A TeV-scale model for neutrino mass, dark matter and baryon asymmetry of the universe and its phenomenology

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Based on [JHEP06(2025)036] and recent work

Introduction

Higgs was found in 2012, but **the structure of Higgs sector is still unknown.**

The number of Higgs field, representation, symmetry, ⋯

Physics of electroweak symmetry breaking, details of phase transition

Related to BSM phenomena

- **ν oscillation**
- **Dark matter**
- **Baryon asymmetry**

Radiative seesaw
WIMP dark matter
Electroweak baryogenesis

Related Higgs physics

Testable with various experiments

↓

Approaching new physics from Higgs physics

Q. Can we explain these 3 BSM phenomena simultaneously at TeV scale?

M. Aoki, S. Kanemura and O. Seto (2009)

→We focus on Aoki-Kanemura-Seto (AKS) model

Aoki-Kanemura-Seto model

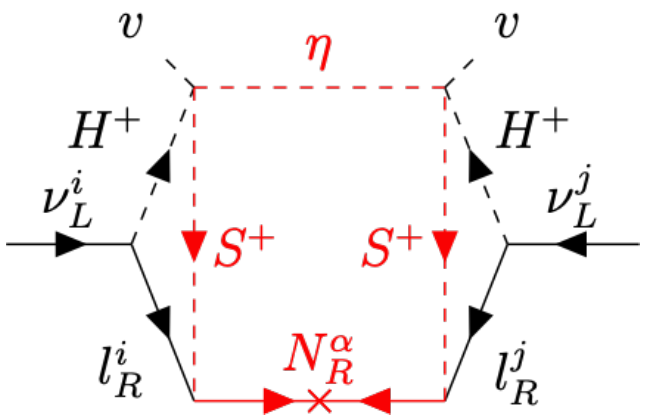
Aoki-Kanemura-Seto (AKS) model can explain 3 BSM phenomena simultaneously at TeV scale

M. Aoki, S. Kanemura and O. Seto (2009)

Z_2 **symmetry**
- **Tiny ν mass via radiative correction**
- **Dark matter candidate** (Z_2 odd neutral particle)

Baryon asymmetry : **Electroweak baryogenesis(EWBG)**

Energy scale : **TeV→Testable at collider**



3-loop neutrino mass generation

$$M_{ij} \sim \underbrace{\left(\frac{1}{16\pi^2}\right)^3}_{\sim 10^{-6}} \times \underbrace{\left(\frac{m_l}{v}\right)^2}_{\sim 10^{-4}} \times \frac{v^2}{m_N} < \text{eV}$$

$\tilde{Z}_2$ for FCNC

	Z_2	$\tilde{Z}_2$ (Softly broken)
ϕ_1	$+$	$+$
ϕ_2	$+$	$-$
N_R^α	$-$	$-$
S^+	$-$	$+$
Dark matter → η	$-$	$-$

Particle content

SM + **Extended Higgs** + **Right-handed ν**

- **Extended Higgs** → additional Higgs doublet ϕ_2 + singlet η, S^+
- **Right-handed neutrino** N_R^α $\alpha = 1,2,3$
- **Softly broken $\tilde{Z}_2$ symmetry** → suppress Flavor Changing Neutral Current
- **Exact Z_2 symmetry** → η , S^+, N_R^α are odd

AKS model = Type-X 2HDM + $N_R^\alpha, S^\pm, \eta$ with Z_2

	Z_2	$\tilde{Z}_2$ (Softly broken)
ϕ_1	+	+
ϕ_2	+	−
N_R^α	−	−
S^+	−	+
Dark matter → η	−	−

Lagrangian

Type-X 2HDM + $N_R^\alpha, S^\pm, \eta$

Stationary condition $\mathrm{Im}\,[\mu_{12}^2] - \frac{1}{2}\mathrm{Im}\,[\lambda_5] v_1 v_2 = 0$

$\rightarrow \mu_{12}^2, \lambda_5$ are not independent

Higgs potential

$$V = -\mu_1^2|\phi_1|^2 - \mu_2^2|\phi_2|^2 - (\mu_{12}^2\phi_1^\dagger\phi_2 + \mathrm{h.c.}) + \mu_S^2|S|^2 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4$$
$$+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \left(\frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right) + \frac{\lambda_S}{4}|S|^4 + \frac{\lambda_\eta}{4!}\eta^4 + \frac{\xi}{2}|S|^2\eta^2$$
$$+ \sum_{a=1}^{2}\left(\rho_a|\phi_a|^2|S|^2 + \frac{1}{2}\sigma_a|\phi_a|^2\eta^2\right) + (2\kappa\tilde{\phi}_1^\dagger\phi_2 S^-\eta + \mathrm{h.c.})$$

CP phase θ_5 ($\lambda_5 = |\lambda_5|e^{i\theta_5}$)

Portal coupling

Phase of κ will vanish by rephasing of S^-

The physical CP phase in Higgs potential is only θ_5

	Z_2	$\tilde{Z}_2$ (Softly broken)
ϕ_1	+	+
ϕ_2	+	−
N_R^α	−	−
S^+	−	+
η	−	−

Neutrino Yukawa

$$\mathcal{L} \supset -h_i^\alpha\overline{(N_R^\alpha)^c}l_R^i S^+ + \mathrm{h.c.}$$

$\alpha = 1,2,3,\quad i = 1,2,3,$

h_i^α : 3×3 complex matrix

CP violation (CP phase ψ_1, ψ_2, ψ_3 +PMNS phase $\delta, \alpha_1, \alpha_2$)

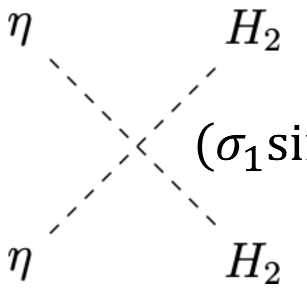
Dark matter

$$V \supset + \sum_{a=1}^{2} \left(\rho_a |\phi_a|^2 |S^+|^2 + \frac{1}{2}\sigma_a |\phi_a|^2 \eta^2 \right)$$

DM-Higgs interaction

η : Dark matter

Dominant contribution to the relic density



$(\sigma_1 \sin^2\beta + \sigma_2 \cos^2\beta) \simeq \sigma_1$

$\tan\beta = 18$

$\sigma_1 = 0.0841$
$\rightarrow \Omega h^2 \simeq 0.12$

DM direct detection

spin-independent cross section for $\eta N \rightarrow \eta N$

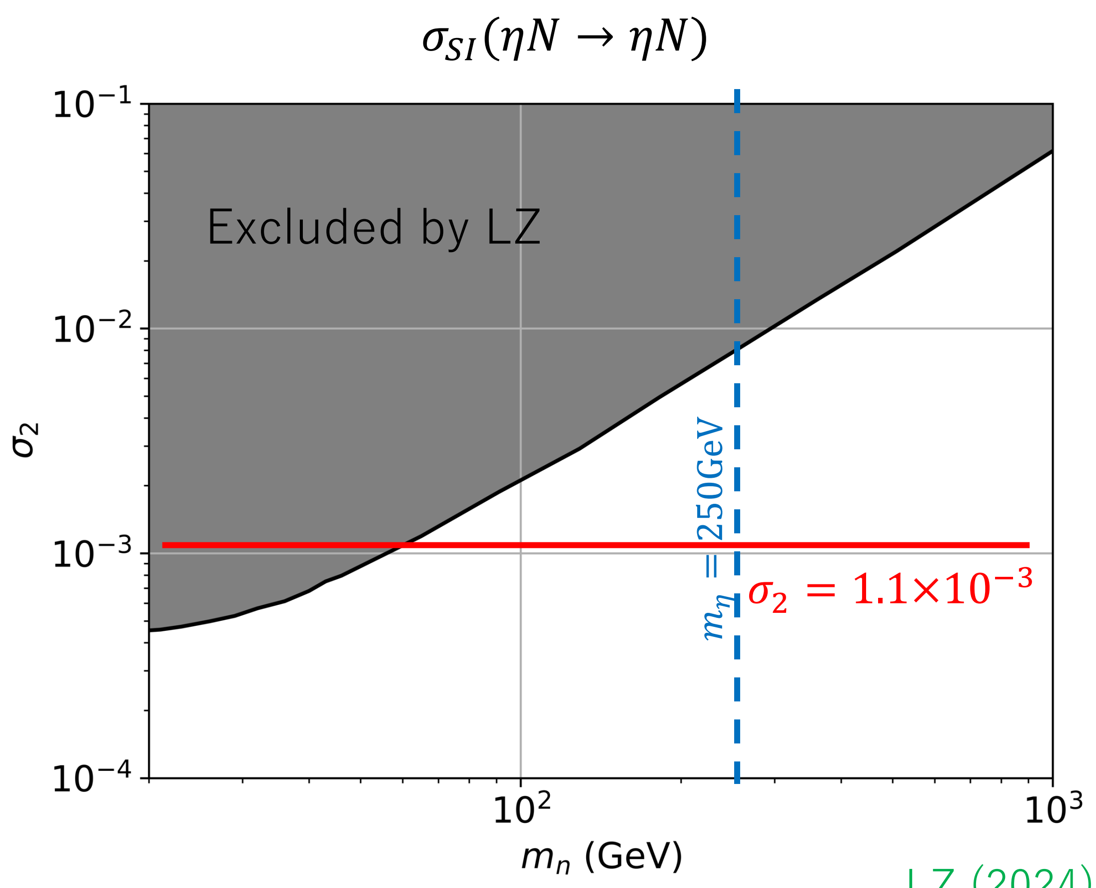
$$\sigma_{\rm SI} \simeq \frac{g^2 m_N^2 v^2}{4\pi (m_\eta + m_N)^2 m_{H_1}^4} (\sigma_1 \cos\beta + \sigma_2 \sin\beta)^2$$

$m_N \simeq 1$ GeV : nucleon mass

$g \simeq 10^{-3}$: coupling for nucleon-Higgs

Shifman, et al (1978)

$(\sigma_1 \cos\beta + \sigma_2 \sin\beta) \simeq \sigma_2$



LZ (2024)

K. Enomoto, S.Kanemura, ST (2024)

Electroweak Baryogenesis

Electroweak Baryogenesis

Kuzmin, Rubakov and Shaposhnikov (1985)

(1) B violation ➡ **Sphaleron Transition**

(2) C, CP violation ➡ **CP violation in extended Higgs sector**

(3) Departure from thermal equilibrium Sakharov (1967) ➡ **Sphaleron decoupling →Strongly 1st order EWPT**

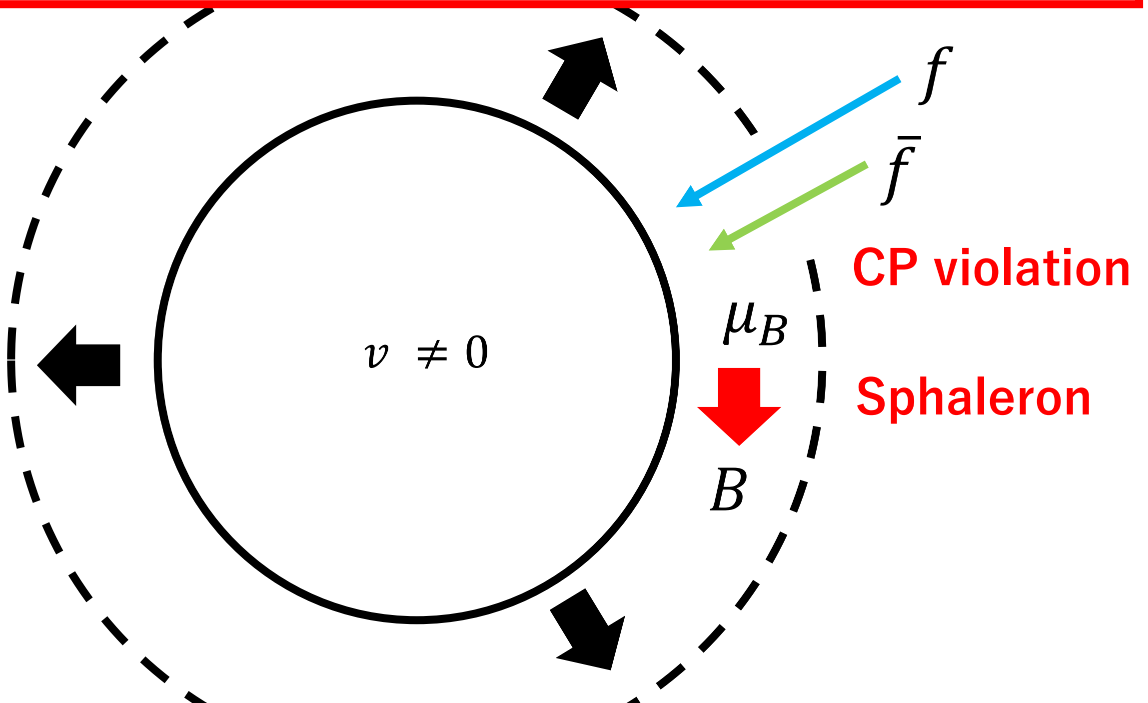
Charges accumulate around the bubble wall due to the CPV

⬇

B number is generated by sphaleron

⬇

Sphaleron decouples inside the bubble wall and B number remains



Electric dipole moment in our model

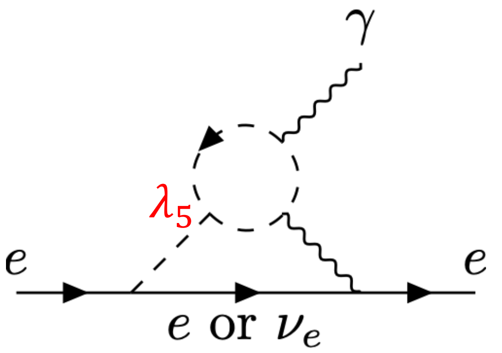
Sufficient CP phase ($\theta_5 \sim O(1)$) for EWBG is severely constrained by electron EDM experiments ($|d_e| < 4.1\times10^{-30}$ ecm).

Roussy et al. (JILA) (2023)

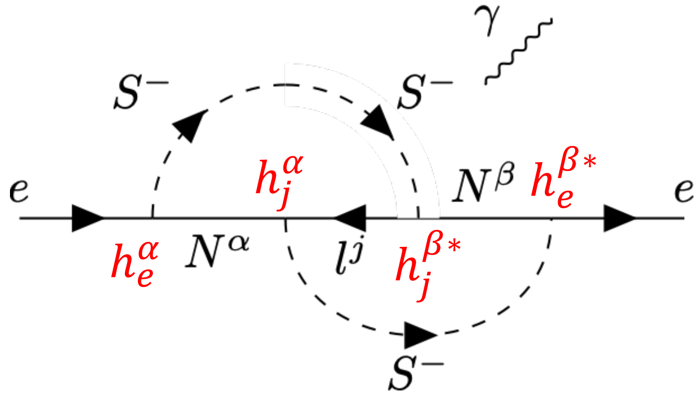
$$\mathcal{L} \supset -h_i^\alpha \overline{(N_R^\alpha)^c} l_R^i S^+ + \text{h.c.}$$

K. Enomoto, S.Kanemura, ST (2024)

Electron EDM can be small by considering following contribution



$+$

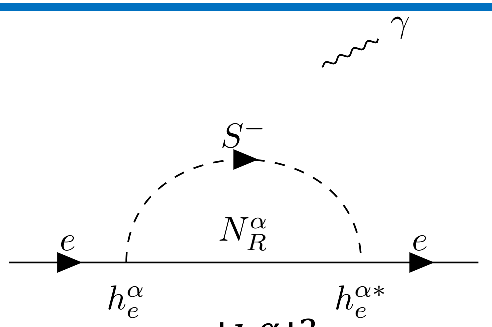


$< 4.1\times10^{-30}\ ecm$

Barr, Zee (1990)
Altmannshofer, et al(2020)

Contribution in 2HDM
(Barr-Zee contribution)

Additional contribution in CPV AKS model



$\propto |h_e^\alpha|^2$

Imaginary part = 0 in 1-loop

$|d_e| \simeq 8.3\times10^{-31}\ ecm < 4.1\times10^{-30}\ ecm$

$\theta_5 \simeq -0.090\pi$

$m_{H^1} \simeq 125$ GeV, $m_{H^2} \simeq 207$ GeV,
$m_{H^3} = m_{H^\pm} \simeq 373$ GeV

Strongly 1st Order Phase Transition

Sphaleron decoupling → $\Gamma_{sph}^{br} < H(T_c)$

Γ_{sph}^{br}:Sphaleron rate in broken phase
$H(T_c)$:Hubble const. at transition temp.

➡ Strongly 1st order EWPT $\dfrac{\varphi_c}{T_c} > 1$

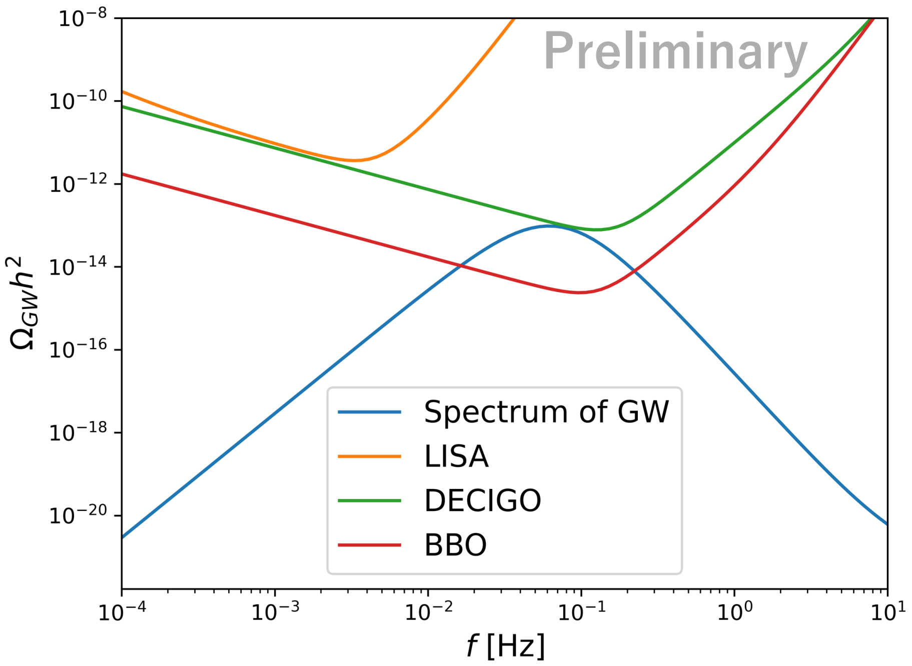
$m_{H^1} \simeq 125$ GeV, $m_{H^2} \simeq 207$ GeV,
$m_{H^3} = m_{H^\pm} \simeq 373$ GeV
$M \simeq 210$ GeV, $m_S = 325$ GeV,
$\mu_S = 20$ GeV,$\theta_5 \simeq -0.090\pi$

→non-decoupling effects of additional scalars

This effect gives a large deviation in hhh coupling

Kanemura, Kiyoura, Okada, Senaha, Yuan (2002)
Kanemura, Okada, Senaha, Yuan (2004)

$$\Delta R \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}} \simeq 36\ \%$$

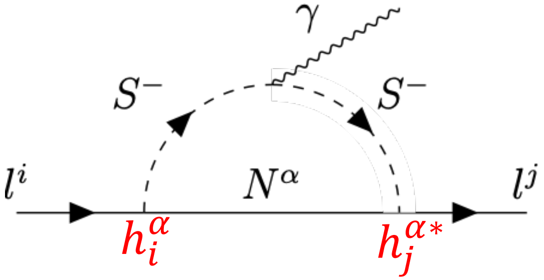


GW from strongly 1st order EWPT

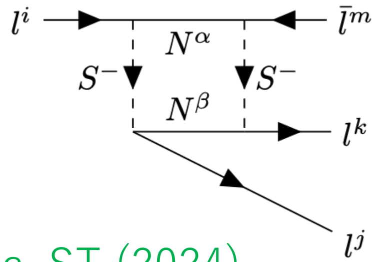
→testable at BBO,DECIGO

Lepton flavor violation

$l^i \to l^j \gamma$



$l^i \to l^j\, l^k\, \bar{l}^m$

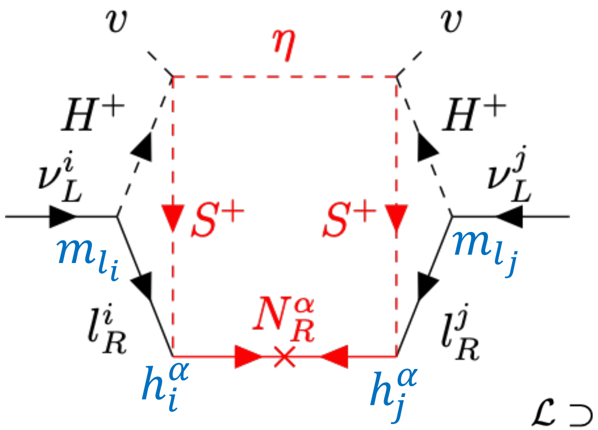


To explain ν mass, h_i^α follow **an inverted hierarchy of lepton masses**

⬇

The LFV decays with e tends to be enhanced

$$(M_\nu)_{ij} \sim h_i^\alpha h_j^\alpha \left(\frac{1}{16\pi^2}\right)^3 \times \left(\frac{m_l}{v}\right)^2 \times \frac{v^2}{m_N}$$



$$\mathcal{L} \supset -h_i^\alpha \overline{(N_R^\alpha)^c} l_R^i S^+ + \text{h.c.}$$

K. Enomoto, S.Kanemura, ST (2024)

	Prediction	Exp. bounds	
$\mu \to e\gamma$	2.3×10^{-14}	3.1×10^{-13}	MEG-II(2024
$\tau \to e\gamma$	1.8×10^{-11}	3.3×10^{-8}	BaBar(2010)
$\tau \to \mu\gamma$	2.0×10^{-17}	4.4×10^{-8}	BaBar(2010)
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}	Mu3e(2023)
$\tau \to 3e$	3.1×10^{-12}	2.7×10^{-8}	BaBar(2010)
$\tau \to 3\mu$	2.6×10^{-23}	2.1×10^{-8}	Belle (2010)
$\tau \to e\mu\bar{e}$	3.1×10^{-17}	1.8×10^{-8}	Belle (2010)
$\tau \to \mu\mu\bar{e}$	1.4×10^{-17}	1.7×10^{-8}	Belle (2010)
$\tau \to e\mu\bar{\mu}$	8.3×10^{-19}	2.7×10^{-8}	Belle (2010)

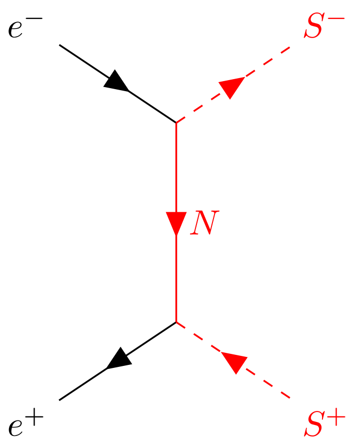
$m_S = 325$ GeV $(m_{N^1}, m_{N^2}, m_{N^3}) = (400, 900, 1400)$ GeV

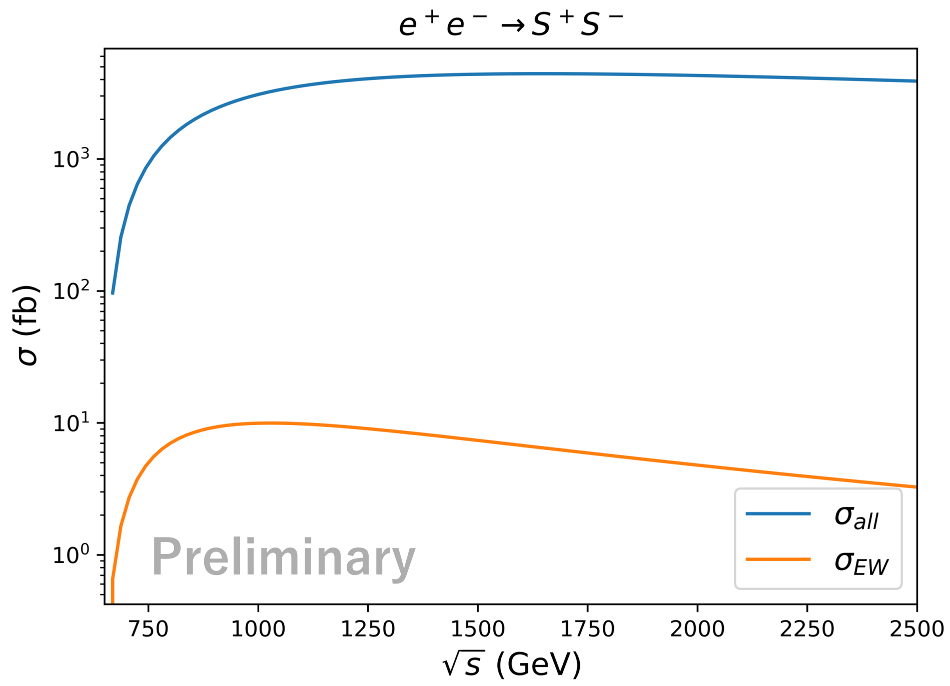
$$h_i^\alpha \simeq \begin{pmatrix} 1.3e^{-0.16\pi i} & 0.0028e^{-0.90\pi i} & 0.011e^{-0.042\pi i} \\ 0.51e^{-0.36\pi i} & 0.039e^{-0.0055\pi i} & 0.0039e^{-0.35\pi i} \\ 1.4e^{-0.45\pi i} & 0.015e^{-9.8\pi i} & 0.0076e^{-0.58\pi i} \end{pmatrix}$$

Phenomenology in collider experiments

$S^{\pm}$ Production

Production : Drell-Yan process
t-channel process
(lepton collider)





$S^+ \to H^{\pm *}\eta \to \tau\nu\eta$ is the main decay channel
$e^+e^- \to S^+S^- \to \tau\bar{\tau}E$ (E : missing energy)

LHC can produce $S^{\pm}$ by Drell-Yan process

$pp \to S^+S^-$ (MadGraph)

$$\sqrt{s} = 13\ \text{TeV} : \sigma = 0.976\ \text{fb}$$
$$\sqrt{s} = 14\ \text{TeV} : \sigma = 1.14\ \text{fb}$$

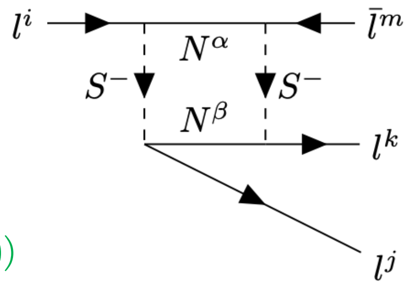
Additional Higgs H_2, H_3 can be tested at future HL-LHC by

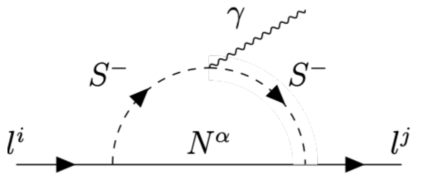
$H_2, H_3 \to \tau\bar{\tau}, t\bar{t}$ $\quad$ $H_2, H_3 \to ZH_1, H_1H_1$

Test at future experiments

LFV

	Prediction	Exp. bound	Expected sensitivity	
$\mu \to e\gamma$	2.3×10^{-14}	3.1×10^{-13}	6×10^{-14}	MEG-II(2018)
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}	1×10^{-16}	Mu3e phase-II(2020)
$\tau \to 3e$	3.1×10^{-12}	2.7×10^{-8}	4×10^{-10}	Belle-II(2018)





Electron EDM

Future ACME-III aim : $|d_e| < 10^{-30}$ ecm

$$|d_e| \simeq 8.3 \times 10^{-31}\ ecm$$

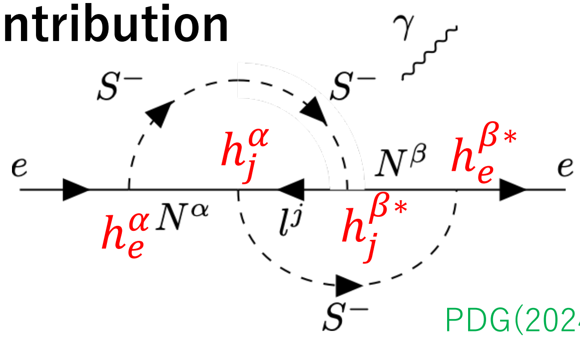
Neutron, proton EDM

$\tan\beta = 18$

Quark Yukawa couplings are suppressed by $\cot\beta$ (Type-X 2HDM)

EDM cancellation does not work for neutron, proton EDMs
→**Future neutron, proton EDM can test CP violation**

Lepton contribution



PDG(2024)

$|d_n| < 1.8\times10^{-26}$ ecm

$|d_p| < 2.1\times10^{-25}$ ecm

Summary

- AKS model can explain 3 BSM phenomena simultaneously at the TeV scale.
- We introduce CP violation into the original AKS model (2009).
- AKS model can avoid the electron EDM constraint while keeping O(1) CP phase.
- We show the testability of AKS model with various experiments (collider, flavor, DM, neutrinos, EDMs, GW)

Back up

Casas-Ibarra parametrization

$$h = \frac{(16\pi^2)^{\frac{3}{2}}}{|\kappa \tan\beta|}\sqrt{\Lambda} R \sqrt{D} U^{\dagger}_{\mathrm{PMNS}}(M_L^{-1})$$

$$\Lambda_{\alpha\beta} = \frac{1}{m_\alpha(F_{1\alpha}+F_{2\alpha})}\delta_{\alpha\beta} \quad D \equiv \mathrm{diag}(m_{\nu^1}, m_{\nu^2}, m_{\nu^3}) \qquad M_L = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

$$R = \frac{1}{c_{\psi_1}c_{\psi_2}c_{\psi_3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\gamma_1} & s_{\gamma_1} \\ 0 & -s_{\gamma_1} & c_{\gamma_1} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & is_{\psi_1} \\ 0 & -is_{\psi_1} & 1 \end{pmatrix} \begin{pmatrix} c_{\gamma_2} & 0 & s_{\gamma_2} \\ 0 & 1 & 0 \\ -s_{\gamma_2} & 0 & c_{\gamma_2} \end{pmatrix}$$
$$\times \begin{pmatrix} 1 & 0 & is_{\psi_2} \\ 0 & 1 & 0 \\ -is_{\gamma_2} & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{\gamma_3} & s_{\gamma_3} & 0 \\ -s_{\gamma_3} & c_{\gamma_3} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & is_{\psi_3} & 0 \\ -is_{\psi_3} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Transport equation

$$\begin{cases} -D_{1t}\mu_t' + u_t' + \gamma v_w (m_t^2)' Q_{2t}\mu_t - K_{0t}\overline{\Gamma}_t = -S_{1t}, \\ -D_{2t}\mu_t' - v_w u_t' + \gamma v_w (m_t^2)' Q_{t2}\mu_t + (m_t^2)'\overline{R}_t u_t + \Gamma_{t,\mathrm{tot}} u_t + v_w K_{0t}\overline{\Gamma}_t = -S_{2t}. \end{cases}$$

$$\begin{cases} -D_{1b}\mu_b' + u_b' - K_{0b}\overline{\Gamma}_b = 0, \\ -D_{2b}\mu_b' - v_w u_b' + \Gamma_{b,\mathrm{tot}} u_b + v_w K_{0b}\overline{\Gamma}_b = 0. \end{cases}$$

$$\begin{cases} -D_{1t}\mu_{t^c}' + u_{t^c}' + \gamma v_w (m_t^2)' Q_{2t}\mu_{t^c} - K_{0t}\overline{\Gamma}_{t^c} = -S_{1t}, \\ -D_{2t}\mu_{t^c}' - v_w u_{t^c}' + \gamma v_w (m_t^2)' Q_{t2}\mu_{t^c} + (m_t^2)'\overline{R}_t u_{t^c} + \Gamma_{t,\mathrm{tot}} u_{t^c} + v_w K_{0t}\overline{\Gamma}_{t^c} = -S_{2t}. \end{cases}$$

$$\begin{cases} -D_{1h}\mu_h' + u_h' - K_{0h}\overline{\Gamma}_h = 0, \\ -D_{2h}\mu_h' - v_w u_h' + \Gamma_{h,\mathrm{tot}} u_h + v_w K_{0h}\overline{\Gamma}_h = 0. \end{cases}$$

$$S_{li} = -\gamma v_w (m_i^2 \theta_i')' Q_{li}^8 + \gamma v_w m_i^2 \theta_i' (m_i^2)' Q_{li}^9, \quad (l = 1, 2).$$

Collision rate

$$\overline{\Gamma}_t = \Gamma_{ss}\Big((1+9D_{0t})\mu_t + 10\mu_b + (1-9D_{0t})\mu_{t^c}\Big)$$
$$+\Gamma_W(\mu_t - \mu_b) + \Gamma_y(\mu_t + \mu_{t^c} + \mu_h) + 2\Gamma_m(\mu_t + \mu_{t^c}),$$
$$\overline{\Gamma}_b = \Gamma_{ss}\Big((1+9D_{0t})\mu_t + 10\mu_b + (1+9D_{0t})\mu_{t^c}\Big)$$
$$+\Gamma_W(\mu_b - \mu_t) + \Gamma_y(\mu_b + \mu_{t^c} + \mu_h),$$
$$\overline{\Gamma}_{t^c} = \Gamma_{ss}\Big((1+9D_{0t})\mu_t + 10\mu_b + (1-9D_{0t})\mu_{t^c}\Big)$$
$$+2\Gamma_m(\mu_{t^c} + \mu_t) + \Gamma_y(2\mu_{t^c} + \mu_t + \mu_b + 2\mu_h),$$
$$\overline{\Gamma}_h = \frac{3}{4}\Gamma_y(2\mu_h + \mu_t + \mu_b + 2\mu_{t^c}) + \Gamma_h\mu_h.$$

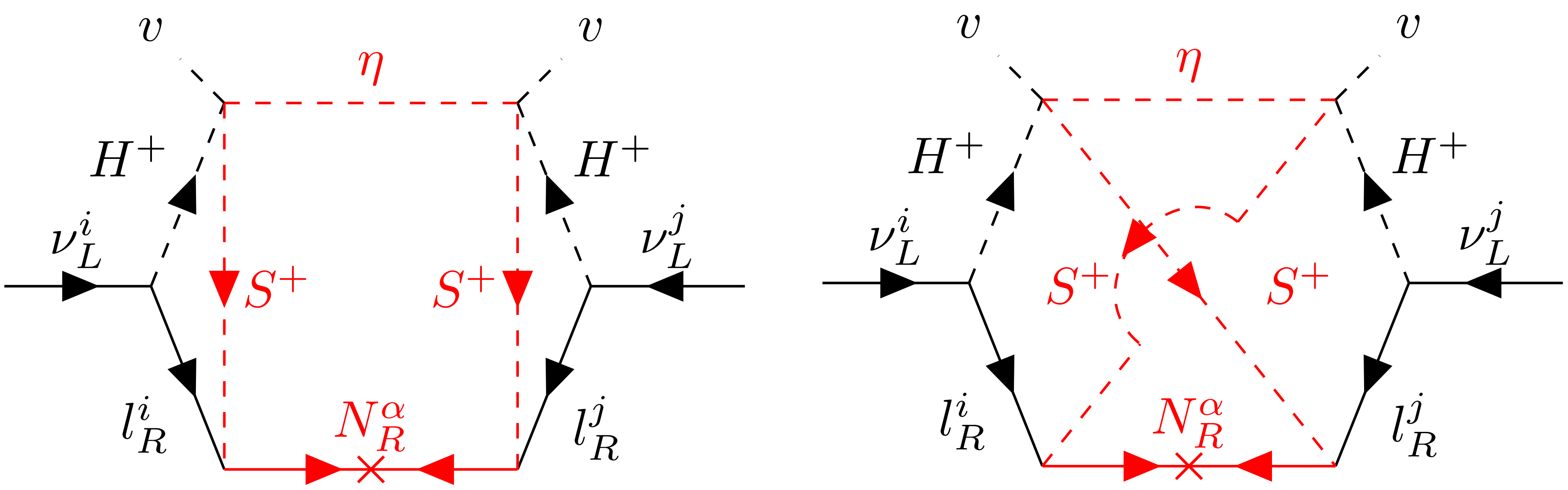
Baryon asymmetry

$$\mu_{B_L} = \frac{1}{2}(1 + 4D_{0t})\mu_t + \frac{1}{2}(1 + 4D_{0b})\mu_b - 2D_{0t}\mu_{t^c}.$$

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_w g_* T_n} \int_0^\infty dz \; \mu_{B_L} f_{\rm sph}(z) \exp\left(-\frac{45\Gamma_{\rm sph} z}{4v_w}\right),$$

$$f_{\rm sph}(z) = \min\left\{1, \; \frac{2.4T}{\Gamma_{\rm sph}} e^{-\frac{40 v_n(z)}{T}}\right\}.$$

Neutrino mass matrix



$$(M_\nu)_{ij} = \frac{(\kappa \tan\beta)^2 m_{l^i} m_{l^j}}{(16\pi^2)^3} \sum_{\alpha=1}^{3} h_i^\alpha h_j^\alpha m_{N^\alpha} (F_{1\alpha} + F_{2\alpha})$$

$$F_{n\alpha} = \int \tilde{d}^4 x \int_0^\infty du \int_0^\infty dv \frac{8\sqrt{uv}\tilde{F}(a_n, b_N)}{(u + m_{H^\pm}^2)(v + m_{H^\pm}^2)}$$

Yukawa interaction in Type-X 2HDM

$$
\begin{aligned}
\mathcal{L}_y = & - m_{u^i}\bar{u}^i u^i - m_{d^i}\bar{d}^i d^i - m_{l^i}\bar{l}^i l^i \\
& - \sum_a H_a \left\{ \frac{m_{u^i}}{v}\bar{u}^i (R_{1a} + R_{2a}\cot\beta - iR_{3a}\cot\beta\gamma_5) u^i \right. \\
& \qquad\qquad + \frac{m_{d^i}}{v}\bar{d}^i (R_{1a} + R_{2a}\cot\beta + iR_{3a}\cot\beta\gamma_5) d^i \\
& \qquad\qquad \left. + \frac{m_{l^i}}{v}\bar{l}^i (R_{1a} + R_{2a}\tan\beta + iR_{3a}\tan\beta\gamma_5) l^i \right\} \\
& - \frac{\sqrt{2}}{v}\{\cot\beta\bar{u}^i V_{ij}(m_{d^i}P_R - m_{u^i}P_L)d^j H^+ + \tan\beta m_{l^i}\bar{\nu}^i P_R l^i H^+ + \text{h.c.}\}
\end{aligned}
$$

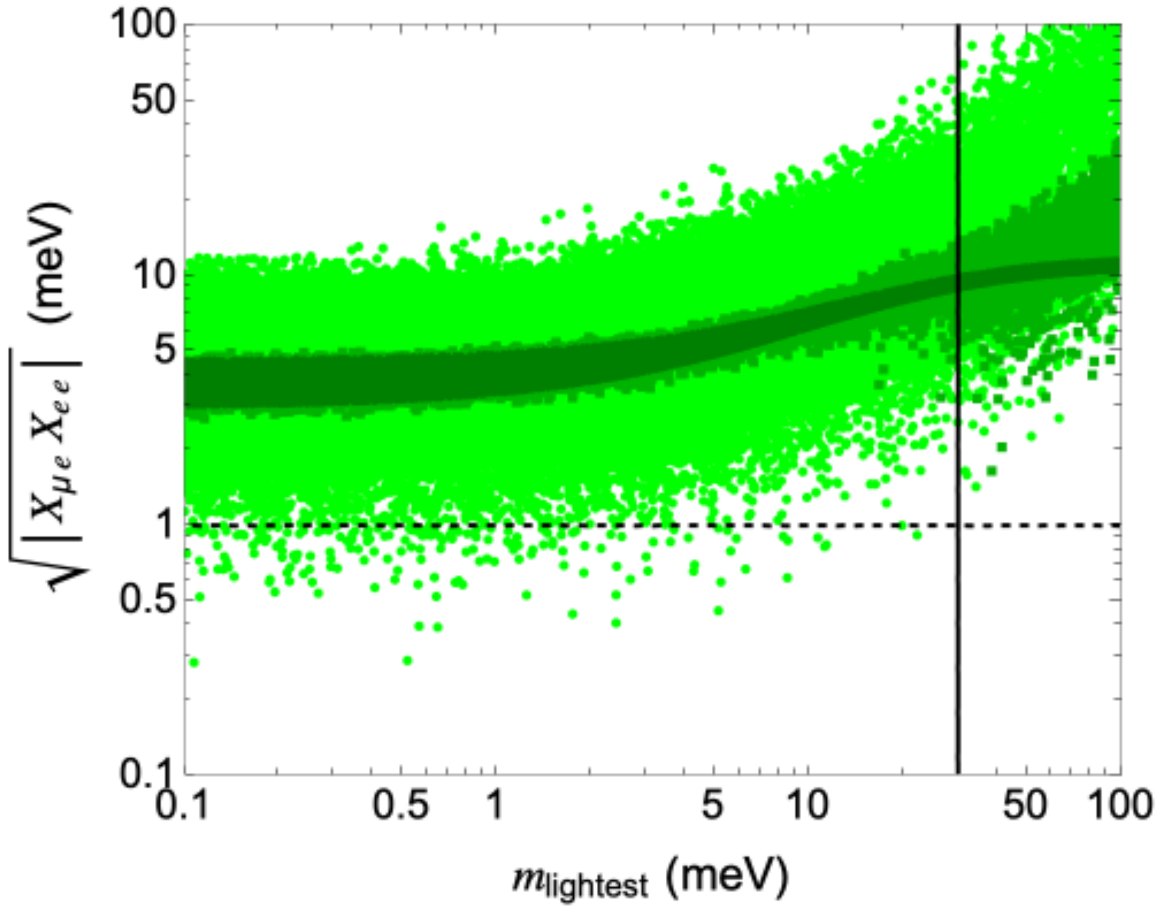
Benchmark scenario

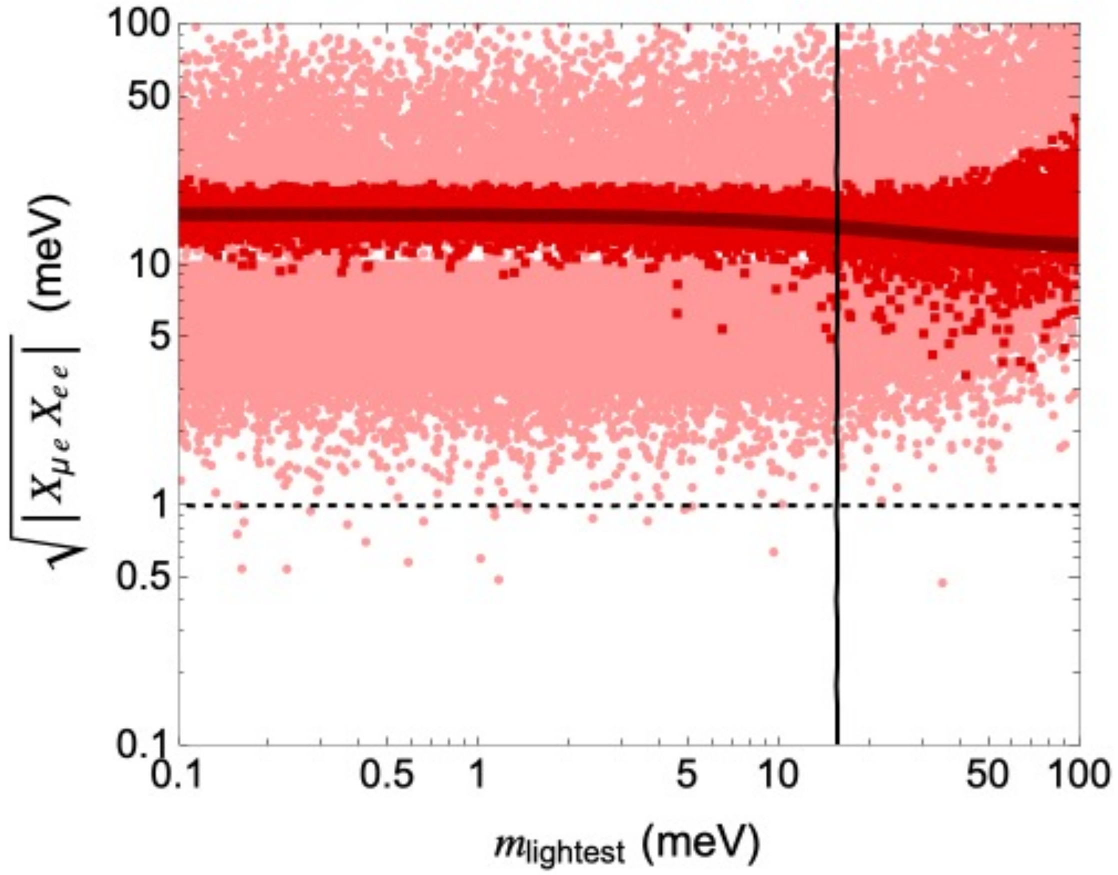
$$m_{H^1} \simeq 125\ \text{GeV},\ m_{H^2} \simeq 207\ \text{GeV},\ m_{H^3} = m_{H^\pm} \simeq 373\ \text{GeV}$$
$$M \simeq 210\ \text{GeV},\ m_S = 325\ \text{GeV},\ m_\eta = 250\ \text{GeV}$$
$$(m_{N^1}, m_{N^2}, m_{N^3}) = (400, 900, 1400)\ \text{GeV}$$

$$\sigma_1 = 0.0841, \sigma_2 = 1.1\times 10^{-3}$$
$$m_{\nu^1} = 8.1\ \text{meV},\ \kappa \tan\beta = 45, \tan\beta = 18, \theta_5 \simeq -0.090\pi$$

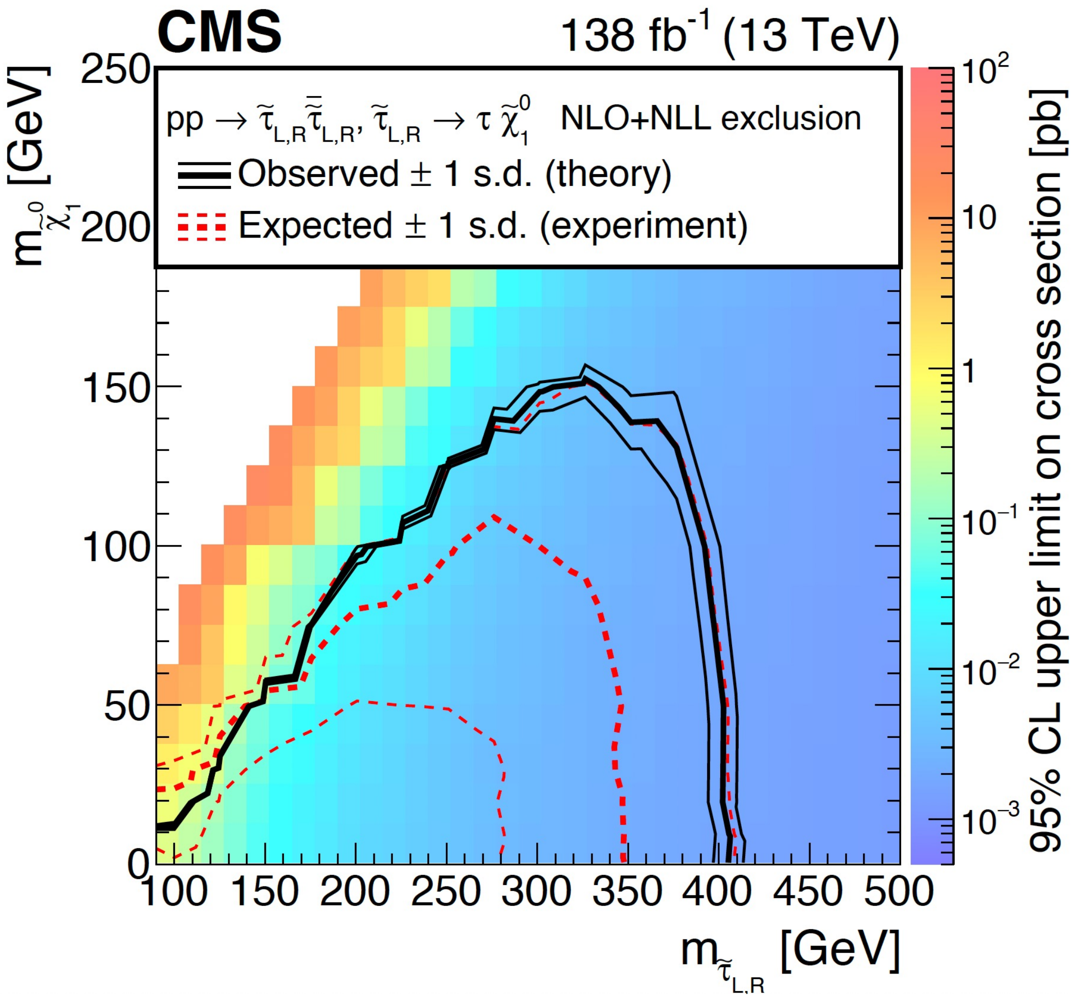
$$h_i^\alpha \simeq \begin{pmatrix} 1.3e^{-0.16\pi i} & 0.0028e^{-0.90\pi i} & 0.011e^{-0.042\pi i} \\ 0.51e^{-0.36\pi i} & 0.039e^{-0.0055\pi i} & 0.0039e^{-0.35\pi i} \\ 1.4e^{-0.45\pi i} & 0.015e^{-9.8\pi i} & 0.0076e^{-0.58\pi i} \end{pmatrix}$$

LFV constraint

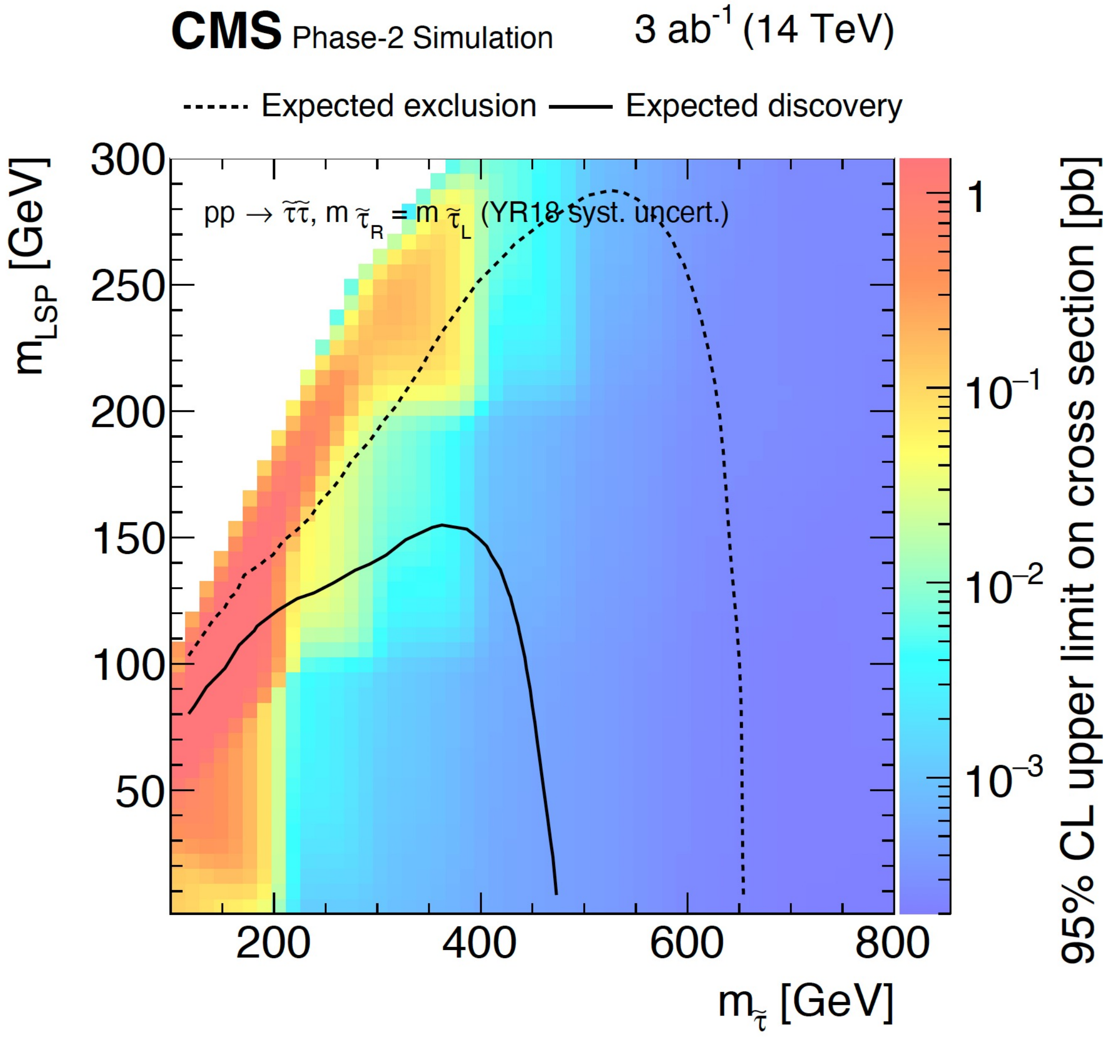




Stau search

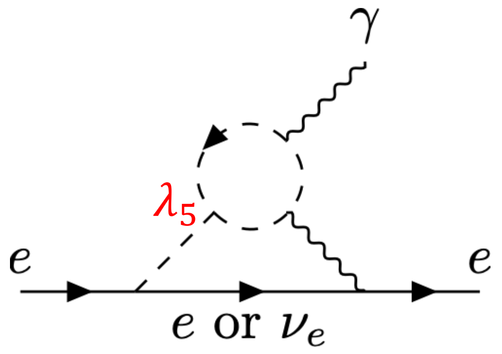


CMS (2022)

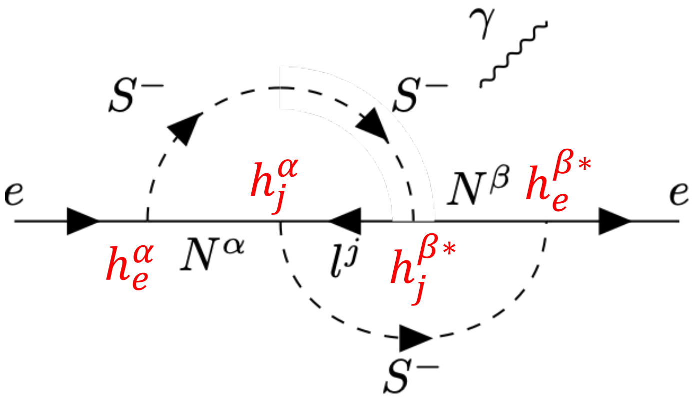


CMS (2019)

Electric dipole moment in our model



+



$< 4.1\times10^{-30}e\mathrm{cm}$

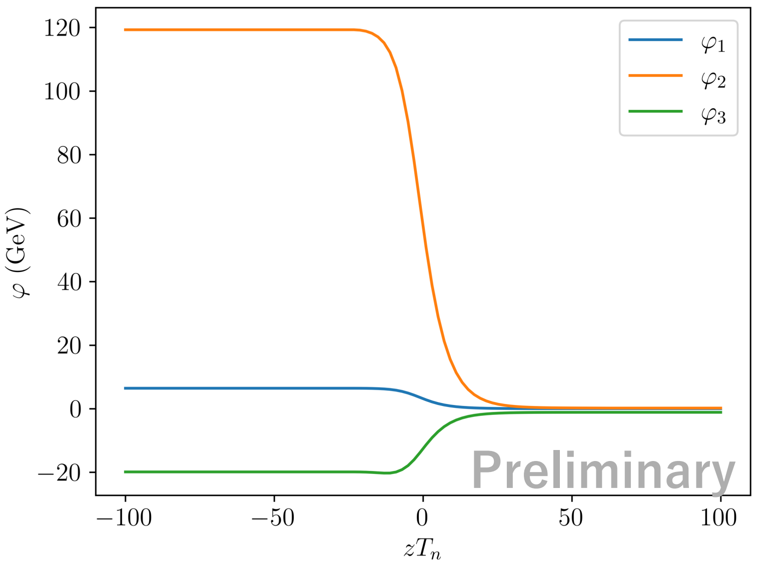
Contribution in 2HDM
(Barr-Zee contribution)

Additional contribution in CPV AKS model

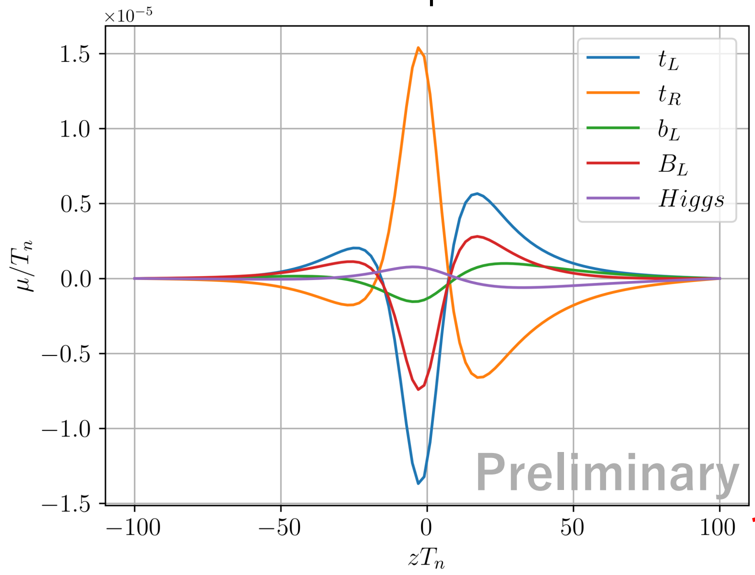
$-1.1232\times10^{-29}e\mathrm{cm} \quad + \quad 1.1314\times10^{-29}e\mathrm{cm} \quad = \quad \mathbf{8.3\times10^{-31}e\mathrm{cm}}$

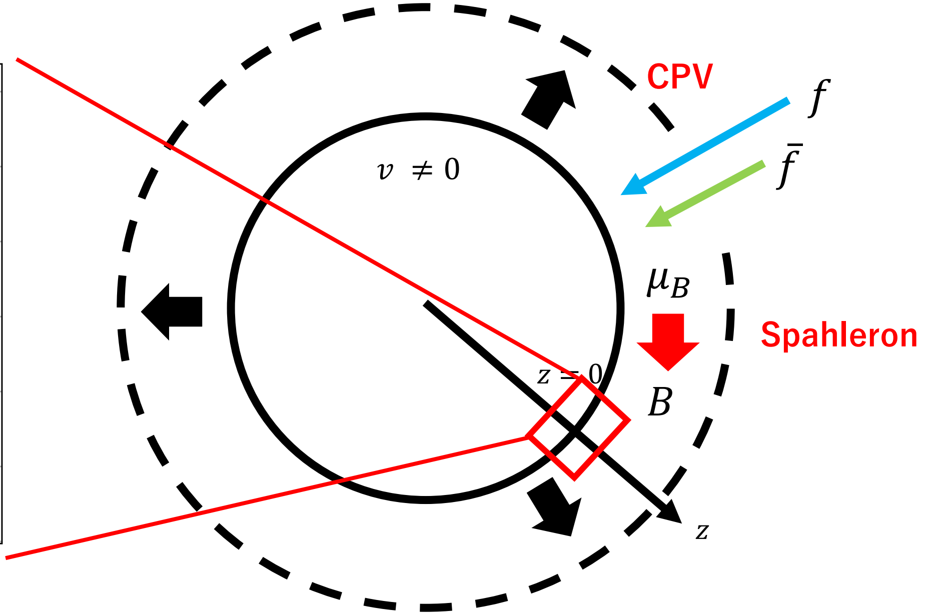
Baryon asymmetry

Bubble profile



Chemical potential





Top transport scenario with WKB approx.

CosmoTransition

Wainwright (2011)

Cline, Joyce, Kainulainen (2000)
Fromme, Huber (2006)
Cline, Kainulainen (2020)

$$\phi_1^{cl} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \varphi_1 \end{pmatrix}$$

$$\phi_2^{cl} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \varphi_2 + i\varphi_3 \end{pmatrix}$$

Chemical potential outside the wall convert to baryon asymmetry by Sphaleron

$m_{H^1} \simeq 125$ GeV, $m_{H^2} \simeq 207$ GeV,
$m_{H^3} = m_{H^\pm} \simeq 373$ GeV
$M \simeq 210$ GeV, $m_S = 325$ GeV,
$\mu_S = 20$ GeV, $\theta_5 \simeq -0.090\pi$

Observed : $\eta_B = \frac{n_B}{n_\gamma} = (6.04 - 6.20)\times 10^{-10}$ From CMB Planck (2018)

$$\eta_B \simeq 6.07\times 10^{-10}$$

M. Aoki, K. Enomoto, S.Kanemura, ST (2025)

Details of Benchmark scenario

$$R_h = \begin{pmatrix} 0.999898 & 0.00774 & 0.0120 \\ -0.00598 & 0.990 & -0.141 \\ 0.0130 & -0.141 & 0.98995 \end{pmatrix}$$

$$R_h^T M_h^2 R_h = \begin{pmatrix} 125 & 0 & 0 \\ 0 & 207 & 0 \\ 0 & 0 & 373 \end{pmatrix}^2$$

$$\lambda_1 \simeq 3.47$$
$$\lambda_2 \simeq 0.259$$
$$\lambda_3 \simeq 3.34$$
$$\lambda_4 \simeq -1.56$$
$$\lambda_5 \simeq -1.53 + 0.32i$$
$$S \simeq -0.012$$
$$T \simeq 0$$
$$U \simeq -2.05 \times 10^{-5}$$