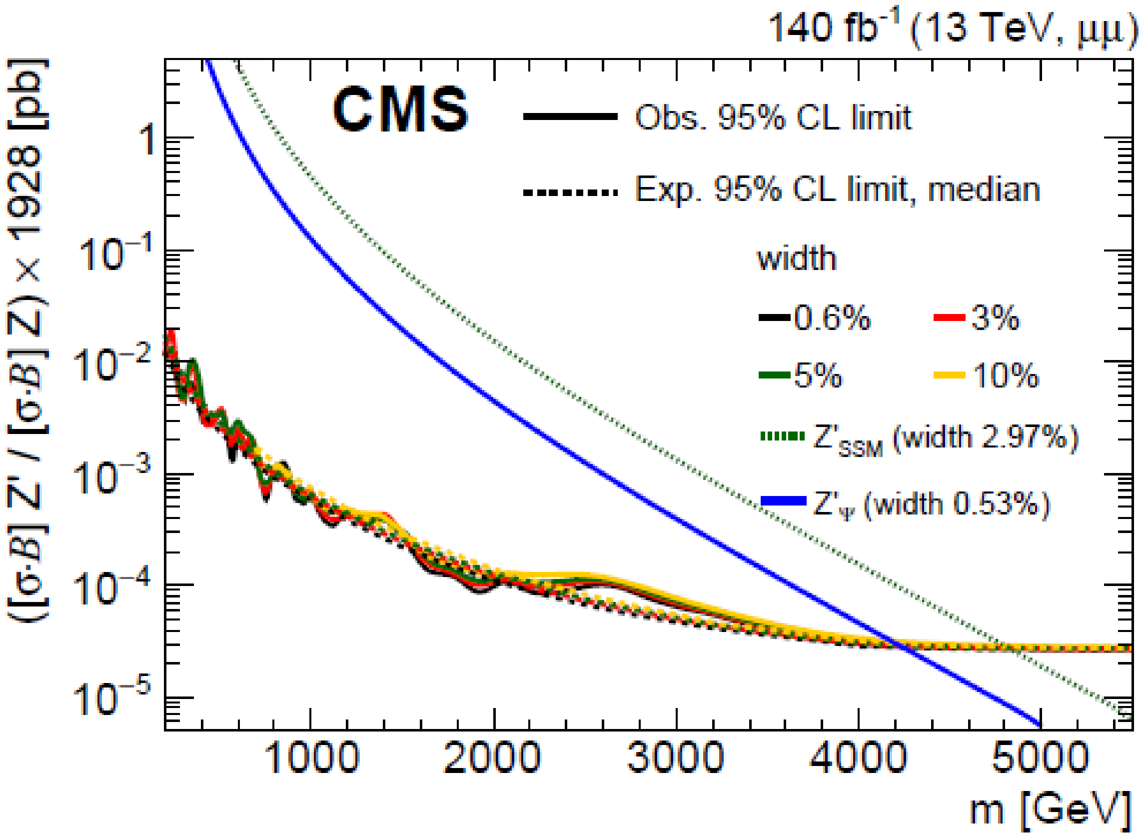


ATLAS, arXiv:2201.08269

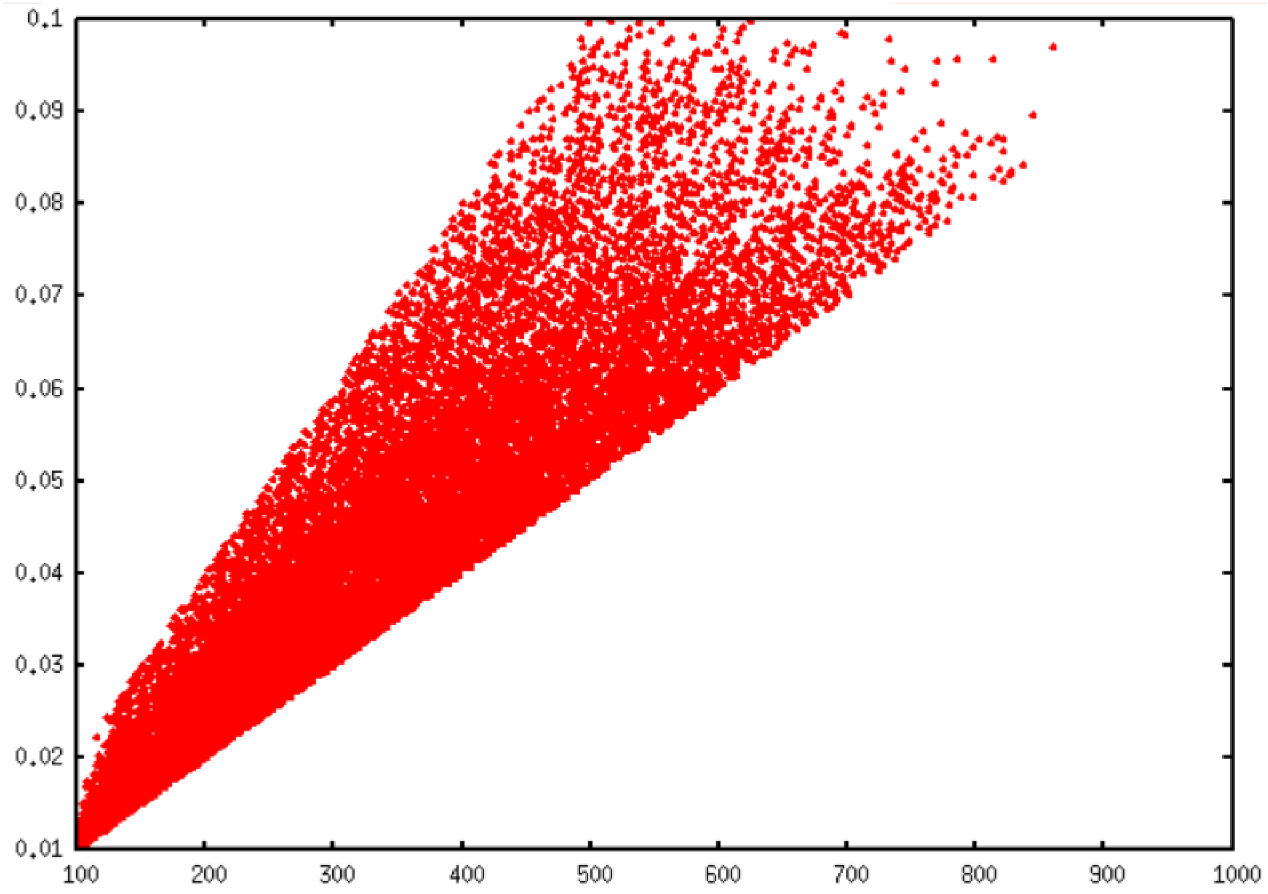
Iguro et al., arXiv:2205.03187

Constraints from Z' Searches





Results: Type IV



g_X

$m_{Z'}$

Type II: Leptophobic $U(1)_H$

- Leptophobic $U(1)_H$: less constrained by the Drell-Yan process.

	q_L^i	u_R^i	d_R^i	l_L^i	e_R^i	n_R^i	H_1
$SU(3)_c$	3	3	3	1	1	1	1
$SU(2)$	2	1	1	2	1	1	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	1/2
$U(1)_H$	$b(1+a)$	$-2b(1+a)$	$b(1+a)$	0	0	$b\left(\pm\sqrt{\frac{a(9+14a)}{2}}-3(1+a)\right)$	0

TABLE I: General charge assignments of the SM fermions under the SM gauge group and the Leptophobic $U(1)_H$ E_6 subgroup.

	H_2	D_L^i	D_R^i	L_L^i	L_R^i	N_L^i	Φ_k	φ
$SU(3)_c$	1	3	3	1	1	1	1	1
$SU(2)$	2	1	1	2	2	1	1	1
$U(1)_Y$	1/2	−1/3	−1/3	−1/2	−1/2	0	0	0
$U(1)_H$	$-3b(1+a)$	$-b(2+3a)$	b	ab	$b(3+4a)$	$b\left(\pm\sqrt{\frac{a(9+14a)}{2}}+3(1+a)\right)$	X_k	X_φ

TABLE II: Charge of the new particle content under the SM gauge group and the Leptophobic $U(1)_H$ E_6 subgroup.

- The b variable is arbitrary and merely rescale the $U(1)_H$ coupling.

- Any specific model must be defined by the charge a and the $\pm$ signal of $n^i_{R,L}$.

Type IV

- Charge assignment of a type IV model

$$\mathcal{L}_Y = -Y_u^{ij}\overline{Q_L^i}\widetilde{H}_1 u_R^j - Y_d^{ij}\overline{Q_L^i}H_2 d_R^j - Y_e^{ij}\overline{L_L^i}H_1 e_R^j - Y_n^{ij}\overline{L_L^i}\widetilde{H}_2 \nu_R^j + h.c.,$$

Fields	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_H$
Q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0
u_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	u
d_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	0
L_L^i	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	$-u$
ν_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	0
H_1	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	u
H_2	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0
q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$u+\epsilon$
q_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	ϵ
ℓ_L^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	$-u-2\epsilon$
ℓ_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	-2ϵ

gauge anomaly condition:
$u = \epsilon$ or $\epsilon = 0$

Results

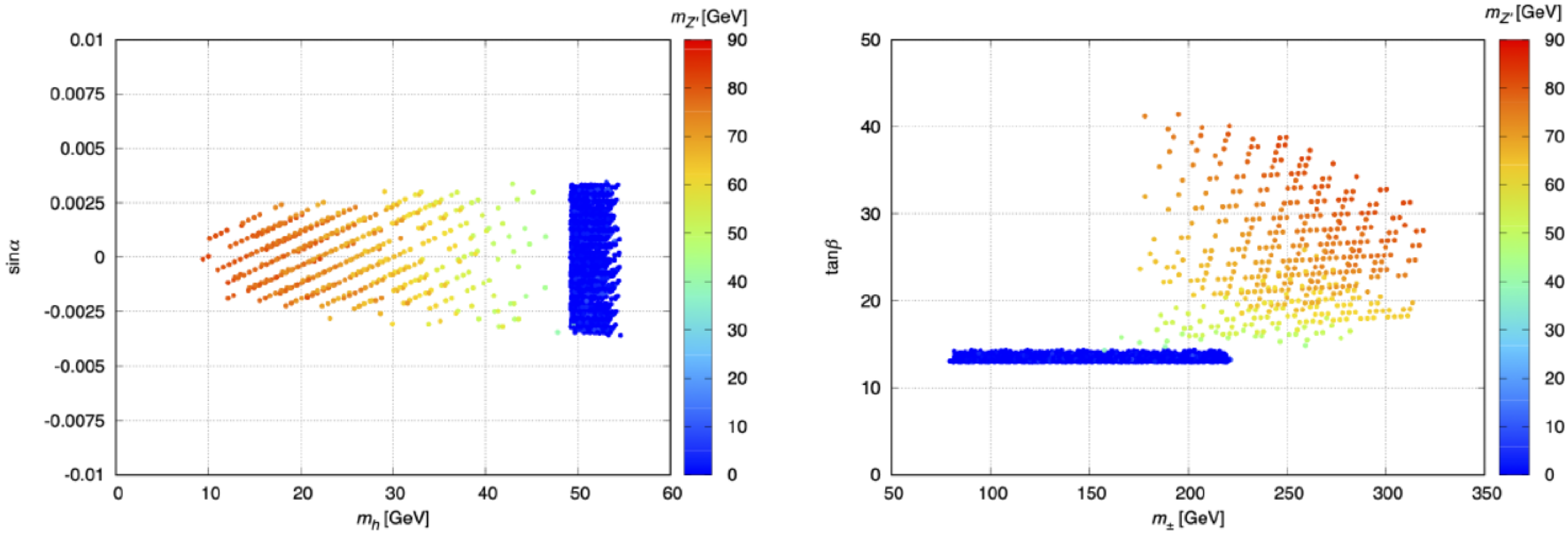


FIG. 3. Allowed parameter set of $(m_h, \sin\alpha)$ (left) and $(m_\pm, \tan\beta)$ (right).