Collider phenomenology of the TeV-scale model with a common origin of ν mass, dark matter and baryon asymmetry

Kazuki Enomoto
(KAIST in Korea) NTU in Taiwan from August

- Mayumi Aoki[1], KE, Shinya Kanemura[2], PRD 107 (2023) 11, 115022
- KE, Shinya Kanemura[2], Sora Taniguchi[2], arXiv: 2403.13613
- Mayumi Aoki[1], KE, Shinya Kanemura[2], Sora Taniguchi[2], work in progress

1 Kanazawa University, 2. Osaka University

Problems in the SM and the extended Higgs sector

- The standard model (SM) cannot explain some phenomena.

  e.g.) **tiny ν mass**, **dark matter (DM)**, **baryon asymmetry** of the universe (BAU), etc.

- The entire structure of the Higgs sector has not been revealed.

Extended Higgs sectors as the origin of the unexplained phenomena

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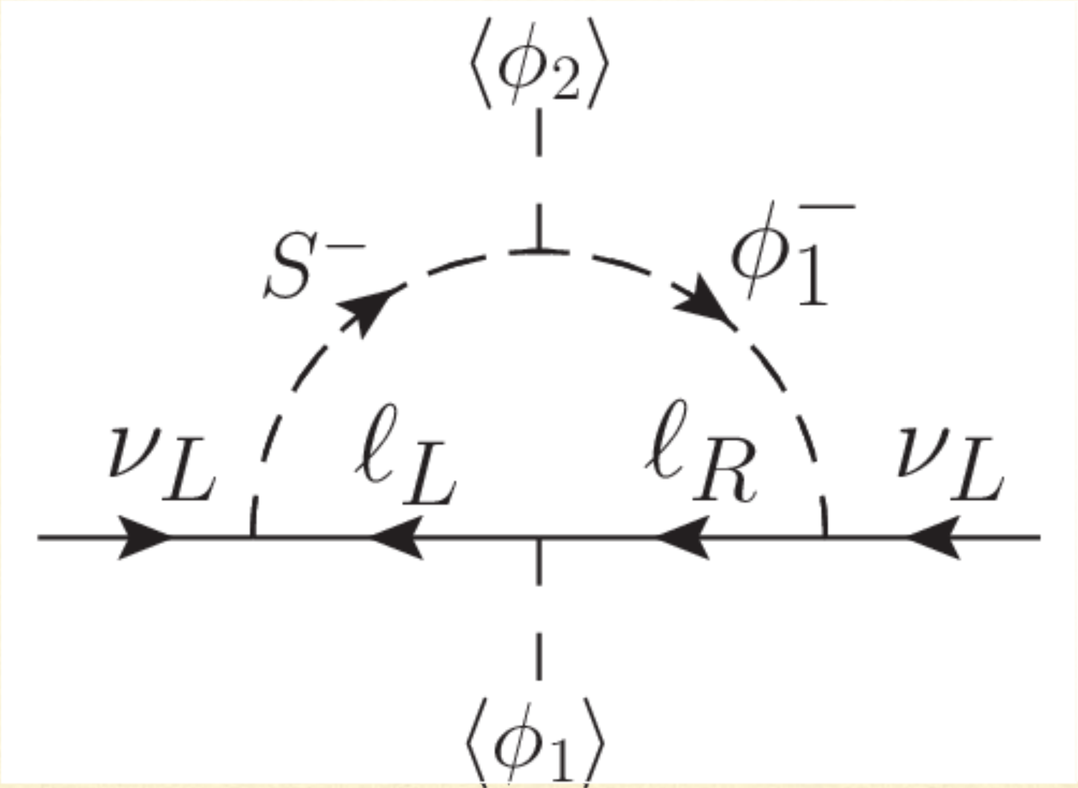
Extended Higgs sectors as the origin of the unexplained phenomena

Example) **Radiative seesaw models** (loop-level ν mass generation)

Loop suppressions can make new physics scale $\mathcal{O}(1)$ TeV **Testable scenario!!**

Zee, PLB (1980)



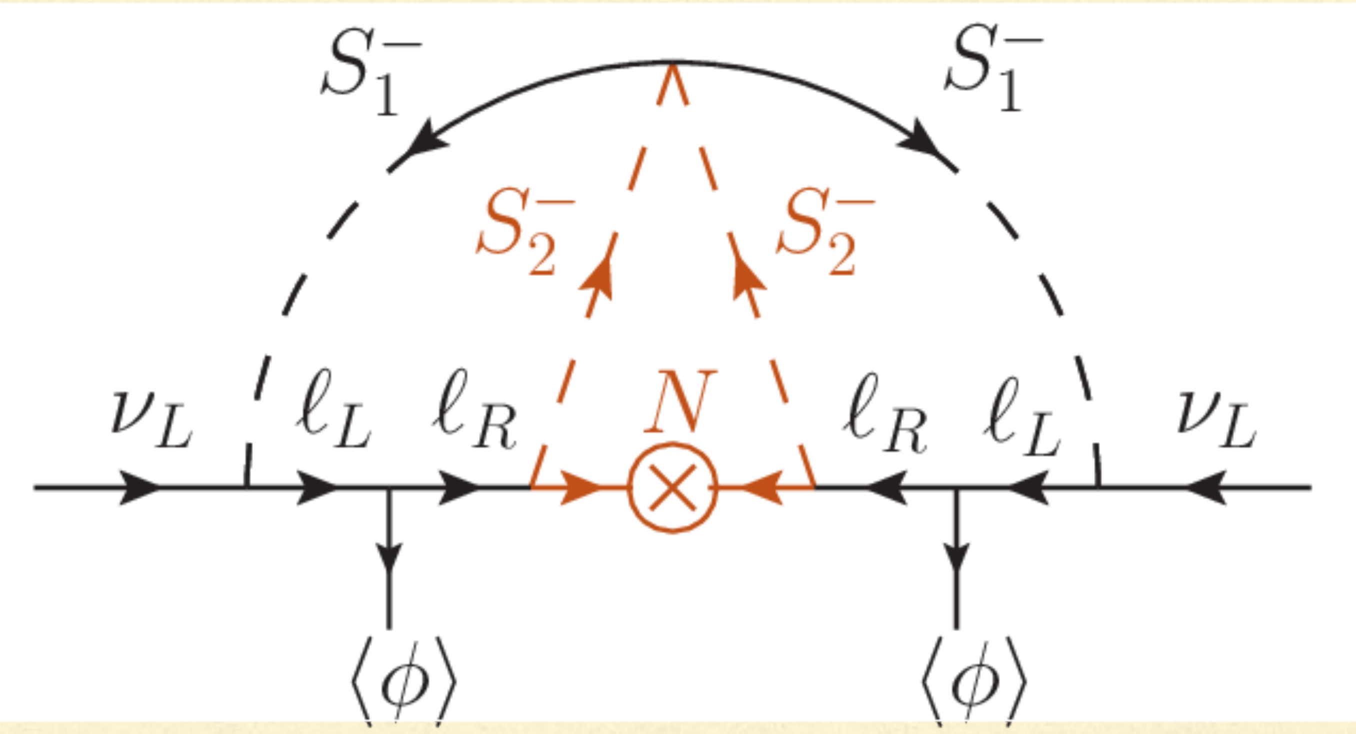
Two Higgs doublets

$$\phi_1, \quad \phi_2$$

A charged singlet

$$S^\pm$$

Krauss, Nasri, Trodden, PRD (2003)



Z_2-odd particles

Two charged singlets

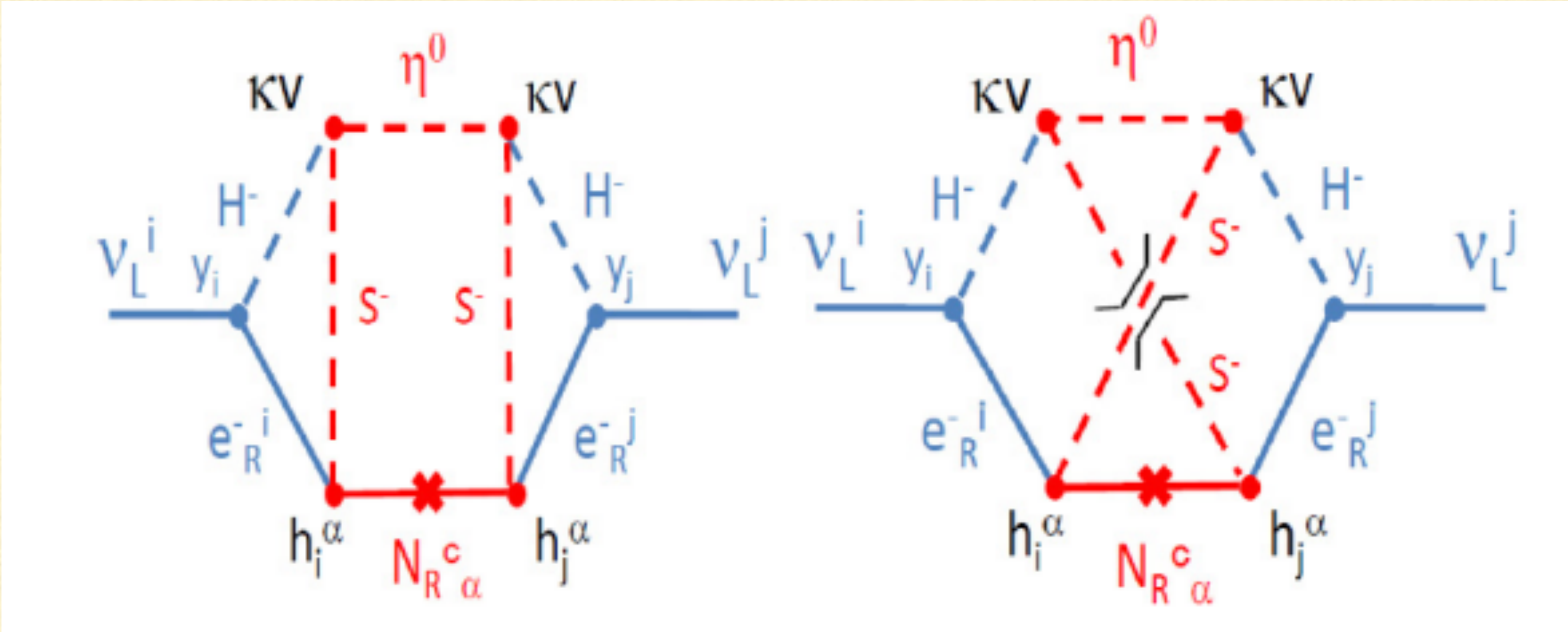
$$S_1^\pm, \ S_2^\pm$$

Right-handed neutrinos

N **dark matter!**

TeV-scale model for ν mass, dark matter, and the BAU

- **AKS model**; a radiative seesaw model that simultaneously explains DM and BAU
  Aoki, Kanemura, Seto, PRL (2009)



  - Neutrino mass is generated at **the three-loop level**.
  - **New exact Z_2 symmetry** is imposed.
  - A real singlet scalar or a Majorana fermion is **DM**.
  - The extended Higgs sector includes **CP-violating (CPV) phases**.
  - Electroweak phase transition (EWPT) can be **strongly first-order** due to **the non-decoupling effect** of the additional scalar bosons.
  - The BAU is expected to be produced by **electroweak baryogenesis (EWBG)**

In the original paper, CPV phases were neglected, and the BAU had not been evaluated.

We extended the original model with CPV and have evaluated the BAU.

Aoki, KE, Kanemura, PRD (2023)

New particles in the model

Dark sector (Z_2-odd)

Extended Higgs sector

Two Higgs doublets

$$\phi_1, \quad \phi_2$$

Charged singlet

$$S^{\pm}$$

Real singlet

$$\eta$$

Right-handed neutrinos

$$N_R^i$$

$$i = 1,2,3$$

Physical scalars in the Higgs doublets,

$$H^{\pm}, H_1, H_2, H_3$$

H_1 is the 125GeV Higgs boson

(Other degrees of freedom are NG modes)

New particles in the model

(Z_2-even) $H^{\pm},\ H_2,\ H_3$

(Z_2-odd) $S^{\pm},\ \eta,\ N^i$

$(N^i = N_R^i + N_R^{ic})$

The Higgs alignment and CPV phases in the Higgs potential

- **Masses of neutral Higgs bosons**

The doublets in the Higgs basis Davidson, Haber PRD (2005)

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}G^+ \\ v + h_1 + iG^0 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}H^+ \\ h_2 + ih_3 \end{pmatrix}$$

The mass mixing is generated by

$$V \ni \frac{\lambda_5}{2}(\phi_1^\dagger \phi_2)^2 + \lambda_6 |\phi_1|^2 (\phi_1^\dagger \phi_2) + \mathrm{h.c.}$$

$$M_{\text{neutral}} \propto \begin{array}{c} \begin{array}{ccc} h_1 & h_2 & h_3 \end{array} \\ \begin{pmatrix} M_{11} & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ & M_{22} & -\mathrm{Im}[\lambda_5]/2 \\ & & M_{33} \end{pmatrix} \end{array} \begin{array}{c} h_1 \\ h_2 \\ h_3 \end{array}$$

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In the limit

$$\lambda_6 \to 0 \quad \Rightarrow$$

Mixings vanish [Higgs alignment].

$h_i = H_i$ are mass eigenstates ($i = 1,2,3$)

Kanemura, Kubota, Yagyu (2020); KE, Kanemura, Mura (2022);

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rephasing ϕ_2

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rephasing $S^{\pm}$

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rephasing $S^\pm$

Even in the Higgs alignment,
we still have **3 CPV phases** in the potential,
which is necessary for EWBG.

The flavor alignment in the Yukawa interactions

- Generally, both ϕ_1 and ϕ_2 has Yukawa interactions with the SM fermions.

$$\mathscr{L}_Y = \underbrace{-\frac{m_{f^i}}{v}\overline{f^i_L}\, f^i_R H_1}_{\text{SM Yukawa}} + \underbrace{(y_2^f)_{ij}\overline{f^i_L}\, f^j_R (H_2 + iH_3)}_{\text{Non-diagonal interaction } y_2^f} + \mathrm{h.c.} \qquad (i,j=1,2,3)$$

$\Rightarrow$ *FCNC!*

(FCNC = Flavor Changing Neutral Current)

- To avoid FCNC,
  - In the original AKS model, the softly broken Z_2 is imposed. Glashow, Weinberg, PRD (1977)
  - In the current model, we assume **the flavor alignment**

$$y_2^f = \underbrace{\frac{1}{v}\begin{pmatrix} m_{f^1} & 0 & 0 \\ 0 & m_{f^2} & 0 \\ 0 & 0 & m_{f^3} \end{pmatrix}}_{\text{SM Yukawa}} \begin{pmatrix} \zeta_{f^1} & 0 & 0 \\ 0 & \zeta_{f^2} & 0 \\ 0 & 0 & \zeta_{f^3} \end{pmatrix} \qquad \zeta_f^i \in \mathbb{C}$$

For quarks,

$$\zeta_{u^1} = \zeta_{u^2} = \zeta_{u^3} \equiv \zeta_u, \quad \zeta_{d^1} = \zeta_{d^2} = \zeta_{d^3} \equiv \zeta_d$$

Pich, Tuzon, PRD (2009)

5 CPV phases

$$\arg[\zeta_u],\ \arg[\zeta_d],\ \arg[\zeta_e],\ \arg[\zeta_\mu],\ \arg[\zeta_\tau]$$

Summary of the model and a benchmark scenario

Important points of the model

New particles: (Z_2-even) $H^\pm$, H_2, H_3 (Z_2-odd) $S^\pm$, η, N^i

Alignment: $\lambda_6 = 0$ & $(y_2^f)_{ij} \propto m_{f^i} \zeta_{f^i} \delta_{ij}$

(H_1 is the SM Higgs) (No FCNC)

CP-violation: $\lambda_7,\ \rho_{12},\ \sigma_{12}$ & $\zeta_u,\ \zeta_d,\ \zeta_e,\ \zeta_\mu,\ \zeta_\tau$

Mass of new particles in the benchmark scenario

Z_2 even: $m_{H^+} = 250$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

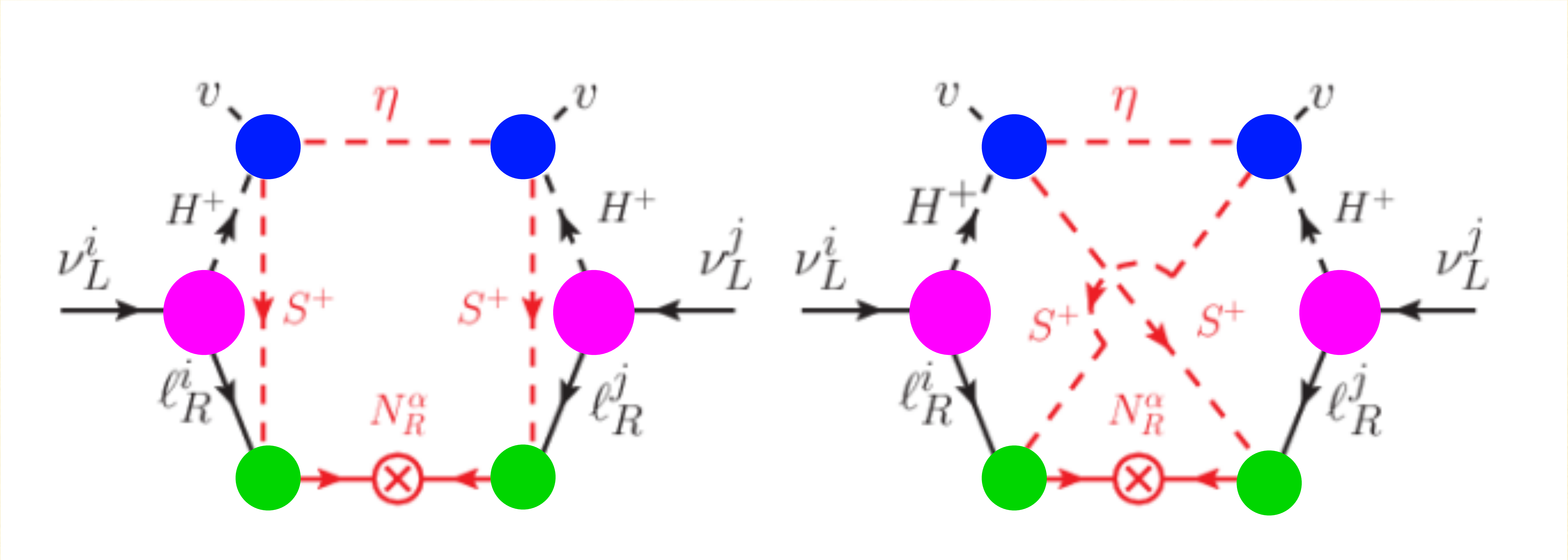
Z_2 odd: $m_S = 400$ GeV, $m_\eta = 63$ GeV

$(m_{N_1},\ m_{N_2},\ m_{N_3}) = (3000,\ 3500,\ 4000)$ GeV

We have checked the benchmark scenario can avoid all of the current experimental and theoretical constraints.

In this talk, we discuss only BSM phenomena and the constraints of LFV and EDMs

Neutrino mass in the model



$$\kappa\, \tilde{\phi}_1 \phi_2 S^- \eta \qquad h_i^\alpha\, \overline{(N_R^\alpha)^c}\, \ell_{iR} S^+ \qquad \zeta_{\ell^i} y_{\ell^i}\, \overline{\ell_R^i} \nu_L^i H^-$$

$$\left(y_e|\zeta_e|,\, y_\mu|\zeta_\mu|,\, y_\tau|\zeta_\tau|\right) = \left(0.25, 0.25, 2.5\right) \times 10^{-3}$$

$$\theta_{\ell^i} = -2.94 \qquad h_i^\alpha \simeq \begin{pmatrix} 1.0\, e^{-0.31i} & 0.2\, e^{0.30i} & 1.0\, e^{-2.4i} \\ 1.1\, e^{-1.9i} & 0.21\, e^{-1.8i} & 1.1\, e^{2.3i} \\ 0.45\, e^{2.7i} & 1.3\, e^{-0.033i} & 0.10\, e^{0.63i} \end{pmatrix}$$

$$\kappa = 2.0$$

$\Rightarrow$

Normal ordering m_ν w/ $m_{\nu^1} \simeq 0.006$ eV

$$\delta \simeq 1.36\pi, \quad \alpha_1 \simeq 0, \quad \alpha_2 \simeq -\pi/2$$

$$m_{\beta\beta} \simeq 1 \text{ meV}, \quad \Sigma m_{\nu^i} = 0.067 \text{ eV}$$

$m_{\beta\beta} < 35$ meV $\qquad \Sigma m_{\nu^i} < 0.12$ eV

KamLAND-Zen (2023) Planck (2018)

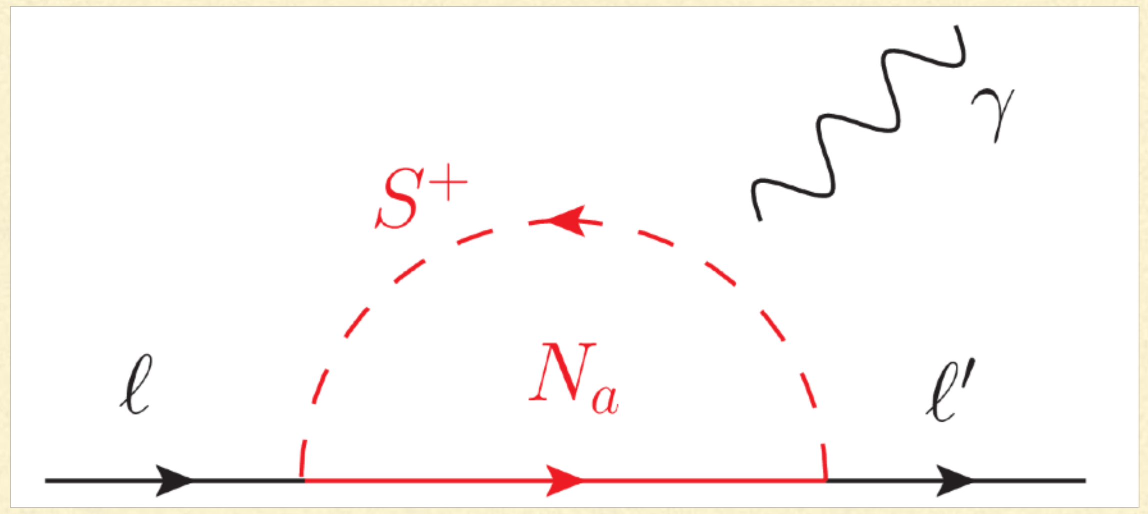
Constraint on the lepton flavor violation

LFV couplings $h_i^\alpha\,\overline{(N_R^\alpha)^c}\,\ell_{iR}\,S^+$

$$m_S = 400\ \text{GeV},\qquad M_N = \{3000,\ 3500,\ 4000\}\ \text{GeV}$$

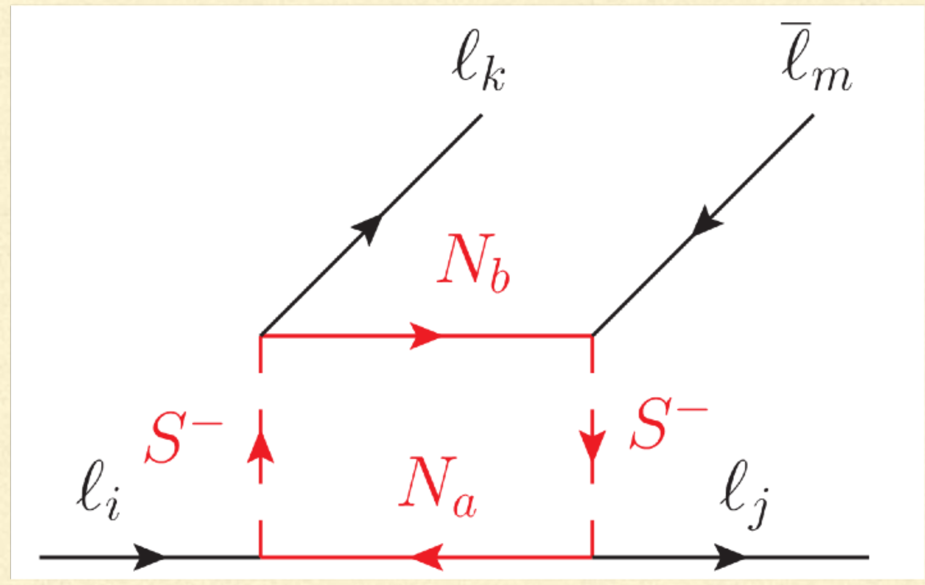
$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

■$\ell \to \ell'\gamma$



Processes	BR	Upper limits
$\mu \to e\gamma$	1.4×10^{-14}	4.2×10^{-13}
$\tau \to e\gamma$	5.3×10^{-10}	3.3×10^{-8}
$\tau \to \mu\gamma$	1.1×10^{-11}	4.4×10^{-8}

■$\ell_i \to \ell_j \ell_k \overline{\ell}_m$



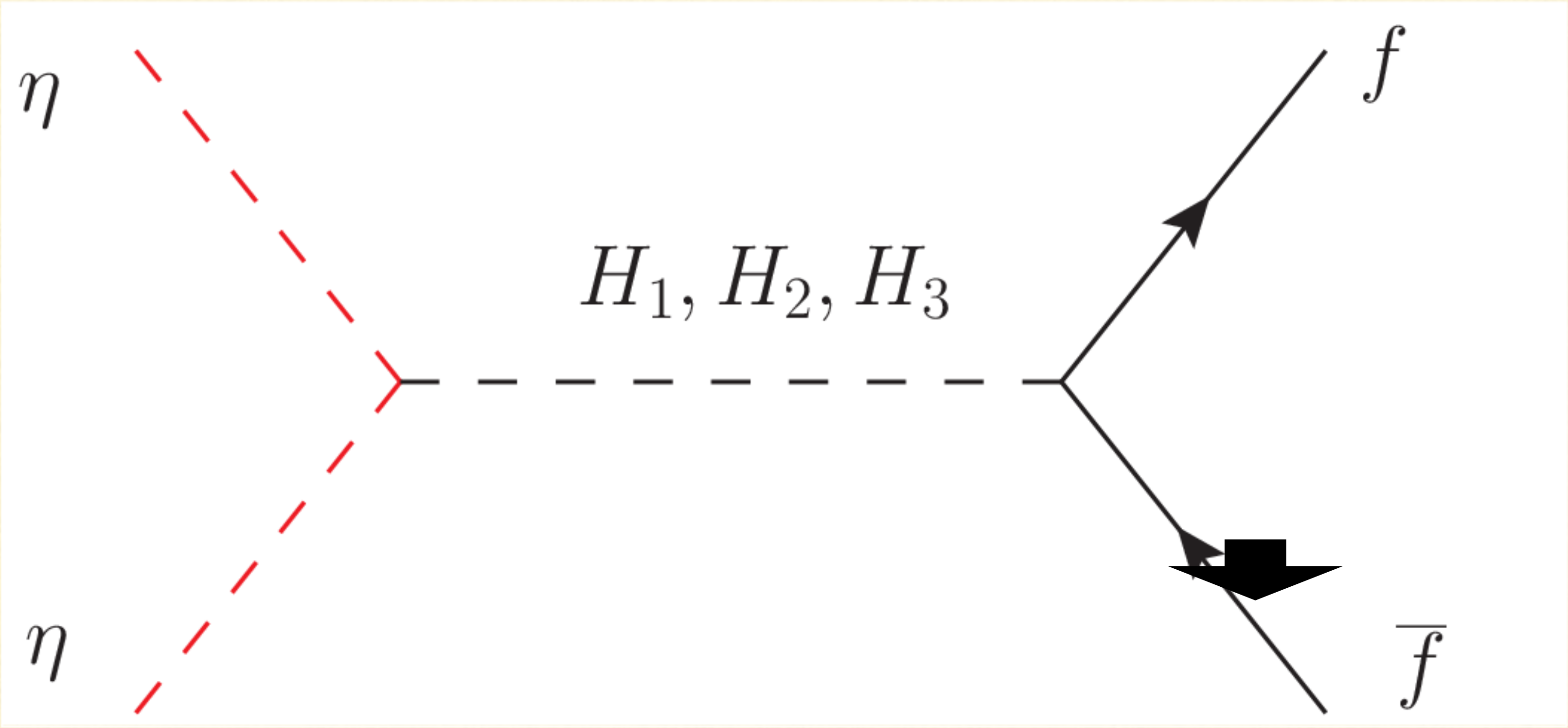
Processes	BR	Upper limits
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	6.2×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	2.4×10^{-11}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1.5×10^{-8}
$\tau \to e\mu\bar{\mu}$	9.6×10^{-11}	2.7×10^{-8}

Dark matter in the model and its constraint

Heavy N^i are necessary to avoid the constraint of the LFV processes

The real singlet scalar η is the DM particle

Dominant annihilation channel



We have also considered

$$\eta\eta \to ZZ, \quad W^+W^-, \quad \gamma\gamma$$

$$m_\eta = 63\ \mathrm{GeV},\ m_{H_2} = 420\ \mathrm{GeV},\ m_{H_3} = 250\ \mathrm{GeV}$$

$$\sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \quad \theta_\rho = -2.94$$

$$\Rightarrow$$

$$\Omega_\eta h^2 \simeq 0.12, \quad \sigma_{\mathrm{SI}} = 2.3 \times 10^{-48}\ \mathrm{cm}^2$$

$\Omega_{\mathrm{DM}} h^2 = 0.120(01)$ Planck (2018)

$\sigma_{\mathrm{SI}} \lesssim 10^{-47}$ LZ (2022)

η is the Higgs portal DM

Baryogenesis in the model

- Strongly 1st-order EWPT can occur by **the non-decoupling effect** of the new scalars

$$m_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2, \quad m_{H_{2,3}}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)v^2, \quad m_S^2 = \mu_S^2 + \frac{1}{2}\rho_1 v^2$$

$$m_{H^+} = 250 \text{ GeV}, \quad m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = 250 \text{ GeV}, \quad m_S = 400 \text{ GeV}$$
$$\lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \rho_1 \simeq 1.90$$

We have evaluated one-loop effective potential in Landau gauge

$$\Delta R \equiv \lambda_{hhh}/\lambda_{hhh}^{SM} - 1 = 38\ \%$$

$$v_n/T_n = 1.74 > 1$$

v_n: VEV at $T = T_n$
T_n: nucleation temperature

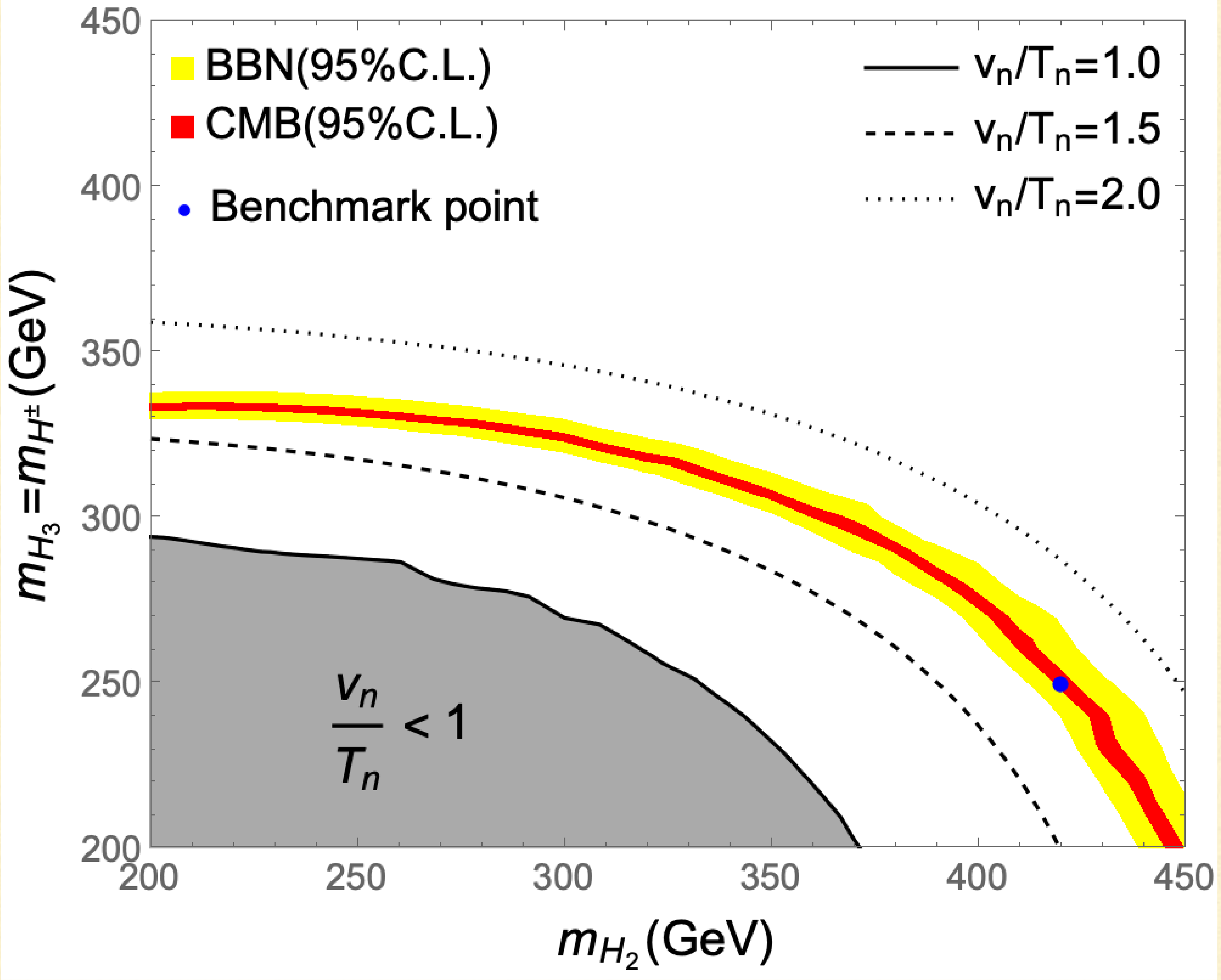
- We have evaluated the BAU generated by **the top transport scenario** with **the WKB app.** (the wall velocity $v_\mathrm{w} = 0.1$) Cline, Joyce, Kainulainen (2000) Fromme, Huber (2007) Cline, Kainulainen (2020)

$$\theta_7 = -2.34, \quad \theta_u = 0.245, \quad \theta_e = -2.94$$

For successful EWBG,

$$m_{H_2}, m_{H_3}, m_{H^\pm} \simeq 200 \text{ GeV-}400 \text{ GeV}$$

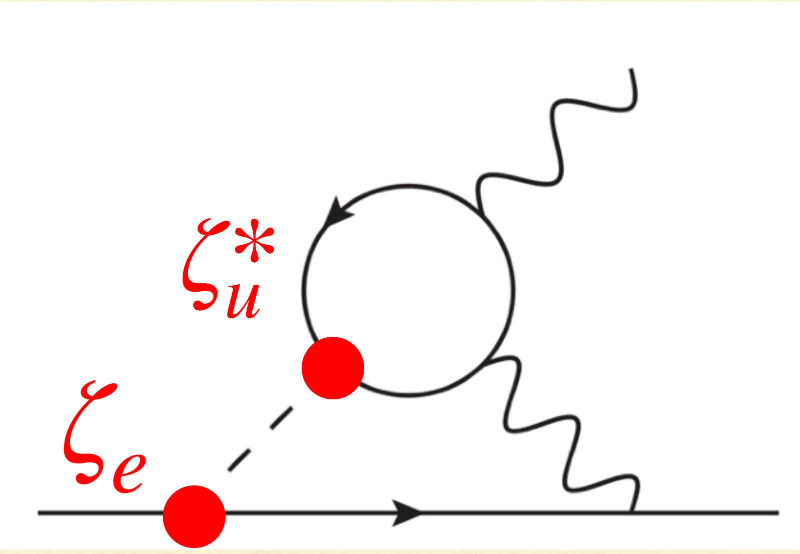
is favored.



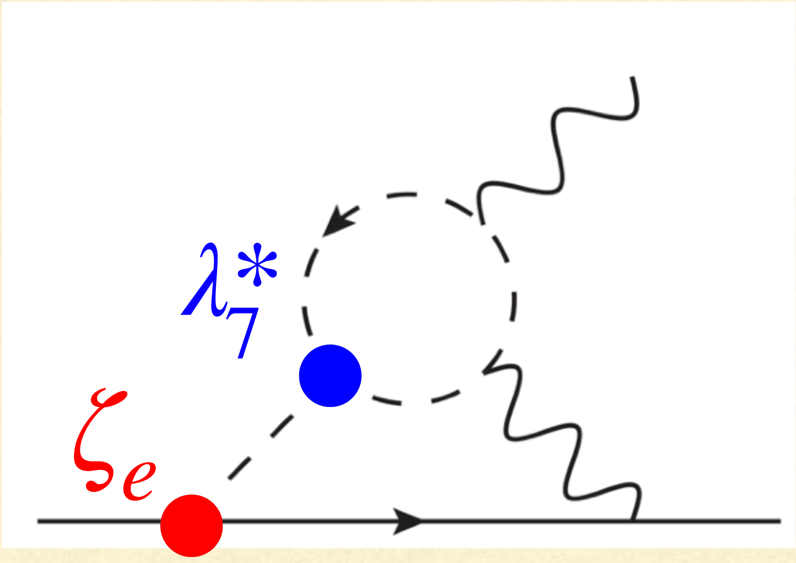
Constraints on the CPV phase in the model: EDMs

electron EDM (eEDM) $|d_e| < 4.0 \times 10^{-30}$ e cm Roussy, et al (2022)

eEDM can be small by **destructive interference** Kanemura, Kubota, Yagyu (2020)



$+$



$\propto \sin(\theta_u - \theta_e)$ $\propto \sin(\theta_7 - \theta_e)$

$$m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = m_{H^\pm} = 250 \text{ GeV}$$
$$\theta_7 = -2.34, \quad \theta_u = 0.245, \quad \theta_e = -2.94$$

$\rightarrow$ $|d_e| = 0.22 \times 10^{-30}$ e cm

neutron EDM (nEDM) $|d_n| < 1.8 \times 10^{-26}$ e cm

chromo EDM Barr, Zee (1990)

Weinberg ope. Weinberg (1989)

4 fermi interaction Khatsimovsky, Khriplovich, Yelkhovsky (1988)

In the BS, $|d_n| \sim 10^{-30}$ e cm

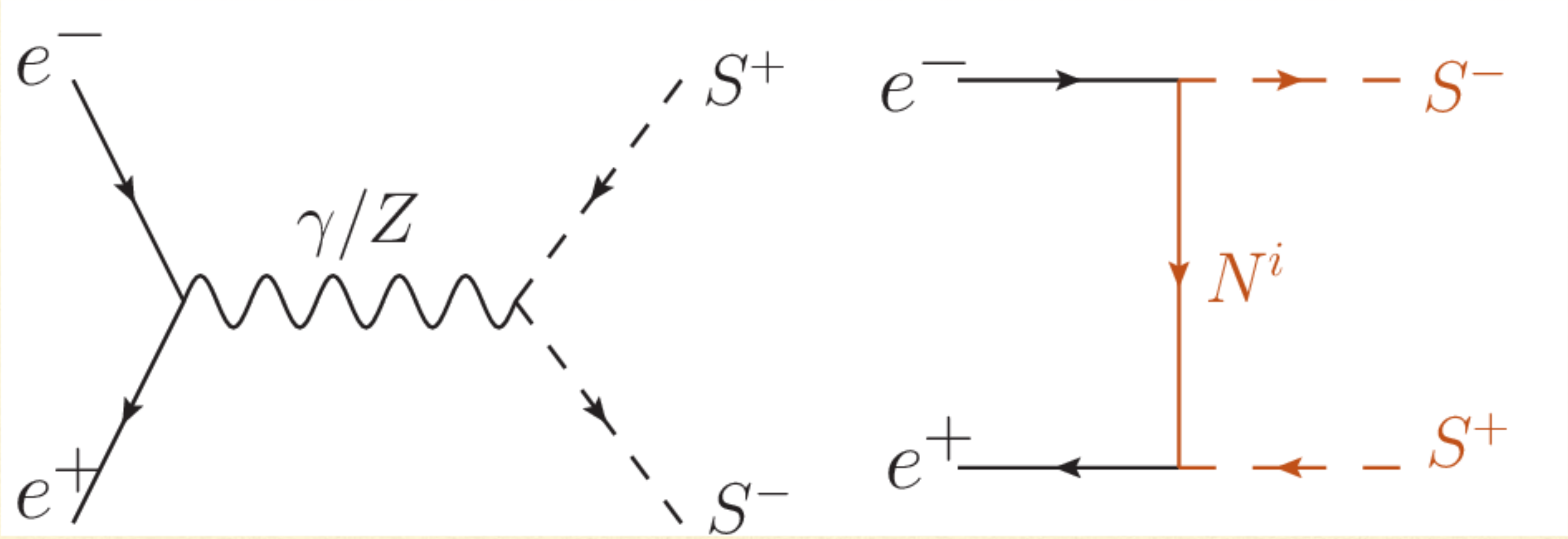
Phenomenology at e^+e^- colliders

- **Pair production of $S^\pm$**

$S^\pm$ cannot be too light (LFV constraint) and too heavy (ν mass)

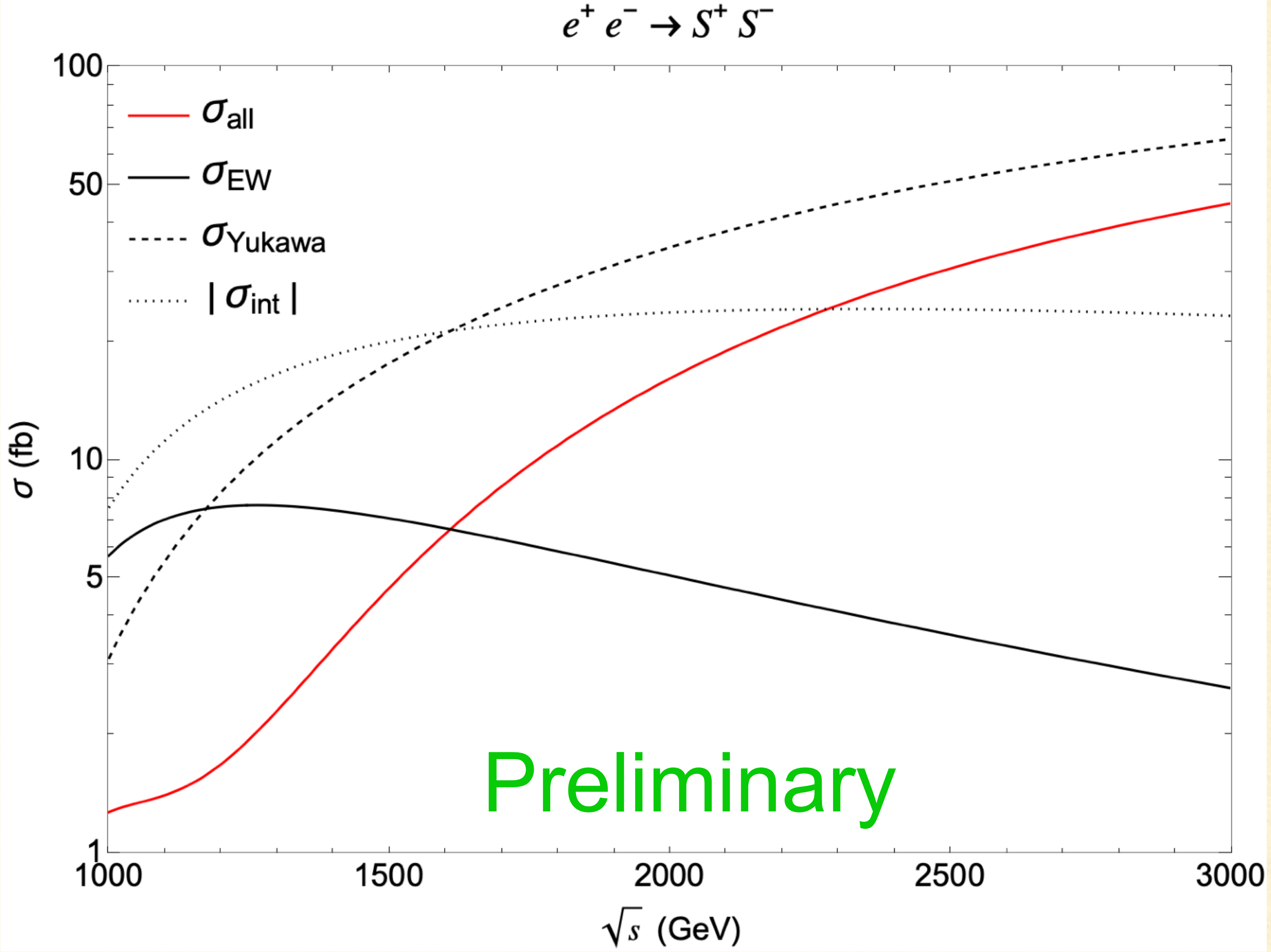
$m_S \simeq 400$ GeV is favored in the model. $e^+e^- \to S^+S^-$ **is allowed with $\sqrt{s} \gtrsim 800$ GeV**

- **Cross section**



$\mathcal{O}(1)$ fb is expected with $\sqrt{s} = 1\text{-}2$ TeV

$\mathcal{O}(10)$ fb is expected with $\sqrt{s} = 2\text{-}3$ TeV



Signal from S^+S^-

- **3-body interactions for $S^\pm$** $\quad h_i^\alpha \overline{N_R^{ic}} \ell_{iR} S^+$ and $\kappa v S^+ H^- \eta$

  $m_N \simeq \mathcal{O}(1)$ TeV is favored to avoid the LFV constraints

  $m_{H^\pm} \simeq 200\text{-}400$ GeV is favored for EWBG

  $\Rightarrow \quad \mathrm{Br}(S^\pm \to H^\pm \eta) \simeq 100\ \%$

- **Decay of $H^\pm$**

  In the benchmark scenario, $\mathrm{Br}(H^\pm \to tb) \simeq 100\ \%$ $\quad$ (For $H^\pm \to \tau\nu,\ cs$, $\mathrm{Br} < 10^{-3}$)

The signal) $S^+S^- \to H^+H^-\cancel{E} \to 2t2b\cancel{E}$

- **SM background**

$$e^+e^- \to 2t2b\nu_\ell\bar{\nu}_\ell$$

via $e^+e^- \to W^+W^-Z, \quad t\bar{t}hZ, \quad \nu_e\bar{\nu}_e V^*V^*$

(VBS)

Preliminary

	$\sqrt{s} = 1$ TeV	2 TeV	3 TeV
Signal	**1.276 (fb)**	**16.22 (fb)**	**45.28 (fb)**
BG	**0.0133 (fb)**	**0.0279 (fb)**	**0.0490 (fb)**
S/B	96	581	924

We have used MadGraph for the evaluation.

The detailed study is a future work.

Other phenomenology at e^+e^- colliders

- **Azimuthal angle distribution of $H_{2,3} \to \tau\bar{\tau}$** Kanemura, Kubota, Yagyu (2021)

$$e^+e^- \to H_2H_3(\nu\bar{\nu}), \quad H_2 \text{ or } H_3 \to \tau\bar{\tau} \to \text{hadrons} + \not{E}$$

The CPV phase in ζ_τ can be measured by observing the azimuthal angle distribution of τ Jeans, Wilson (2018)

- **Diphoton decays: $H_{1,2} \to \gamma\gamma$** Kanemura, Katayama, Mondal, Yagyu (2023)

$e^+e^- \to Z^* \to H_1H_2 \to 4\gamma$ can be sizable when the CPV phases in the Higgs potential is $\mathcal{O}(1)$

- **Non-decoupling effect of the additional sclalars**

Non-decoupling effect of the additional scalars can change the Higgs properties.

[Higgs triple coupling] Kanemura, et al (2003) Kanemura, et al (2004)

$$\boxed{\Delta R \equiv \lambda_{hhh}/\lambda_{hhh}^{SM} - 1 = 38\ \%}$$

[Higgs diphoton decay]

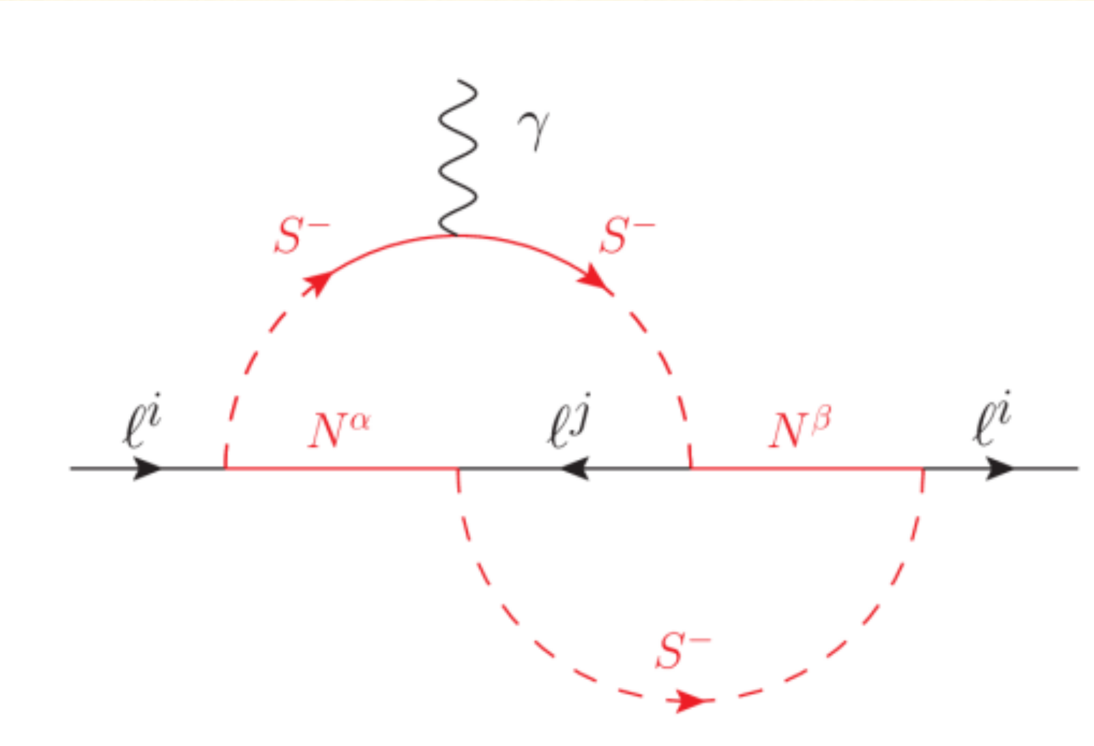
$$\boxed{\sigma \times \mathrm{Br} = 100 \pm 4\ \mathrm{fb}}$$ @ LHC

1.5σ deviation from the SM

consistent with the current LHC data

The model with softly broken Z_2 (current work)

- We removed the softly broken Z_2 in the original AKS model, instead, we assume the flavor alignment.
- We are investigating the possibility of the model with the softly broken Z_2.
- In this case, all of ζ_f are real (no CP violation), and the destructive interference in the eEDM cannot work.
- Instead, the CPV phases in h^i_ℓ induces other eEDM diagrams at 2-loop.



- We have shown that the constraint on the eEDM can be avoided by considering these diagrams.

KE, Kanemura, Taniguchi (2023)

- EWBG in the model with the softly broken Z_2 is the work in progress.

Aoki, KE, Kanemura, Taniguchi, work in progress

Summary of this presentation

- The extended Higgs sector may be the origin of phenomena beyond the SM.
- The AKS model is the TeV-scale model (testable model) which can explain tiny neutrino mass, dark matter, and the baryon asymmetry simultaneously.
- We have extended the original AKS model and have shown one benchmark scenario where all 3 problems can be explained while avoiding all the current experimental and theoretical constraints.
- Future high-energy e^+e^- colliders are powerful tools to probe this model.
- Now, we are revisiting the model with the softly broken Z_2 symmetry.

Backup Slides

The Higgs potential in the model

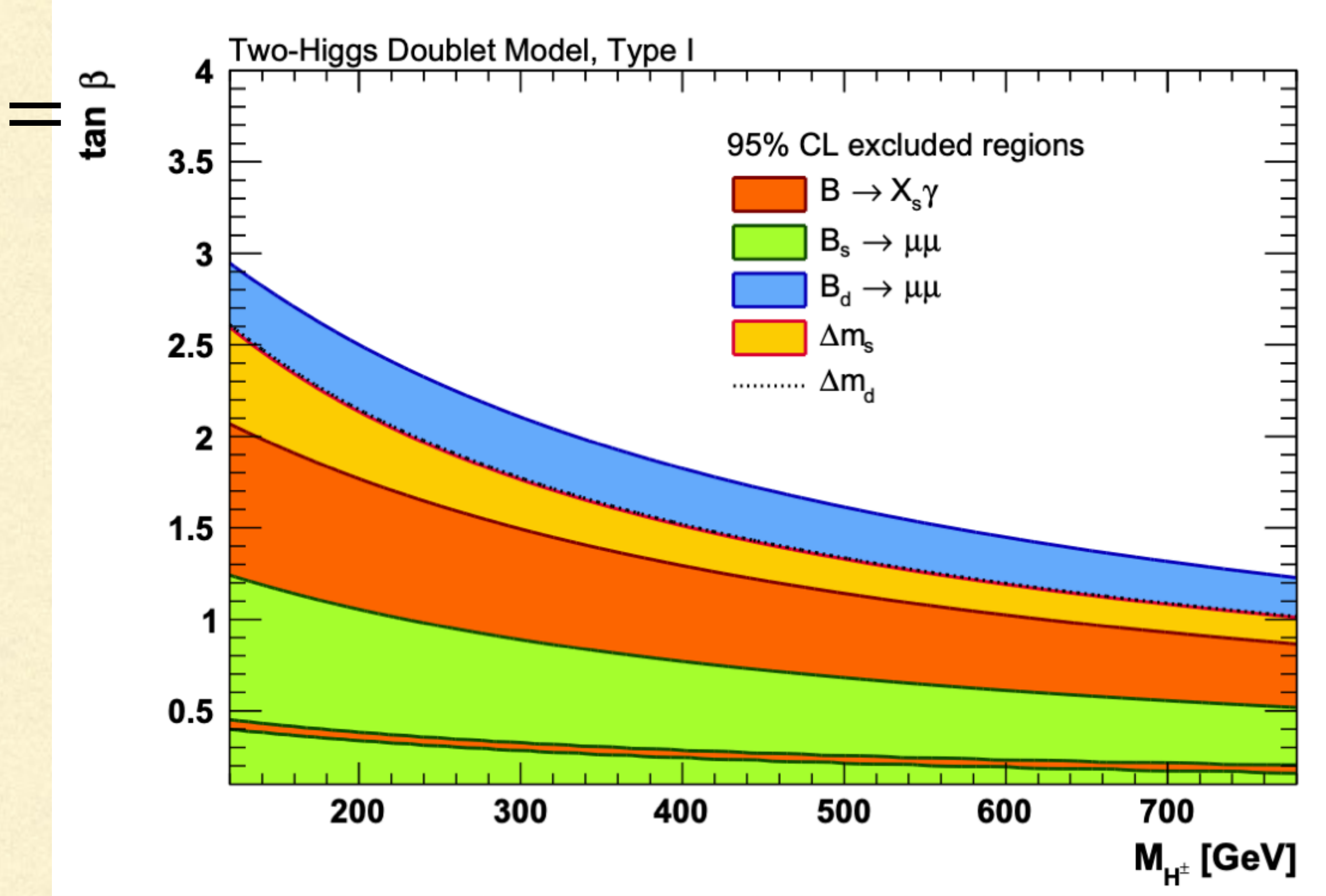
$$V = \sum_{a=1}^{2}\left(\mu_a^2|\Phi_a|^2 + \frac{\lambda_a}{2}|\Phi_a|^4\right) + (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$
$$+ \left\{\left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2) + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right\} + \mu_S^2|S^+|^2 + \frac{\mu_\eta^2}{2}\eta^2$$
$$+ \left\{\left(\rho_{12}|S^+|^2 + \frac{\sigma_{12}}{2}\eta^2\right)(\Phi_1^\dagger\Phi_2) + 2\kappa(\tilde{\Phi}_1^\dagger\Phi_2)S^-\eta + \text{h.c.}\right\}$$
$$+ \sum_{a=1}^{2}\left(\rho_a|S^+|^2 + \frac{\sigma_a}{2}\eta^2\right)|\Phi_a|^2 + \frac{\lambda_S}{4}|S^+|^4 + \frac{\lambda_\eta}{4!}\eta^4 + \frac{\xi}{2}|S^+|^2\eta^2,$$

Constraint from flavor experiments

Figures from Haller, Hoecker, Kogler, Mooing, Peiffer, Stelzer, EPJC (2018)

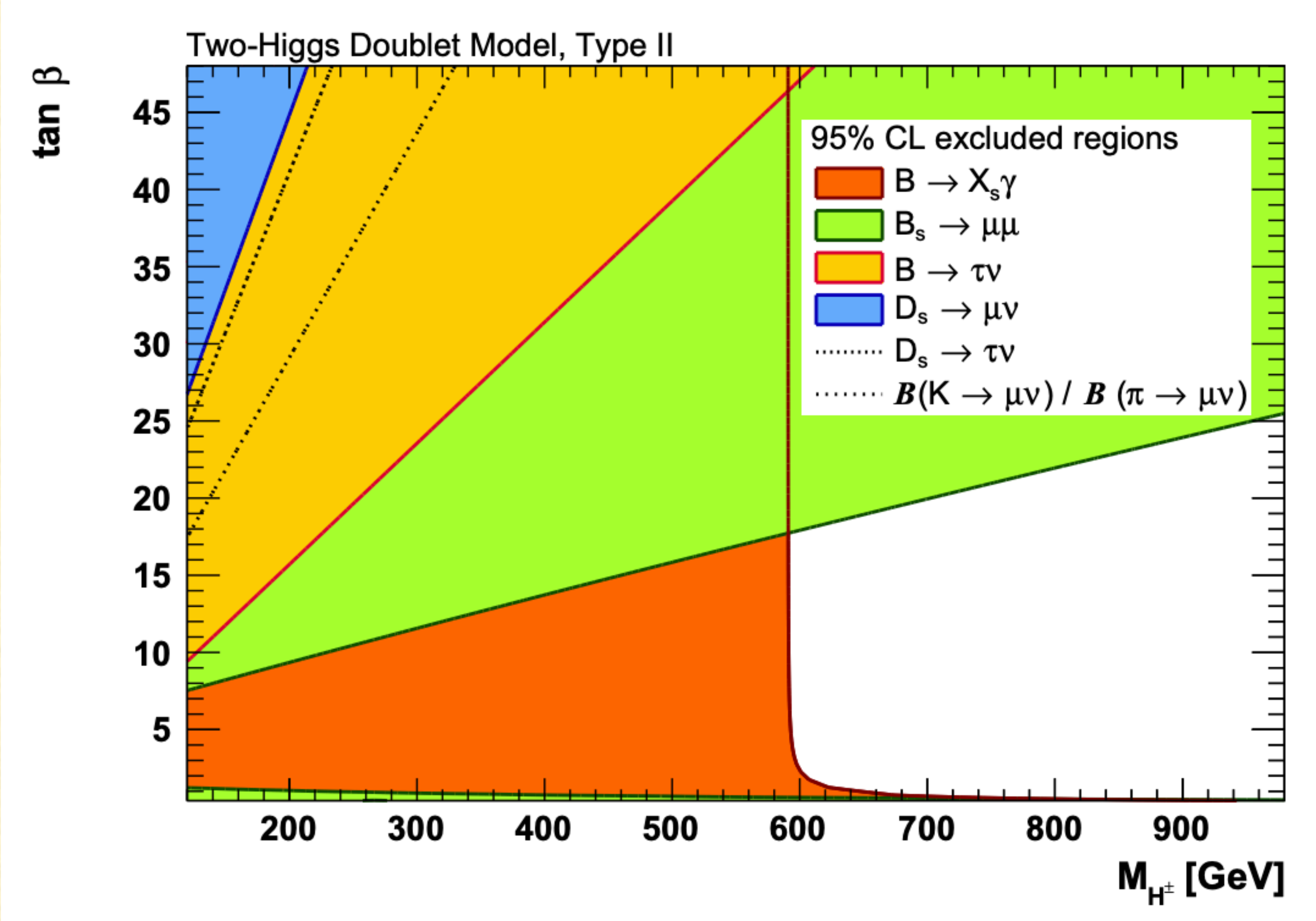
$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



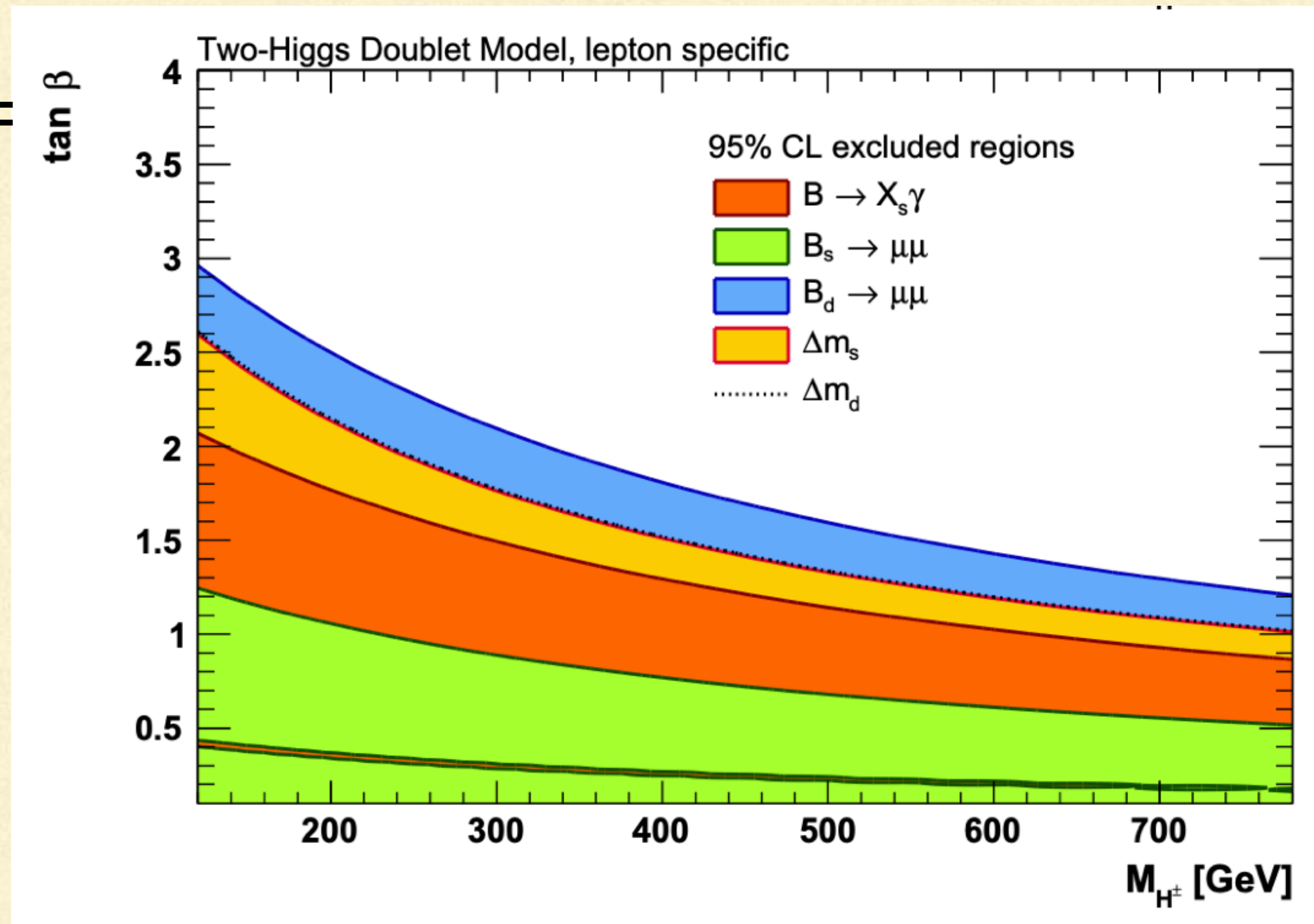
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



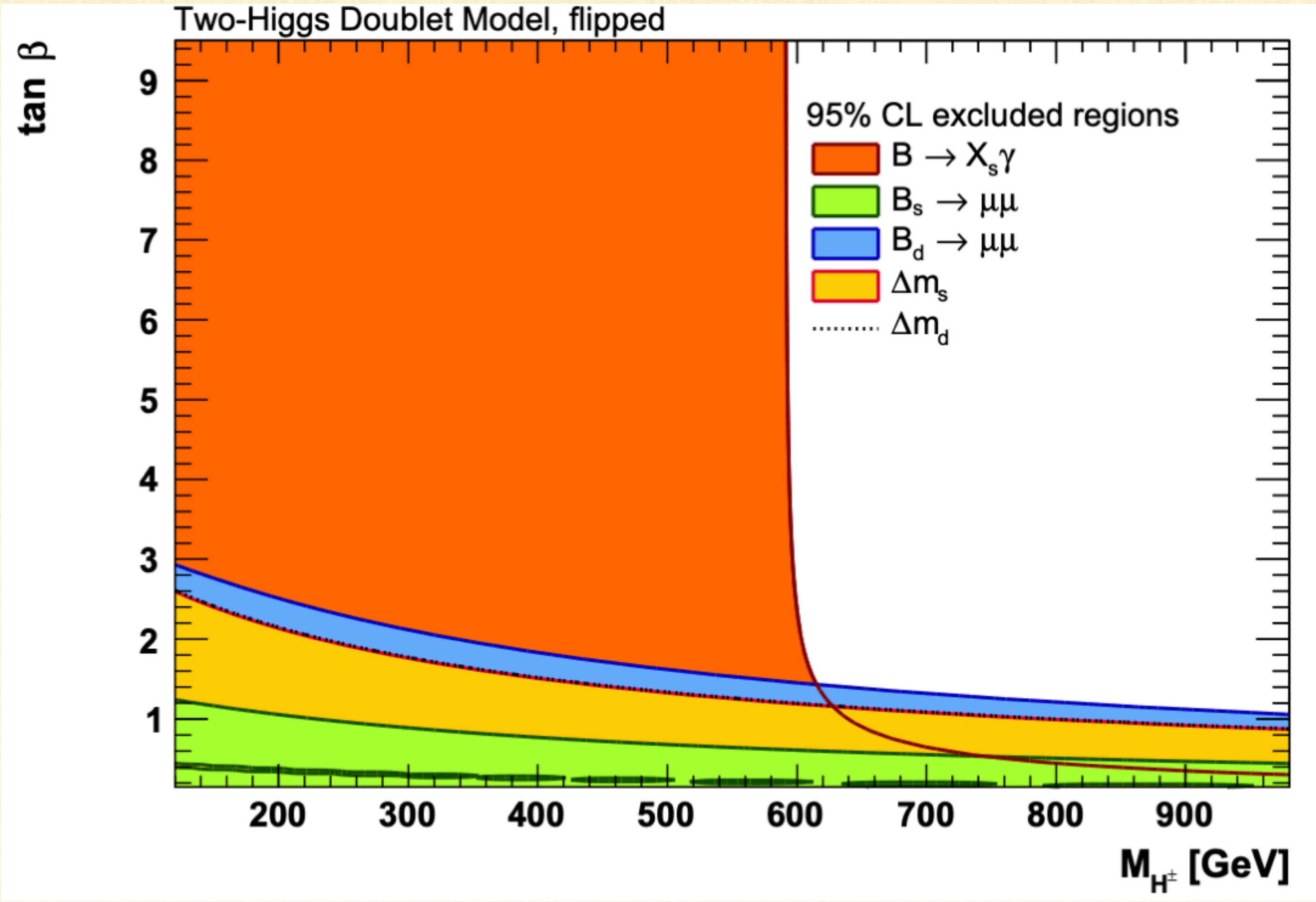
$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$

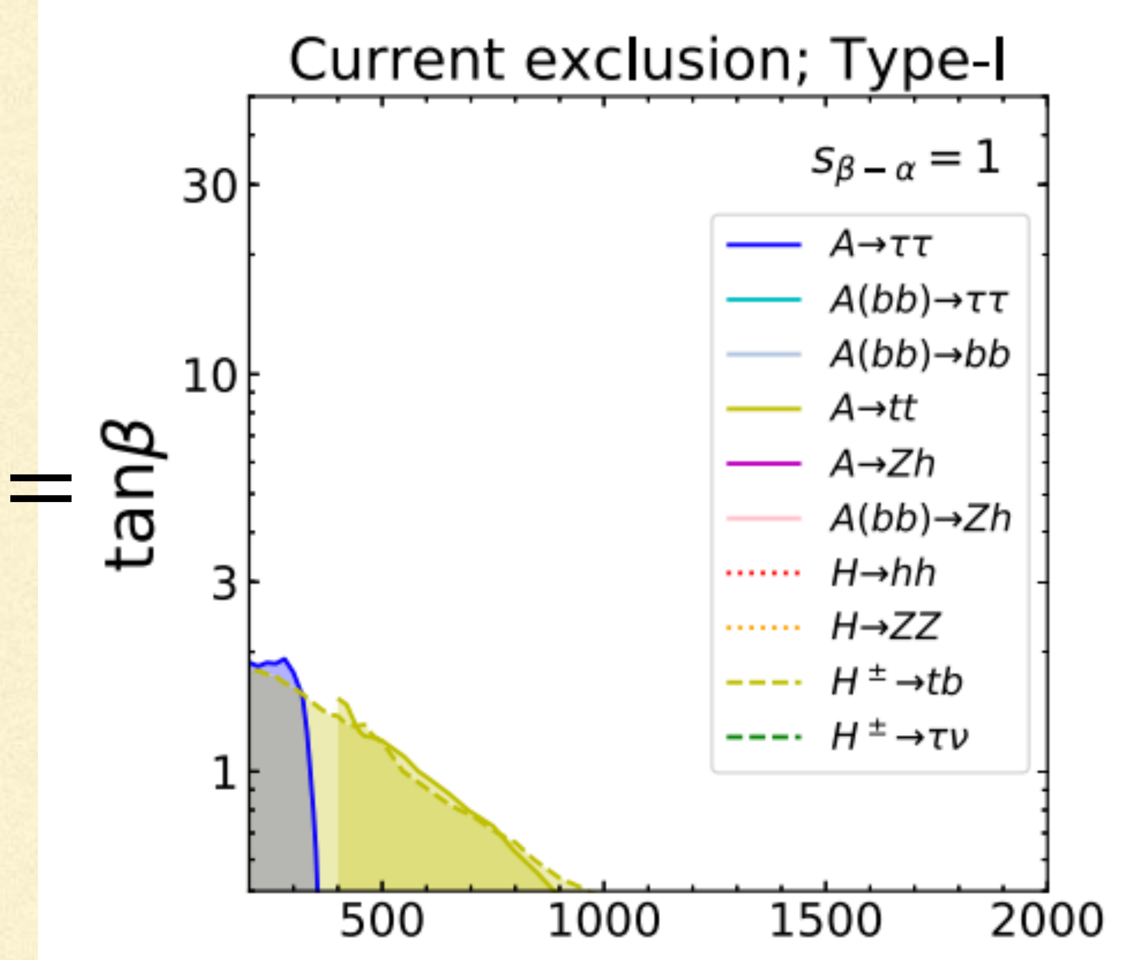


Constraint from flavor experiments

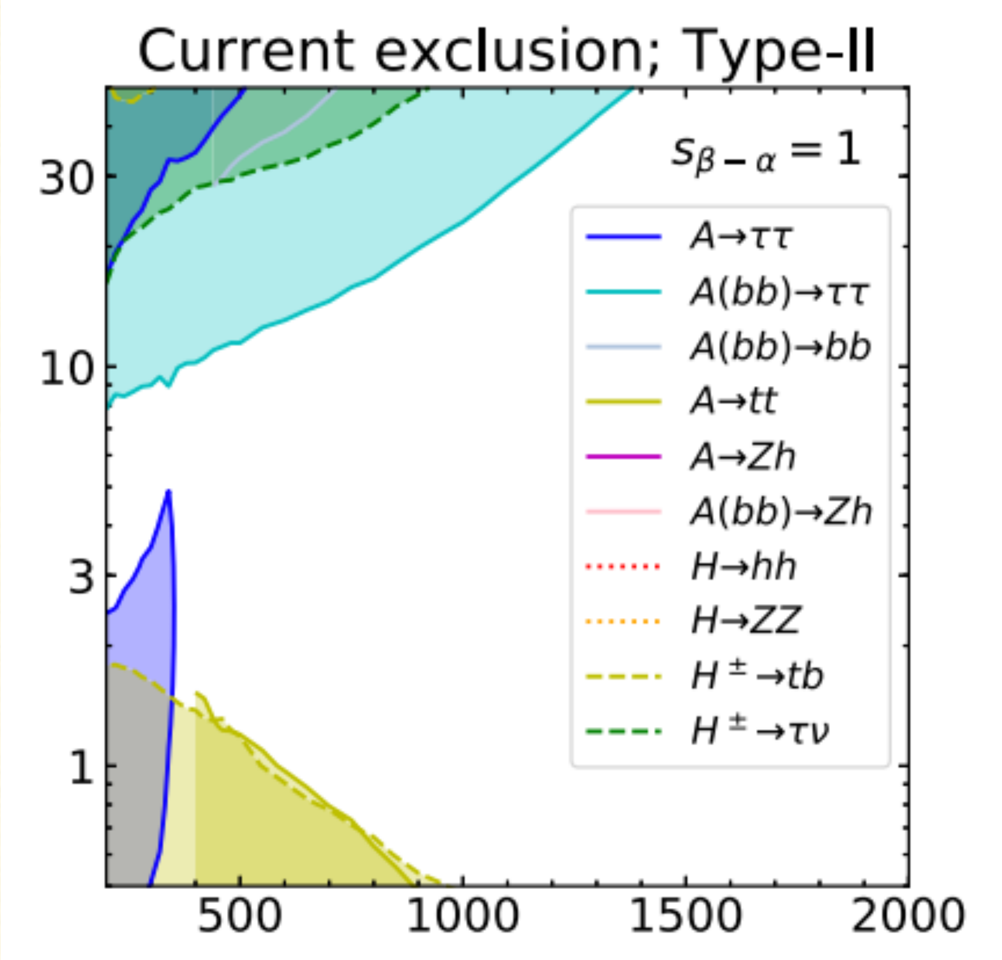
Figures from Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB (2021)

$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$

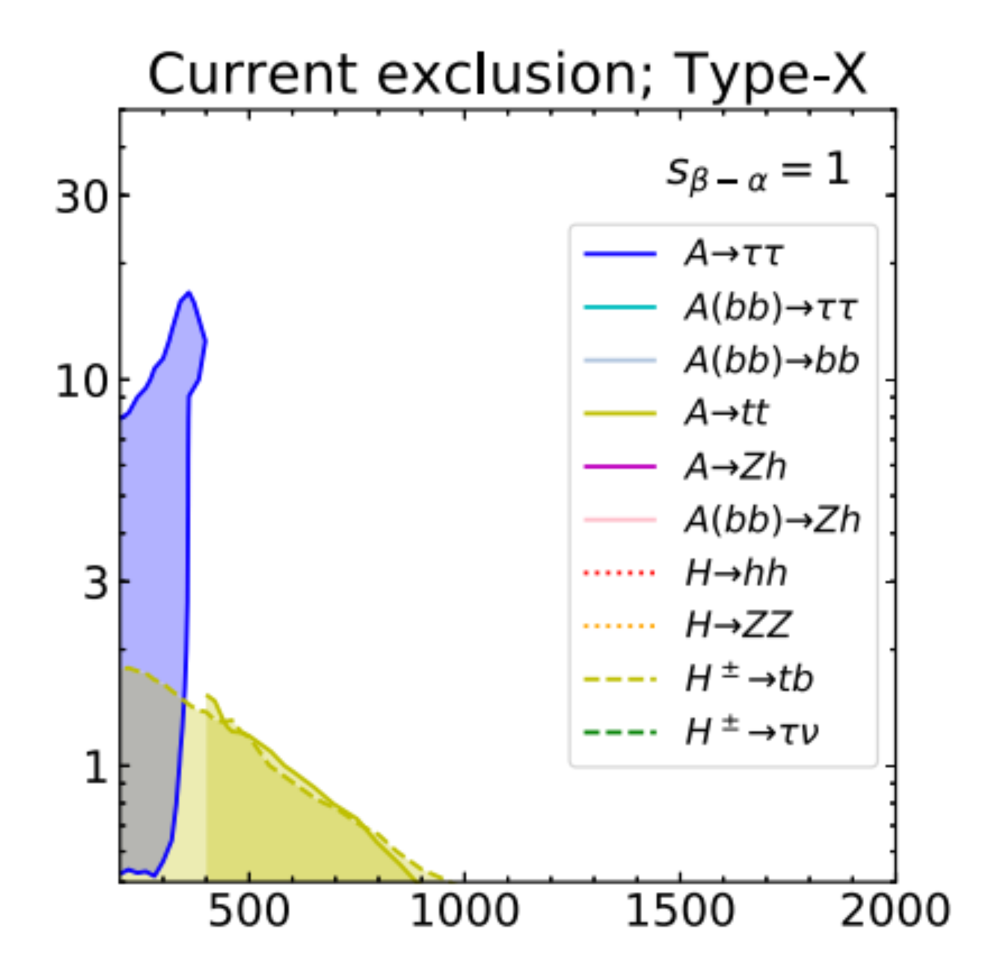
$\frac{1}{|\zeta_u|} =$



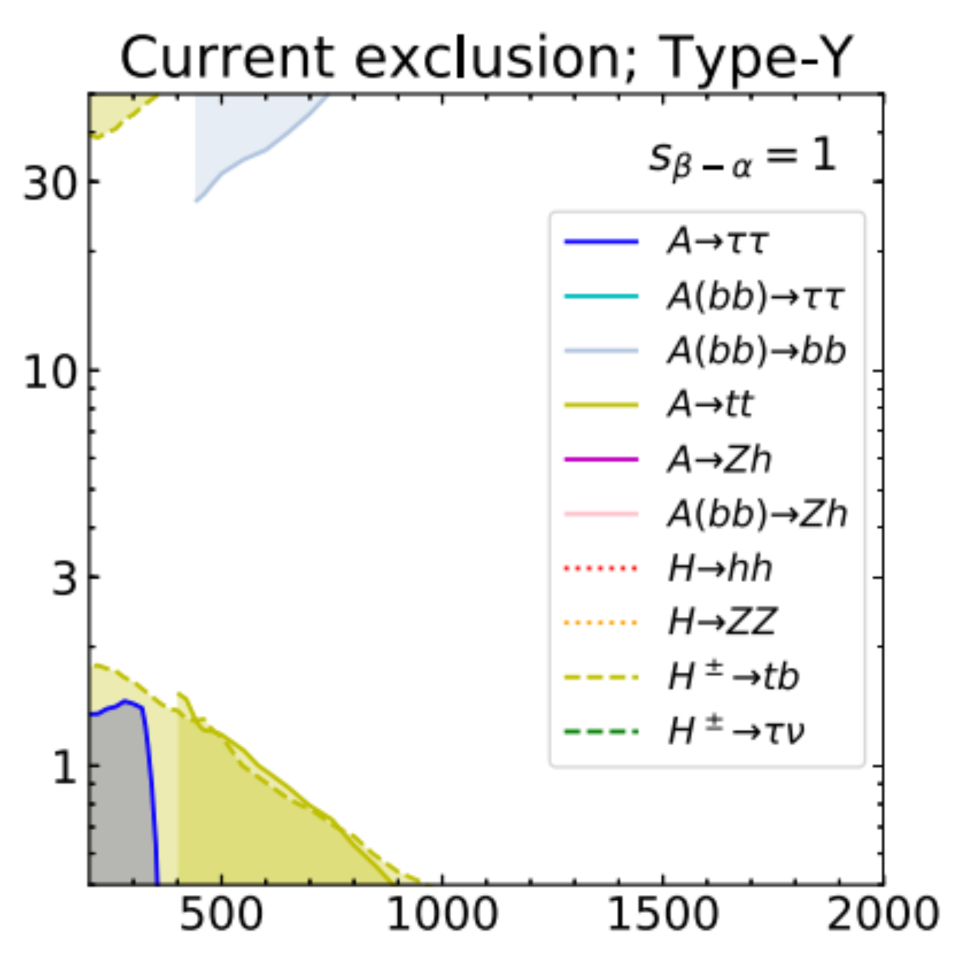
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$

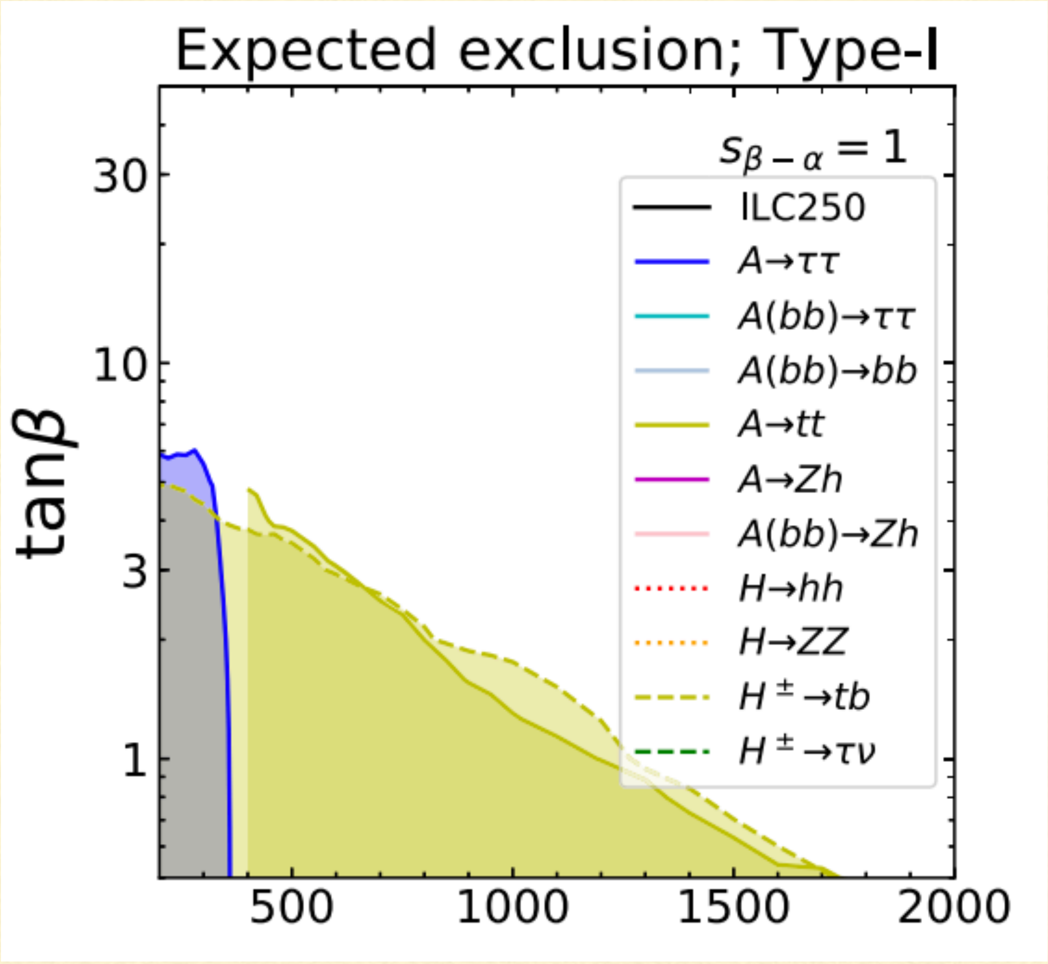


Future direct search at HL-LHC

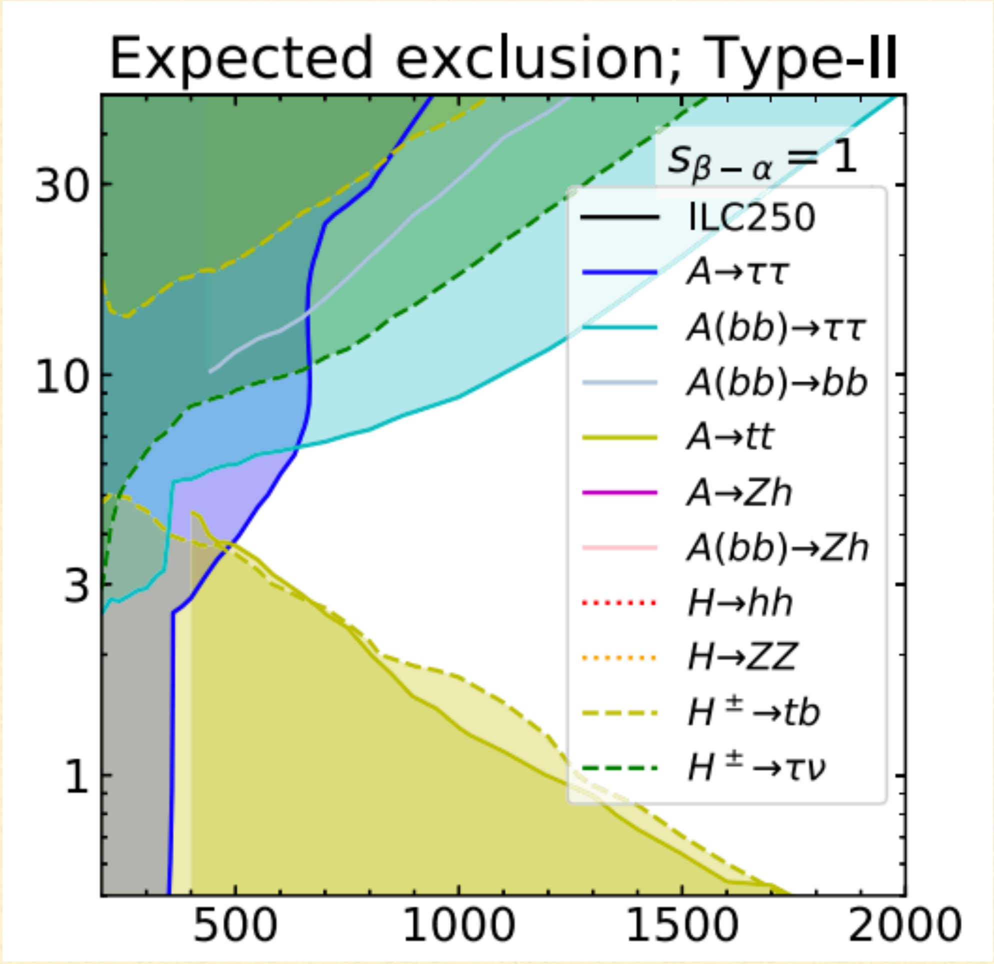
Figures from Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB (2021)

$$\frac{1}{|\zeta_u|} =$$

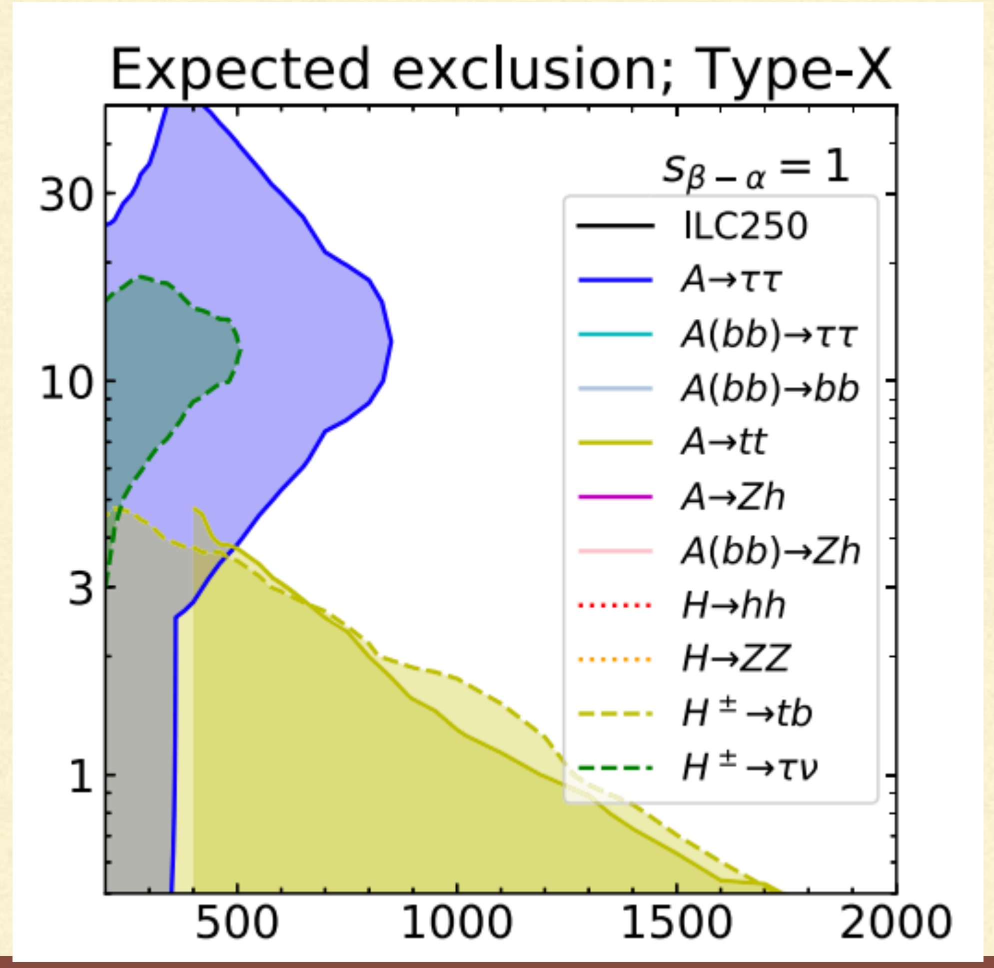
$$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$$



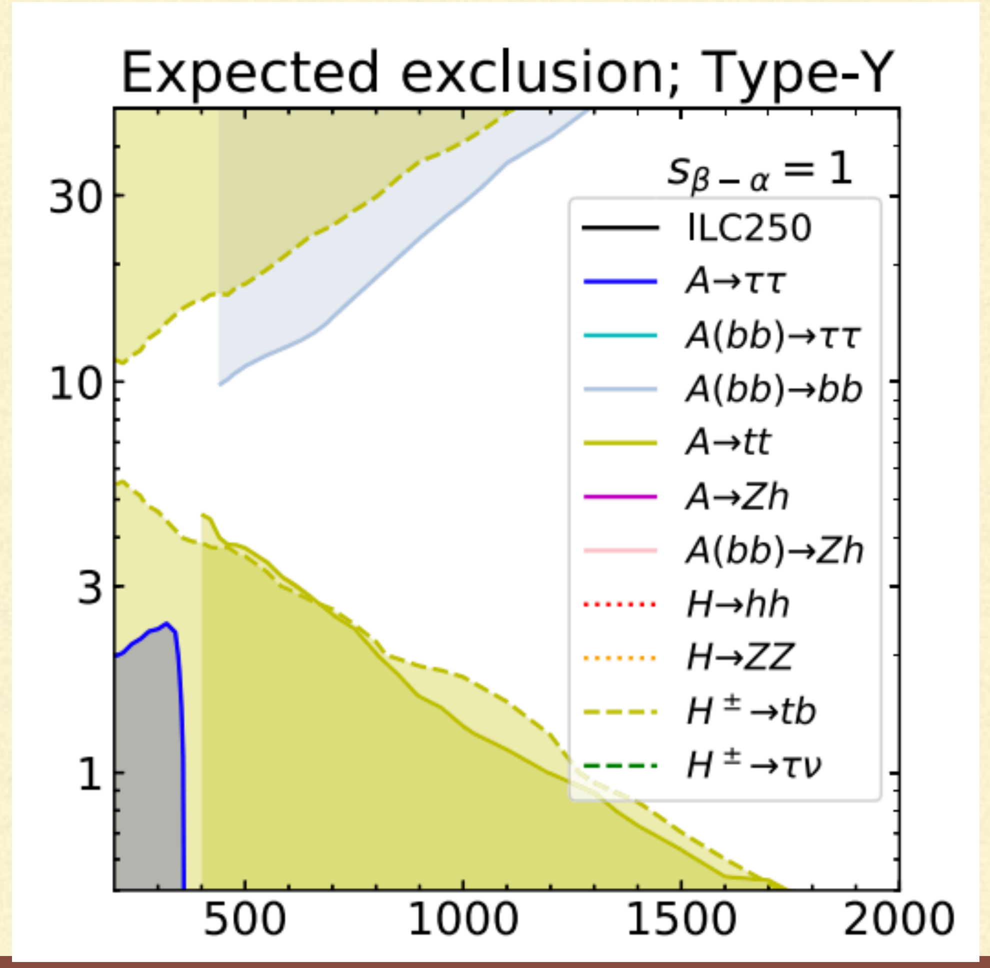
$$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$$



$$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$$



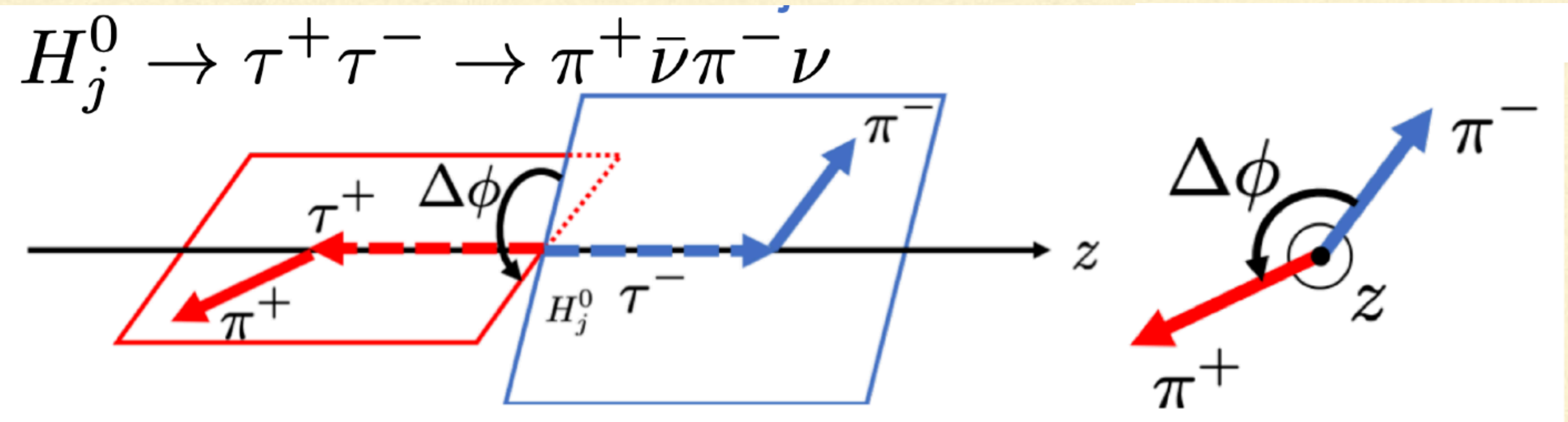
$$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$$



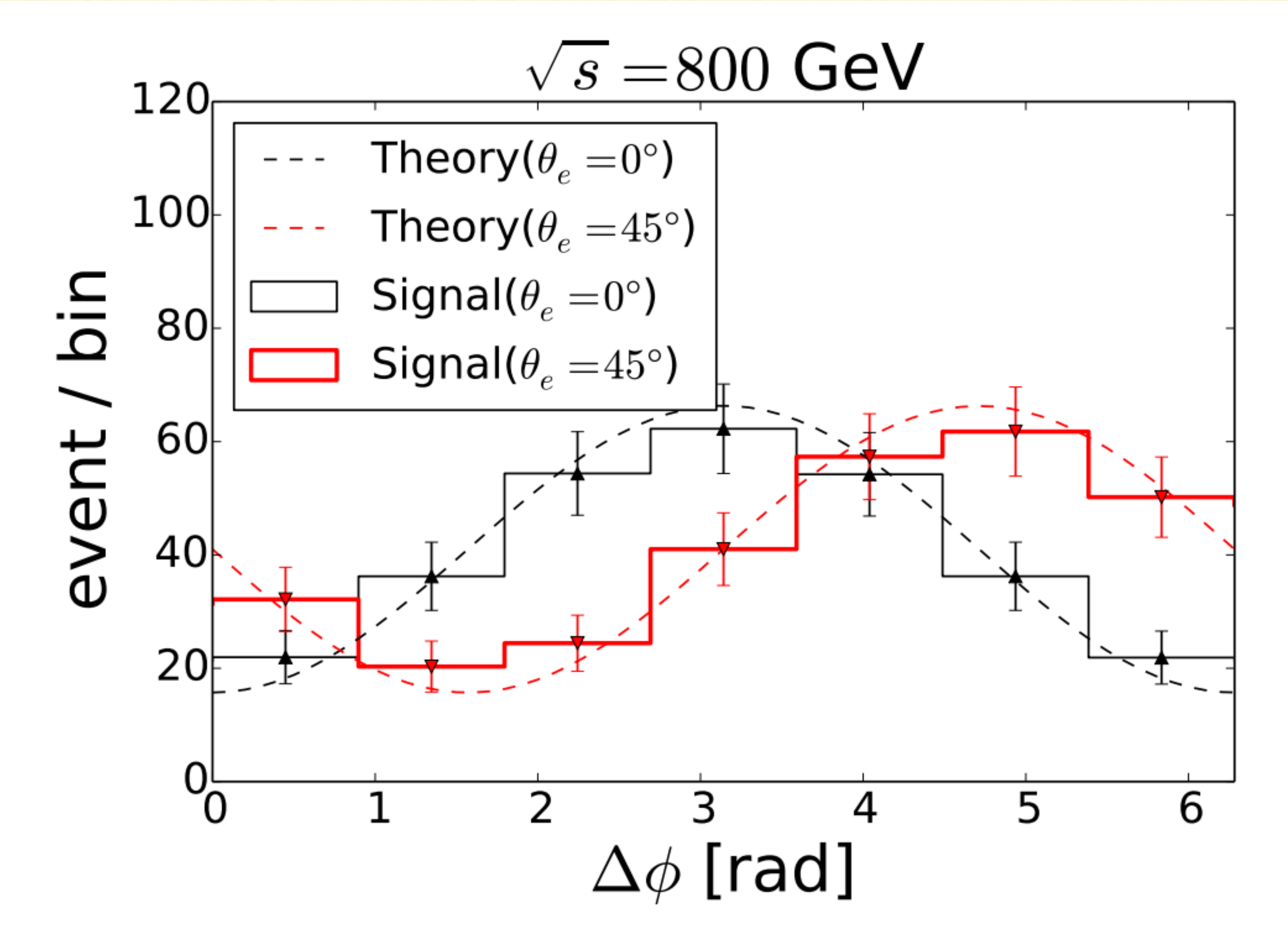
Future test of CP-violation in ζ_τ

At e^+e^- collider

$$e^+e^- \to H_2H_3 \to \tau^+\tau^- b\bar{b}$$



Kanemura, Kubota, Yagyu, JHEP (2021)



$M = 240,$	$m_{H_2^0} = 280,$	$m_{H_3^0} = 230,$	$m_{H^\pm} = 230$	(in GeV)
$\lvert\zeta_u\rvert = 0.01,$	$\lvert\zeta_d\rvert = 0.1,$	$\lvert\zeta_e\rvert = 0.5,$	$\lvert\lambda_7\rvert = 0.3,$	$\lambda_2 = 0.5$
$\theta_u = 1.2,$	$\theta_d = 0,$	$\theta_e = \pi/4,$	$\theta_7 = -1.8$	(in radian)

Bubble profiles and nucleation temperature

Euclidean action : $S_E = \int \mathrm{d}^d x \left\{ \frac{1}{2}(\partial_\mu \varphi)^2 + V_{eff}(\varphi) \right\}$ Finite temperature $d = 3$

Rate of the nucleation per volume : $\Gamma / V = \omega T^4 e^{-S_E/T} \quad \big(\omega = \mathcal{O}(1)\big)$

Probability of the bubble nucleation per one Hubble volume is $\mathcal{O}(1)$ ➡ $\boxed{\frac{S_E}{T_n} \sim 140}$ T_n: Nucleation temperature

Bubble profile is given by the bounce solution

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}\rho^2} + \frac{2}{\rho}\frac{\mathrm{d}\varphi}{\mathrm{d}\rho} = \nabla V_{eff}$$

(Boundary)

$$\varphi(\infty) = \varphi_F \qquad \left.\frac{\mathrm{d}\varphi}{\mathrm{d}\rho}\right|_{\rho=0} = 0$$

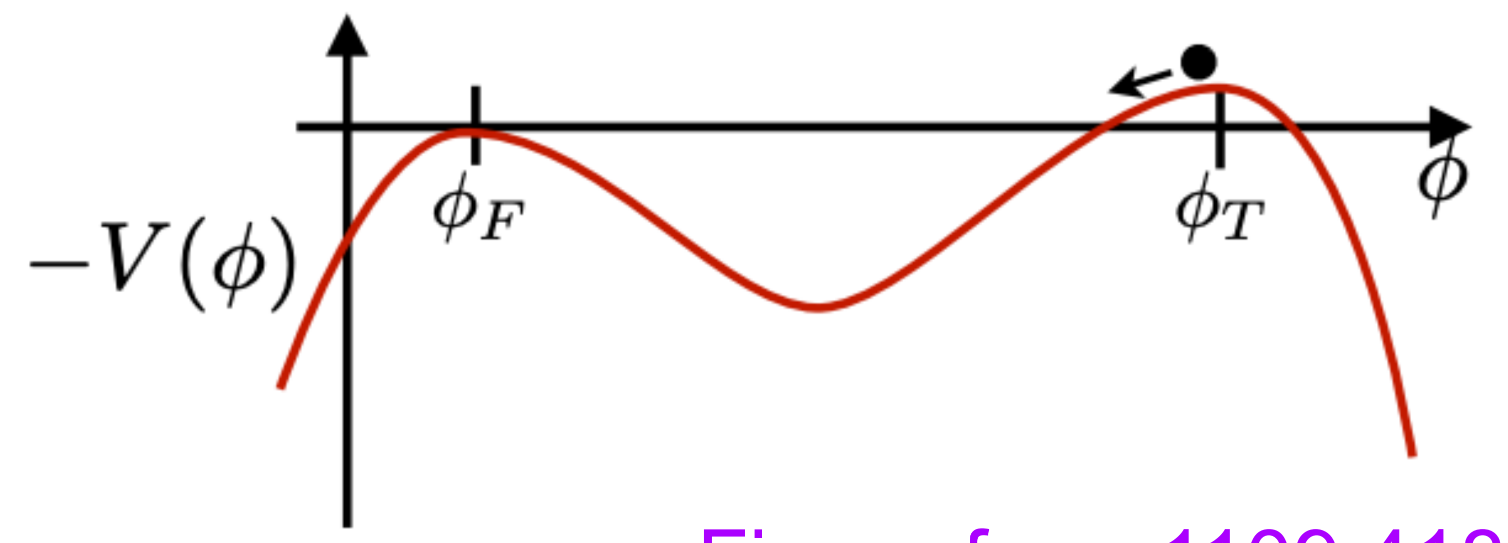


Figure from 1109.4189

Wall width dependence of BAU

In the WKB method, generated baryon asymmetry is roughly estimated as

$$\eta_B \sim \int_0^{\infty} \mathrm{d}z \, \frac{S(z)}{T^3} - A \int_{-\infty}^{\infty} \mathrm{d}z \frac{S(z)}{T^3}$$

Cline, Laurent, PRD (2021)

A is a function of v_w and L_w

v_w : wall velocity

L_w : wall width

When A has a certain value, the first and second terms are canceled.

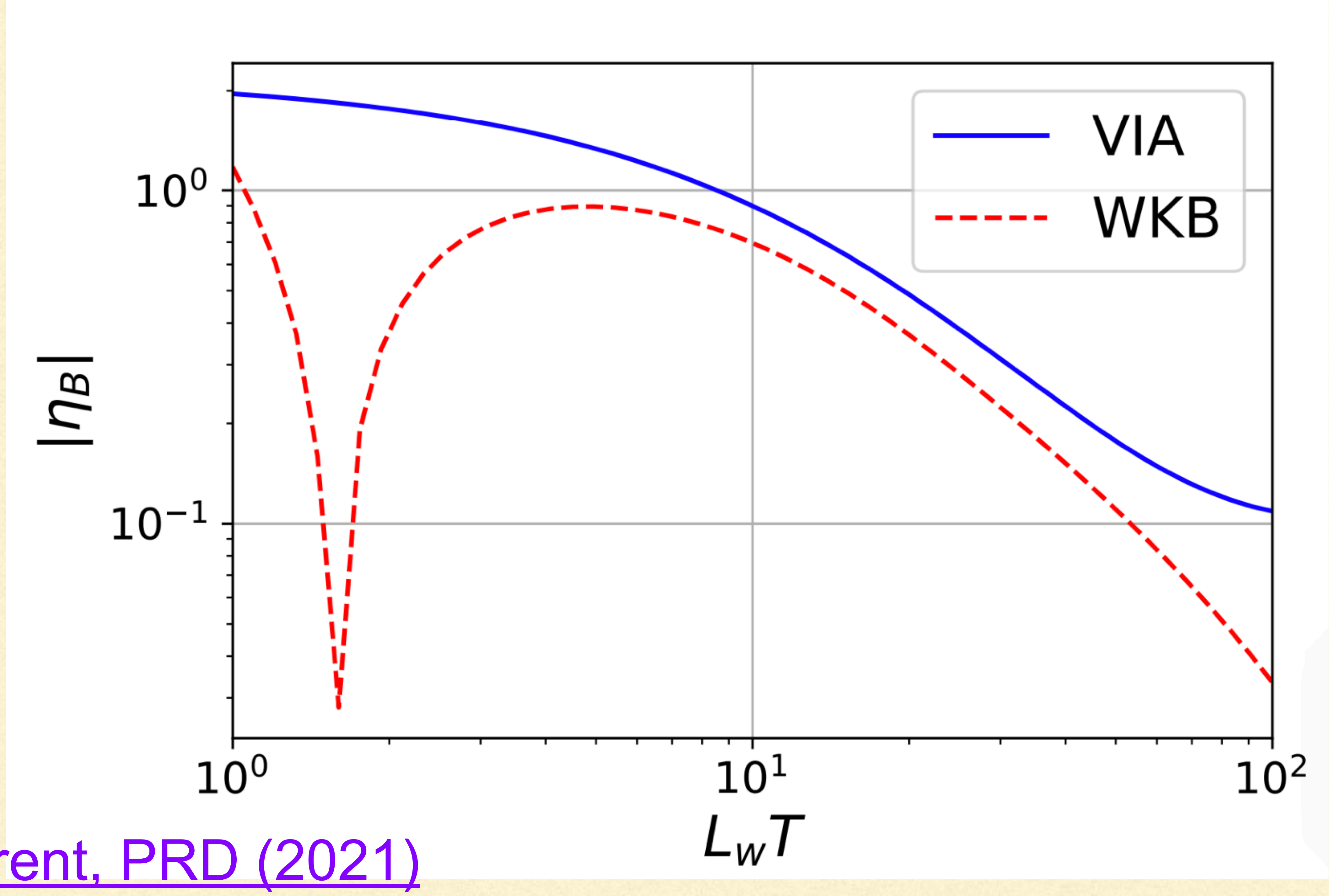


Figure from Cline, Laurent, PRD (2021)

Relativistic effect in BAU

We used the linear expansion by the wall velocity v_w

Effects of higher order terms : Cline, Kainulainen, PRD (2020)

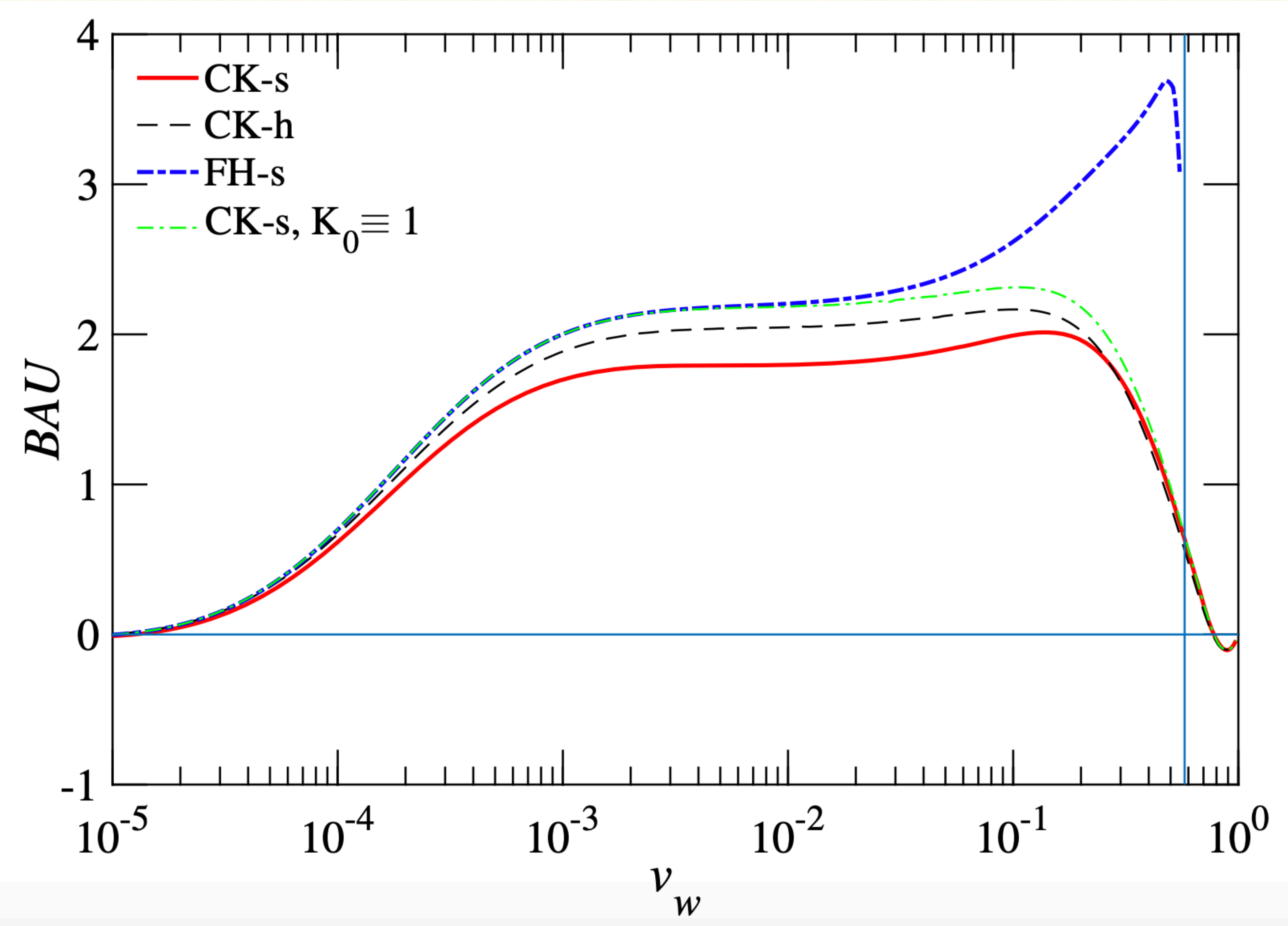


Figure from Cline, Kainulainen, PRD (2020)

Velocity dependence of η_B

$\ell \sim \frac{1}{T}$: Mean free path

Charge is accumulated within ℓ (Gray region)

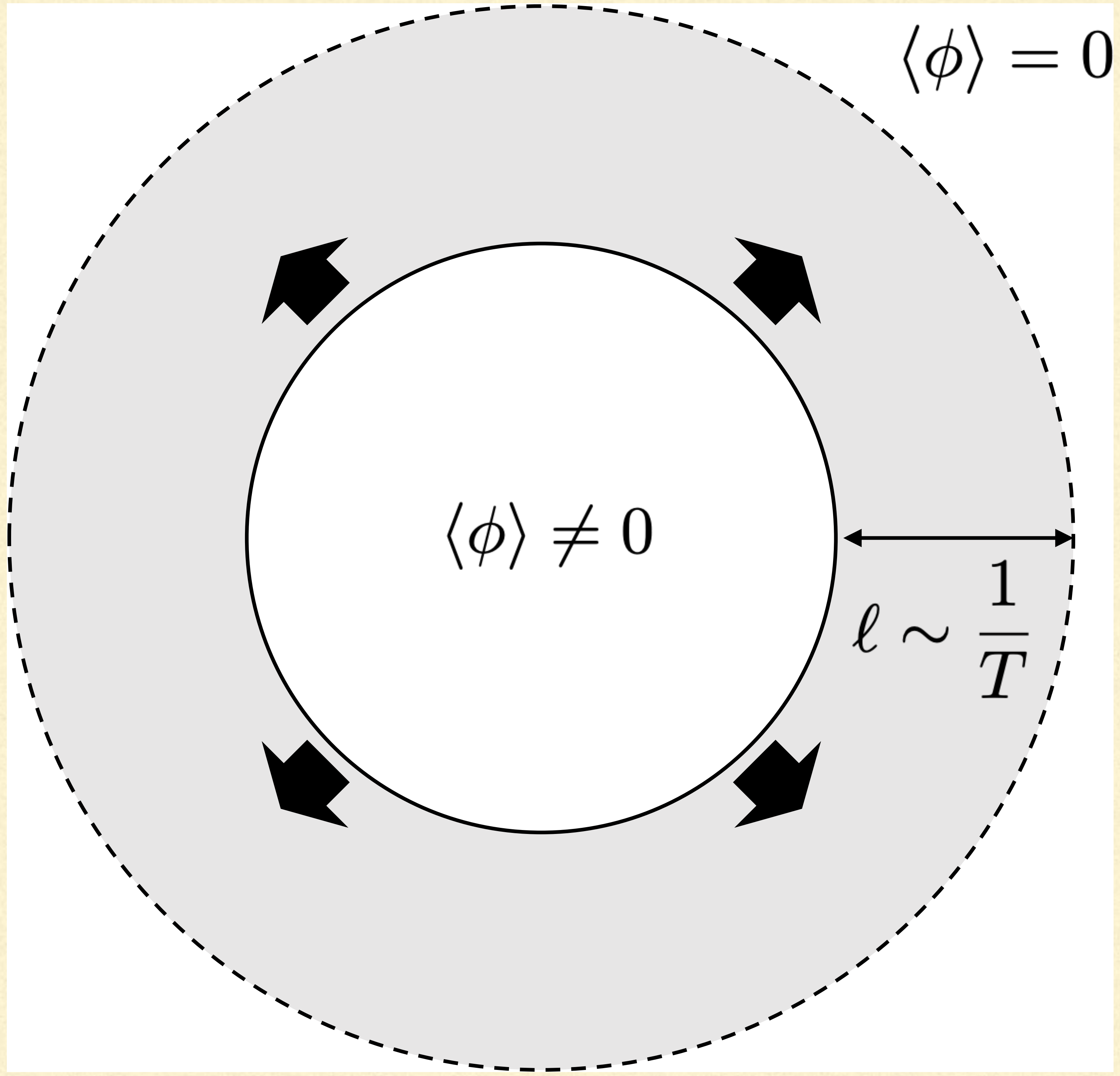
Time for accumulation to enter the bubble

$$t = \frac{\ell}{v_w} \sim \frac{1}{v_w T}$$

# of sphaleron tran.

before the charge enters the bubble

$$N = \Gamma_{sph}^{sym} \times t \sim \frac{\Gamma_{sph}^{sym}}{v_w T}$$



N is too large (small v_w)

➡ washed-out

N is too small (large v_w)

➡ too short time

$$\frac{n_B}{s} \propto \boxed{\frac{\Gamma_{sph}^{sym}}{v_w T}} \int d\hat{z}\, \frac{\mu_{q_L}(\hat{z})}{T} \exp\left(-\boxed{\frac{\Gamma_{sph}^{sym}}{v_w T}}\hat{z}\right)$$

$$\hat{z} = zT$$

The benchmark scenario

Masses of New particle

Z_2 even: $m_{H^+} = 250$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

Z_2 odd: $m_S = 400$ GeV, $m_\eta = 63$ GeV

$(M_{N_1}, M_{N_2}, M_{N_3}) = (3000, 3500, 4000)$ GeV

Higgs potential

$\mu_2^2 = (50\ \text{GeV})^2,\quad \mu_s^2 = (320\ \text{GeV})^2,\quad \mu_\eta^2 \simeq (62.7\ \text{GeV})^2,\quad \mu_{12}^2 = 0$

$\lambda_2 = 0.1,\quad \lambda_3 \simeq 1.98,\quad \lambda_4 \simeq 1.88,\quad \lambda_5 \simeq 1.88,\quad \lambda_6 = 0,$

$|\lambda_7| = 0.821,\quad \rho_1 \simeq 1.90,\quad |\rho_{12}| = 0.1,\quad \rho_2 = 0.1,$

$\sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \kappa = 2.0,\quad \lambda_S = \lambda_\eta = \xi = 1$

$\theta_7 = -2.34,\quad \theta_\rho = -2.94,\quad \theta_\sigma = 0$

The benchmark scenario

Yukawa interactions

$$y_u|\zeta_u| \simeq 2.2\times10^{-6},\quad y_c|\zeta_u| \simeq 1.3\times10^{-3},\quad y_t|\zeta_u| \simeq 0.17,$$

$$y_d|\zeta_d| \simeq 4.7\times10^{-6},\quad y_s|\zeta_d| \simeq 9.3\times10^{-5},\quad y_b|\zeta_d| \simeq 4.2\times10^{-3},$$

$$y_e|\zeta_e| \simeq 2.5\times10^{-4},\quad y_\mu|\zeta_\mu| \simeq 2.5\times10^{-4},\quad y_\tau|\zeta_\tau| \simeq 2.5\times10^{-3},$$

$$\theta_u = \theta_d = 0.245,\quad \theta_e = \theta_\mu = \theta_\tau = -2.94$$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

Messes of the scalar bosons

$$m_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2, \quad m_{H_2}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2,$$

$$m_{H_3}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2,$$

$$m_{S^+}^2 = \mu_s^2 + \frac{1}{2}\rho_1 v^2, \quad m_\eta^2 = \mu_\eta^2 + \frac{1}{2}\sigma_1 v^2$$

$$m_{H^+} = 250 \text{ GeV}, \quad m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = 250 \text{ GeV}$$

$$m_S = 400 \text{ GeV}, \quad m_\eta = 63 \text{ GeV}$$

$$\mu_2^2 = (50 \text{ GeV})^2, \quad \mu_s^2 = (330 \text{ GeV})^2, \quad \mu_\eta^2 \simeq (62.7 \text{ GeV})^2,$$

$$\lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \rho_1 \simeq 1.90, \quad \sigma_1 = 1.1 \times 10^{-3}$$

CPV phases in the Yukawa matrix h

$$h_i^\alpha \, \overline{(N_R^\alpha)^c} \, \ell_R^i \, S^+$$

The Yukawa matrix h includes nine phases.

Three of them can be zero by rephasing lepton fields.

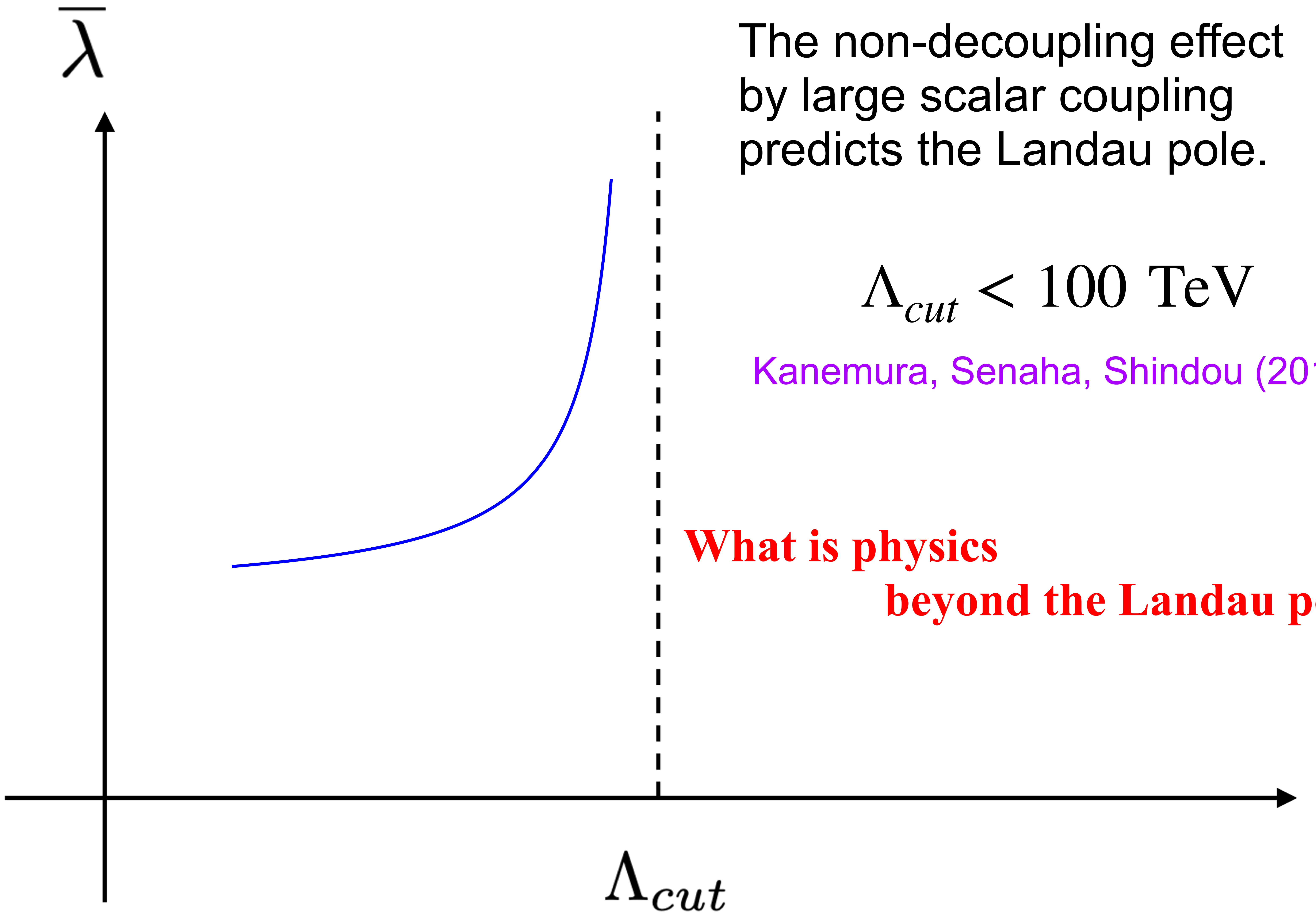
$$\begin{pmatrix} e_{L,R} \\ \mu_{L,R} \\ \tau_{L,R} \end{pmatrix} \to P_\phi \begin{pmatrix} e_{L,R} \\ \mu_{L,R} \\ \tau_{L,R} \end{pmatrix} \quad \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \to P_\phi \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \quad P_\phi \equiv \begin{pmatrix} e^{i\phi_e} & 0 & 0 \\ 0 & e^{i\phi_\mu} & 0 \\ 0 & 0 & e^{i\phi_\tau} \end{pmatrix}$$

This rephasing can eliminate 3 phases from the PMNS matrix.

$$\begin{pmatrix} \nu'_{eL} \\ \nu'_{\mu L} \\ \nu'_{\tau L} \end{pmatrix} = P_\phi \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \qquad U_{\text{PMNS}} = P_\phi U'_{\text{PMNS}}$$

U_{PMNS} includes only 3 CPV phases: δ_{CP}, α_1, α_2

Landau pole and new physics



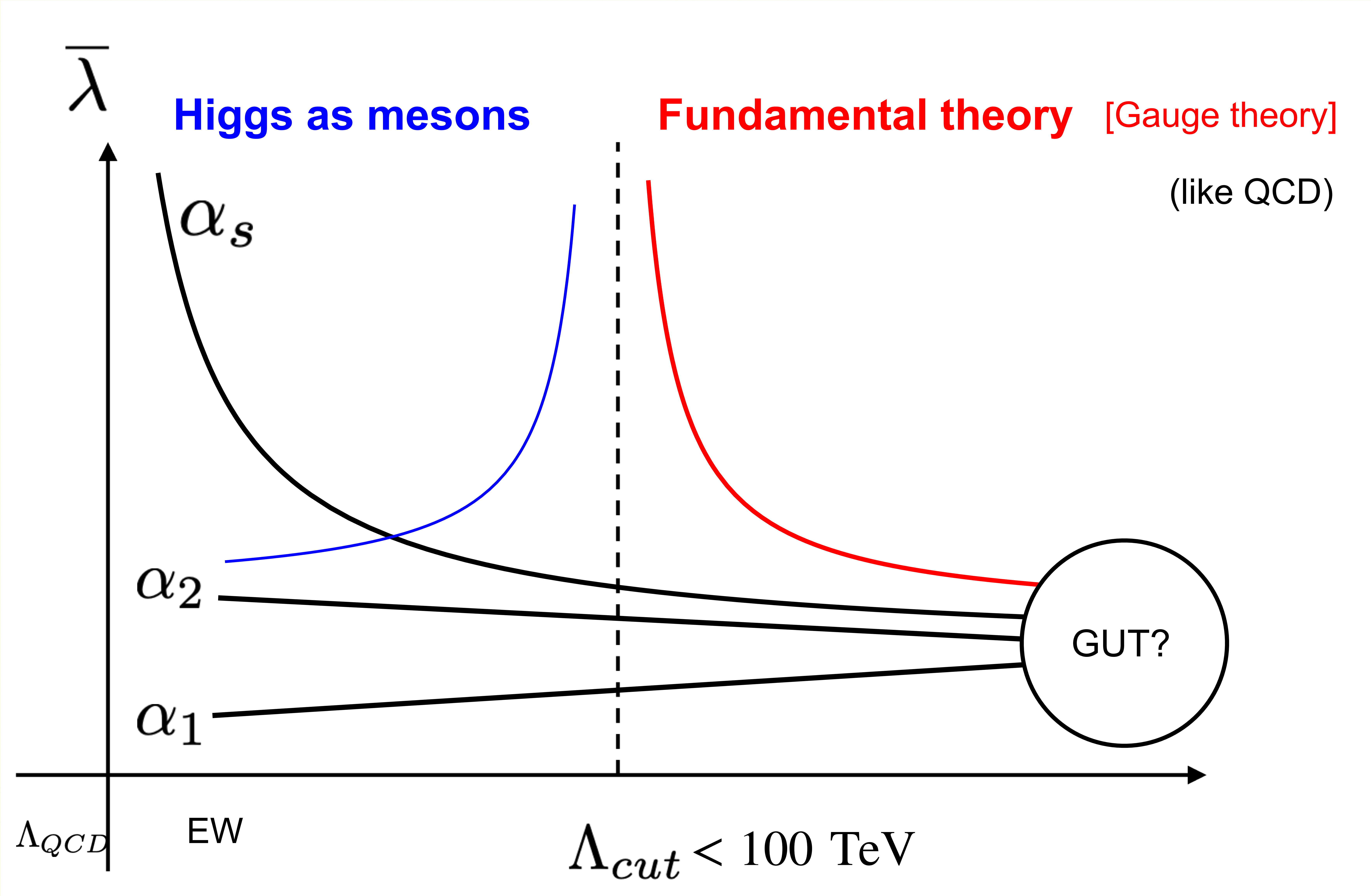
The non-decoupling effect by large scalar coupling predicts the Landau pole.

$$\Lambda_{cut} < 100 \text{ TeV}$$

Kanemura, Senaha, Shindou (2011)

What is physics beyond the Landau pole？

Landau pole and new physics



Landau pole and new physics

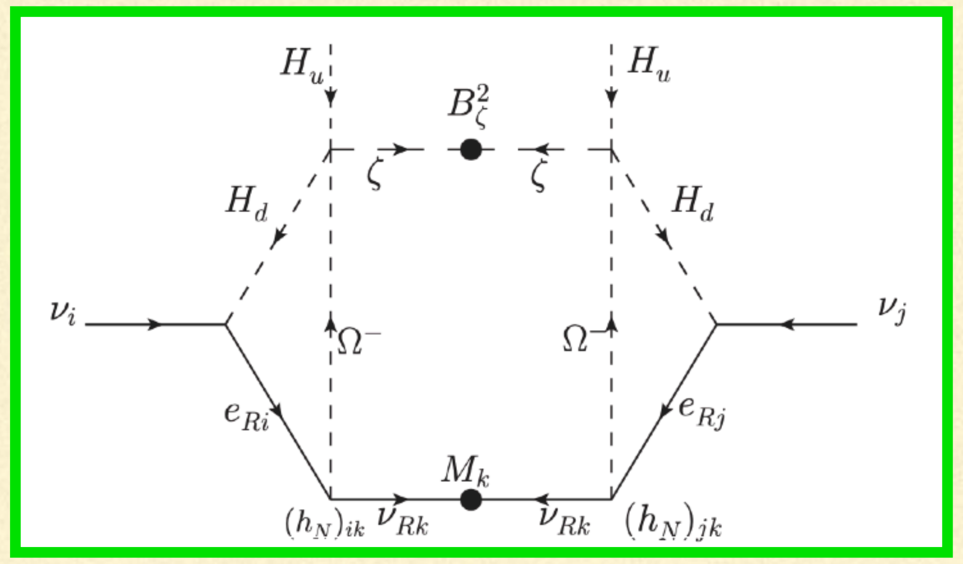
E.g.) SUSY $SU(2)_H$ gauge theory   Kanemura, Shindou, Yamada, PRD (2012)

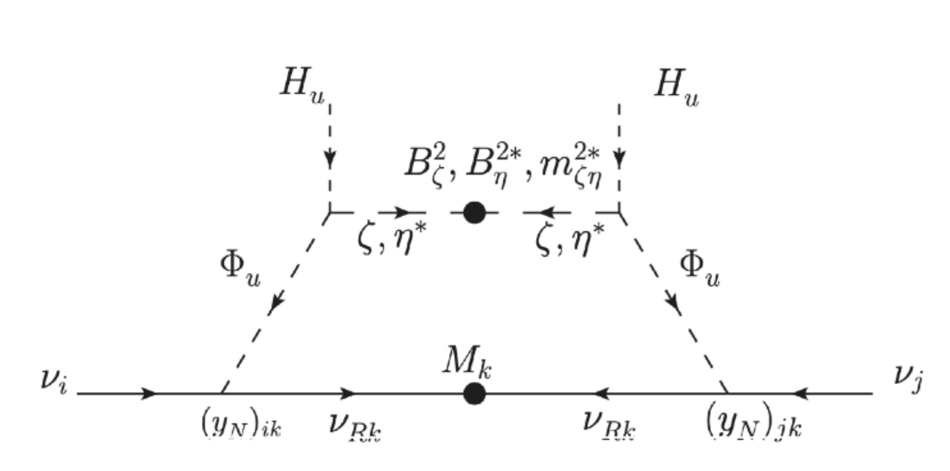
Higgs as mesons

Field	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Z_2
H_u	1	2	$+1/2$	$+1$
H_d	1	2	$-1/2$	$+1$
Φ_u	1	2	$+1/2$	-1
Φ_d	1	2	$-1/2$	-1
Ω^+	1	1	$+1$	-1
Ω^-	1	1	-1	-1
$N,\ N_\Phi,\ N_\Omega$	1	1	0	$+1$
$\zeta,\ \eta$	1	1	0	-1

Gauge theory

Superfield	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	1	2	0	$+1$
T_3	1	1	$+1/2$	$+1$
T_4	1	1	$-1/2$	$+1$
T_5	1	1	$+1/2$	-1
T_6	1	1	$-1/2$	-1





ALL scalar fields in the model can be included!