SUSY@LHC without R-Parity

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Lunch Seminar @ UT/Hongo

B. C. Allanach et al.
R-Parity violating minimal supergravity at the LHC
arXiv: 0710.2034 [hep-ph]

Contents

(if we have time, that is,
if I'm not trapped anywhere.)

B. C. Allanach et al.
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1. SUSY and R-Parity

- SUSYだと陽子崩壊が起きるから R-Parityを課すのがいいよ。

SUSY and R-parity

- **Standard Model (SM)**
  - VERY NICE theory!!
  - But has some problems…. such as
    - Hierarchy problem, Neutrino mass, ….

→ The most hopeful theory is…..

- **SUSY** (or Models with supersymmetry)

SUSY and R-parity

But **SUSY** also has some problems.

- Many Particles (do they exist?),
- Many Models (How to break SUSY?),
- Many Parameters (Real values are…?)

And furthermore,

Proton decays!!!

Proton decay @ MSSM

Under MSSM (Minimal Supersymmetric Standard Model), we have following interactions:

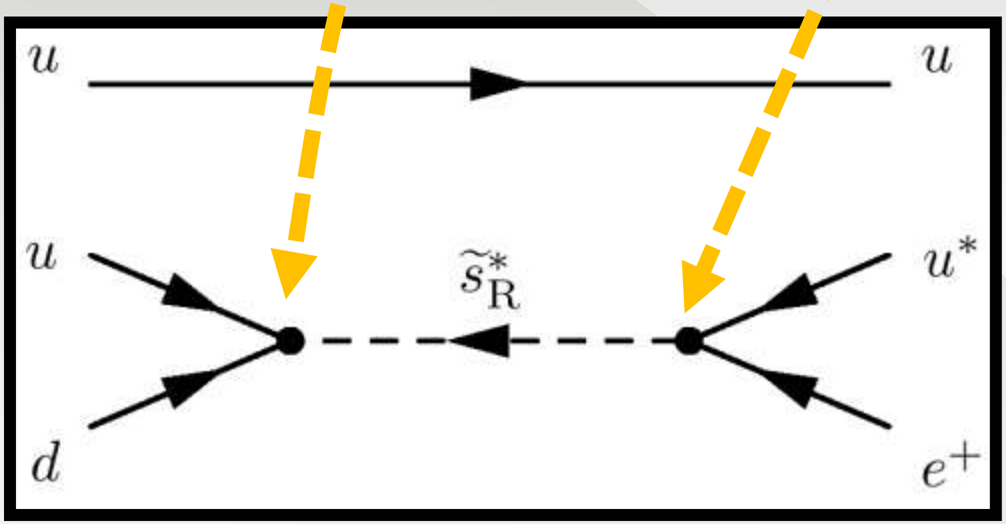
$$W \ni H_u H_d, \quad H_d L \bar{E}, \quad H_d Q \bar{D}, \quad H_u Q \bar{U},$$
$$H_u L, \quad L L \bar{E}, \quad L Q \bar{D}, \quad \bar{U} \bar{D} \bar{D}$$

And then……

Proton decay @ MSSM

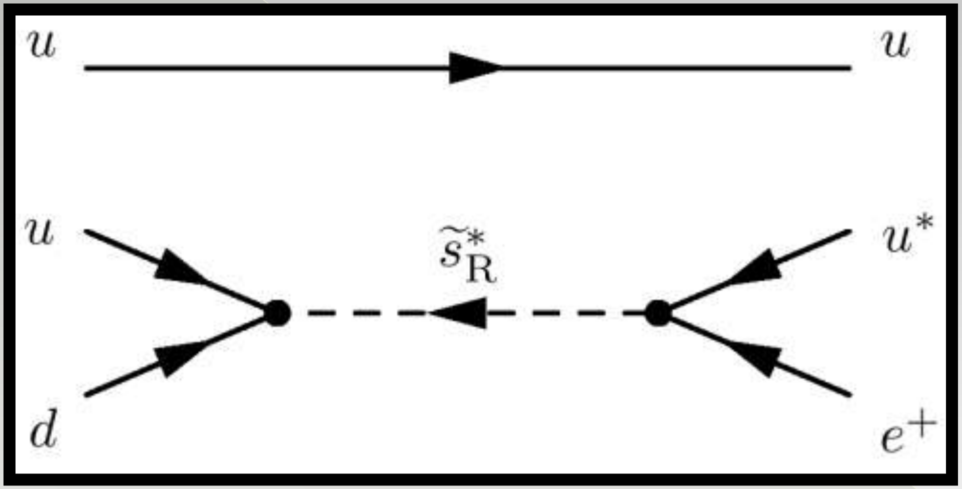
Proton decays!!

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



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

Proton decay @ MSSM



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

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

$$\Gamma \sim \left|\lambda'^{112}\lambda''^{112}\right|^2 \frac{m_{\rm proton}^5}{m_{\tilde{s}}^4} < \frac{1}{10^{29}\ {\rm yr}}$$

$$\therefore \left|\lambda'^{112}\lambda''^{112}\right| < 5 \times 10^{-23} \cdot \left(\frac{m_{\tilde{s}}}{1\ {\rm TeV}}\right)^2$$

Unreasonably constrained!

SUSY and R-parity

- How should we do?
  → Review the Standard Model case.

- Why does not proton decay under SM?

→ Because

Baryon number B and **Lepton Number** L
are accidentally conserved.

Proton decay @ SM

Under SM, 湯川 interactions are only

$$\mathcal{L}_{\text{yukawa}} = y_u \bar{U} H Q + y_d \bar{D} H^\dagger Q + y_e \bar{E} H^\dagger L$$

and their Hermitian conjugates.

→ ***B*** and ***L*** are accidentally conserved
by the gauge symmetry.

→ Proton decay, e.g. $p \to e^+ \pi^0$, is forbidden.

Proton decay @ SM

- Roughly speaking,
  Proton decay, such as

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

is *B*-/*L*-violating process.

- Therefore,

"Protect *B* and *L* as SM"

may be a good solution.

Prot

MSSM conserves neither B nor L!

However, under SUSY models, possible interactions are:

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

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

L violating!

OK (B / L conserving)

B violating!

SUSY and R-parity

$$\boxed{\begin{array}{c} W \ni H_u H_d, \quad H_d L\bar{E}, \quad H_d Q\bar{D}, \quad H_u Q\bar{U}, \\ H_u L, \quad LL\bar{E}, \quad LQ\bar{D}, \quad \bar{U}\bar{D}\bar{D} \end{array}}$$

- We want to omit these B/L-breaking terms.

→ We introduce **R-Parity**.

$$R_p = (-1)^{3B-L+2s}$$

(s : spin)

SUSY and R-parity

$$\boxed{\begin{array}{l} W \ni H_u H_d, \quad H_d L \bar{E}, \quad H_d Q \bar{D}, \quad H_u Q \bar{U}, \\ \quad \cancel{H_u L}, \quad \cancel{L L \bar{E}}, \quad \cancel{L Q \bar{D}}, \quad \cancel{\bar{U} \bar{D} \bar{D}} \end{array}}$$

- R-Parity forbids these interactions.
  - → B/L are conserved again!
  - → **Proton become stable** again!!!

SUSY and R-parity

- And as you know, since

$$R_p = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for superpartners,} \end{cases}$$

R-Parity makes LSP stable,

(Lightest Supersymmetric Particle)

$\therefore$ LSP $\rightarrow$ a Candidate

for Dark Matter!!

2. Other Ways

- でも実はR-Parityじゃない対称性でもいいよ

Other ways

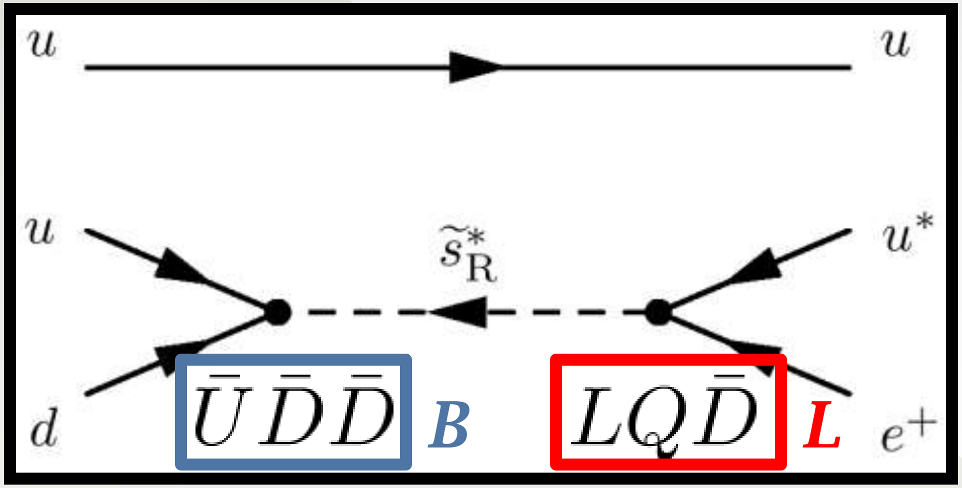
- But Why R-Parity?
  - Evidence for R-Parity conserving? No!
  - No other symmetry can prohibit Proton Decay? No!

… Actually we don't have to

BELIEVE R-Parity conservation.

Proton decay @ MSSM

- Roughly speaking,
  Proton Decay needs
  both B-violating and L-violating term.



More precise?

Proton decay @ MSSM

- Or a bit precisely,
  Proton decay doesn't occur if

  - Baryon number is conserved
    OR
  - (Lepton number is conserved
    and $m_{\mathrm{LSP}} > m_{\mathrm{proton}}$)

More precise?

Other ways

- Therefore we can easily find "other ways."

Other ways

$$\boxed{\begin{array}{c} W \ni H_u H_d, \quad H_d L\bar{E}, \quad H_d Q\bar{D}, \quad H_u Q\bar{U}, \\ \boxed{H_u L, \quad LL\bar{E}, \quad LQ\bar{D},} \quad \boxed{\cancel{\bar{U}\bar{D}\bar{D}}} \end{array}}$$

L-violate *B*-violate

- Baryon Parity $(-1)^{3B}$
  - Proton → not decay

Good!

Other ways

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

L-violate *B*-violate

- Lepton Parity $(-1)^L$
  - Proton → not decay if $m_{\mathrm{LSP}} > m_{\mathrm{proton}}$ **Good!**

Other ways

$$W \ni H_u H_d, \quad H_d L \bar{E}, \quad H_d Q \bar{D}, \quad H_u Q \bar{U},$$
$$\underbrace{\cancel{H_u L}, \quad \cancel{L L \bar{E}}, \quad \cancel{L Q \bar{D}},}_{L\text{-violate}} \quad \underbrace{\cancel{\bar{U} \bar{D} \bar{D}}}_{B\text{-violate}}$$

- R-Parity $(-1)^{3B-L+2s}$
  - Proton → not decay **Good!**
  - LSP → can be DM **Lucky!**

Other ways

- That is,
  we can ADD
  B- **or** *L*-violating interactions!!

[Example]

$$W = \mu H_u H_d + y_e H_d L\bar{E} + y_d H_d Q\bar{D} + y_u H_u Q\bar{U} + bLH_u$$

$$W = \mu H_u H_d + y_e H_d L\bar{E} + y_d H_d Q\bar{D} + y_u H_u Q\bar{U} + bLH_u + \lambda LL\bar{E}$$

$$W = \mu H_u H_d + y_e H_d L\bar{E} + y_d H_d Q\bar{D} + y_u H_u Q\bar{U} + \lambda''\bar{U}\bar{D}\bar{D}$$

Other Ways

NOTE

- From a practical viewpoint,
  "Which symmetry is installed?"
  is **a secondary concern**.

- What is important is
  "Which terms are
  in Lagrangian?"

3. What I'm studying

What I'm studying

- By the way,

What I'm studying

almost ALL

studies on LHC

What I'm studying

is assuming

R-Parity conservation.

What I'm studying

However, as we've seen,

We can violate R-Parity!

What I'm studying

- R-Parity violation introduce

additional interactions

to the Lagrangian.

What I'm studying

- Therefore if R-Parity is violated, we will observe

different

LHC event

from R-Parity conserving case.

What I'm studying

Then, if R-parity is violated,

What will happen in LHC?

What I'm studying

Then, if R-parity is violated,

What [illegible] [illegible]pen in LHC?

UNKNOWN!!!

What I'm studying

Therefore

I'm interested in

What I'm studying

LHC study

without

R-Parity.

What I'm studying

But Why is this theme not explored?

What I'm studying

Is there some PROBLEM?

4. Why not explored?

- R-Parityを仮定しないと，LHCでのSUSY eventの検出がとてもむつかしくなるから。

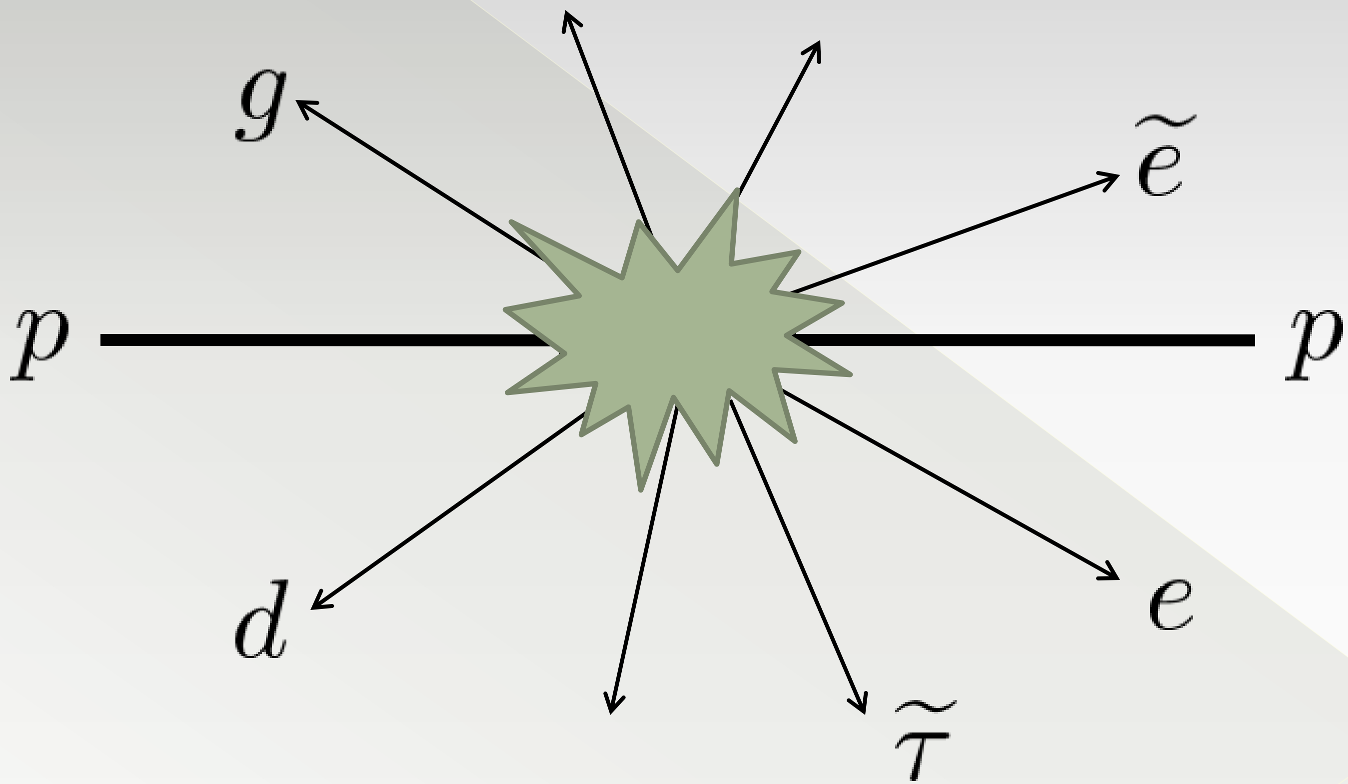
Why not explored?

- If R-parity is conserved…

$$p \longrightarrow \qquad \longleftarrow p$$

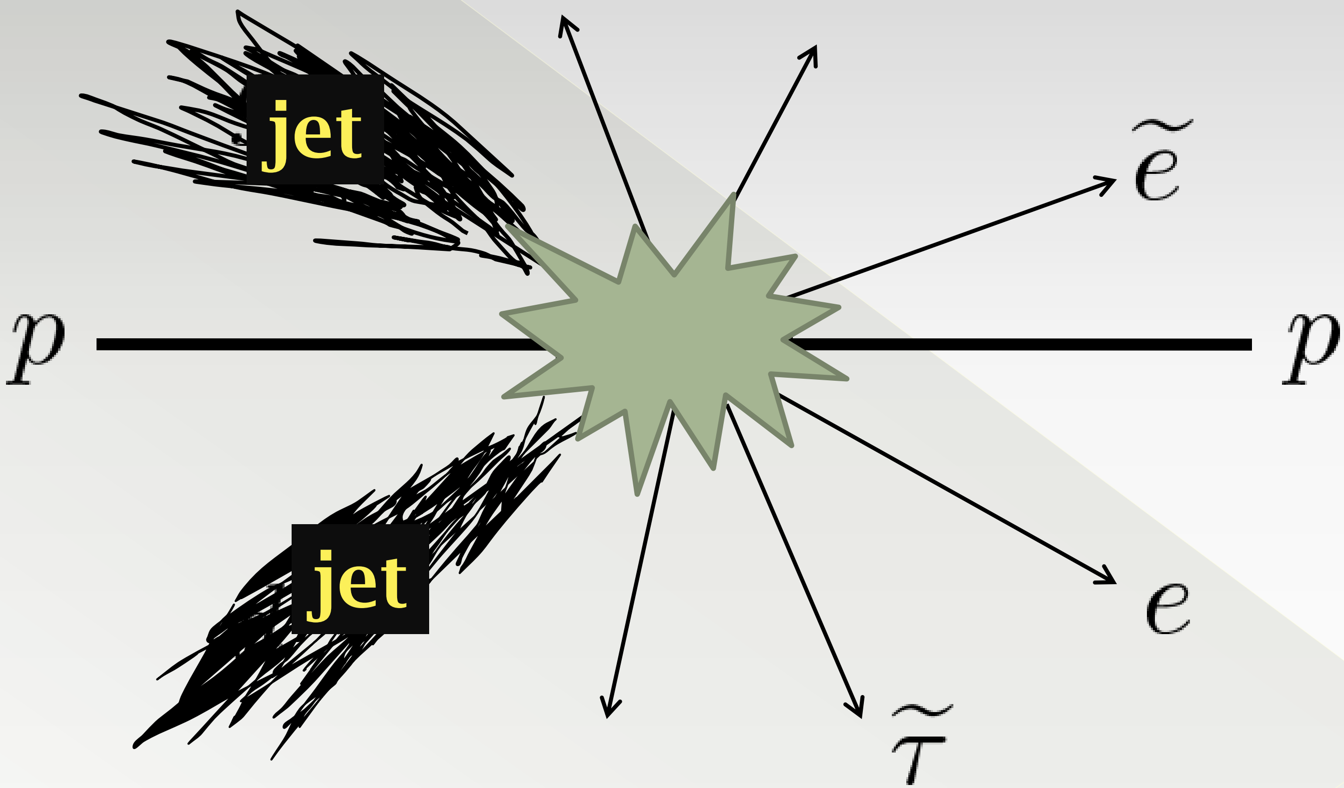
Why not explored?

- If R-parity is conserved…



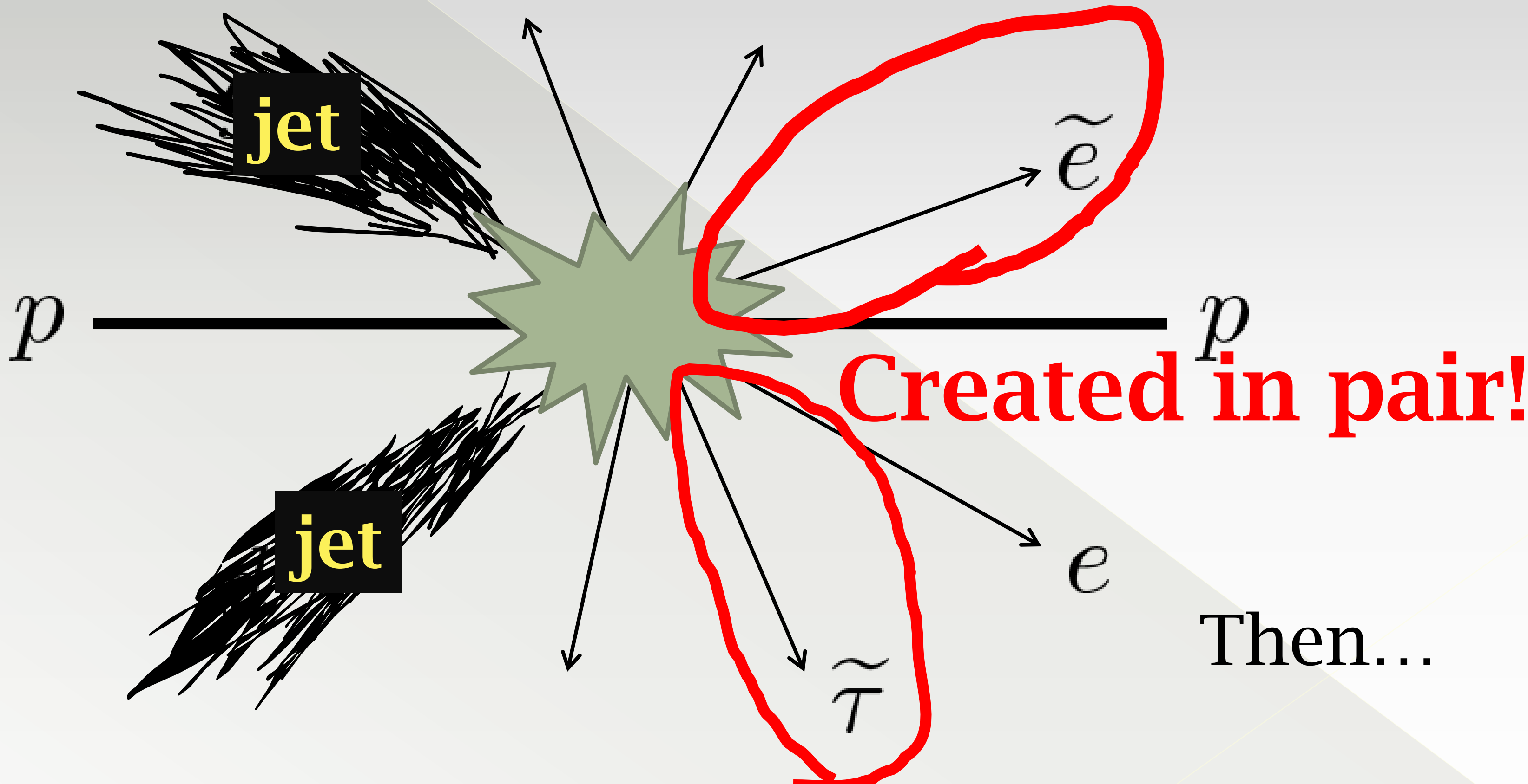
Why not explored?

- If R-parity is conserved…



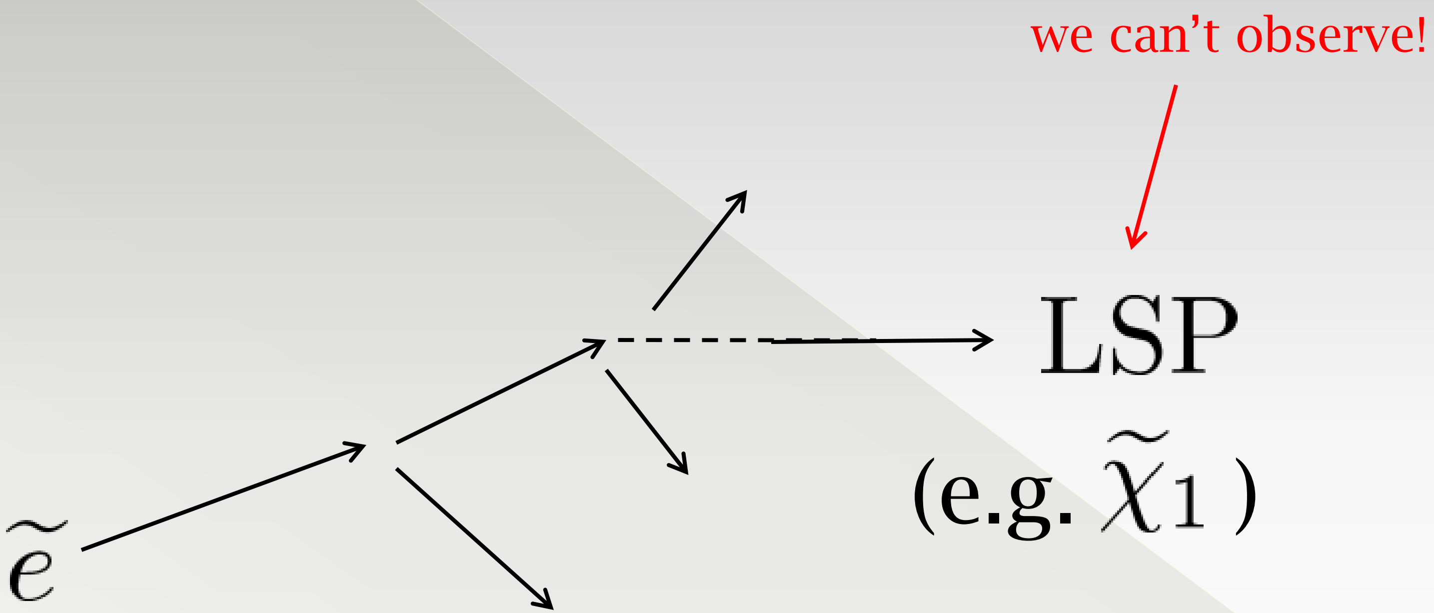
Why not explored?

- If R-parity is conserved…



Then…

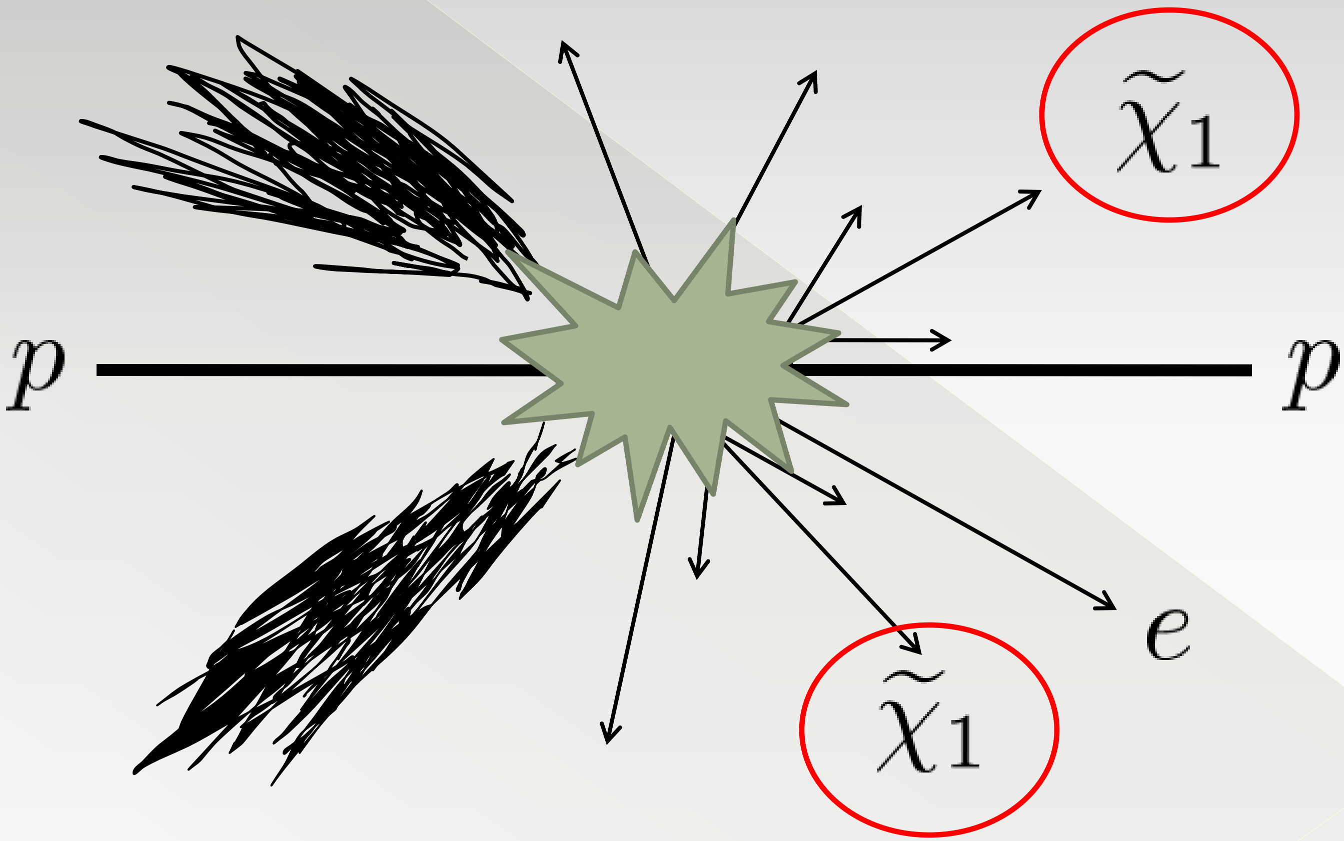
Why not explored?



Therefore

Why not explored?

Here, These LSPs are NOT observed!!!



Why not explored?

Here, These LSPs are NOT observed!!!

→ Momentum seems to be NOT conserved.

→ Large "Missing Energy"

$$\not{p}_{\mathrm{T}} \sim 100\,\mathrm{GeV}$$

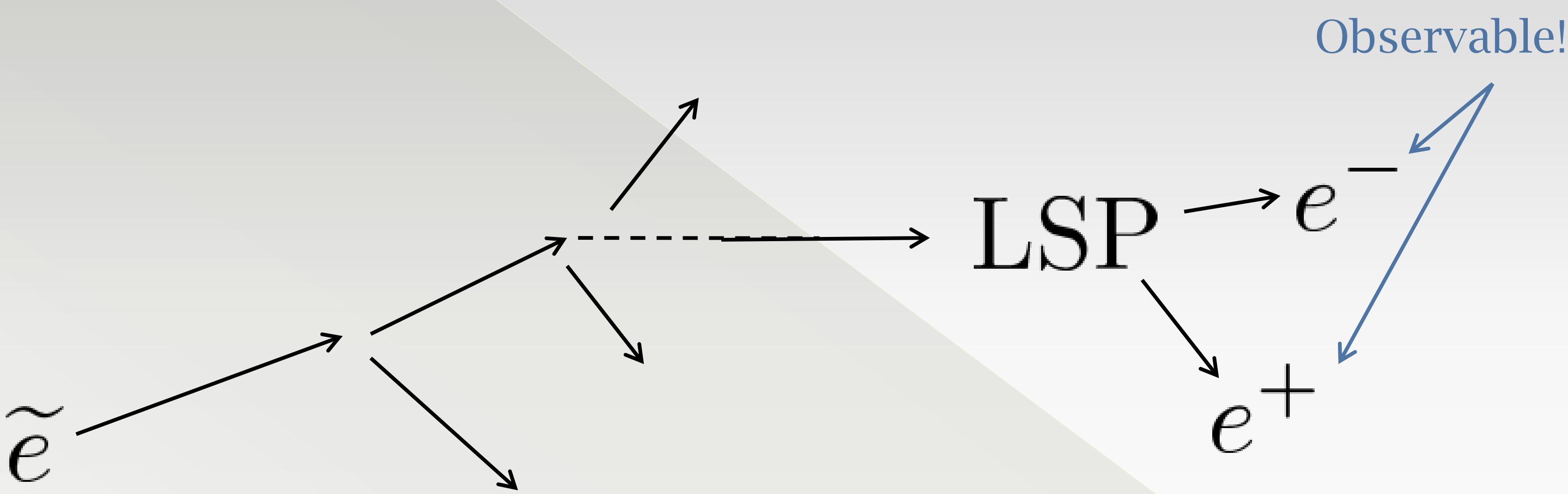
This would be a good SUSY signal.

Why not explored?

- However, if R-Parity is not conserved,

LSP DOES DECAY!!

Why not explored?



Therefore

Why not explored?

Here, These LSPs are N[redacted]ved!!!

→ Momen[redacted]be
NOT [redacted]

→ Larg[redacted]

This would be a go[redacted]gnal.

Why not explored?

- No more "Large $\not{p}_T$" signal

Why not explored?

- Then how can we "detect" SUSY in LHC-experiment?

This is what I want to study!

- …… It is "case by case."
- So, SUSY/LHC without R-Parity is difficult.

5. Exemplary Study

- この分野での過去の研究を紹介します。

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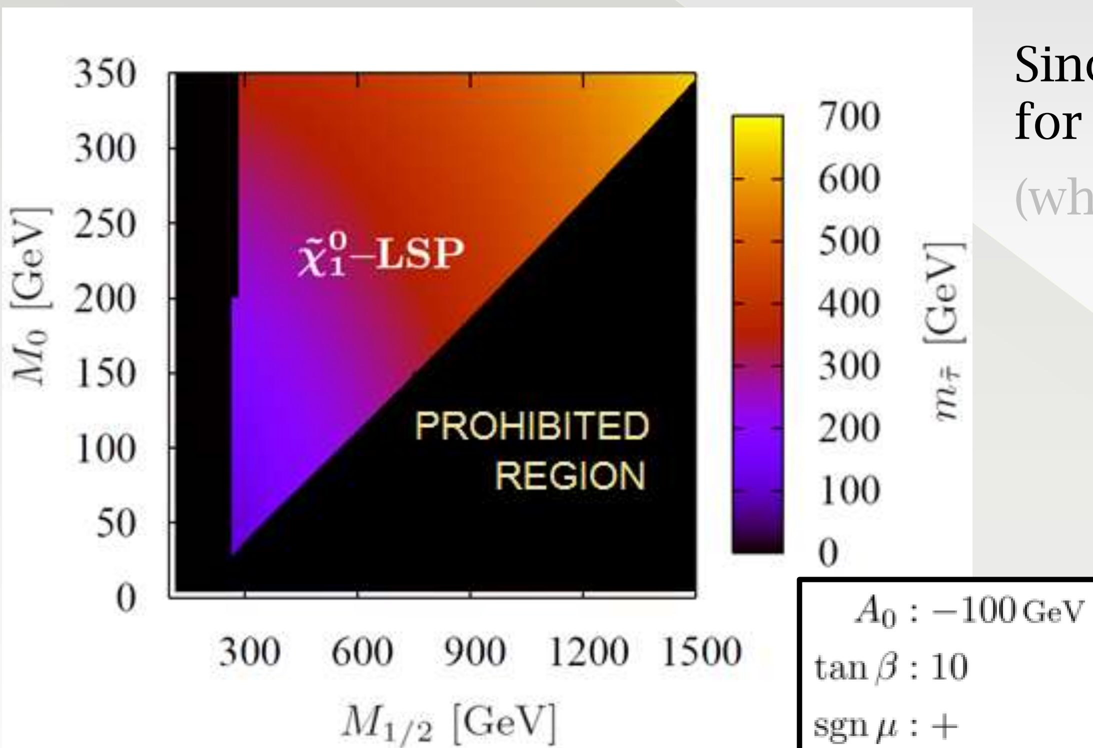
Exemplary Study

- SUSY model : mSUGRA
- R-parity : Broken
- LSP : $\widetilde{\tau}\ (148\,\mathrm{GeV})$

Now STAU is LSP.

- If R-parity is conserved,
  LSP = DM must be neutral.

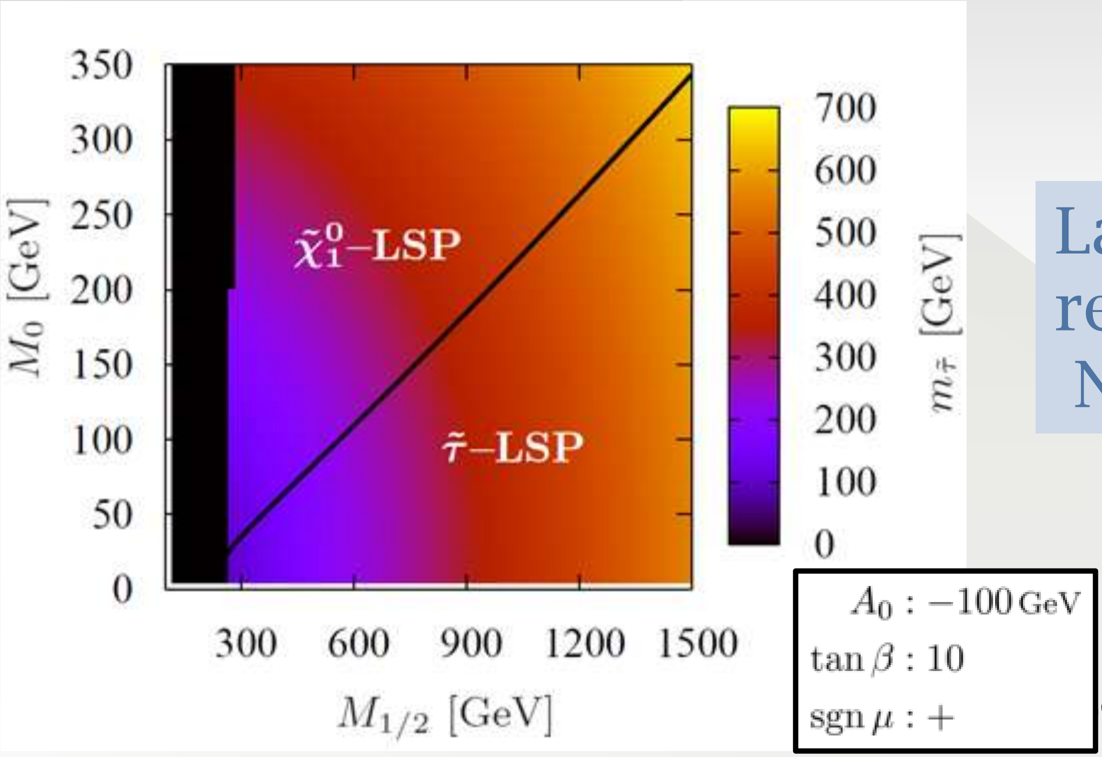


Since DM must be neutral for cosmological reason.

(which I don't know well)

Now STAU is LSP.

- But if no R-parity, then LSP can be charged, and…



Large parameter region is
NOW OPEN!!

Exemplary Study

- Then,
  what is observed in LHC?

Exemplary Study

- The paper discussed $L_1 L_2 \bar{E}_1$ case & $L_3 Q_1 \bar{D}_1$ case.
- But today we focus only on $L_1 L_2 \bar{E}_1$ case.

Exemplary Study

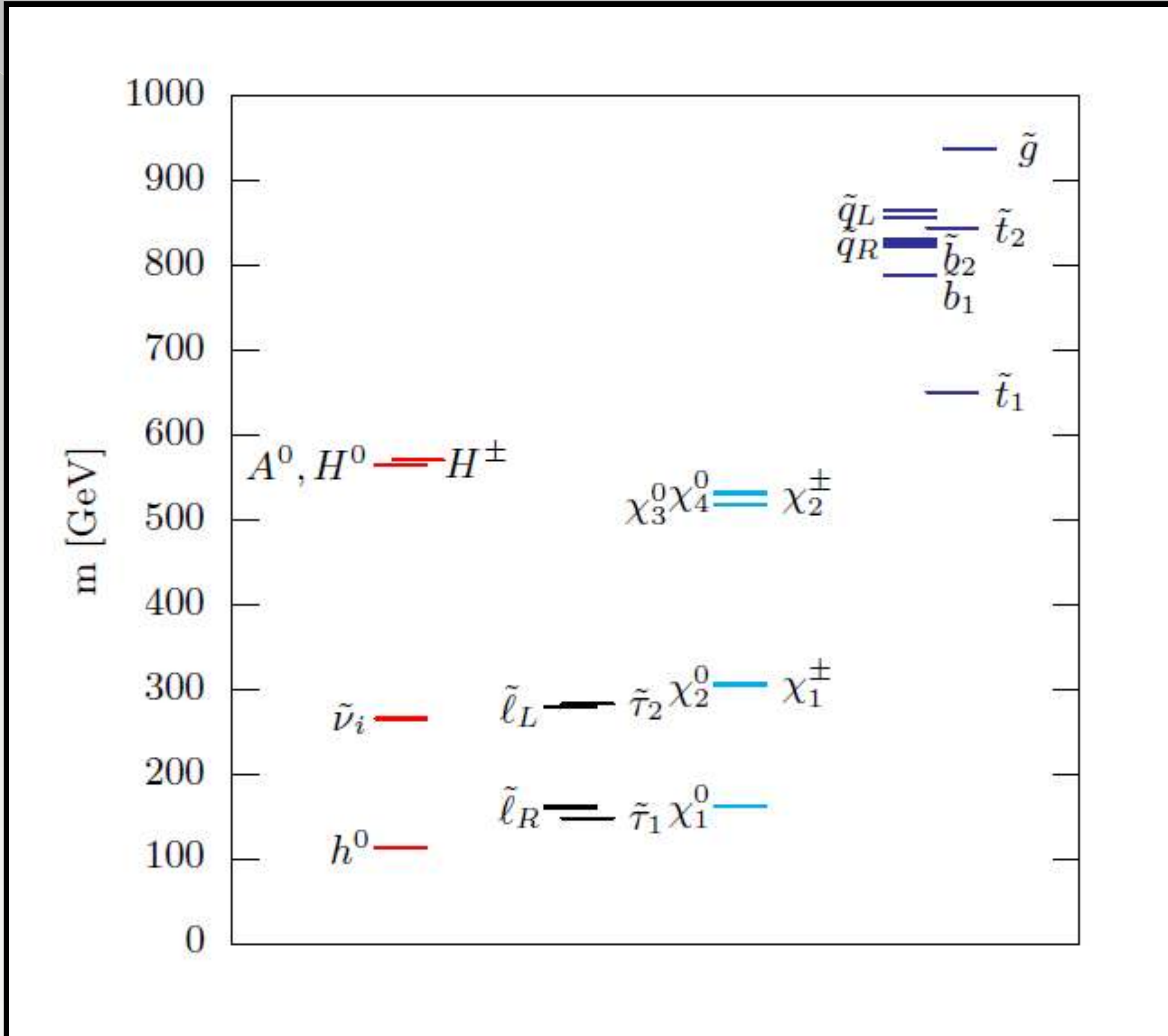
$L_1 L_2 \bar{E}_1$ case

- Only $L_1 L_2 \bar{E}_1$ is available, i.e.

$$W = (\text{R conserving}) + \lambda L_1 L_2 \bar{E}_1$$

Parameters

$$M_0 = A_0 = 0\,\text{GeV}$$
$$M_{1/2} = 400\,\text{GeV}$$
$$\tan\beta = 13$$
$$\text{sgn}(\mu) = +$$
$$\lambda = 0.032@M_{\text{GUT}}$$



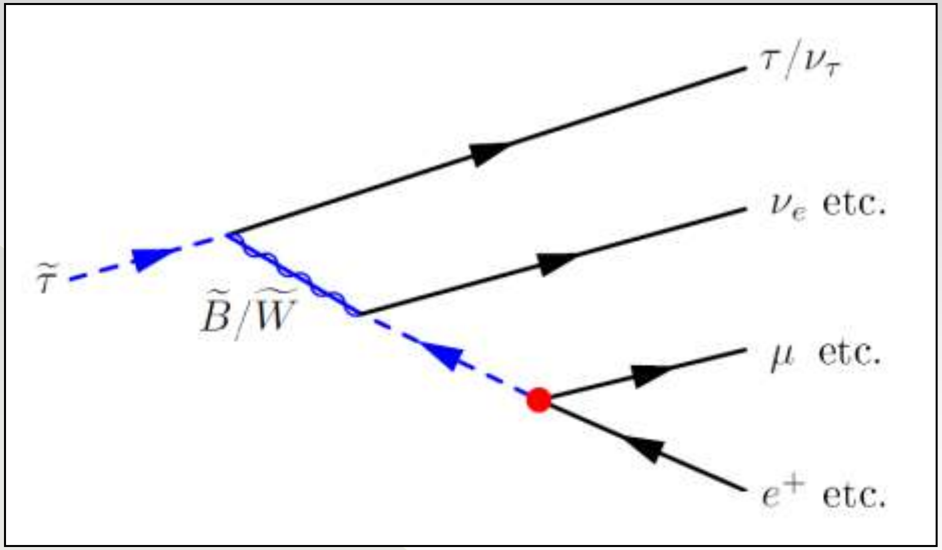
1000
900
800
700
600
500
400
300
200
100
0
m [GeV]
$\tilde{g}$
$\tilde{q}_L$
$\tilde{t}_2$
q_R
$\tilde{b}_2$
b_1
$\tilde{t}_1$
A^0, H^0
$H^\pm$
$\chi_3^0\chi_4^0$
$\chi_2^\pm$
$\tilde{\ell}_L$
$\tilde{\tau}_2\chi_2^0$
$\chi_1^\pm$
$\tilde{\nu}_i$
$\tilde{\ell}_R$
$\tilde{\tau}_1\chi_1^0$
h^0

$L_1 L_2 \bar{E}_1$ case

- LSP $\widetilde{\tau}$ will decay into 4-leptons.

[Example]

$$\widetilde{\tau} \longrightarrow \tau \nu_e \mu e^+$$



- NLSP $\widetilde{e}^-_{\mathrm{R}}$ will decay as

$$\widetilde{e}^-_{\mathrm{R}} \longrightarrow e^- \nu_\mu, \quad \mu^- \nu_e.$$

$L_1 L_2 \bar{E}_1$ case

Simulation Result

Events with sparticle pair production are:

e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
2	2	2	2	yes	35 %
3	2	2	2	yes	12 %
2	3	2	2	yes	8.3 %
3	3	2	2	yes	7.3 %
2	2	2	1	yes	4.7 %
2	2	3	2	yes	4.3 %
2	2	3	3	yes	1.4 %
4	3	2	2	yes	1.1 %

•Each event is acompanied by 2-4 jets.
•Total cross section is $\sigma_{\text{tot}} = 4.8 \times 10^3$ fb.
(100-1000events per year @ LHC's best)

$L_1 L_2 \bar{E}_1$ case

Features:
- Multi lepton final state (≧4)
- Multi tau final state (≧4, in general)
- Missing energy (from neutrinos)

◎Simula

Events with s

e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
2	2	2	2	yes	35 %
3	2	2	2	yes	12 %
2	3	2	2	yes	8.3 %
3	3	2	2	yes	7.3 %
2	2	2	1	yes	4.7 %
2	2	3	2	yes	4.3 %
2	2	3	3	yes	1.4 %
4	3	2	2	yes	1.1 %

- Each event is acompanied by 2-4 jets.
- Total cross section is $\sigma_{\text{tot}} = 4.8 \times 10^3\,\text{fb}$.

(100-1000events per year @ LHC's best)

$L_1 L_2 \bar{E}_1$ case

- **Key point**
  - Many τ s → Identification of τ is important for LHC!

τ is observed as jet, and

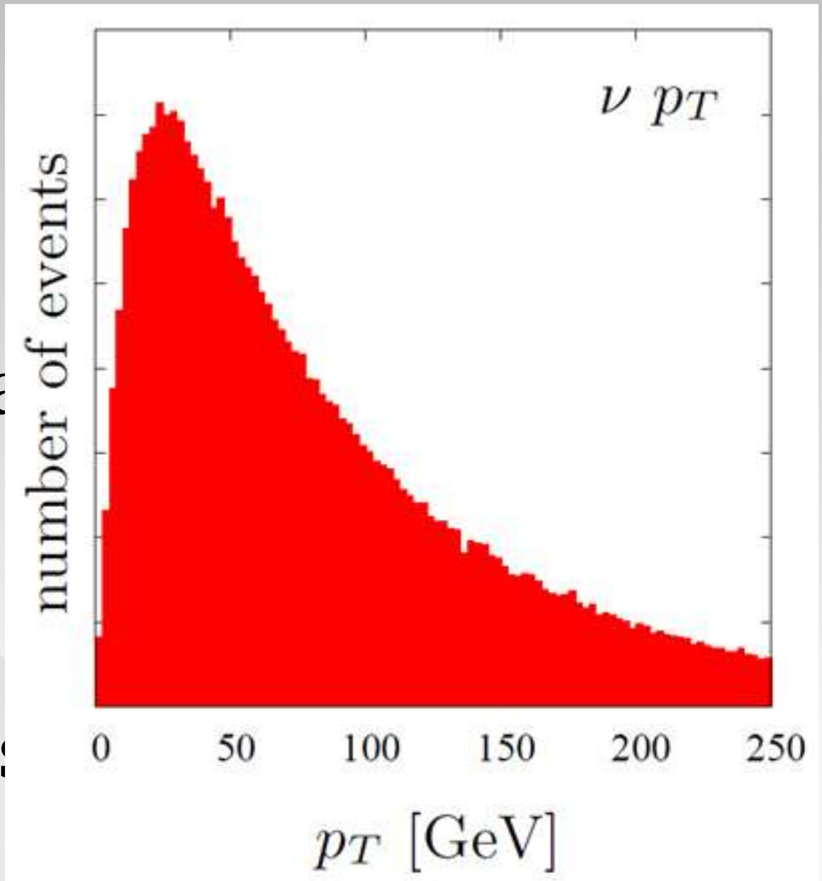
  - Few jets (2-4) → Not so difficult to identify.

And also

  - $\not{p}_{\mathrm{T}}$ is also a good sign, because…

$L_1 L_2 \bar{E}_1$ case

- Key point
  - Many τs → Identifica
    imp



τ is observed as jet, and

  - Few jets (2-4) → Not

And also

  - $\not{p}_{\mathrm{T}}$ is also a good sign, because…

    Peak of $\not{p}_{\mathrm{T}}$ is lower than LSP-missing.

$L_1 L_2 \bar{E}_1$ case

- **Conclusion**

In this $L_1 L_2 \bar{E}_1$ case,

- Multi tau
- Multi lepton
- $\not{p}_{\mathrm{T}}$ (but not so large as O(100) GeV)

are good signs of SUSY events.

$L_1 L_2 \bar{E}_1$ case

But really?

- We can really distinguish tau-jets?
- No Backgrounds?
  (i.e. Aren't similar final states created by SM events?)
- Detector simulation!
- How about on other parameter points?

$\rightarrow$ Need improvement!

(or more detailed analysis.)

That’s all.

Thank you for listening.

Appendix

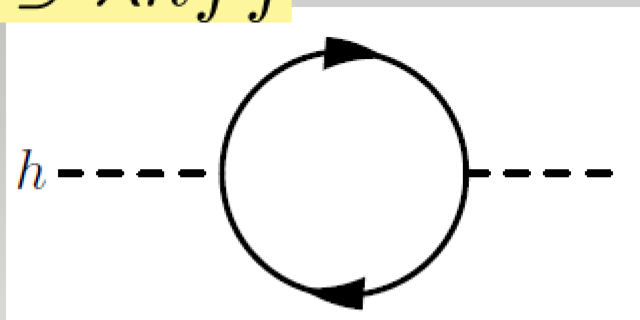
- Superpotential

Hierarchy Problem

- In Standard Model with Higgs,

Hierarchy Problem

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



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

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

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

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

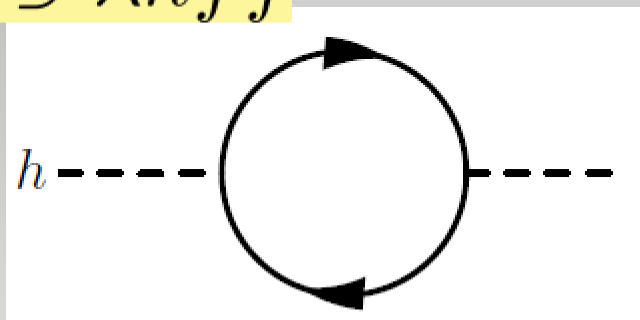
$$\therefore\ \mathrm{O}(10^{30}) - \mathrm{O}(10^{30}) \rightarrow 10^4\ !?$$

Hierarchy Problem

- In MSSM (or other SUSY models),

Hierarchy Problem

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

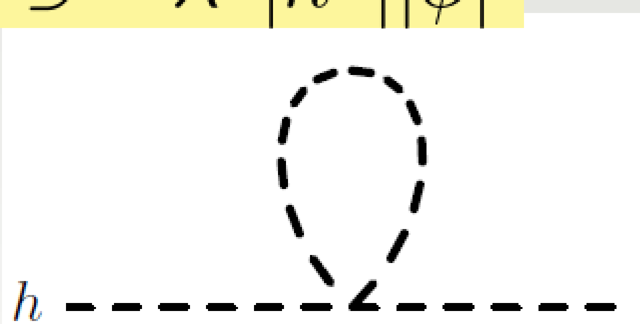


$$-\frac{|\lambda|^2}{8\pi^2}\Lambda^2$$

And its superpartner goes round!

Cancelled!

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



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