Light and Heavy Scalar Resonances in the GNMSSM with Correct Dark Matter Relic Abundance

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with Prof. Junjie Cao, Prof. Yao-Bei Liu and Dr. Xinglong Jia

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Outline

- Motivation
- Scalar Resonances near 95.4 GeV and 650 GeV
- GNMSSM interpretation
- Conclusion

Motivation

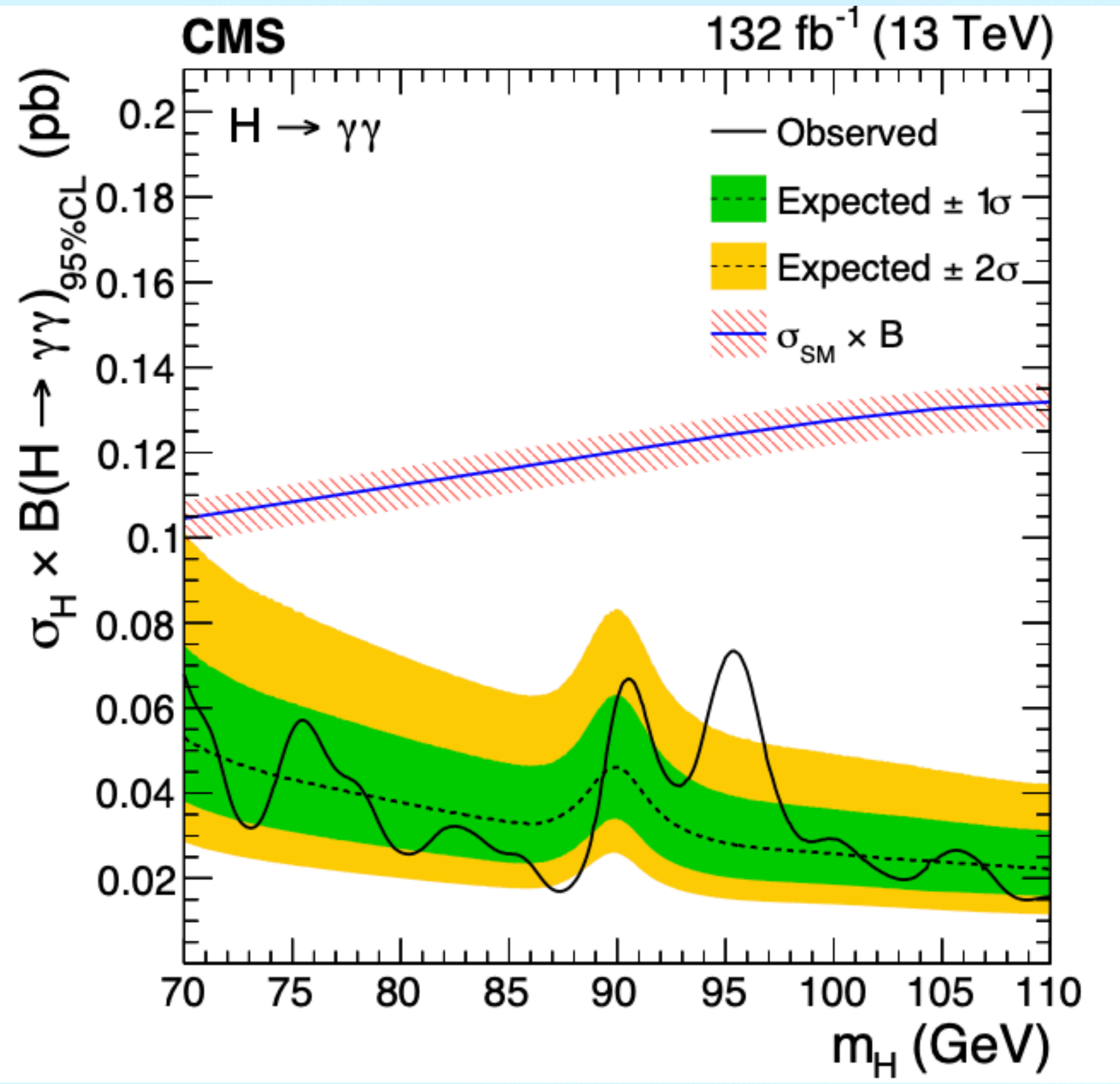
BSM New physics must exist:

- ➢ Dark matter and Dark energy
- ➢ Matter-Antimatter asymmetry
- ➢ Neutrino mass
- ➢ Hierarchy problem
- ➢ Unification of forces
- ➢ ……

Experimental hints:

- Extra Higgs searches
- Lepton g-2
- Flavor Anomalies
- Sparticles in Compressed Scenarios
- Galactic Center γ-ray excess
- ……

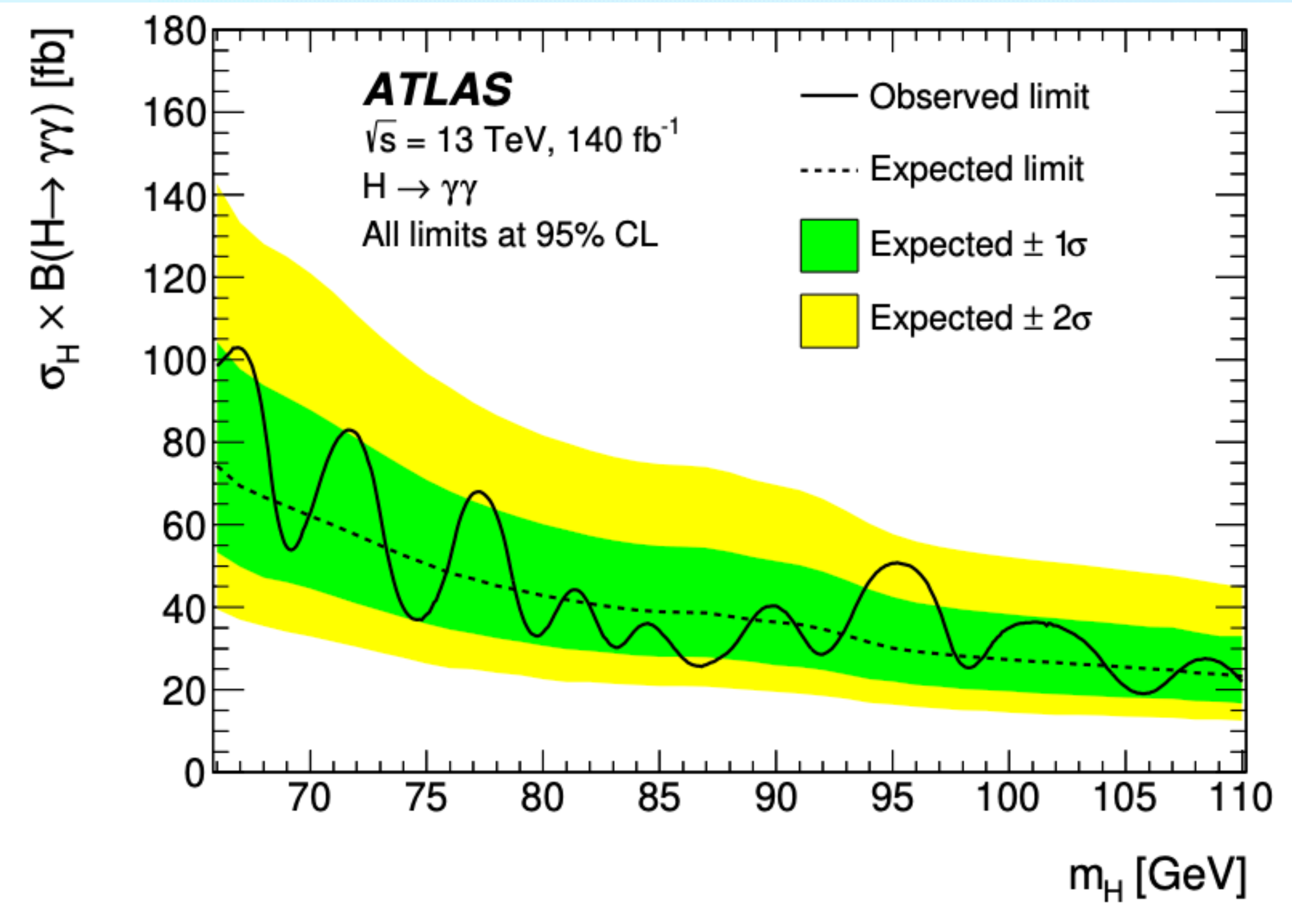
95.4 GeV Excesses at colliders



CMS-PAS-HIG-20-002

- ✦ 2015, $19.7fb^{-1}$, 8TeV: 97GeV, 2.0σ
- ✦ 2018, $35.9fb^{-1}$, 13TeV: 95GeV, 2.8σ
- ✦ 2023, Run-2, 13TeV: 95GeV, 2.9σ

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



CERN-EP-2024-166，JHEP 01 (2025) 053

- ✦ 2018, $80fb^{-1}$: Nothing
- ✦ 2023, Run-2: 95GeV, 1.7σ

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

Combined result in the di-photon channel: $\mu_{\gamma\gamma}^{\text{exp}} \equiv \mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08}\ (3.1\sigma)$

T. Biekötter *et al.*, PRD (2024)109:035005.

Besides, a local excess in the di-tau channel at 95 GeV observed by CMS: $\mu_{\tau\bar{\tau}}^{\text{exp}} = 1.38^{+0.69}_{-0.55}\ (2.6\sigma)$

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

At LEP, a local excess near 98 GeV in $e^+e^- \to Z\phi \to Z(b\bar{b})$ channel: $\mu_{b\bar{b}}^{\text{exp}} = 0.117 \pm 0.057\ (2.3\sigma)$

LEP collaborations, PLB(2003)565:61-75; Junjie Cao *et al.*, PRD(2017)95:116001.

Heavy Scalar Resonance Anomaly

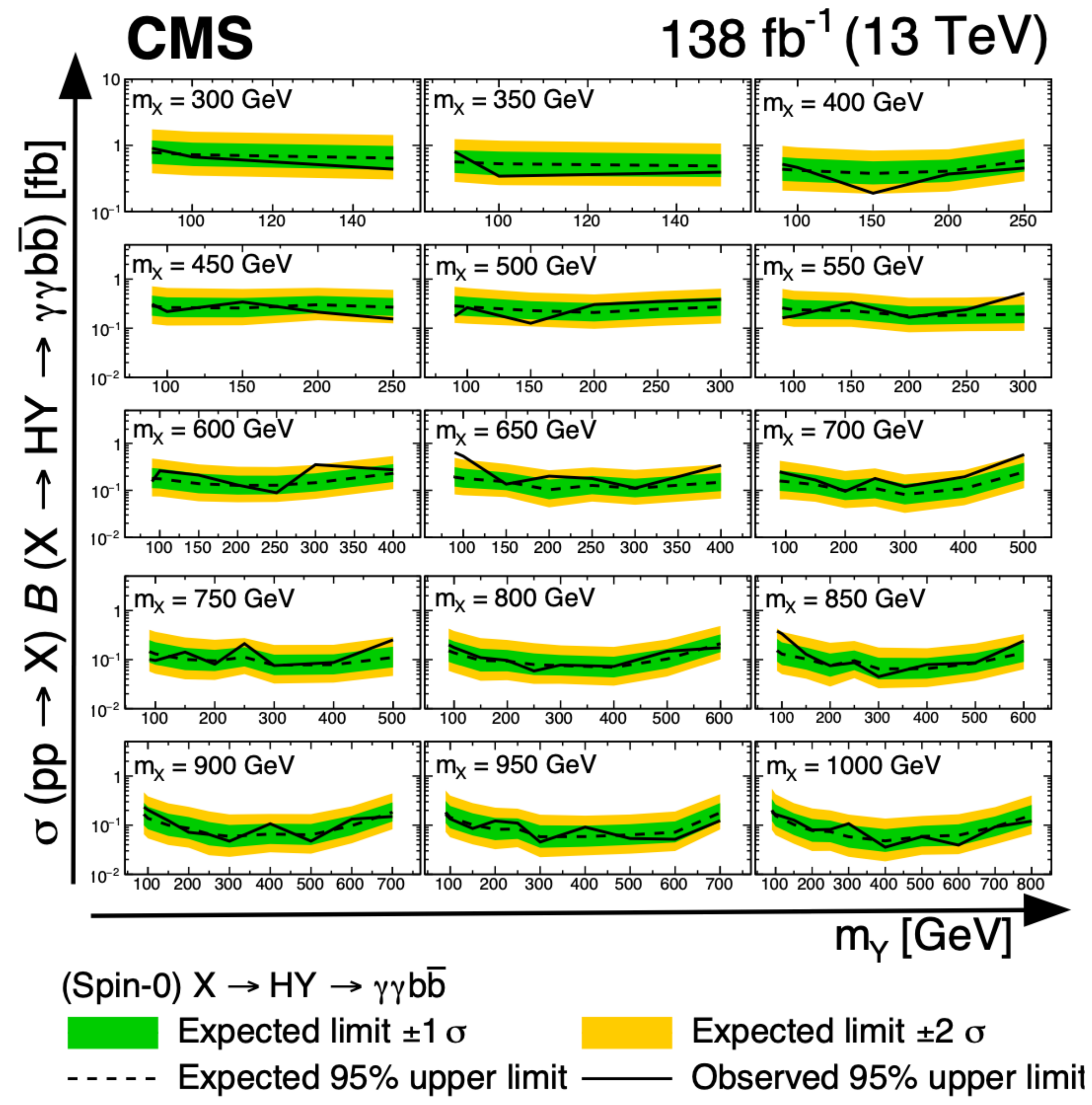
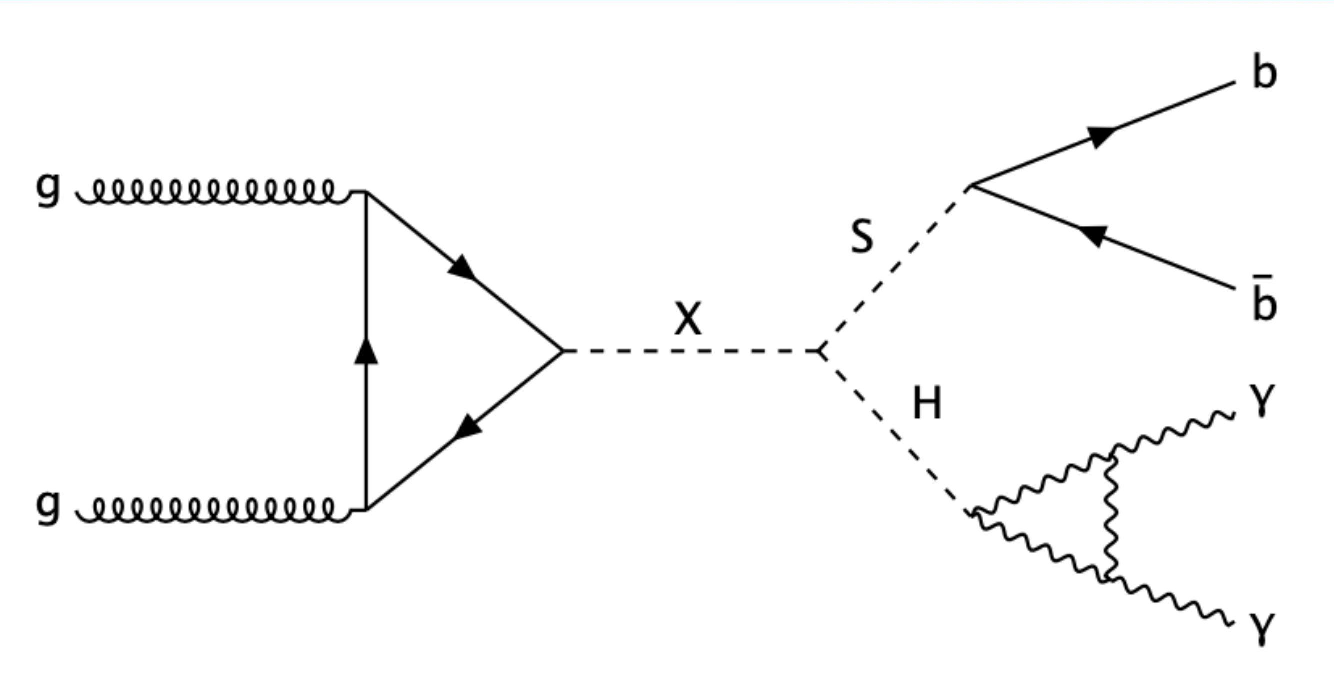


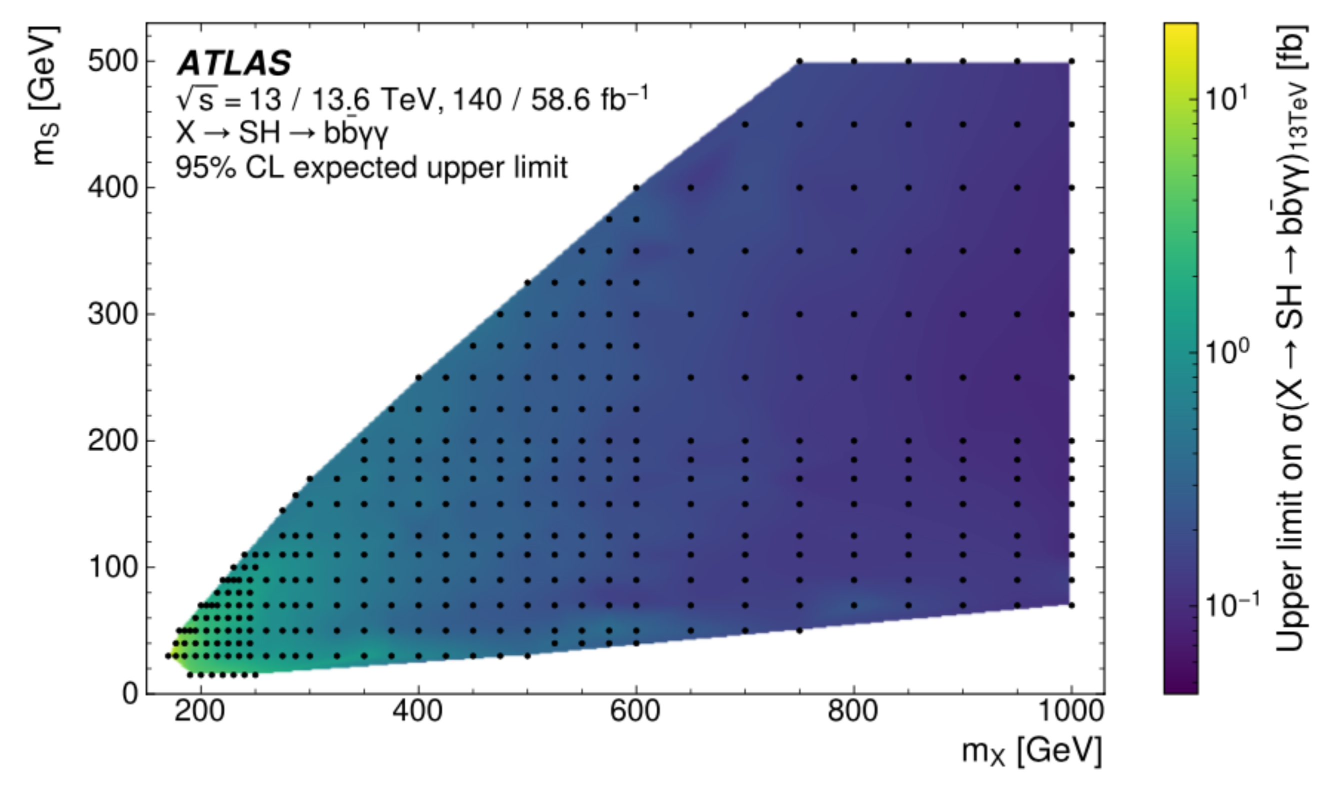
Figure 7: Expected and observed 95% CL exclusion limit on production cross section for pp → X → HY → $\gamma\gamma b\bar{b}$ signal. The dashed and solid black lines represent expected and observed limits, respectively. The green and yellow bands represent the ±1 and ±2 standard deviations for the expected limit. The middle plot in the 3rd row shows the largest excess observed for m_X = 650 GeV and m_Y = 90 GeV.

CMS-HIG-21-011, *JHEP* 05 (2024) 316



$$\sigma(gg \to X \to H_{\rm SM}(\gamma\gamma) + S(b\bar{b})) = 0.35^{+0.17}_{-0.13}\ {\rm fb}$$

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

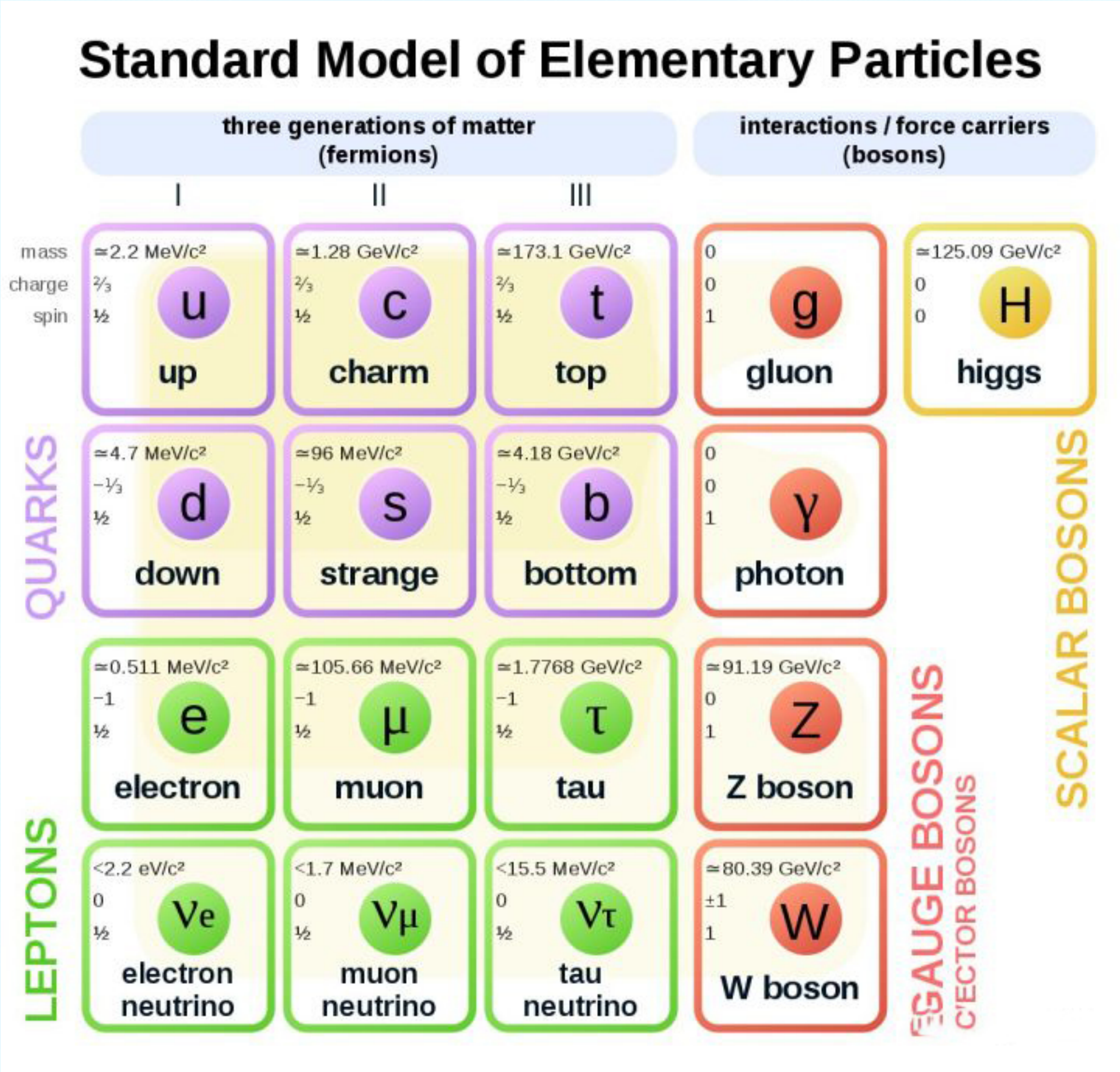


CERN-EP-2025-204

A global (local) excess of 2.8σ (3.8σ) at $(m_X, m_S) = (650, 90)$ GeV was seen by CMS using Run-2 data [*JHEP* 05 (2024) 316] , but not observed in the later CMS report [*JHEP* 12 (2025) 178], and not in the ATLAS analyses [*JHEP* 11 (2024) 047] and [CERN-EP-2025-204] either.

Cosidering an upper 95% CL limit of approximately 3 fb on $\sigma(X \to H_{\rm SM}(\tau\bar{\tau}) + \phi(b\bar{b}))$ [*JHEP* 11 (2021) 057] , $\sigma_{\gamma\gamma b\bar{b}}$ should be less than 0.1 fb.

Supersymmetry



超对称变换：

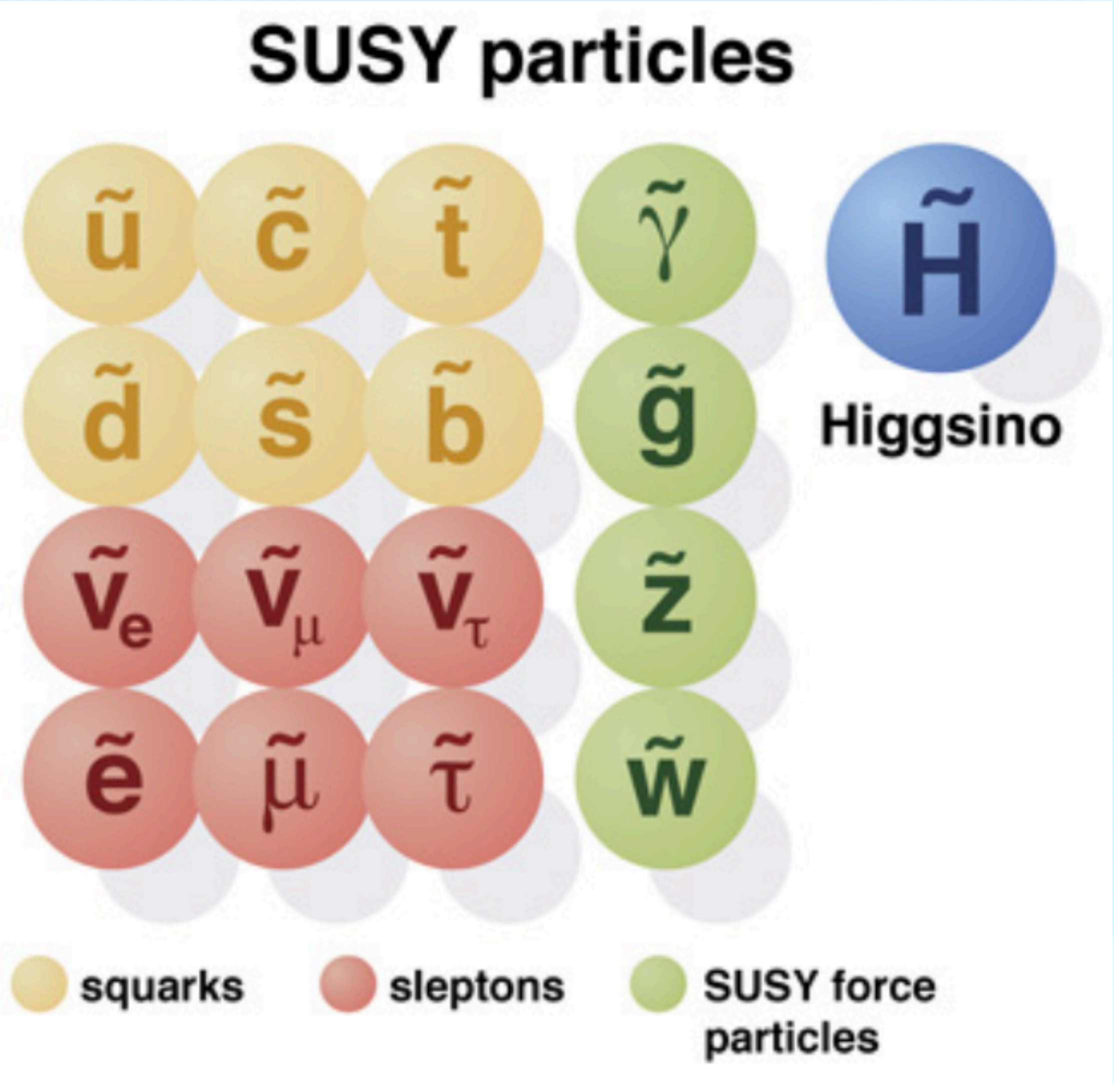
$Q|\text{玻色子}\rangle = |\text{费米子}\rangle,$

$Q|\text{费米子}\rangle = |\text{玻色子}\rangle$

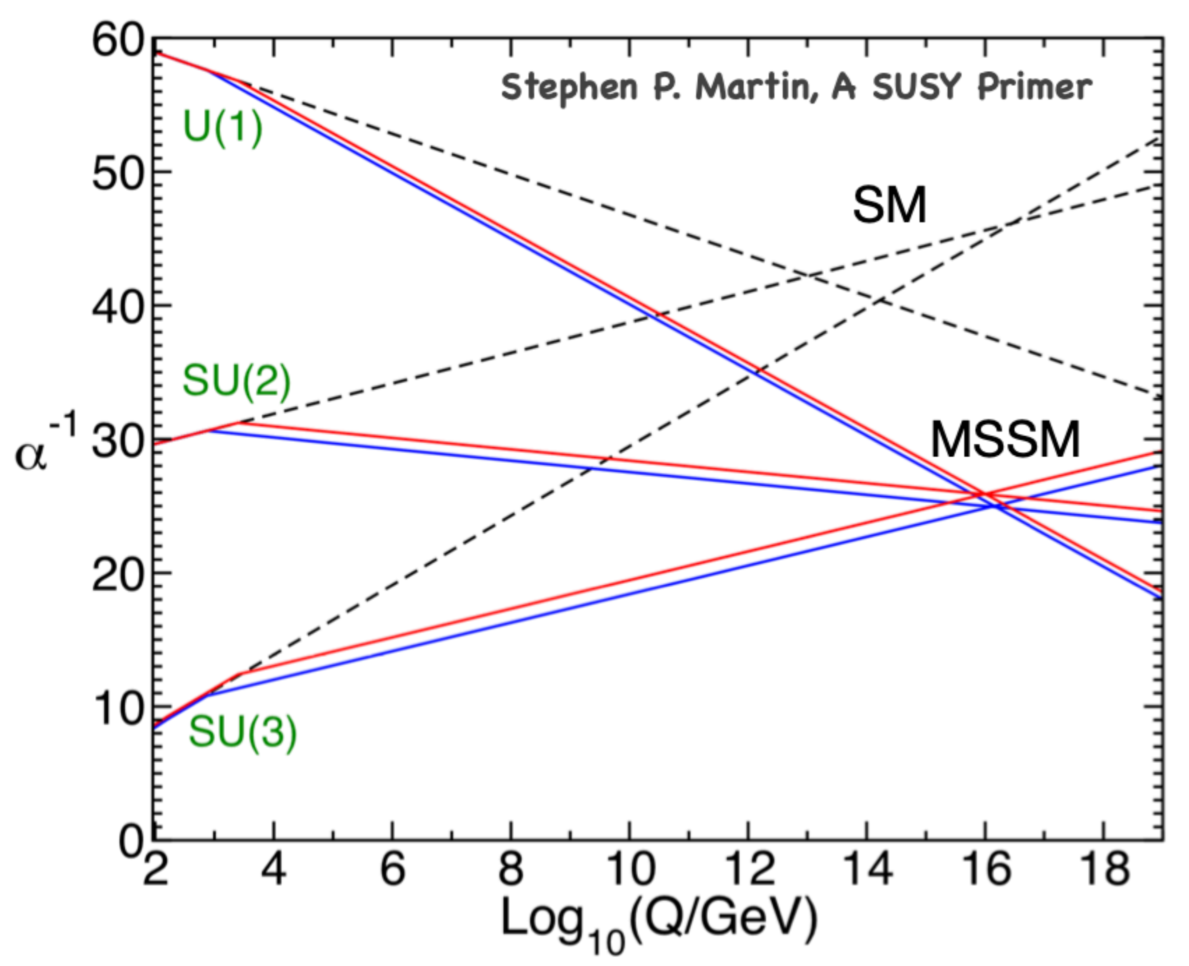
旋量生成元：

Q_a^i及其厄米共轭$Q_a^{\dagger i}$，

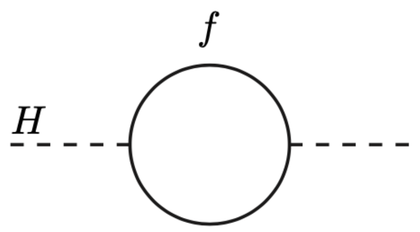
构成超庞加莱代数

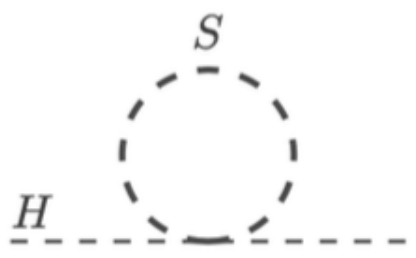


Gauge Unification



Natural EW scale





$$m_h^2 = m_0^2 - \delta m_h^2,$$

$$\delta m_h^2 = -\frac{Y_f^2}{8\pi^2}\left[\Lambda^2 + \ldots\right],$$

$$\mathscr{L}_s = -\lambda_s |H|^2 |S|^2$$

$$\delta m_h^2|_s = \frac{\lambda_s}{16\pi^2}\left[\Lambda^2 + \ldots\right]$$

LSP DM Candidates

- Collisionless WIMP
- Self-Interactions DM
- Asymmetric DM
- Freeze-in DM
- Axion and axino

General Next-to-Minimal Supersymmetric Standard Model (GNMSSM)

❖ **Chiral Superfield**

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(\mathrm{U}(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$

❖ **Superpotential —— no ad hoc symmetry!**

$$W = W_{Yukawa} + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{s}^3 + \mu \hat{H}_u \cdot \hat{H}_d + \frac{1}{2}\mu' \hat{s}^2 + \xi \hat{S}$$

- Solve domain wall and tapole problem in $\mathbb{Z}_3 - $ NMSSM.
- $\mathbb{Z}_3$-violating terms originate from unified theories with $\mathbb{Z}_4^R$.
- The $\xi \hat{S}$ term can be eliminated by field redefinitions.

DM sector

- **Neutralino mass matrix in the base** $\psi \equiv (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta & 0 \\ & M_2 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta & 0 \\ & & 0 & -\mu_{tot} & -\frac{1}{\sqrt{2}}\lambda v \sin\beta \\ & & & 0 & -\frac{1}{\sqrt{2}}\lambda v \cos\beta \\ & & & & m_N \end{pmatrix}$$

with $\mu_{tot} \equiv \lambda v_s/\sqrt{2} + \mu$, $m_N \equiv \sqrt{2}\kappa v_s + \mu'$. Diagonalizing $\mathcal{M}$ gives five mass eigenstates: $\tilde{\chi}_i^0 = N_{i1}\psi_1^0 + N_{i2}\psi_2^0 + N_{i3}\psi_3^0 + N_{i4}\psi_4^0 + N_{i5}\psi_5^0$.

Assume $\tilde{\chi}_1^0$ LSP as sole DM candidates, $\tilde{\chi}_1^0$ should be $\tilde{S}$- or $\tilde{B}$- like to reproduce the correct relic abundance while complying with the stringent direct detection experiments .

DM sector

★ **DM annihilation channels:**

- $\tilde{S}$-dominated $\tilde{\chi}_1^0$ ($m_{\tilde{\chi}_1^0} \simeq m_N$)

  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_s A_s, h_s h_s, A_s A_s, \ldots;$

  $\tilde{S} - \tilde{H}, \tilde{W}$ coannihilation

- $\tilde{B}$-dominated $\tilde{\chi}_1^0$ ($m_{\tilde{\chi}_1^0} \simeq M_1$)

  A_S-funnel into $h_s A_H$;

  $\tilde{B} - \tilde{H}, \tilde{W}$ coannihilation

★ **DM-nucleon Scattering cross section:**

$$\sigma^{SI}_{\tilde{\chi}_1^0-N} \simeq 5 \times 10^{-45}\text{cm}^2 \times \left(\frac{V_h^{SM} C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h} + V_{h_s}^{SM} C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_s}}{0.1}\right)^2,$$

$$C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i} \simeq \frac{\sqrt{2}\mu_{tot}}{v}\left(\frac{\lambda v}{\mu_{tot}}\right)^2 \frac{V_{h_i}^{SM}(m_{\tilde{\chi}_1^0}/\mu_{tot} - \sin 2\beta)}{1-(m_{\tilde{\chi}_1^0}/\mu_{tot})^2} + \ldots,$$

$$\sigma^{SD}_{\tilde{\chi}_1^0-N} \simeq 10^{-39}\text{cm}^2 \times \left(\frac{C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z}}{0.1}\right)^2,$$

$$C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z} = \frac{m_Z}{\sqrt{2}v}(N_{13}^2 - N_{14}^2) \propto \frac{\cos 2\beta}{1-(m_{\tilde{\chi}_1^0}/\mu_{tot})^2},$$

Blind Spot: $m_{\tilde{\chi}_1^0}/\mu_{tot} \approx \sin 2\beta$ for SI; $\cos 2\beta$ vanishes when $\tan\beta \approx 1$ for SD.

Higgs sector

★ **Soft-breaking terms:**

$$-\mathscr{L}_{soft} = \left[\lambda A_\lambda S H_u \cdot H_d + \frac{1}{3}\kappa A_\kappa S^3 + m_3^2 H_u \cdot H_d + \frac{1}{2} m_S'^2 S^2 + \xi' S + h.c.\right] + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2,$$

★ **CP-even Squared Mass Matrix in** $(H_{\rm NSM}, H_{\rm SM}, {\rm Re}[S])$ **with**

$$H_{NSM} = \sqrt{2}{\rm Re}(\cos\beta H_u^0 - \sin\beta H_d^0),$$
$$H_{SM} = \sqrt{2}{\rm Re}(\sin\beta H_u^0 + \cos\beta H_d^0),$$

$$\mathscr{M}_{S,11}^2 = m_A^2 + \frac{1}{2}(2m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$$

$$\mathscr{M}_{S,12}^2 = -\frac{1}{4}(2m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$

$$\mathscr{M}_{S,13}^2 = \sqrt{2}\lambda\mu_{tot} v(\delta - 1)\cot 2\beta,$$

$$\mathscr{M}_{S,22}^2 = m_Z^2\cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta,$$

$$\mathscr{M}_{S,23}^2 = \sqrt{2}\lambda\mu_{tot} v\delta,$$

$$\mathscr{M}_{S,33}^2 = m_B^2,$$

$$h_i = V_{h_i}^{\rm NSM} H_{\rm NSM} + V_{h_i}^{\rm SM} H_{\rm SM} + V_{h_i}^{\rm S} {\rm Re}[S]$$

CP odd Mass Matrix in $(A_{NSM}, Im[S])$ **with** $A_{NSM} = \sqrt{2}Im(\cos\beta H_u^0 + \sin\beta H_d^0)$:

$$\mathscr{M}_{P,11}^2 = m_A^2, \quad \mathscr{M}_{P,22}^2 = M_C^2, \quad \mathscr{M}_{P,12}^2 = \frac{\lambda v}{\sqrt{2}}(A_\lambda - m_N),$$

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

Paraameters in terms of masses : $m_3^2 = F(m_A^2) \quad A_\kappa = F(m_B^2) \quad \mu' = F(m_C^2)$
$(m_C = 800\ {\rm GeV})$

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

h_s —— 95.4 GeV CP-even Scalar

1. Normalized $\gamma\gamma$ signal strength

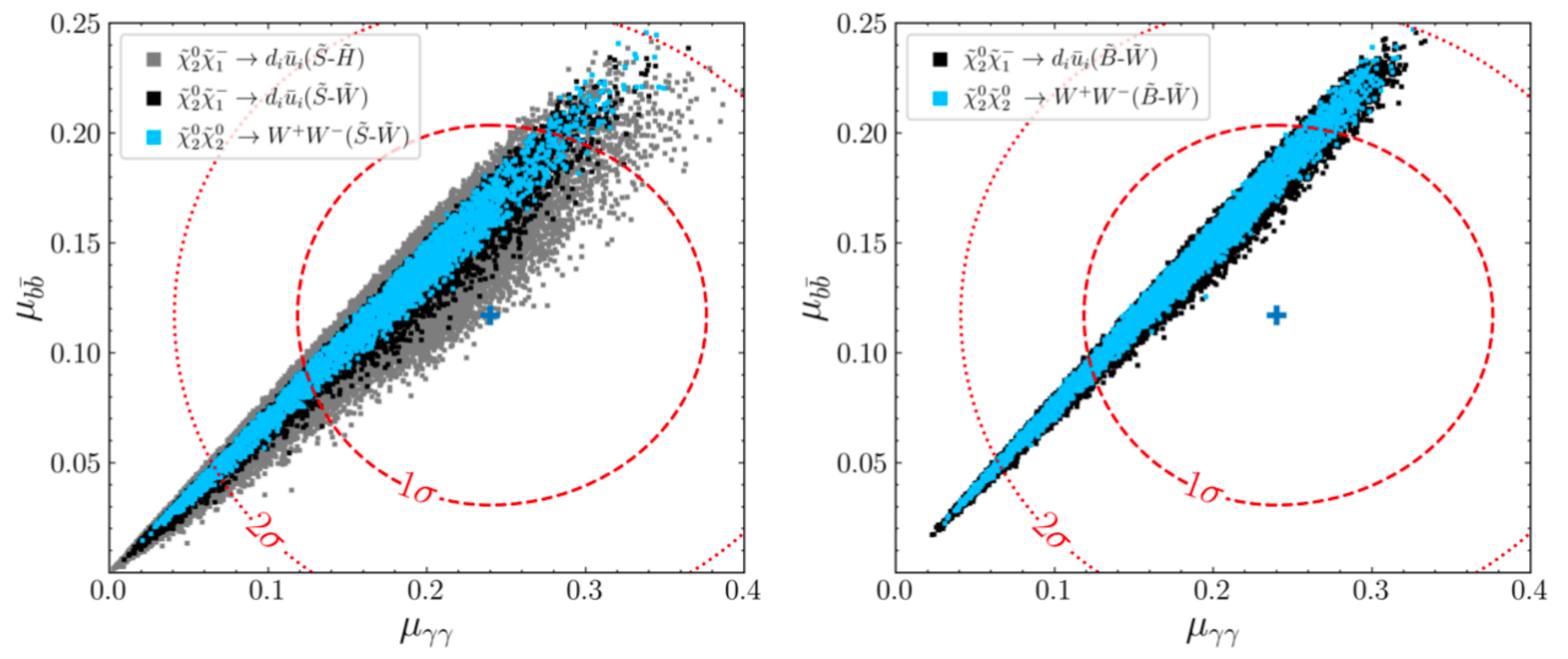
$$\mu_{\gamma\gamma} = \frac{\sigma_{\rm SUSY}(pp \to h_s)}{\sigma_{\rm SM}(pp \to h_s)} \times \frac{{\rm Br}_{\rm SUSY}(h_s \to \gamma\gamma)}{{\rm Br}_{\rm SM}(h_s \to \gamma\gamma)} \simeq |C_{h_s gg}|^2 \times |C_{h_s\gamma\gamma}|^2 \times {\rm R}_{\rm Width},$$

2. Normalized $b\bar{b}$ signal strength

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

$$1/{\rm R}_{\rm Width} \simeq 0.801 \times |C_{h_sb\bar{b}}|^2 + 0.083 \times |C_{h_s\tau\bar{\tau}}|^2 + 0.041 \times |C_{h_sc\bar{c}}|^2 + 0.067 \times |C_{h_sg\bar{g}}|^2 + \ldots$$

Explanation of $\gamma\gamma$ and $b\bar{b}$ excesses near 95.4 GeV



- 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%, $\chi^2_{\gamma\gamma+b\bar{b}} \simeq 0.27$

Scalar Resonances near 95.4 and 650 GeV

- **The cross section of $gg \to H \to h(\gamma\gamma) + h_s(b\bar{b})$ in the GNMSSM:**

$$\sigma_{\gamma\gamma b\bar{b}} = \sigma(gg \to H) \times \mathrm{Br}_{\mathrm{SUSY}}(H \to hh_s) \times \mathrm{Br}_{\mathrm{SUSY}}(h \to \gamma\gamma) \times \mathrm{Br}_{\mathrm{SUSY}}(h_s \to b\bar{b}),$$

  - Light scalar (h_s) : singlet-like CP-even boson with mass of 95.4 ± 1 GeV ;
  - SM-like Higgs (h): the Higgs boson dicovered at LHC with mass of 125 ± 3GeV
  - Heavy scalar (H): doublet-like CP-even boson with mass of 650 ± 25 GeV.

- **The χ^2 function:**

$$\chi^2_{650+95} = \left(\frac{\sigma_{\gamma\gamma b\bar{b}} - 0.35}{0.13}\right)^2 + \left(\frac{\mu_{\gamma\gamma} - 0.24}{0.08}\right)^2 + \left(\frac{\mu_{b\bar{b}} - 0.117}{0.057}\right)^2$$

Scalar Resonances near 95.4 and 650 GeV

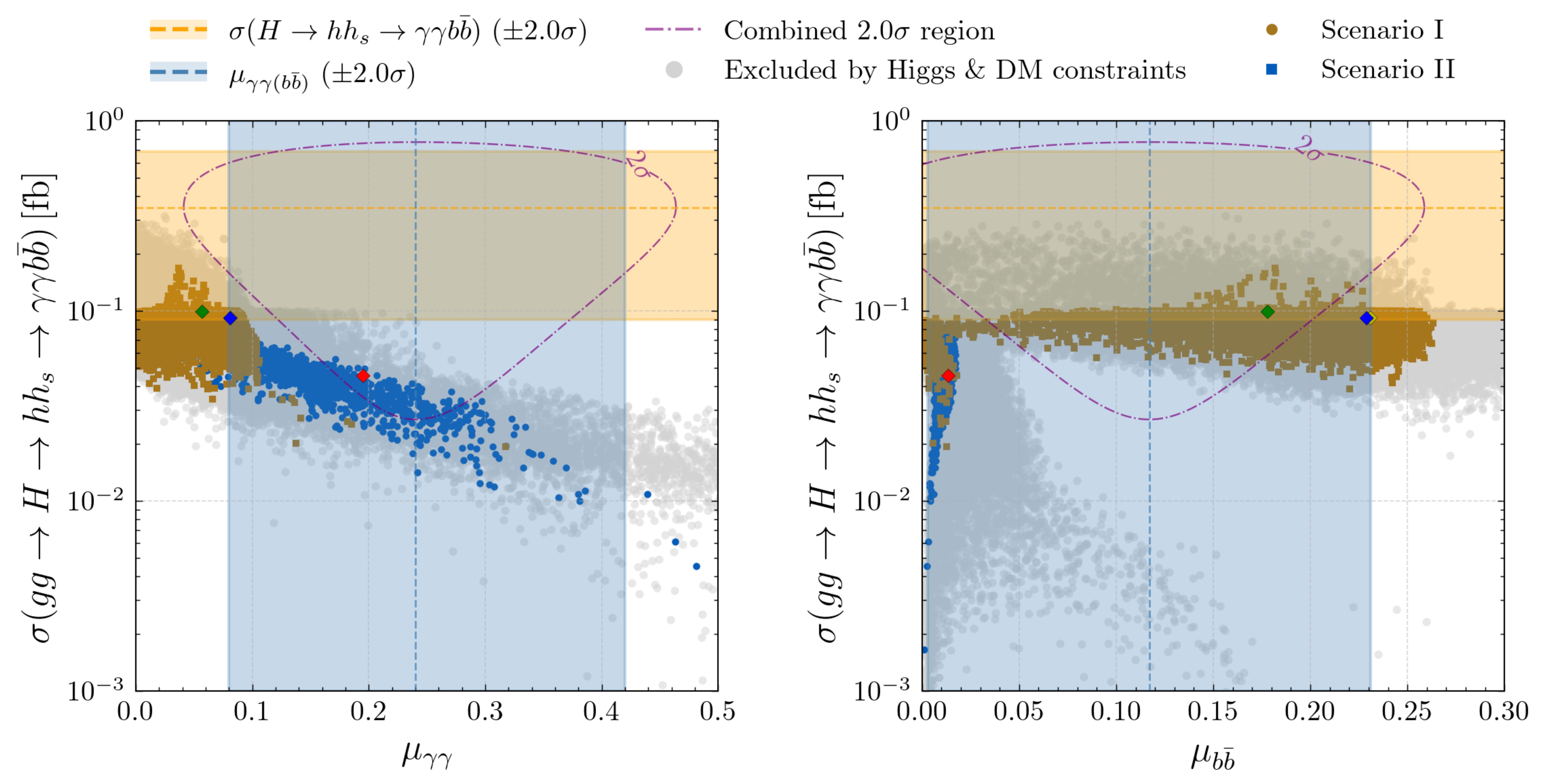
$$\mathscr{L} = \exp(\frac{1}{2}\chi^2_{650+95}) \times \mathscr{L}_{\rm Res}$$

The required restrictions include:

- **Higgs data fit** using *HiggsSignals-2.6.2*
- **Extra Higgs searches** using *HiggsBounds-5.10.2*
- **DM relic density:** 20% uncertainties of $\Omega h^2 = 0.120$
- **DM-nucleon scattering cross sections:** LZ-2025
- **B physics observables:** $B_s \to \mu^+\mu^-$ and $B \to X_s\gamma$
- **Vacuum stability** using *Vevacious++*
- **Electroweak precision observables:** S,T,U

Parameter	Prior	Range
$\mu_{\rm tot}$/TeV	Flat	$0.5 \sim 1.0$
$\mu_{\rm eff}$/TeV	Flat	$-1.0 \sim 1.0$
m_A/TeV	Flat	$0.50 \sim 0.65$
m_B/TeV	Flat	$0.09 \sim 0.12$
m_N/TeV	Flat	$-1.0 \sim 1.0$
A_t/TeV	Flat	$1.0 \sim 3.0$
M_1/TeV	Flat	$-1.0 \sim -0.2$
M_2/TeV	Flat	$0.2 \sim 1.0$
λ	Flat	$0.5 \sim 0.7$
κ	Flat	$-0.5 \sim 0.5$
δ	Flat	$-0.05 \sim 0.05$
$\tan\beta$	Flat	$1.0 \sim 2.0$

Scalar Resonances near 95.4 and 650 GeV



✦ **Scenario I** ($\approx 92\%$):

A_s funnel annihilation or coannihilation with $\tilde{S}$-like $\tilde{\chi}_2^0$s, typically into the $h_s A_H$ final state.

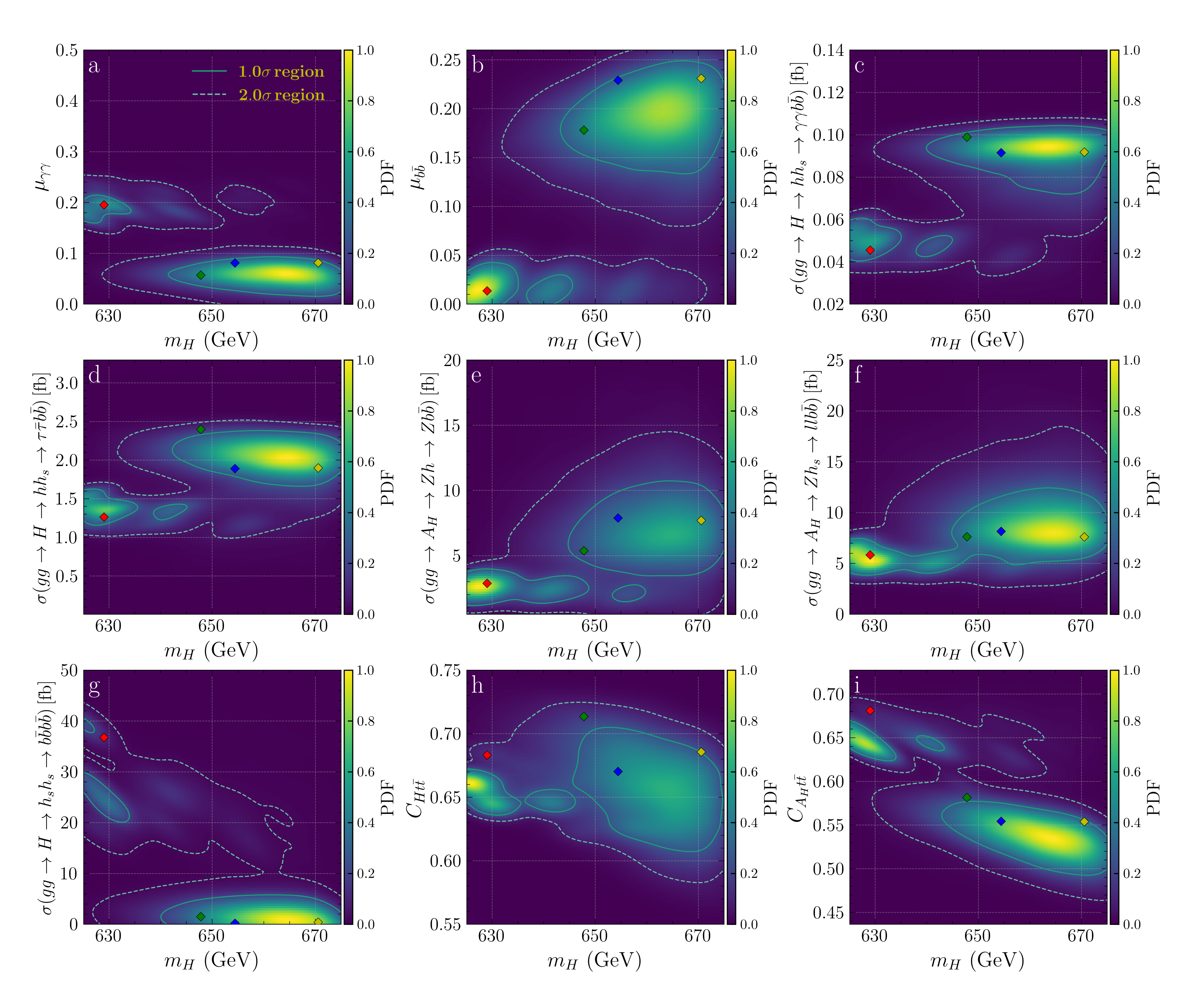
A few points can interpret the $\sigma_{\gamma\gamma b\bar{b}}$ and μ_{rr} and $\mu_{b\bar{b}}$ excesses at the 2σ level at the same time.

✦ **Scenario II** ($\approx 8\%$):

coannihilation with $\tilde{H}$-like $\tilde{\chi}_2^0$s or $\tilde{\chi}_1^{\pm}$s, favoring the $h_s A_s$ final state.

$\sigma_{\gamma\gamma b\bar{b}}$ can reach at most 0.08 fb. It can achieves an overall 2σ fit when combining the $\sigma_{\gamma\gamma b\bar{b}}$ and μ_{rr} excess, i.e., $\chi^2_{\sigma_{\gamma\gamma b\bar{b}}} + \chi^2_{\mu_{rr}} \leq 6.18$

Scalar Resonances near 95.4 and 650 GeV



✦ **Scenario I** (≈68% Bayesian evidence):

640 GeV $\lesssim m_H \lesssim$ 675 GeV

$0.02 \lesssim \mu_{\gamma\gamma} \lesssim 0.09, \quad 0.14 \lesssim \mu_{b\bar{b}} \lesssim 0.25,$

0.07 fb $\lesssim \sigma(gg \to H \to hh_s \to \gamma\gamma b\bar{b}) \lesssim$ 0.105 fb

$C_{A_Ht\bar{t}} \lesssim 0.60$

✦ **Scenario II** (≈23% Bayesian evidence):

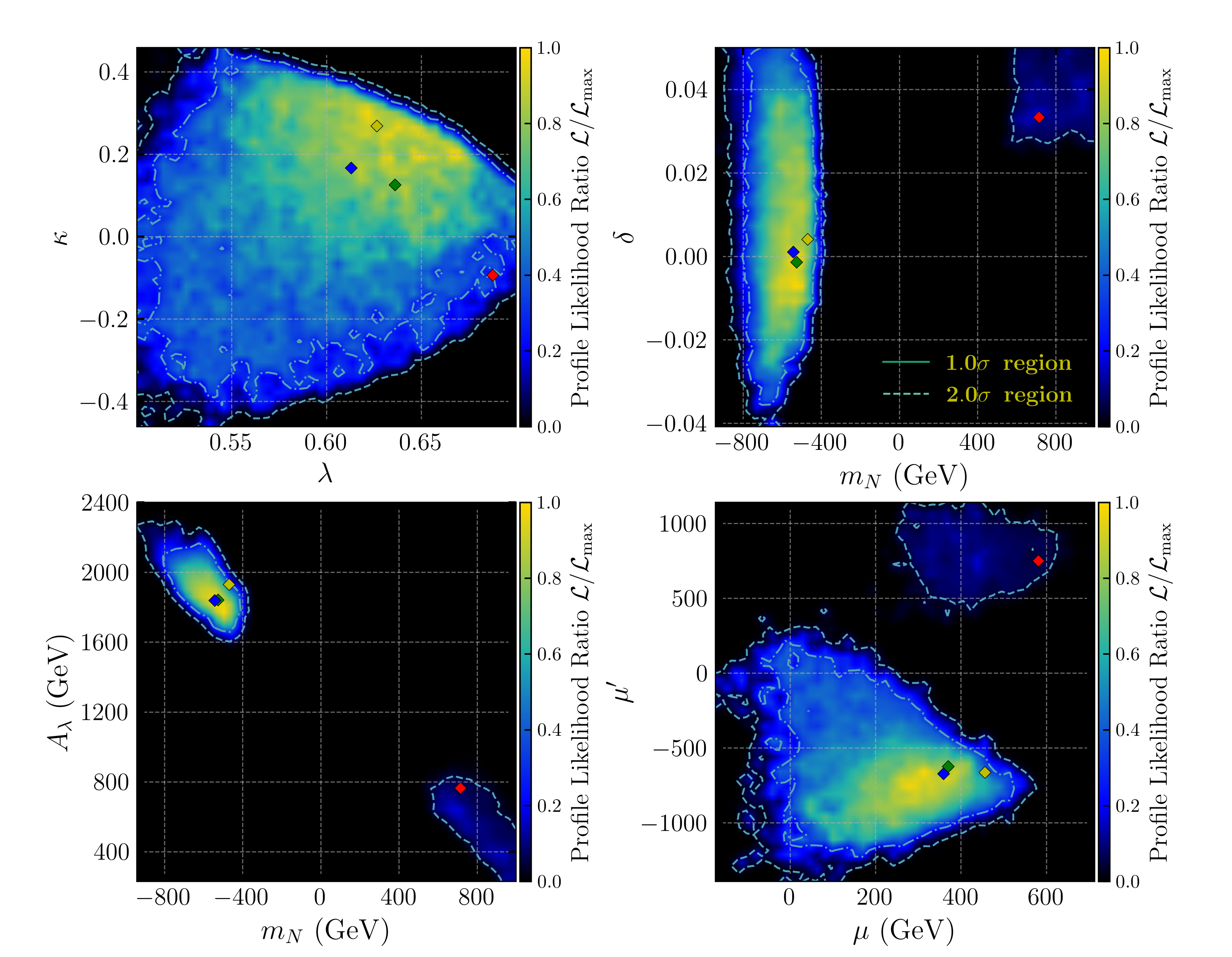
625 GeV $\lesssim m_H \lesssim$ 640 GeV

$0.16 \lesssim \mu_{\gamma\gamma} \lesssim 0.21, \quad 0.0 \lesssim \mu_{b\bar{b}} \lesssim 0.04,$

0.04 fb $\lesssim \sigma(gg \to H \to hh_s \to \gamma\gamma b\bar{b}) \lesssim$ 0.06 fb

$C_{A_Ht\bar{t}} \gtrsim 0.60$

Scalar Resonances near 95.4 and 650 GeV



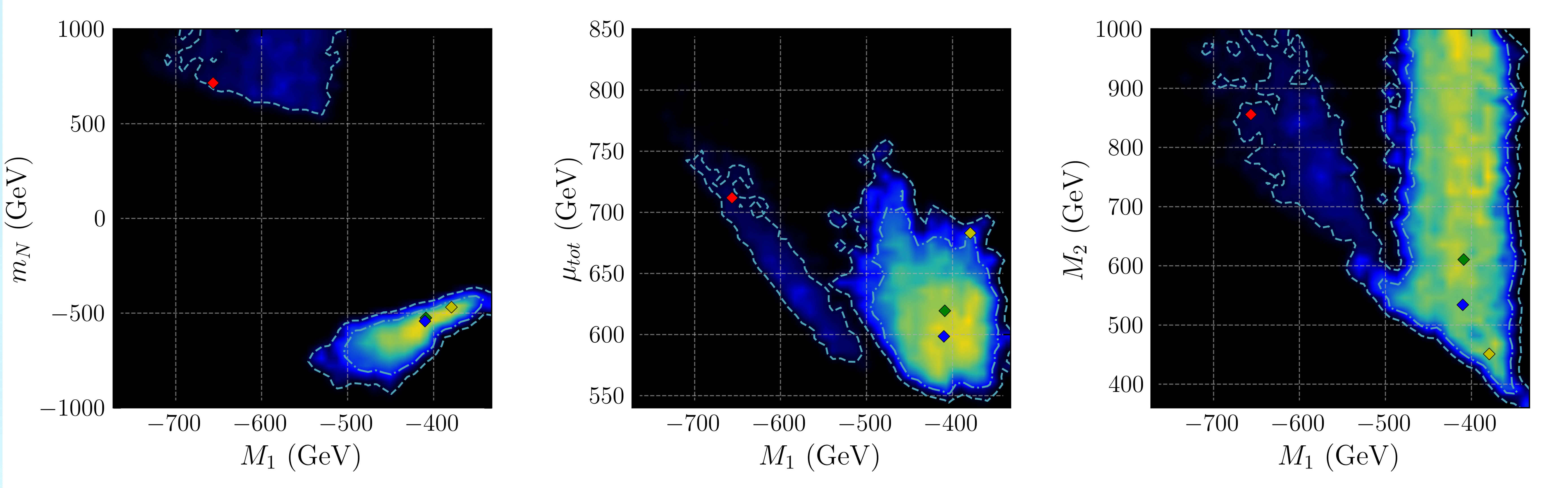
Two-dimensional PL functions projection

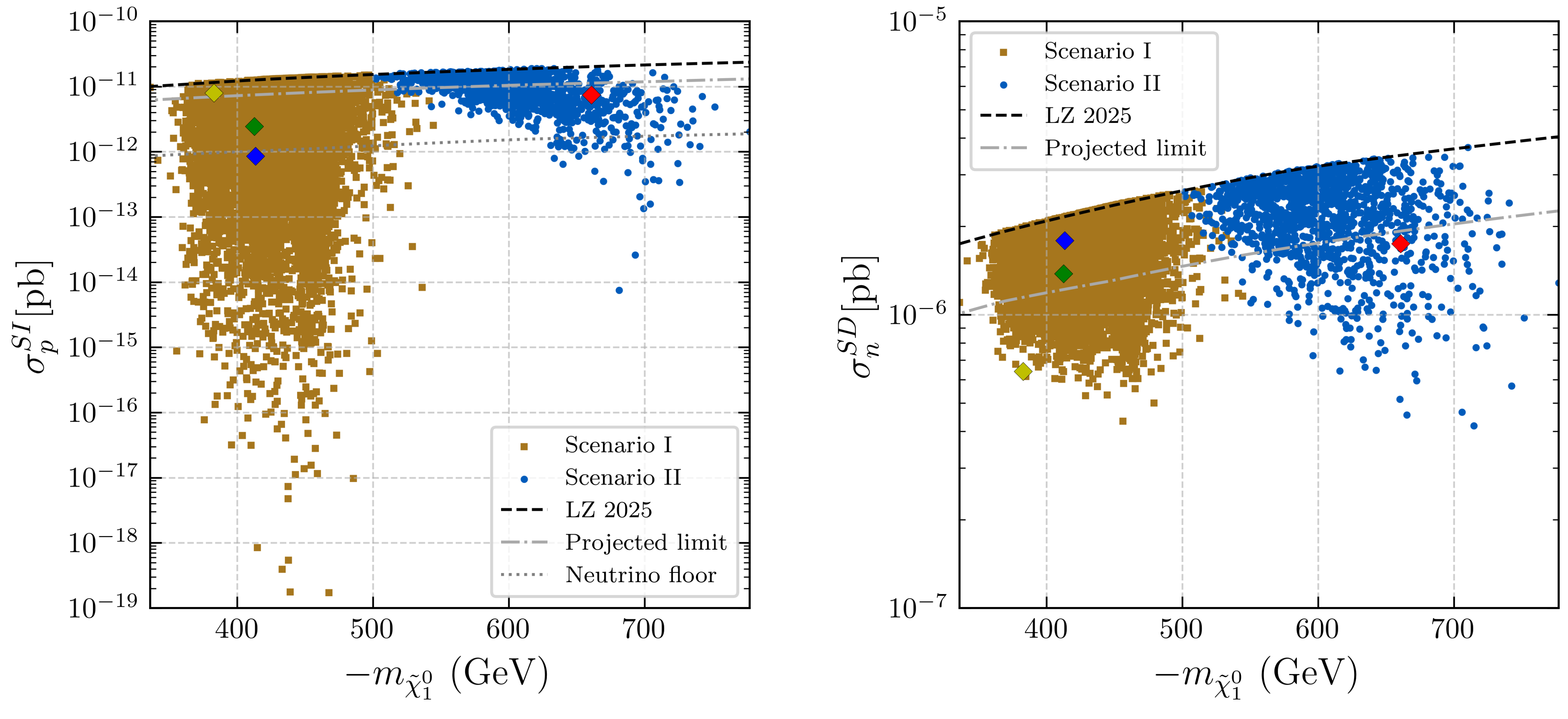
- ✦Best point yields a combined value of $\chi^2_{650+95} + \chi^2_{125} \simeq 162$.
- ✦prefers relatively large and positive λ, κ.
- ✦The behavior in (A_λ, m_N) follows $A_\lambda + m_N \simeq 2\mu_{tot}$ given $\tan\beta \simeq 1.6$ to keep δ small enough.
- ✦ **Scenario I**:

  $m_N \lesssim -390\,\mathrm{GeV}, \quad A_\lambda \gtrsim 1600\,\mathrm{GeV}, \quad \mu' \lesssim 400\,\mathrm{GeV}$
- ✦ **Scenario II**:

  $m_N \gtrsim 550\,\mathrm{GeV}, \quad A_\lambda \lesssim 800\,\mathrm{GeV}, \quad \mu' \gtrsim 500\,\mathrm{GeV}$

Scalar Resonances near 95.4 and 650 GeV





✦ **Scenario I**:

$-500\,\text{GeV} \lesssim M_1 \lesssim -300\,\text{GeV}\,,$

s-channel $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_s A_H$ enhanced when $2m_{\tilde{\chi}_1^0} \simeq m_{A_s} \simeq 800\,\text{GeV},$

or coannihilation with $\tilde{S}$ via $\tilde{\chi}_2^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_2^0 \to h_s A_H\,,$

✦ **Scenario II**:

$M_1 \lesssim -500\,\text{GeV},$

coannihilation with $\tilde{H}$ via $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_2^0\tilde{\chi}_2^0 \to h_s A_s,\ \tilde{\chi}_1^+\tilde{\chi}_2^0 \to u\bar{d}, h_s W^+,$

Conclusion

- The singlet-like scalar h_s in the GNMSSM can simultaneously account for the $\gamma\gamma$ and $b\bar{b}$ excesses at a 1σ level without conflicting with all other constraints. DM physics significantly influences the unified explanation and favors $\tilde{S}$-like DM case.
- The heavy scalar H near 650 GeV decaying into h and h_s can also account for the observed $\gamma\gamma b\bar{b}$ signal at a 2σ level, characterized by small $\tan\beta$ and large λ, which is theoretically well-motivated for elevating the mass of the 125 GeV Higgs boson h.
- The unified interpretation prefers a $\tilde{B}$-like $\tilde{\chi}_1^0$ DM. The measured relic density is achieved mainly through A_s funnel annihilation or coannihilation with $\tilde{S}$-like $\tilde{\chi}_2^0$s.
- Future colliders experiments, e.g. HL-LHC, ILC and CEPC, are worth looking forward to.

THANKS FOR YOUR ATTENTION

h_s —— 95.4 GeV CP-even Scalar

Tree level normalized couplings:

$$C_{h_s t\bar{t}} = V_{h_s}^{\rm SM} + V_{h_s}^{\rm NSM}\cot\beta \simeq V_{h_s}^{\rm SM}, \quad C_{h_s b\bar{b}} = V_{h_s}^{\rm SM} - V_{h_s}^{\rm NSM}\tan\beta, \quad C_{h_s VV} = V_{h_s}^{\rm SM},$$

$$C_{h_s c\bar{c}} = C_{h_s t\bar{t}}, \quad C_{h_s \tau\bar{\tau}} = C_{h_s b\bar{b}}, \quad C_{h_s gg} \simeq C_{h_s t\bar{t}}, \quad C_{h_s \gamma\gamma} \simeq V_{h_s}^{\rm SM},$$

Considering loop mediated by quarks and squarks: $C_{h_s gg}$ and $C_{h_s\gamma\gamma}$ deviates from $C_{h_s t\bar{t}}$ by 4% and 11%;

Contributions from charginos and charged Higgs to $C_{h_s\gamma\gamma}$ are not crucial

Central values of $\mu_{\gamma\gamma}$ and $\mu_{b\bar{b}}$ corresponds to:

$$V_{h_s}^{\rm SM} \simeq 0.35, \ \ (V_{h_s}^{\rm SM} - V_{h_s}^{\rm NSM}\tan\beta) \simeq 0.81 \times V_{h_s}^{\rm SM} \simeq 0.28,$$

$$\mathrm{Br}_{\rm SUSY}(h_s \to \gamma\gamma) \simeq 1.77 \times \mathrm{Br}_{\rm SM}(h_s \to \gamma\gamma) \simeq 2.5 \times 10^{-3},$$

$$\mathrm{Br}_{\rm SUSY}(h_s \to b\bar{b}) \simeq 0.95 \times \mathrm{Br}_{\rm SM}(h_s \to b\bar{b}) \simeq 76.1\,\%\,,$$

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

$$V_{h_s}^{\rm NSM} \simeq \frac{V_{h_s}^{S}}{\sqrt{2}} \times \frac{\lambda v \bar{A}_\lambda \cos 2\beta}{m_A^2}, \quad \lambda\left(\mu_{tot} - \bar{A}_\lambda \sin\beta\cos\beta\right) \simeq \frac{V_{h_s}^{\rm SM} V_{h_s}^{S}}{\sqrt{2}} \times \frac{m_{h_s}^2 - m_h^2}{v},$$

$$m_B^2 \simeq m_{h_s}^2 |V_{h_s}^S|^2 + m_h^2 |V_{h_s}^{\rm SM}|^2, \quad \mathcal{M}_{S,22}^2 \simeq m_h^2 |V_{h_s}^S|^2 + m_{h_s}^2 |V_{h_s}^{\rm SM}|^2,$$

with $\bar{A}_\lambda \equiv A_\lambda + m_N$. This implies that

$$\lambda \simeq 0.06 \times \left(\frac{V_{h_s}^{\rm SM}}{0.35}\right) \times \left(\frac{\mu_{tot} - \bar{A}_\lambda \sin\beta\cos\beta}{100\ \text{Gev}}\right)^{-1},$$

$$\lambda \gtrsim 0.017 \times \frac{1}{|\cos 2\beta|} \times \left(\frac{\tan\beta}{50}\right)^{-1} \times \left(\frac{\bar{A}_\lambda}{2\ \text{TeV}}\right)^{-1} \times \left(\frac{m_A}{2\ \text{TeV}}\right)^{2},$$