Baryon and lepton numbers

in two scenarios of leptogenesis

A. Kartavtsev

`akartavt@het.physik.uni-dortmund.de`

Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

Baryon asymmetry of the Universe

Baryon asymmetry of the Universe $Y_B = (6.0 \pm 1.0) \cdot 10^{-10}$

Baryon asymmetry of the Universe

Baryon asymmetry of the Universe $Y_B = (6.0 \pm 1.0) \cdot 10^{-10}$

Sakharov conditions

- baryon (lepton) number non–conservation
- C and CP violation
- deviation from thermal equilibrium

Baryon asymmetry of the Universe

Baryon asymmetry of the Universe $Y_B = (6.0 \pm 1.0) \cdot 10^{-10}$

Sakharov conditions

- baryon (lepton) number non–conservation
- C and CP violation
- deviation from thermal equilibrium

Theoretical models

- Majorana leptogenesis (Fukugita, Yanagida, Phys. Lett. B 174, 45)
- Dirac leptogenesis (Lindner et al., Phys. Rev. Lett. 84, 4039)
- non–thermal leptogenesis (Lazarides, Shafi, Phys. Lett. B 258, 305)
- Affleck–Dine mechanism (Affleck, Dine, Nucl. Phys. B 249, 361)

The supersymmetric E_6 model

Y	I_3	P
$1/3$	$\pm1/2$	Q
$-4/3$	0	u^c
$2/3$	0	d^c
-1	$\pm1/2$	L
2	0	e^c
0	0	N
1	$\pm1/2$	H_u
-1	$\pm1/2$	H_d
$-2/3$	0	D
$2/3$	0	D^c
0	0	S

- naturally follows from breaking of superstring $E_8^{'} \bigotimes E_8$
- contains other GUT candidates
- allows chiral representations
- gauge anomalies cancel out

The supersymmetric E_6 model

Y	I_3	P
$1/3$	$\pm 1/2$	Q
$-4/3$	0	u^c
$2/3$	0	d^c
-1	$\pm 1/2$	L
2	0	e^c
0	0	N
1	$\pm 1/2$	H_u
-1	$\pm 1/2$	H_d
$-2/3$	0	D
$2/3$	0	D^c
0	0	S

- naturally follows from breaking of superstring $E_8^{'} \bigotimes E_8$
- contains other GUT candidates
- allows chiral representations
- gauge anomalies cancel out
- contains right–handed neutrino

$$W = \lambda_1^{ijk} N^i (L^j H_u^k) + \lambda_2^{ijk} S^i (H_u^j H_d^k) \ldots$$

The supersymmetric E_6 model

Y	I_3	P
$1/3$	$\pm 1/2$	Q
$-4/3$	0	u^c
$2/3$	0	d^c
-1	$\pm 1/2$	L
2	0	e^c
0	0	N
1	$\pm 1/2$	H_u
-1	$\pm 1/2$	H_d
$-2/3$	0	D
$2/3$	0	D^c
0	0	S

- naturally follows from breaking of superstring $E_8^{'} \bigotimes E_8$
- contains other GUT candidates
- allows chiral representations
- gauge anomalies cancel out
- contains right–handed neutrino

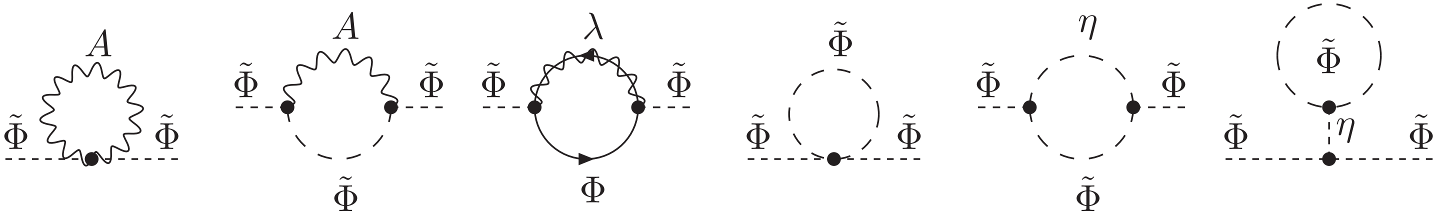
$$W = \lambda_1^{ijk} N^i (L^j H_u^k) + \lambda_2^{ijk} S^i (H_u^j H_d^k) \ldots$$

- both Majorana and Dirac scenarios of leptogenesis are allowed

Breaking of $B{-}L$ in the E_6 model

Majorana mass term can be generated dynamically

- spontaneous breaking of $B-L$ requires introduction of non-renormalizable terms of superpotential
- the symmetry is broken by vevs of right–handed scalar neutrinos of two additional generations
- scale of symmetry breaking is $\sim 10^{14}$ GeV, mass of the right–handed neutrino is $\sim 10^{11}$ GeV
- allowed intermediate symmetry groups are $SU_C(3) \otimes SU_L(2) \otimes U^2(1)$ and $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$
- large loop corrections cancel due to supersymmetry



Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

$$\mathcal{L} = \lambda N (L H_u)$$

Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

$$\mathcal{L} = \lambda N (L H_u)$$

Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

$$\mathcal{L} = \lambda N(LH_u)$$

Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

$$\mathcal{L} = \lambda_1^{ij1} N^i (L^j H_u^1) + \lambda_1^{ij2} N^i (L^j H_u^2) + \lambda_1^{ij3} N^i (L^j H_u^3) + \ldots$$

Leptogenesis with Dirac neutrino

- the decaying heavy particle is a Higgs–like scalar
- lepton number is conserved at classical level

Comparison of the scenarios

Common for both scenarios

- neutrino–neutrino–Higgs vertex plays crucial role
- CP is violated due to complexity of Yukawa couplings
- the decaying heavy particle is produced thermally
- baryon and lepton numbers are violated by sphalerons

$$\mathcal{L} = \lambda N(LH_u) + \frac{1}{2}M\bar{N}N^c + \ldots$$

Leptogenesis with Majorana neutrino

- the heavy decaying particle is a Majorana fermion
- lepton number is violated by Majorana mass term

Sphalerons

Properties

- sphaleron transitions affect only left$-$handed fields
- in thermal equilibrium in $10^2\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$ range

Sphalerons

Properties

- sphaleron transitions affect only left–handed fields
- in thermal equilibrium in $10^2\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$ range
- sphalerons violate B and L but conserve $B-L$

$$B+L$$

Sphalerons

Properties

- sphaleron transitions affect only left–handed fields
- in thermal equilibrium in $10^2\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$ range
- sphalerons violate B and L but conserve $B - L$
- sphalerons imply that for left–handed fermions

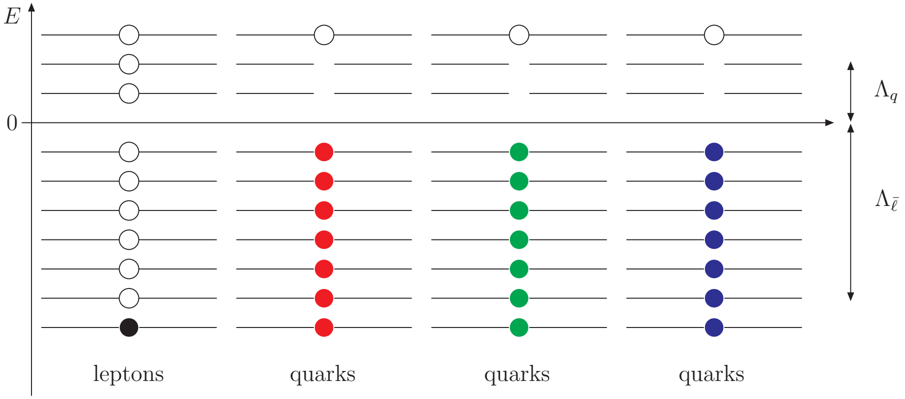
$$3B + L = 0$$

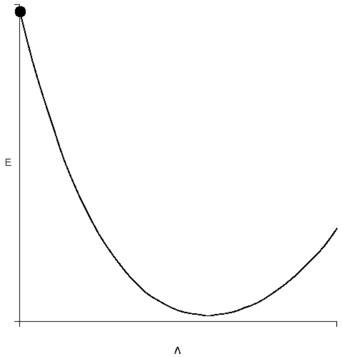
Sphalerons

Properties

- sphaleron transitions affect only left–handed fields
- in thermal equilibrium in $10^2\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$ range
- sphalerons violate B and L but conserve $B - L$
- sphalerons imply that for left–handed fermions

$$(1 + 1 + 1)B + L = 0$$



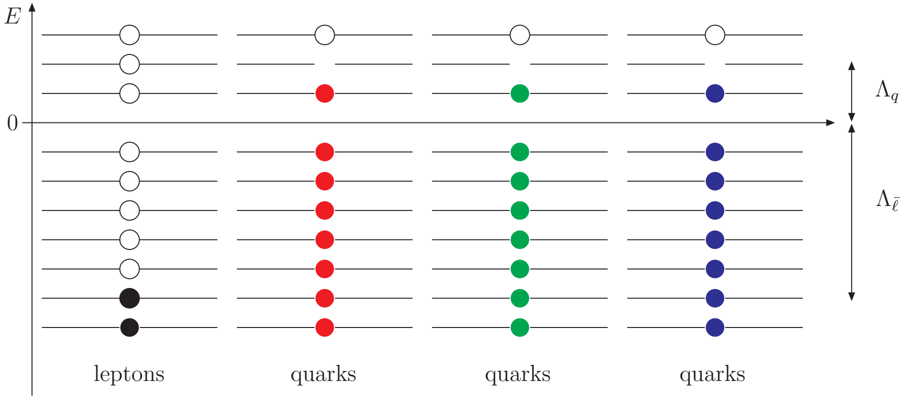


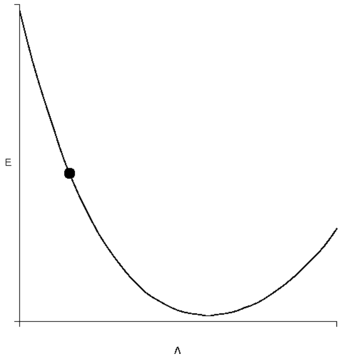
Sphalerons

Properties

- sphaleron transitions affect only left–handed fields
- in thermal equilibrium in $10^2\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$ range
- sphalerons violate B and L but conserve $B - L$
- sphalerons imply that for left–handed fermions

$$(1+1+1)B + L = 0$$



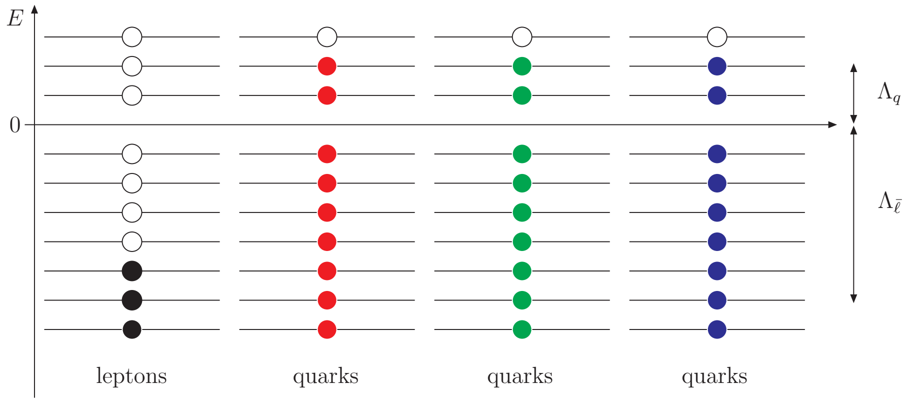


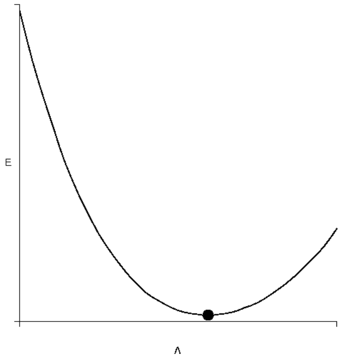
Sphalerons

Properties

- sphaleron transitions affect only left–handed fields
- in thermal equilibrium in $10^2 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$ range
- sphalerons violate B and L but conserve $B - L$
- sphalerons imply that for left–handed fermions

$$(1 + 1 + 1)B + L = 0$$





B and L above the phase transition

At $T_{EW} \leq T \ll M_{N,H}$ in both scenarios

- left$-$handed neutrino is a Weyl fermion
- no additional asymmetry is generated
- scattering processes partially wash out the asymmetry

B and L above the phase transition

At $T_{EW} \leq T \ll M_{N,H}$ in both scenarios

- left–handed neutrino is a Weyl fermion
- no additional asymmetry is generated
- scattering processes partially wash out the asymmetry

Total baryon and lepton numbers are proportional to $B - L$

$$
\begin{aligned}
B &= \frac{8N + 4mc_-}{22N + 13mc_-}(B - L) \approx 0.36\,(B - L) \\
L &= -\frac{14N + 9mc_-}{22N + 13mc_-}(B - L) \approx -0.64\,(B - L)
\end{aligned}
$$

due to thermal Higgs mass

Q_{em} above the phase transition

At $T_{EW} \leq T \ll M_{N,H}$ in both scenarios

- charge carried by up–type quarks is very small

$$Q_u = \frac{4mc_-}{22N + 13mc_-}(B-L)$$

- there is an excess of down–type quarks

$$Q_d = -\frac{8N + 2mc_-}{22N + 13mc_-}(B-L)$$

- and total electric charge of leptons is positive

$$Q_\ell = \frac{8N + 6mc_-}{22N + 13mc_-}(B-L)$$

Q_{em} above the phase transition

At $T_{EW} \leq T \ll M_{N,H}$ in both scenarios

- charge carried by up–type quarks is very small

$$Q_u \approx \quad 0.03\,(B-L)$$

- there is an excess of down–type quarks

$$Q_d \approx -0.34\,(B-L)$$

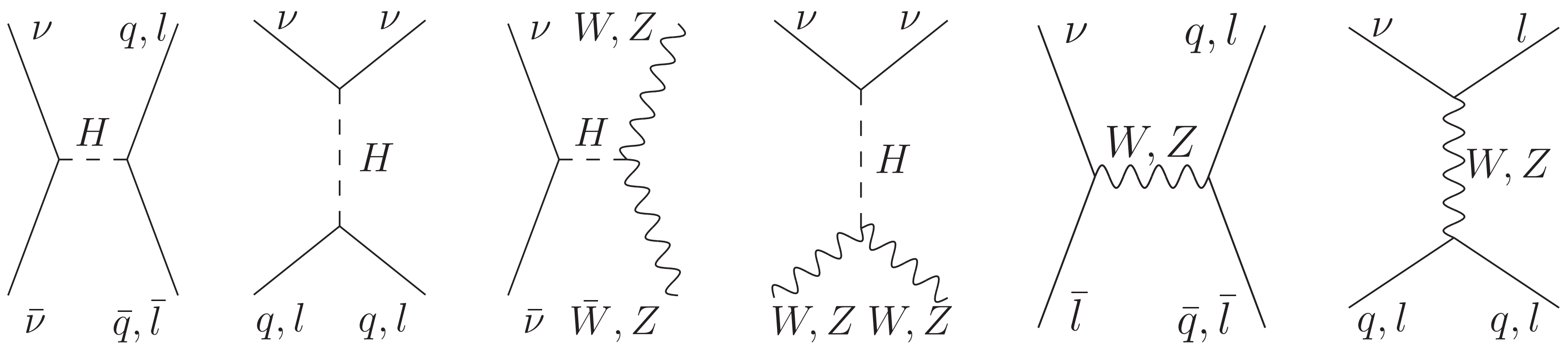
- and total electric charge of leptons is positive

$$Q_\ell \approx \quad 0.37\,(B-L)$$

Leptogenesis with Dirac neutrino

Washout processes include

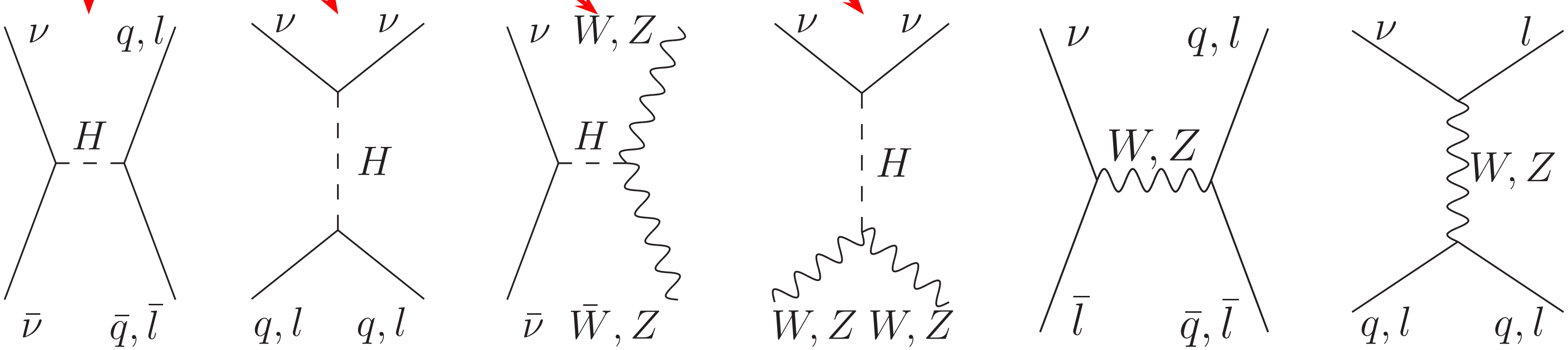
- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons



Leptogenesis with Dirac neutrino

Washout processes include

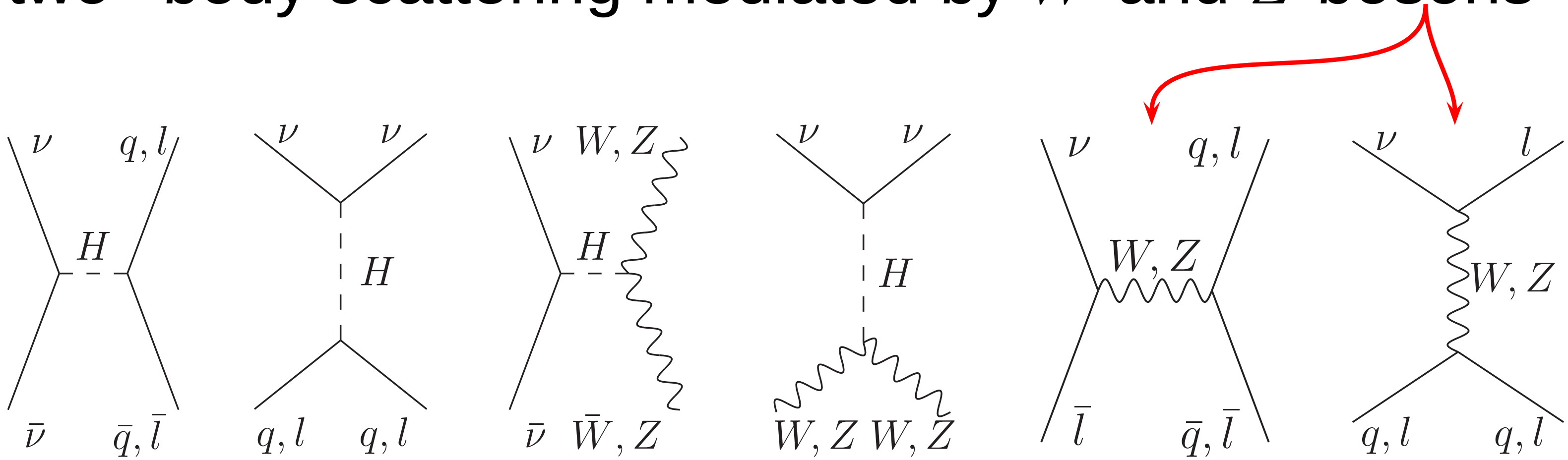
- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons



Leptogenesis with Dirac neutrino

Washout processes include

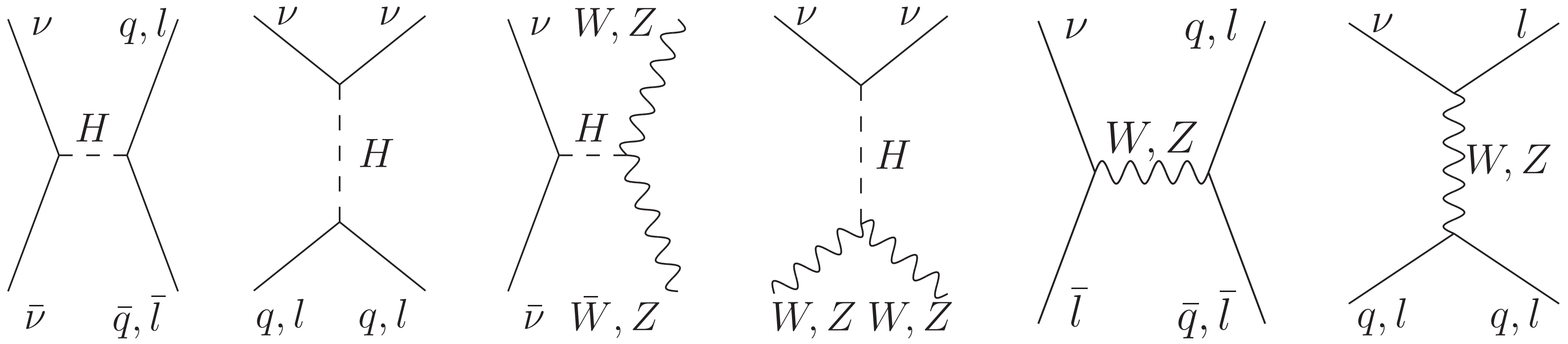
- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons



Leptogenesis with Dirac neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons

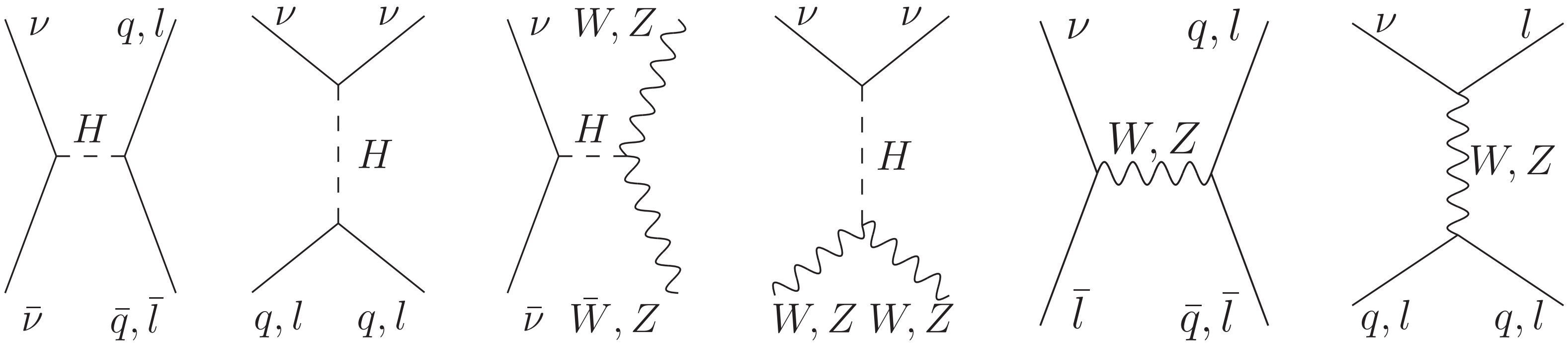


$$\gamma_s^t \approx \gamma_t^t \approx \frac{g^4 T^4}{512\pi^5}\left(\frac{m_\nu}{M_W}\frac{m_t}{M_W}\right)^2$$

Leptogenesis with Dirac neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons

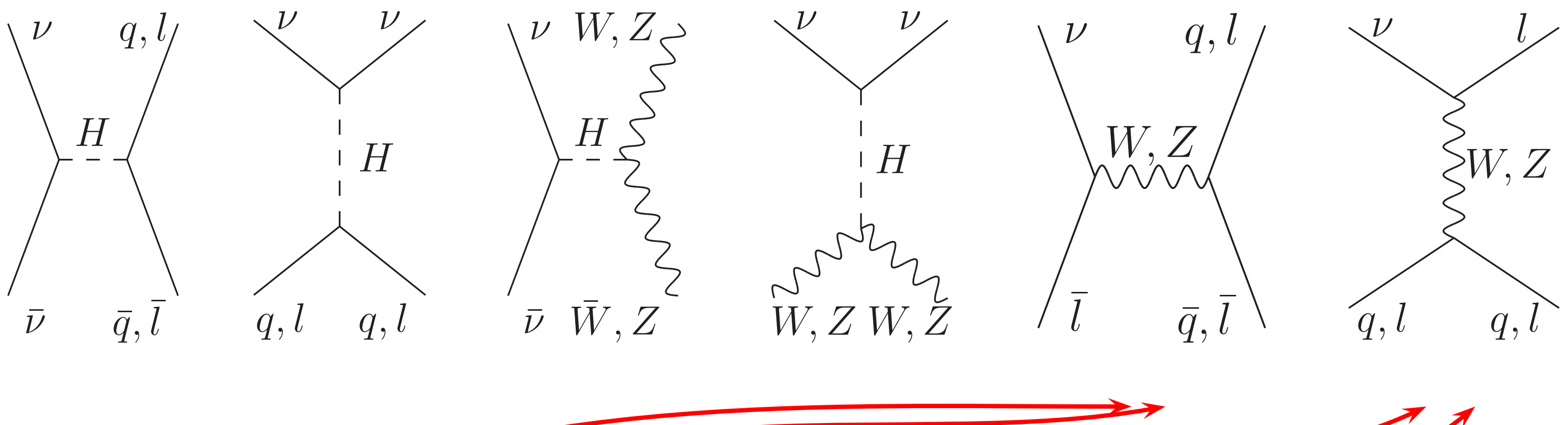


$$\gamma_s^W \approx 2\gamma_s^Z \approx 2\gamma_t^W \approx 2\gamma_t^Z \approx \frac{g^4 T^4}{128\pi^5}\left(\frac{m_\nu}{M_W}\frac{T}{M_W}\right)^2$$

Leptogenesis with Dirac neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons

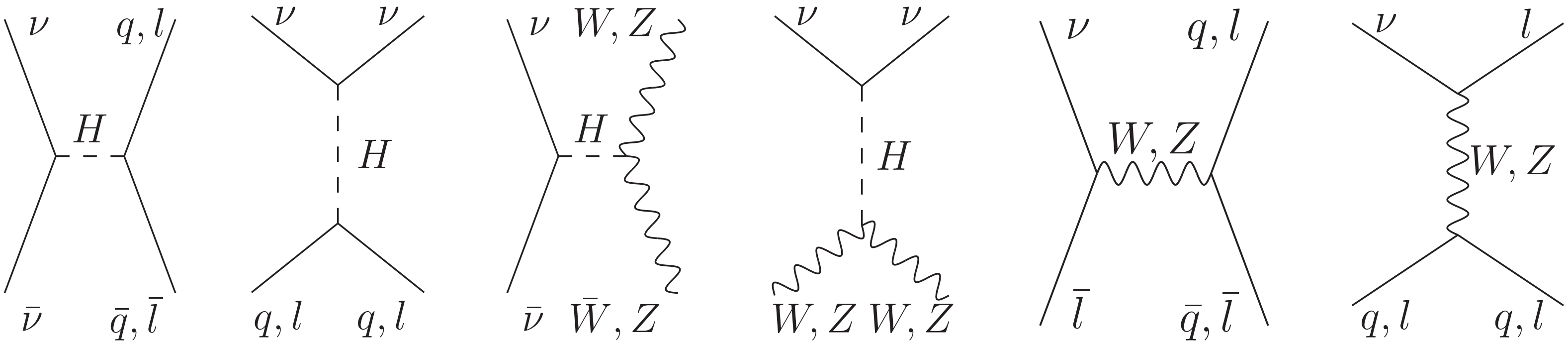


$$\gamma_s^{cc} \approx 2\gamma_s^{nc} \approx \gamma_t^{cc} \approx 2\gamma_t^{nc} \approx \frac{g^4 T^4}{512\pi^5}\left(\frac{m_\nu}{M_W}\,\frac{m_t}{M_W}\right)^2$$

Leptogenesis with Dirac neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons

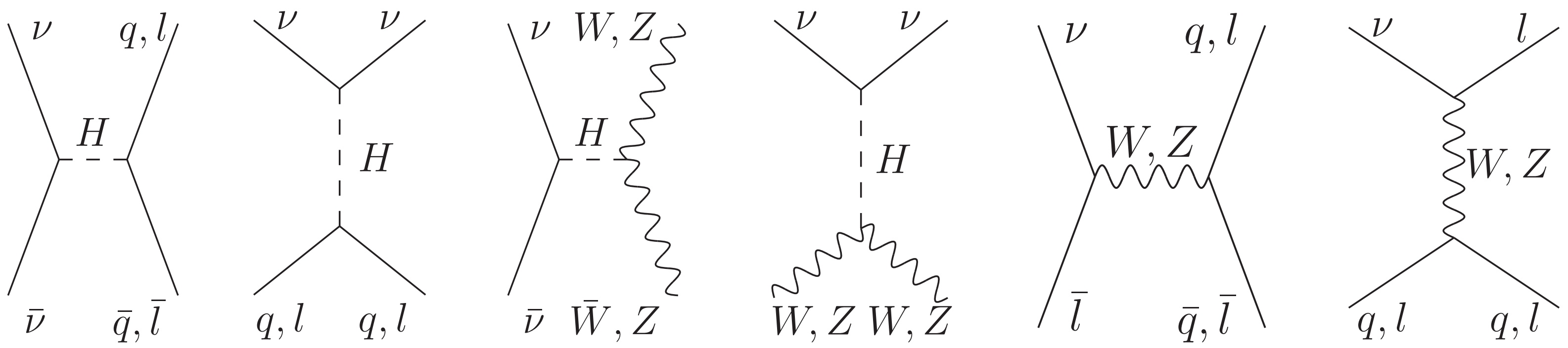


$$\frac{x\gamma_s^t}{sH} \approx \frac{x\gamma_t^t}{sH} \approx \frac{x\gamma_s^{cc}}{sH} \approx 2\frac{x\gamma_s^{nc}}{sH} \approx \frac{x\gamma_t^{cc}}{sH} \approx 2\frac{x\gamma_t^{nc}}{sH} \sim 10^{-13}$$

Leptogenesis with Dirac neutrino

Washout processes include

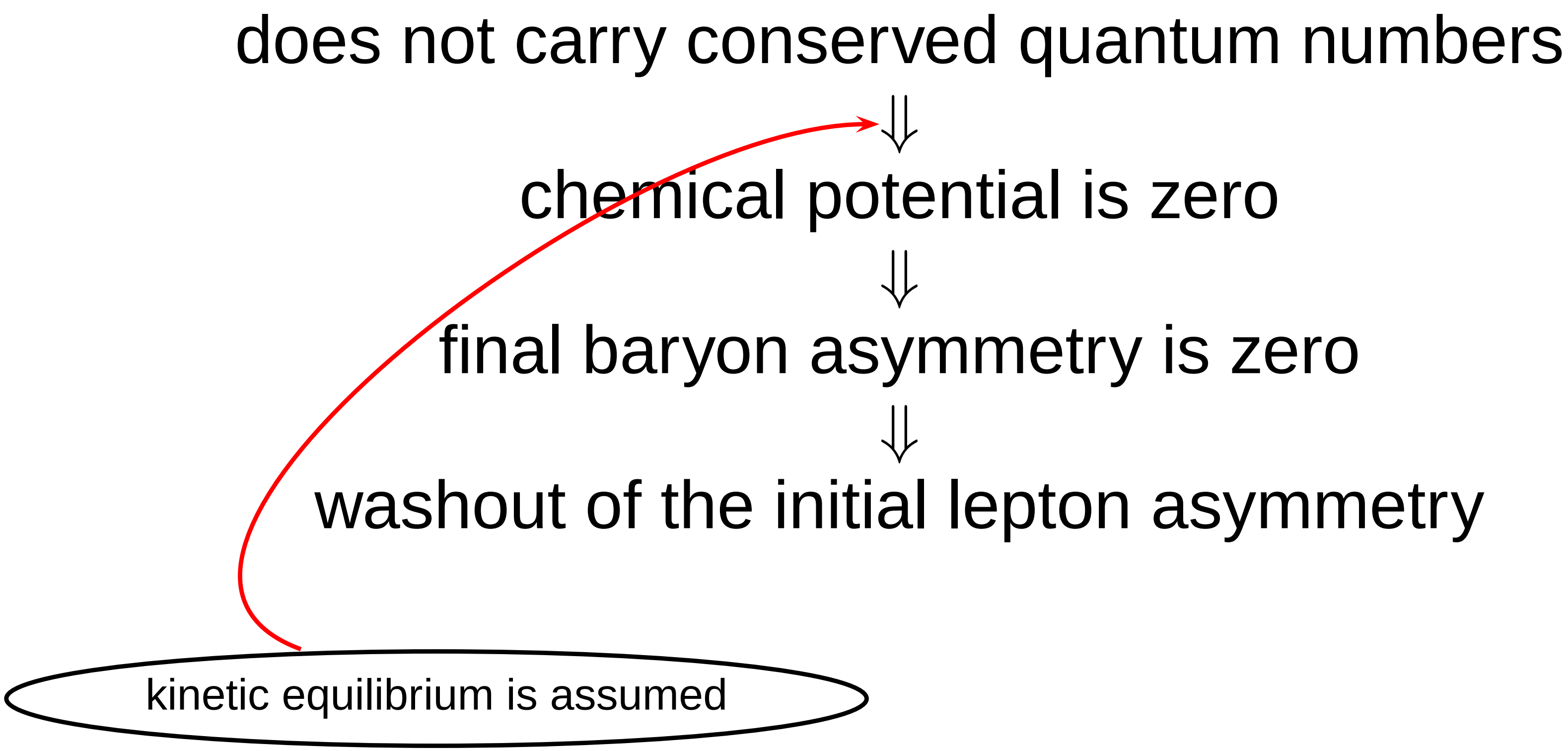
- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons



$$\frac{x\gamma_s^W}{sH} \approx 2\frac{x\gamma_s^Z}{sH} \approx 2\frac{x\gamma_t^W}{sH} \approx 2\frac{x\gamma_t^Z}{sH} \sim 10^{-13}\left(\frac{T}{M_W}\right)^2$$

Leptogenesis with Majorana neutrino

Properties of Majorana fermion



does not carry conserved quantum numbers

$\Downarrow$

chemical potential is zero

$\Downarrow$

final baryon asymmetry is zero

$\Downarrow$

washout of the initial lepton asymmetry

kinetic equilibrium is assumed

Leptogenesis with Majorana neutrino

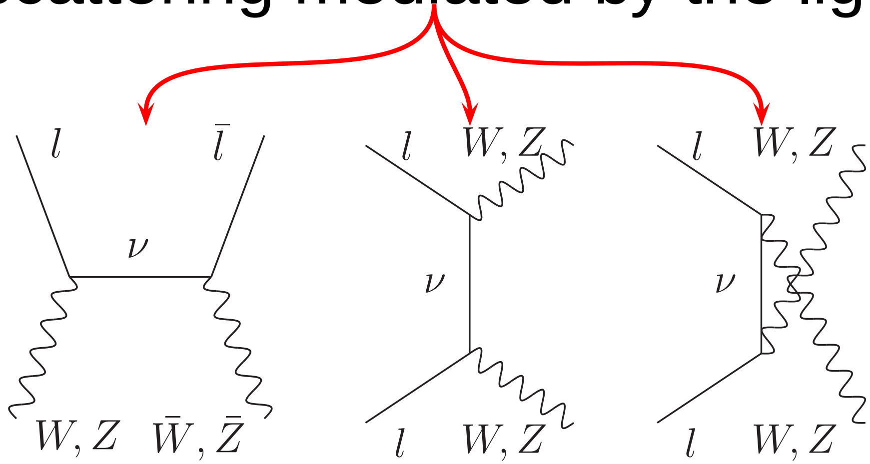
Washout processes include

- Higgs mediated two$-$body scattering processes
- two$-$body scattering mediated by W and Z bosons

Leptogenesis with Majorana neutrino

Washout processes include

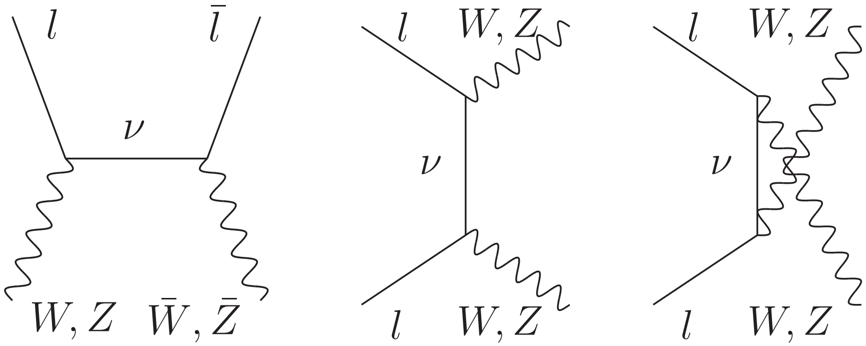
- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons
- two–body scattering mediated by the light neutrino



Leptogenesis with Majorana neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons
- two–body scattering mediated by the light neutrino

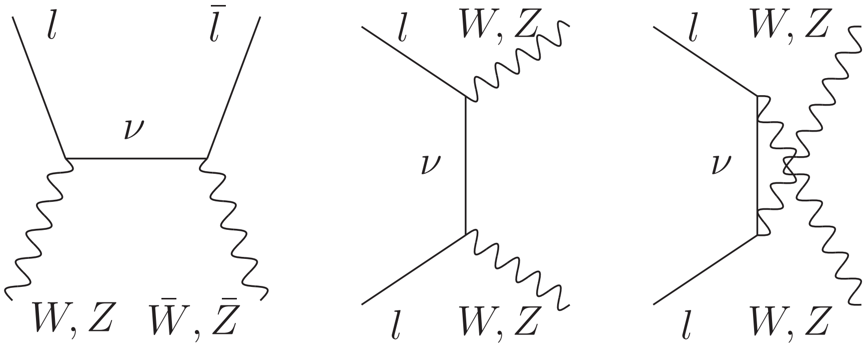


$$\gamma_s^W = \frac{g^4T^4}{(4\pi)^5}\left(\frac{m_\nu}{M_W}\right)^2\left(\frac{T}{M_W}\right)^2 , \gamma_{t+u}^W = \frac{9\,g^4T^4}{\pi^5}\left(\frac{m_\nu}{M_W}\right)^2\left(\frac{T}{M_W}\right)^6$$

Leptogenesis with Majorana neutrino

Washout processes include

- Higgs mediated two–body scattering processes
- two–body scattering mediated by W and Z bosons
- two–body scattering mediated by the light neutrino



$$\frac{x\gamma_s^W}{sH} \sim 10^{-13}\left(\frac{T}{M_W}\right)^2, \quad \frac{x\gamma_{t+u}^W}{sH} \sim 10^{-10}\left(\frac{T}{M_W}\right)^6$$

B and L below the phase transition

At $T < T_{EW}$ in both scenarios

- washout processes are too slow to affect lepton number
- final lepton and baryon numbers are given by

$$B = \quad \frac{8N + 4\bar{m}}{24N + 13\bar{m}}(B - L) + \Delta B \approx \quad 0.32\,(B - L) + \Delta B$$

$$L = -\frac{16N + 9\bar{m}}{24N + 13\bar{m}}(B - L) + \Delta L \approx -0.68\,(B - L) + \Delta L$$

- final baryon number is nonzero even if total $B - L = 0$

$$\Delta B = \Delta L = \frac{14N + 8\bar{m}}{24N + 13\bar{m}} \frac{\Delta}{3}, \qquad \Delta = \Sigma_i\,(L/N - L_i)\,(1 - c_{\ell_i})$$

Q_{em} below the phase transition

At $T < T_{EW}$ in both scenarios

- if $B - L \ll \Delta$, then there is an excess of up quarks

$$Q_u = \frac{4\bar{m}}{24N + 13\bar{m}}(B - L) + \frac{24N + 8\bar{m}}{24N + 13\bar{m}}\frac{\Delta}{3}$$

- if $B - L \gg \Delta$, then there is an excess of down quarks

$$Q_d = -\frac{8N + 2\bar{m}}{24N + 13\bar{m}}(B - L) - \frac{2N + 4\bar{m}}{24N + 13\bar{m}}\frac{\Delta}{3}$$

- total charge of leptons depends on the Δ to $B - L$ ratio

$$Q_l = \frac{8N + 6\bar{m}}{24N + 13\bar{m}}(B - L) - \frac{22N + 14\bar{m}}{24N + 13\bar{m}}\frac{\Delta}{3}$$

Q_{em} below the phase transition

At $T < T_{EW}$ in both scenarios

- if $B-L \ll \Delta$, then there is an excess of up quarks

$$Q_u \approx \quad 0.07\,(B-L) + 0.30\,\Delta$$

- if $B-L \gg \Delta$, then there is an excess of down quarks

$$Q_d \approx -0.28(B-L) - 0.04\Delta$$

- total charge of leptons depends on the Δ to $B-L$ ratio

$$Q_l \approx \quad 0.36\,(B-L) - 0.32\,\Delta$$

Summary

- the two scenarios naturally emerge in extensions of the SM, a good example is the supersymmetric E_6 model
- sphaleron transitions imply that for left–handed fermions

$$3B + L = 0$$

- in both scenarios washout processes below the phase transition are too slow to erase lepton asymmetry
- right after the phase transition $|Q_u| < |Q_d|$ and $Q_\ell > 0$
- approximately 30% of the initial $B - L$ is converted into baryon number