ELECTROWEAK BARYOGENESIS: a pheno review

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The Sakharov Conditions

Three ingredients required to generate a matter–antimatter asymmetry

B

Baryon Number Violation

Electroweak sphalerons are active and unsuppressed at high temperature.

CP

C and CP Violation

Matter and antimatter processes must proceed at measurably different rates.

≠

Departure from Equilibrium

Requires a strongly first-order electroweak phase transition — bubbles of true vacuum nucleating and expanding through the plasma.

All three must hold at once — and, as the next slide shows, the Standard Model fails two of them.

Why the Standard Model Fails

✓

Baryon Number Violation

Present — sphalerons are active and unsuppressed at high T.

✗

C and CP Violation

CKM-matrix CP violation is many orders of magnitude too small.

✗

Departure from Equilibrium

125 GeV Higgs mass → a smooth crossover, not a first-order transition (confirmed on the lattice).

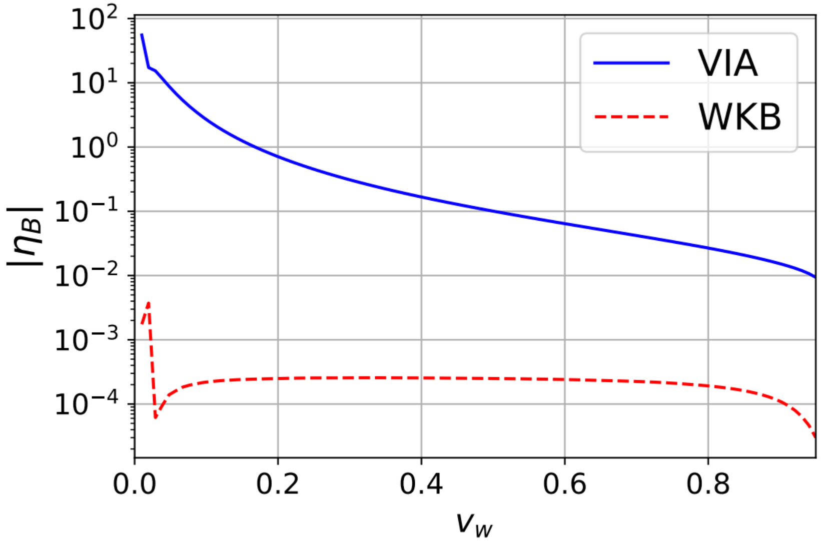
Conclusion: physics beyond the Standard Model is required to supply both extra CP violation and a strong first-order phase transition.

Uncertainty in EWBG Calculation: VIA vs WKB

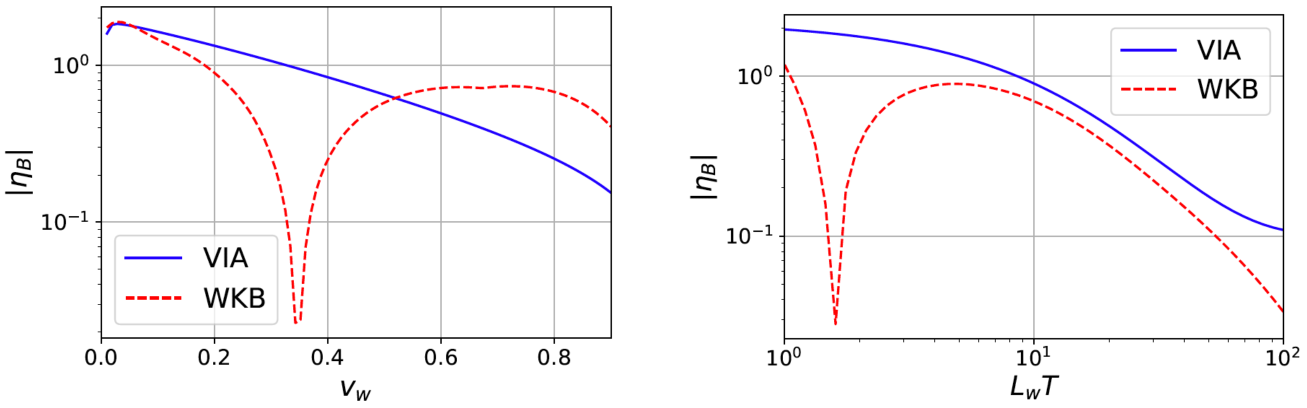
Cline, Laurent ‘21

Scalar singlet
dim 5 term

$$\mathcal{L}_\tau = \frac{y_\tau}{\sqrt{2}} \bar{\tau}_L h \left(1 + \frac{is}{\Lambda}\right) \tau_R + \text{H.c.}$$



2HDM
charm-top
mixing



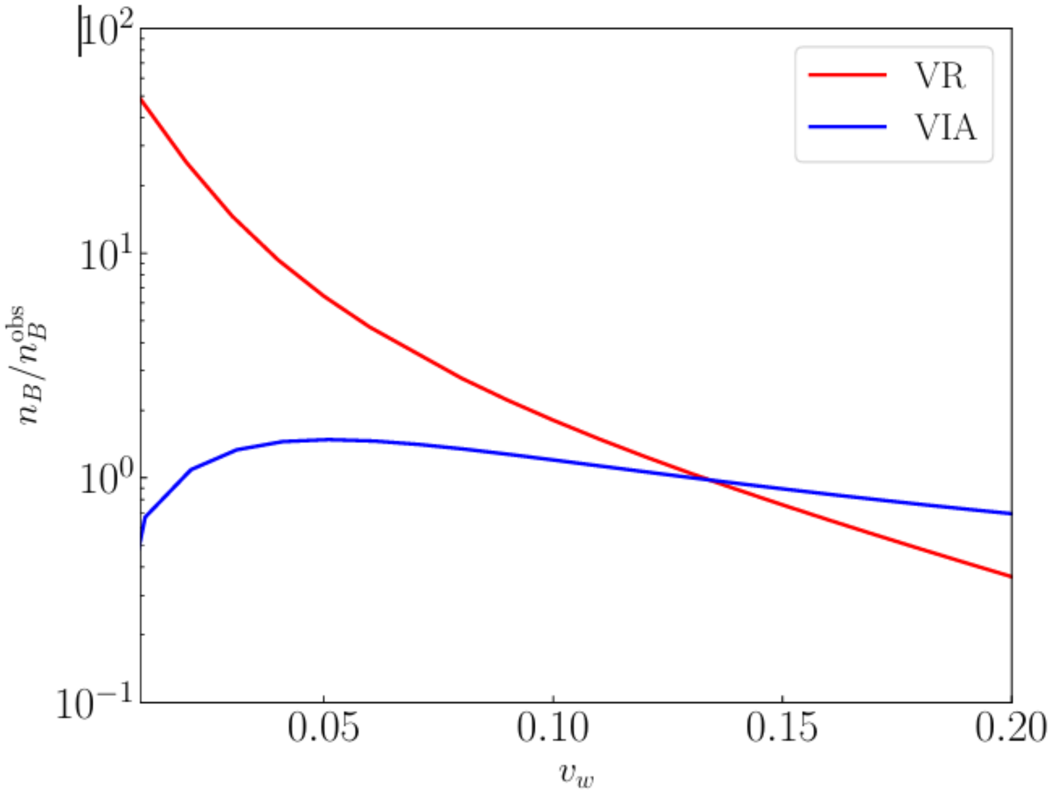
Kainulainen ’21
Postma, van der Vis, White, 22

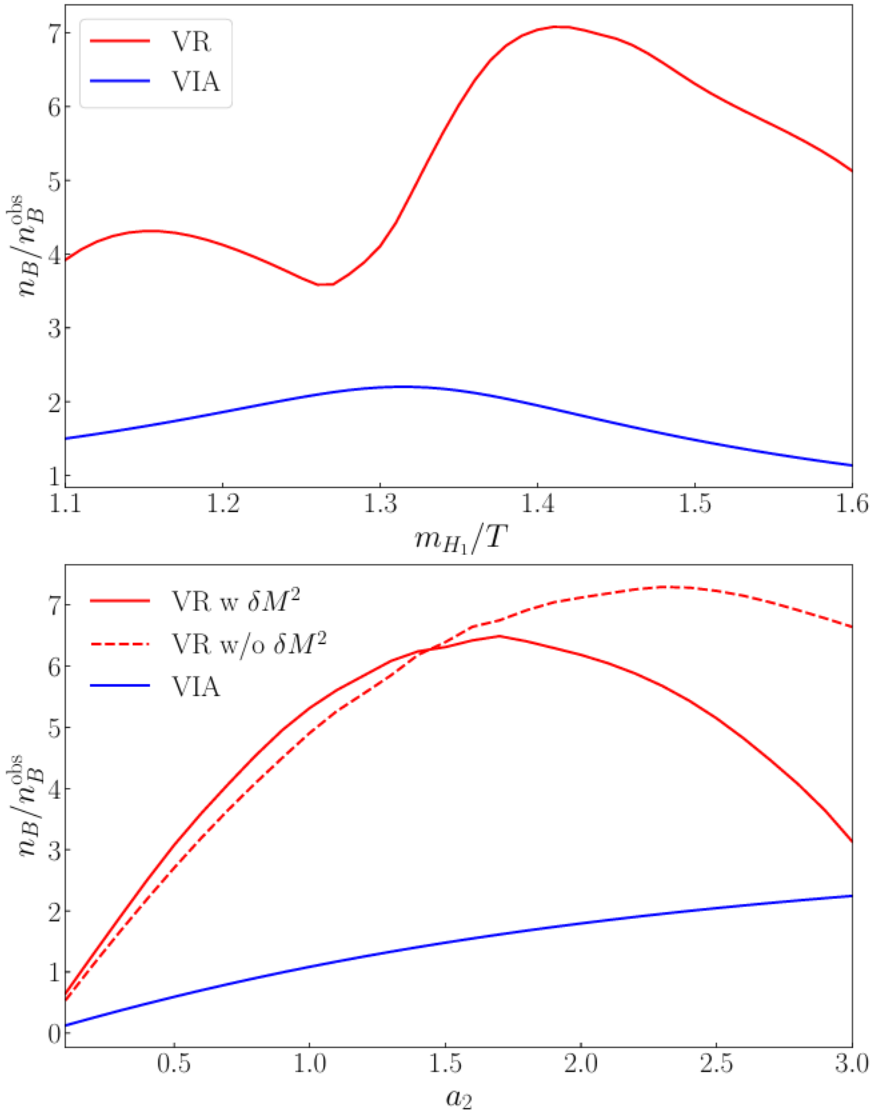
More recently shown VIA exactly cancels at leading order

Cirigliano, Lee,Tulin ‘11
Li, Ramsey-Musolf, Yu ‘24

Uncertainties in calculation: VIA vs VR

VIA versus VR in a 2HDM





The Model Landscape

Six leading BSM routes to a strong first-order electroweak phase transition

MSSM (Light Stop)

Higgsino-gaugino CP violation; transition strengthened by a light right-handed stop.

NMSSM (Singlino)

Extra singlet superfield aids the transition; CP violation from the singlino-higgsino sector.

2HDM / C2HDM

Heavy scalar non-decoupling drives the transition; CP phase in Higgs-top Yukawa coupling.

Scalar Singlet Extension

Higgs-portal singlet reshapes the potential; CP violation via singlet-top effective operator.

Composite Higgs (pNGB)

Confinement-scale dilaton dynamics; CP violation tied to varying Yukawa couplings.

SMEFT (dim-6 Yukawa)

No new scalar: a dimension-6 top/bottom/tau Yukawa operator supplies CP violation directly.

LHC Constraints at a Glance

The binding Run-2/3 constraint on the strong-transition parameter space, per model

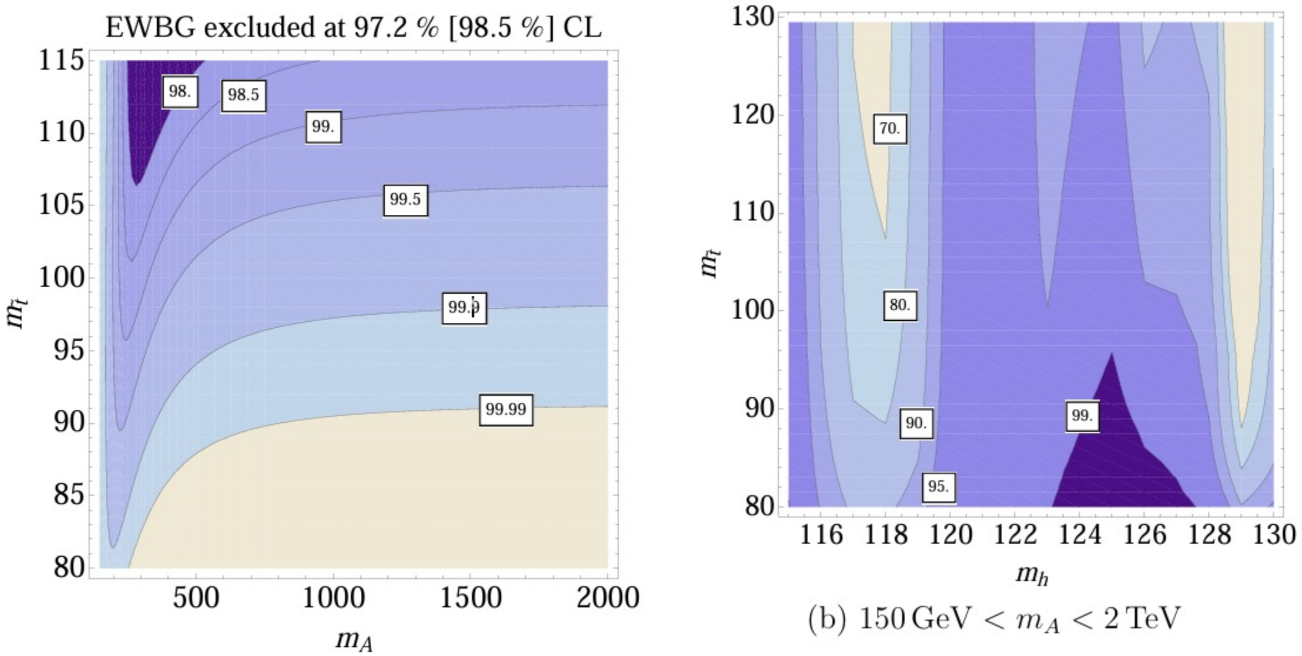
Model	Binding LHC Constraint	Status
MSSM (light stop)	Direct stop searches (>1 TeV) + Higgs signal strengths	EXCLUDED
NMSSM (singlino)	Relaxed stop/Higgs-mass tension; general SUSY scale still rising	SQUEEZED
2HDM / C2HDM	Alignment limit from Higgs-coupling data; heavy-Higgs searches	FADING
Singlet extension	Higgs invisible width + signal-strength shifts; light-mass region closing	VIABLE
Composite Higgs	Direct resonance searches bound the dilaton / vector sector	VIABLE
SMEFT (dim-6 Yukawa)	$h \to \tau\tau / b\bar{b}$ rate + CP-structure measurements bound Re/Im Yukawa directly	VIABLE

Direct production/resonance searches now dominate only for MSSM; elsewhere the frontier is shifting to indirect precision measurements.

MSSM — Actual LHC Constraint

Exclusion from combined ATLAS/CMS Higgs signal-strength data

Prior to Higgs discovery



MSSM — Light Stop

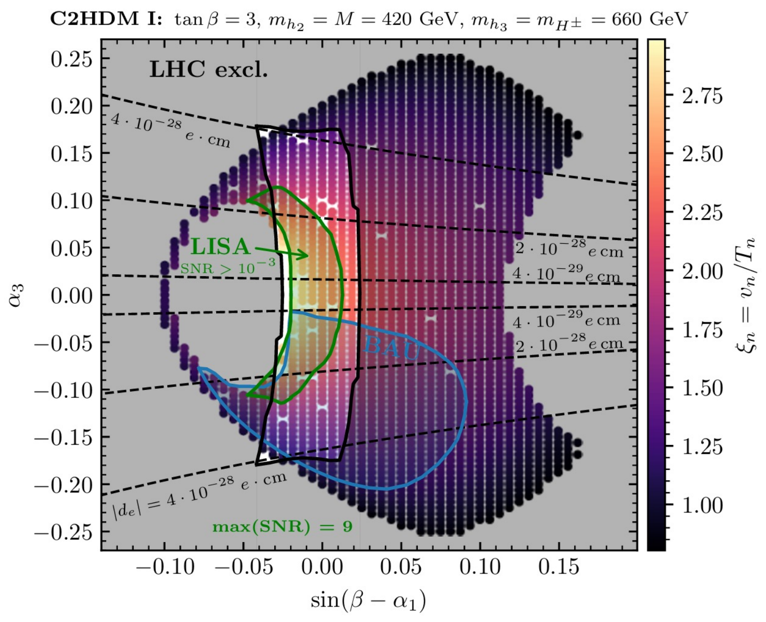
Excluded

- Requires a right-handed stop lighter than the top quark to strengthen the transition
- Direct LHC stop-mass limits now exceed ~1 TeV — roughly an order of magnitude too heavy
- Higgs production/decay-rate measurements independently rule out stop-catalyzed EWB
- Closed on LHC grounds alone

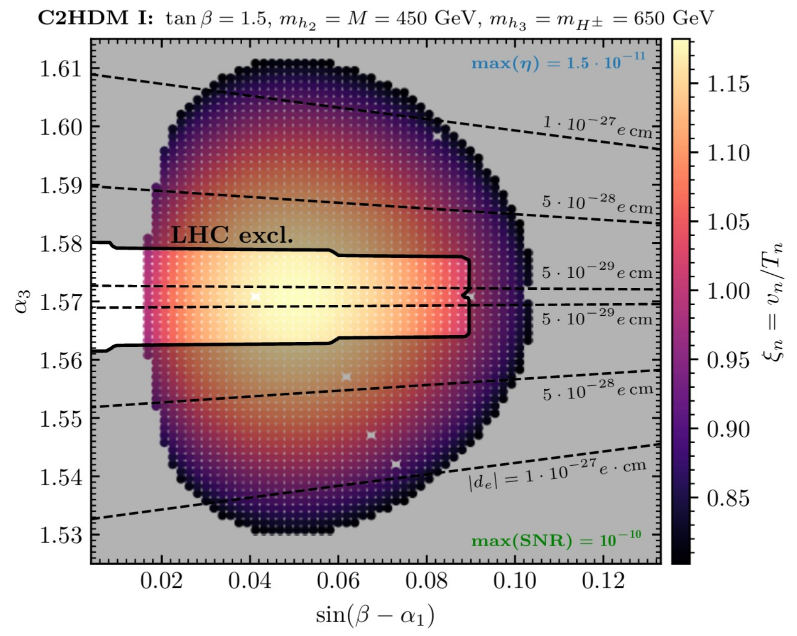
Curtin, Jaiswal & Meade, "Excluding Electroweak Baryogenesis in the MSSM," JHEP 08 (2012) 005, arXiv:1203.2932 — Fig. 3 (exclusion in the (m_A, m_stop_R) plane for m_h = 125 GeV) and Fig. 4 (exclusion in the (m_h, m_stop_R) plane). These combine ATLAS/CMS Higgs signal-strength measurements to exclude the light-stop scenario at >90–98% CL.

2HDM / C2HDM — with recent LHC Constraints

CP-violating benchmark planes confronted with LHC Run-2 HiggsTools limits



(a) **BP-SG**: smoking-gun scenario for a strong first-order EWPT with a mass gap between a lighter and mainly CP-even state h_2 and a heavier mainly CP-odd state h_3.



(b) **BP-ISG**: inverted smoking gun scenario with a ligher and mainly CP-odd state h_2 and a heavier and mainly CP-even state h_3.

Biekötter & Olea-Romacho, “Benchmarking a fading window: electroweak baryogenesis in the C2HDM, LHC constraints after Run 2 and prospects for LISA,” JHEP 12 (2025) 040, arXiv:2505.09670 —) showing LHC-excluded regions overlaid on the CP-violating parameter space, alongside predicted electron EDM and LISA SNR contours.

2HDM / C2HDM: A Fading Window

- Structural tension: a strong transition needs large non-decoupling radiative corrections from heavy scalars (H, A, H±)
- But LHC Higgs-coupling data is pushing the model toward the alignment / decoupling limit — the opposite regime
- Comprehensive 2025 Run-2 study defines CP-violating benchmark planes: the allowed region is shrinking, not closed
- Testable at HL-LHC and LISA
- Electron EDM currently constrain the CP phase and strongly restricts parameter space

NMSSM — Actual EDM Constraint

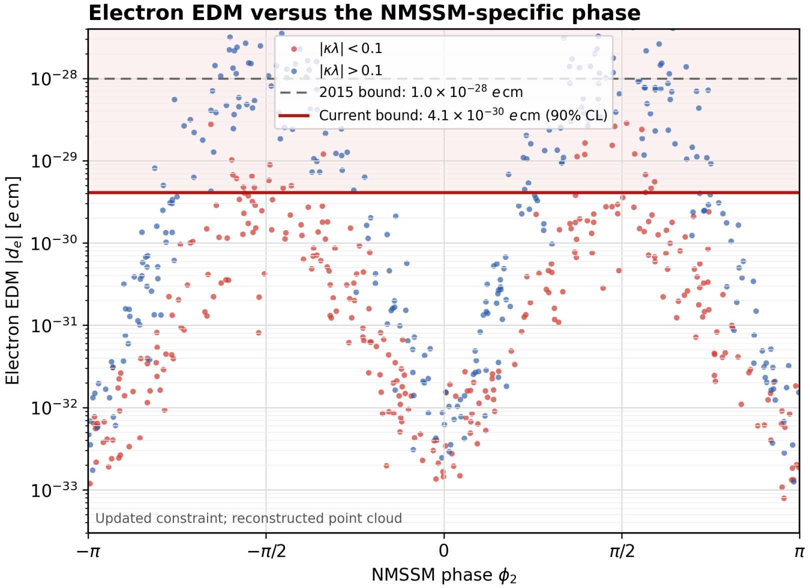
Additonal 2HDM contributions

Electron EDM vs. NMSSM-specific CP-violating phase

$$W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

$$-\mathcal{L}_{\rm soft} \supset \lambda A_\lambda\, S H_u H_d + \frac{\kappa}{3} A_\kappa\, S^3 + m_S^2|S|^2 + \text{h.c.}$$

$$\mu_{\rm eff} = \lambda\langle S\rangle\,, \qquad \text{tree-level CP violation} \propto |\kappa\lambda|\sin(\phi_1-\phi_2)$$



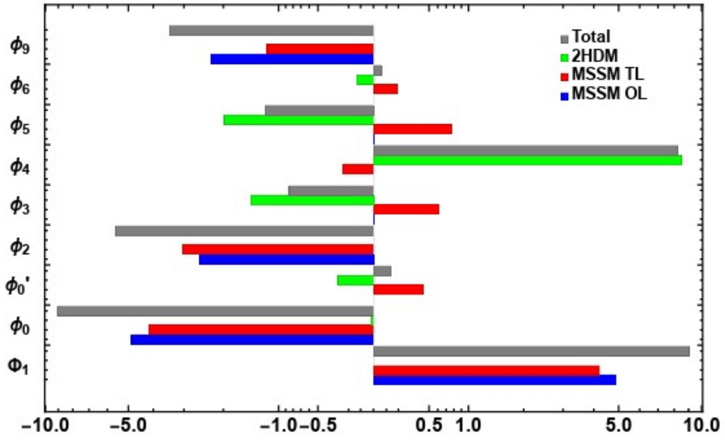


Figure 4: Magnitudes of three groups of electron EDM diagrams caused by individual CP-violating phases with $\sin(\phi) = 0.01$. The lengths of bars are shown in unit of $d_e^{\rm Exp} = 4.1\times10^{-30}$ e cm. Parameters are explained in text.

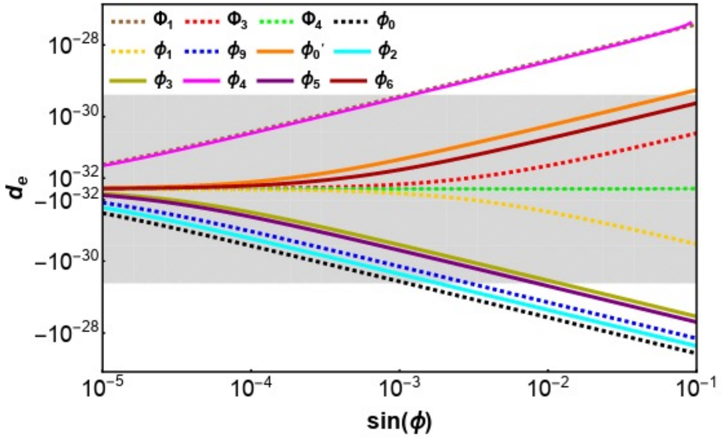


Figure 5: Magnitudes of electron EDM (in unit of e cm) induced by MSSM phases (dash curves) and NMSSM phases (solid curves). The gray region denotes the current experimental bound. Parameters are explained in text.

King, Mühlleitner, Nevzorov & Walz, "Exploring the CP-violating NMSSM: EDM Constraints and Phenomenology," Nucl. Phys. B901 (2015) 526, arXiv:1508.03255
Kaifei Ninga, Michael Ramsey-Musolf, "Revisting the Electron EDM in the MSSM", *Phys.Lett.B* 869 (2025) 139867, arXiv:2507:06327

SUSY Scenarios Under Pressure

NMSSM: from a closed case to a shrinking one

NMSSM — Singlino-Driven

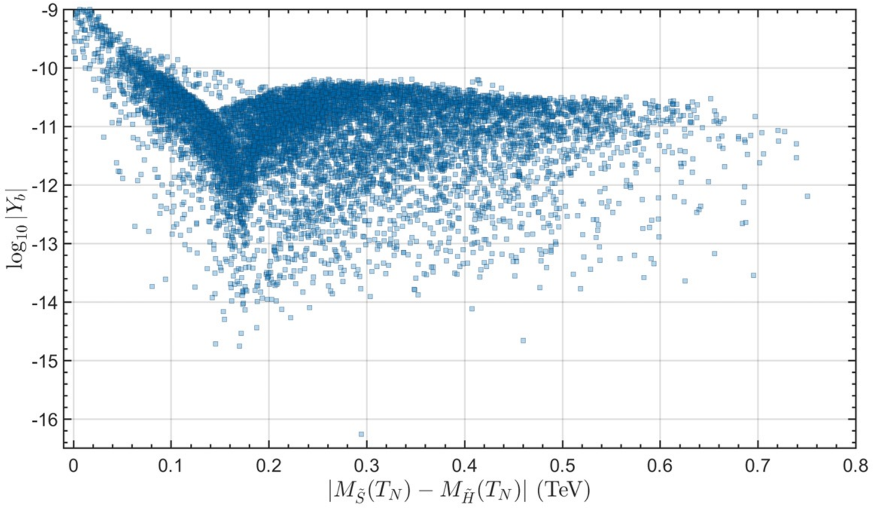
SQUEEZED

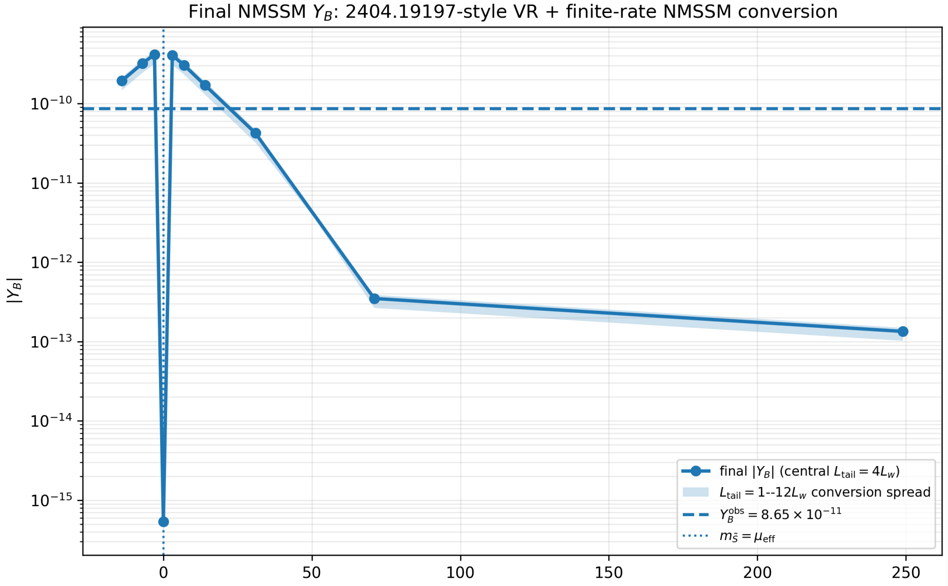
- Singlino itself is collider-invisible; the real handle is compressed higgsino pair production (the 'golden channel': $\tilde{\chi}2^{0}\tilde{\chi}1\pm \rightarrow \tilde{\chi}1^{0}Z^{*}\ \tilde{\chi}1^{0}W\pm^{*}$)
- Earlier searches disfavor higgsino $\lesssim$250 GeV with singlino $\lesssim$100 GeV; electron EDM (Barr-Zee, higgsino-singlino phase) remains the dominant constraint
- 2025 twist: ATLAS and CMS both see a mild, consistent soft-lepton excess — recently shown compatible with a GUT-based singlino-LSP NMSSM scenario
- Squeezed by EDM and compressed-spectrum searches, but a live, unconfirmed excess now points at exactly this corner

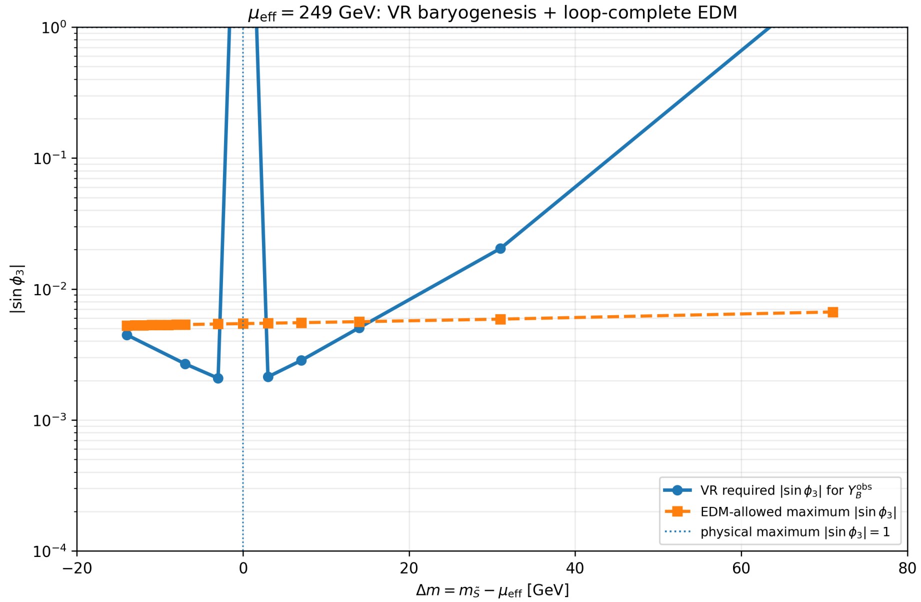
NMSSM — updated BAU with VR

Preliminary using VR

Akula et al ‘17







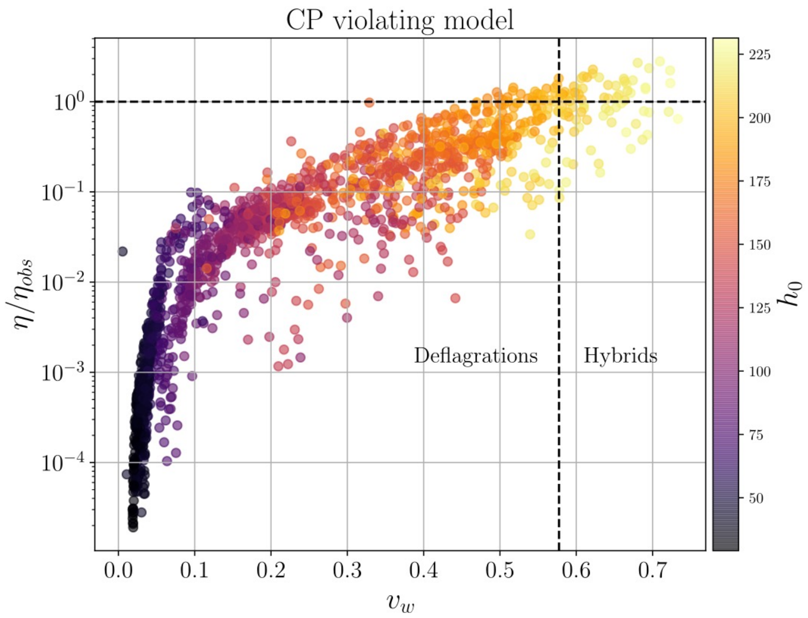
$$
\begin{aligned}
T_N &= 100\ \text{GeV},\\
\lambda = \kappa &= 0.39,\\
\tan\beta &= 4.18,\\
\mu_{\rm eff} &= 249\ \text{GeV},\\
m_{\tilde{S}} &\simeq 246\ \text{GeV},\\
m_{\tilde{S}} - \mu_{\rm eff} &\simeq -3\ \text{GeV},\\
v_w &= 0.05,\\
L_w &= 5/T,\\
\Delta\beta &= 0.05,\\
|\sin\phi| &= 0.01,\\
|Y_B| &\simeq 4.15 \times 10^{-10}.
\end{aligned}
$$

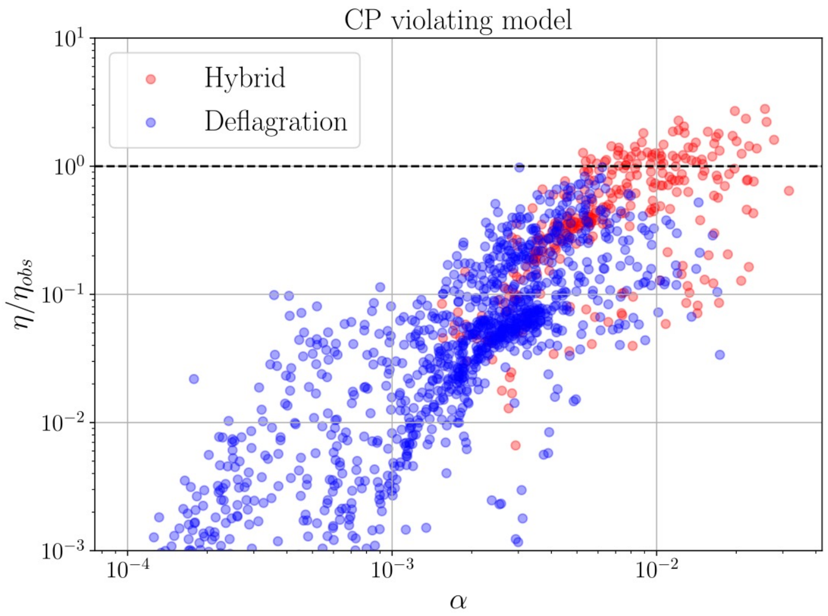
Singlet Extension — Baryon Asymmetry

Ellis, Lewicki, Merchand, No & Zych, JHEP 01 (2023) 093, arXiv:2210.16305 — Fig. 10

$$V(h,s) = -\mu_h^2\,\tfrac{1}{2}h^2 + \lambda_h\,\tfrac{1}{4}h^4 + \mu_{hs}\,h^2 s + \tfrac{1}{4}\lambda_{hs}\,h^2 s^2 + \tfrac{1}{2}\mu_s^2 s^2 + \mu_3\,s^3 + \tfrac{1}{4}\lambda_s\,s^4$$

$$\mathcal{L} \supset y_t\,\bar{Q}\,\tilde{\Phi}\,t_R\left(i\,\frac{s}{\Lambda_{\rm CP}}\right) + \text{h.c.}$$





- Left: baryon yield η/η_obs rises with wall velocity v_w — the observed value (dashed line) is reached most easily in the hybrid regime
- Right: η/η_obs vs. transition strength α — viable points sit at small α (≲ 0.03), not the large-α region a strong GW signal would need

Singlet Extension — GW Spectra

Ellis, Lewicki, Merchand, No & Zych, JHEP 01 (2023) 093, arXiv:2210.16305 — Figs. 6 & 7

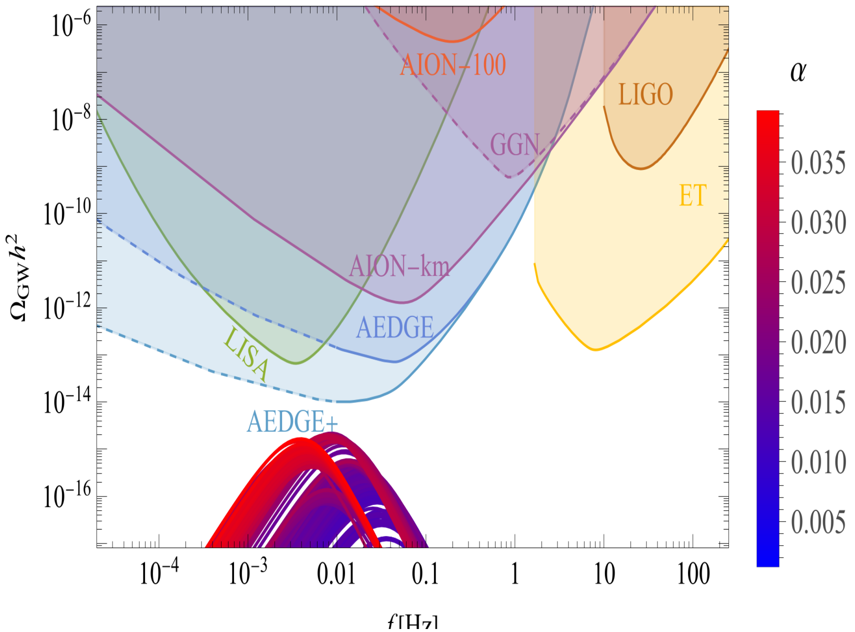


Fig. 6 — weak-wall (hydrodynamic) points: viable-BAU region

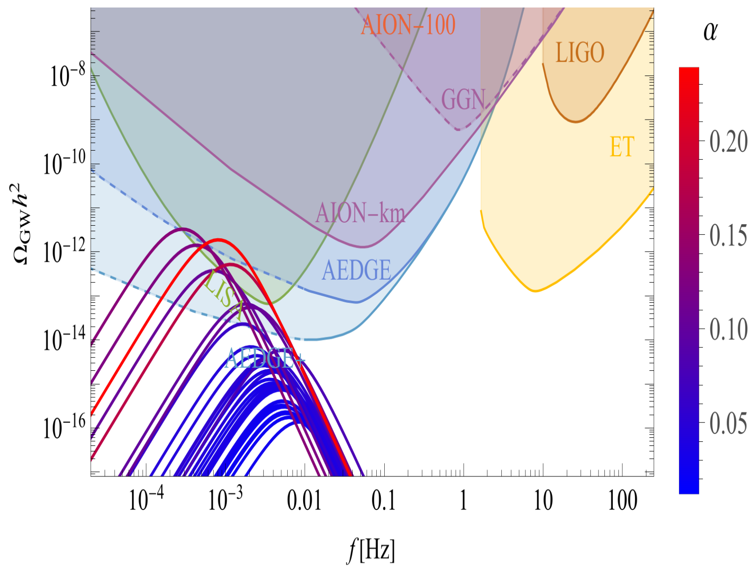


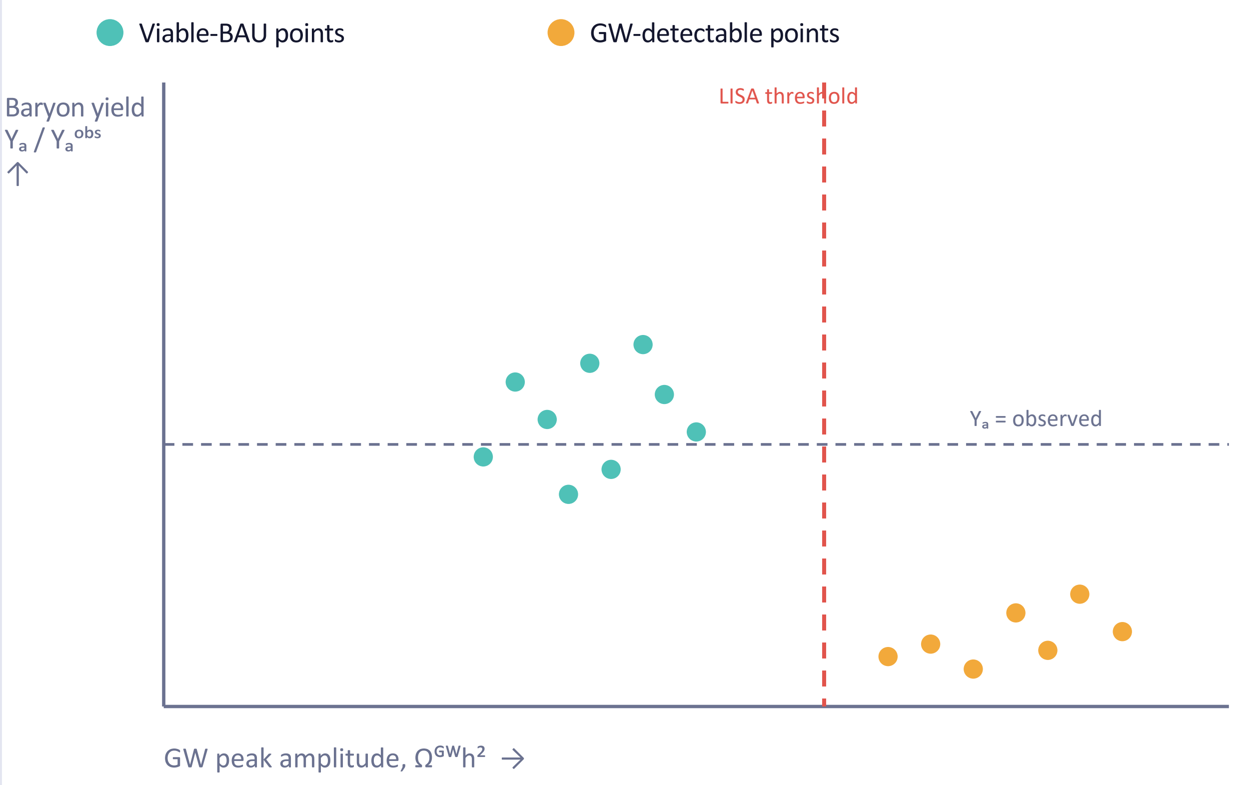
Fig. 7 — relativistic-wall points: "not suitable for baryogenesis"

(α ≲ 0.04, hydrodynamic walls) is the GW-relevant — but baryogenesis-viable — population from the previous slide; Right assumes v_w≈1 and is explicitly excluded from baryogenesis.

Spotlight: Singlet Extension — GW vs. BAU

Ellis, Lewicki, Merchand, No & Zych (2022)

- CP violation from a dimension-5 singlet–top effective operator
- Points giving a viable baryon yield cluster at low GW amplitude
- Points with LISA-detectable GW amplitude give insufficient baryon yield
- The two populations are essentially disjoint across the scanned parameter space

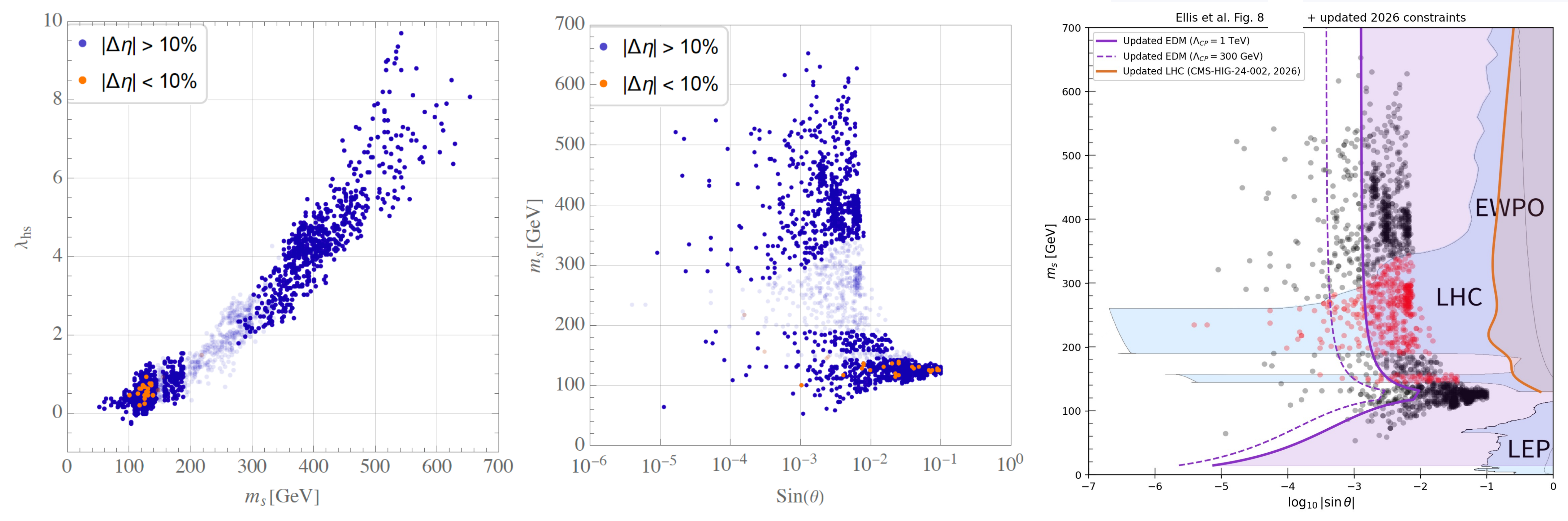


Schematic representation

Singlet Extension — Actual Constraint Plot

Updated constraints

Combined BAU + LHC + EDM allowed parameter space



Ellis, Lewicki, Merchand, No & Zych, "The Scalar Singlet Extension of the Standard Model: Gravitational Waves versus Baryogenesis," JHEP 01 (2023) 093, arXiv:2210.16305 — Fig. 13. Left: (m_s, λ_hs) plane; right: (sinϑ, m_s) plane. Sparse regions (190–300 GeV and ~150 GeV) reflect direct LHC ZZ/WW exclusions; orange points give a baryon yield within 10% of the observed value.

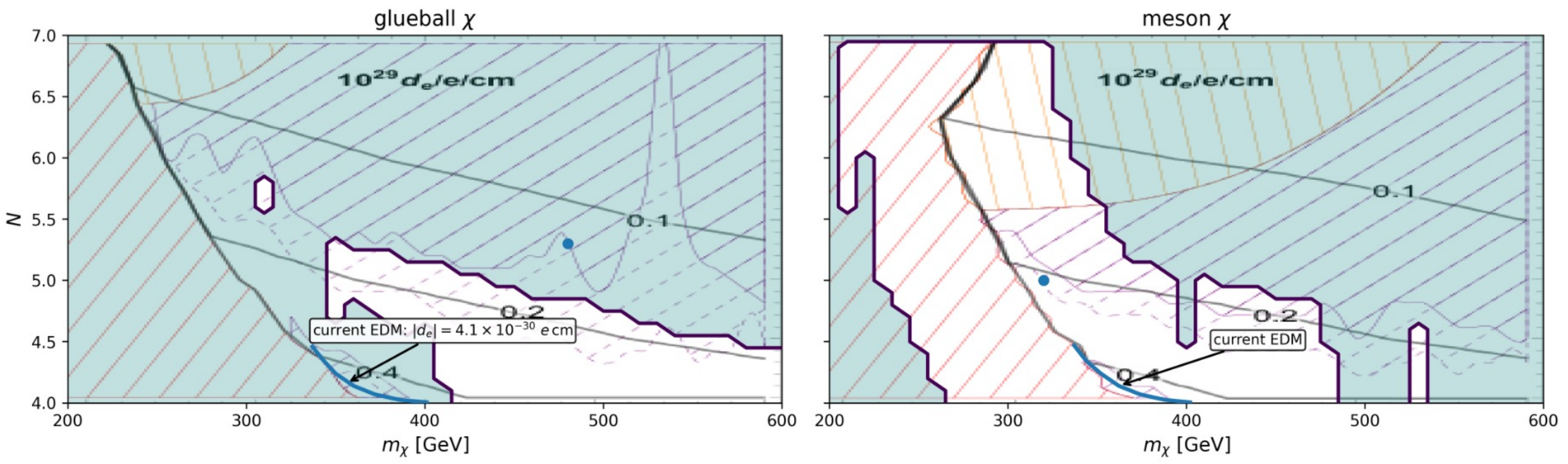
Composite Higgs — Actual LHC Constraint

PRELIMINARY with additional constraints

Resonance searches and Higgs-coupling bounds on the dilaton sector

$$V(h,\chi) = \chi^4\left[-\frac{c_1}{2}\left(\frac{h}{f}\right)^2 + \frac{c_2}{4}\left(\frac{h}{f}\right)^4 + \epsilon\left(c_3 - c_4 \ln\frac{\chi}{f_\chi}\right)\right]$$

$$\mathcal{L} \supset -y_c(\chi)\,\bar{Q}_L H c_R + \text{h.c.}\,, \qquad y_c(\chi) = |y_c|\left(\frac{\chi}{f_\chi}\right)^\Delta e^{i\theta(\chi)}$$



Bruggisser, von Harling, Matsedonskyi & Servant, "Status of Electroweak Baryogenesis in Minimal Composite Higgs," JHEP 08 (2023) 012, arXiv:2212.11953 — figures confronting the model with the latest LHC resonance searches and Higgs-coupling measurements, showing the surviving dilaton/vector mass range.

Singlet Extension & Composite Higgs

Two viable frameworks, bounded from different directions

Scalar Singlet Extension

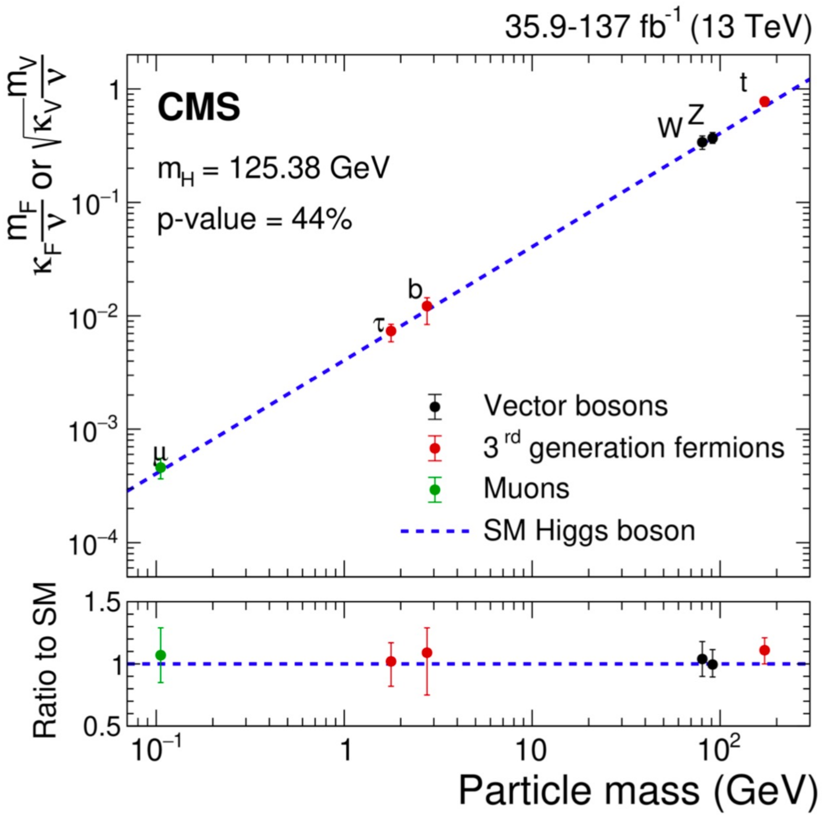
- Higgs invisible-decay bounds already exclude low singlet masses
- Triple-Higgs / di-Higgs production is the sharpest handle: probes the transition-relevant self-coupling directly
- A true gauge singlet is collider-elusive unless it mixes sizeably with the Higgs
- Main current LHC handle: indirect, via Higgs signal-strength deviations
- EDM constraints closing regions of viable BAU

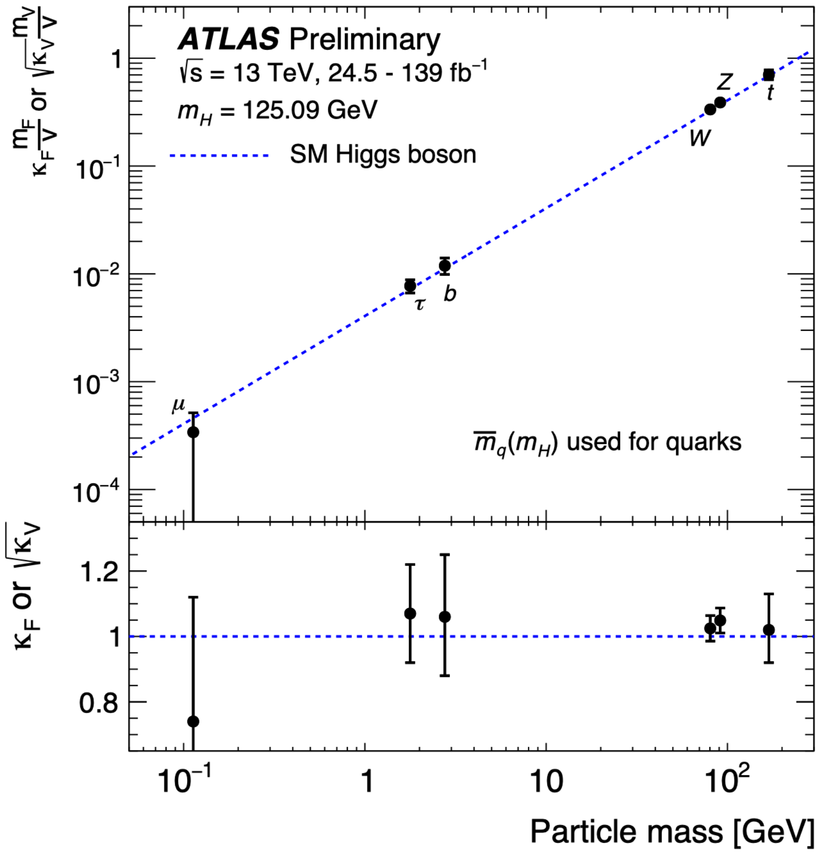
Composite Higgs (pNGB)

- Higgs as a pseudo-Nambu-Goldstone boson from new strong dynamics
- Tightest constraint comes from direct LHC resonance searches bounding the dilaton / vector mass
- CP violation is built into the varying-Yukawa structure, not a free phase
- EDM often binds tighter than colliders on the CP-violating sector itself

SMEFT — LHC Yukawa Coupling Measurement

The empirical baseline the dim-6 operator perturbs





CMS Collaboration, combined Higgs coupling measurements, CMS-HIG-19-006 / arXiv:2009.04363 (35.9–137 fb⁻¹, 13 TeV).
ATLAS Collaboration, arXiV:2019.032221

SM EFT Framework

Fuchs, ML, Nir, Viernik ‘19,’20,’20

See also de Vries et al, ‘18

- Dim-6 term with real and imaginary Yukawa couplings in Lagrangian:

$$L_{\mathrm{Yuk}} = y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + iX_I^f)|H|^2 \overline{F_L} F_R H + \mathrm{h.c.}$$

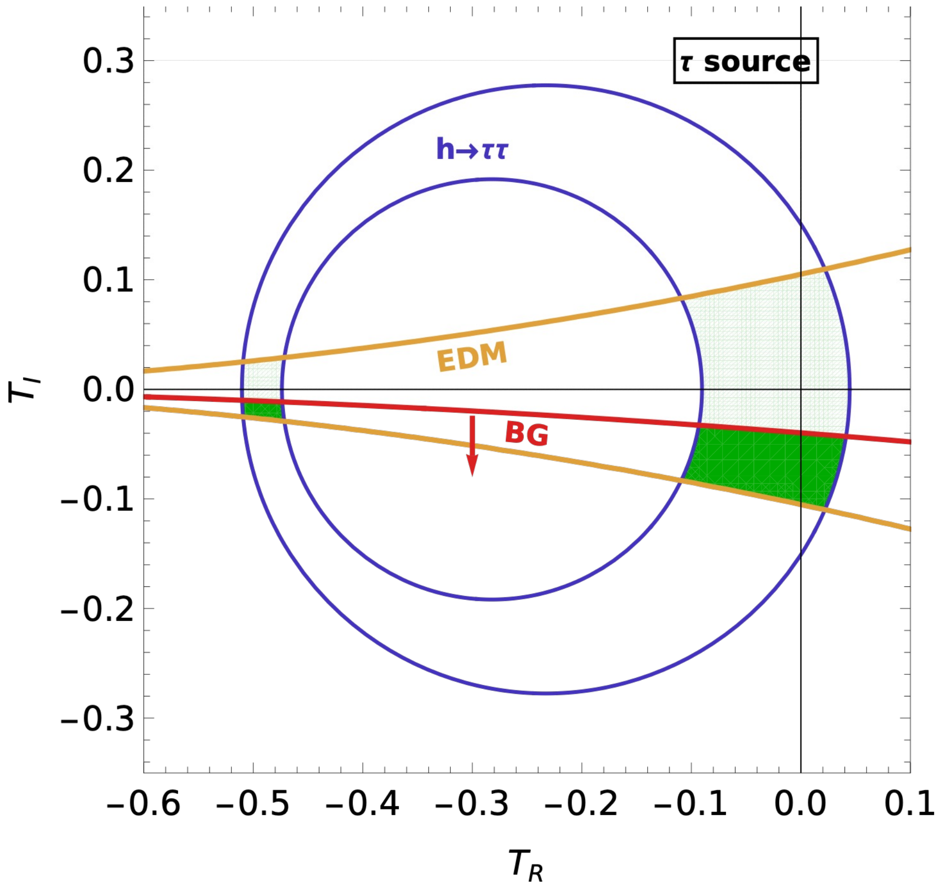
- Allows for new CPV interactions
- Changes the fermion mass and the corresponding Yukawa coupling relation.
- No additional scalar fields present

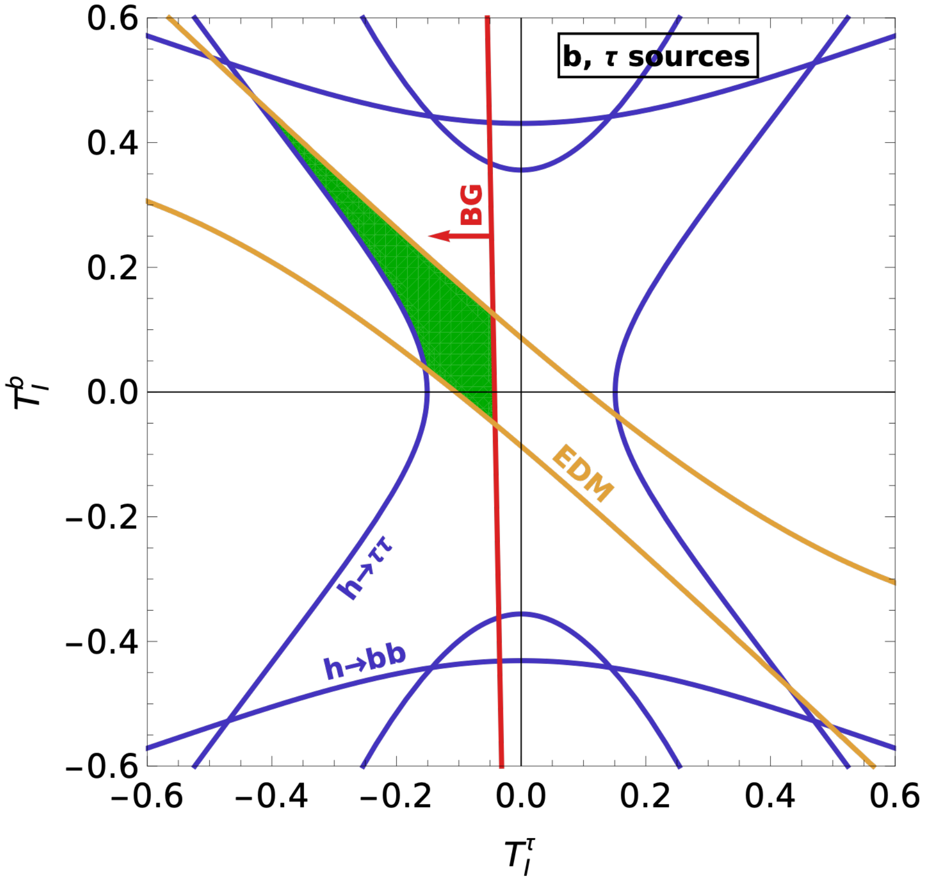
Use as parameters of the model the ratio of dim 6 to dim 4 contribution to the fermion mass:

$$\boxed{T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{y_f}, \qquad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{y_f}}$$

SMEFT — Old Constraint Plot

Combined H→ττ/b$\bar{b}$ rate + electron EDM + BAU + CP-structure bounds



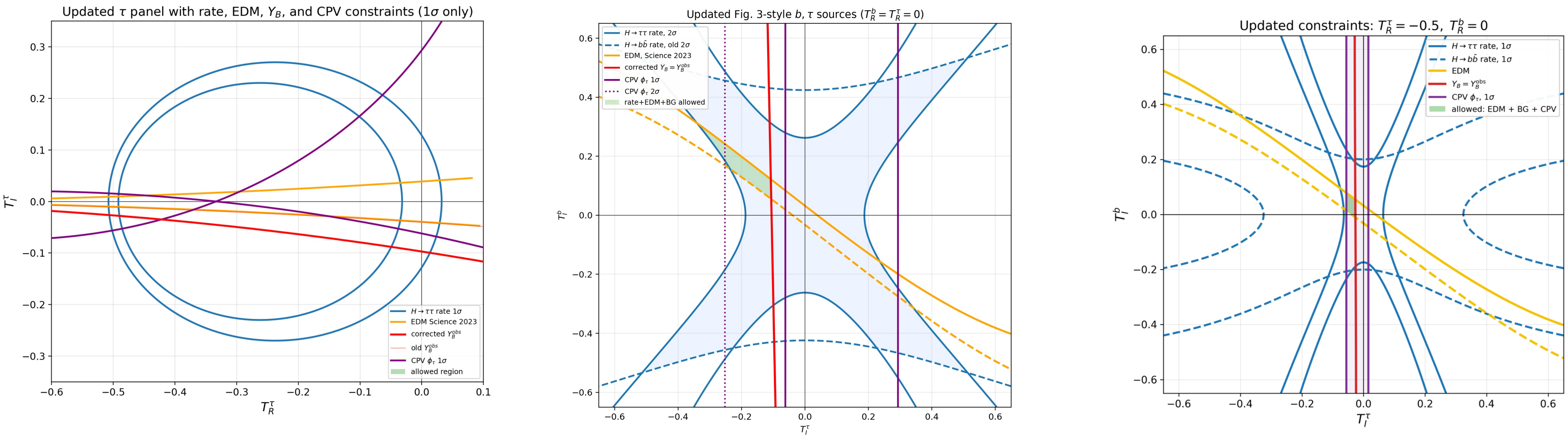


(Fuchs, Losada, Nir & Viernik, '18/'20;

SMEFT — Actual Constraint Plot (2026 Update)

ACTUAL FIGURE

Combined H→ττ/bb̄ rate + electron EDM + BAU + CP-structure bounds



Losada et al., SMEFT dim-6 top/bottom/tau Yukawa framework (Fuchs, Losada, Nir & Viernik, '18/'20; updated 2026 analysis). Combined b–τ source plane (T_I^τ, T_I^b) at T_R^b = T_R^τ = 0: blue = H→ττ/bb̄ rate bounds (2σ), orange = electron EDM (Science 2023), red = Y_B = Y_B^obs, purple = CP-violation in h→ττ angular distributions.

SMEFT: Direct Yukawa CP Violation

No new scalar field — CP violation lives in the top/bottom/tau Yukawa coupling itself

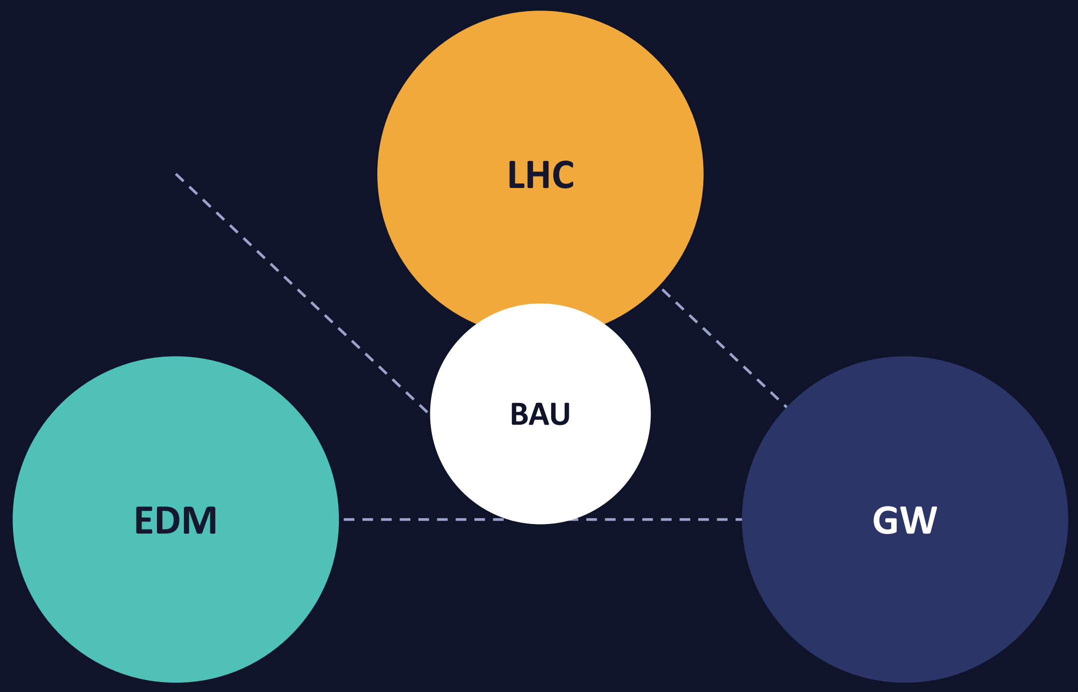
- Dimension-6 operator rescales the Yukawa magnitude and adds an imaginary phase — no extra scalar needed
- The phase transition itself must be supplied by separate new physics (assumed, not derived, in this framework); CP violation and BAU production are studied independently of what drives the transition
- Constrained simultaneously by: Higgs signal-strength rates ($h \to \tau\tau$, $h \to b\bar{b}$), CP-odd angular distributions in $h \to \tau\tau$, the electron EDM, and the requirement Y_B
- Third-generation sources are now all EDM-limited; Two flavor solutions remain but highly constrained by non observation of CP violating Higgs decays

Per-Model: BAU, EDM, and GW

Model	Tightest Constraint	EDM Tension	GW Prospects
MSSM	LHC (stop mass, Higgs rates)	Moot — already excluded	Not relevant
NMSSM	Electron EDM	Severe, now dominant	Secondary probe
2HDM / C2HDM	EDM, with LHC closing in parallel	Severe unless flavor-aligned	Promising in surviving corner (LISA)
Singlet Ext.	LHC di-boson / invisible-Higgs	Severe if $\langle s \rangle \neq 0$; evadable if $=0$	Anti-correlated with viable BAU region
Composite Higgs	LHC resonance searches	Tied to flavor structure	Plausible, less quantified
SMEFT (dim-6)	$h \to \tau\tau / b\bar{b}$ rate + CP-structure	Severe for t, b; tau source survives	Not addressed (transition mechanism external)

The Three-Way Squeeze

LHC, electron EDM, and gravitational waves pull on the same few parameters



- Larger CP violation → easier to match the observed baryon asymmetry, but predicts a larger electron EDM
- Stronger transition → easier sphaleron freeze-out, but often in tension with LHC data and can suppress the GW-visible baryogenesis window
- Suppressing the CP phase to evade EDM typically suppresses the GW signal too, since both track the same non-decoupling dynamics

Key Takeaways

EDM is now the leading model-independent squeeze

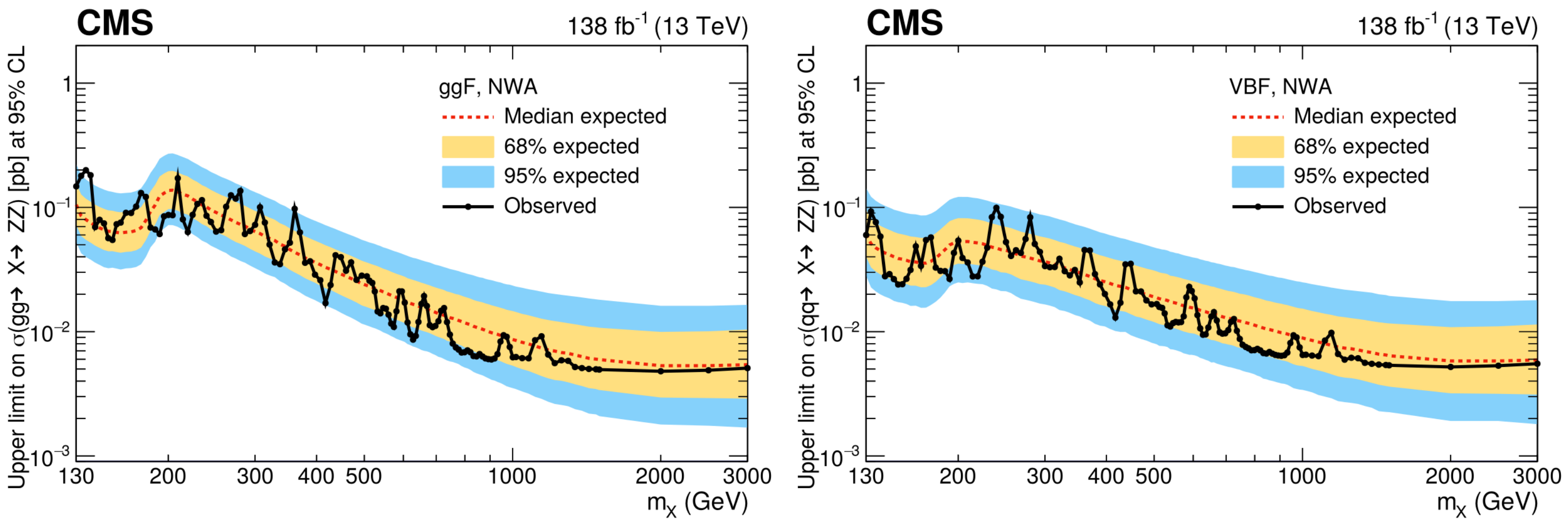
Except for MSSM and composite Higgs, where direct LHC production limits already bind tighter.

GW is not a uniform ally of EWBG

In the singlet extension, the GW-visible and BAU-viable regions of parameter space are largely o

Updated LHC Constraint

CMS-HIG-24-002, arXiv:2605.26462 — Fig. 8 (ggF & VBF)



- Full 138 fb^{-1} Run 2, one unified analysis, 130 GeV–3 TeV —
- Observed limit tracks the 68% expected band across the whole range; no significant excess (largest local fluctuation 3.0σ at 137.8 GeV, only 1.8σ global)
- σ(pp→X→ZZ) excluded down to ~0.05–0.1 pb at low mass, ~0.005 pb at high mass — directly tightens the (sinθ, m_s) region