SUSY without *R*-Parity: Cosmological Constraints

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Thesis Oral Examinations @ UT/Komaba

along my magisterial thesis

"Supersymmetry without *R*-parity: Its Phenomenology"
(*R*-parityの保存を課さない超対称理論の現象論的側面)

Outline

[Review]

1. **SUSY without *R*-Parity**
2. **Cosmological Constraints**
3. **Our Result (1. LFV)**
4. **Our Result (2. RpV)**
5. **Conclusion**

[Our Work]

The "**Our Work**" is…

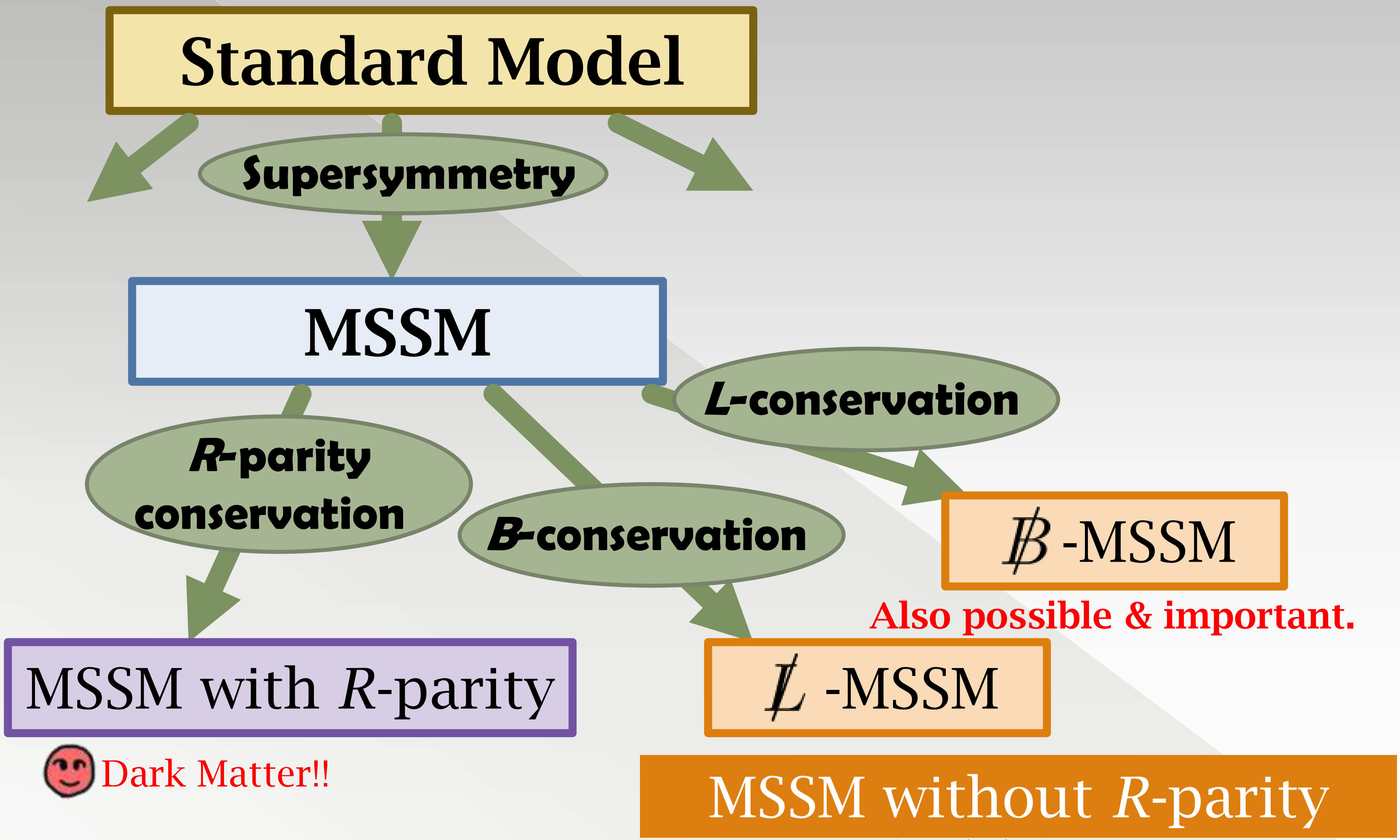
M. Endo, K. Hamaguchi and **Sho Iwamoto**
Cosmological Constraints on R-parity violation
arXiv: 0912.0585 [hep-ph] (2009)

1. SUSY without *R*-parity

We usually impose the *R*-parity on the MSSM.

But we have other choices than the *R*-parity, and it's also important.

Introductive Diagram



SUSY without *R*-parity

Standard Model

Very successful model

One unnaturalness

"Hierarchy problem"

Extra dimension

Others…

Various Extensions…

Supersymmetry

MSSM

(Minimal Supersymmetric Standard Model)

SUSY without *R*-parity

Standard Model

Supersymmetry

MSSM

~~"Hierarchy problem"~~ Solved

Proton decay problem

Proton decay @ MSSM

MSSM Superpotential:

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

$$\boxed{L H_{\rm u}, \quad L L \bar{E}, \quad L Q \bar{D},} \quad \boxed{\bar{U} \bar{D} \bar{D}}$$

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

Both $\not{B}$ ***and*** $\not{L}$ $\rightarrow$ proton decay

Proton decay @ MSSM

> ***Both*** $\not{B}$ ***and*** $\not{L}$
> invoke decay of proton.

→ *3 choices* to avoid this problem!

Usual choice because….

- To forbid $\not{B}$ & $\not{L}$ with *R*-parity etc.
- To impose B-conservation with Baryon-parity etc.
- To impose L-conservation with Lepton-parity etc.
  with the assumption that $m_{\mathrm{LSP}} > m_{\mathrm{proton}}$.

Why *R*-parity?

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

R-parity conservation →

- ***NO*** *B*- and *L*-violating events (proton decay etc.)

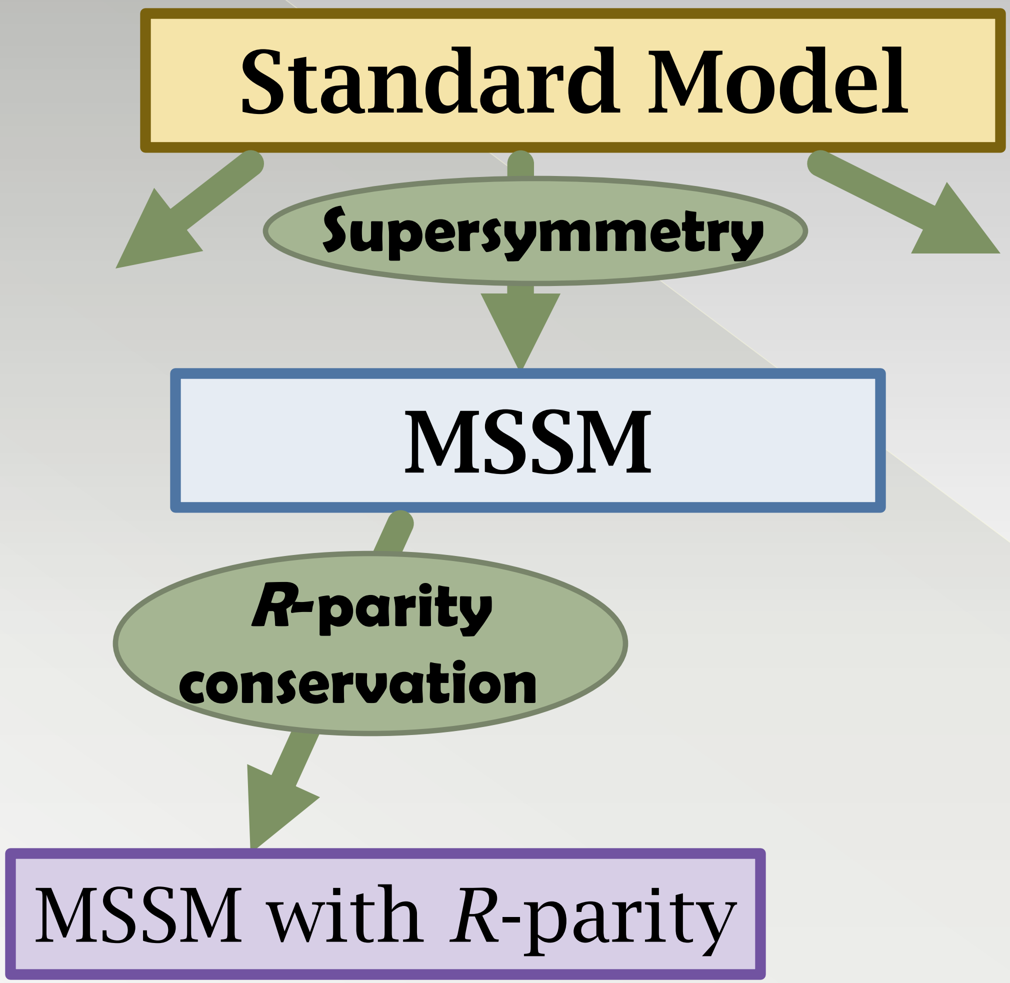
  We've never observed!

- Since
$$P_R = \begin{cases} +1 & \text{for SM particles,} \\ -1 & \text{for superparticles,} \end{cases}$$
  the LSP cannot decay! [Lightest Supersymmetric Particle]

  → **A candidate for the *Dark Matter*!**

$$\boxed{\begin{array}{lllll} W \ni & H_\mathrm{u}H_\mathrm{d}, & H_\mathrm{d}L\bar{E}, & H_\mathrm{d}Q\bar{D}, & H_\mathrm{u}Q\bar{U}, \\ & \cancel{LH_\mathrm{u}}, & \cancel{LL\bar{E}}, & \cancel{LQ\bar{D}}, & \cancel{\bar{U}\bar{D}\bar{D}} \end{array}}$$

Introductive Diagram



Dark Matter!!

Without *R*-parity

We have *3 choices.*

- To forbid *B*- & *L*-violation with *R*-parity etc.
- To impose *B*-conservation with Baryon-parity etc.

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

$\not{L}$

- To impose *L*-conservation with Lepton-parity etc. (and to assume $m_\mathrm{LSP} > m_\mathrm{proton}$.)

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

$\not{B}$

Without *R*-parity

That is,

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

- MSSM with *R*-parity $\to W = W_{\mathrm{RPC}}$
- $\not{L}$-MSSM $\to$

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

- $\not{B}$-MSSM $\to W_{\not{B}} = W_{\mathrm{RPC}} + \underset{(j<k)}{\lambda''_{ijk}} \bar{U}_i \bar{D}_j \bar{D}_k$

Without *R*-parity

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

That is,

We can install

New RpV interactions!

(*R*-parity violating)

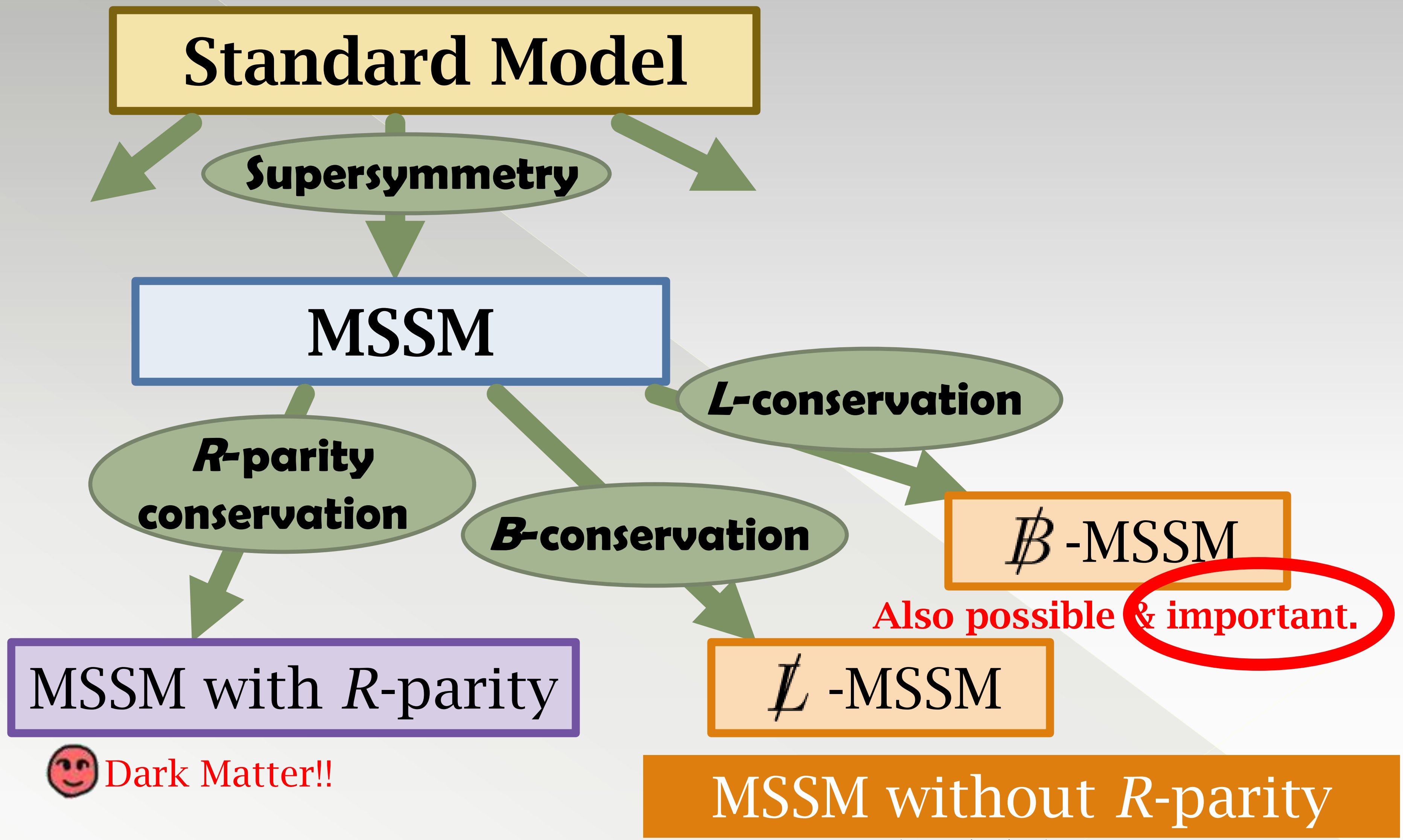
$(i < j)$

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

$(j < k)$

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

Introductive Diagram



Why Important?

?

- What's the **Dark Matter**?
- Is **SUSY** the truth?

⇓

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

R-parity is **Conserved**

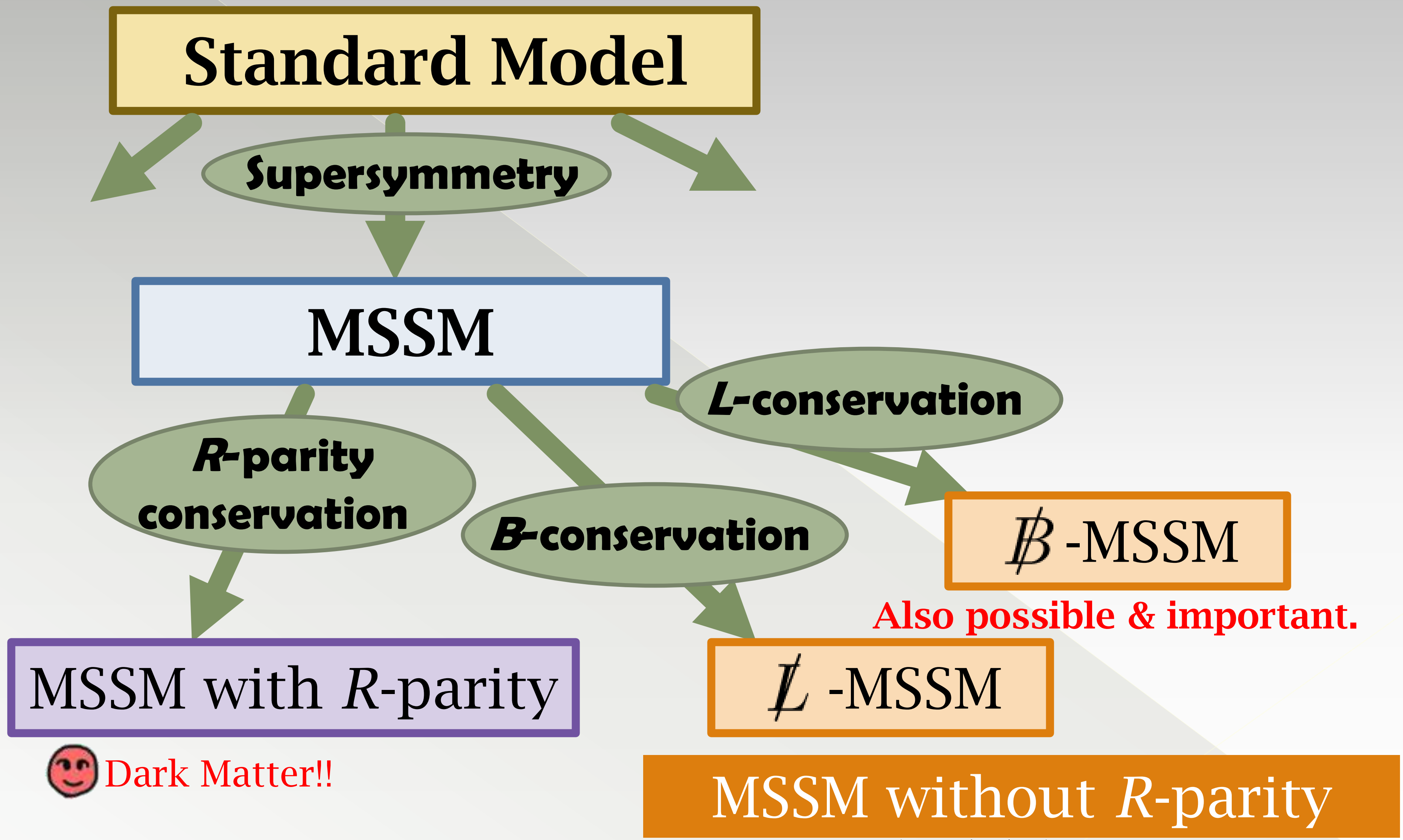
(missing transverse momentum)

→ LSP yields **Large** $\not{p}_{\mathrm{T}}$

→ Used as a signal

Then if not? → We have to study!

Introductive Diagram



What I studied

- What I studied (with Hamaguchi, Endo)

  = A detailed analysis of

  cosmological constraints

  on these RpV couplings.

  ↓

much more **stringent**

than from collider experiments.

2. Cosmological Constraints

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

Baryon asymmetry of the Universe

- Current university:

There's **Baryon,**

and no anti-baryon.

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

However, if we have

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

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

in the early universe.

And if **frequently enough**,

$\rightarrow$ achieve **Equilibrium** : $B = 0$.

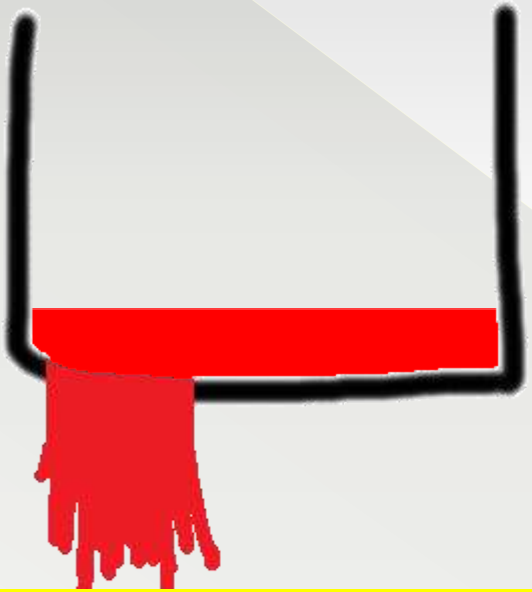
$\rightarrow \lambda''$ **must be small enough!**

(Bouquet and Salati, 1987)

Wash-out with $\not B$-viol. $\not B$

- That is, if

LARGE $\not B$, then



“WASH-OUT” occurs!!

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

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

- This story

  does not end here.

- The $\not{L}$-violation also washes-out

  the Baryon asymmetry

  in the presence of the **Sphaleron**!!

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

Kuzmin, Rubakov, Shaposhnikov, 1985; Ringwald, 1988

Sphaleron

In the early universe $T \gtrsim 100\,\mathrm{GeV}$

$\rightarrow$ the sphaleron process is frequent.

(by thermal effects)

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

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

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

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

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

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

Kuzmin, Rubakov, Shaposhnikov, 1985; Ringwald, 1988

Sphaleron

In the early universe $T \gtrsim 100\,\mathrm{GeV}$

$\rightarrow$ the **sphaleron** process is frequent.

Sphaleron converts

Baryon $\rightleftarrows$ Anti-lepton

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

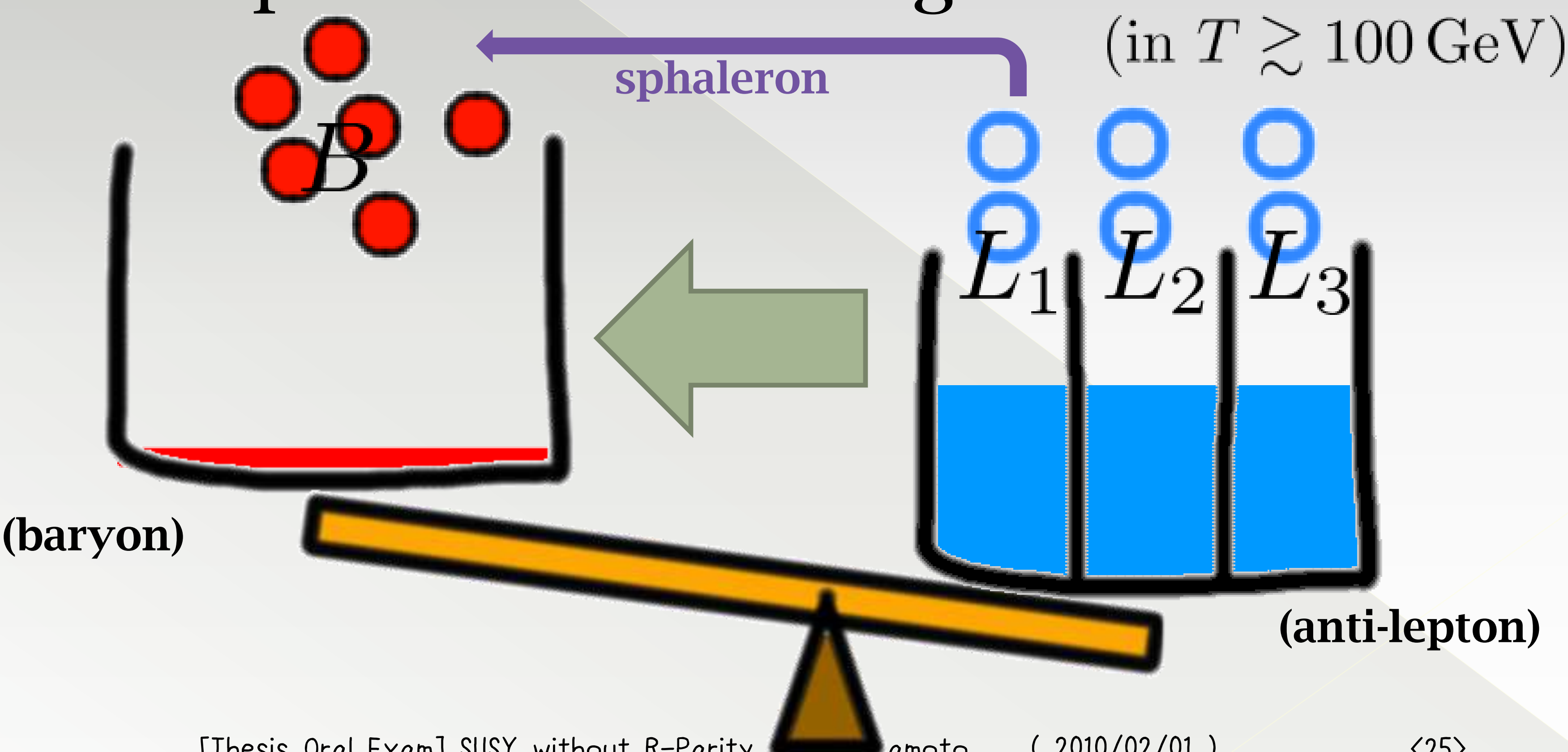
$$= uddcsstbb\nu_e\nu_\mu\nu_\tau$$

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

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

Sphaleron's Effect

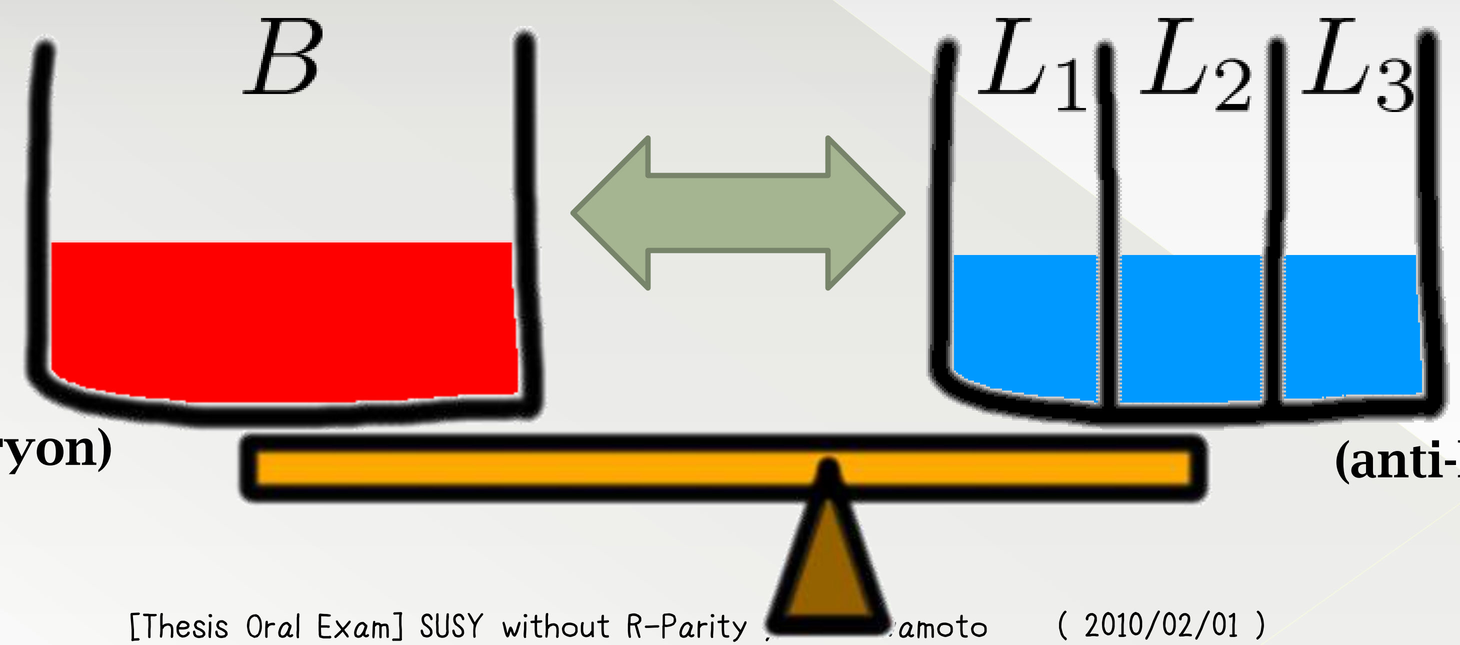
- If Baryon is short…
  sphaleron works right to left.



Sphaleron's Effect

- If Baryon is short…
  sphaleron works right to left.

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

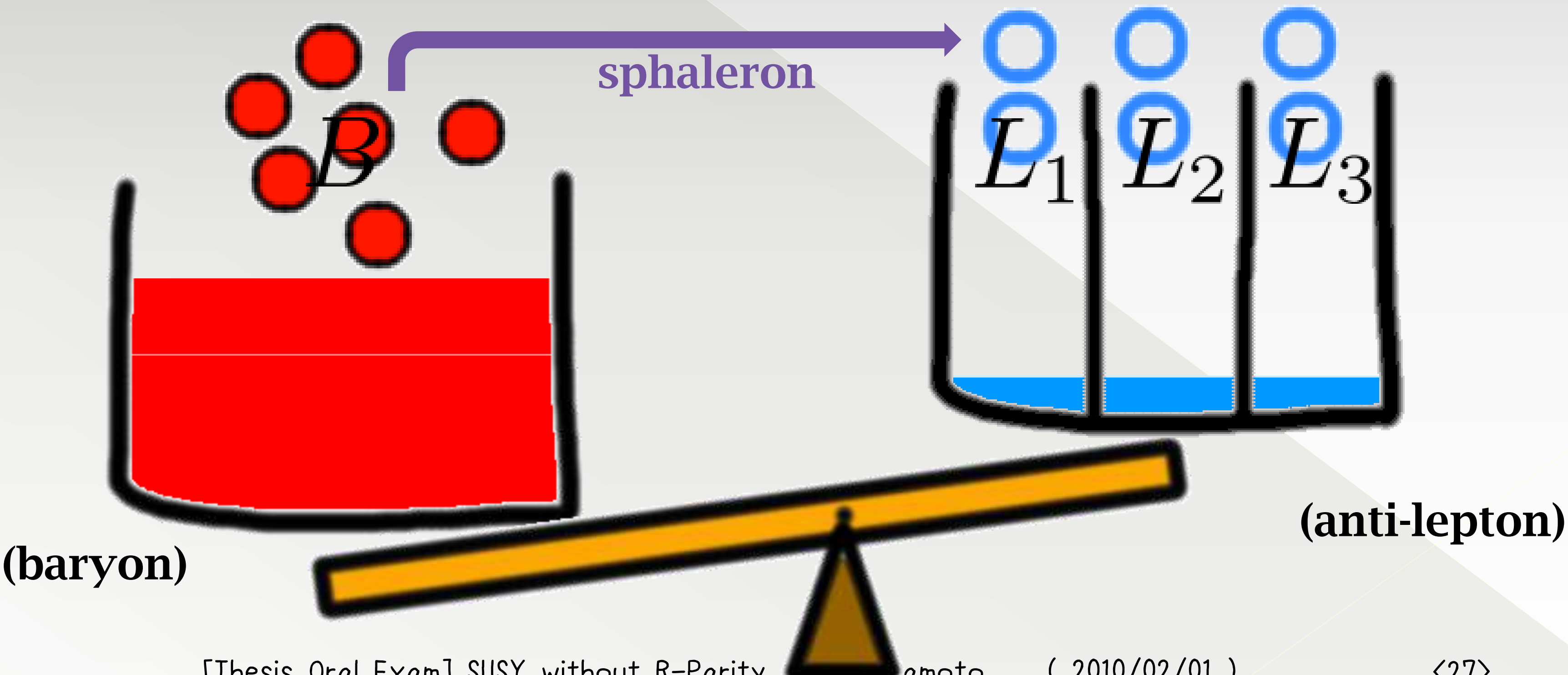


(baryon) **(anti-lepton)**

Sphaleron's Effect

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

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



Sphaleron's Effect

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

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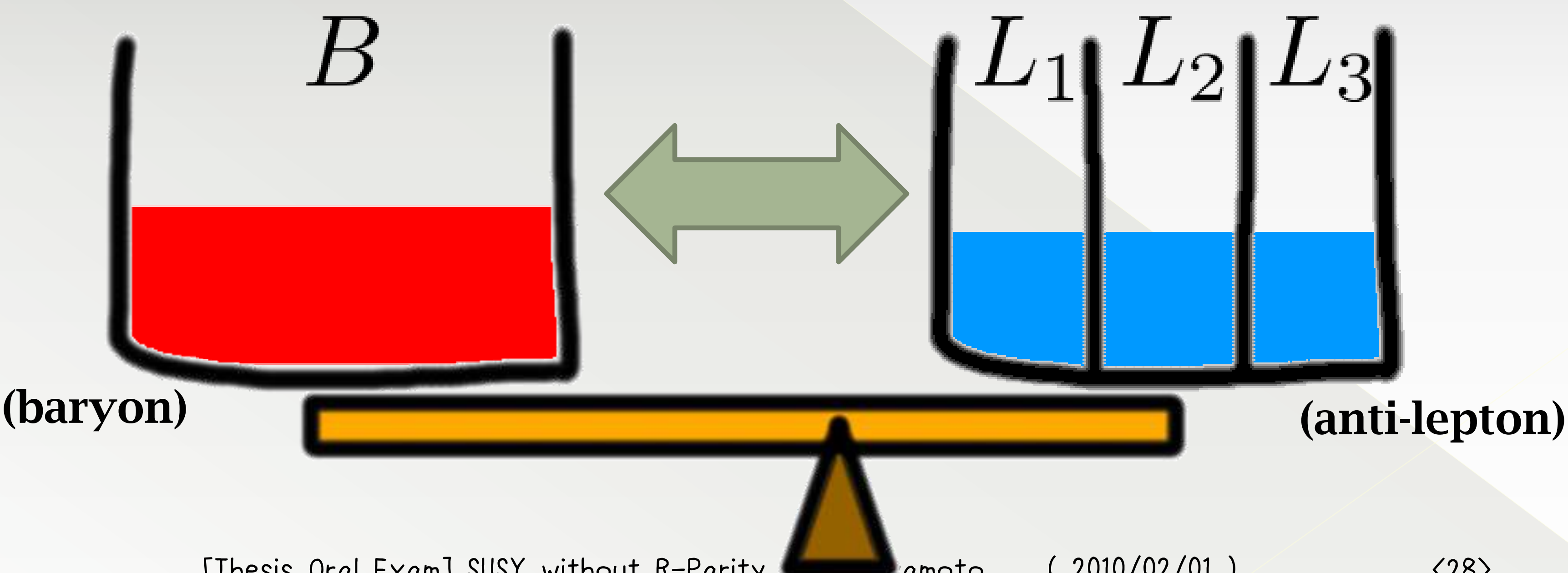
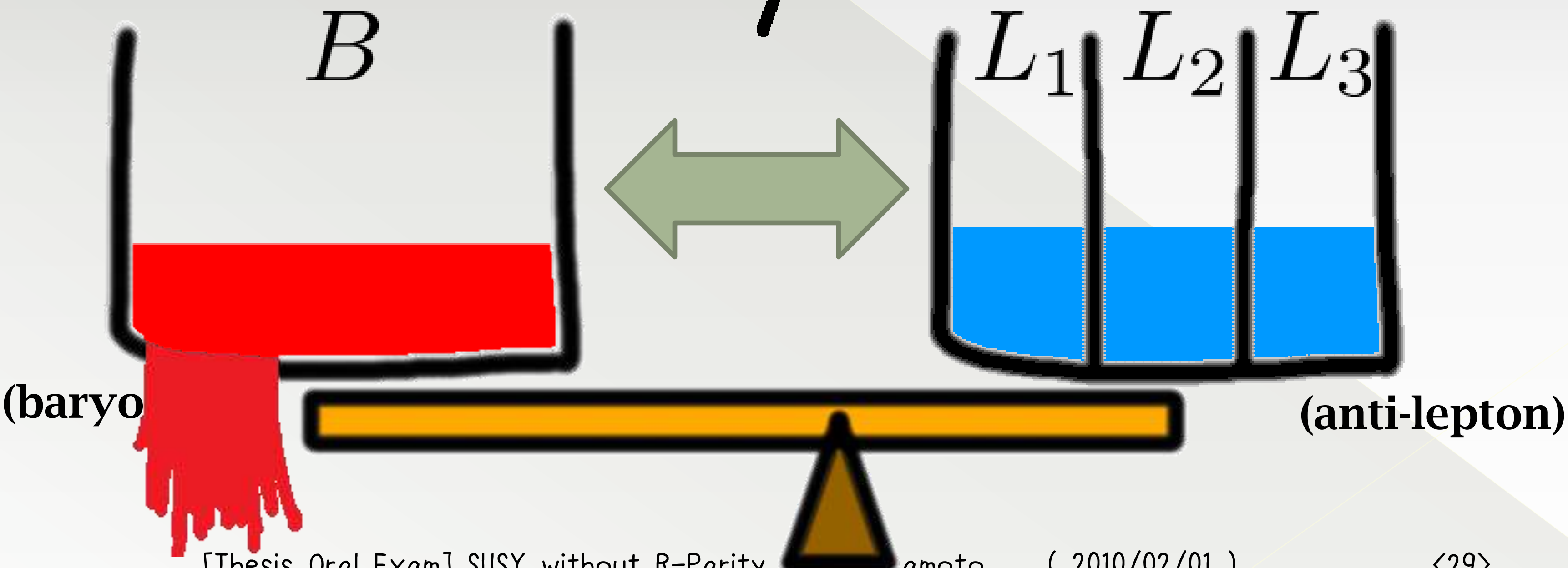


Wash-out with B-viol. $\not{B}$

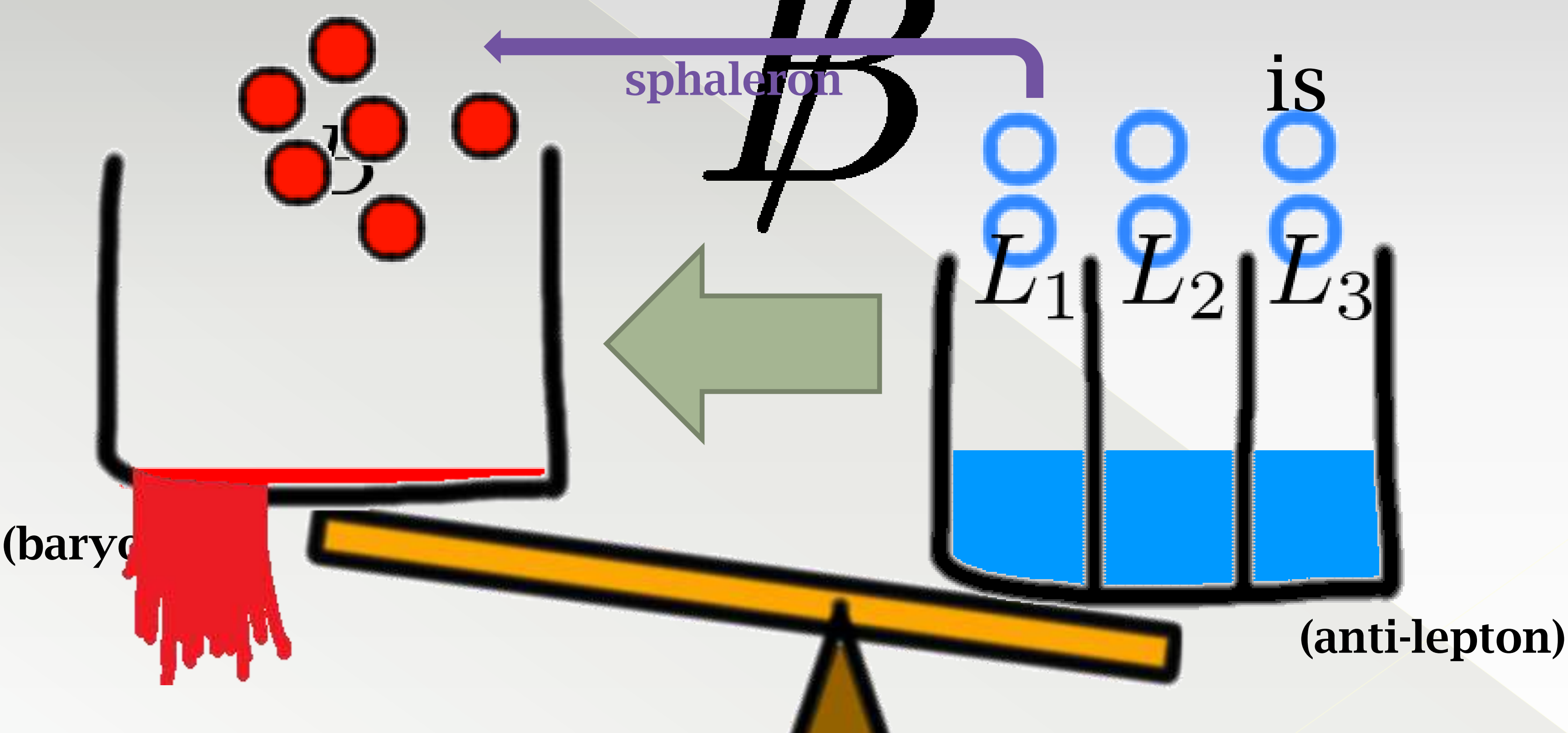
- Thus, actually the previous

$\not{B}$ is



Wash-out with $\cancel{B}$-viol. $\cancel{B}$

- Thus, actually the previous $\cancel{B}$ is

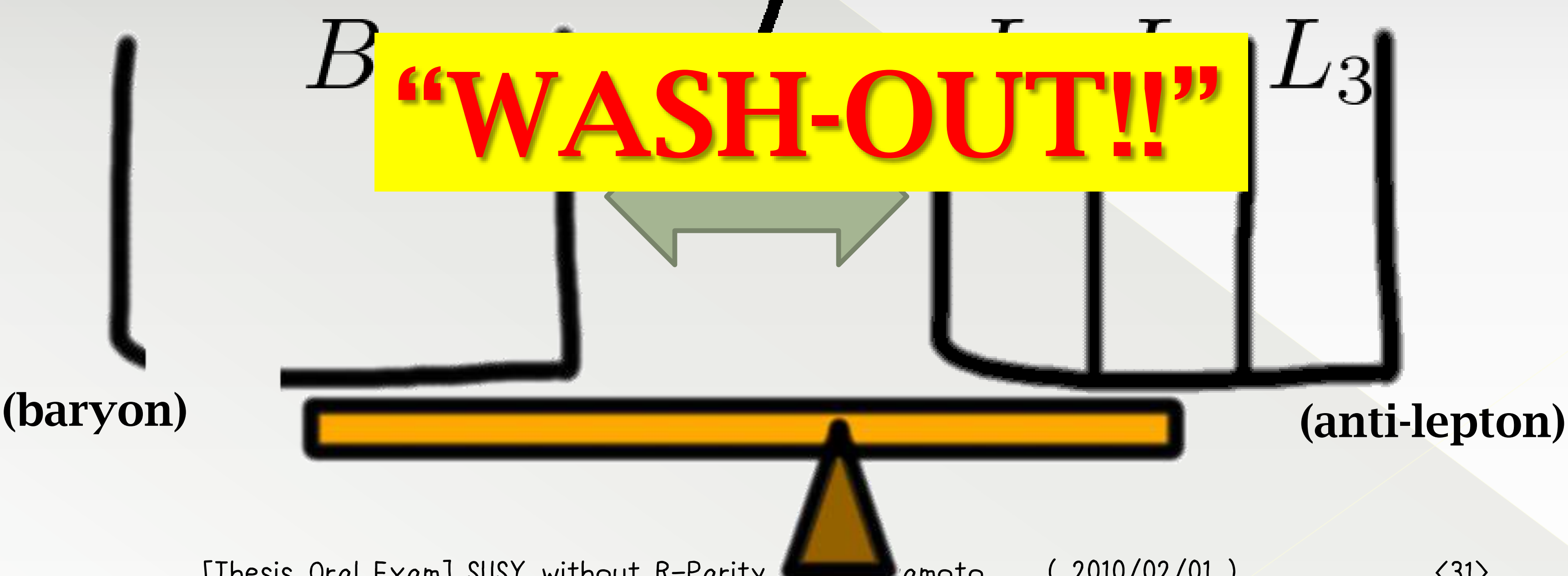


Wash-out with B-viol. $\not{B}$

- Thus, actually the previous

$$\not{B}$$

is

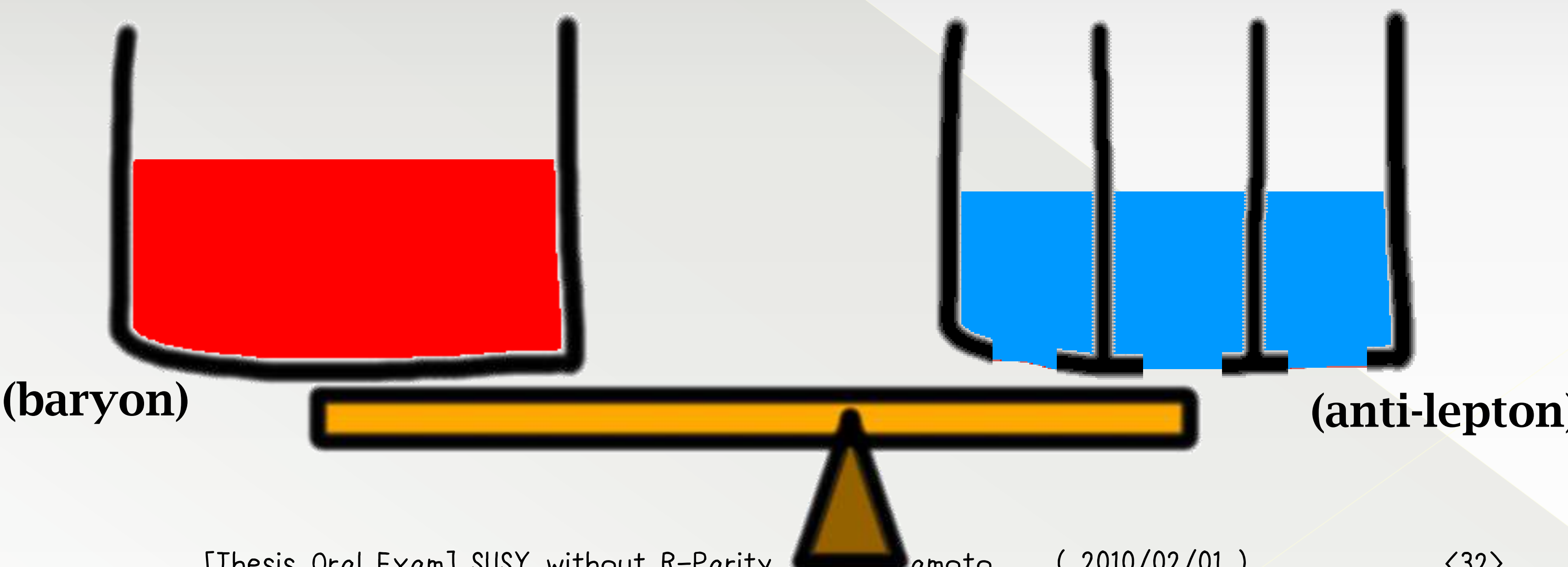


Wash-out with L-viol. $\not{L}$

- Therefore, if

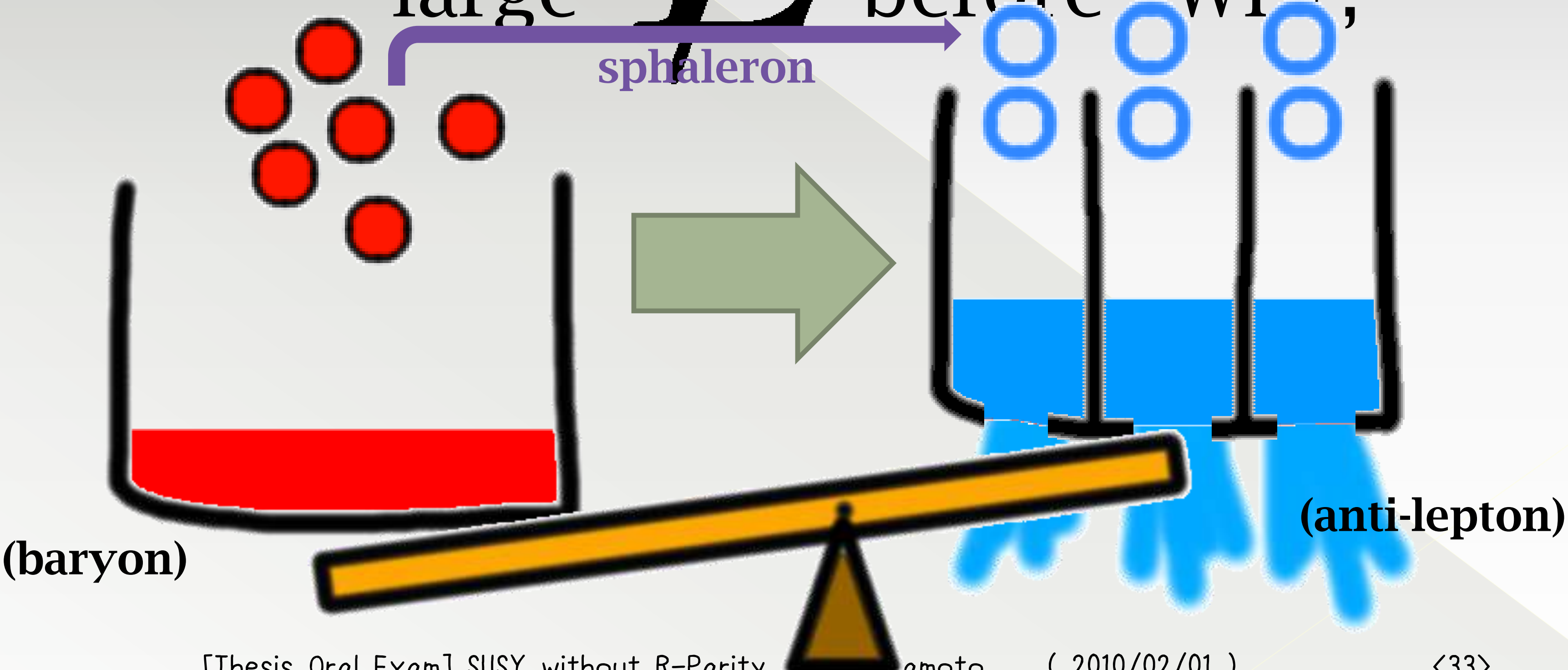
$$(\text{e.g. } \tilde{l} \rightleftarrows l^* e \text{ from } LL\bar{E})$$

large $\not{L}$ before EWPT,



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

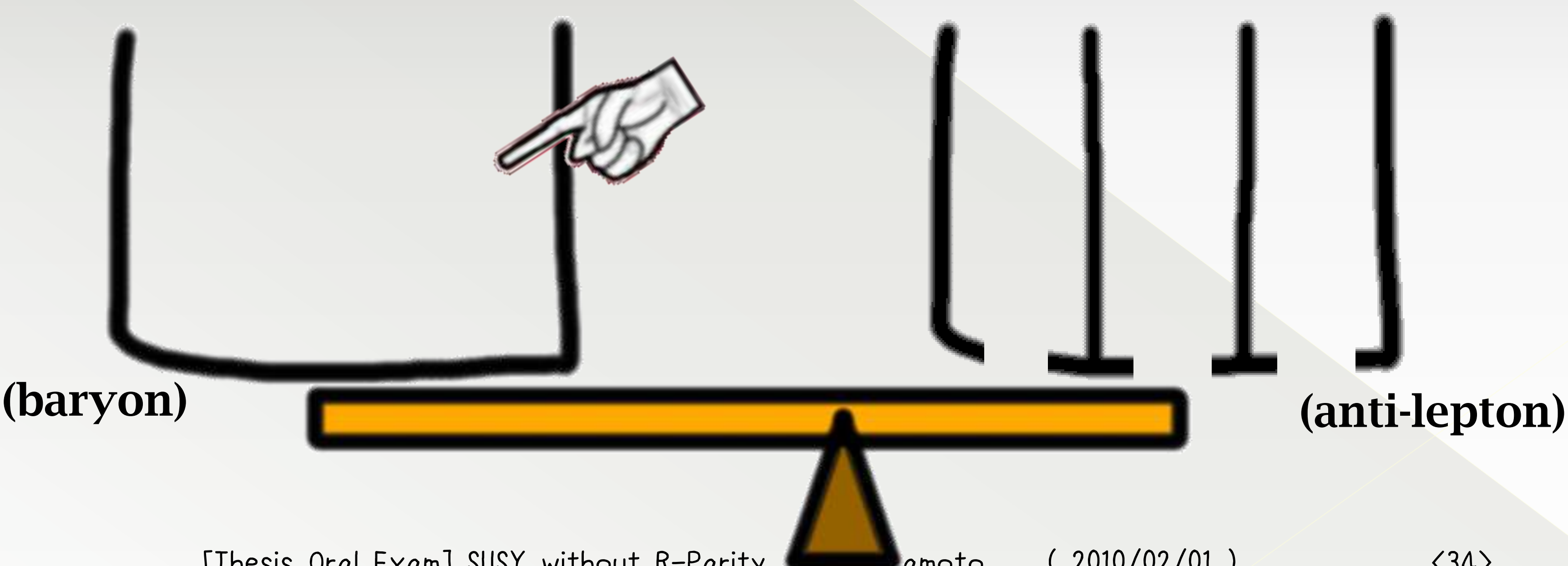
- Therefore, if large $\not{L}$ before EWPT, (e.g. $\tilde{l} \rightleftarrows l^* e$ from $LL\bar{E}$)



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

- Therefore, if $\not{L}$ (e.g. $\tilde{l} \rightleftarrows l^{*}e$ from $LL\bar{E}$)

"WASH-OUT" occurs!!



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

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

- But

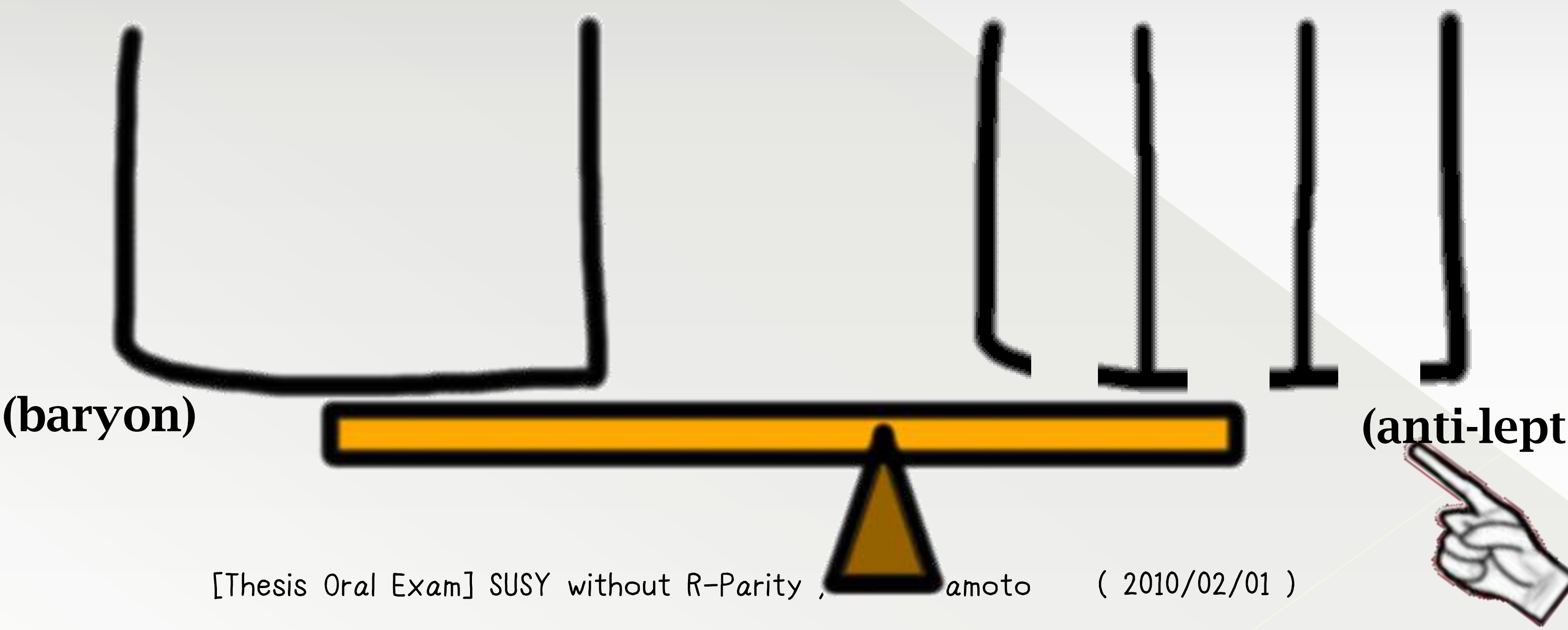
NOTE ONE IMPORTANT POINT!

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

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

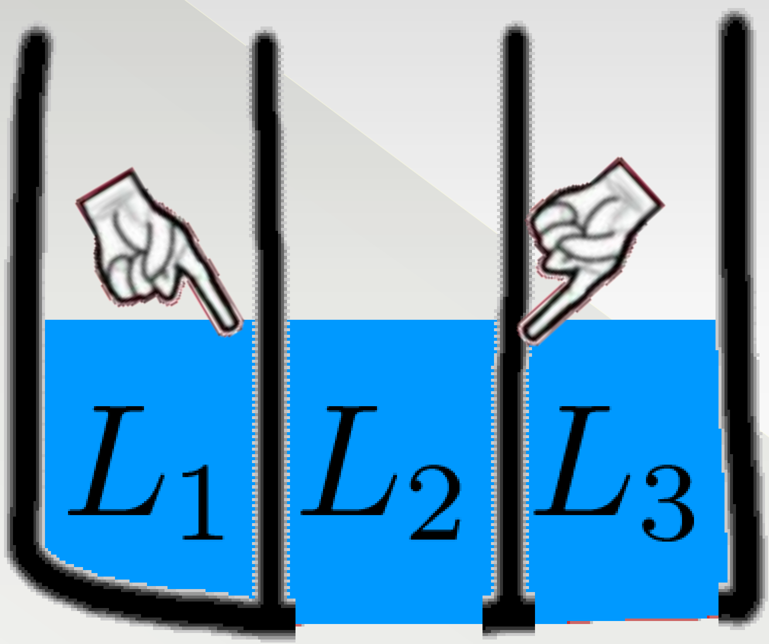
- But

NOTE ONE IMPORTANT POINT!



Wash-out with $\cancel{L}$-viol. $\cancel{L}$

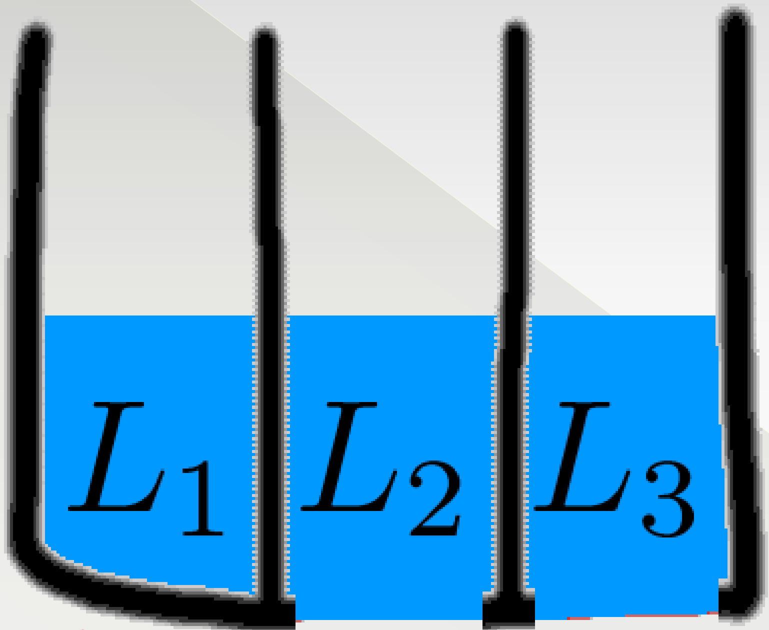
- If the Lepton Flavor is not violated



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

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

- And if **at least one** of L_i is not violated,

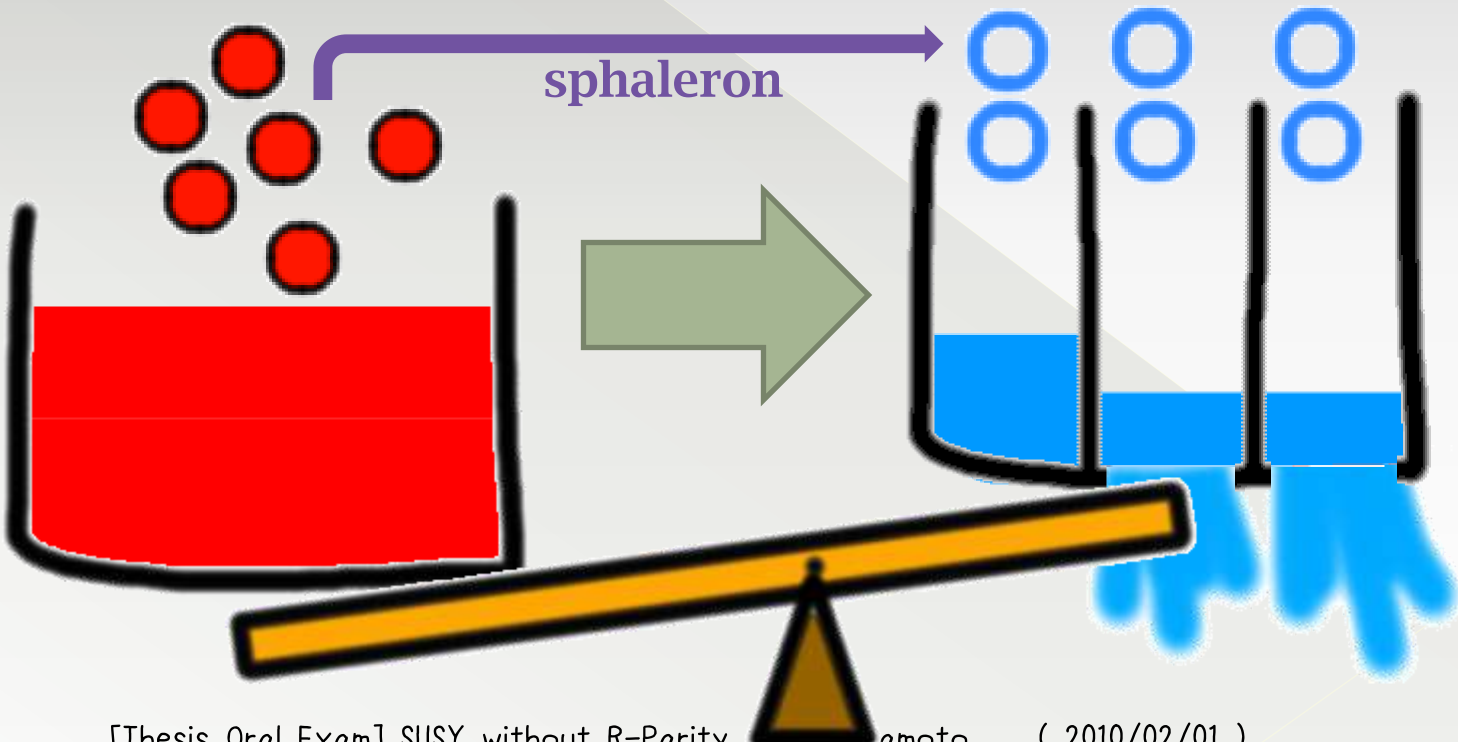


Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

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

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

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

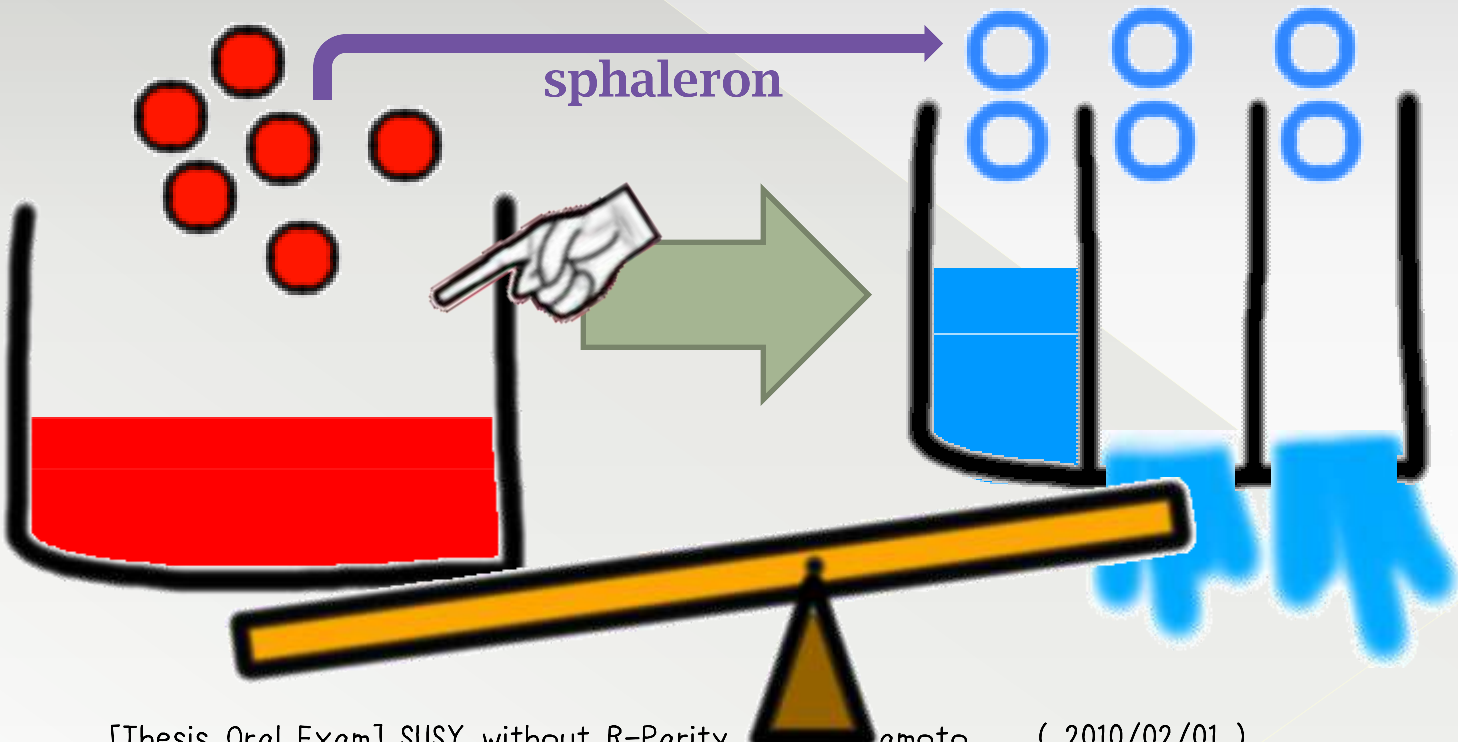


Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

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

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

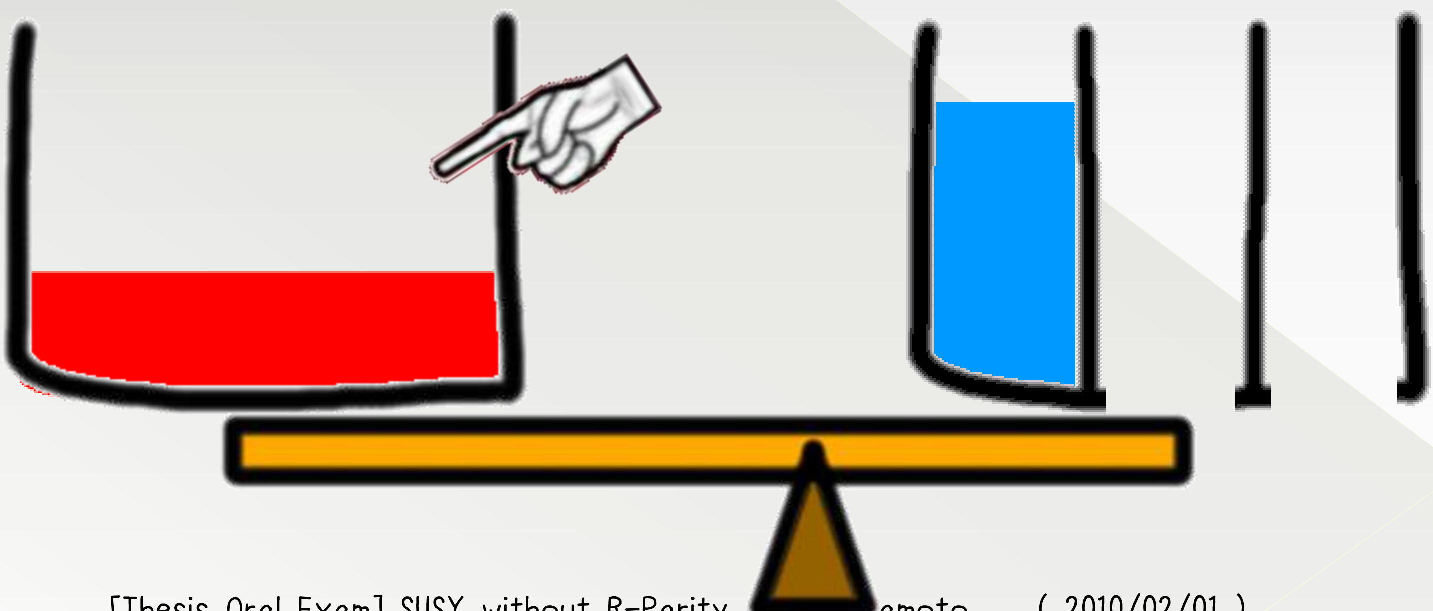
Wash-out with $\not{L}$-viol. $\not{L}$



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

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

Baryon SURVIVES!!!

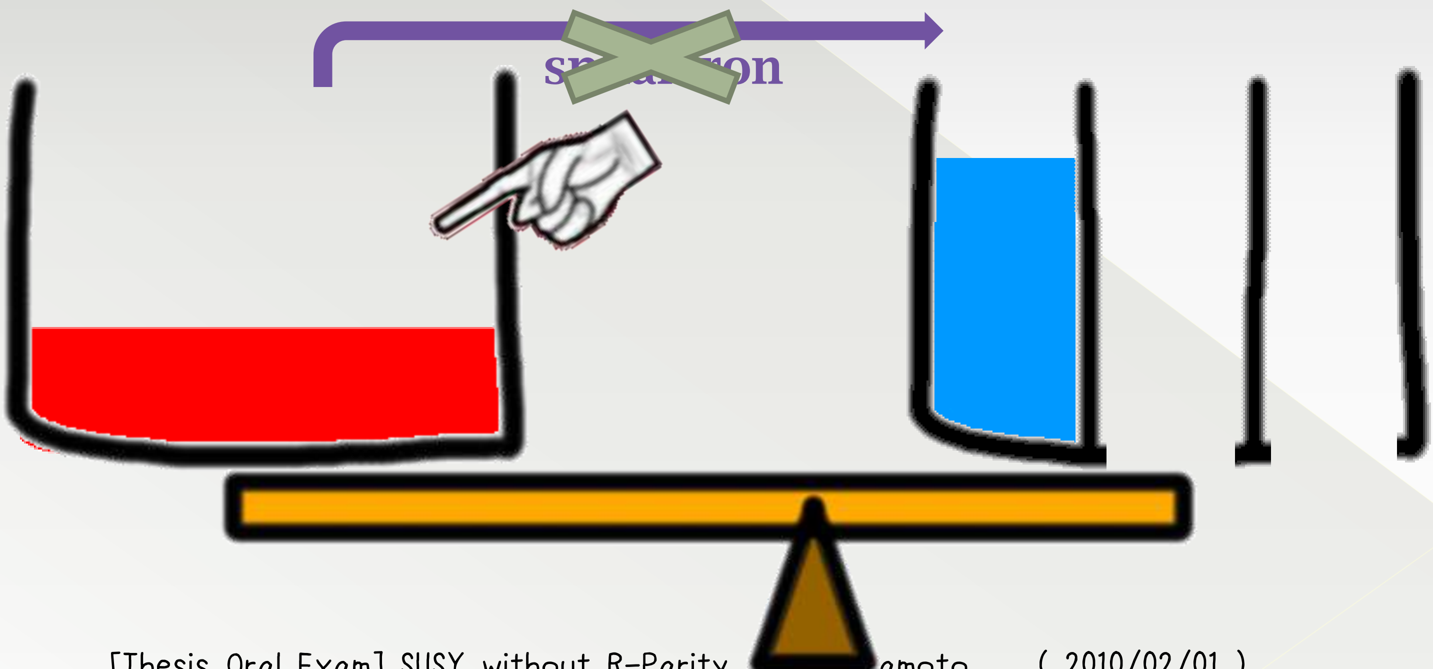


Campbell, Davidson, et al., 1992; Dreiner and Ross, 1983

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

Now *B* and *L* are **balanced**,
and thus no more process.

Baryon SURVIVES!!!



Endo, Hamaguchi, and IWAMOTO, 2009

Wash-out with *L*-viol.

- But remember!

The Standard Model

Endo, Hamaguchi, and IWAMOTO, 2009

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

- But remem

(tiny)
Lepton Flavor Violation

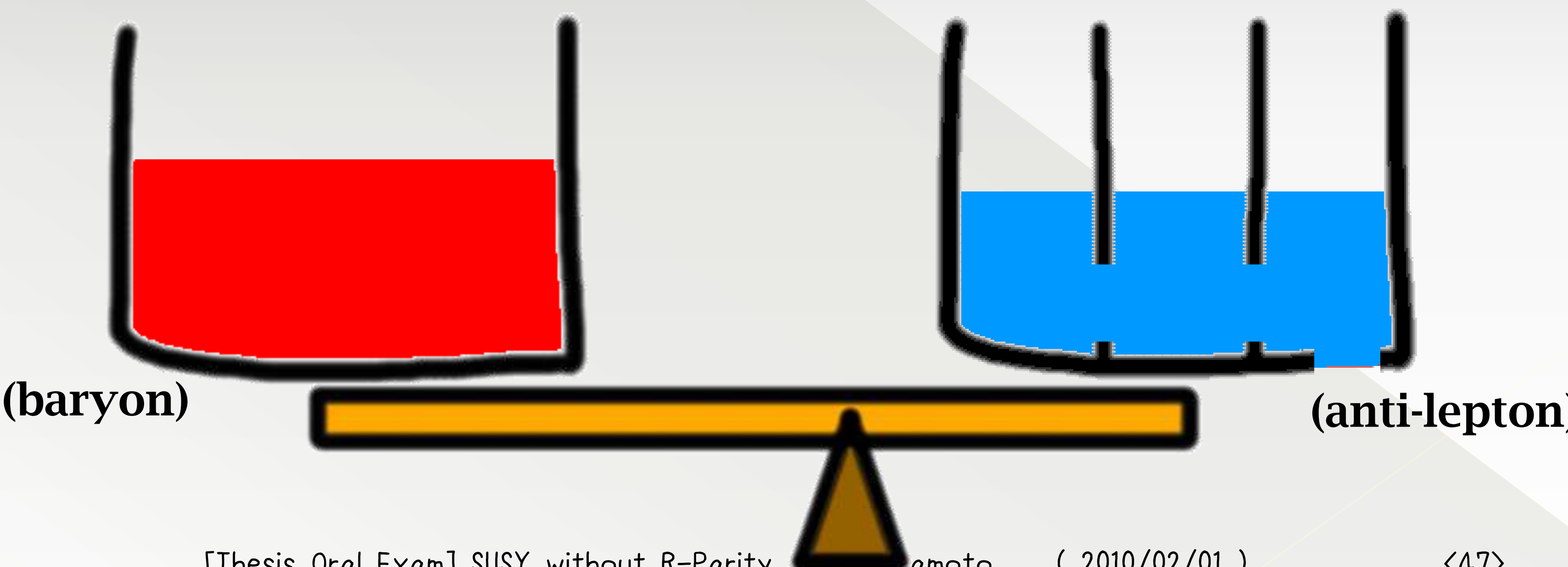
The Standard Model

The MSSM

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

- Therefore,

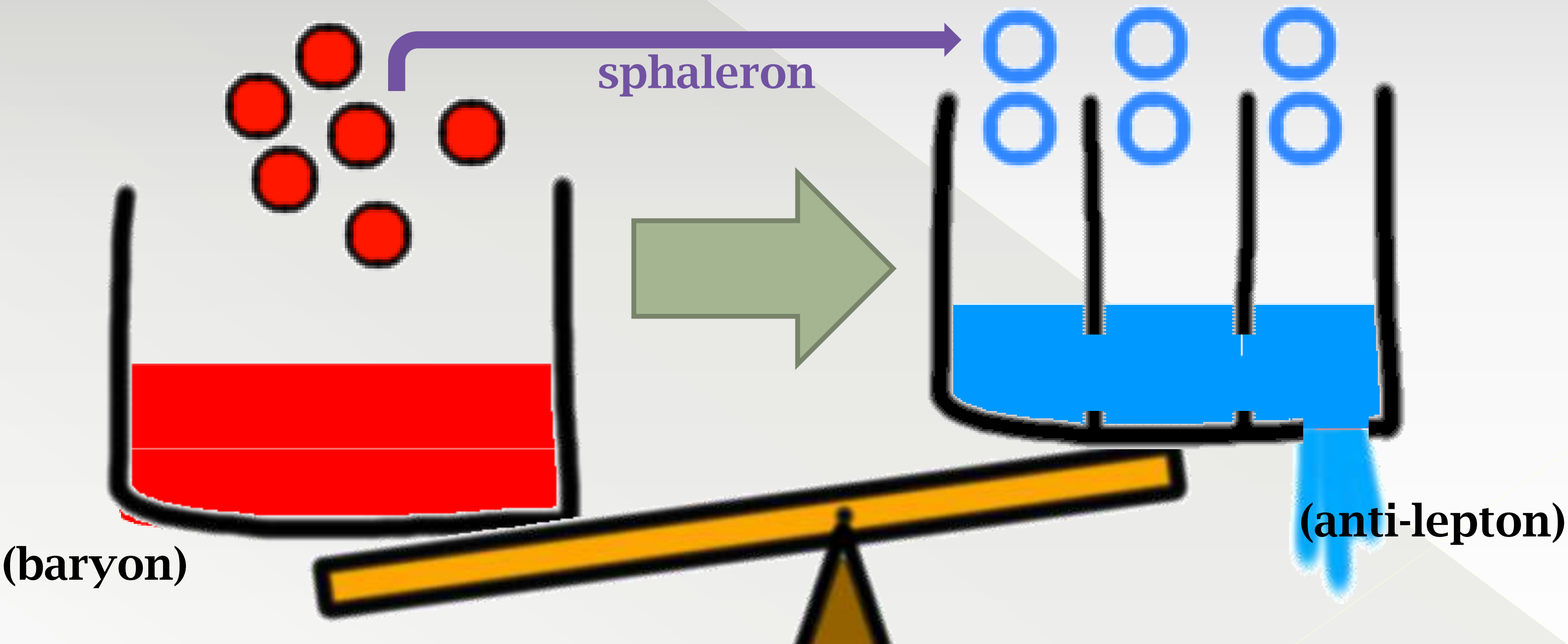
  Only One *L*-violation would…



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

- Therefore,

  Only One L-violation would…

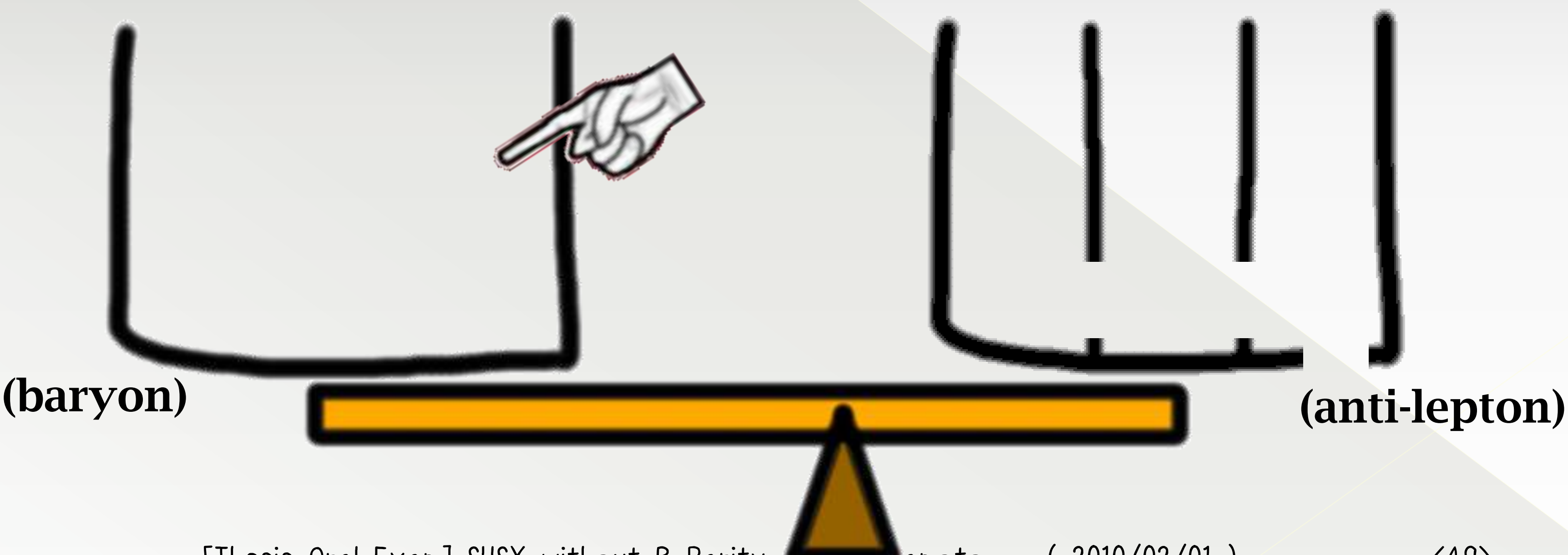


Wash-out with L-viol. $\not{L}$

- Therefore,

  Only One L-violation would…

  Do "WASH-OUT" !!



Now We Know

- When $T \gtrsim 100\,\mathrm{GeV}$
  → *L*-viol. invades Baryon Assymetry.

- Especially
  Lepton Flavor Mixing & One L-viol.
  → Baryon Wash-Out

Now We Know

If all flavors are mixed

? How Large LFV needs?

→ All L-violation must be small enough.

? How SMALL?

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

Now We Know

If all flavors are mixed

? How Large LFV needs?

These are our study!

→ All L-violation must

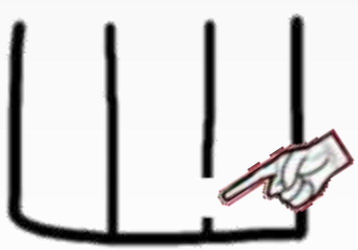
? How SMALL?

be small enough.

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

3. Our Result: Lepton Flavor Violation

- To mix the Lepton Flavors, how large mixing interaction do we need??



Methods

Set up:

- MSSM; **before EWPT**;
- Ignoring *R*-parity violating at first;

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

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

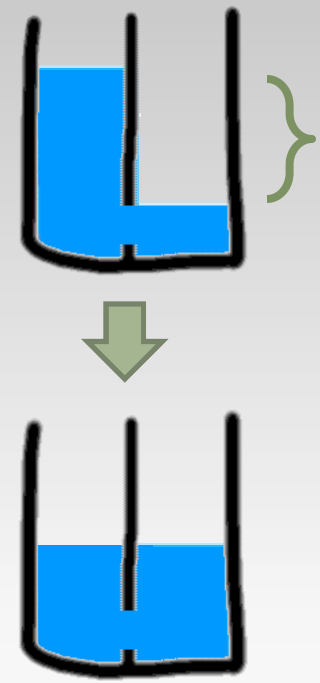
$\uparrow$ Diagonalize ➡ $\uparrow$ Not diagonal (Flavor viol.)

Methods

- We consider the time evolution of $L_i - L_j$.

Lepton number density in *i*-th generation

- By LFV, $L_i - L_j \to 0$.



Boltzmann Equation:

Dilution, due to the expansion of the universe.

number density

$$\frac{\mathrm{d}}{\mathrm{d}t} n_A = \boxed{-3Hn_A} + (\text{interaction})$$

time

Hubble parameter

Methods

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

- 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' process.

Approximations:

- Ignoring the mass of Higgs bosons.
- All particles obey Maxwell-Boltzmann distribution.

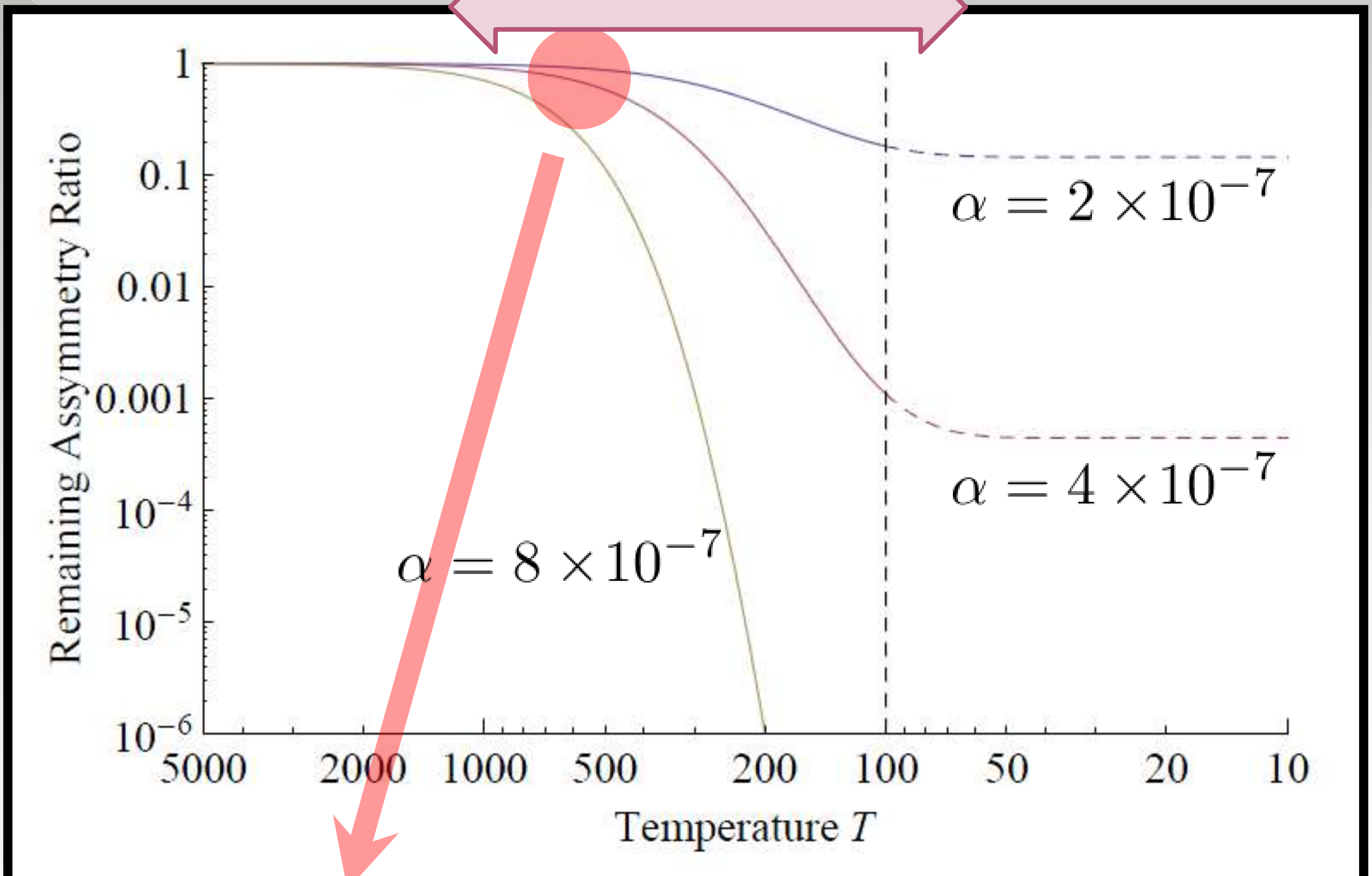
  (instead of Bose/Fermi distrib.)
- Shutting off the sphaleron at T=100GeV.

Result

$$W \ni \alpha H_d L_i \bar{E}_j$$

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

$$\frac{(L_i - L_j)(T)}{(L_i - L_j)_{\text{init}}}$$



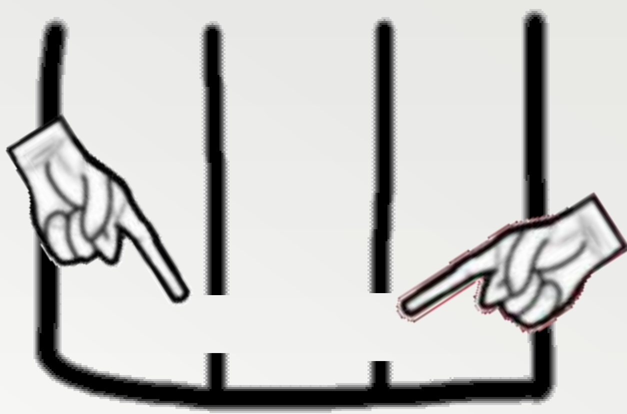
$$m_{\widetilde{H}} = 600\,\text{GeV}, \quad m_{\tilde{l}} = m_{\tilde{e}} = 200\,\text{GeV}$$

Conclusion

$$W \ni \alpha H_{\mathrm{d}} L_i \bar{E}_j$$

$\alpha \gtrsim 3 \times 10^{-7}$

$\rightarrow$ MIXED



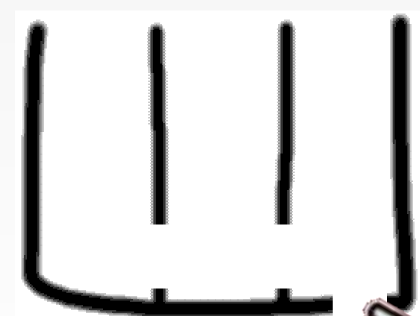
All Flavors are MIXED

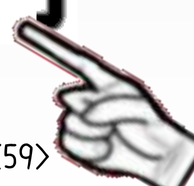
$\downarrow$

All *L*-viol. must be **small.**

4. Our Result: *R*-parity Violation

- Now Lepton flavors are mixed.
  Then how about
  the constraints on
  RpV couplings?





Methods

Set up:

- MSSM; before EWPT;
- **Lepton flavors are mixed.**
- *R*-parity violated.

Method: The same.

→ **We examined the time-evolution of**

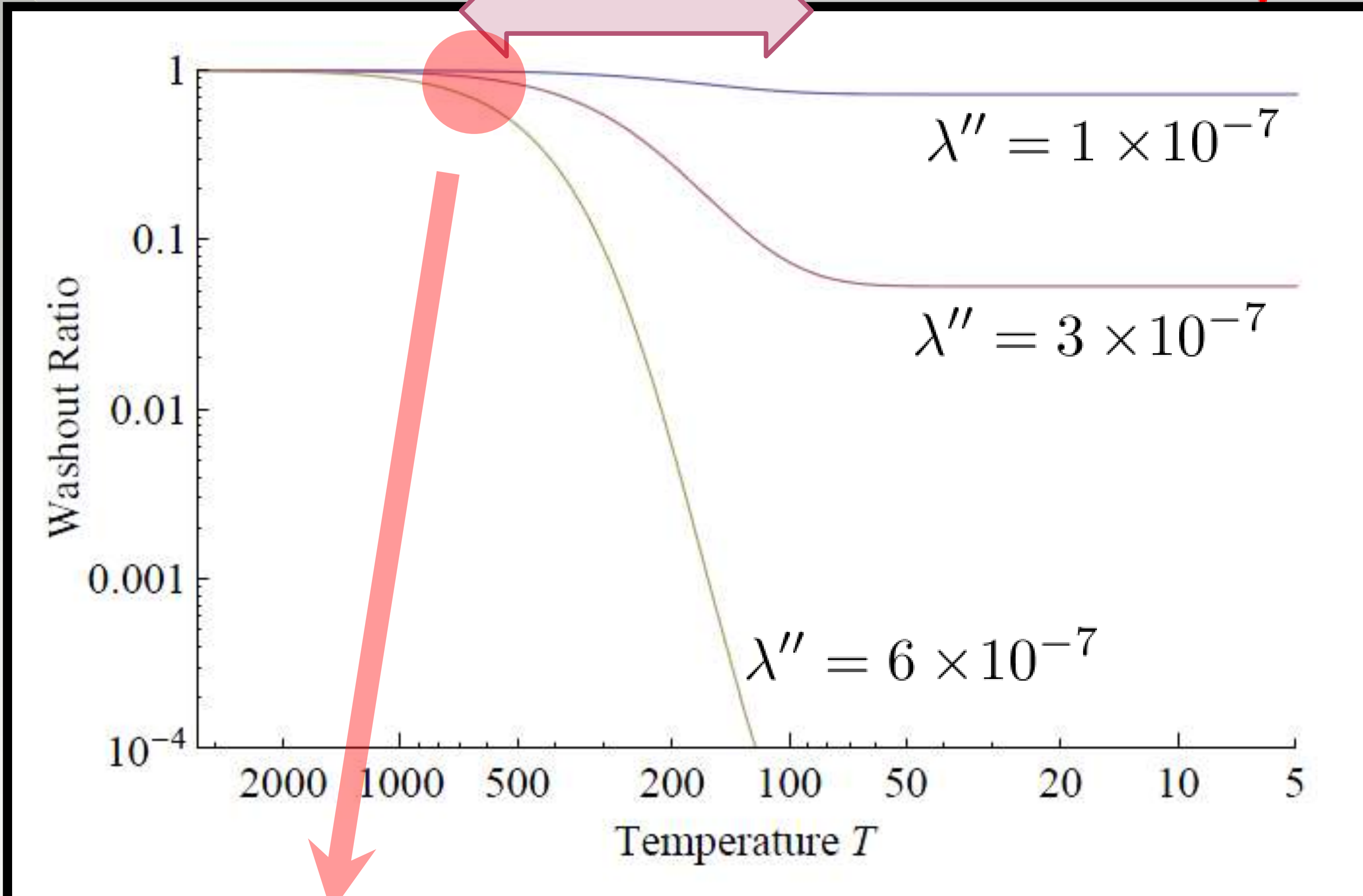
B and L (in number density).

Result

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

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

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



$$m_{\tilde{q}} = 600\,\mathrm{GeV}$$

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

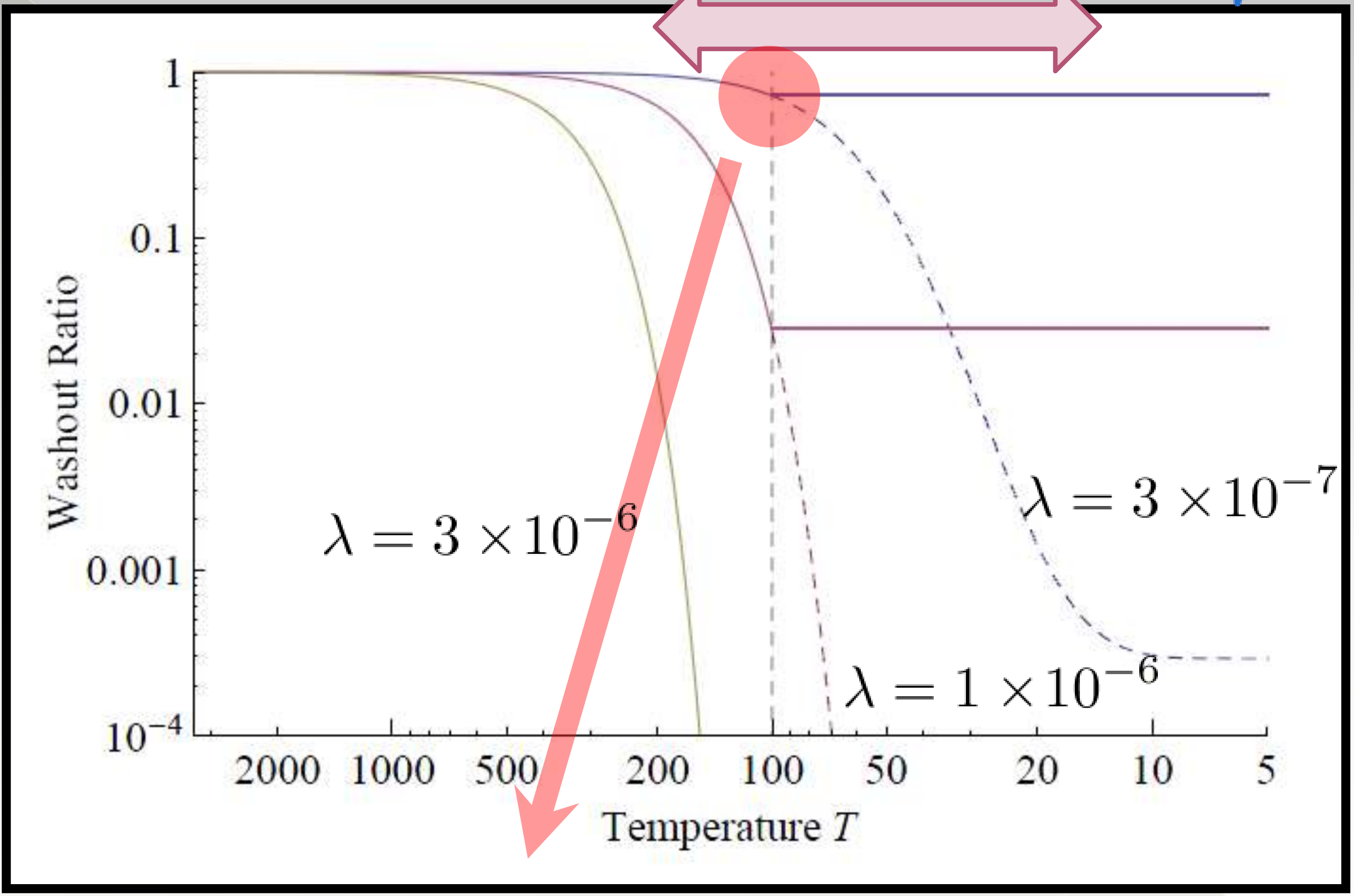
Result

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

$\tilde{l} \rightleftarrows ll$

$\not{L}$

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



$m_{\tilde{l}} = 100\,\mathrm{GeV}$

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

Conclusion

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

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

From similar analysis:

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

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

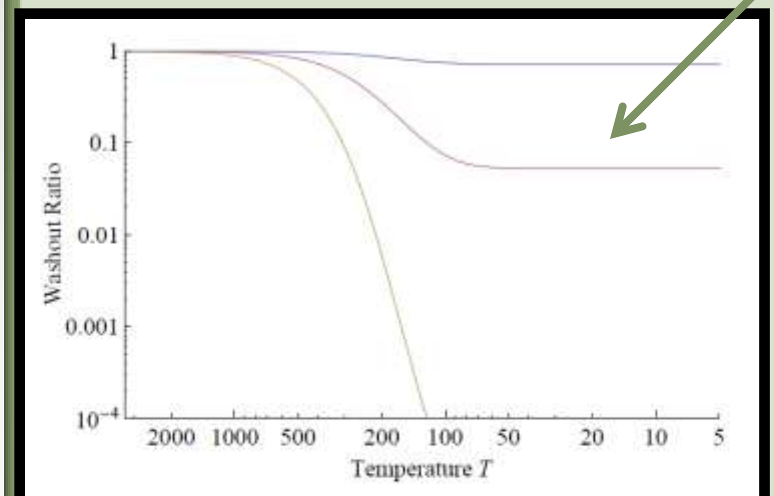
(For all *i*, *j*, *k*)

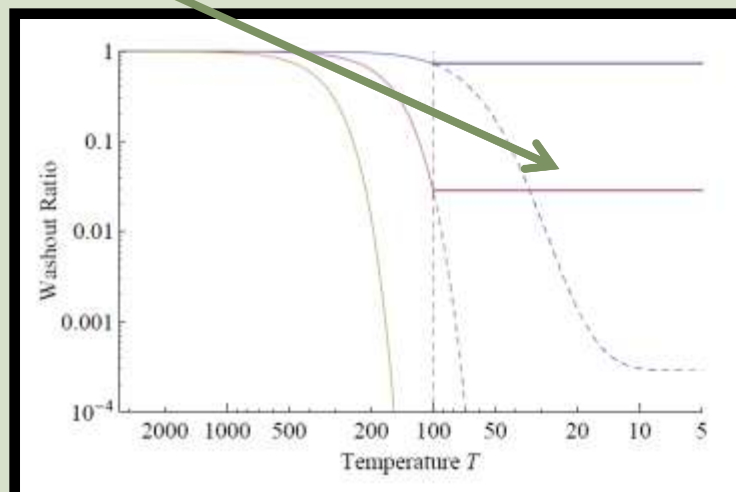
$$W_{\not{L}} = W_{\mathrm{RPC}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_{\mathrm{u}}$$

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

Note

- We can **avoid** this "wash-out" with
  to create current *B*-asymm.
  HERE (in $T < 100\mathrm{GeV}$).





5. Conclusion

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

Wash-out by B-viol.

$\not{B}$

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

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

$\rightarrow$ Wash-out !!

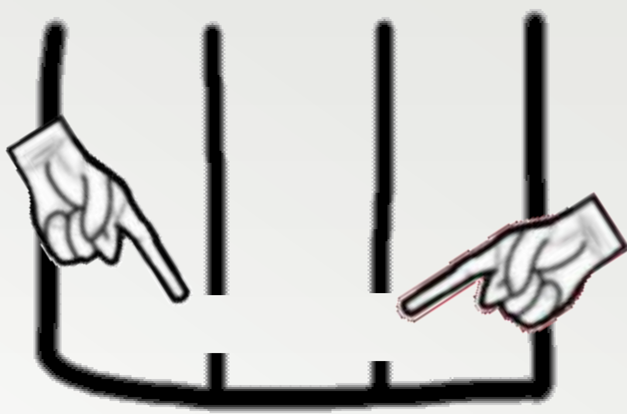
$$m_{\tilde{q}} = 600\,\mathrm{GeV}, \quad m_{\tilde{H}} = 300\,\mathrm{GeV}, \quad m_{\tilde{l}} = 100\,\mathrm{GeV}$$

Lepton Flavor Violation

$$W \ni \alpha H_{\mathrm{d}} L_i \bar{E}_j \quad (i \neq j)$$

$$\alpha \gtrsim 3 \times 10^{-7}$$

$\rightarrow$ MIXED



All Flavors are MIXED

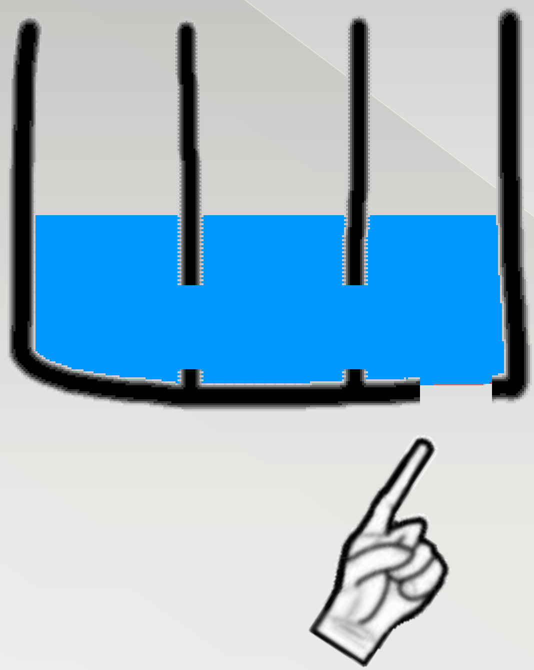
$\downarrow$

All *L*-viol. must be **small.**

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

$\not{L}$

If all Flavors are MIXED,



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

$$\text{or } \lambda' \gtrsim 3 \times 10^{-7}$$

$$\text{or } \kappa \gtrsim 1.5 \times 10^{-6}$$

$\rightarrow$ Wash-out !!

$$W \ni \lambda_{ijk} L_i L_j \bar{E}_k, \quad \lambda'_{ijk} L_i Q_j \bar{D}_k, \quad \kappa_i L_i H_{\mathrm{u}}$$

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

Application (LHC)

- Stringent RpV-constraint

  $\to$ LSP is a bit "long-lived."

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

$$\Gamma_{\tilde{\tau}\to l_i \nu_j} \simeq \frac{|\lambda_{ij3}|^2}{8\pi} m_{\tilde{\tau}}$$

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

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

Application (LHC)

- Stringent RpV-constraint

  → LSP is a bit "long-lived."

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

To be a good signal of RpV-MSSM?

→ Future works!
(of my following years.)

That's all.

Thank you for listening.

Appendices

- Hierarchy Problem
- Rate of Proton Decay
- Collider Constraints
- Sphaleron
- The Other Results

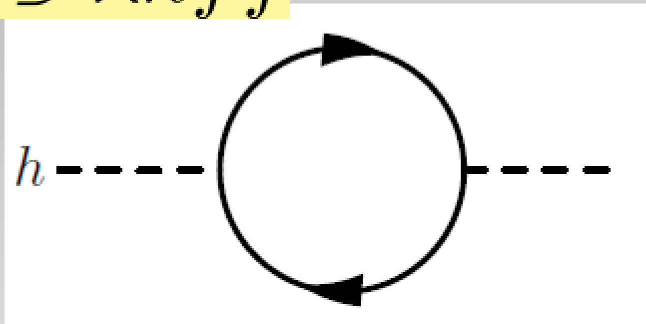
A. Hierarchy Problem

Hierarchy Problem

- In Standard Model with Higgs,

Hierarchy Problem

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



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

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

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

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

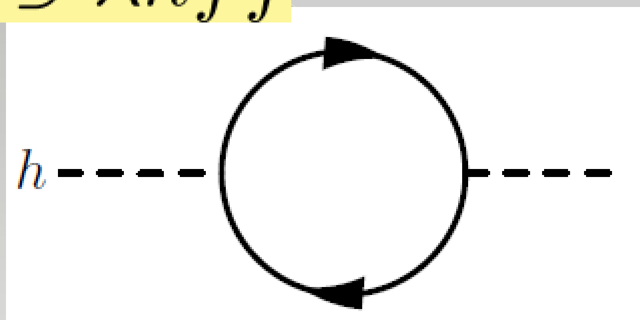
$$\therefore \mathrm{O}(10^{30}) - \mathrm{O}(10^{30}) \to 10^4 \;!?$$

Hierarchy Problem

- In MSSM (or other SUSY models),

Hierarchy Problem

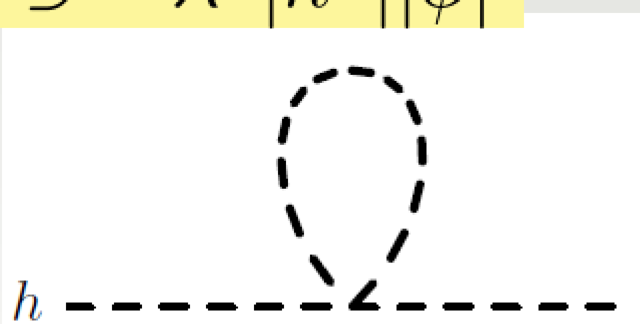
$\mathcal{L} \ni \lambda h \bar{f} f$



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

And its superpartner goes round!

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



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

Cancelled!

B. Rate of Proton Decay

Proton decay @ MSSM

MSSM Superpotential contains:

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

$$\boxed{LH_{\mathrm{u}}, \quad LL\bar{E}, \quad LQ\bar{D},} \quad \boxed{\bar{U}\bar{D}\bar{D}}$$

L violating   *B* violating

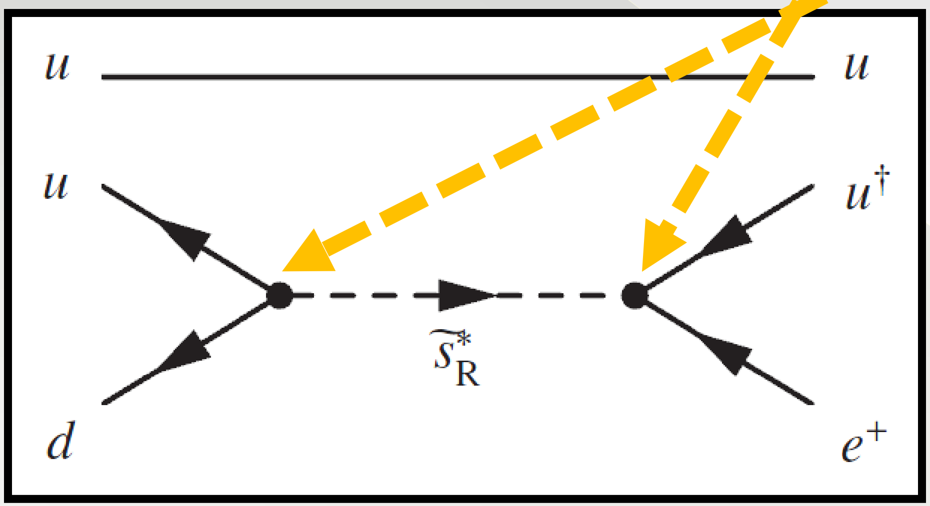
Violation of ***both B and L***

invoke decay of proton as…

Proton decay @ MSSM

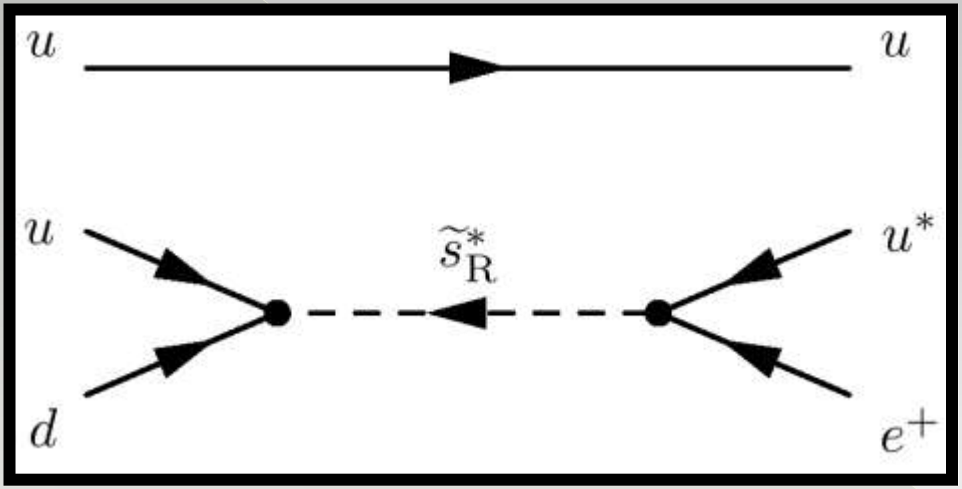
$$W \ni \; H_{\mathrm{u}}H_{\mathrm{d}}, \quad H_{\mathrm{d}}L\bar{E}, \quad H_{\mathrm{d}}Q\bar{D}, \quad H_{\mathrm{u}}Q\bar{U},$$

$$\boxed{LH_{\mathrm{u}}, \quad LL\bar{E}, \quad LQ\bar{D},} \quad \boxed{\bar{U}\bar{D}\bar{D}}$$



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

Rate of Proton Decay



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

(*i*, *j*, *k* for generations.)

$$\Gamma \sim |\lambda'_{112}\lambda''_{112}|^2 \frac{m_{\rm proton}^5}{m_{\tilde{s}_R}^4} < \frac{1}{10^{33}\,{\rm yr}}$$

$$\therefore |\lambda'_{112}\lambda''_{112}| < 5 \times 10^{-27} \cdot \left(\frac{m_{\tilde{s}_R}}{1\,{\rm TeV}}\right)^2$$

C. Collider Constraints

The RpV interactions
are constrained
by several experimental facts.

Constraints

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

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

- The RpV parameters

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

  $\rightarrow$ experimental constraints

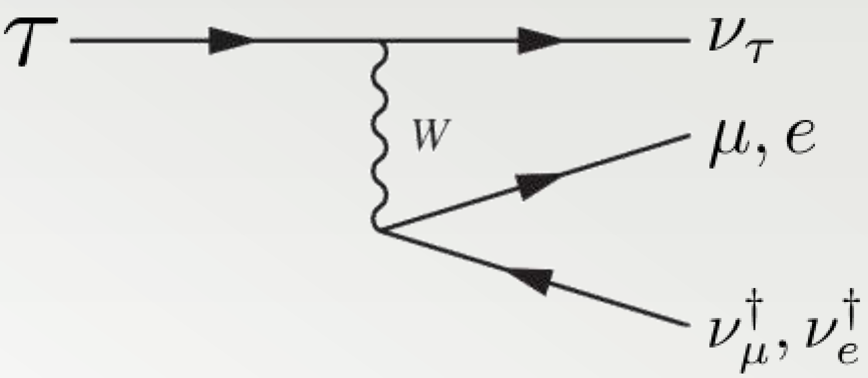
And the **constraints are important**
to study RpV-MSSM.

Constraints

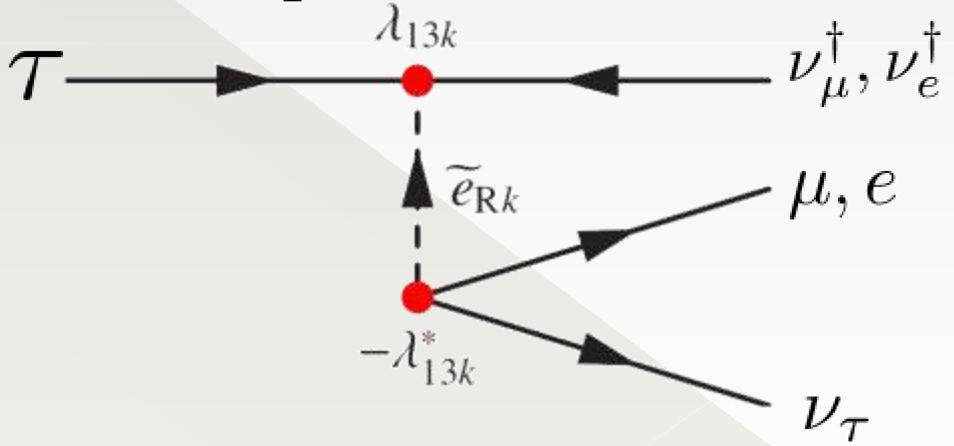
- Example:

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

Standard Model



RpV-MSSM



Constraints

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

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

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

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

Additional Contribution!

D. Sphaleron

Sphaleron

Sphaleron (a 'wobbly' process) is a **non-perturbative** solution of the Standard Model (SM).

Roughly speaking,

$$\mathcal{O}_{\rm sph} = \Pi_i (udd\nu)_i$$
$$= uddcsstbb\nu_e\nu_\mu\nu_\tau$$

Sphaleron

$$\mathcal{O}_{\rm sph} = uddcsstbb\nu_e\nu_\mu\nu_\tau$$

For example:

$$\bar{u} + \bar{d} \to d + c + 2s + t + 2b + \nu_e + \nu_\mu + \nu_\tau$$

Note!

Sphaleron processes:

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

$\to$ Converts $B \rightleftarrows L$!!!

Sphaleron

$$\mathcal{O}_{\text{sph}} = uddc \ldots$$

Only in the early universe…

For exampl…

$$\bar{u} + \bar{d} \longrightarrow d + c + 2s + t + 2b + \nu_e + \nu_\mu + \nu_\tau$$

Note!

Sphaleron processes:

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

$\rightarrow$ Converts $B \rightleftarrows L$!!!

Sphaleron

- The sphaleron process:
  - Generally → EXTREMELY rare
  - Thermal effect → enhanced

- The effect is present when

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

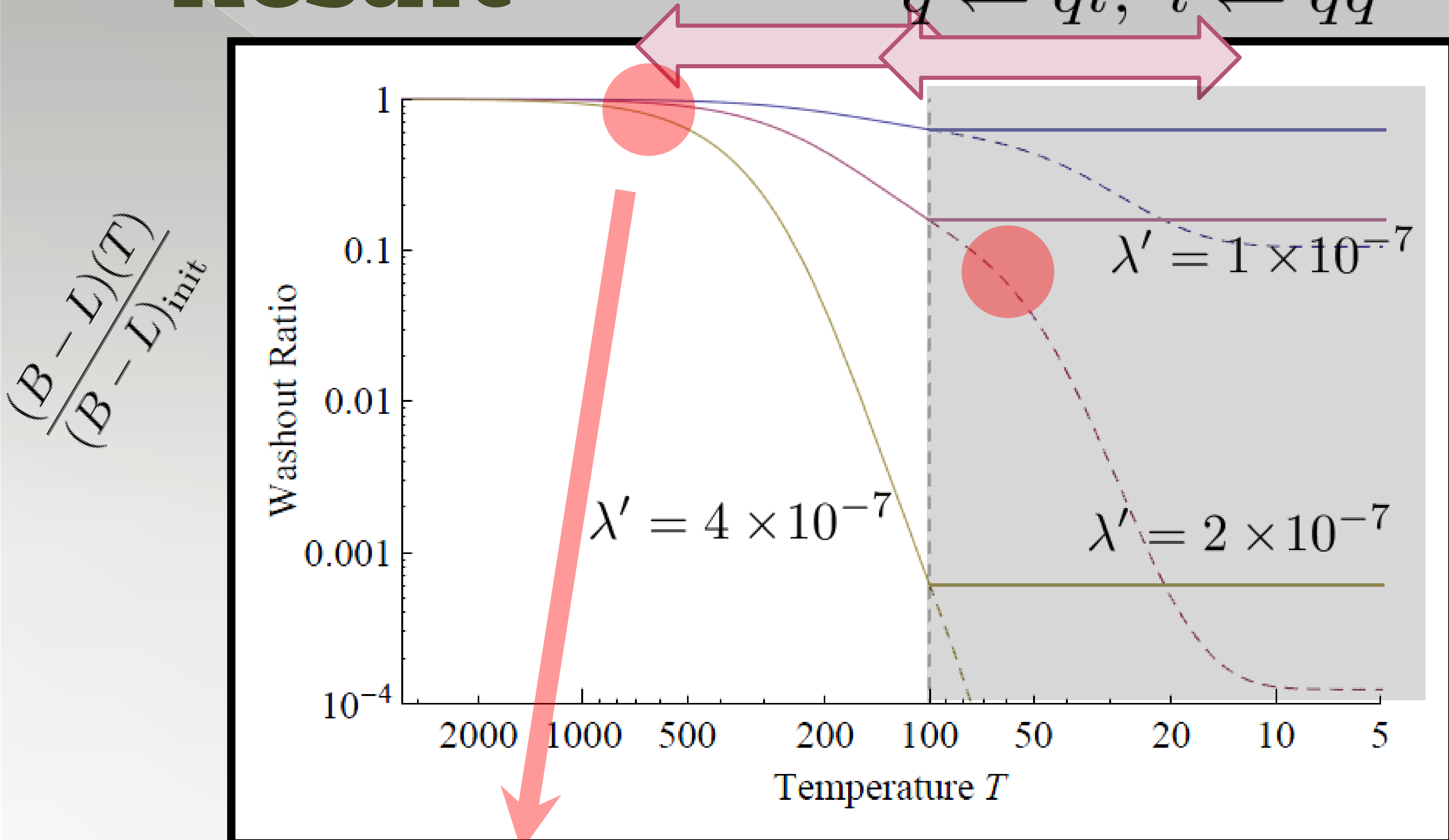
(Before the electroweak phase transition.)

E. The Other Results

Result

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

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

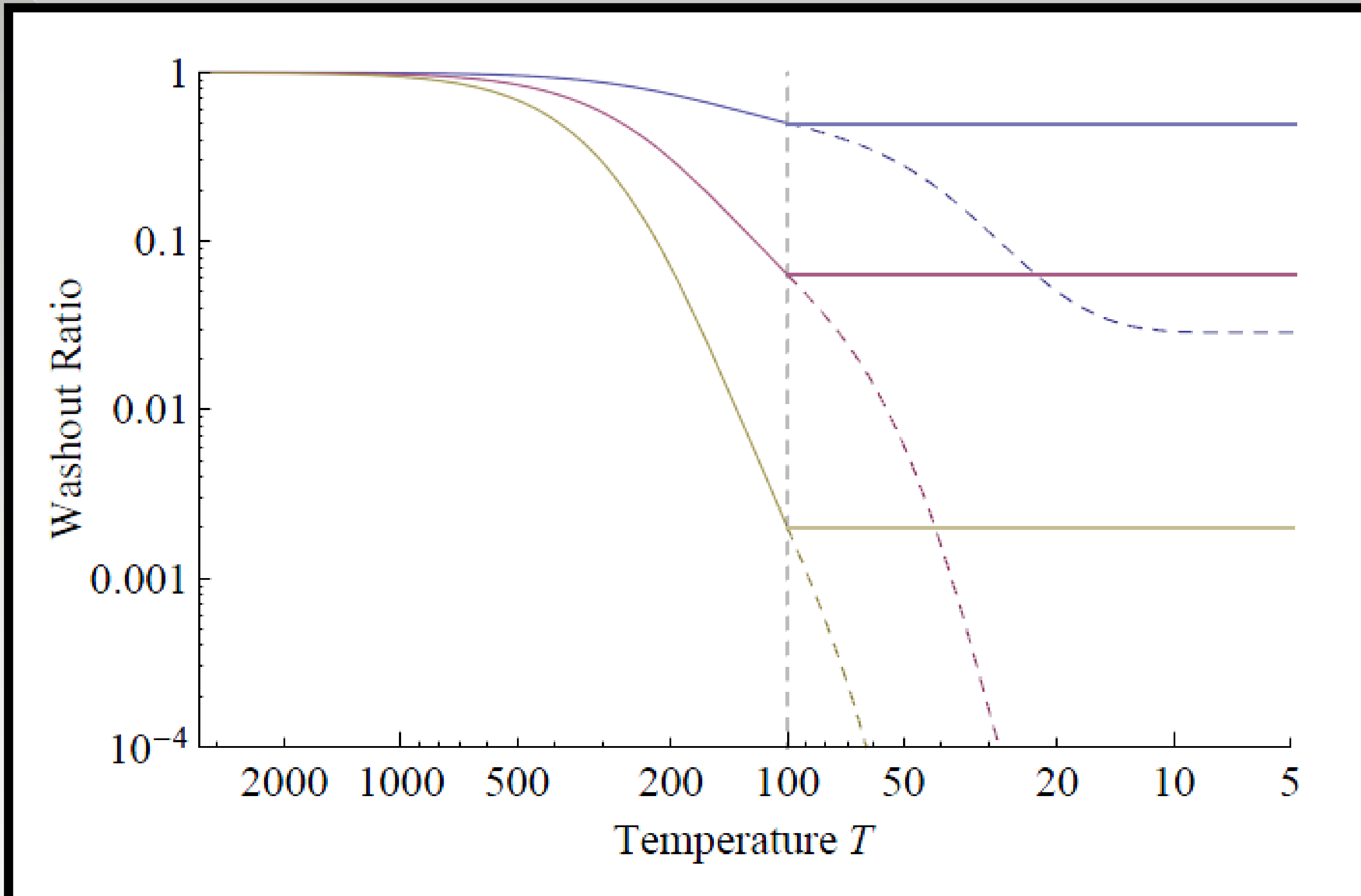


$m_{\tilde{q}} = 600\,\mathrm{GeV}$ $\quad (m_{\tilde{H}} = 300\,\mathrm{GeV}, \; m_{\tilde{l}} = 100\,\mathrm{GeV})$

$$W \ni \kappa L H_{\rm u}$$

Result

$$\frac{(B-L)(T)}{(B-L)_{\rm init}}$$



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