SPICE
Simulation Package for Including Flavor in Collider Events

by **Engelhard, Feng, IG, Sanford, Yu**

arxiv:0904.1415 [hep-ph]
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Outline

- Generation Dependence in SUSY.
- SPICE – Sneak Peek.
- When Looking at Flavor.
- Motivation – Supersymmetric flavor violating models.
- SPICE – Structure and Interfaces.
- Output and Applications.
- Conclusions.

Generation Dependence in SUSY

Usually, we look at models with degenerate scalar masses:

GMSB mSUGRA (AMSB)

For these, the only source of generational mixings comes from the Yukawa matrices:

Minimal Flavor Violation (MFV)

BUT !

There is room for flavor dependence beyond MFV

SPICE – Sneak Peek

SPICE is general tool designed to enable lepton flavor violation (LFV) searches with event generators.

Defining SUSY models at a high energy scale, SPICE combines:

A Spine model:

GMSB

AMSB

mSUGRA

…

Lepton Flavor Violation:

User defined

Random number

U(1) symmetries

SUSY Spectrum + Decay Witdhs + BRs

When Looking at Flavor …

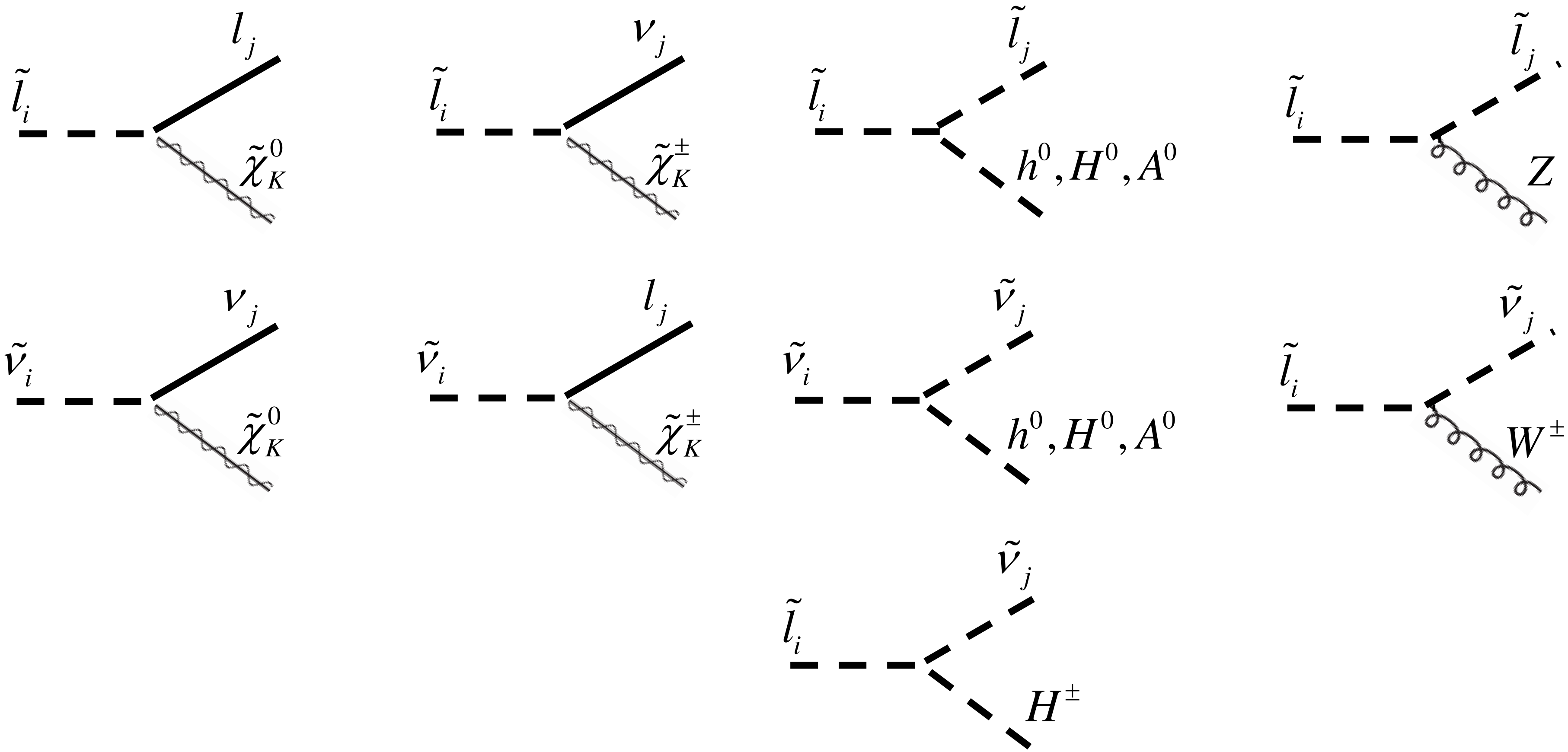
When we look at models with intergenerational interactions we need to take into account:

1. Decay Modes: a. generalizations of existing ones.
   b. inherently new decay modes.

2. Spectrum Calculation:
   adjust the boundary conditions for calculators .

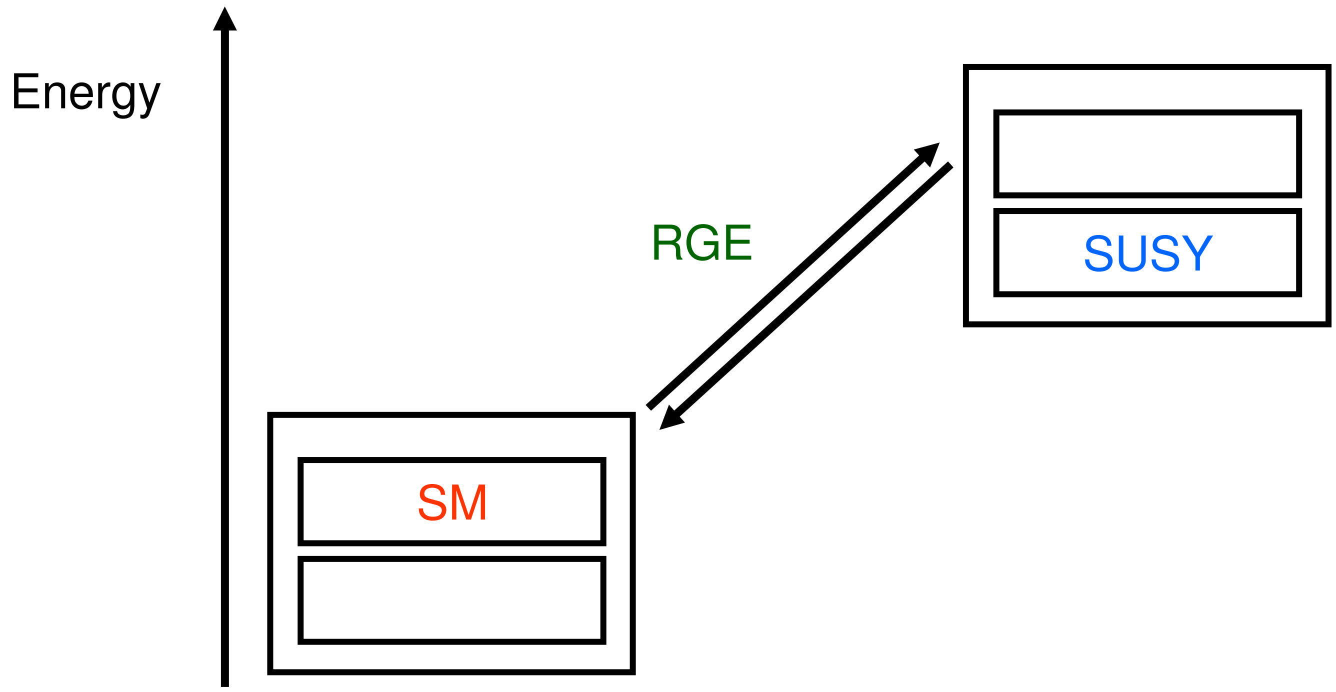
Decay Modes in LFV models

What are the signatures of the new flavor interactions:



Spectrum Calculation in LFV models

Spectrum calculators iteratively solve the following problem:



Problem: Matching of boundary conditions needs to be changed.

Motivation - Supersymmetric Lepton Flavor Violating Models

SUSY Gauge – Gravity hybrid models (**Feng, Lester, Nir & Shadmi arXiv:0712.0674**)

$$\tilde{M}^2_{\tilde{L}_L} = \tilde{m}^2_L 1_{3\times3} + m_E m_E^\dagger + x\tilde{m}^2_L X_L$$

$$\tilde{M}^2_{\tilde{E}_R} = \tilde{m}^2_R 1_{3\times3} + m_E m_E^\dagger + x\tilde{m}^2_R X_R$$

from Planck suppressed operators. Arbitrary structure

Here

$$x \sim \frac{1}{N_{mess}} \left(\frac{\pi}{\alpha_2}\right)^2 \left(\frac{M_{mess}}{M_{Plank}}\right)^2$$

is the ratio of gravity to gauge contributions.

SUSY LFV Models

- The gravity contributions can generally have an arbitrary structure.
- To maintain experimental constraints, a flavor symmetry is imposed.
- When the symmetry breaks (Froggatt-Nielsen) the entries of the mass matrices are parametrically suppressed.
- For U(1) symmetries:

$$\begin{cases} L_1\left(Q_{L_1 1},\, Q_{L_1 2},\ldots.\right) \\ L_2\left(Q_{L_2 1},\, Q_{L_2 2},\ldots.\right) \\ L_3\left(Q_{L_3 1},\, Q_{L_3 2},\ldots.\right) \end{cases} \qquad \begin{cases} \bar{E}_1\left(Q_{E_1 1},\, Q_{E_1 2},\ldots.\right) \\ \bar{E}_2\left(Q_{E_2 1},\, Q_{E_2 2},\ldots.\right) \\ \bar{E}_3\left(Q_{E_3 1},\, Q_{E_3 2},\ldots.\right) \end{cases}$$

- One finds up to O(1) coefficients:

$$\left(\tilde{M}^2_{L_L}\right)_{i,j} = C^{(L_L)}{}_{i,j}\lambda^{Q_{L\,i}-Q_{L\,j}}$$

$$\left(\tilde{M}^2_{E_R}\right)_{i,j} = C^{(E_R)}{}_{i,j}\lambda^{Q_{E_R\,i}-Q_{E_R\,j}} \qquad \lambda \sim 0.2$$

$$\left(M\right)_{i,j} = C_{i,j}\lambda^{Q_{L_L\,i}+Q_{E_R\,j}}$$

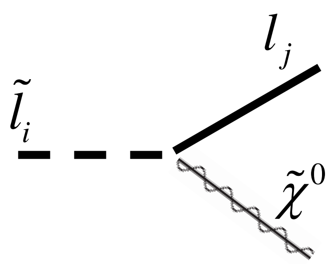
SUSY LFV Models

The mass squared matrices (in the fermion mass basis) are

$$L_{mass} = \left(\tilde{e}_L^*, \tilde{\mu}_L^*, \tilde{\tau}_L^*, \tilde{e}_L^*, \tilde{\mu}_L^*, \tilde{\tau}_L^*\right) \begin{pmatrix} \tilde{M}_{LL}^2 & \tilde{M}_{LR}^2 \\ \tilde{M}_{RL}^2 & \tilde{M}_{RR}^2 \end{pmatrix} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}$$

The combination of Degeneracy and Alignment, yields a **<u>non trivial flavor structure</u>**:

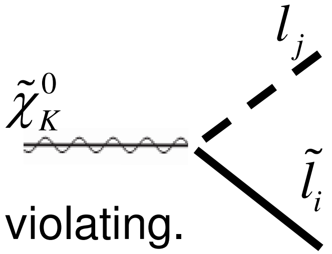
$$\boxed{\tilde{l}_\alpha = U^{\tilde{l}}_{\alpha,i} \tilde{l}_i^{Mass}} \longrightarrow$$



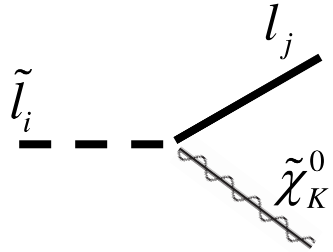
$$\sim \# U^{\tilde{l}}_{j,i}$$

SUSY LFV Models - Phenomenology

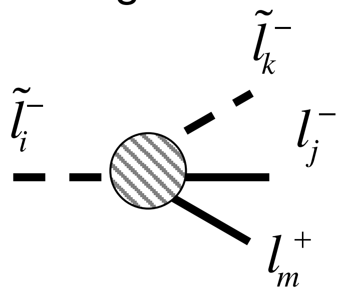
1. Chargino and Neutralino decays can now be flavor violating.



2. Slepton decays are now flavor violating.



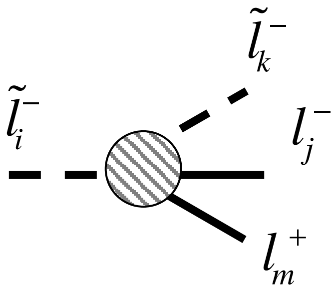
3. In GMSB models the slepton(s) can be the NLSP. Only 3-body slepton decays are available which are now flavor violating.



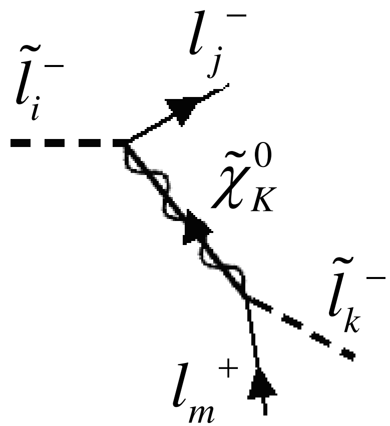
SUSY LFV Models - Phenomenology

The only possible decays modes for the light sleptons are 3 body decay modes:

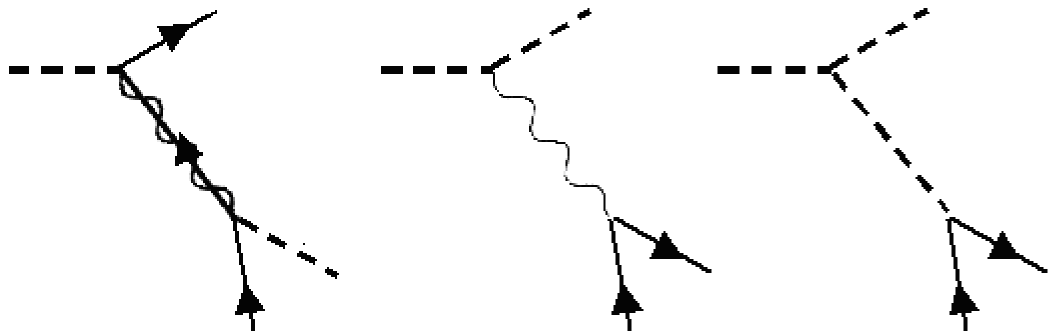
Feng, IG, Sanford, Shadmi & Yu, arXiv:0904.1416v1 [hep-ph]. :



$m \neq j$

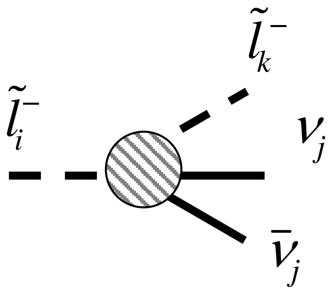


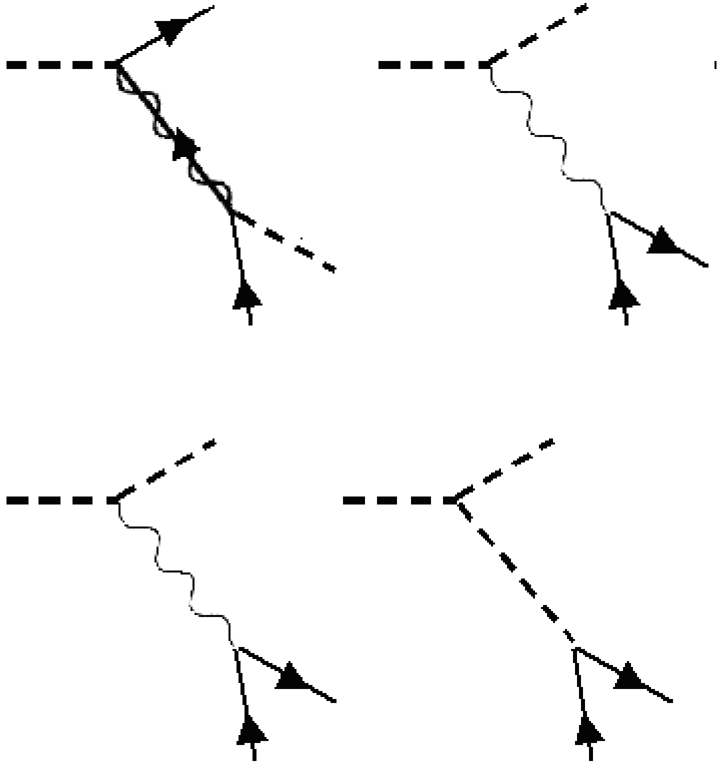
$m = j$

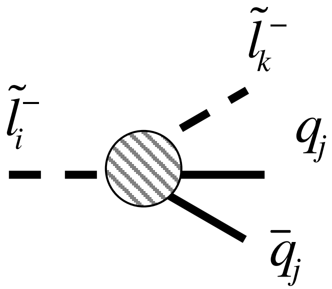


SUSY LFV Models - Phenomenology

And, generically new phenomena:

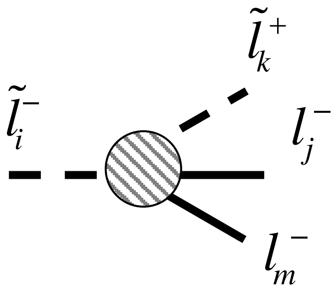


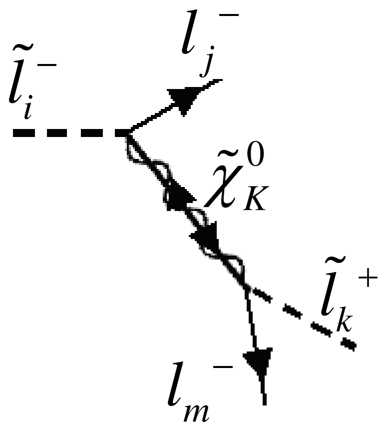


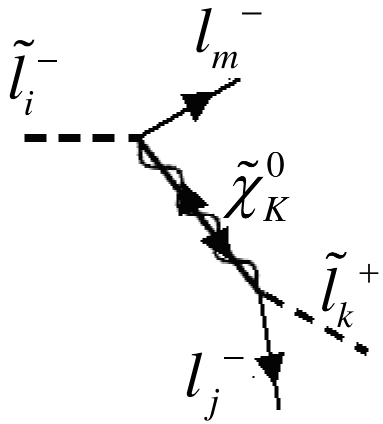


SUSY LFV Models - Phenomenology

And charge flip modes







HOW TO IMPLEMENT ?

↓

SPICE

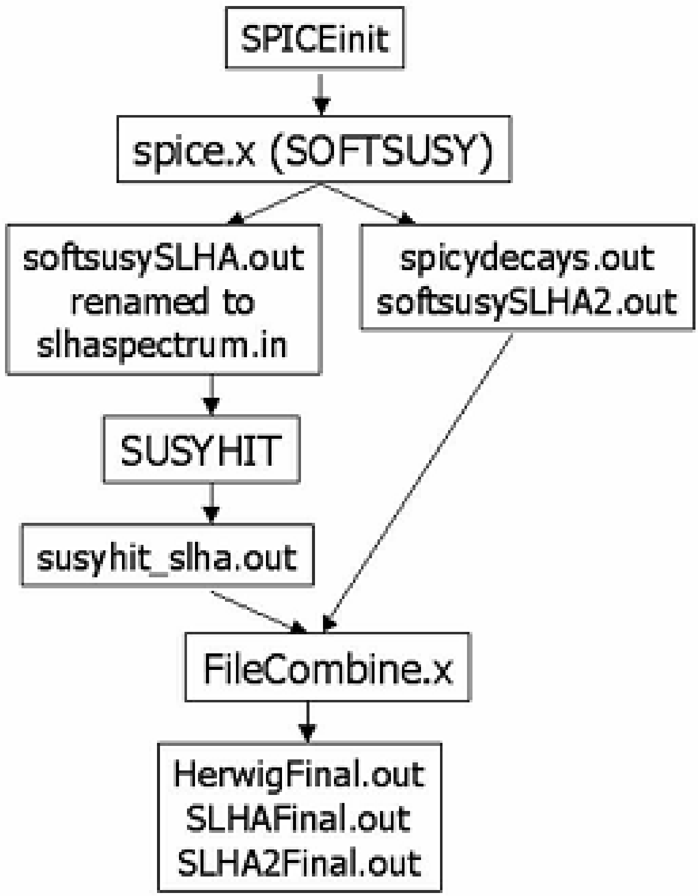
SPICE – General Structure

1. User-supplied SPICEinit file is read by spice.x.

2. spice.x uses SOFTSUSY to generate the mass spectrum and calculates lepton flavor-violating decay widths.

3. SUSYHIT uses output from spice.x and calculates flavor-conserving decay widths.

4. FileCombine.x combines the output from spice.x and SUSYHIT to create HerwigFinal.out, SLHAFinal.out, and SLHA2Final.out, which can be used to generate collider events.



Interface with SoftSUSY – Calculating the Spectrum

SPICE provides a simple interface for spectrum calculation via SoftSusy.

The model parameters are specified in an input file *SPICEInit.* in the following form:

```
gmsb 5 4.6e6 3.4e4 1.0 10 1
x 0.1
lambda 0.2
nCharges 2
L1 2 0
L2 0 2
L3 0 2
E1 2 1
E2 2 -1
E3 0 -1
Lep -0.3838 0 0 0.8706 -1.8682 -1.5408 1.0450 0.3574 1.8554
XL -3.4989 -1.2001 0.4059 -1.2001 -1.2705 1.1746 0.4059 1.1746 1.4293
XR -1.0368 0.9976 -0.06188 0.9976 -0.8616 0.2204 -0.06188 0.2204 0.6544
```

SUSY Breaking Parameters (GMSB, mSUGRA, AMSB):
N5, Mmsg, Λ, Cgrav, $\tan(\beta)$, $\mathrm{sgn}(\mu)$

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x 0.1 — Relative Gravity to Gauge contribution

lambda 0.2

nCharges 2

L1 2 0

L2 0 2

L3 0 2

E1 2 1

E2 2 -1

E3 0 -1

Lep -0.3838 0 0 0.8706 -1.8682 -1.5408 1.0450 0.3574 1.8554

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```

Froggat-Nielsen small parameter

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```

Number of U(1) flavor symmetries

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```

Charges for each lepton superfield (lines L1 through E3)

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```

O(1) coefficients

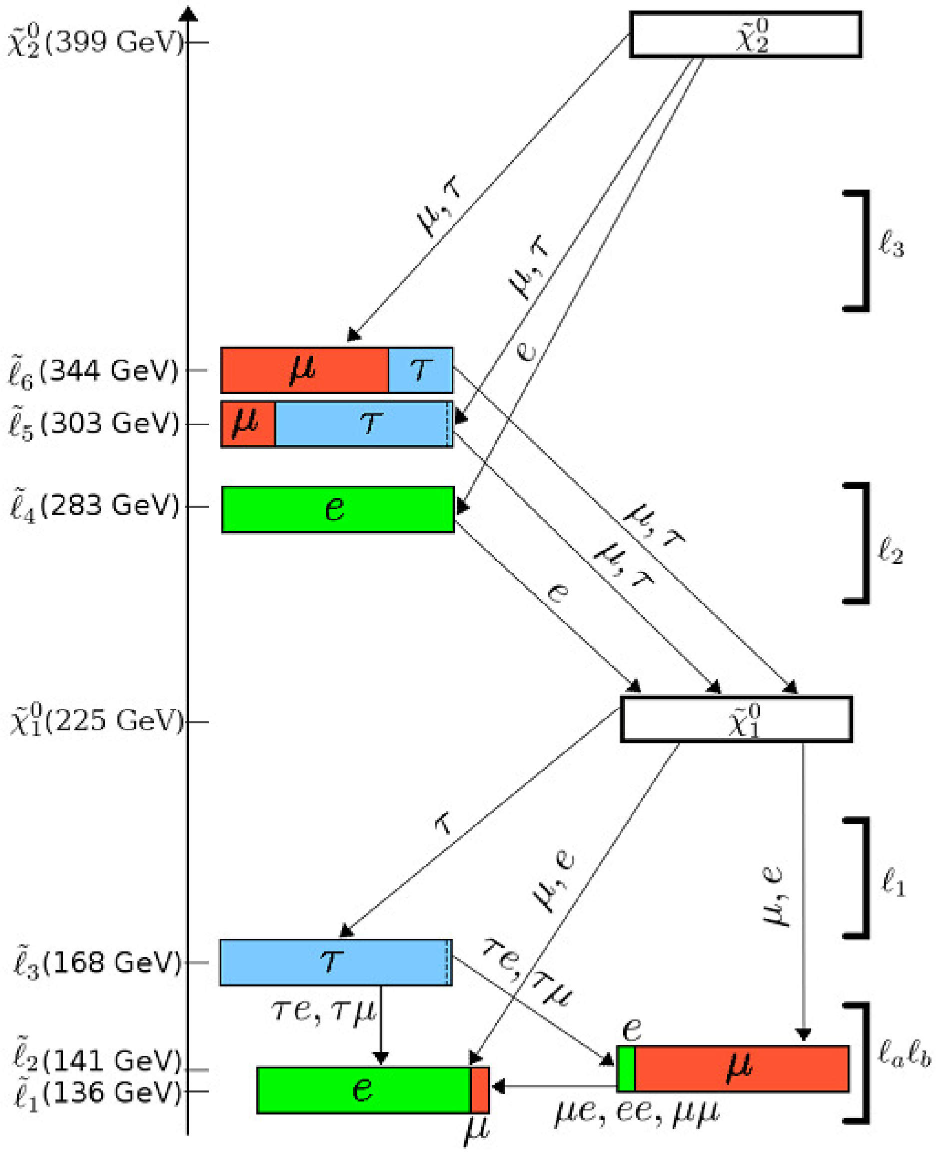
Example Model

As a first stage for LHC signatures the choice was to focus on:

- R-parity conserving models.
- Slepton NLSP (with Gravitino LSP) scenario.

<u>The implications:</u>

- A metastable charged particle leaving a track in the detector.
- Low SUSY background.
- No 2-Body Decay Modes for sleptons lighter than Neutralino1 – Only 3-Body


$\tilde{\chi}_2^0$(399 GeV)
$\tilde{\ell}_6$(344 GeV)
$\tilde{\ell}_5$(303 GeV)
$\tilde{\ell}_4$(283 GeV)
$\tilde{\chi}_1^0$(225 GeV)
$\tilde{\ell}_3$(168 GeV)
$\tilde{\ell}_2$(141 GeV)
$\tilde{\ell}_1$(136 GeV)
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
μ, τ
μ, τ
e
μ, τ
μ, τ
e
τ
μ, e
μ, e
$\tau e, \tau\mu$
$\tau e, \tau\mu$
$\mu e, ee, \mu\mu$
ℓ_3
ℓ_2
ℓ_1
$\ell_a \ell_b$

SPICE – Calculating the LFV Branching Ratios

Once a spectrum is obtained, SPICE calculates the relevant decays widths:

- All leptonic flavor general supersymmetric decays modes.

- No CPV is taken into account.

- A temporary file is created containing the data

Interface with SUSYHIT – Calculating the Branching Ratios

SPICE (SoftSusy): Outputs the spectrum into a SLHA1 file.

↓

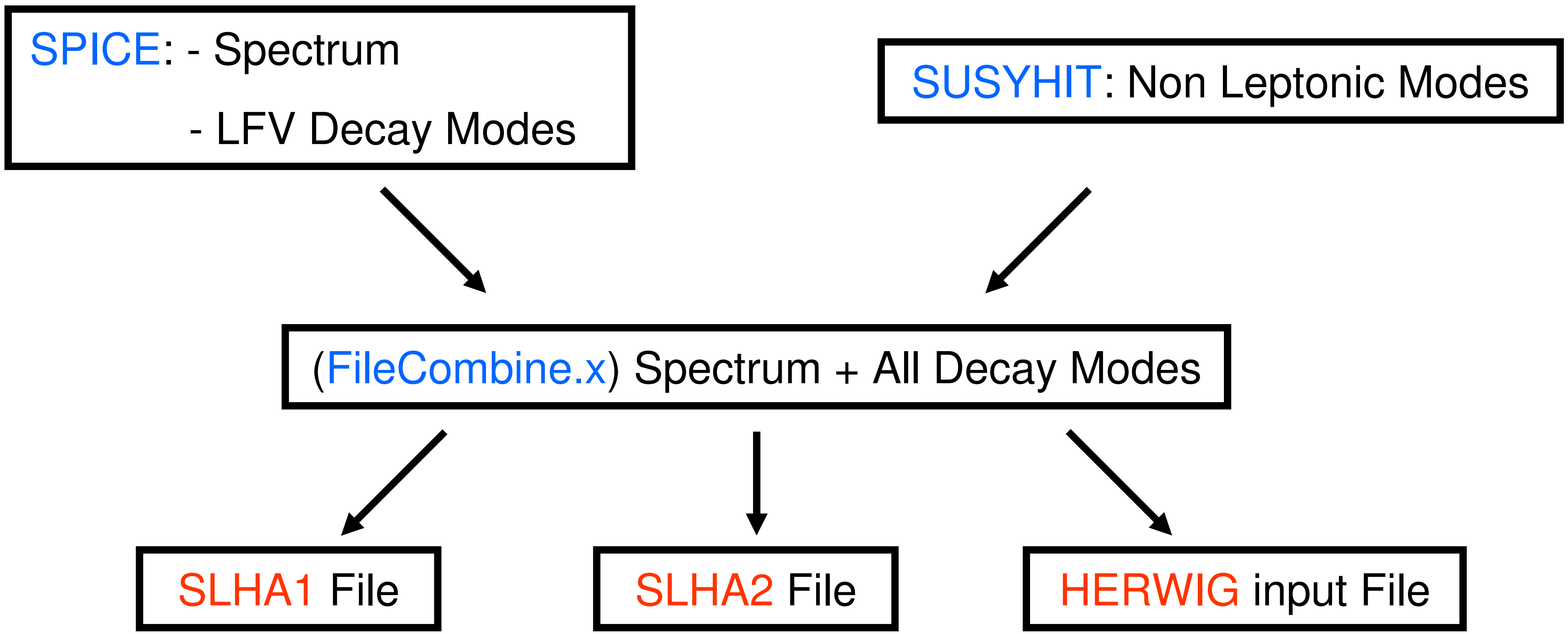
SUSYHIT: The SLHA1 file is inputted into SUSYHIT

↓

Non LFV decay file is outputted

Output

SPICE combines its temporary file with the SUSYHIT output:



Example: Part of an SLHA file with flavor violating interaction

```
#           PDG          Width
DECAY  1000013     4.65952678e-11
#         BR              NDA      ID1            ID2       ID3
     1.66677764e-02    3     1000011        11       -11
     3.93419480e-10    3     1000011        12       -12
     1.15723769e-03    3     1000011        11       -13
     5.06943552e-17    3     1000011        12       -14
     2.02559118e-07    3     1000011        11       -15
     7.84485998e-18    3     1000011        12       -16
     8.86470670e-02    3    -1000011        11        11
     5.49643900e-01    3    -1000011        11        13
     1.81001882e-04    3    -1000011        11        15
     1.99477024e-09    3     1000011         2        -2
     2.58421060e-09    3     1000011         1        -1
     2.38827791e-01    3     1000011        13       -11
     1.04231543e-14    3     1000011        14       -12
     1.65816726e-02    3     1000011        13       -13
…
…
…
```

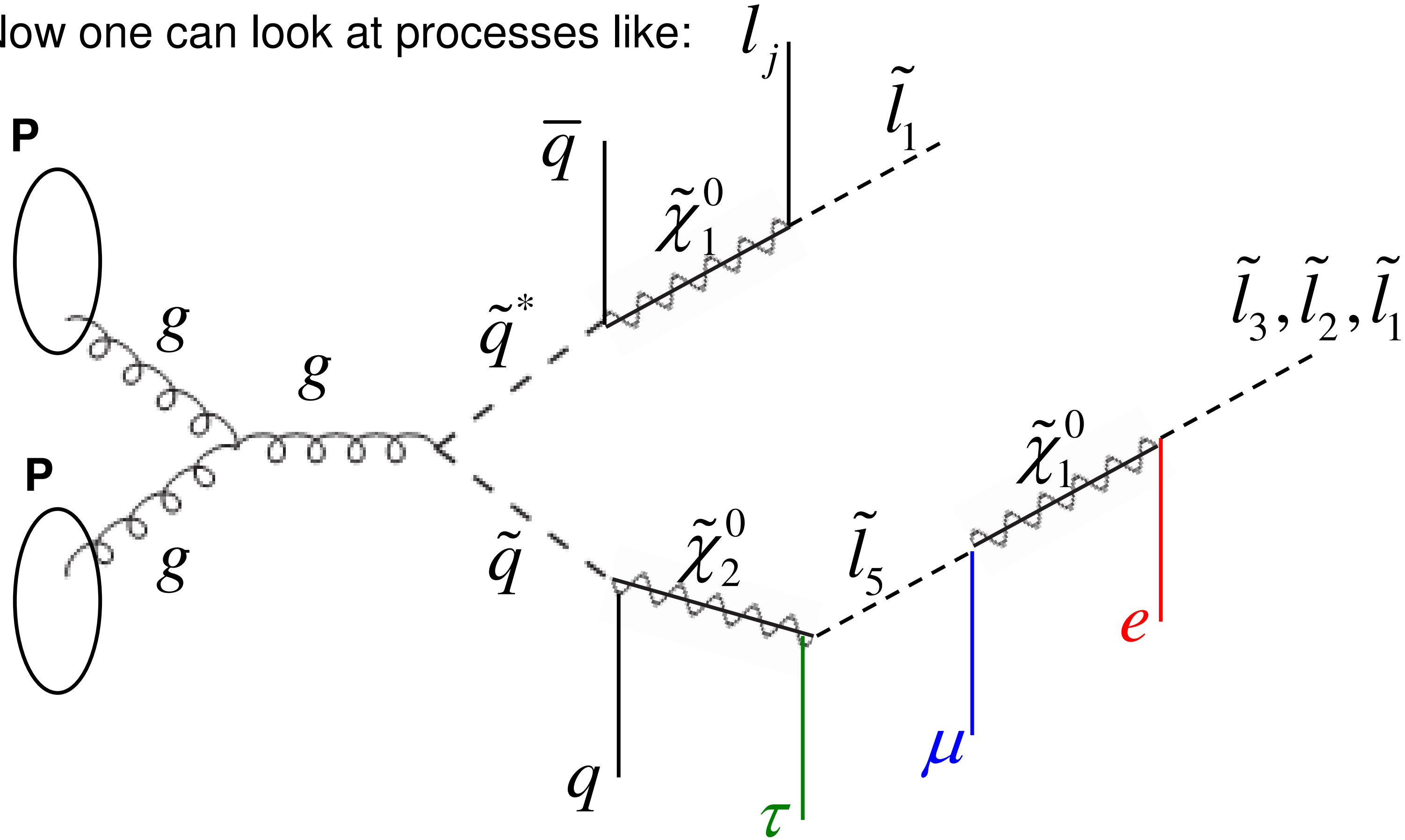
$$\tilde{l}_2 \approx 0.97\,\tilde{e}_R + 0.03\,\tilde{\mu}_R$$

Note the flavor violation
And charge flip modes

One of the leading modes

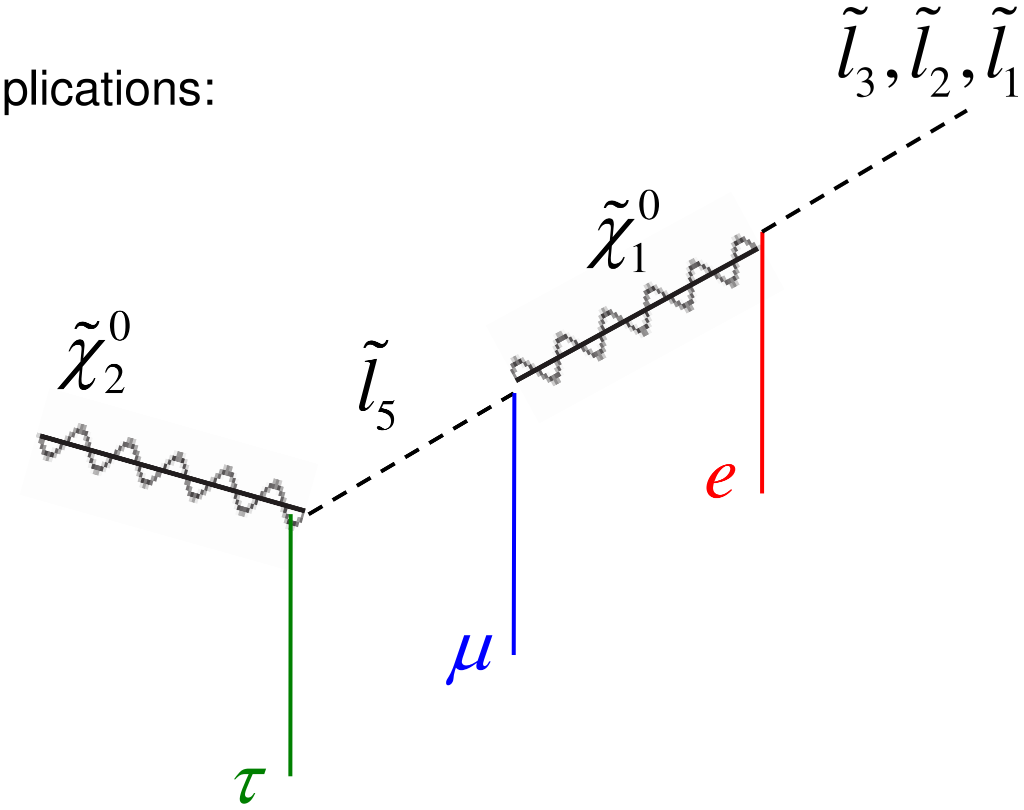
Applications

Now one can look at processes like:



Applications

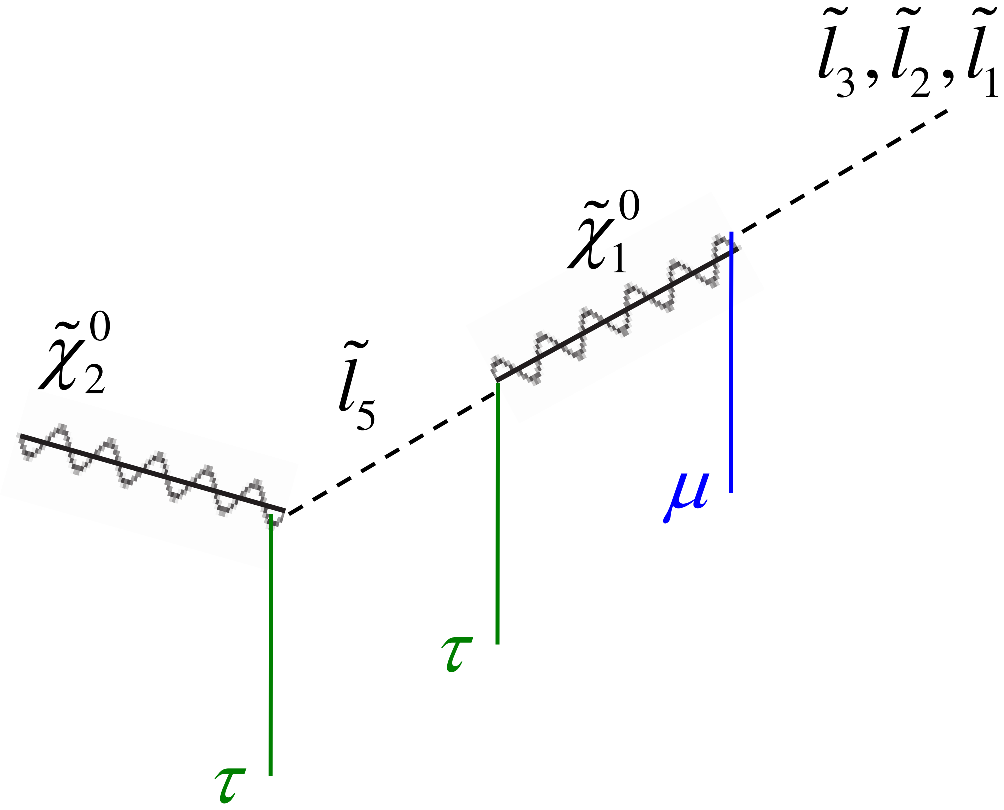
Focusing on LFV implications:



Can see: Feng, French, IG, Lester, Nir, Shadmi, Sanford, Yu, arxiv:0910.1618 [hep-ph]

Applications

Can change to:



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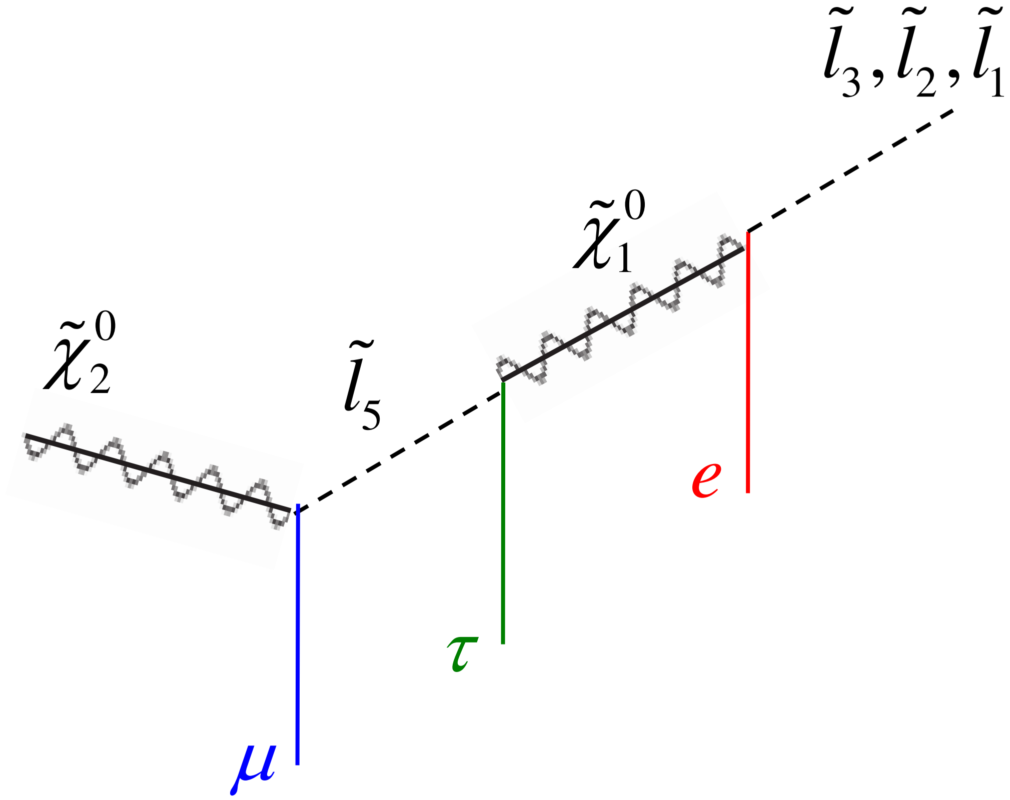
Applications

Or to:



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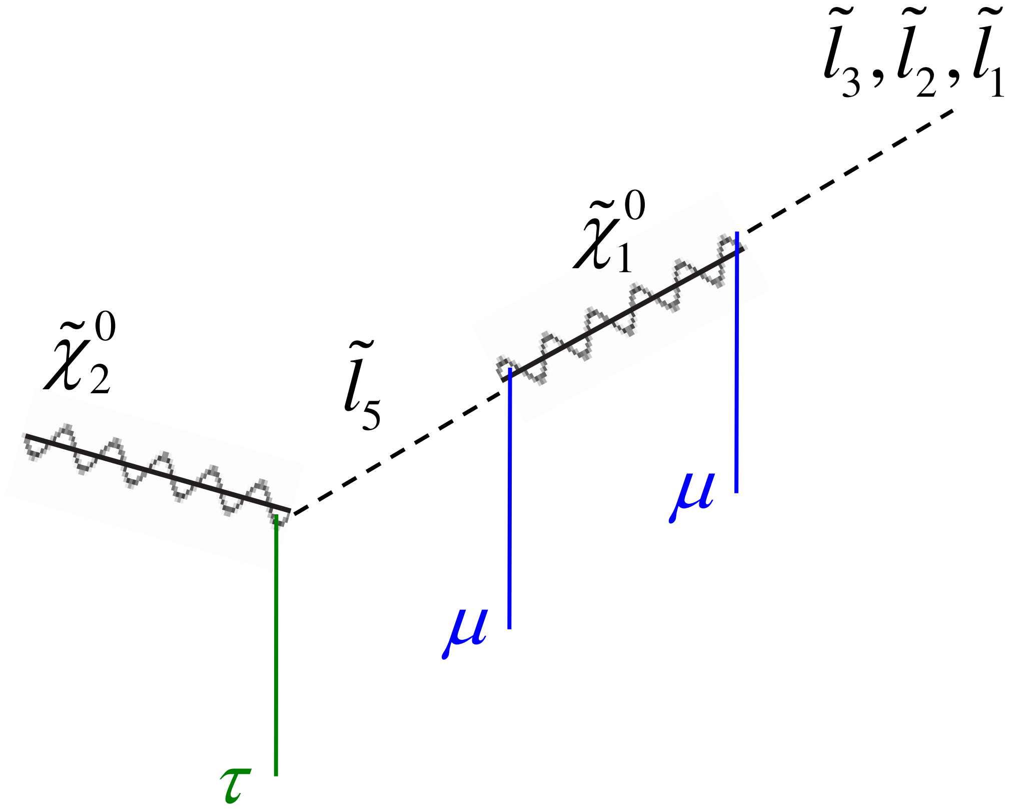
Applications

Can change to:



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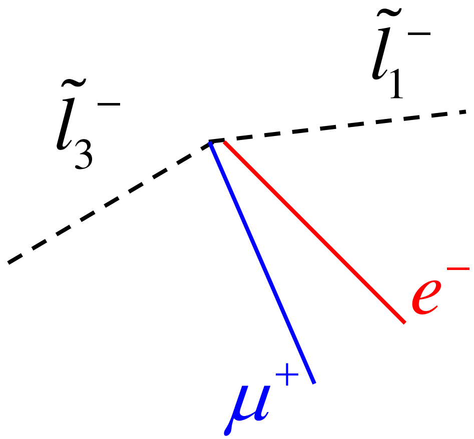
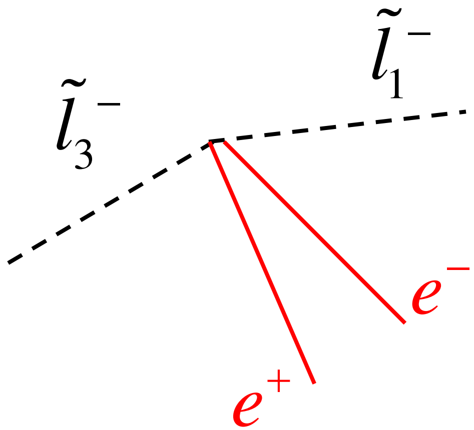
Applications

And as for the 3-Body decay:



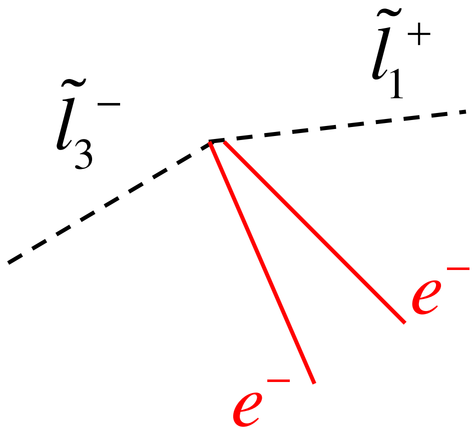
Applications

or



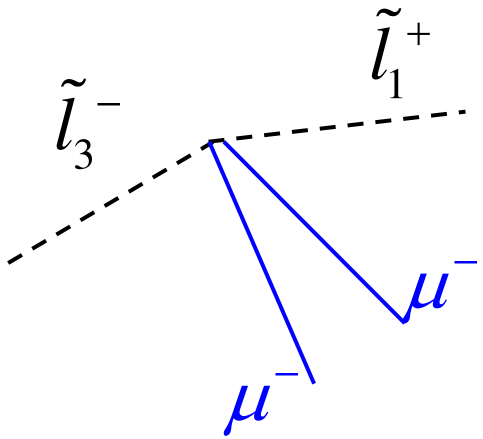
Applications

or



Applications

And as for the 3-Body decay:



Conclusions

- FV can lead to interesting signatures at the LHC.
- SPICE – A general tool designed to incorporate lepton flavor violation in SUSY searches.
- SPICE – Generates spectrum and decay widths (SLHA, HERWIG output files).
- SPICE is publically available at:

  http://hep.ps.uci.edu/~spice/

- SPICE can add flavor to any SUSY model (mSUGRA, GMSB, …)

The End

Auxiliary Slides

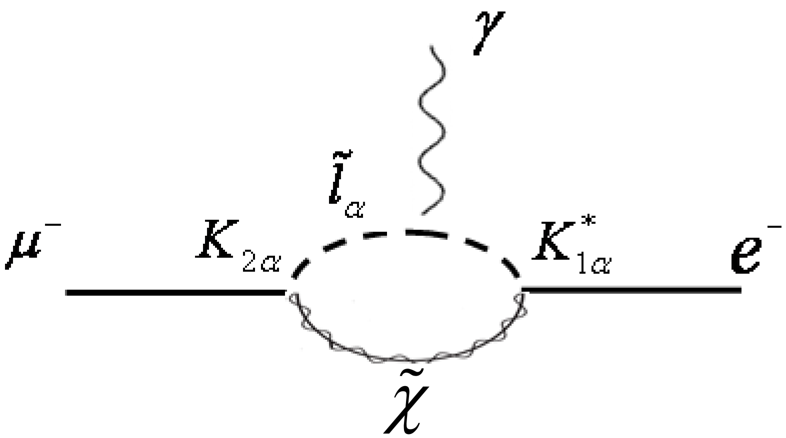
Spectrum For Example Model

# MW	24	80.387
# h0	25	111.497
# H0	35	560.809
# A0	36	560.413
# H+	37	566.345
# ~g	1000021	1225.739
# ~neutralino(1)	1000022	224.825
# ~neutralino(2)	1000023	398.869
# ~chargino(1)	1000024	399.531
# ~neutralino(3)	1000025	-470.727
# ~neutralino(4)	1000035	521.280
# ~chargino(2)	1000037	522.023
# ~gravitino	1000039	3.70668000e-08
# ~e_1	1000011	135.832
# ~e_2	1000013	140.780
# ~e_3	1000015	168.295
# ~e_4	2000011	282.863
# ~e_5	2000013	303.410
# ~e_6	2000015	343.529

# ~d_1	1000001	1039.563
# ~d_2	1000003	1050.826
# ~d_3	1000005	1050.827
# ~d_4	2000001	1050.922
# ~d_5	2000003	1093.584
# ~d_6	2000005	1093.585
# ~u_1	1000002	944.883
# ~u_2	1000004	1053.100
# ~u_3	1000006	1053.102
# ~u_4	2000002	1061.506
# ~u_5	2000004	1090.843
# ~u_6	2000006	1090.844
# ~nu_1	1000012	271.399
# ~nu_2	1000014	334.461
# ~nu_3	1000016	293.848

The SUSY Flavor Problem

Is the new SUSY theory consistent with the bounds on flavor changing processes ?



$$\sim \quad \delta_{i,j} = \frac{\Delta m^2_{i,j} K_{i,j}}{\tilde{m}^2}$$

Process	Bound
BR(μ→eγ)	1.2 x 10^(-11)
BR(μ→eee)	1.1 x 10^(-12)
BR(μ→e in Nuclei (Ti))	1.1 x 10^(-12)

The SUSY Flavor Problem

The constrained quantity is $\delta_{i,j}$:

- Decoupling – slepton average mass scale very high.

$$\tilde{m}^2 \quad \text{very large}$$

- Alignment – slepton and lepton mass bases are simultaneously diagonal.

$$K = \left(U^{slepton}\right)^\dagger U^{lepton} \sim 1_{3\times3}$$

- Degeneracy – slepton mass squared matrix ~ Identity.

$$\tilde{M}^2_{LL} \sim \tilde{m}^2_L 1_{3\times3} \quad \tilde{M}^2_{RR} \sim \tilde{m}^2_R 1_{3\times3} \longrightarrow$$

MFV:

GMSB,

AMSB,

mSUGRA

Experimental Boudns on LFV

	Mass (MeV)	(g-2)/2	d (10^(–26) e cm)
e	0.5	1.159 × 10^(-3)	(0.07 ± 0.07)
μ	105	1.165 × 10^(-3)	(3.7 ± 3.4) × 10^(7)
τ	1776	> –0.052 and < 0.013	Re(dτ) = –0.22 to 0.45 × 10^(7) Im(dτ) = –0.25 to 0.008 × 10^(7)

Process	Bound
BR(μ→eγ)	1.2 x 10^(-11)
BR(μ→eee)	1.1 x 10^(-12)
BR(μ→e in Nuclei (Ti))	1.1 x 10^(-12)
BR(τ→eγ)	1.1 x 10^(-7)
BR(τ→eee)	2.7 x 10^(-7)

Process	Bound
BR(τ→eμμ)	2 x 10^(-7)
BR(τ→μγ)	6.8 x 10^(-8)
BR(τ→μμμ)	2 x 10^(-7)
BR(τ→μee)	2.4 x 10^(-7)

Version Consistency

1. SoftSusy – 3.0.16

2. SusyHit – 1.3

3. HERWIG – 6.5

References

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