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: $H_\mathrm{u} H_\mathrm{d}, \quad H_\mathrm{d} L \bar{E}, \quad H_\mathrm{d} Q \bar{D}, \quad H_\mathrm{u} Q \bar{U},$

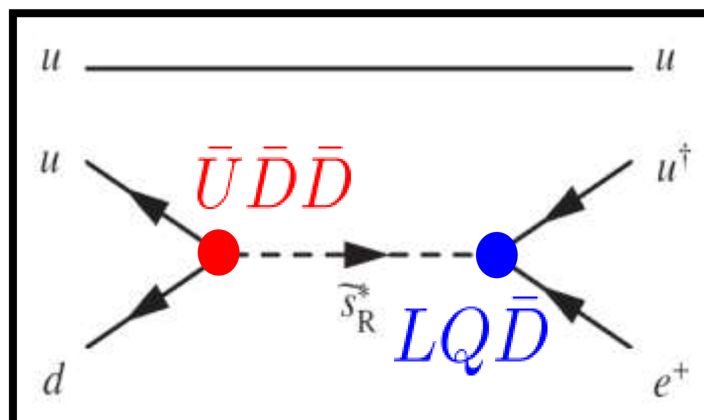
Rp. violating: $L H_\mathrm{u}, \quad L L \bar{E}, \quad L Q \bar{D}, \quad \bar{U} \bar{D} \bar{D}$

$\not{L}$ $\qquad$ $\not{B}$

Both $\not{B}$ and $\not{L}$

⇨ **Proton Decay**

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



Proton Decay Problem

With *R*-Parity Conservation

Rp. conserving: H_uH_d, $H_dL\bar{E}$, $H_dQ\bar{D}$, $H_uQ\bar{U}$,

Rp. violating: ~~LH_u,~~ ~~$LL\bar{E}$,~~ ~~$LQ\bar{D}$,~~ ~~$\bar{U}\bar{D}\bar{D}$~~

$\not{L}$ $\not{B}$

~~Both $\not{B}$ and $\not{L}$~~

⇨ **Proton is Stable.**

And LSP would be DM.

Proton Decay Problem

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

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

(Here DM problem is solved.)

~~**Both $\not{B}$ and $\not{L}$**~~

Proton is Stable. 

d 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.)

- $\not{L}$ -MSSM [Assuming B is conserved.]

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

- $\not{B}$ -MSSM [Assuming L is conserved, and $m_{\mathrm{LSP}} > m_{\mathrm{proton}}$.]

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

What we studied

Our Study: **Cosmological Constraints**

on **these RpV interactions** (couplings).

- $\not{L}$ -MSSM [Assuming B is conserved.]

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

- $\not{B}$ -MSSM [Assuming L is conserved, and $m_{\rm LSP} > m_{\rm proton}$]

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

2. Cosmological Constraints

"The violation of R-parity ($\not{B}$ or $\not{L}$) may spoil the current Baryon Asymmetry of the Universe."

Baryon Asymmetry of the Universe

The Universe

baryon ≫ **anti-baryon**

⇨ Some mechanism for baryogenesis

Bouquet and Salati, 1987

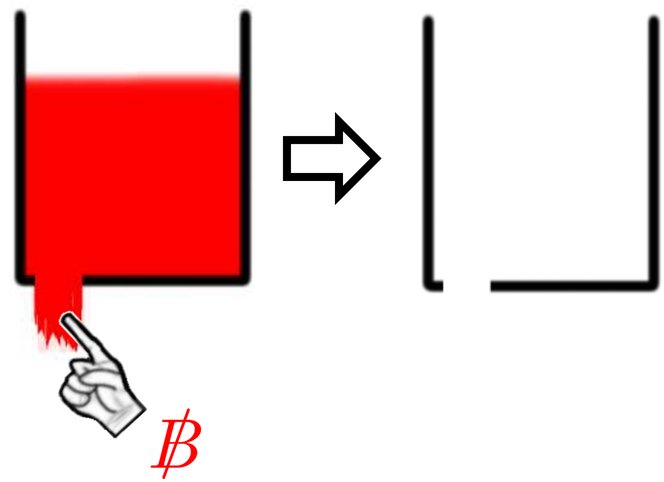
Wash-out with B-viol.

However,

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

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

$\Rightarrow \quad B \to 0$



Pedagogical Note

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

Bouquet and Salati, 1987

Wash-out with *B*-viol.

However,

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

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

Large $\not{B}$ spoils Baryogenesis. ("wash-out")

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

$\not{B}$

Sphaleron

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

Kuzmin, Rubakov, Shaposhnikov, 1985; Ringwald, 1988

Go more precisely!

"**Sphaleron process**"

- Active in early universe $T \gtrsim 100\,\mathrm{GeV}$

  (by thermal effects)

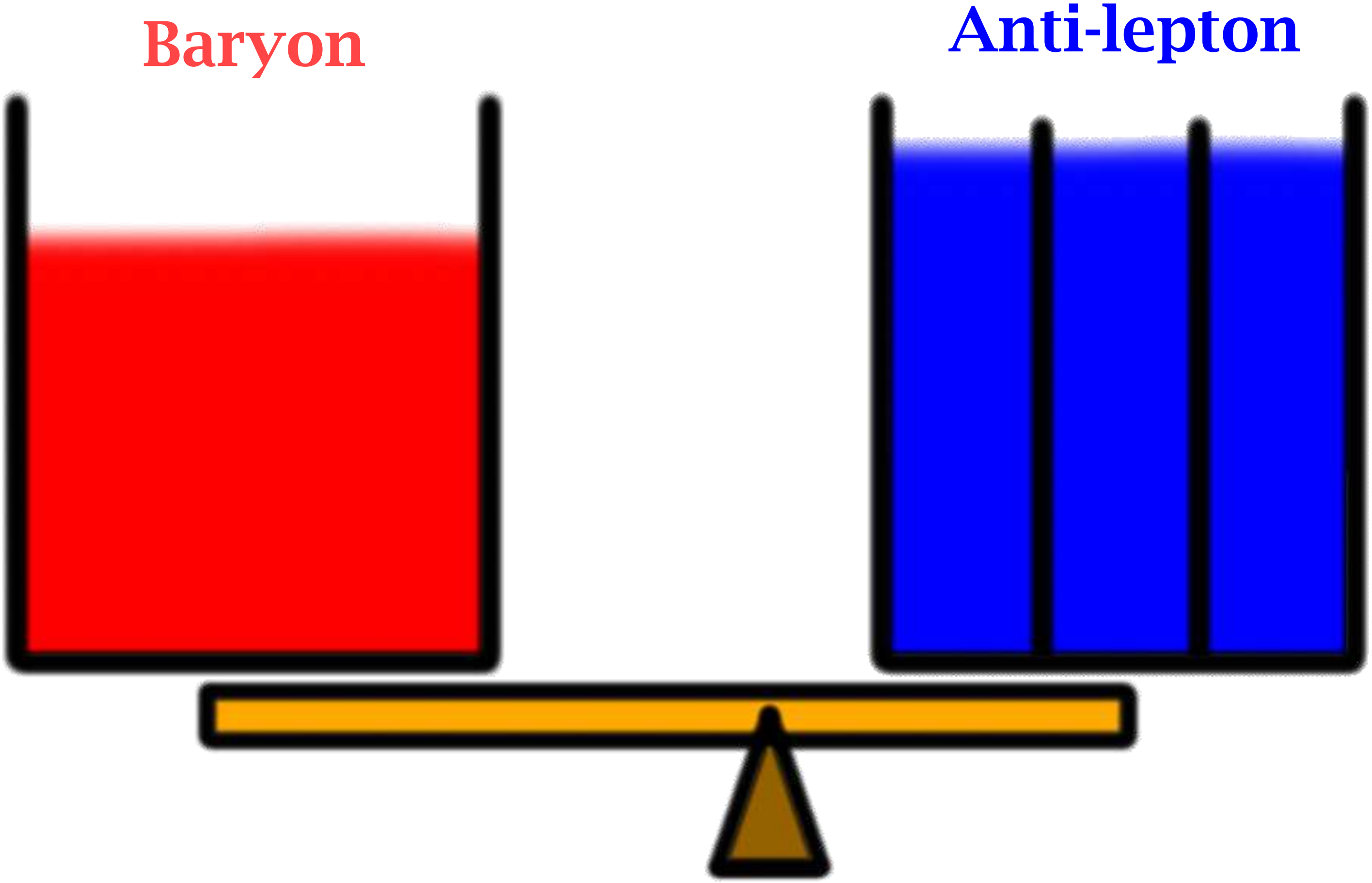
- Converts baryon $\rightleftarrows$ anti-lepton

$\Downarrow$

Equilibrium in early universe

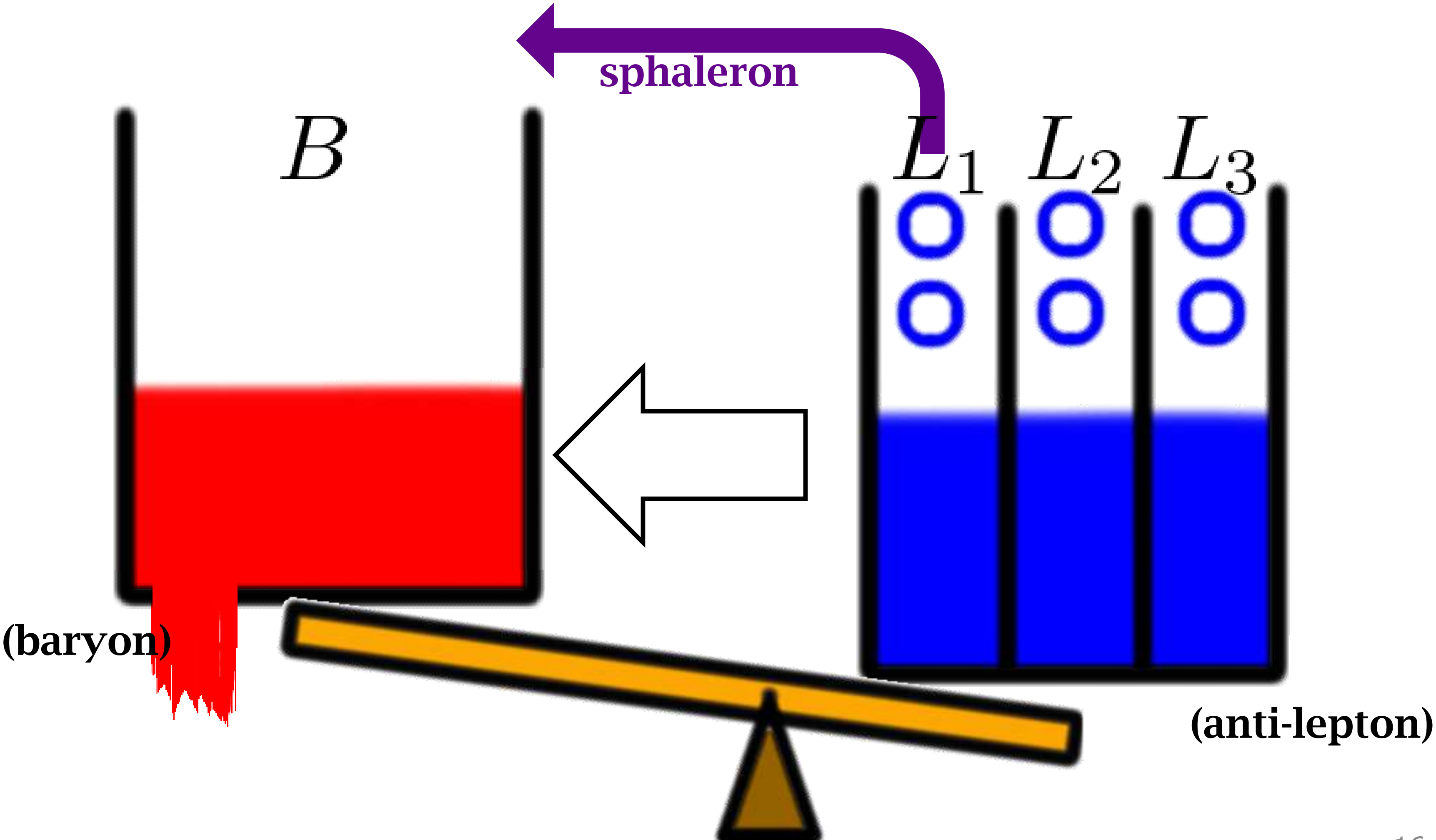
Sphaleron's Effect

On a See-Saw!



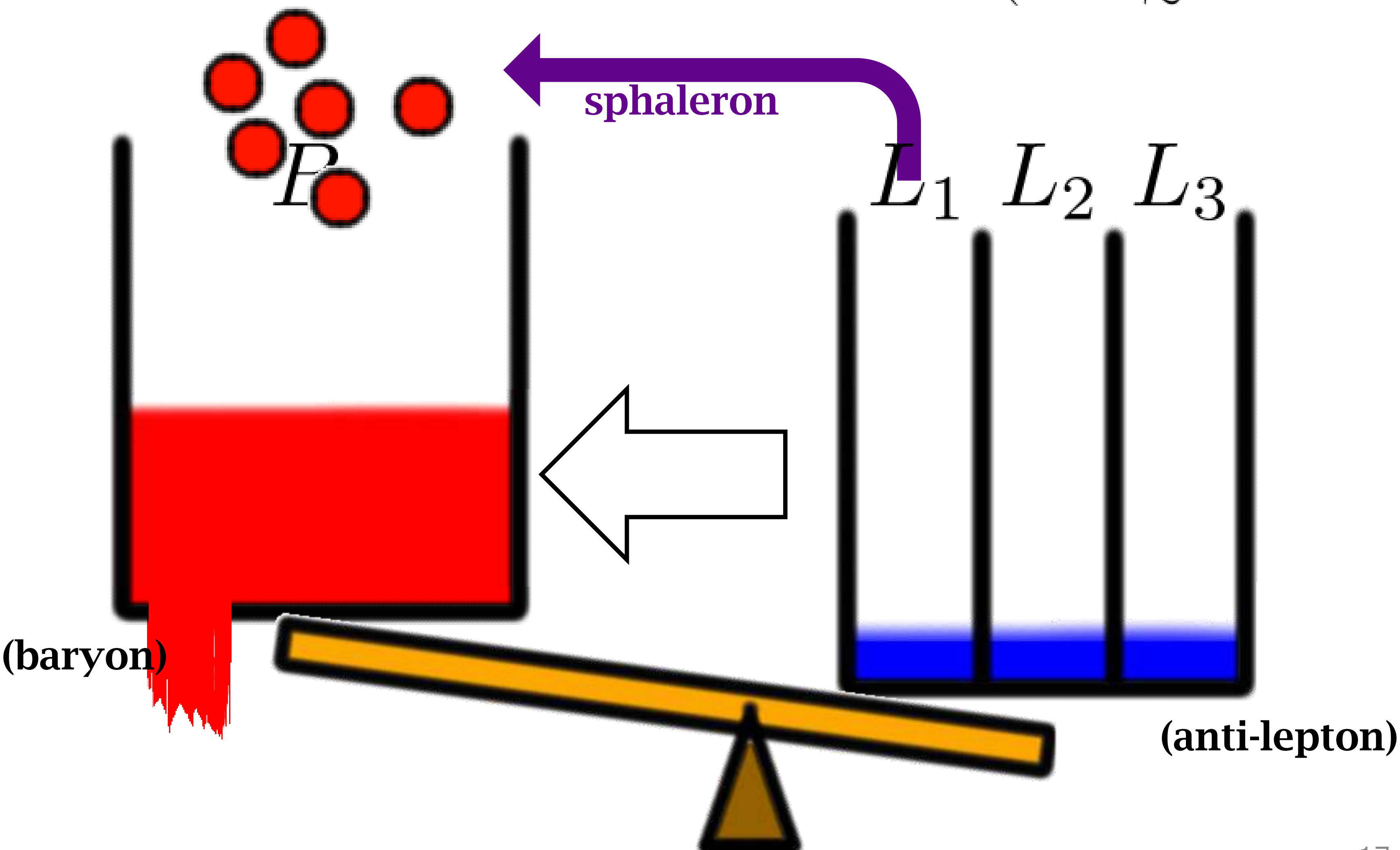
Sphaleron's Effect

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



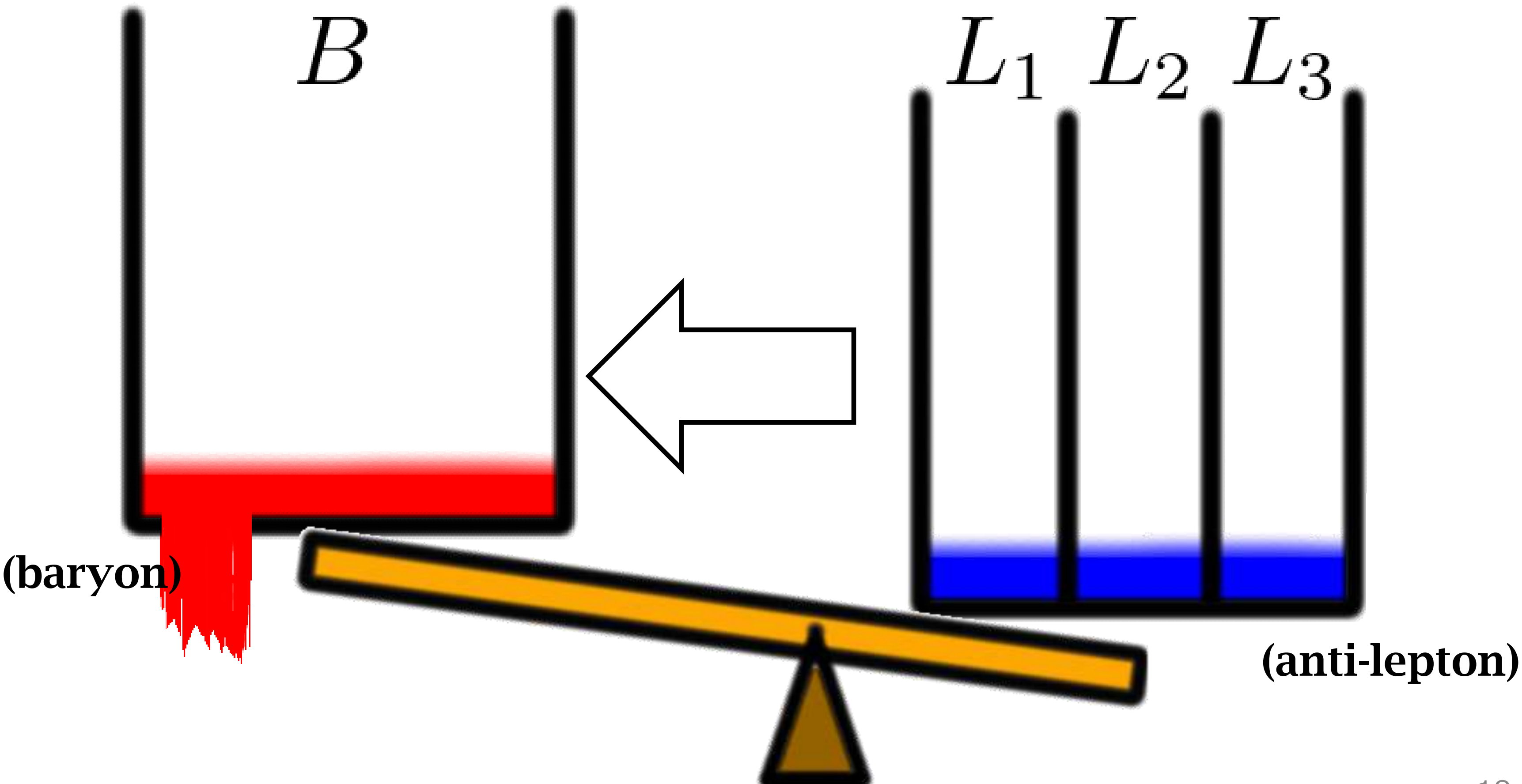
Sphaleron's Effect

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



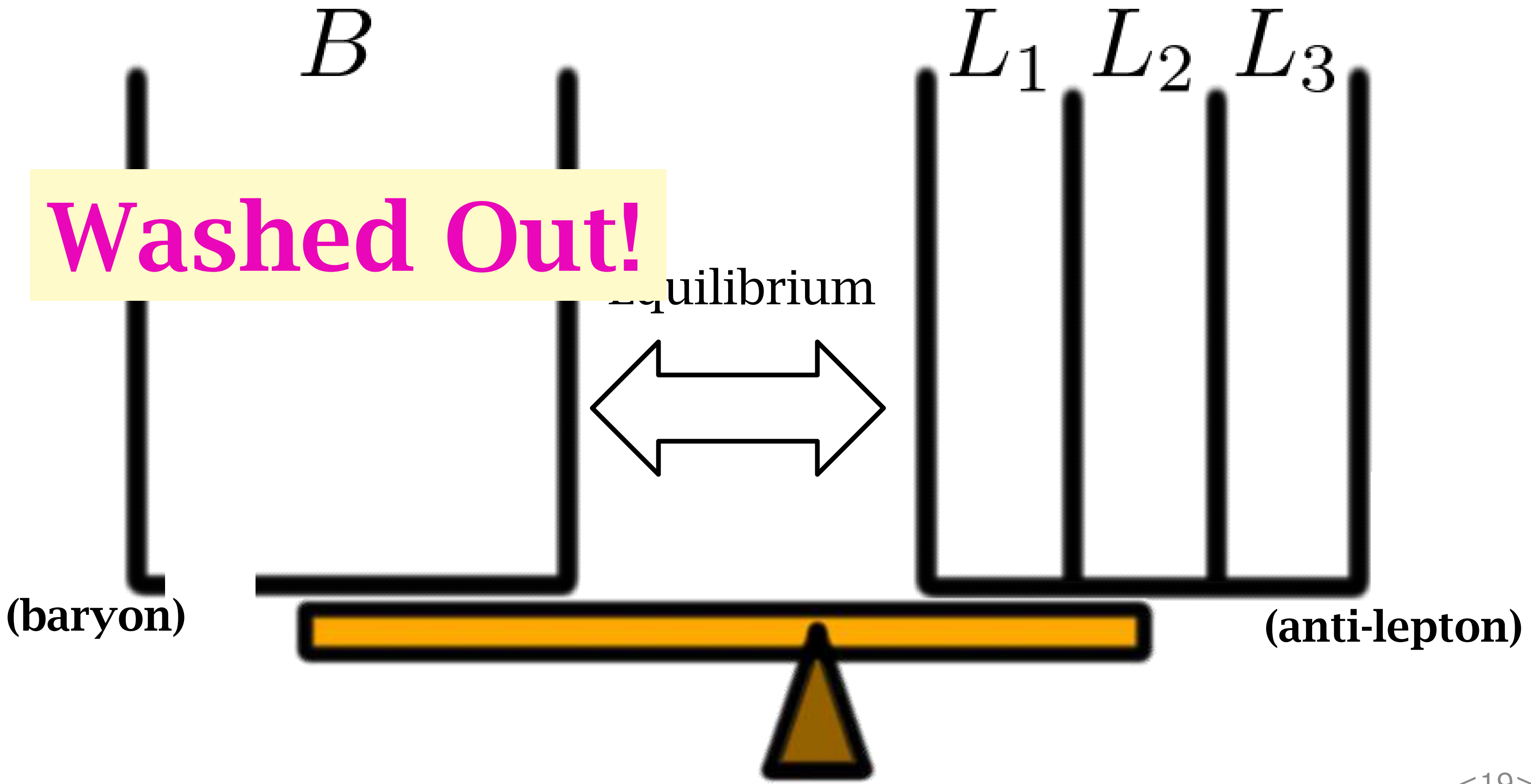
Sphaleron's Effect

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



Sphaleron's Effect

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



Bouquet and Salati, 1987

LESSON

◉ $\not{B}$-MSSM : Large $\not{B}$ = wash out

⇨ $\not{B}$ couplings (λ'') = small enough

? How small must be?

→ Discussed Later

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

Wash-out with L-viol.

This story

does not end here!

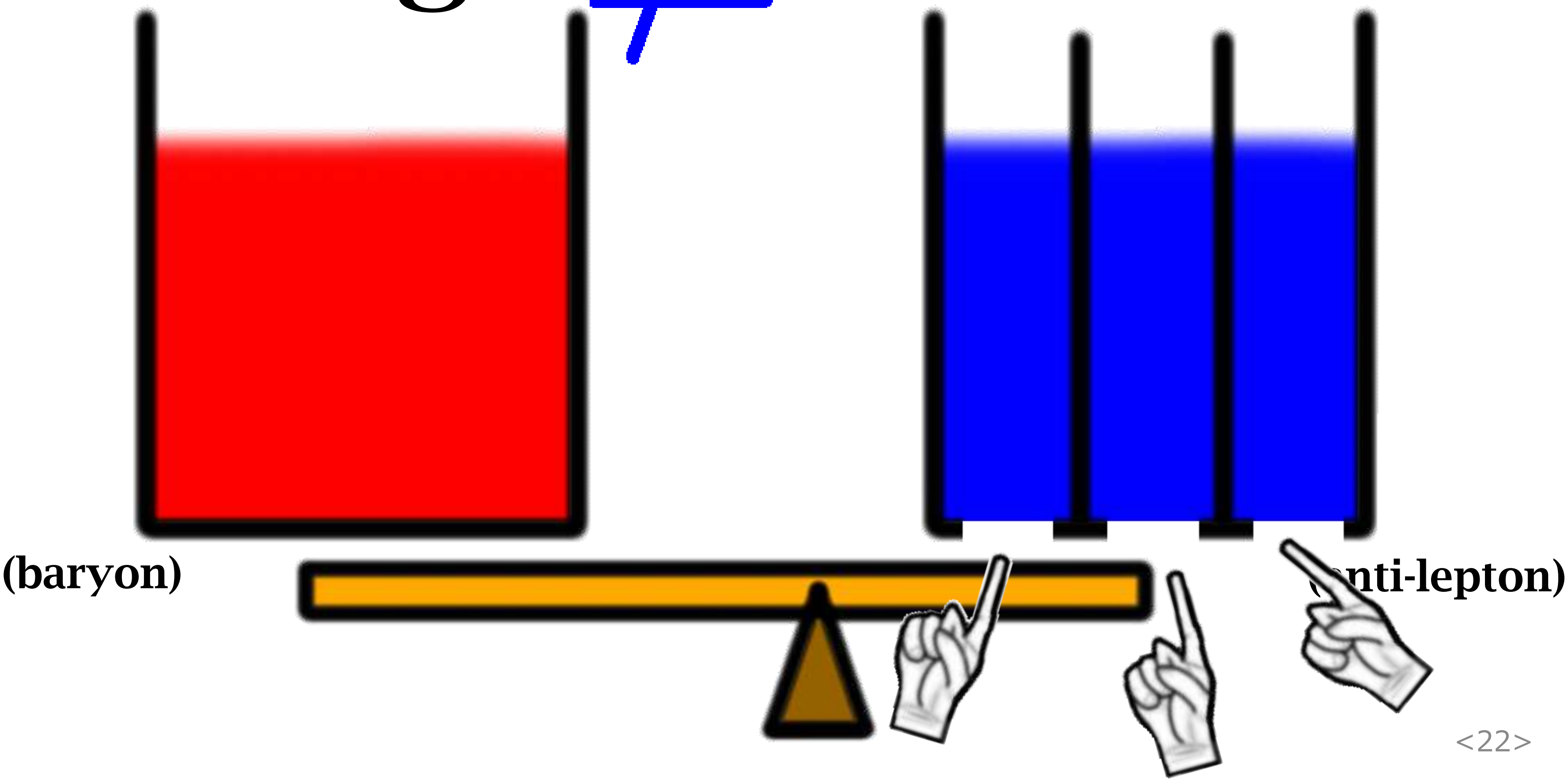
$$\not{L}$$

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

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

- If

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



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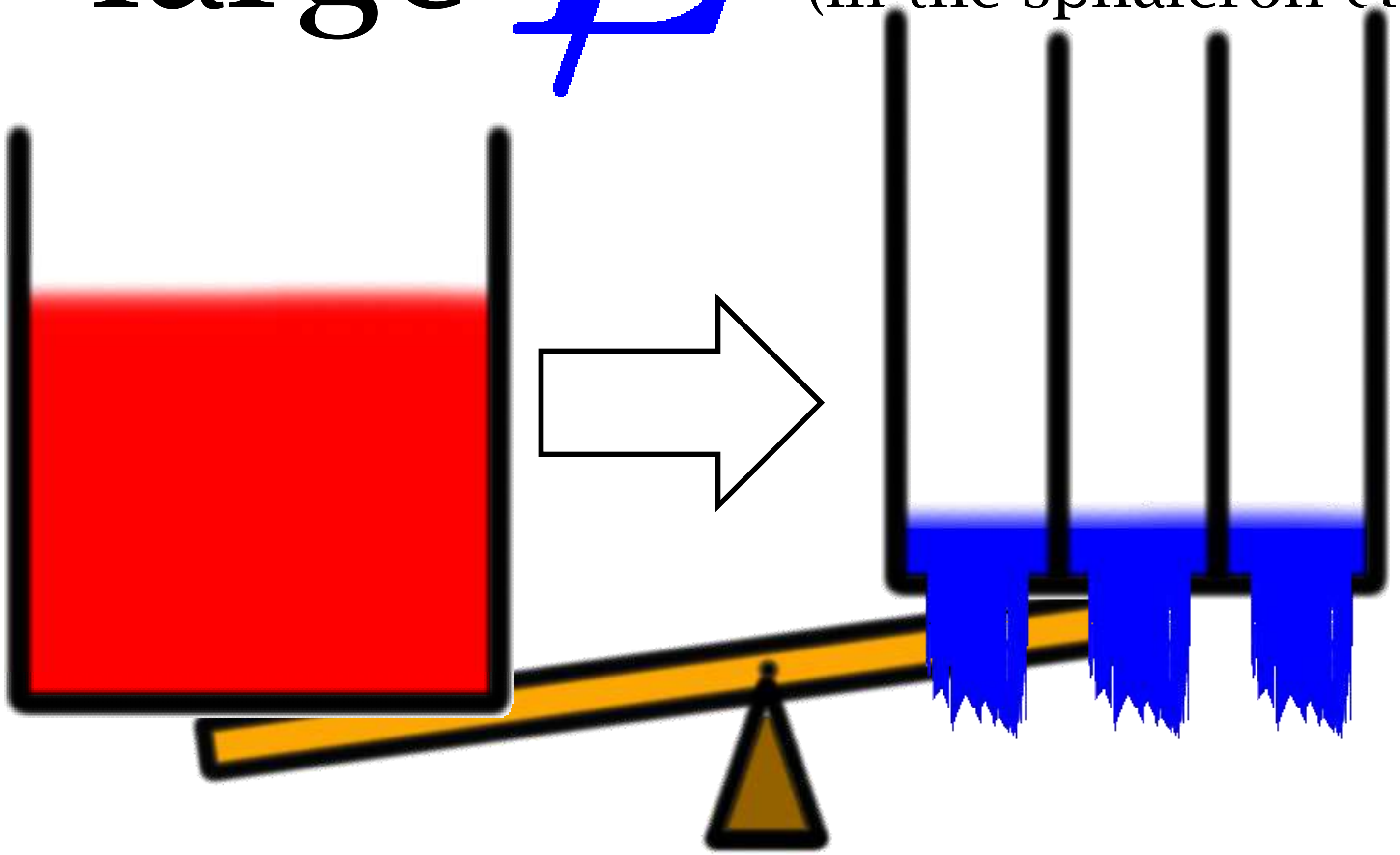
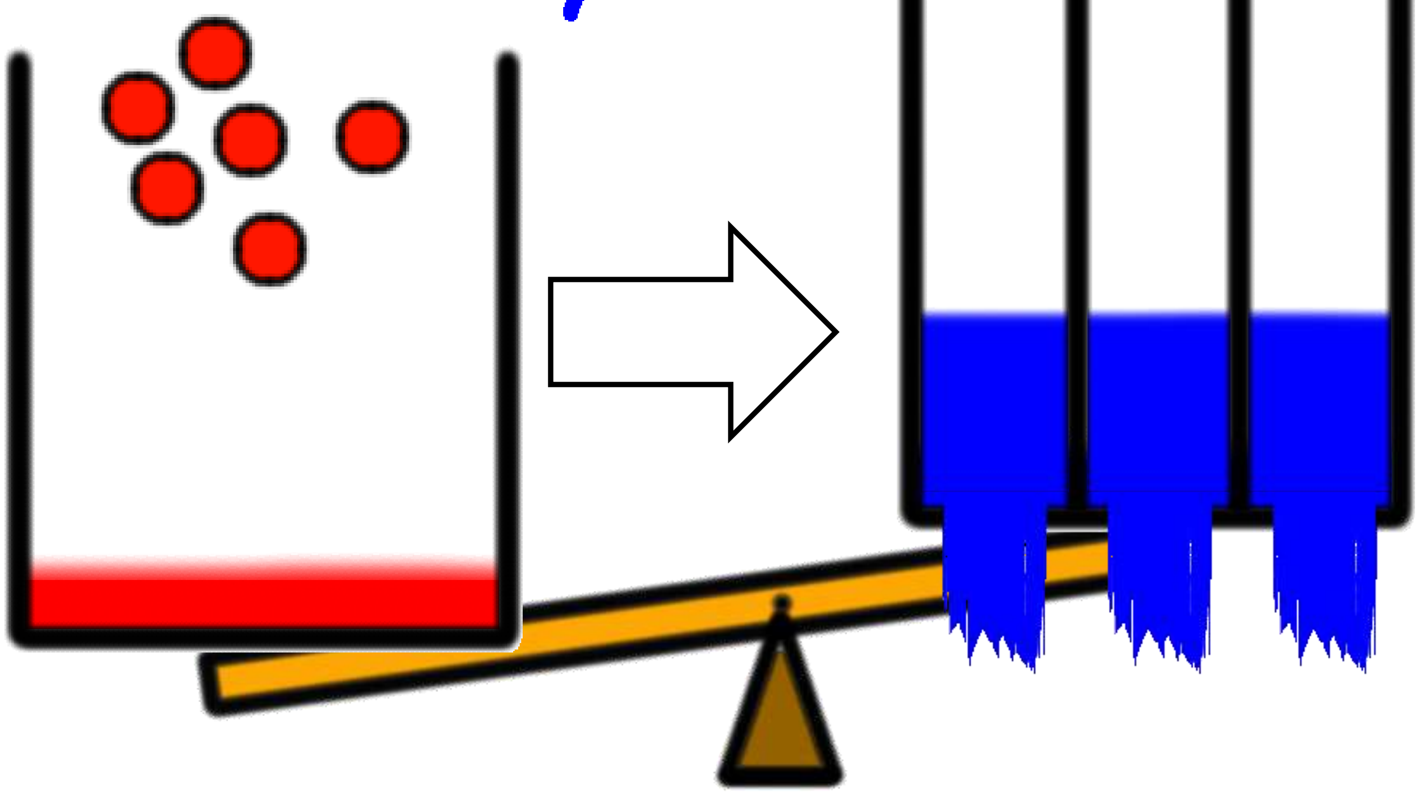


Kuzmin, Rubakov and Shaposhnikov, 1985
Campbell, Davidson, Ellis and Olive, 1992

Wash-out with L-viol.

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

sphaleron



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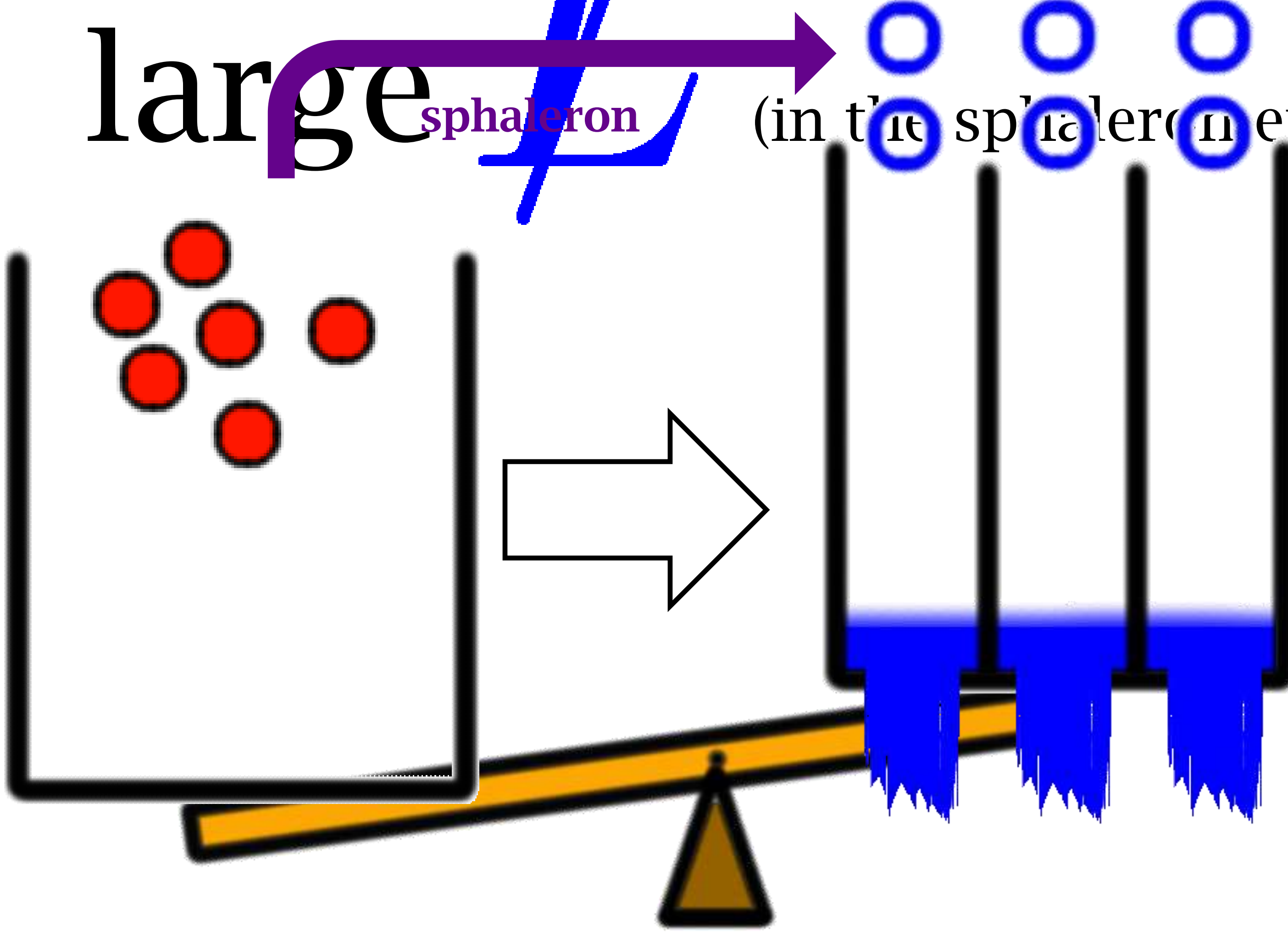
Wash-out with L-viol.

- If

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



Kuzmin, Rubakov and Shaposhnikov, 1985
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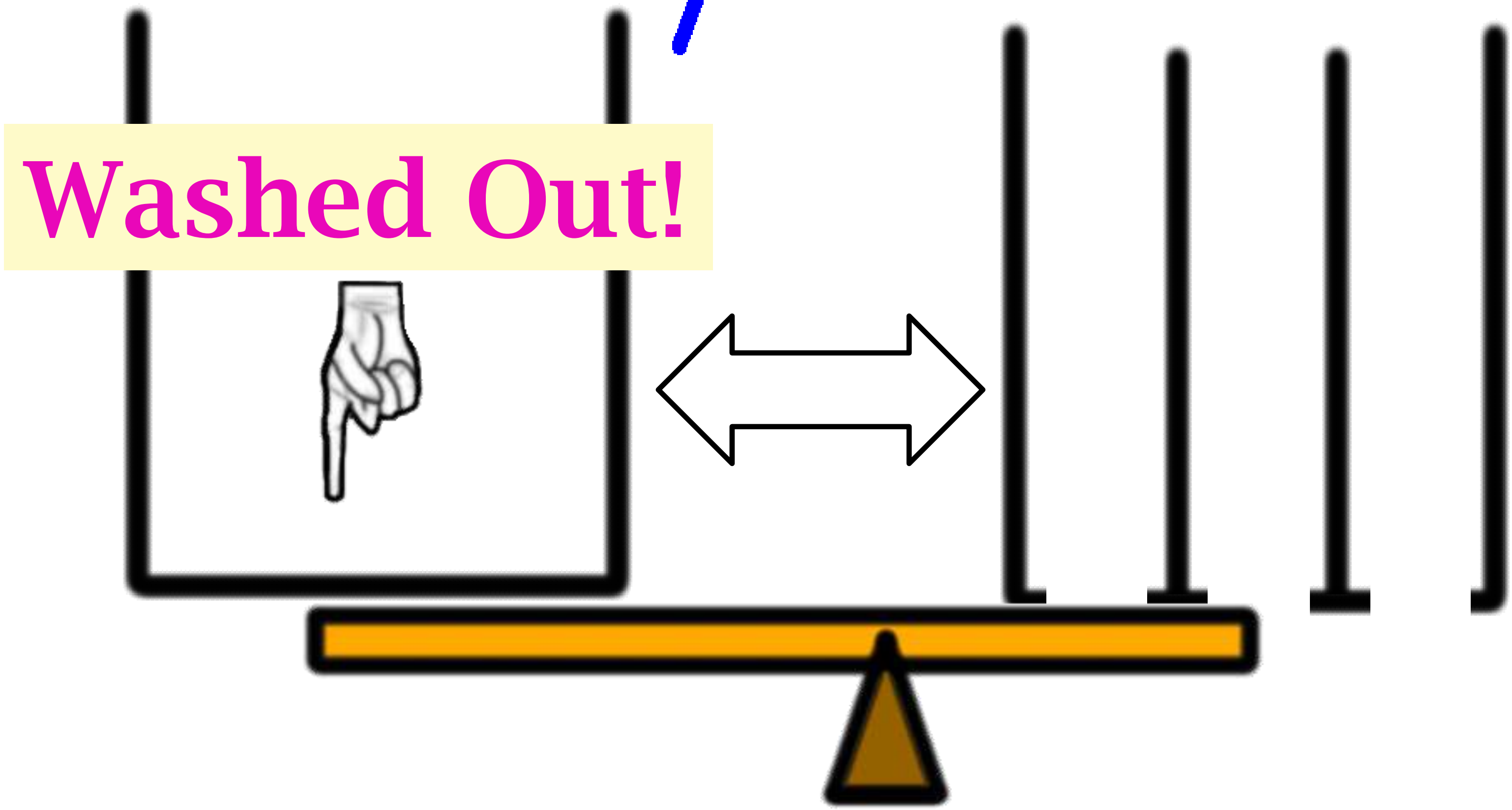
Wash-out with L-viol. $\not{L}$

- If

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



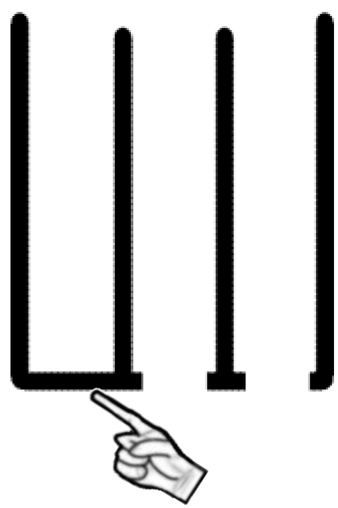
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.

Point

⇨ “Wash out”

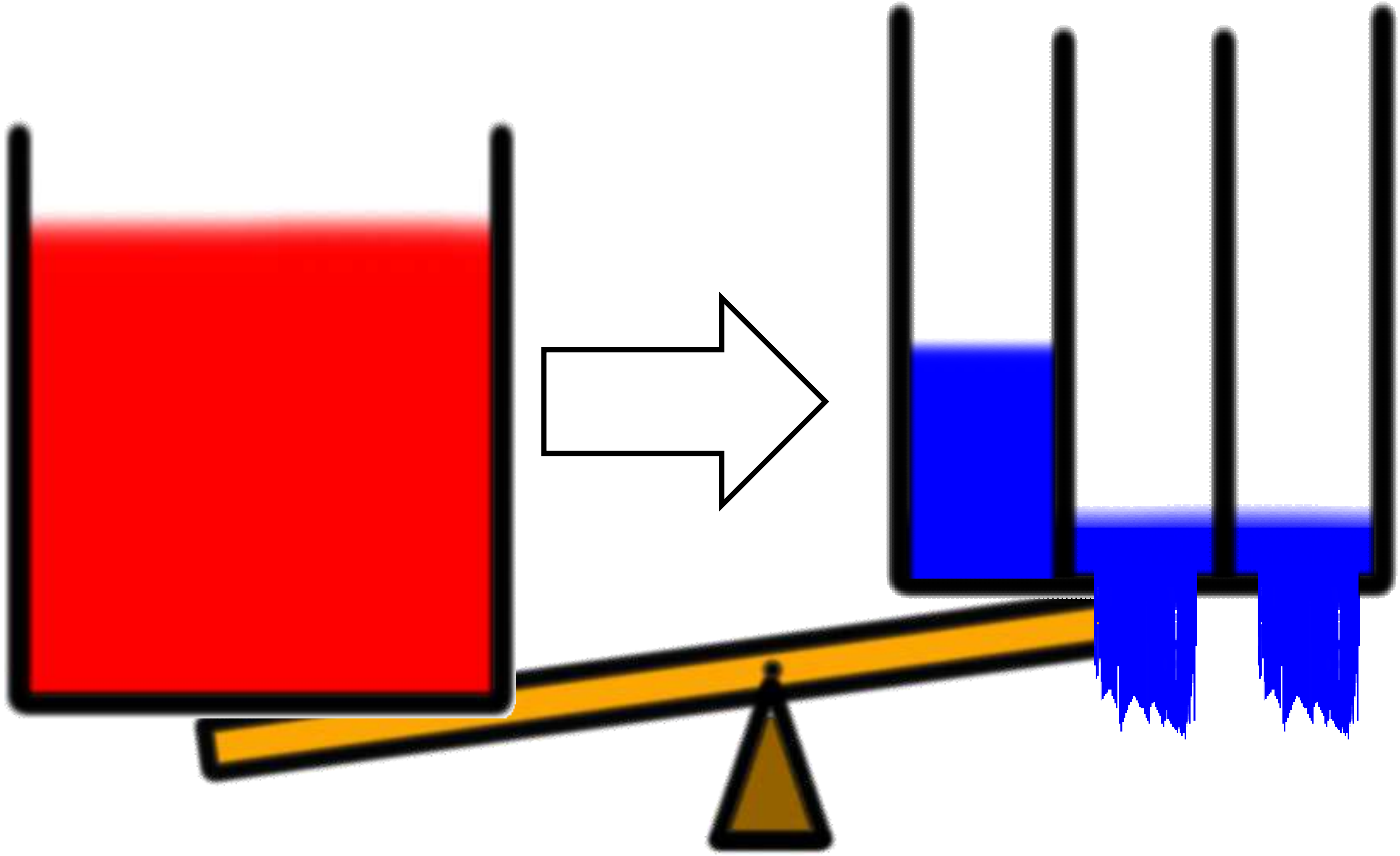
Then
How about



?

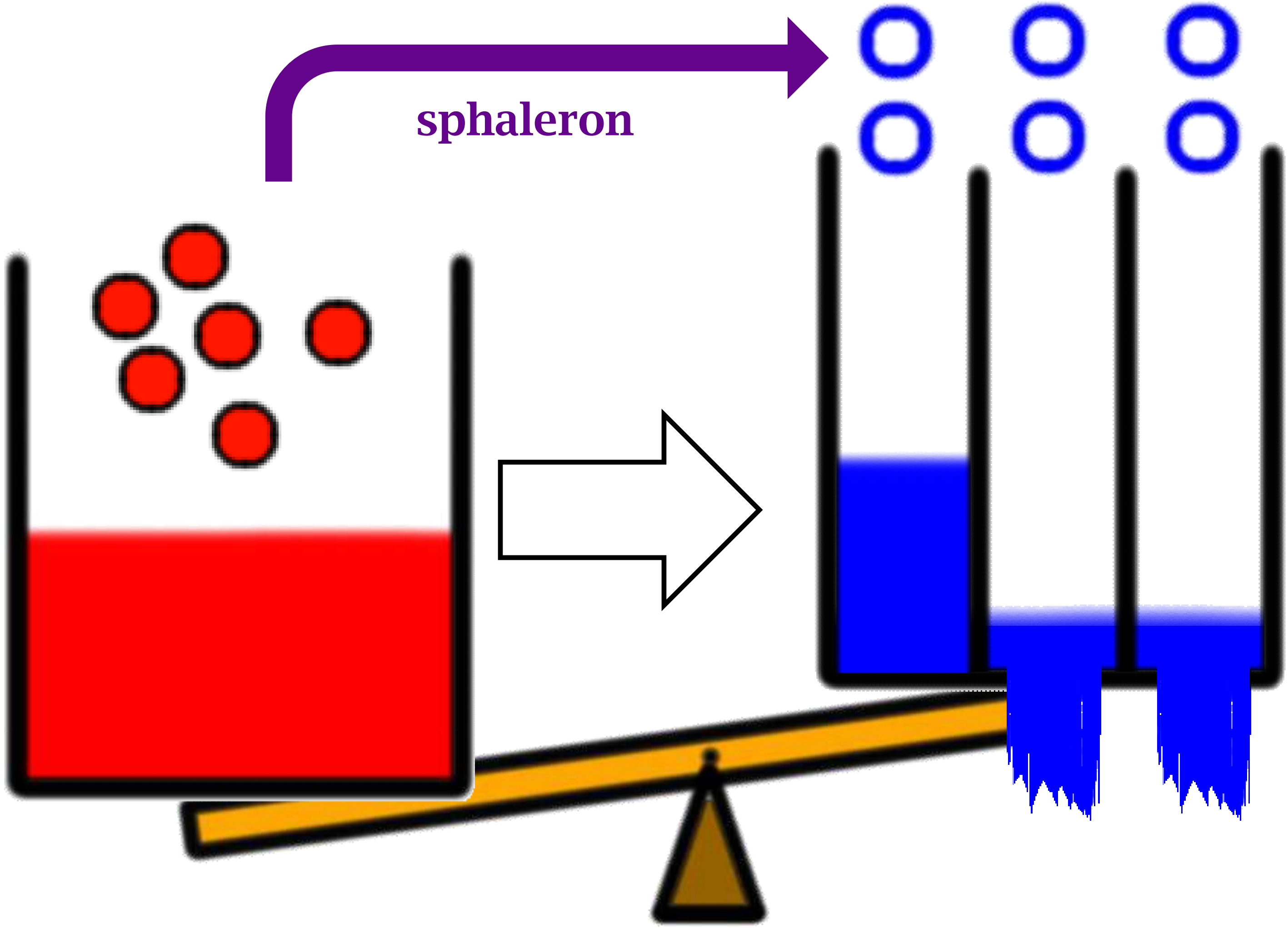
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with L-viol.



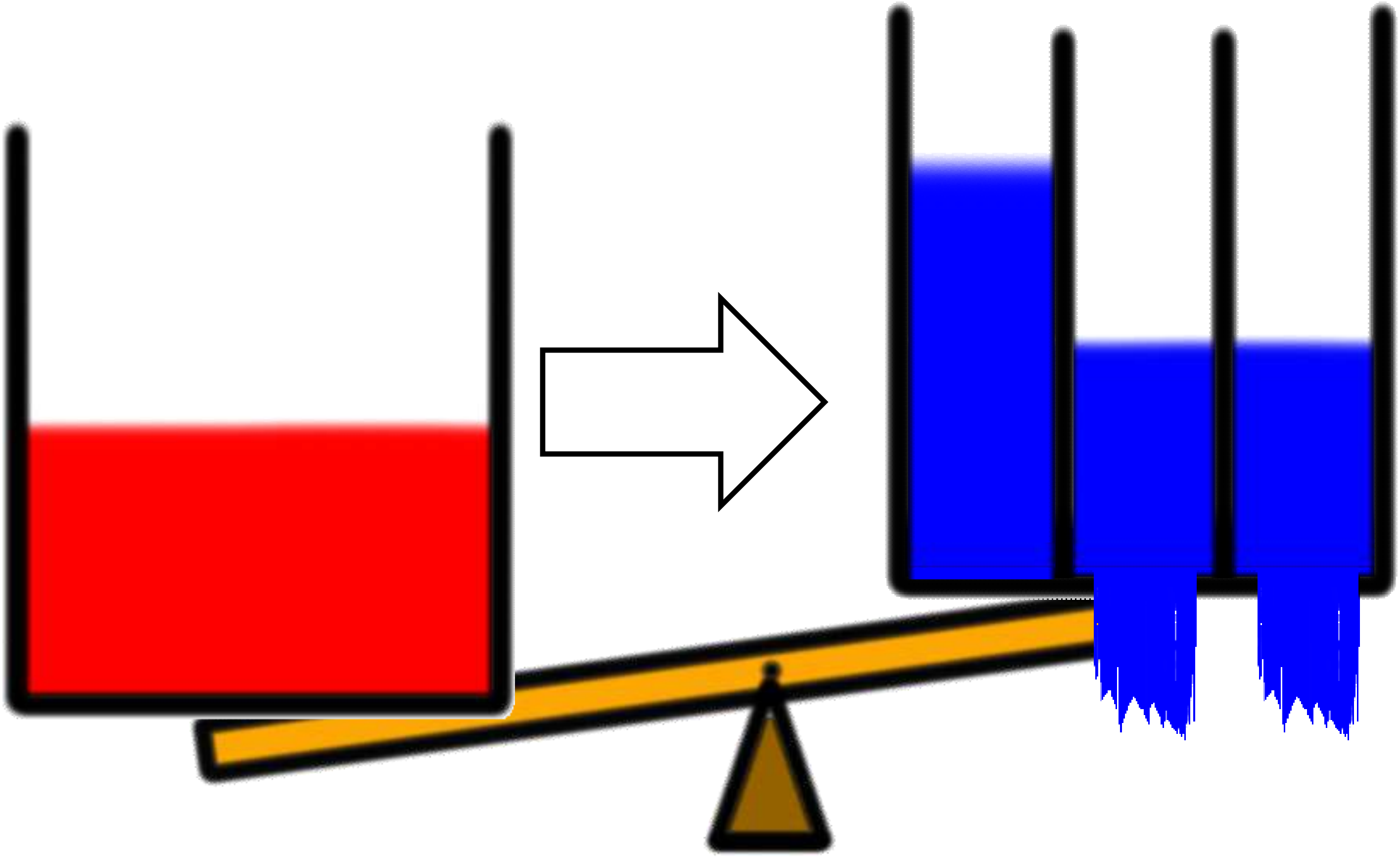
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with L-viol.

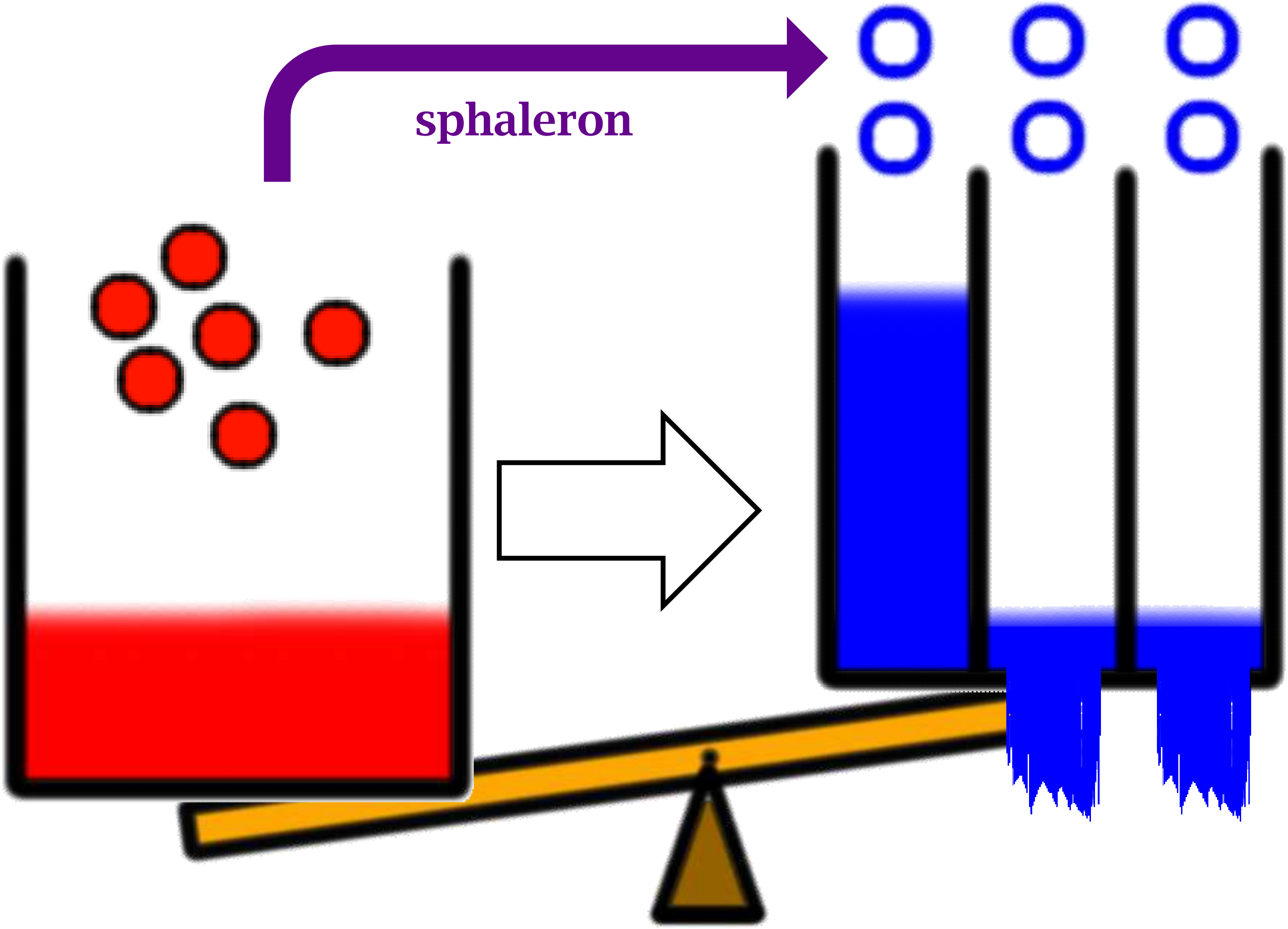


Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

Wash-out with *L*-viol.



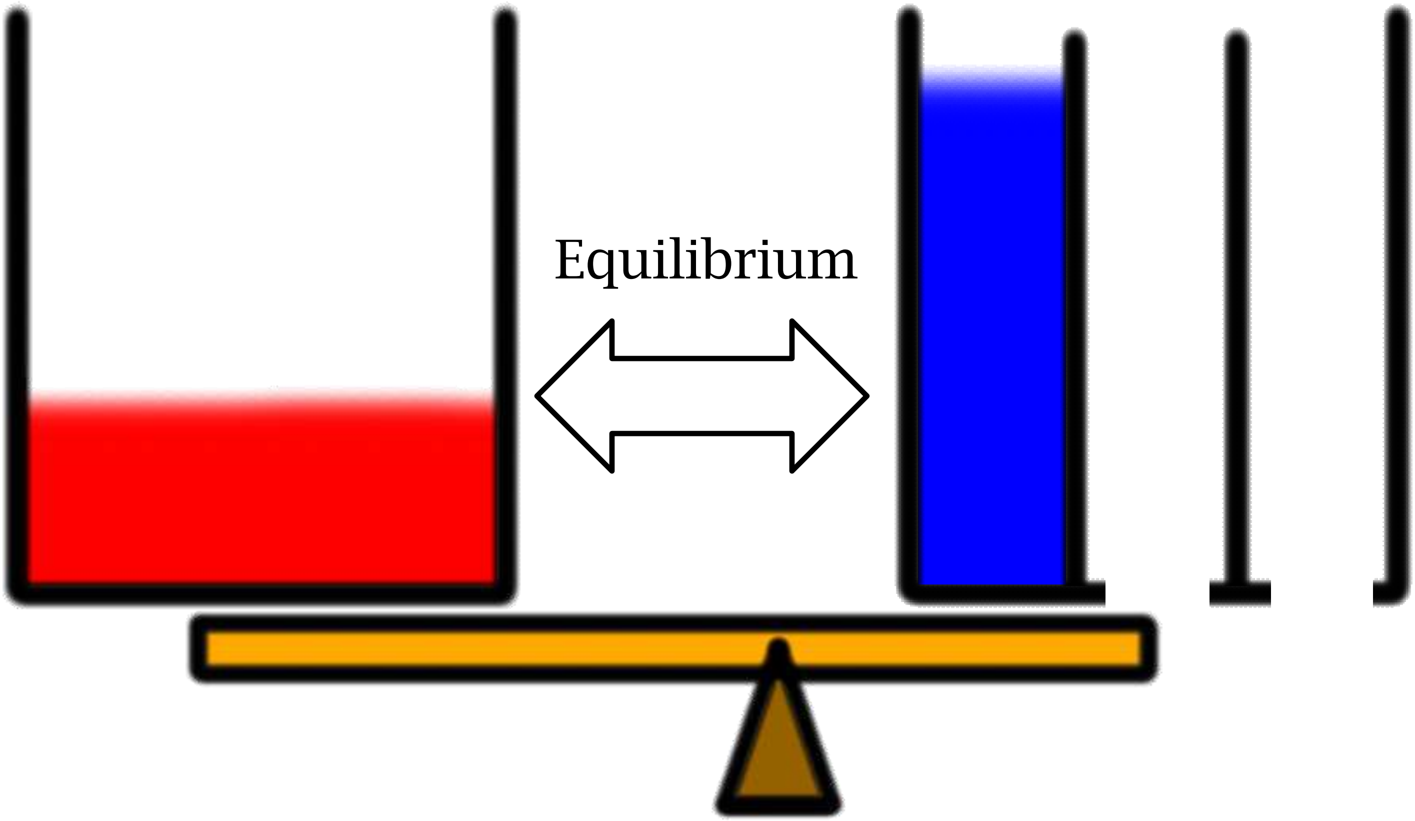
Wash-out with L-viol.



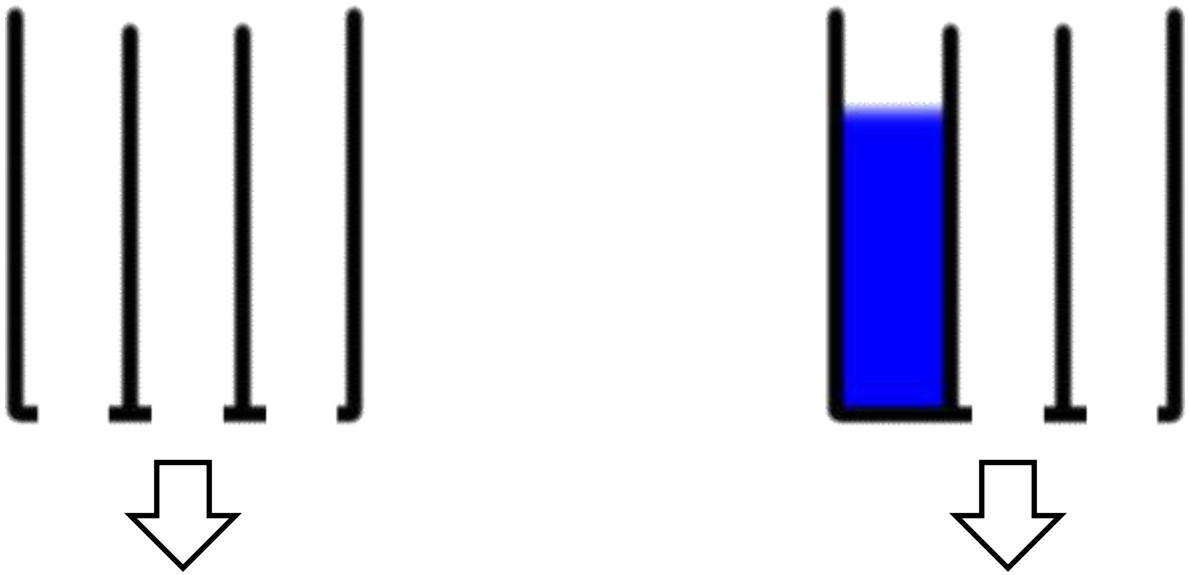
Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

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

Baryon has survived!



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



Wash-out! **Baryon Survives.**

Point

All L_i 's leak in sphaleron era

$\Longrightarrow$ “Wash out”

Endo, Hamaguchi, and SI, 2009

Wash-out with *L*-viol.

Our Attention

In MSSM, generally,

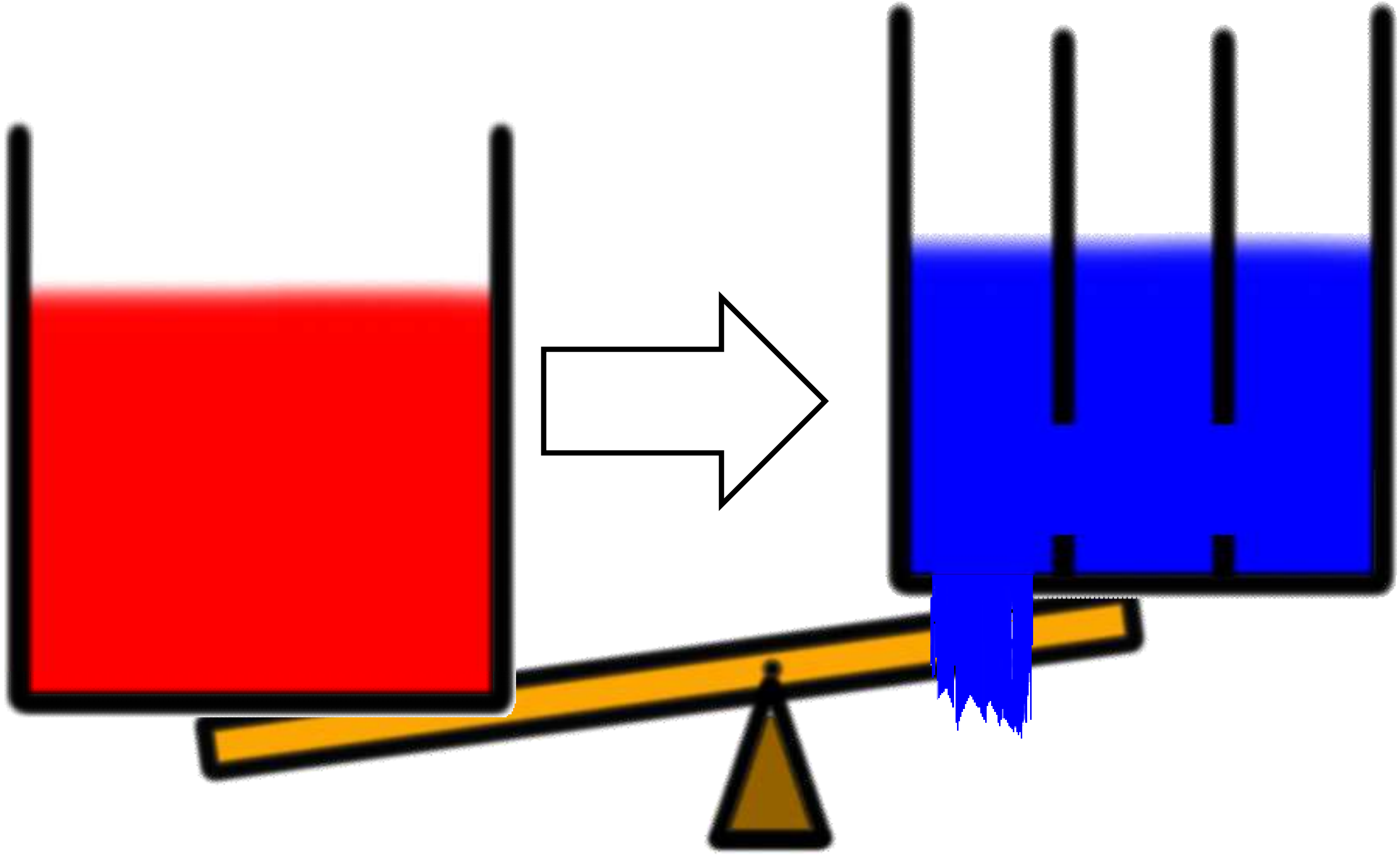
We have LFVs!!!

The Standard Model　　The MSSM

Endo, Hamaguchi, and SI, 2009

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

Under **LFV**, only one $\not{L}$ would ...

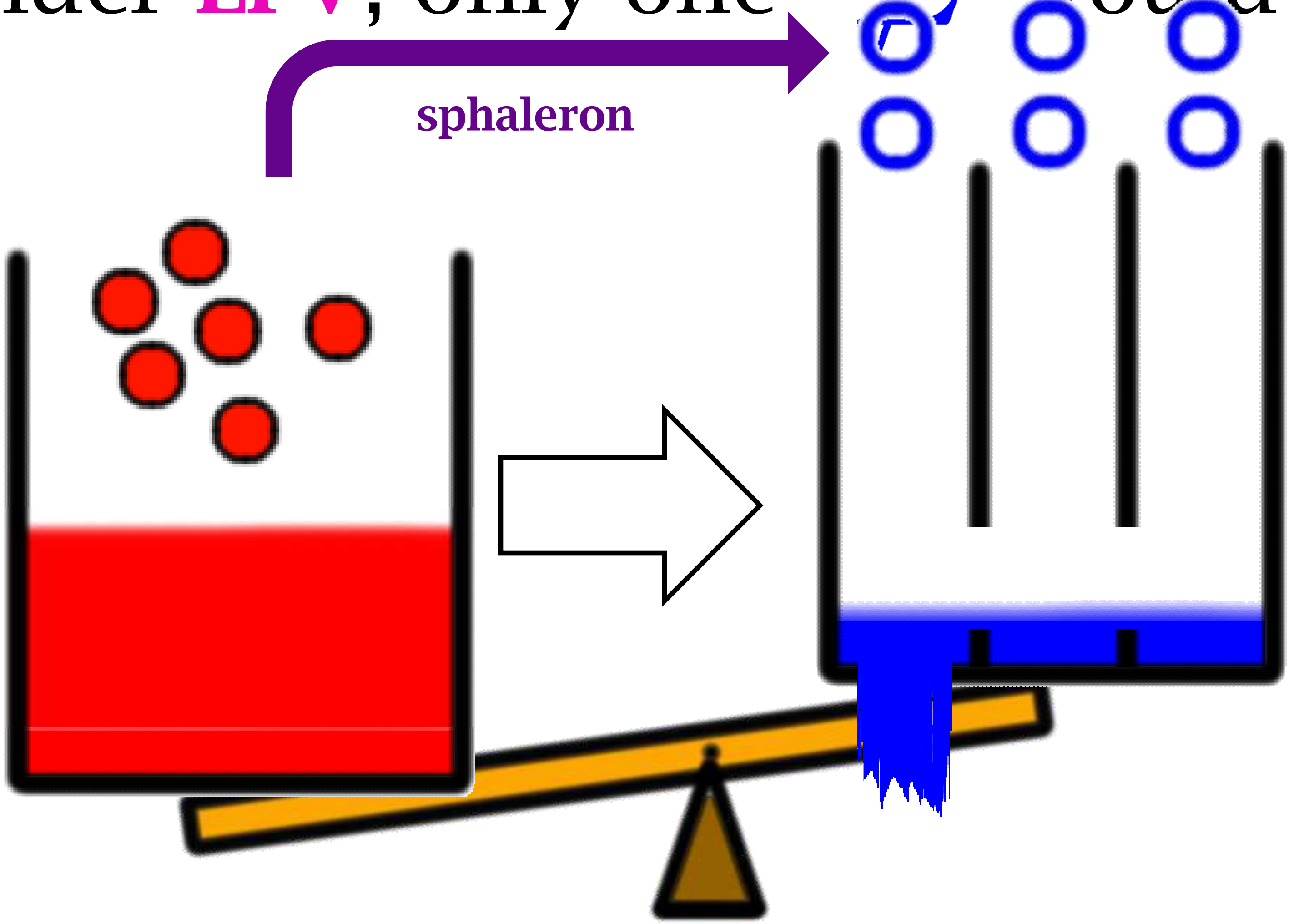


Wash-out with *L*-viol.

Endo, Hamaguchi, and SI, 2009

$\not{L}$

Under **LFV**, only one $\not{L}$ would ...

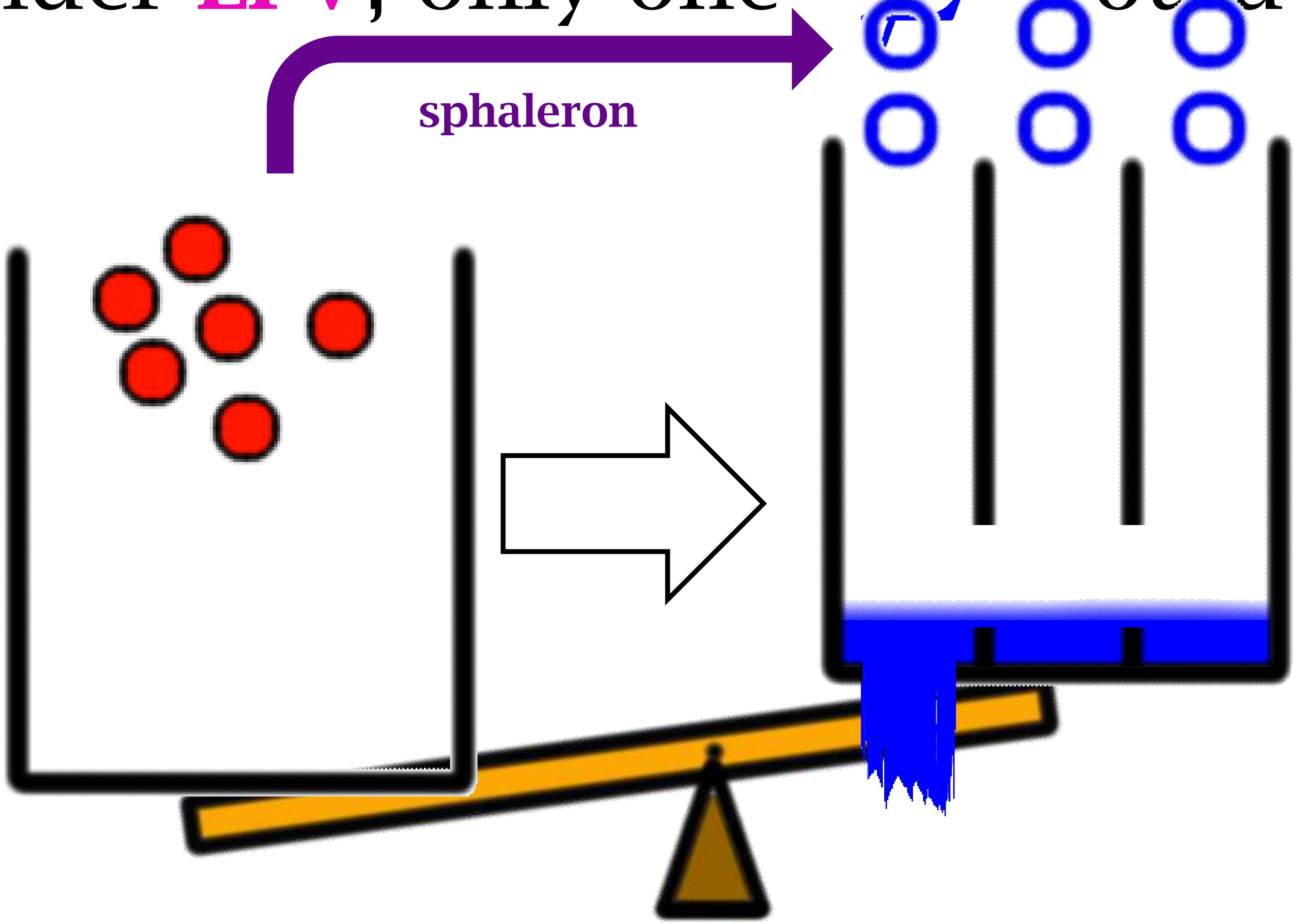


Wash-out with *L*-viol.

Endo, Hamaguchi, and SI, 2009

$\not{L}$

Under **LFV**, only one $\not{L}$ would ...



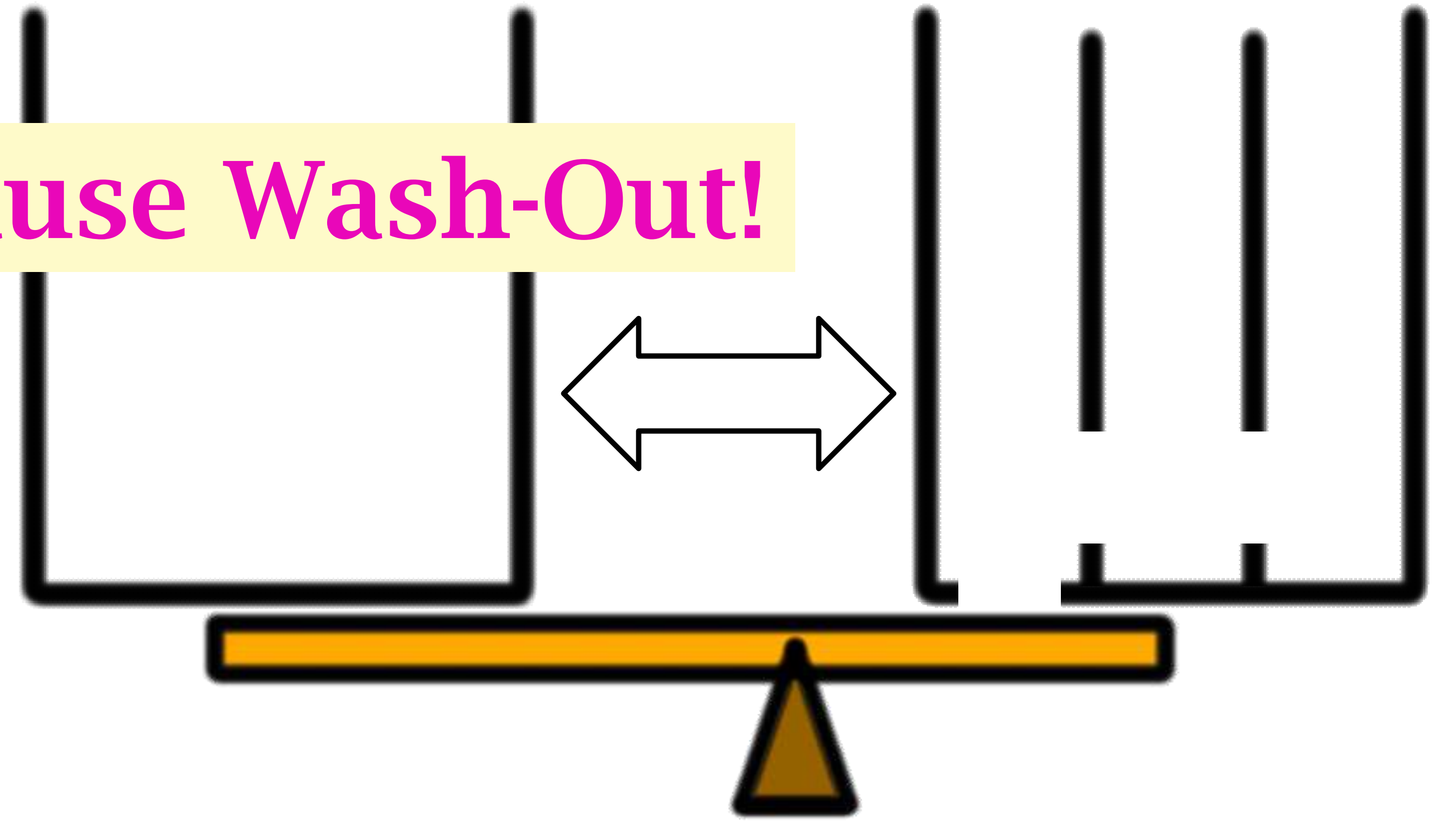
Endo, Hamaguchi, and SI, 2009

Wash-out with L-viol.

$\not{L}$

Under **LFV**, only one $\not{L}$ would ...

cause Wash-Out!



LESSON

- $\not{B}$-MSSM : Large $\not{B}$ = wash out

  $\Rightarrow$ $\not{B}$ couplings (λ'') = small enough

- $\not{L}$-MSSM : (in sphaleron era)

  All L_i leak via Large $\not{L}$ (directly) or **LFV**

  = wash out

  $\Rightarrow$ **Assuming large LFV,**

  $\not{L}$ couplings ($\kappa, \lambda, \lambda'$) = small enough

LESSON

? How large?

? How small must be?

There are our main target!

◉ $\not{L}$-MSSM : (in sphaleron era)

All L_i leak via Large $\not{L}$ (directly) or **LFV**

= wash out

⇨ **Assuming large LFV,**

$\not{L}$ couplings $(\kappa, \lambda, \lambda')$ = small enough

3. Method and Results

LESSON

? How large?

? How small must be?

- $\not{L}$-MSSM : (in sphaleron era)

  All L_i leak via Large $\not{L}$ (directly) or LFV

  = wash out

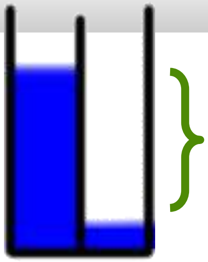
⇒ **Assuming large LFV,**

$\not{L}$ couplings $(\kappa, \lambda, \lambda')$ = small enough

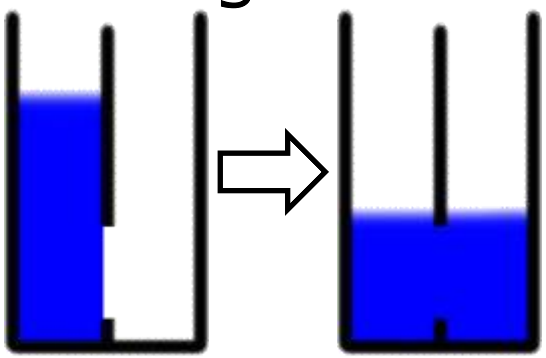
Method

Lepton number density of *i*-th generation

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

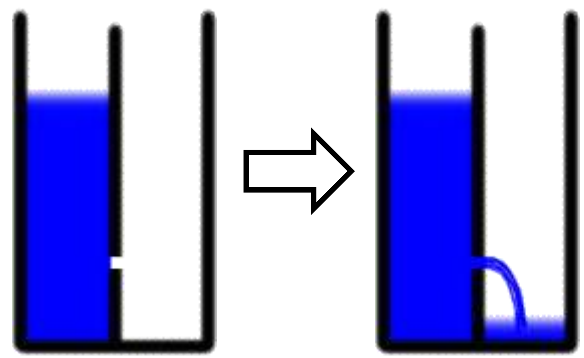


Large LFV



$$L_i - L_j \to 0$$

Tiny LFV

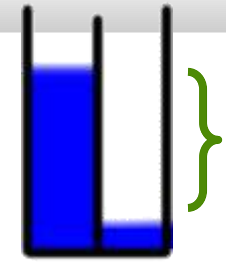


$$L_i - L_j \not\to 0$$

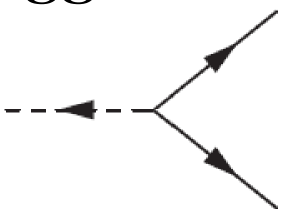
Method

Lepton number density of *i*-th generation

We calculated $\dfrac{\mathrm{d}}{\mathrm{d}t}(L_i - L_j)$ by **Boltzmann Eq.**

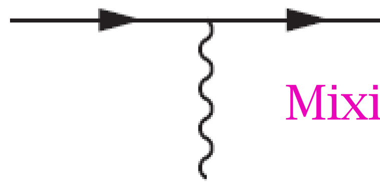


Higgs Yukawa



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

Gauge inter.



Soft mass

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

Mixing angle

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

Diagonalize

LFV

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

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

Method

Example)

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

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

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

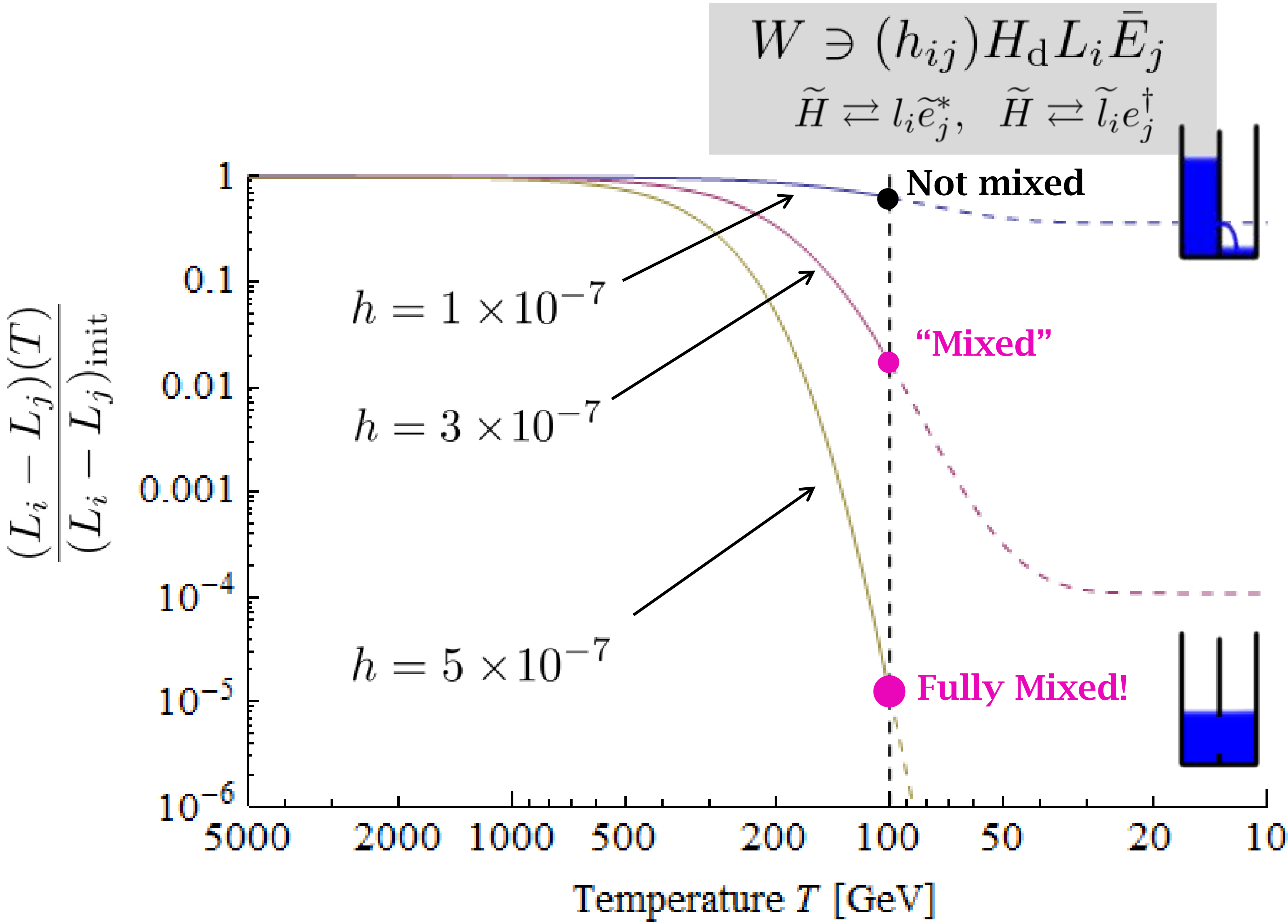
$$(m^2_{\bar{E}})_{ij} \widetilde{\bar{e}}^*_i \widetilde{\bar{e}}_j$$

Mixing process:

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

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

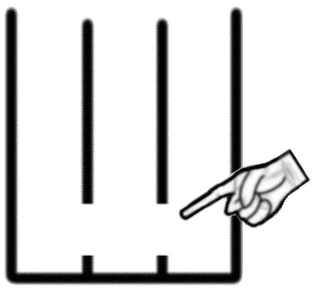
$$h_{ij} := h_i \theta^{\bar{E}}_{ij} + h_j \theta^{L}_{ji}$$



$m_{\widetilde{H}} = 300\,\mathrm{GeV}, \; m_{\widetilde{l}} = m_{\widetilde{e}} = 100\,\mathrm{GeV}$

Conclusion (LFV)

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



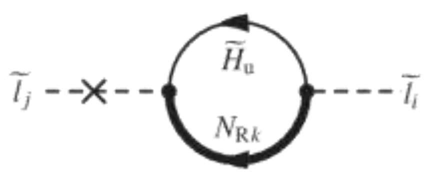
$$h \gtrsim 3\times 10^{-7} \longrightarrow \text{MIXED}$$

$$\left(\begin{array}{r}\theta_{23}, \theta_{13} \gtrsim 3\times 10^{-6}, \\ \theta_{12} \gtrsim 7\times 10^{-5}.\end{array}\right)$$

•**Well-Expected LFV**

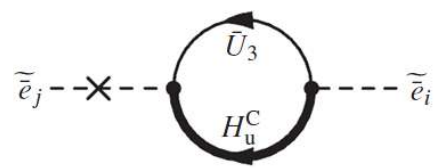
Cf.) Theoretical Expectation

1: ν_{R}



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

2: SU(5) GUT



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

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

LESSON

? How large?

? How small must be?

◉ $\not{L}$-MSSM : (in sphaleron era)

All L_i leak via Large $\not{L}$ (directly) or LFV

= wash out

⇨ **Assuming large LFV,**

$\not{L}$ couplings $(\kappa, \lambda, \lambda')$ = small enough

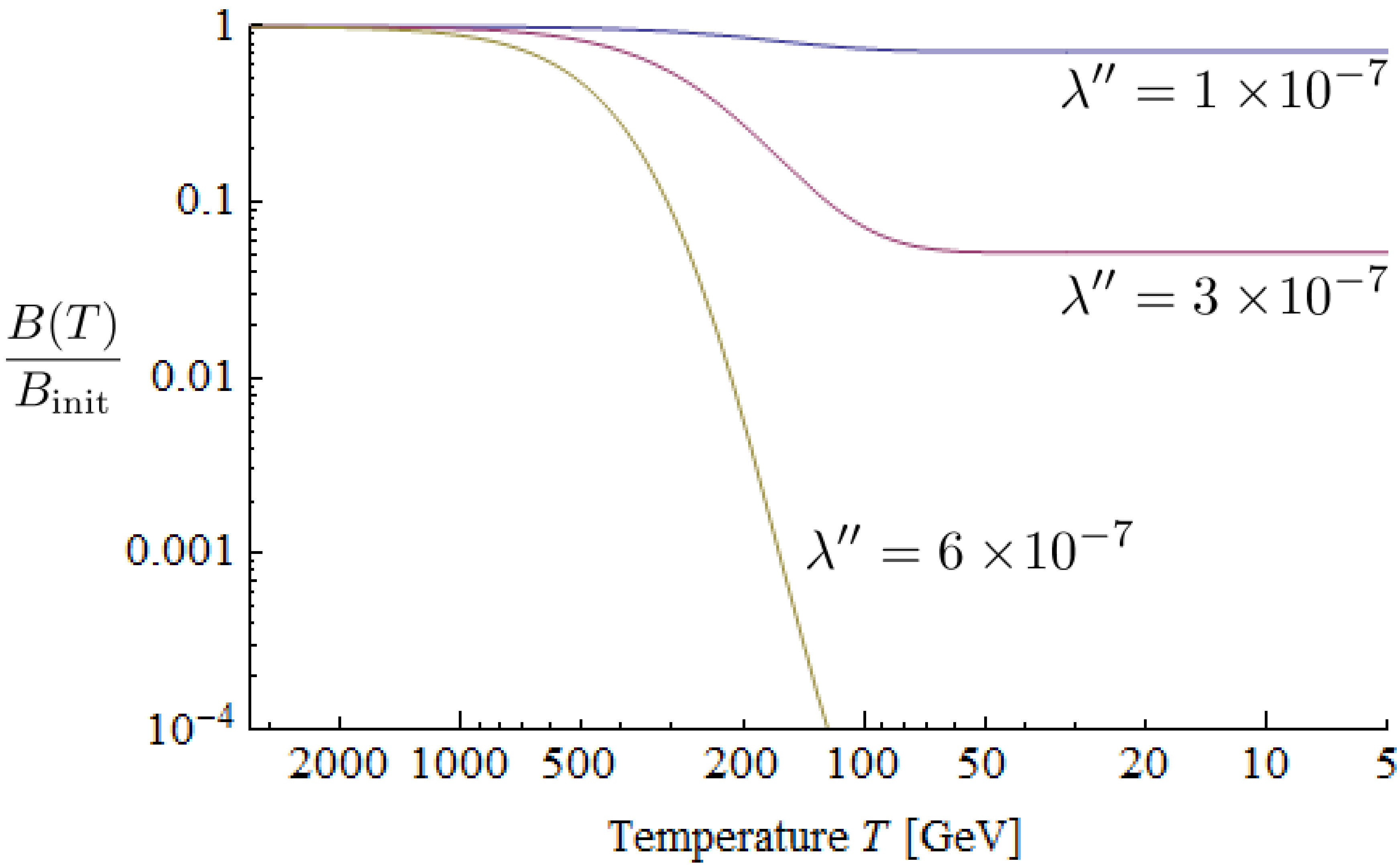
Method (RpV)

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

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

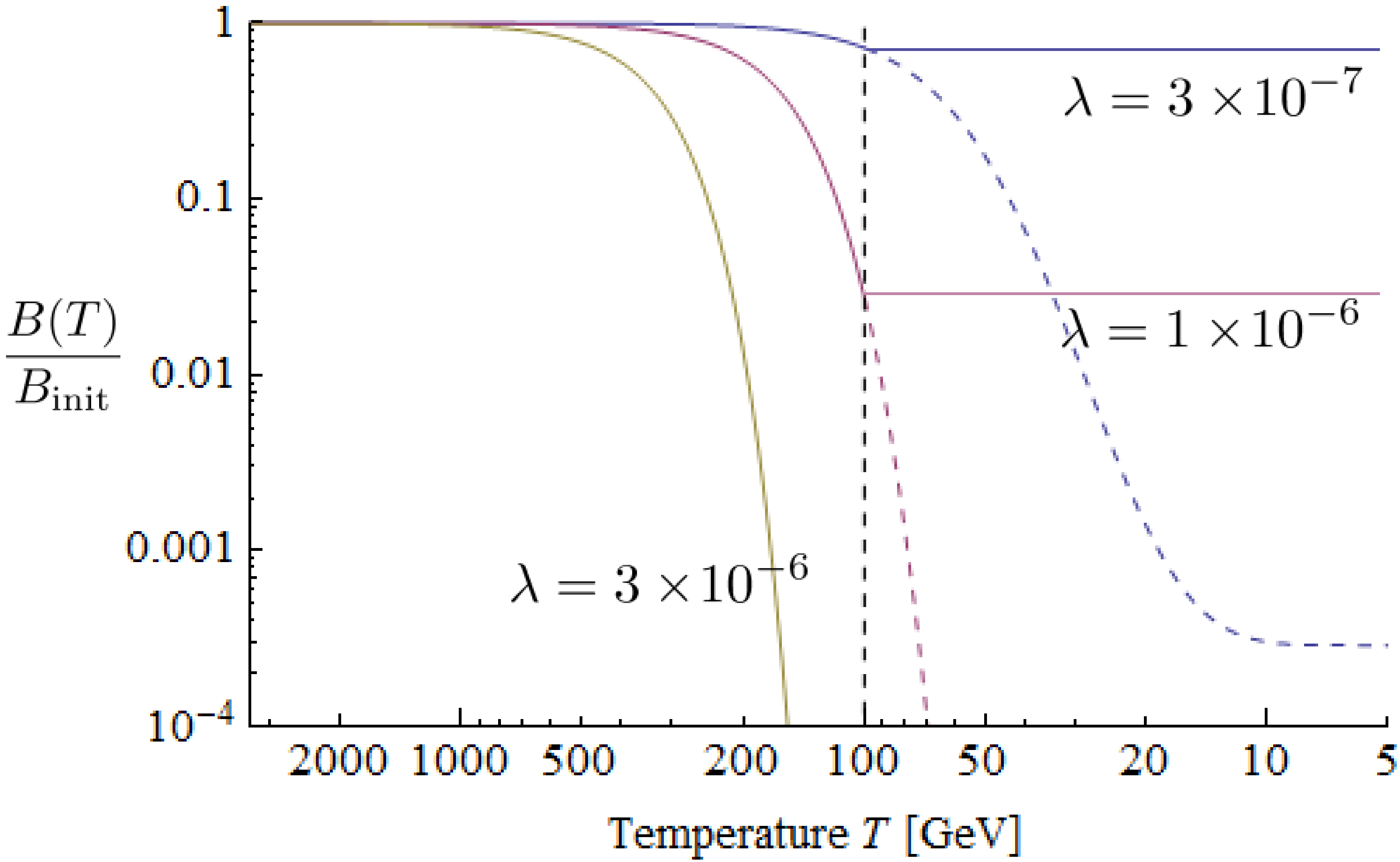
$$\left(\frac{\mathrm{d}}{\mathrm{d}t}(B-L) \sim \frac{79}{28}\frac{\mathrm{d}B}{\mathrm{d}t} \quad \text{in sphaleron era}\right)$$

$$W_{\not B} \ni \lambda'' \bar{U}_i \bar{D}_j \bar{D}_k$$



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

$W_{\not{L}} \ni \lambda L_i L_j \bar{E}_k$



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

Conclusion (RpV)

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

$$\lambda \lesssim 1\times 10^{-6}$$
$$\lambda' \lesssim 3\times 10^{-7}$$
$$\kappa \lesssim 1\times 10^{-6}\cdot\mu$$

Under LFV

$(W \ni \mu H_{\mathrm{u}} H_{\mathrm{d}})$

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

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

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

Conclusion (RpV)

Very Stringent Constraints!

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

$$\lambda \lesssim 1 \times 10^{-6}$$
$$\lambda' \lesssim 3 \times 10^{-7}$$
$$\kappa \lesssim 1 \times 10^{-6} \cdot \mu$$
$$\lambda'' \lesssim 4 \times 10^{-7}$$

Under LFV (for λ, λ', κ)

$(W \ni \mu H_\mathrm{u} H_\mathrm{d})$

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

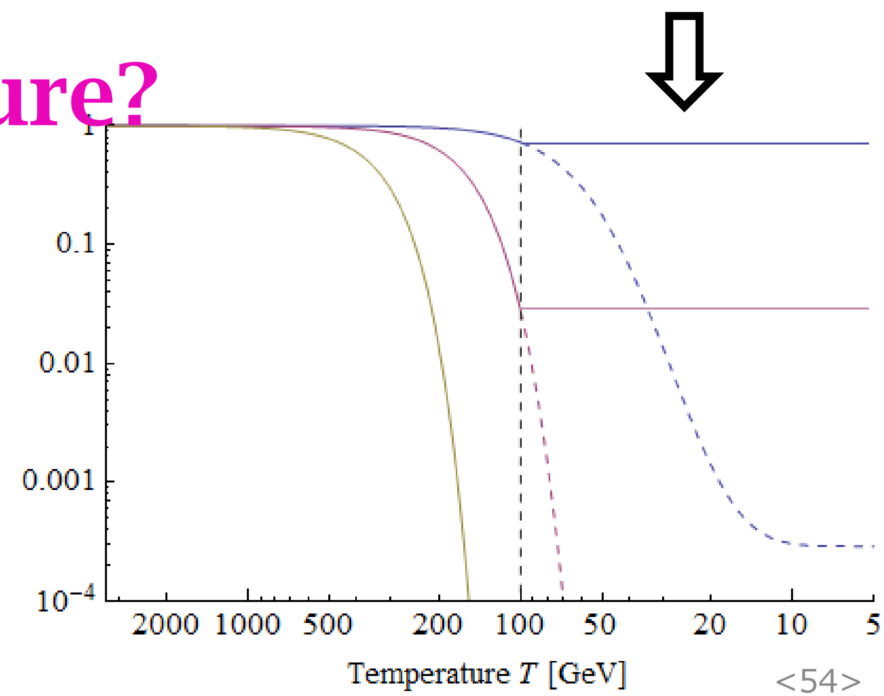
$$W_{\not{L}} = W_\mathrm{RPC} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_\mathrm{u}$$
$$W_{\not{B}} = W_\mathrm{RPC} + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

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

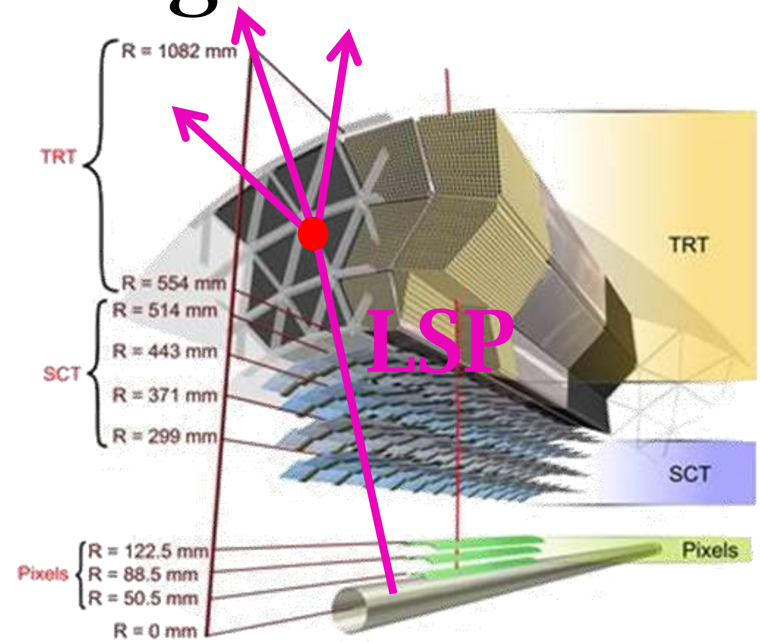
“Kink track” observed?

Consequence of our Result

Our Result

Very small
R-parity violation

⇨ Long-lived LSP



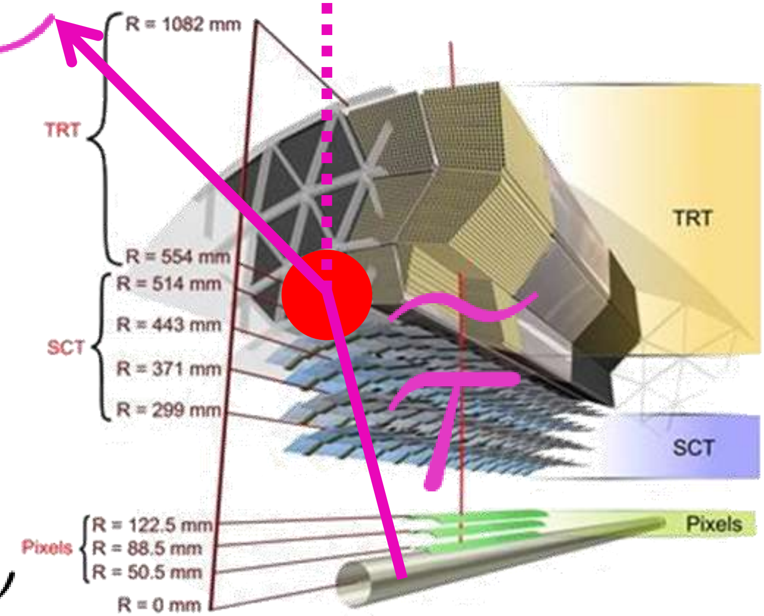
LSP might decay in Detector.

Consequence of our Result

Our Result

Very small
R-parity violation

⇨ Long-lived LSP



<u>Example</u>

$\widetilde{\tau}_{\mathrm{R}}$-LSP (200GeV)

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

⇨ Decay : $\widetilde{\tau} \to e\nu, \tau\nu$

$[c\tau \sim 30\,\mathrm{cm}]$

“Kink track” observed?

[Work in progress]

Consequence of our Result

According to our PRELIMINARY calculation,

if $\lambda \sim 10^{-(8\ldots9)}$,

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

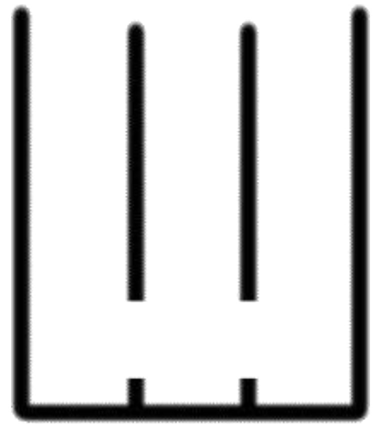
will be generated (& might be observed?)

in LHC/ATLAS.

"Kink track" observed?

Summary

MSSM ⟹ **LFV!!**



R-parity is not a must.

$\not{B}$ **&** $\not{L}$ **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

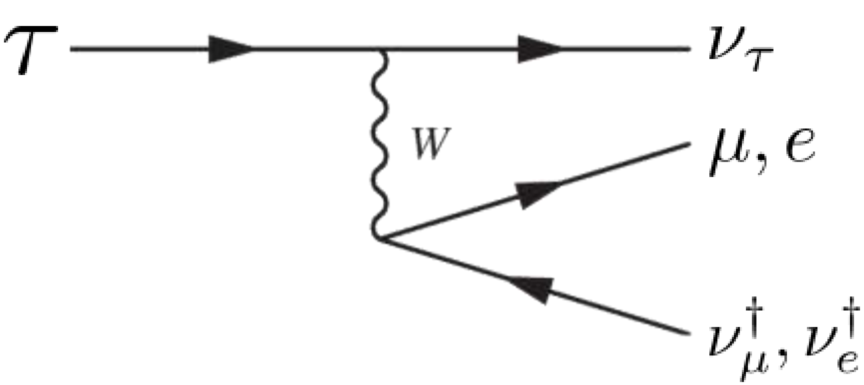
"The RpV interactions are constrained
by several experimental facts."

Constraints

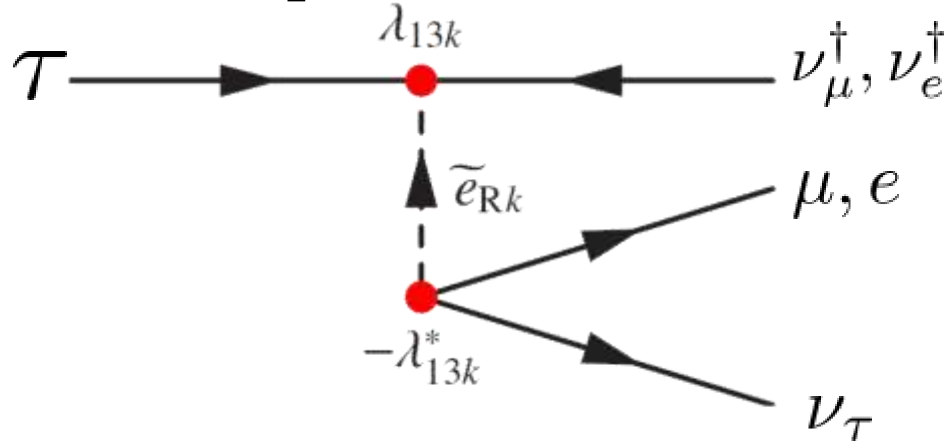
- Example:

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

Standard Model



RpV-MSSM



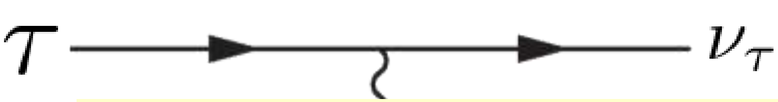
Additional Contribution!

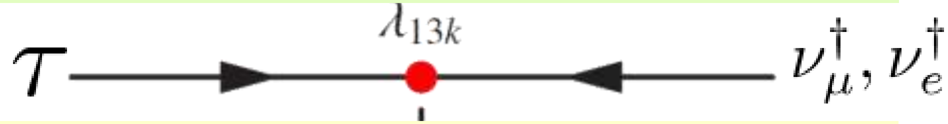
Constraints

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

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

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



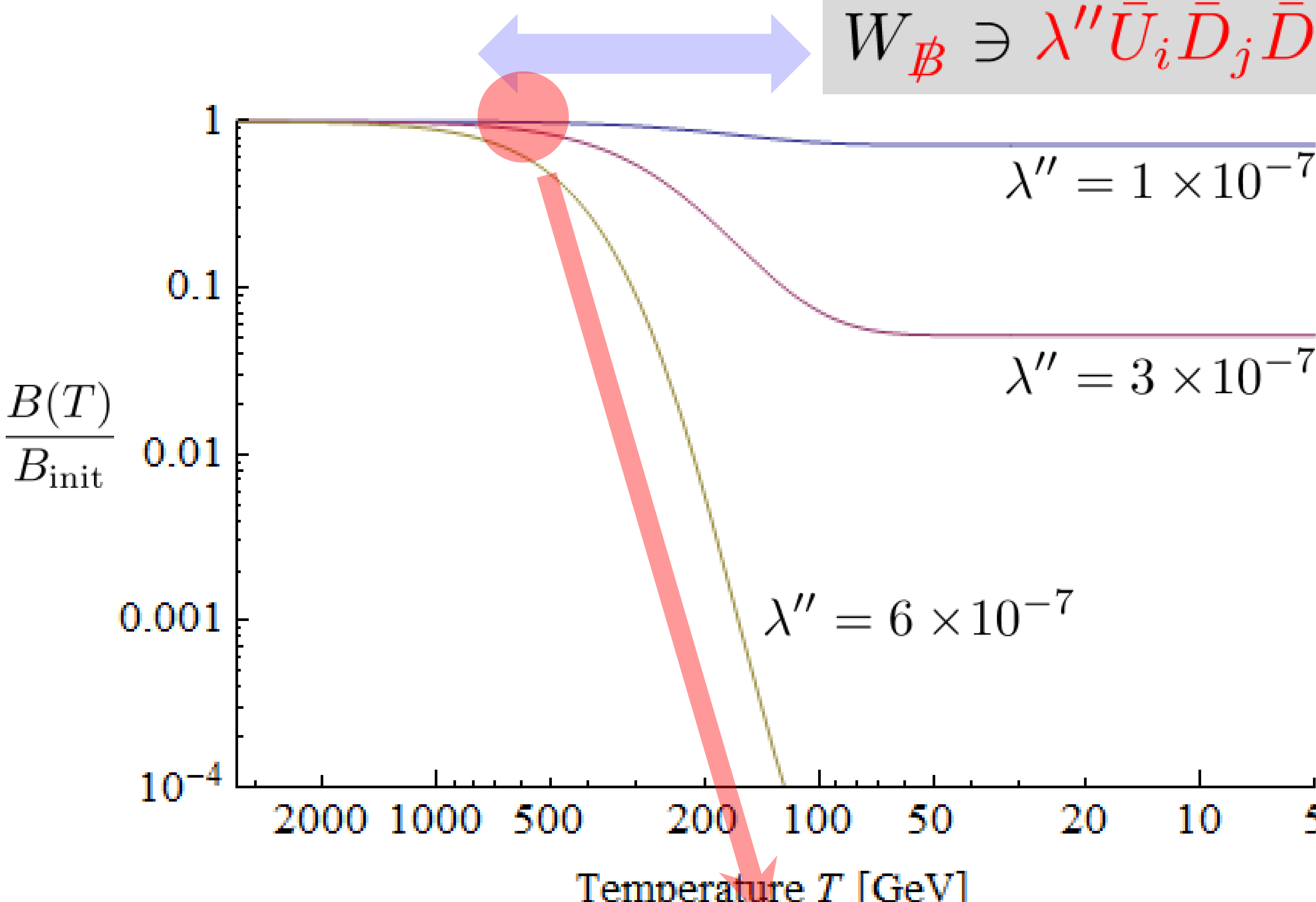


$$-0.051^2 < \sum_k \left[|\lambda_{13k}|^2 - |\lambda_{23k}|^2\right] \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{e}_{\mathrm{R}\,k}}}\right)^2 < 0.051^2$$

Additional Contribution!

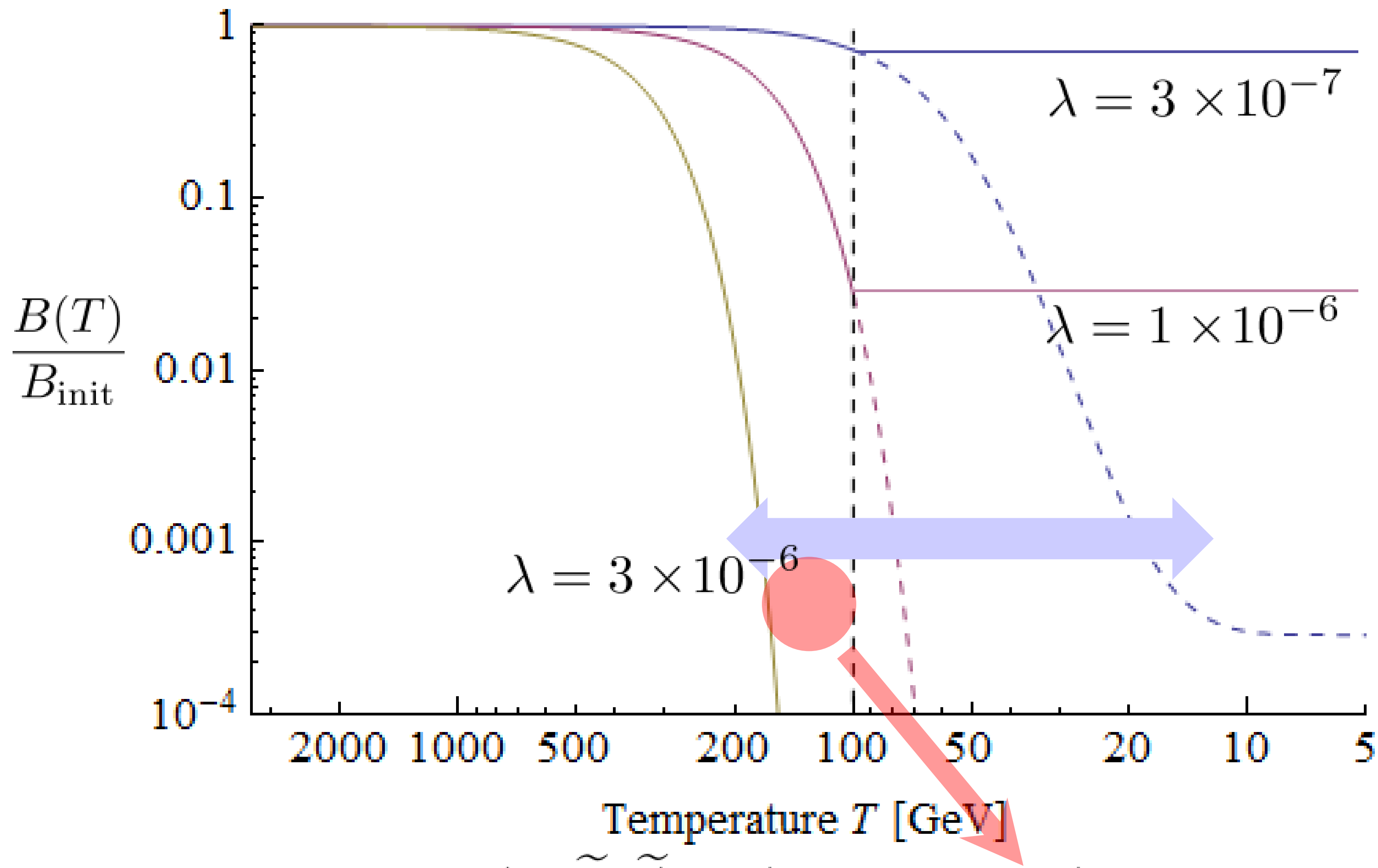
D. RpV Results

$W_{\not{B}} \ni \lambda'' \bar{U}_i \bar{D}_j \bar{D}_k$



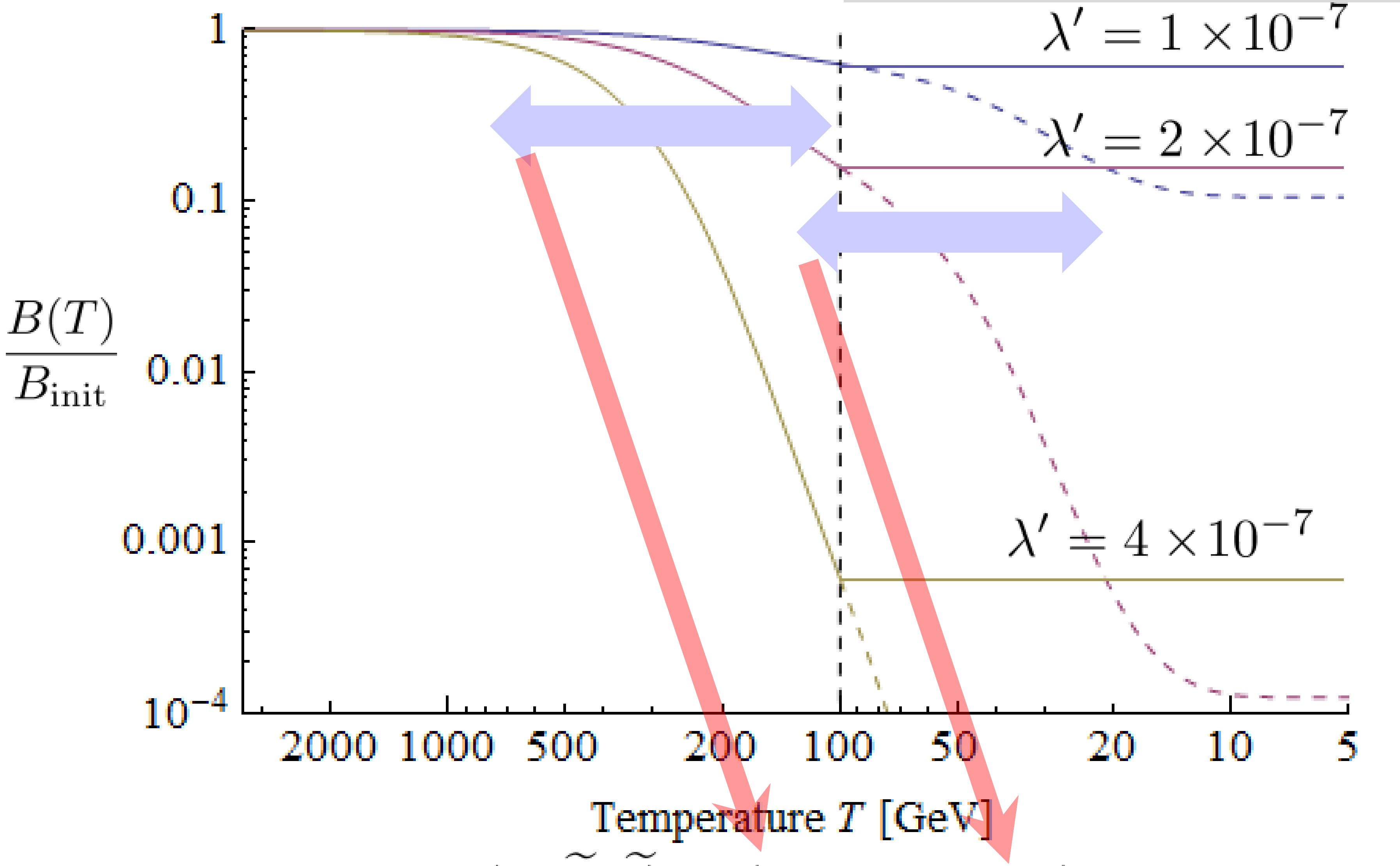
for mass of $(\tilde{q}, \widetilde{H}, \tilde{l}) = (600, 300, 100)$ GeV

$W_{\not L} \ni \lambda L_i L_j \bar{E}_k$



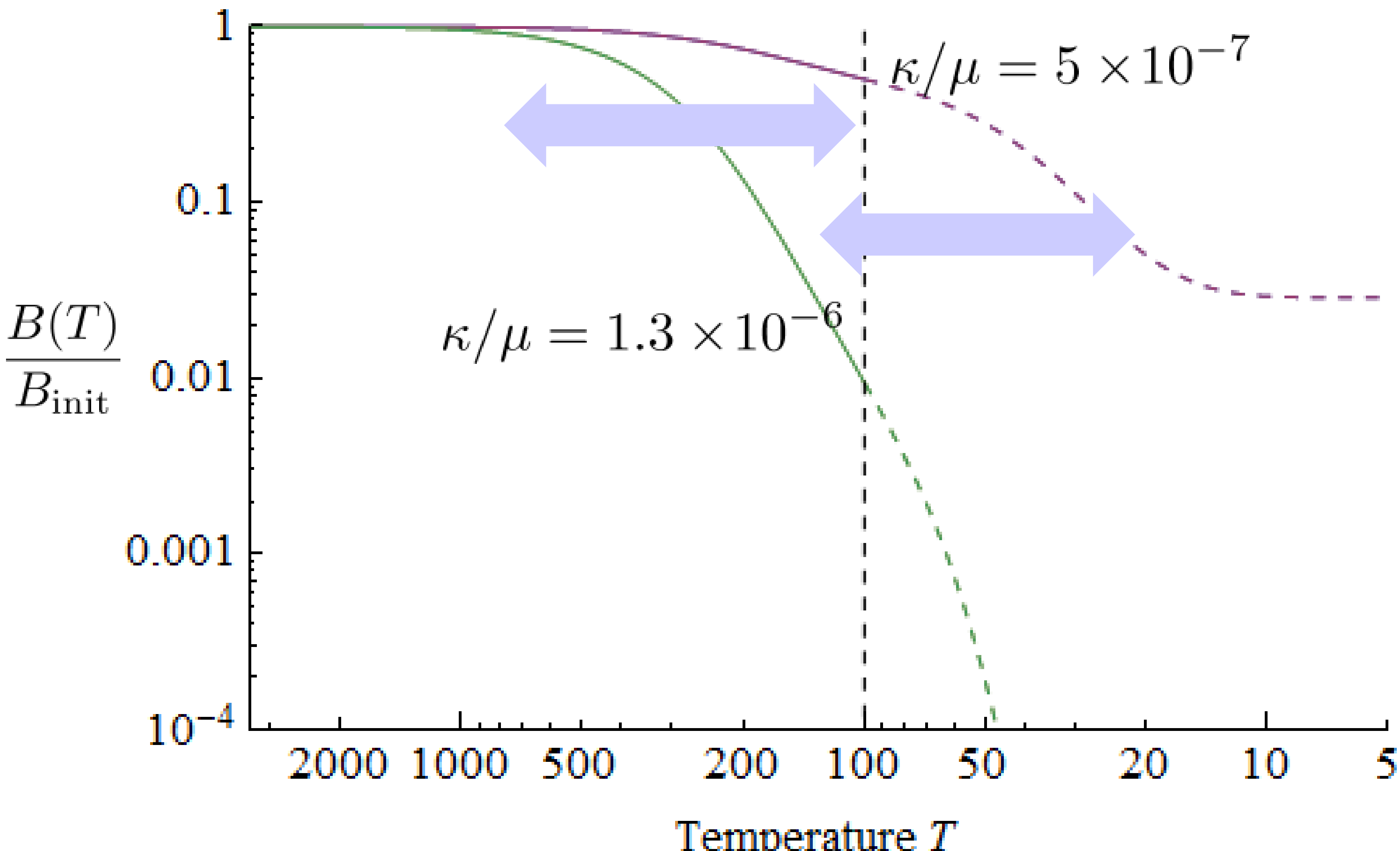
for mass of $(\widetilde{q}, \widetilde{H}, \widetilde{l}) = (600, 300, 100)$ GeV

$W_{\not L} \ni \lambda' L_i Q_j \bar{D}_k$



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

$$W_{\not L} \ni \kappa L_i H_u$$

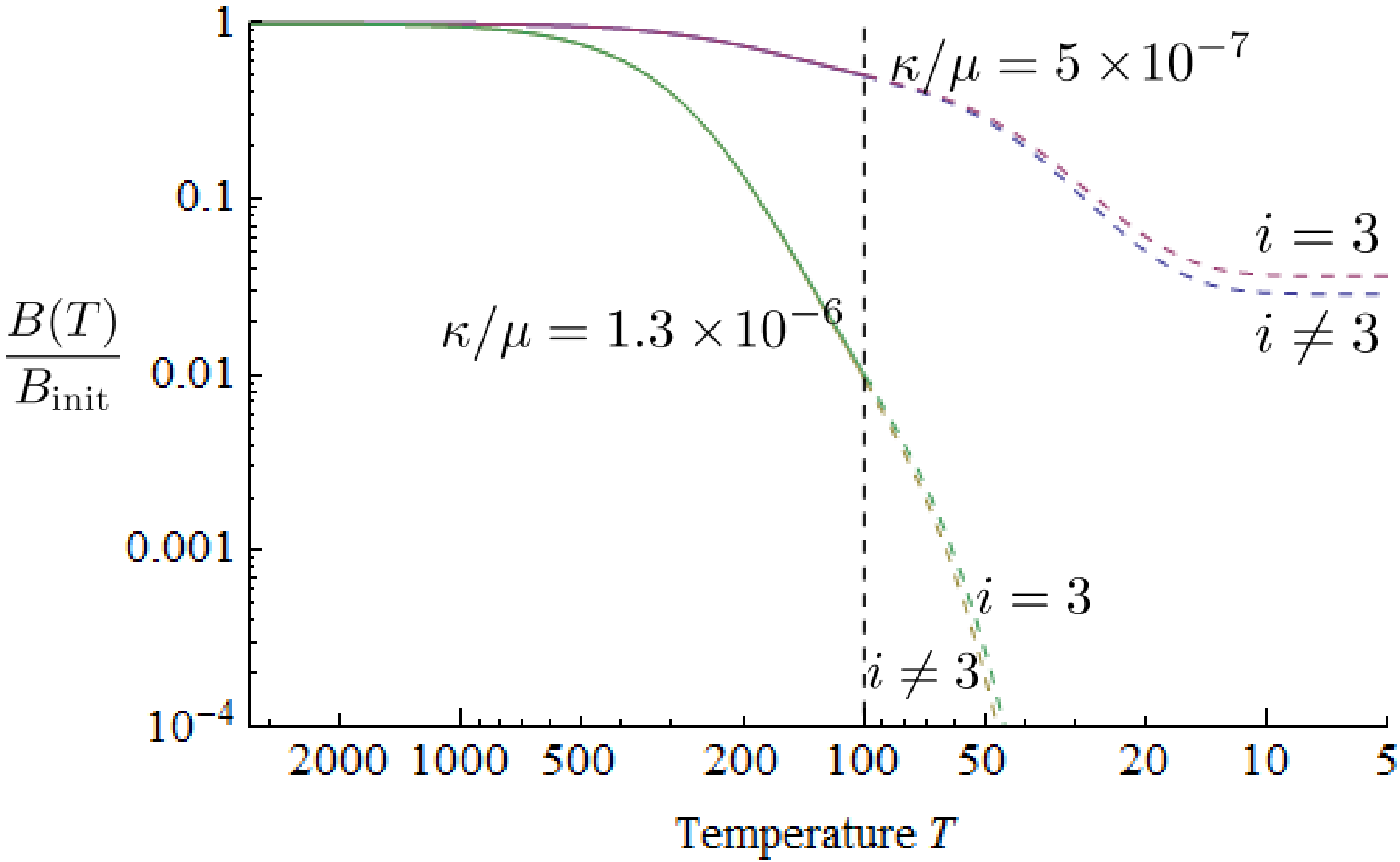


for mass of $(\widetilde{q}, \widetilde{H}, \widetilde{l}) = (600, 300, 100)$ GeV
$\tan\beta = 10$

D′. RpV Results [Detail]

Very Detail.

$W_{\not L} \ni \kappa L_i H_u$



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

$$\mu H_{\mathrm{u}} H_{\mathrm{d}} + \kappa_i L_i H_{\mathrm{u}}$$

$$\Longrightarrow H'_{\mathrm{d}} \simeq H_{\mathrm{d}} + \epsilon_i L_i \quad (\epsilon_i := \kappa_i/\mu)$$

$$\Longrightarrow W_{\mathrm{RPC}} \ni y_d H_{\mathrm{d}} Q\bar{D} \longrightarrow -\epsilon_i y_d L_i Q\bar{D}$$

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

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

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

E. Method [Detail]

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

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

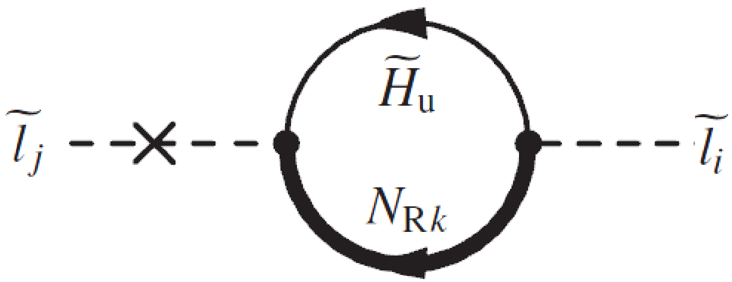
and the antiparticles' processes.

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

F. LFV : Theory & Experiments

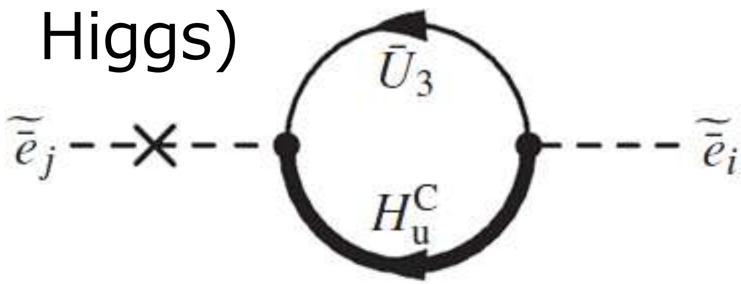
Theoretical Expectation

Right-handed neutrino



$$\Longrightarrow \; (\Delta m_L^2)_{ij} \qquad \delta_{ij}^L \sim 10^{-5}\left(\frac{M_R}{10^{10}\mathrm{GeV}}\right)$$

SU(5) GUT (Colored Higgs)



$$\Longrightarrow \; (\Delta m_{\bar{E}}^2)_{ij} \qquad \delta_{ij}^{\bar{E}} \sim 10^{-(1-4)}$$

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

MEGA Result / MEG Prospect

$$\delta^L_{21} \sim \sqrt{10^{4\ldots5}\mathrm{Br}(\mu \to e\gamma)} \left(\frac{\tan\beta}{10}\right)^{-1} \left(\frac{m_{\mathrm{soft}}}{400\,\mathrm{GeV}}\right)^2$$

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

$$\delta^L_{21} \lesssim 10^{-3}$$

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

$$\delta^L_{21} \Rightarrow 10^{-4}$$