95 and 125 GeV Higgs boson excesses in the left-right supersymmetric standard model

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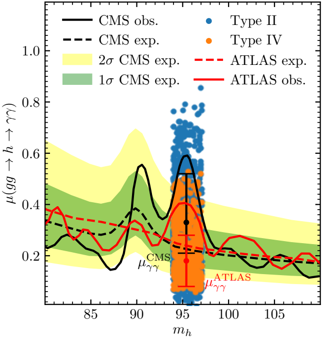
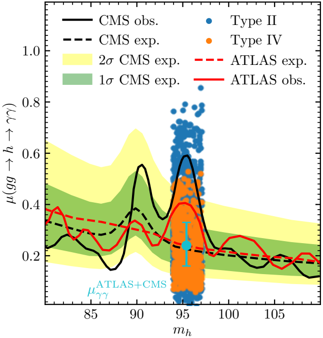
Contents

I. Motivation



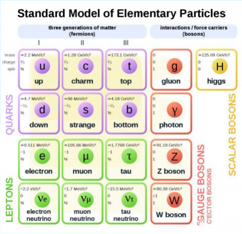


95 GeV 信号超出与理论假设

- **实验搜寻：** CMS 基于8 TeV 与13 TeV 数据（综合光度分别为19.7和35.9 fb^{-1}）对标量双光子共振进行了搜寻。
- **观测异常：** 实验数据在95.3 GeV 处展现出**2.8**σ 的局部信号超出(Local Excess)。
- **物理假设：** 我们假设在95 GeV 附近存在一个全新的、更轻的标量粒子（即本模型中**最轻的Higgs 玻色子**）。

II. LRSSM

2.1 Supersymmetry



Standard Model of Elementary Particles

超对称变换：

$Q|玻色子\rangle = |费米子\rangle$

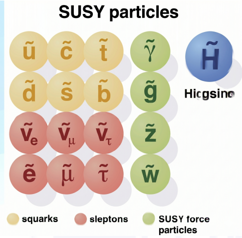
$Q|费米子\rangle = |玻色子\rangle$

$\Longrightarrow$

引入旋量生成元：

Q_a^i 及其厄米共轭$Q_a^{\dagger i}$

$N = 1$ 构成超庞加莱代数



SUSY particles & Gauge Coupling

定义超势：$W = L^i\phi_i + \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k$

手征超场相互作用：$\mathcal{L}_{int} = -\frac{1}{2}\frac{\delta^2 W}{\delta\phi_i\delta\phi_j}\psi_i\psi_j + \frac{\delta W}{\delta\phi_i}F_i + c.c.$

$\mathcal{L}_s = -\lambda_s|H|^2|S|^2 \qquad \delta m_h^2|_s = \frac{\lambda_s}{16\pi^2}[\Lambda^2 + \ldots]$

II. LRSSM

2.2 The Left-Right Supersymmetric Model (LRSSM)

- **Gauge Group**

$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- **Chiral Superfields**

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes \mathrm{SU(2)} \otimes \mathrm{SU(2)} \otimes \mathrm{SU(3)})$
$\hat{q}_L$	$\tilde{q}_L$	q_L	3	$(\frac{1}{3}, \mathbf{2}, \mathbf{1}, \mathbf{3})$
$\hat{q}_R$	$\tilde{q}_R$	q_R	3	$(-\frac{1}{3}, \mathbf{1}, \mathbf{2}, \overline{\mathbf{3}})$
$\hat{l}_L$	$\tilde{l}_L$	l_L	3	$(-1, \mathbf{2}, \mathbf{1}, \mathbf{1})$
$\hat{l}_R$	$\tilde{l}_R$	l_R	3	$(1, \mathbf{1}, \mathbf{2}, \mathbf{1})$
$\hat{\Phi}_1$	Φ_1	$\tilde{\Phi}_1$	1	$(0, \mathbf{2}, \mathbf{2}, \mathbf{1})$
$\hat{\Phi}_2$	Φ_2	$\tilde{\Phi}_2$	1	$(0, \mathbf{2}, \mathbf{2}, \mathbf{1})$
$\hat{\delta}_L$	δ_L	$\tilde{\delta}_L$	1	$(2, \mathbf{3}, \mathbf{1}, \mathbf{1})$
$\hat{\Delta}_L$	Δ_L	$\tilde{\Delta}_L$	1	$(-2, \mathbf{3}, \mathbf{1}, \mathbf{1})$
$\hat{\Delta}_R$	Δ_R	$\tilde{\Delta}_R$	1	$(-2, \mathbf{1}, \mathbf{3}, \mathbf{1})$
$\hat{\delta}_R$	δ_R	$\tilde{\delta}_R$	1	$(2, \mathbf{1}, \mathbf{3}, \mathbf{1})$
$\hat{S}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1}, \mathbf{1})$

II. LRSSM

- **Superpotential**

$$
\begin{aligned}
W = & \; Q_L^T Y_Q^i \Phi_i Q_R + L_L^T Y_L^i \Phi_i L_R + L_L^T h_{LL} \delta_L L_L \\
& + L_R^T h_{RR} \Delta_R L_R + \lambda_L S \mathrm{Tr}[\Delta_L \delta_L] + \lambda_R S \mathrm{Tr}[\Delta_R \delta_R] \\
& + \lambda_3 S \mathrm{Tr}[\tau_2 \Phi_1^T \tau_2 \Phi_2] + \lambda_4 S \mathrm{Tr}[\tau_2 \Phi_1^T \tau_2 \Phi_1] \\
& + \lambda_5 S \mathrm{Tr}[\tau_2 \Phi_2^T \tau_2 \Phi_2] + \lambda_S S^3 + \xi_F S
\end{aligned}
$$

- **Higgs field**

$$
\Phi_1 = \begin{pmatrix} \Phi_{11}^+ & H_{11}^0 \\ H_{12}^0 & \Phi_{12}^- \end{pmatrix} \sim (1,2,2,0), \qquad \Phi_2 = \begin{pmatrix} \Phi_{21}^+ & H_{21}^0 \\ H_{22}^0 & \Phi_{22}^- \end{pmatrix} \sim (1,2,2,0),
$$

$$
\Delta_L = \begin{pmatrix} \frac{\Delta_L^-}{\sqrt{2}} & H_{\Delta_L}^0 \\ \Delta_L^{--} & \frac{-\Delta_L^-}{\sqrt{2}} \end{pmatrix} \sim (1,3,1,-2), \qquad \delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ H_{\delta_L}^0 & \frac{-\delta_L^+}{\sqrt{2}} \end{pmatrix} \sim (1,3,1,2),
$$

$$
\delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ H_{\delta_R}^0 & \frac{-\delta_R^+}{\sqrt{2}} \end{pmatrix} \sim (1,1,3,2), \qquad \Delta_R = \begin{pmatrix} \frac{\Delta_R^-}{\sqrt{2}} & H_{\Delta_R}^0 \\ \Delta_R^{--} & \frac{-\Delta_R^-}{\sqrt{2}} \end{pmatrix} \sim (1,1,3,-2),
$$

$$
S = H_S^0 \sim (1,1,1,0)
$$

II. LRSSM

- **CP-even Neutral**

  5×5: $(Re[H_{12}^0], Re[H_{21}^0], Re[H_{\Delta_R}^0], Re[H_{\delta_R}^0], Re[H_S^0])$

  2×2: $(Re[H_{11}^0], Re[H_{22}^0])$ & $(Re[\Delta_L^0], Re[\delta_L^0])$

- **CP-odd Neutral**

  5×5: $(Im[H_{12}^0], Im[H_{21}^0], Im[H_{\Delta_R}^0], Im[H_{\delta_R}^0], Im[H_S^0])$

  2×2: $(Im[H_{11}^0], Im[H_{22}^0])$ & $(Im[\Delta_L^0], Im[\delta_L^0])$

- **Singly Charged**

  4×4: $(\Phi_{12}^{\pm}, \Phi_{21}^{\pm}, \Delta_R^{\pm}, \delta_R^{\pm})$

  2×2: $(\Phi_{11}^{\pm}, \Phi_{22}^{\pm})$ & $(\Delta_L^{\pm}, \delta_L^{\pm})$

- **Doubly Charged**

  2×2: $(\Delta_R^{\pm\pm}, \delta_R^{\pm\pm})$ & $(\Delta_L^{\pm\pm}, \delta_L^{\pm\pm})$

II. LRSSM

3.2 添加的质量修正

- 单圈有效势

$$\Delta V = \sum_i \frac{n_i}{64\pi^2} m_i^4(\phi_1, \phi_2, \phi_{\Delta_R}, \phi_{\delta_R}, \phi_s) \times \left(\log \frac{m_i^2(\phi_1, \phi_2, \phi_{\Delta_R}, \phi_{\delta_R}, \phi_s)}{Q^2} - \frac{3}{2} \right).$$

$$\Delta V = V_t + V_b + V_\tau + V_{\nu_R} + V_{\tilde{u}_i} + V_{\tilde{d}_i} + V_{\tilde{e}_i} + V_{\tilde{\nu}_i} + V_{W_1,W_2} + V_{Z,Z'} + V_{\chi_i^0} + V_{H_i^\pm} + V_{\chi_i^\pm}.$$

- 双圈有效势

$$V_2 = 2J(m_t^2, m_t^2) - 4m_t^2 I(m_t^2, m_t^2, 0) + \{2m_{\tilde{t}1}^2 I(m_{\tilde{t}1}^2, m_{\tilde{t}1}^2, 0) + 2L(m_{\tilde{t}1}^2, m_{\tilde{g}}^2, m_t^2)$$
$$- 4m_t m_{\tilde{g}} s_{2\tilde{\theta}} c_{\varphi-\tilde{\varphi}} I(m_{\tilde{t}1}^2, m_{\tilde{g}}^2, m_t^2) + \frac{1}{2}(1 + c_{2\tilde{\theta}}^2) J(m_{\tilde{t}1}^2, m_{\tilde{t}1}^2) + \frac{s_{2\tilde{\theta}}^2}{2} J(m_{\tilde{t}1}^2, m_{\tilde{t}2}^2)$$
$$+ [m_{\tilde{t}1} \leftrightarrow m_{\tilde{t}2}, s_{2\tilde{\theta}} \to -s_{2\tilde{\theta}}]\},$$

- **Pole Mass**

$$\det[\Gamma_{ij}(p^2)] = 0, -i\Gamma_{ij}(p^2) = p^2\delta_{ij} - M_{ij,0}^2 - \Delta M_{ij}^2(p^2),$$

$$\Delta M_{ij}^2(p^2) = \Pi_{ij}(p^2) - \Pi_{ij}(0) - \frac{\partial^2 \Delta V}{\partial\phi_i \partial\phi_j}$$

III.95 GeV Excesses

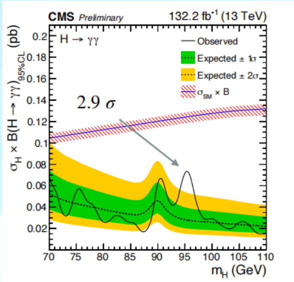
$\gamma\gamma$

$\Rightarrow$ 2015, 19.7fb^{-1},8TeV: 97GeV, 2.0σ

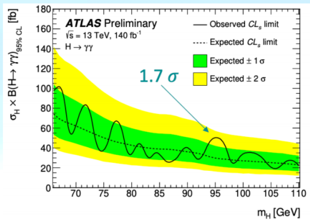
$\Rightarrow$ 2018, 35.9fb^{-1}, 13TeV: 95GeV, 2.8σ

$\Rightarrow$ 2023, Run-2,13TeV: 95GeV, 2.9σ

$\mu_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$



CMS-PAS-HIG-20-002



C. Arcangeletti, LHC Seminar, June 2023

$\Rightarrow$ 2018, 80fb^{-1}: Nothing

$\Rightarrow$ 2023, Run-2: 95GeV, 1.7σ

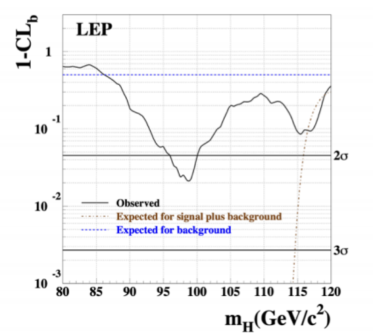
$\mu_{\gamma\gamma} = 0.18 \pm 0.10$

Combined result: $$\mu_{\gamma\gamma}^{\text{exp}} \equiv \mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = \frac{\sigma(pp \to \phi \to \gamma\gamma)}{\sigma_{\text{SM}}(pp \to H_{\text{SM}} \to \gamma\gamma)} = \mathbf{0.24^{+0.09}_{-0.08}}\ (\mathbf{3.1}\sigma)$$

Phys.Rev.D 109 (2024) 3, 035005

III. 95 GeV Excesses

$b\bar{b}$



Phys.Lett.B565:61-75,2003

LEP $e^+e^- \to Z\phi \to Z(b\bar{b})$:

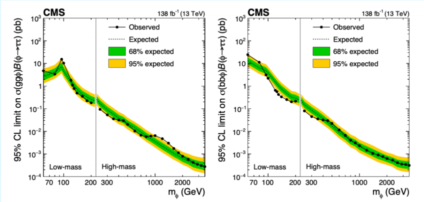
background-only,
$\sqrt{s} = 189 - 209$ GeV

$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057\ (2.3\sigma)$

at 98 GeV

III. 95 GeV Excesses

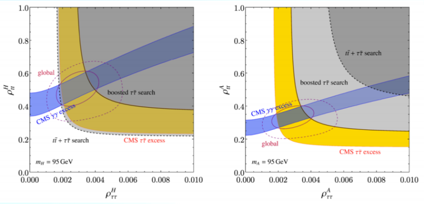
$\tau\bar{\tau}$



JHEP 07 (2023) 073

Eur. Phys. J. C 83 (2023) 1138

$$\mu^{\mathbf{exp}}_{\tau\bar{\tau}} = 1.38^{+0.69}_{-0.55}$$



For a CP-even scalar, excluded at 1σ level by ATLAS $t\bar{t}+\tau\bar{\tau}$ search

Eur. Phys. J. C 82, 1053 (2022)

model-independently ruled out by $t\bar{t}\phi$ search

Phys. Rev. D 108 (2023) 075011

Phys. Rev. D 110 (2024) 012013

III. 95.4 GeV Excesses

- μ_{NP}^{bb} **and** $\mu_{NP}^{\gamma\gamma}$

$b\bar{b}$ Final State

$$\mu_{NP}^{bb} = \frac{\sigma^{NP}(Z^* \to Zh_1)}{\sigma^{SM}(Z^* \to Zh_1)} \times \frac{Br^{NP}(h_1 \to b\bar{b})}{Br^{SM}(h_1 \to b\bar{b})}$$

$$\approx |C_{h_1 VV}|^2 \times \frac{\Gamma^{NP}_{h_1 \to b\bar{b}}}{\Gamma^{SM}_{h_1 \to b\bar{b}}} \times \frac{\Gamma^{SM}_{tot}}{\Gamma^{NP}_{tot}}$$

$$\approx \frac{|C_{h_1 VV}|^2 \times |C_{h_1 dd}|^2}{|C_{h_1 dd}|^2 (Br^{SM}_{h_1 \to b\bar{b}} + Br^{SM}_{h_1 \to \gamma\gamma}) + |C_{h_1 uu}|^2 (Br^{SM}_{h_1 \to gg} + Br^{SM}_{h_1 \to c\bar{c}})}$$

$\gamma\gamma$ Final State

$$\mu_{NP}^{\gamma\gamma} = \frac{\sigma^{NP}(gg \to h_1)}{\sigma^{SM}(gg \to h_1)} \times \frac{Br^{NP}(h_1 \to \gamma\gamma)}{Br^{SM}(h_1 \to \gamma\gamma)}$$

$$\approx \frac{\Gamma^{NP}_{h_1 \to gg}}{\Gamma^{SM}_{h_1 \to gg}} \times \frac{\Gamma^{NP}_{h_1 \to \gamma\gamma}}{\Gamma^{SM}_{h_1 \to \gamma\gamma}} \times \frac{\Gamma^{SM}_{tot}}{\Gamma^{NP}_{tot}}$$

$$\approx \frac{|C_{h_1 uu}|^2 \times |C_{h_1 \gamma\gamma}|^2}{|C_{h_1 dd}|^2 \left(Br^{SM}_{h_1 \to b\bar{b}} + Br^{SM}_{h_1 \to \tau\tau}\right) + |C_{h_1 uu}|^2 \left(Br^{SM}_{h_1 \to gg} + Br^{SM}_{h_1 \to c\bar{c}}\right)}$$

III. 95 GeV Excesses

- **Loop-induced Diphoton Coupling**

The effective coupling ratio $|C_{h_1\gamma\gamma}|^2$ includes contributions from top-quark and W-boson loops:

$$|C_{h_1\gamma\gamma}|^2 = \frac{\left|\frac{4}{3}C_{h_1tt}A_{1/2}(\tau_t) + C_{h_1VV}A_1(\tau_W)\right|^2}{\left|\frac{4}{3}A_{1/2}(\tau_t) + A_1(\tau_W)\right|^2}$$

$A_{1/2}(x)$ and $A_1(x)$ are the standard kinematic form factors.

- **Tree-level Couplings relative to SM**

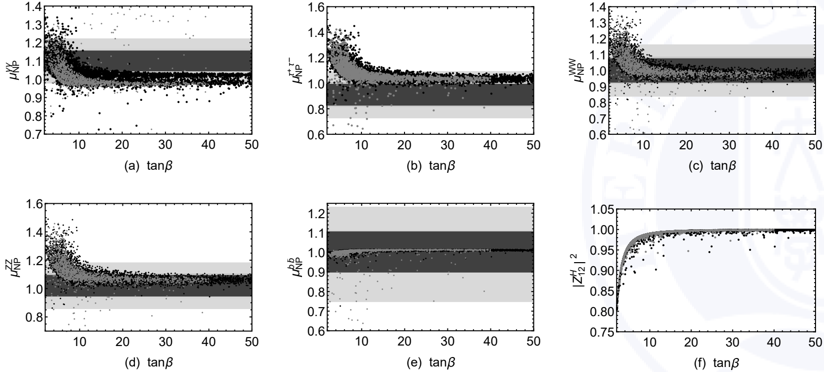
The ratios of vertices between h_1 and SM particles ($W^\pm$, up-type, and down-type quarks) are determined by the CP-even Higgs mixing matrix Z_H:

$$C_{h_1d\bar{d}} = \frac{Z^H_{11}}{\cos\beta}, \quad C_{h_1u\bar{u}} = \frac{Z^H_{12}}{\sin\beta}, \quad C_{h_1VV} = Z^H_{11}\cos\beta + Z^H_{12}\sin\beta.$$

IV. Numerical results

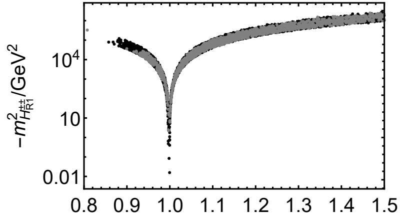
4.1 Numerical Results for the 125 GeV Higgs State Only

- **Signal Strengths of the 125 GeV Higgs Boson**

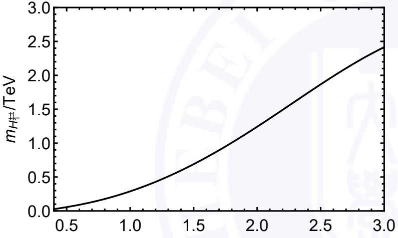


IV. Numerical results

- **Mass Corrections of the Doubly Charged Higgs Bosons**



(a) $\tan\beta_R$

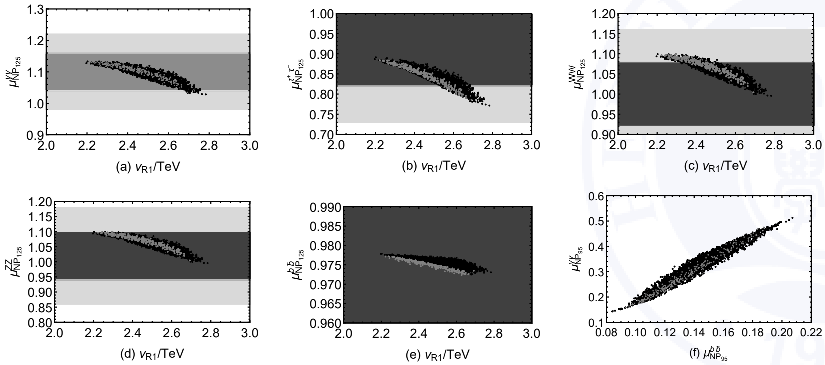


(b) h_{RR}

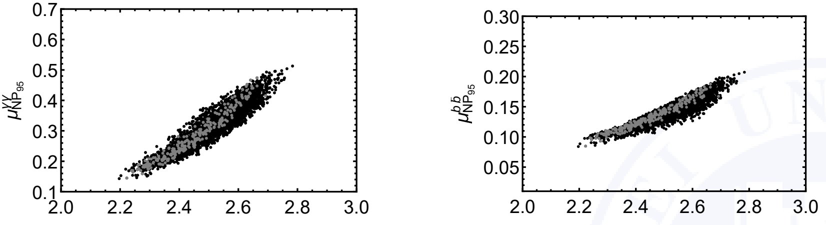
IV. Numerical results

4.2 Numerical Results for Coexisting 95 GeV and 125 GeV Higgs States

• Signal Strengths of the 95 GeV and 125 GeV Higgs Bosons

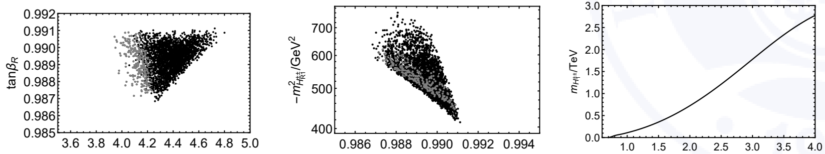


IV. Numerical results



(a) v_{R1}/TeV (b) v_{R1}/TeV

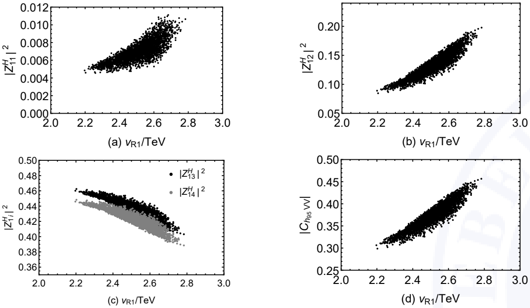
- **Mass Corrections of the Doubly Charged Higgs Bosons**

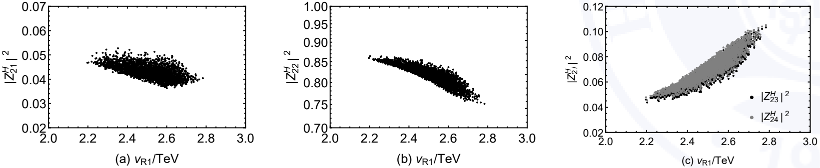


(a) $\tan\beta$ (b) $\tan\beta_R$ (c) h_{RR}

IV. Numerical results

- **Compositions of the 95 GeV and 125 GeV Higgs Bosons**





V. Conclusion

1. The LRSSM provides a robust framework to simultaneously explain the 95 GeV and 125 GeV Higgs boson excesses.

2. Incorporating one- and two-loop effective potential corrections is essential for precise predictions of Higgs pole masses and signal strengths.

3. The theoretical signal strengths successfully account for the 95 GeV excesses in $\gamma\gamma$ and $b\bar{b}$ channels (within $1-2\sigma$) while remaining highly consistent with current LHC precision measurements for the 125 GeV state across all major decay channels.

4. Radiative corrections ensure that doubly charged Higgs boson masses ($H^{\pm\pm}$) satisfy the experimental lower limit of 1.3 TeV.

Thanks!