

Relativistic and Spectator Effects in Leptogenesis with heavy Sterile Neutrinos

Philipp Klose

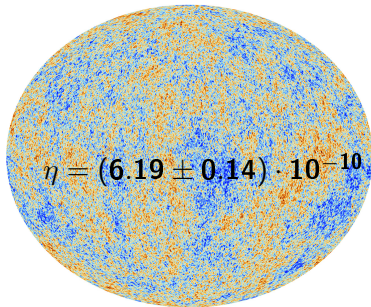
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Planck 2019

See also: [arxiv:1904.09956](https://arxiv.org/abs/1904.09956),

written in Collaboration with Prof. Björn Garbrecht and Dr. Carlos Tamarit

Baryogenesis via Leptogenesis



Three Generations of Matter (Fermions) spin $\frac{1}{2}$

| | I | II | III | |
|---------|------------------------------|----------------------------|----------------------------|-----------------------------|
| mass | 2.4 MeV | 1.27 GeV | 171.2 GeV | |
| charge | $\frac{2}{3}$ | $\frac{2}{3}$ | $\frac{2}{3}$ | 0 |
| name | u up | c charm | t top | g gluon |
| | Left Right | Left Right | Left Right | 0 |
| Quarks | d down | s strange | b bottom | γ photon |
| | Left Right | Left Right | Left Right | 0 |
| | ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | 91.2 GeV Z weak force |
| | 0 eV | 0 eV | 0 eV | 0 |
| Leptons | e electron | μ muon | τ tau | 80.4 GeV W weak force |
| | Left Right | Left Right | Left Right | \pm |

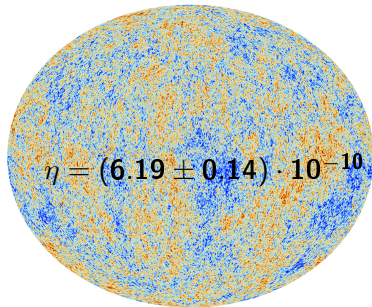
Bosons (Forces) spin 1

spin 0

>114 GeV
H
Higgs boson

spin 0

Baryogenesis via Leptogenesis



Three Generations of Matter (Fermions) spin ½

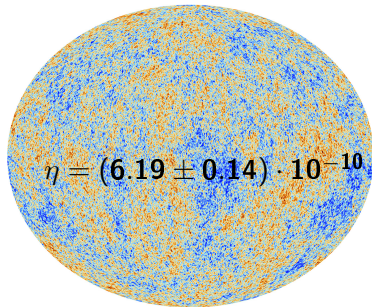
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- Baryon Asymmetry \Rightarrow Standard Model needs more *CP*-violation

Baryogenesis via Leptogenesis

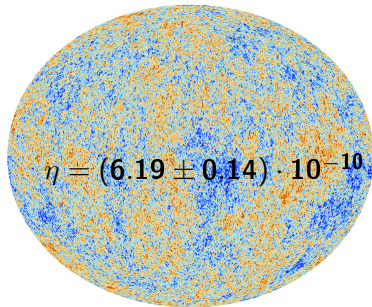


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- One Solution: Add right-handed Majorana Neutrinos

Baryogenesis via Leptogenesis



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Bosons (Forces) spin 1

- Baryon Asymmetry ⇒ Standard Model needs more *CP*-violation
- One Solution: Add right-handed Majorana Neutrinos
- Standard Model transforms Lepton into Baryon asymmetry

High-Scale Leptogenesis from First Principles

Good: Nonrelativistic Semiclassical Boltzmann Equations

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Better: Generalized Relativistic Boltzmann Equations from Closed Time Path Formalism

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“New” Physics we add:

- Thermal corrections for intermediate temperatures
- Helicity dependence of N_1 interactions
- Interplay of relativistic and spectator effects

See also:

- Phys. Lett. B 174 (1986), p. 45-47 for initial leptogenesis paper
- arXiv:1404.2915 for partially equilibrated spectators
- arXiv:1002.0022 and arXiv:1012.3784 for thermal corrections
- arXiv:1002.1326 and arXiv:1007.4783 for leptogenesis from first principles

Minimal Model for Leptogenesis

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \overline{N}_i (i \not{\partial} - M_i) N_i - (F_i \overline{N}_i \tilde{\phi} P_L I_{\parallel} + \text{h.c.})$$

- 2 sterile Neutrinos N_1, N_2
- Hierarchical Masses $10^{10} \text{ GeV} \lesssim M_1 \ll M_2$
- N_i couple to single lepton flavour combination I_{\parallel}

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Free Parameters

- 1** Washout Strength:

$$K \equiv \frac{\Gamma(N_1 \rightarrow l\phi)}{H(M_1 = T)}$$

- 2** N_1 Decay Asymmetry:

$$\epsilon \equiv \frac{\Gamma(N_1 \rightarrow l\phi) - \Gamma(N_1 \rightarrow \bar{l}\phi)}{\Gamma(N_1 \rightarrow l\phi) + \Gamma(N_1 \rightarrow \bar{l}\phi)}$$

Generalized Relativistic Boltzmann Equations

Yields: $B - L$ Asymmetry $\Leftrightarrow Y_{B-L} = \frac{1}{s}(n_B - n_L)$

N_1 number densities $\Leftrightarrow Y_{N_1\text{even/odd}} = \frac{1}{s}(n_{N_1,+} \pm n_{N_1,-})$

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$$\frac{d}{dx} Y_{B-L} = +\tilde{\Gamma} Y_{N_1\text{odd}} - \epsilon_{\text{eff}} \Gamma (Y_{N_1\text{even}} - Y_{N_1\text{eq}}) + \eta_{N_1} \Gamma (Y_{I_{\parallel}} + \frac{1}{2} Y_{\phi})$$

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- $\Gamma, \tilde{\Gamma}, \epsilon_{\text{eff}} \Leftrightarrow$ Thermally corrected N_1 interaction rates, decay asymmetry
- Intermediate Temperatures \Rightarrow Independent helicity difference $Y_{N_1\text{odd}}$

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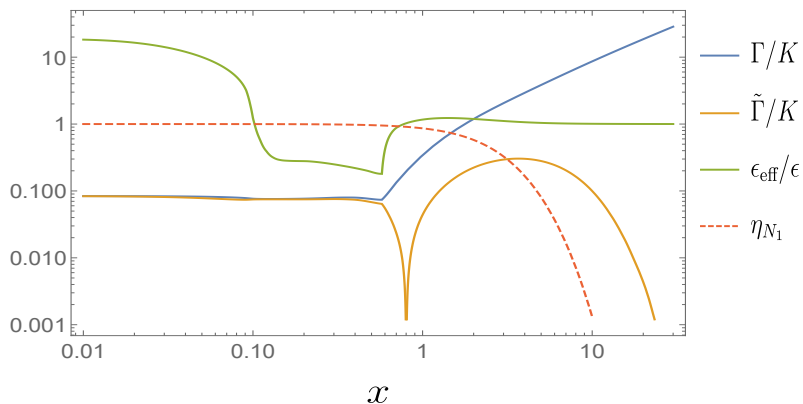
■ $\Gamma, \tilde{\Gamma}, \epsilon_{\text{eff}} \Leftrightarrow$ **Thermally corrected** N_1 interaction rates, decay asymmetry

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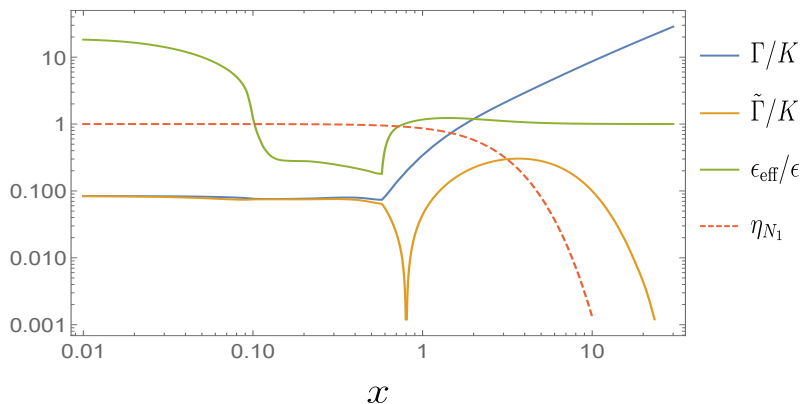
\Rightarrow Encode thermal bath via efficiency κ_f :

$$Y_{B-L}(x \rightarrow \infty) = \epsilon_0 Y_{N_{1,\text{eq}}}(x_0) \cdot \kappa_f$$

Numerics for the Transport Coefficients

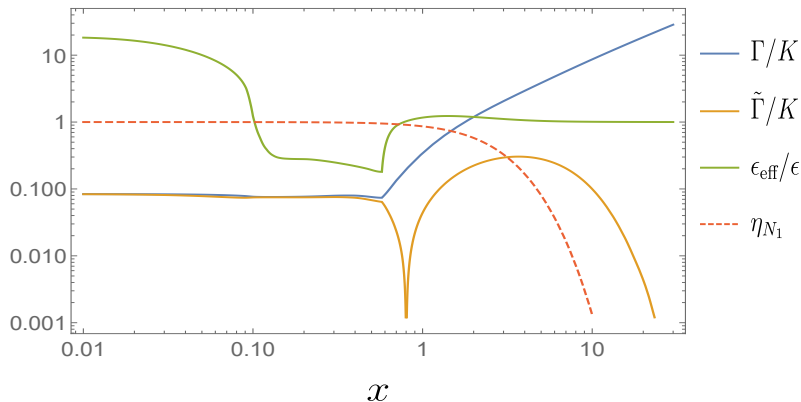


Numerics for the Transport Coefficients



- We computed leading log thermal corrections

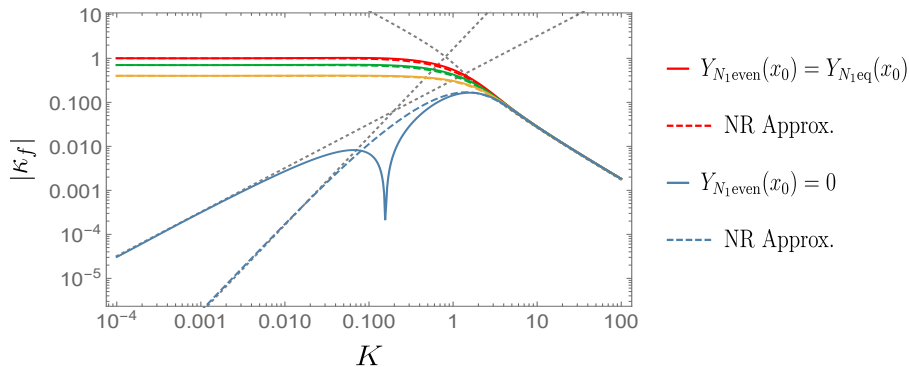
Numerics for the Transport Coefficients



- We computed leading log thermal corrections
- Higgs decays important for ϵ_{eff} at high temperatures

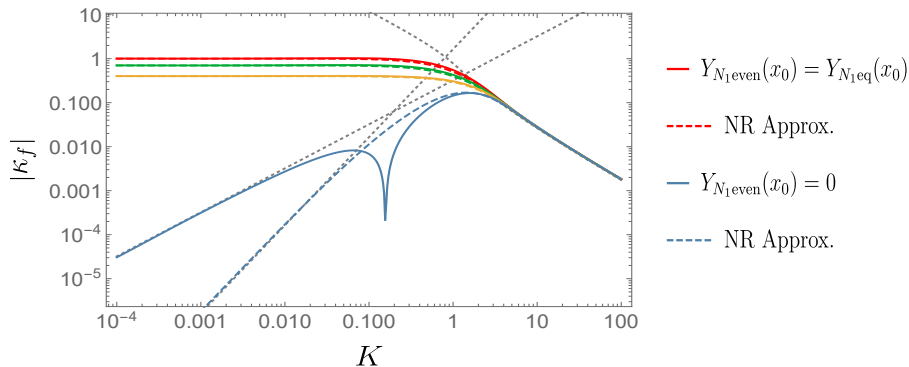
Corrected Weak Washout Efficiency Scaling

■ Leptogenesis without Spectators:



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⇒ Corrected Efficiency Scaling for $K \ll 1$ & $Y_{N_{1\text{eq}}}(x_0) = 0$:

$$\kappa_f \approx -0.32 K + O(K^2)$$

vs.

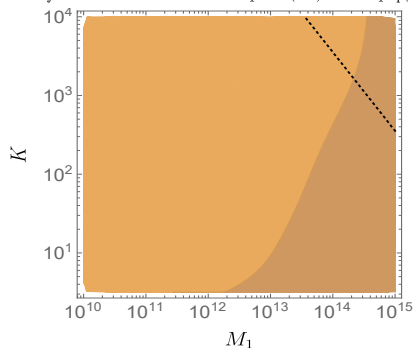
$$\kappa_f^{\text{NR}} \approx 1.65 K^2$$

Strong Washout Initial Condition Dependence

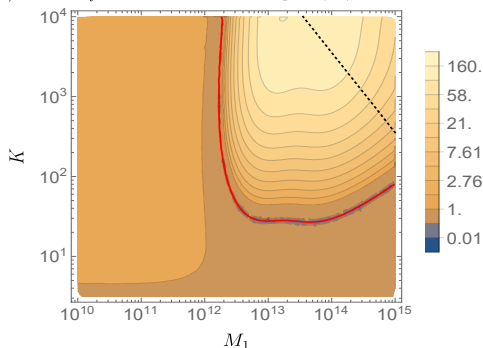
- Realistic Model for $M_1 \sim 10^{13}$ GeV

⇒ Dynamic b-Yukawa & weak Sphaleron interactions

κ_f enhancement for $Y_{N_{1\text{even}}}(x_0) = Y_{N_{1\text{eq}}}(x_0)$



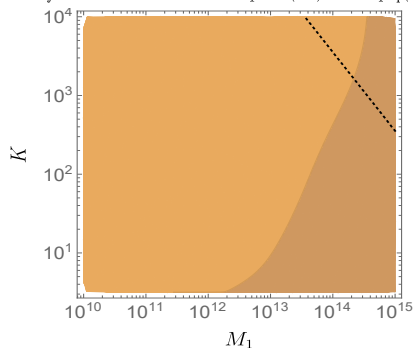
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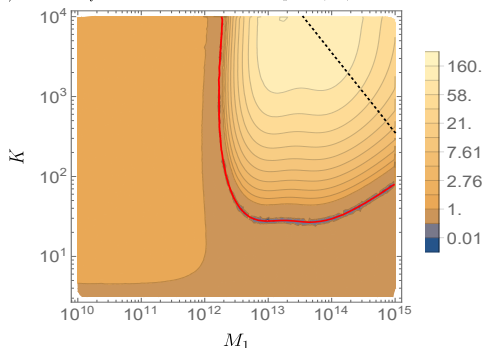
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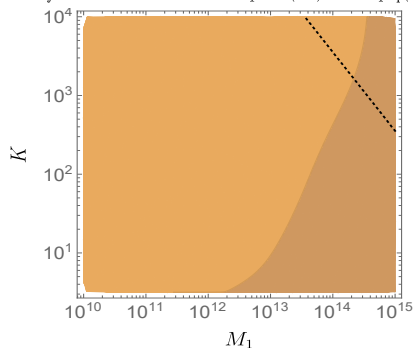


- Equal Baseline Efficiency

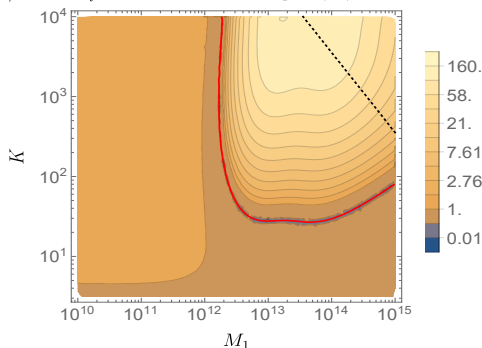
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κ_f enhancement for $Y_{N_{1\text{even}}}(x_0) = 0$



- Equal Baseline Efficiency
- $\sim 10^2$ Enhancement and Initial condition dependence !

Take Home Messages

- Summary:**
- We derived Generalized Relativistic Boltzmann Equations from First Principles

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- Interplay Relativistic Effects & Spectators \Rightarrow Strong Washout Initial Condition Dependence

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- Interplay Relativistic Effects & Spectators \Rightarrow Strong Washout Initial Condition Dependence

$\sim 10^2$ **Enhancement for vanishing initial N_1 abundance!**

Details on Γ , $\tilde{\Gamma}$

Decay Rates:

$$\Gamma = \mathcal{K} \frac{1}{2} (\gamma_{\text{LNC}} + \gamma_{\text{LNV}}), \quad \tilde{\Gamma} \equiv \mathcal{K} \frac{1}{2} (\gamma_{\text{LNC}} - \gamma_{\text{LNV}})$$

where

$$\gamma_{\text{LNC}} \equiv \left\langle \frac{32\pi}{T_{\text{com}}} \frac{(k_\mu + \tilde{k}_\mu) \hat{\Sigma}_{N_1}^{A\mu}(k)}{k_0} \right\rangle$$
$$\gamma_{\text{LNV}} \equiv \left\langle \frac{32\pi}{T_{\text{com}}} \frac{(k_\mu - \tilde{k}_\mu) \hat{\Sigma}_{N_1}^{A\mu}(k)}{k_0} \right\rangle$$

Sterile Neutrino Momenta:

$$\tilde{k}^\mu \equiv \frac{1}{2} h \text{tr} [P_h \gamma^5 \gamma^\mu \not{k}] = (|\mathbf{k}|, k_0 \hat{\mathbf{k}}), \quad k^2 = M_1^2 a^2(t)$$

Thermal Average:

$$\langle X(\mathbf{k}) \rangle = \frac{2}{n_{N_1, \text{eq}}} \int \frac{d^3 \mathbf{k}}{(2\pi)^3} X(k) \frac{1}{e^{\beta k_0} + 1}$$

Details on ϵ_{eff}

Source Term:

$$\epsilon_{\text{eff}}\Gamma = \epsilon_0 K \left\langle \frac{(32\pi)^2}{T} \frac{\hat{\Sigma}_{N_1\mu} \hat{\Sigma}_{N_1\mu}}{k_0} \right\rangle$$

Reduced Selfenergy Decomposition:

$$\hat{\Sigma}_{N_1}^\mu = \frac{1}{k^2} [k^\mu (\hat{\Sigma}_{N_1}^\alpha k_\alpha) - \tilde{k}^\mu (\hat{\Sigma}_{N_1}^\alpha \tilde{k}_\alpha)]$$

\Rightarrow

$$\begin{aligned} \epsilon_{\text{eff}}\Gamma &= \epsilon_0 K \left\langle \frac{k_0}{T} \frac{T^2}{M_1^2 a^2(t)} \frac{(32\pi)^2}{T^2} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu + \tilde{k}^\mu)}{k_0} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu - \tilde{k}^\mu)}{k_0} \right\rangle \\ &\approx \epsilon_0 K \frac{T^2}{M_1^2 a^2(t)} \left\langle \frac{k_0}{T} \right\rangle \left\langle \frac{32\pi}{T} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu + \tilde{k}^\mu)}{k_0} \right\rangle \left\langle \frac{32\pi}{T} \frac{\hat{\Sigma}_{N_1\mu}(k^\mu - \tilde{k}^\mu)}{k_0} \right\rangle \\ &= \epsilon_0 K \frac{T^2}{M_1^2 a^2(t)} \left\langle \frac{k_0}{T} \right\rangle \gamma_{\text{LNC}} \gamma_{\text{LNV}} \end{aligned}$$

Reduced Sterile Neutrino Selfenergy

$$\hat{\Sigma}_{N_1}^\mu(k) = f_F^{-1}(k_0) \int \frac{d^4 p}{(2\pi)^4} f_F(p_0) f_B(k_0 - p_0) \Delta_\phi^A(k-p) \text{tr} [\gamma^\mu S_I^A(p)]$$

Spectral Functions:

$$S_I^A(p) = P_L \left[(\not{p} - \Sigma_I^{\mathcal{H}}(p)) \cdot \frac{\Gamma_I}{\Omega_I^2 + \Gamma_I^2} - \Sigma_I^A(p) \frac{\Omega_I}{\Omega_I^2 + \Gamma_I^2} \right] P_R ,$$

$$\Delta_\phi^A(q) = \frac{\Gamma_\phi}{\Omega_\phi^2 + \Gamma_\phi^2}$$

$$\Gamma_\phi(q) = \Pi_\phi^A , \quad \Gamma_I(p) = 2 (p_\mu - \Sigma_{I,\mu}^{\mathcal{H}}) \cdot \Sigma_I^{A,\mu} ,$$

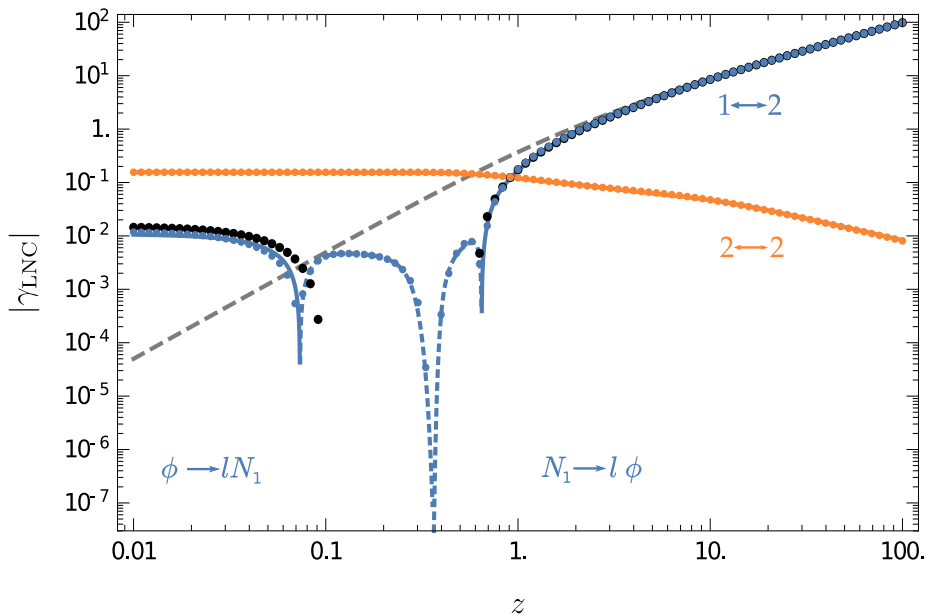
$$\Omega_\phi(q) = q^2 - \Pi_\phi^{\mathcal{H}} , \quad \Omega_I(p) = (p_\mu - \Sigma_{I,\mu}^{\mathcal{H}})^2 - (\Sigma_{I,\mu}^A)^2$$

Standard Model HTL Selfenergies:

$$\Pi^{\mathcal{H},\text{HTL}} = m_\phi^2 , \quad \Sigma_I^{\mathcal{H},\text{HTL}}(p) = \frac{m_I^2}{4} \frac{\vec{p}}{|\mathbf{p}|^2} \ln \left| \frac{p_0 + |\mathbf{p}|}{p_0 - |\mathbf{p}|} \right| - \frac{m_I^2}{2} \frac{\hat{p}}{|\mathbf{p}|^2} ,$$

$$\Pi^{A,\text{HTL}} = 0 , \quad \Sigma_I^{A,\text{HTL}}(p) = \frac{m_I^2}{4} \frac{\vec{p}}{|\mathbf{p}|^2} 2\pi \theta(-p^2) .$$

Individual Contributions to γ_{LNC}



Individual Contributions to γ_{LNV}

