





## **Interpretation of 95 GeV Excesses in NMSSM in light** of Current Dark Matter Detection Constraints

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- Physical Review D 2024, 109(07): 075001, with Prof. Junjie Cao and Dr. Xinglong Jia
  - 1/16 连经伟 HIST & HNU

## Outline

• Motivation • 95 GeV excesses • Higgs Sector in the Z<sub>3</sub>-NMSSM • Numerical results Conclusion





## **BSM New physics must exist**

#### **Motivation:**

. . . . . .

- > Dark matter and Dark energy
- > Matter-Antimatter asymmetry
- > Neutrino mass
- > Hierarchy problem
- > Strong CP problem
- > Unification of forces

#### **Other important hints:**

- New Higgs searches
- muon g-2 anomaly





 $\Delta m_h^2 = -\frac{Y_f^2}{8\pi^2} [\Lambda^2 + ...],$ 



### **95.4 GeV Excesses at colliders**



 $\Rightarrow$  2015, 19.7*fb*<sup>-1</sup>, 8TeV:

97GeV,  $2.0\sigma$ 

 $\Rightarrow$  2018, 35.9*fb*<sup>-1</sup>, 13TeV:

95GeV,  $2.8\sigma$ 

- ◆ 2023, Run-2, 13TeV: 95GeV,  $2.9\sigma$ 
  - $\mu_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$

Combined result:  $\mu_{\gamma\gamma}^{exp} \equiv \mu_{\gamma\gamma}^{ATLAS+CMS} = -$ 

T. Biekötter, S. Heinemeyer, G. Weiglein, Phys.Rev.D 109 (2024) 3, 035005.



CERN-EP-2024-166, JHEP 01 (2025) 053

$$\frac{\sigma(pp \to \phi \to \gamma\gamma)}{\sigma_{\rm SM}(pp \to H_{\rm SM} \to \gamma\gamma)} = 0.24^{+0.09}_{-0.08} (3.1\sigma)$$

#### 95.4 GeV Excesses at collider





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A local excess in  $e^+e^- \rightarrow Z\phi \rightarrow Z(b\bar{b})$  channel at 98 GeV at LEP:

 $\mu_{b\bar{b}}^{\exp} = 0.117 \pm 0.057 \ (2.3\sigma)$ 

LEP collaborations, Phys.Lett.B 565:61-75, 2003

A local excess in the di-tau channel at 95 GeV observed by CMS:

$$\mu_{\tau\bar{\tau}}^{\exp} = 1.38^{+0.69}_{-0.55} \ (2.6\sigma)$$

A. Tumasyan et al., JHEP 07 (2023) 073 U. Ellwanger et al., Eur. Phys. J. C 83 (2023) 1138





## Supersymmetry

超对称变换: Q| 玻色子 $\rangle = |$  费米子 $\rangle$ , Q|费米子 $\rangle = |$ 玻色子 $\rangle$ 

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

定义超势:  $W = L^i d$ 

手征超场相互作用:

 $\mathscr{L}_{int} = -$ 

C

H

#### **Standard Model of Elementary Particles**



$$\phi_i + \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k,$$

$$-\frac{1}{2}\frac{\delta^2 W}{\delta\phi_i\delta\phi_j}\psi_i\psi_j + \frac{\delta W}{\delta\phi_i}F_i + c.c,$$

$$\mathscr{L}_{s} = -\lambda_{s} |H|^{2} |S|^{2}$$
$$\delta m_{h}^{2}|_{s} = \frac{\lambda_{s}}{16\pi^{2}} [\Lambda^{2} + \dots]$$





#### Higgs Sector in the Z<sub>3</sub>-NMSSM

**Superpotential and Soft-breaking terms**  $W_{Z_3} \supset \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3, \quad -\mathcal{L}_{soft} \supset \left(\lambda A_\lambda S H_u \cdot \hat{S}^3 + \frac{1}{3} \kappa \hat{S}^3\right)$  $\bigstar$  CP-even Higgs boson Mass in ( $H_{NSM}$ ,  $\mathcal{M}_{S,11}^2 = m_A^2 + \frac{1}{2}(2m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$ **MSSM** li  $\mathcal{M}_{S,12}^2 = -\frac{1}{4}(2m_Z^2 - \lambda^2 v^2)\sin 4\beta,$ S field m  $\mathscr{M}_{S.13}^2 = \sqrt{2\lambda\mu\nu(\delta-1)\cot 2\beta},$  $\mathscr{M}_{S,22}^{2} = m_{Z}^{2}\cos^{2}2\beta + \frac{1}{2}\lambda^{2}v^{2}\sin^{2}2\beta,$ Singlet C  $\mathscr{M}_{S,23}^2 = \sqrt{2\lambda\mu v\delta},$  $\mathscr{M}^2_{S,33} = m^2_B,$  $h_i = V_{h_i}^{\text{NSM}} H_{\text{NSM}} + V_{h_i}^{\text{SM}} H_{\text{SM}} + V_{h_i}^{\text{SM}} \text{Re}[S]$ 

$$H_{u} \cdot H_{d} + \frac{1}{3}\kappa A_{\kappa}S^{3} + \text{h.c.} )$$
  
$$H_{SM}, H_{S} \text{ with } \qquad H_{NSM} = \sqrt{2}\text{Re}(\cos\beta H_{u}^{0} - \sin\beta H_{d}^{0}),$$
  
$$H_{SM} = \sqrt{2}\text{Re}(\sin\beta H_{u}^{0} + \cos\beta H_{d}^{0}),$$

ike CP odd Higgs boson : 
$$M_A^2 = \frac{2\mu}{\sin 2\beta} (A_\lambda + \frac{\kappa}{\lambda}\mu),$$

**ixing factor** : 
$$\delta = 1 - \frac{A_{\lambda} + m_N}{2\mu} \sin 2\beta$$
,

Singlino Mass :  $m_N = \sqrt{2\kappa v_s}$ ,

$$CP \text{ even Higgs boson} : m_B^2 = \frac{\lambda^2 v^2 A_\lambda \sin 2\beta}{4\mu} + \frac{\mu}{\lambda} (\kappa A_\kappa + 4\kappa^2 \frac{\mu}{\lambda})$$

3 CP-even Scalars:  $h_s$ , h, H; 2 CP-odd Scalars:  $A_s$ ,  $A_H$ ; and a pair of charged scalars:  $H^{\pm}$ .

## 95.4 GeV Excesses in the Z<sub>3</sub>-NMSSM



 
 Table 3 Some BSM Higgs masses, the nature of the LSP, NLSP, the
 lightest slepton, and the corresponding masses for five BMpoints. All dimensionful parameters are given in GeV

	BP1	BP2	BP3	BP4	BP5
$M_{H3}$	3966	4852	4367	2069	5592
$M_{A1}$	21	18	31	206	260
LSP	singl	singl	singl	singl	bino
$M_{\rm LSP}$	9.0	43.9	62.9	157	44.1
NLSP	$wino^{\pm}$	wino $^{\pm}$	bino	bino	wino <sup>0</sup>
M <sub>NLSP</sub>	115	107	74.8	164	113
Slepton	$\tilde{\nu}_{ au}$	$\tilde{\nu}_e$	$\tilde{e}_{R.h.}$	$\tilde{\nu}_e$	$\tilde{\nu}_{ au}$
M <sub>Slepton</sub>	140	171	255	165	93.4



	BP1	BP2	BP3	BP4	BP5
$\mu_{bb}^{LEP}$	$1.18  imes 10^{-2}$	0.115	0.106	0.105	0.116
$\mu_{\gamma\gamma}^{LHC}$	0.331	$8.01 \times 10^{-2}$	$8.01 \times 10^{-2}$	$8.75  imes 10^{-2}$	0.130
$\mu^{LHC}_{ au au}$	$1.28 \times 10^{-2}$	0.112	0.102	$9.34 \times 10^{-2}$	0.117
$\sigma_p^{SI}$	$3.43 \times 10^{-11}$	$4.98\times10^{-12}$	$1.59\times10^{-12}$	$1.49 \times 10^{-13}$	$8.90 \times 10^{-1}$
$\sigma_n^{SD}$	$3.66 \times 10^{-5}$	$3.12 \times 10^{-7}$	$1.15 \times 10^{-7}$	$1.06 \times 10^{-7}$	$4.40 \times 10^{-1}$

U. Ellwanger et al., Eur. Phys. J. C 84, 526 (2024).

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-12-7

### 95.4 GeV Scalar in Z<sub>3</sub>-NMSSM

#### Normalized $\gamma\gamma$ signal strength

$$\mu_{\gamma\gamma} = \frac{\sigma_{\rm SUSY}(pp \to h_s)}{\sigma_{\rm SM}(pp \to h_s)} \times \frac{{\rm Br}_{\rm SUSY}(h_s \to \gamma\gamma)}{{\rm Br}_{\rm SM}(h_s \to \gamma\gamma)} \simeq |C_{h_sgg}|^2 \times |C_{h_s\gamma\gamma}|^2 \times {\rm R}_{\rm Width},$$

#### Normalized bb signal strength

$$\mu_{b\bar{b}} = \frac{\sigma_{\rm SUSY}(e^+e^- \to Zh_s)}{\sigma_{\rm SM}(e^+e^- \to Zh_s)} \times \frac{{\rm Br}_{\rm SUSY}(h_s \to b\bar{b})}{{\rm Br}_{\rm SM}(h_s \to b\bar{b})} \simeq \left| C_{h_s VV} \right|^2 \times |C_{h_s b\bar{b}}|^2 \times {\rm R}_{\rm Width},$$

 $1/R_{\text{Width}} \simeq 0.801 \times |C_{h_s b\bar{b}}|^2 + 0.083 \times |C_{h_s \tau\bar{\tau}}|^2 + 0.041 \times |C_{h_s c\bar{c}}|^2 + 0.067 \times |C_{h_s g\bar{g}}|^2 + \dots$ 200

## 95.4 GeV Scalar in Z<sub>3</sub>-NMSSM

#### Tree level normalized couplings:

$$\begin{split} C_{h_{s}t\bar{t}} &= V_{h_{s}}^{\text{SM}} + V_{h_{s}}^{\text{NSM}} \cot \beta \simeq V_{h_{s}}^{\text{SM}}, \quad C_{h_{s}b\bar{b}} = V_{h_{s}}^{\text{SM}} - V_{h_{s}}^{\text{NSM}} \tan \beta, \quad C_{h_{s}VV} = V_{h_{s}}^{\text{SM}}, \\ C_{h_{s}c\bar{c}} &= C_{h_{s}t\bar{t}}, \quad C_{h_{s}\tau\bar{\tau}} = C_{h_{s}b\bar{b}}, \quad C_{h_{s}gg} \simeq C_{h_{s}t\bar{t}}, \quad C_{h_{s}\gamma\gamma} \simeq V_{h_{s}}^{\text{SM}}, \\ \hline \text{Considering loop mediated by quarks and squarks:} \\ C_{h_{s}gg} \text{ and } C_{h_{s\gamma\gamma}} \text{ deviates from } C_{h_{s}t\bar{t}} \text{ by } 4\% \text{ and } 11\%; \end{split}$$

$$\begin{aligned} \text{Central values of } \mu_{\gamma\gamma} \text{ and } \mu_{b\bar{b}} \text{ corresponds to:} \\ V_{h_{s}}^{\text{SM}} \simeq 0.35, \quad (V_{h_{s}}^{\text{SM}} - V_{h_{s}}^{\text{NSM}} \tan \beta) \simeq 0.81 \times V_{h_{s}}^{\text{SM}} \simeq 0.28, \\ \text{Br}_{\text{SUSY}}(h_{s} \rightarrow \gamma\gamma) \simeq 1.77 \times \text{Br}_{\text{SM}}(h_{s} \rightarrow \gamma\gamma) \simeq 2.5 \times 10^{-3}, \end{aligned}$$

 $Br_{SUSY}(h_s \rightarrow bb) \simeq 0.95 \times Br_{SM}(h_s \rightarrow bb)$ 

$$(b\bar{b}) \simeq 76.1\%$$
,



## 95.4 GeV Scalar in Z<sub>3</sub>-NMSSM

#### Using eigenstate equation, in the limit $m_{h_s,h} \ll m_A$ :

$$m_B^2 \simeq m_{h_s}^2 |V_{h_s}^S|^2 + m_h^2 |V_{h_s}^{SM}|^2, \quad V_{h_s}^{SM} \simeq \frac{\sqrt{2}\delta\lambda\mu\nu}{m_h^2 - m_B^2} V_{h_s}^S, \quad V_{h_s}^{NSM} \simeq \frac{\sqrt{2}(1 - \delta)\lambda\mu\nu\cot 2\beta}{m_A^2 - m_{h_s}^2} V_{h_s}^S,$$
  
(a)  $m_B$  is constrained within a narrow range (~ 100 GeV)  
(b)  $\tan\beta \lesssim 10$  for  $m_A \simeq 2$  TeV,  $m_B \simeq 100$  GeV and  $\delta \lesssim 0.3$ ;  
(c) To predict  $V_{h_s}^{NSM} \tan\beta \simeq 0.07$ , the following approximation is inferred:  
 $\delta\lambda \simeq 0.03 \times (\frac{\mu}{200 \text{ GeV}})^{-1},$ 

for electroweakinos.

it points towards  $\delta\lambda \lesssim 0.03$  considering  $\mu \gtrsim 200$  GeV from LHC searches

### **Numerical Results**

$$\mathscr{L}_{\gamma\gamma+b\bar{b}} = \exp\left[-\frac{1}{2}\left(\frac{\mu_{\gamma\gamma}-0.24}{0.08}\right)^2 - \frac{1}{2}\left(\frac{\mu_{b\bar{b}}-0.117}{0.057}\right)^2\right]_{m_{h_s} \simeq 95 \text{GeV}}$$

- ✓ Masses of Higgs bosons:  $m_{h_s} \sim 95.4 \text{ GeV}, m_h \sim 125 \text{ GeV}$
- Higgs data fit using HiggsSignals-2.6
- Extra Higgs searches using HiggsBon
- **DM relic density:** 20% uncertainties of
- DM-nucleon scattering cross section
- ✓ **B physics observables:**  $B_s \rightarrow \mu^+ \mu^-$  at
- Vacuum stability using Vevacious++

AParameterPriorRange
$$\mu/\text{TeV}$$
Flat $0.3 \sim 1.4$  $\mu/\text{TeV}$ Flat $0.3 \sim 1.4$  $m_B/\text{GeV}$ Flat $80 \sim 124$  $\Delta f \Omega h^2 = 0.120$  $M_1/\text{TeV}$ Flat $M_1/\text{TeV}$ Flat $-1.0 \sim -1.0$  $M_2/\text{TeV}$ Flat $0.3 \sim 1.4$  $M_2/\text{TeV}$ Flat $0.001 \sim 0.4$  $M B \rightarrow X_s \gamma$  $\lambda$ Flat $0.001 \sim 0.4$  $M B \rightarrow X_s \gamma$  $\lambda$ Flat $0.001 \sim 0.4$ 



## **Numerical Results**



- Scan yields > 28000 points, about 21000 samples explains the anomalies at  $2\sigma$ . • Relic density :  $\tilde{B}$ -like  $\tilde{\chi}_1^0$  coannihilating with  $\tilde{W}$ ;
- $^{+}W^{-}$ , 20.4%,  $\mu \gtrsim 780 \text{ GeV}$
- DM Direct Detection: large  $\mu$  and blind spot  $-m_{\tilde{\chi}_1^0}/\mu \simeq \sin 2\beta \simeq 0.72$ • Bayesian evidence:  $\tilde{\chi}_2^0 \tilde{\chi}_1^- \rightarrow d_i \bar{u}_i (i = 1, 2, 3), 79\%, \mu \gtrsim 450 \text{ GeV}$

$$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \to W^+$$

### **Numerical Results**









## **Numerical Results Explanation in the General NMSSM** $W = W_{Z_3} + \mu \hat{H}_u \cdot \hat{H}_d + \frac{1}{2}\mu'\hat{s}^2 + \xi\hat{S}$



• Bayesian evidence:  $\tilde{S}$ -like  $\tilde{\chi}_1^0$ , coannihilating with  $\tilde{H}$ , 53%,  $\chi^2_{\gamma\gamma+b\bar{b}} \simeq 0.0$  $\tilde{B}$ -like  $\tilde{\chi}_1^0$ , coannihilating with  $\tilde{W}$ , 47%,  $\chi^2_{\nu\nu+b\bar{b}} \simeq 0.27$ 15/16 连经伟 HIST & HNU



#### Conclusion

- particles.
- $\tilde{H}$  that dominates the DM annihilation process in the GNMSSM.
- to larger contributions from chargino loops to  $C_{h_s\gamma\gamma}$ .
- Future colliders experiments, e.g. HL-LHC, CEPC, are worth looking forward to.

• The  $\mathbb{Z}_3$ -NMSSM can simultaneously account for the  $\gamma\gamma$  and bb excesses at a  $1\sigma$  level, without conflicting with constraints from Higgs data fit, B-physics, the Planck and LZ experiments, the vacuum stability considerations, as well as the LHC's searches SUSY

• The interpretation favors the  $\tilde{B}$ -dominated  $\tilde{\chi}_1^0$ s as DM candidates achieving the measured relic abundance primarily by co-annihilating with  $\tilde{W}$ s. While, it is  $\tilde{S}$  co-annihilating with

• Case-I can predict signal strengths closer to the central values compared to Case-II due



# Thanks for your attention