Zoltán Trócsányi

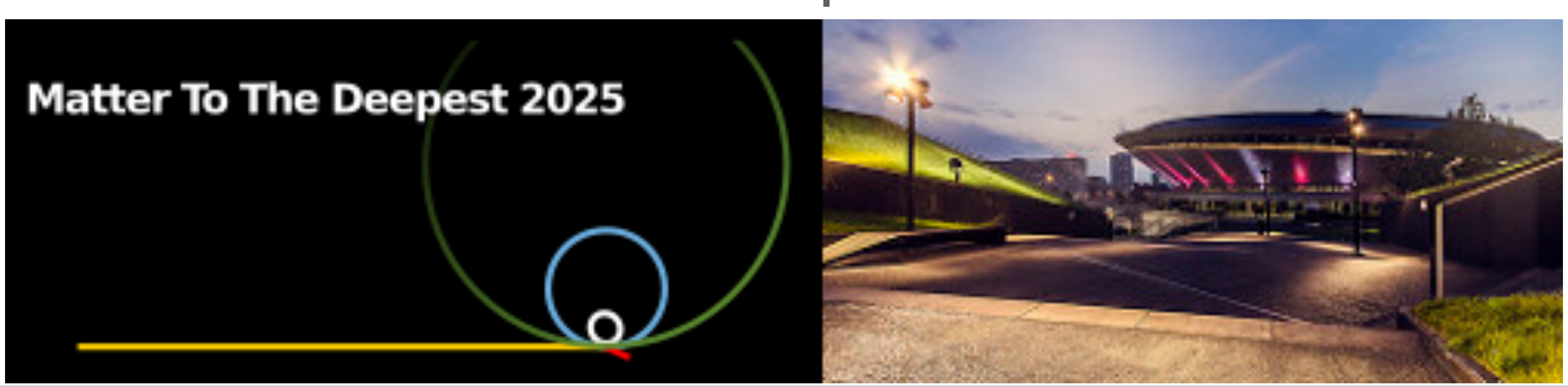
LEPTOGENESIS IN U(1) EXTENSIONS OF THE STANDARD MODEL

based on

arXiv:1812.11189 (*Symmetry*), 2301.07961 (*JHEP*), 2409.07180 (JHEP), 2509.nnnn

with K. Seller, Zs. Szép

Katowicze, 16 September, 2025



OUTLINE

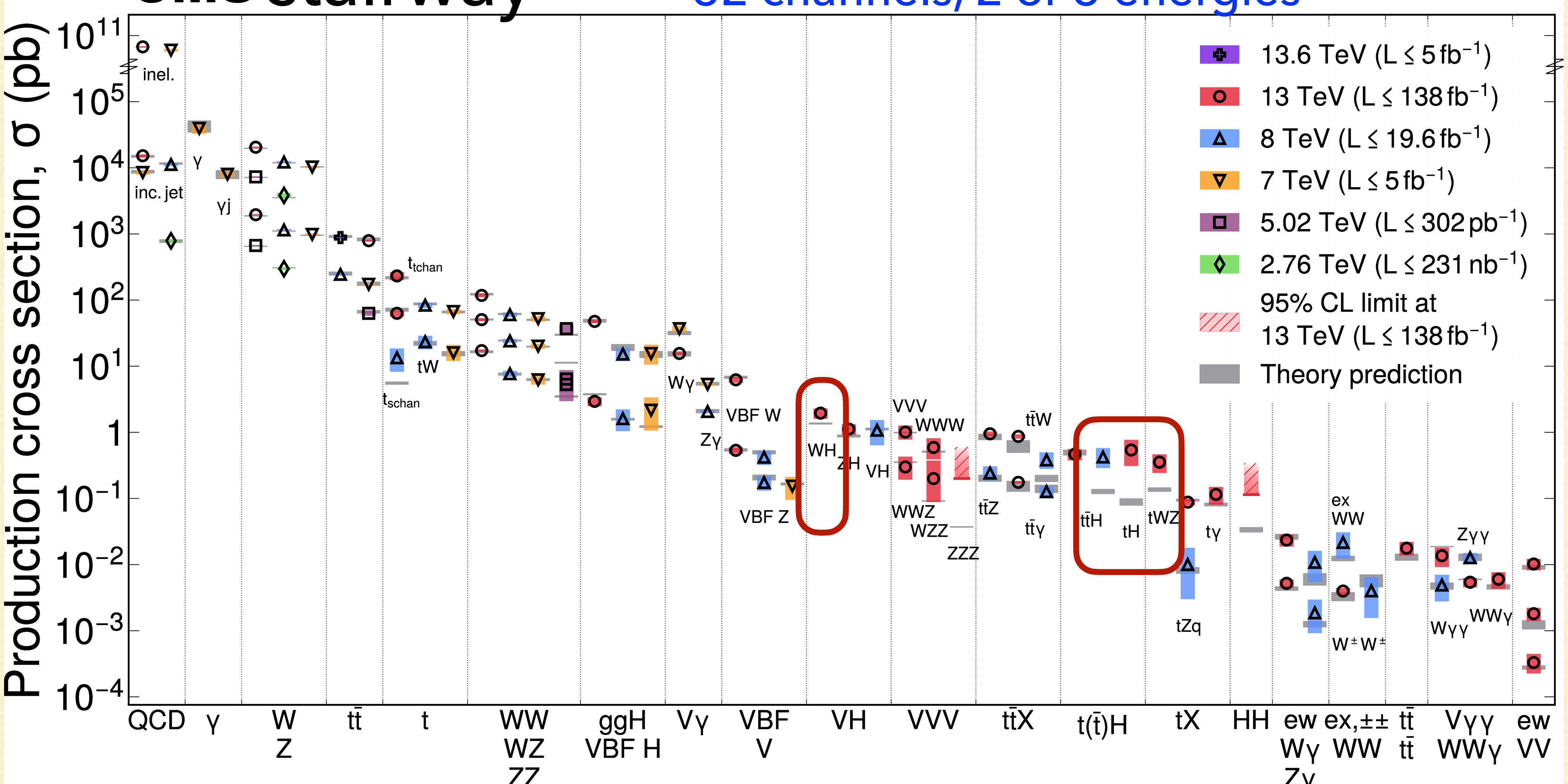
Rough estimates of BSM effects can easily be deceptive

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

Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely

CMS stairway   32 channels, 2 or 3 energies



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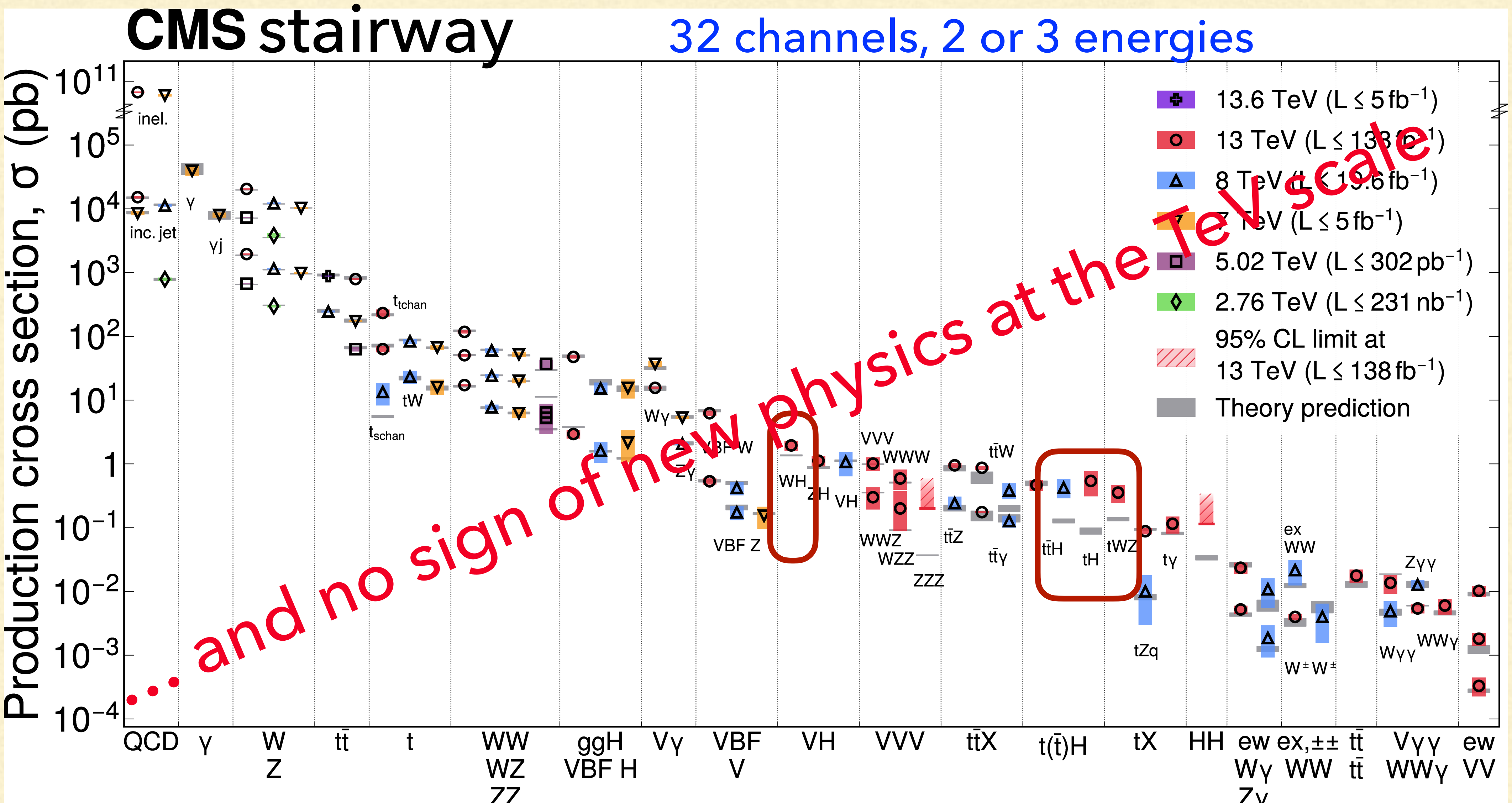

Status of particle physics: cosmic and intensity frontiers

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 th present Universe
3. Existing baryon asymmetry cannot be explained by CP asymmetry SM, $\eta \simeq 6.0 \cdot 10^{-10}$ from combined BBN and CMB

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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)

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- Too heavy
- Interact too weakly

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Anomalies:

- Muon anomalous magnetic moment
- 2-3σ excesses at LHC experiments
- X17 and X38 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

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Baryon asymmetry is our focus today

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Status of particle physics: cosmic and intensity frontiers

In this talk we focus on lepto-baryogenesis

through thermal leptogenesis

3. Existing baryon asymmetry cannot be explained by CP asymmetry in SM, $\eta \simeq 6.0 \cdot 10^{-10}$ from combined BBN and CMB

(Presentations at previous MTTD workshops focused on neutrinos and DM)

Lepto-baryogenesis has two steps

1. Leptogenesis in a BSM

   followed by

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

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

Neutrino masses and leptogenesis

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

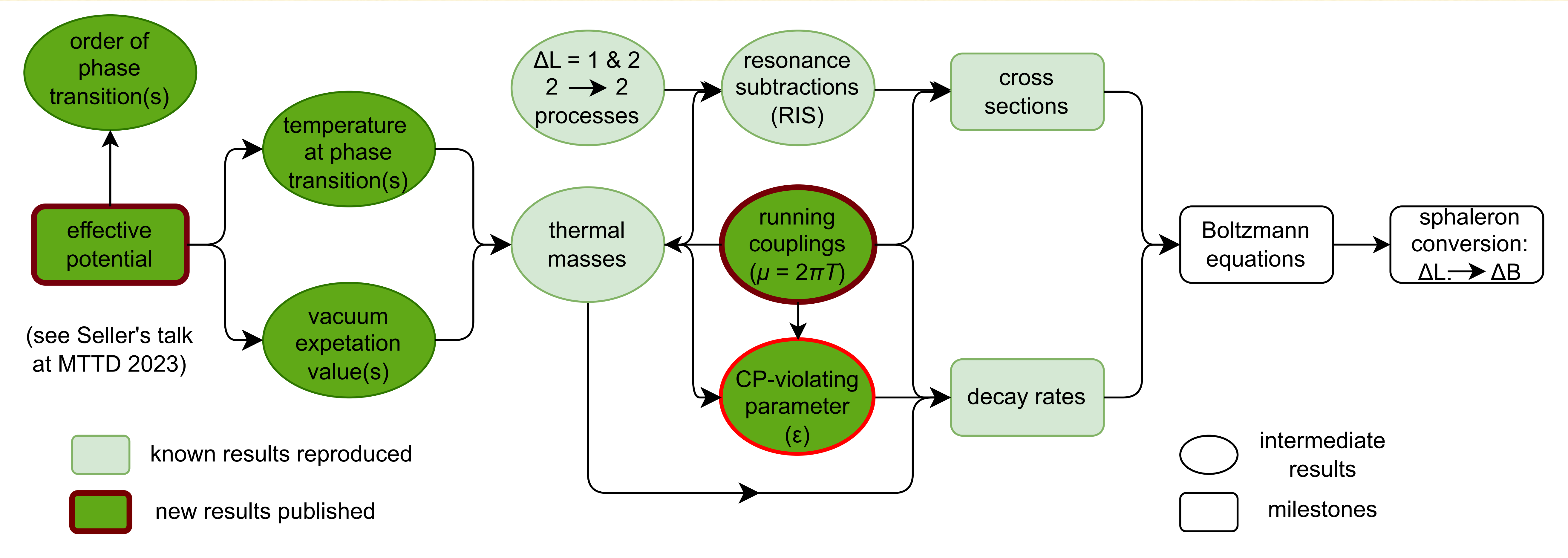
Decays of such RHNs lead to a non-vanishing ΔL that can be estimated either by

- 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 $\mathscr{Y}_{\Delta \mathrm{L}} = \mathscr{Y}_{\ell} - \mathscr{Y}_{\bar{\ell}}$

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

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- $z = \Lambda/T$ inverse temperature

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

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- $z = \Lambda/T$ inverse temperature
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- $H(z)$ Hubble parameter when $T = \Lambda/z$

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

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

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

CP asymmetry factor

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

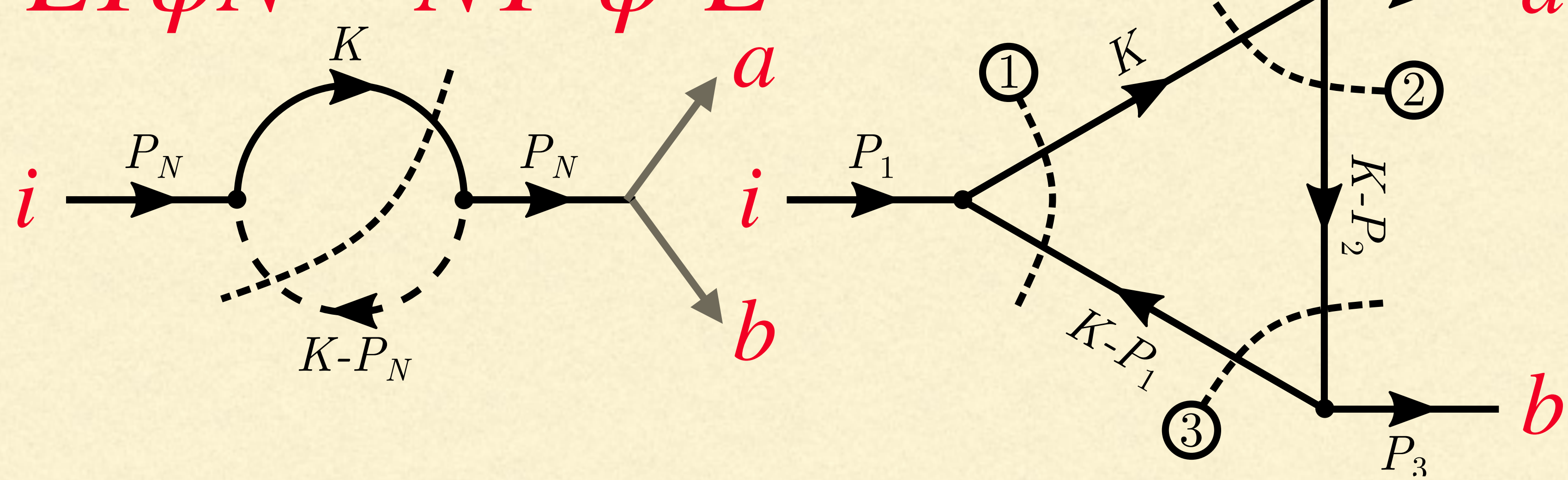
asymmetry is generated by CP-violating decays of the sterile neutrinos, which is proportional to the CP asymmetry factor ϵ

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

CP asymmetry factor

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

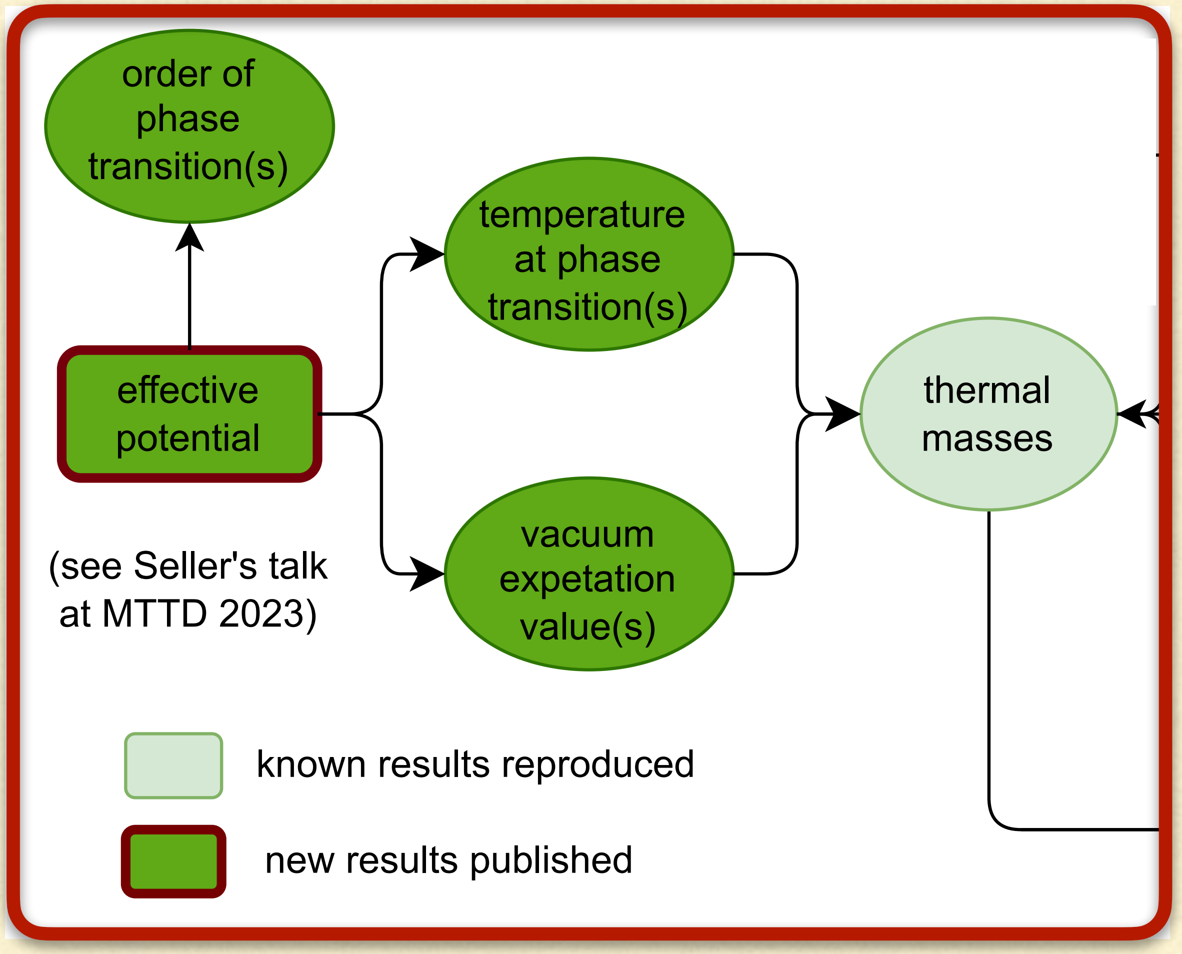
K. Seller, Z. Szép, Z.T., *CP violation at finite temperature*, JHEP **09** (2025) 034 [arXiv:2409.07180 [hep-ph]]

and

CP asymmetry factor at finite temperature, to appear in EPJC **09** (2025) [arXiv:2509.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

- Introduced at MTTD 2019 (Katowice)
- 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]

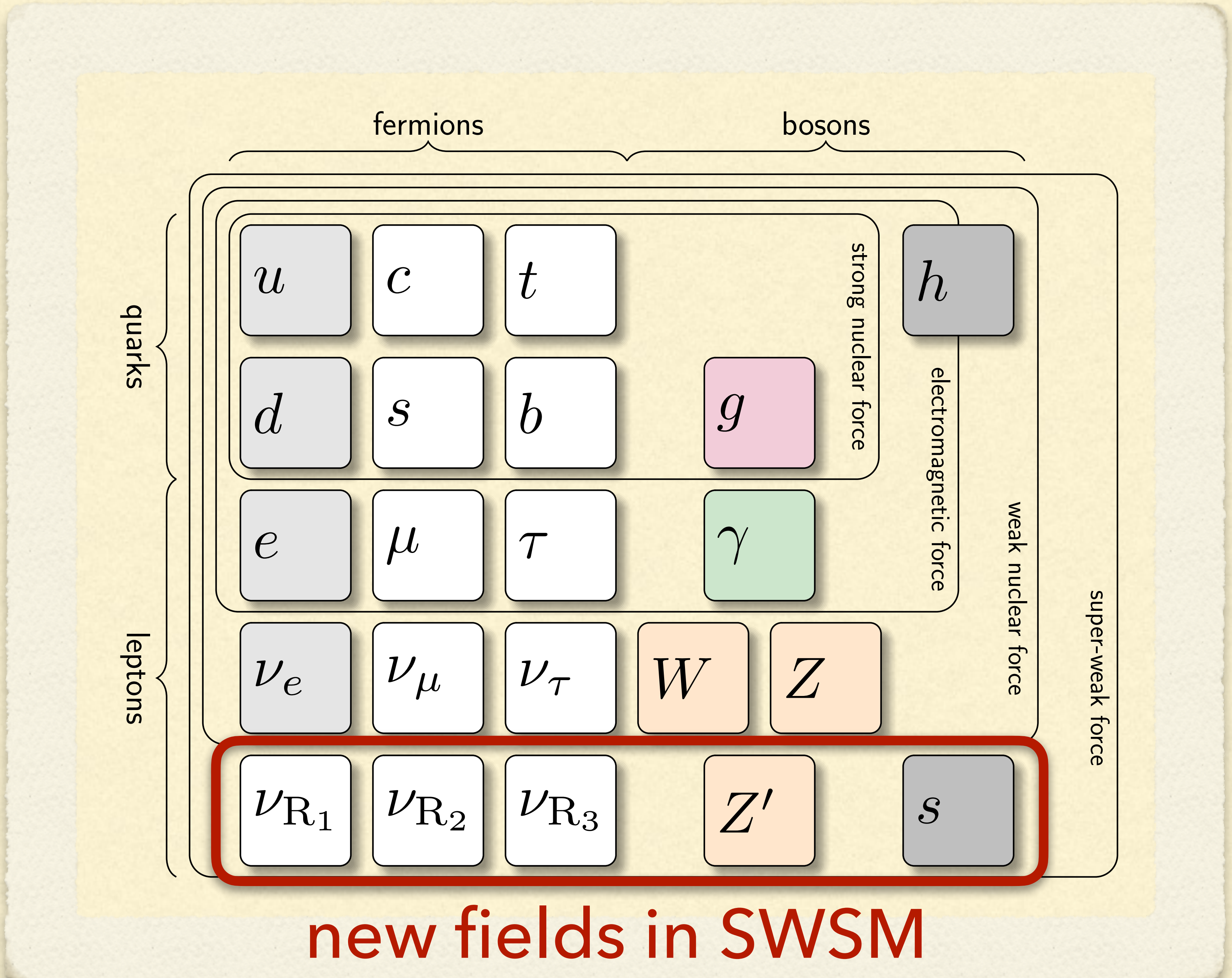
Superweak extension of SM (SWSM)

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

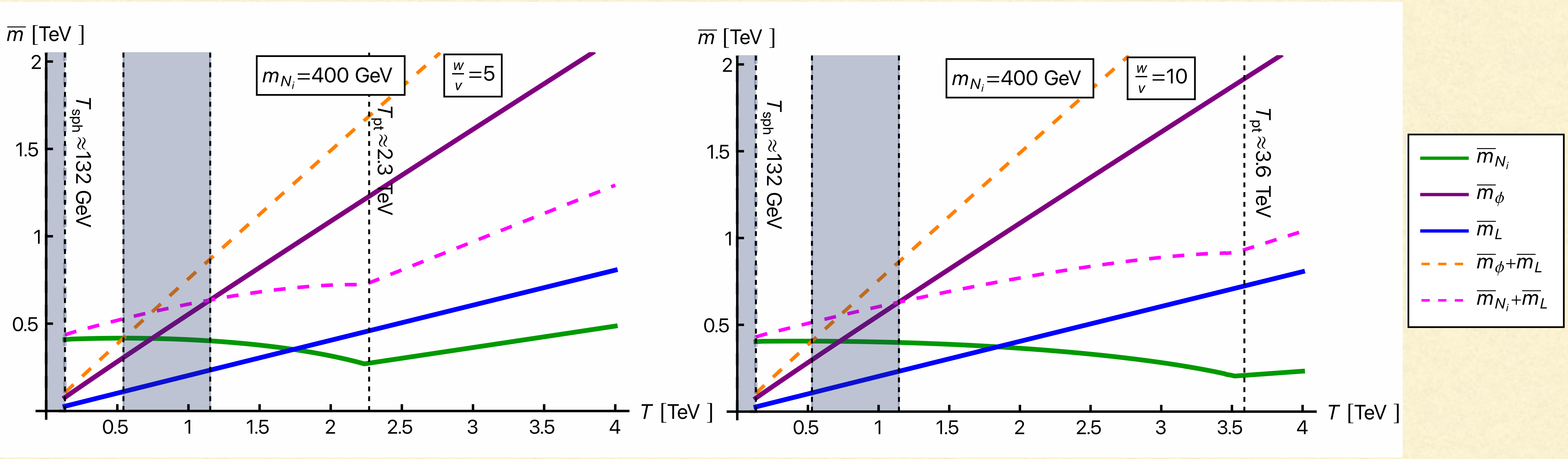
renormalizable gauge theory, including all dim 4 operators allowed by G (except $F_{\mu\nu}\tilde{F}^{\mu\nu}$)

- $U(1)_z$ 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)



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

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- $z_a = m_a/T$,
-

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

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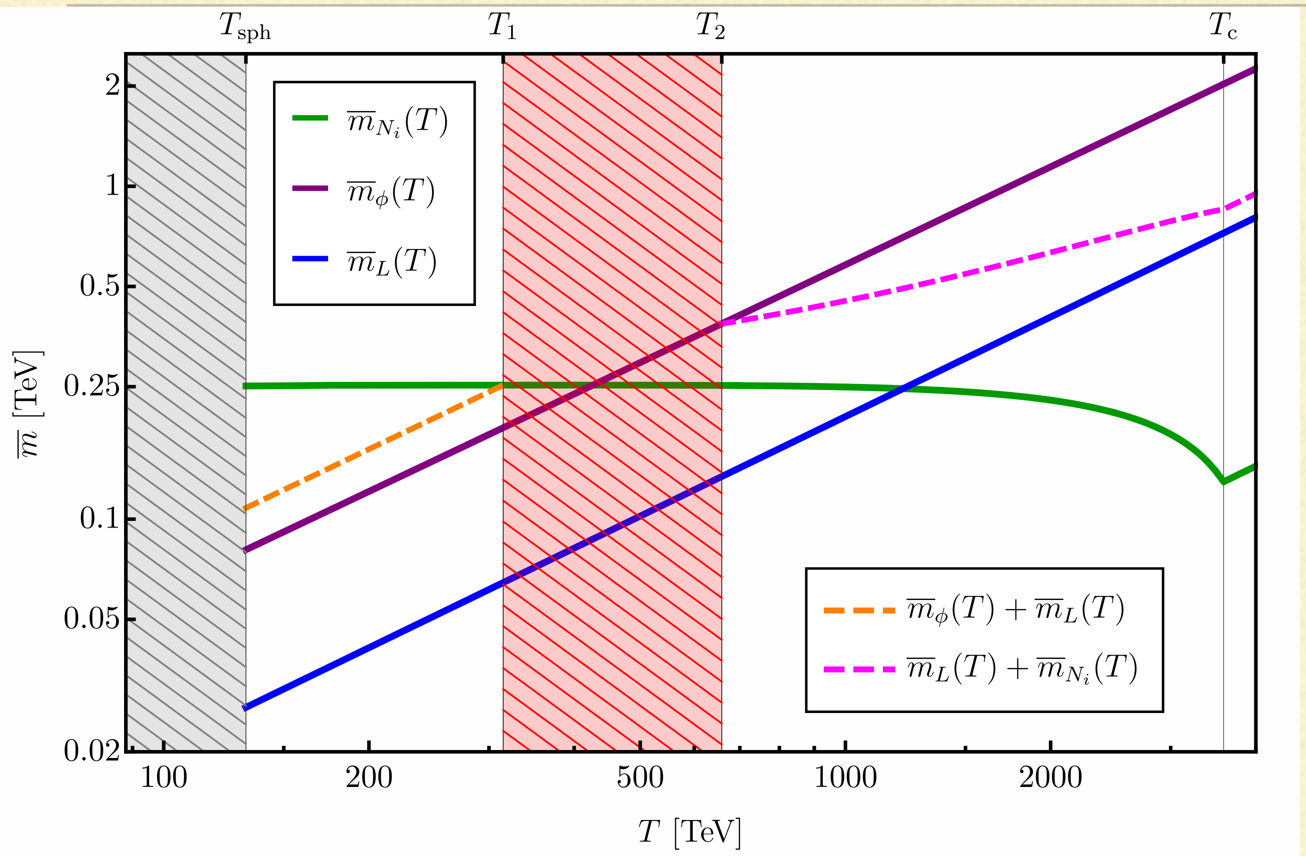
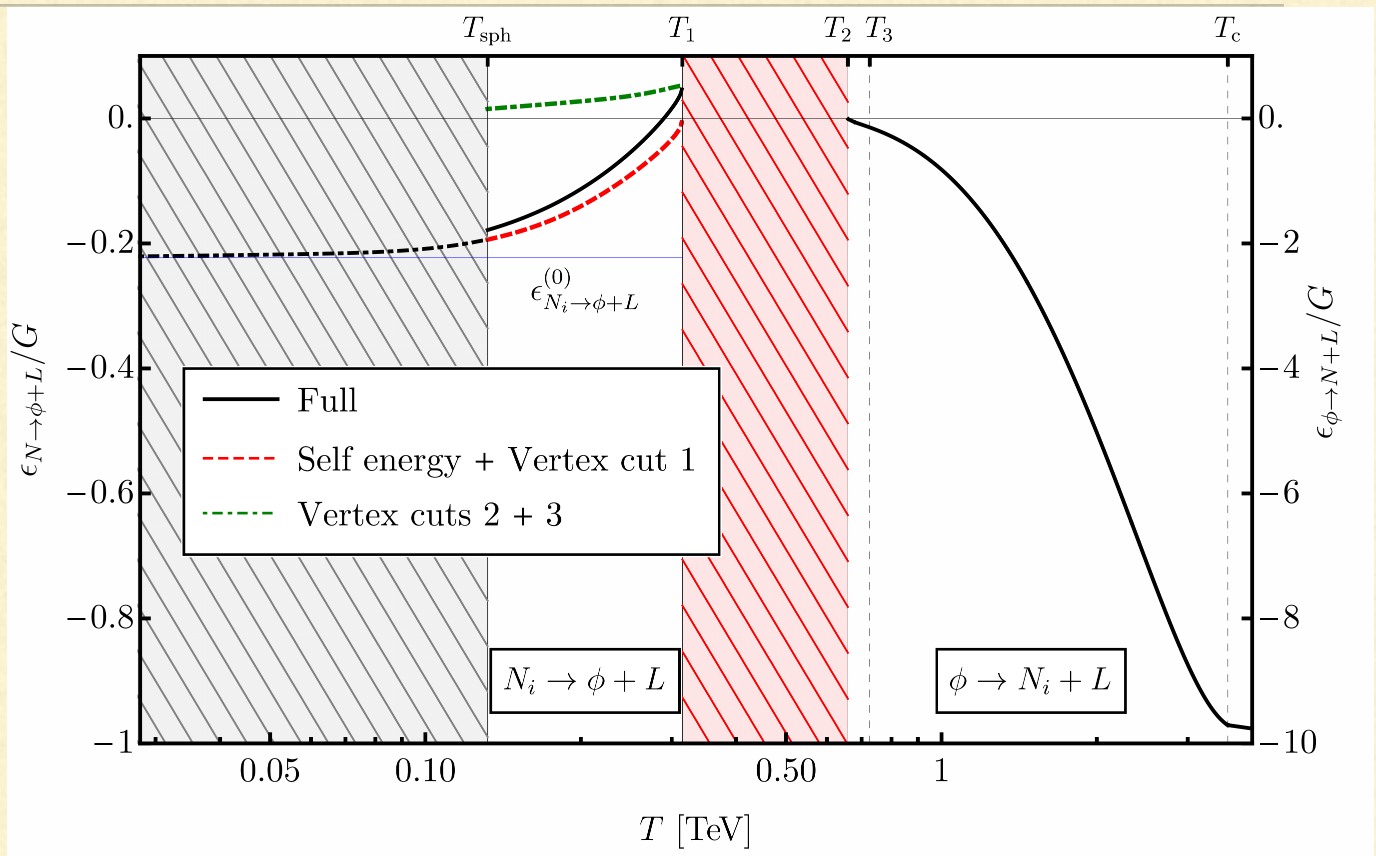
- $z_a = m_a/T$,
- $f_{B/F}(y) = [\exp(y) \mp 1]^{-1}$ statistical factor,
- $\mathrm{t}(p) =$ B(ose) or F(ermi) giving the statistics type of p

Leptogenesis step 2: compute CP ϵ





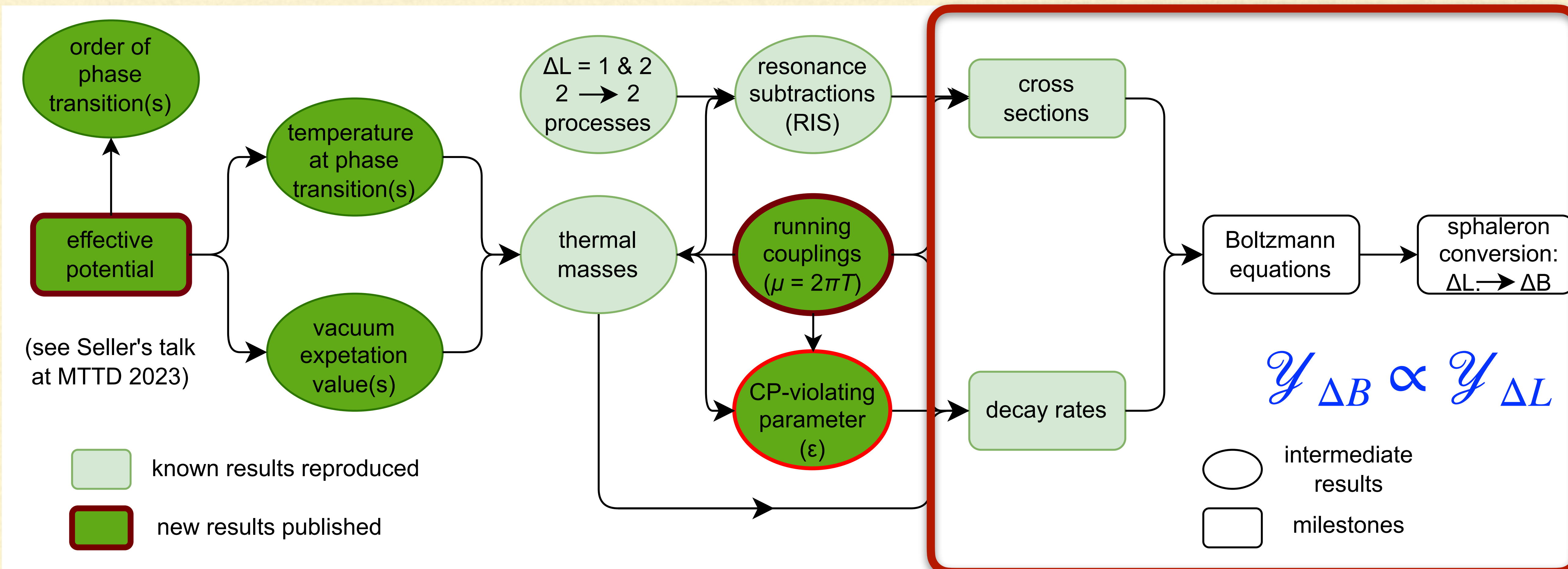
Left: thermal masses when vacuum masses m_{N_j} = 1.1 m_{N_i} = 275 GeV, m_χ = 650 GeV and $w_0 = 10v$.

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

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the end

Appendix

Charge assignment from gauge invariant neutrino interactions

field	$SU(3)_{\rm c}$	$SU(2)_{\rm L}$	y_j	$z_j^{(a)}$	$z_j^{(b)}$	$r_j = z_j/z_\phi - y_j^{(c)}$
$U_{\rm L},\ D_{\rm L}$	3	2	$\frac{1}{6}$	Z_1	$\frac{1}{6}$	0
$U_{\rm R}$	3	1	$\frac{2}{3}$	Z_2	$\frac{7}{6}$	$\frac{1}{2}$
$D_{\rm R}$	3	1	$-\frac{1}{3}$	$2Z_1 - Z_2$	$-\frac{5}{6}$	$-\frac{1}{2}$
$\nu_{\rm L},\ \ell_{\rm L}$	1	2	$-\frac{1}{2}$	$-3Z_1$	$-\frac{1}{2}$	0
$\nu_{\rm R}$	1	1	0	$Z_2 - 4Z_1$	$\frac{1}{2}$	$\frac{1}{2}$
$\ell_{\rm R}$	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

Particle model

New fields: 3 right-handed neutrinos ν_{R}^f, a new scalar χ, and new $\mathrm{U}(1)_z$ gauge boson B'

- fermion fields (Weyl spinors):

$$\psi_{q,1}^f = \begin{pmatrix} U^f \\ D^f \end{pmatrix}_{\mathrm{L}} \qquad \psi_{q,2}^f = U_{\mathrm{R}}^f , \qquad \psi_{q,3}^f = D_{\mathrm{R}}^f$$

$$\psi_{l,1}^f = \begin{pmatrix} \nu^f \\ \ell^f \end{pmatrix}_{\mathrm{L}} \qquad \boxed{\psi_{l,2}^f = \nu_{\mathrm{R}}^f ,} \qquad \psi_{l,3}^f = \ell_{\mathrm{R}}^f$$

- with extended U(1) part of the covariant derivative:

$$\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i}(y g_y B_\mu \boxed{+ z g_z B'_\mu})$$

- the new U(1) kinetic term includes kinetic mixing:

$$\mathcal{L} \supset -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \boxed{- \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}}$$

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:

$$\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i}(yg_yB_\mu + zg_zB'_\mu)$$

- 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

$$g'_z = g_z/\sqrt{1-\epsilon^2}$$

$$\eta = \epsilon g_y/g_z.$$

Neutral currents

- covariant derivative: $\mathscr{D}_\mu^{\textsf{neut.}} \supset -\mathrm{i}(\mathcal{Q}_A A_\mu + \mathcal{Q}_Z Z_\mu + \mathcal{Q}_{Z'} Z'_\mu)$
- effective couplings:
  - $\mathcal{Q}_A = (T_3 + y)|e| \equiv \mathcal{Q}_A^{\mathrm{SM}}$
  - $\mathcal{Q}_Z = \underbrace{(T_3 \cos^2\theta_{\mathrm{W}} - y \sin^2\theta_{\mathrm{W}}) g_{Z^0}}_{\mathcal{Q}_Z^{\textsf{SM}}} \cos\theta_Z - (z - \eta y) g_z \sin\theta_Z$
  - $\mathcal{Q}_{Z'} = (T_3 \cos^2\theta_{\mathrm{W}} - y \sin^2\theta_{\mathrm{W}}) g_{Z^0} \sin\theta_Z + (z - \eta y) g_z \cos\theta_Z$
- $Z - Z'$ **mixing is small**, the weak neutral current is only modified at order $\mathrm{O}(g_z^2/g_{Z^0}^2)$

Mixing in the neutral gauge sector

$$\begin{pmatrix} \hat{B}^\mu \\ W^{3\,\mu} \\ \hat{B}'^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{\rm W} & -\cos\theta_Z \sin\theta_{\rm W} & -\sin\theta_Z \sin\theta_{\rm W} \\ \sin\theta_{\rm W} & \cos\theta_Z \cos\theta_{\rm W} & \cos\theta_{\rm W} \sin\theta_Z \\ 0 & -\sin\theta_Z & \cos\theta_Z \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix}$$

where θ_W is the Weinberg angle & θ_Z is the $Z - Z'$ mixing, implicitly: $\tan(2\theta_Z) = 2\kappa/(1-\kappa^2-\tau^2)$, with

$$\kappa = \cos\theta_{\rm W}(\gamma'_y - 2\gamma'_z) \qquad \tau = 2\cos\theta_{\rm W}\gamma'_z \tan\beta$$

$$\gamma'_y = (\epsilon/\sqrt{1-\epsilon^2})(g_y/g_{\rm L}) \quad \gamma'_z = g'_z/g_{\rm L} \qquad \tan\beta = w/v$$

$$\left(\sin\theta_Z = {\rm sgn}\,(\kappa) \left[\frac{1}{2}\left(1 - \frac{1-\kappa^2-\tau^2}{\sqrt{(1+\kappa^2+\tau^2)^2 - 4\tau^2}}\right)\right]^{1/2}, \qquad \cos\theta_Z = \left[\frac{1}{2}\left(1 + \frac{1-\kappa^2-\tau^2}{\sqrt{(1+\kappa^2+\tau^2)^2 - 4\tau^2}}\right)\right]^{1/2} \right)$$

Masses of the neutral gauge bosons

$$M_Z^2 = \left(\frac{M_W}{\cos\theta_\mathrm{W}}\right)^2 \left[(\cos\theta_Z - \kappa\sin\theta_Z)^2 + (\tau\sin\theta_Z)^2\right]$$

$$M_{Z'}^2 = \left(\frac{M_W}{\cos\theta_\mathrm{W}}\right)^2 \left[(\sin\theta_Z + \kappa\cos\theta_Z)^2 + (\tau\cos\theta_Z)^2\right].$$

obeying $(Z \to Z') \Rightarrow (\cos\theta_Z, \sin\theta_Z) \to (\sin\theta_Z, -\cos\theta_Z)$

Rough estimates of gauge parameters

- Gauge coupling, g_z:

  in order to avoid SM precision constraints $\mathrm{O}(g_z/g_{Z^0}) \ll 1$

- Vacuum expectation value of χ singlet, w:

  in the gauge sector rather use the mass of Z' & assume that $M_{Z'} \ll M_Z$

- $Z - Z'$ mixing angle, θ_Z:

$$\tan(2\theta_Z) = \frac{4\zeta_\phi g_z}{g_{Z^0}} + \mathcal{O}\left(\frac{g_z^3}{g_{Z^0}^3}\right) \ll 1$$

- $\mathrm{U}(1)_y \otimes \mathrm{U}(1)_z$ gauge mixing parameter, η:

  its value can be determined from RGE: $0 \leq \eta \lesssim 0.66$

- Masses of sterile neutrinos:

  assume N_1 to be light (keV-MeV scale), while $M_{2,3} = \mathrm{O}(M_{Z^0})$

Neutral current couplings

$$\Gamma^{\mu}_{V\bar{f}f} \;=\; -\mathrm{i}e\gamma^{\mu}(C^{R}_{V\bar{f}f}P_R + C^{L}_{V\bar{f}f}P_L)$$

for neutrinos

$$eC^{L}_{Z\nu\nu} = \frac{g_{\mathrm{L}}}{2\cos\theta_{\mathrm{W}}}\Big[\cos\theta_Z - (\gamma'_y - \gamma'_z)\sin\theta_Z\cos\theta_{\mathrm{W}}\Big]\,, \quad eC^{R}_{Z\nu\nu} = -\frac{g_{\mathrm{L}}}{2}\gamma'_z\sin\theta_Z\,,$$

$$eC^{L}_{Z'\nu\nu} = \frac{g_{\mathrm{L}}}{2\cos\theta_{\mathrm{W}}}\Big[\sin\theta_Z + (\gamma'_y - \gamma'_z)\cos\theta_Z\cos\theta_{\mathrm{W}}\Big]\,, \quad eC^{R}_{Z'\nu\nu} = \frac{g_{\mathrm{L}}}{2}\gamma'_z\cos\theta_Z\,,$$

obeying $\boxed{(Z \to Z') \Rightarrow (\cos\theta_Z, \sin\theta_Z) \to (\sin\theta_Z, -\cos\theta_Z)}$

Neutral current couplings: approximations

$$\Gamma^{\mu}_{V\bar{f}f} = -\mathrm{i}e\gamma^{\mu}(C^{R}_{V\bar{f}f}P_R + C^{L}_{V\bar{f}f}P_L)$$

can be rewritten as

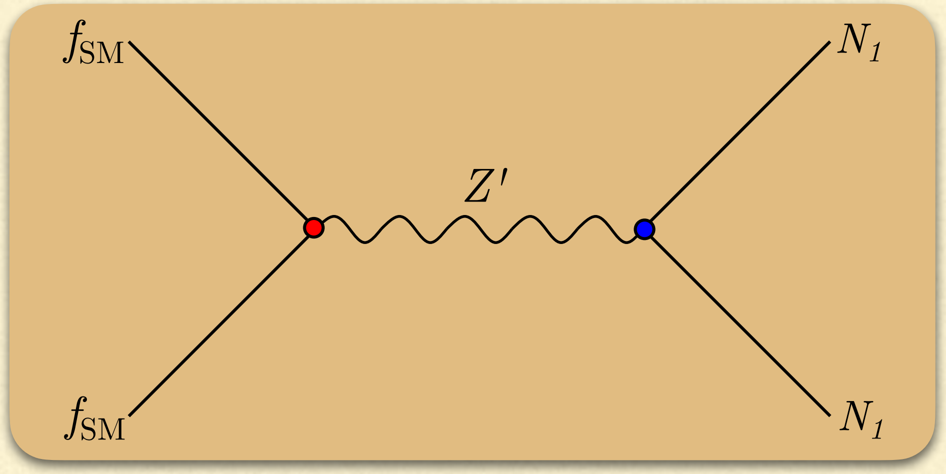
$$\Gamma^{\mu}_{Z'ff} = -\,\mathrm{i}g_z\gamma^{\mu}\left[q_f\cos^2\theta_{\mathrm{W}}(2-\eta) + (z_f - 2y_f) + \mathcal{O}(g_z^2/g_{Z^0}^2)\right]$$

for neutrinos: $\Gamma^{\mu}_{Z'\nu_i\nu_i} \simeq \Gamma^{\mu}_{Z'N_1N_1} \simeq -\,\mathrm{i}\frac{g_z}{2}\gamma^{\mu}$

for electrons: $\Gamma^{\mu}_{Z'ee} \simeq -\,\mathrm{i}g_z\gamma^{\mu}\left[(\eta-2)\cos^2\theta_{\mathrm{W}} + \frac{1}{2}\right]$

Production of DM in freeze-out scenario

- We consider $M_1 = \mathrm{O}(10)\,\mathrm{MeV} \Rightarrow$ decoupling happens at $T_{\mathrm{dec}} = \mathrm{O}(1)\,\mathrm{MeV}$
  At this temperature electrons and SM neutrinos are abundant, negligible amounts of heavier fermions
- Relevant cross section for the production process



$$N_1 N_1 \to f_{\mathrm{SM}} f_{\mathrm{SM}}: \quad \sigma_t \propto g_z^4 \sqrt{1 - \frac{4M_1^2}{s}} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$

Resonant production of DM

Need to increase $\langle \sigma v_{\mathrm{Mol}} \rangle$ without increasing g_z (excluded experimentally): exploit resonant production ($2M_1 \lesssim M_{Z'}$)

- the integral:

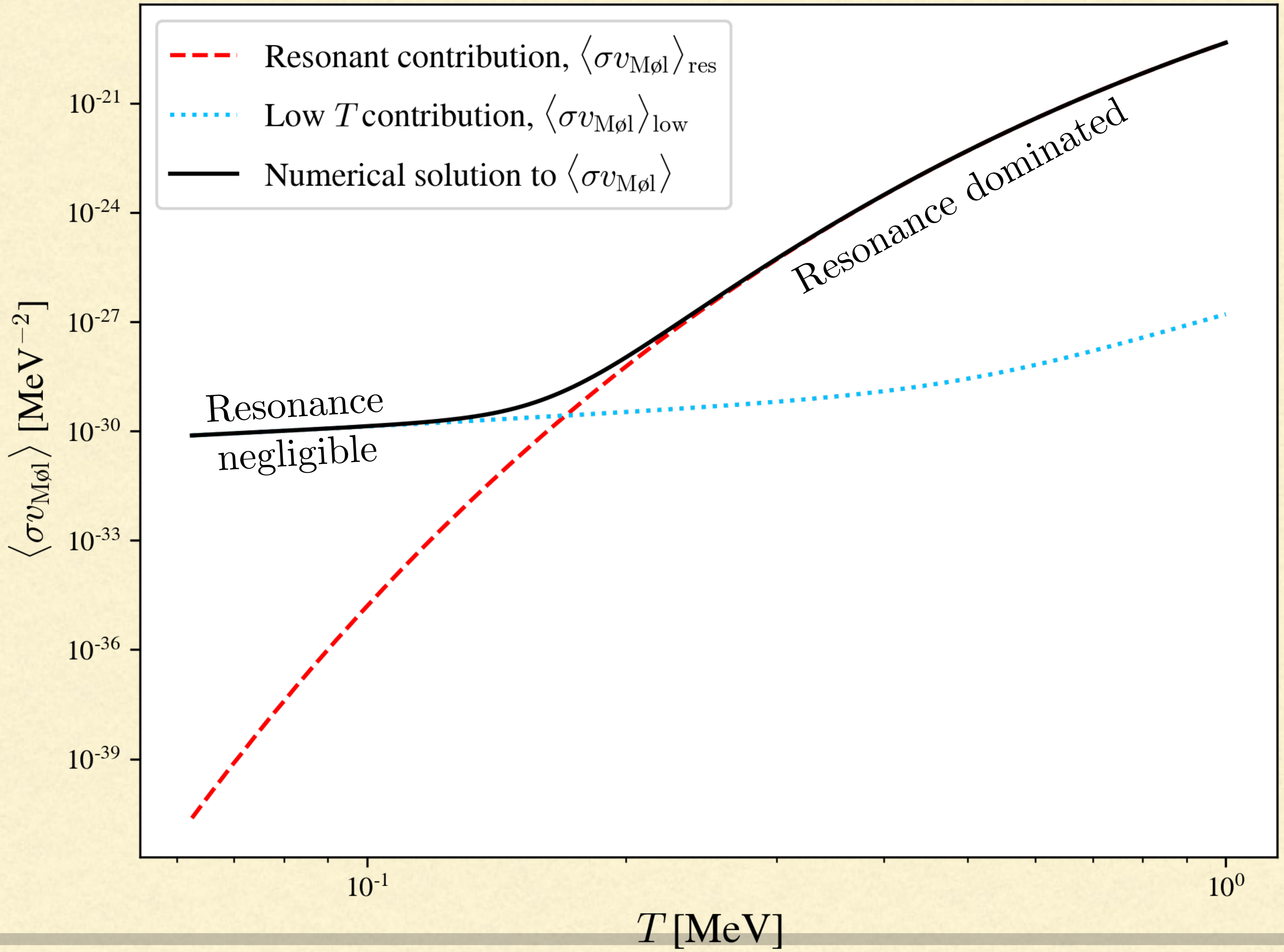
$$\langle \sigma v_{\mathrm{Mol}} \rangle = (\ldots) \int_{4M_1^2}^{\infty} \mathrm{d}s \underbrace{\frac{(\ldots)}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}}_{\text{strongly peaked around } s = M_{Z'}^2} \times K_1\left(\frac{\sqrt{s}}{T}\right)$$

- the Bessel function K_1 vanishes exponentially at large arguments

- $T_{\mathrm{dec}} \approx 0.1 M_1$, hence $K_1(10 M_{Z'}/M_1)$ can be small at the resonance $s = M_{Z'}^2$ depending on the ratio $M_{Z'}/M_1$

Resonant amplification: example

calculated within the SWSM for $M_1 = 10\,\mathrm{MeV}$ & $M_{Z'} = 30\,\mathrm{MeV}$



Masses of the neutral gauge bosons again

can also be expressed with chiral couplings:

$$M_Z^2 = \frac{v^2 e^2}{\cos^2\theta_{\mathrm{G}}}\left(C^L_{Z\nu\nu} - C^R_{Z\nu\nu}\right)^2$$

$$M_{Z'}^2 = \frac{v^2 e^2}{\sin^2\theta_{\mathrm{G}}}\left(C^L_{Z'\nu\nu} - C^R_{Z'\nu\nu}\right)^2$$

which are crucial for checking gauge independence

Neutral current couplings on mass basis

recall: $$\Gamma^{\mu}_{V\bar{f}f} = -\mathrm{i}e\gamma^{\mu}(C^{R}_{V\bar{f}f}P_R + C^{L}_{V\bar{f}f}P_L)$$

which reads **on the basis of propagating mass eigenstates as**

$$\boxed{\mathbf{\Gamma}^{\mu}_{V\nu_i\nu_j} = -\mathrm{i}e\gamma^{\mu}\left(\mathbf{\Gamma}^{L}_{V\nu\nu}P_L + \mathbf{\Gamma}^{R}_{V\nu\nu}P_R\right)_{ij}}$$

where

$$\mathbf{\Gamma}^{L}_{V\nu\nu} = C^{L}_{V\nu\nu}\mathbf{U}_L^{\dagger}\mathbf{U}_L - C^{R}_{V\nu\nu}\mathbf{U}_R^{T}\mathbf{U}_R^{*}$$

$$\mathbf{\Gamma}^{R}_{V\nu\nu} = -C^{L}_{V\nu\nu}\mathbf{U}_L^{T}\mathbf{U}_L^{*} + C^{R}_{V\nu\nu}\mathbf{U}_R^{\dagger}\mathbf{U}_R = -\left(\mathbf{\Gamma}^{L}_{V\nu\nu}\right)^{*}$$

and also: $$\boxed{\mathbf{\Gamma}_{S_k/\sigma_k\,\nu_i\nu_j} = \left(\mathbf{\Gamma}^{L}_{S_k/\sigma_k\,\nu\nu}P_L + \mathbf{\Gamma}^{R}_{S_k/\sigma_k\,\nu\nu}P_R\right)_{ij}}$$

$$\mathbf{\Gamma}^{L}_{S_k\nu\nu} = -\mathrm{i}\left[\left(\mathbf{M}\mathbf{U}_L^{\dagger}\mathbf{U}_L + \mathbf{U}_L^{T}\mathbf{U}_L^{*}\mathbf{M}\right)\frac{(\mathbf{Z}_S)_{k1}}{v} + \mathbf{U}_R^{\dagger}\mathbf{M}_N\mathbf{U}_R^{*}\frac{(\mathbf{Z}_S)_{k2}}{w}\right]$$

$$\mathbf{\Gamma}^{L}_{\sigma_k\nu\nu} = -\left[\left(\mathbf{M}\mathbf{U}_L^{\dagger}\mathbf{U}_L + \mathbf{U}_L^{T}\mathbf{U}_L^{*}\mathbf{M}\right)\frac{(\mathbf{Z}_G)_{k1}}{v} + \mathbf{U}_R^{\dagger}\mathbf{M}_N\mathbf{U}_R^{*}\frac{(\mathbf{Z}_G)_{k2}}{w}\right]$$

$$\mathbf{\Gamma}^{R}_{S_k/\sigma_k\,\nu\nu} = -\left(\mathbf{\Gamma}^{L}_{S_k/\sigma_k\,\nu\nu}\right)^{*}$$

Neutrino mass matrix at one-loop order

calculation is simple conceptually

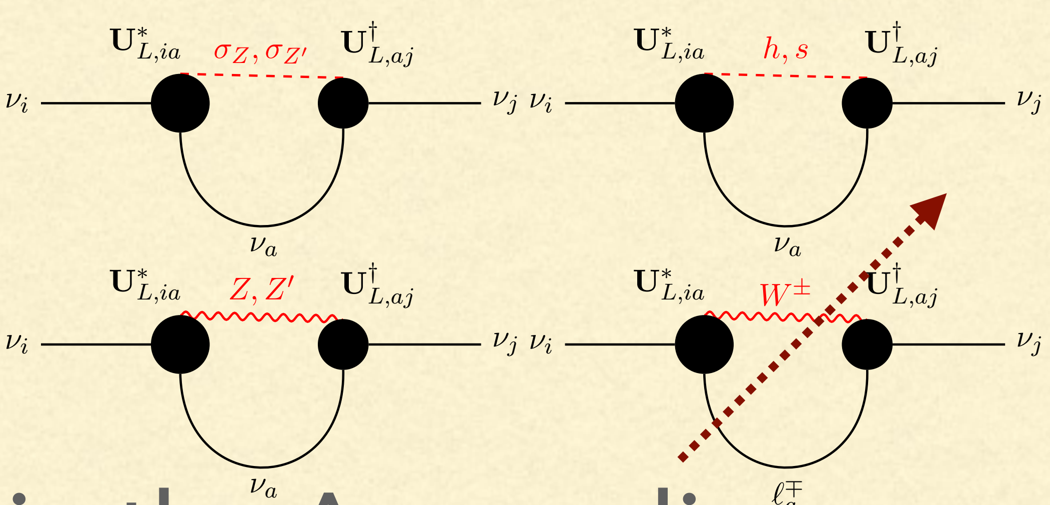
self energy can be decomposed as

$$\boxed{\mathrm{i}\boldsymbol{\Sigma}(p) = \mathbf{A}_L(p^2)\not{p}P_L + \mathbf{A}_R(p^2)\not{p}P_R + \mathbf{B}_L(p^2)P_L + \mathbf{B}_R(p^2)P_R}$$

and

$$\delta\mathbf{M}_L = \mathbf{U}_L^*\mathbf{B}_L(0)\mathbf{U}_L^\dagger$$

takes contributions from



with Feynman rules given in the Appendix

Neutrino mass matrix at one-loop order

calculation involves "miracles" technically

neutral vectors – with notation $\mathbf{m}_\ell^{(n)} = \mathrm{diag}\left(\frac{m_1^n}{\ell^2 - m_1^2}, \ldots, \frac{m_6^n}{\ell^2 - m_6^2}\right)$:

$$\delta \mathbf{M}_L^V = \mathrm{i} e^2 \left(C_{V\nu\nu}^L - C_{V\nu\nu}^R\right)^2 \int \frac{\mathrm{d}^d\ell}{(2\pi)^d} \mathbf{U}_L^* \left[\frac{d\, \mathbf{m}_\ell^{(1)}}{\ell^2 - M_V^2} + \frac{\mathbf{m}_\ell^{(3)}}{M_V^2}\left(\frac{1}{\ell^2 - \xi_V M_V^2} - \frac{1}{\ell^2 - M_V^2}\right)\right] \mathbf{U}_L^\dagger$$

scalars:

$$\delta \mathbf{M}_L^{S_k} = \mathrm{i} \int \frac{\mathrm{d}^d\ell}{(2\pi)^d} \mathbf{U}_L^* \mathbf{M} \mathbf{m}_\ell^{(1)} \mathbf{M} \mathbf{U}_L^\dagger \left(\frac{(\mathbf{Z}_S)_{k1}}{v}\right)^2 \frac{1}{\ell^2 - M_{S_k}^2}$$

Goldstones:

$$\delta \mathbf{M}_L^{\sigma_V} = -\mathrm{i} \int \frac{\mathrm{d}^d\ell}{(2\pi)^d} \mathbf{U}_L^* \mathbf{M} \mathbf{m}_\ell^{(1)} \mathbf{M} \mathbf{U}_L^\dagger \left(\frac{(\mathbf{Z}_\mathrm{G})_{V1}}{v}\right)^2 \frac{1}{\ell^2 - \xi_V M_V^2}$$

Neutrino mass matrix at one-loop order

calculation involves "miracles" technically

neutral vectors – with notation $\mathbf{m}_\ell^{(n)} = \mathrm{diag}\left(\frac{m_1^n}{\ell^2 - m_1^2}, \ldots, \frac{m_6^n}{\ell^2 - m_6^2}\right)$:

$$\delta\mathbf{M}_L^V = \mathrm{i}e^2\left(C^L_{V\nu\nu} - C^R_{V\nu\nu}\right)^2 \int \frac{\mathrm{d}^d\ell}{(2\pi)^d}\mathbf{U}_L^*\left[\frac{d\,\mathbf{m}_\ell^{(1)}}{\ell^2 - M_V^2} + \frac{\mathbf{m}_\ell^{(3)}}{M_V^2}\left(\frac{1}{\ell^2 - \xi_V M_V^2} - \frac{1}{\ell^2 - M_V^2}\right)\right]\mathbf{U}_L^\dagger$$

scalars:

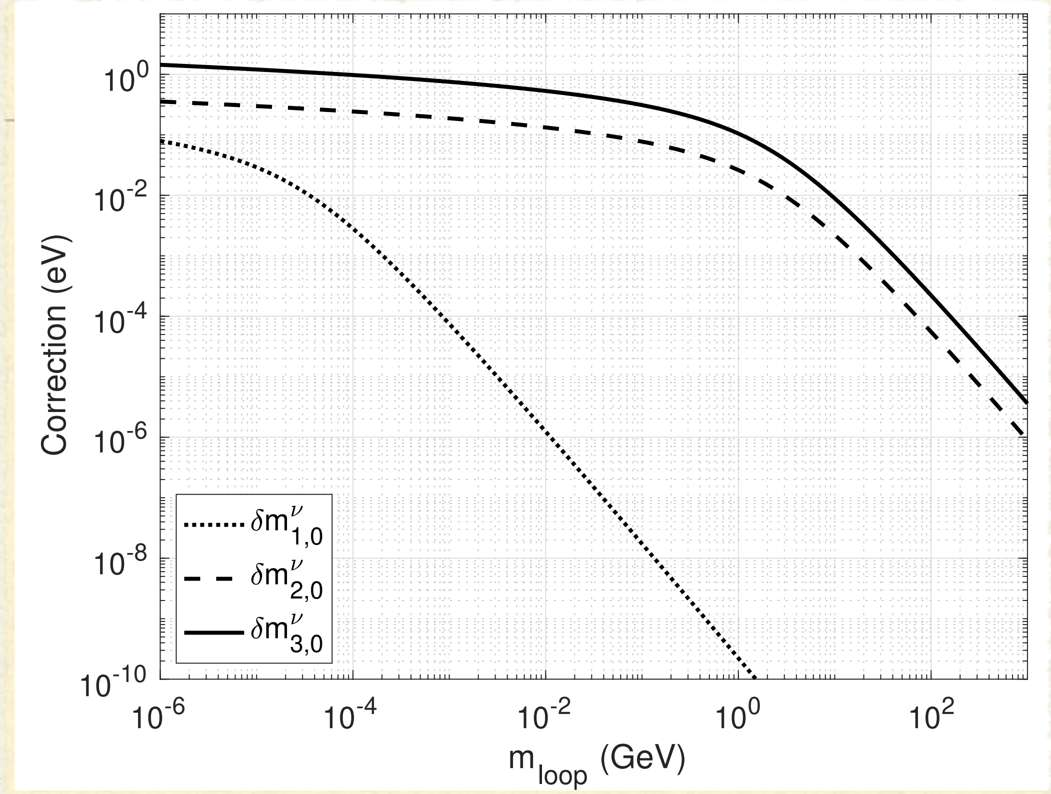
$$\delta\mathbf{M}_L^{S_k} = \mathrm{i}\int \frac{\mathrm{d}^d\ell}{(2\pi)^d}\mathbf{U}_L^*\mathbf{M}\mathbf{m}_\ell^{(1)}\mathbf{M}\mathbf{U}_L^\dagger\left(\frac{(\mathbf{Z}_S)_{k1}}{v}\right)^2\frac{1}{\ell^2 - M_{S_k}^2}$$

Goldstones:

$$\delta\mathbf{M}_L^{\sigma_V} = -\mathrm{i}e^2\left(C^L_{V\nu\nu} - C^R_{V\nu\nu}\right)^2 \int \frac{\mathrm{d}^d\ell}{(2\pi)^d}\mathbf{U}_L^*\frac{\mathbf{m}_\ell^{(3)}}{M_V^2}\mathbf{U}_L^\dagger\frac{1}{\ell^2 - \xi_V M_V^2}$$

gauge terms cancel

Numerical estimates



Eigenvalues of the matrix F as a function of the mass of the boson in the loop m_{loop}, assuming m_1^{tree} = 0.01 eV, m_4^{tree} = 30 keV, $m_5^{tree} \approx m_6^{tree}$ = 2.5 GeV, and normal neutrino mass hierarchy

eigenvalues can be large, but coupling suppression tames the relative correction to the tree-level mass below percent level

Scanning couplings for vacuum stability: allowed region of scalar couplings at 2 loops

- For given input $\{\lambda_\phi(m_t), \lambda_\chi(m_t), \lambda(m_t), y_x(m_t)\}$
- Check $w^{(1)}(m_t) > 0$ (VEV of 2nd scalar exists)
- Run RGE and check
  - stability
  - perturbativity