



Baryogenesis from Parity Solution to the Strong CP Problem

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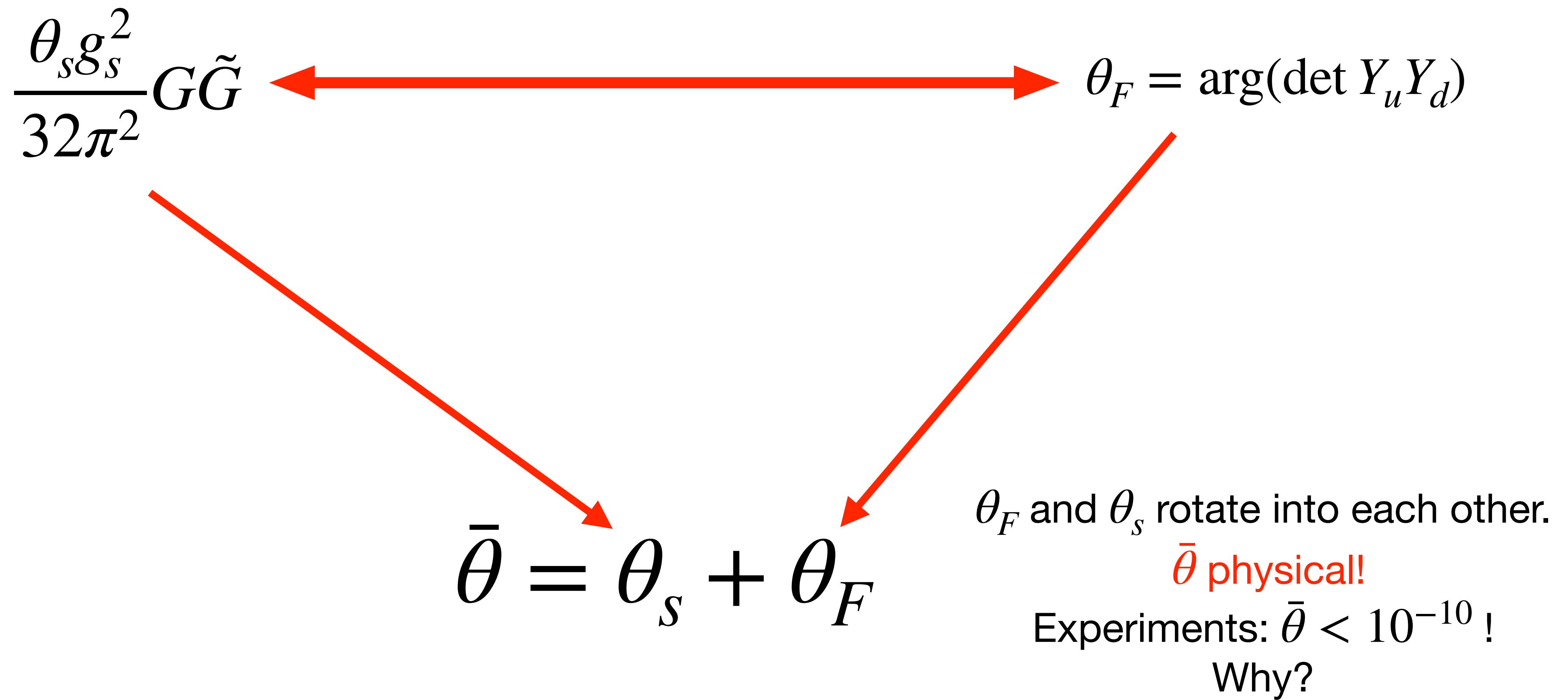


Unsolved problems in particle physics

- The Strong CP problem
- Baryon number asymmetry of the universe (BAU)
- Origin of neutrino mass



The Strong CP Problem





Parity Solution to the Strong CP (1): Particle Content

- Gauge group: $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$.

	H_L	H_R	q_i	\bar{q}_i	ℓ_i	$\bar{\ell}_i$	U_i	\bar{U}_i	D_i	\bar{D}_i	E_i	\bar{E}_i
$SU(3)_c$	1	1	3	$\bar{3}$	1	1	3	$\bar{3}$	3	$\bar{3}$	1	1
$SU(2)_L$	2	1	2	1	2	1	1	1	1	1	1	1
$SU(2)_R$	1	2	1	2	1	2	1	1	1	1	1	1
$U(1)_X$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$-\frac{1}{6}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	-1	1

- Symmetric Higgs potential: $-\frac{1}{2}\mu_L^2 h_L^2 - \frac{1}{2}\mu_R^2 h_R^2 + \frac{1}{4}\lambda(h_L^4 + h_R^4) + \frac{\lambda_{LR}}{4}h_L^2 h_R^2$
- Yukawa: $y_u \bar{q} U H_R^\dagger + y_d \bar{q} D H_R + \bar{y}_u q \bar{U} H_L^\dagger + \bar{y}_d q \bar{D} H_L + y_e \bar{\ell} E H_R + \bar{y}_e \ell \bar{E} H_L$
- Extra Dirac mass term: $m_{ij}^u \bar{U}^i U^j + m_{ij}^d \bar{D}^i D^j + m_{ij}^e E_i \bar{E}_j$

[K. S. Babu and R. N. Mohapatra,
Phys. Rev. D41 (1990) 1286],
[L. J. Hall and K. Harigaya, 1803.08119]
[N. Craig et al, 2012.13416]



Parity Solution to Strong CP (2): Fermion Masses

Masses generated from: $y_u \bar{q} U H_R^\dagger + \bar{y}_u q \bar{U} H_L^\dagger + m_{ij}^u U \bar{U}$

- $yv_R \gg m^u$: SM quark q , \bar{U} has yv_L , mirror quark \bar{q} , U has yv_R .
- $yv_R \ll m^u$: integrate out heavy fermion \bar{U} , U . SM fermion q, \bar{q} have $\frac{y_u \bar{y}_u}{M} q \bar{q} H_L^\dagger H_R^\dagger$

Parity: $q \leftrightarrow \bar{q}^\dagger, \bar{U} \leftrightarrow U^\dagger, H_L \leftrightarrow H_R^\dagger$

Forces $y_u = \bar{y}_u^\dagger, y_d = \bar{y}_d^\dagger$

From each theory $\theta_F = \arg(y_u y_d) + \arg(\bar{y}_u \bar{y}_d) = 0$

θ_s directly forbidden by parity ($G\tilde{G}$ violates parity)



Options for Neutrino Masses

Dirac Type:

$$c_{ij}^D \ell_i \bar{\ell}_j H_L^\dagger H_R^\dagger + \text{h.c.},$$

m_{ν_R} : same as SM ones, behaves as dark radiation.

Radiative inverse seesaw:

$$\chi_i \left(y_{ij}^\chi \ell_j H_L^\dagger + y_{ij}^{\chi*} \bar{\ell}_j H_R^\dagger \right) + m_{\chi,i} \chi_i^2,$$

m_{ν_R} : $y^\chi \nu_R$, decays into SM lepton and Higgs. Can be heavy.

m_{ν_L} : generated by loops. $m_\nu \sim \frac{(y^\chi)^2}{16\pi^2} \frac{m_\chi v_L^2}{(y^\chi v_R)^2} = \frac{1}{16\pi^2} \frac{m_\chi v_L^2}{v_R^2} \sim 0.1 \text{ eV} \frac{m_\chi}{10 \text{ MeV}} \left(\frac{100 \text{ TeV}}{v_R} \right)^2$,

Other options also available.

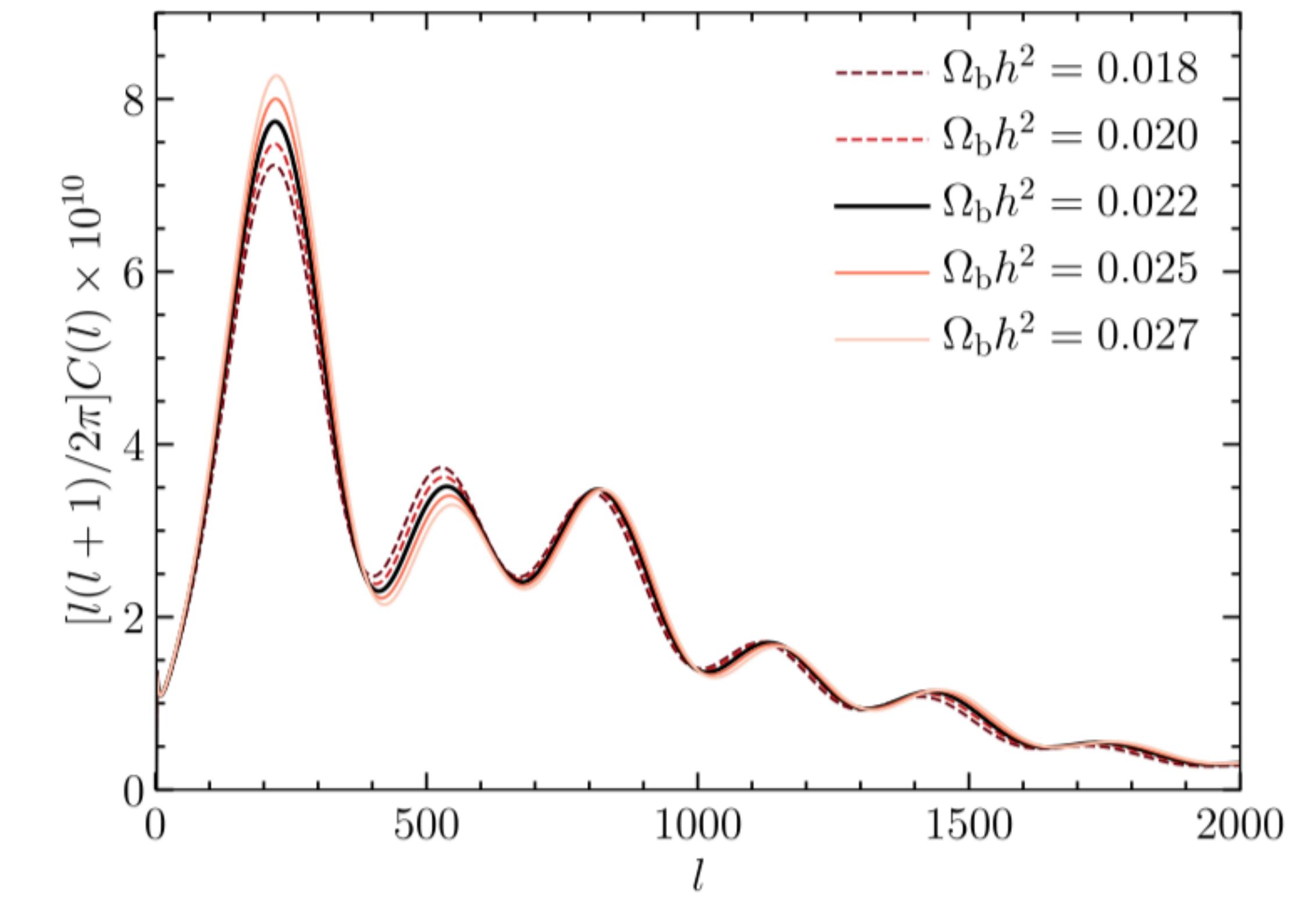
[K.Harigaya and IW, 2210.16207]

[P. S. B. Dev and A. Pilaftsis, 1209.4051]



Baryon Number Asymmetry (Baryogenesis)

- matter > anti-matter
- Define
 $n_B = n_{\text{baryon}} - n_{\text{anti-baryon}}$
- $\Omega_b h^2 \simeq 0.022, \frac{n_B}{s} \simeq 9 \times 10^{-11}$
- What's the origin?



Planck 2018b



Sakharov Condition

- **Baryon number violation**

SM: sphaleron process. Violates $B + L$ but keeps $B - L$.

- **C and CP violation**

SM: CKM (too small), or UV scale new physics, model dependent.

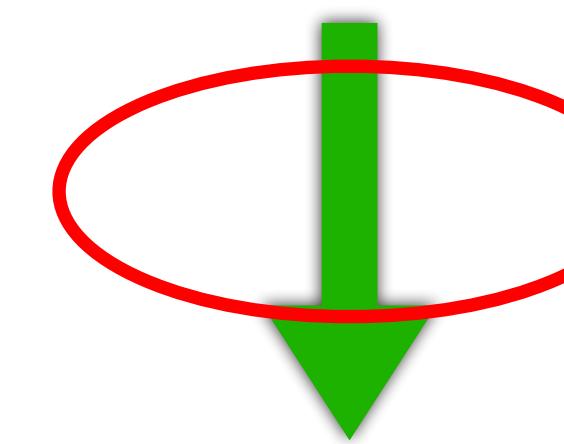
- **Out of thermal equilibrium**

SM: a strong 1st-order electroweak phase transition (need BSM!)



Basic Framework of Baryogenesis in Parity-Symmetric Model

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



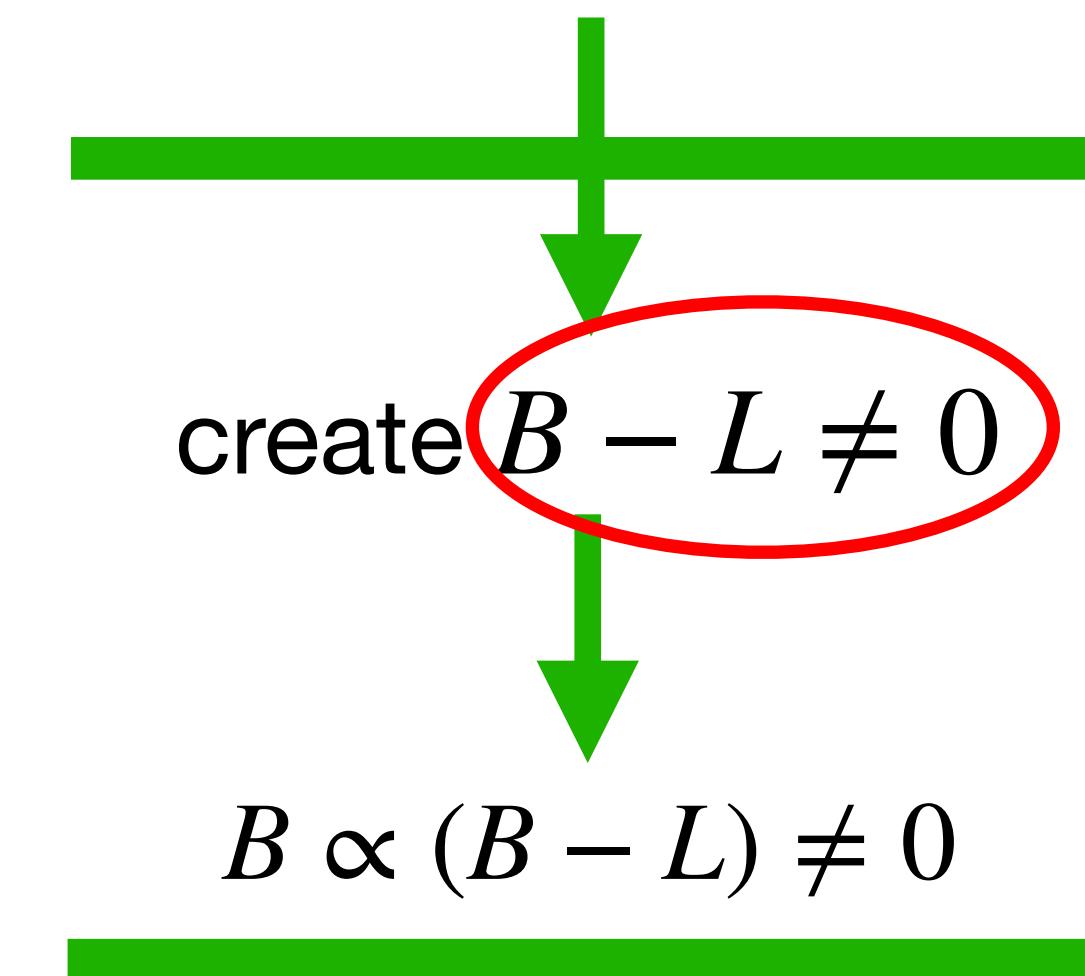
Need to be
strong 1st
order

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



$$SU(3) \times U(1)_{\text{em}}$$

CP-violation, B violation...etc



create $B - L \neq 0$

Need $B - L$ anomaly !

But $\partial_\mu j^\mu_{B-L} = 0$

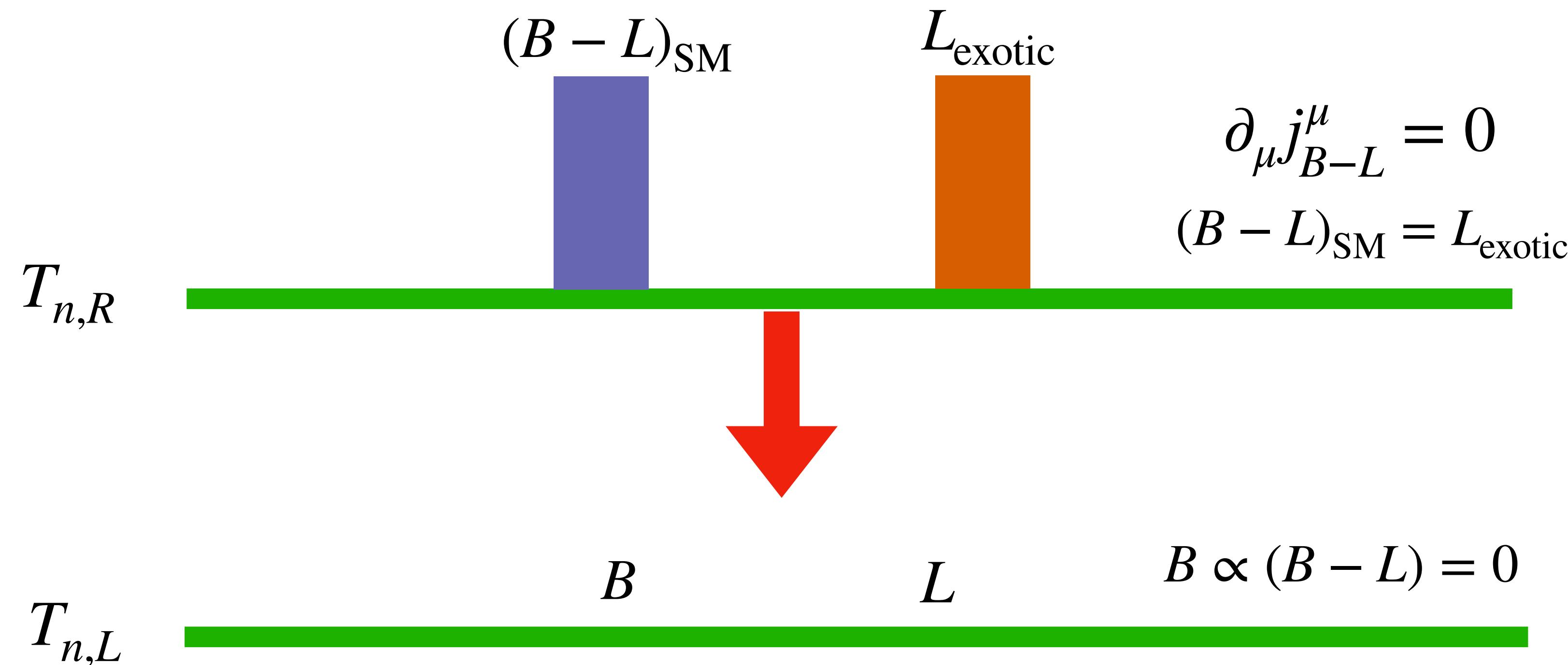
Need some trick!

Remember: $B - L$ is non-anomalous in SM

Any B will be washed out if there is no primordial
non-zero $B - L$



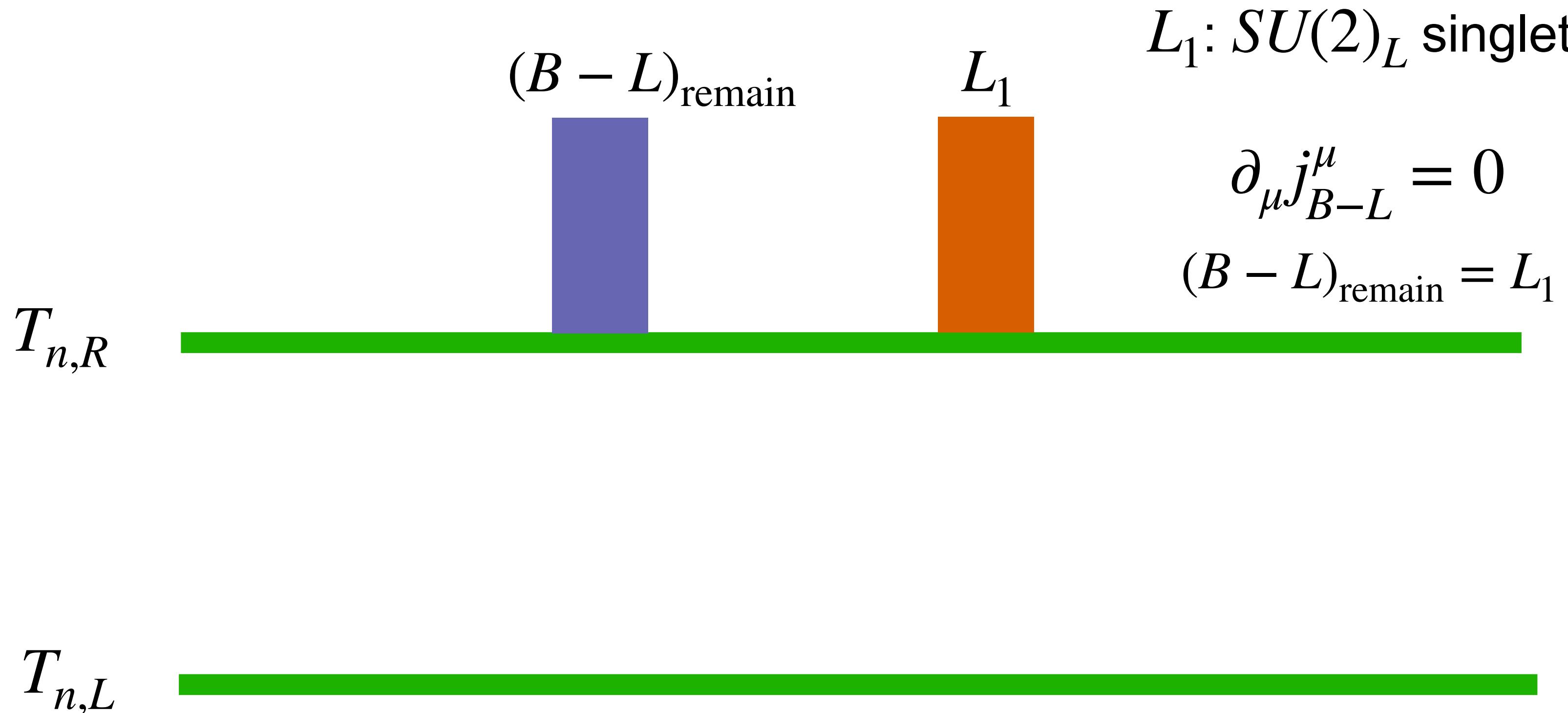
Effective $B - L$: basic framework



Should avoid this!

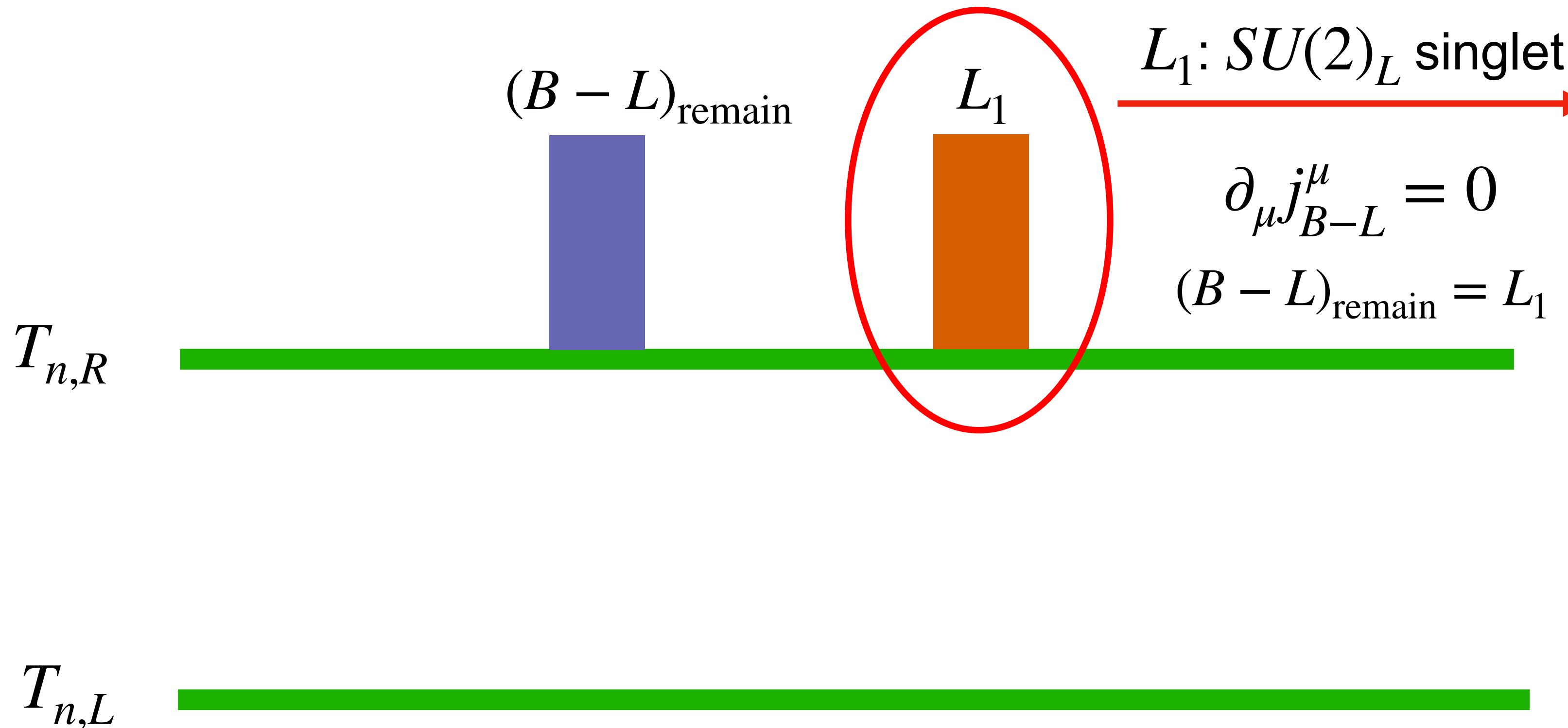


Effective $B - L$: basic framework



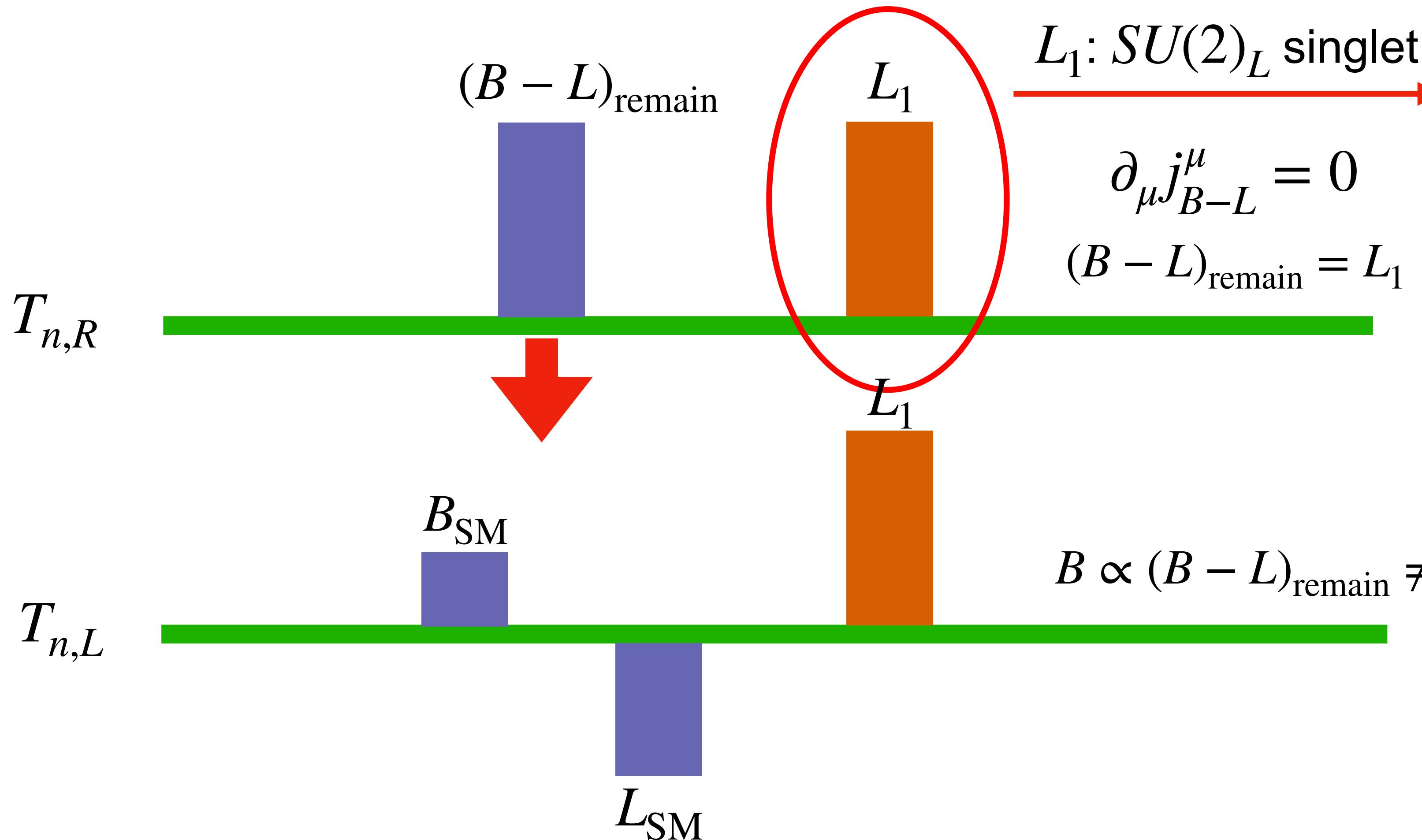


Effective $B - L$: basic framework



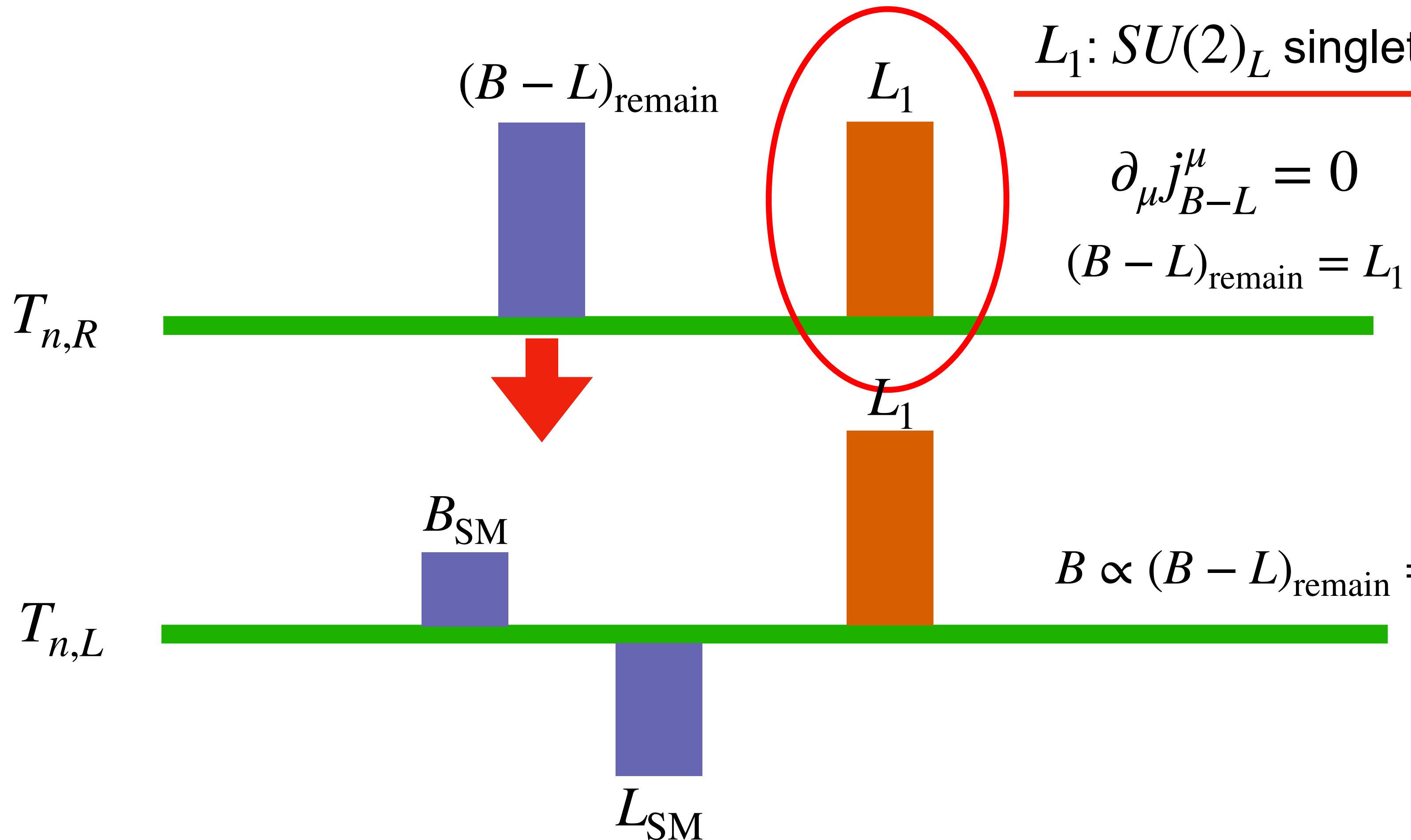


Effective $B - L$: basic framework





Effective $B - L$: basic framework



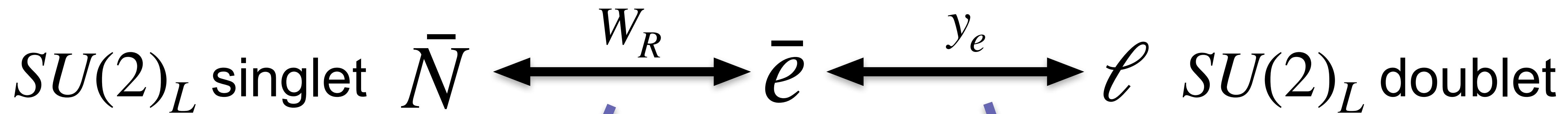


Effective $B - L$

- $yv_R \gg m^e$: SM lepton ℓ, \bar{E} has yv_L , mirror lepton $\bar{\ell}, E$ has yv_R .
SM right-handed charged lepton is $\bar{\ell}$. **Right-handed singlet case.**
- $yv_R \ll m^e$: integrate out heavy fermion \bar{E}, E . SM fermion $\ell, \bar{\ell}$ have $\frac{y_e \bar{y}_e}{M} \ell \bar{\ell} H_L^\dagger H_R^\dagger$.
SM right-handed charged lepton is $\bar{\ell}$. **Right-handed doublet case.**



Effective $B - L$: $SU(2)_R$ doublet case



Decouple:

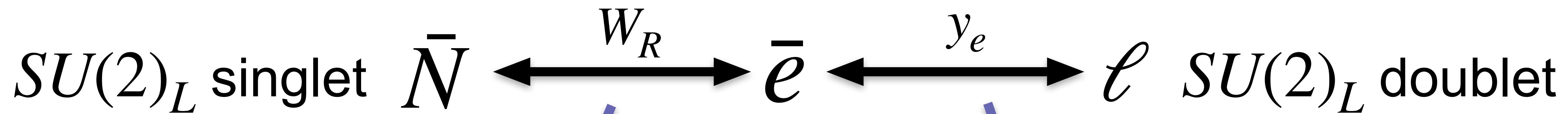
light neutrino: $T_D \simeq 10^8 \text{ GeV} \left(\frac{\nu_R}{10^{10} \text{ GeV}} \right)^{4/3}$.

Effective **after** $T \sim 8.5 \times 10^4 \text{ GeV}$
for $\nu_R > 5 \times 10^7 \text{ GeV}$

Heavy neutrino: another
Boltzmann suppression,
decouple earlier.



Effective $B - L$: $SU(2)_R$ doublet case



Decouple earlier than when second step is effective.

Effective **after** $T \sim 8.5 \times 10^4$ GeV
for $v_R > 5 \times 10^7$ GeV

v_R too large,
no signal

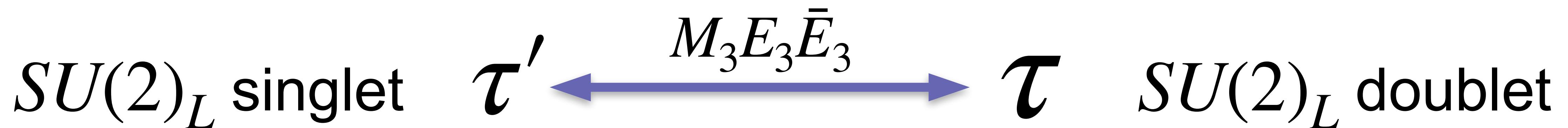
$$\frac{(B - L)_{\text{SM}}}{s} = -\frac{n_{\bar{N}_1}}{s} = -\frac{1}{2} \left. \frac{n_{\bar{\ell}_1}}{s} \right|_{T \sim v_R},$$



Effective $B - L$: $SU(2)_R$ singlet case

$$\begin{aligned}\mathcal{L} = & x_{ij} \ell_i \bar{E}_j H_L + x_{ij}^* \bar{\ell}_i E_j H_R + M_{ij} E_i \bar{E}_j \\ & y_\tau \ell_3 \bar{E}_3 H_L + y_\tau^* \bar{\ell}_3 E_3 H_R + M_3 E_3 \bar{E}_3 + \text{h.c.}\end{aligned}$$

Small M_3 $m_{\tau'} = m_\tau \frac{v_R}{v_L}$

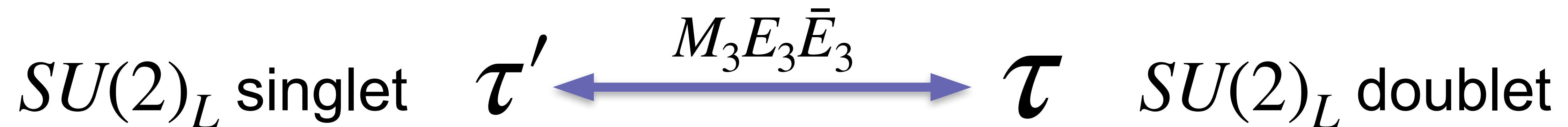


Require M_3 term decouple before $T = m_{\tau'}$

$$M_3 < 20 \text{ MeV} \left(\frac{v_R}{100 \text{ TeV}} \right)^{3/2}$$



Effective $B - L$: $SU(2)_R$ singlet case



$$\frac{(B - L)_{\text{SM}}}{s} = - \left. \frac{n_{\bar{\ell}_3}}{s} \right|_{T \sim v_R} .$$

$$m_{\tau'} = m_\tau \frac{\nu_R}{\nu_L}$$

Other generations are possible. All predicts a lepton with $m_{\ell'} = m_\ell \frac{\nu_R}{\nu_L}$



Approaches to Strong 1st Order Phase Transition

- Purely running λ : require $v_R > 2 \times 10^8 \text{GeV}$
- Option 1: possible extra fermions to speed up running.
- Option 2 (more promising): scalar extensions to the Higgs potential.



Scalar Extension: An Example

$$V_0(h, S) = -\frac{1}{2}\mu_H^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}AS(h^2 - 2v^2).$$



V_0 = Higgs terms

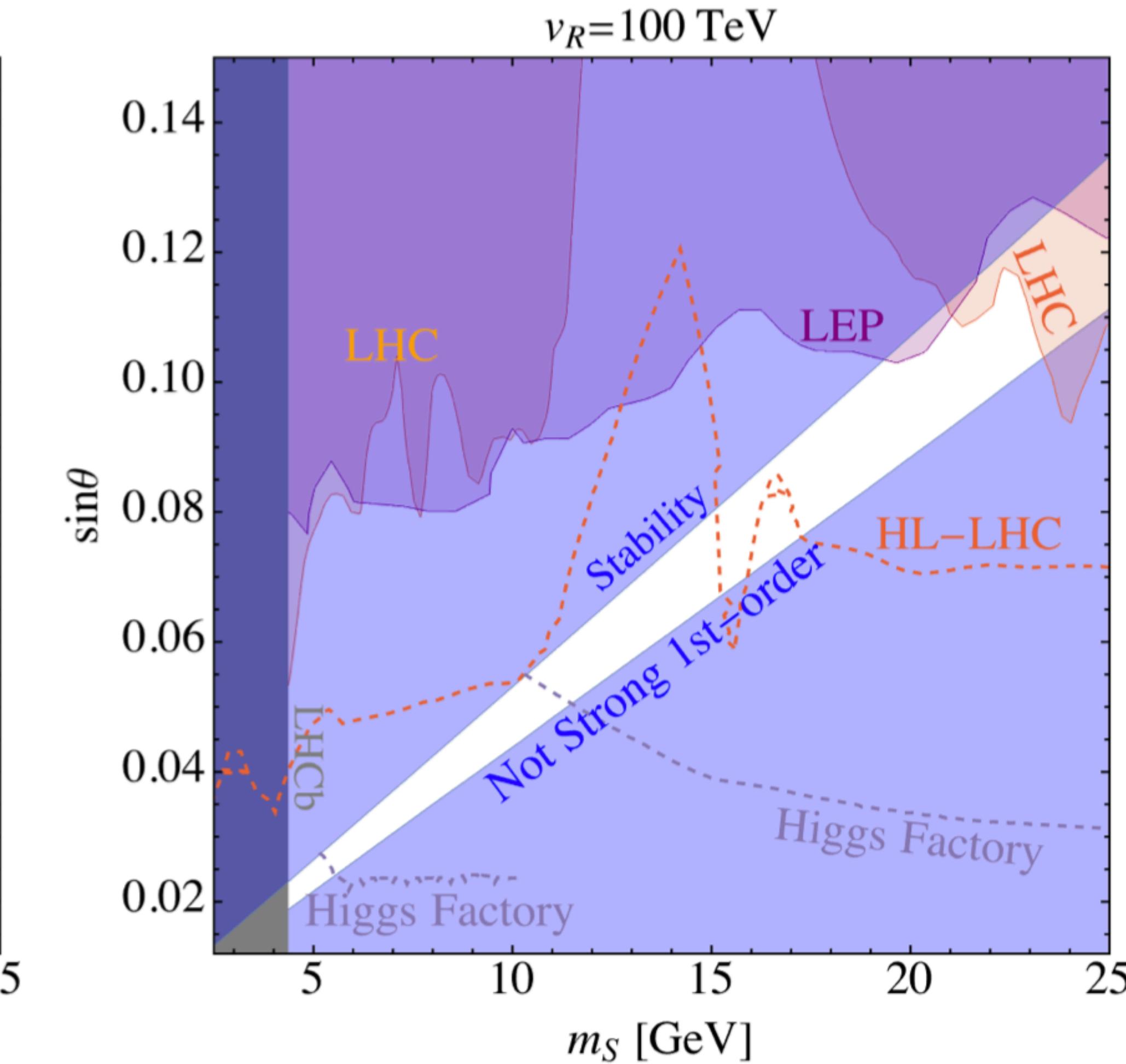
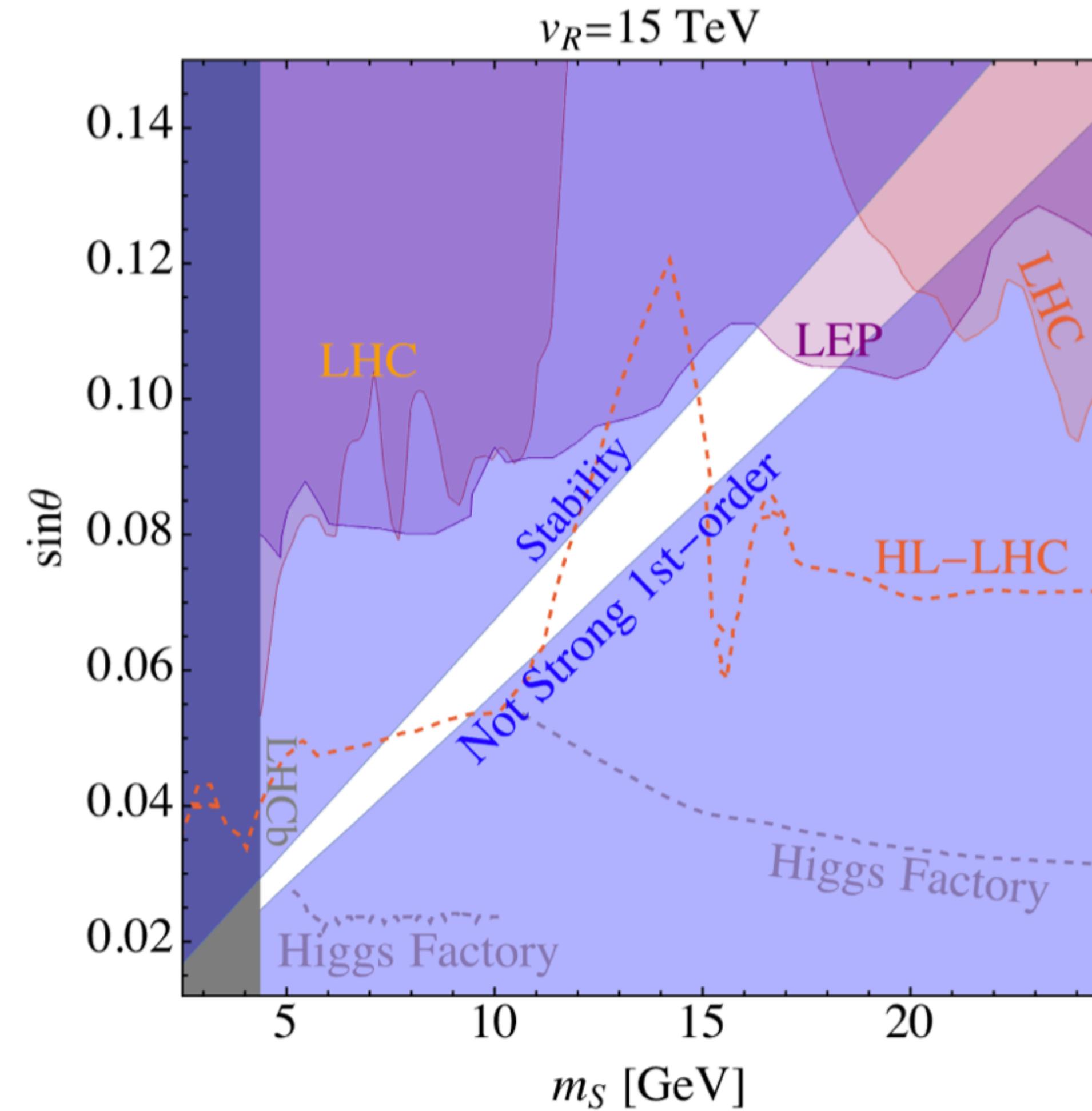
$$+\frac{1}{2}\mu_S^2 S_R^2 - \frac{1}{2}AS_R(h_R^2 - 2v_R^2)$$

+ S_L terms

$$\langle S_{L,R} \rangle = \frac{A}{2\mu_S^2}(h_{L,R}^2 - 2v_{L,R}^2). \quad V_0(h_L, h_R, \langle S_L \rangle, \langle S_R \rangle) = -\frac{1}{2}\mu_{H_L}^2 h_L^2 - \frac{1}{2}\mu_{H_R}^2 h_R^2 + \frac{1}{4}\left(\lambda - \frac{A^2}{2\mu_S^2}\right)(h_L^4 + h_R^4) + \frac{1}{4}\lambda_{LR}h_L^2 h_R^2.$$



Scalar Extension Example: Parameter Space





Example: Local Baryogenesis

Running approach

Effective operator $\frac{g^2}{32\pi^2}\theta(H_R)W_R\tilde{W}_R.$

Solve along the bubble wall $\dot{n}_{\ell_3} = \frac{\Gamma_{Rs}}{T^3}\dot{\theta}T^2$, $\Gamma_{Rs} = \kappa\alpha_R^5 T^4$.

$$Y_B = \frac{n_B}{s} = \frac{28}{79} \frac{1}{s} \kappa \alpha_R^5 T^3 \delta\theta = 8.6 \times 10^{-11} \frac{\delta\theta}{0.02}$$

e.g. $\frac{g^2}{32\pi^2 M^2} |H_R|^2 W_R \tilde{W}_R$

$$Y_B = \frac{n_B}{s} = \left. \frac{28}{79} \frac{1}{s} \frac{4\Gamma_{sph}\sigma^2\alpha_R^2 T}{M^2 g^2} \right|_{T=T_n} \simeq 8.9 \times 10^{-11} \left(\frac{1.7 T_n}{M} \right)^2$$

Remind:
 WW violates CP!

Scalar extension approach

$$\mathcal{L} = \frac{\alpha_R}{8\pi} \frac{S_R W_R \tilde{W}_R}{M}$$

$$Y_B \simeq 8.7 \times 10^{-11} \left(\frac{v_R}{20 \text{ TeV}} \right) \left(\frac{T_n}{0.2 v_R} \right)^2 \left(\frac{40 v_R}{M} \right) \left(\frac{10 \text{ GeV}}{\mu_S} \right)$$

For old literature using $\mathcal{L}_{CP} \propto \frac{\sin(\delta)}{M^2} h^2 W \tilde{W}$:

[A. Cohen and B. Kaplan, Phys.Lett.B 199 (1987) 251-258,

Nucl.Phys.B 308 (1988) 913-928]

[M. Dine et al, Phys.Lett.B 257 (1991) 351-356]
[M. Dine, hep-ph/9206220]

[K. Harigaya and IW, 2207.02867]
[K. Harigaya and IW, 2210.16207]



Collier Signals: Heavy Gauge Bosons and Neutral Leptons

$$m_{W_R} = m_W \frac{v_R}{v_L} = 6.5 \text{ TeV} \frac{v_R}{15 \text{ TeV}},$$
$$m_{Z'} = m_Z \frac{v_R}{v_L} = 7.4 \text{ TeV} \frac{v_R}{15 \text{ TeV}}.$$

Heavy neutral leptons (radiative inverse seesaw only):

$$\theta_{\nu N}^2 \simeq \left(\frac{v_L}{v_R} \right)^2 = 3.3 \times 10^{-5} \left(\frac{30 \text{ TeV}}{v_R} \right)^2$$



Collier Signals: $SU(2)_L$ singlet τ'

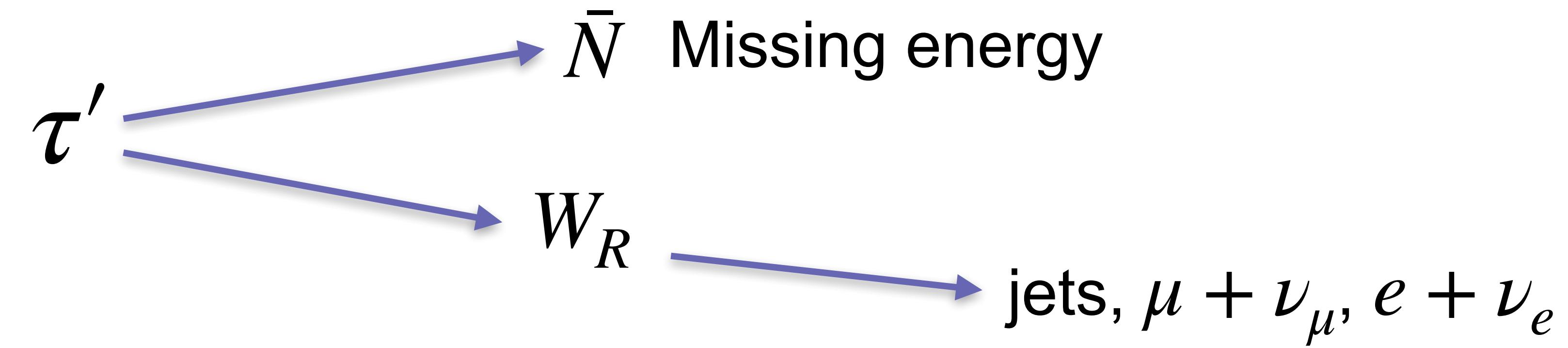
- τ' decays into right-handed neutrino \bar{N} .

$$m_{\tau'} = m_\tau \frac{v_R}{v_L} \simeq 150 \text{ GeV} \frac{v_R}{15 \text{ TeV}}$$

- The topology depends on the mass relation between \bar{N} and τ' :
 - Light \bar{N} : Dirac Mass, Majorana mass....
 - Heavy \bar{N} : radiative inverse seesaw.
 - Heavier than τ'
 - Lighter than τ'



Collier Signals of $SU(2)_L$ singlet τ' : light \bar{N}

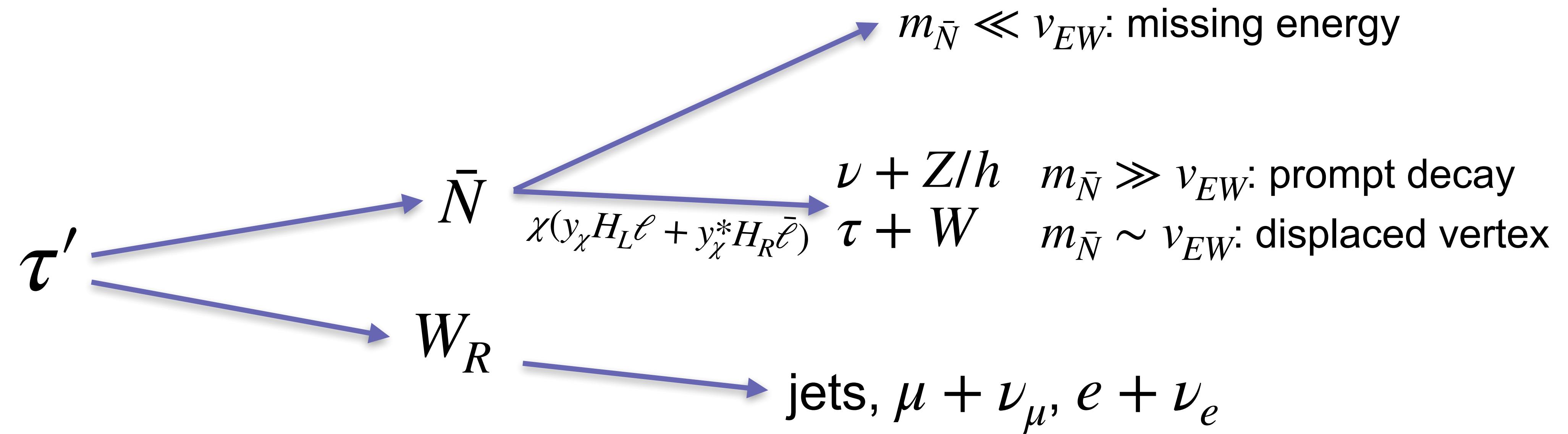


$$m_{\tau'} = m_\tau \frac{v_R}{v_L} \simeq 150 \text{ GeV} \frac{v_R}{15 \text{ TeV}}$$

No $\tau + \nu_\tau$ here!



Collier Signals of $SU(2)_L$ singlet τ' : heavy \bar{N} (lighter than τ')

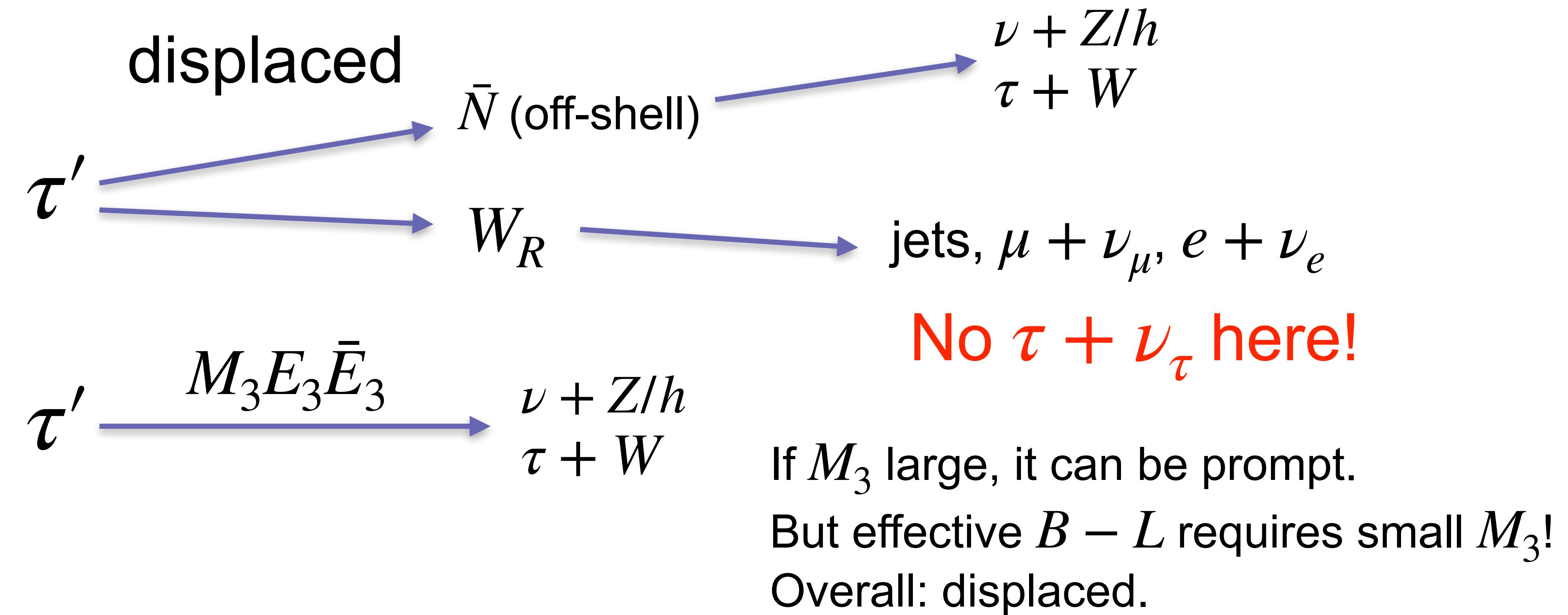


$$m_{\tau'} = m_\tau \frac{v_R}{v_L} \simeq 150 \text{ GeV} \frac{v_R}{15 \text{ TeV}}$$

No $\tau + \nu_\tau$ here!



Collier Signals of $SU(2)_L$ singlet τ' : heavy \bar{N} (heavier than τ')



$$m_{\tau'} = m_\tau \frac{v_R}{v_L} \simeq 150 \text{ GeV} \frac{v_R}{15 \text{ TeV}}$$



Summary

- Parity solution to the Strong CP problem can be compatible with electroweak-like baryogenesis, if the fermion content satisfy some constraints.
- A strong 1st order phase transition can be achieved in different approaches.
- Predicted heavy gauge bosons and leptons in the collider experiments.



Backup



Electric Dipole Moment

Running approach

$$\begin{aligned}\frac{d_e}{e} &\simeq 1 \times 10^{-30} \text{ cm} \left(\frac{20 \text{ TeV}}{M} \right)^2 \frac{\ln(M^2/m_h^2)}{8} \\ &\simeq 1 \times 10^{-30} \text{ cm} \left(\frac{Y_B}{8.9 \times 10^{-11}} \right) \left(\frac{20 \text{ TeV}}{v_R} \right)^2 \left(\frac{v_R}{1.7T_n} \right)^2 \frac{\ln(M^2/m_h^2)}{8}\end{aligned}$$

Scalar extension approach

$$\begin{aligned}\frac{d_e}{e} &\simeq 1 \times 10^{-31} \text{ cm} \left(\frac{20 \text{ TeV}}{v_R} \right) \left(\frac{40v_R}{M} \right) \left(\frac{\mu_S}{10 \text{ GeV}} \right) \\ &\simeq 1 \times 10^{-31} \text{ cm} \left(\frac{Y_B}{8.7 \times 10^{-11}} \right) \left(\frac{20 \text{ TeV}}{v_R} \right)^2 \left(\frac{0.2v_R}{T_n} \right)^2 \left(\frac{\mu_S}{10 \text{ GeV}} \right)^2\end{aligned}$$



Decay length of τ'

heavy \bar{N} lighter than τ' : $1 \text{ mm} \left(\frac{10 \text{ GeV}}{m_{N_3}} \right)^6 \left(\frac{m_{\tau'}}{200 \text{ GeV}} \right)^3$

\bar{N} heavier than τ' , W_R mediation: $8 \text{ mm} \times \frac{m_{\tau'}}{200 \text{ GeV}} \frac{6}{N_f}$

\bar{N} heavier than τ' , M_3 mediation: $0.1 \text{ mm} \left(\frac{3 \text{ MeV}}{M_3} \right)^2 \frac{m_{\tau'}}{200 \text{ GeV}}$