

Cosmological Constraints on *R*-Parity Violating SUSY

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Based on

M. Endo, K. Hamaguchi and SI.

Cosmological Constraints on R-parity violation.

JCAP 1002:032, 2010. [[arXiv: 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.*

JCAP 1002:032, 2010. [[arXiv: 0912.0585](#)]

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 → solved!

😞 Proton decay problem

WHY?

→ 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: LH_u , $LL\bar{E}$, $LQ\bar{D}$, $\bar{U}\bar{D}\bar{D}$

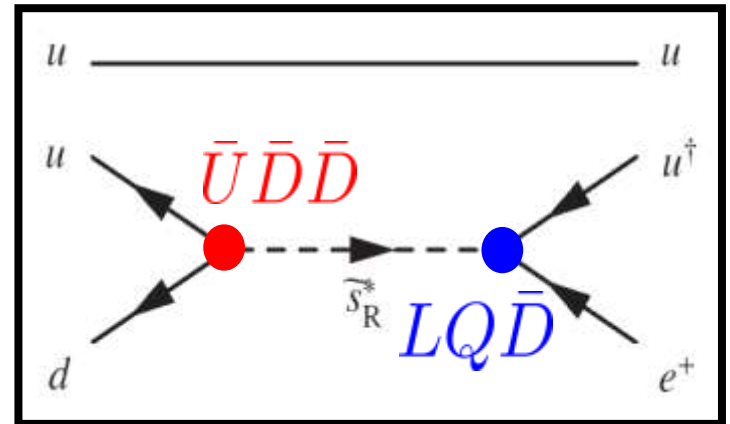
\cancel{L}

\cancel{B}

Both \cancel{B} and \cancel{L}

\Rightarrow Proton Decay

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

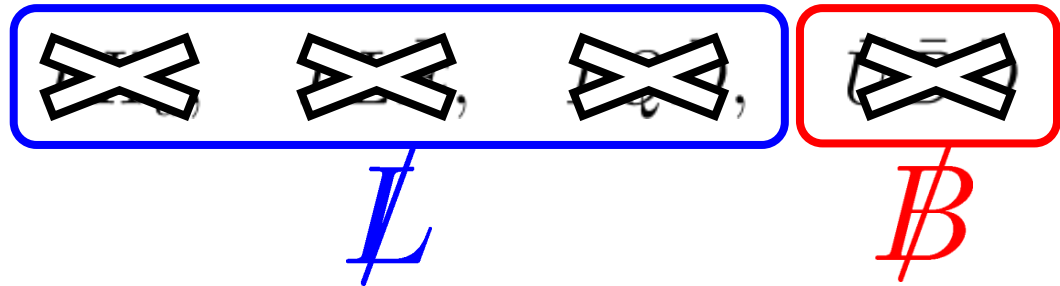


Proton Decay Problem

With R -Parity Conservation

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

R_p . violating:



~~Both B and 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.]

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

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

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

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

What we studied

Our Study: **Cosmological Constraints**
on these RpV interactions (couplings).

- \odot \cancel{L} -MSSM [Assuming B is conserved.]
 $W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U},$
 $L H_u, LL \bar{E}, L Q \bar{D}$
- \odot \cancel{B} -MSSM [Assuming L is conserved, and $m_{\text{LSP}} > m_{\text{proton}}$.]
 $W \ni H_u H_d, H_d L \bar{E}, H_d Q \bar{D}, H_u Q \bar{U}, \bar{U} \bar{D} \bar{D}$

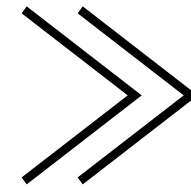
2. Cosmological Constraints

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

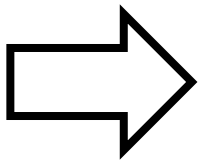
Baryon Asymmetry of the Universe

The Universe

baryon



anti-baryon



Some mechanism for
baryogenesis

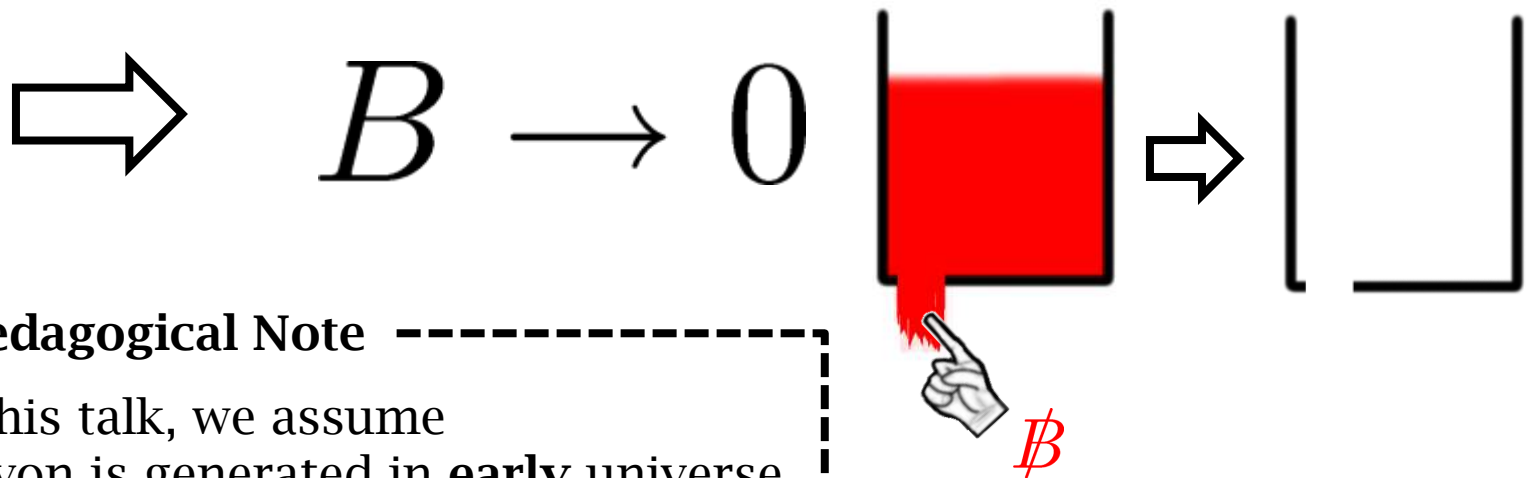


Wash-out with B -viol.

However,

if MSSM has \not{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 $T \gg 100 \text{ GeV.}$)

Wash-out with B -viol.

However,

if MSSM has \not{B} , ($W \ni \lambda'' \bar{U} \bar{D} \bar{D}$)

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

Large \not{B} spoils Baryogenesis.
 (“wash-out”)

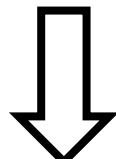
$\Rightarrow \lambda''$ must be small enough.



Sphaleron

Go more precisely!

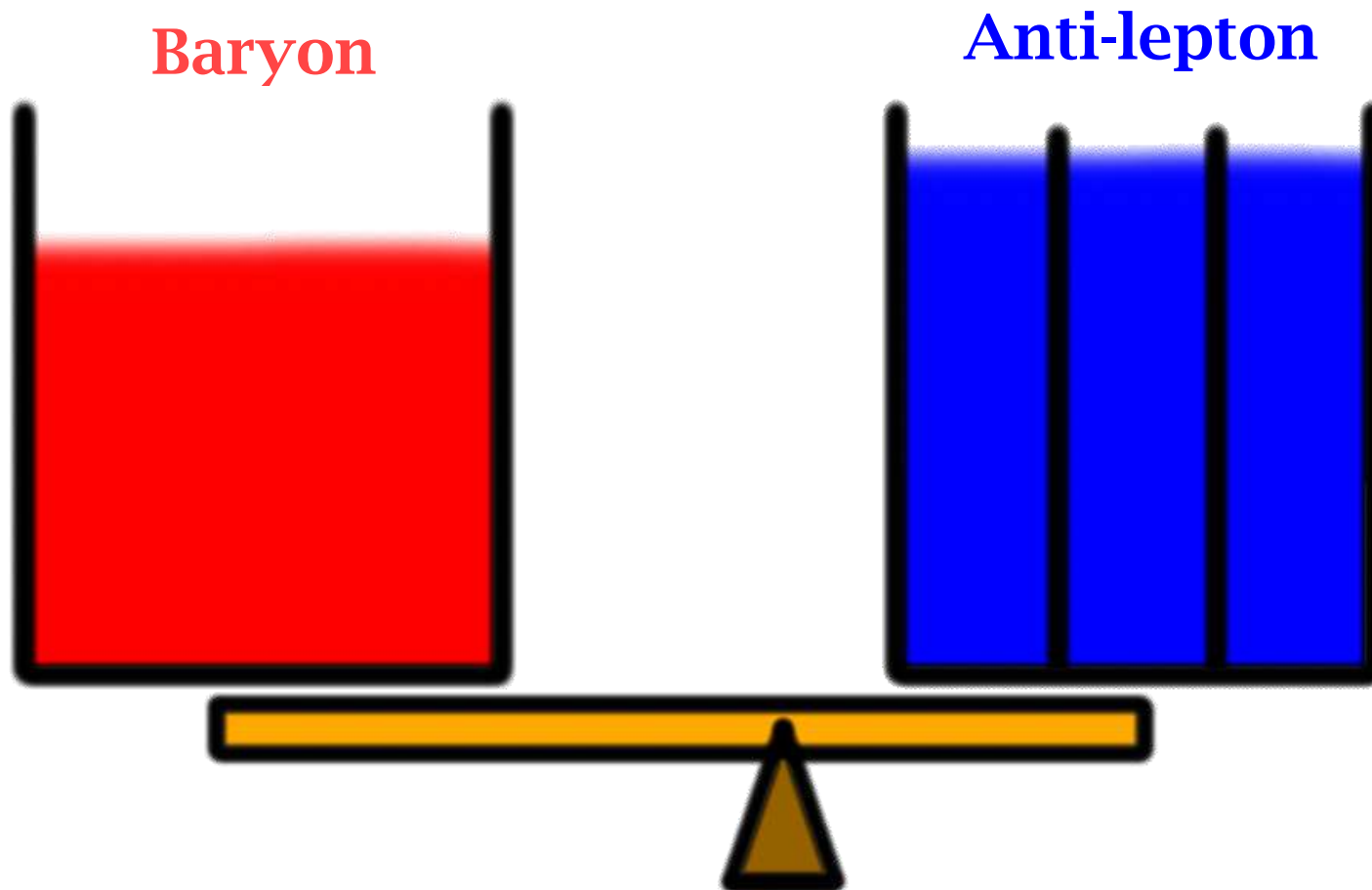
“Sphaleron process”

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

Equilibrium in early universe



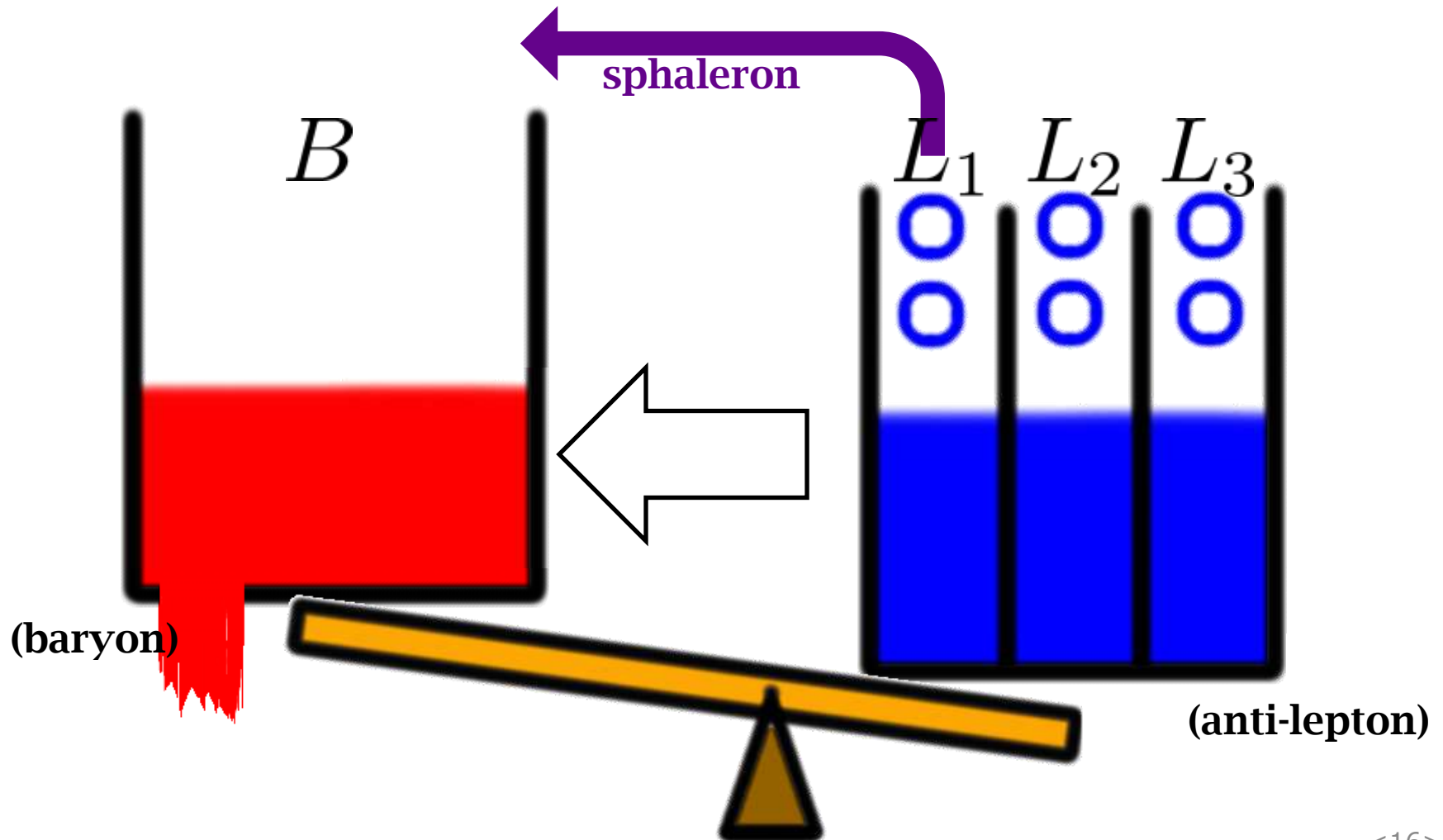
Sphaleron's Effect

On a See-Saw!



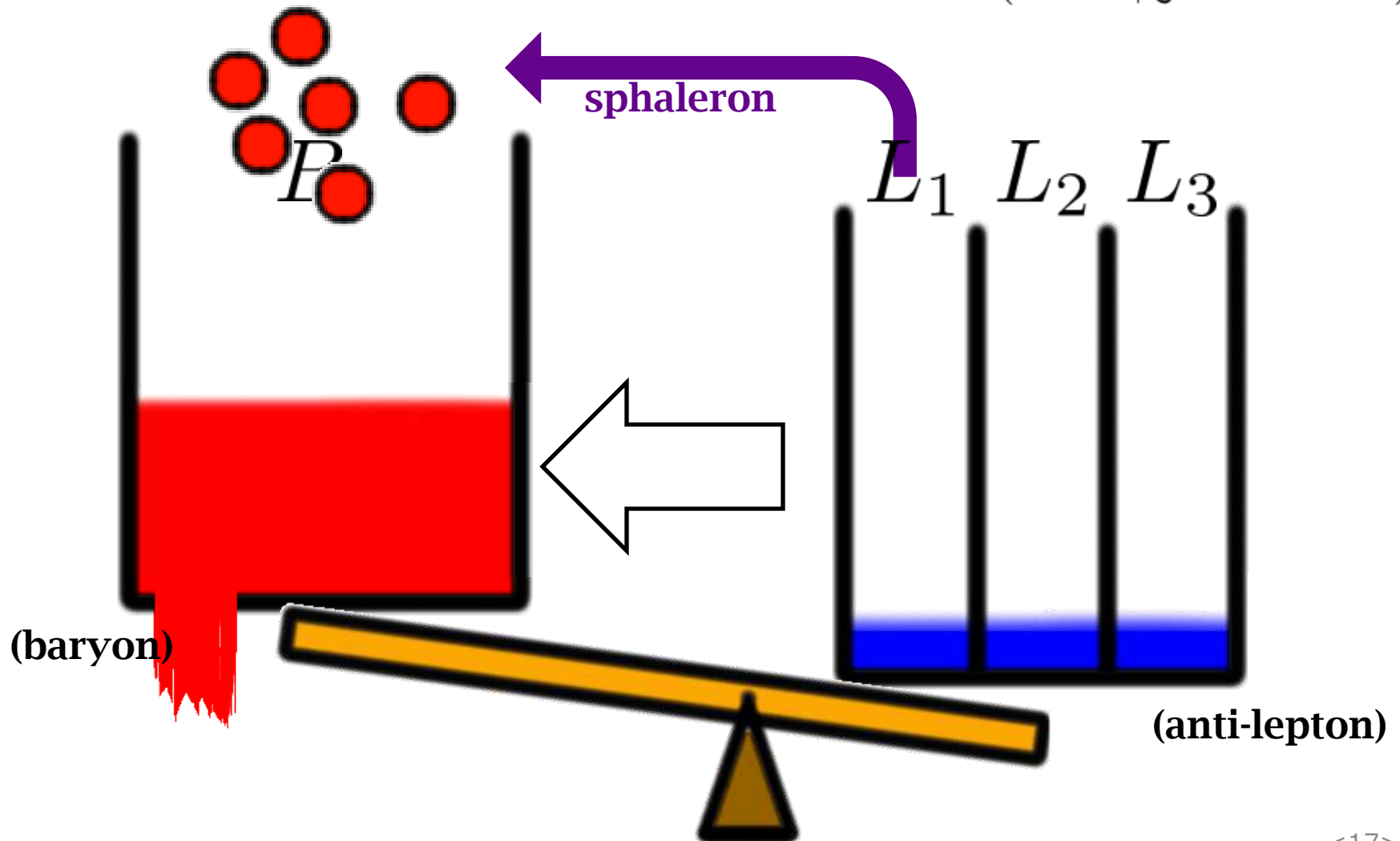
Sphaleron's Effect

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



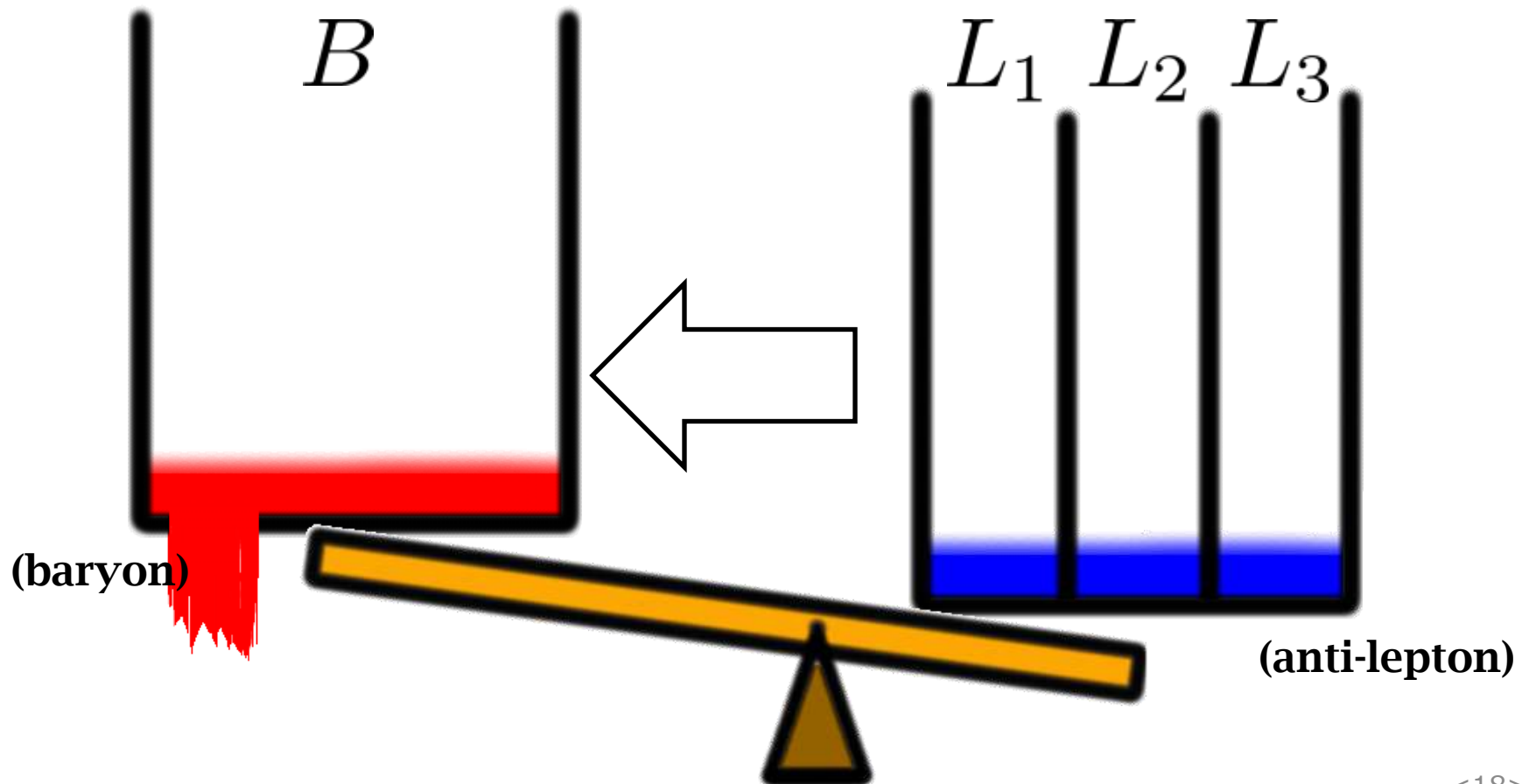
Sphaleron's Effect

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



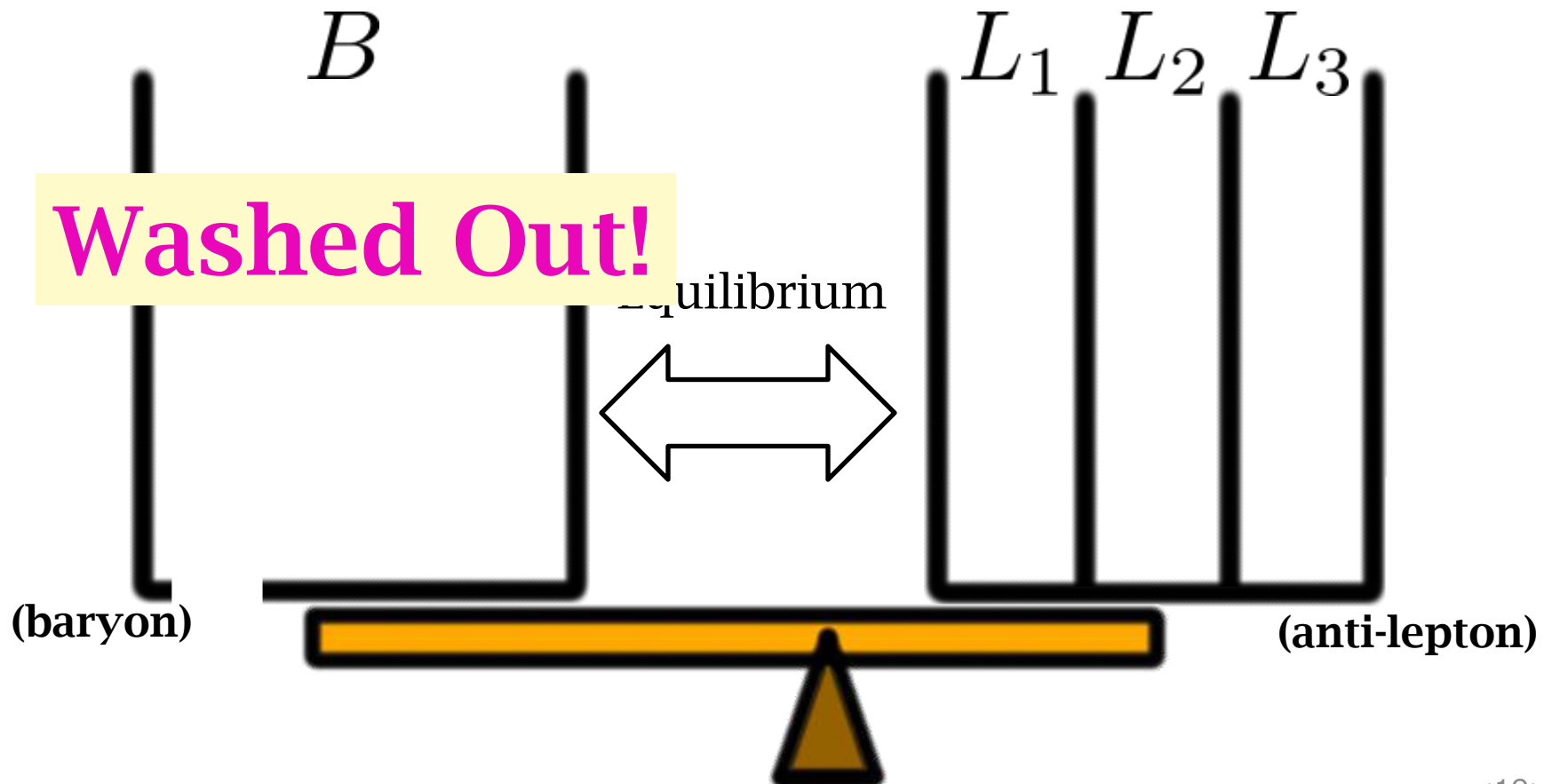
Sphaleron's Effect

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



Sphaleron's Effect

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



LESSON

◎ B -MSSM : Large B = wash out 😞

⇒ B couplings (λ'') = small enough

Ⓢ How small must be?

→ Discussed Later

Wash-out with L -viol.



This story

does not end here!

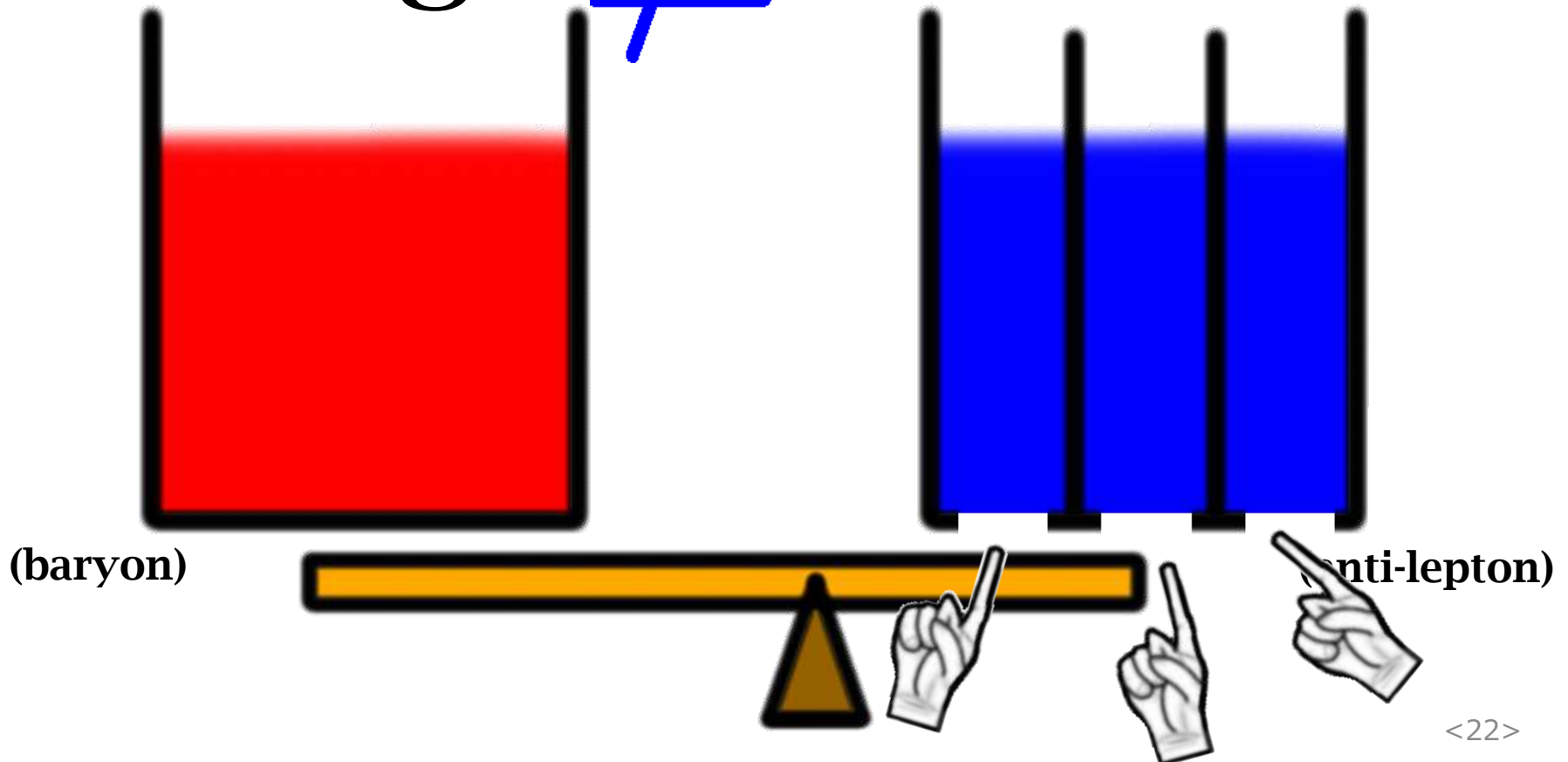


Wash-out with L -viol.

⊙ If

large

(in the sphaleron era),



Wash-out with L -viol.

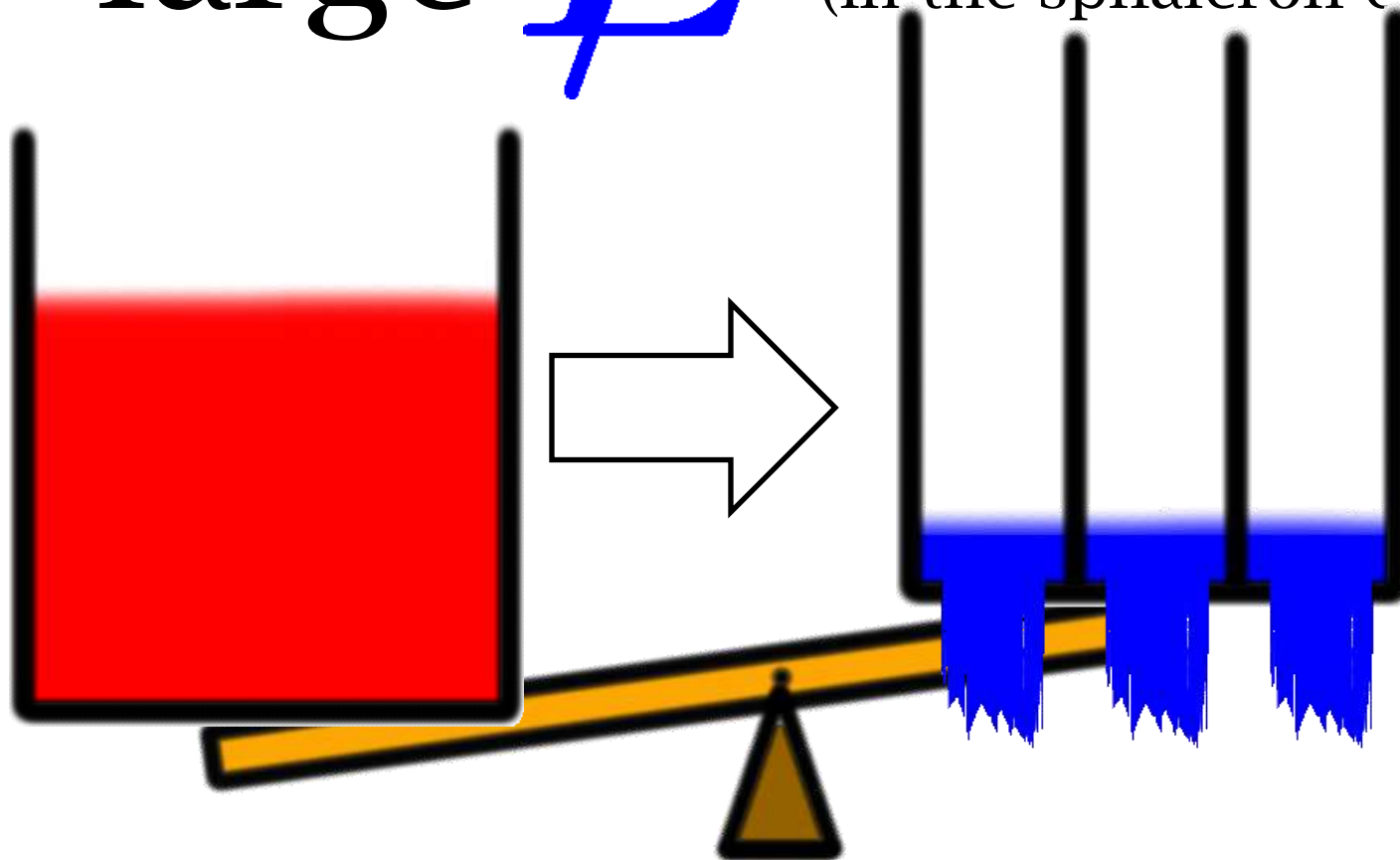
L

◉ If

large

L

(in the sphaleron era),



Wash-out with L -viol.

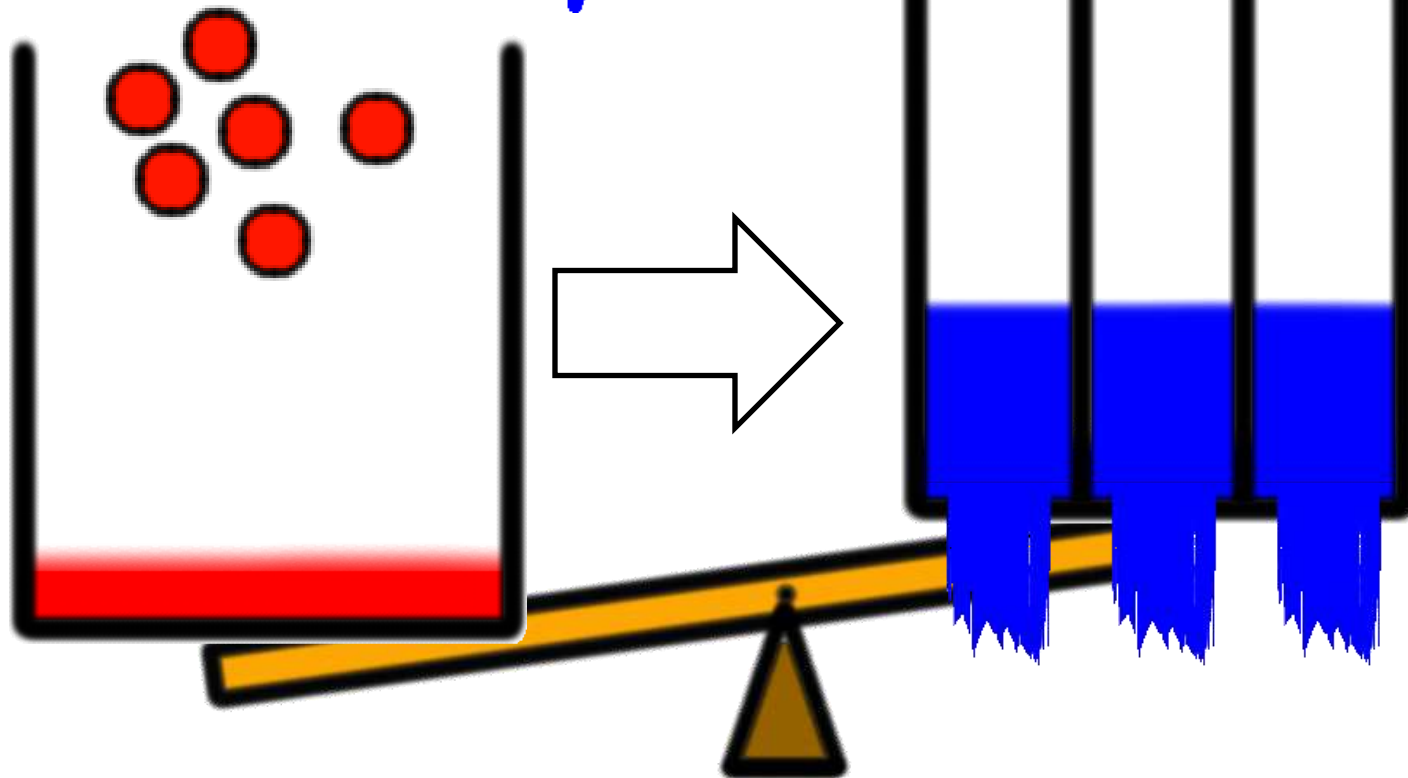


⊙ If

large

sphaleron

(in the sphaleron era),



Wash-out with L -viol.

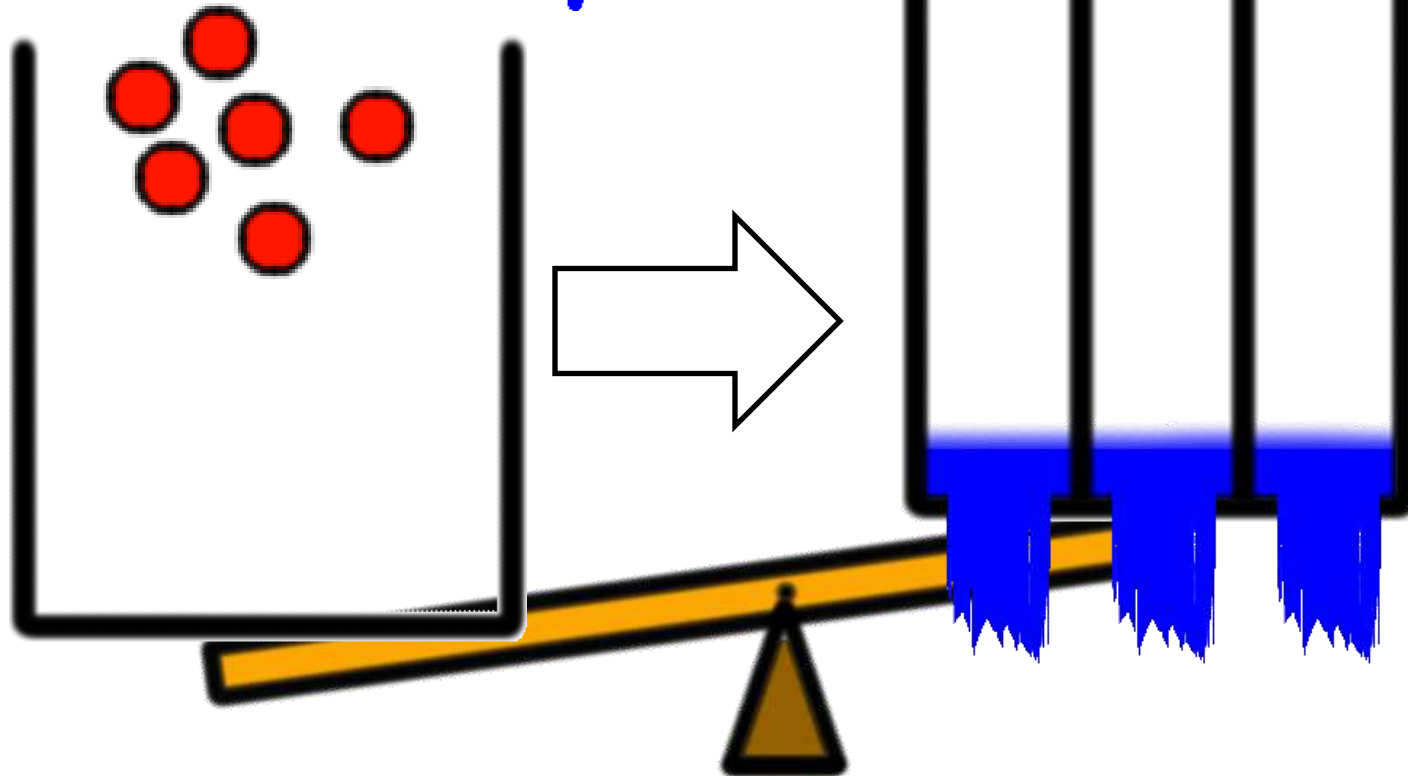


⊙ If

large

sphaleron

(in the sphaleron era),



Wash-out with L -viol.



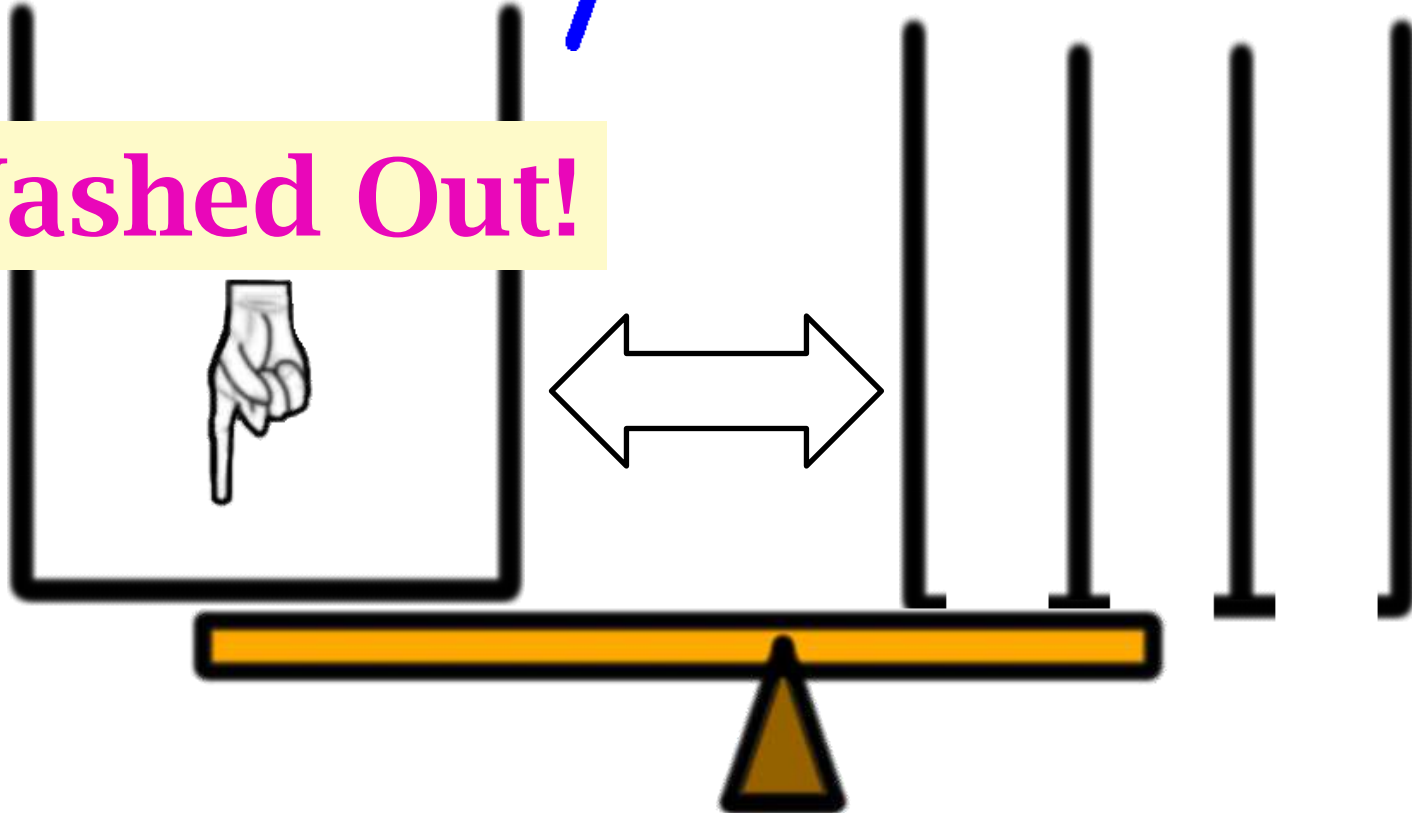
◉ If

large



(in the sphaleron era),

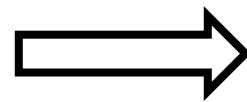
Washed Out!



Wash-out with L -viol.



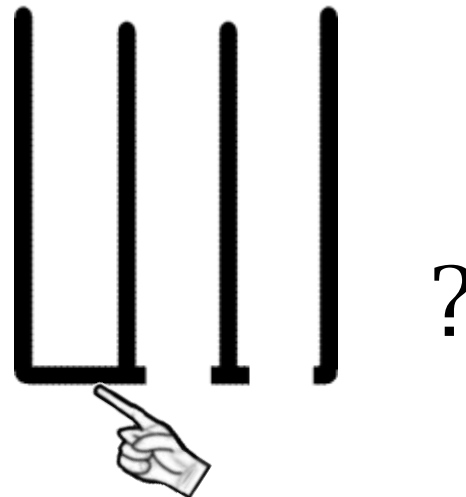
Point



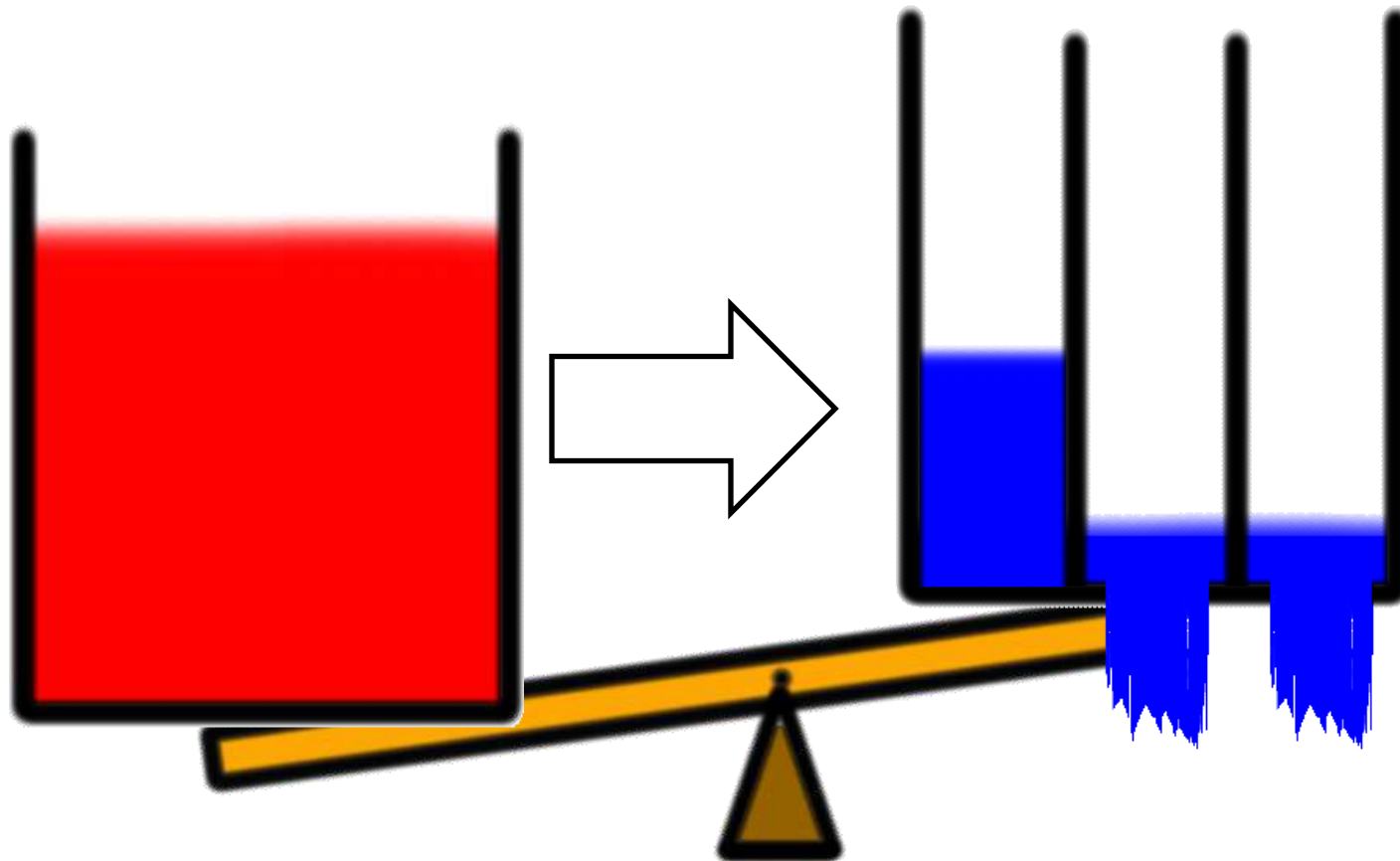
“Wash out”

Then

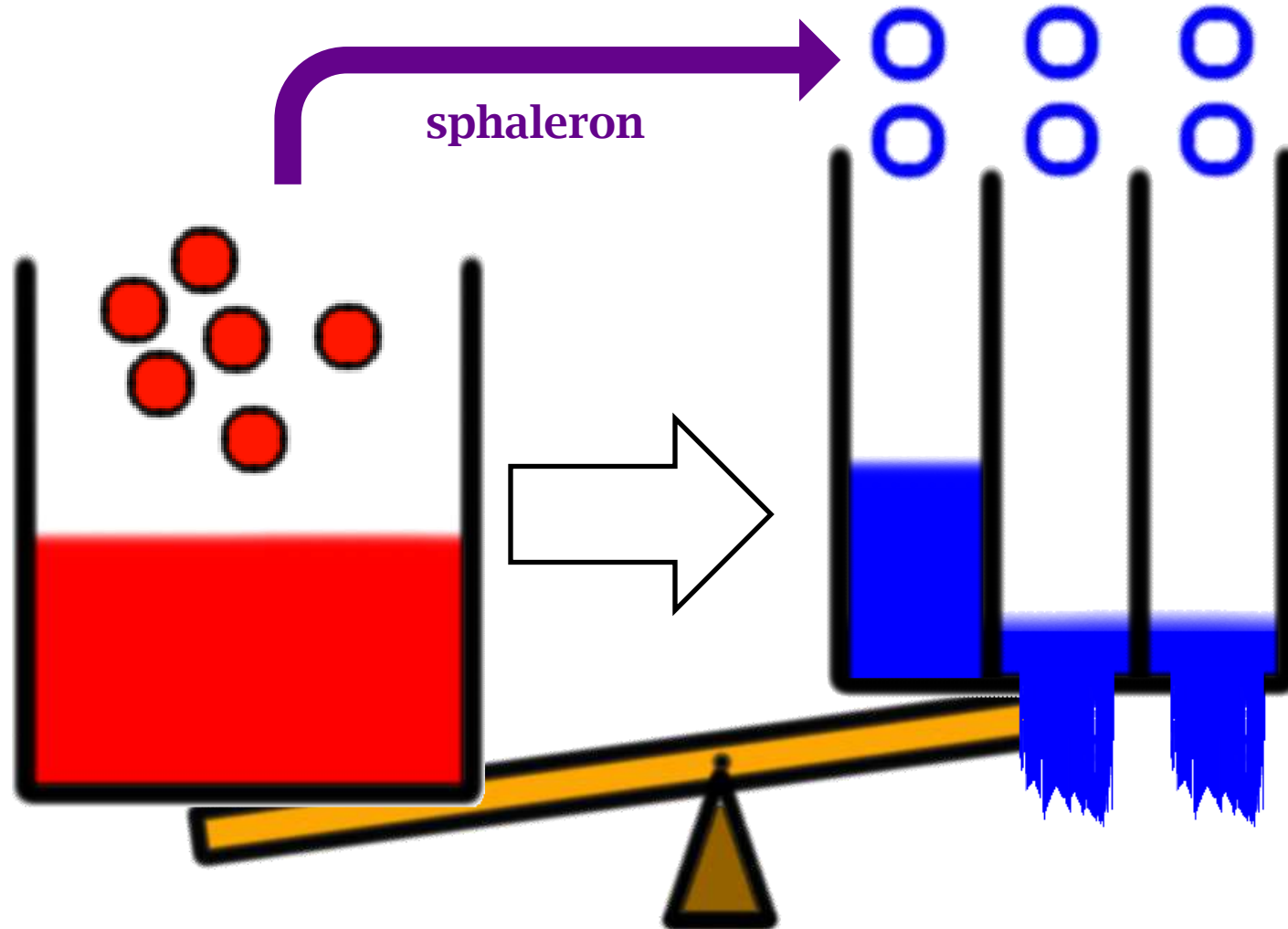
How about



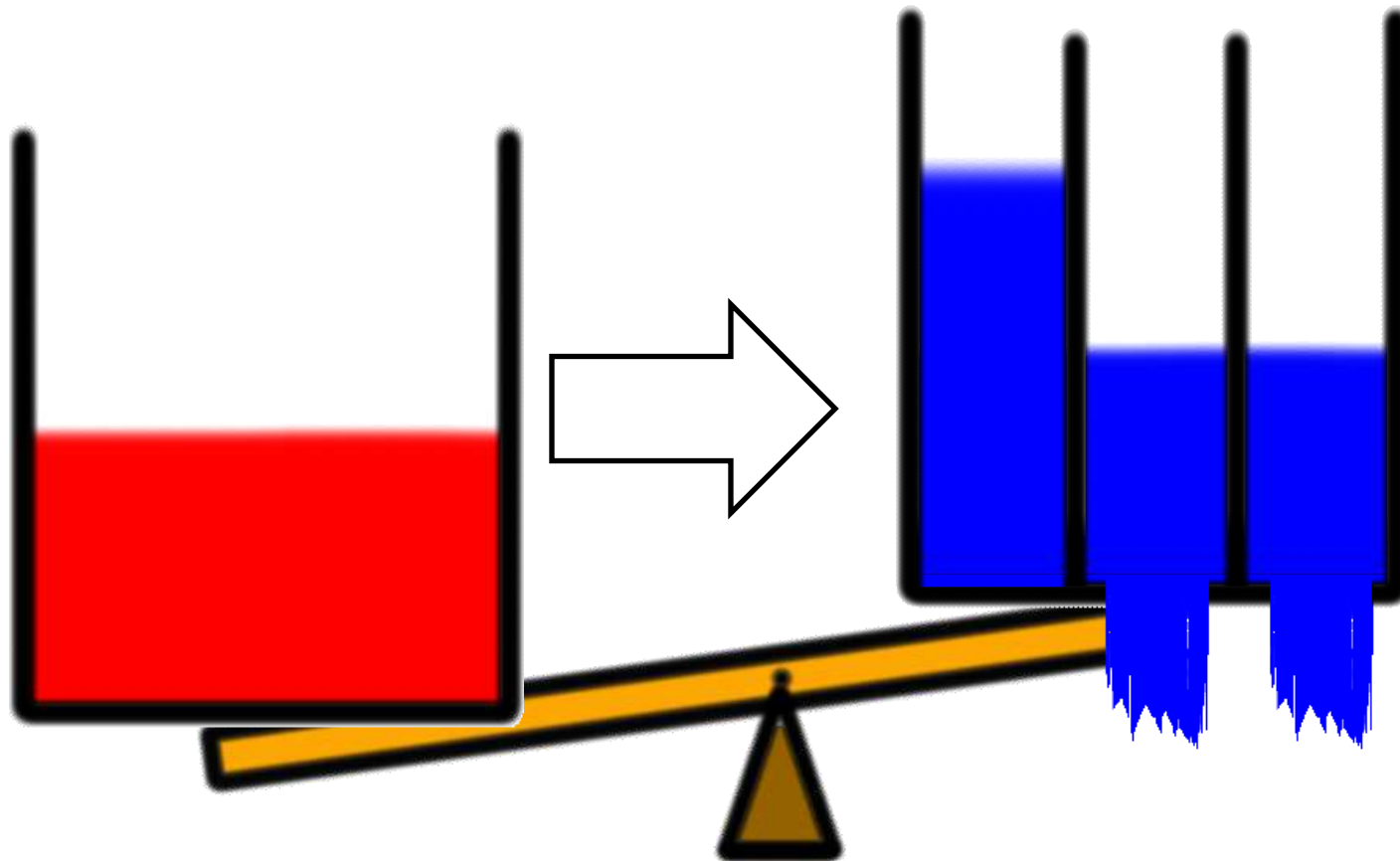
Wash-out with L -viol.



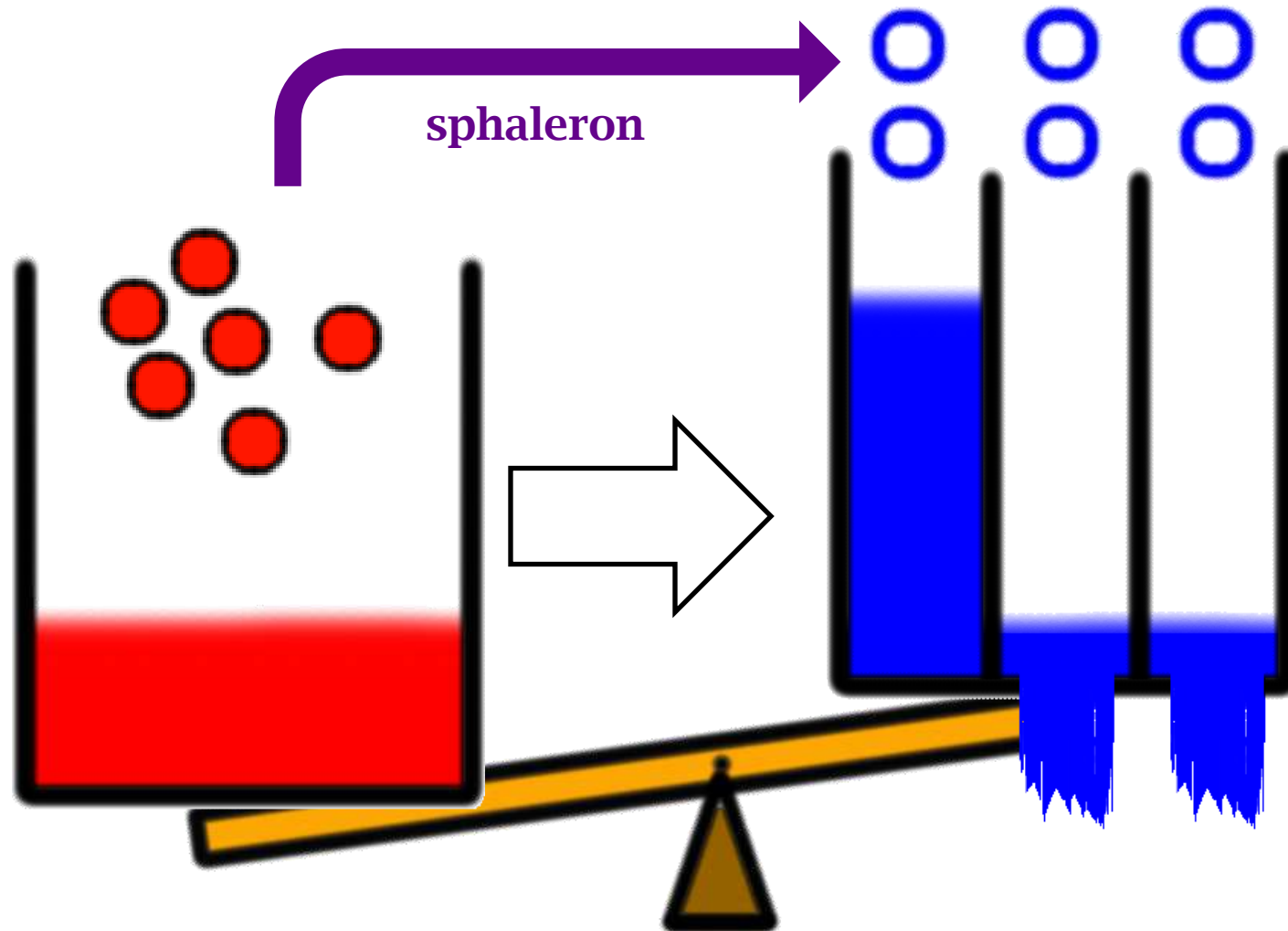
Wash-out with L -viol.



Wash-out with L -viol.



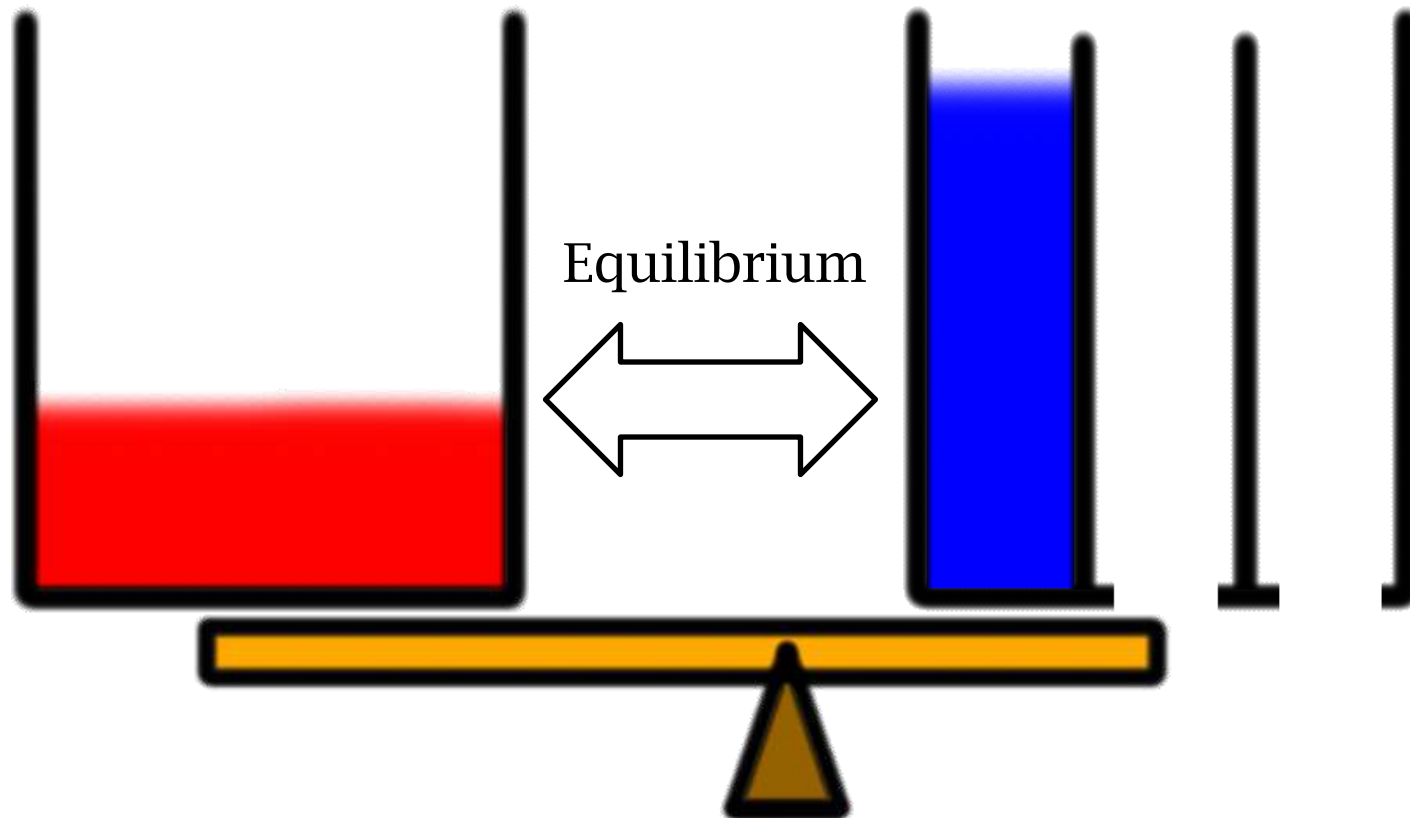
Wash-out with L -viol.



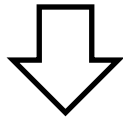
Wash-out with L -viol.



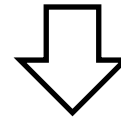
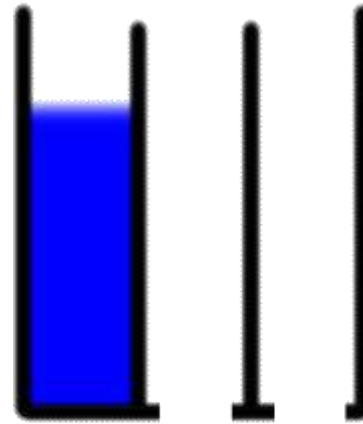
Baryon has survived!



Wash-out with L -viol.

 L 

Wash-out! 🤢



Baryon Survives. 😊

Point

All L_i 's leak in sphaleron era

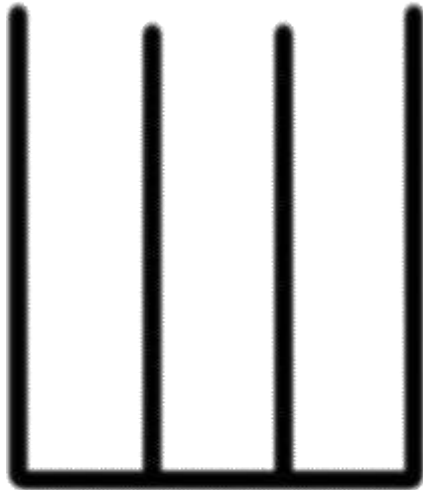
⇒ “Wash out”

Wash-out with L -viol.

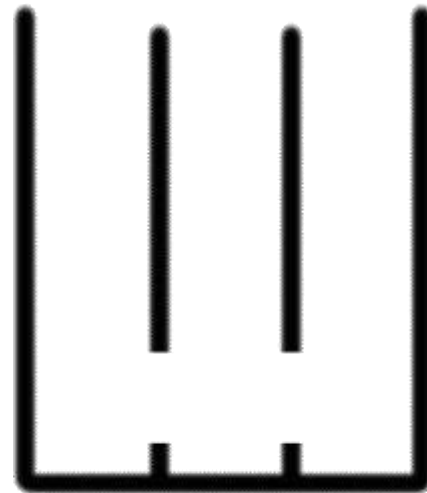
Our Attention

In MSSM, generally,

We have **LFVs!!!**



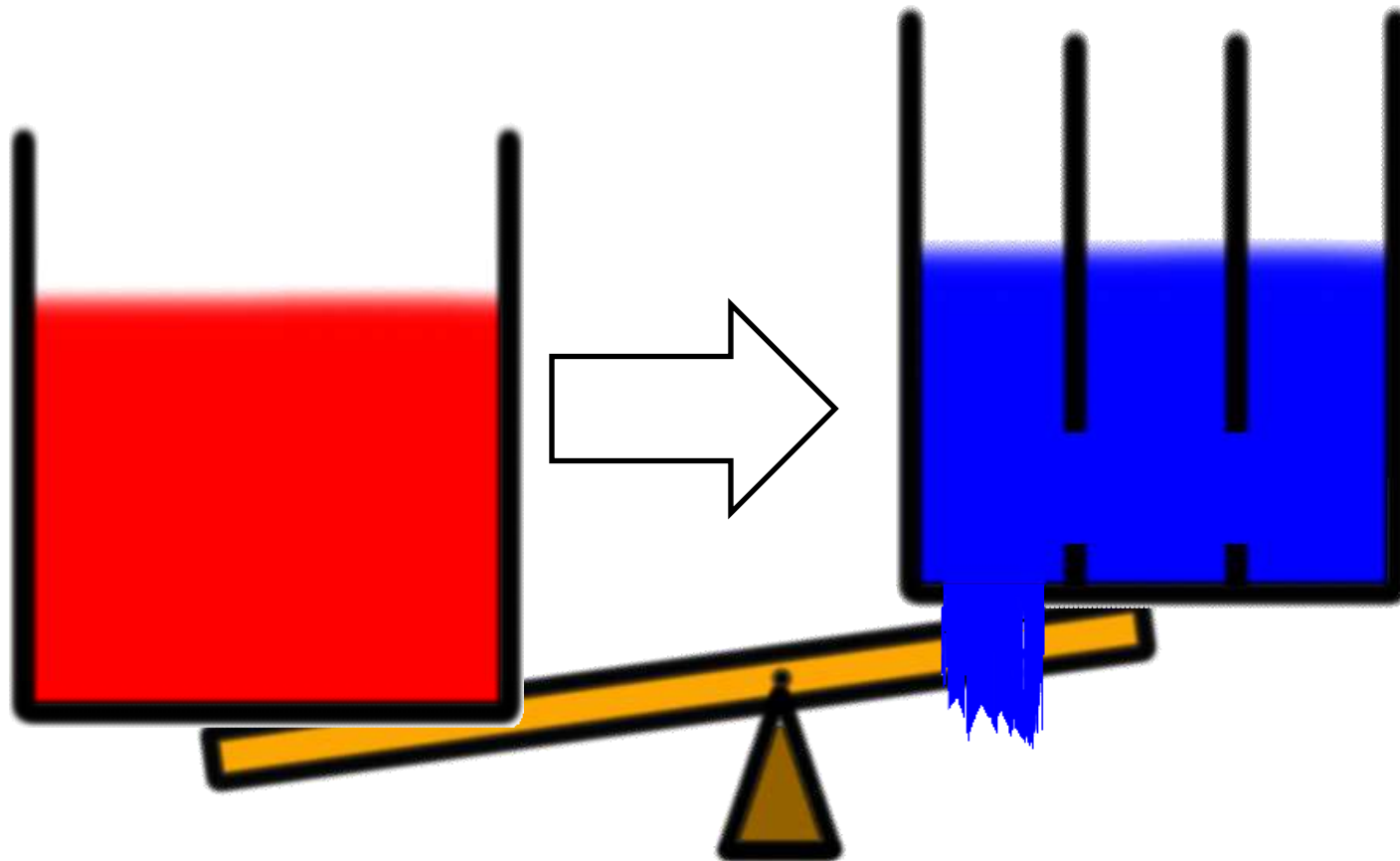
The Standard Model



The MSSM

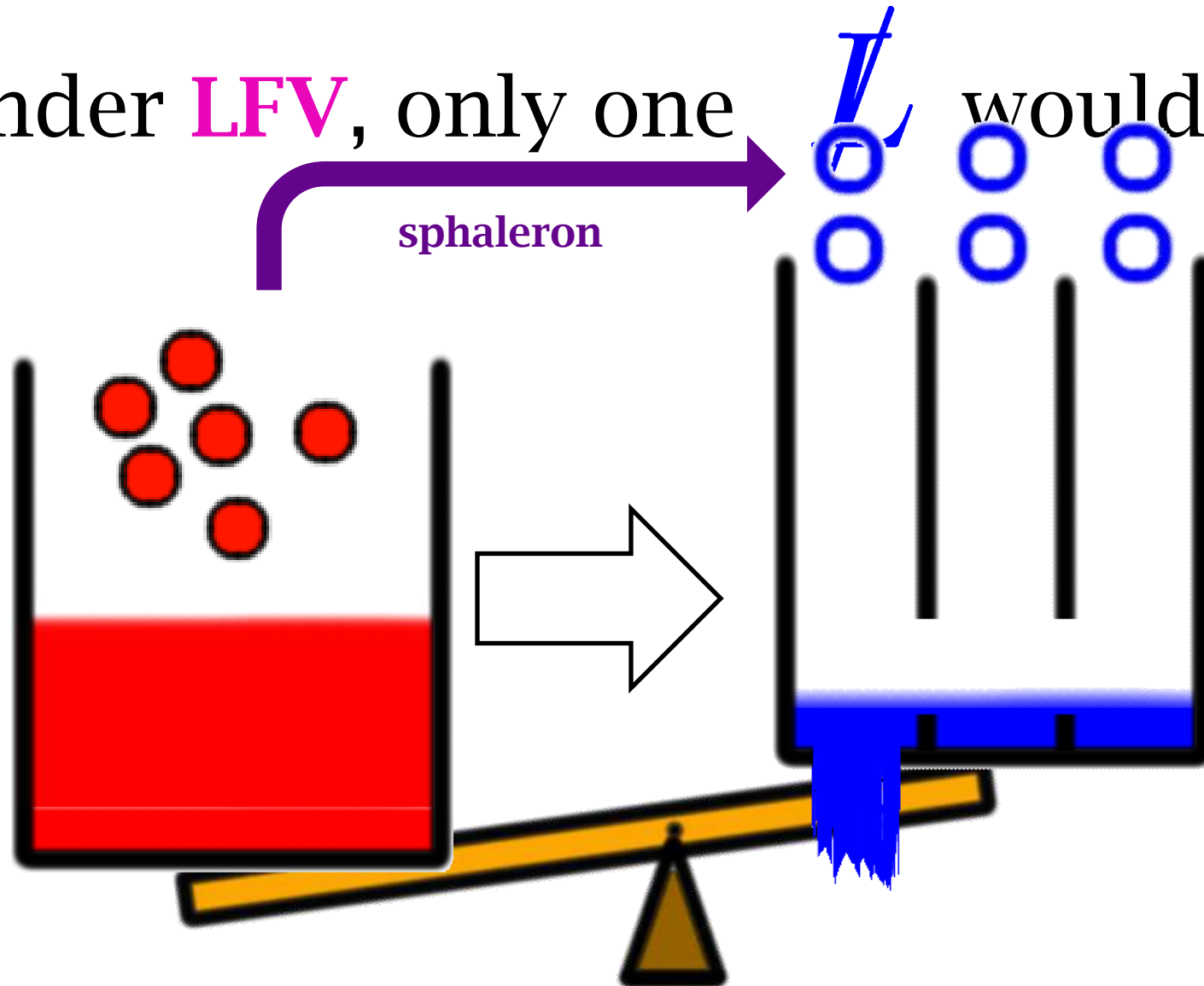
Wash-out with L -viol.

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



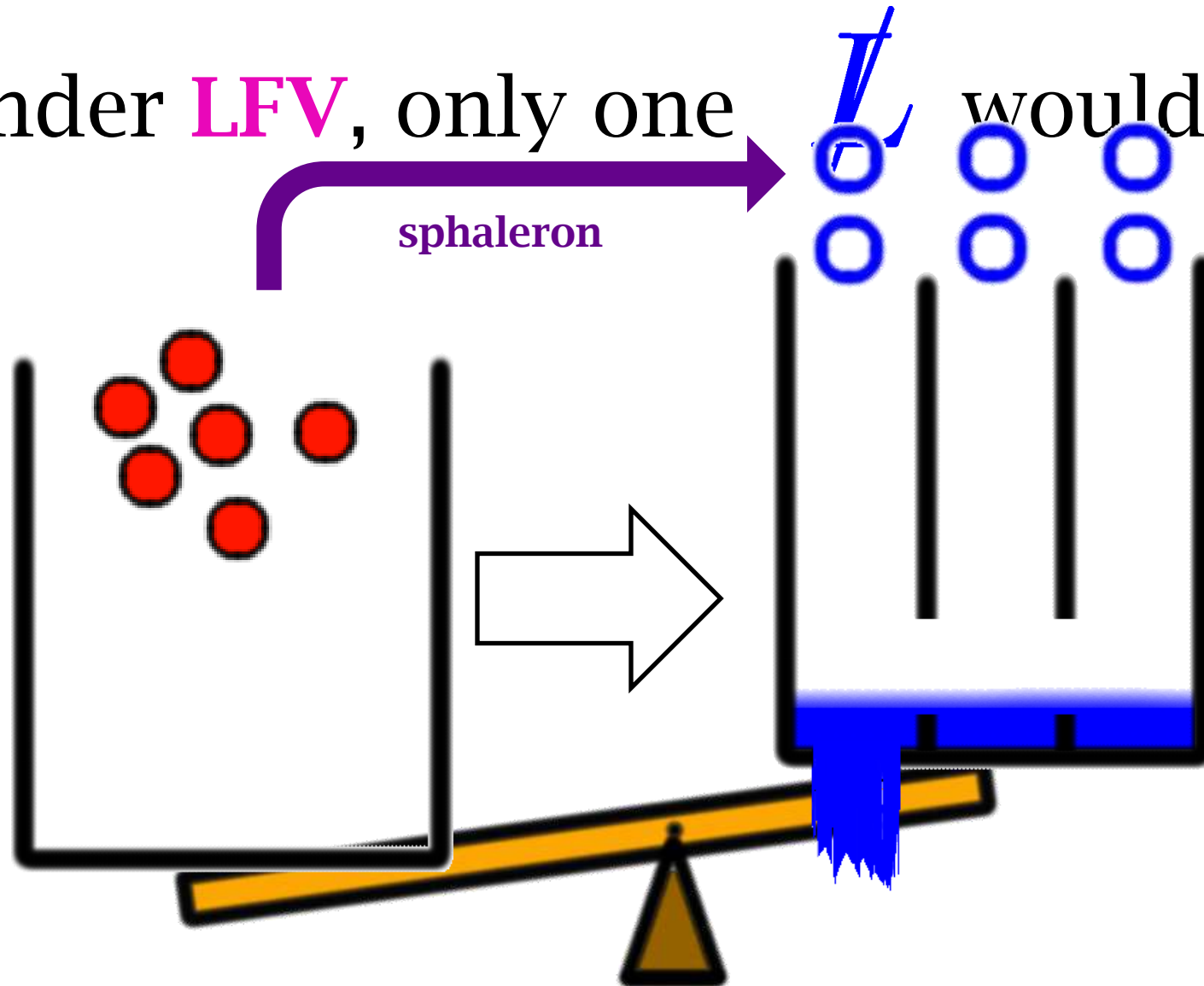
Wash-out with L -viol.

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



Wash-out with L -viol.

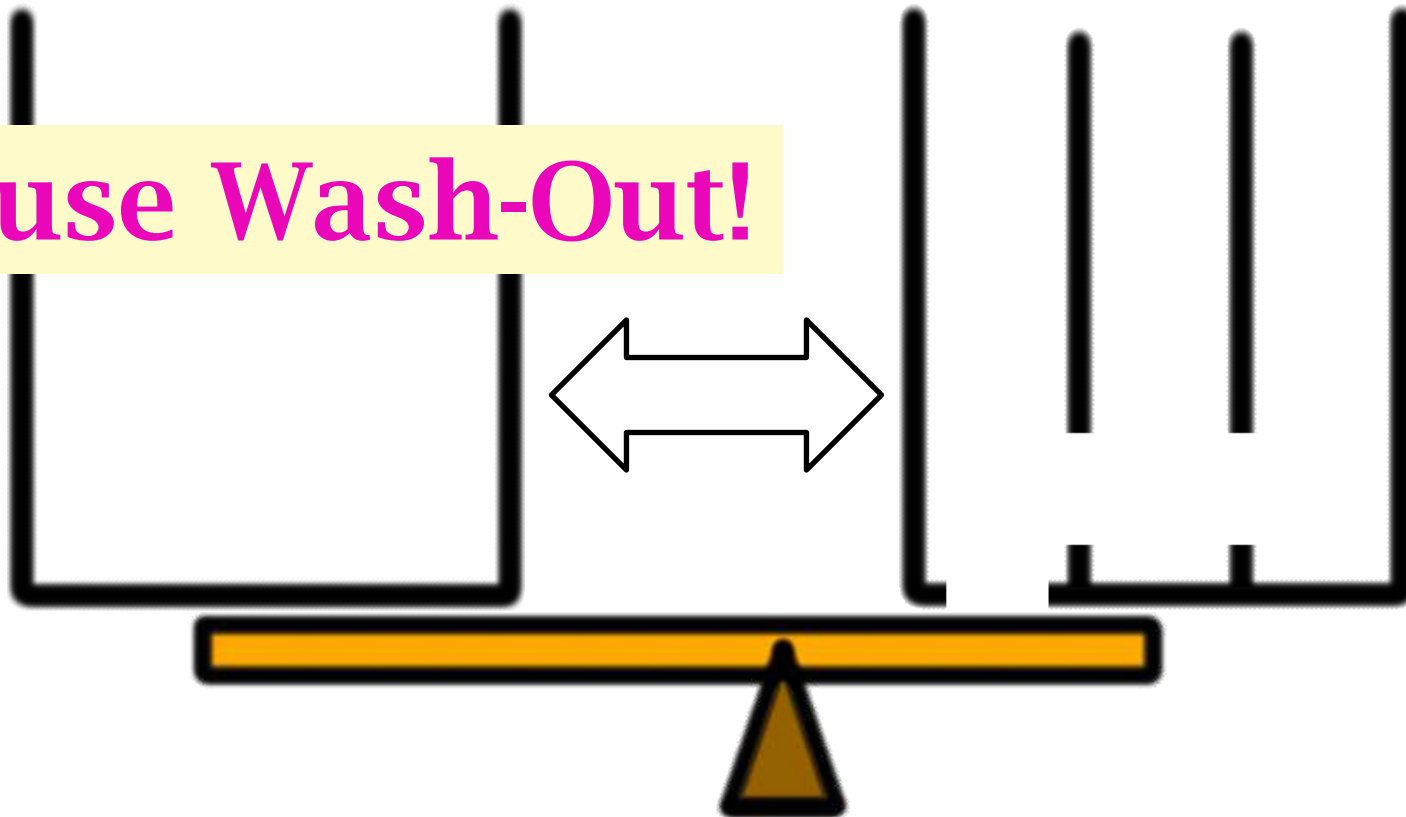
Under **LFV**, only one L would ...



Wash-out with L -viol.

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

cause Wash-Out!



LESSON

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

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

⊙ \cancel{L} -MSSM : (in sphaleron era)

All L_i leak via Large \cancel{L} (directly) or LFV
= wash out 😞

\Rightarrow Assuming large LFV,
 \cancel{L} couplings ($\kappa, \lambda, \lambda'$) = small enough

LESSON

? How large?

? How small must be?

There are our main target!

⊙ \cancel{L} -MSSM : (in μ phaleron era)

All L_i leak via Large \cancel{L} (directly) or LFV
= wash out ☹️

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

3. Method and Results

LESSON

? How large?

? How small must be?

◎ \cancel{L} -MSSM : (in phaleron era)

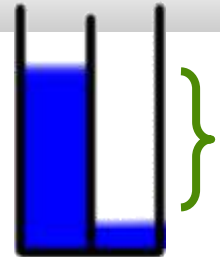
All L_i leak via Large \cancel{L} (directly) or LFV
= wash out ☹️

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

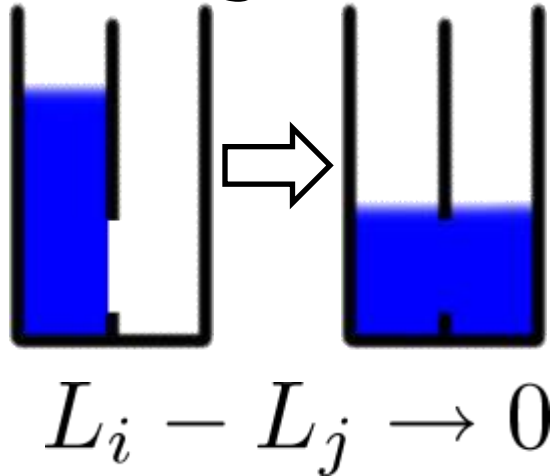
Method

Lepton number density of i -th generation

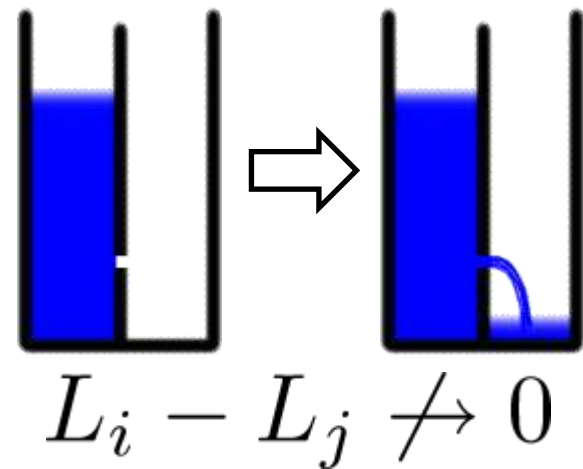
We calculated $\frac{d}{dt} (L_i - L_j)$ by Boltzmann Eq.



Large LFV



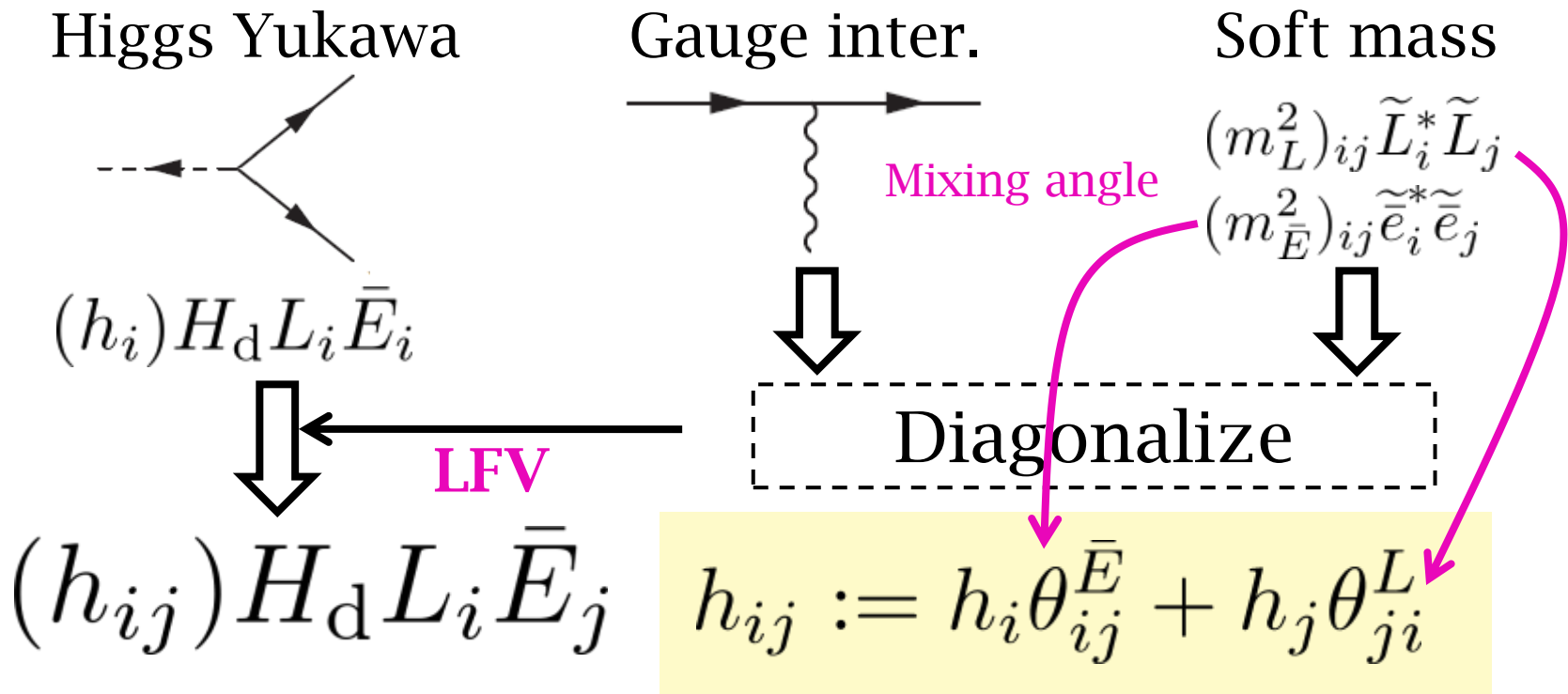
Tiny LFV



Method

Lepton number density of i -th generation

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



Method

Example)

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

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

Mixing process:

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

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

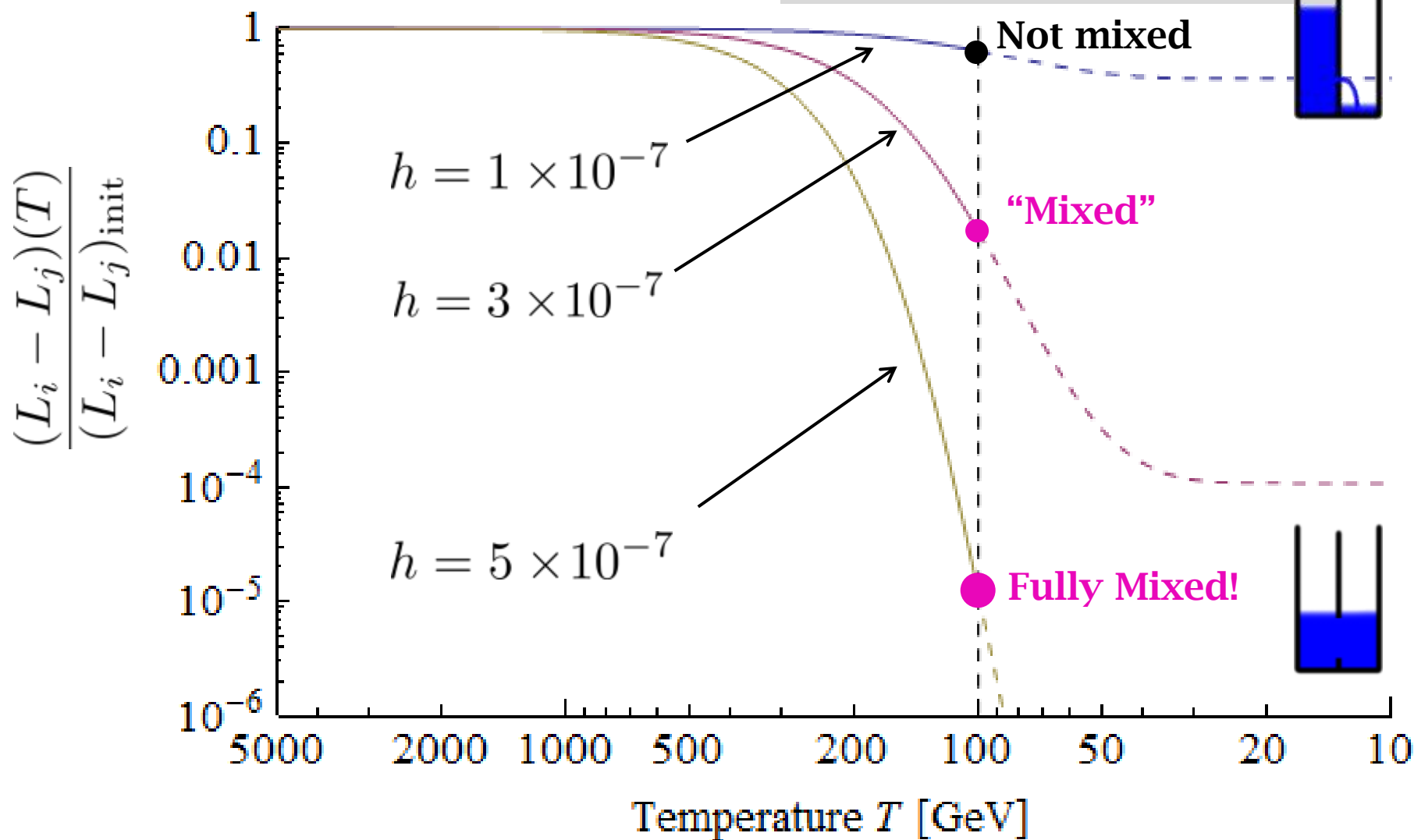
$$h_{ij} := h_i \theta_{ij}^{\bar{E}} + h_j \theta_{ji}^L$$

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

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

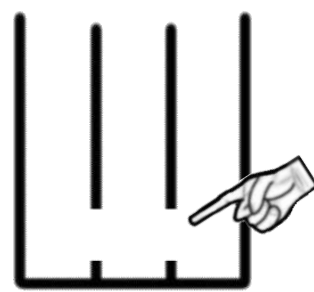
$$W \ni (h_{ij}) H_d L_i \bar{E}_j$$

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



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

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

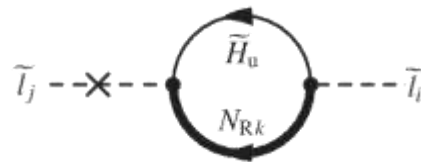


$$h \gtrsim 3 \times 10^{-7} \rightarrow \text{MIXED}$$

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

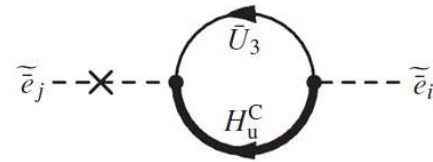
Cf.) Theoretical Expectation

1: ν_R



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

2: SU(5) GUT



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

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

LESSON

? How large?

? How small must be?

⊙ \cancel{L} -MSSM : (in phaleron era)

All L_i leak via Large \cancel{L} (directly) or LFV

= wash out ☹️

⇒ Assuming large LFV,

\cancel{L} couplings $(\kappa, \lambda, \lambda') = \text{small enough}$

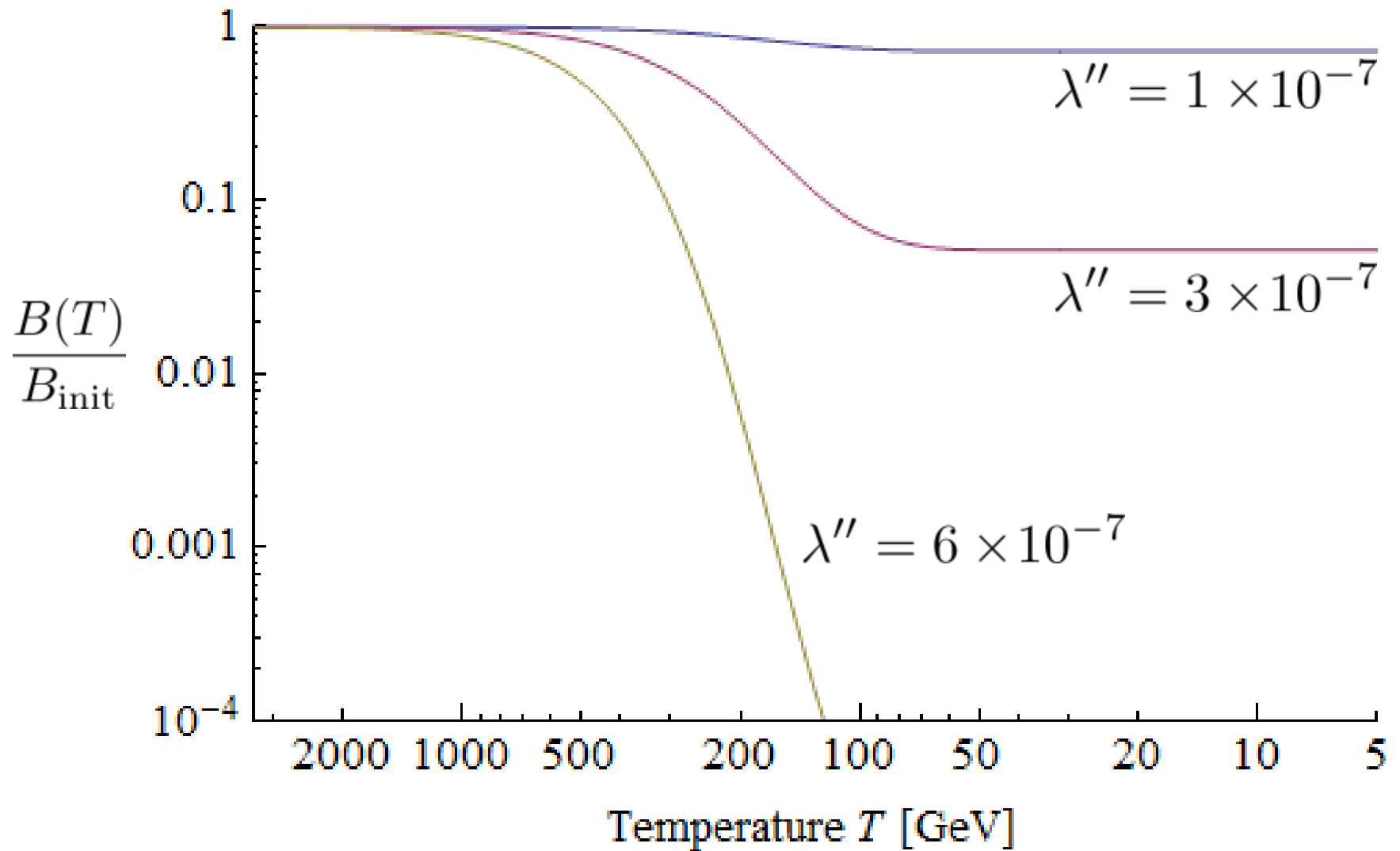
Method (RpV)

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

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

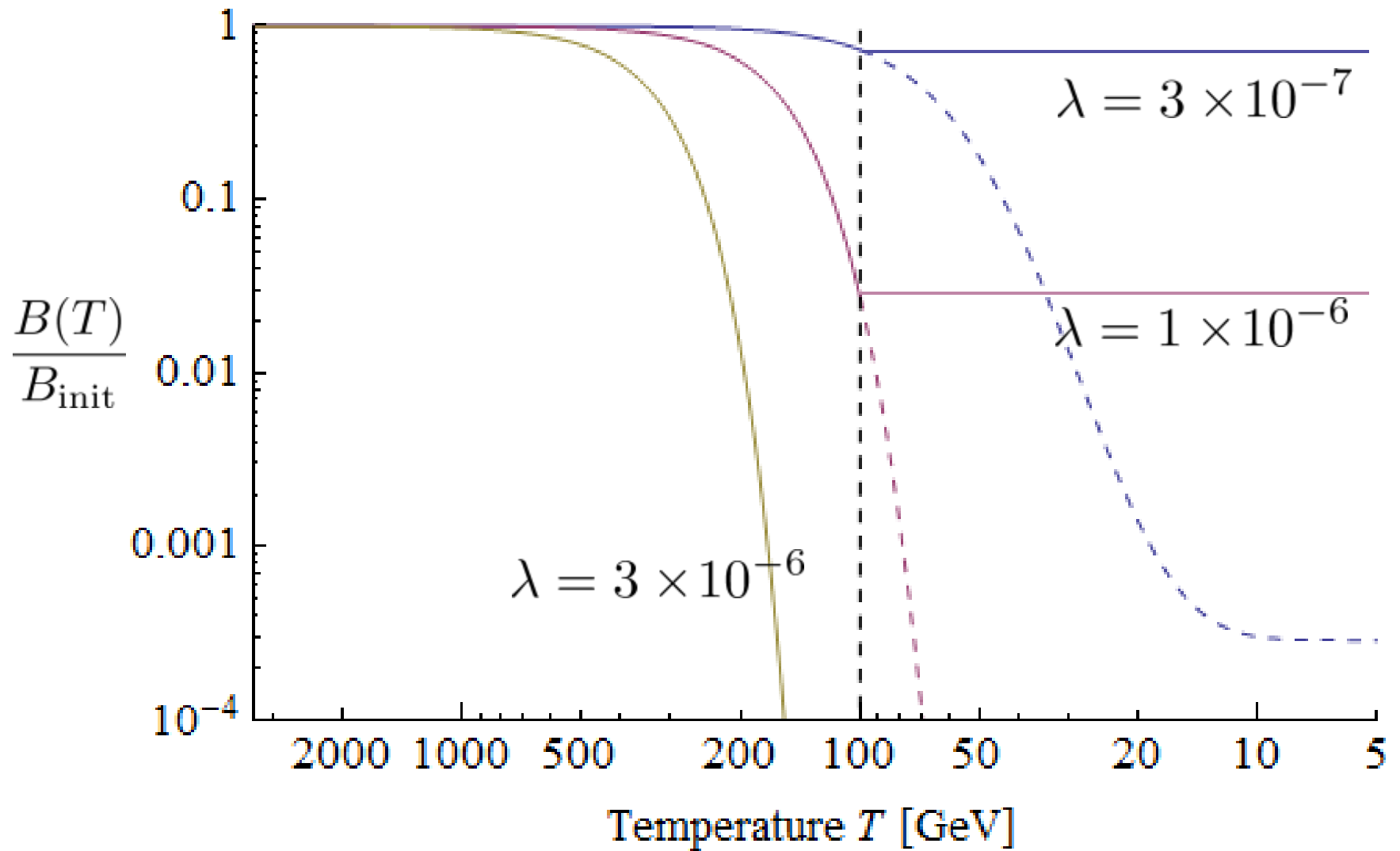
$$\left(\frac{d}{dt} (B - L) \sim \frac{79}{28} \frac{dB}{dt} \quad \text{in sphaleron era} \right)$$

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



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

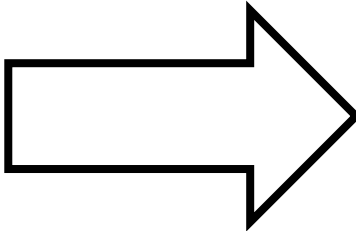
$$W_{\mathcal{L}} \ni \lambda L_i L_j \bar{E}_k$$



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

Conclusion (RpV)

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



$$\left. \begin{aligned}
 \lambda &\lesssim 1 \times 10^{-6} \\
 \lambda' &\lesssim 3 \times 10^{-7} \\
 \kappa &\lesssim 1 \times 10^{-6} \cdot \mu \\
 \lambda'' &\lesssim 4 \times 10^{-7}
 \end{aligned} \right\} \text{Under LFV}$$

$(W \ni \mu H_u H_d)$

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

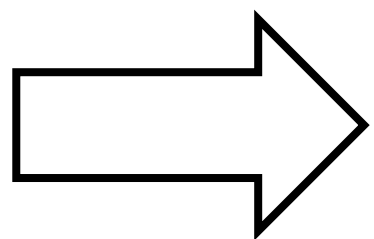
$$W_{\textcolor{blue}{L}} = W_{\text{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u$$

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

Conclusion (RpV)

Very Stringent Constraints!

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



$$\left. \begin{aligned}
 \lambda &\lesssim 1 \times 10^{-6} \\
 \lambda' &\lesssim 3 \times 10^{-7} \\
 \kappa &\lesssim 1 \times 10^{-6} \cdot \mu \\
 \lambda'' &\lesssim 4 \times 10^{-7}
 \end{aligned} \right\} \text{Under LFV}$$

($W \ni \mu H_u H_d$)

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

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

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

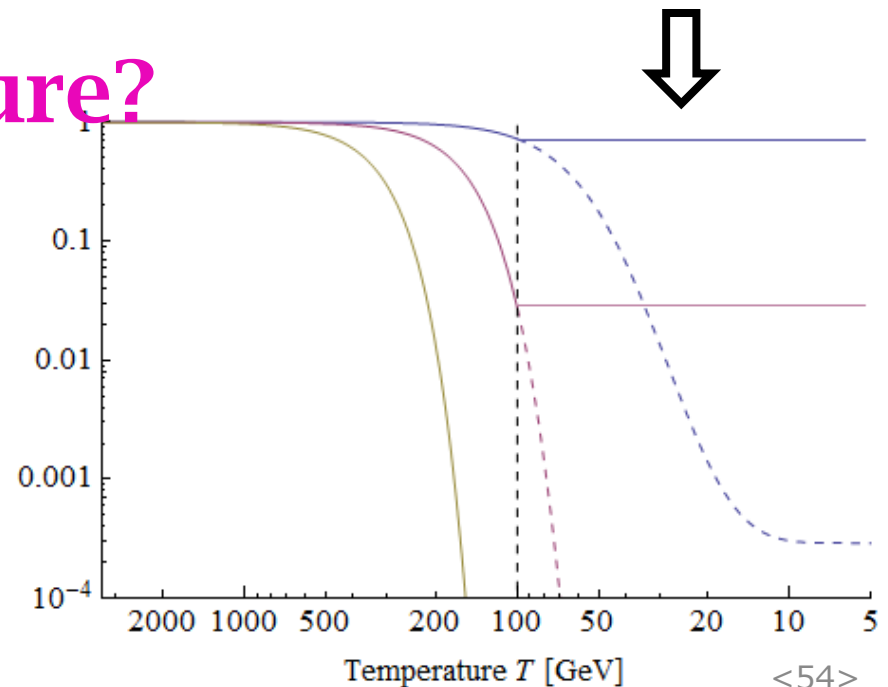
Some Loopholes

Some **loopholes**!

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

◎ **Baryogenesis**
in Low-temperature?

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



[Work in progress]

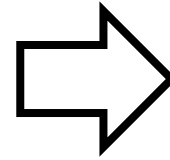
4. Application in LHC

“Kink track” observed?

Consequence of our Result

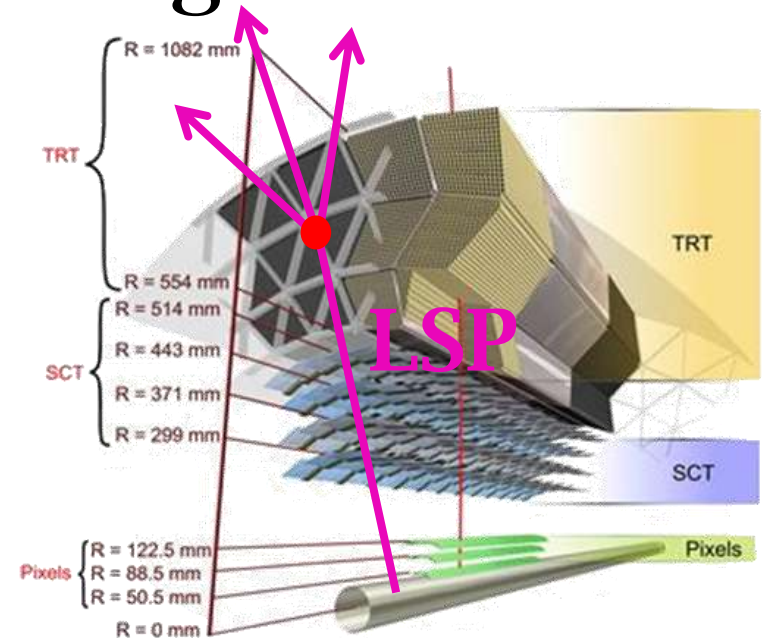
Our Result

Very small
 R -parity violation



Long-lived LSP

LSP might decay
in Detector.



Consequence of our Result

Our Result

Very small
 R -parity violation

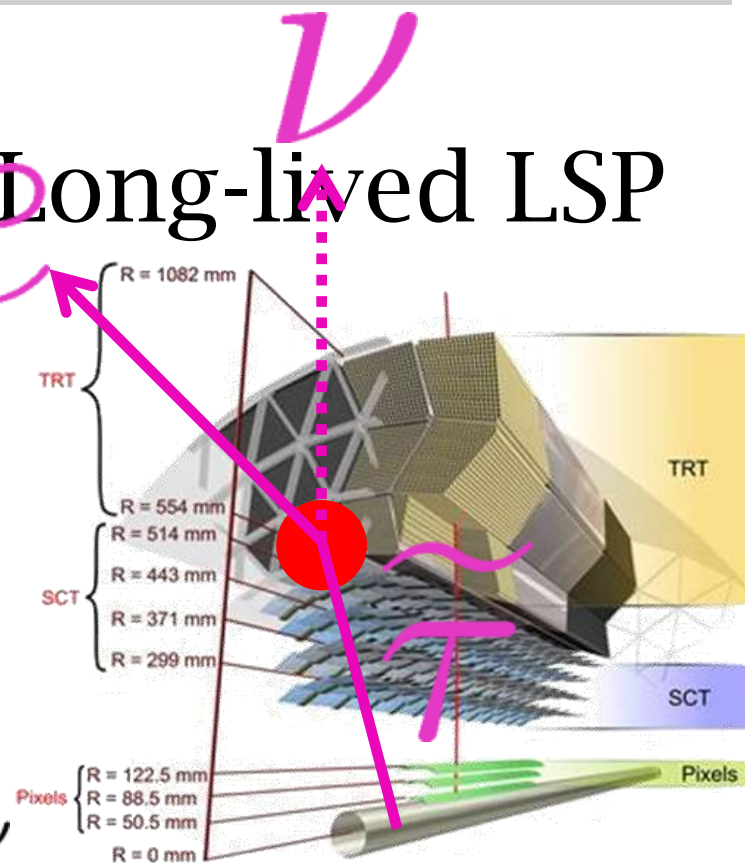
⇒ Long-lived LSP

Example

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

$$W_{\text{RPV}} = \lambda L_1 L_3 \bar{E}_3; \lambda = 10^{-8}$$

⇒ Decay : $\tilde{\tau} \rightarrow e\nu, \tau\nu$
[$c\tau \sim 30$ cm]



“Kink track” observed?

Consequence of our Result

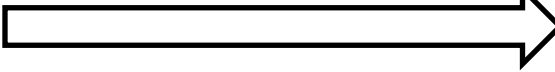
According to our **PRELIMINARY** calculation,
if $\lambda \sim 10^{-(8\dots 9)}$,

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

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

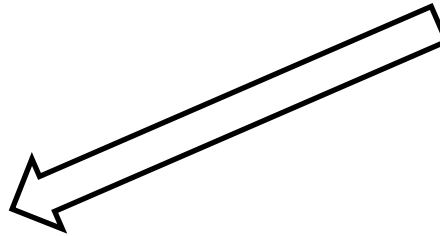
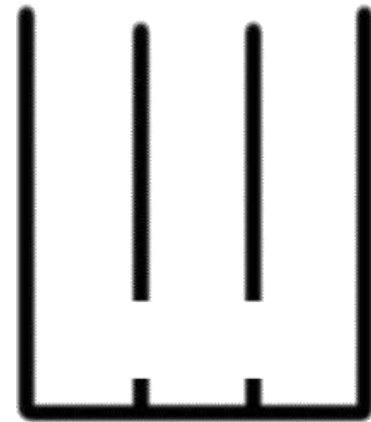
“Kink track” observed?

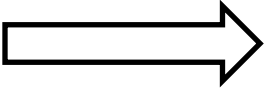
Summary

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

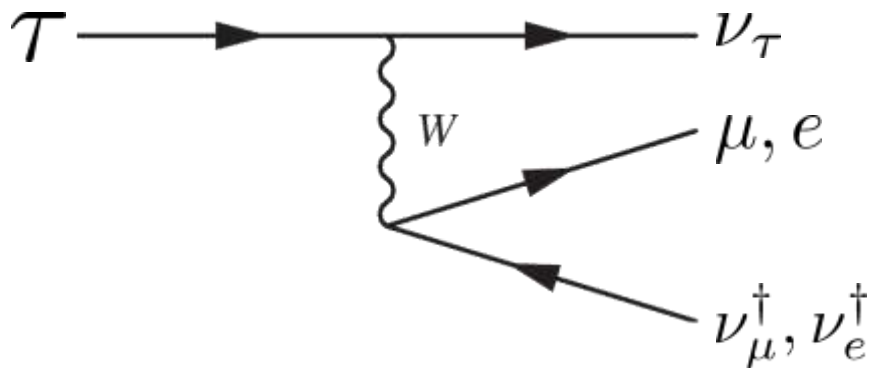
“The RpV interactions are constrained
by several experimental facts.”

Constraints

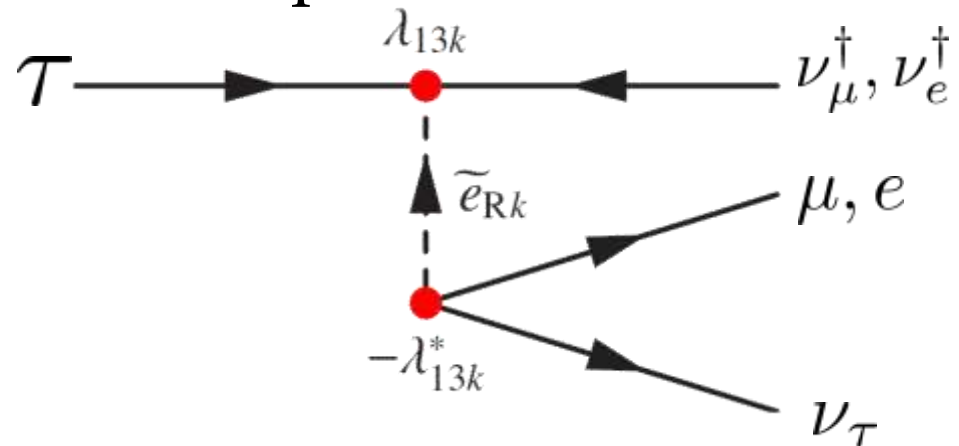
⊙ Example:

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

Standard Model



RpV-MSSM



Additional Contribution!

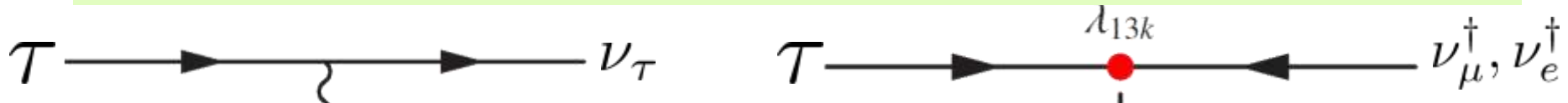
Constraints

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

$$R_\tau = \frac{\Gamma(\tau \rightarrow \nu_\tau \gamma)}{\Gamma(\tau \rightarrow \nu_\tau \text{had})}$$

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

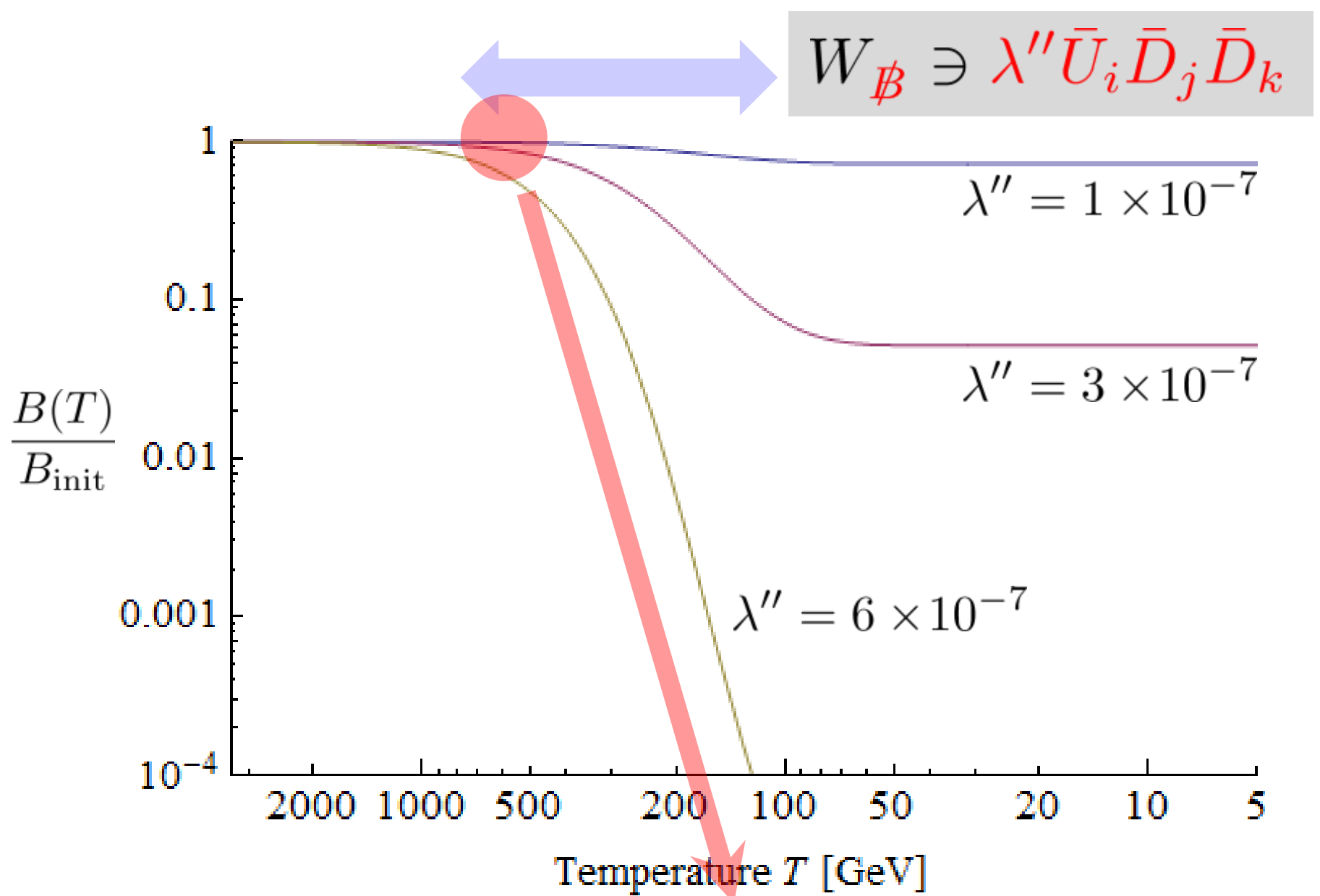
$$(R_\tau)_{\text{SM}} = 1.028$$



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

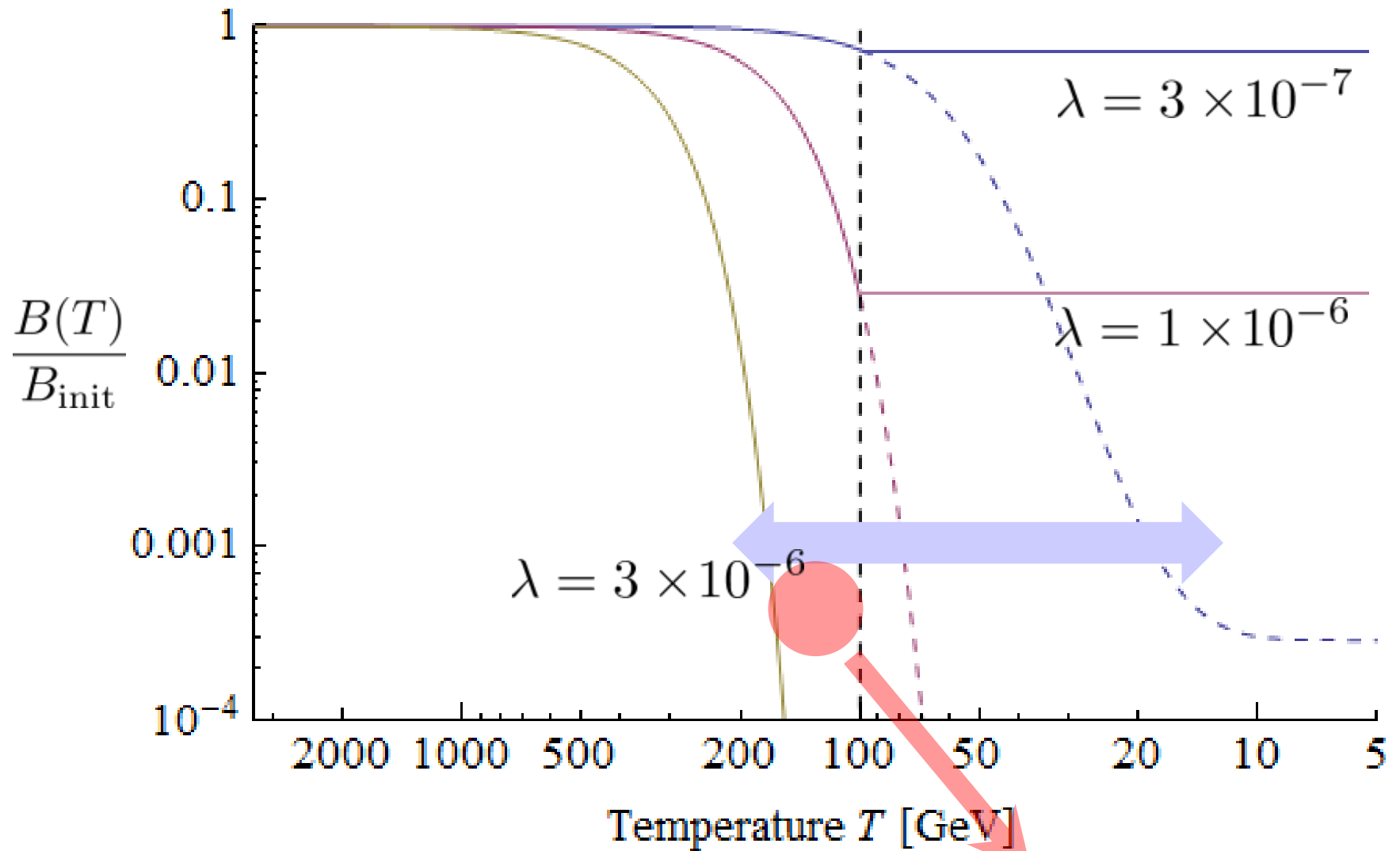
Additional Contribution!

D. RpV Results



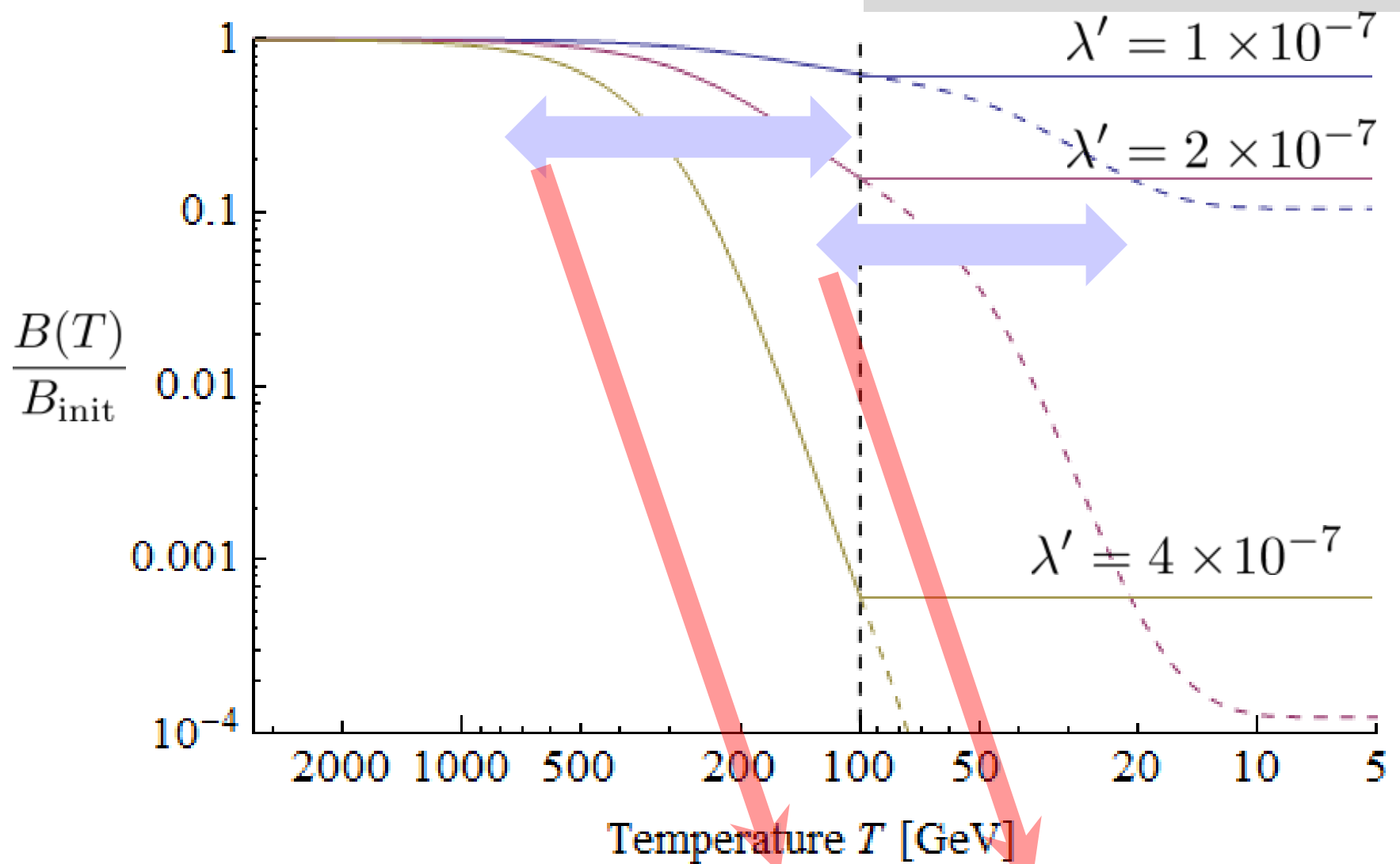
for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

$$W_{\mathcal{L}} \ni \lambda L_i L_j \bar{E}_k$$



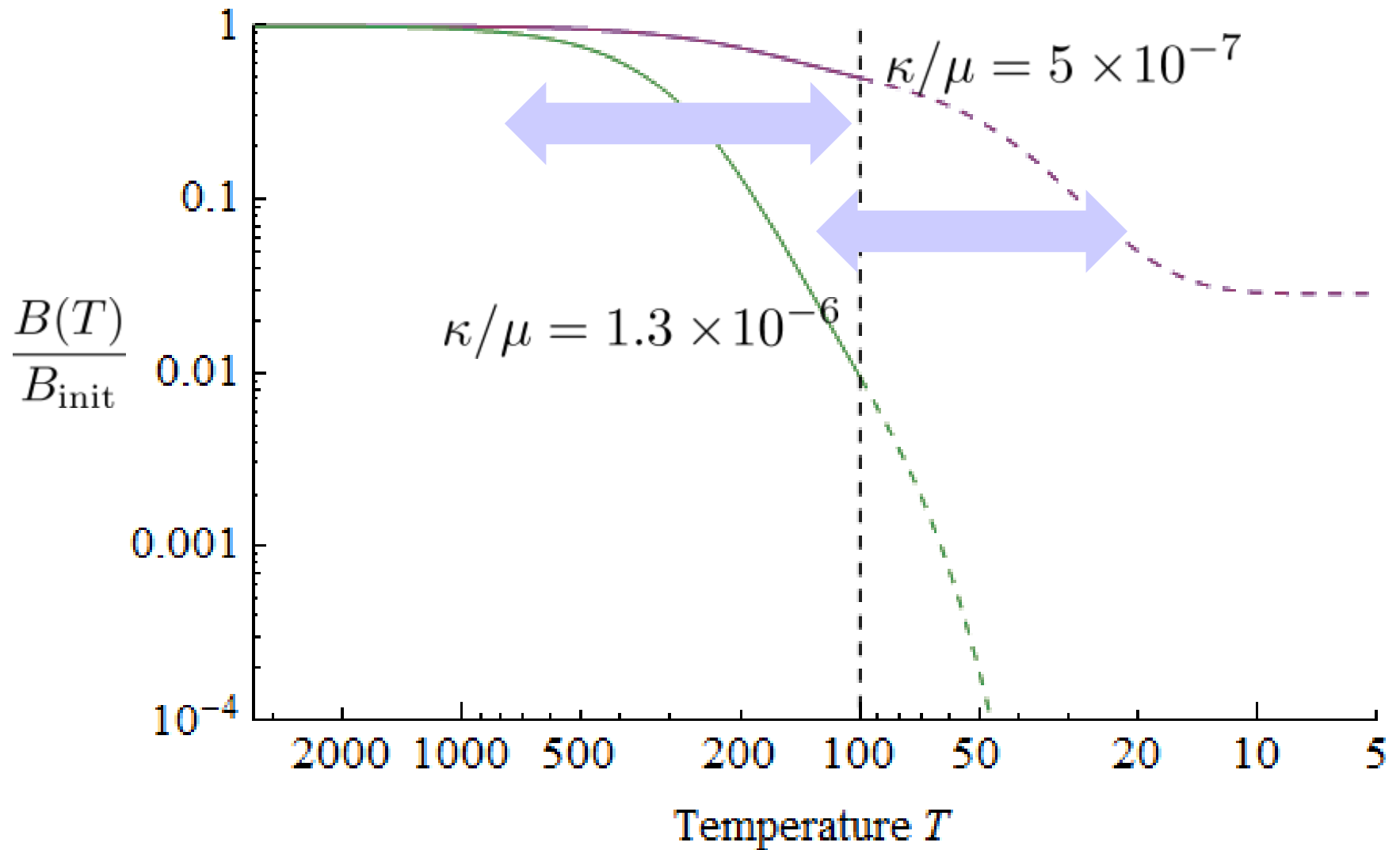
for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

$$W_{\underline{L}} \ni \lambda' L_i Q_j \bar{D}_k$$



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

$$W_{\mathcal{L}} \ni \kappa L_i H_u$$

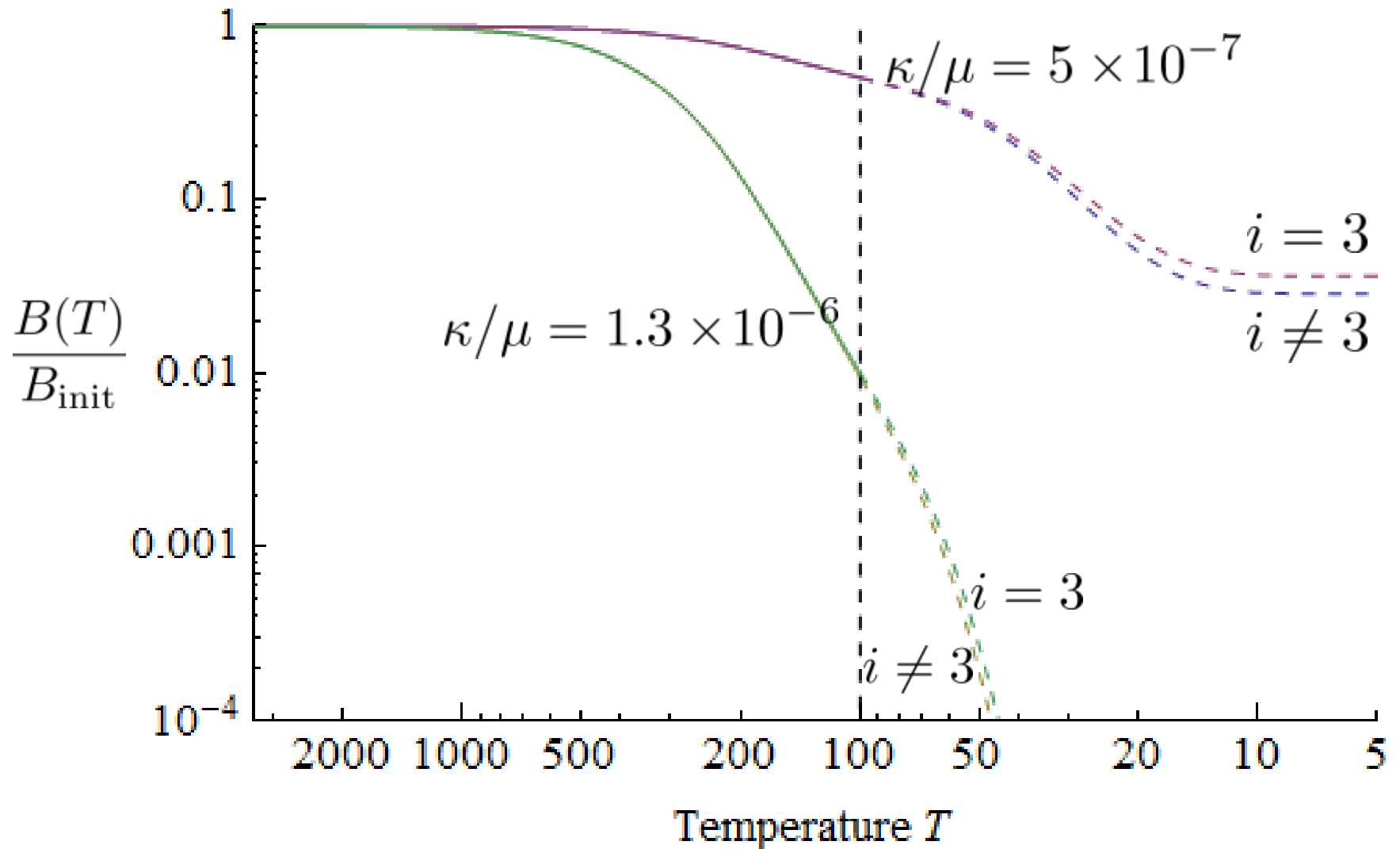


for mass of $(\tilde{q}, \tilde{H}, \tilde{l}) = (600, 300, 100)$ GeV
 $\tan \beta = 10$

D'. RpV Results [Detail]

Very Detail.

$$W_{\mathcal{L}} \ni \kappa L_i H_u$$



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

$$\mu H_u H_d + \kappa_i L_i H_u$$

$$\implies H'_d \simeq H_d + \epsilon_i L_i \quad (\epsilon_i := \kappa_i / \mu)$$

$$\implies W_{\text{RPC}} \ni y_d H_d Q \bar{D} \longrightarrow -\epsilon_i y_d L_i Q \bar{D}$$

$$y_d \frac{174 \text{ GeV}}{\tan \beta} \simeq m_d \quad [\tan \beta = 10]$$

$$\implies W \ni \epsilon_i \frac{m_d \tan \beta}{174 \text{ GeV}} L_i Q \bar{D} \simeq (0.25 \epsilon_i) L_i Q \bar{D}$$

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

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

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

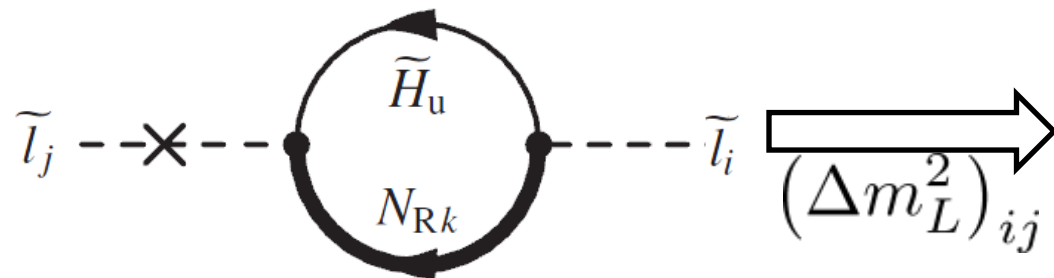
and the antiparticles' processes.

- ⊙ 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

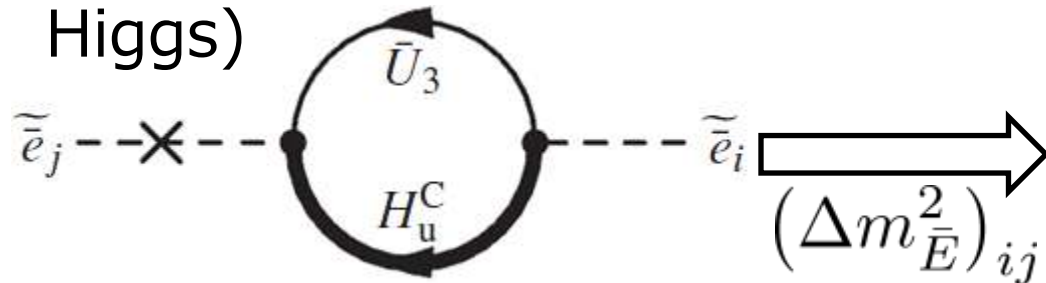
Theoretical Expectation

Right-handed neutrino



A Feynman diagram showing a loop process. On the left, a dashed line labeled \tilde{l}_j enters a loop from the left, marked with a cross. The loop consists of two vertices connected by two internal lines: a top arc labeled \tilde{H}_u and a bottom arc labeled N_{Rk} . On the right, a dashed line labeled \tilde{l}_i exits the loop. A large arrow points from the loop to the right, labeled $(\Delta m_L^2)_{ij}$. To the right of the arrow is the expression $\delta_{ij}^L \sim 10^{-5} \left(\frac{M_R}{10^{10} \text{GeV}} \right)$.

SU(5) GUT (Colored Higgs)



A Feynman diagram showing a loop process. On the left, a dashed line labeled \tilde{e}_j enters a loop from the left, marked with a cross. The loop consists of two vertices connected by two internal lines: a top arc labeled \bar{U}_3 and a bottom arc labeled H_u^C . On the right, a dashed line labeled \tilde{e}_i exits the loop. A large arrow points from the loop to the right, labeled $(\Delta m_{\bar{E}}^2)_{ij}$. To the right of the arrow is the expression $\delta_{ij}^{\bar{E}} \sim 10^{-(1-4)}$.

<75>

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

MEGA Result / MEG Prospect

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

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

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

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

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