



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

1. ***R*-Parity violating SUSY** JUMP
2. **Cosmological Constraints** JUMP
3. **Our Results** JUMP
4. **Application for LHC** JUMP

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 \rightarrow solved!

 Proton decay problem

Why does Proton decay?

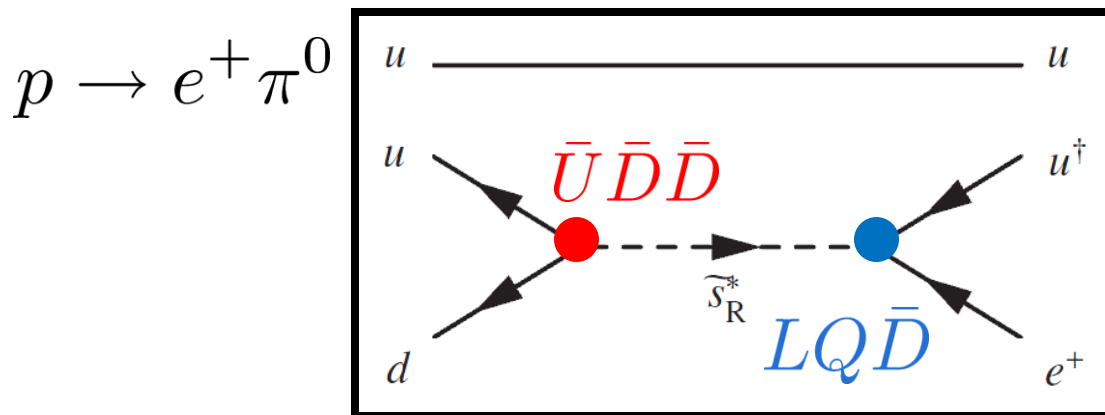
Proton Decay Problem

- Superpotential of the MSSM

$$W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U}, \quad W \supset \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

\cancel{L} $LH_u, LL\bar{E}, LQ\bar{D}, \bar{U}\bar{D}\bar{D}$ \cancel{B}

Both \cancel{B} and $\cancel{L} \Rightarrow$ Proton Decay ☹️



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

R-parity

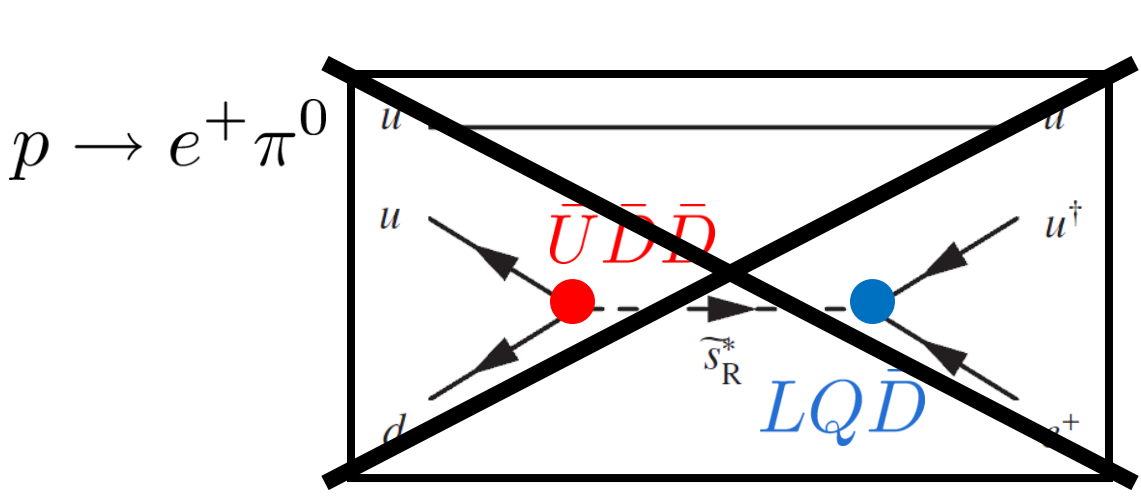
$$P_R := (-1)^{3B-L+2s} \quad (s: \text{spin})$$

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

$$W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U},$$

$$\cancel{L} \cancel{L H_u}, \cancel{L L \bar{E}}, \cancel{L Q \bar{D}}, \cancel{\bar{U} \bar{D} \bar{D}} \cancel{B}$$

~~Both B and L~~ \Rightarrow Proton is stable.



$\tau \sim \infty$ 😊

SUSY without R -parity

However, since **proton decay needs both B and L** ,
we have **other two possibilities!**

- ◉ To forbid B with Baryon-parity etc.

$$W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U},$$

$$L H_u, L L \bar{E}, L Q \bar{D}, \cancel{U \bar{D} \bar{D}} \quad (\text{Allowing } L)$$

- ◉ To forbid L with Lepton-parity etc.

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

$$W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U},$$

$$\cancel{L H_u}, \cancel{L L \bar{E}}, \cancel{L Q \bar{D}}, U \bar{D} \bar{D} \quad (\text{Allowing } B)$$

SUSY without R -parity

That is, **we can install $R_p V$ interactions additionally.**

- ⊙ MSSM with R -parity $\rightarrow W = W_{\text{RPC}}$

$$W_{\text{RPC}} = \mu H_u H_d + y_{uij} H_u Q_i \bar{U}_j + y_{dij} H_d Q_i \bar{D}_j + y_{eij} H_d L_i \bar{E}_j$$

- ⊙ \cancel{L} -MSSM \rightarrow

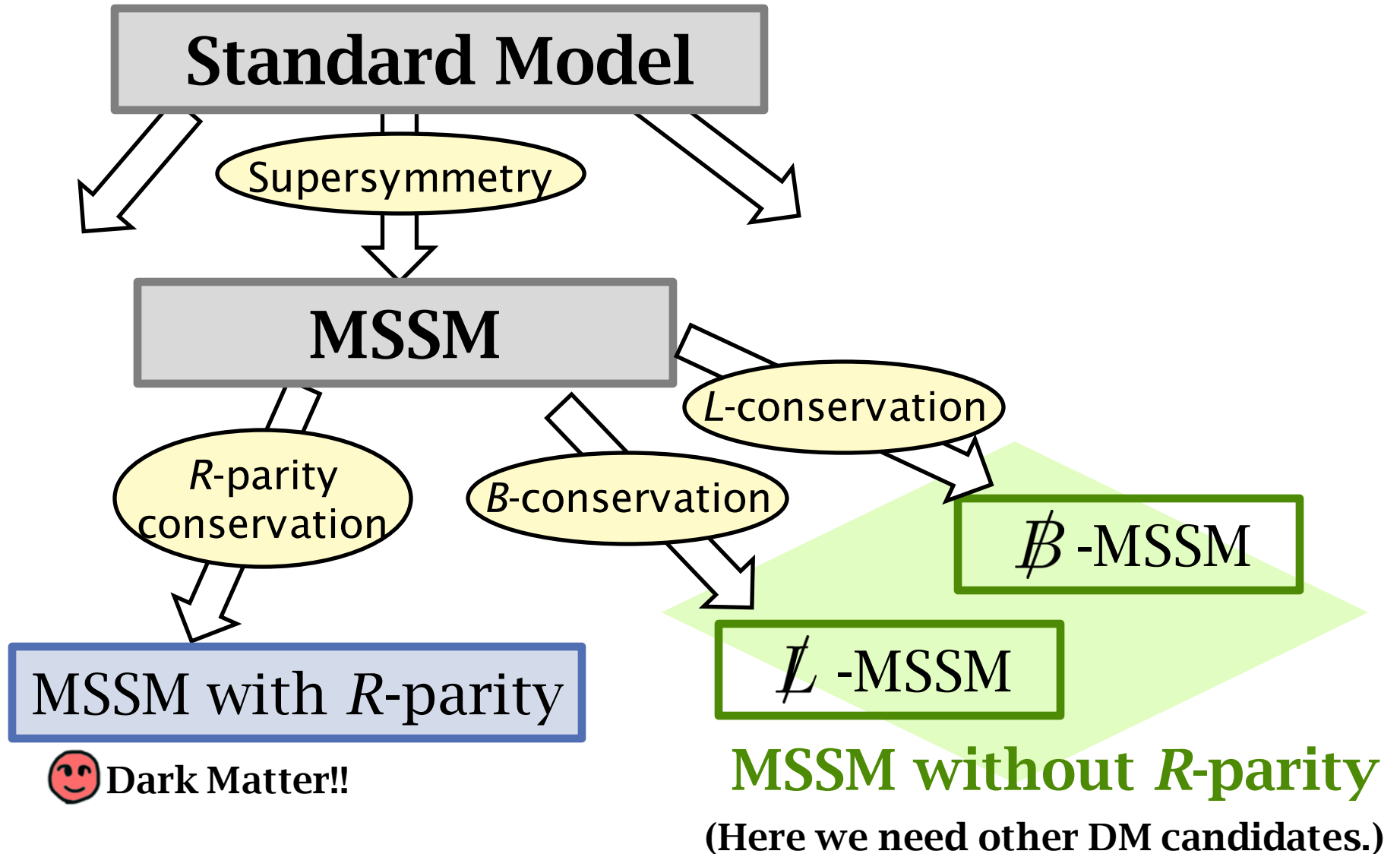
$$W_{\cancel{L}} = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

- ⊙ \cancel{B} -MSSM \rightarrow

$$W_{\cancel{B}} = W_{\text{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

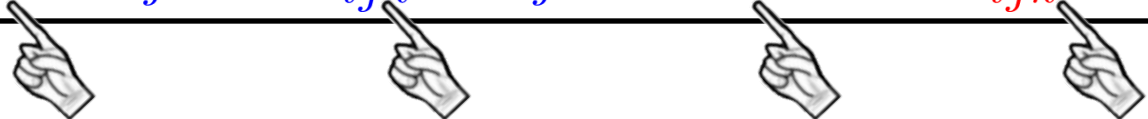
MSSM without R -parity

Introductory Diagram



What I studied

Can we constraint such **exotic** couplings?

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


⇒ **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.


$$T \gtrsim 100 \text{ GeV}$$

Baryon Asymmetry of the Universe

Current universe:

There's **Baryon**,

and no anti-baryon.



Wash-out with B -viol.

~~B~~

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



in the early universe.

And if frequently enough,

→ achieve **Equilibrium** : $B = 0$.

→ **No Baryon Asymmetry!**

“WASH-OUT”



→ λ'' must be **small enough!**

Wash-out with B -viol.



- That is, if

LARGE , then

“WASH-OUT” occurs!!



But this is a bit **naïve** view...

We have to consider **“sphaleron.”**

Sphaleron

$$\begin{aligned}\mathcal{O}_{\text{sph}} &= \Pi_i (udd\nu)_i \\ &= uddcsstbb\nu_e\nu_\mu\nu_\tau \\ \Delta B &= \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \frac{1}{3} \\ \Delta L &= 1 \quad 1 \quad 1\end{aligned}$$

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

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

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

Sphaleron converts

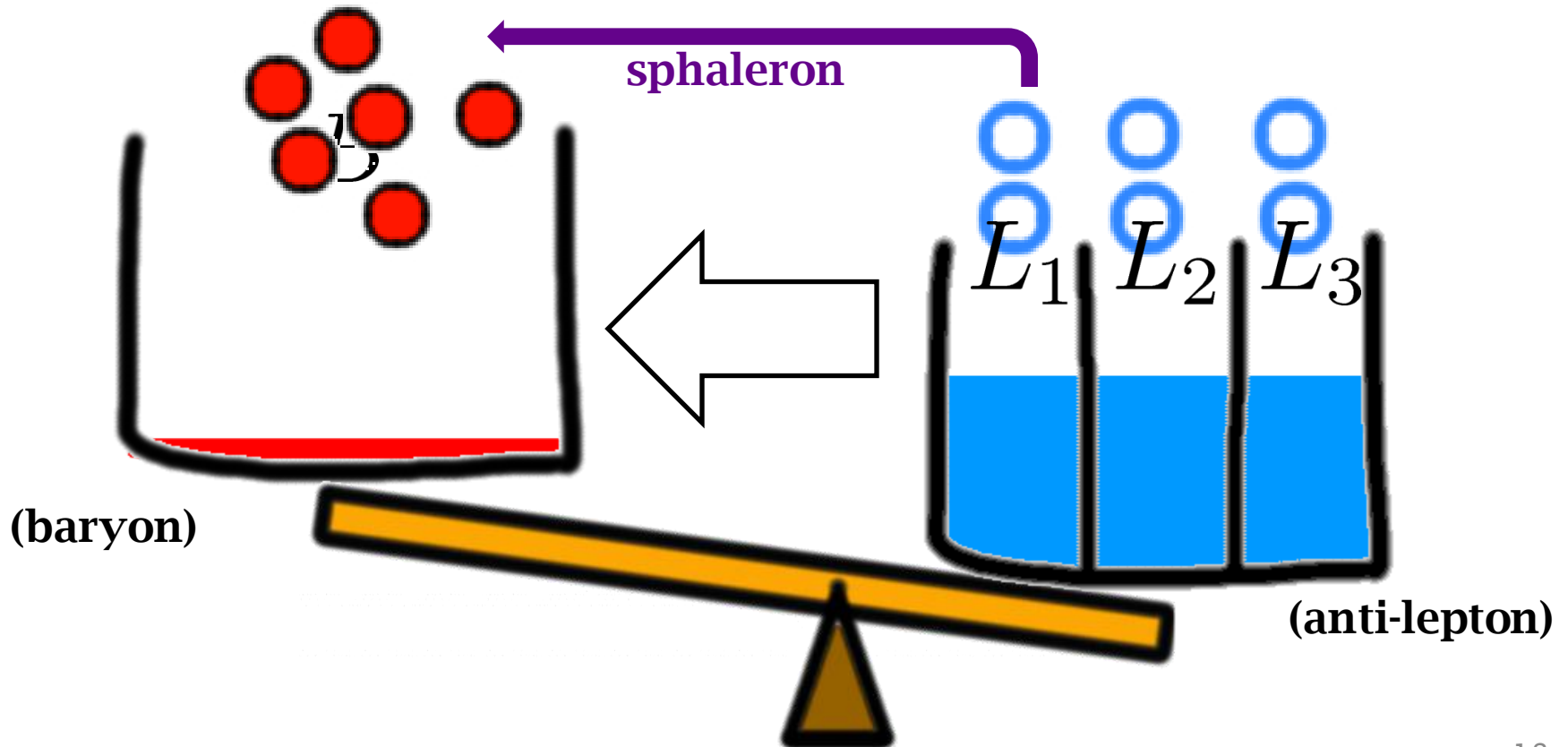
Baryon \rightleftharpoons Anti-lepton

→ **Equilibrium.**



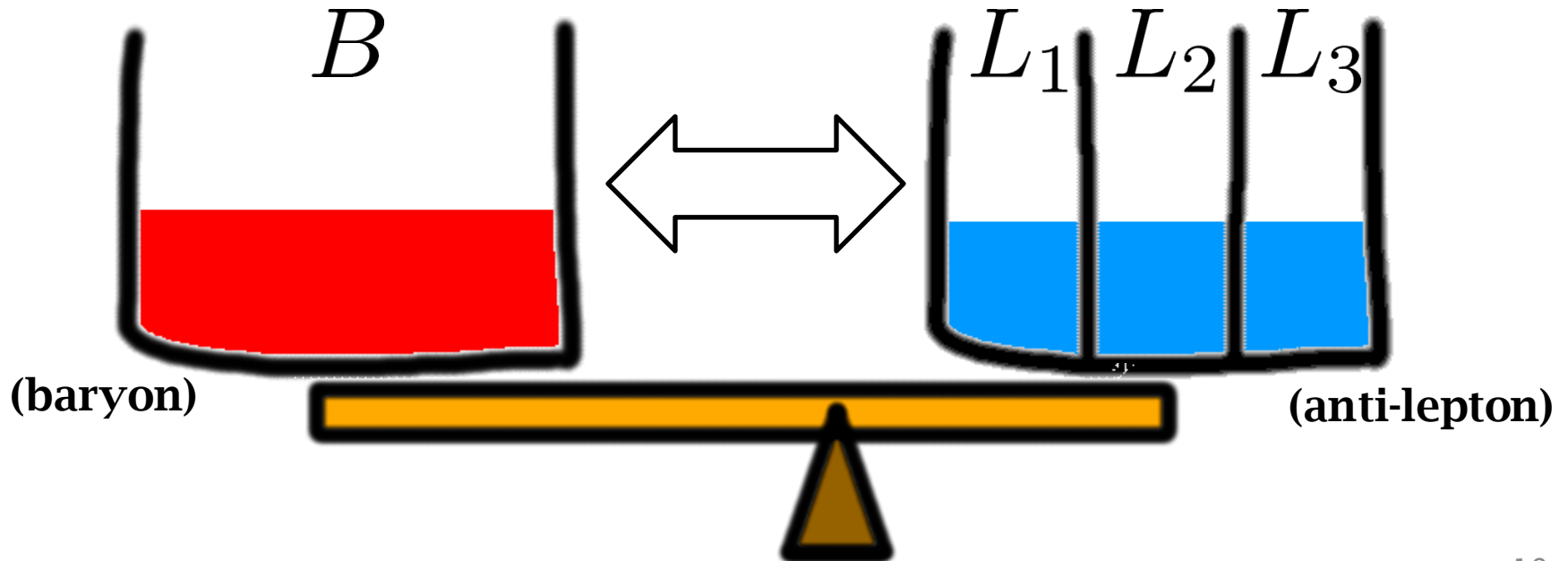
Sphaleron's Effect

If Baryon is short... (in $T \gtrsim 100 \text{ GeV}$)
sphaleron works right to left



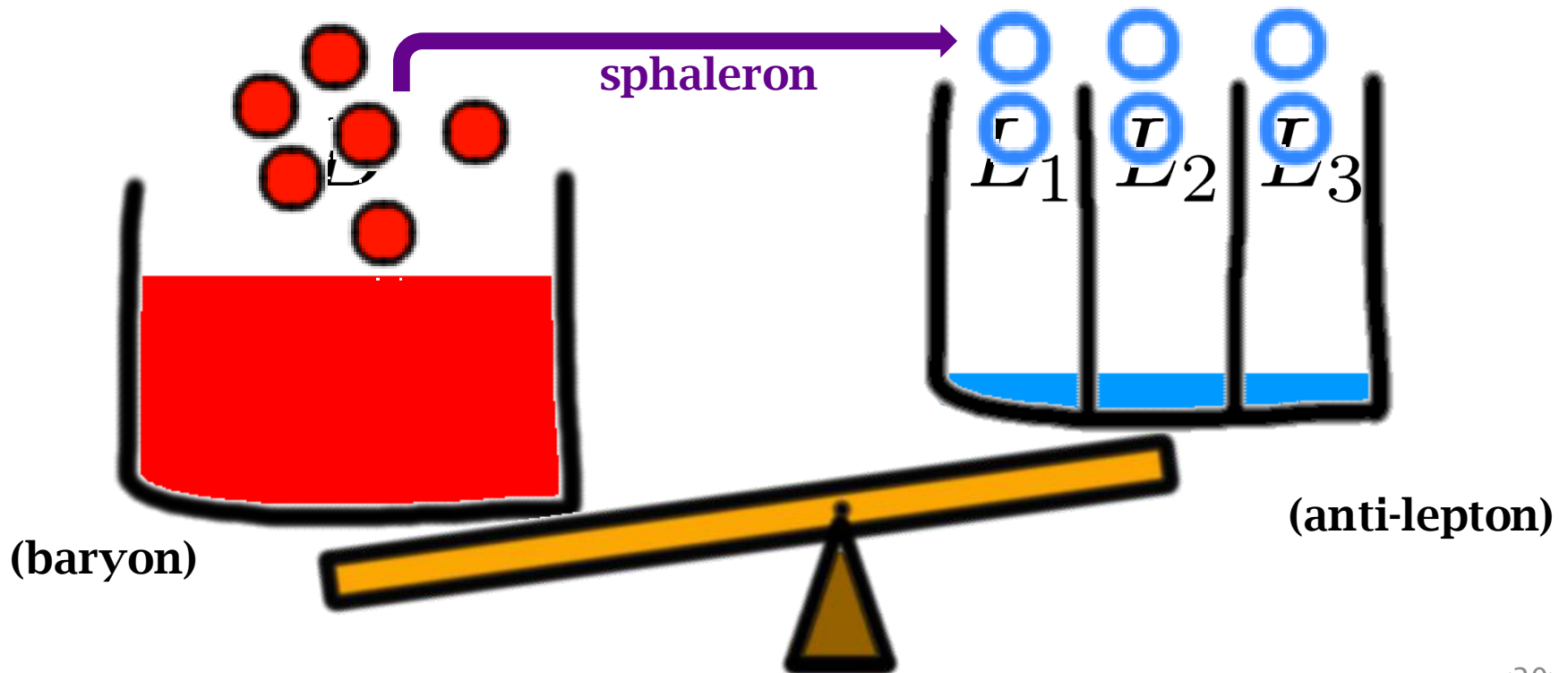
Sphaleron's Effect

If Baryon is short... (in $T \gtrsim 100 \text{ GeV}$)
sphaleron works right to left
and achieve **Equilibrium**.



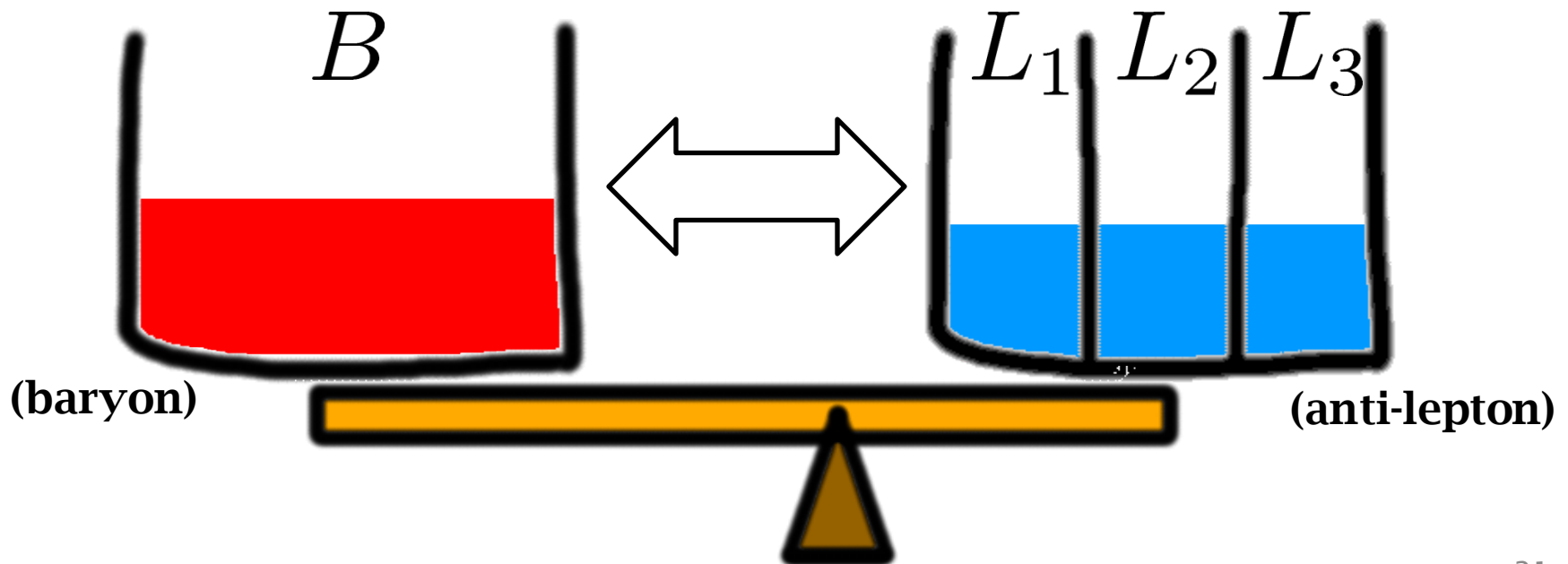
Sphaleron's Effect

Also when (anti-)Lepton is short, (in $T \gtrsim 100 \text{ GeV}$)
sphaleron does left to right



Sphaleron's Effect

Also when (anti-)Lepton is short, (in $T \gtrsim 100 \text{ GeV}$)
sphaleron does left to right
and achieve **Equilibrium**.



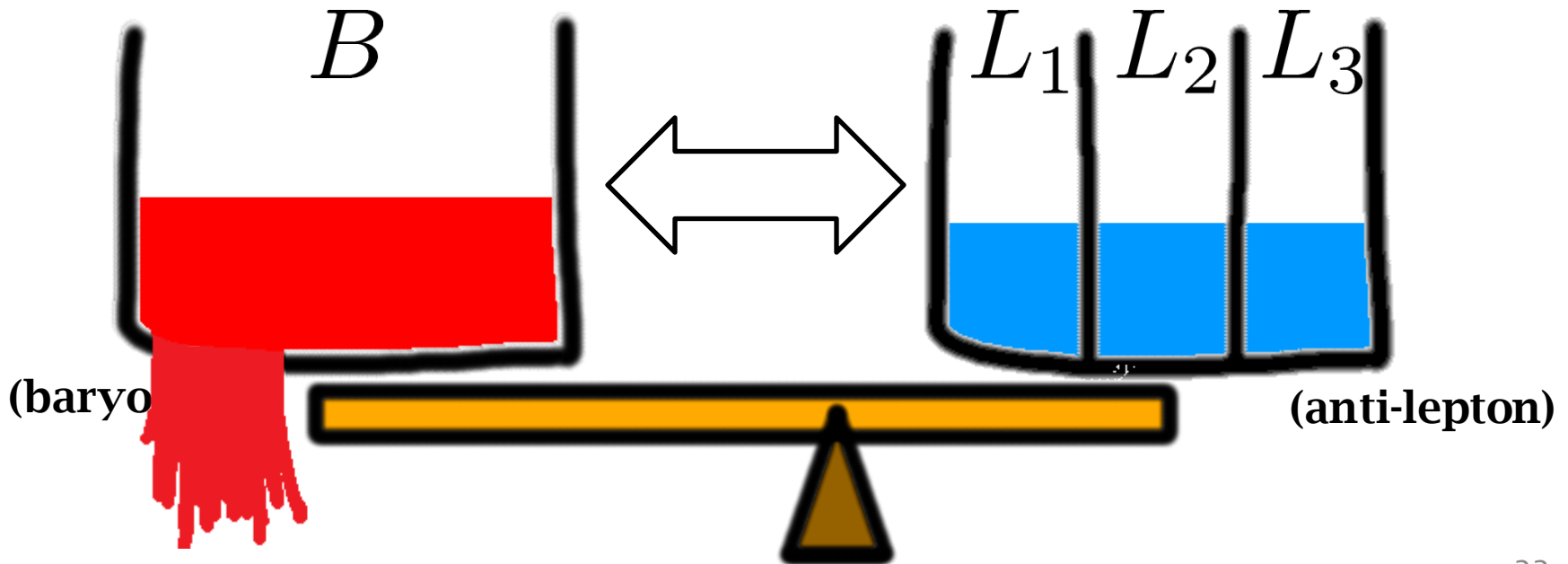
Wash-out with B -viol.

~~B~~

Thus, actually the previous wash-out by

~~B~~

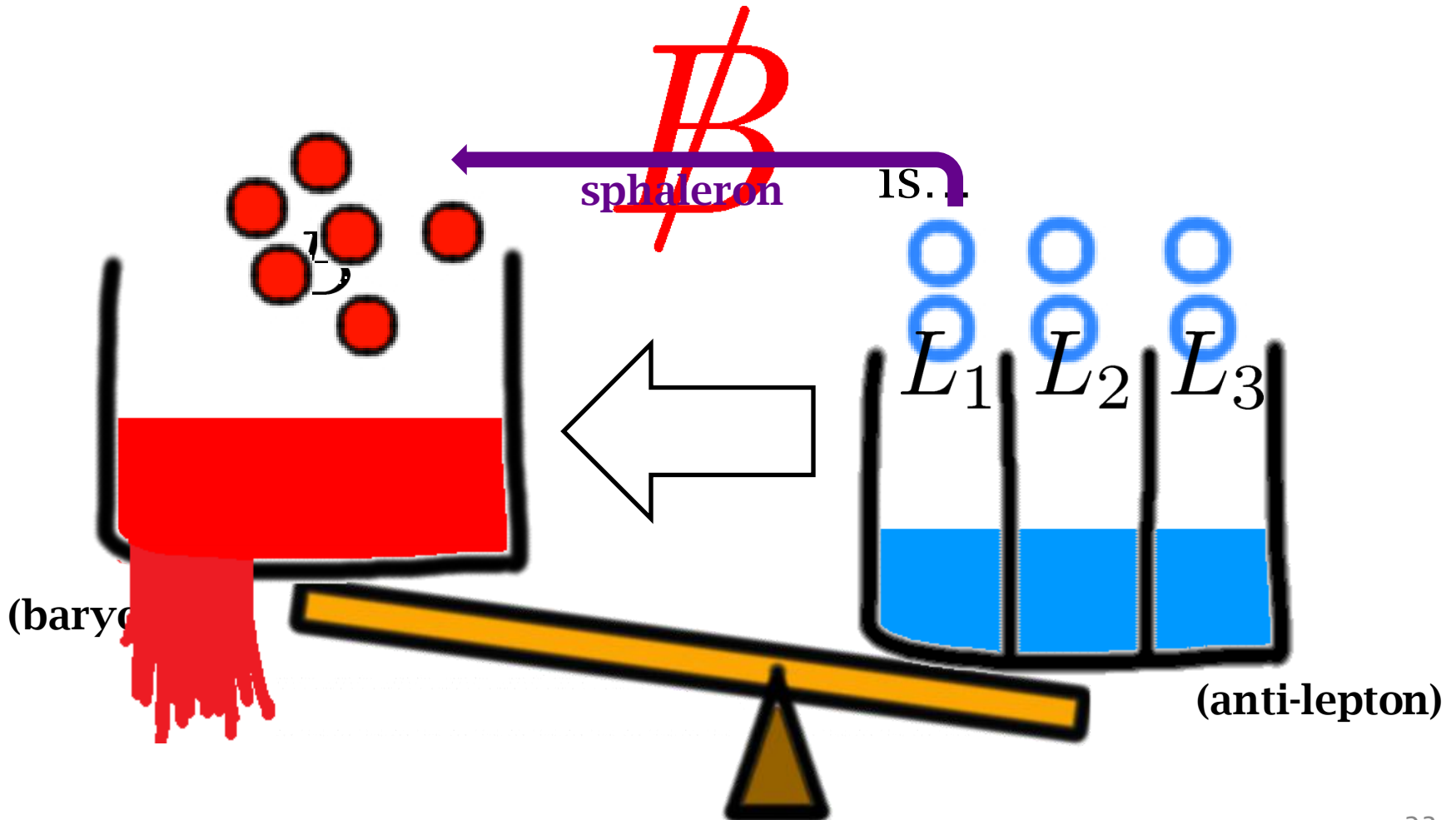
is...



Wash-out with B -viol.

~~B~~

Thus, actually the previous wash-out by

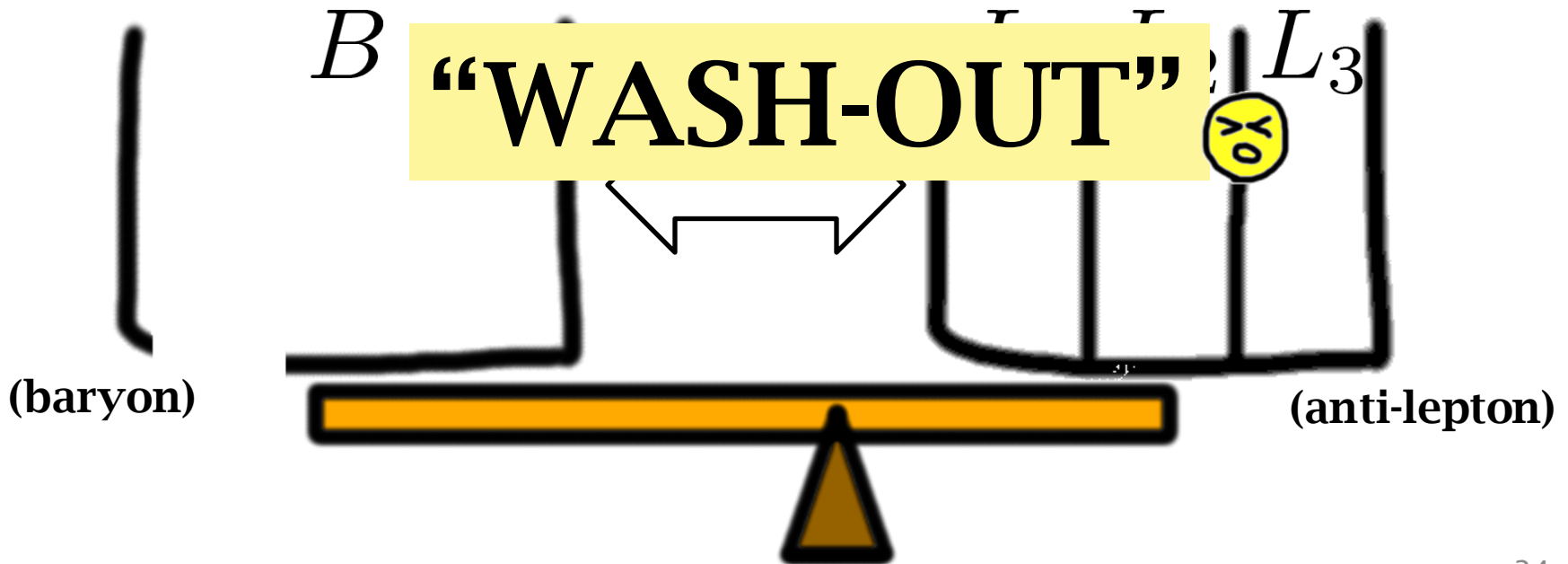


Wash-out with B -viol.

~~B~~

Thus, actually the previous wash-out by

~~B~~ is...



Wash-out with *L*-viol.



This story

does not end here!



Wash-out with L -viol.



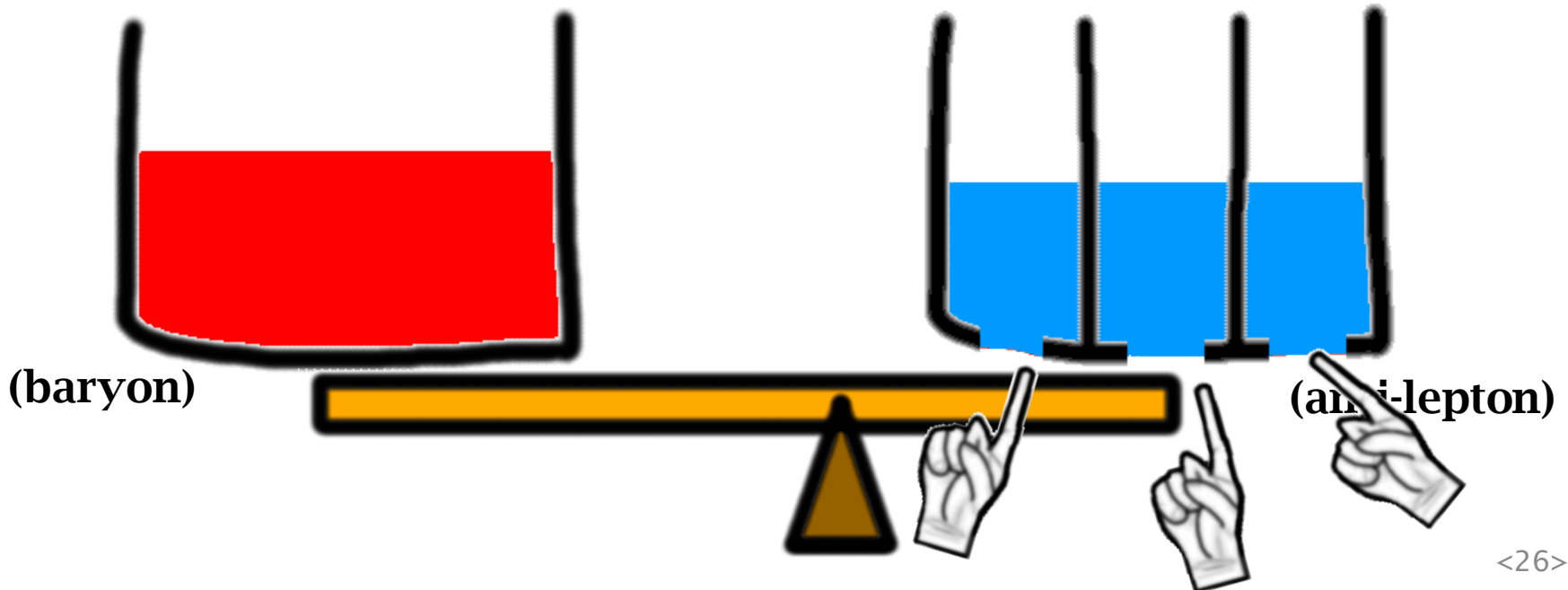
⊙ If

large



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

(in the sphaleron era),



Wash-out with L -viol.



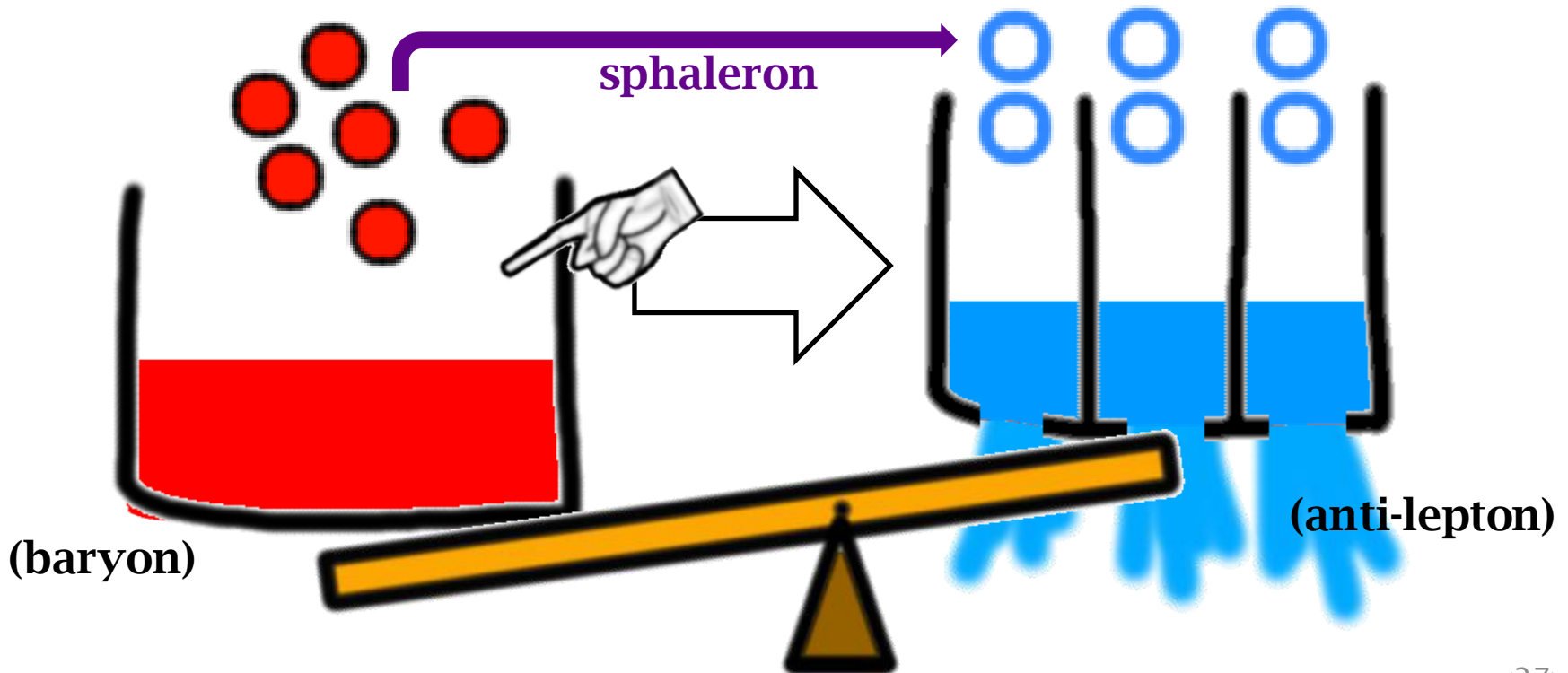
⊙ If

large



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

(in the sphaleron era),



Wash-out with L -viol.



○ If

large



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

(in the sphaleron era),

Wash-out occurs!!



(baryon)



(anti-lepton)

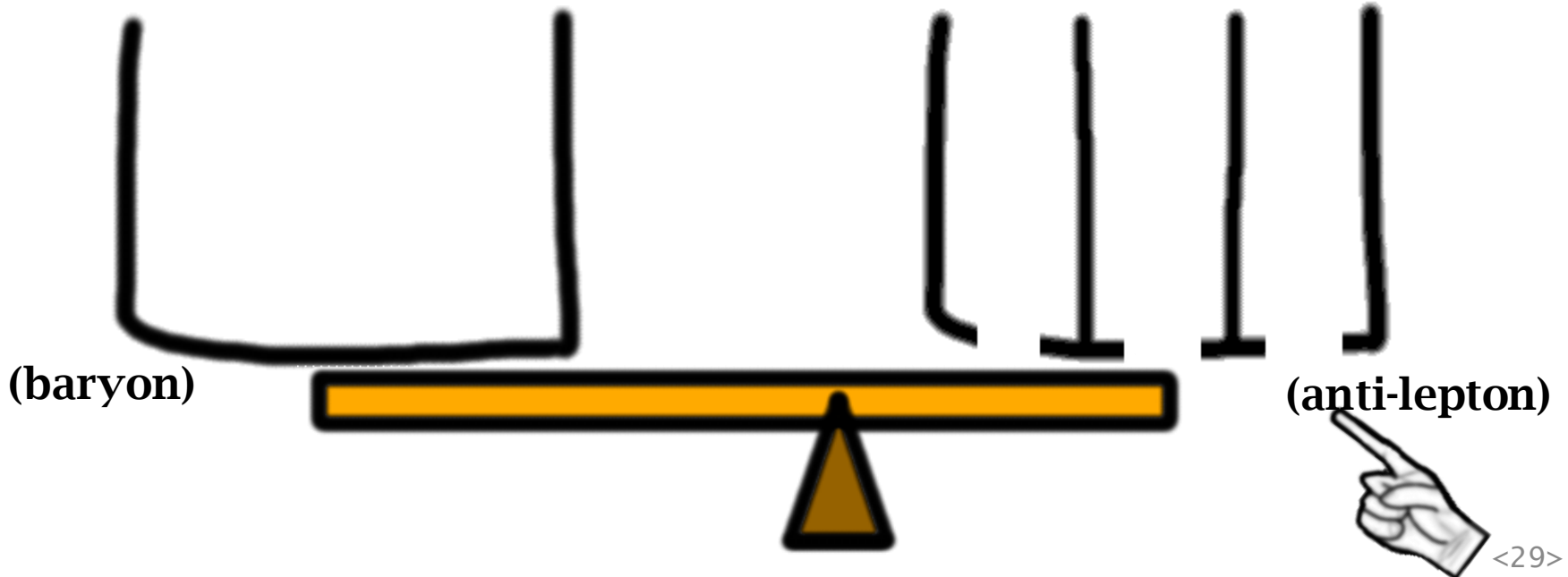


Wash-out with L -viol.

But

NOTE ONE

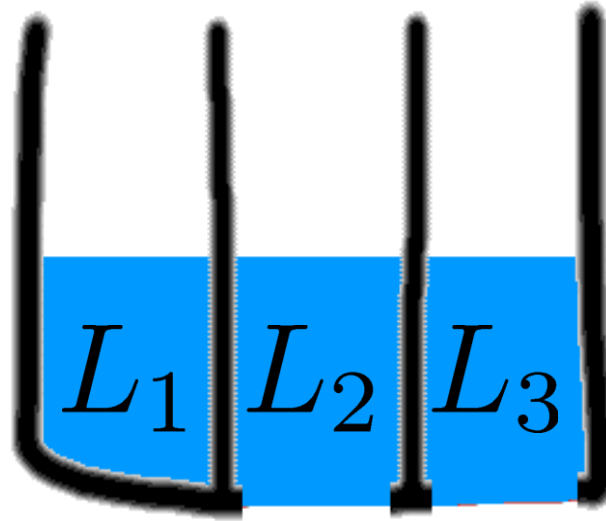
IMPORTANT POINT!



Wash-out with L -viol.

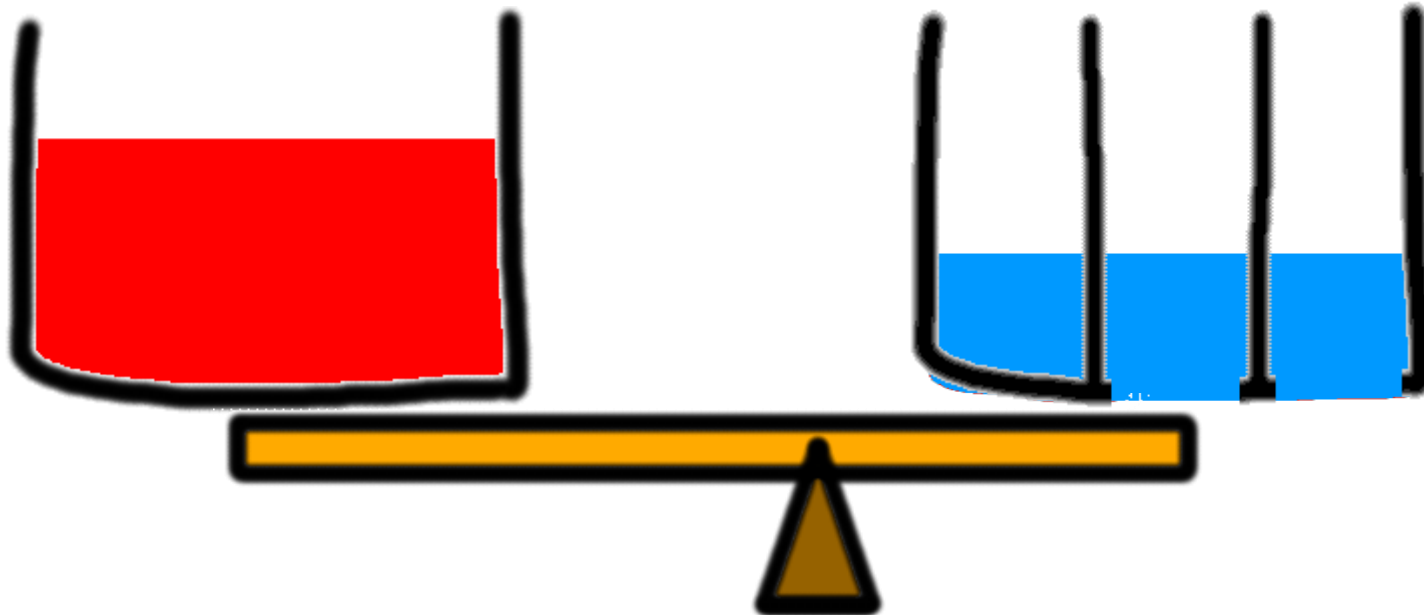


Imagine this case.



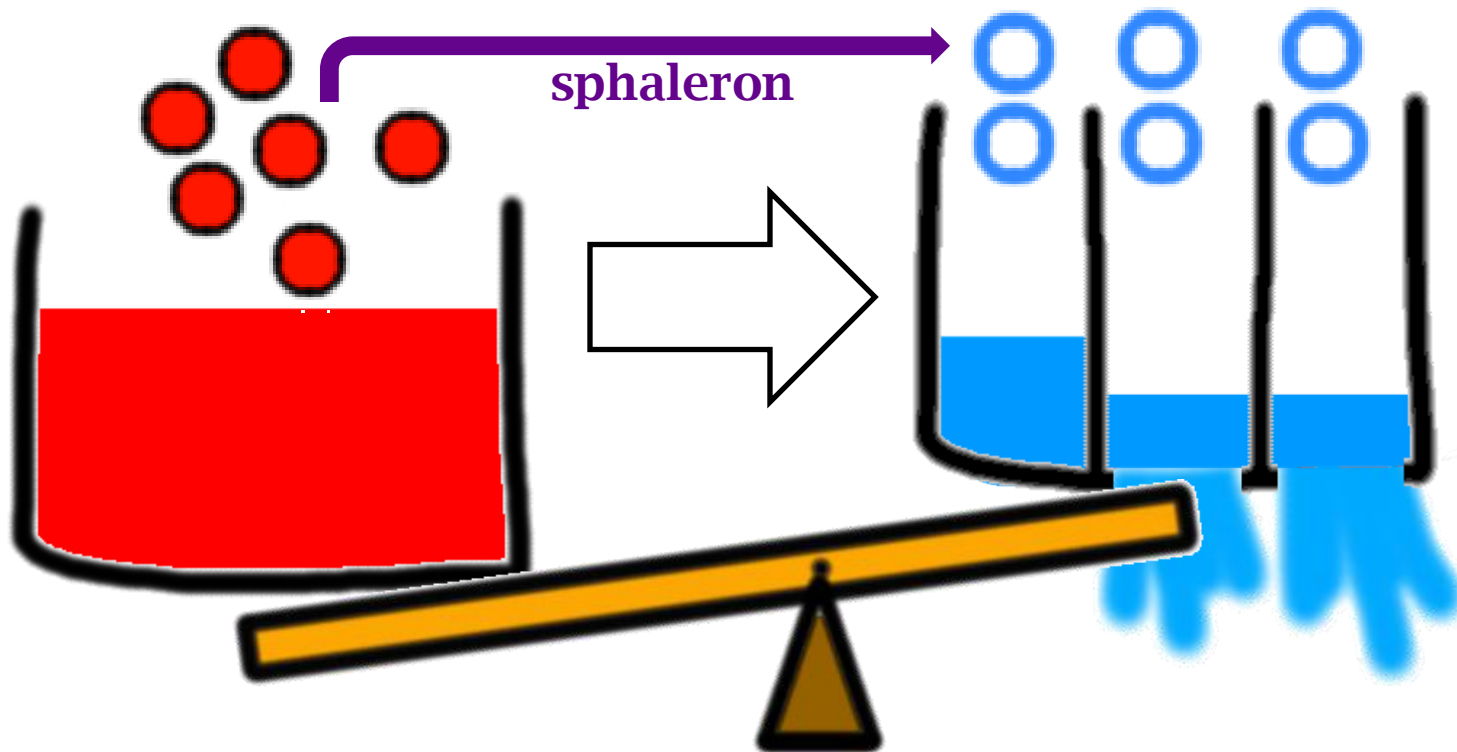
If the **Lepton Flavor** is **NOT** violated,
and
if at least **one** of L_i is **conserved**,

Wash-out with *L*-viol.

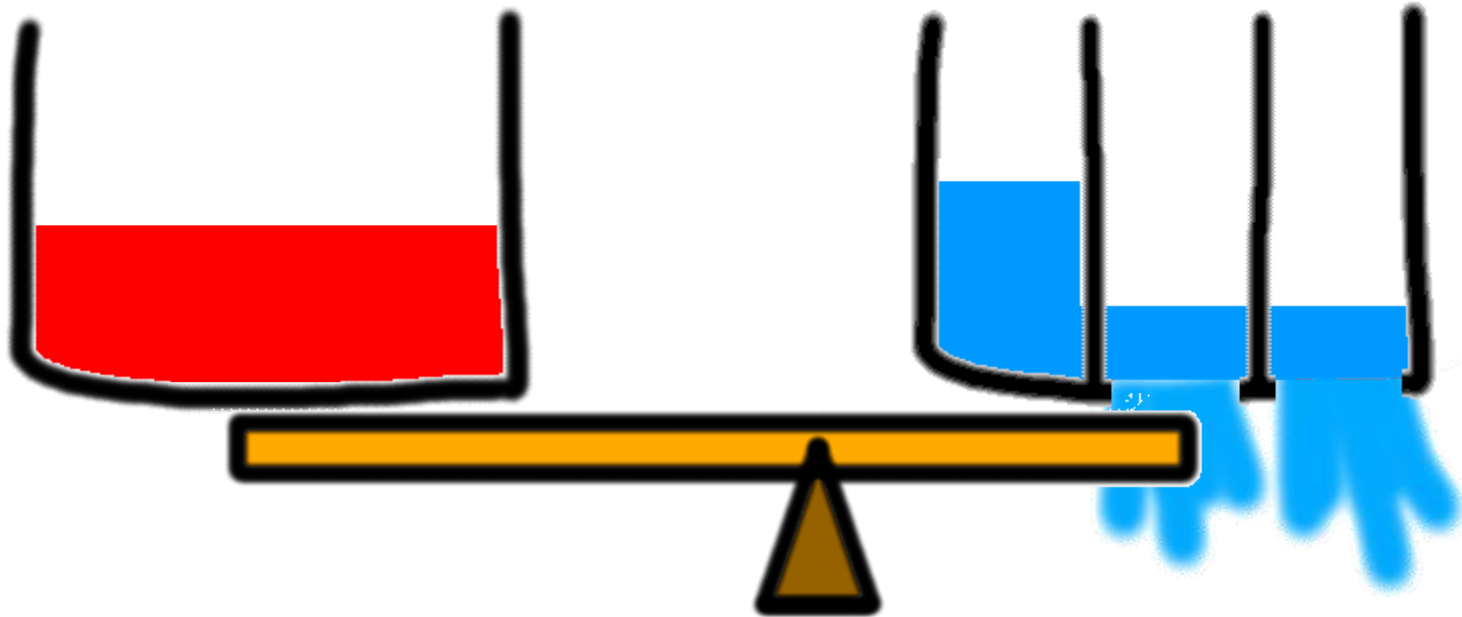




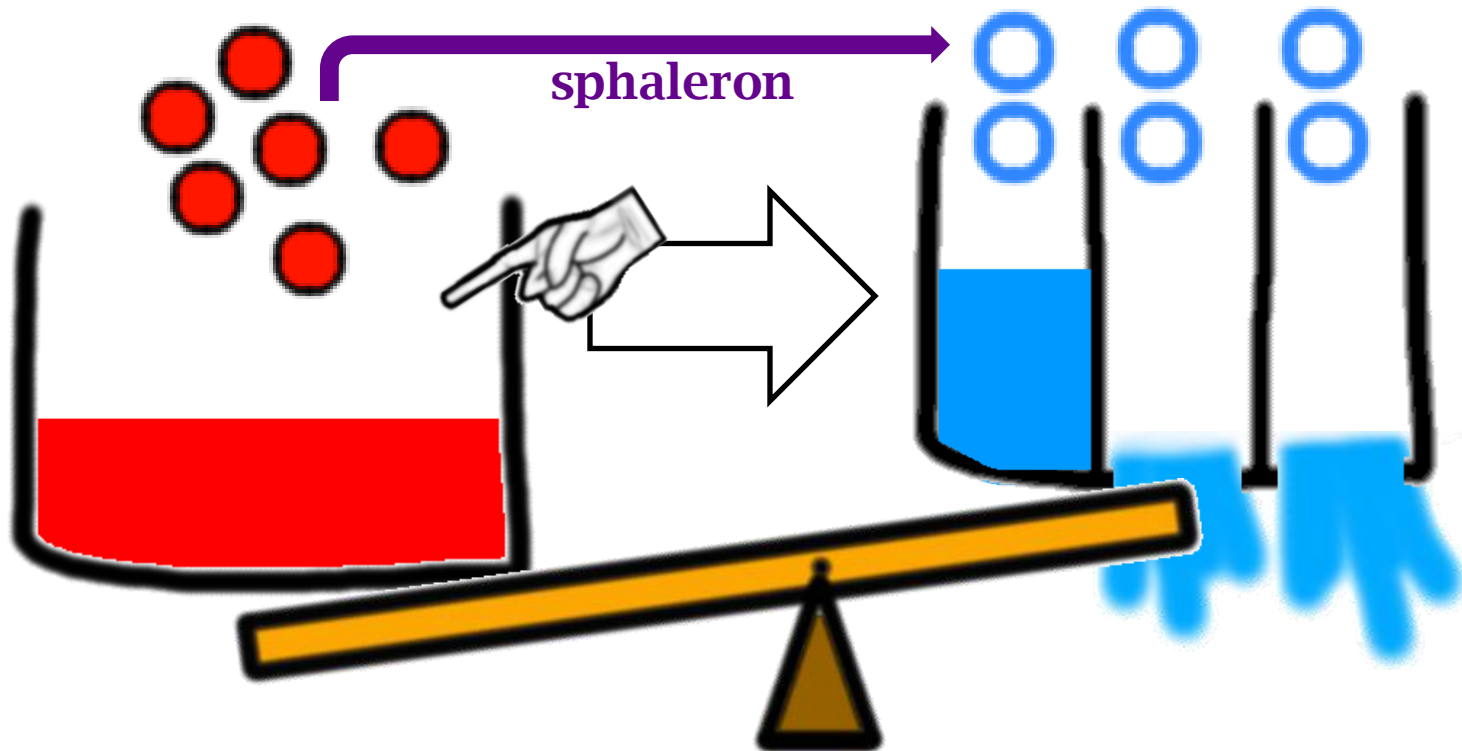
Wash-out with L -viol.



Wash-out with *L*-viol.



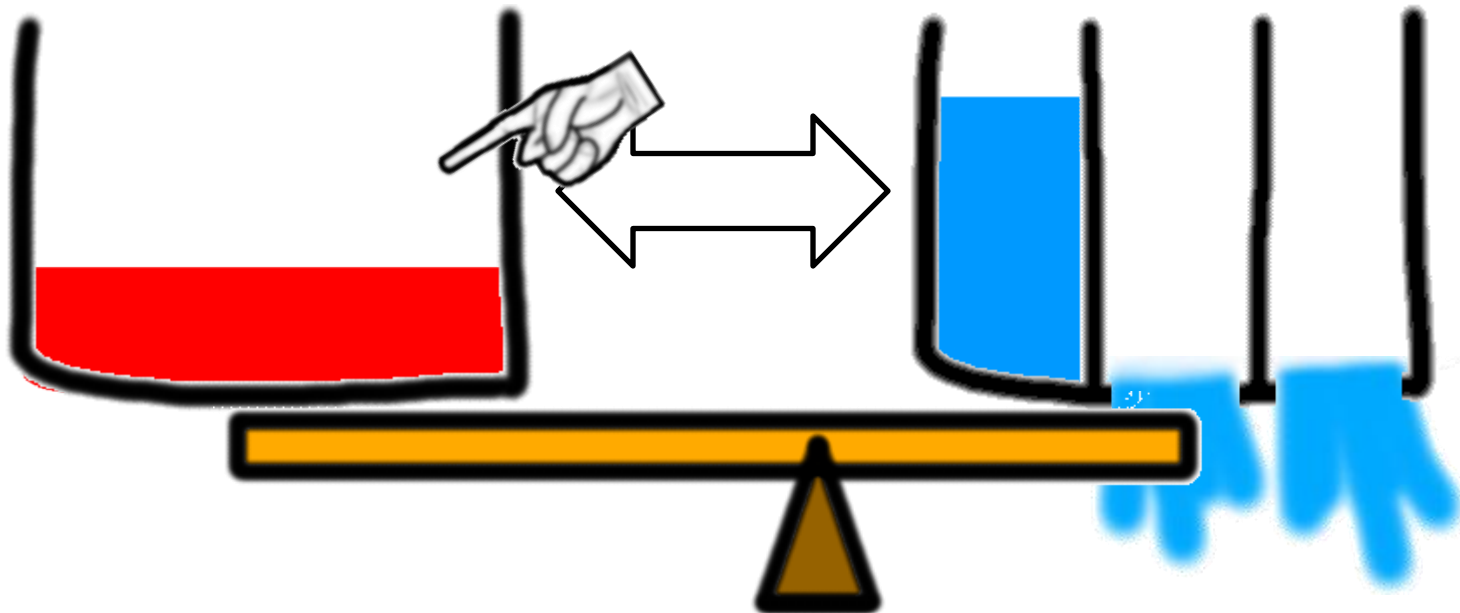
Wash-out with L -viol.



Wash-out with *L*-viol.

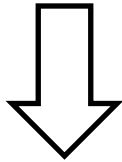


Baryon SURVIVES!!!

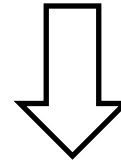
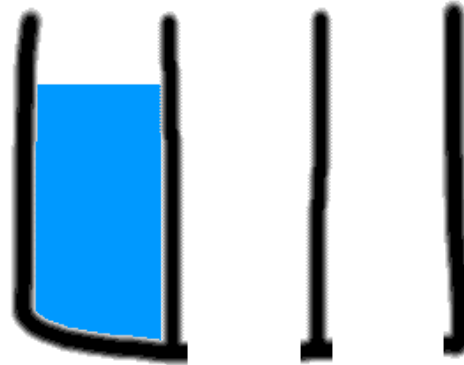


Wash-out with L -viol.

L



Wash-out! 😞



Baryon Survives. 😊

The “leptonic” wash-out needs **three** L s
if there’s no LFV.

Wash-out with L -viol.



But remember!

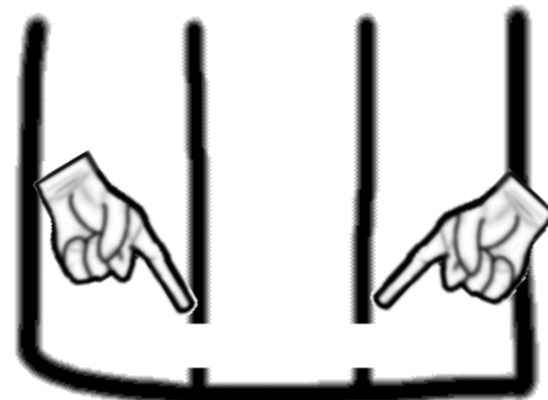
In MSSM,

We have LFVs in general!!!

As Shimomura-san mentioned.

The Standard Model

The MSSM

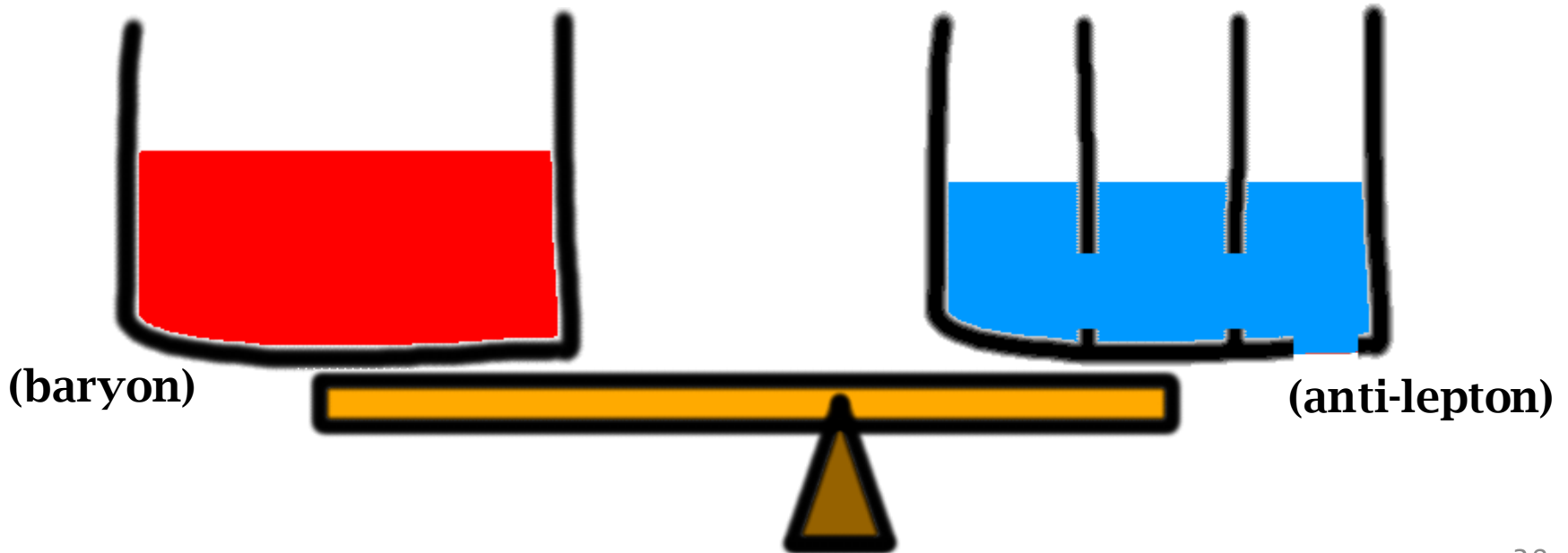


Wash-out with L -viol.

L

Therefore,

Only One L would...

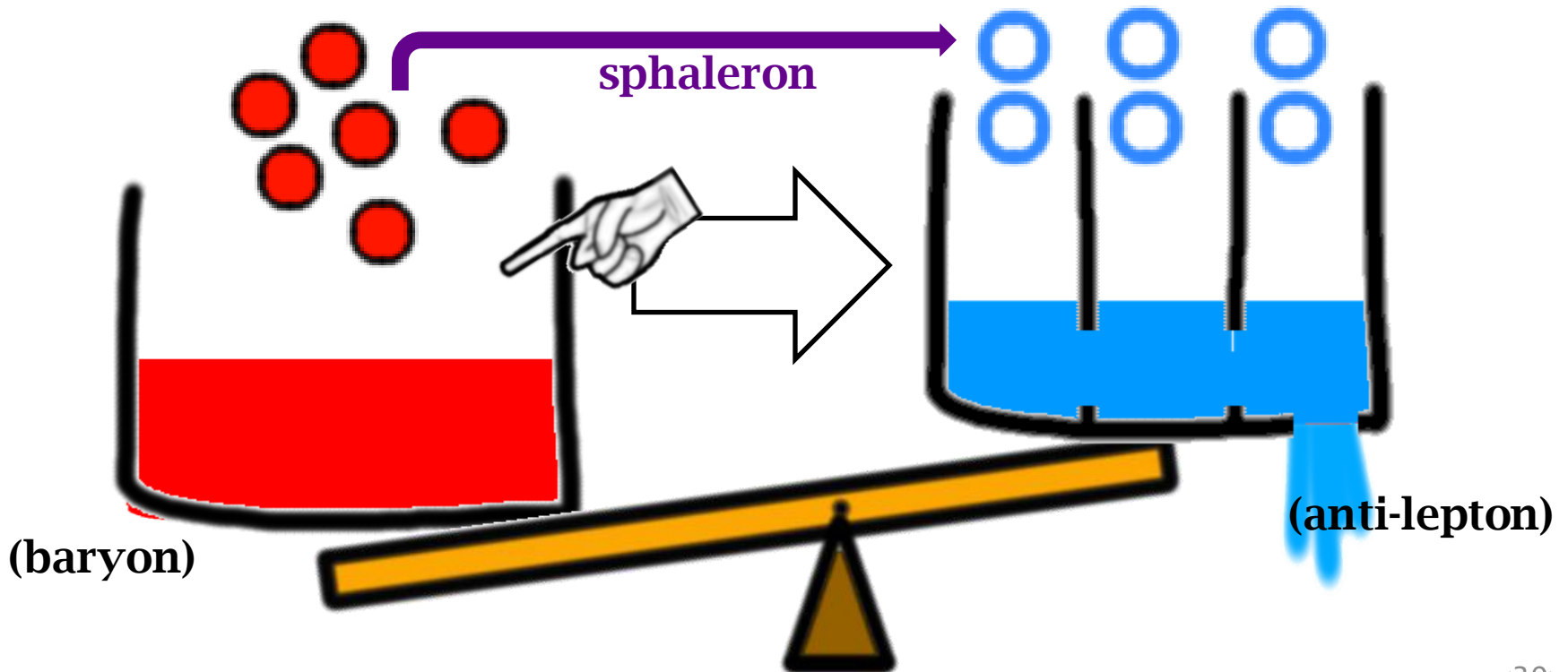


Wash-out with L -viol.

L

Therefore,

Only One L would...

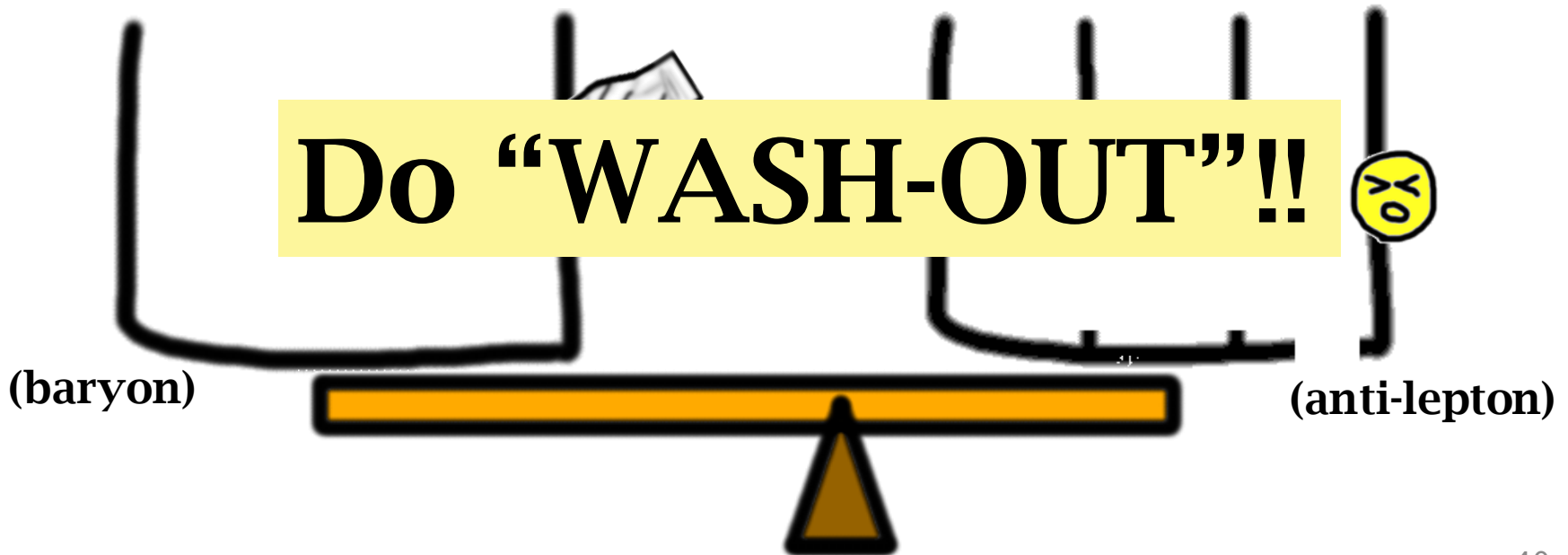


Wash-out with L -viol.



Therefore,

Only One  would...



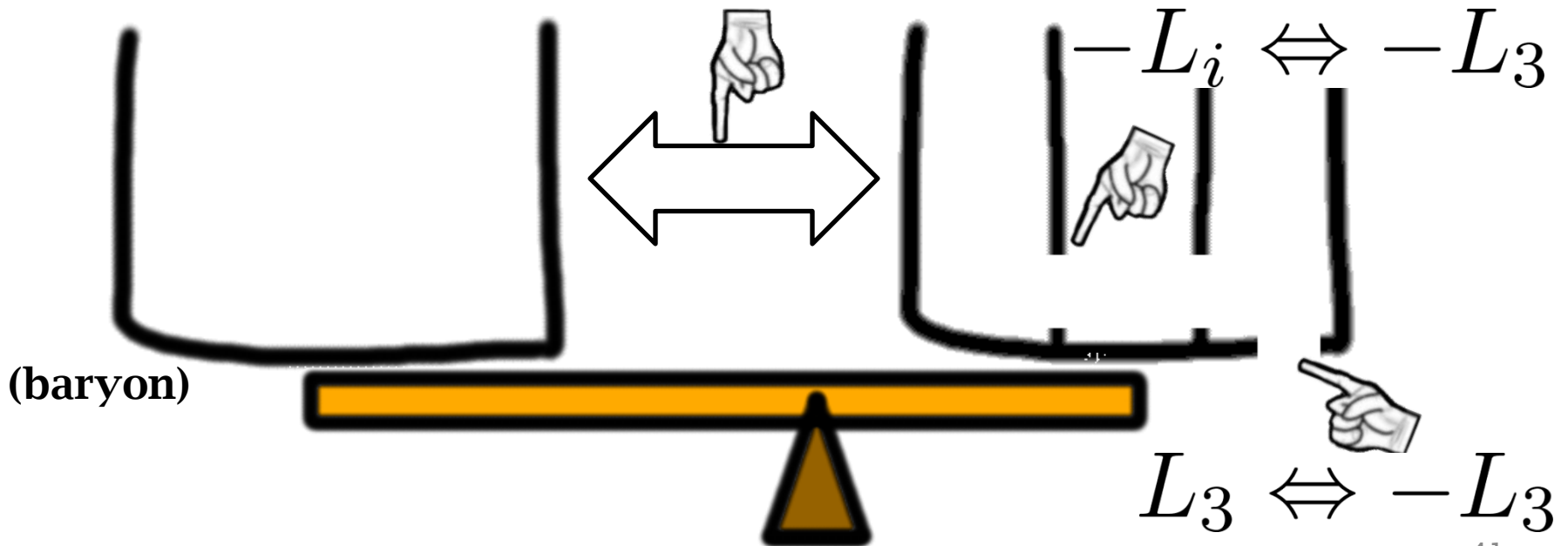
Wash-out with L -viol.

L

Therefore,

Only One L would...

$$B \Leftrightarrow -L$$



Wash-out with ~~L~~ -viol.

~~L~~

Therefore,

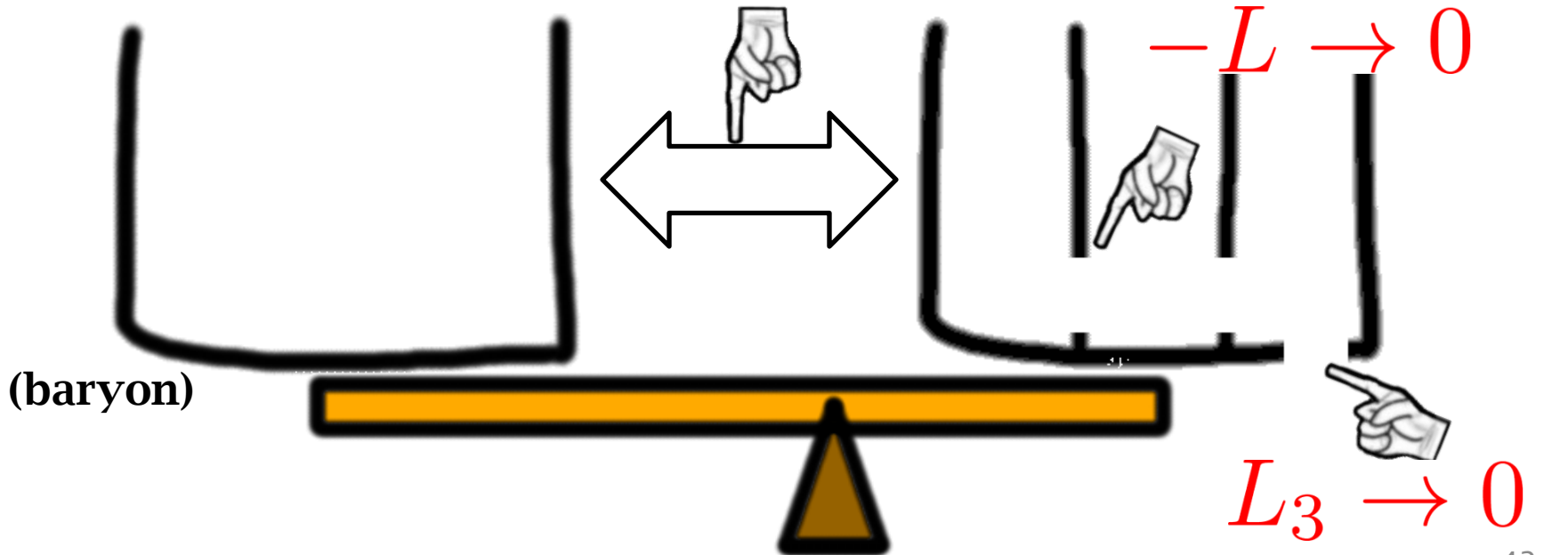
Only One ~~L~~ would...

$B \rightarrow 0$

$-L \rightarrow 0$

(baryon)

$L_3 \rightarrow 0$



These are what we studied!

To **avoid** the WASH-OUT,

⊙ All \cancel{B} must be small enough, and

⊙ If all flavors are mixed

→ All \cancel{L} must be small enough.

$$W_{\cancel{L}} = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

$$W_{\cancel{B}} = W_{\text{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

These are what we studied!


To **avoid** the WASH-OUT,

⊙ All B must be small enough, and 

⊙ If all flavors are mixed  **When MIX?**

→ All L must be small enough.

$$W_L = W_{RPC} + \lambda_{ijk} L_i L_j \bar{E}_k + \dots$$
$$W_B = W_{RPC} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$




 **How SMALL must be?**

And we will claim that...

To **avoid** the WASH-OUT,

- ◉ All \cancel{B} must be **This is naturally expected!** 
- ◉ If all flavors are mixed

→ All L must be small enough.

$$W_L = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$


$$W_{\cancel{B}} = W_{\text{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$



All of them are severely constrained!

3. Our Results

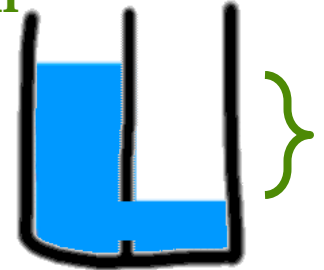
Methods

Lepton number density in i -th generation

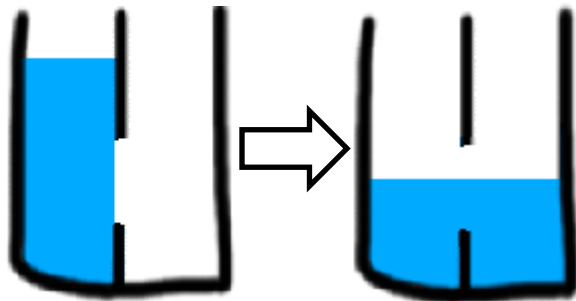
We calculated

$$\frac{d}{dt} (L_i - L_j)$$

by Boltzmann Eq.



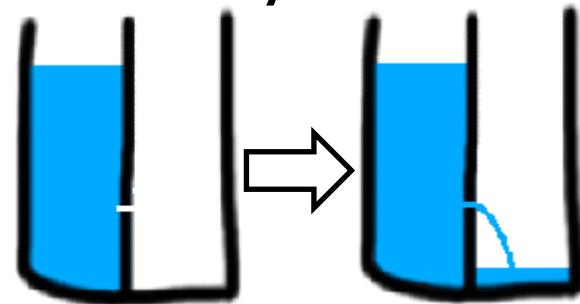
Large LFV



$$L_i - L_j \rightarrow 0$$

(All L must be small.)

Tiny LFV



$$L_i - L_j \not\rightarrow 0$$

Methods

$$(h_i) H_d L_i \bar{E}_i$$

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

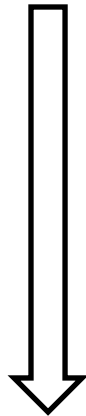
$$(m_{\bar{E}}^2)_{ij} \tilde{e}_i^* \tilde{e}_j \quad \text{LFV}$$

Generally **NOT** diagonal

As Shimomura-san discussed.

Methods

$$(h_i) H_d L_i \bar{E}_i$$



LFV $(h_{ij}) H_d L_i \bar{E}_j$

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

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

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

LFV

Diagonalize
by θ rotation

“mixing angle”



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

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

Methods

For example

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

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

LFV $(h_{ij}) H_d L_i \bar{E}_j \quad \Longrightarrow \quad \tilde{H} \Leftrightarrow l_i \tilde{e}_j^*, \quad \tilde{H} \Leftrightarrow \tilde{l}_i e_j^\dagger$
causes Mixing.

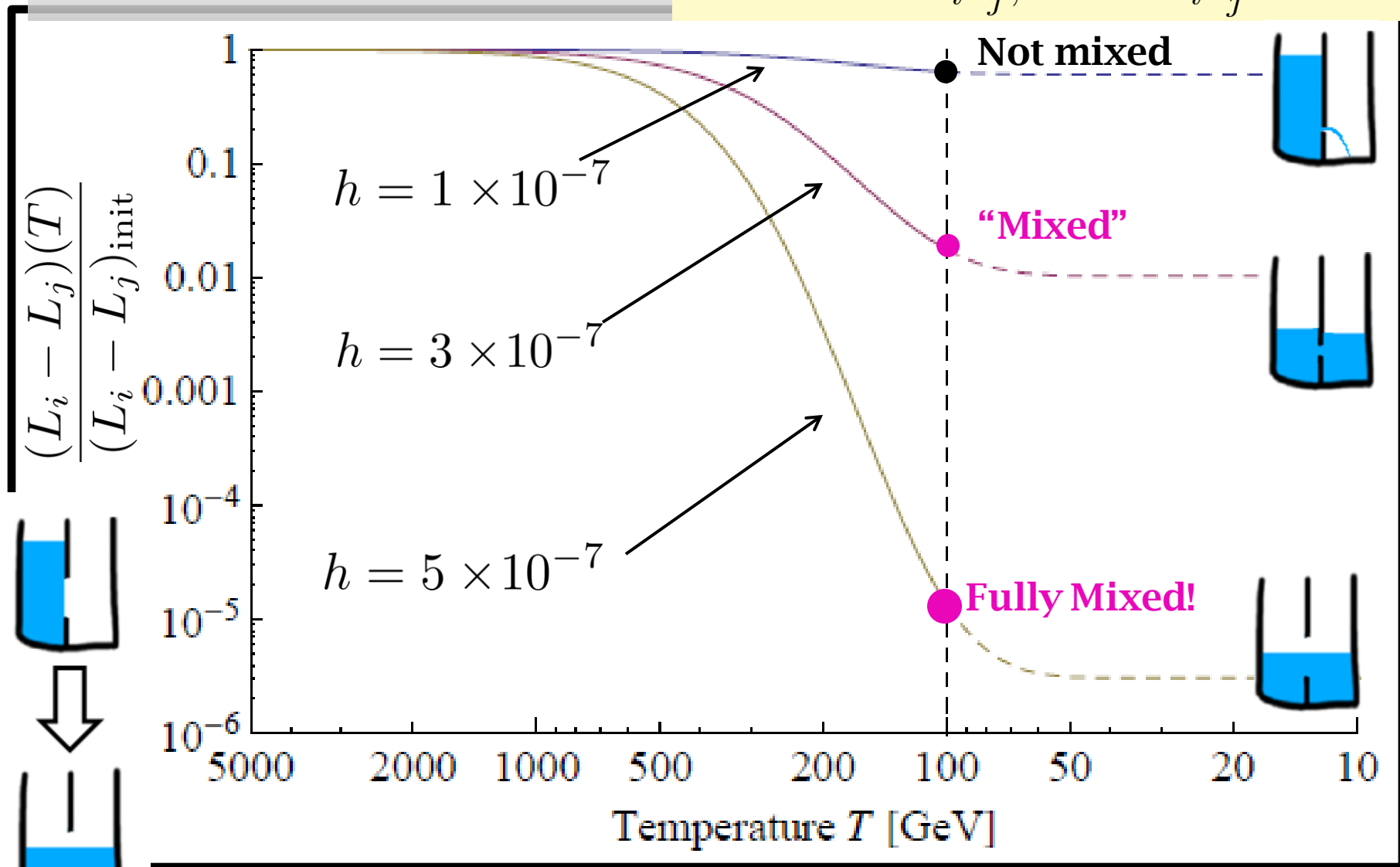
$$h_{ij} = h_i \theta_{ij}^{\bar{E}} + h_j \theta_{ji}^L$$



Result

$$W \ni (h_{ij}) H_d L_i \bar{E}_j$$

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



$$m_{\tilde{H}} = 600 \text{ GeV}, \quad m_{\tilde{l}} = m_{\tilde{e}} = 200 \text{ GeV}$$

Conclusion

$$W \ni (h_{ij}) H_d L_i \bar{E}_j$$
$$\tilde{H} \Leftrightarrow l_i \tilde{e}_j^*, \quad \tilde{H} \Leftrightarrow \tilde{l}_i e_j^\dagger$$



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

This corresponds to

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

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

By the way,

Remember:

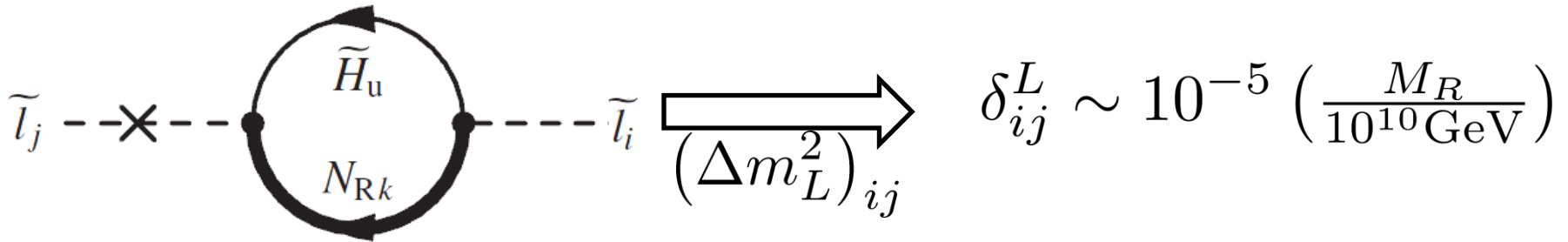
$$h_{23} \simeq \left(0.006 \cdot \theta_{23}^{\bar{E}} + 0.1 \cdot \theta_{32}^L \right) \left(\frac{\tan \beta}{10} \right)$$

Conclusion

$$W \ni (h_{ij}) H_d L_i \bar{E}_j$$

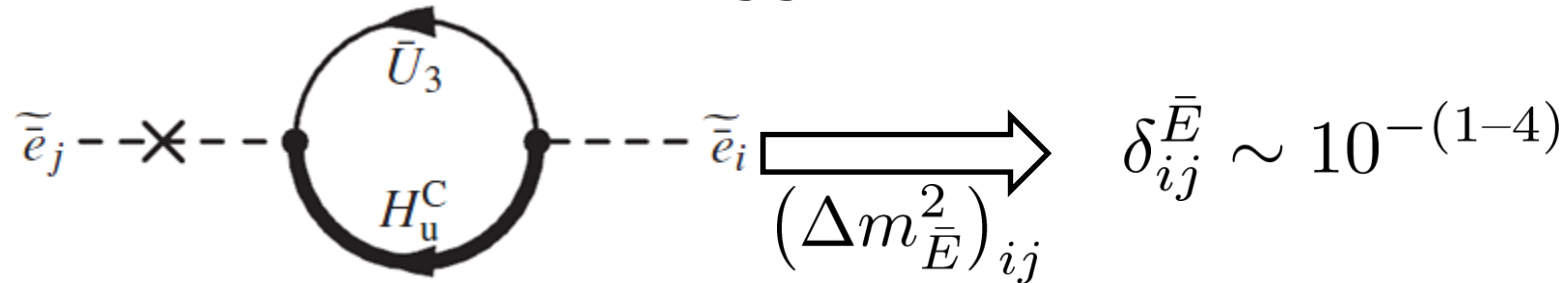
$$\tilde{H} \Leftrightarrow l_i \tilde{e}_j^*, \quad \tilde{H} \Leftrightarrow \tilde{l}_i e_j^\dagger$$

Right-handed neutrino



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

SU(5) GUT (Colored Higgs)



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

where

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

Conclusion

$$W \ni (h_{ij}) H_d L_i \bar{E}_j$$
$$\tilde{H} \Leftrightarrow l_i \tilde{e}_j^*, \quad \tilde{H} \Leftrightarrow \tilde{l}_i e_j^\dagger$$



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

Naturally Expected!

Expected Value

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

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

Experimental Reach

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

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

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

Now We Know

This is naturally expected!

To avoid the WASH-OUT,

- All B must be small enough, and
- If all flavors are mixed

→ All L must be small enough.

$$W_L = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

$$W_B = W_{\text{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$



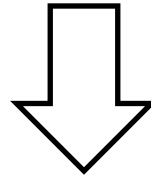
These are ALL
severely constrained!

Constraints on RpVs

- ⊙ In a similar manner...

$$\frac{d}{dt} (B - L)$$

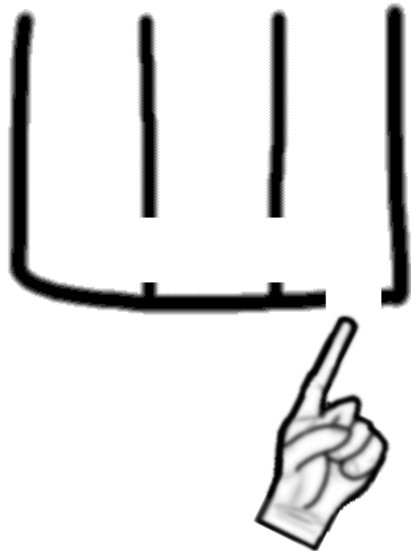
→ calculated by the Boltzmann Eq.



We obtained the bounds for

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

Just the results...



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

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

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

$$\lambda'' \lesssim 4 \times 10^{-7} \quad (\text{For all } i, j, k)$$

$$W_{\mathcal{L}} = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

$$W_{\mathcal{B}} = W_{\text{RPC}} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

For

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

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 \rightarrow LSP \cancel{p}_T Signal 😊

Then if not?

\rightarrow **LSP decays!**

How to detect RpV-SUSY? 😞

Application for LHC

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

→ LSP is a bit “long-lived.”

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

$$\tilde{\tau} \rightarrow l \nu$$

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

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

To be a good signal of RpV-SUSY?

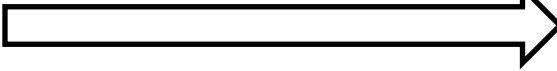
→ Future works!

That's all.

Thank you

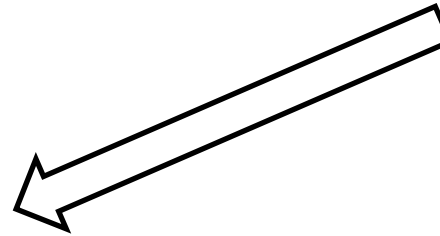
for listening.

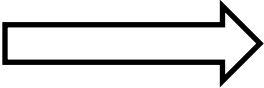
Summary

MSSM 

R-parity is
not a must.

LFV!!



~~*B*~~ & ~~*L*~~ are 
ALL small.

LSP would be
a bit **long-lived**
even if
NO *R*-Parity.

Appendices

- A) Hierarchy Problem** JUMP
- B) Weak points of RpV-MSSM** JUMP
- C) Collider Constraints** JUMP
- D) The RpV Results** JUMP
- E) Several Details** JUMP
- F) Experimental LFV Bounds** JUMP

A. Hierarchy Problem

“In the Standard Model,
the quantum correction for the mass of the Higgs
requires a miraculous cancellation as

$$O(10^{30}) - O(10^{30}) \rightarrow 10^4 \text{ !?}”$$

Hierarchy Problem

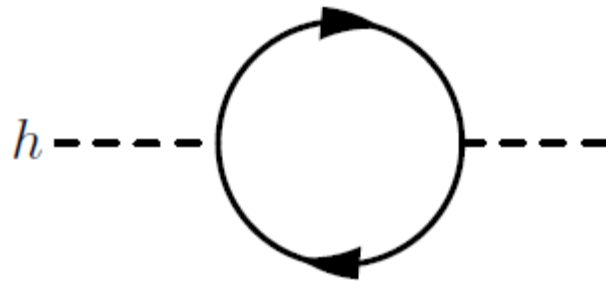
In the

Standard Model

with Higgs,

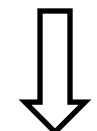
Hierarchy Problem

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



$$\Rightarrow \Delta m_{\text{higgs}}^2 = -\frac{|\lambda|^2}{8\pi^2} \Lambda^2 + \text{finite}$$

$\Lambda \sim 10^{15} \text{ GeV}$



$$m_{\text{higgs}}^2 \sim m_{\text{bare}}^2 + \Delta m_{\text{higgs}}^2$$



$m_{\text{higgs}} \sim 100 \text{ GeV}$

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

Hierarchy Problem

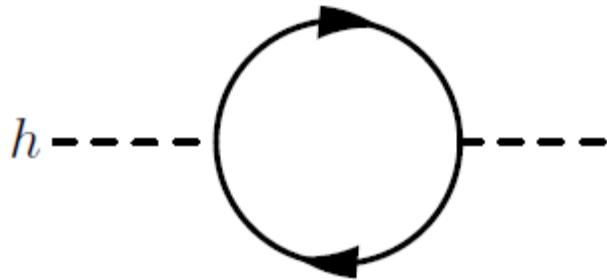
⊙ In

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!

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



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



Cancelled!

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

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

→ experimental constraints

And the constraints are important
to study RpV-MSSM.

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

or

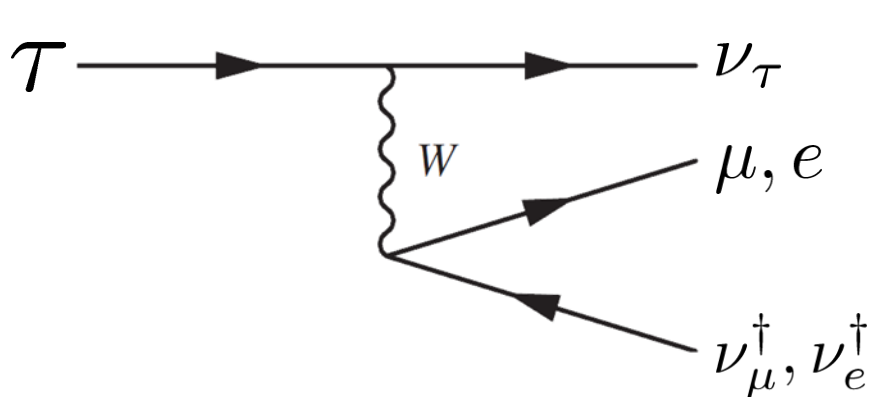
$$= \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Constraints

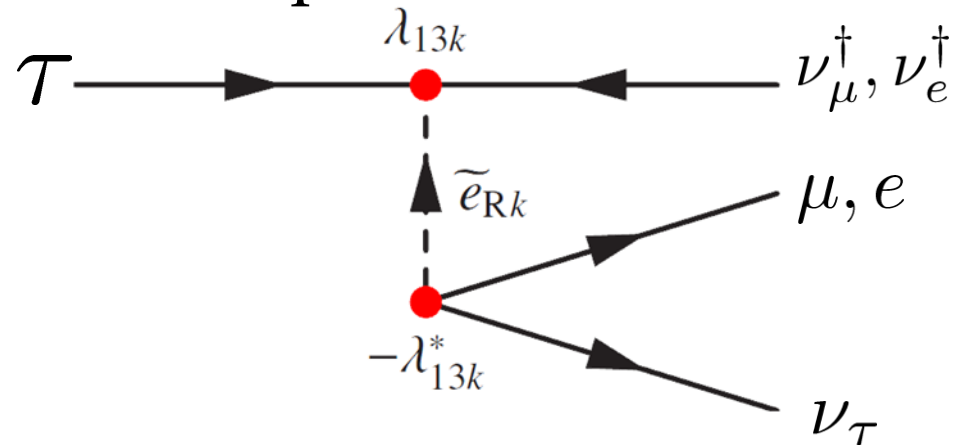
⊙ Example:

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

Standard Model



RpV-MSSM



Additional Contribution!

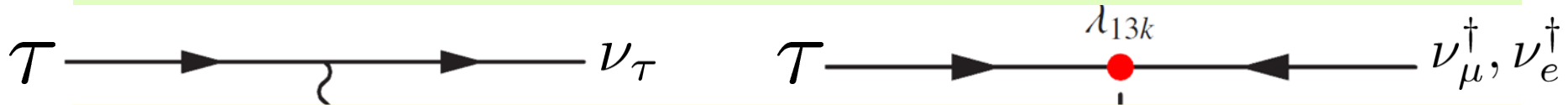
Constraints

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

$$R_\tau = \frac{\Gamma(\tau \rightarrow \nu_\tau) + \Gamma(\tau \rightarrow \nu_\mu, \nu_e)}{\Gamma(\tau \rightarrow \nu_\tau)}$$

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

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



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

ν_τ

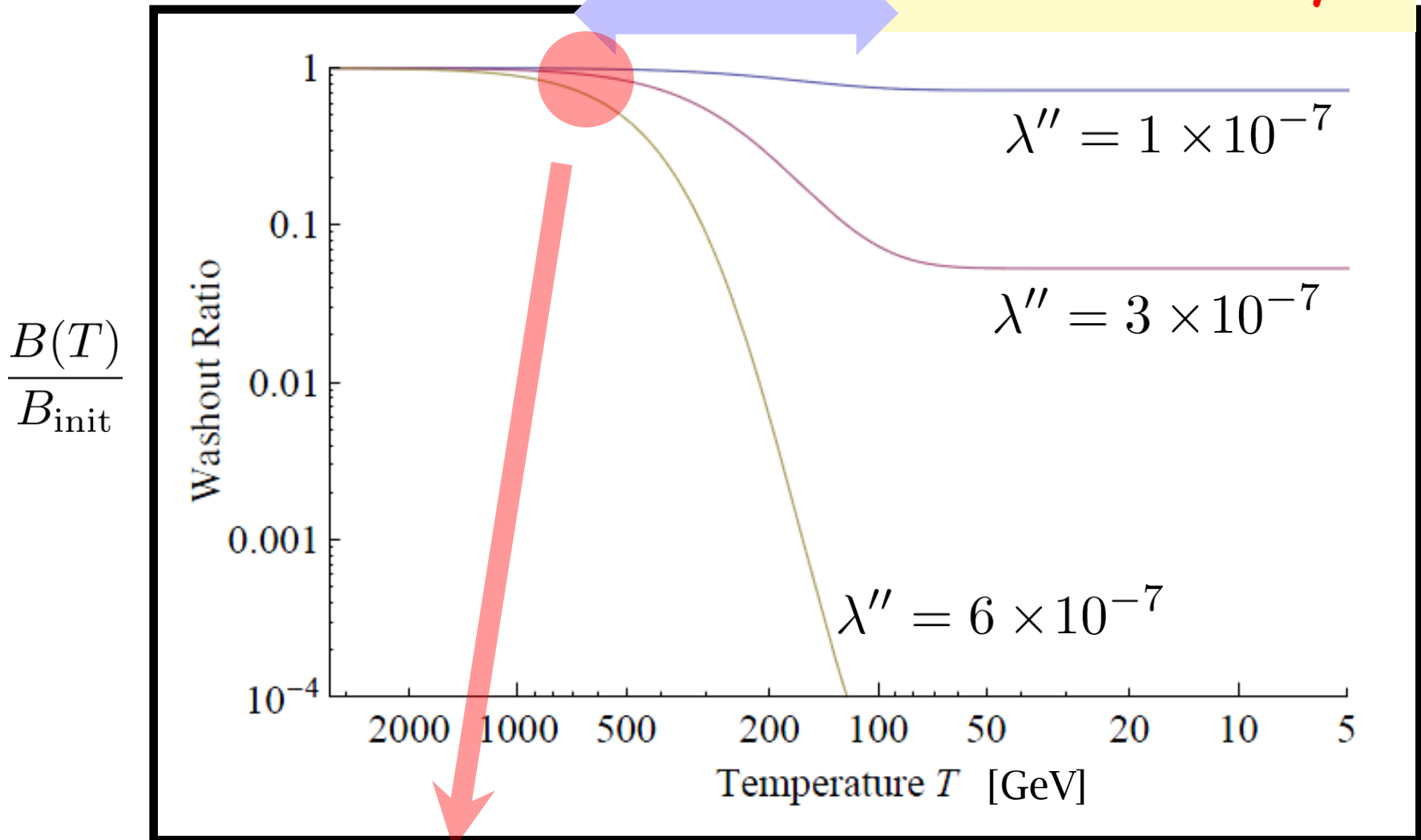
Additional Contribution!

D. RpV Results

RpV Result

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

$$\tilde{q}^* \rightleftharpoons qq \quad \cancel{B}$$

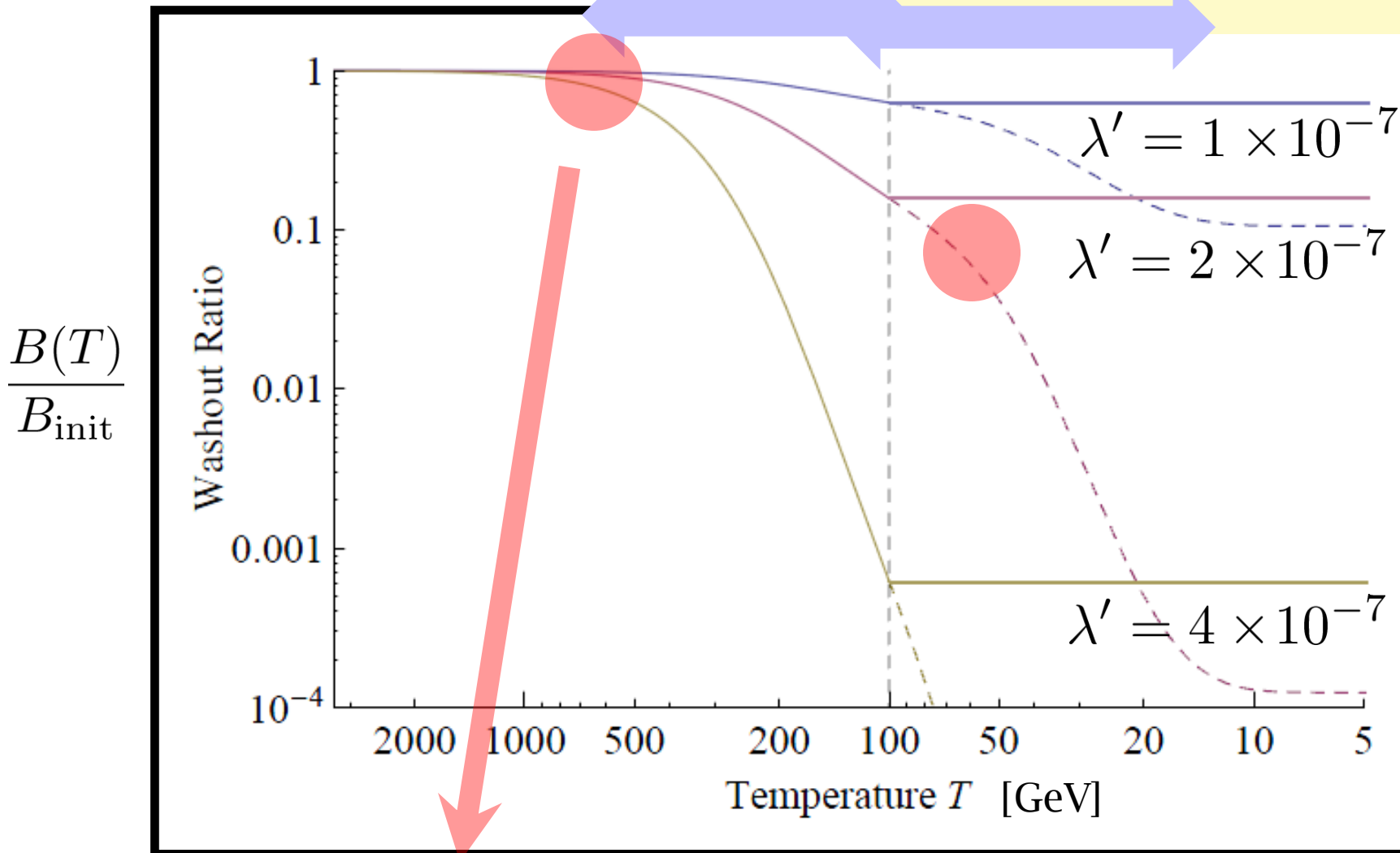


$$m_{\tilde{q}} = 600 \text{ GeV} \quad (m_{\tilde{H}} = 300 \text{ GeV}, m_{\tilde{l}} = 100 \text{ GeV})$$

RpV Result

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

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



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

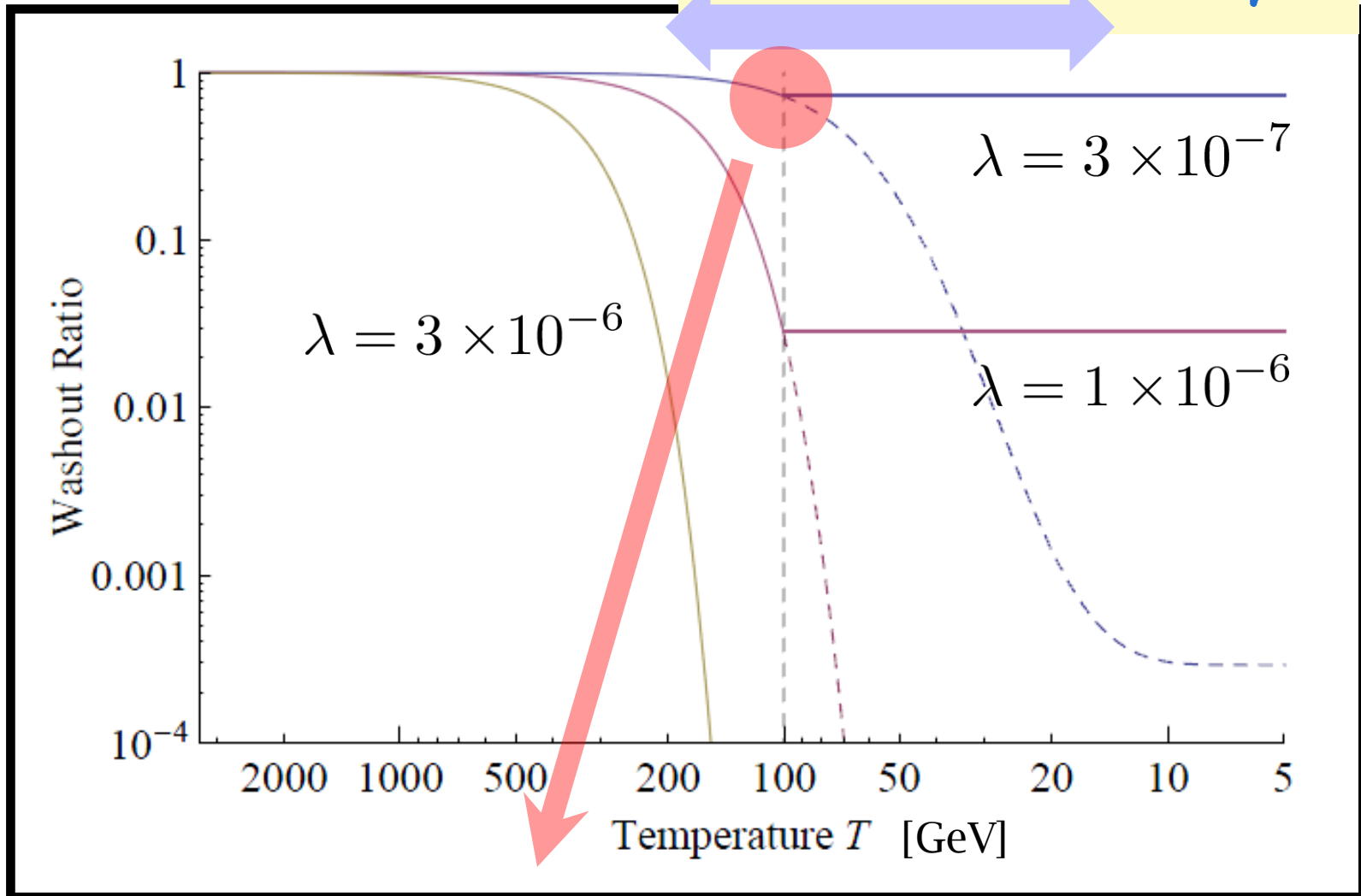
RpV Result

$$W \ni \lambda L L \bar{E}$$

$$\tilde{l} \rightleftharpoons ll$$



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

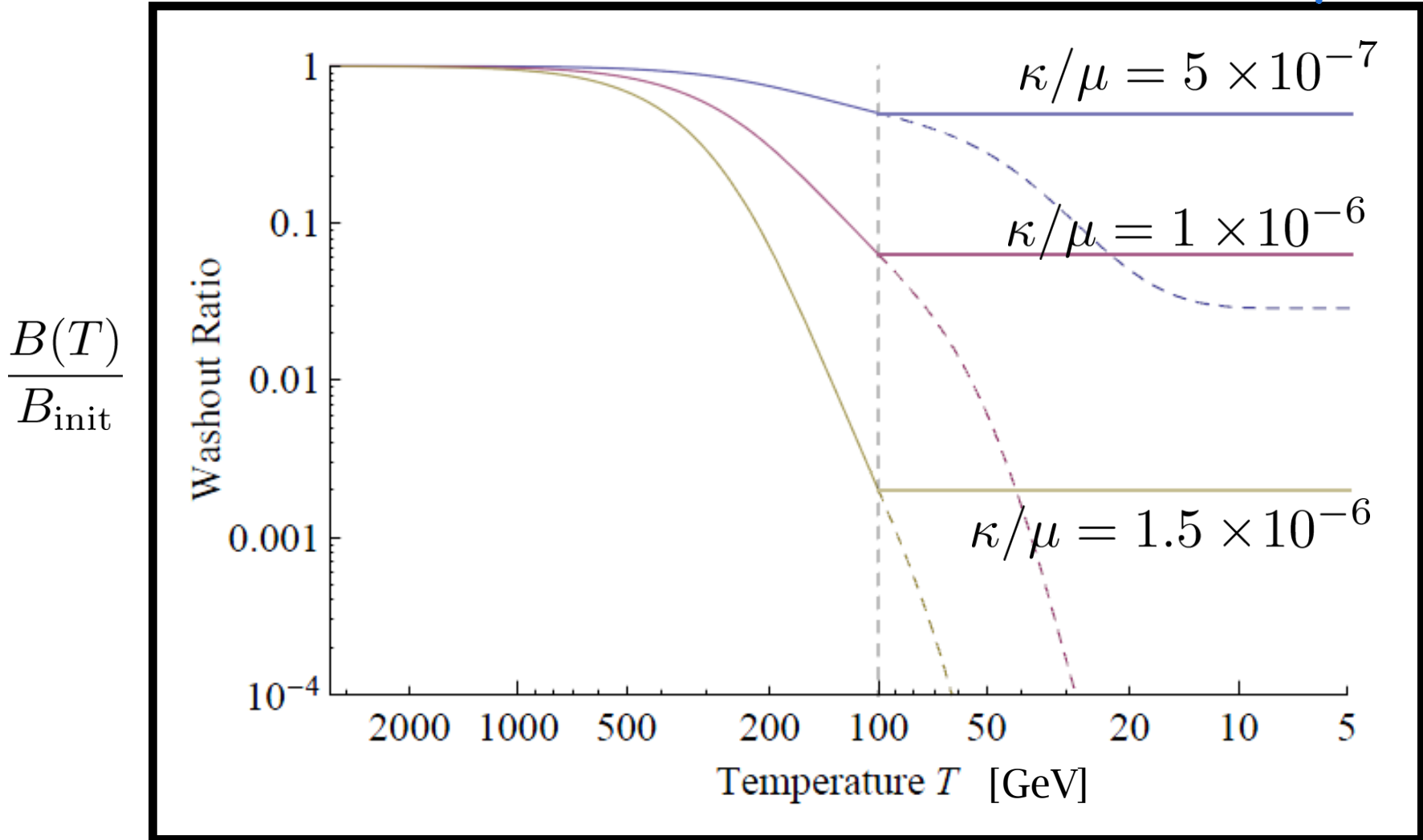


$$m_{\tilde{l}} = 100 \text{ GeV} \quad (m_{\tilde{q}} = 600 \text{ GeV}, m_{\tilde{H}} = 300 \text{ GeV})$$

$$W \ni \kappa L H_u$$



RpV Result



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

E. Several Details

Approximations we used

Set up $(y_e)_{ij} H_d L_i \bar{E}_j$

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

Approximations

- ⊙ We consider only the decay of Higgsino

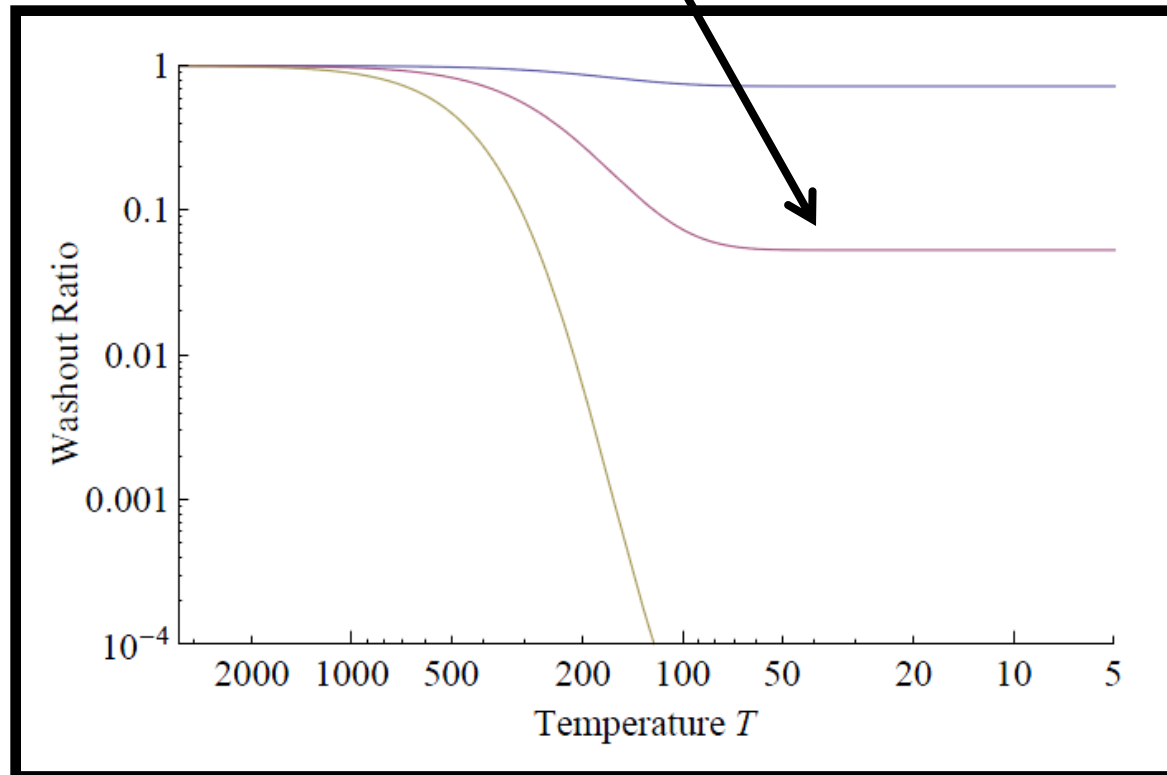
$$\tilde{H} \rightleftharpoons l_i \tilde{e}_j^*, \quad \tilde{H} \rightleftharpoons \tilde{l}_i e_j^\dagger$$

and the antiparticles' processes.

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

Some Loophole

- ◉ We can avoid any “wash-out”
with creating the current B -asymmetry
HERE. ($T \lesssim 100$ GeV era)



F. Experimental LFV Bounds

MEGA Result / MEG Prospect

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

$$\text{MEGA} : \text{Br} < 1.2 \times 10^{-11}$$

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

$$\text{MEG} : \text{Br} \Rightarrow \text{O}(10^{-13})$$

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