Introducing SuperLFV, an SLHA Tool

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Charged

Lepton Flavor Violation

- Charged LFV is forbidden by the SM*.

*with massless neutrinos

e.g., $\mu^+ \not\to e^+\gamma$

$\tau^- \not\to \mu^+\mu^-\mu^-$

- Neutrinos always accompany lepton flavor changes.

e.g., $\mu^- \to e^-\bar{\nu}_e\nu_\mu(\gamma)$ BR = 100% - 0.0034%

$\mu^- \to e^-\bar{\nu}_e\nu_\mu + e^+e^-$ BR = 0.0034%

- If neutrino masses are included in the SM,

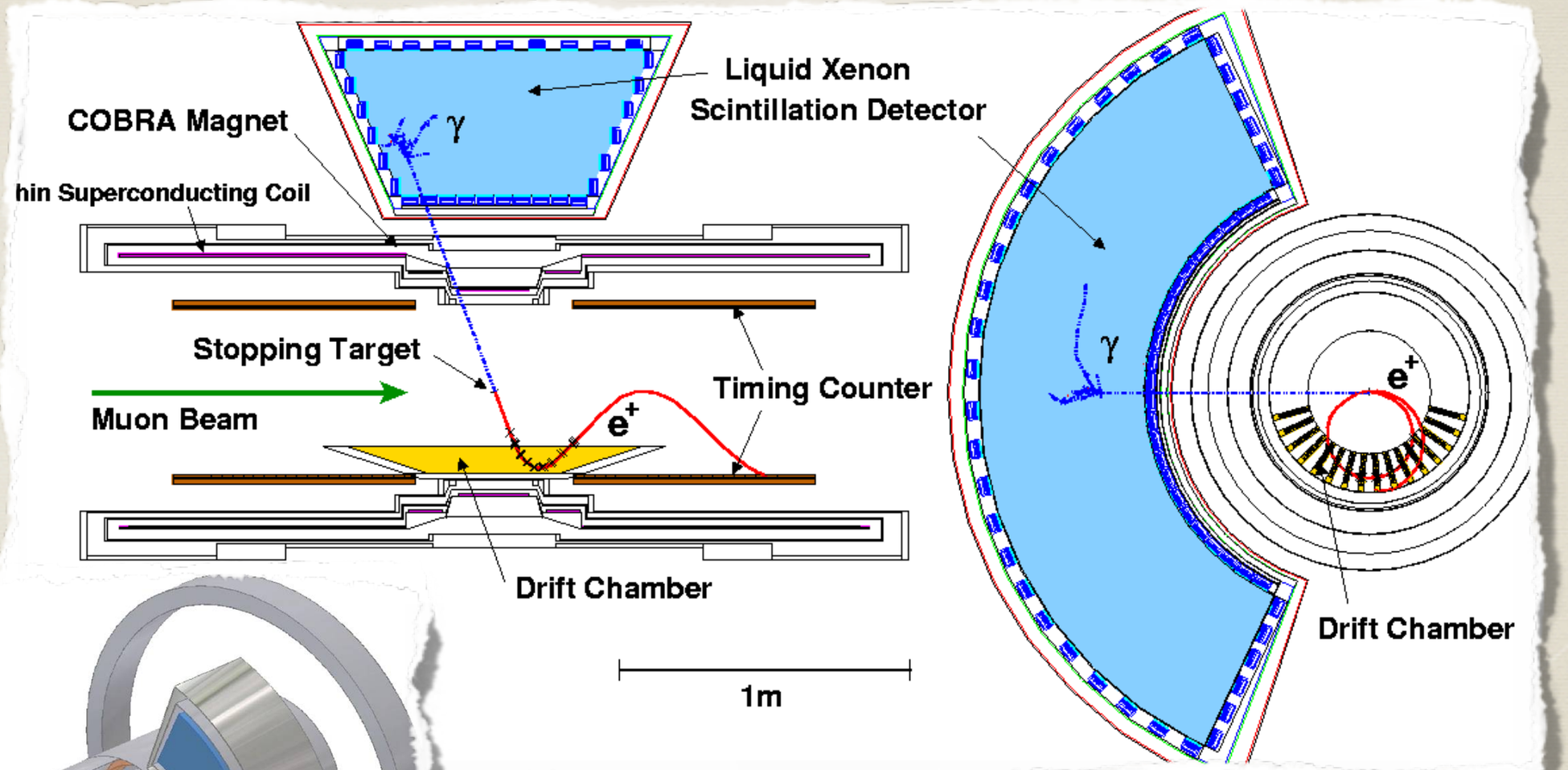
$$BR(\mu \to e\gamma) \sim \mathcal{O}\left(\frac{m_\nu^4}{m_W^4}\right).$$

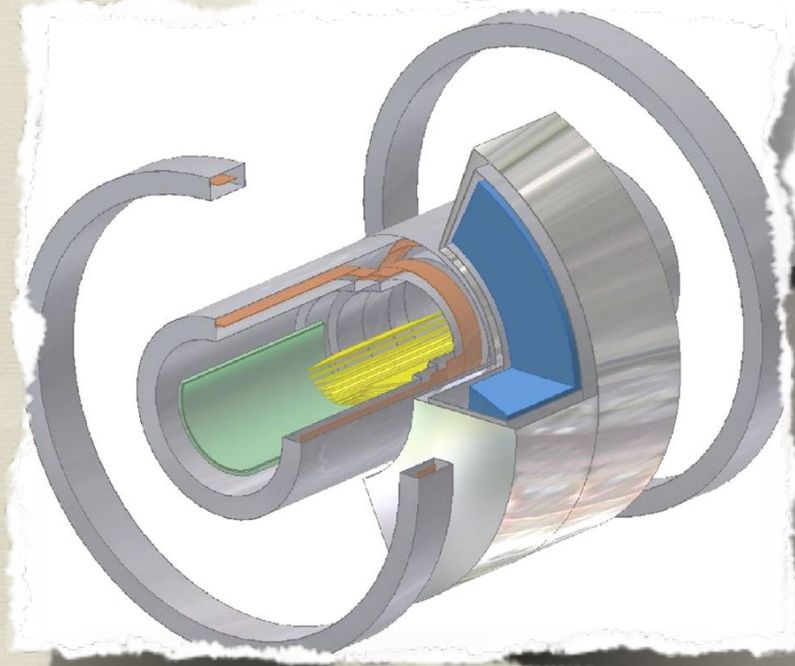
Observable LFV = new physics!

The MEG Experiment

Paul Scherrer Institut, Switzerland

Operating since 2008





~360 trillion muon decays observed.

No $\mu \rightarrow e\gamma$.

Keep looking.

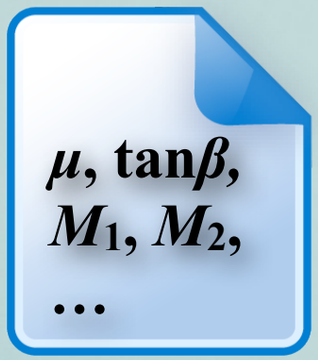
SuperLFV

…is an SLHA observables calculator

SLHA:
Susy **L**es **H**ouches **A**ccord,
A common file format for susy models

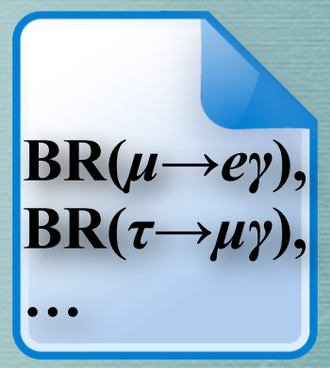
Use implemented models.

Use your own models.



SLHA spectrum file (masses and couplings at the soft scale)

Calculates physical masses, mixings, couplings, and observables (currently with MSSM as low energy theory)



LFV observables

Independence from existing spectrum generators: greater model selection

Calculational Procedure

1. Couplings and mass parameters are input at m_{soft}.

   $e.g.,\ g_Y,\ g_2,\ y_e,\ U_{\text{PMNS}},\ M_1,\ M_2,\ m^2_{\tilde{L}},\ A_e,\ \ldots$

2. Calculate masses and mixing matrices.

   $$e.g.,\ \ [\tilde{e}^\dagger_L\ \tilde{e}^\dagger_R] \begin{bmatrix} m^2_{\tilde{e}LL} & m^{2\dagger}_{\tilde{e}LR} \\ m^2_{\tilde{e}LR} & m^2_{\tilde{e}RR} \end{bmatrix} \begin{bmatrix} \tilde{e}_L \\ \tilde{e}_R \end{bmatrix} \rightarrow 6 \text{ charged sleptons}$$

3. Calculate (primitive) couplings for mass states.

   $$e.g.,\ \tilde{\nu}_i \bar{e}_j (c^{e_L}_{ijA} P_L + c^{e_R}_{ijA} P_R) \tilde{\chi}^-_A + \text{h.c.}$$

4. Calculate (loop-generated) effective couplings.

   $$e.g.,\ \frac{e m_{e_i}}{2} \bar{e}_i \sigma_{\mu\nu} F^{\mu\nu} (A^{ij}_{2L} P_L + A^{ij}_{2R} P_R) e_j + \text{h.c.}$$

5. Calculate observables.

   $e.g.,\ \sigma(\tau \rightarrow \mu\gamma)$

4½. Leading log RGE for A_{2L} and A_{2R} only.

$$e.g.,\ A_{2L}(m_\mu) = A_{2L}(m_{\text{soft}}) \left(1 - \frac{4\alpha}{\pi} \ln \frac{m_{\text{soft}}}{m_\mu}\right)$$

Otherwise no RG running!

Observables Included

Observable	Limit	Future
$\mu^+ \to e^+\gamma$	5.7×10^{-13}	10^{-13} MEG [6]
$\tau^+ \to e^+\gamma$	3.3×10^{-8}	2.3×10^{-9} SuperB [9]
$\tau^+ \to \mu^+\gamma$	4.4×10^{-8}	3×10^{-9} Belle II [8], 1.8×10^{-9} [9]
$\mu \to eee$	1.0×10^{-12}	10^{-15} MUSIC [10], 10^{-16} Mu3e [11]
$\tau \to eee$	2.7×10^{-8}	2×10^{-10} [9]
$\tau \to \mu\mu\mu$	2.1×10^{-8}	1×10^{-9} [8], 2×10^{-10} [9]
μ^- SiC $\to e^-$ SiC	none	10^{-14} DeeMe
μ^- Al $\to e^-$ Al	none	10^{-16} COMET [13], Mu2e [14]
μ^- Ti $\to e^-$ Ti	4.3×10^{-12}	10^{-18} PRISM/PRIME [15]

SuperLFV calculates these branching ratios.

(muon conversion in SiC not implemented).

LFV in the MSSM

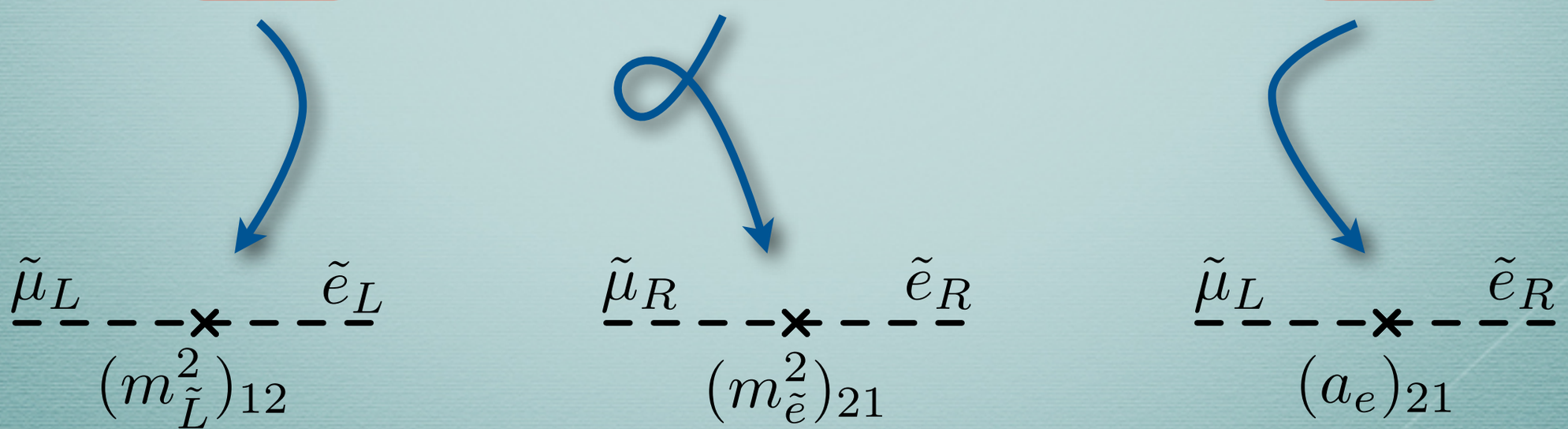
4 Sources

e.g., from seesaw

e.g., from SU(5) GUT

no mainstream source

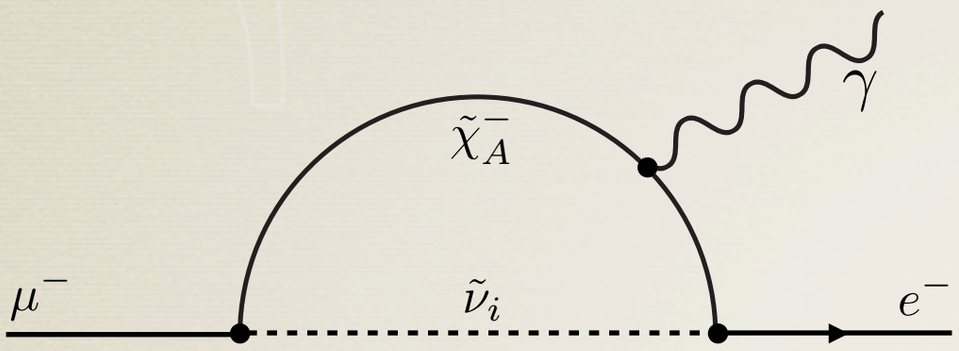
$$-\mathcal{L}_{\rm soft} \supset \tilde{L}_i^\dagger (m^2_{\tilde{L}})_{ij} \tilde{L}_j + \tilde{e}_{Ri} (m^2_{\tilde{e}})_{ij} \tilde{e}^*_{Rj} + (H_d^\alpha \epsilon_{\alpha\beta} \tilde{L}_i^\beta (a_e)_{ij} \tilde{e}^*_{Rj} + \text{h.c.})$$



LFV in D-terms also allowed.

Example Calculation

$\mu \to e\gamma$

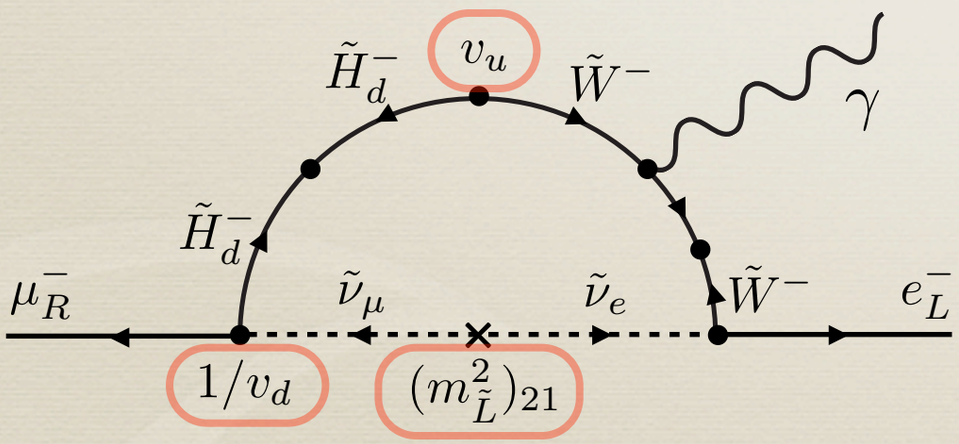


- Mediated by chargino (neutralino) loops
- New contributions to electromagnetic interactions:

$$-\mathcal{L}_{\text{eff}} \supset eq^2 A_\mu \bar{e}_i \gamma^\mu (A_{1L}^{ij} P_L + A_{1R}^{ij} P_R) e_j + \frac{e m_{e_i}}{2} \bar{e}_i \sigma_{\mu\nu} F^{\mu\nu} (A_{2L}^{ij} P_L + A_{2R}^{ij} P_R) e_j + \text{h.c.}$$

Doesn't contribute to on-shell $\mu \to e\gamma$

Magnetic dipole operator



- Gauge-interaction states illustrate analytic behavior.
- $\mu \to e\gamma$ generally scales with $\tan\beta$ (when source is slepton mass-mixing; e.g., seesaw).

Basic Usage

Java — bash — 80×24

```
Jirachi > cat input.spc
# Minimal parameter input template for Super LFV
BLOCK gauge Q=  1.00000000E+03
   1    3.62831933E-01       # g_Y
   2    6.45857032E-01       # g_2
   3    1.07837289E+00       # g_3
BLOCK Yu Q=  1.00000000E+03
  1  1     8.49362382E-06    # y_u
  2  2     3.59564127E-03    # y_c
  3  3     8.70775686E-01    # y_t
BLOCK Yd Q=  1.00000000E+03
  1  1     1.36464619E-04    # y_d
  2  2     2.86579735E-03    # y_s
  3  3     1.36927282E-01    # y_b
BLOCK Ye Q=  1.00000000E+03
  1  1     2.98272756E-05    # y_e
  2  2     6.16732139E-03    # y_mu
  3  3     1.03764817E-01    # y_tau
BLOCK VCKM Q=  1.00000000E+03
   1  1     9.74192032E-01
   1  2     2.25694592E-01
   1  3     3.44018712E-03
   2  1    -2.25645361E-01
   2  2     9.73359257E-01
```

SLHA spectrum file

SuperLFV output

Java — bash — 80×24

```
Jirachi > superlfv
SuperLFV 1.0

Observable:  BR(l -> l' gamma)
  BR(mu- -> e- gamma) = 1.891993318E-14
  BR(tau- -> e- gamma) = 8.773022513E-36
  BR(tau- -> mu- gamma) = 1.925024531E-34

Observable:  R(mu N -> e N)
  BR(mu Ti -> e Ti) = 1.197657937E-16
  BR(mu Al -> e Al) = 7.041410720E-17

Observable:  BR(l -> l' l' l')
  BR(mu- -> e- e- e+) = 1.311991365E-16
  BR(tau- -> e- e- e+) = 1.734152699E-38
  BR(tau- -> mu- mu- mu+) = 9.690935025E-38

Jirachi >
```

Option:

View Contributions

-w option displays contributions

Java — bash — 135×24

```
Jirachi > superlfv -w
SuperLFV 1.0

Observable:  BR(l -> l' gamma)
  BR(mu- -> e- gamma) = 1.891993318E-14 = 4.863598412E-16 (neutralino) + 2.547321573E-14 (chargino) + -7.039642383E-15 (interference)
  BR(tau- -> e- gamma) = 8.773022513E-36 = 8.773022513E-36 (neutralino) + 0.00000000000 (chargino) + 0.00000000000 (interference)
  BR(tau- -> mu- gamma) = 1.925024531E-34 = 1.925024531E-34 (neutralino) + 0.00000000000 (chargino) + 0.00000000000 (interference)

Observable:  R(mu N -> e N)
  BR(mu Ti -> e Ti) = 1.197657937E-16 = 1.183098421E-16 (photon) + 4.215919742E-21 (Z) + 2.478523420E-20 (box) + 1.412481247E-18 (photo
n-Z) + 1.446955094E-20 (photon-box) + -3.747044298E-25 (box-Z)
  BR(mu Al -> e Al) = 7.041410720E-17 = 6.963784569E-17 (photon) + 2.033309030E-21 (Z) + 1.346881951E-20 (box) + 7.525761385E-19 (photo
n-Z) + 8.183434335E-21 (photon-box) + -1.918211880E-25 (box-Z)

Observable:  BR(l -> l' l' l')
  BR(mu- -> e- e- e+) = 1.311991365E-16 = 1.310090795E-16 (photon) + 1.976479608E-22 (Z) + 1.526445905E-19 (box) + 3.721503371E-20 (pho
ton-Z) + -8.019854714E-26 (photon-box) + -1.805389839E-25 (box-Z)
  BR(tau- -> e- e- e+) = 1.734152699E-38 = 1.745199500E-38 (photon) + 1.332714361E-41 (Z) + 1.463584005E-43 (box) + -1.239682877E-40 (p
hoton-Z) + 9.410783621E-46 (photon-box) + 2.583869308E-44 (box-Z)
  BR(tau- -> mu- mu- mu+) = 9.690935025E-38 = 9.778772382E-38 (photon) + 2.142948770E-40 (Z) + 1.264161273E-40 (box) + -1.090834989E-39
 (photon-Z) + -4.009104874E-42 (photon-box) + -1.242404788E-40 (box-Z)

Jirachi >
```

Gain insights on analytical behavior.

Options:

Display spectra, display couplings

Java — bash — 105×24

```
Spectrum:  Charged sleptons
  Masses:
  m2_e1 = 6.052707465E04
  m2_e2 = 6.376245232E04
  m2_e3 = 6.377409414E04
  m2_e4 = 4.160578137E05
  m2_e5 = 4.221118179E05
  m2_e6 = 4.221332878E05

  Mixing matrices:
  U_e =
  -9.110035956E-19  3.003274668E-15  0.999784
  0.08621816137  -0.99627553490  4.956493417E
  0.99627628127  0.08621809678  -4.274129627E
  7.633941527E-22  4.531569693E-18  -0.020758
  -3.415966935E-09  -0.00122407083  4.0131729
  5.919859989E-06  1.693127777E-11  2.1543932


Spectrum:  Squarks
  Masses:
  m2_u1 = 3.662621404E05
  m2_u2 = 5.726255696E05
  m2_u3 = 7.180402438E05
```

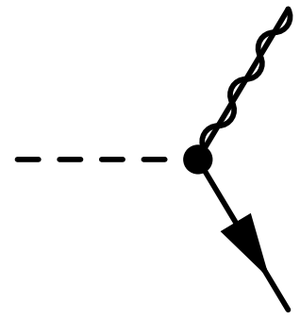
Display masses and mixings.

Java — bash — 90×12

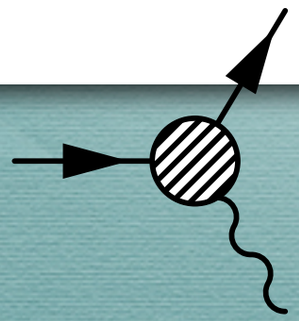
```
Jirachi > superlfv -C
SuperLFV 1.0

Couplings:  Sfermion-fermion-chargino tree-level couplings
  c^uR_111 = -1.744984279E-08 = -8.724921394E-09 (higgsino_u)
  c^uR_112 = 9.431730515E-08 = 4.715865257E-08 (higgsino_u)
  c^uR_121 = 5.116539218E-05 = 2.558269609E-05 (higgsino_u)
  c^uR_122 = -2.765515980E-04 = -1.382757990E-04 (higgsino_u)
  c^uR_131 = -0.31580159397 = -0.15790079698 (higgsino_u)
  c^uR_132 = 1.70692399147 = 0.85346199574 (higgsino_u)
  c^uR_211 = 5.715891321E-09 = 2.857945661E-09 (higgsino_u)
  c^uR_212 = -3.089468899E-08 = -1.544734450E-08 (higgsino_u)
```

Display (effective) couplings.



```
Couplings:  lepton-photon-lepton 1-loop vector and tensor couplings
  A_1R^11 = 9.604168151E-09 = 1.283972049E-09 (neutralino) + 8.320196103E-09 (chargino)
  A_1R^12 = -6.564753992E-14 = -1.765258224E-14 (neutralino) + -4.799495768E-14 (chargino)
  A_1R^13 = 8.132763928E-28 = 8.132763928E-28 (neutralino) + 0.00000000000 (chargino)
  A_1R^21 = -6.564753992E-14 = -1.765258224E-14 (neutralino) + -4.799495768E-14 (chargino)
  A_1R^22 = 9.604923201E-09 = 1.284201890E-09 (neutralino) + 8.320721312E-09 (chargino)
  A_1R^23 = -2.353389164E-24 = -2.353389164E-24 (neutralino) + 0.00000000000 (chargino)
  A_1R^31 = 8.132763928E-28 = 8.132763928E-28 (neutralino) + 0.00000000000 (chargino)
  A_1R^32 = -2.353389164E-24 = -2.353389164E-24 (neutralino) + 0.00000000000 (chargino)
  A_1R^33 = 9.824686898E-09 = 1.351881361E-09 (neutralino) + 8.472805537E-09 (chargino)
  A_1L^11 = 2.164656263E-10 = 2.164656197E-10 (neutralino) + 6.559414902E-18 (chargino)
  A_1L^12 = -1.198826025E-20 = -7.033254706E-21 (neutralino) + -4.955005544E-21 (chargino)
```



SuperLFV:

Summary, Outlook

- Calculates LFV observables in supersymmetric models.
- Independence from SLHA spectrum calculators.
- Options to view contributions to quantities. Allows insights.
- Future extensions on a demand-basis.

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