ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

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DEBRECEN

LEPTO-BARYOGENESIS

based on

arXiv:1812.11189 (*Symmetry*), 2301.07961 (*JHEP*), 2409.07180 (JHEP), 2509.nnnn
with K. Seller, Zs. Szép and also1812.07180 by B. Garbrecht

ELTE seminar, 21 October, 2025

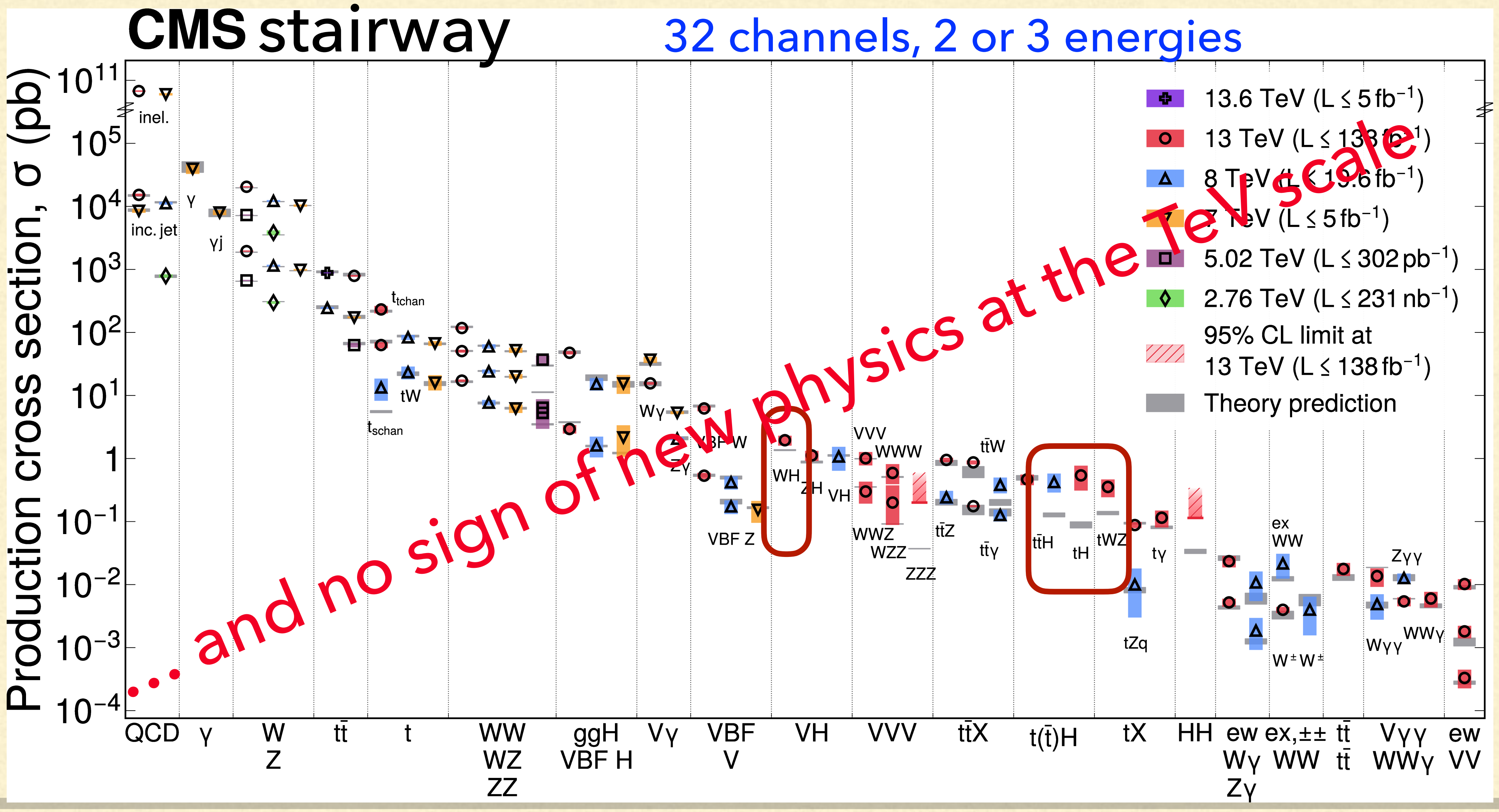
OUTLINE

Rough estimates of BSM effects can easily be deceptive

1. Motivation: status of particle physics
   - Colliders
   - Cosmology
2. Sakharov's conditions
3. Elements of lepto-baryogenesis
4. Superweak $U(1)_z$ extension of SM (SWSM)
5. Outlook

Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely



Status of particle physics: cosmic and intensity frontiers

Established observations

require physics beyond SM,

but

do not suggest rich BSM physics

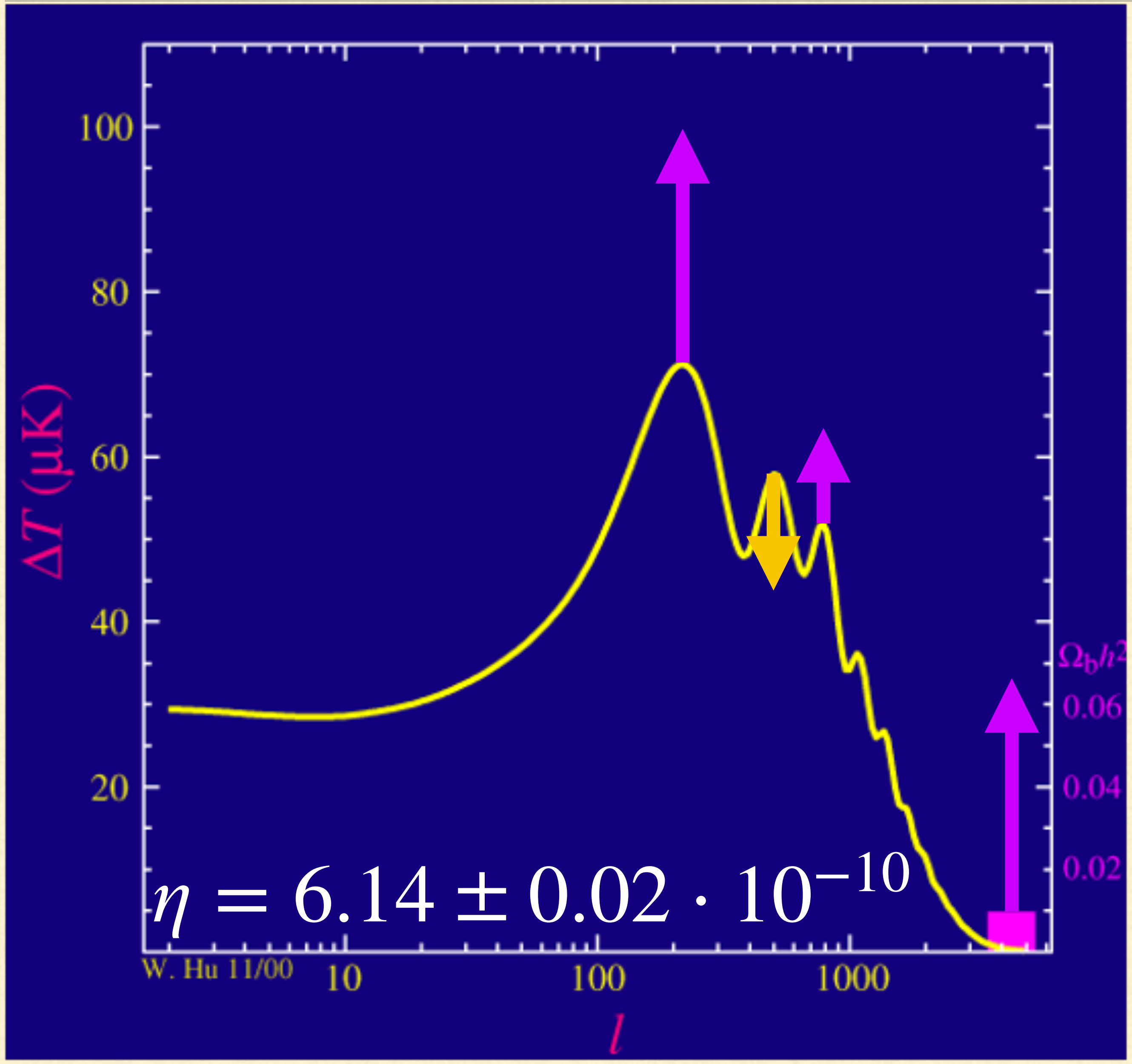
What is not explained or weird in the standard model?

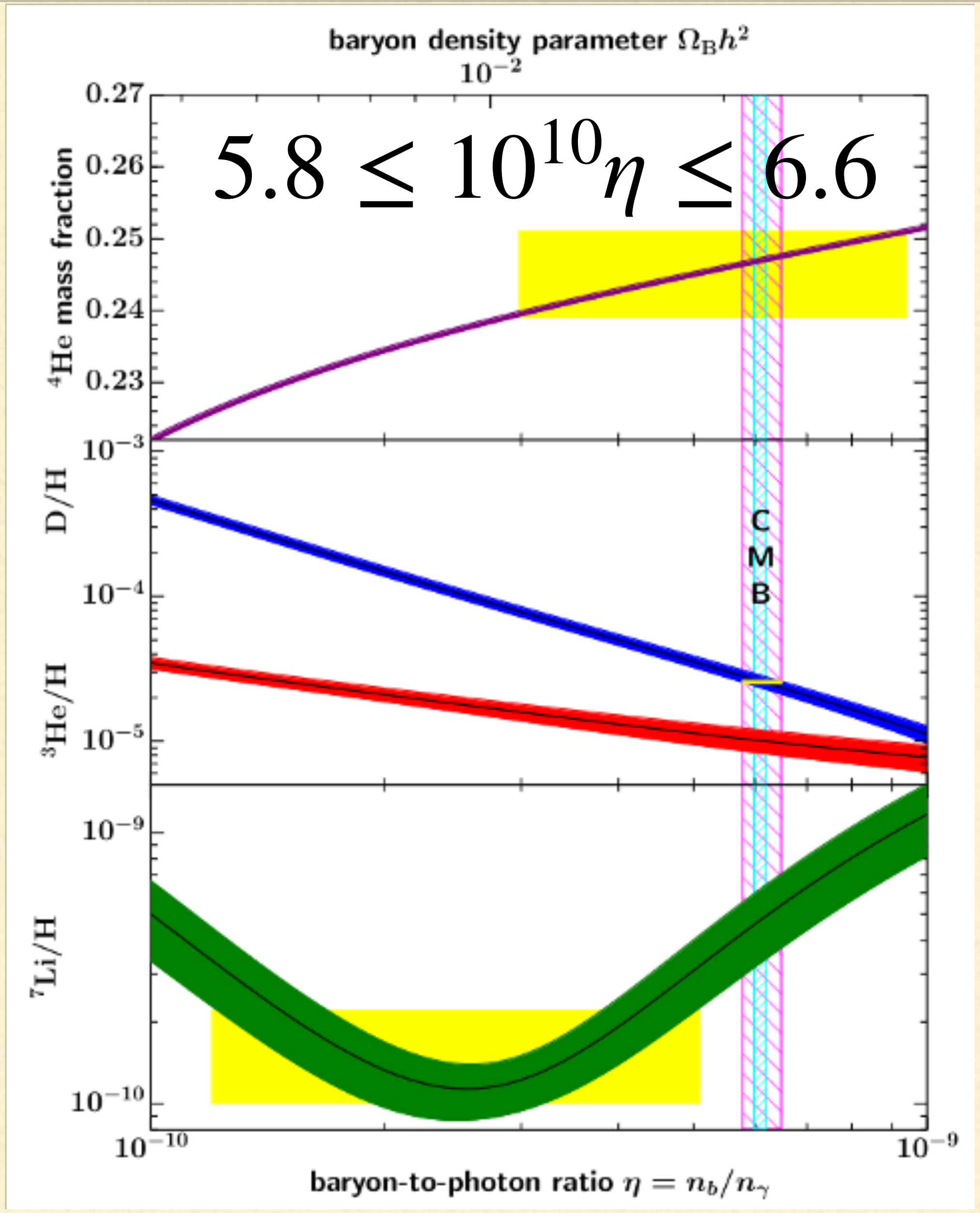
Does not fit:

- Neutrino masses
- Dark matter and energy
- Baryon asymmetry

1. Neutrino flavours oscillate
2. Universe at large scale described precisely by cosmological SM: ΛCDM (Ω_m =0.3) ; inflation of the early, accelerated expansion of the present Universe
3. Existing baryon asymmetry cannot be explained by CP asymmetry in SM, baryon to photon ratio at large scales: $\eta \simeq 6.0 \cdot 10^{-10}$

Baryon asymmetry in the Universe from
CMB power spectrum & BBN nucleosynthesis





ratio of the odd and even peaks strongly depends on η

abundances of light elements strongly depend on η

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Puzzles in the scalar sector:

- Lagrangian and its parameters
- Yukawa couplings
- Connection to inflation
- Vacuum stability (λ too small)
- Naturalness (μ is dimensional)

$$\mathscr{L} \supset \mathscr{L}_S = \mu^2 |\phi|^2 + \lambda |\phi|^4 + ?$$

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Hidden new particles:

- Too heavy
- Interact too weakly

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Anomalies:

- Muon anomalous magnetic moment
- 2-3σ excesses at LHC experiments
- X17 and E38 anomalies
- CDF II result for M_W

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Anomalies:

Not addressed in this talk, they seem to fade away or not related fundamental physics

What is not explained or weird in the standard model?

Does not fit:

- Neutrino masses
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- Baryon asymmetry

Baryon asymmetry is our focus today

Hidden new particles:

- Too heavy
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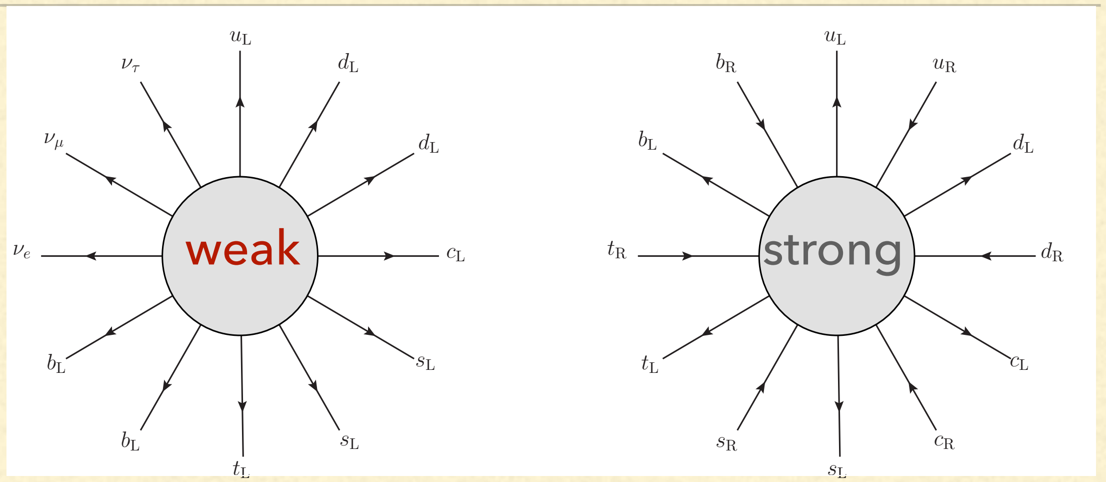
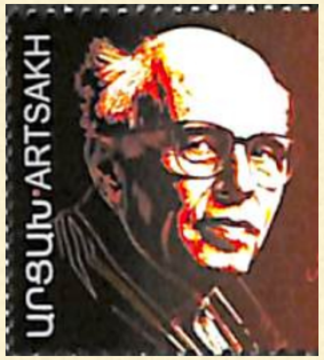
Sakharov's conditions for baryogengesis are fulfilled in the SM, but not enough

1. Baryon number violation
   ✓ exists in the SM
   weak sphaleron process:
   $\Delta(B+L)=6,\ \Delta(B-L)=0$

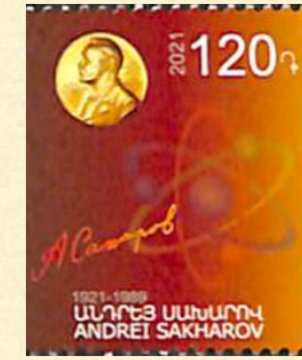


't Hooft vertices

2. C & CP violation
   ✓ C violation exists in the SM in weak interactions
   - CP violation exists in the SM in the quark sector (CKM), but falls short by almost 10 orders of magnitude
3. Deviation from equilibrium at phase boundaries in phase transitions
   - phase transition exists in the SM scalar sector, but only cross-over instead of strong 1st order



Sakharov's conditions for baryogengesis may be enough in extensions of SM



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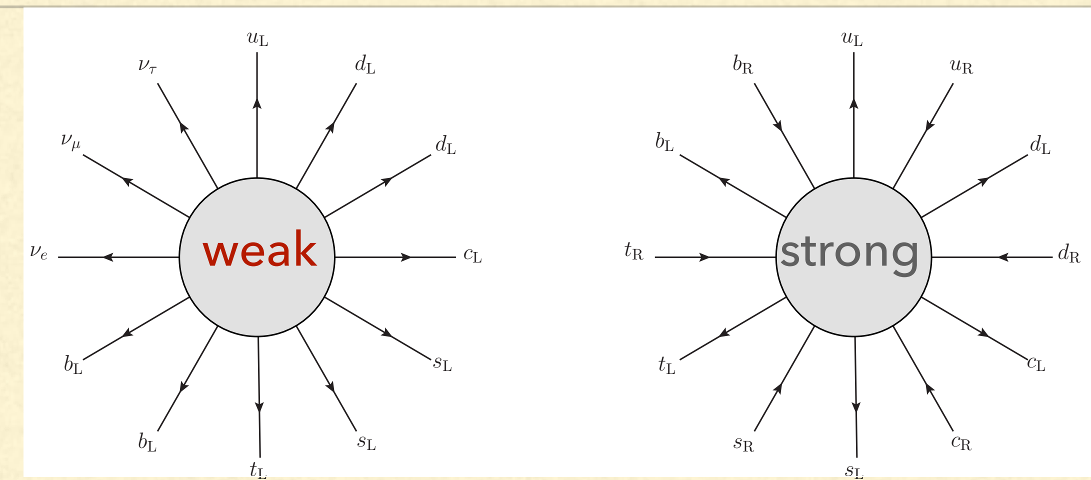

't Hooft vertices

2. C & CP violation
   ✓ C violation exists in the SM in weak interactions
   ✓ CP violation in decays and oscillations of right-handed neutrinos
3. Deviation from equilibrium
   ✓ in production and decay of RHNs

Estimate of lepto-baryogenesis has two steps

1. Leptogenesis in a beyond the standard model (BSM)

   followed by computing the effect of

2. sphaleron processes in the SM:
   violates $B + L$, but conserves $B - L$

   - Suppressed exponentially with decreasing temperature, but
     unsuppressed above $T_{\rm sph} \simeq 132\,{\rm GeV}$

Neutrino masses and leptogenesis

...can naturally be explained by adding right-handed neutrinos (RHNs) to the particle spectrum with Majorana mass terms:

$$\mathscr{L} \supset \frac{1}{2} \left(\overline{\nu_{\mathrm{L}}} \ \ \overline{\nu_{\mathrm{R}}^c} \right) \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D \\ \mathbf{M}_D^T & \mathbf{M}_M \end{pmatrix} \begin{pmatrix} \nu_{\mathrm{L}}^c \\ \nu_{\mathrm{R}} \end{pmatrix},$$

which gives active neutrino masses with the see-saw formula $\mathbf{M}_\nu = \mathbf{M}_D \mathbf{M}_M^{-1} \mathbf{M}_D^T$

=> $\mathbf{M}_M$ sets the scale of leptogenesis

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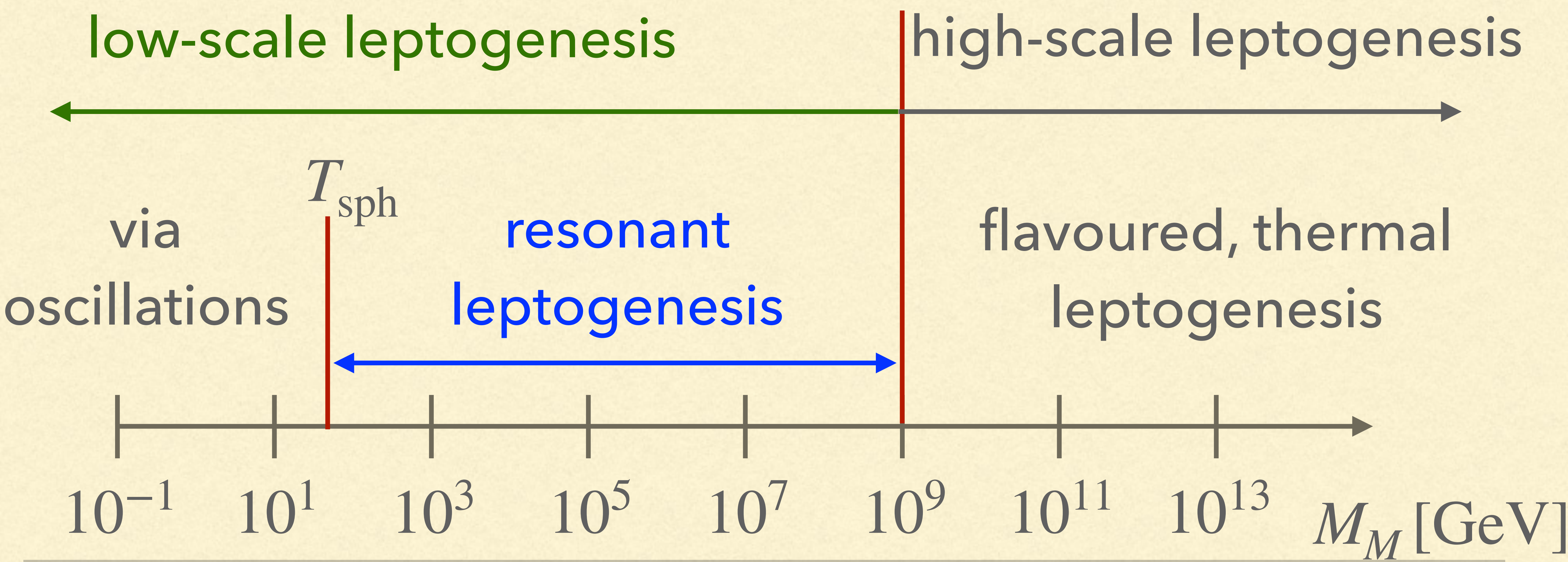


Neutrino masses and leptogenesis

...can naturally be explained by adding right-handed neutrinos (RHNs) to the particle spectrum with Majorana mass terms

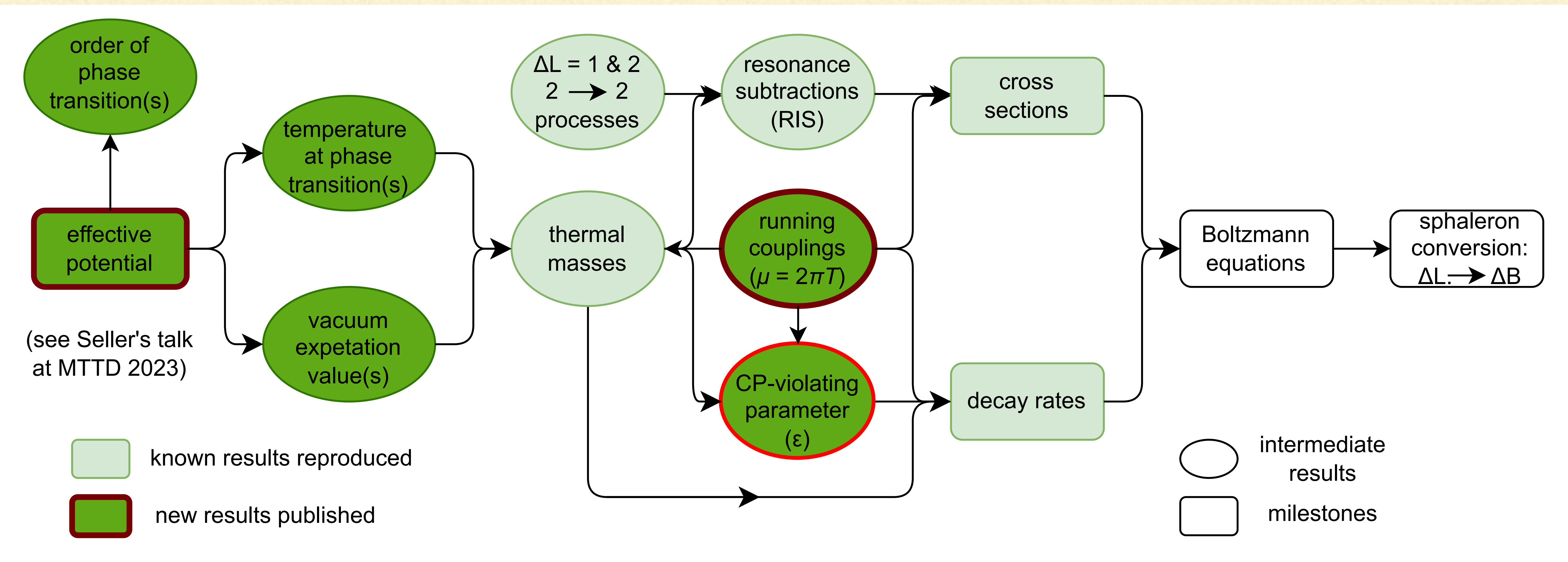
Decays of such RHNs lead to a non-vanishing ΔL that can be estimated either by

- Kadanoff-Baym eqs. of non-equilibrium QFT, or
- semiclassical Boltzmann eqs.

(can be obtained from KB employing quasi-particle approximation, valid "near" equilibrium)

Boltzmann approach is much simpler technically: easier to apply in specific models

...which does not mean it is simple – relies on several (?) ingredients:



Boltzmann eq. for comoving lepton density asymmetry $\mathcal{Y}_{\Delta\mathrm{L}} = \mathcal{Y}_{\ell} - \mathcal{Y}_{\bar{\ell}}$

$$\frac{\mathrm{d}\mathcal{Y}_{\Delta\mathrm{L}}}{\mathrm{d}z} = \frac{1}{sHz}\left[\left(\epsilon\gamma_{\mathrm{D}} - \gamma_{ab\to N\ell}\frac{\mathcal{Y}_{\Delta\mathrm{L}}}{\mathcal{Y}_{\ell}^{\mathrm{eq}}}\right)\left(\frac{\mathcal{Y}_{N}}{\mathcal{Y}_{N}^{\mathrm{eq}}} - 1\right) - W\mathcal{Y}_{\Delta\mathrm{L}}\right]$$

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- $z = \Lambda/T$ inverse temperature

Boltzmann eq. for comoving lepton density asymmetry $\mathscr{Y}_{\Delta L} = \mathscr{Y}_{\ell} - \mathscr{Y}_{\bar{\ell}}$

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- $z = \Lambda/T$ inverse temperature
- $s(z)$ entropy density when $T = \Lambda/z$

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- $\gamma_{ab\to\mathrm{leptons}}(T)$ thermal rate for $ab \to$ leptons

Boltzmann eq. for comoving lepton density asymmetry $\mathscr{Y}_{\Delta L} = \mathscr{Y}_{\ell} - \mathscr{Y}_{\bar{\ell}}$

$$\frac{d\mathscr{Y}_{\Delta L}}{dz} = \frac{1}{sHz}\left[\left(\epsilon\gamma_D - \gamma_{ab\to N\ell}\frac{\mathscr{Y}_{\Delta L}}{\mathscr{Y}_{\ell}^{eq}}\right)\left(\frac{\mathscr{Y}_N}{\mathscr{Y}_N^{eq}} - 1\right) - W\mathscr{Y}_{\Delta L}\right]$$

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- $\gamma_{ab\to \mathrm{leptons}}(T)$ thermal rate for $ab \to$ leptons
- $\mathscr{Y}_{\ell}^{eq}$ equilibrium value of the lepton abundance

Boltzmann eq. for comoving lepton density asymmetry $\mathscr{Y}_{\Delta \mathrm{L}} = \mathscr{Y}_{\ell} - \mathscr{Y}_{\bar{\ell}}$

$$\frac{\mathrm{d}\mathscr{Y}_{\Delta \mathrm{L}}}{\mathrm{d}z} = \frac{1}{sHz}\left[\left(\epsilon\gamma_{\mathrm{D}} - \gamma_{ab\to N\ell}\frac{\mathscr{Y}_{\Delta \mathrm{L}}}{\mathscr{Y}_{\ell}^{\mathrm{eq}}}\right)\left(\frac{\mathscr{Y}_{N}}{\mathscr{Y}_{N}^{\mathrm{eq}}} - 1\right) - W\mathscr{Y}_{\Delta \mathrm{L}}\right]$$

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- s entropy density
- $H(z)$ Hubble parameter when $T = \Lambda/z$
- $\gamma_{ab\to \mathrm{leptons}}(T)$ thermal rate for $ab \to$ leptons
- $\mathscr{Y}_{\ell}^{\mathrm{eq}}$ equilibrium value of the lepton abundance
- W collection of terms emerging from the scattering processes, leads to equilibration (washout of asymmetry)

CP asymmetry factor

$$\frac{\mathrm{d}\mathscr{Y}_{\Delta\mathrm{L}}}{\mathrm{d}z} = \frac{1}{sHz}\left[\left(\epsilon\gamma_{\mathrm{D}} - \gamma_{ab\to N\ell}\frac{\mathscr{Y}_{\Delta\mathrm{L}}}{\mathscr{Y}_{\ell}^{\mathrm{eq}}}\right)\left(\frac{\mathscr{Y}_N}{\mathscr{Y}_N^{\mathrm{eq}}} - 1\right) - W\mathscr{Y}_{\Delta\mathrm{L}}\right]$$

asymmetry is generated by CP-violating decays of the sterile neutrinos, given by γ_D, and proportional to the CP asymmetry factor from

the decay $a \to b + c$ and CP-conjugate decay $\bar{a} \to \bar{b} + \bar{c}$

$$\epsilon_{a\to b+c} = \frac{\gamma_{a\to b+c} - \gamma_{\bar{a}\to\bar{b}+\bar{c}}}{\gamma_{a\to b+c} + \gamma_{\bar{a}\to\bar{b}+\bar{c}}}$$

(other terms decrease $\mathscr{Y}_{\Delta L}$, i.e. lead to washout)

CP asymmetry factor

Often used as constant coming from $T = 0$ QFT:

$$\epsilon^{(0)}_{N_i \to \phi + L}(x) = \frac{G}{8\pi}\sqrt{x}\left\{\frac{1}{1-x} + \left[1 + (1+x)\log\left(\frac{x}{1+x}\right)\right]\right\}$$

➡ $G = \mathrm{Im}\left[(\mathrm{K}_{ij})^2\right] \Big/ \mathrm{K}_{ii} \neq 0$ with $\mathrm{K} = \mathrm{Y}^\dagger \mathrm{Y}$

coupling factor

CP asymmetry factor at zero density

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- $x = m^2_{N_j}/m^2_{N_i} > 1$: ratio of the squared masses of the Majorana neutrinos

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- ➡ $x = m^2_{N_j}/m^2_{N_i} > 1$: ratio of the squared masses of the Majorana neutrinos
- ➡ for $x \gg 1$: 1st term ≈ twice the 2nd one

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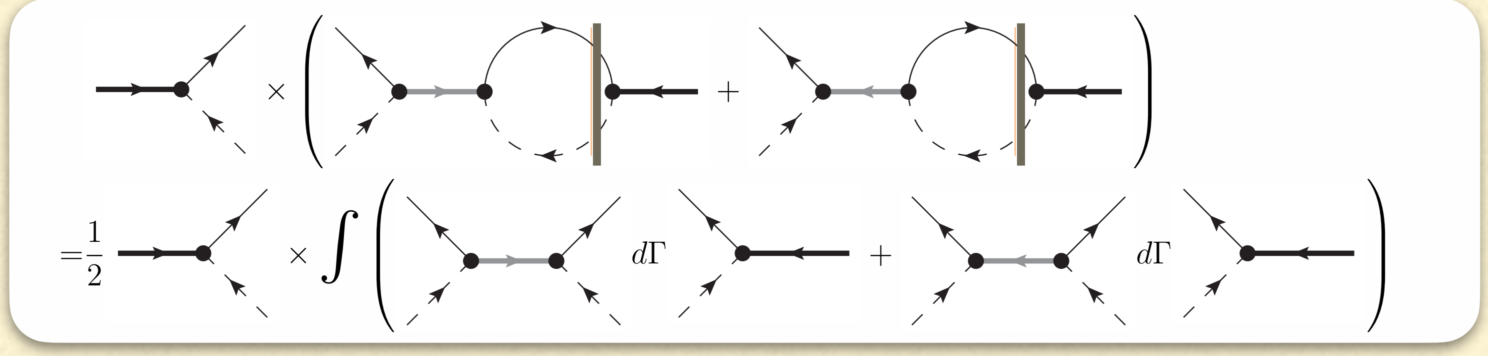
1st term: contribution of the imaginary part of self energy



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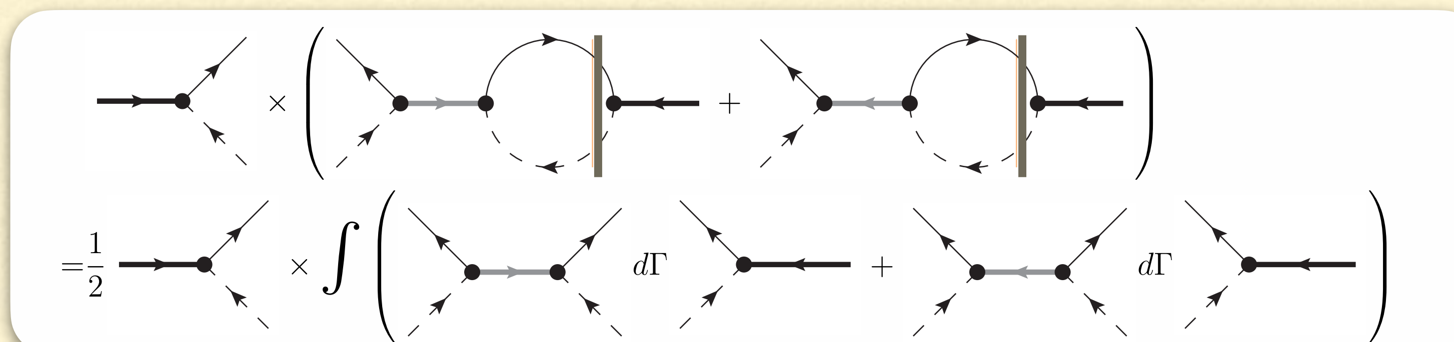
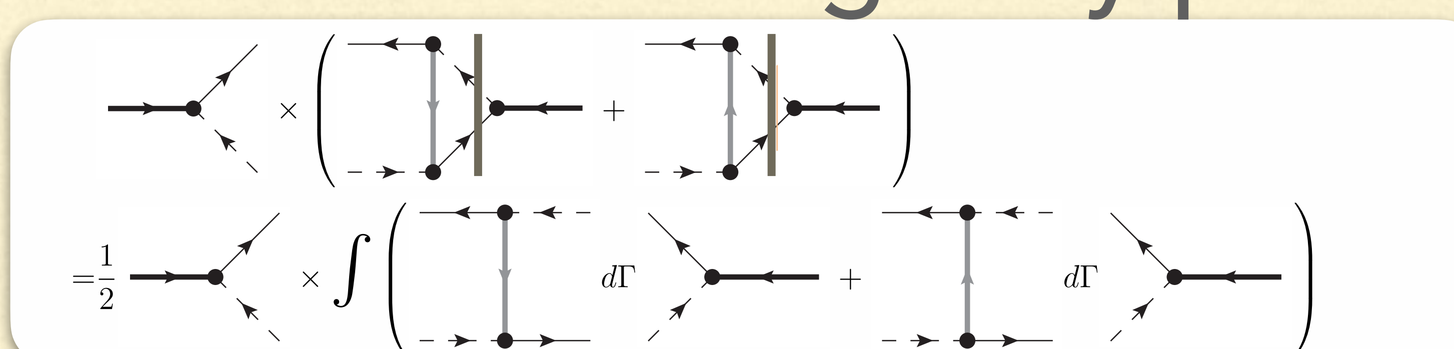


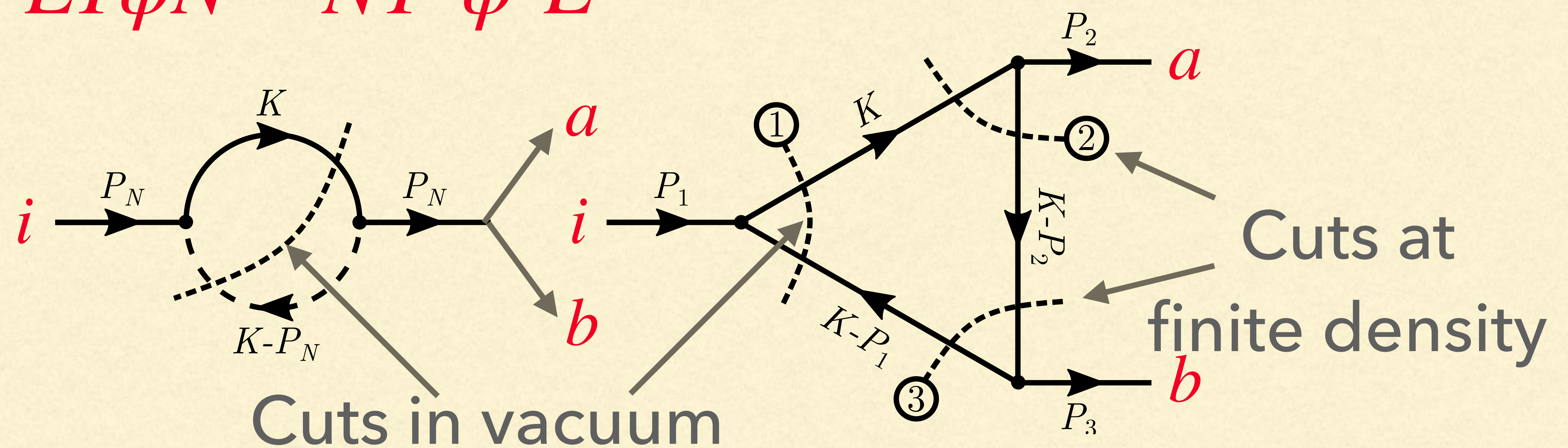
2nd term: contribution of the imaginary part of vertex correction



CP asymmetry factor at finite density

- Two cuts (2 and 3 in the vertex correction)

  $\mathscr{L} \supset \bar{L} Y \tilde{\phi} N - \bar{N} Y^\dagger \tilde{\phi}^\dagger L$



are neglected in standard literature, but may be relevant for low-scale leptogenesis when $m_N \approx T$

Computation of CP asymmetry factor

Detailed computation with explicit integral representations, ready for numerical evaluation are presented in

K. Seller, Z. Szép, Z.T., *CP violation at finite temperature*, JHEP **09** (2025) 034 [arXiv:2409.07180 [hep-ph]]

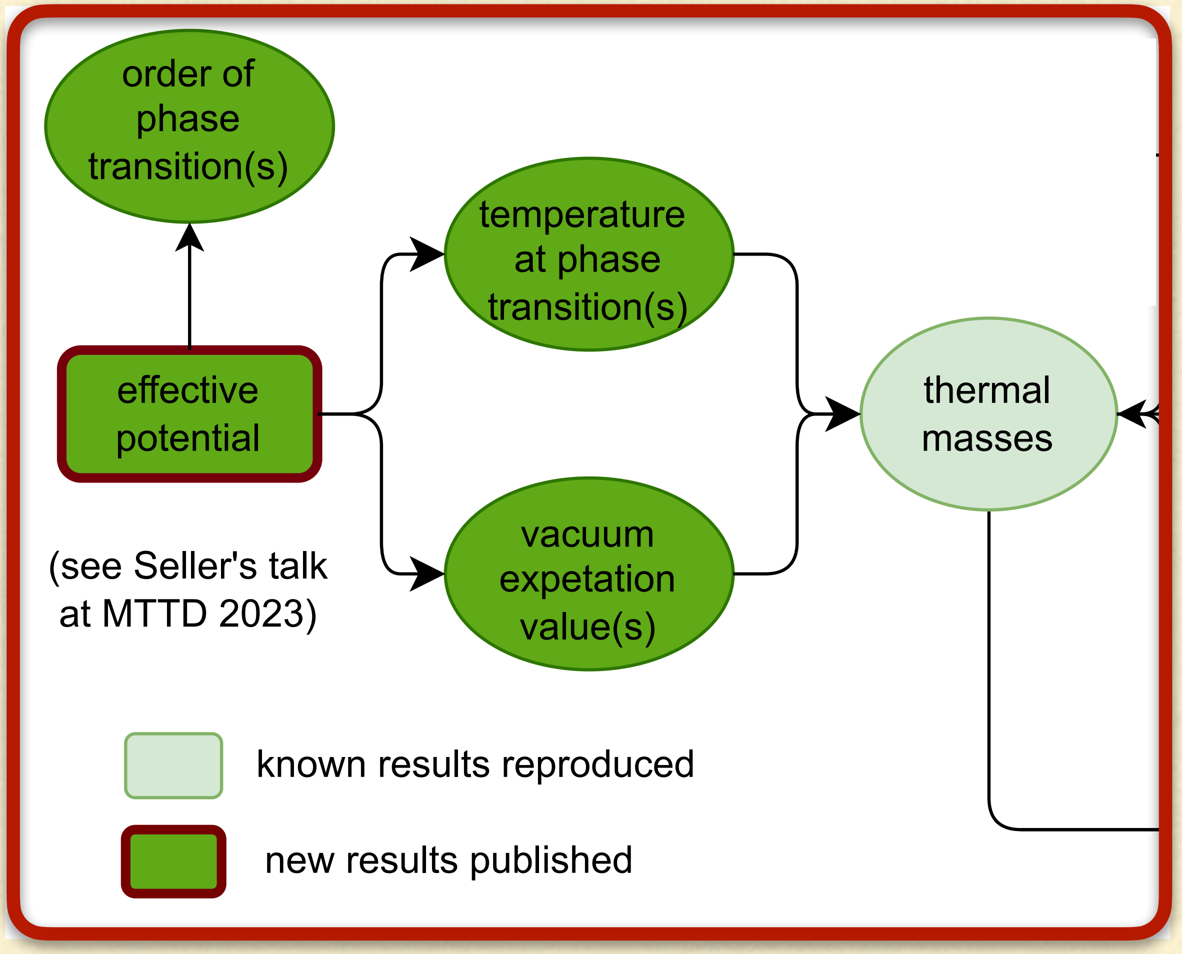
and

CP asymmetry factor at finite temperature, to appear soon

EPJC **11** (2025) [arXiv:2511.nnnn [hep-ph]]

but too technical to repeat here

Step 1: find thermal masses



model dependent input ⇒ choose a model

SuperWeak extension of the Standard Model
SWSM

- designed to
  - explain the origin of neutrino masses and oscillations through Dirac and Majorana neutrino mass terms generated by the SSB of two scalar fields,

[Iwamoto, Kärkäinnen, Péli, ZT, arXiv:2104.14571; Kärkkäinen and ZT, arXiv:2105.13360]

  - Provide a candidate for WIMP dark matter

[Seller, Iwamoto and ZT, arXiv:2104.11248]

  - Provide a viable source of lepto-baryogenesis

[Seller, Szép, ZT, arXiv:2301.07961, 2409.07180]

Parameter space is already partly explored

[Péli and ZT, arXiv:2204.07100, 2305.11931, 2402.14786, 2501.04388]

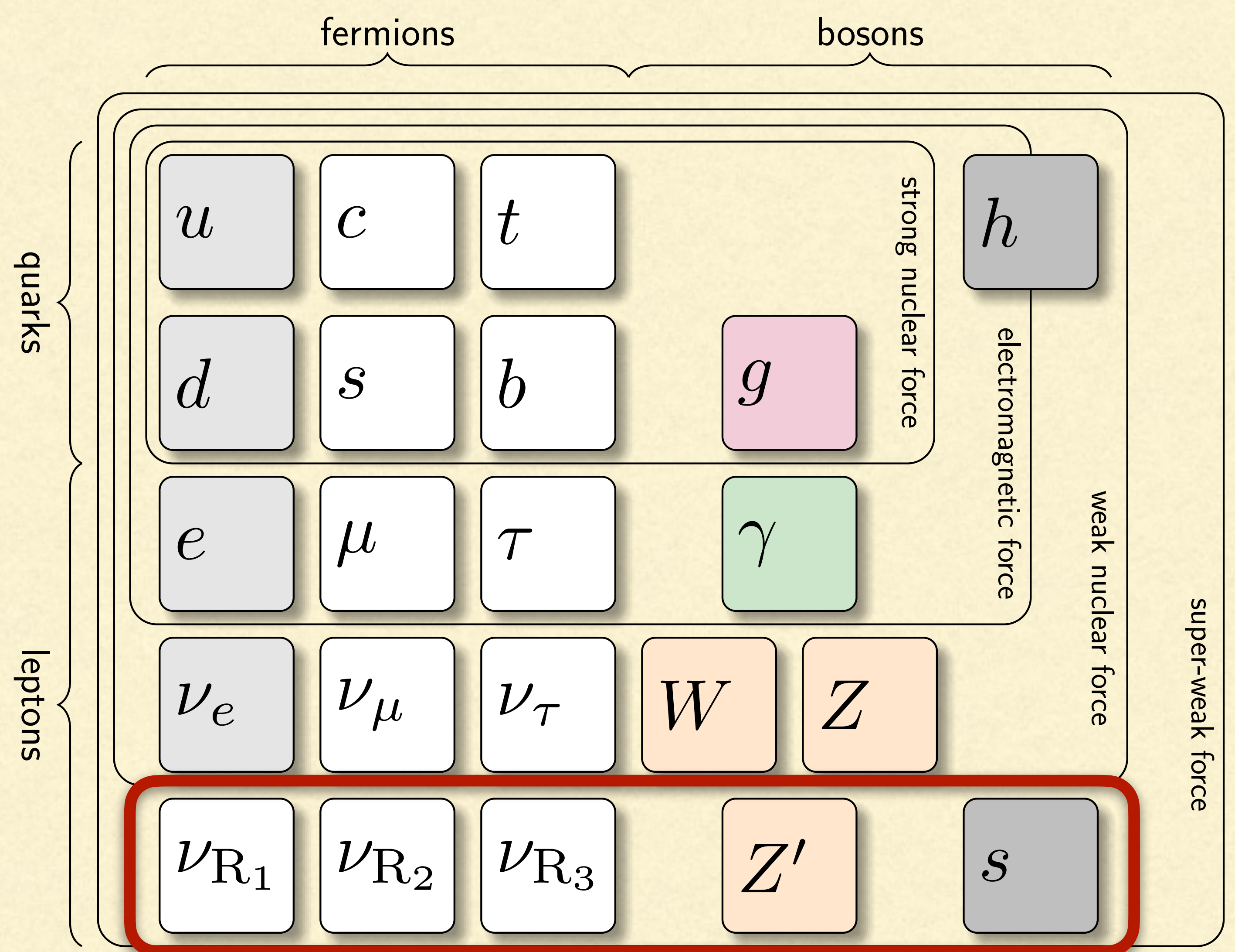
Superweak extension of SM (SWSM)

- Symmetry of the Lagrangian: local $G=G_{SM}\times U(1)_z$ with $G_{SM}=SU(3)_c\times SU(2)_L\times U(1)_Y$

renormalizable gauge theory, including all dim 4 operators allowed by G (except $F_{\mu\nu}\tilde{F}^{\mu\nu}$)

- $U(1)_z$ gauge field must be massive, which requires a second scalar with a non-zero VEV, allowing for Majorana masses for right-handed neutrinos if exist
- z-charges fixed by requirement of
  - gauge and gravity anomaly cancellation and
  - gauge invariant Yukawa terms for neutrino mass generation

Particle content of SWSM
(a take-home picture)



new fields in SWSM

Charge assignment from gauge invariant neutrino interactions

field	$SU(3)_c$	$SU(2)_L$	y_j	z_j (a)	z_j (b)	$r_j = z_j/z_\phi - y_j$ (c)
$U_L,\ D_L$	3	2	$\frac{1}{6}$	Z_1	$\frac{1}{6}$	0
U_R	3	1	$\frac{2}{3}$	Z_2	$\frac{7}{6}$	$\frac{1}{2}$
D_R	3	1	$-\frac{1}{3}$	$2Z_1 - Z_2$	$-\frac{5}{6}$	$-\frac{1}{2}$
$\nu_L,\ \ell_L$	1	2	$-\frac{1}{2}$	$-3Z_1$	$-\frac{1}{2}$	0
ν_R	1	1	0	$Z_2 - 4Z_1$	$\frac{1}{2}$	$\frac{1}{2}$
ℓ_R	1	1	-1	$-2Z_1 - Z_2$	$-\frac{3}{2}$	$-\frac{1}{2}$
ϕ	1	2	$\frac{1}{2}$	z_ϕ	1	$\frac{1}{2}$
χ	1	1	0	z_χ	-1	-1

(a) anomaly free charges (b) from neutrino-scalar interactions (c) from re-parametrization of couplings

Kinetic mixing

- kinetic mixing:
$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$
- covariant derivative:
$$\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i}(y g_y B_\mu + z g_z B'_\mu)$$
- or equivalently can choose basis s. t.:
$$D_\mu^{\mathrm{U}(1)} = -\mathrm{i}\begin{pmatrix} y & z \end{pmatrix}\begin{pmatrix} \hat{g}_{yy} & \hat{g}_{yz} \\ \hat{g}_{zy} & \hat{g}_{zz} \end{pmatrix}\begin{pmatrix} \hat{B}_\mu \\ \hat{B}'_\mu \end{pmatrix}$$

and can parametrize the coupling matrix s.t.:

$$\hat{\mathbf{g}} = \begin{pmatrix} \hat{g}_{yy} & \hat{g}_{yz} \\ \hat{g}_{zy} & \hat{g}_{zz} \end{pmatrix} = \begin{pmatrix} g_y & -\eta g'_z \\ 0 & g'_z \end{pmatrix}\begin{pmatrix} \cos\epsilon' & \sin\epsilon' \\ -\sin\epsilon' & \cos\epsilon' \end{pmatrix}$$ with $$g'_z = g_z/\sqrt{1-\epsilon^2} \qquad \eta = \epsilon g_y/g_z .$$

Mixing in the neutral gauge sector

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_Z & -s_Z \\ 0 & s_Z & c_Z \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} \qquad \begin{array}{l} c_X = \cos\theta_X \\ s_X = \sin\theta_X \end{array}$$

where θ_W is the weak mixing angle & θ_Z is the $Z - Z'$ mixing, implicitly: $\tan(2\theta_Z) = -2\kappa \Big/ \left(1 - \kappa^2 - \tau^2\right)$, with κ and τ effective couplings, functions of the Lagrangian couplings

The expressions for the neutral gauge boson masses are somewhat cumbersome, but exists a nice, compact generalization of the SM mass-relation formula: $\dfrac{M_W^2}{c_W^2} = c_Z^2 M_Z^2 + s_Z^2 M_{Z'}^2$ $\quad \left(M_W = \dfrac{1}{2} g_L v\right)$

Scalars in the SWSM

- Standard ϕ complex SU(2)$_L$ doublet and new χ complex singlet:

$$\mathcal{L}_{\phi,\chi} = [D_\mu^{(\phi)}\phi]^* D^{(\phi)\,\mu}\phi + [D_\mu^{(\chi)}\chi]^* D^{(\chi)\,\mu}\chi - V(\phi,\chi)$$

- with scalar potential

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \left(|\phi|^2, |\chi|^2\right)\begin{pmatrix} \lambda_\phi & \frac{\lambda}{2} \\ \frac{\lambda}{2} & \lambda_\chi \end{pmatrix}\begin{pmatrix} |\phi|^2 \\ |\chi|^2 \end{pmatrix}$$

- After SSB, G → SU(3)$_c$×U(1)$_{QED}$ in R_ξ gauge

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -\mathrm{i}\sqrt{2}\sigma^+ \\ v + h' + \mathrm{i}\sigma_\phi \end{pmatrix} \quad \& \quad \chi = \frac{1}{\sqrt{2}}(w + s' + \mathrm{i}\sigma_\chi)$$

Mixing in the scalar sector

$$\begin{pmatrix} h' \\ s' \end{pmatrix} = \begin{pmatrix} c_S & s_S \\ -s_S & c_S \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

where θ_S is the scalar mixing angle implicitly:

$\tan(2\theta_S) = \lambda v w \Big/ \left(\lambda_\chi w^2 - \lambda_\phi v^2\right)$, with v and w VEVs

5 new parameters:

- in gauge sector: $\{g_z$ and $g_{yz}\}$ or $\{\kappa$ and $\tau\}$ or $\{\theta_Z$ and $M_{Z'}\}$
- in scalar sector: $\{\mu_\chi^2, \lambda_\chi$ and $\lambda\}$ or $\{w, \lambda_\chi$ and $\lambda\}$ or $\{M_S, \theta_S$ and $\lambda\}$

After SSB neutrino mass terms appear

$$-\mathcal{L}_Y^{\ell} = \frac{w + s' + \mathrm{i}\sigma_\chi}{2\sqrt{2}} \overline{\nu_R^c}\, \mathbf{Y}_N\, \nu_R + \frac{v + h' - \mathrm{i}\sigma_\phi}{\sqrt{2}} \overline{\nu_L}\, \mathbf{Y}_\nu\, \nu_R + \mathrm{h.c.}$$

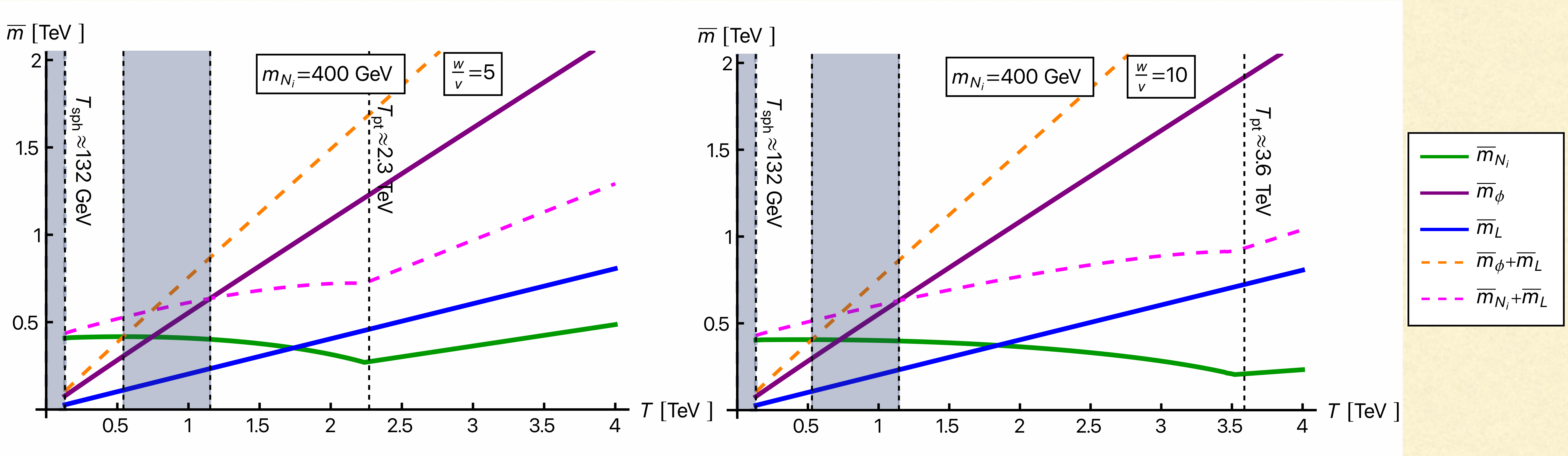
$$\mathbf{M}_M = \frac{w}{\sqrt{2}} \mathbf{Y}_N \qquad \mathbf{M}_D = \frac{v}{\sqrt{2}} \mathbf{Y}_\nu$$

- In flavour basis the full 6×6 mass matrix reads

$$\mathbf{M}_{6\times 6} = \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D \\ \mathbf{M}_D^T & \mathbf{M}_M \end{pmatrix}$$

- ν_L and ν_R have the same q-numbers, can mix, leading to type-I low-scale see-saw
- Dirac and Majorana mass terms appear already at tree level by SSB (not generated radiatively)
- Quantum corrections to active neutrinos are not dangerous [Iwamoto et al, arXiv:2104.14571]

Leptogenesis step 1: find thermal masses



Thermal masses for the lighter ones of the heavy RHNs ($\overline{m}_{N_i}$), the leptons ($\overline{m}_L$) and the Brout-Englert-Higgs field ($\overline{m}_\phi$) in the SWSM at two specific values of the VEV ratio. Vacuum masses are $m_{N_j} = 1.1\ m_{N_i} = 440$ GeV for the neutrinos, and $m_\chi = 650$ GeV for the singlet scalar with the singlet VEV being $w = 5v$ (left) or $w = 10v$ (right)

Leptogenesis step 2: compute CP ϵ

Given by the thermal average of the amplitude level asymmetry factor $\epsilon_{\mathscr{M}}$ (also model dependent):

$$\epsilon_{a\to b+c} = \frac{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\, \epsilon_{\mathscr{M}}(y_a, x) f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\, f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}$$

$$\epsilon_{\mathscr{M}} = = \frac{\left|M_{i,-}^{[1]}\right|^2}{\left|M_{i,+}^{(0)}\right|^2}, \qquad \left|M_{i,\pm}^{[n]}\right|^2 = \sum_{a,b,\alpha}\left[\left\langle \left|\mathscr{M}_{\alpha i}^{ab\,[n]}\right|^2\right\rangle \pm \left\langle \left|\overline{\mathscr{M}}_{\alpha i}^{ab\,[n]}\right|^2\right\rangle\right]$$

n = # of loops

Leptogenesis step 2: compute CP ϵ

Given by the thermal average of the amplitude level asymmetry factor $\epsilon_{\mathscr{M}}$ (also model dependent):

$$\epsilon_{a\to b+c} = \frac{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\,\epsilon_{\mathscr{M}}(y_a, x) f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\, f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}$$

- $z_a = m_a/T$,
-

Leptogenesis step 2: compute CP ϵ

Given by the thermal average of the amplitude level asymmetry factor $\epsilon_{\mathscr{M}}$ (also model dependent):

$$\epsilon_{a\to b+c} = \frac{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1} \mathrm{d}x\, \epsilon_{\mathscr{M}}(y_a, x) f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1} \mathrm{d}x\, f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}$$

- $z_a = m_a/T$,
- $f_{B/F}(y) = [\exp(y) \mp 1]^{-1}$ statistical factors,
-

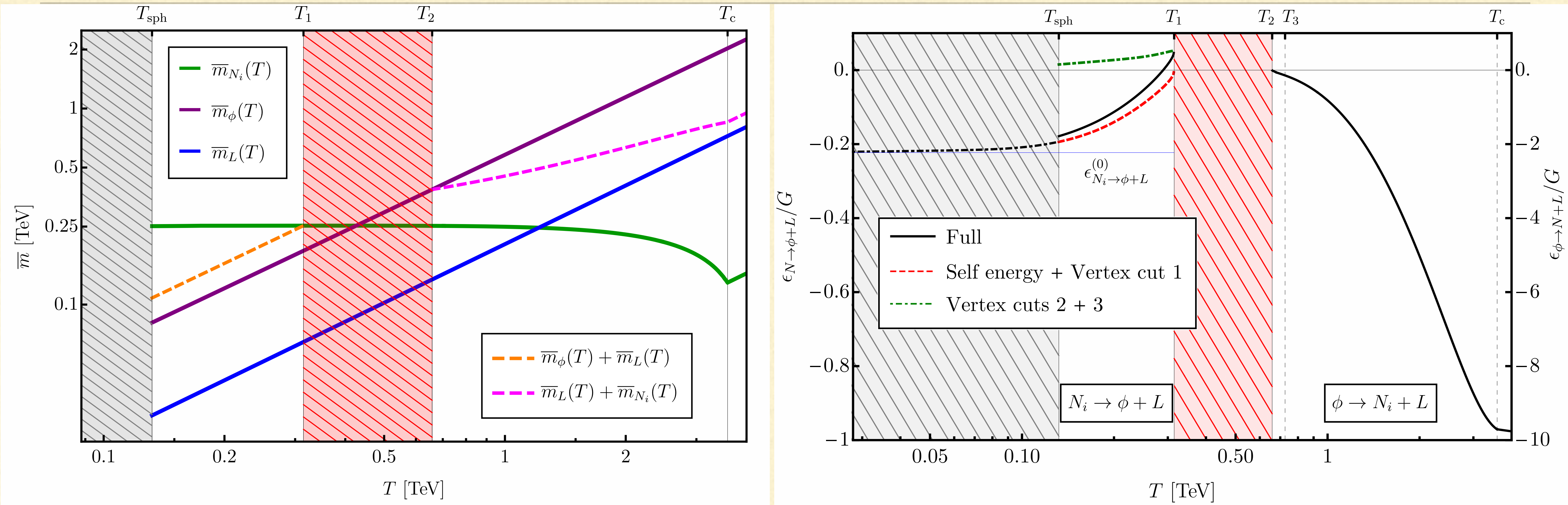
Leptogenesis step 2: compute CP ϵ

Given by the thermal average of the amplitude level asymmetry factor $\epsilon_{\mathscr{M}}$ (also model dependent):

$$\epsilon_{a\to b+c} = \frac{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\,\epsilon_{\mathscr{M}}(y_a, x) f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}{\int_{z_a}^{\infty} \mathrm{d}y_a\, f_{\mathrm{t}(a)}(-y_a)\sqrt{y_a^2 - z_a^2}\int_{-1}^{1}\mathrm{d}x\, f_{\mathrm{t}(b)}(y_b) f_{\mathrm{t}(c)}(y_c)}$$

- $z_a = m_a/T$,
- $f_{B/F}(y) = [\exp(y) \mp 1]^{-1}$ statistical factors,
- $\mathrm{t}(p) =$ B(ose) or F(ermi) giving the statistics type of p

Leptogenesis step 2: compute CP ϵ



Left: thermal masses when vacuum masses are

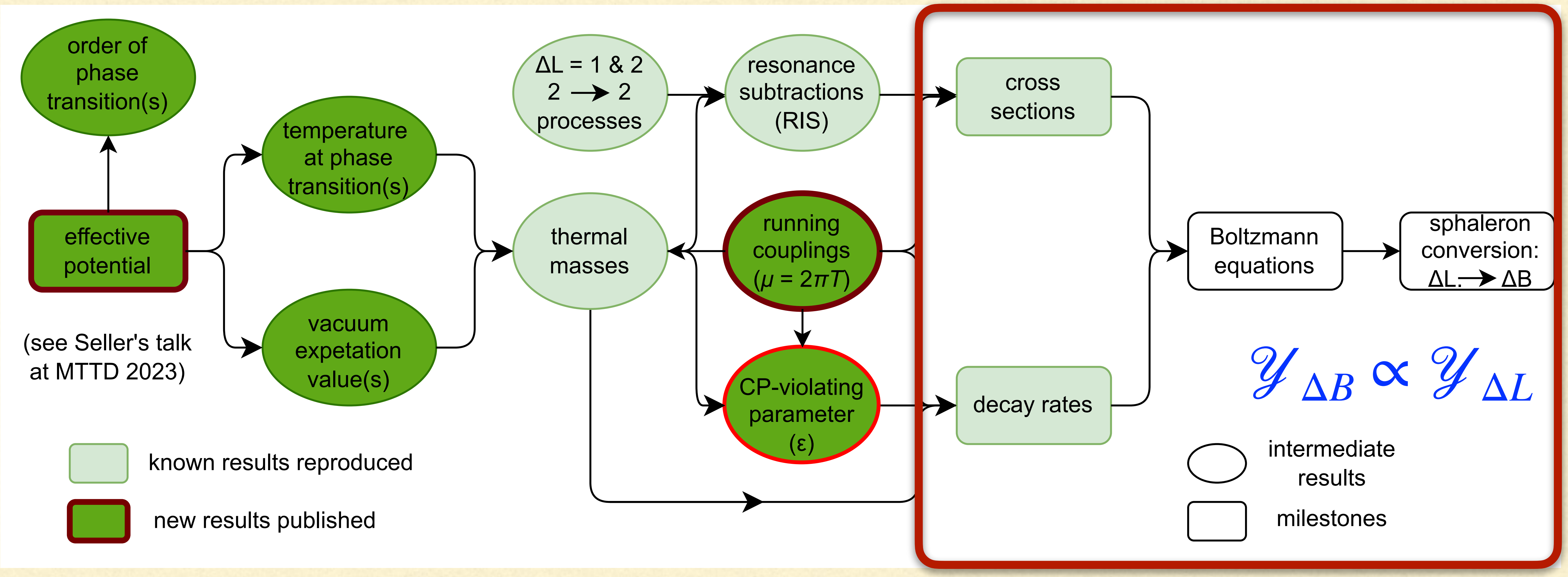
m_{N_j} = 1.1 m_{N_i} = 275 GeV, m_χ = 650 GeV and $w = 10v$.

Right: thermal CP asymmetry factor normalized to couplings

T_i $(i = 1,2,3)$ correspond to the kinematic thresholds:

$m_{N_i}(T_1) = m_\phi(T_1) + m_L(T_1)$, $m_\phi(T_2) = m_{N_i}(T_2) + m_L(T_2)$, $m_\phi(T_3) = m_{N_j}(T_3) + m_L(T_3)$

Coming soon: leptogenesis in the SWSM
(step 3: solving the Boltzmann eqs.)



Outlook:

Constrain the parameter space of SWSM by checking validity of the expected consequences

Does not fit:

- Neutrino masses
- Dark matter and energy
- Baryon asymmetry

Puzzles in the scalar sector:

- Lagrangian and its parameters
- Yukawa couplings
- Connection to inflation
- Vacuum stability (λ too small)
- Naturalness (μ is dimensional)

Hidden new particles:

- Too heavy
- Interact too weakly

Anomalies:

- Muon anomalous magnetic moment
- 2-3σ excesses at LHC experiments
- X17 and E38 anomalies
- CDF II result for M_W

the end