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Phenomenology of Parity solution to the strong CP problem

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Summary

- * The strong CP problem may be solved by Parity symmetry
- * In models with the minimal Higgs content, the Parity breaking scale can be determined by the SM parameters
- * Signals of or constraints on baryogenesis, dark matter, or gauge coupling unification models are correlated with SM parameters

Outline

- * Strong CP problem and Parity solutions
- * Parity breaking
- * Phenomenology

The strong CP problem

$$\mathcal{L} = y_{ij}^u H^\dagger q_i \bar{u}_j + y_{ij}^d H q_i \bar{d}_j + \frac{\theta_{\text{QCD}}}{32\pi^2} G\tilde{G}$$

$$\bar{\theta} = \text{argdet}(m^u m^d) + \theta_{\text{QCD}} < 10^{-10}$$

Despite $y^{u,d}$ having $\mathcal{O}(1)$ complex phases

The strong CP problem

Parity solution

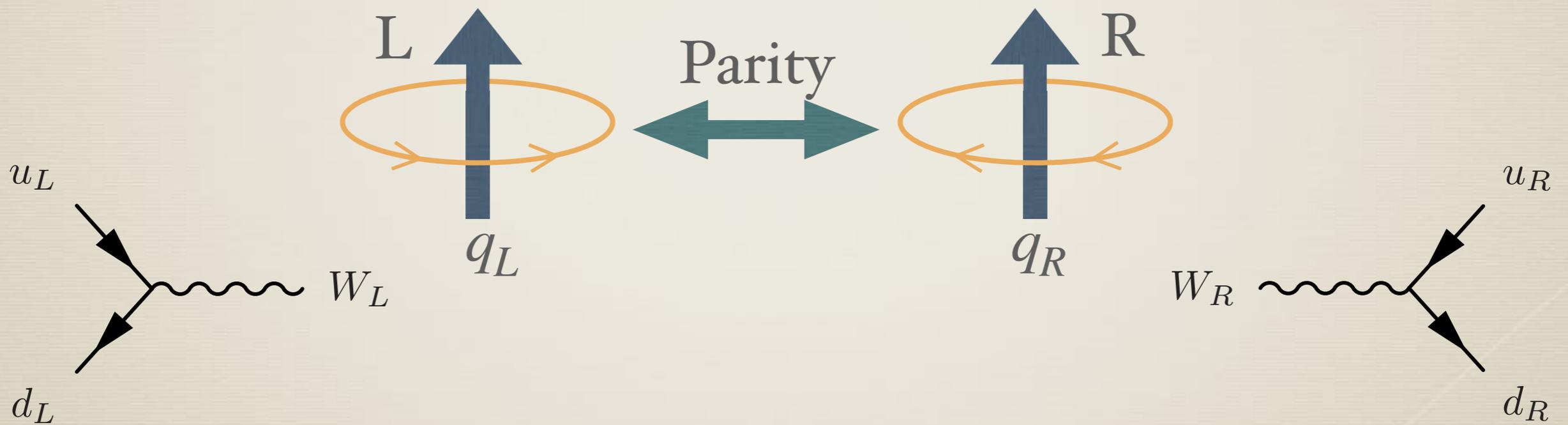
Mohapatra and Senjanovic (1978)

Beg and Tsao (1978)

Babu and Mohapatra (1989)

Barr, Chang and Senjanovic (1991)

Hall and KH (2018,2019)



$$m^{u,d^\dagger} = m^{u,d}, \quad \theta_{\text{QCD}} = 0 \quad \longrightarrow \quad \bar{\theta} = 0$$

Parity solution

* Minimal fermion model

Mohapatra and Senjanovic (1978)

Beg and Tsao (1978)

* Minimal Higgs model

Babu and Mohapatra (1989)

Barr, Chang and Senjanovic (1991)

Hall and KH (2018,2019)

Minimal fermion model

Mohapatra and Senjanovic (1978)

Beg and Tsao (1978)

$SU(2)_L$

$SU(2)_R$

$q = (u, d)$

Parity

$\bar{q} = (\bar{u}, \bar{d})$

$\ell = (\nu, e)$

$\bar{\ell} = (\bar{N}, \bar{e})$

$$q(t, x) \leftrightarrow i\sigma_2 \bar{q}^*(t, -x)$$

Higgses

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$



$$T_R(1,1,3,1)$$

parity



$$T_L(1,3,1,1)$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$Y = X + T_{3R}$$



$$\Phi(1,2,2,0)$$

parity



$$\Phi^*$$

$$SU(3)_c \times U(1)_{EM}$$

$$Q = Y + T_{3L}$$

Yukawa couplings

Let us concentrate on quarks

$(SU(3)_c, SU(2)_L, SU(2)_R, U(1)_X)$

$$q(3,2,1,1/6) \quad \Phi(1,2,2,0) \quad \bar{q}(\bar{3},1,2, -1/6)$$

Parity

$$y_{ij} q_i \Phi \bar{q}_j + y'_{ij} q_i \Phi^* \bar{q}_j$$
$$+ y_{ij}^* q_i^* \Phi^* \bar{q}_j^* + y'^*_{ij} q_i^* \Phi \bar{q}_j^*$$

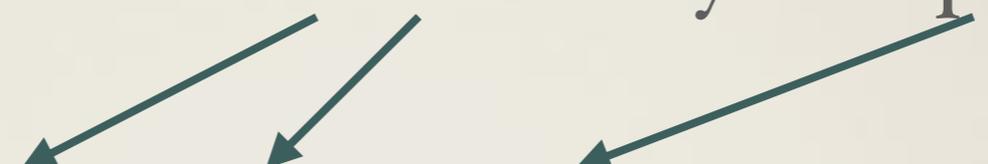
$y = y^\dagger$ because of parity symmetry, so $\det(y)$, $\det(y')$ are real

The strong CP problem is solved?

Wait, the phases of Higgs vev?

Phase of Higgs VEV

Most of the parameters of the Higgs potential are real because of Hermiticity and parity


$$|\Phi|^4, |\Phi|^2, \Phi^2 + \Phi^{*2}$$

$$\Phi \leftrightarrow \Phi^*$$

However, we must introduce $SU(2)_R$ symmetry breaking field T_R and its parity partner T_L

$$e^{i\alpha} |T_R|^2 \Phi^2 + e^{i\alpha} |T_L|^2 \Phi^{*2} + \text{h.c.}$$

$$T_R \gg T_L$$



$$e^{i\alpha} \Phi^2 + e^{-i\alpha} \Phi^{*2}$$

complex Higgs VEV!

Way out

$$e^{i\alpha} |T_R|^2 \Phi^2 + e^{i\alpha} |T_L|^2 \Phi^{*2} \\ + e^{-i\alpha} |T_R|^2 \Phi^{*2} + e^{-i\alpha} |T_L|^2 \Phi^2$$

We must forbid these quartic couplings

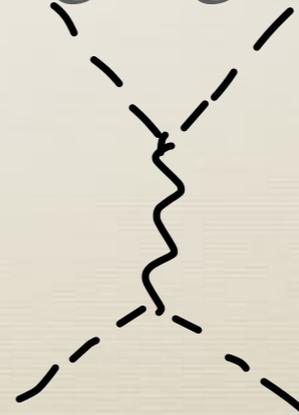
Ex. supersymmetry

Kuchimanchi (1995), Mohapatra and Rasin (1995)

quartic

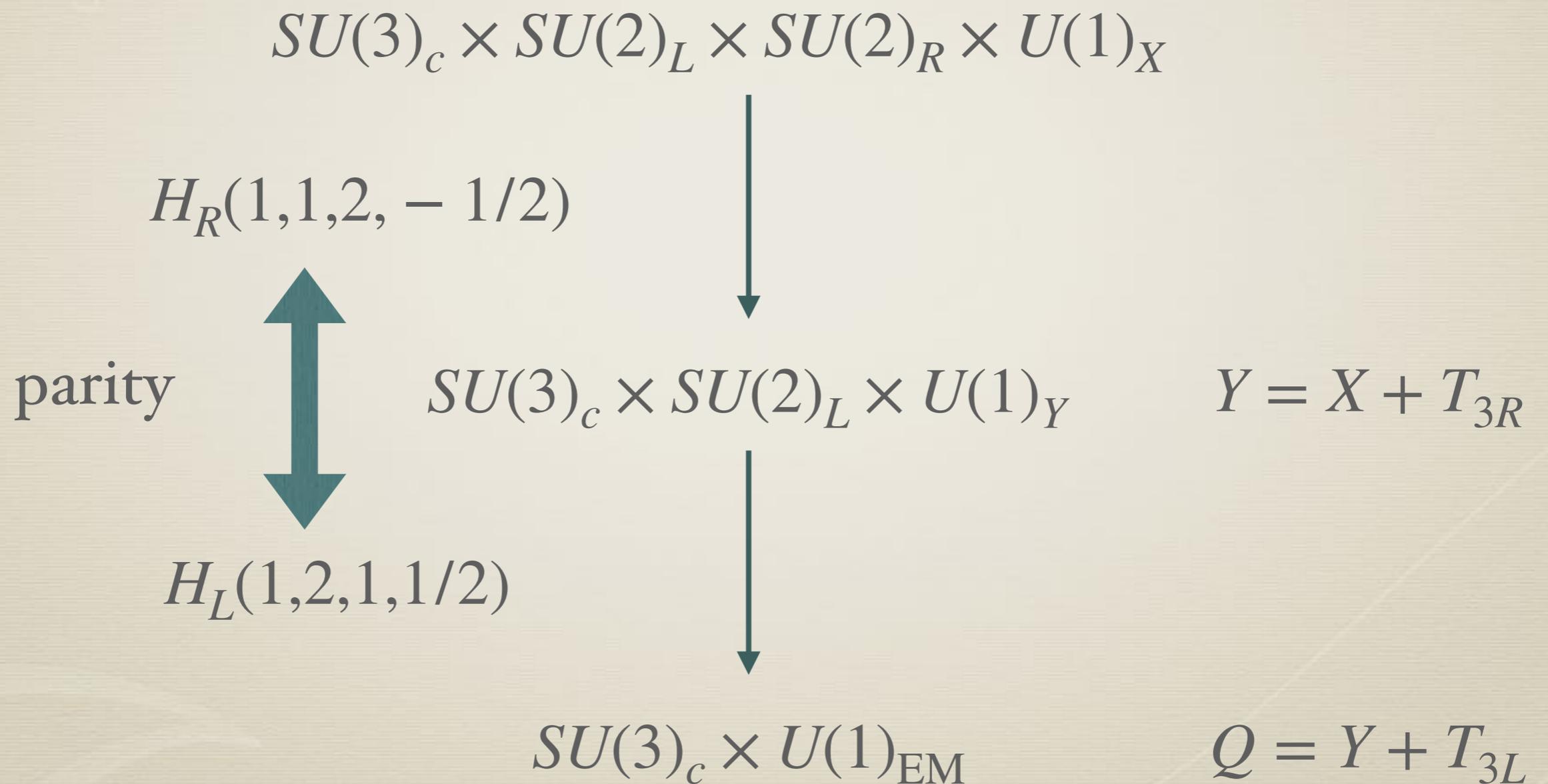


gauge



Minimal Higgs model

Babu and Mohapatra(1989)



Fermion sector?

Let us try the minimal content

$SU(2)_L$		$SU(2)_R$
$q = (u, d)$	Parity	$\bar{q} = (\bar{u}, \bar{d})$
$(3, 2, 1, 1/6)$		$(\bar{3}, 1, 2, -1/6)$
$\ell = (\nu, e)$		$\bar{\ell} = (\bar{N}, \bar{e})$
$(1, 2, 1, -1/2)$		$(1, 1, 2, 1/2)$

But yukawa couplings are forbidden

~~$q\bar{q}H_L$~~

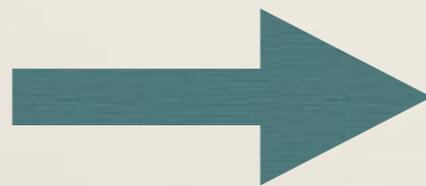
Yukawa couplings

Babu and Mohapatra(1989)

Introduce $SU(2)_L \times SU(2)_R$ singlet, Dirac fermions U, \bar{U}, D, \bar{D}

$$y_{ij}q_i H_L \bar{U}_j + y_{ij}^* \bar{q}_i H_R U_j + M_{ij} U_i \bar{U}_j$$

$$M \gg yv_R$$



$$\frac{y^2}{M} q \bar{q} H_L H_R$$

right-handed quarks $\simeq \bar{q}$

$$M \ll yv_R$$



$$y_{ij} q_i \bar{U}_j H_L$$

right-handed quarks $\simeq \bar{U}$

Yukawa couplings

Babu and Mohapatra(1989)

$$y_{ij}q_i H_L \bar{U}_j + y_{ij}^* \bar{q}_i H_R U_j + M_{ij} U_i \bar{U}_j$$

$$(q \ U) \begin{pmatrix} 0 & y v_L \\ y^\dagger v_R & M \end{pmatrix} \begin{pmatrix} \bar{q} \\ \bar{U} \end{pmatrix}$$

$$\det(m_u) \propto \det(yy^\dagger) \quad \text{is real}$$

Strong CP problem is solved!

(Quantum corrections are found to be small enough)

Hall, KH (2018), de Vries, Draper, and Patel (2021)
Hisano, Kitahara, Osamura, and Yamada (2023)

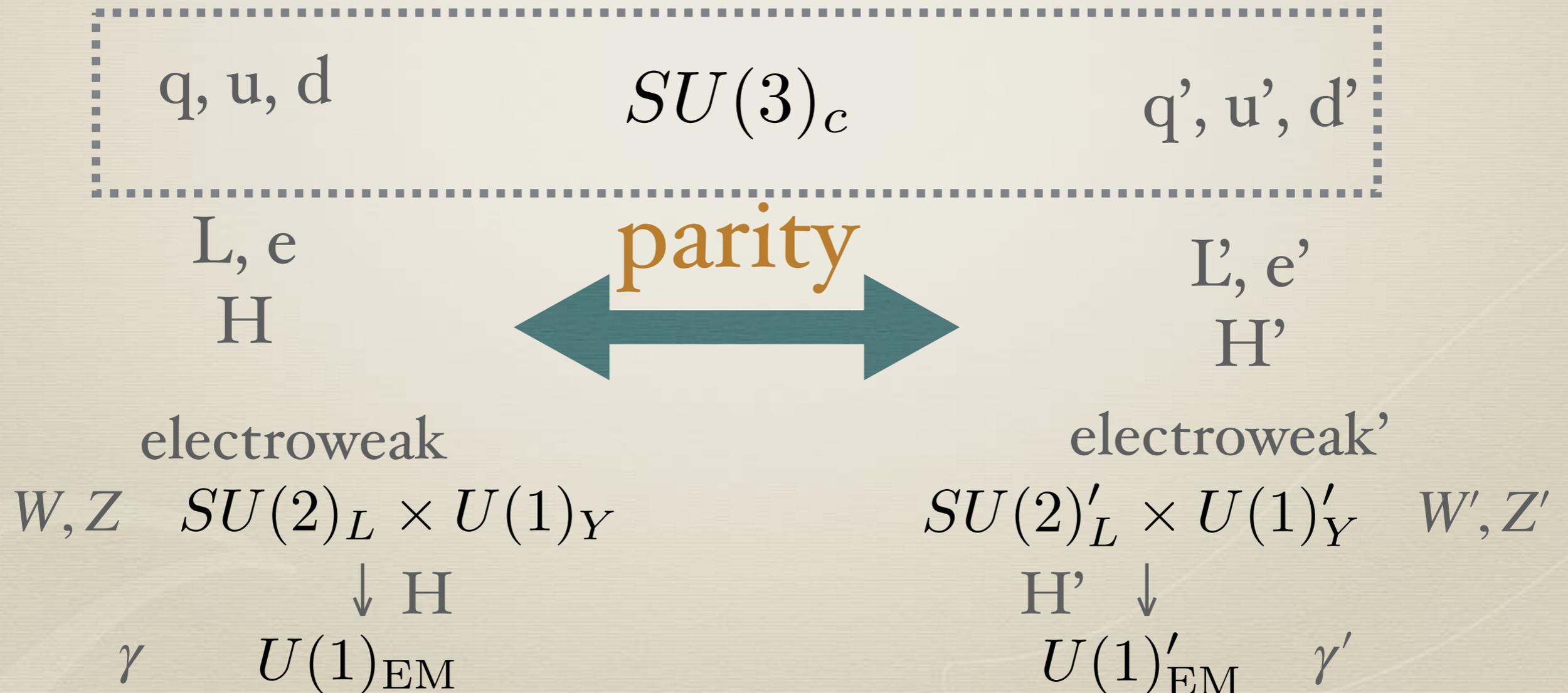
Mirror variant

Barr, Chang and Senjanovic (1991)

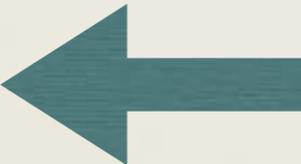
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(2)'_L \times U(1)'_Y$$

SM particles

New particles



Outline

- * Strong CP problem and Parity solutions
- * Parity breaking 
- * Phenomenology

Minimal Higgs model

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$



$$H_R(1,1,2, -1/2)$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



parity



$$H_L(1,2,1,1/2)$$

$$SU(3)_c \times U(1)_{EM}$$

How to obtain $v_R \gg v_L$ despite the parity symmetry?

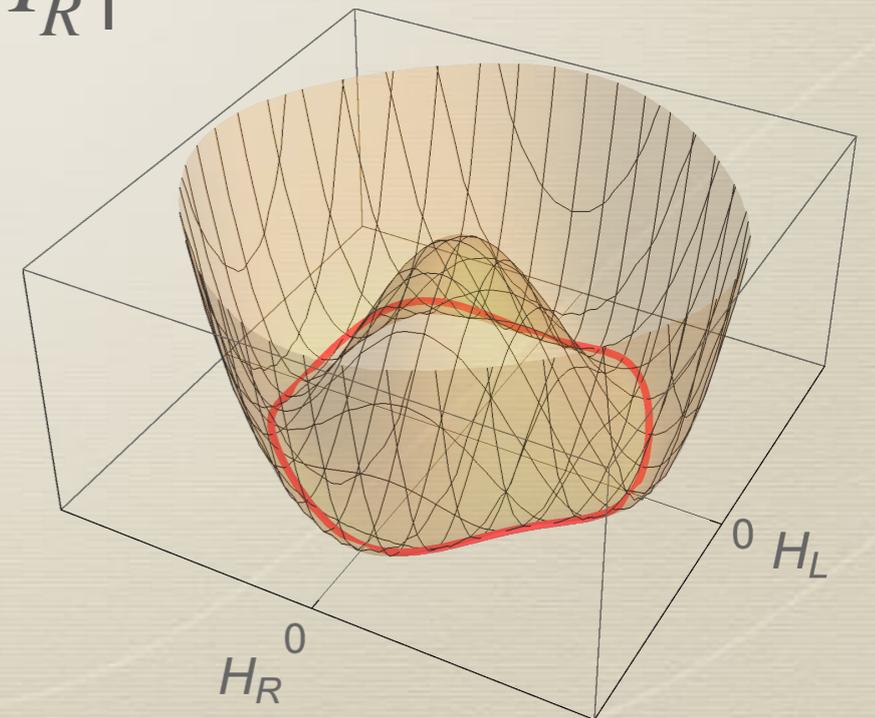
Higgs potential



$$V = \left(\lambda |H_L|^4 - m^2 |H_L|^2 \right) + \left(\lambda |H_R|^4 - m^2 |H_R|^2 \right) + \tilde{y} |H_L|^2 |H_R|^2$$
$$= \lambda \left(|H_L|^2 + |H_R|^2 - v'^2 \right)^2 + y |H_L|^2 |H_R|^2$$

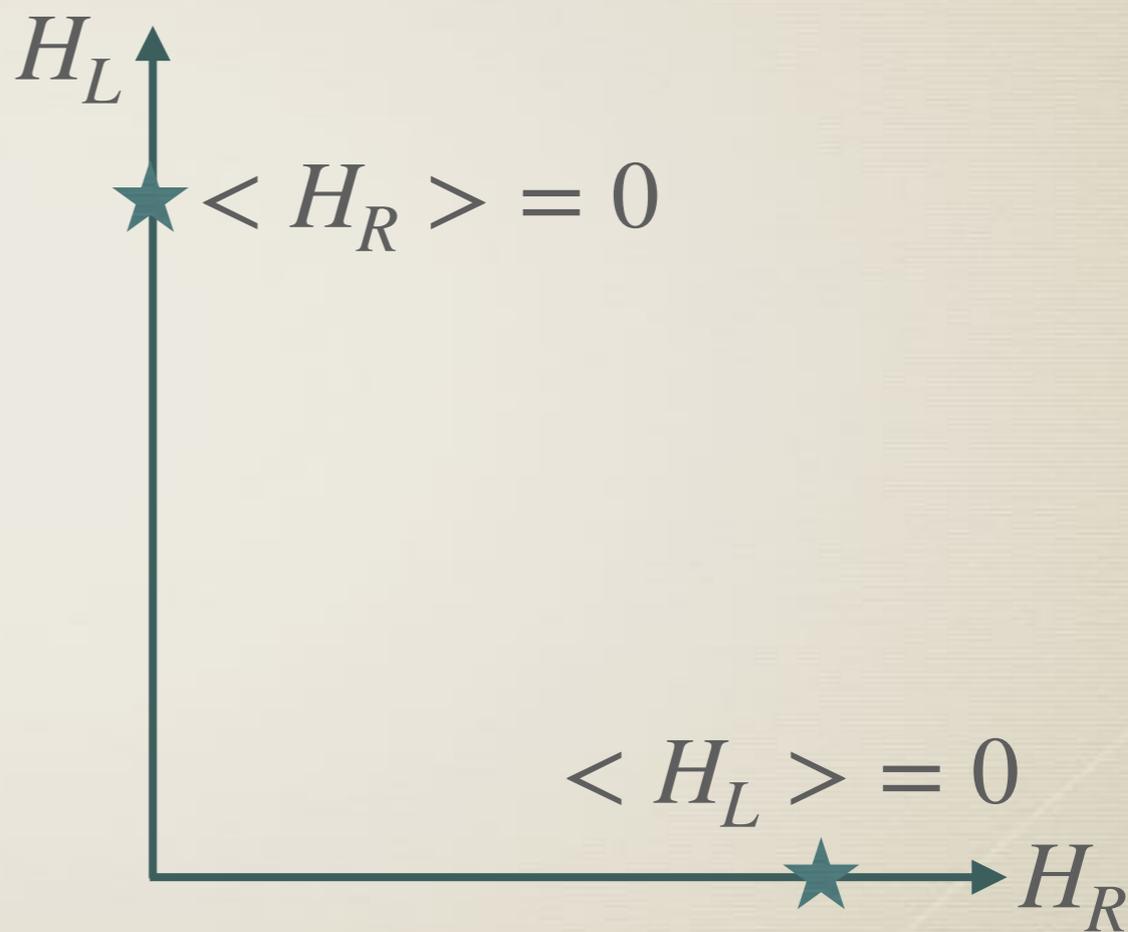
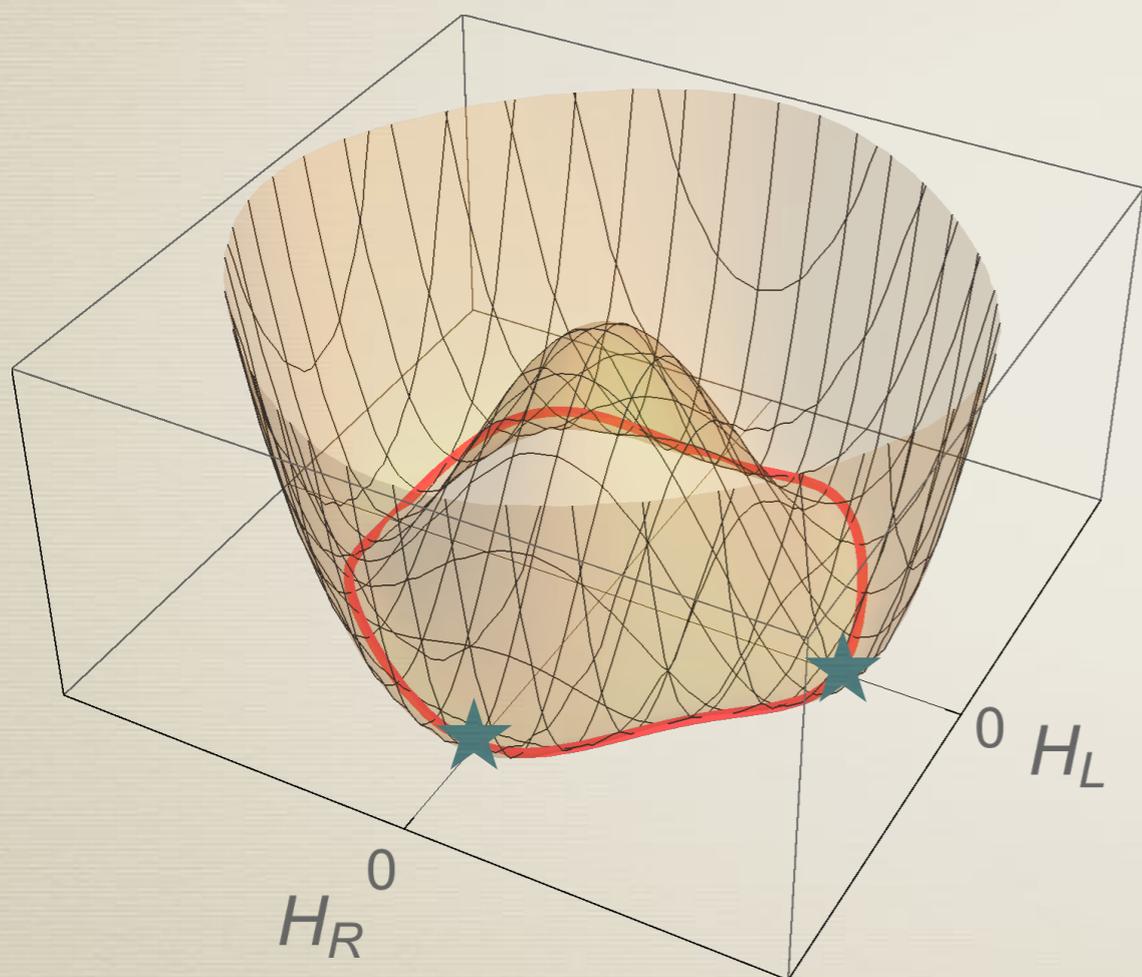
Can we find the minimum with

$$\langle H_L \rangle \ll \langle H_R \rangle \quad ?$$



$$y > 0$$

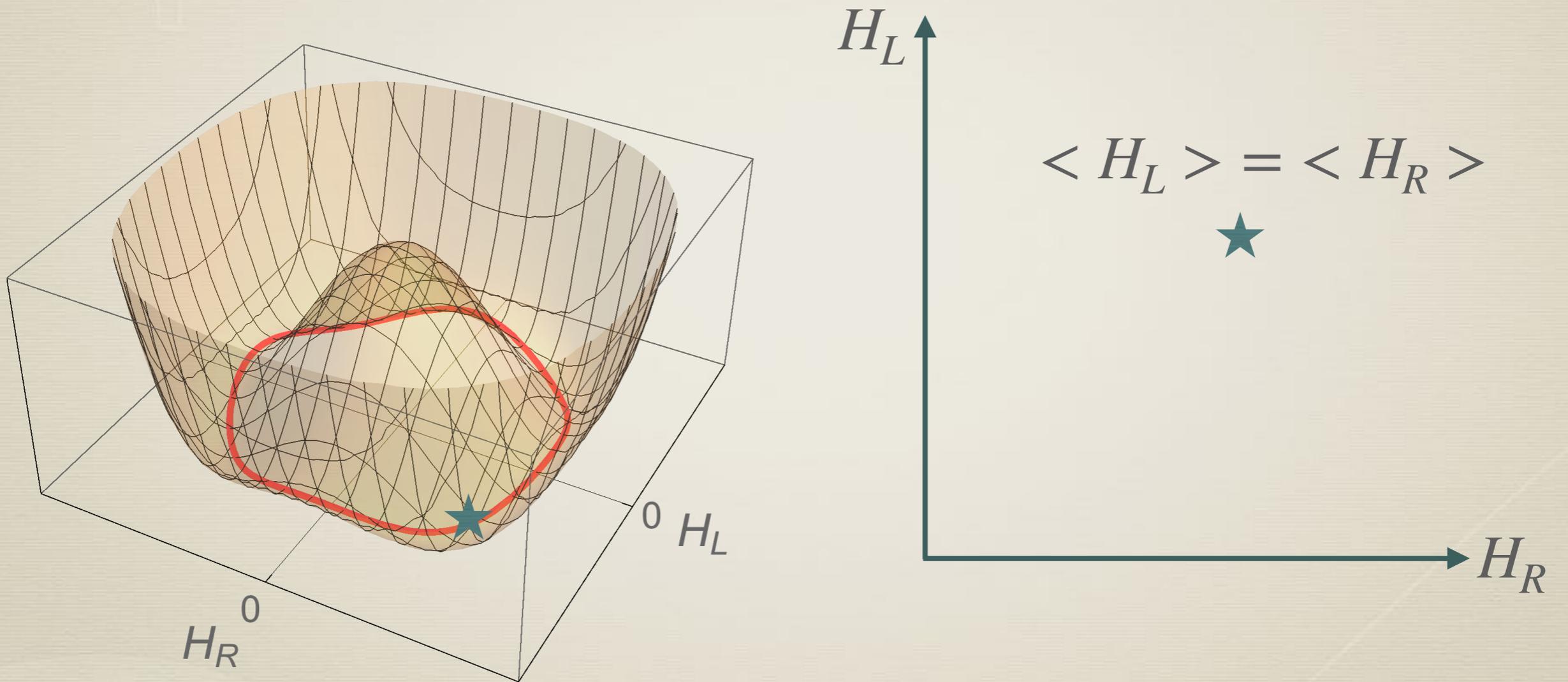
$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + y|H_L|^2|H_R|^2$$



$$0 \neq \langle H_L \rangle \ll \langle H_R \rangle$$

$$y < 0$$

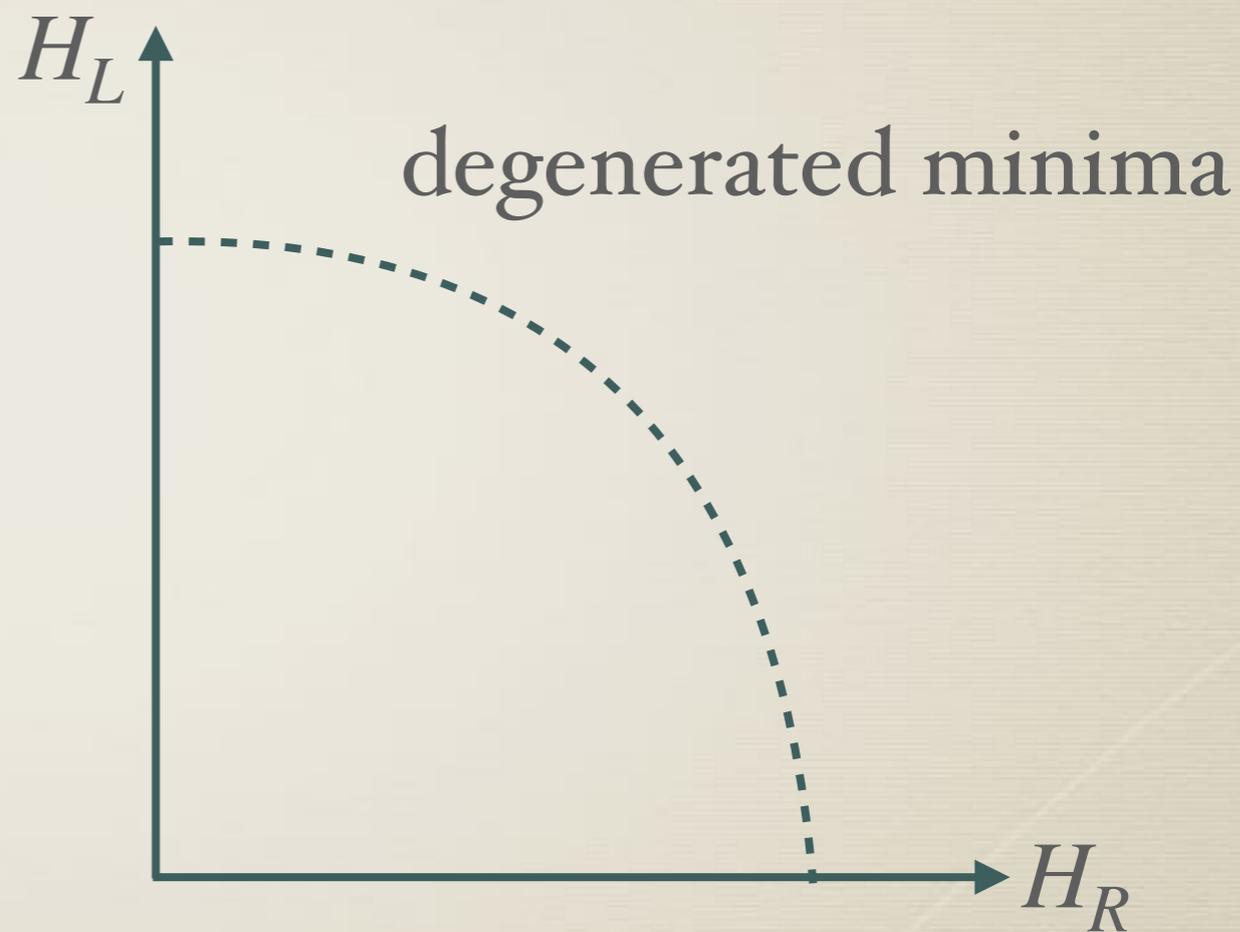
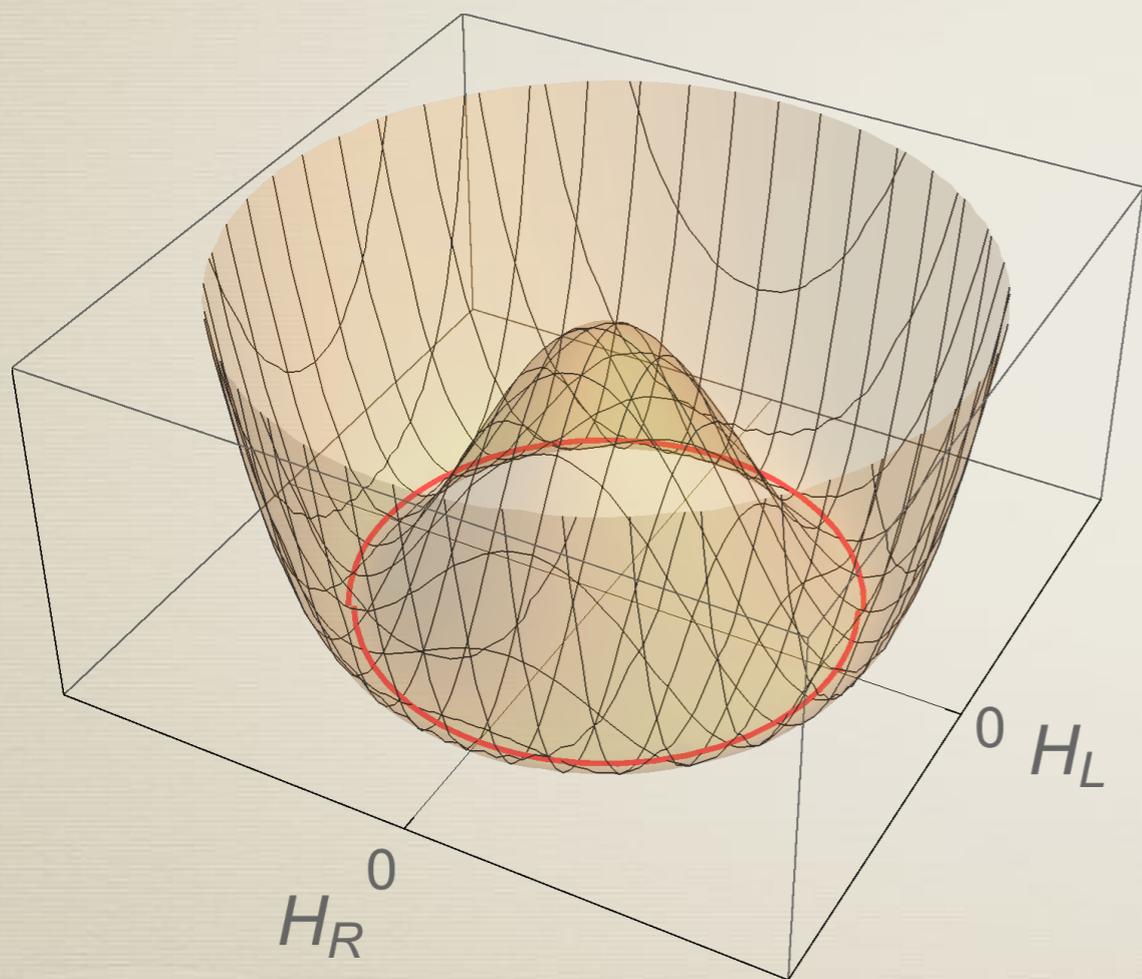
$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + y|H_L|^2|H_R|^2$$



~~$$\langle H_L \rangle \ll \langle H_R \rangle$$~~

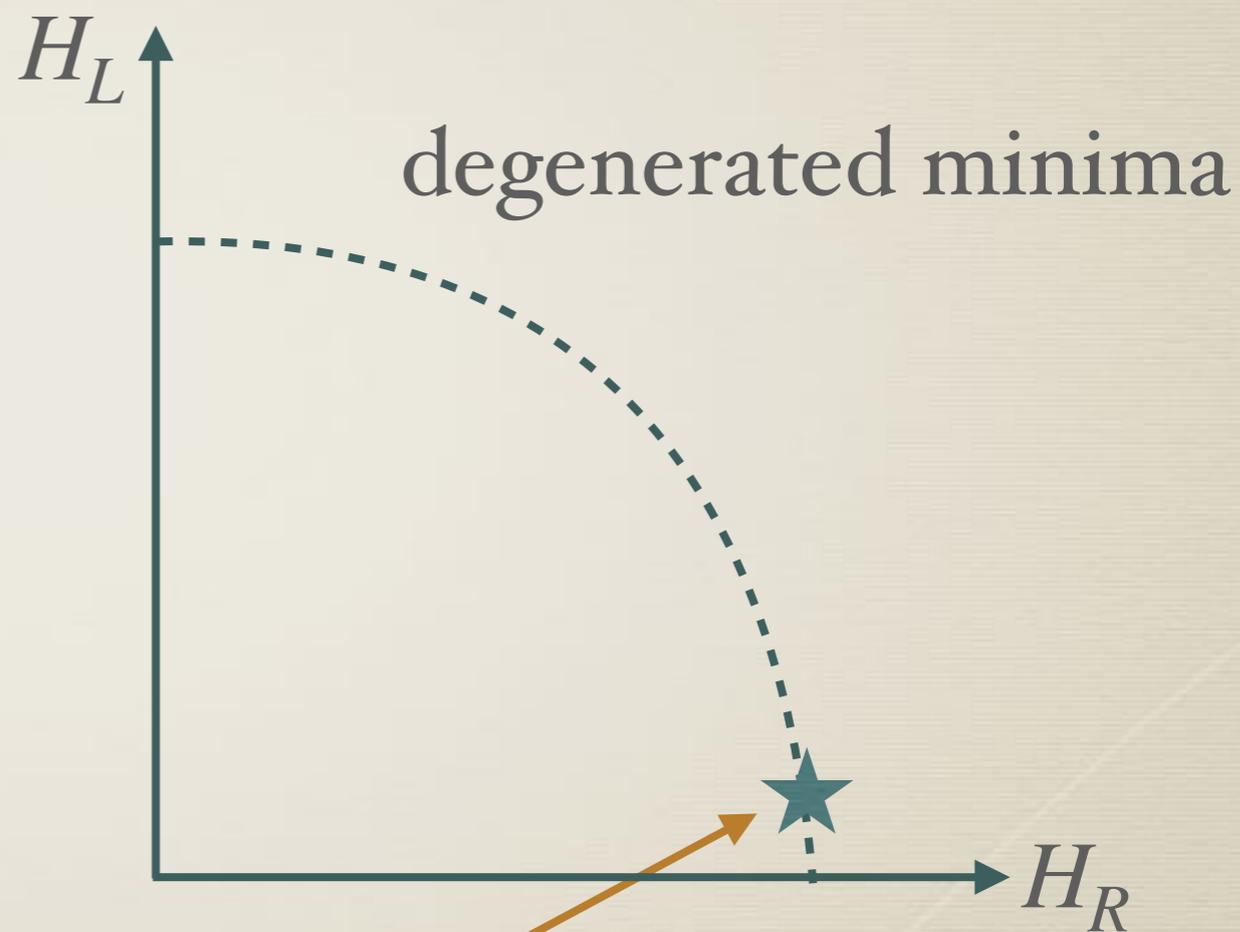
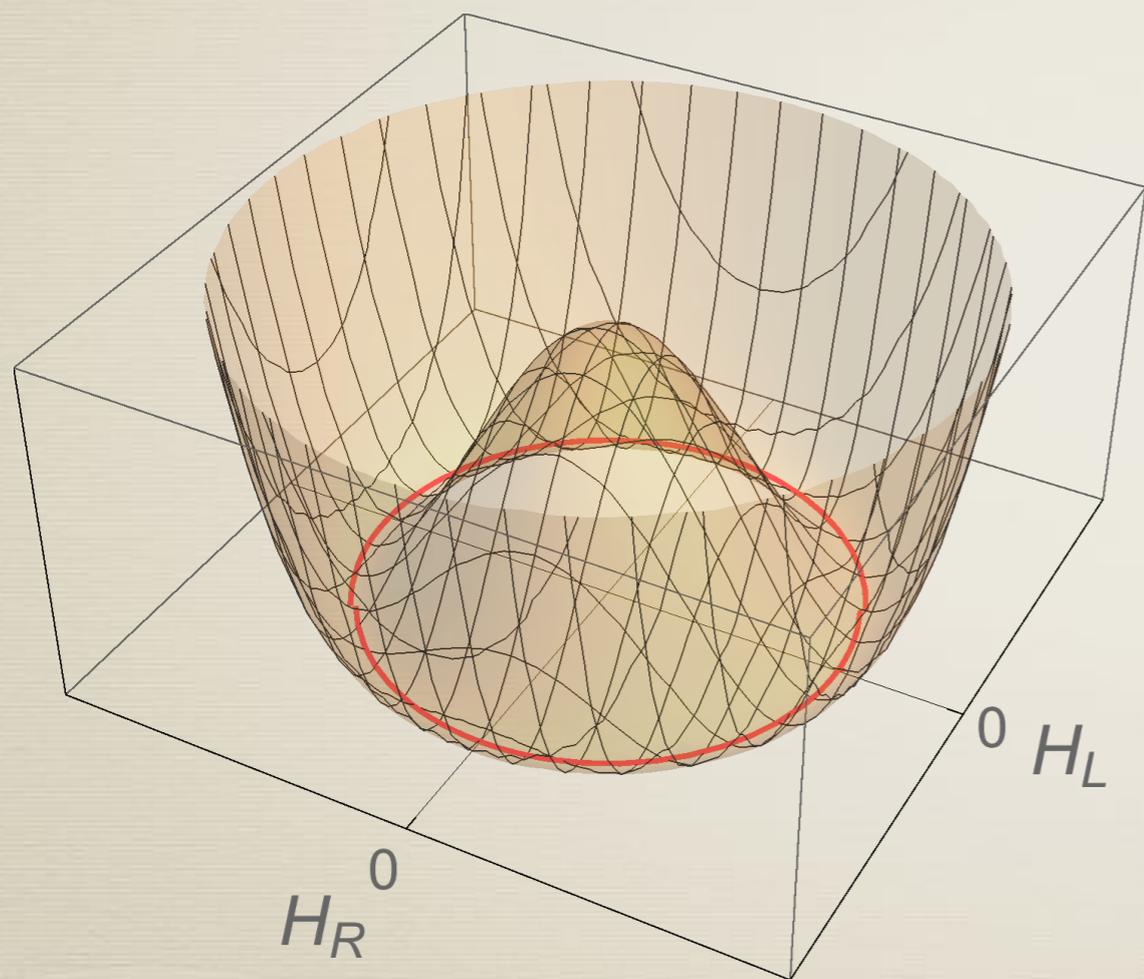
$$y \simeq 0$$

$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + \cancel{y|H_L|^2|H_R|^2}$$



$$y \simeq 0$$

$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + y|H_L|^2|H_R|^2$$



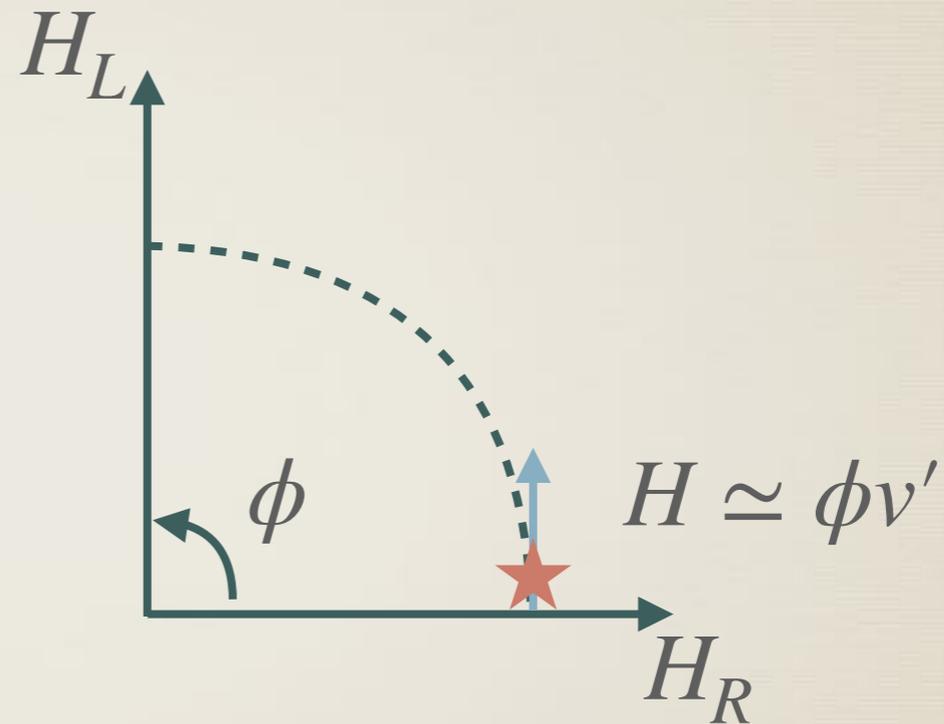
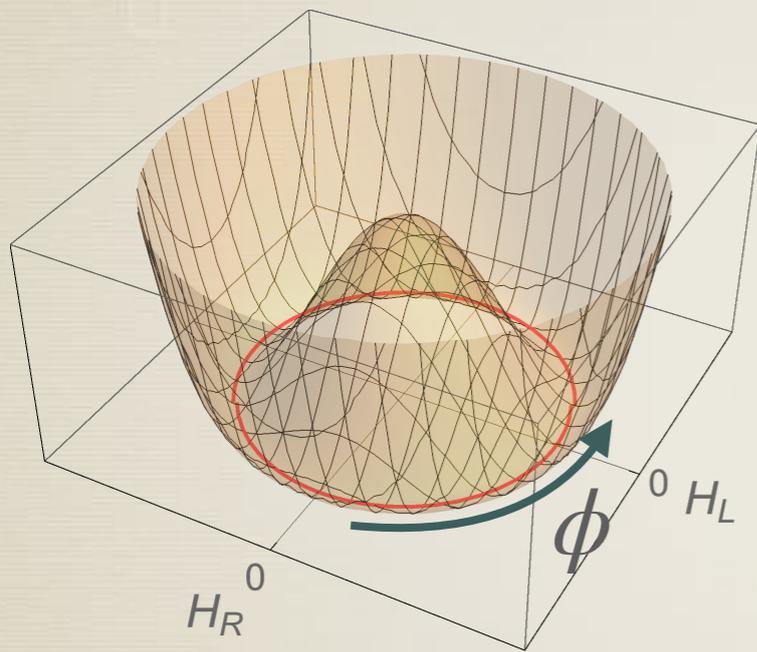
$$\langle H_L \rangle \ll \langle H_R \rangle$$

This point can become a minimum by quantum corrections

Prediction on the quartic coupling

Hall, KH (2018)

$$V \simeq \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + \text{small corrections}$$



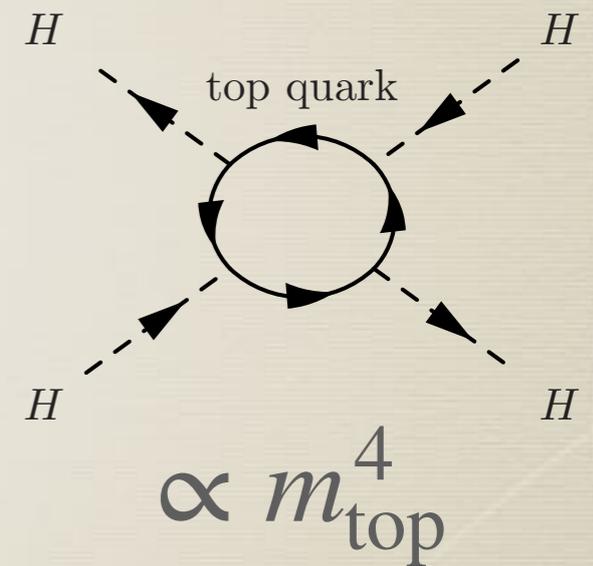
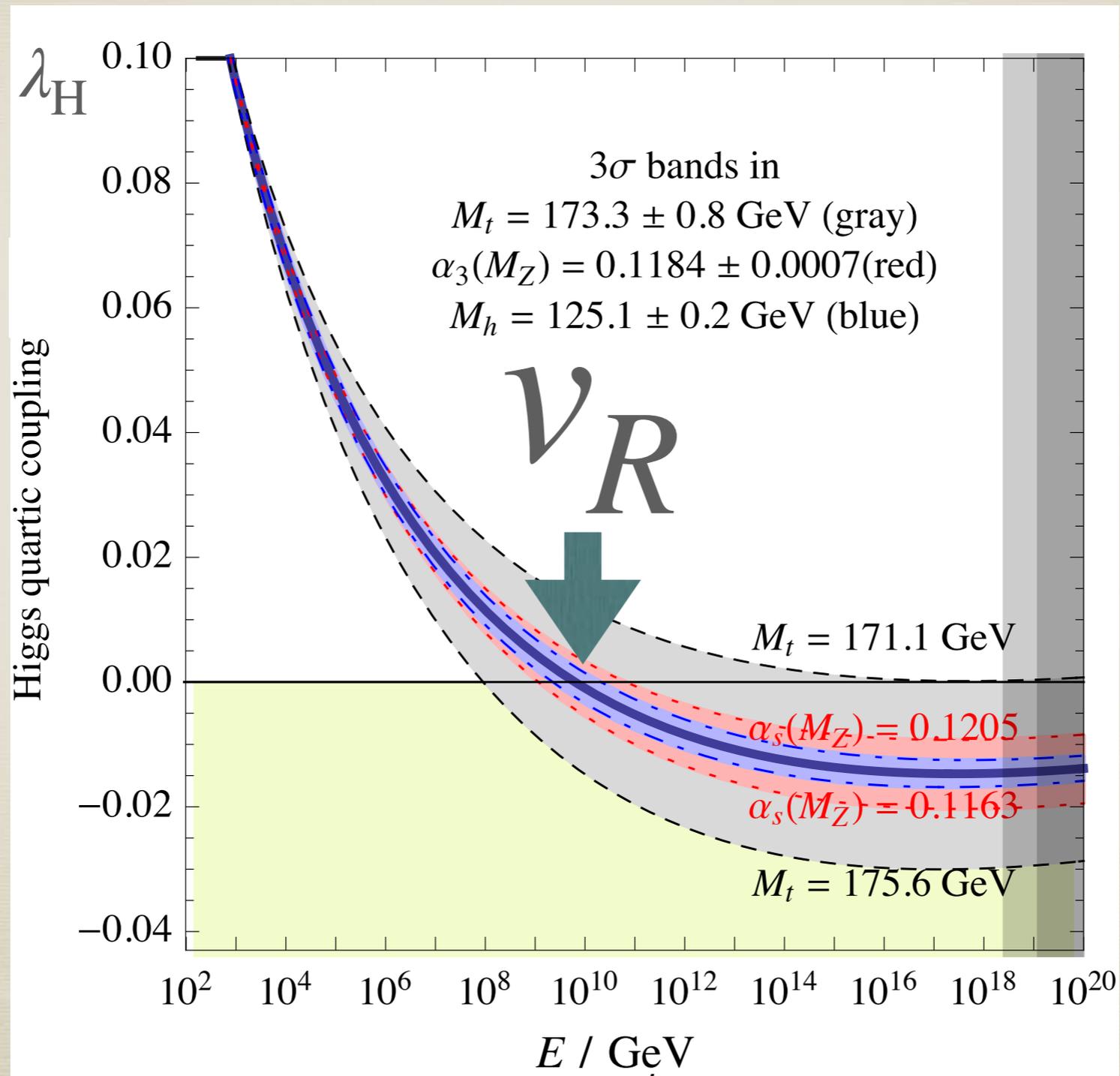
symmetry rotating the vector (H_L, H_R)

Standard Model Higgs is a (pseudo) Nambu-Goldstone boson associated with symmetry breaking by $\langle H_R \rangle = v' = v_R$

$$\lambda_{\text{SM}}(v_R) \simeq 0$$

(up to calculable threshold correction)

Vanishing self coupling



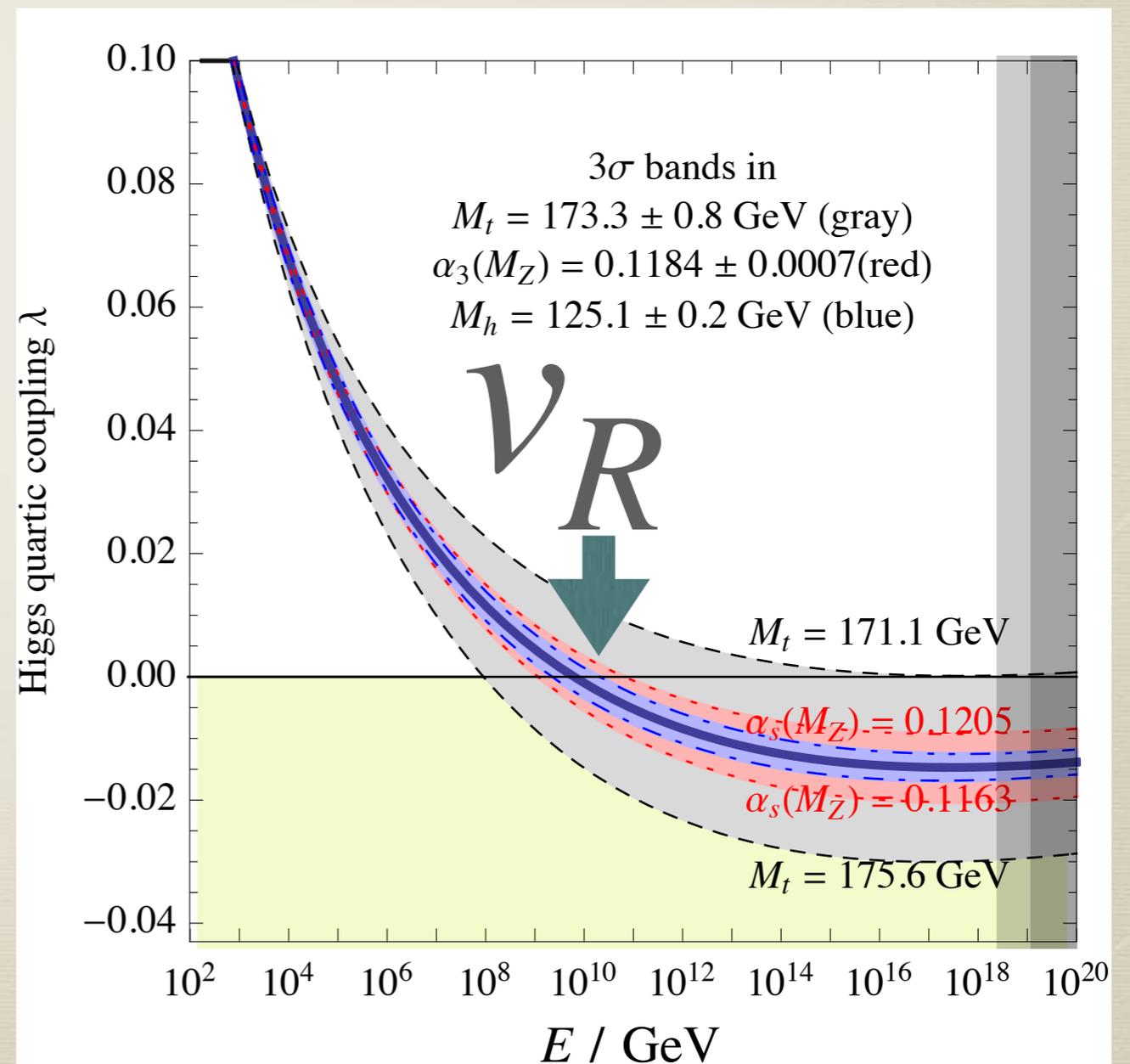
Precise measurement and parity

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

top quark mass
Higgs mass
strong coupling constant



Parity symmetry
breaking scale



Precise measurement and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

top quark mass
Higgs mass
strong coupling constant



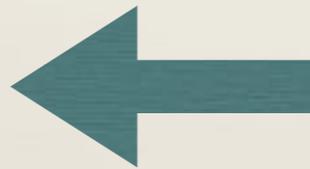
Parity symmetry
breaking scale



Baryogenesis,
Dark matter and its detection,
gauge coupling unification
and proton decay, ...

Outline

- * Strong CP problem and Parity solutions
- * Parity breaking
- * Phenomenology



* Leptogenesis

* $SO(10)$ unification

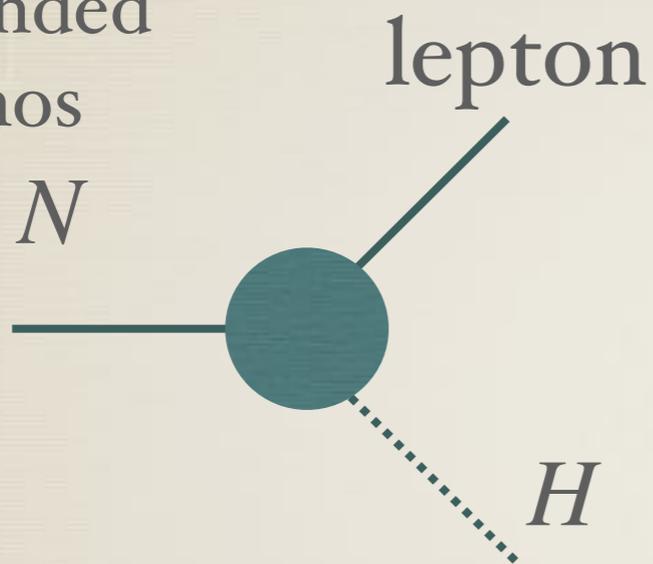
* Mirror electron dark matter

*

Leptogenesis

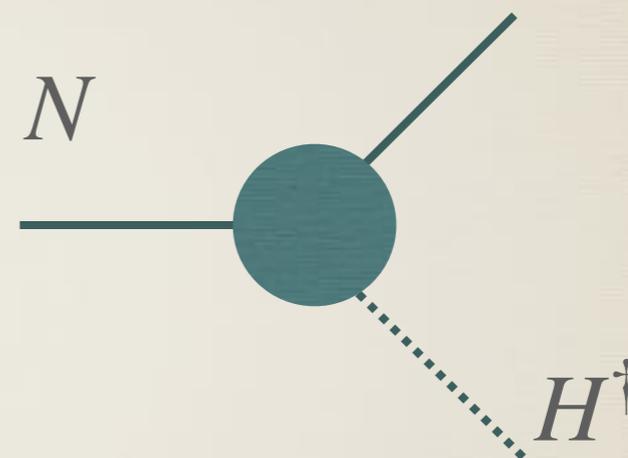
Fukugita and Yanagida (1986)

Right-handed
neutrinos



\neq

anti-lepton



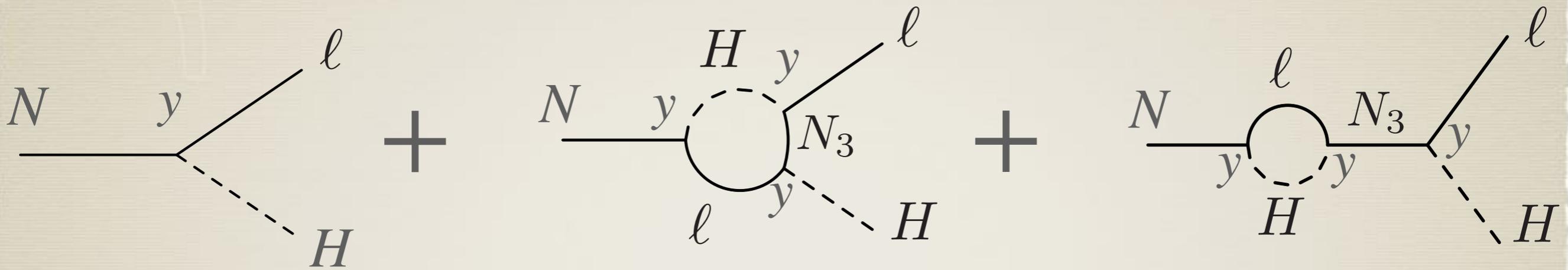
Lepton asymmetry



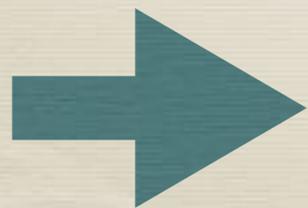
non-perturbative
weak process
(sphaleron)

Baryon asymmetry

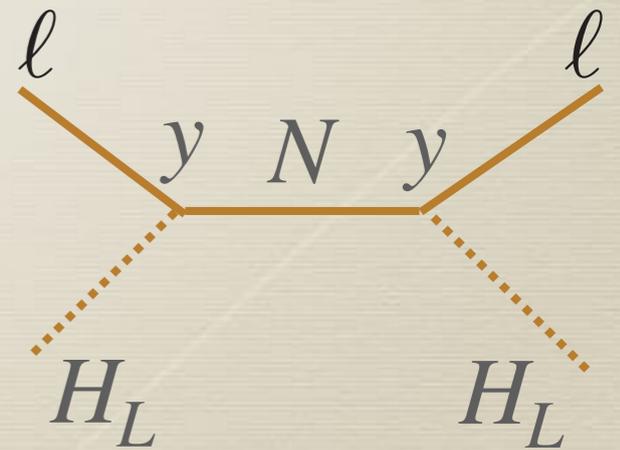
Leptogenesis



$$(\text{asymmetry}) \propto y^2 < \frac{m_\nu M_N}{v_L^2}$$



$$M_N \gtrsim 10^9 \text{ GeV}$$



Davidton and Ibarra (2002)

Leptogenesis

$$\ell = (\nu, e), \quad \bar{\ell} = (N, \bar{e})$$

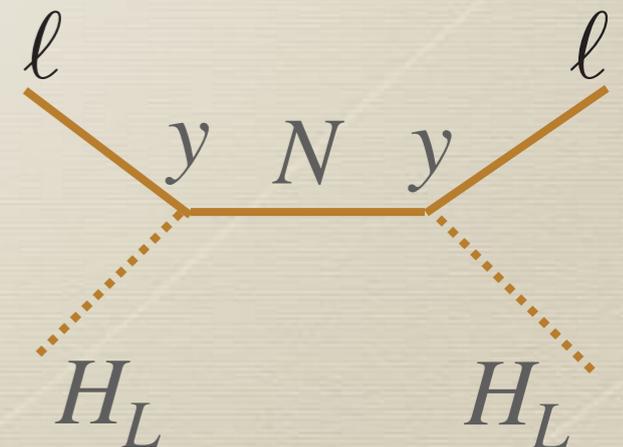
$$\frac{c}{2\Lambda} \ell\ell H_L H_L + \frac{c}{2\Lambda} \bar{\ell}\bar{\ell} H_R H_R + \frac{d}{\Lambda} \ell\bar{\ell} H_L H_R$$

$$\frac{c}{2\Lambda} \ell\ell H_L H_L + \frac{M_N}{2} N N + y \ell N H_L$$

$$M_N = \frac{c}{\Lambda} v_R^2$$

$$y = \frac{v_R}{\Lambda} d$$

$$m_\nu = M_N \left(\frac{v_L}{v_R} \right)^2 - \frac{y^2 v_L^2}{M_N}$$



Leptogenesis

$$10^9 \text{ GeV} < M_N < m_\nu \frac{v_R^2}{v_L^2}$$

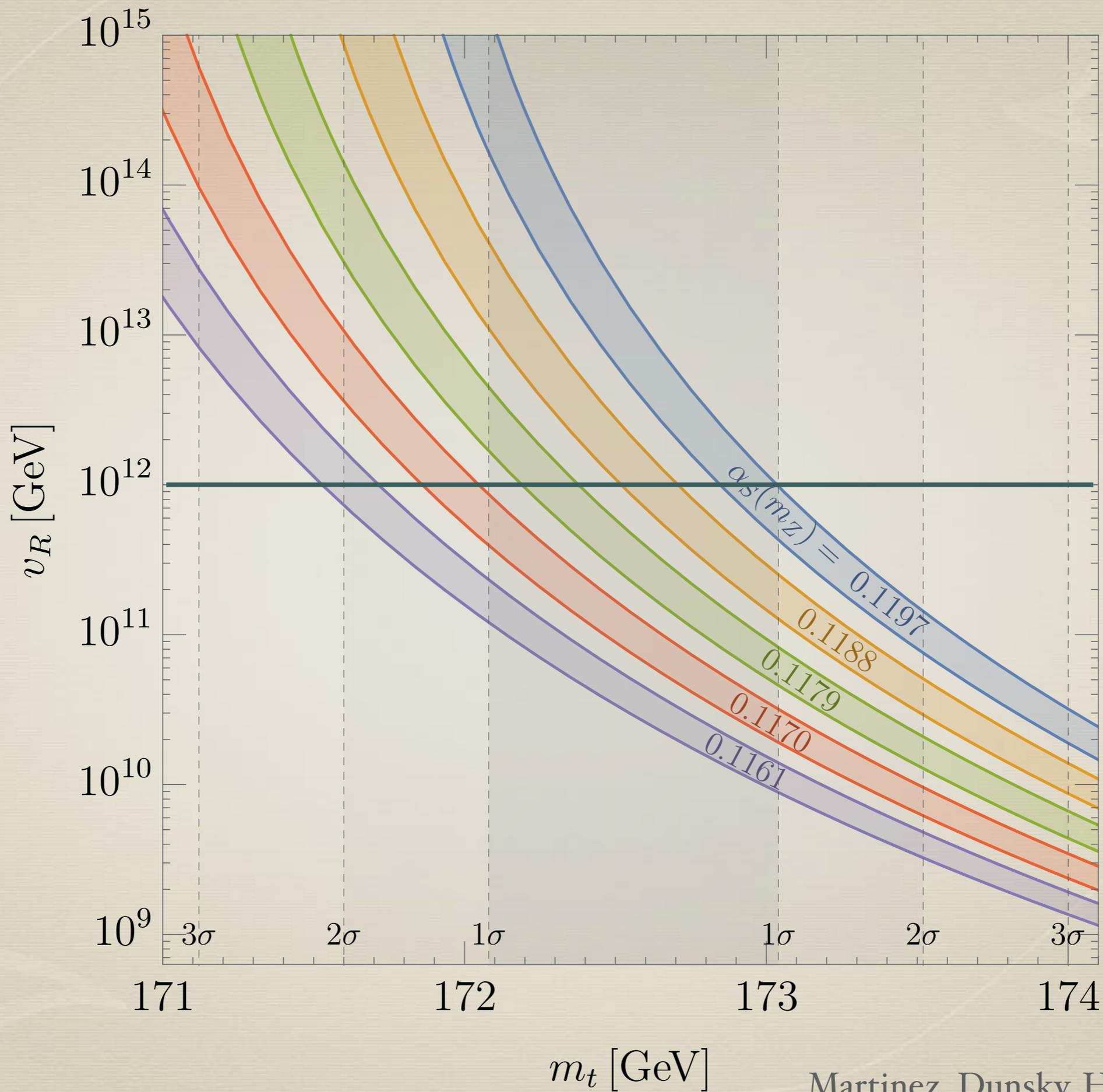
leptogenesis

No fine-tuning in m_ν

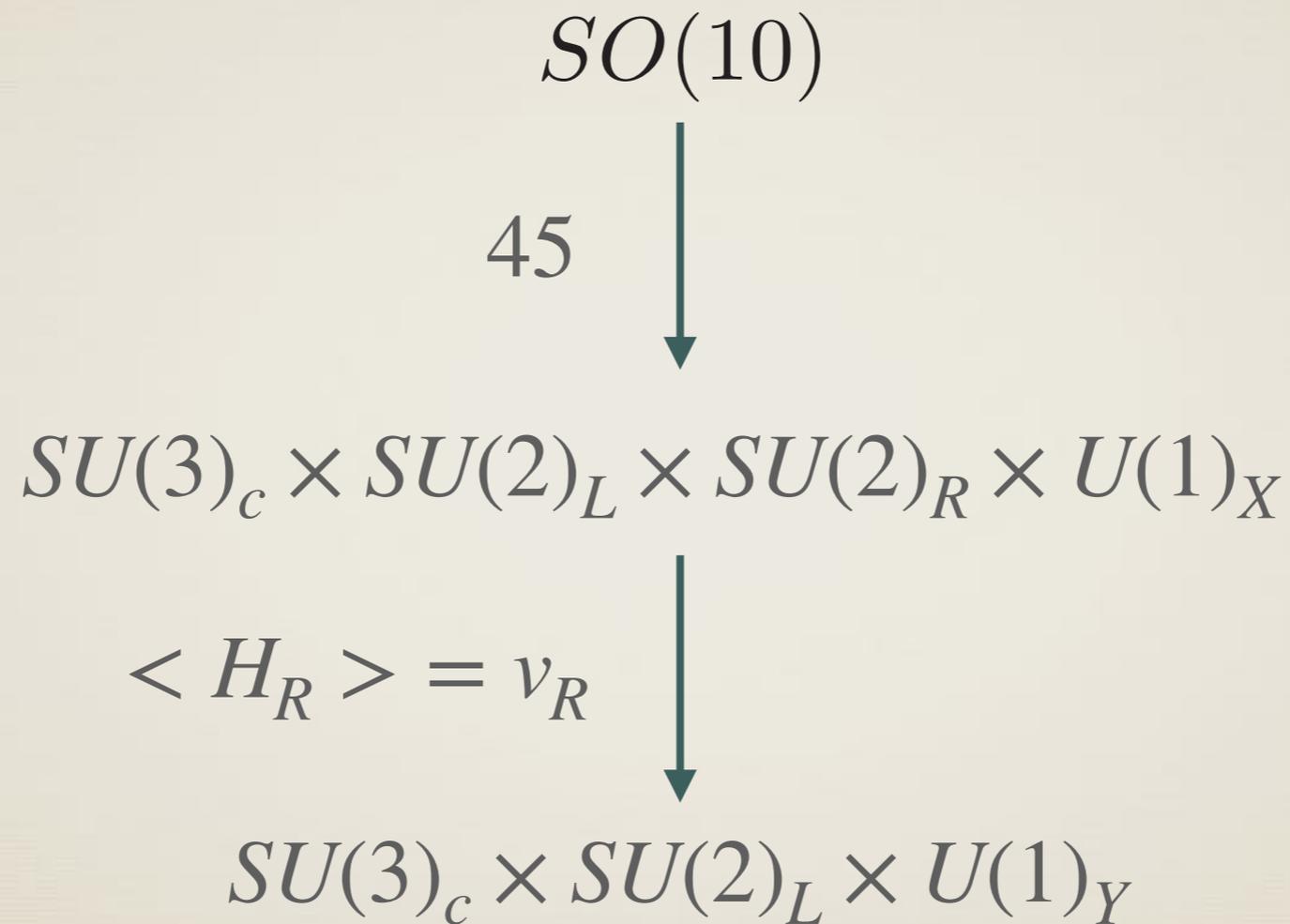
$$v_R \gtrsim 10^{12} \text{ GeV}$$

Martinez, Dunsky, Hall, KH (2023)

(can be relaxed by some degeneracy of right-handed neutrinos)



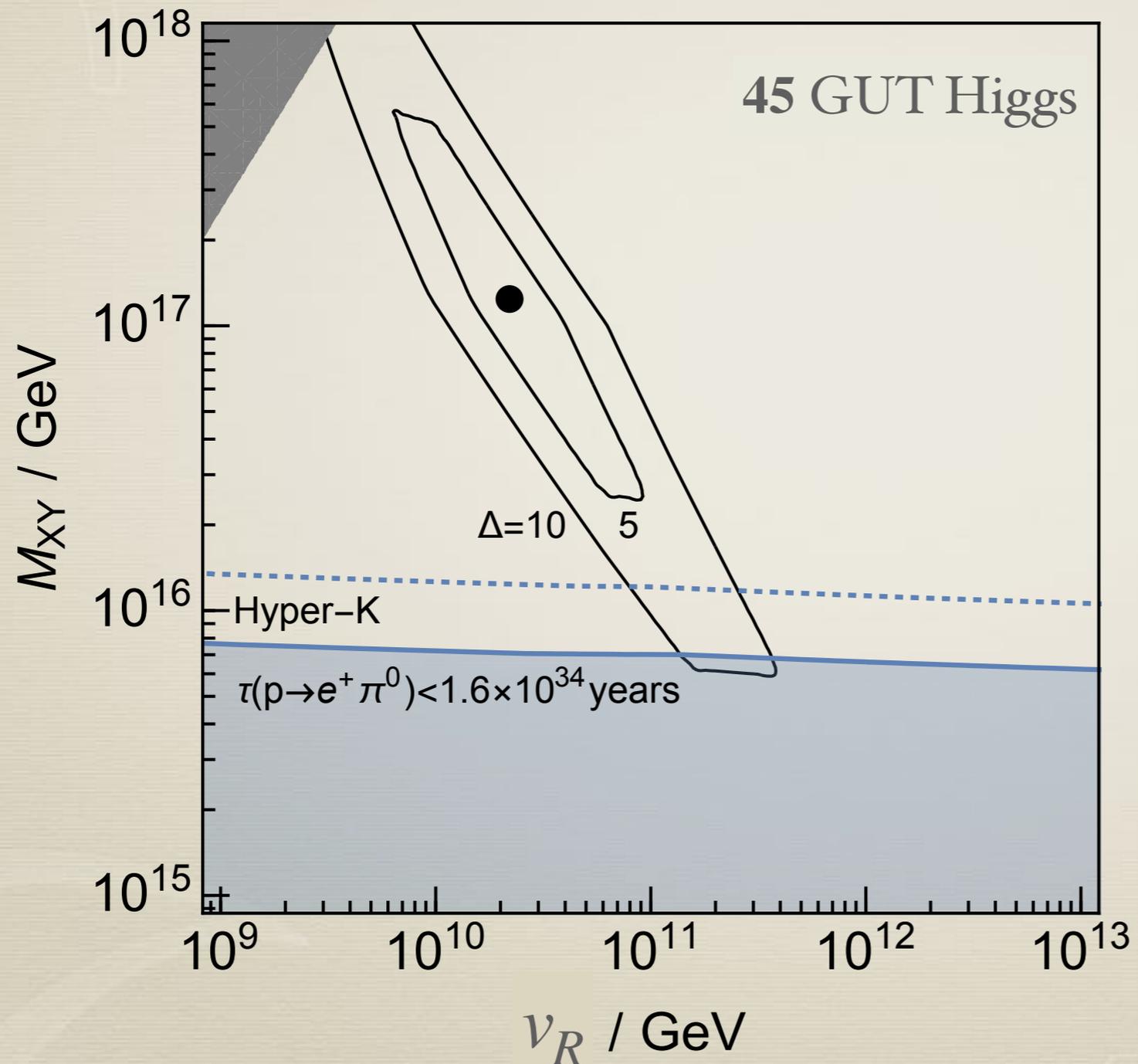
SO(10) unification



Range of v_R is restricted by gauge coupling unification

SO(10) unification

Hall, KH (2019)



There can be quantum corrections from heavy particles around the GUT scale

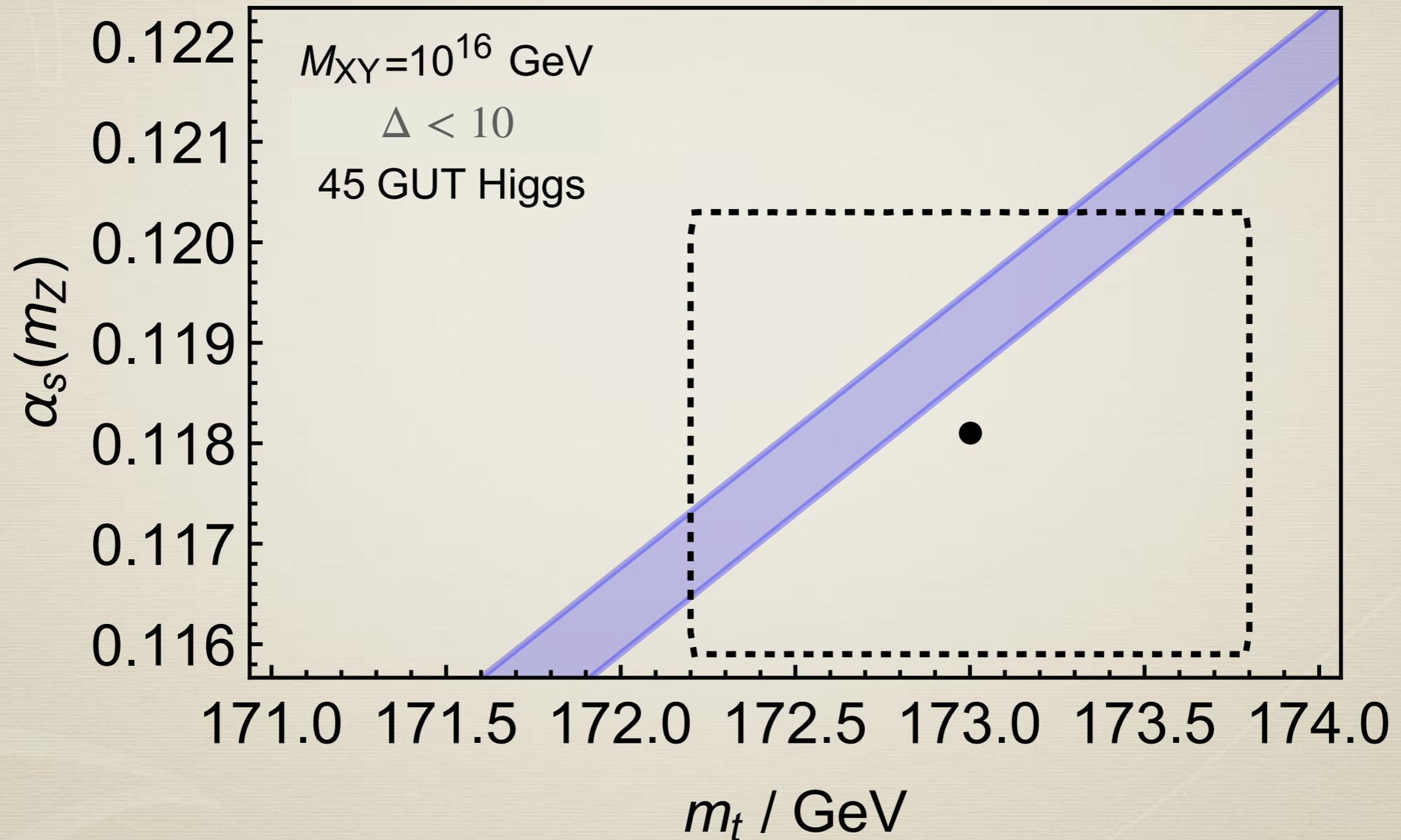
$$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$$

typically

$$\Delta = \text{few} - 10$$

(smaller than SUSY GUT)

SO(10) unification



Mirror electron Dark Matter

SM particles

q, u, d
L, e
H
 γ, W, Z



Mirror particles

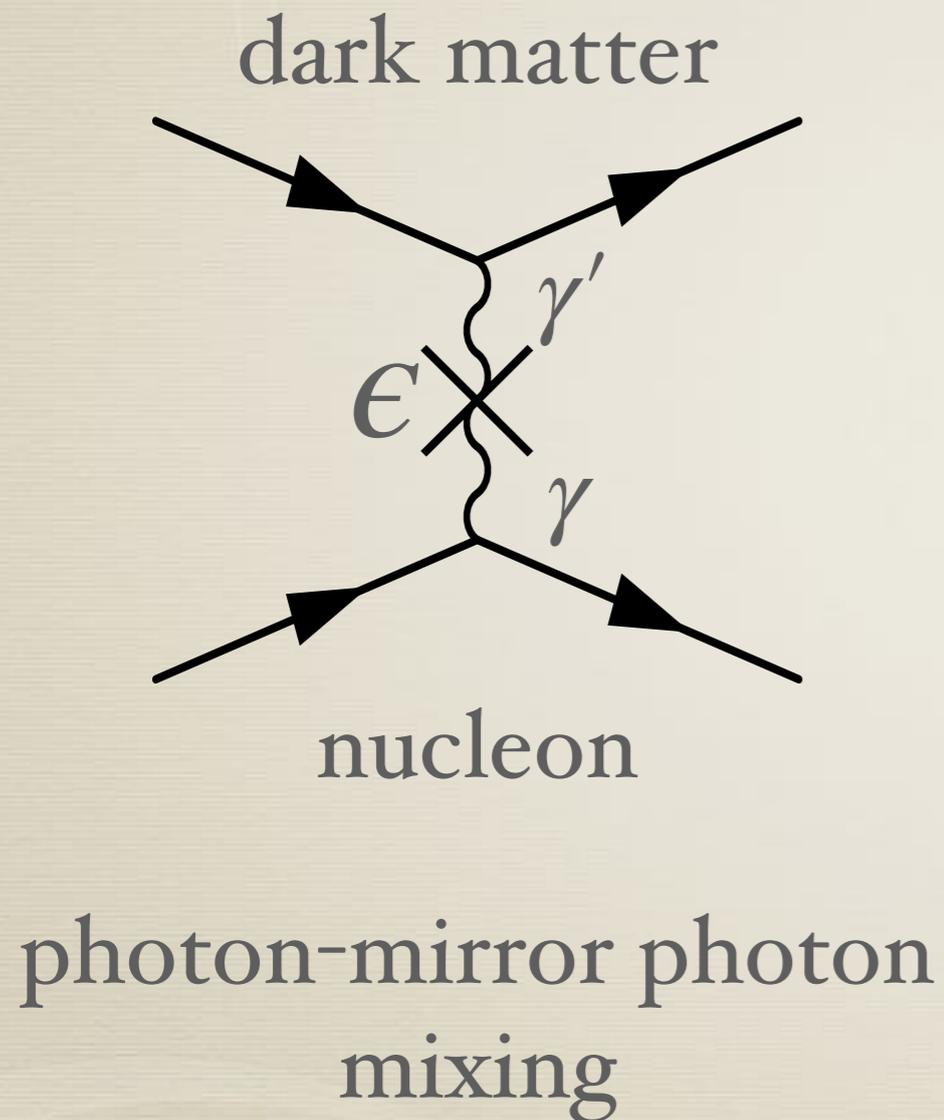
q', u', d'
L', e'
H'
 γ', W', Z'

Mirror electron is stable due to $U(1)_{EM'}$ and
a dark matter candidate with a mass

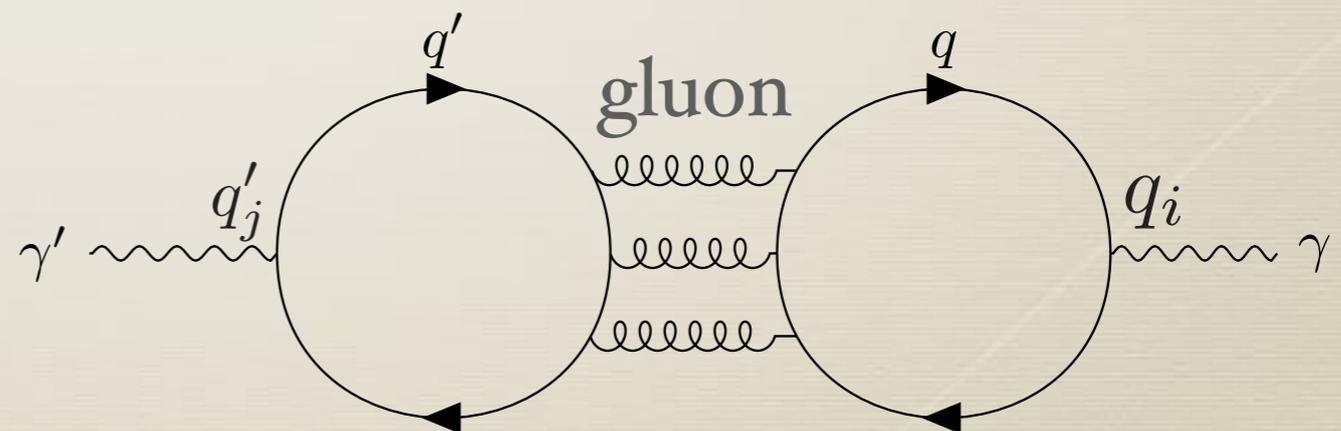
$$m_{e'} = m_e \frac{v_R}{v_L}$$

Mirror electron Dark Matter

Dunsky, Hall, KH (2019)



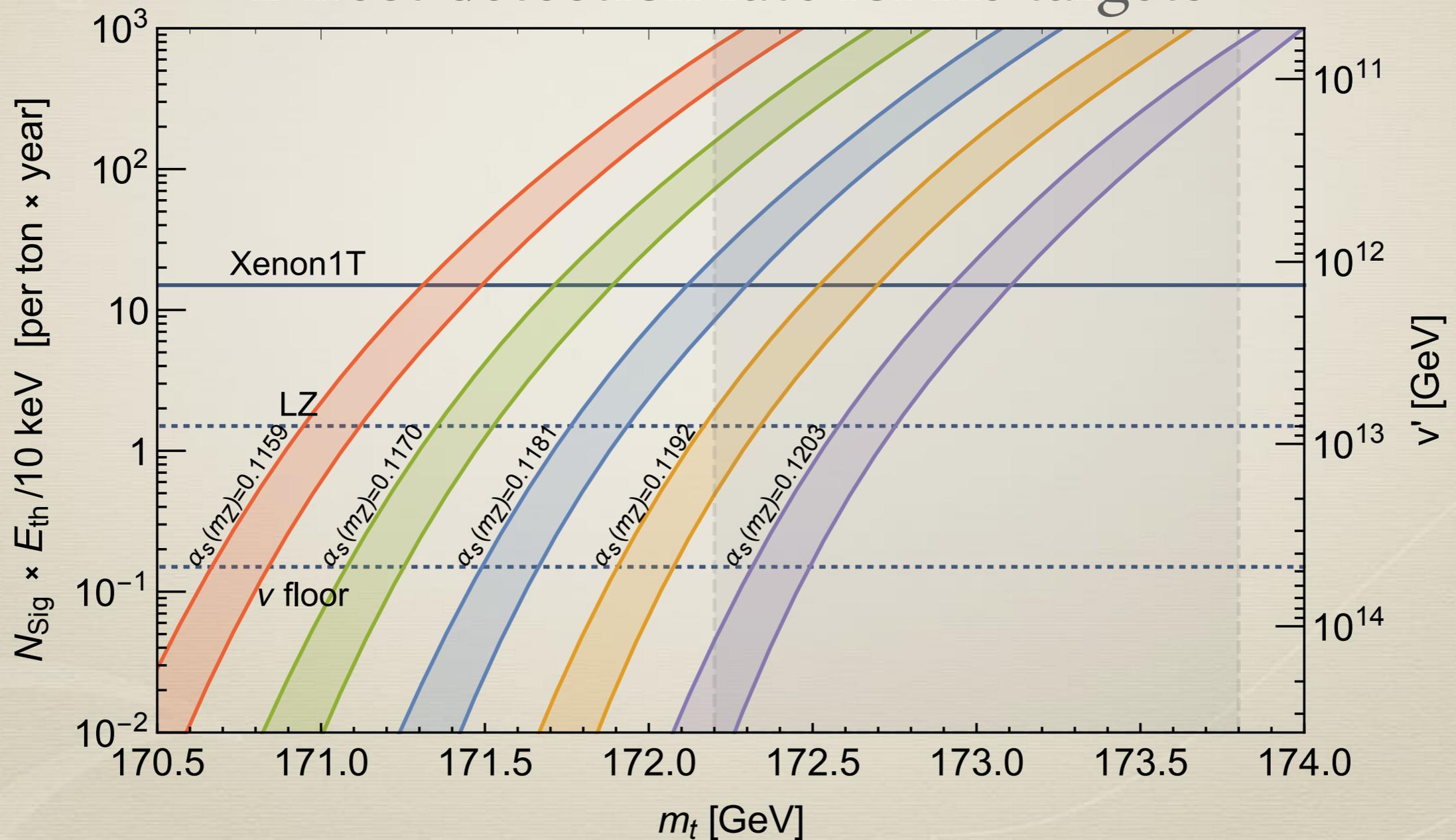
$$\epsilon = \epsilon_{\text{tree}} + \epsilon_{\text{quantum correction}}$$



Mirror electron Dark Matter

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets



Summary

- * The strong CP problem may be solved by Parity symmetry
- * In models with the minimal Higgs content, the Parity breaking scale can be determined by the SM parameters
- * Signals of or constraints on baryogenesis, dark matter, or gauge coupling unification models are correlated with SM parameters

New Physics at LHC and beyond

We should maximize the impact of future colliders



* Searches for new particles

* Searches for deviation from the standard model predictions

$$N_{\text{events}} = N_{\text{SM prediction}} ?$$

* **Precise measurements of standard model parameters**

top quark mass,
strong coupling constant,
Higgs mass, etc.

Any other new physics models
impacted by precise measurements of parameters?

Backup

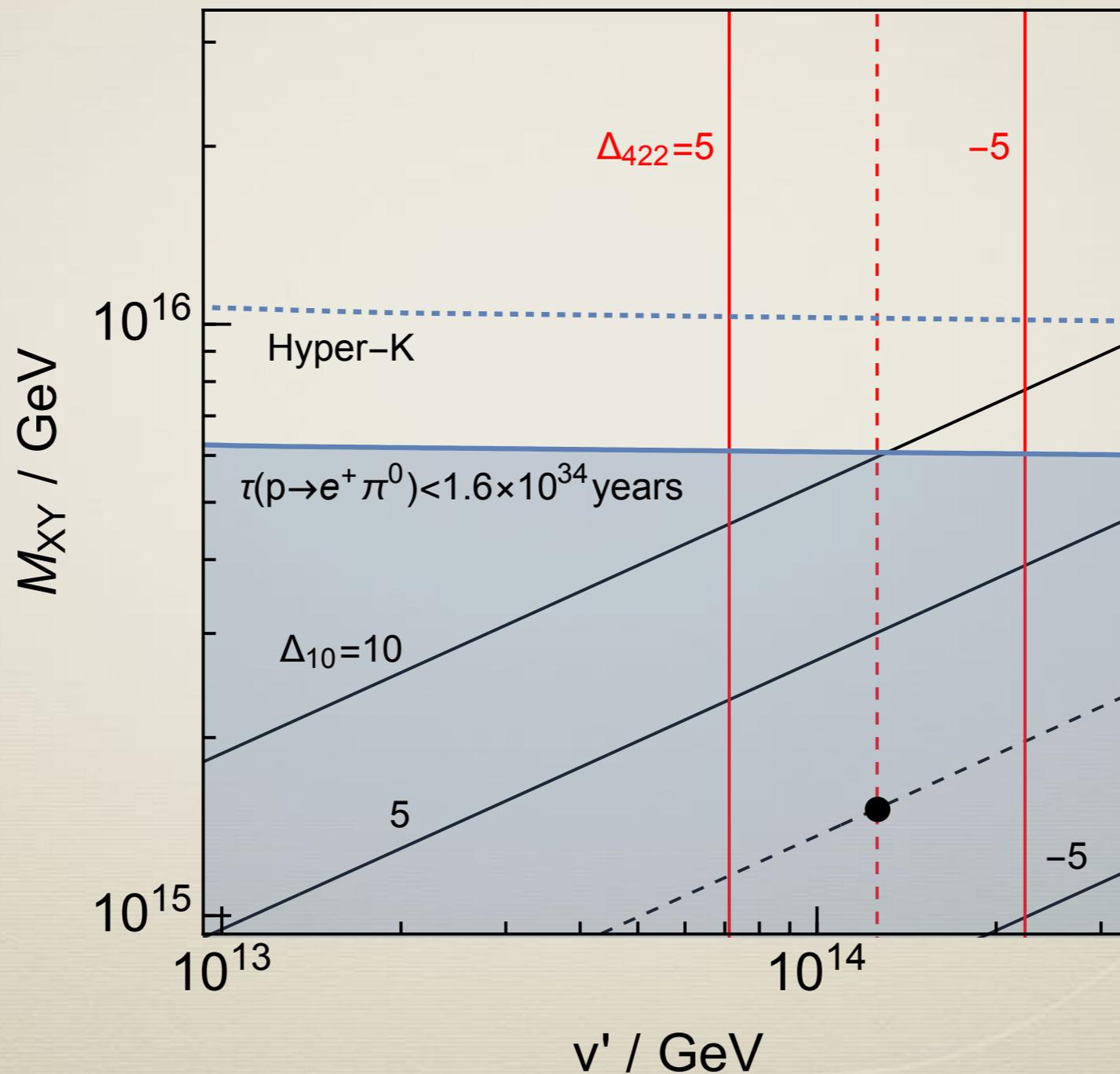
Fine-tuning

$$V = \lambda \left(|H_L|^2 + |H_R|^2 - v_R^2 \right)^2 + y |H_L|^2 |H_R|^2$$

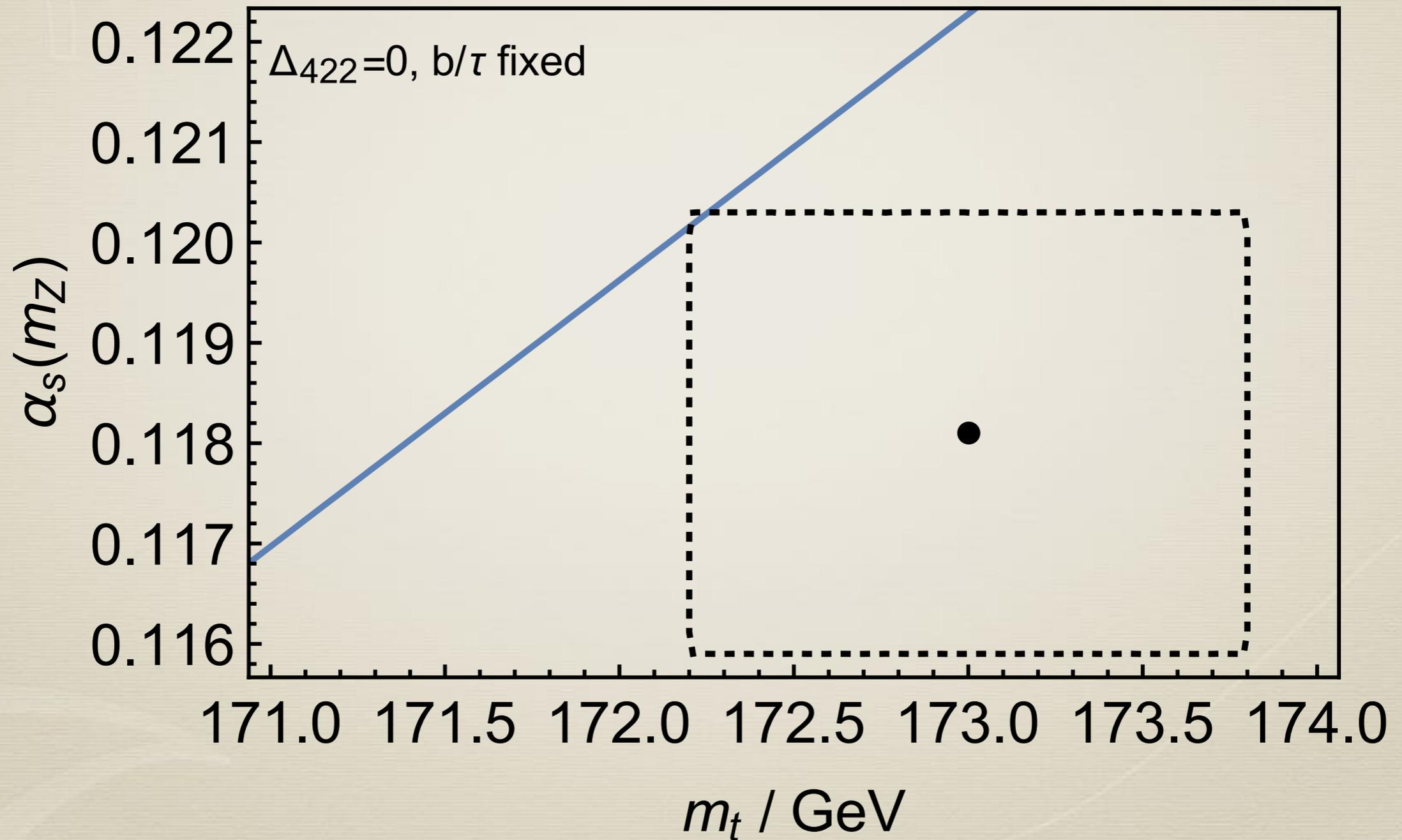

$$\frac{v_R^2}{\Lambda_{\text{cut}}^2} \times \frac{v^2}{v_R^2} = \frac{v^2}{\Lambda_{\text{cut}}^2}$$

Despite the intermediate scale v_R ,
same as that of standard model

Pati-Salam



Pati-Salam

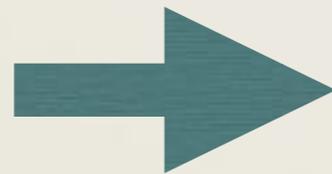


Composition of DM



$$m_{u'u'u'} \simeq 4m_{e'}$$

$$Q_{u'u'u'}^2 = 2^2 = 4Q_{e'}^2$$



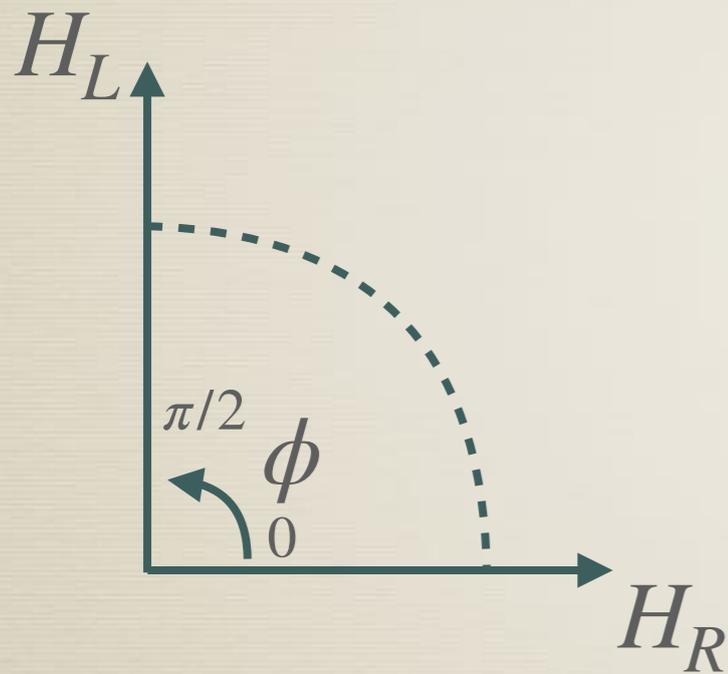
Signal rates are independent of relative fractions

But the abundance of fractionally charged particles, such as $u'ud$, must be suppressed

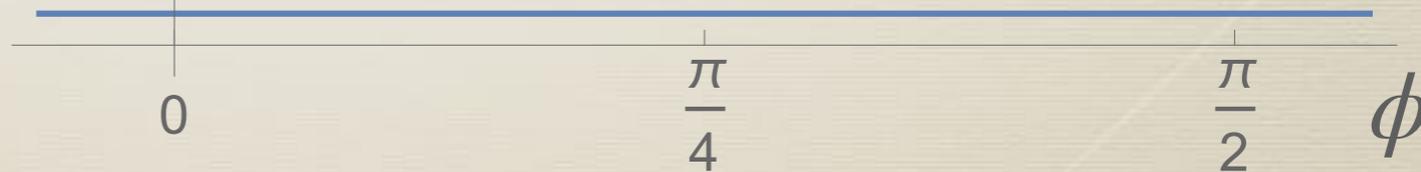
$$y \simeq 0$$

$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2$$

$V(\phi)$ $y = 0$, tree level



angular direction ϕ

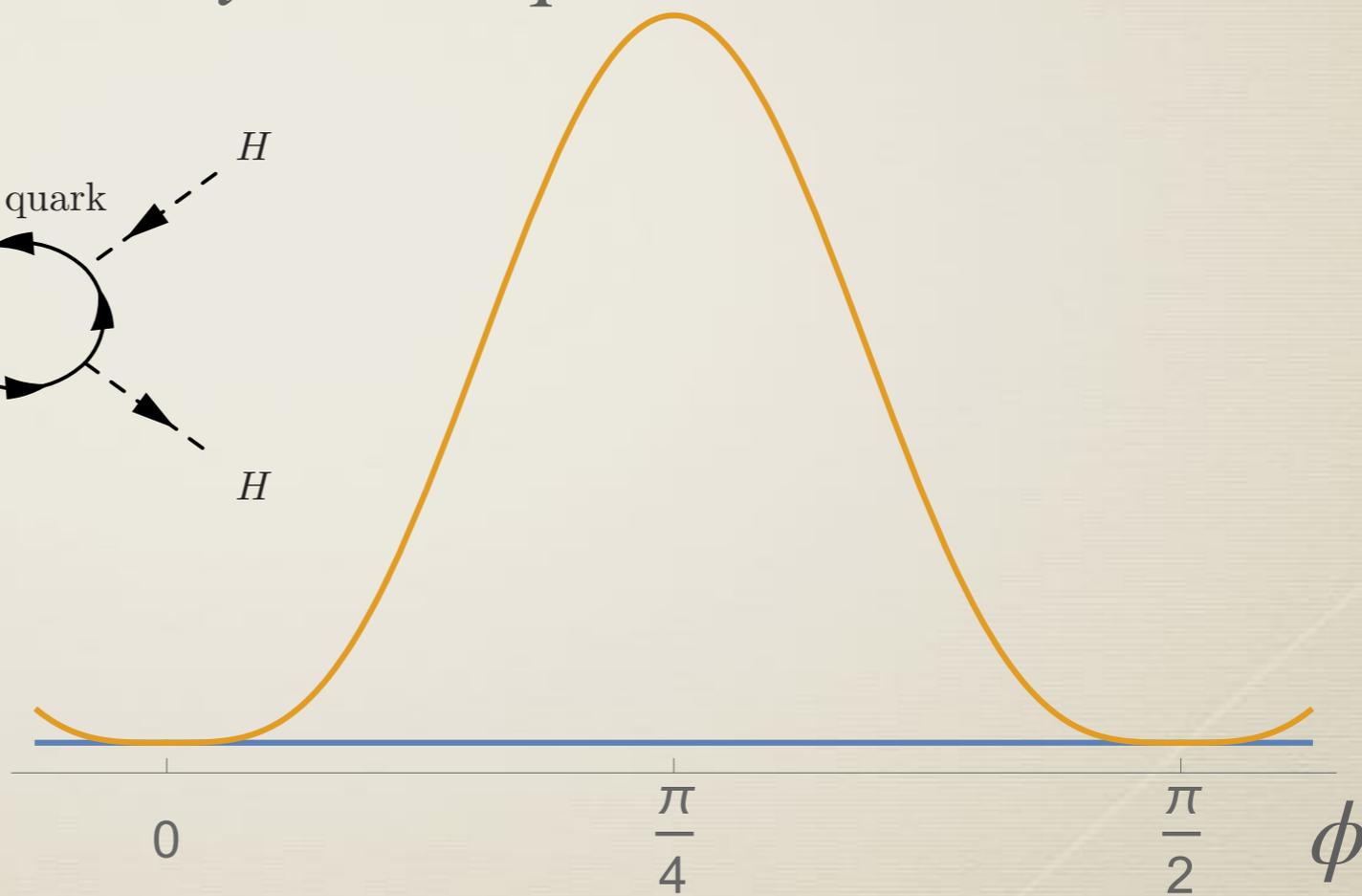
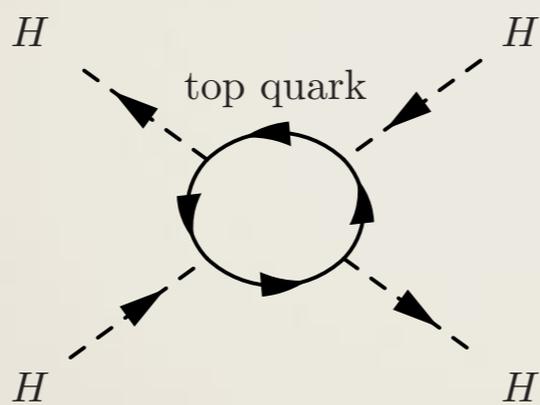
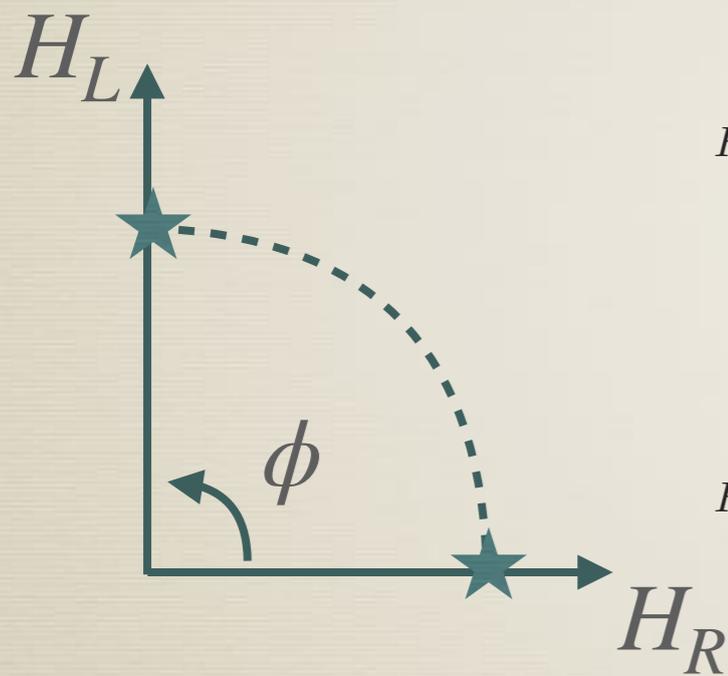


$$y \simeq 0$$

Colemann-Weinberg potential

$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + V_{\text{quantum}}(H_L, H_R)$$

$y = 0$, quantum correction



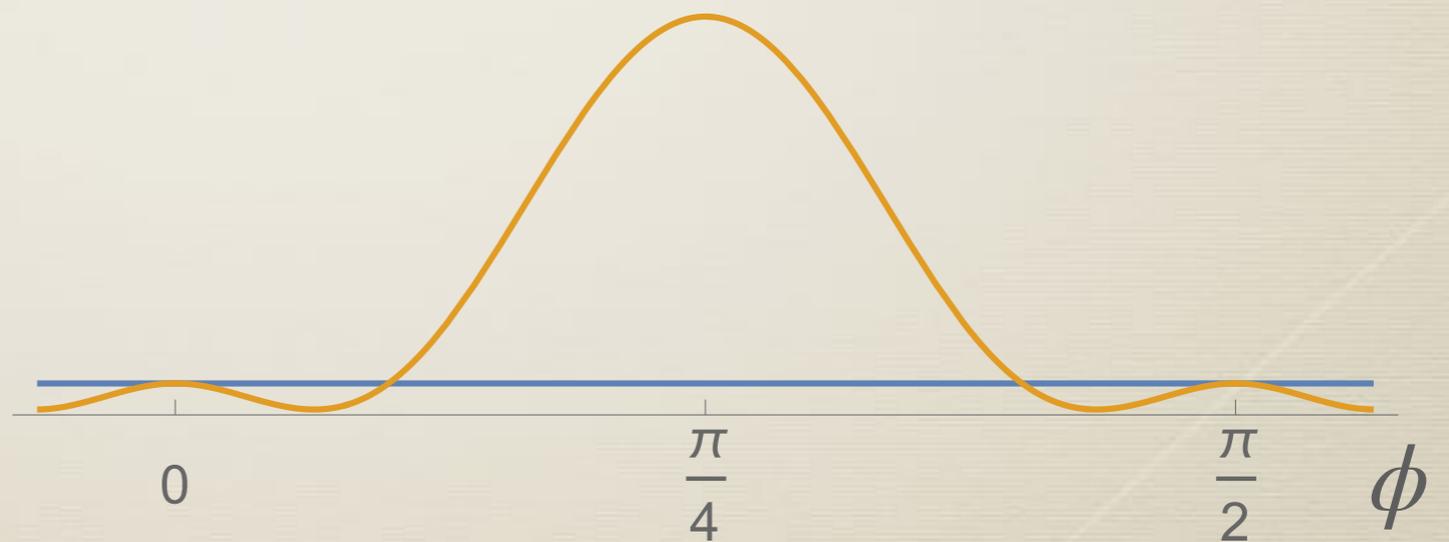
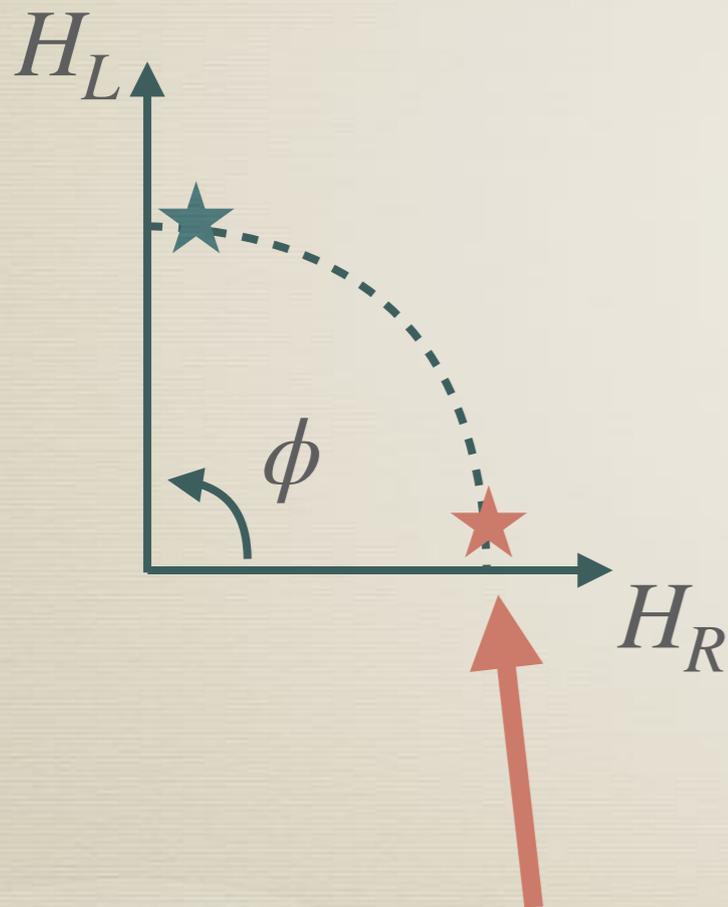
$$y \simeq 0$$

$$V = \lambda(|H_L|^2 + |H_R|^2 - v'^2)^2 + V_{\text{quantum}}(H_L, H_R) + y|H_L|^2|H_R|^2$$

$$y \simeq -\frac{v^2}{v'^2}, \text{ quantum correction}$$



(fine-tuned Higgs mass)



$\langle H_L \rangle \ll \langle H_R \rangle$ is achieved!

Hall, KH (2018)