

Cosmological Constraints on *R*-Parity Violating SUSY

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2010-10-04

2nd Bethe Center Workshop @ Bad Honnef, Deutschland.

Based on

M. Endo, K. Hamaguchi and SI.

Cosmological Constraints on R-parity violation.

JCAP 1002:032, 2010. [[arXiv: 0912.0585](https://arxiv.org/abs/0912.0585)]

Outline

Introduction: R -parity violating SUSY

Main part: Cosmological Constraints

Appendix: Application in LHC

Based on

M. Endo, K. Hamaguchi and SI.

Cosmological Constraints on R -parity violation.

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1. *R*-parity violating SUSY

“The *R*-parity is, though very beautiful, not a must.”

MSSM and R -parity

MSSM

(Minimal Supersymmetric Standard Model)



Hierarchy problem \rightarrow solved!



Proton decay problem

WHY?

\rightarrow Since B and L are violated.

Proton Decay Problem

Interactions in MSSM superpotential

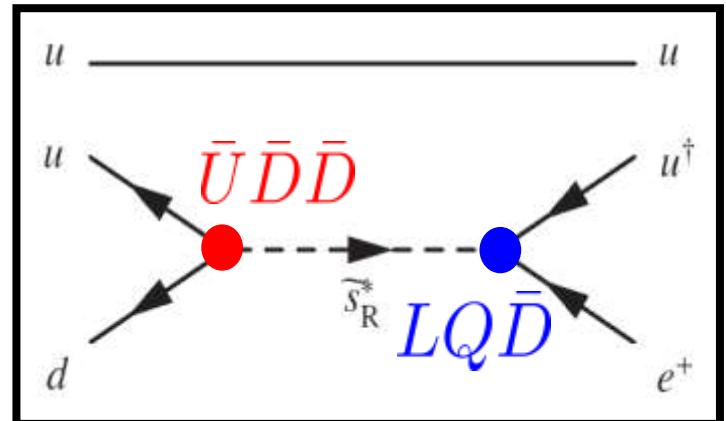
Rp. conserving: $H_u H_d$, $H_d L \bar{E}$, $H_d Q \bar{D}$, $H_u Q \bar{U}$,

Rp. violating: $L H_u$, $L L \bar{E}$, $L Q \bar{D}$, $\bar{U} \bar{D} \bar{D}$

\mathcal{L} \mathcal{B}

Both \mathcal{B} and \mathcal{L}
→ Proton Decay

(example: $p \rightarrow e^+ \pi^0$)

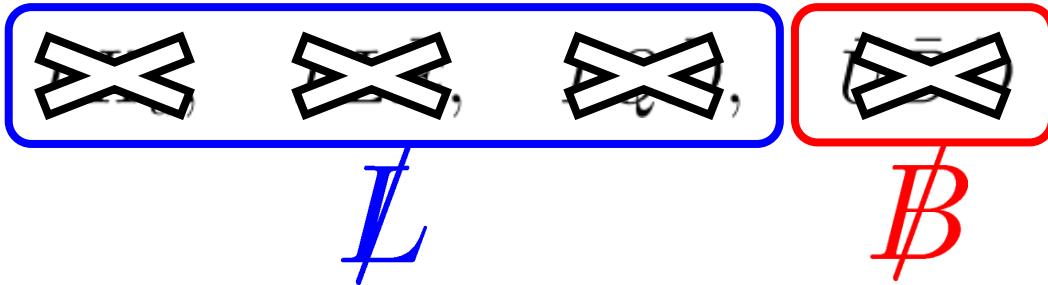


Proton Decay Problem

With *R*-Parity Conservation

Rp. conserving: $H_u H_d$, $H_d L \bar{E}$, $H_d Q \bar{D}$, $H_u Q \bar{U}$,

Rp. violating:



~~Both \bar{B} and \bar{L}~~

→ Proton is Stable. 

And LSP would be DM. 

Proton Decay Problem

- ◎ Imposing R -parity **is not the only way!**

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

(Here DM problem is solved.)

~~Both B and L~~

 Proton is Stable. 
 and LSP would be DM. 

For Stable Proton: 3 choices

- ◎ Imposing R -parity

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

(Here DM problem is solved.)

- ◎ \cancel{L} -MSSM [Assuming B is conserved.]

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

$$L H_u, \quad L L \bar{E}, \quad L Q \bar{D}$$

- ◎ \cancel{B} -MSSM [Assuming L is conserved, and $m_{\text{LSP}} > m_{\text{proton}}$.]

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

What we studied

Our Study: **Cosmological Constraints**

on these RpV interactions (couplings).

- ◎ \mathcal{L} -MSSM [Assuming B is conserved.]

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

$$L H_u, L L \bar{E}, L Q \bar{D}$$

- ◎ \mathcal{B} -MSSM [Assuming L is conserved, and $m_{\text{LSP}} > m_{\text{proto}}$]

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

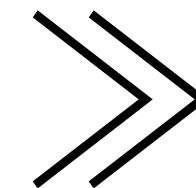
2. Cosmological Constraints

“The violation of R -parity (\cancel{B} or \cancel{L}) may spoil the current Baryon Asymmetry of the Universe.”

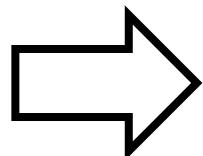
Baryon Asymmetry of the Universe

The Universe

baryon



anti-baryon



Some mechanism for
baryogenesis

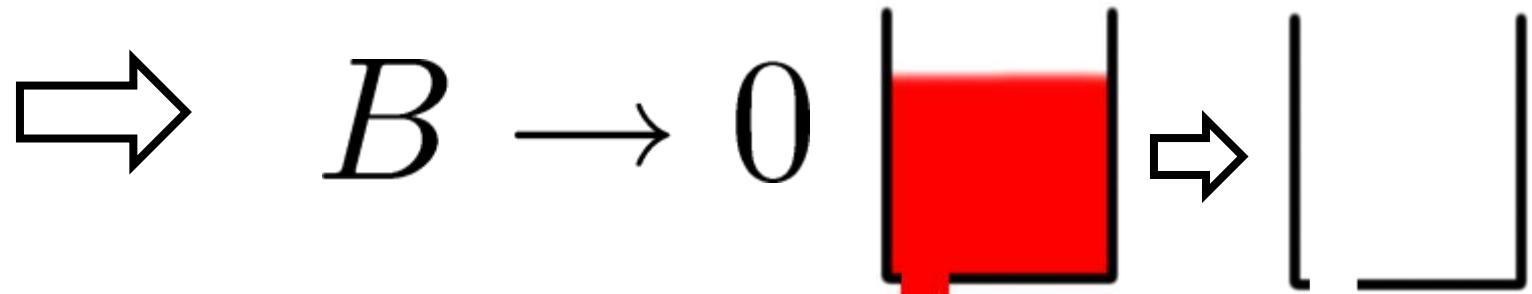


Wash-out with B -viol.

However,

if MSSM has \cancel{B} , ($W \ni \lambda'' \bar{U} \bar{D} \bar{D}$)

$\Delta B = -1$ processes ($\tilde{q} \rightarrow \bar{q} \bar{q}$ etc.)



--- Pedagogical Note -----

In this talk, we assume
Baryon is generated in **early** universe.
(Temperature $T \gg 100$ GeV.)

Wash-out with B -viol.

However,

if MSSM has \cancel{B} , ($W \ni \lambda'' \bar{U} \bar{D} \bar{D}$)

$\Delta B = -1$ processes ($\tilde{q} \rightarrow \bar{q} \bar{q}$ etc.)

Large \cancel{B} spoils Baryogenesis.
("wash-out")

→ λ'' must be small enough.

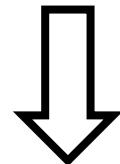


Sphaleron

Go more precisely!

“Sphaleron process”

- Active in early universe $T \gtrsim 100 \text{ GeV}$
(by thermal effects)
- Converts **baryon** \rightleftharpoons **anti-lepton**

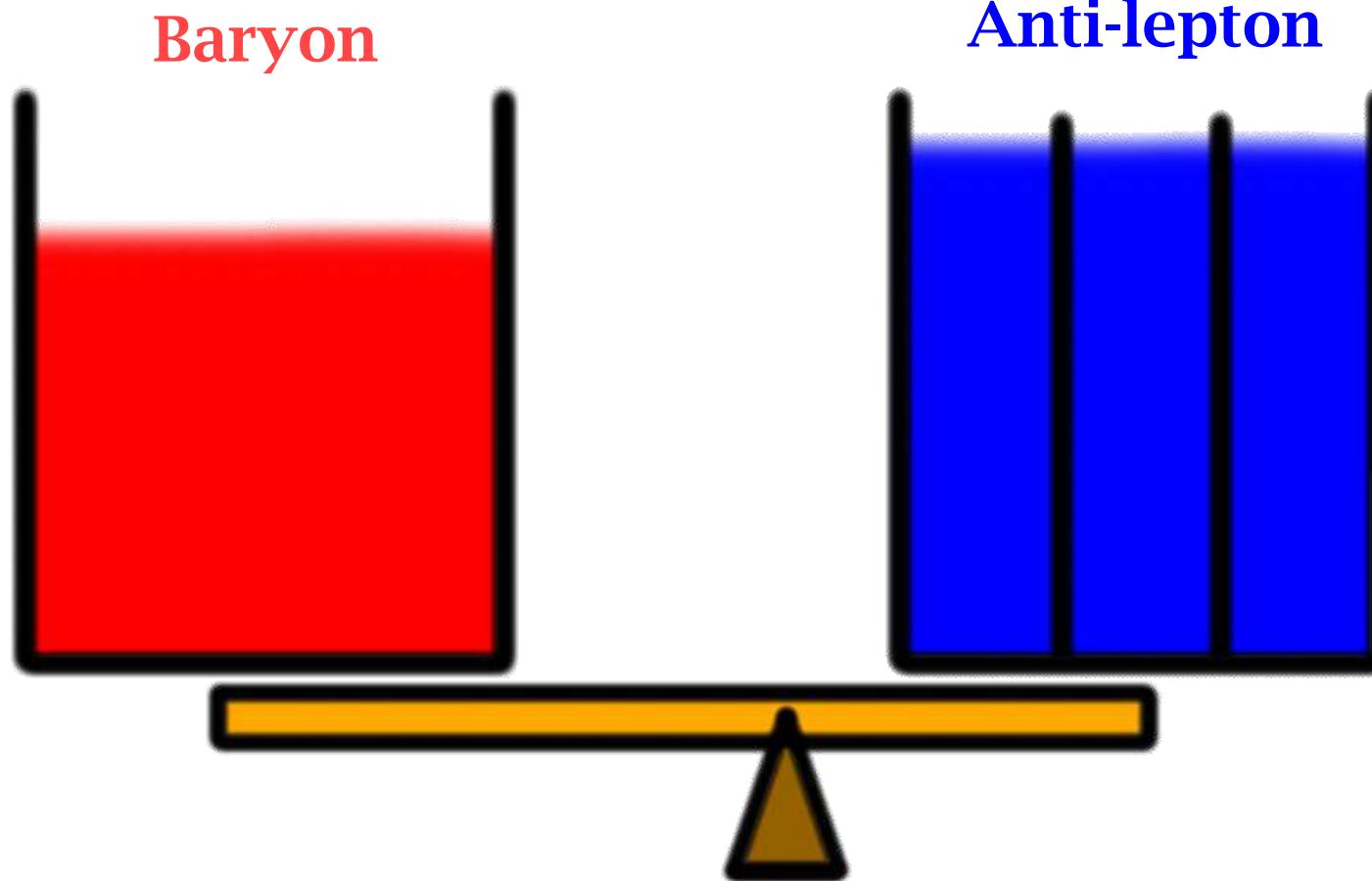


Equilibrium in early universe



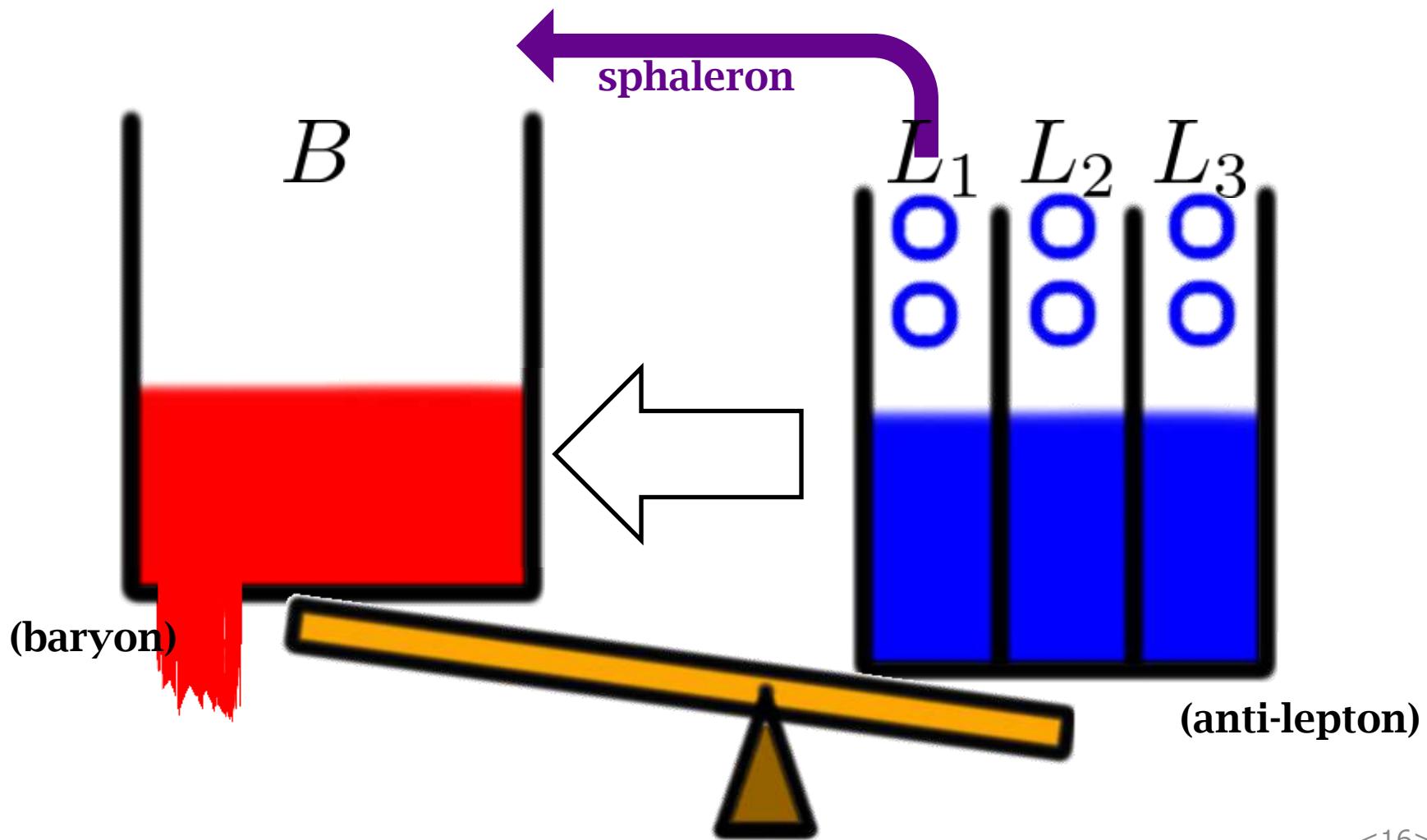
Sphaleron's Effect

On a See-Saw!



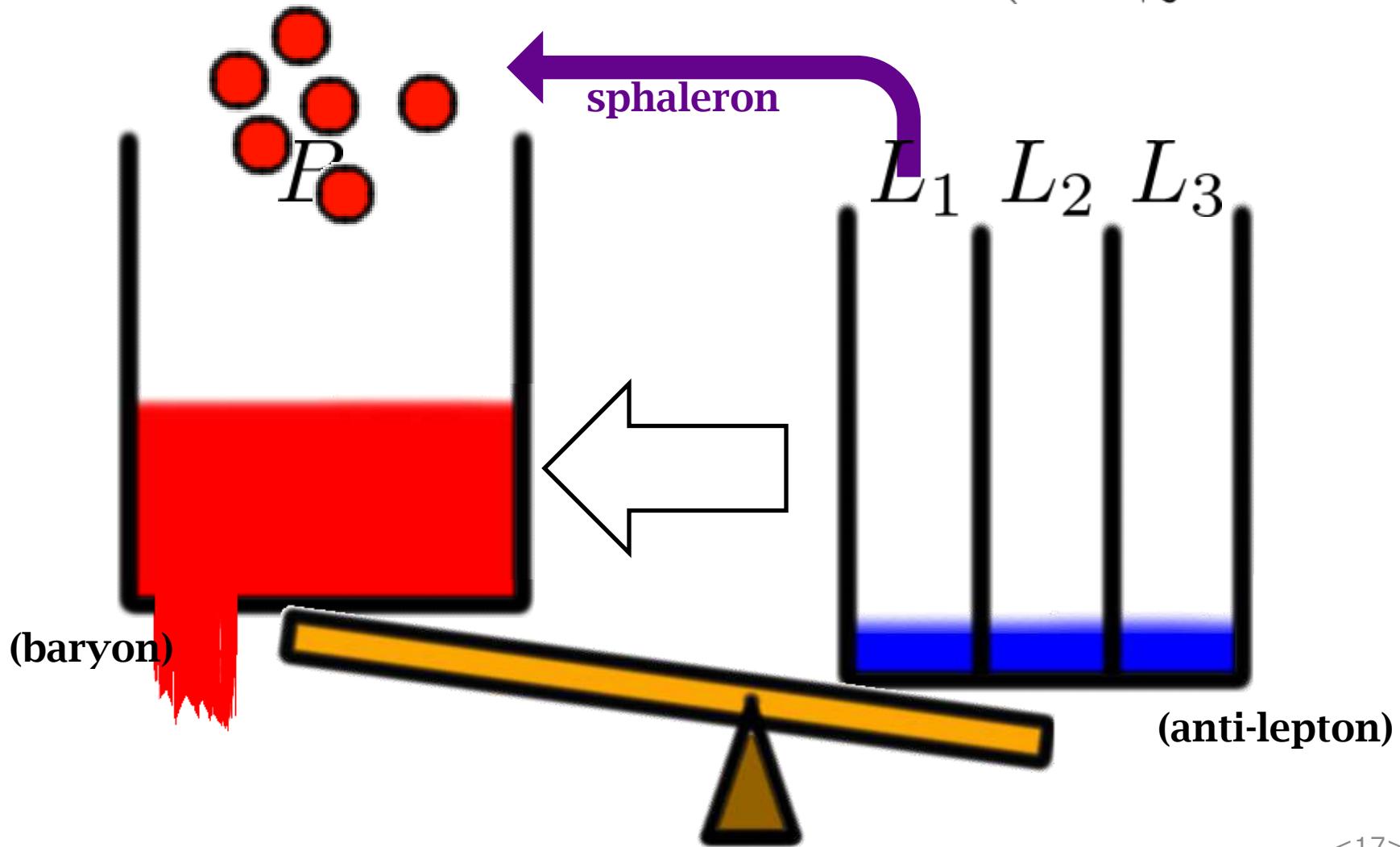
Sphaleron's Effect

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



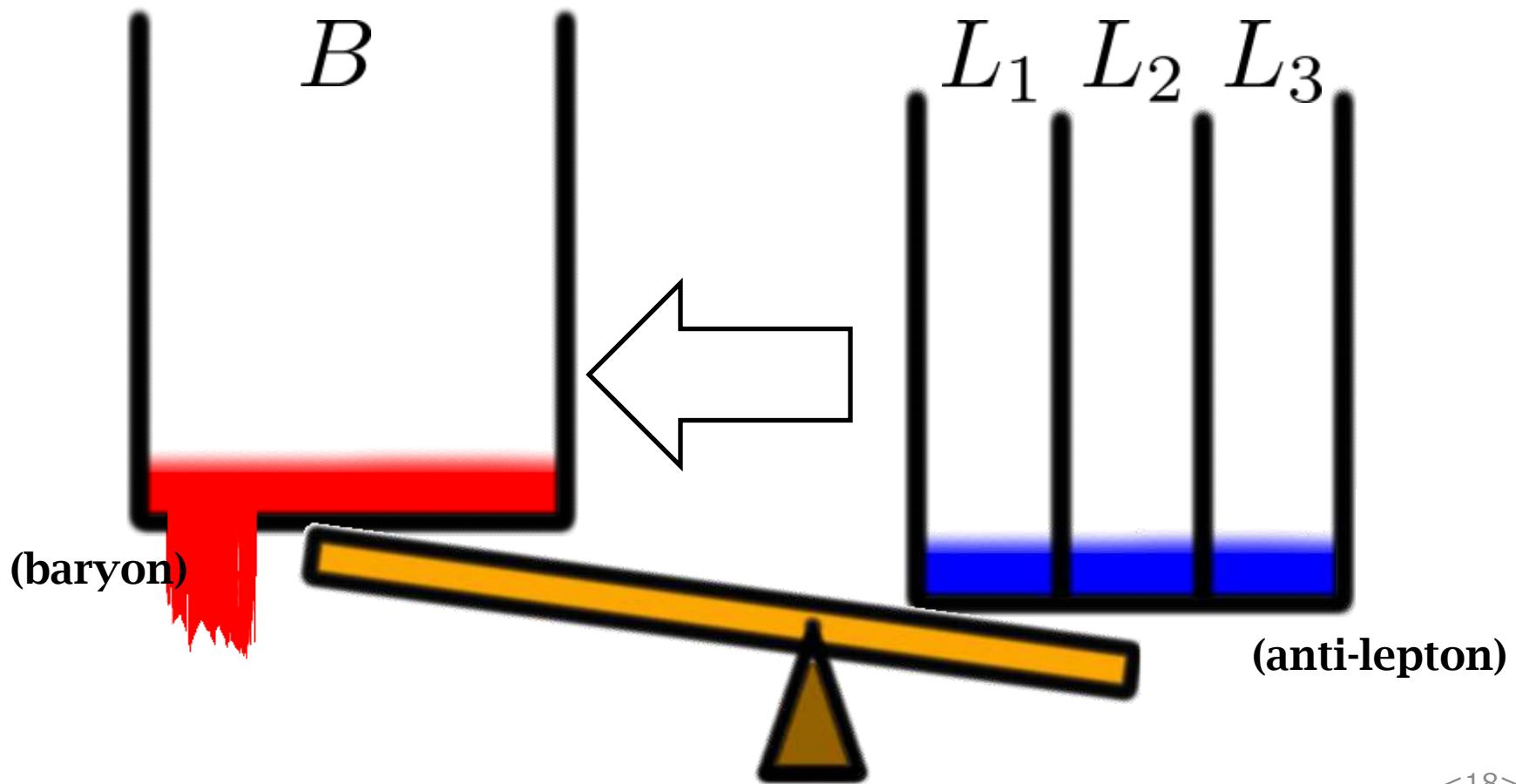
Sphaleron's Effect

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



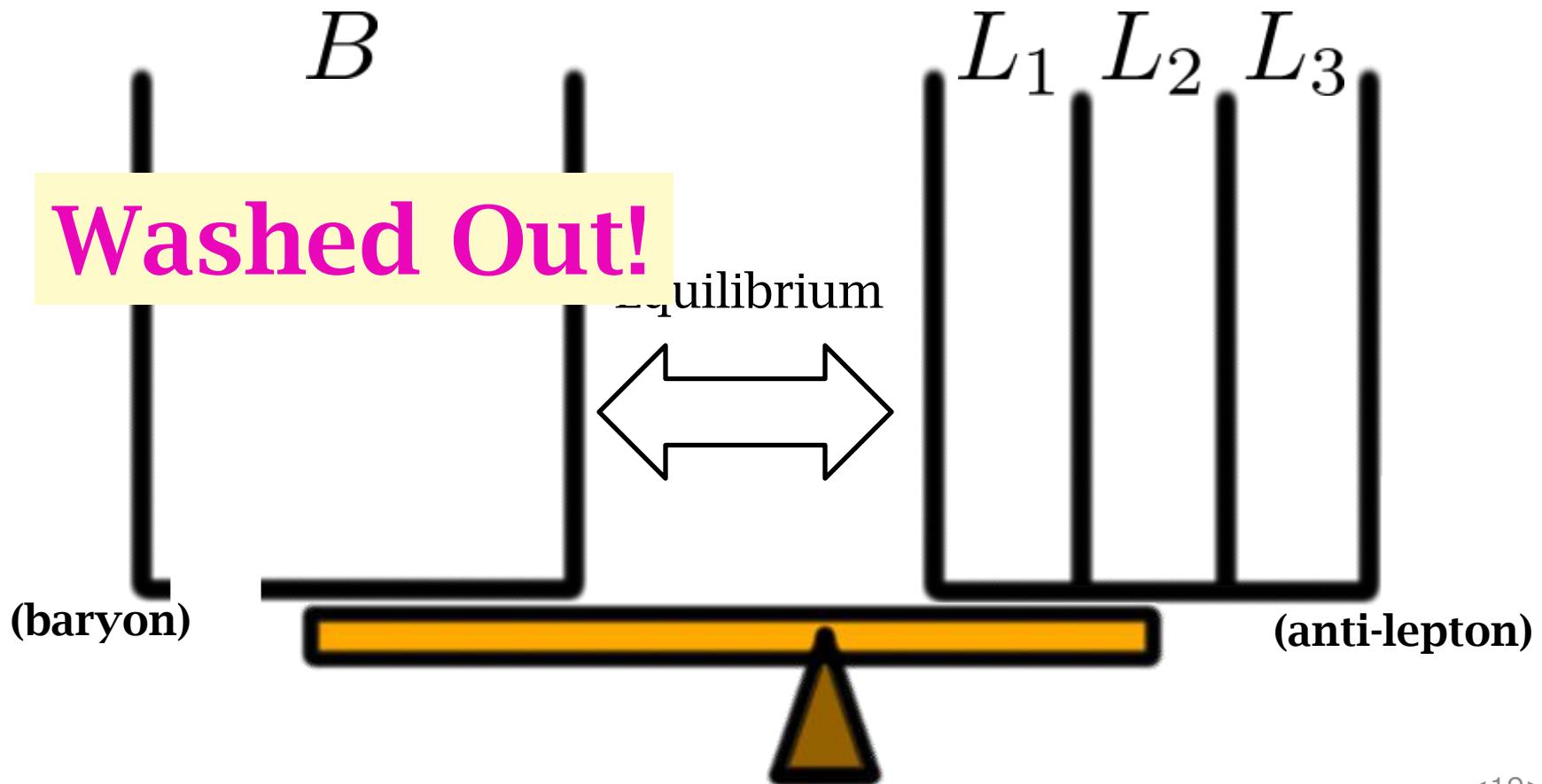
Sphaleron's Effect

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



Sphaleron's Effect

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



LESSON

◎ \cancel{B} -MSSM : Large \cancel{B} = wash out 

⇒ \cancel{B} couplings (λ'') = small enough



How small must be?

→ Discussed Later

Wash-out with L -viol.



This story

does not end here!



Wash-out with L -viol.



◎ If

large



(in the sphaleron era),



(baryon)

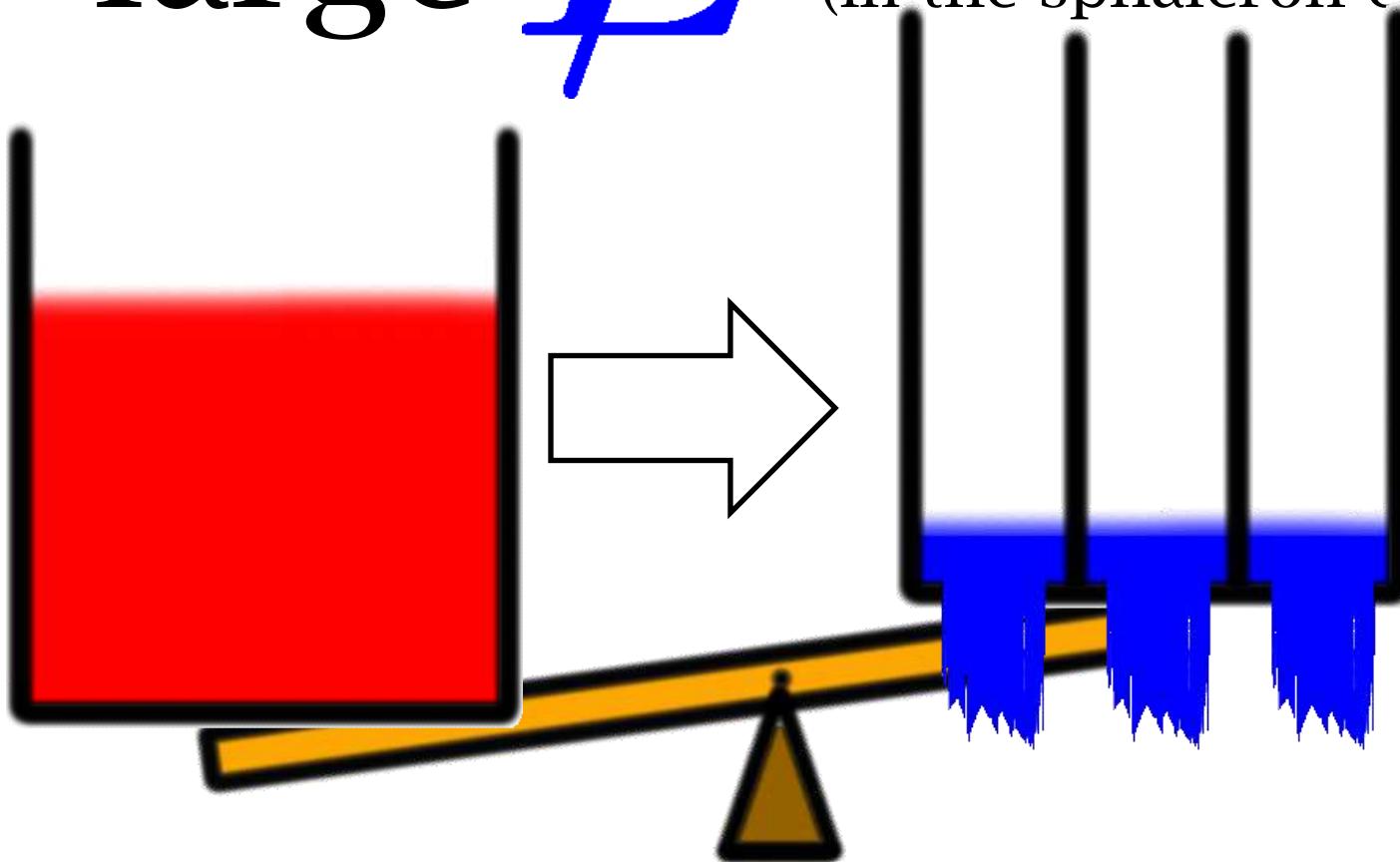




Wash-out with L -viol.

◎ If

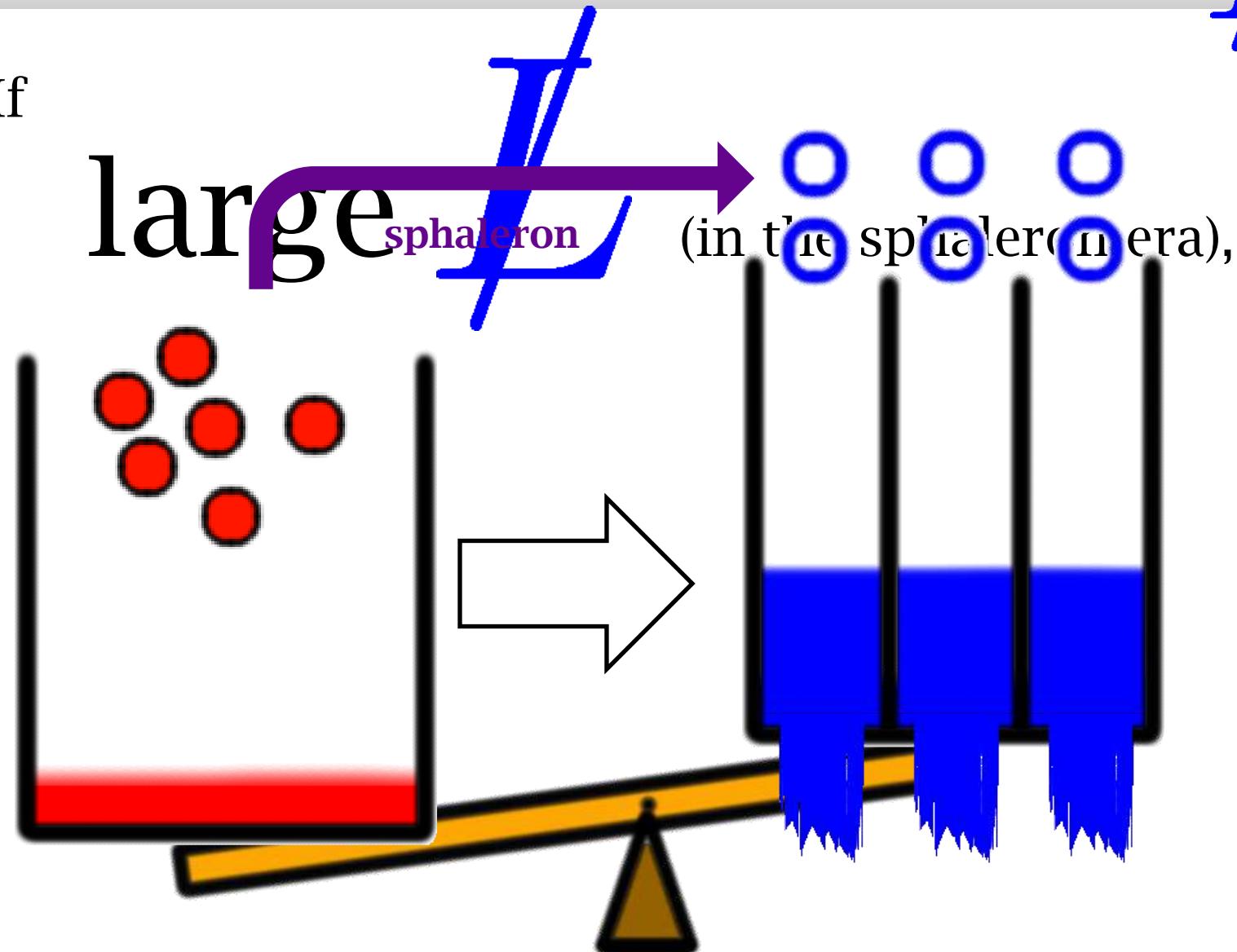
large L (in the sphaleron era),





Wash-out with L -viol.

- ◎ If

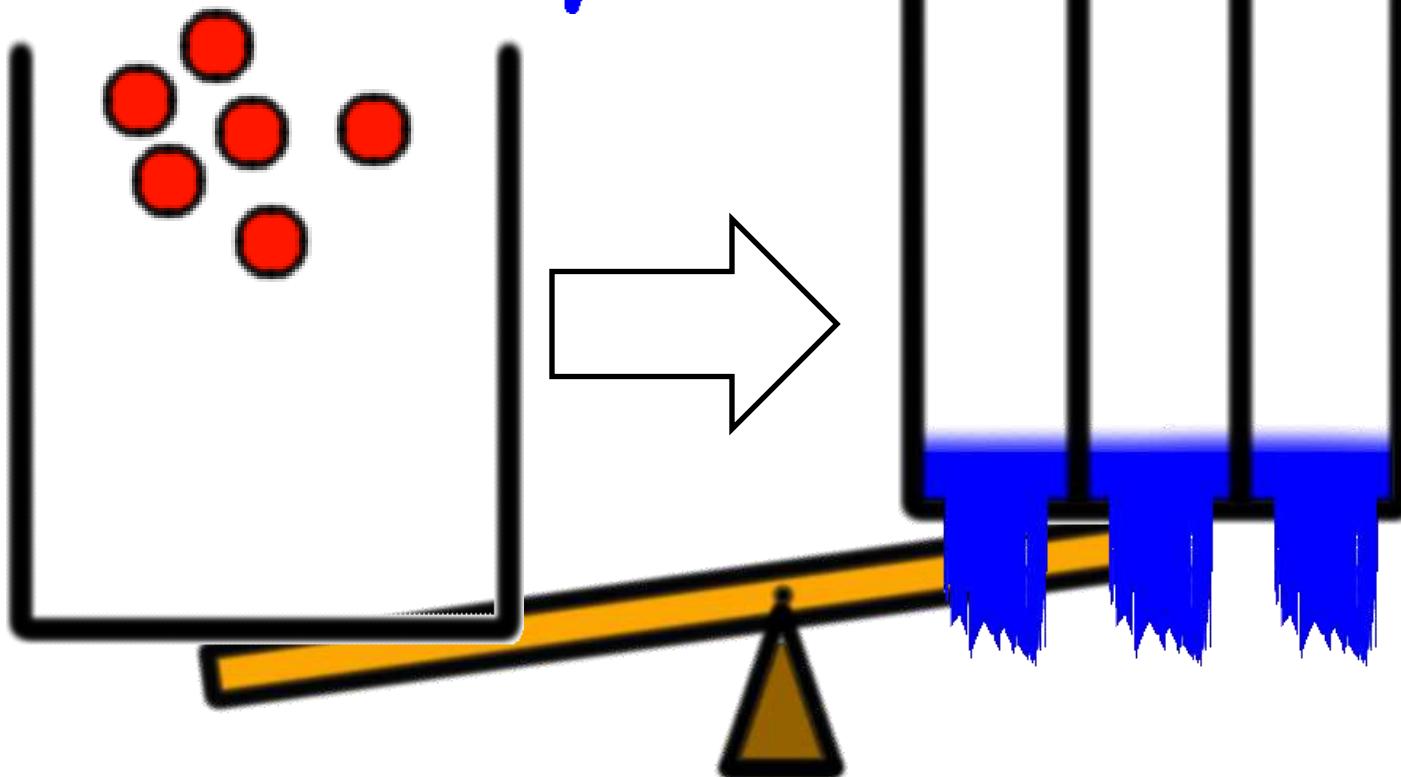




Wash-out with L -viol.

- ◎ If

large \cancel{L} ^{sphaleron} (in the sphaleron era),

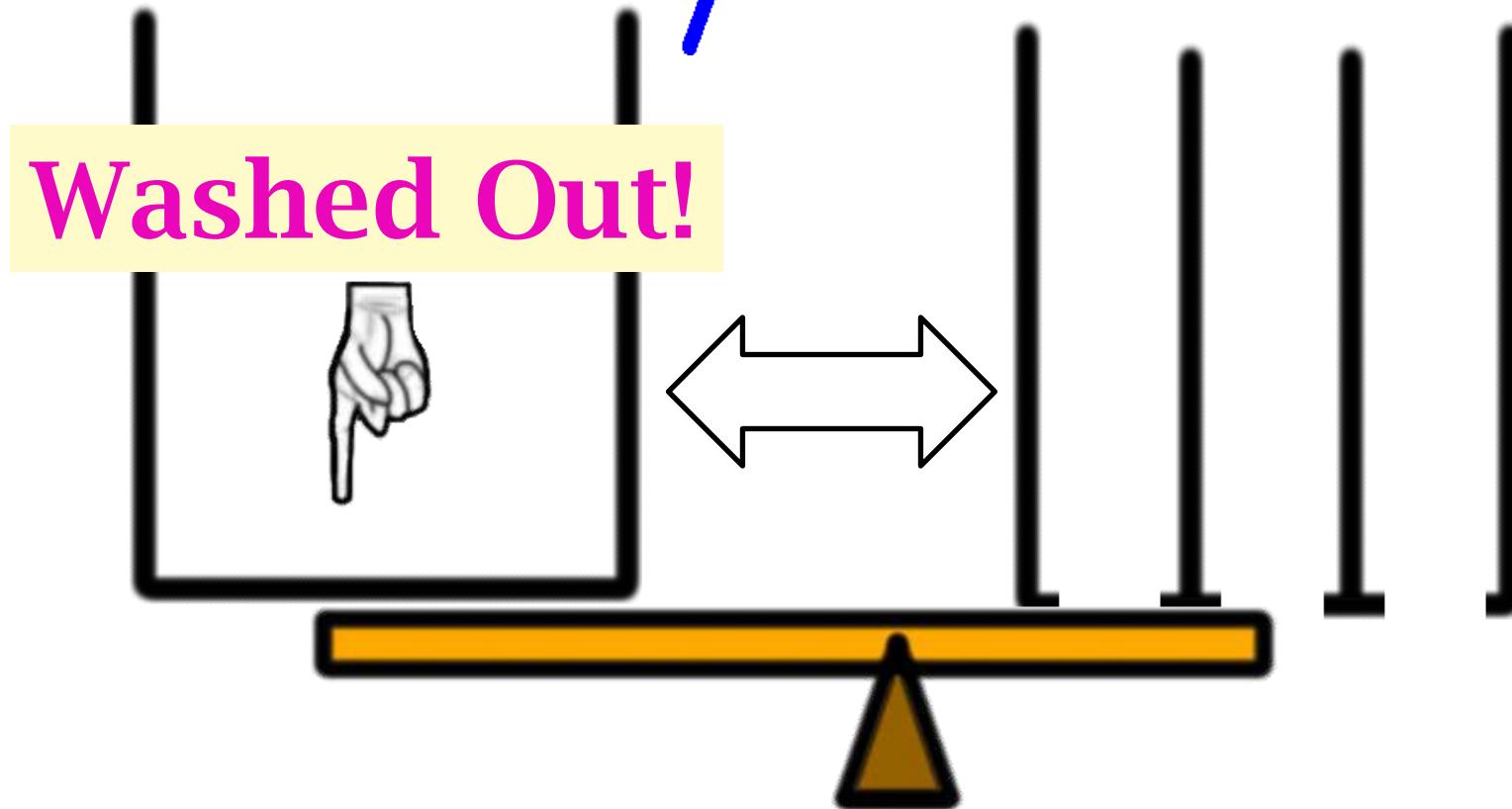


Wash-out with L -viol.



◎ If

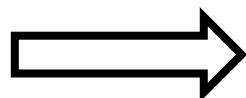
large L (in the sphaleron era),





Wash-out with *L*-viol.

Point



“Wash out”

Then

How about

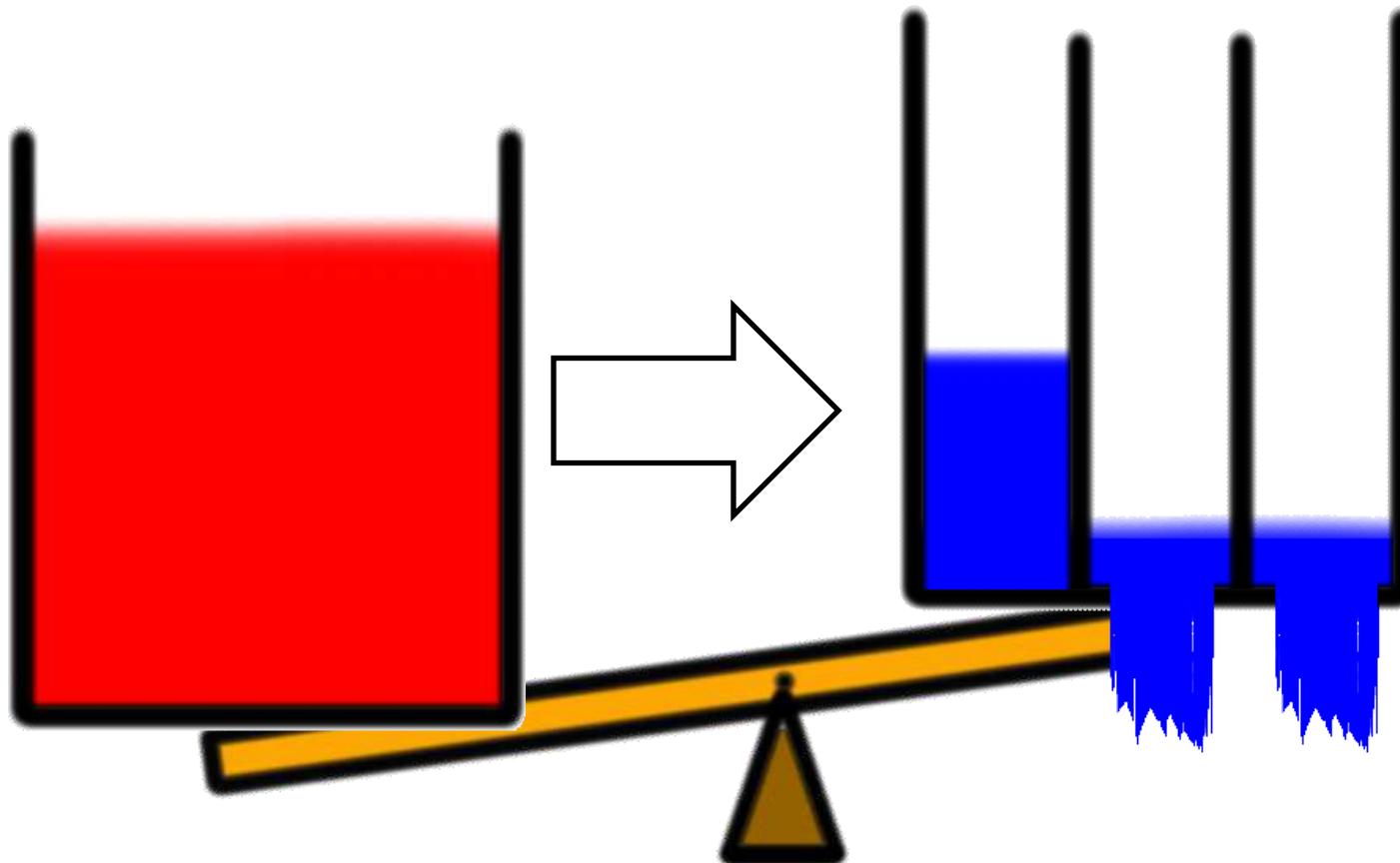


?

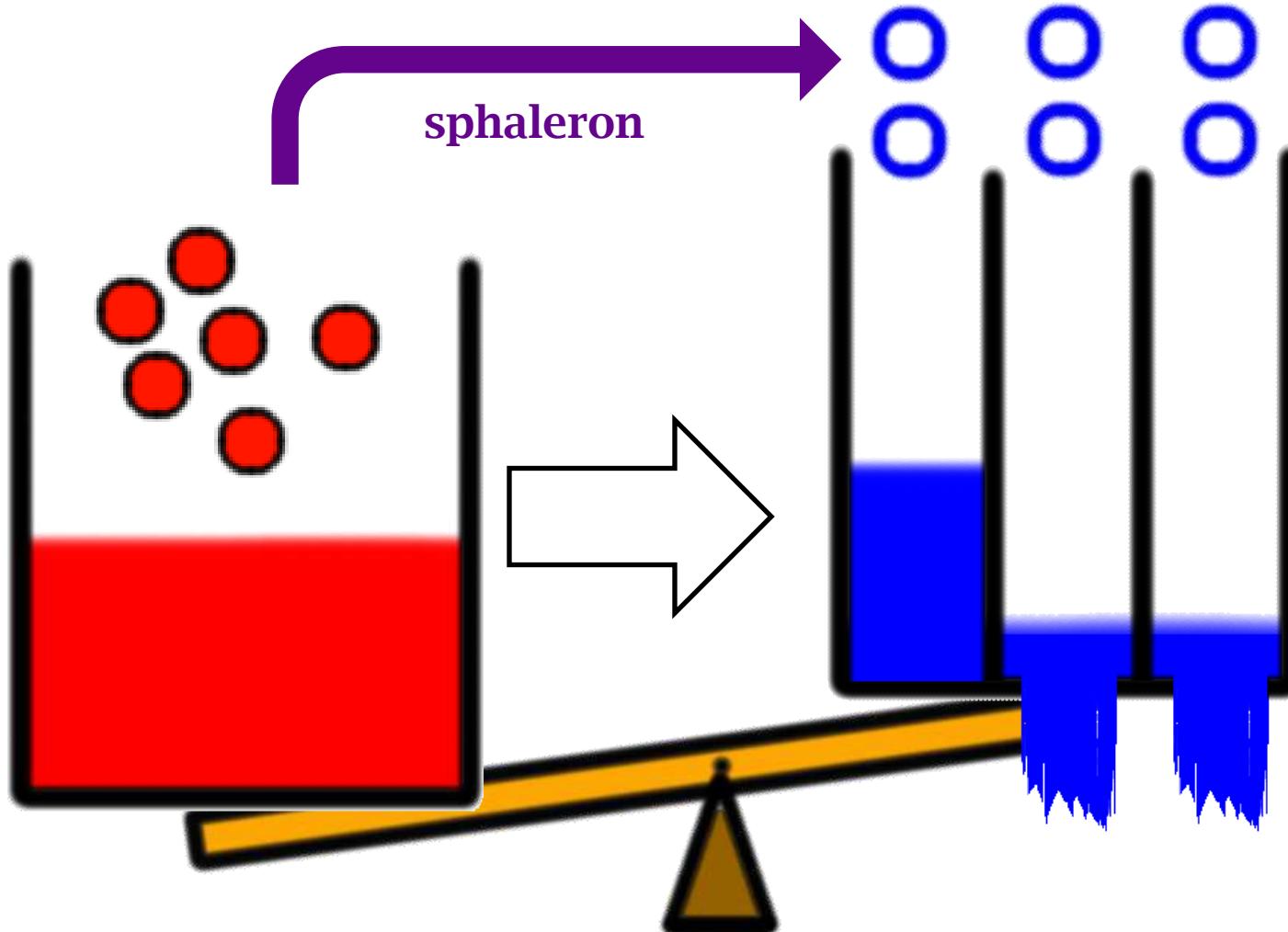




Wash-out with L -viol.

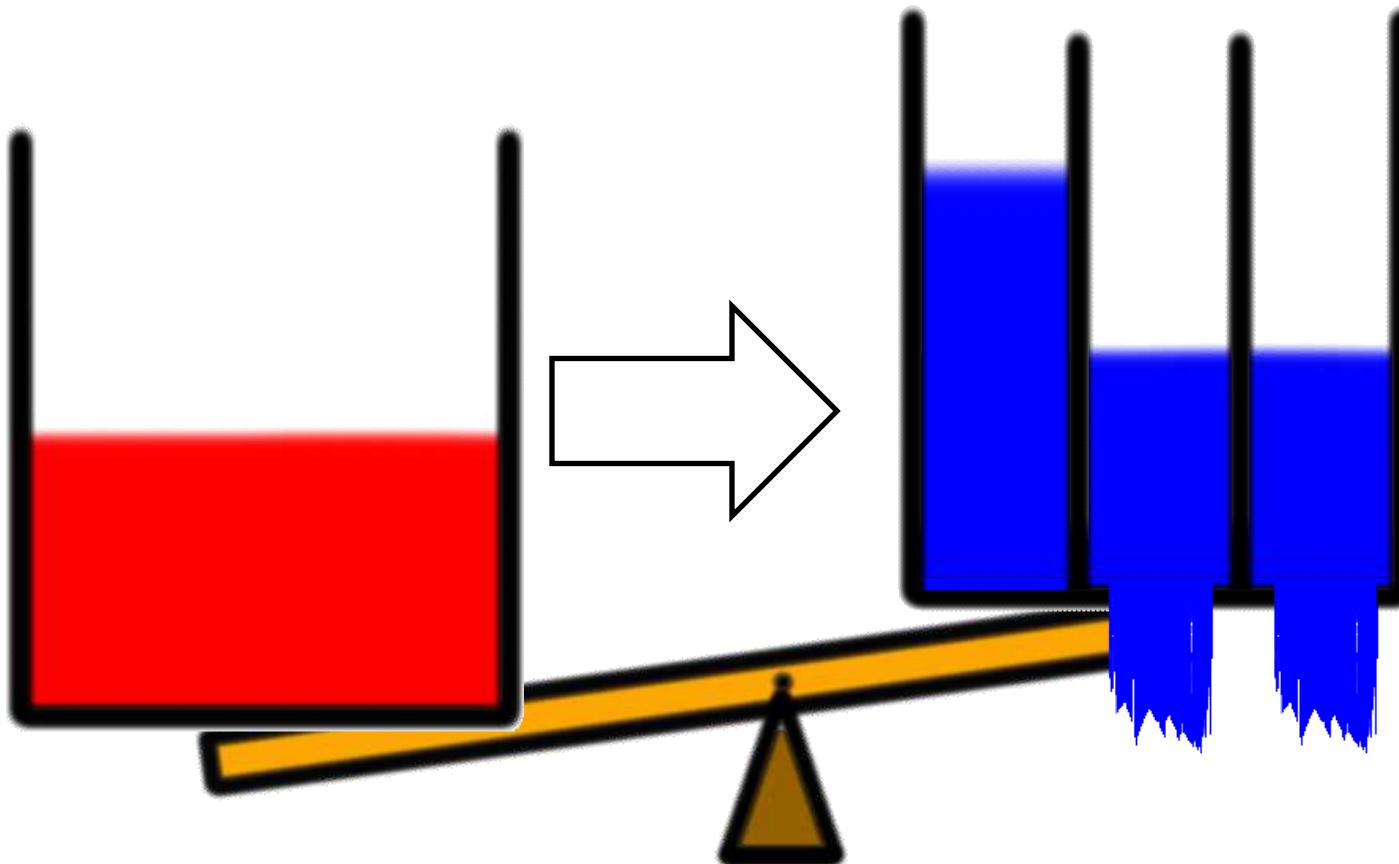


Wash-out with L -viol.

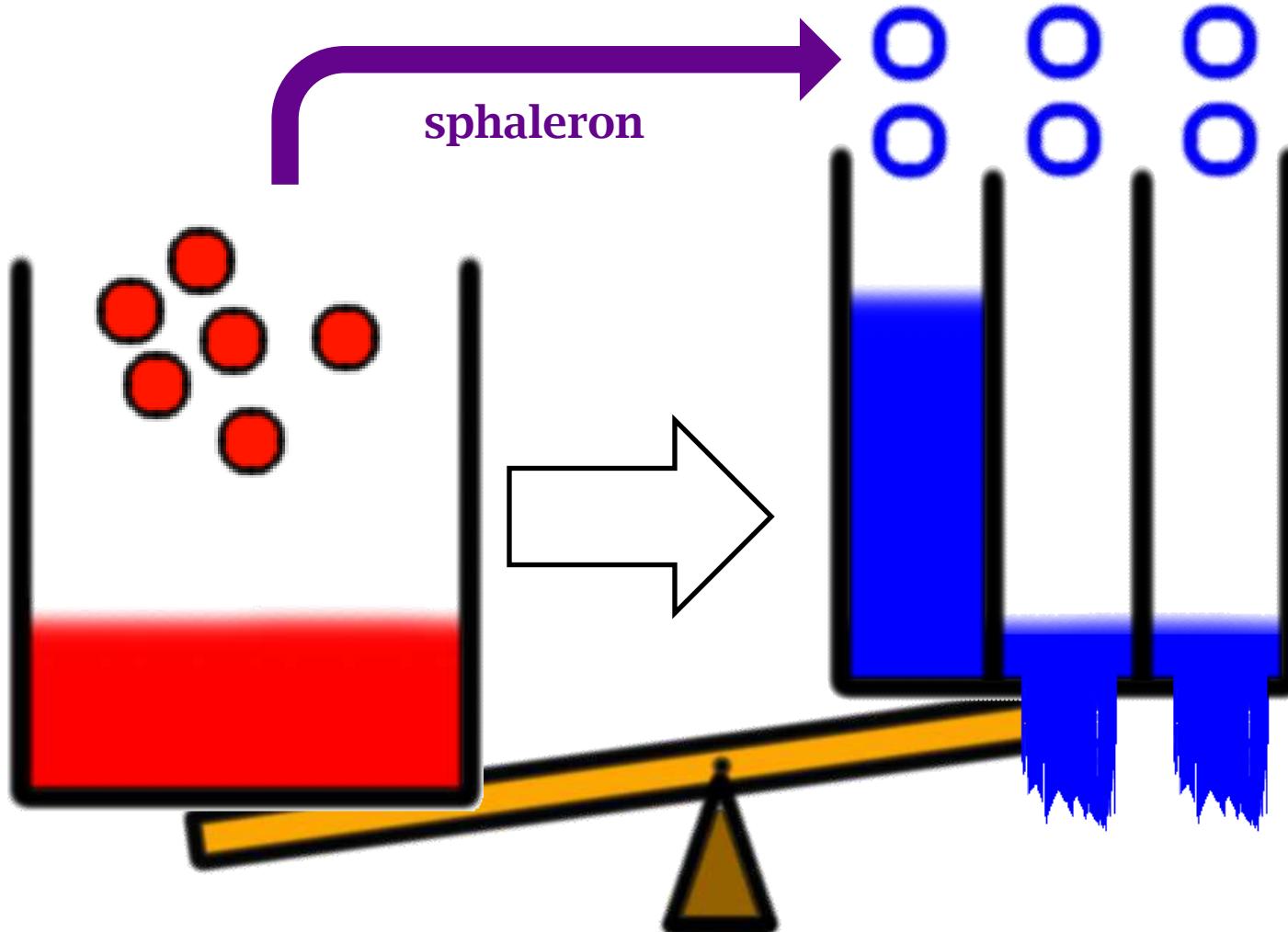




Wash-out with L -viol.

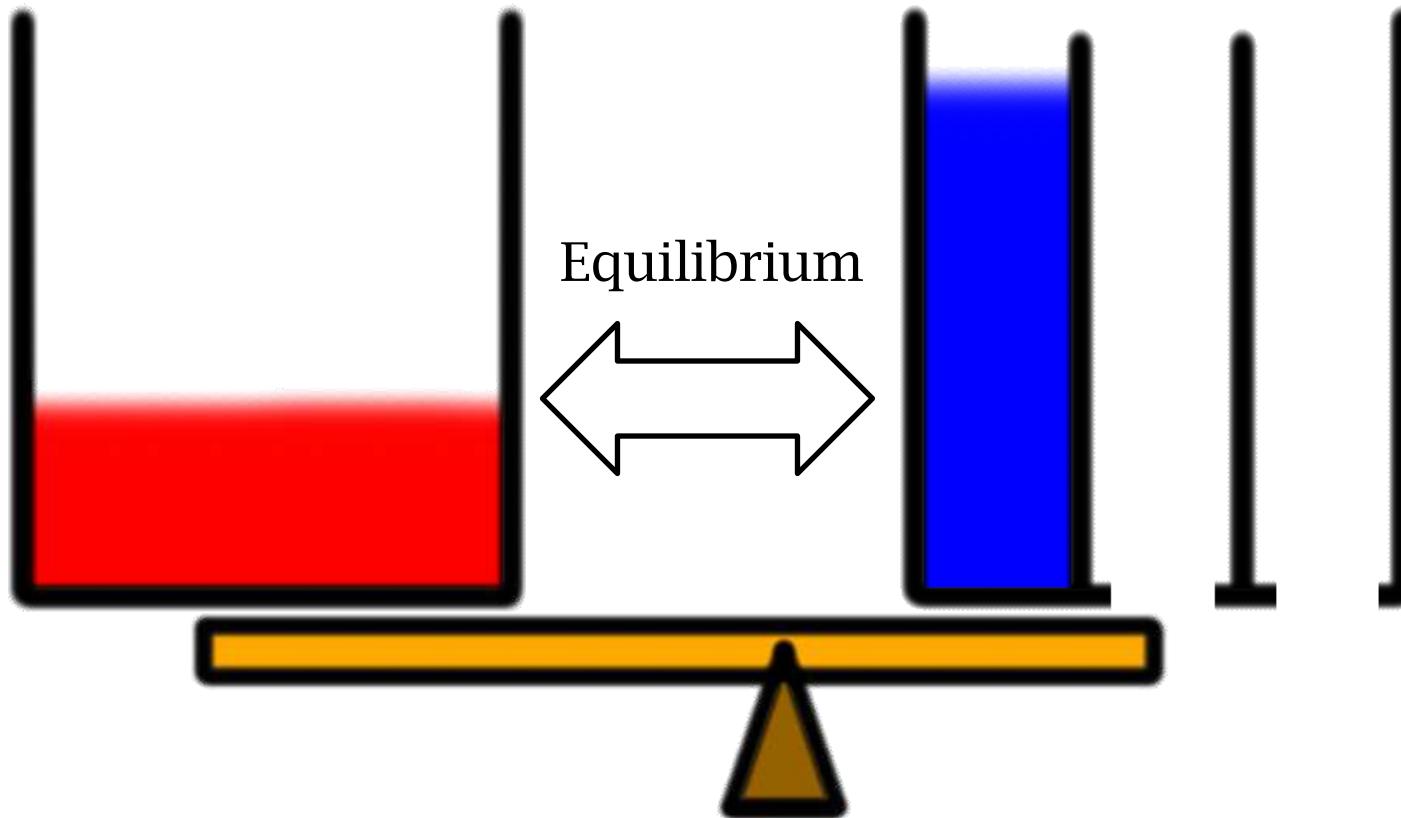


Wash-out with L -viol.



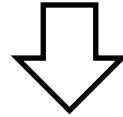
Wash-out with L -viol.

Baryon has survived!

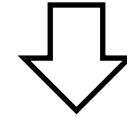
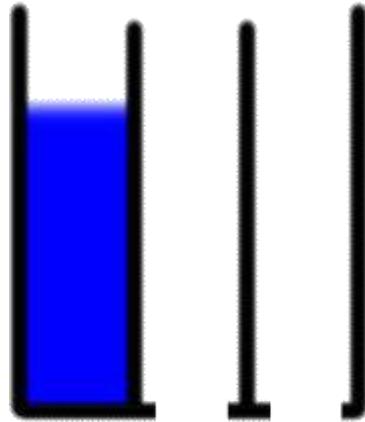


Wash-out with L -viol.

\cancel{L}



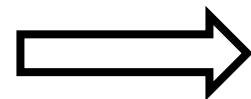
Wash-out! 



Baryon Survives. 

Point

All L_i 's leak in sphaleron era



“Wash out”

Wash-out with L -viol.

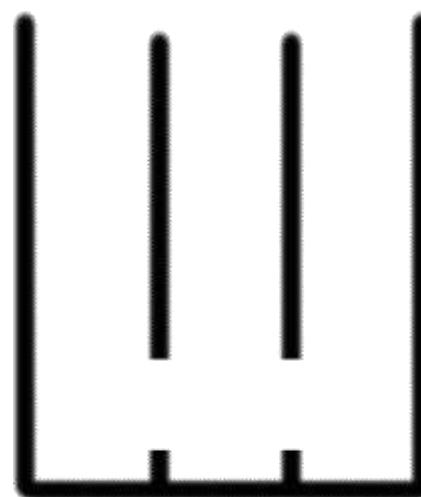
Our Attention

In MSSM, generally,

We have **LFVs!!!**



The Standard Model

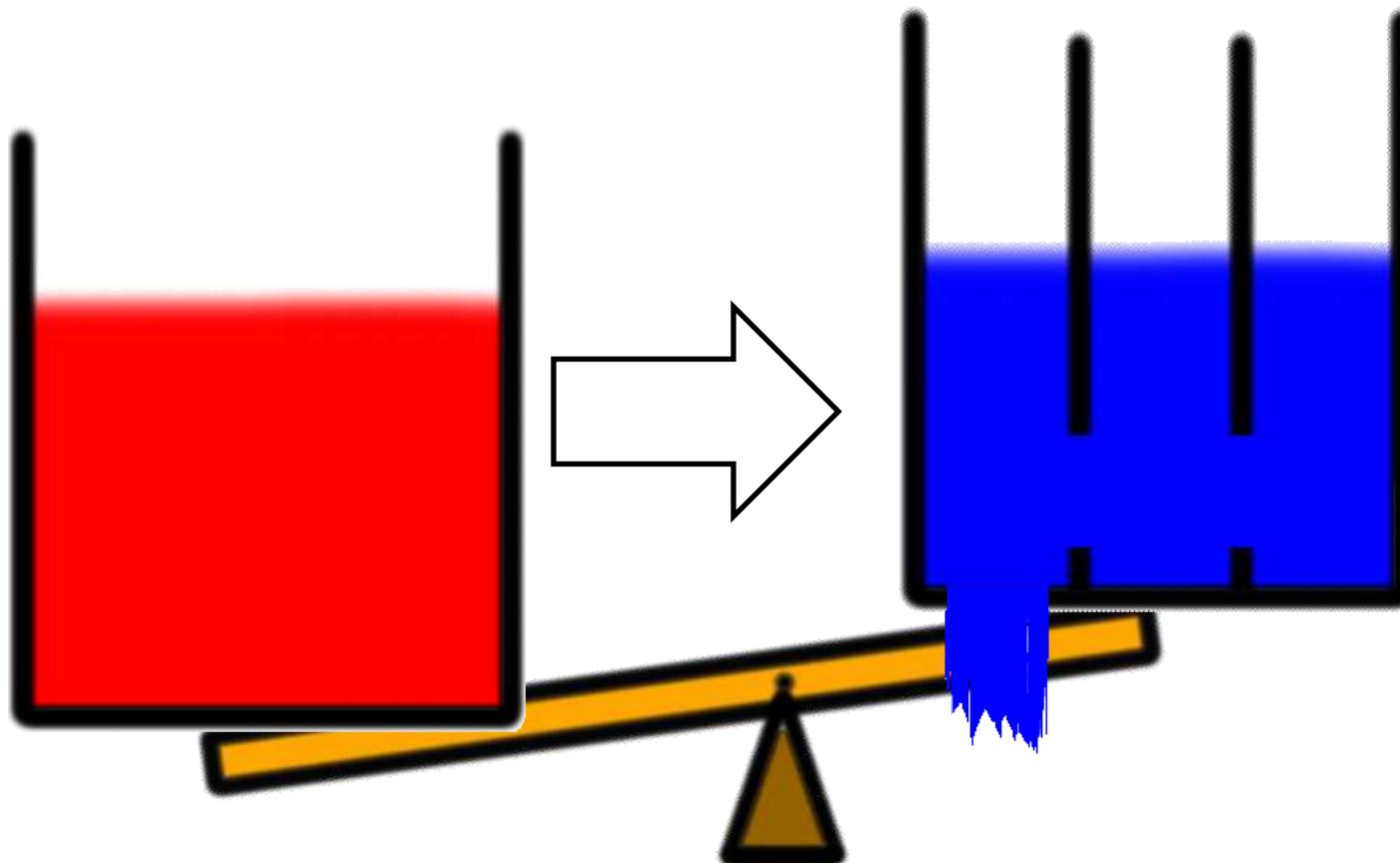


The MSSM

Wash-out with L -viol.

L

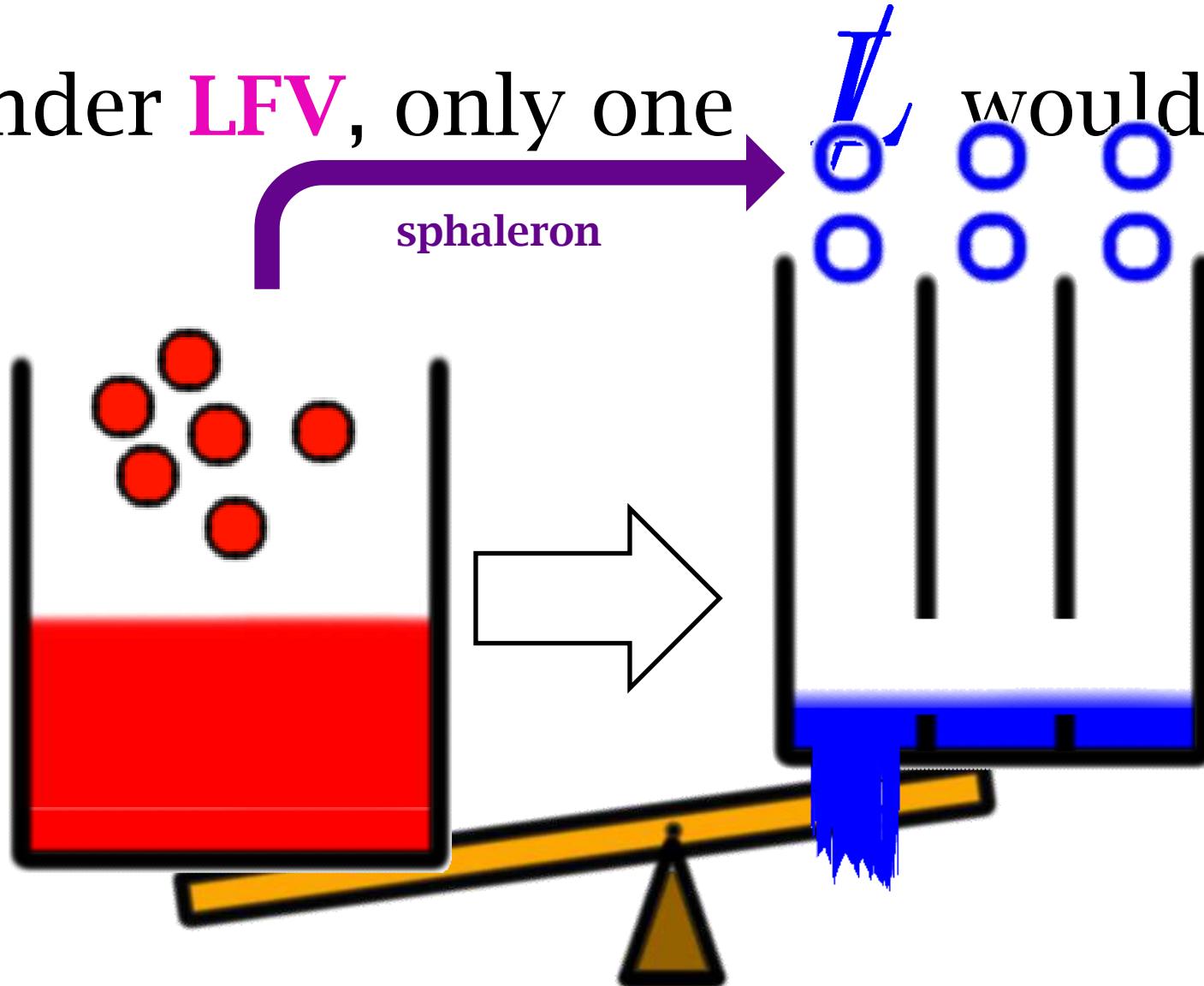
Under **LFV**, only one L would ...





Wash-out with L -viol.

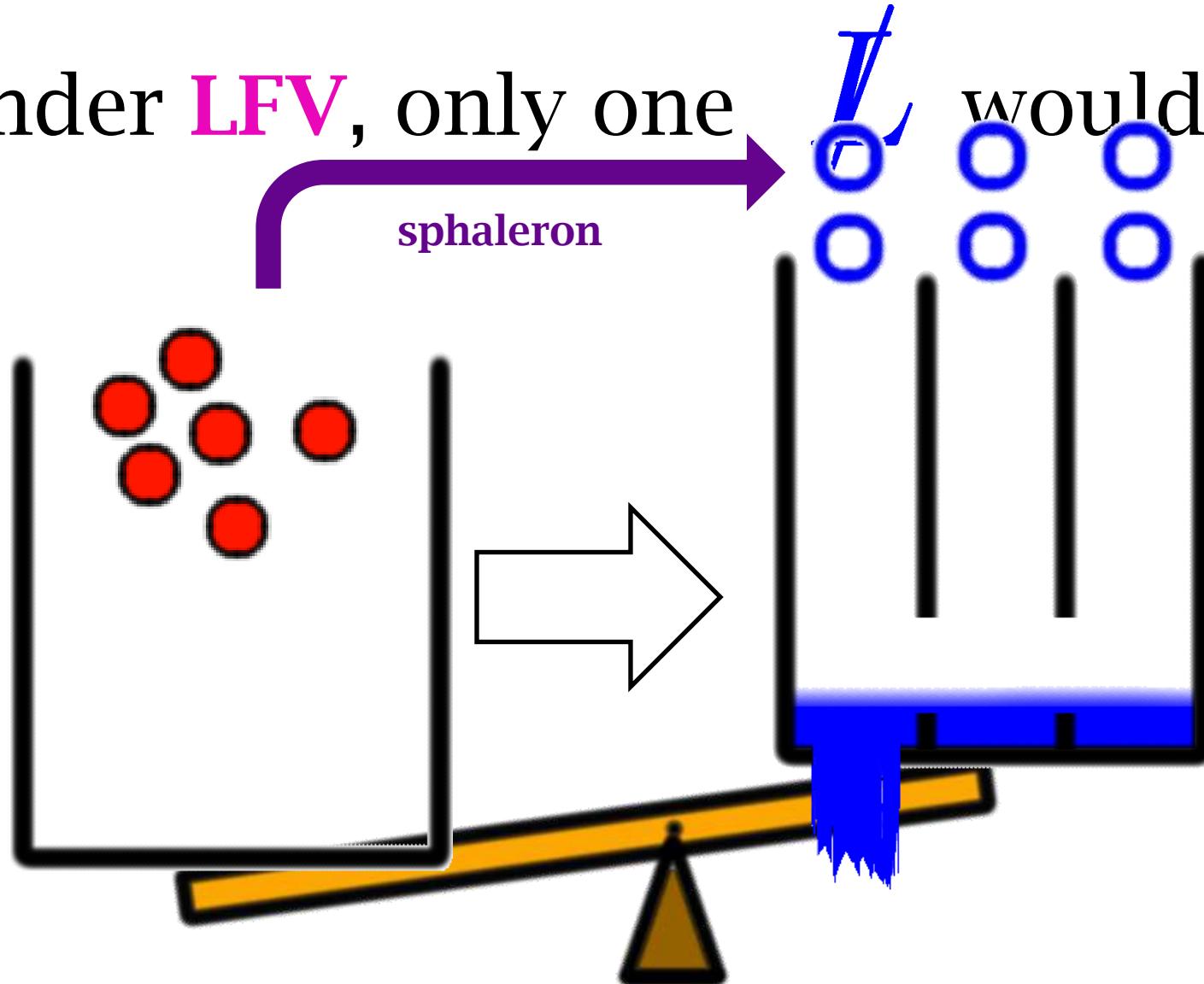
Under **LFV**, only one L would ...





Wash-out with L -viol.

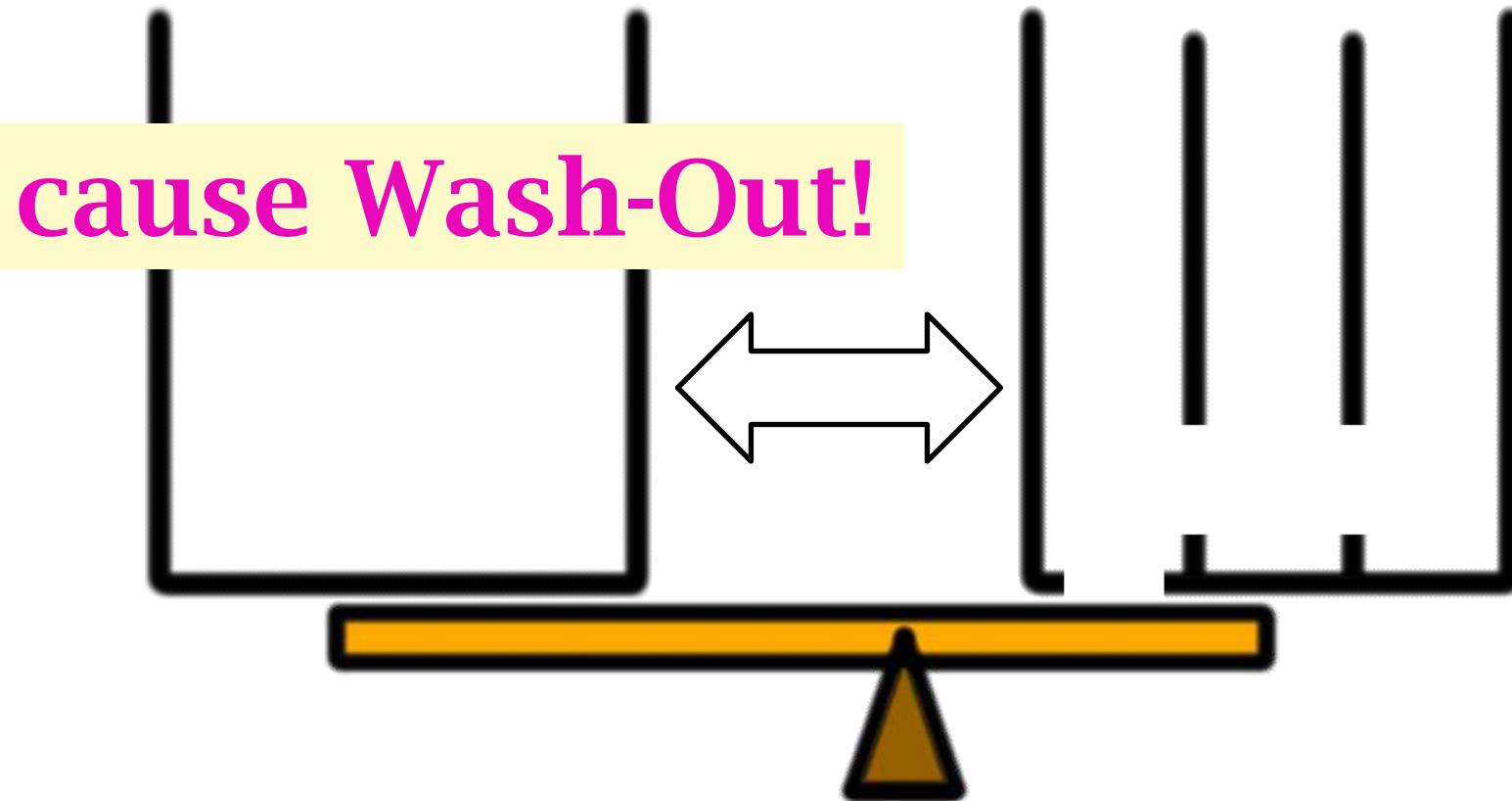
Under **LFV**, only one L would ...



Wash-out with L -viol.

\cancel{L}

Under **LFV**, only one \cancel{L} would ...



LESSON

- ◉ \mathcal{B} -MSSM : Large \mathcal{B} = wash out 
- $\Rightarrow \mathcal{B}$ couplings (λ'') = small enough
- ◉ \mathcal{L} -MSSM : (in sphaleron era)
 All \mathcal{L}_i leak via Large \mathcal{L} (directly) or LFV
 = wash out 
- \Rightarrow Assuming large LFV,
 \mathcal{L} couplings ($\kappa, \lambda, \lambda'$) = small enough

LESSON

?

How large?

?

How small must be?

There are our main target!

◎ L -MSSM : (in phaleron era)

All L_i leak via Large L (directly) or LFV

= wash out 😞

⇒ Assuming large LFV,
 L couplings ($\kappa, \lambda, \lambda'$) = small enough

3. Method and Results

LESSON



How large?



How small must be?

⦿ L -MSSM : (in sphaleron era)

All L_i leak via Large L (directly) or LFV



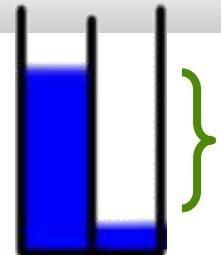
= wash out

⇒ Assuming large LFV,
 L couplings ($\kappa, \lambda, \lambda'$) = small enough

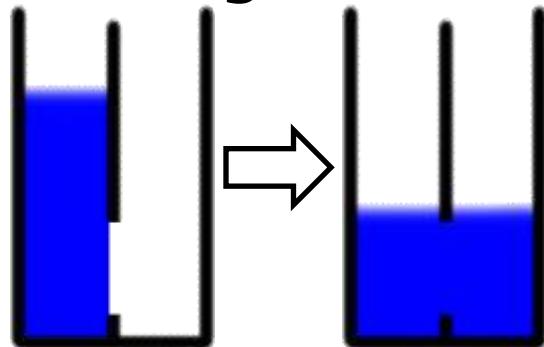
Method

Lepton number density of i -th generation

We calculated $\frac{d}{dt} (L_i - L_j)$ by Boltzmann Eq.

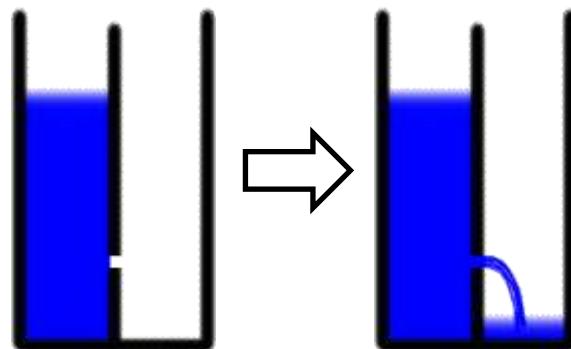


Large LFV



$$L_i - L_j \rightarrow 0$$

Tiny LFV

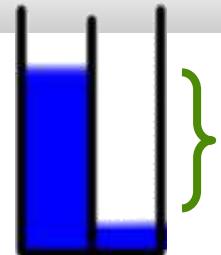


$$L_i - L_j \neq 0$$

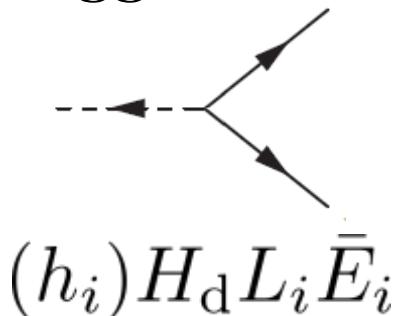
Method

We calculated $\frac{d}{dt} (L_i - L_j)$ by Boltzmann Eq.

Lepton number density of i -th generation



Higgs Yukawa

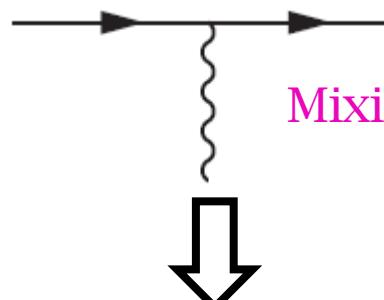


$$(h_i) H_d L_i \bar{E}_i$$

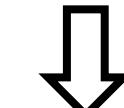
$$(h_{ij}) H_d L_i \bar{E}_j$$

LFV

Gauge inter.



Mixing angle



Diagonalize

Soft mass

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

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

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

Method

Example)

$$h_{23} \simeq \left(\frac{105 \text{ MeV}}{174 \text{ GeV}} \cdot \theta_{23}^{\bar{E}} + \frac{1.78 \text{ GeV}}{174 \text{ GeV}} \cdot \theta_{32}^L \right) \tan \beta$$
$$\simeq (0.006 \cdot \theta_{23}^{\bar{E}} + 0.1 \cdot \theta_{32}^L) \left(\frac{\tan \beta}{10} \right)$$

Mixing process:

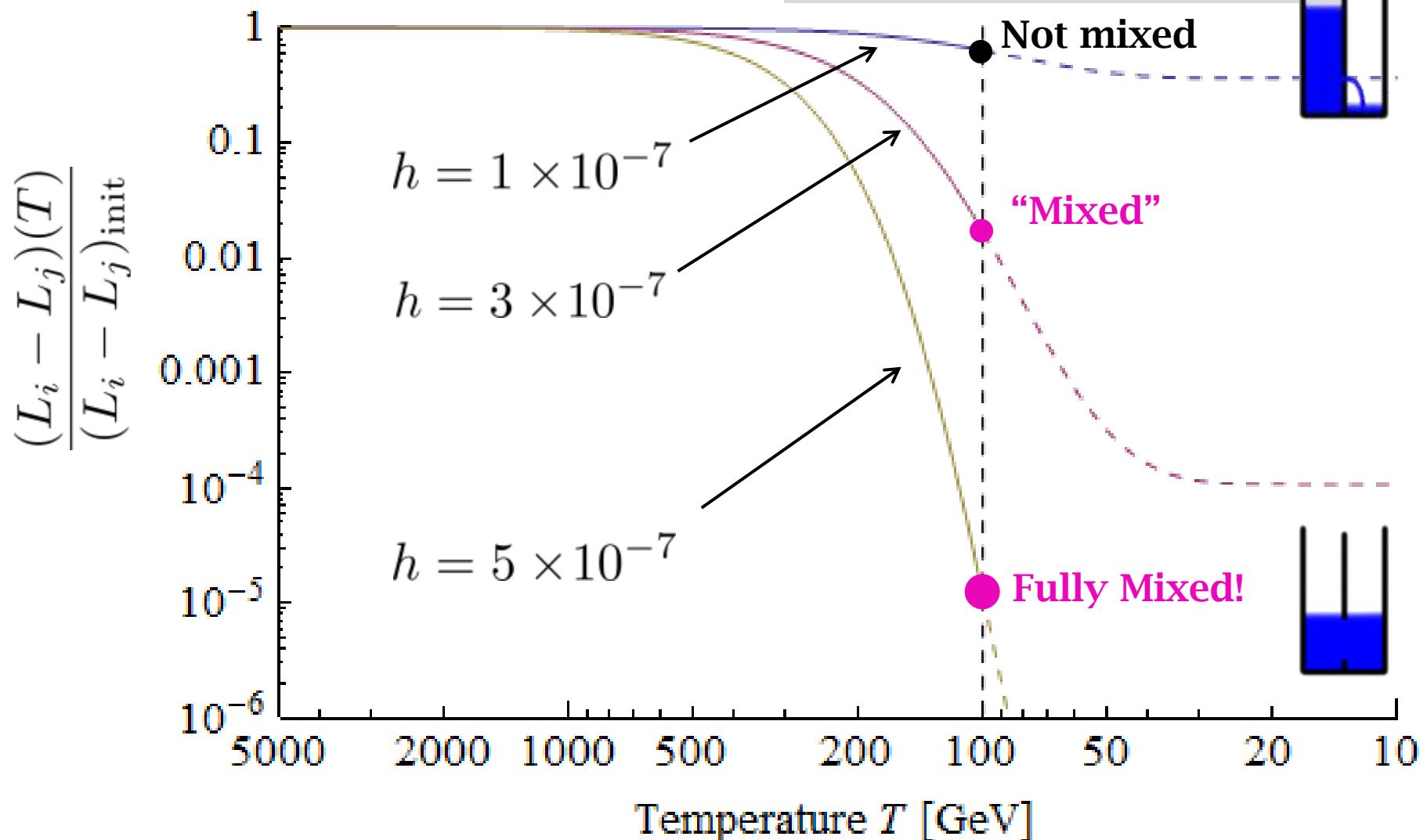
$$\tilde{H} \rightleftarrows l_i \tilde{e}_j^*, \quad \tilde{H} \rightleftarrows \tilde{l}_i e_j^\dagger$$

$$(h_{ij}) H_d L_i \bar{E}_j \quad h_{ij} := h_i \theta_{ij}^{\bar{E}} + h_j \theta_{ji}^L$$

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

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

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



$$m_{\tilde{H}} = 300 \text{ GeV}, \quad m_{\tilde{l}} = m_{\tilde{e}} = 100 \text{ GeV}$$

Conclusion (LFV)

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

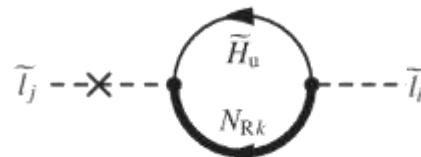


$h \gtrsim 3 \times 10^{-7} \rightarrow \text{MIXED}$

$\left. \begin{array}{l} \theta_{23}, \theta_{13} \gtrsim 3 \times 10^{-6}, \\ \theta_{12} \gtrsim 7 \times 10^{-5}. \end{array} \right\} \cdot \text{Well-Expected LFV}$

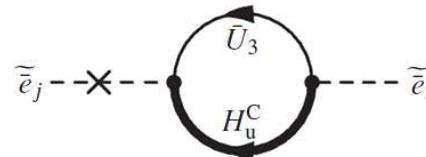
Cf.) Theoretical Expectation

1: ν_R



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

2: SU(5) GUT



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

where $\theta_{ij}^X \simeq \left(\frac{m_X^2}{\Delta m_X^2} \right) \delta_{ij}^X \gg \delta_{ij}^X$.

LESSON



How large?



How small must be?

⦿ L -MSSM : (in η -phaleron era)

All L_i leak via Large L (directly) or LFV

= wash out

⇒ Assuming large LFV,
 L couplings ($\kappa, \lambda, \lambda'$) = small enough

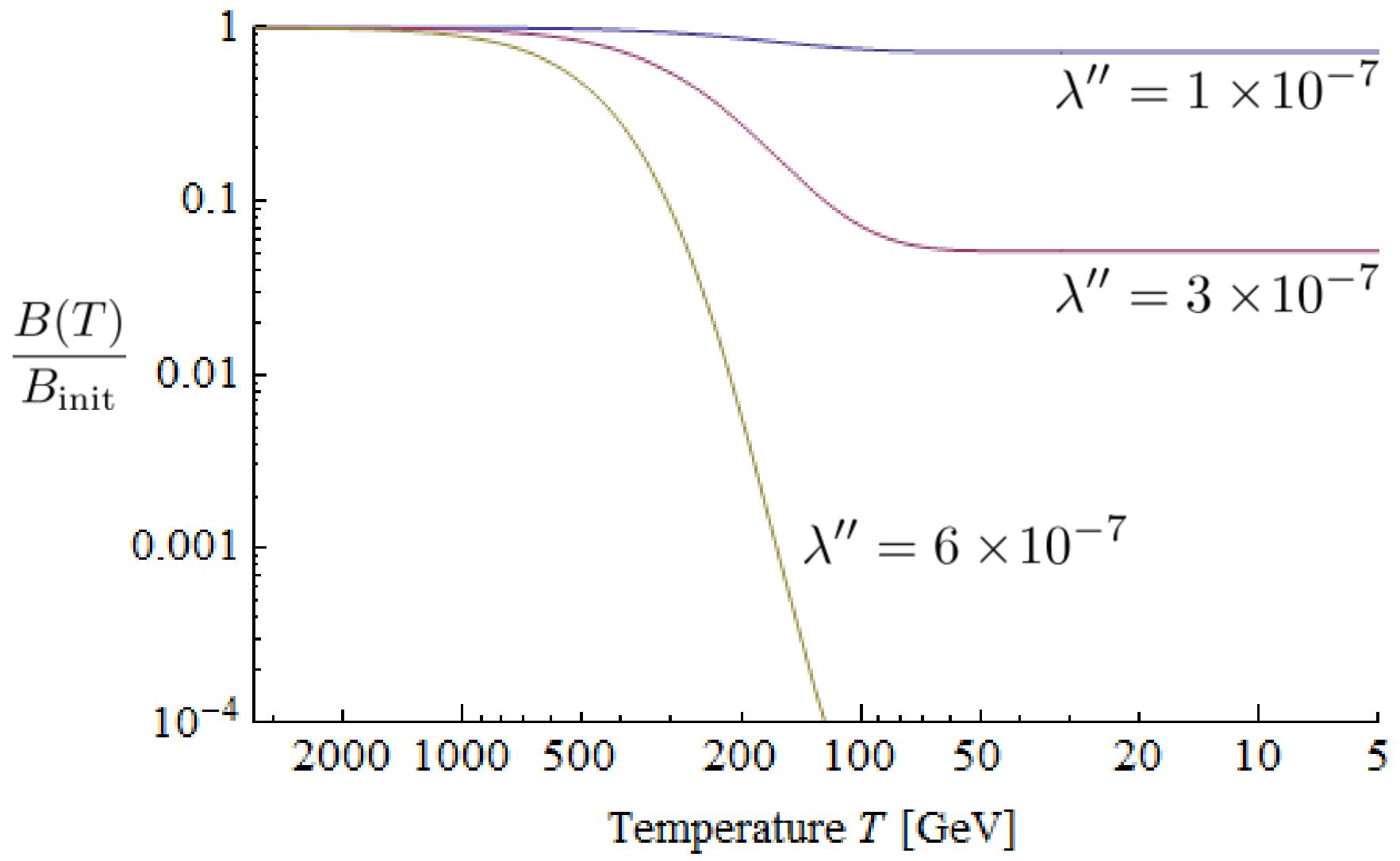
Method (RpV)

Method: **Boltzmann equation** (same as LFV!)

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

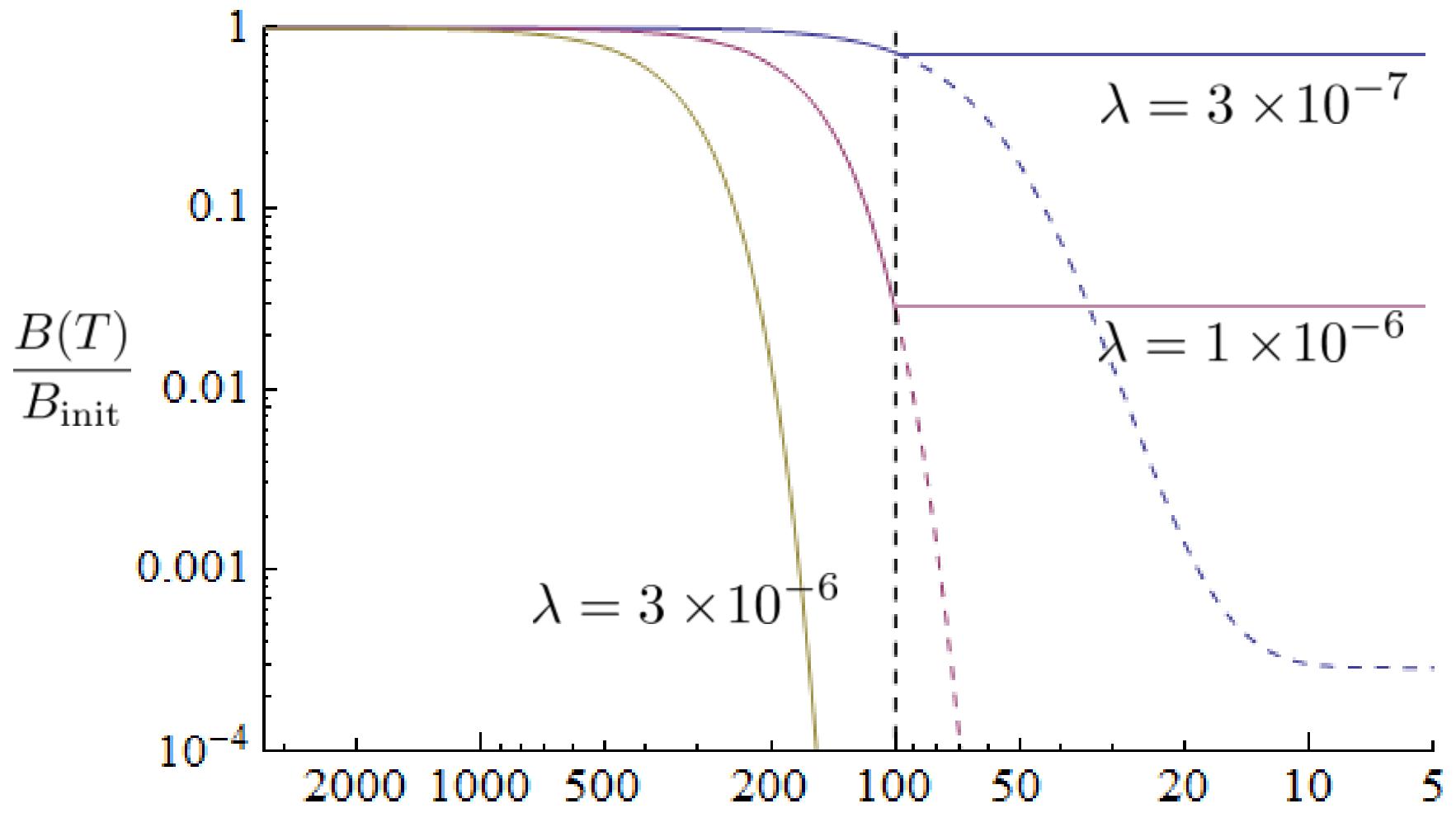
$$\left(\frac{d}{dt} (B - L) \sim \frac{79}{28} \frac{dB}{dt} \quad \text{in sphaleron era} \right)$$

$$W_{\mathcal{B}} \ni \lambda'' \bar{U}_i \bar{D}_j \bar{D}_k$$



for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

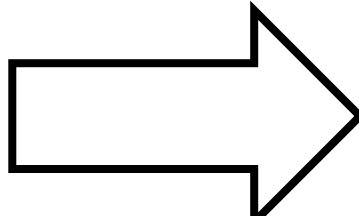
$$W_L \ni \lambda L_i L_j \bar{E}_k$$



for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

Conclusion (RpV)

Method: Boltzmann eq. of $\frac{d}{dt} (B - L)$


$$\left. \begin{array}{l} \lambda \lesssim 1 \times 10^{-6} \\ \lambda' \lesssim 3 \times 10^{-7} \\ \kappa \lesssim 1 \times 10^{-6} \cdot \mu \\ \lambda'' \lesssim 4 \times 10^{-7} \end{array} \right\} \begin{array}{l} \text{Under LFV} \\ (W \ni \mu H_u H_d) \end{array}$$

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

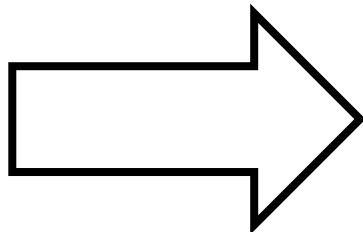
$$W_L = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

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

Conclusion (RpV)

Very Stringent Constraints!

than those from **collider experiments**. (They are $\sim 10^{-2}$).



$$\left. \begin{array}{l} \lambda \lesssim 1 \times 10^{-6} \\ \lambda' \lesssim 3 \times 10^{-7} \\ \kappa \lesssim 1 \times 10^{-6} \cdot \mu \\ \lambda'' \lesssim 4 \times 10^{-7} \end{array} \right\} \begin{array}{l} \text{Under LFV} \\ (W \ni \mu H_u H_d) \end{array}$$

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

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

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

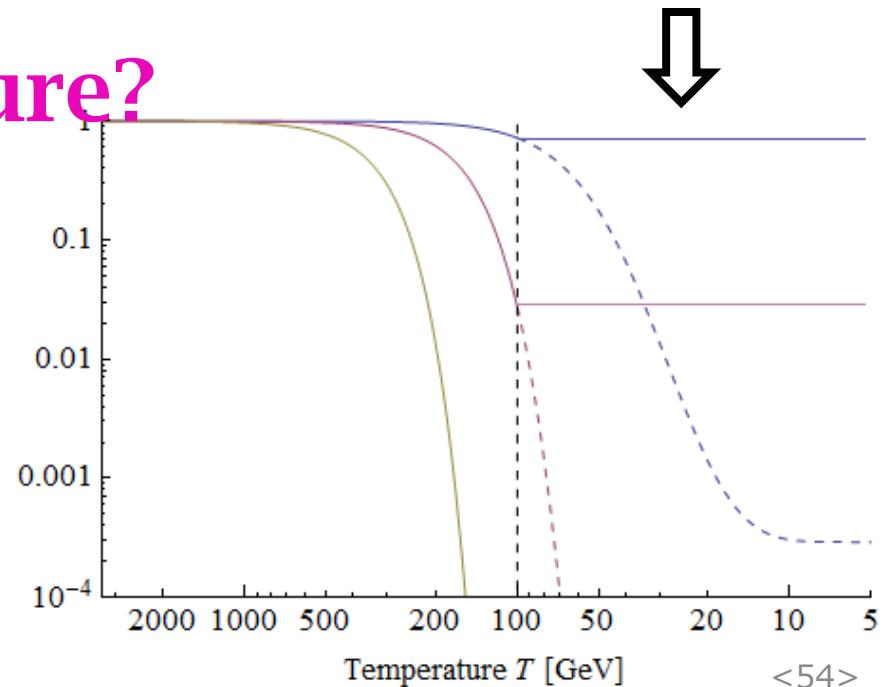
Some Loopholes

Some **loopholes!**

◎ LFV is **extremely small?** $(h < 3 \times 10^{-7})$

◎ **Baryogenesis
in Low-temperature?**

[e.g. Affleck-Dine /
Electroweak Baryogenesis]



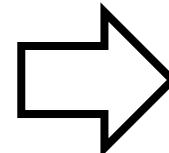
4. Application in LHC

“Kink track” observed?

Consequence of our Result

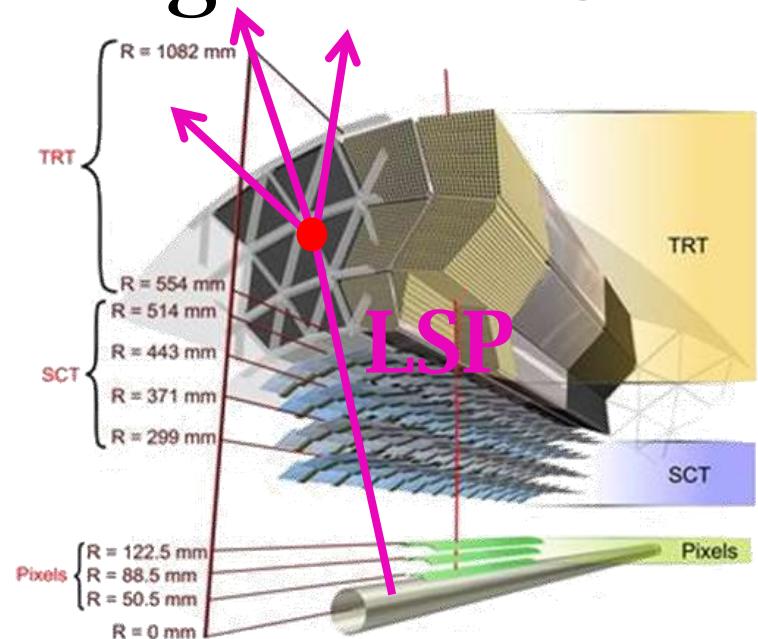
Our Result

Very small
 R -parity violation



Long-lived LSP

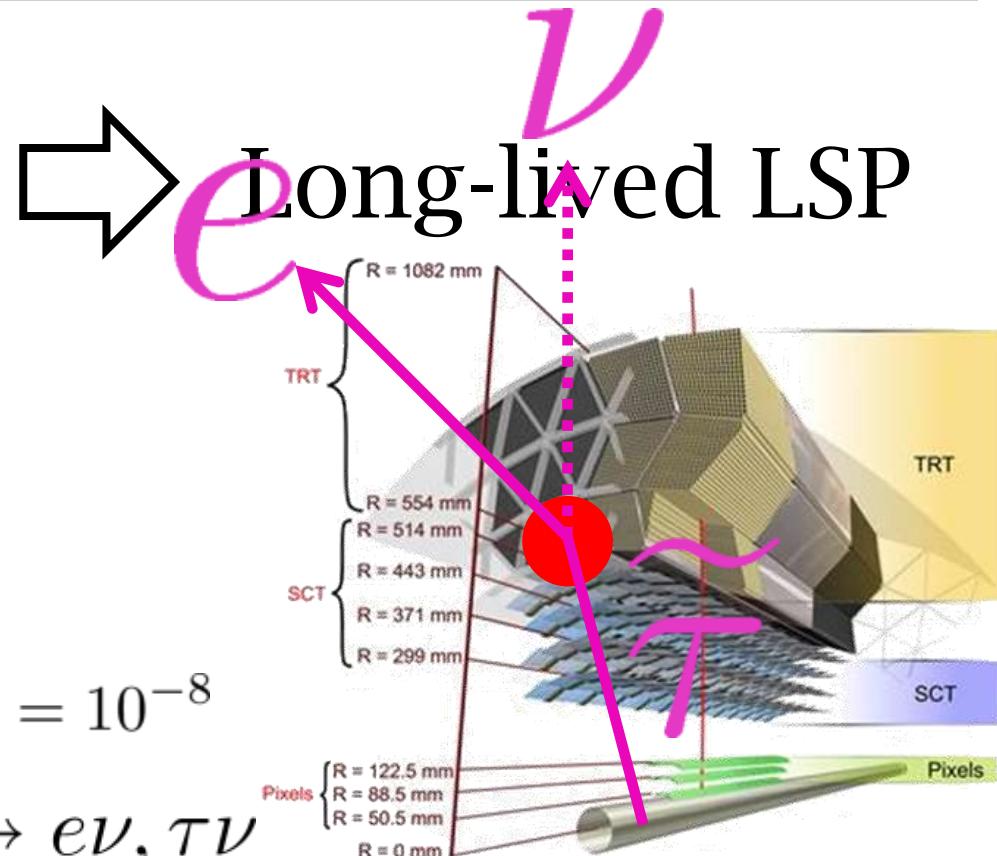
LSP might decay
in Detector.



Consequence of our Result

[Our Result]

Very small
 R -parity violation



Example

$\tilde{\tau}$ R-LSP (200GeV)

$$W_{\text{RPV}} = \lambda \mathbf{L}_1 \mathbf{L}_3 \bar{\mathbf{E}}_3; \quad \lambda = 10^{-8}$$

→ Decay : $\tilde{\tau} \rightarrow e\nu, \tau\nu$

$$[c\tau \sim 30 \text{ cm}]$$

“Kink track” observed?

Consequence of our Result

According to our **PRELIMINARY** calculation,

if $\lambda \sim 10^{-(8\ldots 9)}$,

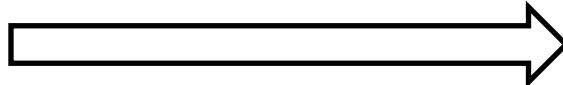
- ◎ 7TeV, 1fb^{-1} 1-10 kink events
- ◎ 14TeV, 10fb^{-1} 1-1000 kink events

will be generated (& might be observed?)
in LHC/ATLAS.

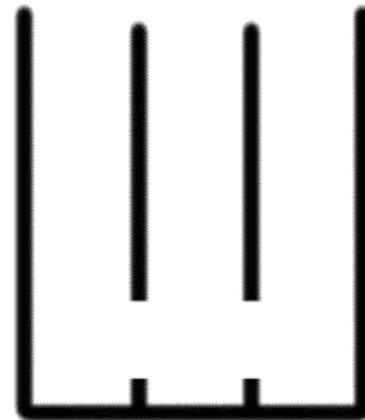
“Kink track” observed?

Summary

MSSM

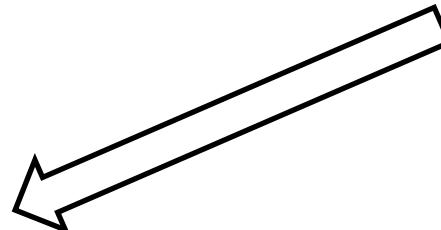


LFV!!



R-parity is
not a must.

B & *L* are
ALL small.



long-lived LSP
→ kink?

Appendices

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

C. Collider Constraints

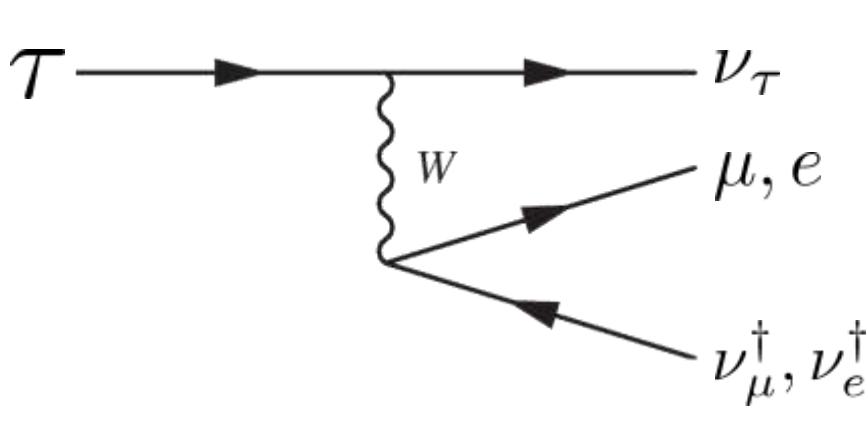
“The RpV interactions are constrained by several experimental facts.”

Constraints

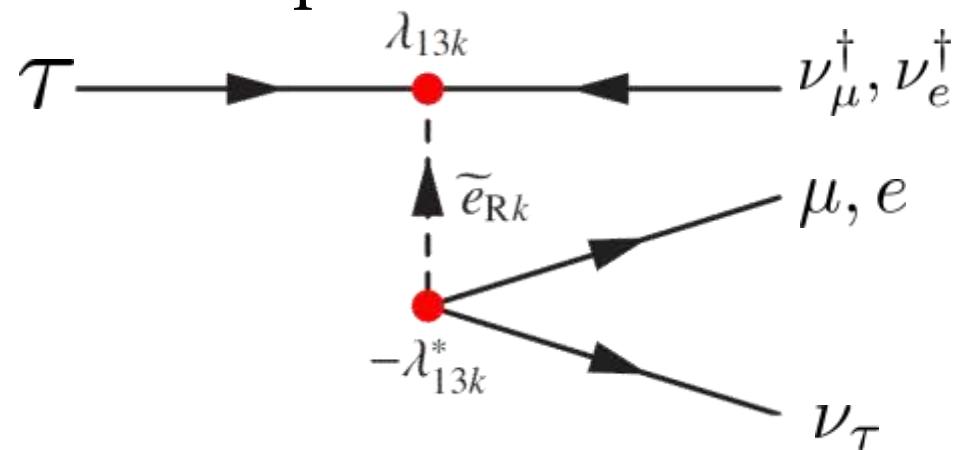
- ◎ Example:

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

Standard Model



RpV-MSSM



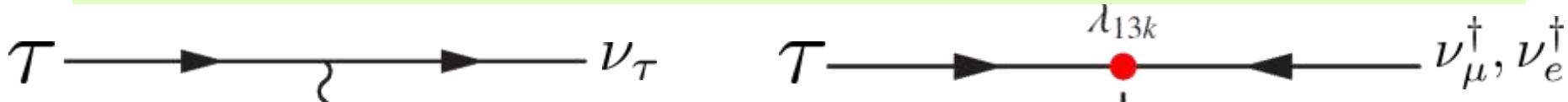
Additional Contribution!

Constraints

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

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

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

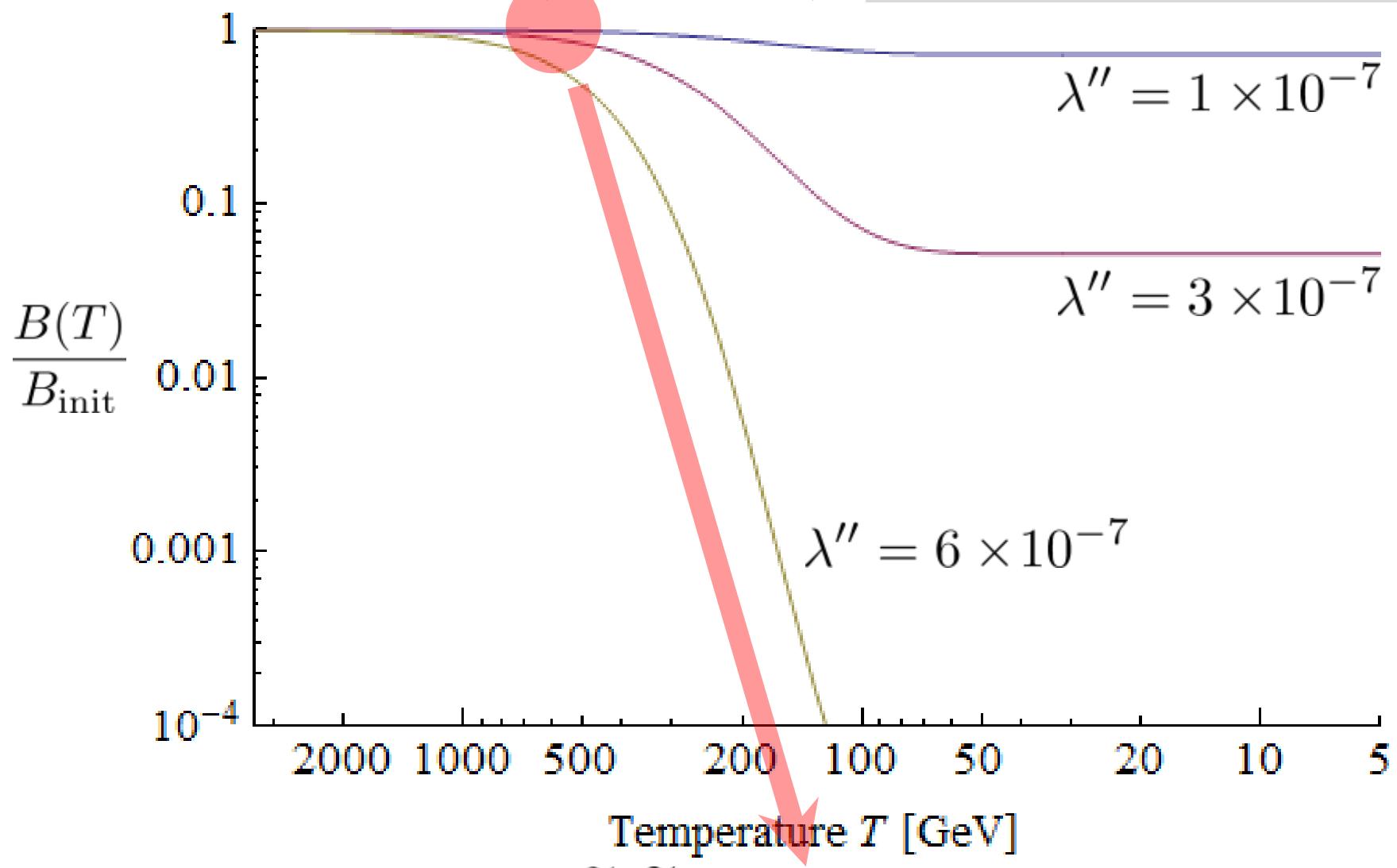


$$-0.051^2 < \sum_k \left[|\lambda_{13k}|^2 - |\lambda_{23k}|^2 \right] \left(\frac{100 \text{ GeV}}{m_{\tilde{e}_{Rk}}} \right)^2 < 0.051^2$$

Additional Contribution!

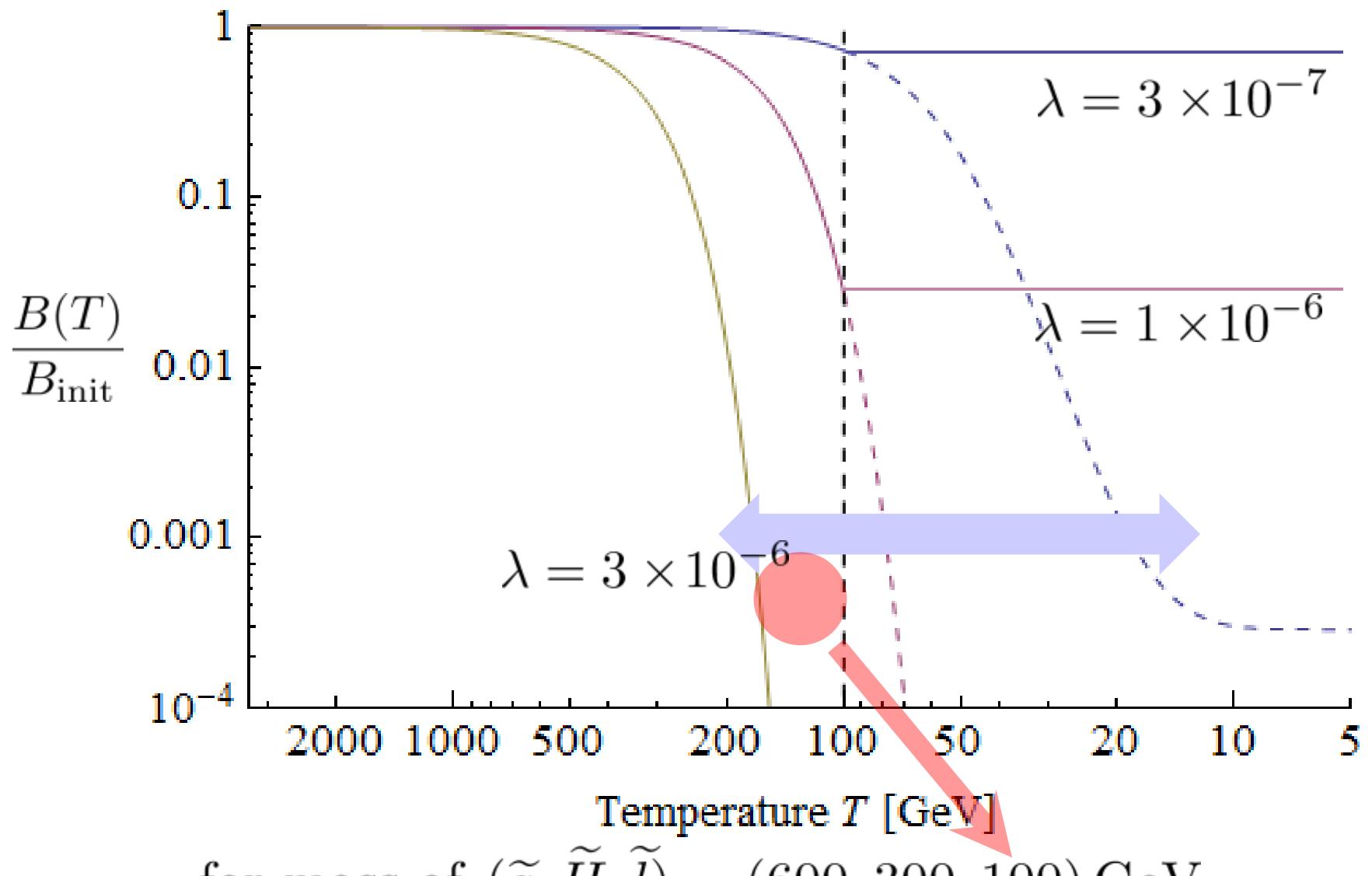
D. RpV Results

$$W_B \ni \lambda'' \bar{U}_i \bar{D}_j \bar{D}_k$$

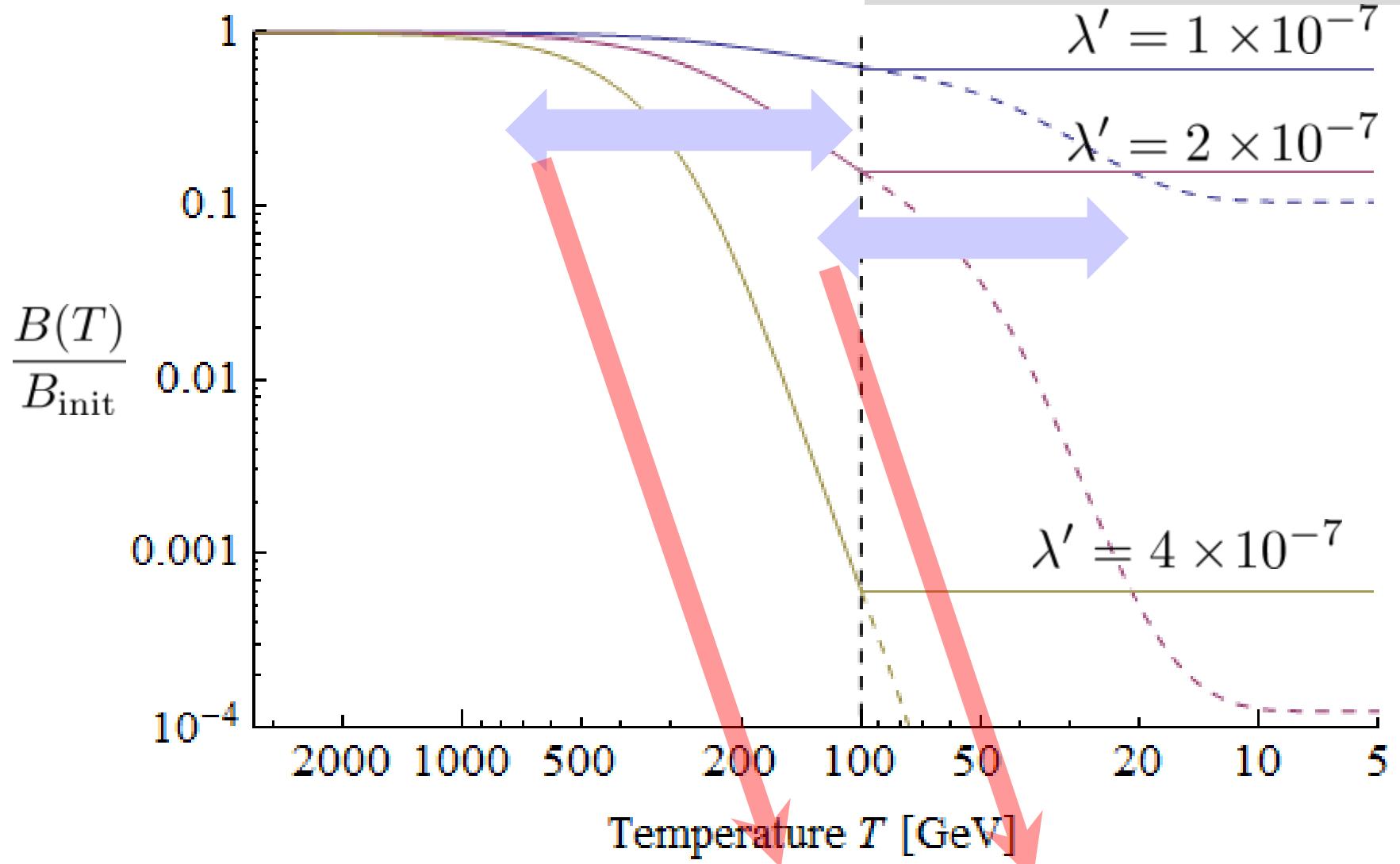


for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

$$W_L \ni \lambda L_i L_j \bar{E}_k$$

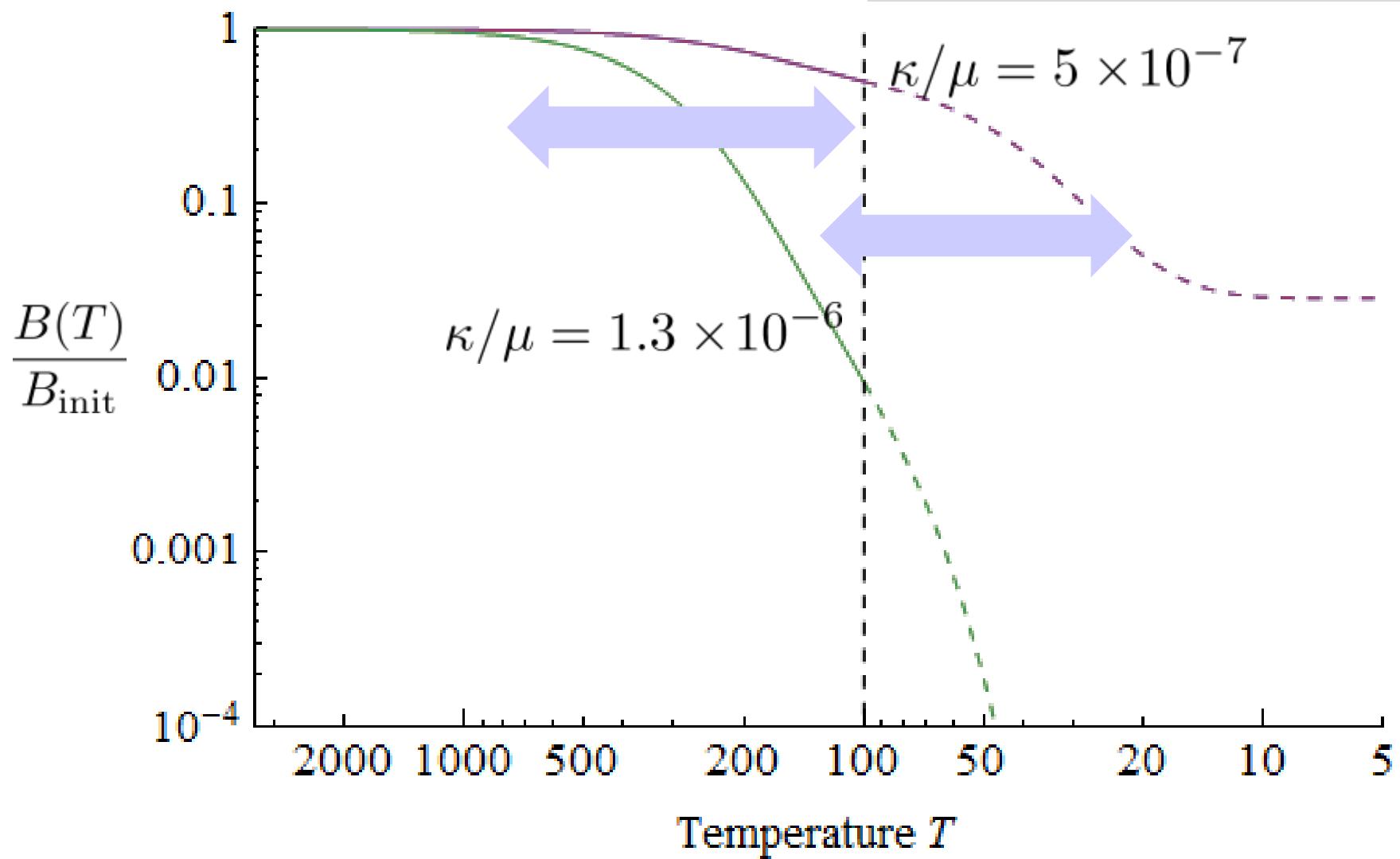


$$W_L \ni \lambda' L_i Q_j \bar{D}_k$$



for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

$$W_L \ni \kappa L_i H_u$$

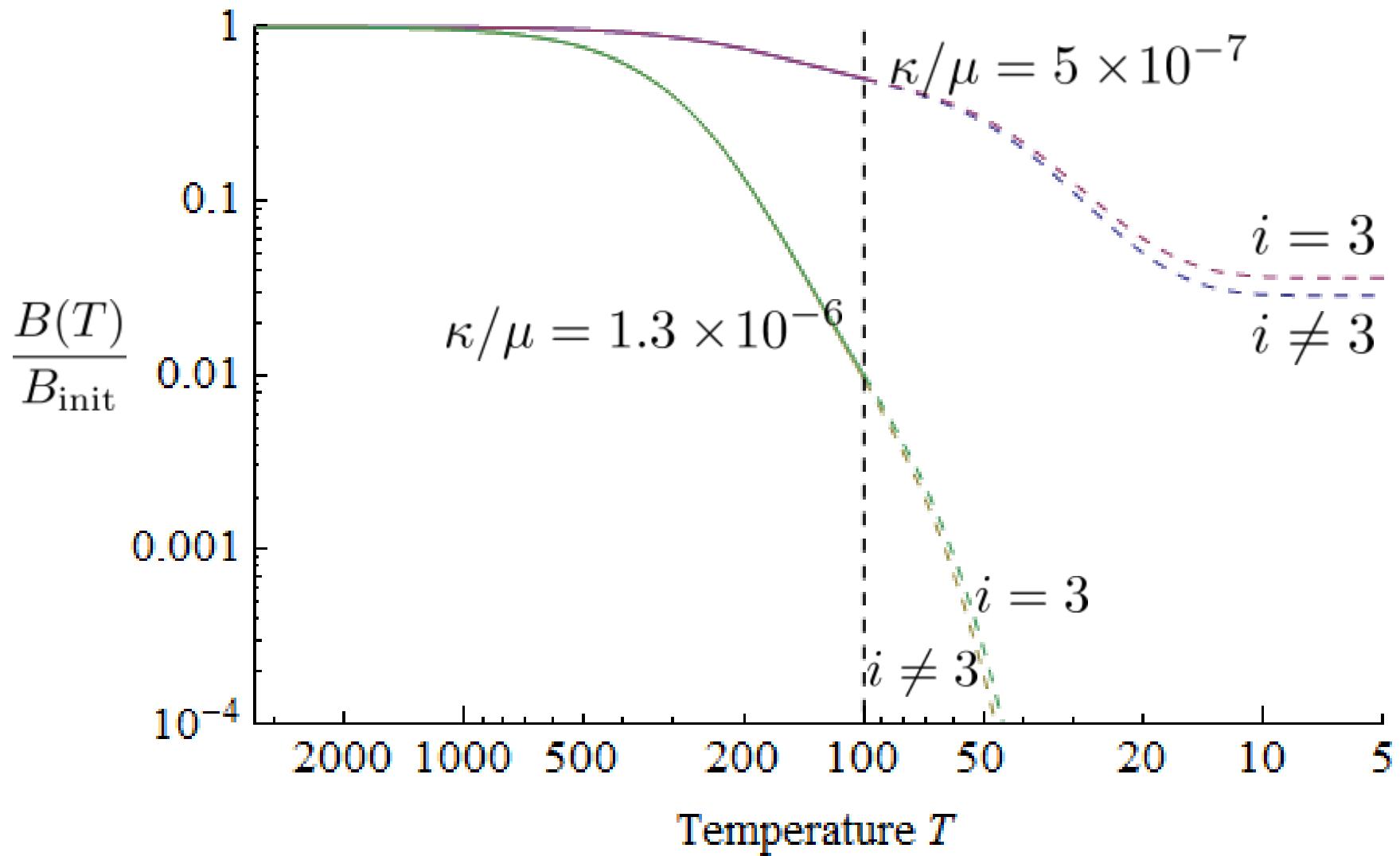


for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100) \text{ GeV}$
 $\tan \beta = 10$

D': RpV Results [Detail]

Very Detail.

$$W_L \ni \kappa L_i H_u$$



for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV
 $\tan \beta = 10$

$$\mu H_{\rm u}H_{\rm d}+\kappa_iL_iH_{\rm u}$$

$$\implies H_{\rm d}'\simeq H_{\rm d}+\epsilon_iL_i\quad (\epsilon_i:=\kappa_i/\mu)$$

$$\implies W_{\rm RPC}\ni y_dH_{\rm d}Q\bar{D}\longrightarrow -\epsilon_iy_dL_iQ\bar{D}$$

$$y_d\frac{174\,\mathrm{GeV}}{\tan\beta}\simeq m_d\qquad [\tan\beta=10]$$

$$\implies W\ni\epsilon_i\frac{m_d\tan\beta}{174\,\mathrm{GeV}}L_iQ\bar{D}\simeq(0.25\epsilon_i)L_iQ\bar{D}$$

$$0.25\epsilon_i\lesssim 3\times 10^{-7}\implies \epsilon_i\lesssim 1.2\times 10^{-6}$$

$$<71>$$

E. Method [Detail]

Approximations we used

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

Set up

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

Approximations

- We consider only the decay of Higgsino

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

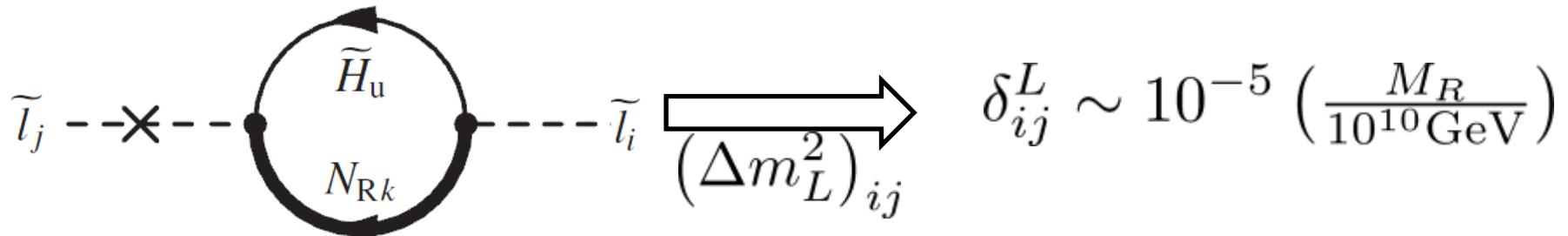
and the antiparticles' processes.

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

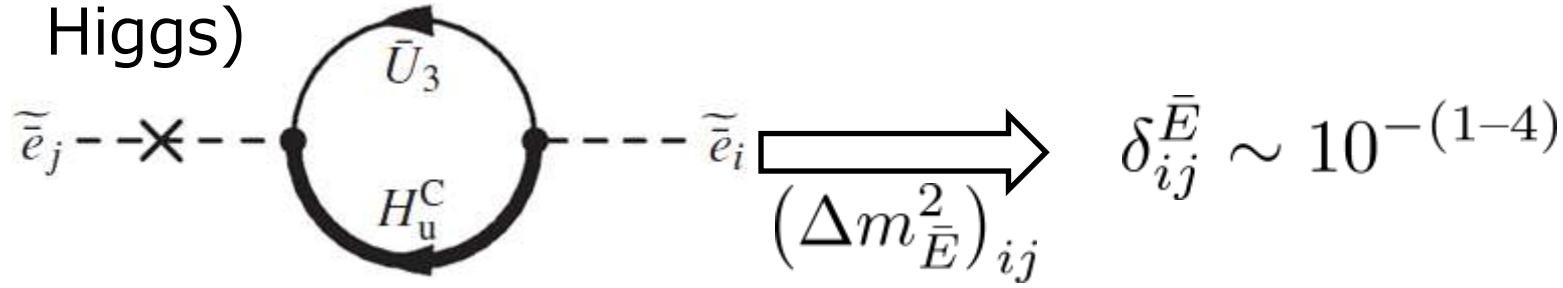
F. LFV : Theory & Experiments

Theoretical Expectation

Right-handed neutrino



SU(5) GUT (Colored Higgs)



<75>

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

MEGA Result / MEG Prospect

$$\delta_{21}^L \sim \sqrt{10^{4...5} \text{Br}(\mu \rightarrow e\gamma)} \left(\frac{\tan \beta}{10} \right)^{-1} \left(\frac{m_{\text{soft}}}{400 \text{ GeV}} \right)^2$$

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

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

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

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