Cosmological Constraints on *R*-Parity violating SUSY under Lepton Flavor Violation

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along the paper
M. Endo, K. Hamaguchi and SI.
Cosmological Constraints on R-parity violation.
arXiv: 0912.0585 [hep-ph] (2009).

Outline

along the paper

M. Endo, K. Hamaguchi and SI.

Cosmological Constraints on R-parity violation.

arXiv: 0912.0585 [hep-ph] (2009).

(about to be published)

1. *R*-parity violating SUSY

“To avoid the Proton Decay in the MSSM,
we usually impose the *R*-parity.
But actually, we have other two choices. ”

MSSM and *R*-parity

MSSM

(Minimal Supersymmetric Standard Model)

- Hierarchy problem → solved!
- Proton decay problem

Why does Proton decay?

Proton Decay Problem

- Superpotential of the MSSM

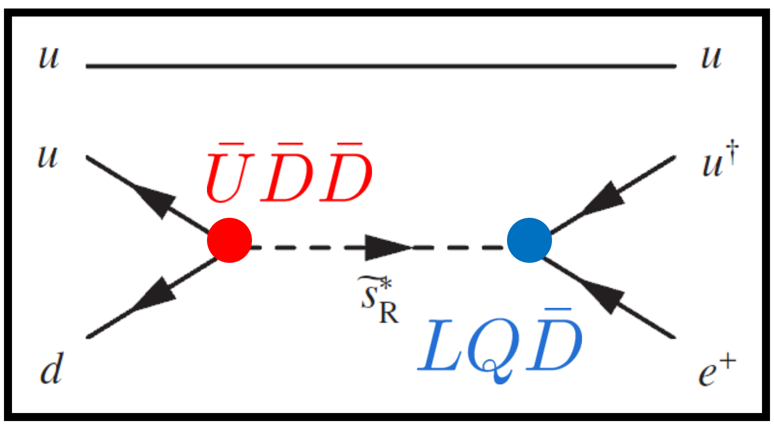
$$W \ni \; H_{\rm u}H_{\rm d}, \quad H_{\rm d}L\bar{E}, \quad H_{\rm d}Q\bar{D}, \quad H_{\rm u}Q\bar{U},$$

$$\not{L} \quad LH_{\rm u}, \quad LL\bar{E}, \quad LQ\bar{D}, \qquad \bar{U}\bar{D}\bar{D} \quad \not{B}$$

$$W \supset \lambda'_{ijk}L_iQ_j\bar{D}_k + \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$

Both $\not{B}$ and $\not{L}$ ⇨ Proton Decay

$$p \to e^+\pi^0$$



$$\tau \sim \frac{(9\times 10^{-13}\,{\rm s})}{|\lambda'_{112}\lambda''_{112}|^2}\left(\frac{m_{\tilde{s}_R}}{1\,{\rm TeV}}\right)^4$$

R-parity

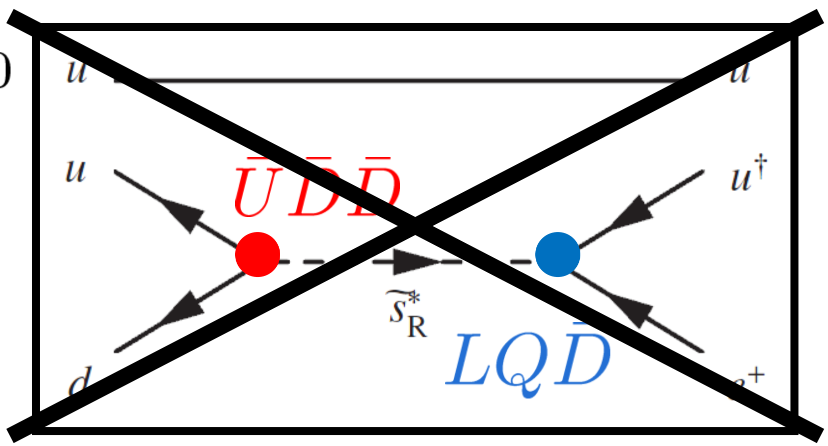
$$P_R := (-1)^{3B-L+2s} \quad (\ s\text{: spin}\ )$$

- Superpotential of the MSSM **with *R*-Parity conservation**

$$W \ni \ H_{\rm u}H_{\rm d},\ \ H_{\rm d}L\bar{E},\ \ H_{\rm d}Q\bar{D},\ \ H_{\rm u}Q\bar{U},$$
$$\not{L}\ \ \cancel{LH_{\rm u}},\ \ \cancel{LL\bar{E}},\ \ \cancel{LQ\bar{D}},\ \ \cancel{\bar{U}\bar{D}\bar{D}}\ \ \not{B}$$

~~**Both $\not{B}$ and $\not{L}$**~~ ⇒ **Proton is stable.**

$p \to e^+\pi^0$



$$\tau \sim \infty$$

SUSY without *R*-parity

However, since **proton decay needs both $\not{B}$ and $\not{L}$,**

we have other two possibilities!

- To forbid $\not{B}$ with Baryon-parity etc.

$$W \ni H_{\rm u}H_{\rm d},\ H_{\rm d}L\bar{E},\ H_{\rm d}Q\bar{D},\ H_{\rm u}Q\bar{U},\ LH_{\rm u},\ LL\bar{E},\ LQ\bar{D},\ \cancel{\bar{U}\bar{D}\bar{D}}$$

(Allowing $\not{L}$)

- To forbid $\not{L}$ with Lepton-parity etc.

with assuming $m_{\rm LSP} > m_{\rm proton}$.

$$W \ni H_{\rm u}H_{\rm d},\ H_{\rm d}L\bar{E},\ H_{\rm d}Q\bar{D},\ H_{\rm u}Q\bar{U},\ \cancel{LH_{\rm u}},\ \cancel{LL\bar{E}},\ \cancel{LQ\bar{D}},\ \bar{U}\bar{D}\bar{D}$$

(Allowing $\not{B}$)

SUSY without *R*-parity

That is, **we can install RpV interactions** additionally.

- MSSM with *R*-parity → $W = W_{\rm RPC}$

$$W_{\rm RPC} = \mu H_{\rm u} H_{\rm d} + y_{{\rm u}ij} H_{\rm u} Q_i \bar{U}_j + y_{{\rm d}ij} H_{\rm d} Q_i \bar{D}_j + y_{{\rm e}ij} H_{\rm d} L_i \bar{E}_j$$

- $\not{L}$-MSSM →

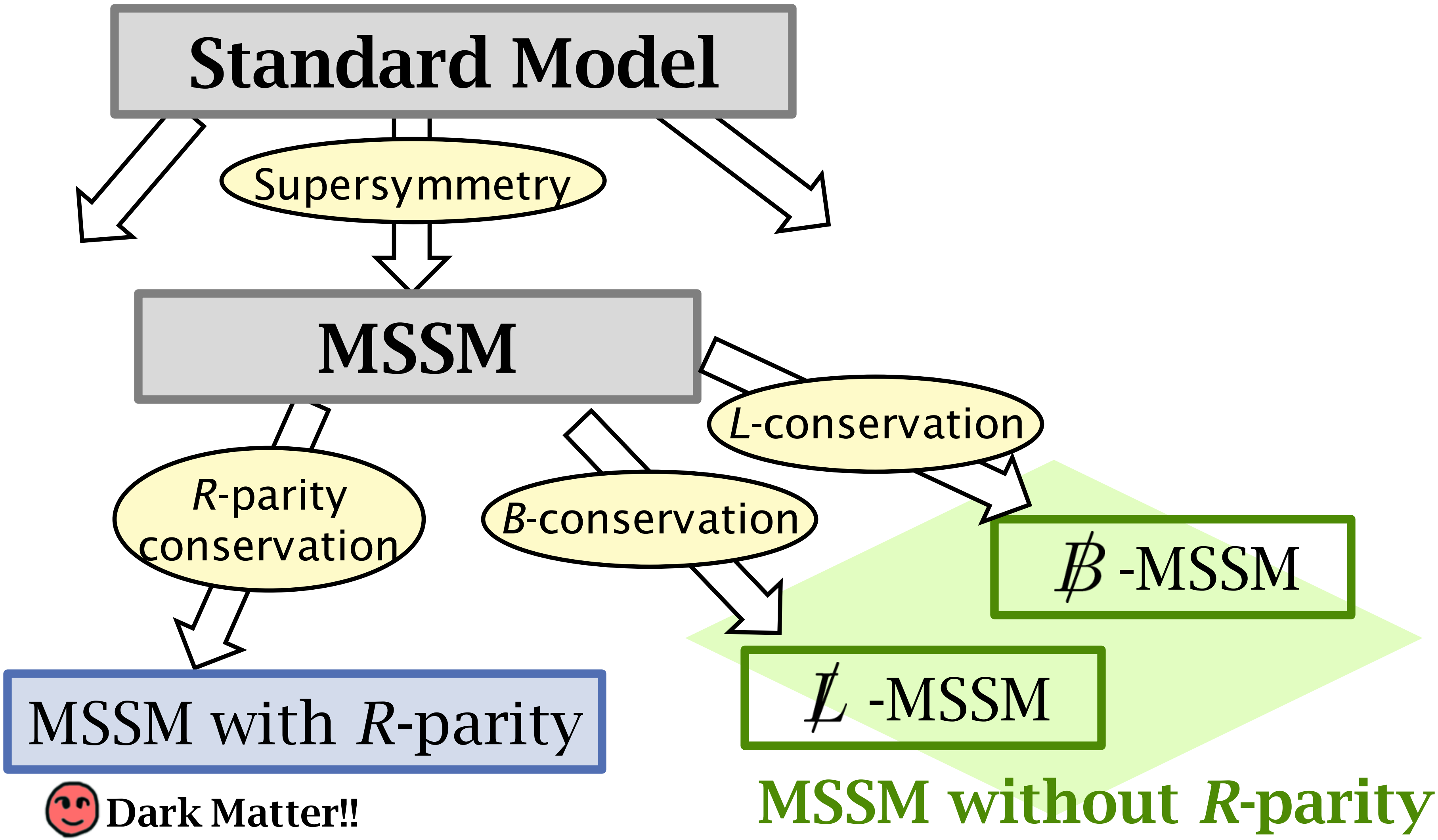
$$W_{\not{L}} = W_{\rm RPC} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\rm u}$$

- $\not{B}$-MSSM →

$$W_{\not{B}} = W_{\rm RPC} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

MSSM without *R*-parity

Introductive Diagram



(Here we need other DM candidates.)

What I studied

Can we constraint such **exotic** couplings?

$$\lambda_{ijk} L_i L_j \bar{E}_k, \ \lambda'_{ijk} L_i Q_j \bar{D}_k, \ \kappa_i L_i H_{\mathrm{u}}; \ \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

⇒ **YES!!**

- **Collider** experiments → various constraints of order $10^{-(1-2)}$.
- We analyzed **cosmological** constraints → much more **stringent!**

(as we will see later…)

2. Cosmological Constraints

"The violation of *R*-parity may spoil
the current Baryon Asymmetry of the Universe."

Baryon Asymmetry of the Universe

Current universe:

There's Baryon,

and no anti-baryon.

Baryon Asymmetry of the Universe

Note:

Today we assume that

Current Baryon Asym. is generated

before EWPT.

$$T \gtrsim 100\,\mathrm{GeV}$$

Baryon Asymmetry of the Universe

Current universe:

There's Baryon,

and no anti-baryon.

Wash-out with *B*-viol. $\not{B}$

However, if we have $W \ni \lambda'' \bar{U} \bar{D} \bar{D}$ interaction,

$$\tilde{q} \rightleftarrows \bar{q}\bar{q}, \qquad \tilde{q}^* \rightleftarrows qq$$

in the early universe.

And if frequently enough,

→ achieve **Equilibrium** : $B = 0$.

→ **No Baryon Asymmetry!** “WASH-OUT” 

→ λ'' must be **small enough!**

Bouquet and Salati, 1987

Wash-out with *B*-viol.

- That is, if

LARGE $\not{B}$, then

“WASH-OUT” occurs!!

But this is a bit **naïve** view…
We have to consider **“sphaleron.”**

Manton, 1983; Klinkhamer and Manton, 1984; 't Hooft, 1976

Kuzmin, Rubakov, Shaposhnikov, 1985; Ringwald, 1988

Sphaleron

$$\mathcal{O}_{\rm sph} = \Pi_i (udd\nu)_i$$

$$\Delta L = 1 \quad 1 \quad 1$$

$$= uddcsstbb\nu_e\nu_\mu\nu_\tau$$

$$\Delta B = \frac{1}{3}\frac{1}{3}\frac{1}{3}\ \frac{1}{3}\frac{1}{3}\ \frac{1}{3}\frac{1}{3}\frac{1}{3}\frac{1}{3}$$

$$\Delta B = 3, \Delta L = 3;\ \ \Delta(B-L) = 0$$

In the early universe (temperature $T \gtrsim 100\,{\rm GeV}$)

→ the **sphaleron** process is **frequent.** (by thermal effects)

Sphaleron converts

Baryon ⇄ Anti-lepton

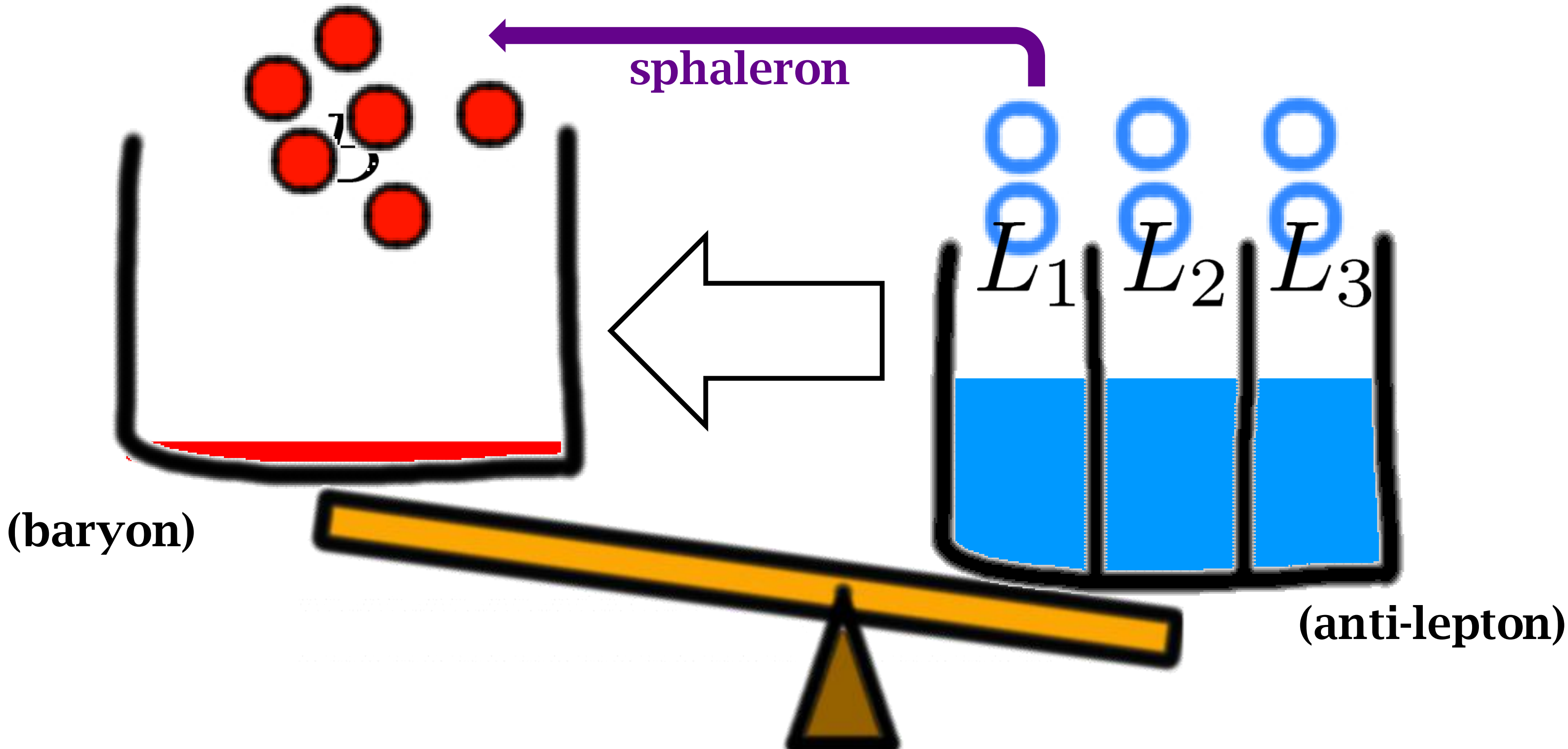
→ **Equilibrium.**

Sphaleron's Effect

$(\text{in } T \gtrsim 100\,\text{GeV})$

If Baryon is short…

sphaleron works right to left

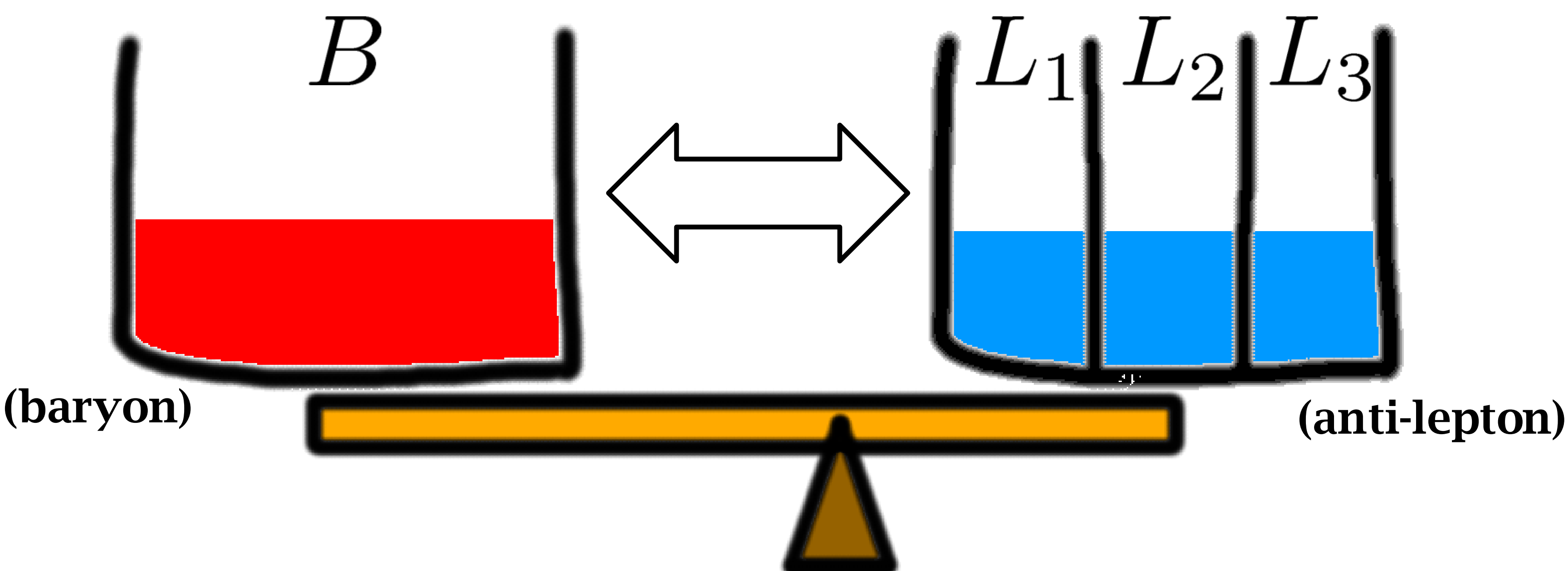


Sphaleron's Effect

If Baryon is short… (in $T \gtrsim 100\,\mathrm{GeV}$)

sphaleron works right to left

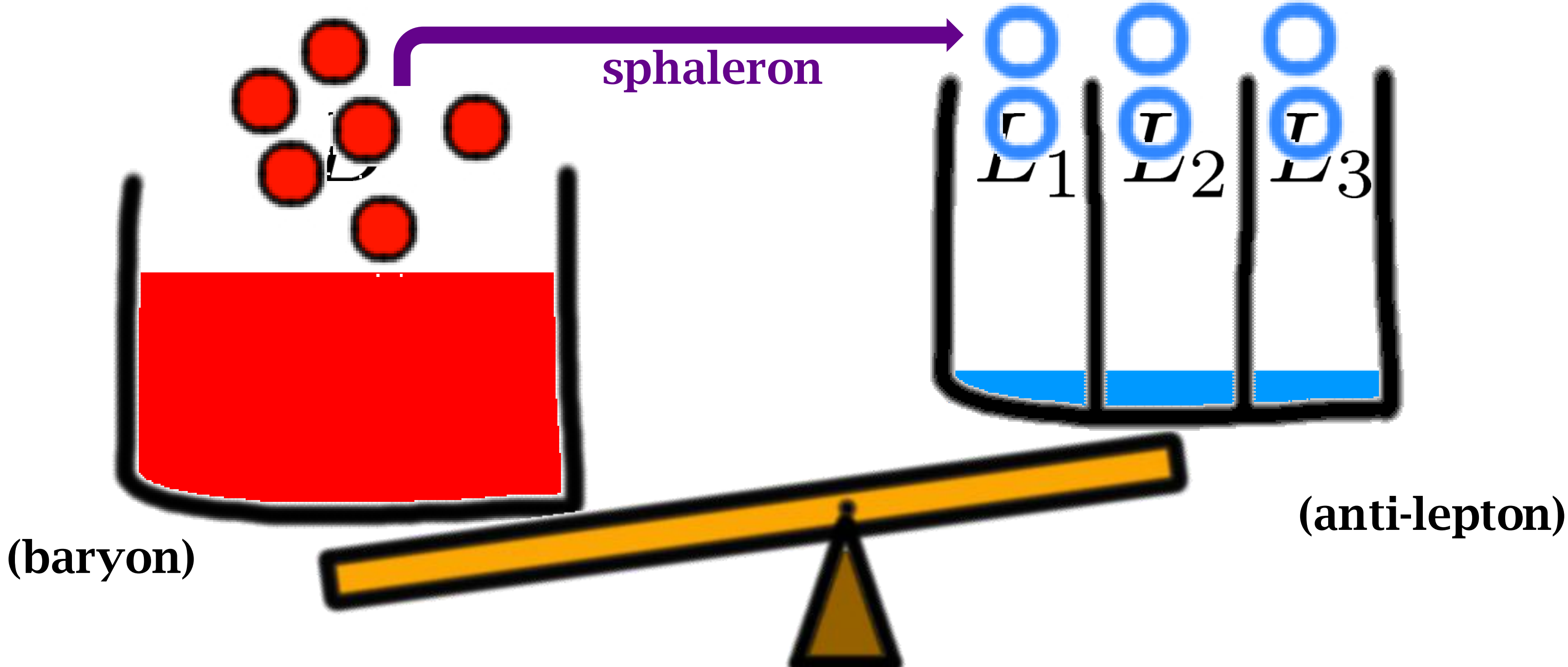
and achieve Equilibrium.



Sphaleron's Effect

$(\text{in } T \gtrsim 100\,\text{GeV})$

Also when (anti-)Lepton is short,
sphaleron does left to right



Sphaleron's Effect

(in $T \gtrsim 100\,\mathrm{GeV}$)

Also when (anti-)Lepton is short,
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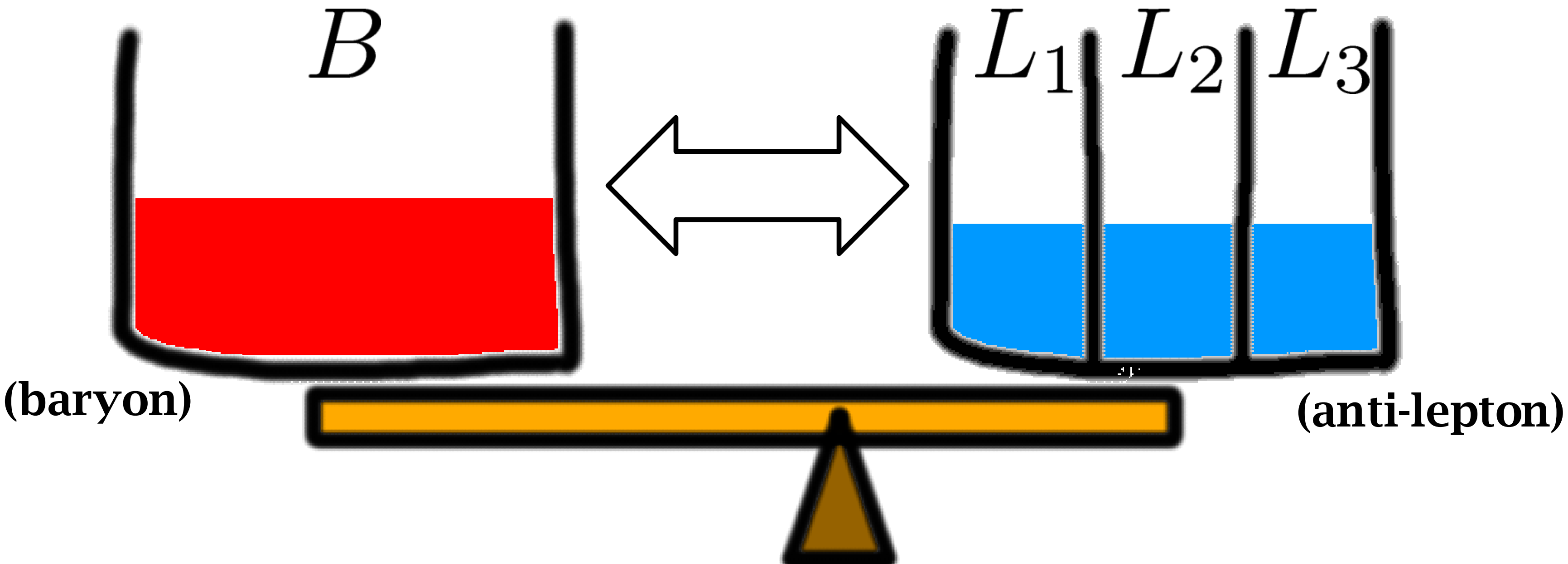
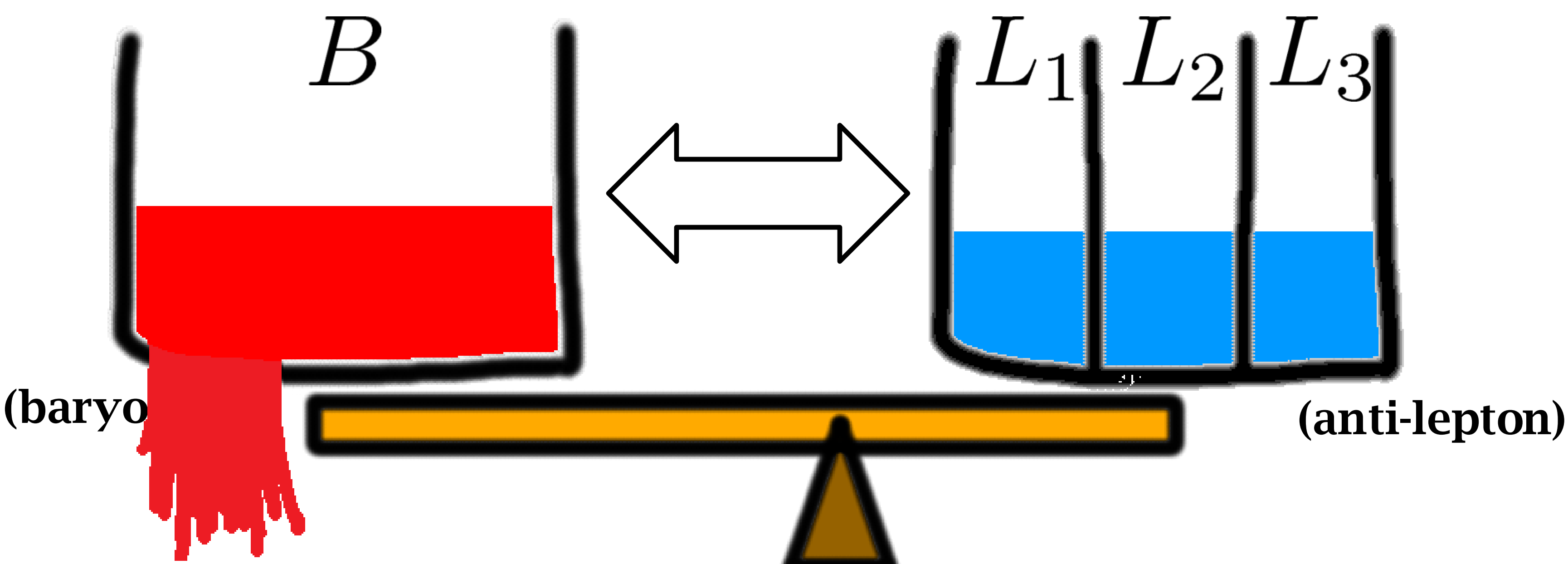


Wash-out with B-viol.

$\not{B}$

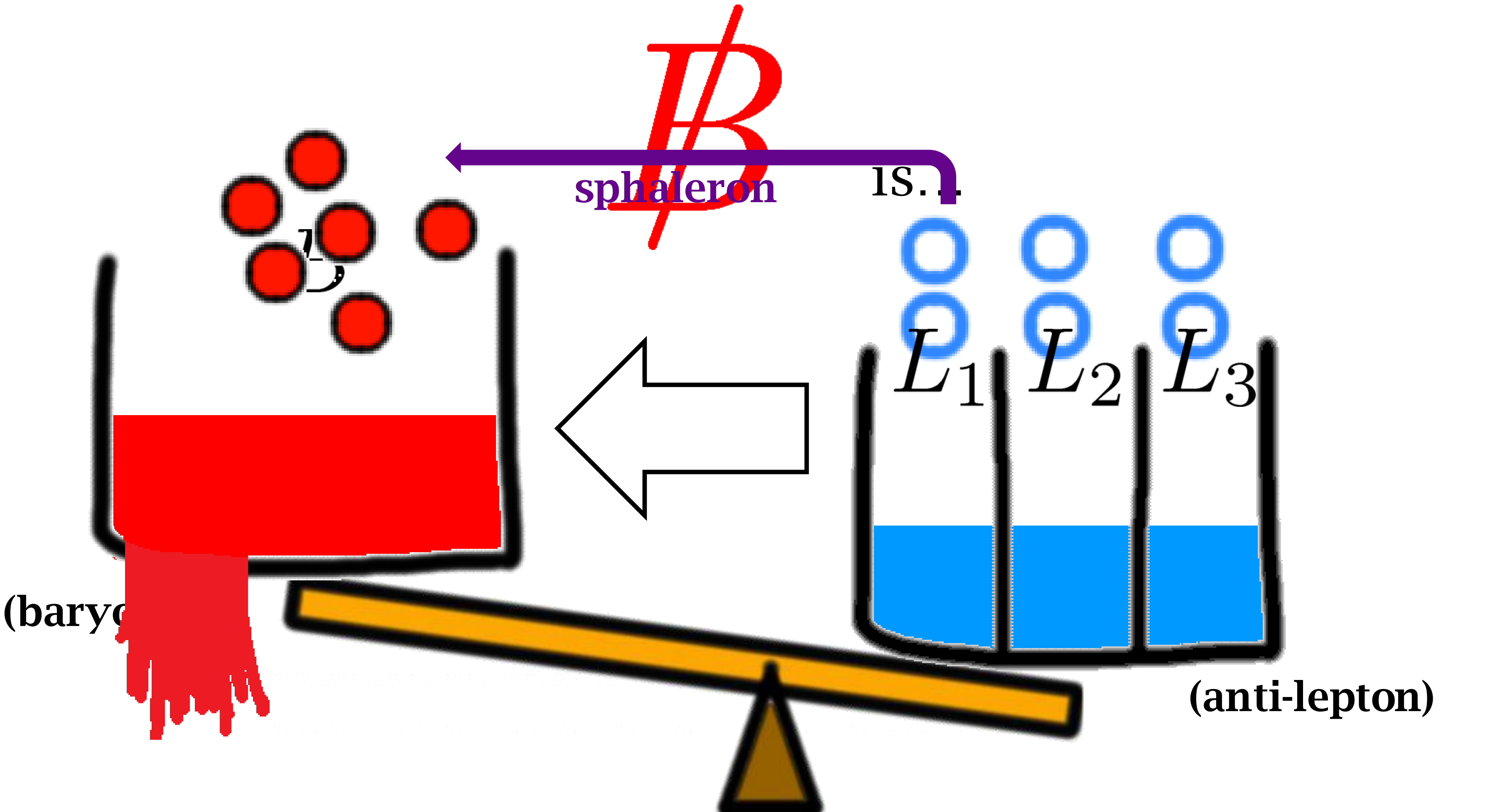
Thus, actually the previous wash-out by

$\not{B}$ is…



Wash-out with B-viol.

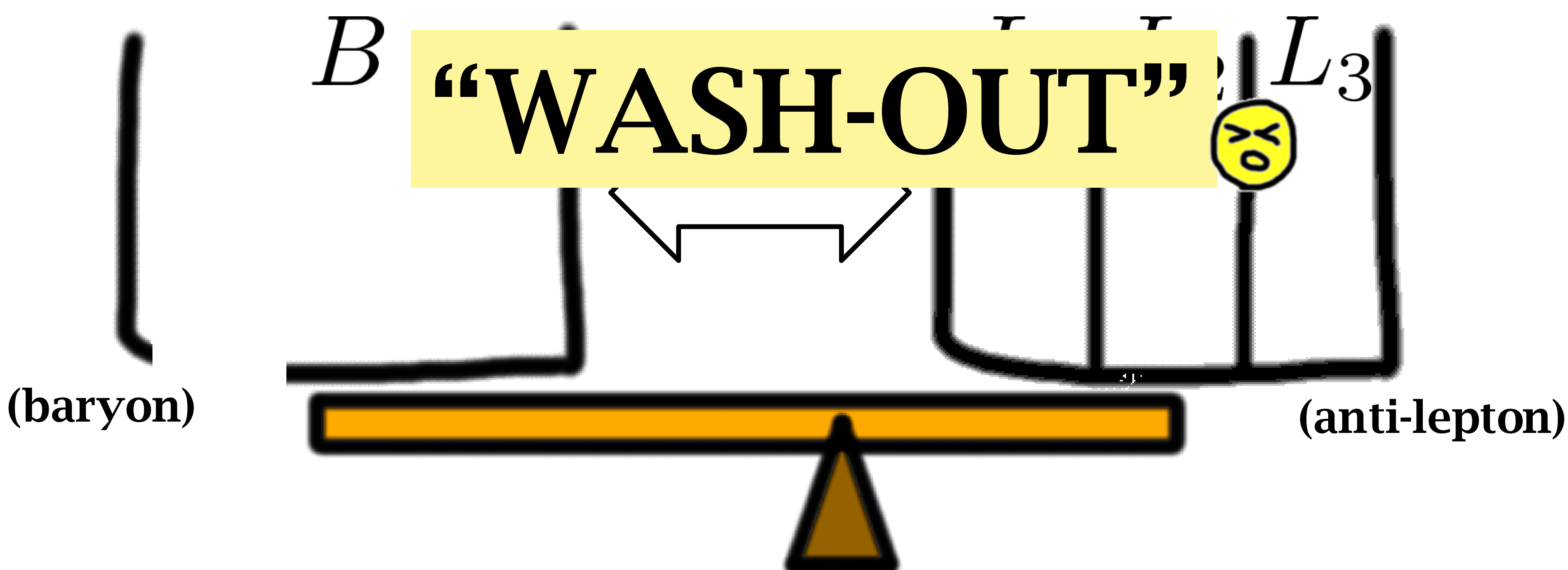
Thus, actually the previous wash-out by



Wash-out with *B*-viol. $\not{B}$

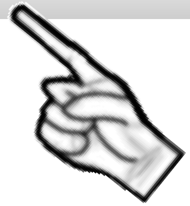
Thus, actually the previous wash-out by

$\not{B}$ is…



Kuzmin, Rubakov and Shaposhnikov, 1985
Campbell, Davidson, Ellis and Olive, 1992

Wash-out with L-viol.

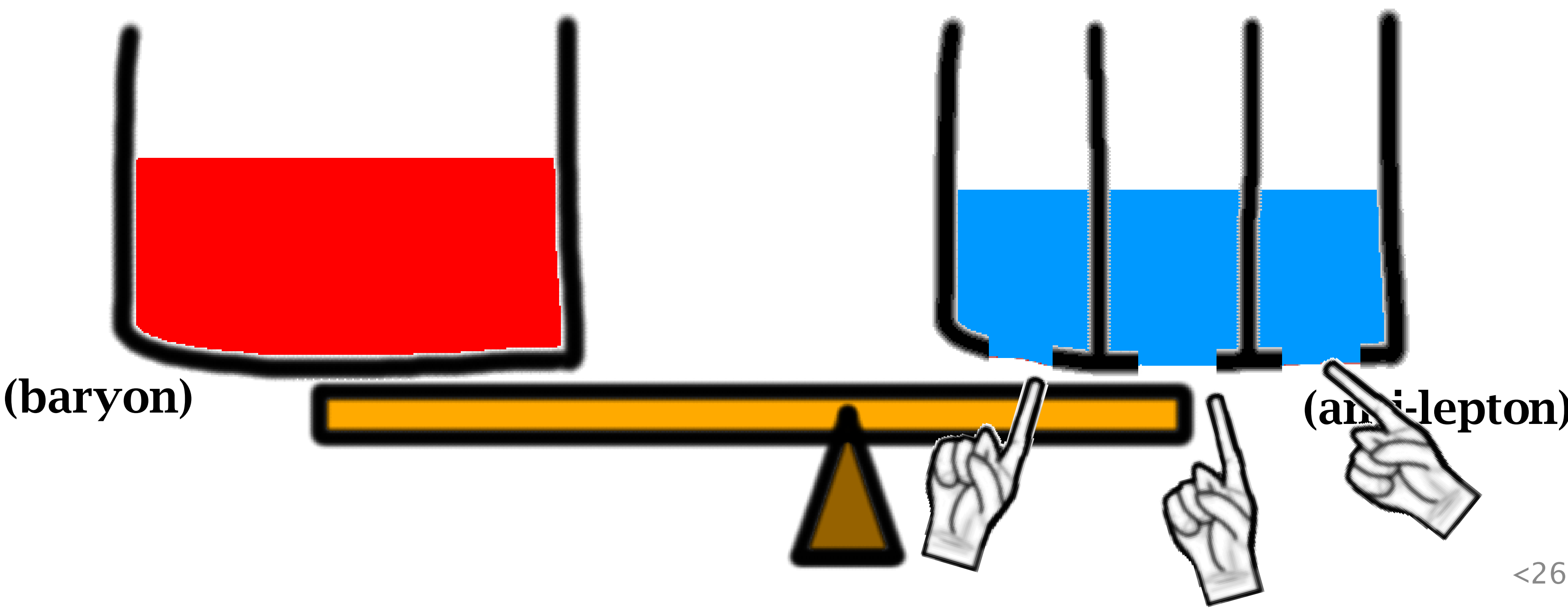


This story does not end here!

$$\not{L}$$

Wash-out with L-viol. $\not{L}$

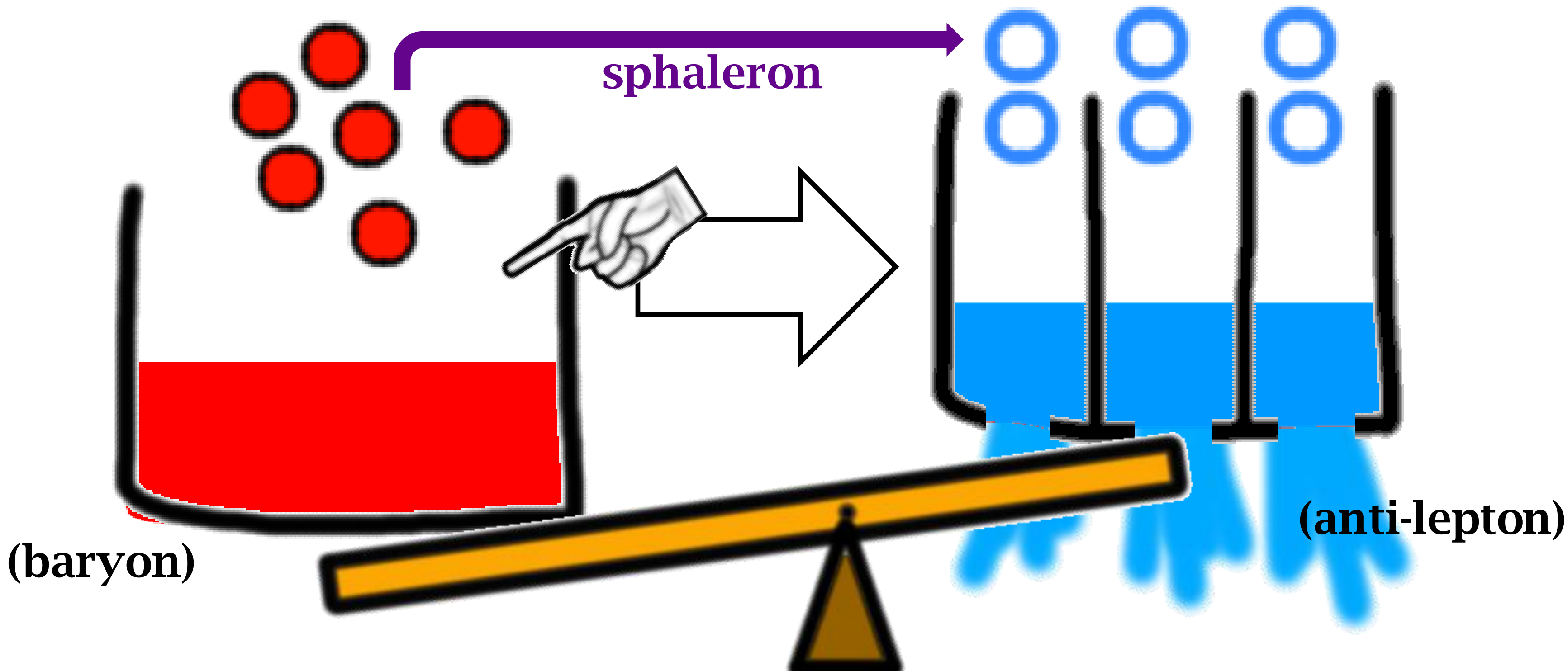
- If large $\not{L}$ (in the sphaleron era), $(\text{e.g. } \tilde{l} \rightleftarrows l^* e \text{ from } LL\bar{E})$



Wash-out with L-viol. $\not{L}$

- If large $\not{L}$ (in the sphaleron era),

$(\text{e.g. } \tilde{l} \rightleftarrows l^* e \text{ from } LL\bar{E})$

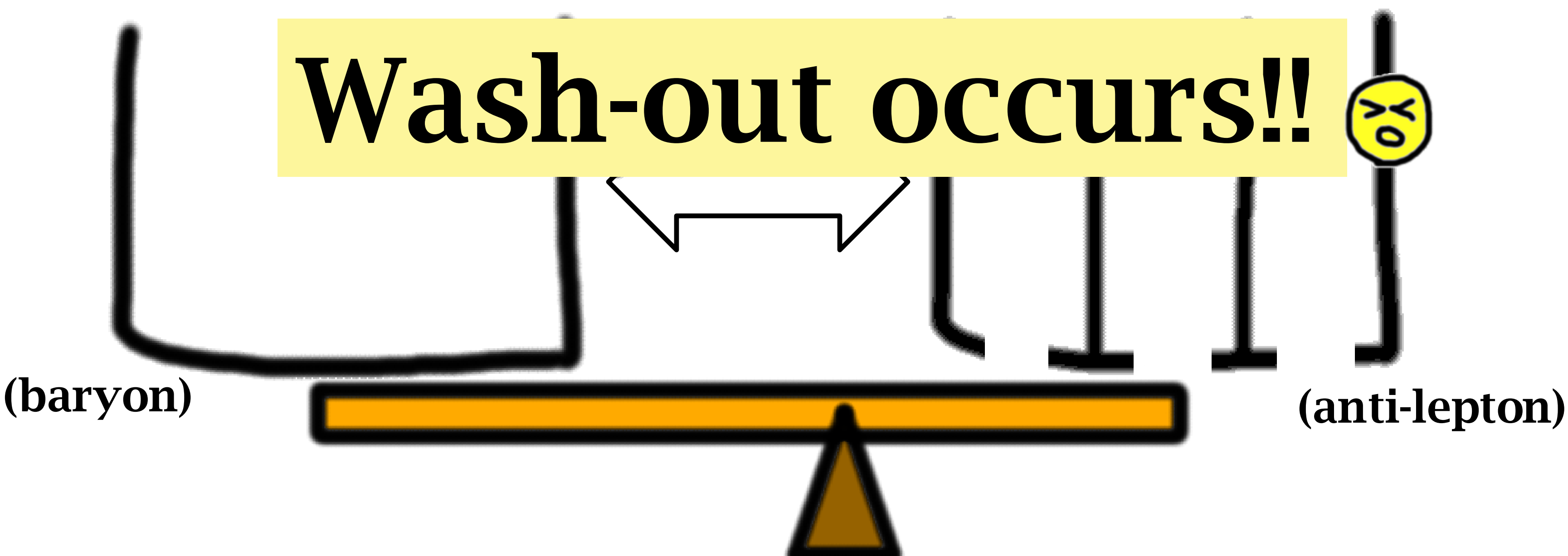


Wash-out with L-viol. $\not{L}$

- If

large $\not{L}$ (in the sphaleron era), (e.g. $\tilde{l} \rightleftarrows l^* e$ from $LL\bar{E}$)

Wash-out occurs!!

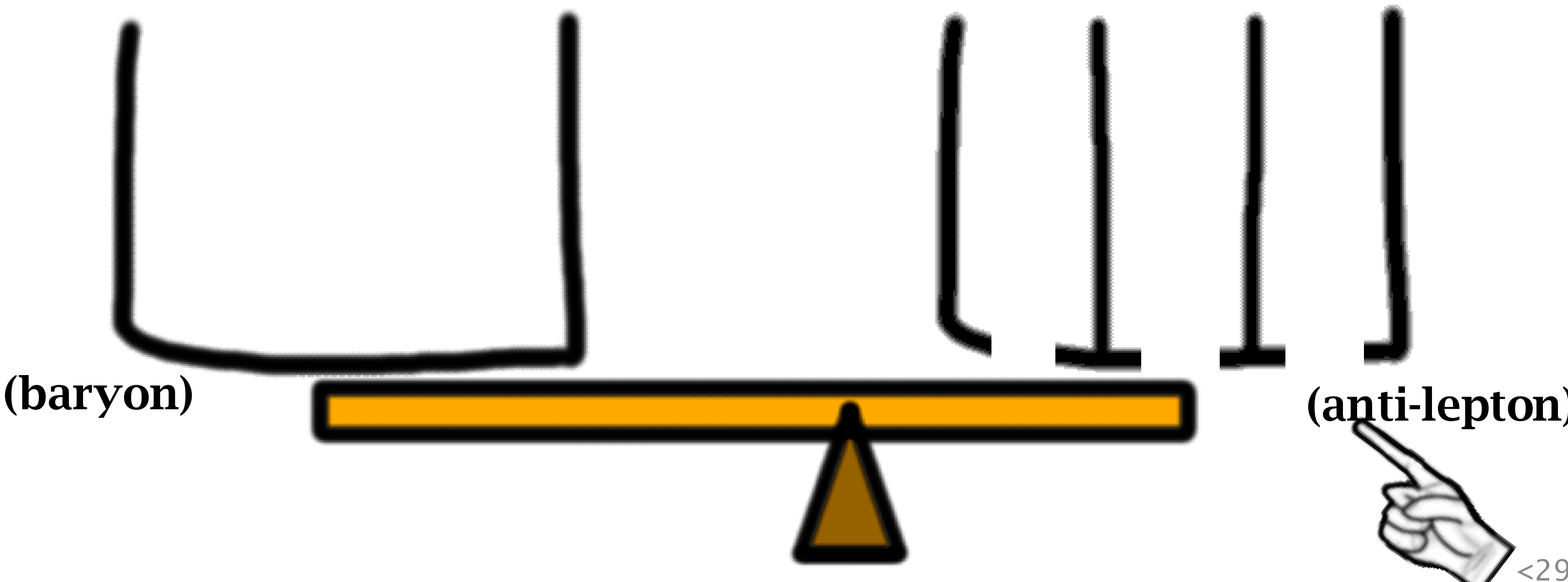


Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.

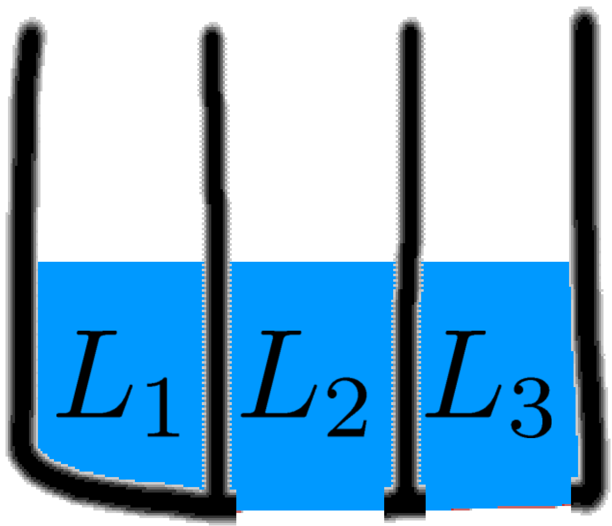
But

NOTE ONE IMPORTANT POINT!



Wash-out with *L*-viol.

Imagine this case.

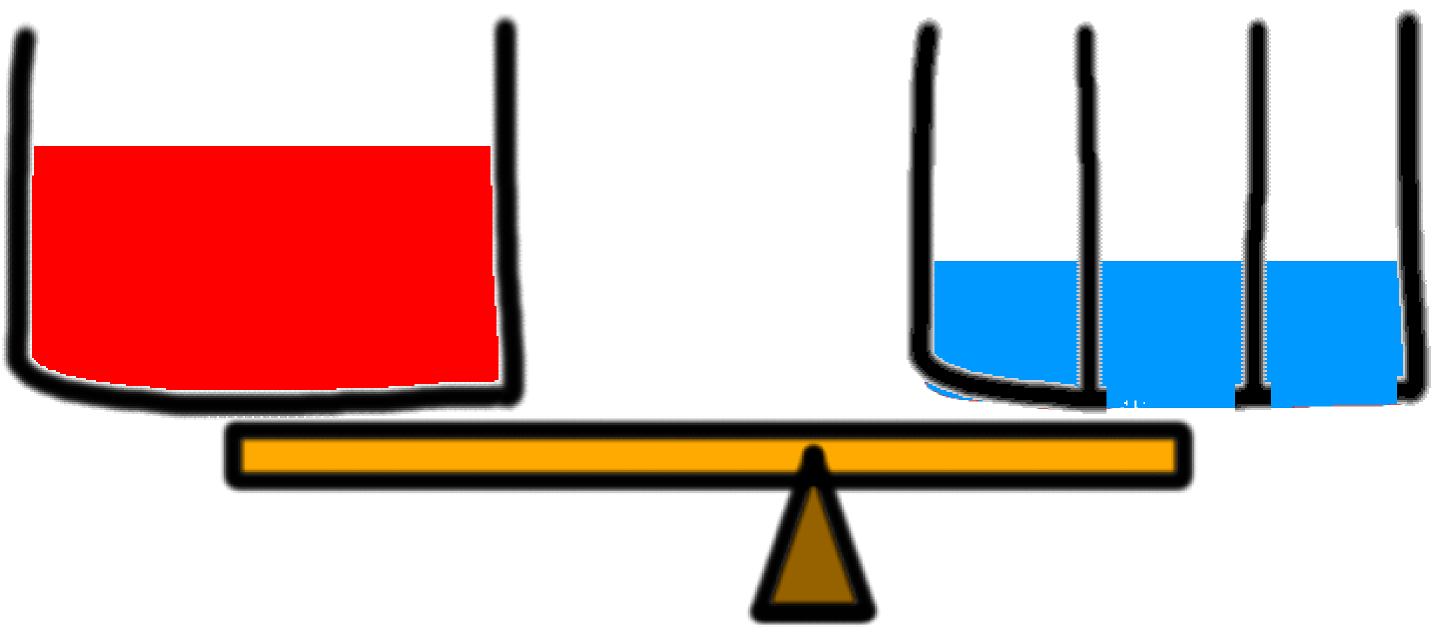


If the **Lepton Flavor** is **NOT violated**,

and

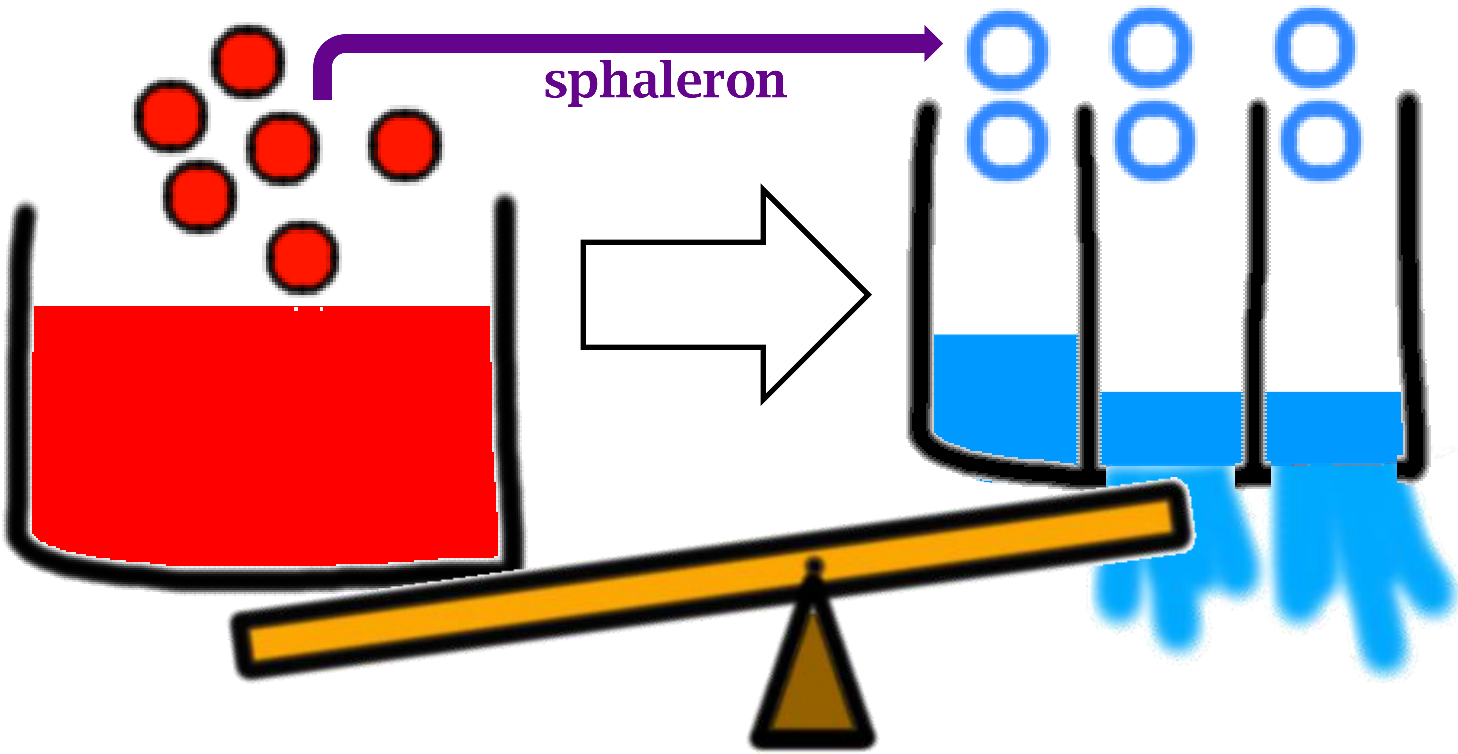
if **at least one** of L_i is **conserved**,

Wash-out with *L*-viol.



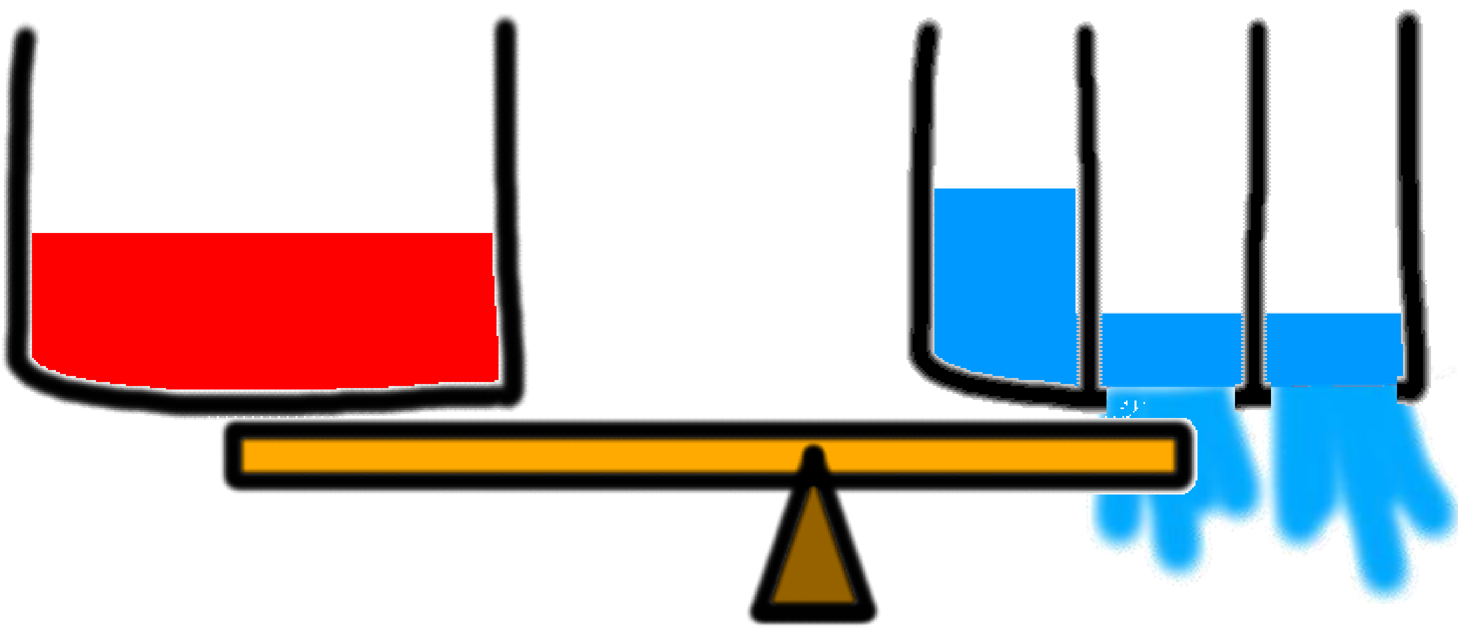
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.



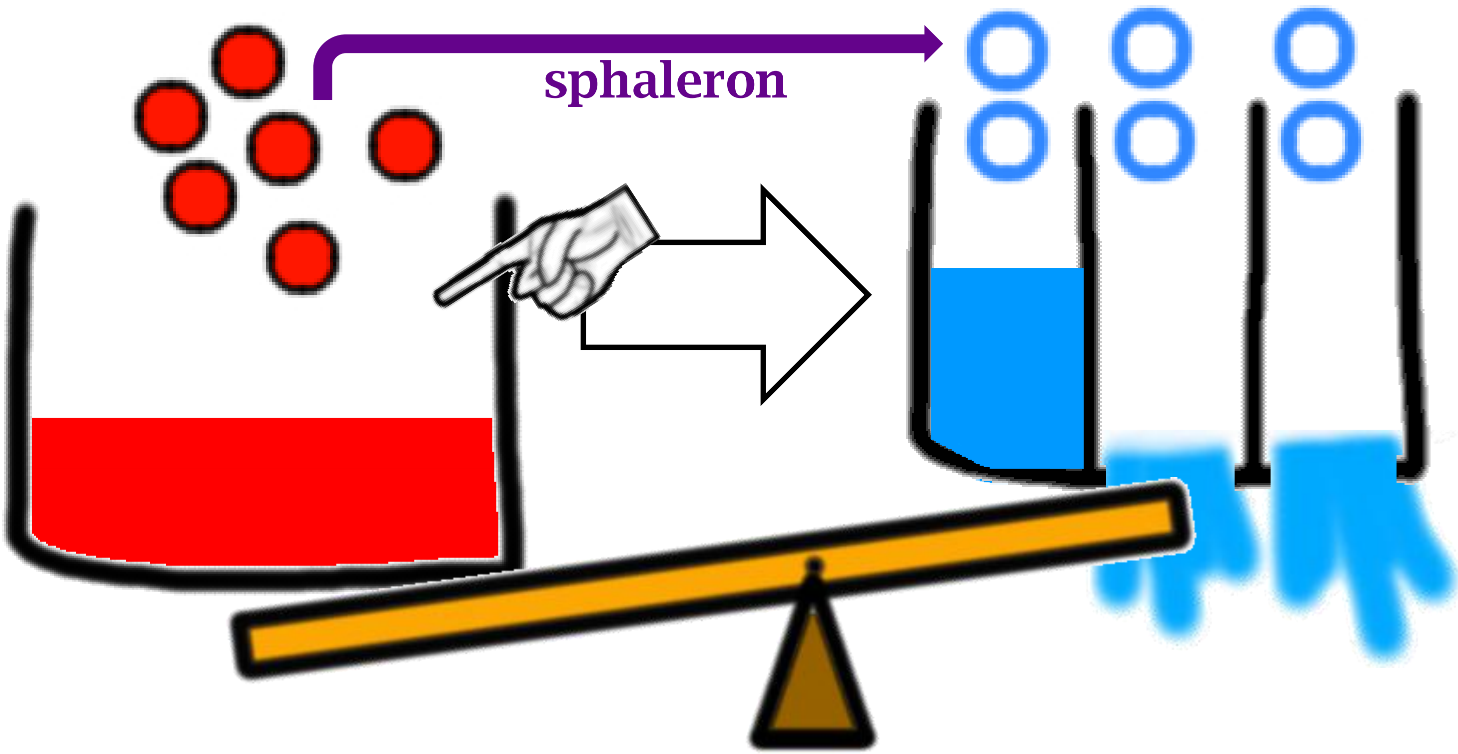
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.



Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

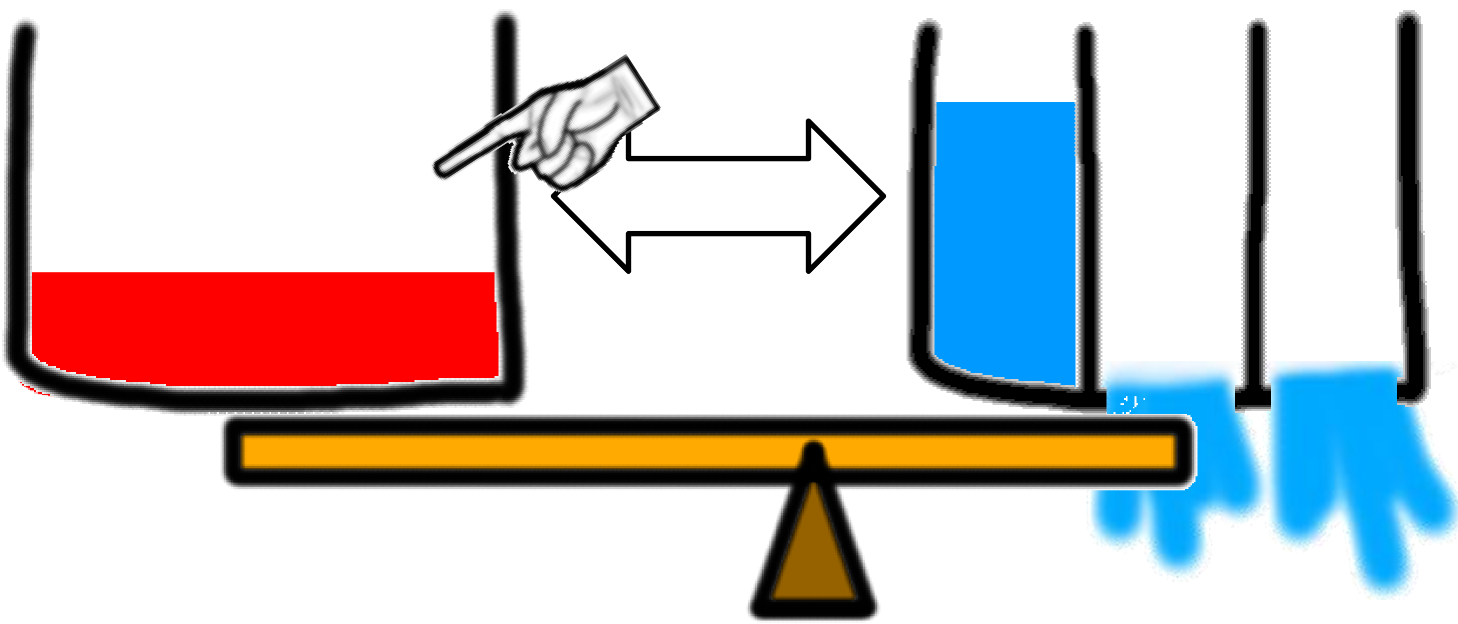
Wash-out with *L*-viol.



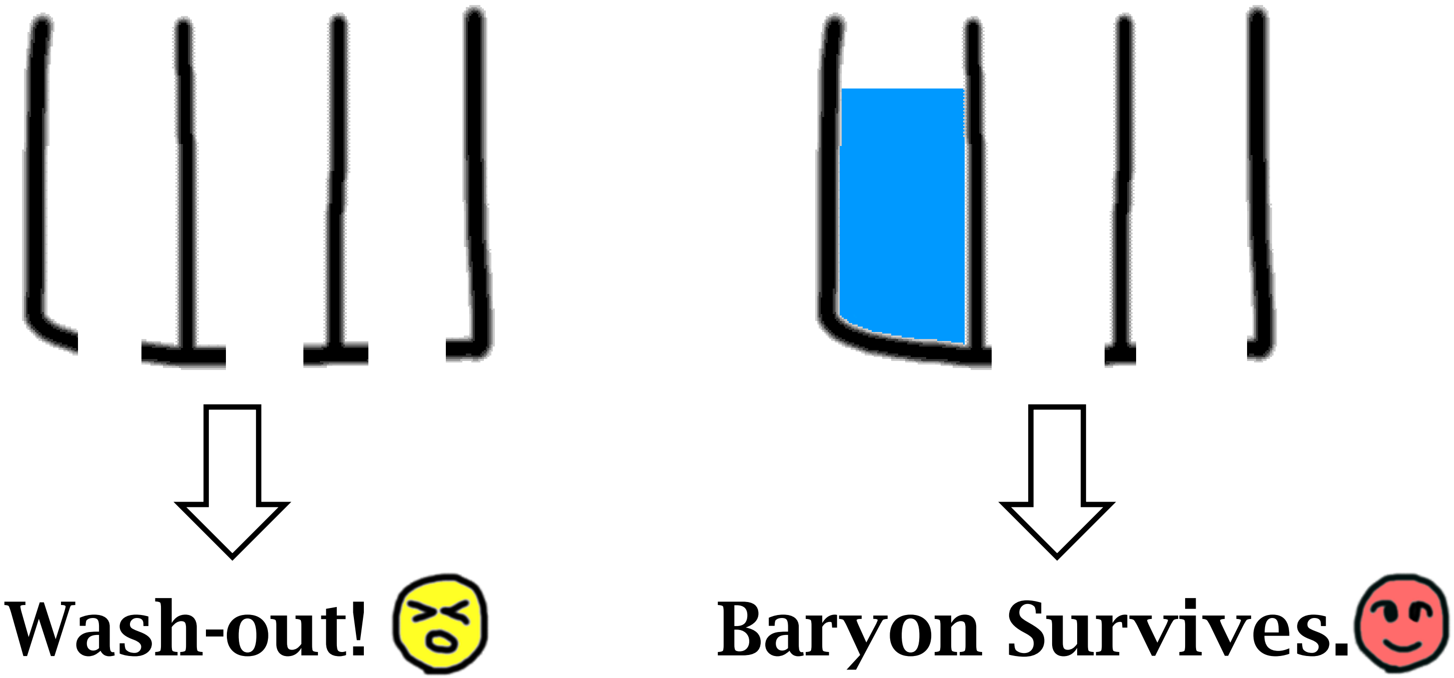
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.

Baryon SURVIVES!!!



Wash-out with *L*-viol.



The **“leptonic”** wash-out needs **three $\not{L}$s**
if there’s no LFV.

Endo, Hamaguchi, and SI, 2009

Wash-out with *L*-viol.

But remember!

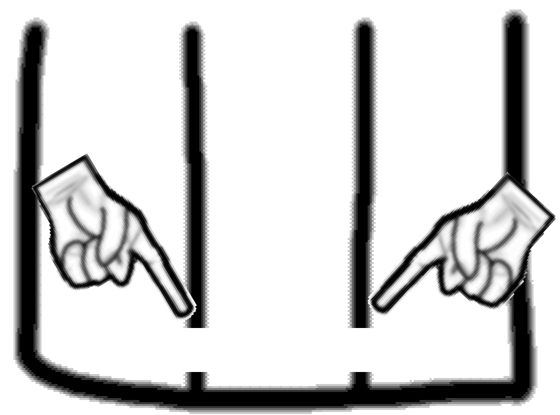
In MSSM,

We have LFVs in general!!!

As Shimomura-san mentioned.

The Standard Model

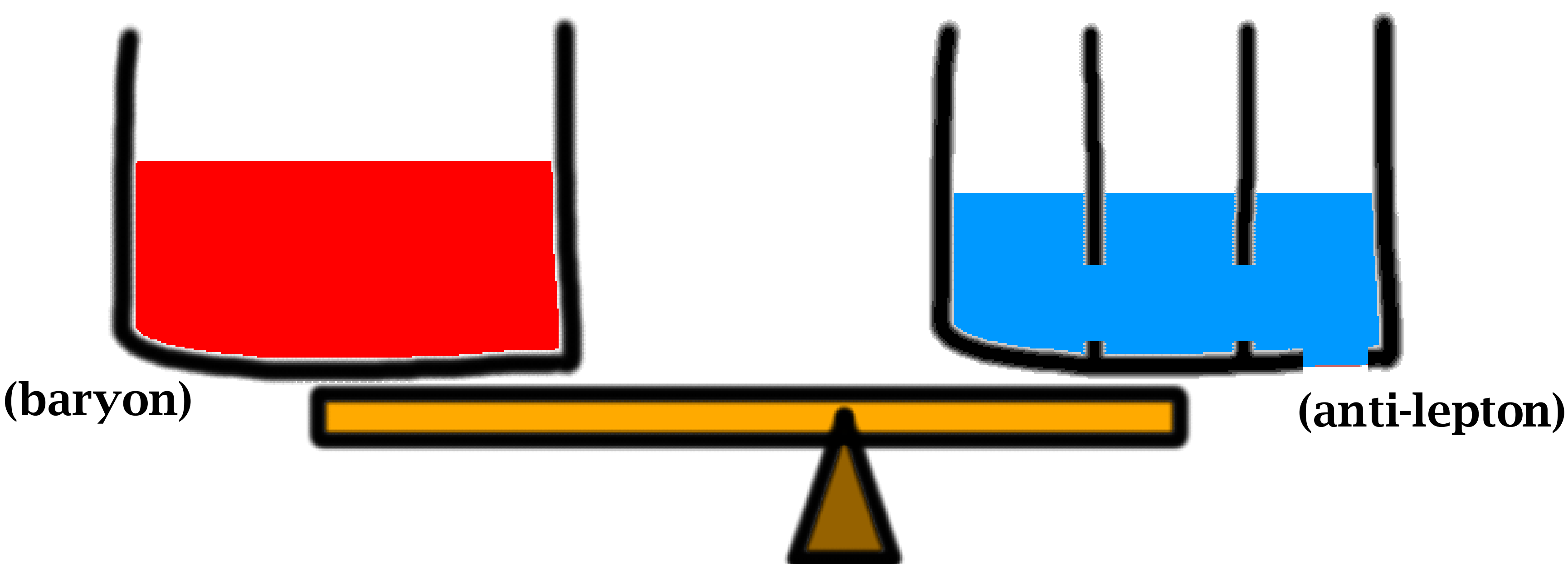
The MSSM



Wash-out with $\not{L}$-viol.

Therefore,

Only One $\not{L}$ would...

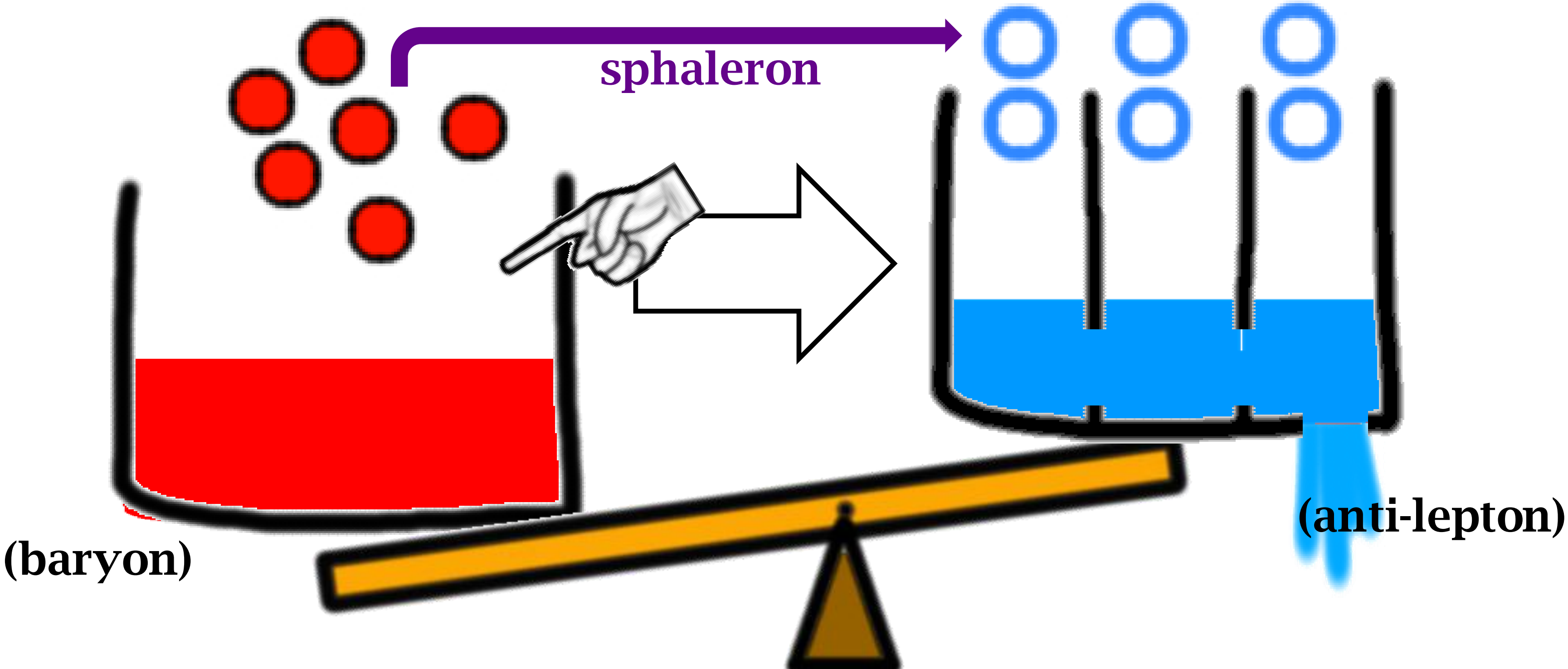


Wash-out with L-viol.

$\not{L}$

Therefore,

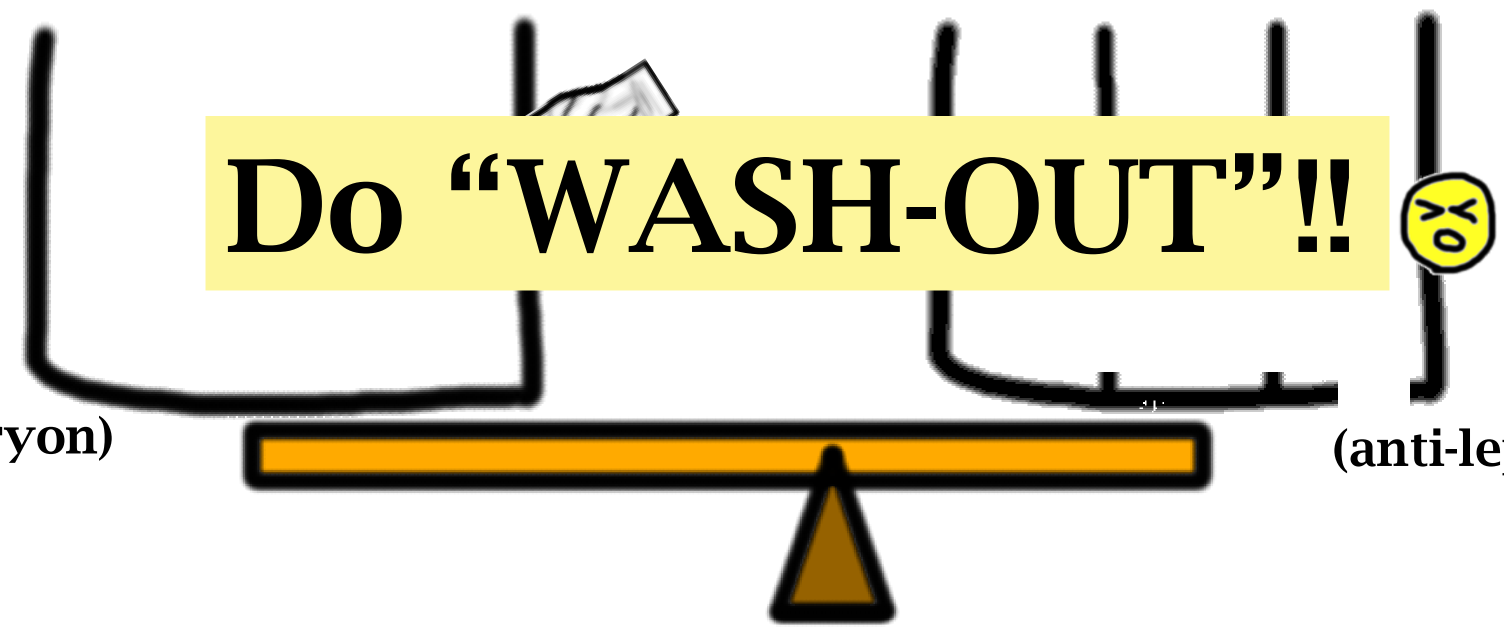
Only One $\not{L}$ would…



Wash-out with $\not{L}$-viol.

Therefore,

Only One $\not{L}$ would…



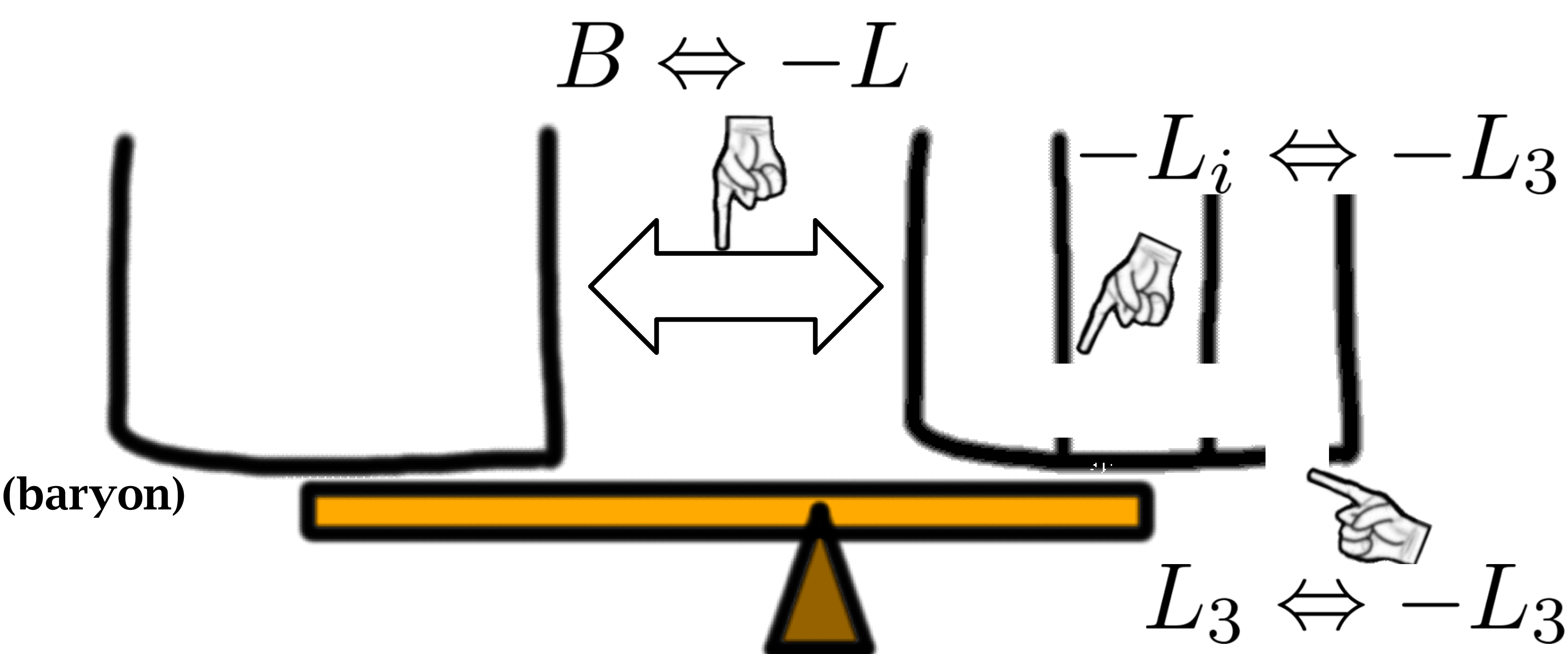
(baryon)

(anti-lepton)

Wash-out with $\not{L}$-viol.

Therefore,

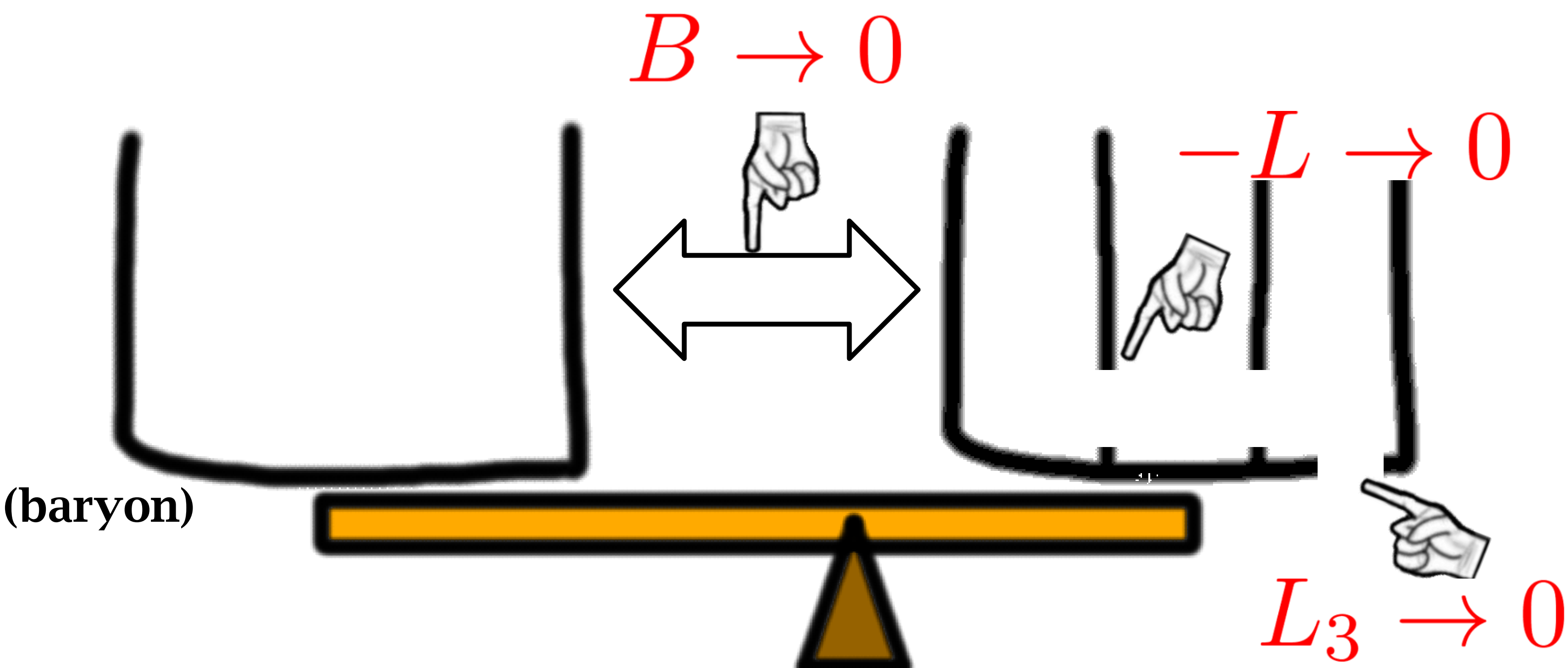
Only One $\not{L}$ would…



Wash-out with L-viol. $\not{L}$

Therefore,

Only One $\not{L}$ would…



These are what we studied!

To **avoid** the WASH-OUT,

- All $\not{B}$ must be small enough, and
- If all flavors are mixed

  $\rightarrow$ All $\not{L}$ must be small enough.

$$W_{\not{L}} = W_{\mathrm{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\mathrm{u}}$$

$$W_{\not{B}} = W_{\mathrm{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

These are what we studied!

To **avoid** the WASH-OUT,

- All $\not{B}$ must be small enough, and

- If all flavors are mixed

When MIX?

$\rightarrow$ All $\not{L}$ must be small enough.

$$W_{\not{L}} = W_{\mathrm{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu_i L_i H_u$$

$$W_{\not{B}} = W_{\mathrm{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

How SMALL must be?

And we will claim that…

To **avoid** the WASH-OUT,

- All $\not{B}$ must be small enough, and

This is naturally expected!

- If all flavors are mixed

  → All $\not{L}$ must be small enough.

$$W_{\not{L}} = W_{\rm RPC} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\rm u}$$

$$W_{\not{B}} = W_{\rm RPC} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

All of them are severely constrained!

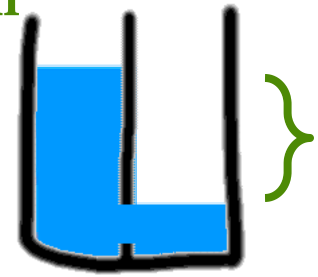
3. Our Results

Methods

Lepton number density in i-th generation

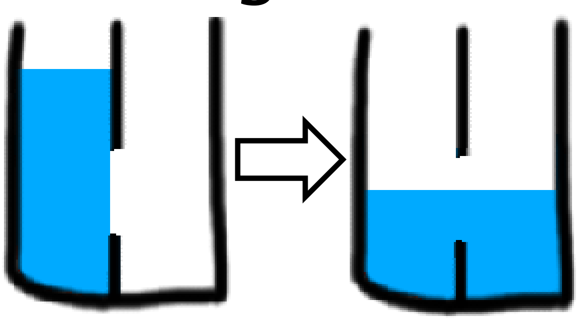
We calculated

$$\frac{\mathrm{d}}{\mathrm{d}t}(L_i - L_j)$$



by **Boltzmann Eq.**

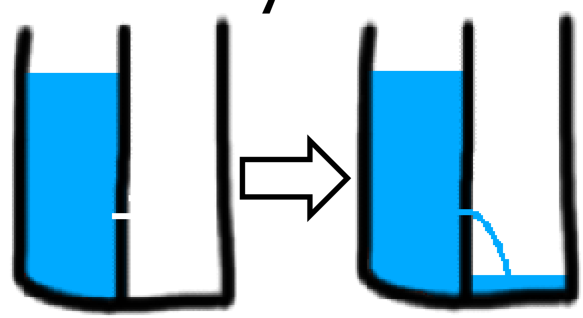
Large LFV



$$L_i - L_j \to 0$$

(All $\not{L}$ must be small.)

Tiny LFV



$$L_i - L_j \not\to 0$$

Methods

$$(h_i) H_{\rm d} L_i \bar{E}_i$$

$$(m^2_L)_{ij} \widetilde{L}^*_i \widetilde{L}_j$$

$$(m^2_{\bar{E}})_{ij} \widetilde{\bar{e}}^*_i \widetilde{\bar{e}}_j$$

LFV

Generally **NOT** diagonal

As Shimomura-san discussed.

Methods

$$(h_i) H_\mathrm{d} L_i \bar{E}_i$$

$$(m_L^2)_{ij} \widetilde{L}_i^* \widetilde{L}_j$$

$$(m_{\bar{E}}^2)_{ij} \widetilde{\bar{e}}_i^* \widetilde{\bar{e}}_j$$ **LFV**

Diagonalize
by θ rotation
"mixing angle"

LFV $$(h_{ij}) H_\mathrm{d} L_i \bar{E}_j$$

$$h_{ij} = h_i \theta_{ij}^{\bar{E}} + h_j \theta_{ji}^{L}$$

$$(m_L^2)_i \widetilde{L}_i^* \widetilde{L}_i$$

$$(m_{\bar{E}}^2)_i \widetilde{\bar{e}}_i^* \widetilde{\bar{e}}_i$$

Methods

For example

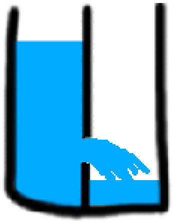
$$h_{23} \simeq \left(0.006 \cdot \theta^{\bar{E}}_{23} + 0.1 \cdot \theta^{L}_{32}\right) \left(\frac{\tan\beta}{10}\right)$$

(We know h_i , because we know the lepton masses.)

LFV $(h_{ij}) H_{\rm d} L_i \bar{E}_j \;\Longrightarrow\; \widetilde{H} \rightleftarrows l_i \widetilde{e}^*_j, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e^\dagger_j$

causes Mixing.

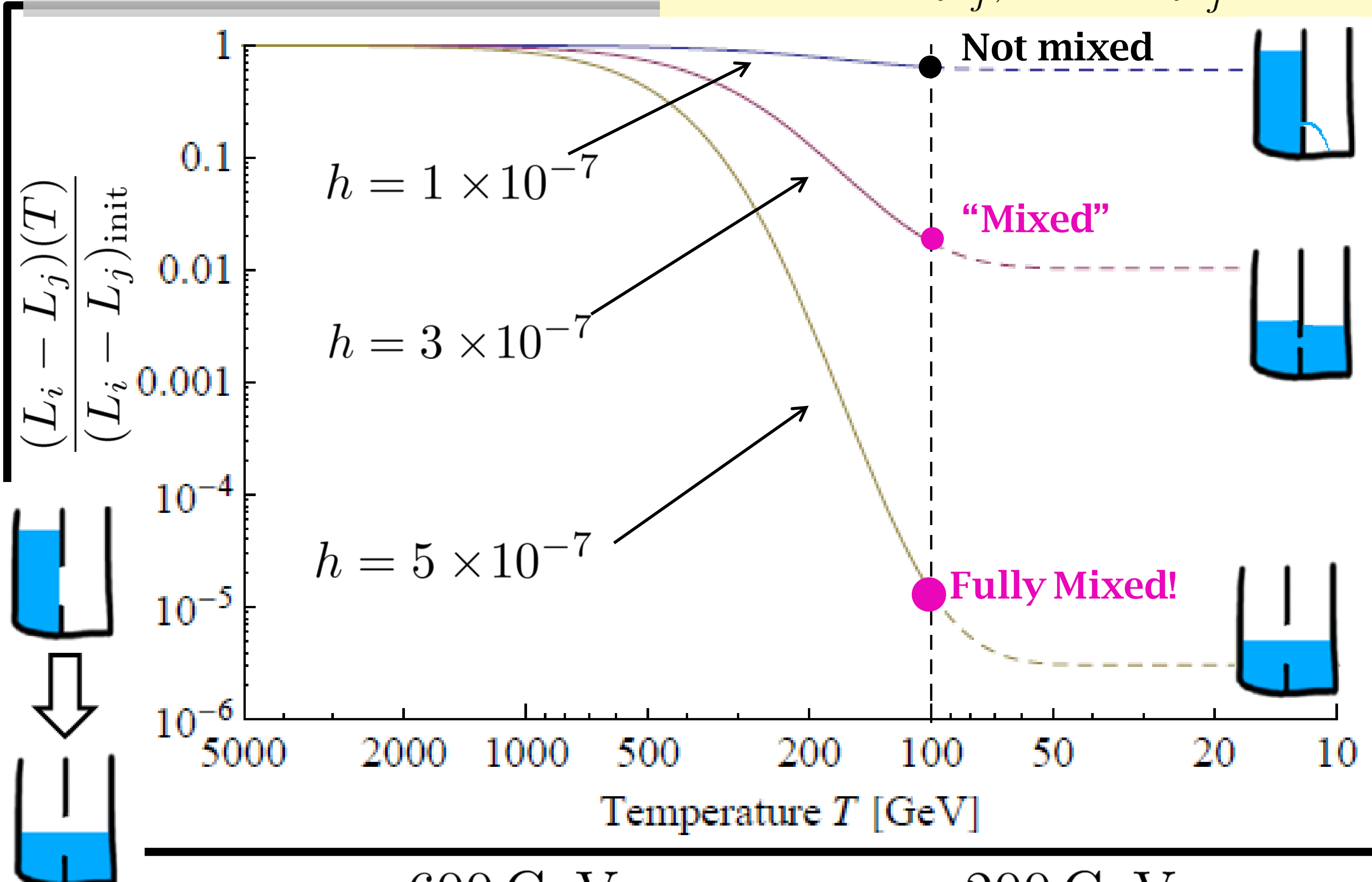
$$h_{ij} = h_i \theta^{\bar{E}}_{ij} + h_j \theta^{L}_{ji}$$



Result

$$W \ni (h_{ij}) H_{\rm d} L_i \bar{E}_j$$

$$\widetilde{H} \rightleftarrows l_i \widetilde{e}_j^*, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e_j^\dagger$$



$$m_{\widetilde{H}} = 600\,{\rm GeV}, \ m_{\widetilde{l}} = m_{\widetilde{e}} = 200\,{\rm GeV}$$

Conclusion

$$W \ni (h_{ij}) H_{\rm d} L_i \bar{E}_j$$

$$\widetilde{H} \rightleftarrows l_i \widetilde{e}^*_j, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e^\dagger_j$$

$$h \gtrsim 3 \times 10^{-7} \ \rightarrow \ \text{MIXED}$$

This corresponds to

$$\theta_{23}, \theta_{13} \gtrsim 3 \times 10^{-6},$$

$$\theta_{12} \gtrsim 7 \times 10^{-5}.$$

By the way,

Remember:

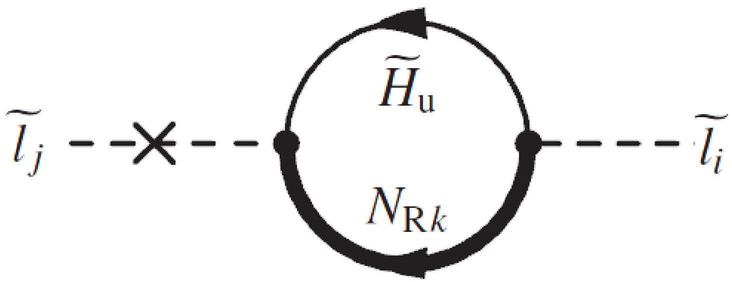
$$h_{23} \simeq \left(0.006 \cdot \theta^{\bar{E}}_{23} + 0.1 \cdot \theta^{L}_{32}\right) \left(\frac{\tan\beta}{10}\right)$$

Conclusion

$$W \ni (h_{ij}) H_{\rm d} L_i \bar{E}_j$$

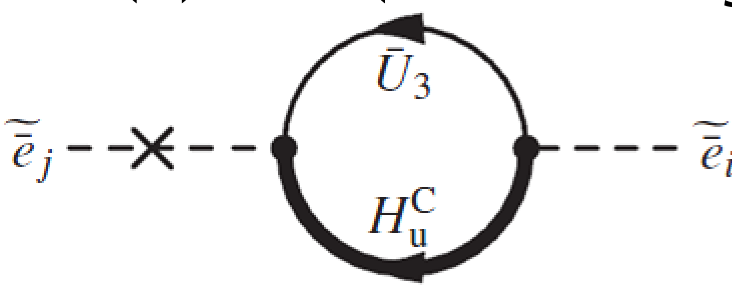
$$\widetilde{H} \rightleftarrows l_i \widetilde{e}_j^{*}, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e_j^{\dagger}$$

Right-handed neutrino



$$\xrightarrow[(\Delta m_L^2)_{ij}]{} \quad \delta_{ij}^{L} \sim 10^{-5} \left(\frac{M_R}{10^{10}\mathrm{GeV}} \right)$$

SU(5) GUT (Colored Higgs)



$$\xrightarrow[(\Delta m_{\bar{E}}^2)_{ij}]{} \quad \delta_{ij}^{\bar{E}} \sim 10^{-(1-4)}$$

$$\text{where} \quad \delta_{ij}^{X} := \frac{(m_X^2)_{ij}}{(m_X^2)_{\rm diag}}.$$

Conclusion

$$W \ni (h_{ij}) H_{\rm d} L_i \bar{E}_j$$

$$\widetilde{H} \rightleftarrows l_i \widetilde{e}_j^*, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e_j^\dagger$$

$$\theta_{23}, \theta_{13} \gtrsim 3 \times 10^{-6}, \qquad \theta_{12} \gtrsim 7 \times 10^{-5}. \quad \longrightarrow \text{MIXED}$$

Naturally Expected!

Expected Value

$$\delta_{ij}^L \sim 10^{-5} \left(\frac{M_R}{10^{10}\mathrm{GeV}}\right)$$

$$\delta_{ij}^{\bar{E}} \sim 10^{-(1-4)}$$

Experimental Reach

$$\text{MEGA} \ : \delta_{21}^L \lesssim 10^{-3}$$

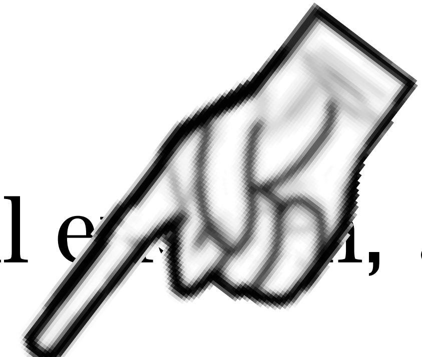
$$\text{MEG} \ : \delta_{21}^L \Rightarrow 10^{-4}$$

$$\left(\theta_{ij} \sim \frac{m_{ij}^2}{m_i^2 - m_j^2} = \frac{m_{\rm diag}^2}{m_i^2 - m_j^2} \delta_{ij} \right)$$

Now We Know

This is naturally expected!

To **avoid** the WASH-OUT,



- All $\not{B}$ must be small enough, and
- If all flavors are mixed

→ All $\not{L}$ must be small enough.

$$W_{\not{L}} = W_{\mathrm{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\mathrm{u}}$$

$$W_{\not{B}} = W_{\mathrm{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

These are ALL severely constrained!

Constraints on RpVs

- In a similar manner…

$$\frac{\mathrm{d}}{\mathrm{d}t}(B-L)$$

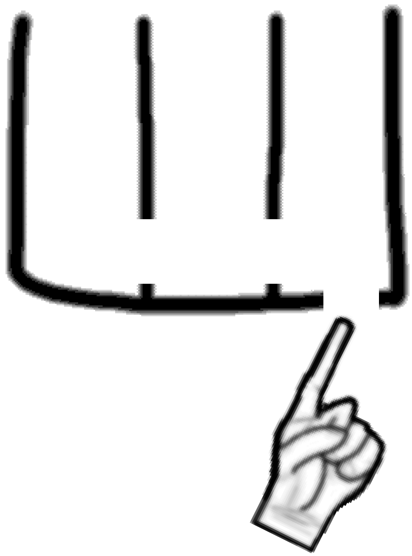
$\rightarrow$ calculated by the Boltzmann Eq.

$\Downarrow$

We obtained the bounds for

***R*-parity violating couplings.**

Just the results…



$$\lambda \lesssim 1 \times 10^{-6}$$

$$\lambda' \lesssim 3 \times 10^{-7}$$

$$\kappa \lesssim 1.5 \times 10^{-6}$$

$$\lambda'' \lesssim 4 \times 10^{-7}$$

(For all *i*, *j*, *k*)

$$W_{\not{L}} = W_{\mathrm{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\mathrm{u}}$$

$$W_{\not{B}} = W_{\mathrm{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

For

$$m_{\tilde{q}} = 600\,\mathrm{GeV}, \;\; m_{\tilde{H}} = 300\,\mathrm{GeV}, \;\; m_{\tilde{l}} = 100\,\mathrm{GeV}.$$

4. Application for LHC

"Now we have a good tool
to study LHC phenomenology of RpV-MSSM."

SUSY Detection @ LHC

- **SUSY detection** in LHC is important.

R-parity is Conserved → LSP $\not{p}_{\rm T}$ Signal

Then if not?

→ **LSP decays!**

How to detect RpV-SUSY?

Application for LHC

Stringent RpV-constraint of order $10^{-(5\text{–}7)}$

→ LSP is a bit "long-lived."

- Example: $W \ni \lambda_{ij3} L_i L_j \bar{E}_3$ ($\widetilde{\tau}$-LSP)

$$\widetilde{\tau} \to l\nu$$

Decay Length $\simeq 50\,\mu\mathrm{m} \left(\frac{\lambda_{ij3}}{10^{-6}}\right)^{-2} \left(\frac{m_{\widetilde{\tau}}}{100\,\mathrm{GeV}}\right)^{-1}$

(cf. tau-lepton: $87\,\mu\mathrm{m}$)

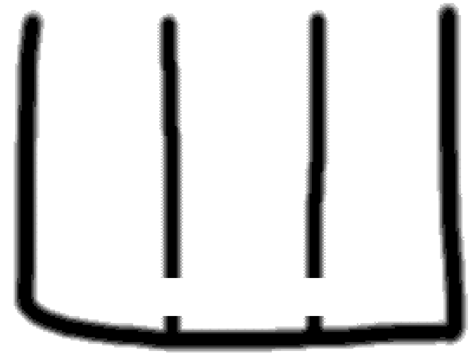
To be a good signal of RpV-SUSY?

→ Future works!

That’s all.
Thank you
for listening.

Summary

MSSM ⟹ **LFV!!**



R-parity is not a must.

$\not{B}$ **& $\not{L}$ are ALL small.** ⟹ LSP would be a bit **long-lived** even if **NO *R*-Parity.**

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Appendices

A. Hierarchy Problem

"In the Standard Model,
the quantum correction for the mass of the Higgs
requires a miraculous cancellation as
$\mathrm{O}(10^{30}) - \mathrm{O}(10^{30}) \rightarrow 10^4$!? "

Hierarchy Problem

In the

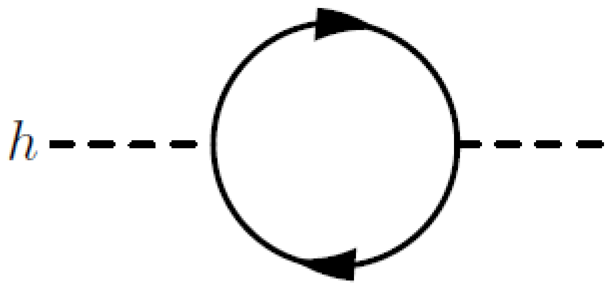
Standard Model

with Higgs,

Hierarchy Problem

$\mathcal{L} \ni \lambda h \bar{f} f$

$\Lambda \sim 10^{15}\,\mathrm{GeV}$



$$\Rightarrow \Delta m^2_{\mathrm{higgs}} = -\frac{|\lambda|^2}{8\pi^2}\Lambda^2 + \mathrm{finite}$$

$$\Downarrow$$

$$m^2_{\mathrm{higgs}} \sim m^2_{\mathrm{bare}} + \Delta m^2_{\mathrm{higgs}}$$

$m_{\mathrm{higgs}} \sim 100\,\mathrm{GeV}$

$$\therefore \mathrm{O}(10^{30}) - \mathrm{O}(10^{30}) \rightarrow 10^4 \;!?$$

Hierarchy Problem

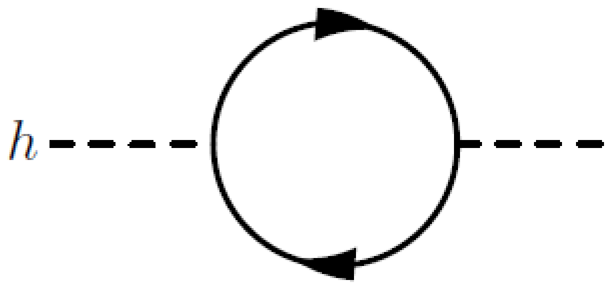
- In

MSSM

(or other SUSY models),

Hierarchy Problem

$\mathcal{L} \ni \lambda h \bar{f} f$

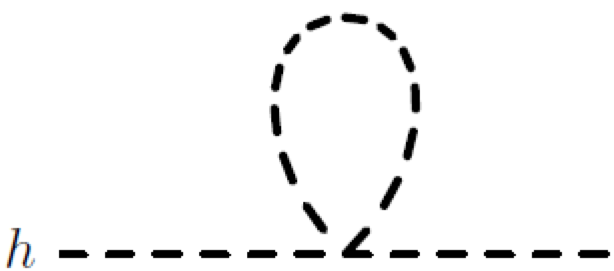


$$-\frac{|\lambda|^2}{8\pi^2}\Lambda^2$$

And its superpartner goes round!

Cancelled!

$\mathcal{L} \ni -\lambda^2 |h^2||\phi|^2$



$$+\frac{|\lambda|^2}{16\pi^2}\Lambda^2 \times 2$$

B. Weak Points of RpV-MSSM

"The RpV-MSSM has some weak points,
but anyway important for the SUSY detection."

Weak point of “RpV-MSSM”

Weak Points

- Anyway we need “some symmetry.”
- Dark Matter → left unsolved.
- GUT compatibility… (´•ω•`)

C. Collider Constraints

"The RpV interactions are constrained
by several experimental facts."

Constraints

The RpV parameters

$$\{\kappa, \lambda, \lambda'\}, \{\lambda''\}$$

$\rightarrow$ experimental constraints

And the constraints are important

to study RpV-MSSM.

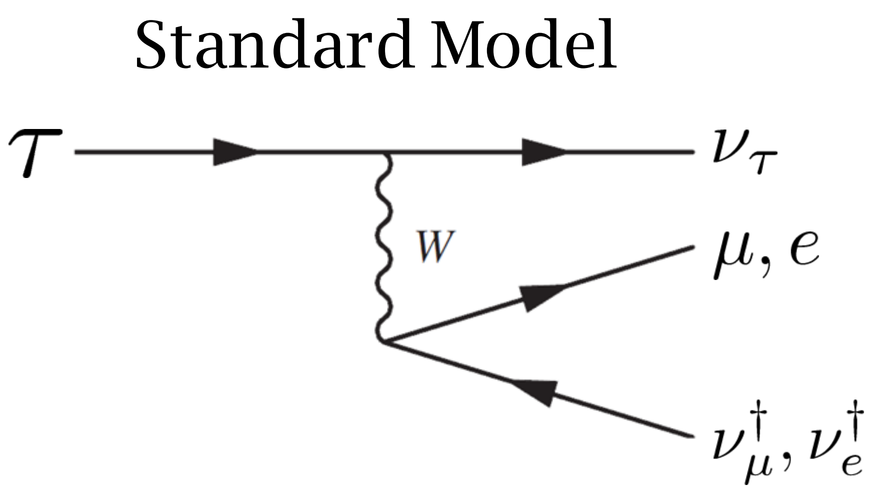
$$W_{\mathrm{RPV}} = \kappa_i L_i H_{\mathrm{u}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$$

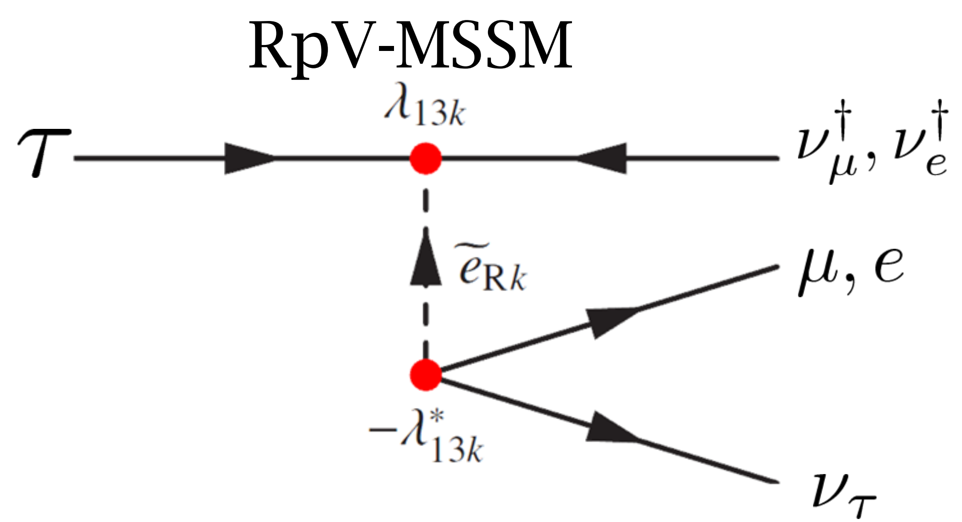
$$\text{or} \quad = \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Constraints

- Example:

$$R_\tau = \frac{\Gamma(\tau \to \nu_\tau\, e\, \nu_e^\dagger)}{\Gamma(\tau \to \nu_\tau\, \mu\, \nu_\mu^\dagger)}$$





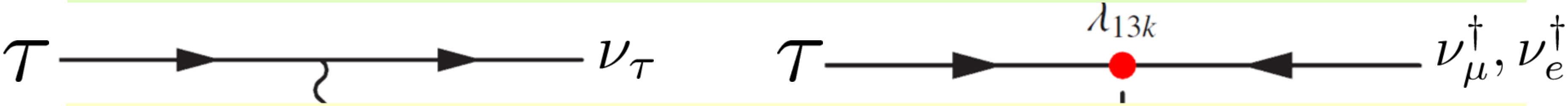
Additional Contribution!

Constraints

$$\frac{R_\tau}{(R_\tau)_{\rm SM}} = 1 + \frac{2}{4\sqrt{2}G_{\rm F}} \sum_k \frac{|\lambda_{13k}|^2 - |\lambda_{23k}|^2}{(m_{\tilde{e}_{{\rm R}k}})^2}$$

$$(R_\tau)_{\rm expm} = 1.028(4)$$

$$(R_\tau)_{\rm SM} = 1.028$$



$$-0.051^2 < \sum_k \left[|\lambda_{13k}|^2 - |\lambda_{23k}|^2\right] \left(\frac{100\,{\rm GeV}}{m_{\tilde{e}_{{\rm R}k}}}\right)^2 < 0.051^2$$

Additional Contribution!

D. RpV Results

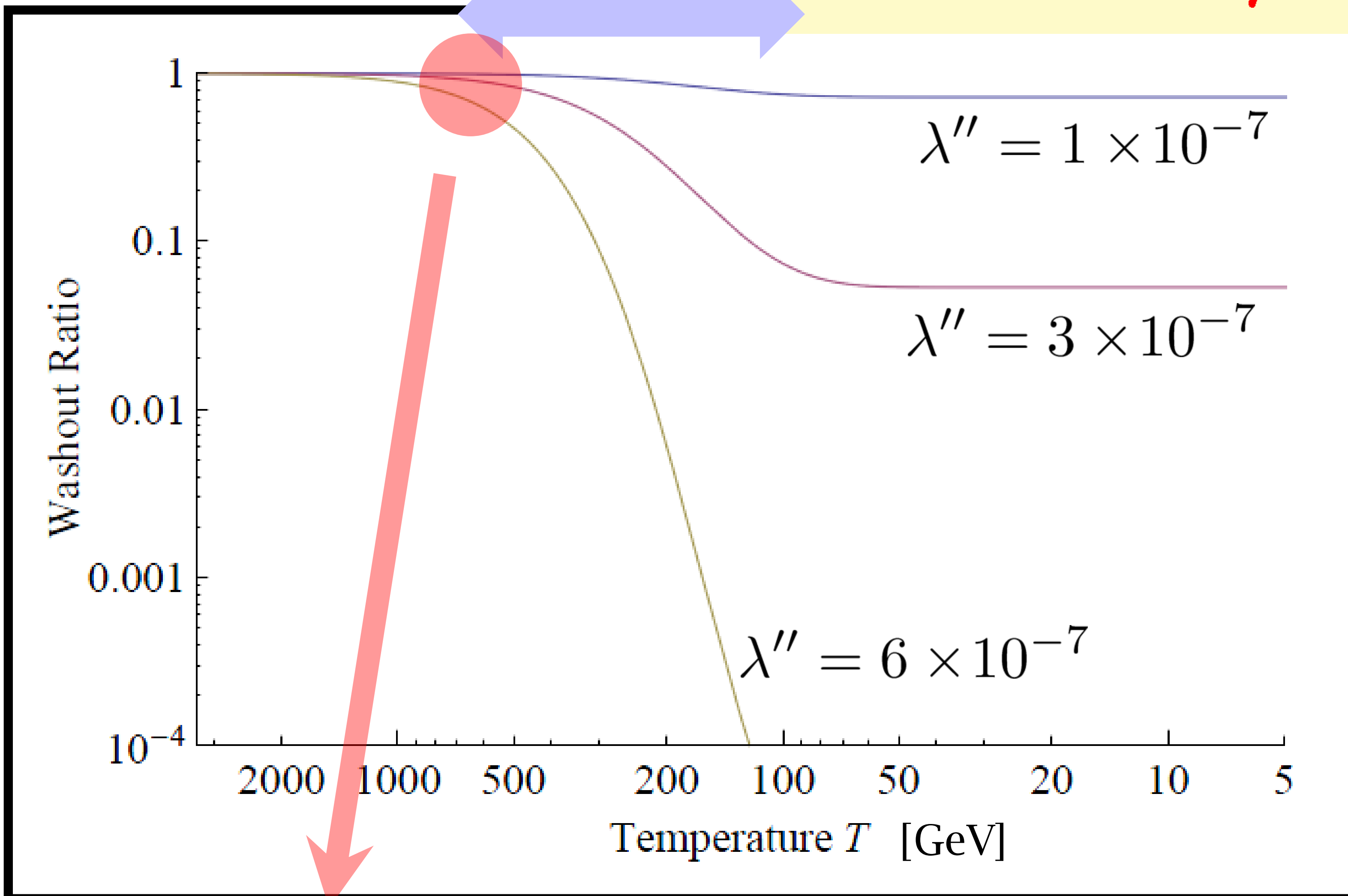
RpV Result

$$W \ni \lambda'' \bar{U}\bar{D}\bar{D}$$

$$\tilde{q}^* \rightleftarrows qq$$

$\not{B}$

$$\frac{B(T)}{B_{\rm init}}$$



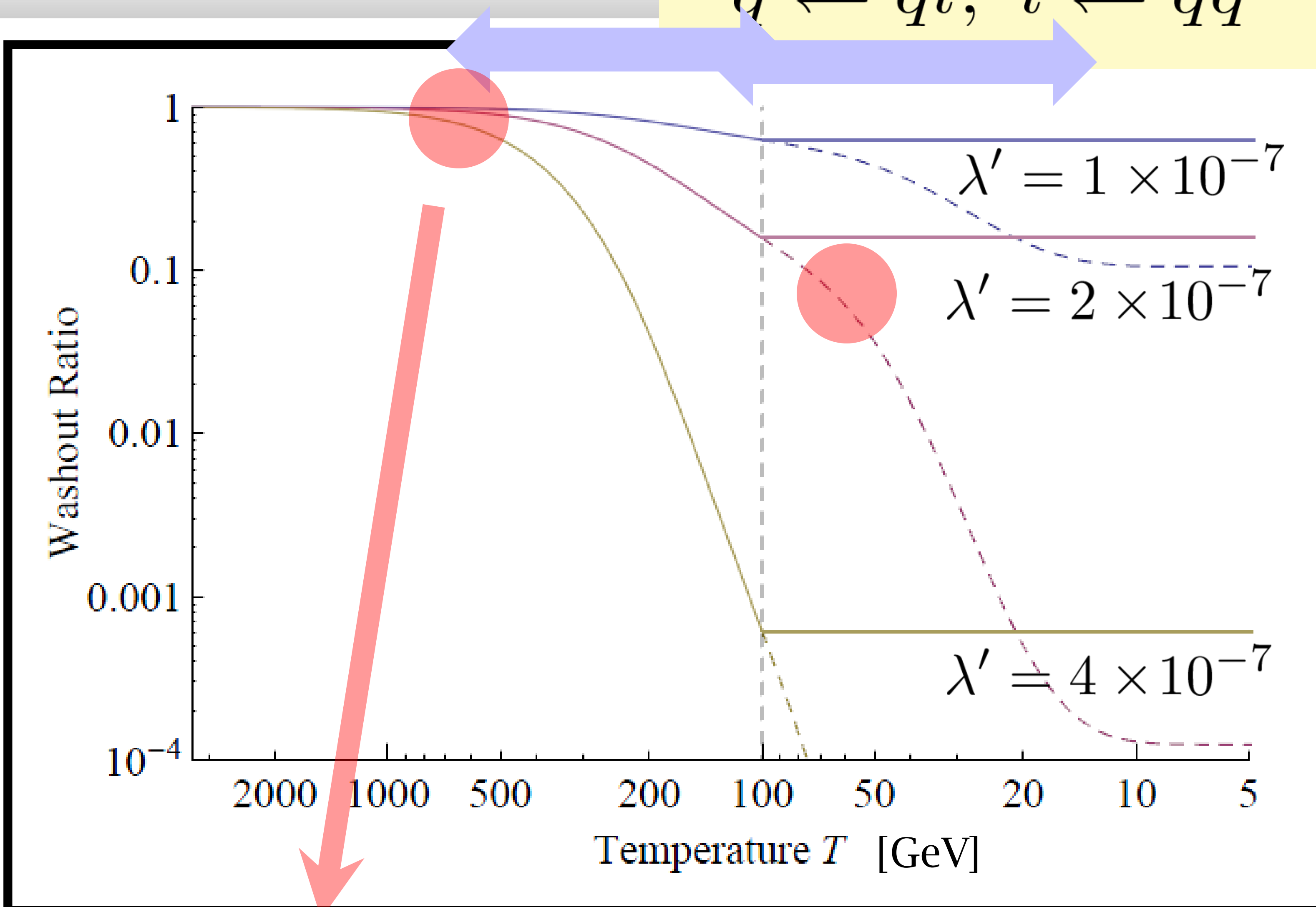
$m_{\tilde{q}} = 600\,\mathrm{GeV}$ $(m_{\tilde{H}} = 300\,\mathrm{GeV},\ m_{\tilde{l}} = 100\,\mathrm{GeV})$

RpV Result

$$W \ni \lambda' L Q \bar{D}$$

$$\tilde{q} \rightleftarrows ql, \ \tilde{l} \rightleftarrows qq^\dagger$$

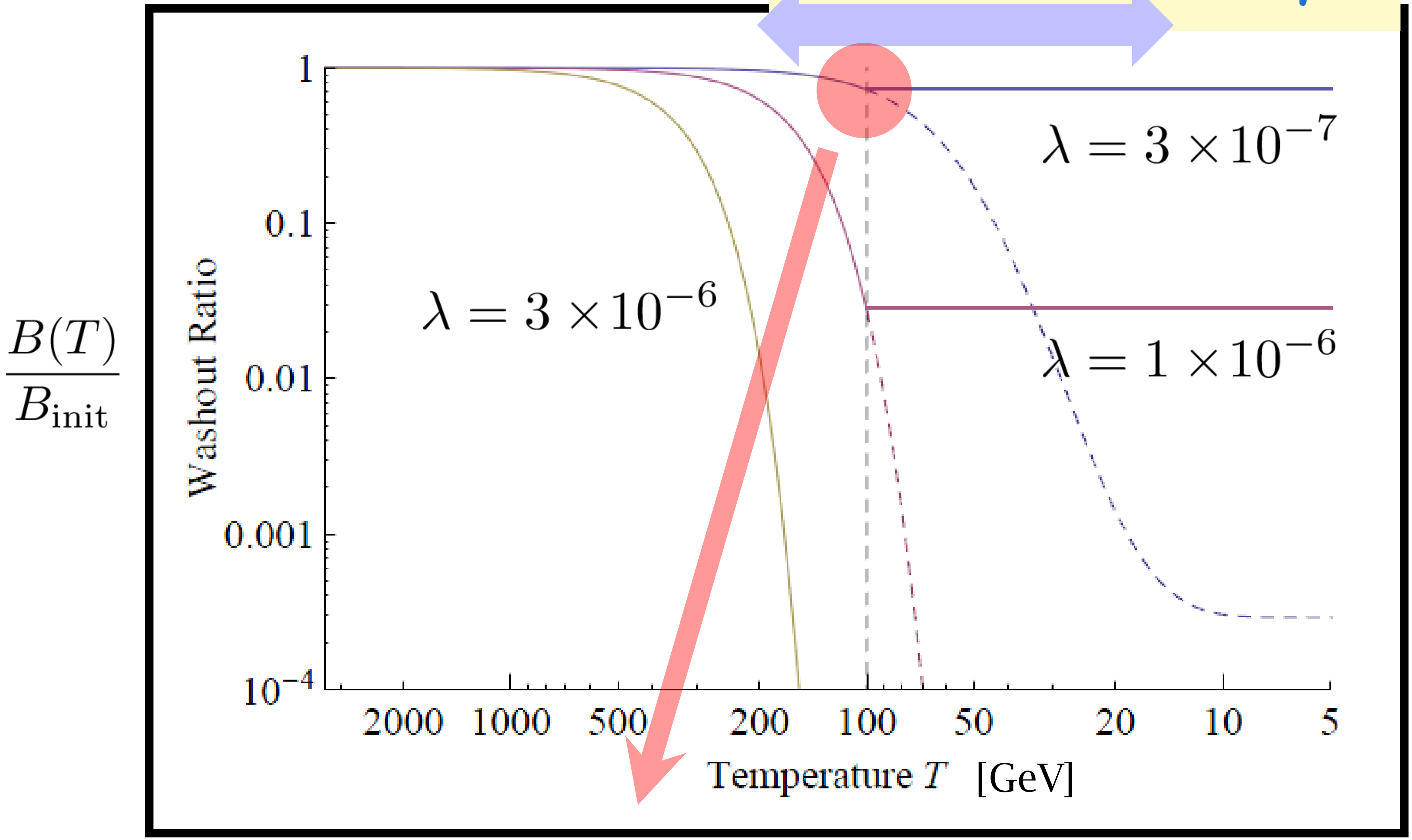
$$\frac{B(T)}{B_{\rm init}}$$



$m_{\tilde{q}} = 600\,\mathrm{GeV}$ $(m_{\tilde{H}} = 300\,\mathrm{GeV},\ m_{\tilde{l}} = 100\,\mathrm{GeV})$

RpV Result

$$W \ni \lambda L L \bar{E}$$
$$\tilde{l} \rightleftarrows ll$$
$\not{L}$



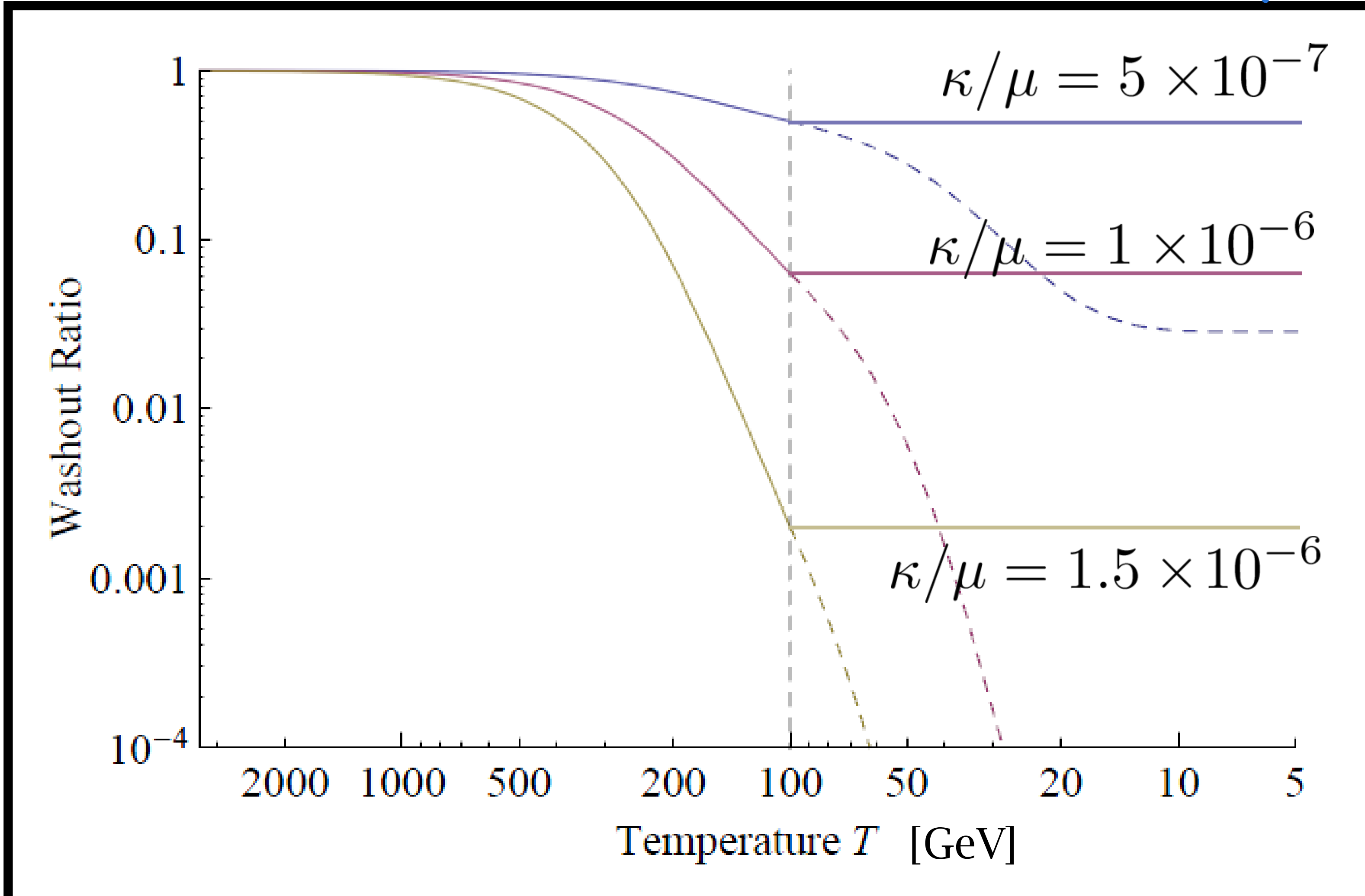
$m_{\tilde{l}} = 100\,\mathrm{GeV}$ $(m_{\tilde{q}} = 600\,\mathrm{GeV},\ m_{\tilde{H}} = 300\,\mathrm{GeV})$

RpV Result

$W \ni \kappa L H_u$

$\not{L}$

$\frac{B(T)}{B_{\text{init}}}$



$m_{\tilde{q}} = 600\,\text{GeV},\ \tan\beta = 10$ $(m_{\tilde{H}} = 300\,\text{GeV},\ m_{\tilde{l}} = 100\,\text{GeV})$

E. Several Details

Approximations we used

$$(y_e)_{ij} H_\mathrm{d} L_i \bar{E}_j$$

Set up

- MSSM; **before EWPT** (sphaleron era: $T \gtrsim 100\,\mathrm{GeV}$)

Approximations

- We consider only the decay of Higgsino

$$\widetilde{H} \rightleftarrows l_i \widetilde{e}_j^*, \quad \widetilde{H} \rightleftarrows \widetilde{l}_i e_j^\dagger$$

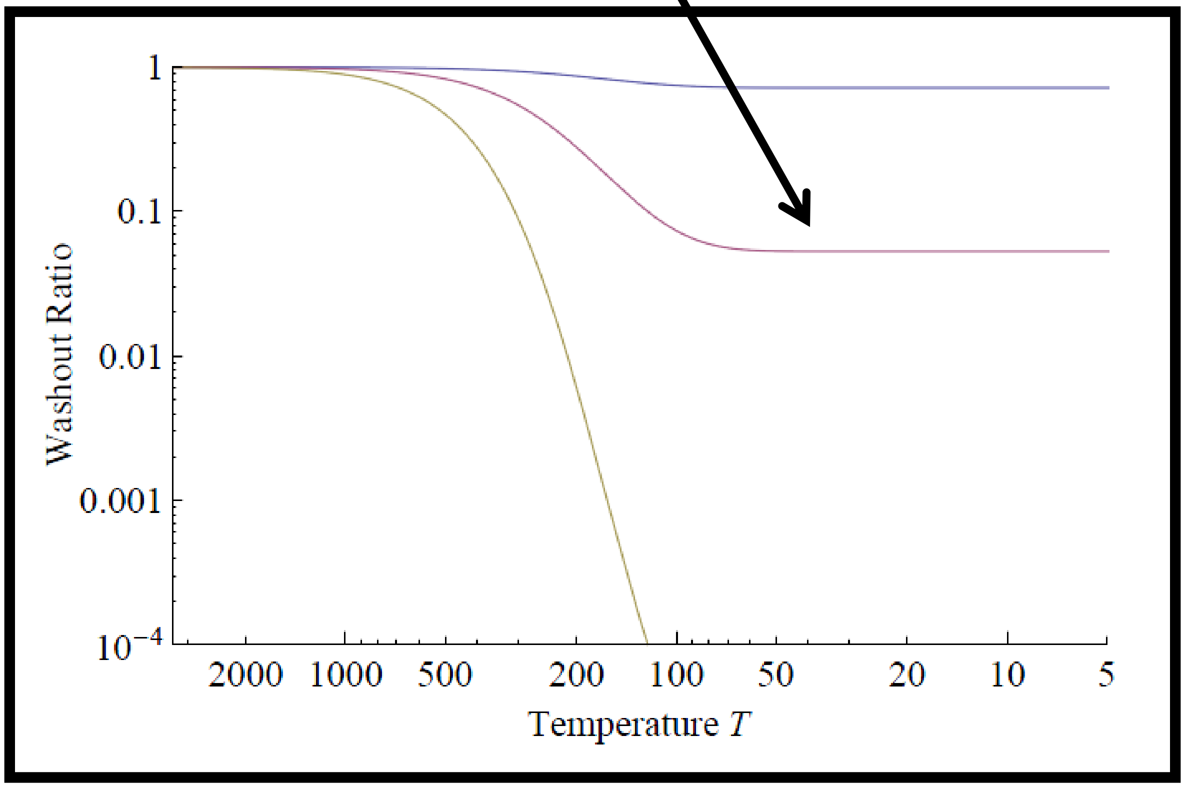
and the antiparticles' processes.

- Mass of Higgs bosons → Ignored
- Fermi/Bose distribution → **Boltzmann** distribution
- Sphaleron → Shut off at $T = 100\,\mathrm{GeV}$.

Some Loophole

- We can avoid any “wash-out”
  with creating the current *B*-asymmetry

HERE. $(T \lesssim 100\,\mathrm{GeV}\ \text{era})$



F. Experimental LFV Bounds

MEGA Result / MEG Prospect

$$\delta_{21}^{L} \sim \sqrt{10^{+(4\text{–}5)}\,\mathrm{Br}(\mu \to e\gamma)}\,\frac{10}{\tan\beta}\left(\frac{m_{\mathrm{soft}}}{400\,\mathrm{GeV}}\right)^2$$

$$\begin{aligned} \mathrm{MEGA}\ &: \mathrm{Br} < 1.2\times 10^{-11} \\ &\quad \delta_{21}^{L} \lesssim 10^{-3} \\ \mathrm{MEG}\ &: \mathrm{Br} \Rightarrow \mathrm{O}(10^{-13}) \\ &\quad \delta_{21}^{L} \Rightarrow 10^{-4} \end{aligned}$$