Revisiting the $\Gamma\left(K \rightarrow e\nu\right)/\Gamma\left(K \rightarrow \mu\nu\right)$ ratio in supersymmetric unified models

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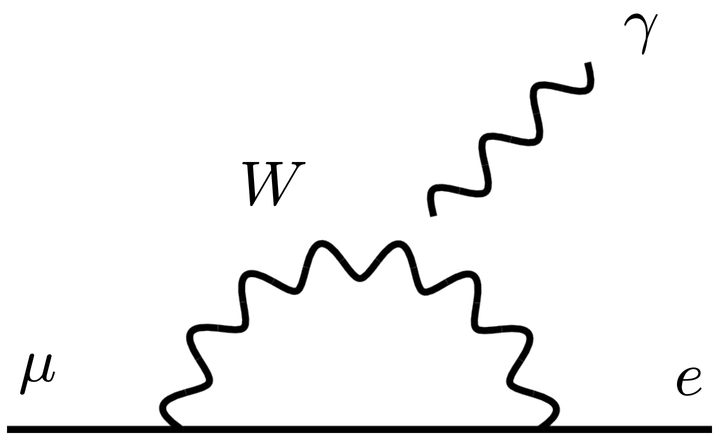
(R.M.F, J.C.Romão and A.M.Teixeira)

Outline

- Lepton Flavor Violation and SUSY
- The R_K observable
- Results of our analysis
- Conclusions

Lepton Flavor Violation and SUSY

- **In the Standard Model**, there is essentially no violation of the flavor of charged leptons (cLFV)
- Non-perturbative processes violate lepton number, but at low energies/temperatures the effect is very small
- **Beyond the SM**: neutrino oscillations do violate lepton flavour. But even with small neutrino masses, cLFV is expected to be negligible



$$\mathrm{BR}\,(\mu \to e\gamma) \sim \frac{\alpha}{4\pi}\left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-47}\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^4$$

Lepton Flavor Violation and SUSY

- **SUSY** extensions of the SM have new sources of quark and lepton flavor violation:

$$-\mathcal{L}_{\rm soft} = \cdots + \tilde{u}^\dagger_R h_u \tilde{Q}\cdot H_u + \tilde{d}^\dagger_R h_d \tilde{Q}\cdot H_d + \tilde{e}^\dagger_R h_e \tilde{L}\cdot H_d + \text{h.c.}$$
$$+\tilde{Q}^\dagger m^2_{\tilde{Q}}\tilde{Q} + \tilde{L}^\dagger m^2_{\tilde{L}}\tilde{L} + \tilde{u}^\dagger_R m^2_{\tilde{u}}\tilde{u}_R + \tilde{d}^\dagger_R m^2_{\tilde{d}}\tilde{d}_R + \tilde{e}^\dagger_R m^2_{\tilde{R}}\tilde{e}_R$$

- Miss-alignment between the soft breaking SUSY masses/trilinear couplings and the Yukawa couplings can lead to **large cLFV** (and FCNC, CP violation)

- **Stringent experimental bounds** ($\ell_i \to \ell_j\gamma$,...) imply that these new sources of cLFV must be small

- **Pion and kaon leptonic decays** are also good new Physics probes (in particular of $m^2_{\tilde{R}}$) Masiero, Paradisi, Petronzio 2006

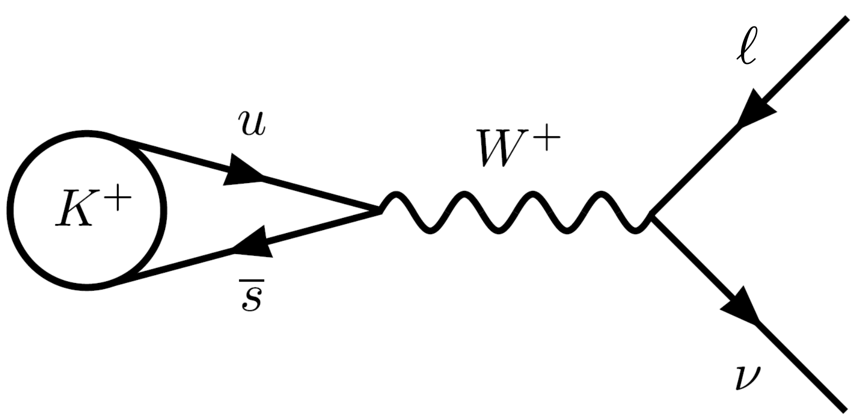
The R_K observable

- $R_K = \Gamma\left(K \to e\nu\right)/\Gamma\left(K \to \mu\nu\right)$ is a **ratio of decay widths**
- **QCD uncertainties** cancel in R_K to a good approximation
- The analogous ratio R_π is known with a better experimental precision, but it is less sensitive to new Physics $(m_K > m_\pi)$

$$R_K^{\text{SM}} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{\text{QED}})$$

$(-3.60 \pm 0.04)\%$

Cirigliano, Rosell 2007

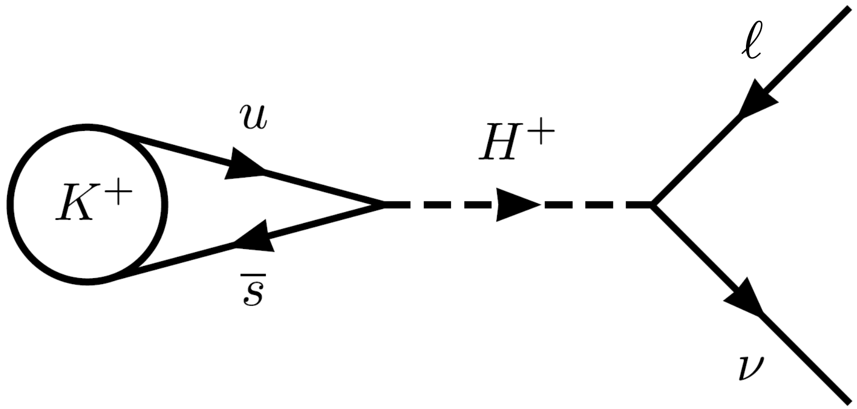


$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

The R_K observable

Goudzovski 2011
(NA62 Collab.)

- **Experimental value**: $R_K^{\text{exp}} = (2.488 \pm 0.010) \times 10^{-5}$
- Equivalently, $R_K^{\text{exp}} = R_K^{\text{SM}}(1 + \Delta r)$ with $\Delta r = (4 \pm 4) \times 10^{-3}$
- In 2HDM type-II the charged Higgs can also mediate the meson decay (destructive interference with the W diagram) Hou 1993



Independent of ℓ

Today decay width: $\Gamma^{\text{SM}}(K^\pm \to \ell^\pm \nu) \left(1 - \tan^2\beta \, \frac{m_K^2}{m_H^2} \frac{m_s}{m_s + m_u}\right)^2$
(tree level)

Consequence: R_K does not change

The R_K observable

- At loop level things change considerably: the $\nu \ell H$ vertex becomes LFV, inducing $K \to e \nu_\tau$ Masiero, Paradisi, Petronzio 2006
- The change to R_K can be very large: $\Delta r \gtrsim \mathcal{O}(1\%)$

Picks up the tau Yukawa coupling

$$\Delta r \propto \tan^6 \beta, \frac{m_\tau^2}{m_e^2}, \left(m^2_{\tilde{R}}\right)^2_{\tau e}$$

Sensitive mainly to the right sleptons mass matrix

Enhanced by the so-called HRS effect

Hall, Rattazzi, Sarid 1993

- Calculation done in the MIA approximation: 1 LFV MI → $\Delta r > 0$

(no interference with the SM process)

1 MI, 2 MI

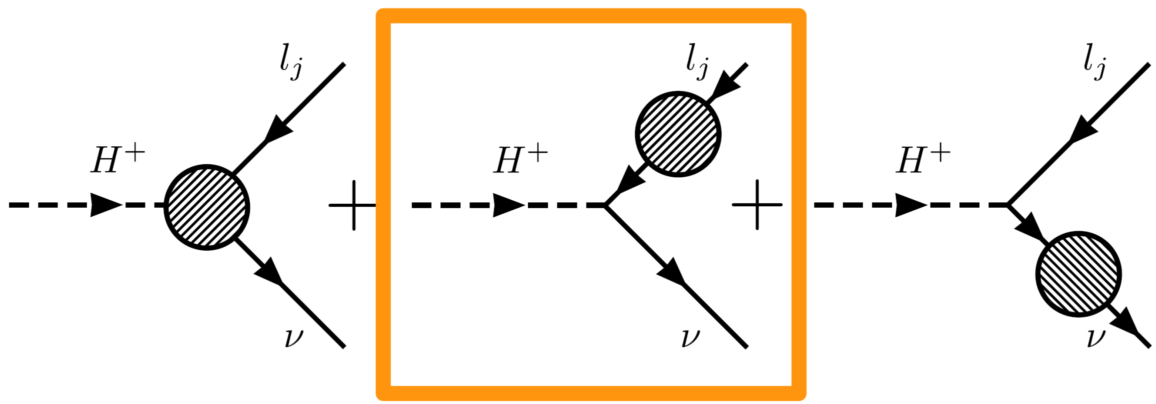
$$\Delta r \sim \frac{X^2 \left(\langle m^2_{\tilde{\ell}} \rangle \prec \langle m^2_{\chi^0} \rangle\right)^2}{4} + 2X \left(m^2_{\tilde{L}}\right)_{e\tau} + X^2 \left(m^2_{\tilde{L}}\right)^2_{e\tau}$$

$$X \equiv \frac{1}{192\pi^2} m_K^2 g'^2 \mu M_1 \frac{\tan^3 \beta}{m^2_{H^\pm}} \frac{m_\tau}{m_e} \frac{\left(m^2_{\tilde{R}}\right)_{\tau e}}{(\overline{m}^2_{\tilde{\ell},\chi^0})^3}$$

$\overline{m}^2_{\tilde{\ell},\chi^0} = \frac{1}{2}(\langle m^2_{\tilde{\ell}} \rangle + \langle m^2_{\chi^0} \rangle)$

The R_K observable

- There are other analyses: Ellis, Lola, Raidal 2009 Girrbach, Nierste 2012
- For a more accurate calculation of R_K we have computed the **radiative effects to the $\nu\ell H$ vertex without the MIA** → lepton kinetic, mass and terms must be renormalized Bellazzini, Grossman, Nachshon, Paradisi 2011



HRS effect: can potentially lead to a large effect

$$\mathcal{L}_0^{H^\pm} = i\,\overline{\ell}_L\left(\mathbf{1}+\eta_L^\ell\right)\partial\!\!\!/\,\ell_L + i\,\overline{\ell}_R\left(\mathbf{1}+\eta_R^\ell\right)\partial\!\!\!/\,\ell_R + i\,\overline{\nu}_L\left(\mathbf{1}+\eta_L^\nu\right)\partial\!\!\!/\,\nu_L - \left[\overline{\ell}_L\left(M^{l0}+\eta_M^\ell\right)\ell_R + \text{h.c.}\right] + \left[\overline{\nu}_L\left(2^{3/4}G_F^{1/2}\,\tan\beta\,M^{l0}+\eta^H\right)\ell_R H^+ + \text{h.c.}\right]$$

The R_K observable

Rotate/**renormalize** fields:

$$\ell_L^{\text{old}} = K_L^\ell \left(\hat{Z}_L^\ell\right)^{-\frac{1}{2}} R_L^\ell \, \ell_L^{\text{new}} \qquad \hat{Z}_L^\ell = K_L^{\ell\,\dagger} \left(\mathbf{1} + \eta_L^\ell\right) K_L^\ell$$

$$\ell_R^{\text{old}} = K_R^\ell \left(\hat{Z}_R^\ell\right)^{-\frac{1}{2}} R_R^\ell \, \ell_R^{\text{new}} \qquad \hat{Z}_R^\ell = K_R^{\ell\,\dagger} \left(\mathbf{1} + \eta_R^\ell\right) K_R^\ell$$

$$\nu_L^{\text{old}} = K_L^\nu \left(\hat{Z}_L^\nu\right)^{-\frac{1}{2}} R_L^\ell \, \nu_L^{\text{new}} \qquad \hat{Z}_L^\nu = K_L^{\nu\,\dagger} \left(\mathbf{1} + \eta_L^\nu\right) K_L^\nu$$

The **renormalized $\nu \ell H$ vertex**: $\mathcal{L}^{H^\pm} \equiv \overline{\nu}_L \, Z^H \, \ell_R \, H^+ + \text{h.c.}$

$$Z^H = 2^{3/4} G_F^{1/2} \tan\beta \, R_L^{\ell\,\dagger} \left(\hat{Z}_L^\nu\right)^{-\frac{1}{2}} K_L^{\nu\,\dagger} K_L^\ell \left(\hat{Z}_L^\ell\right)^{\frac{1}{2}} R_L^\ell M^l$$
$$+ R_L^{\ell\,\dagger} \left(\hat{Z}_L^\nu\right)^{-\frac{1}{2}} K_L^{\nu\,\dagger} \left(-2^{3/4} G_F^{1/2} \tan\beta \, \eta_M^\ell + \eta^H\right) K_R^\ell \left(\hat{Z}_R^\ell\right)^{-\frac{1}{2}} K_R^\ell$$

...up to 1 loop...

$$Z^H = 2^{3/4} G_F^{1/2} \tan\beta \left[\left(\mathbf{1} + \frac{\eta_L^\ell}{2} - \frac{\eta_L^\nu}{2}\right) M^l - \eta_M^\ell\right] + \eta^H$$

Results

Our analysis

$$\delta^{RR}_{\tau e} = \frac{(m^2_{\tilde{R}})_{\tau e}}{m^2_{\tilde{R}}}$$

- We did not try to explain the origin of $\delta^{RR}_{\tau e}$ - we just assumed that it is big and computed the value of Δr for different cases using **SPheno**: Porod 2003, Porod, Staub 2012
  - **Modified cMSSM** (with seesaw I / II)
  - **NUHM**
  - **Unconstrained MSSM** Esteves *et al.* 2010
- We also looked at one **L-R seesaw model**

Why put $\delta^{RR}_{\tau e} \neq 0$ "by hand"?

- cMSSM with seesaw is known to induce cLFV, but not through the right sleptons mass matrix Borzumati, Masiero 1986
- Non-exhaustive analysis of the parameter space of the L-R model showed that $\delta^{RR}_{\tau e} \sim 0.01$ at most (assuming no fine-tunning)

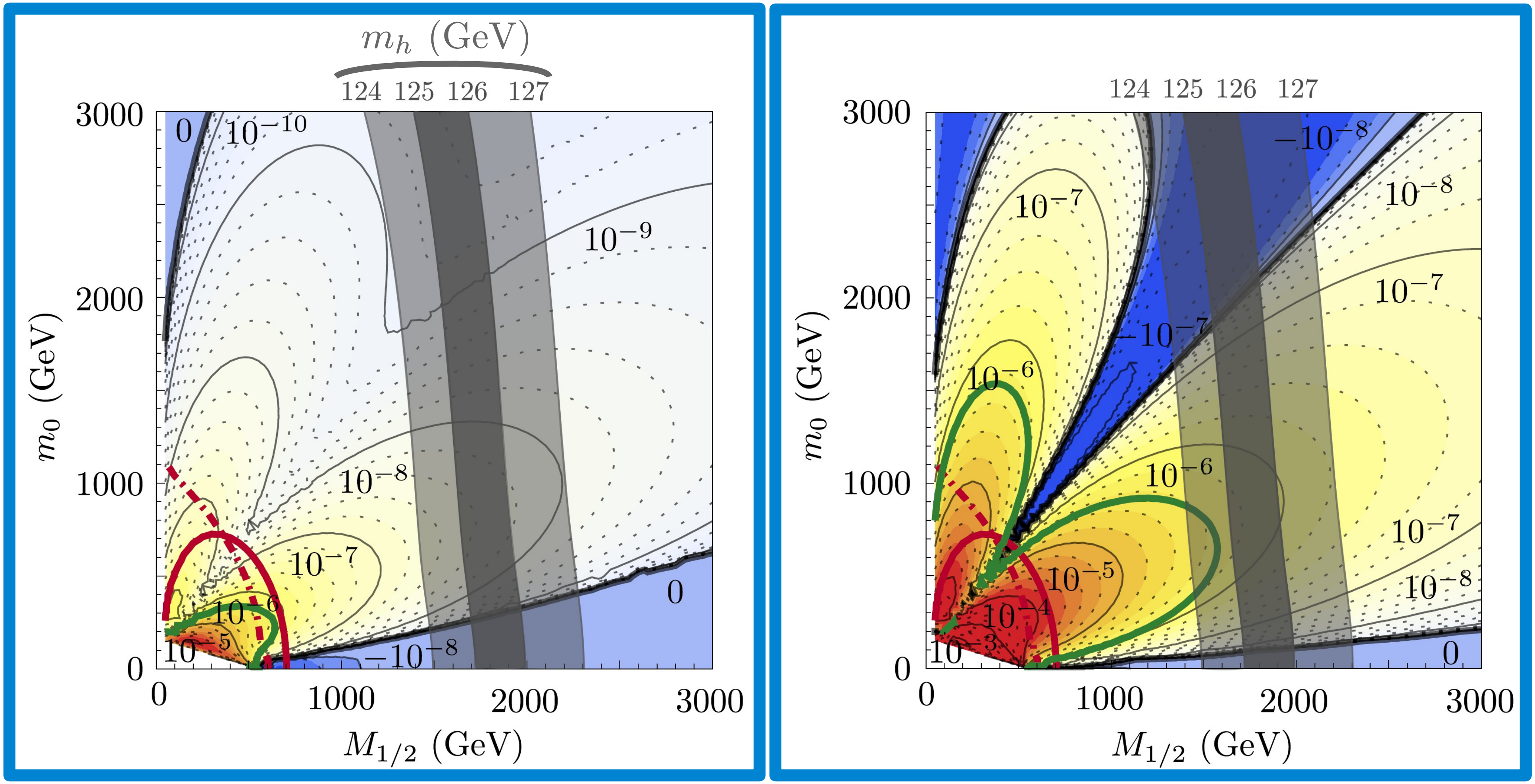
Remainder:
$\Delta r^{exp} \sim 10^{-2}$

Results

Modified cMSSM

seesaw type-I
$\tan\beta = 40$
$A_0 = 0$ GeV

$\delta_{\tau e}^{RR} = 0.1$ $\delta_{\tau e}^{RR} = 0.7$



Br $(\tau \to e\gamma)$ Br $(B_s \to \mu\mu)^*$ Br $(B_u \to \tau\nu)$

*outdated limit (not relevant though)

Results

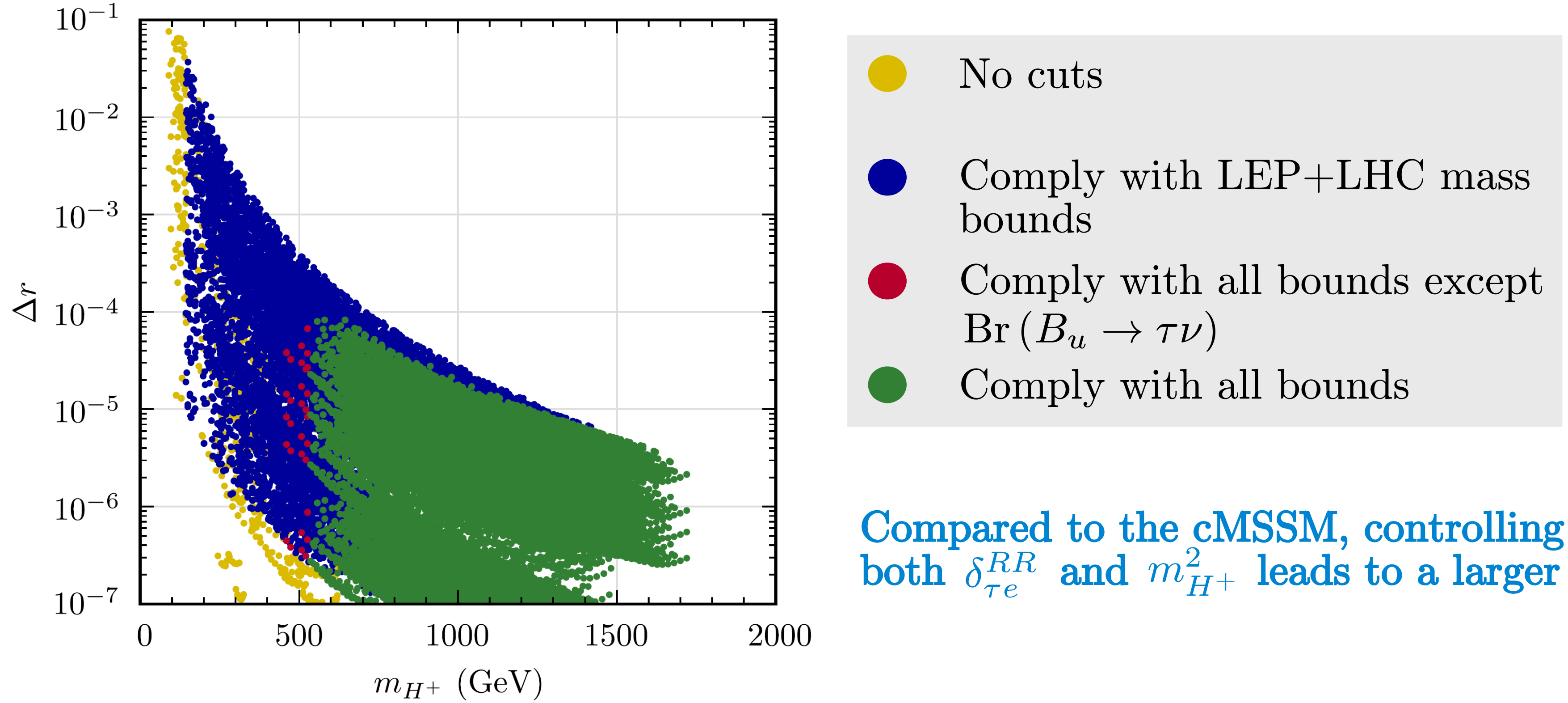
NUHM

Higgs soft SUSY breaking masses are arbitrary

	m_0 (GeV)	$M_{1/2}$ (GeV)	$m^2_{H_1}$, $m^2_{H_2}$ (GeV^2)	$\tan\beta$	δ^{RR}_{31}
Min	0	100	-5.2×10^6	40	0.1
Max	1500	1500	-4.6×10^6	40	0.7

Narrow strip where $m^2_{H_1} \approx m^2_{H_2} \approx$ -2.2^2 TeV leads to a small $m^2_{H^+}$

Ellis, Lola, Raidal 2009



Compared to the cMSSM, controlling both $\delta^{RR}_{\tau e}$ and $m^2_{H^+}$ leads to a larger Δr

Results

Unconstrained MSSM

More freedom than in the NUHM, which should lead to a larger Δr

preferably small

large squark masses don't affect Δr

preferably large

	μ	m_A	M_1, M_2	M_3	A_0	$m_{\tilde{L}}$	$m_{\tilde{e}}$	m_Q, m_U, m_D	$\tan\beta$	δ_{31}^{RR}	other δ_{ij}^{XY}
Min	100	50	100	1100	-1000	100	100	1200	30	0.5	0
Max	3000	1500	2500	2500	1000	2200	2500	5000	60	0.5	0

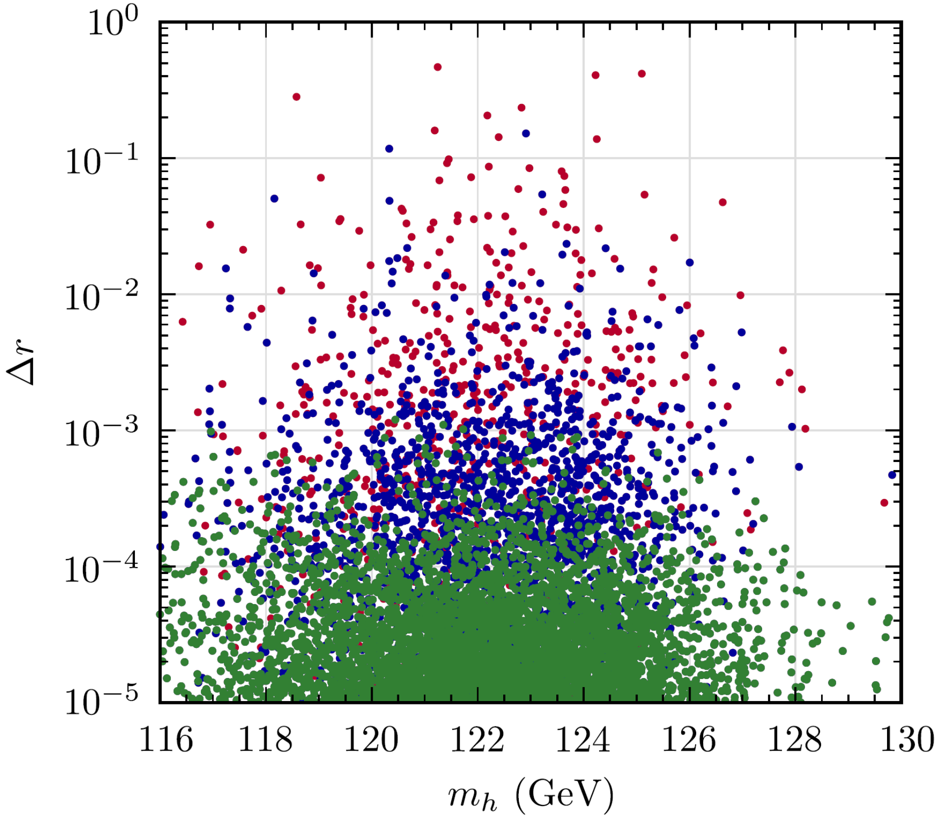
(dimensionful parameters in GeV)

large, constant

Results

Unconstrained MSSM

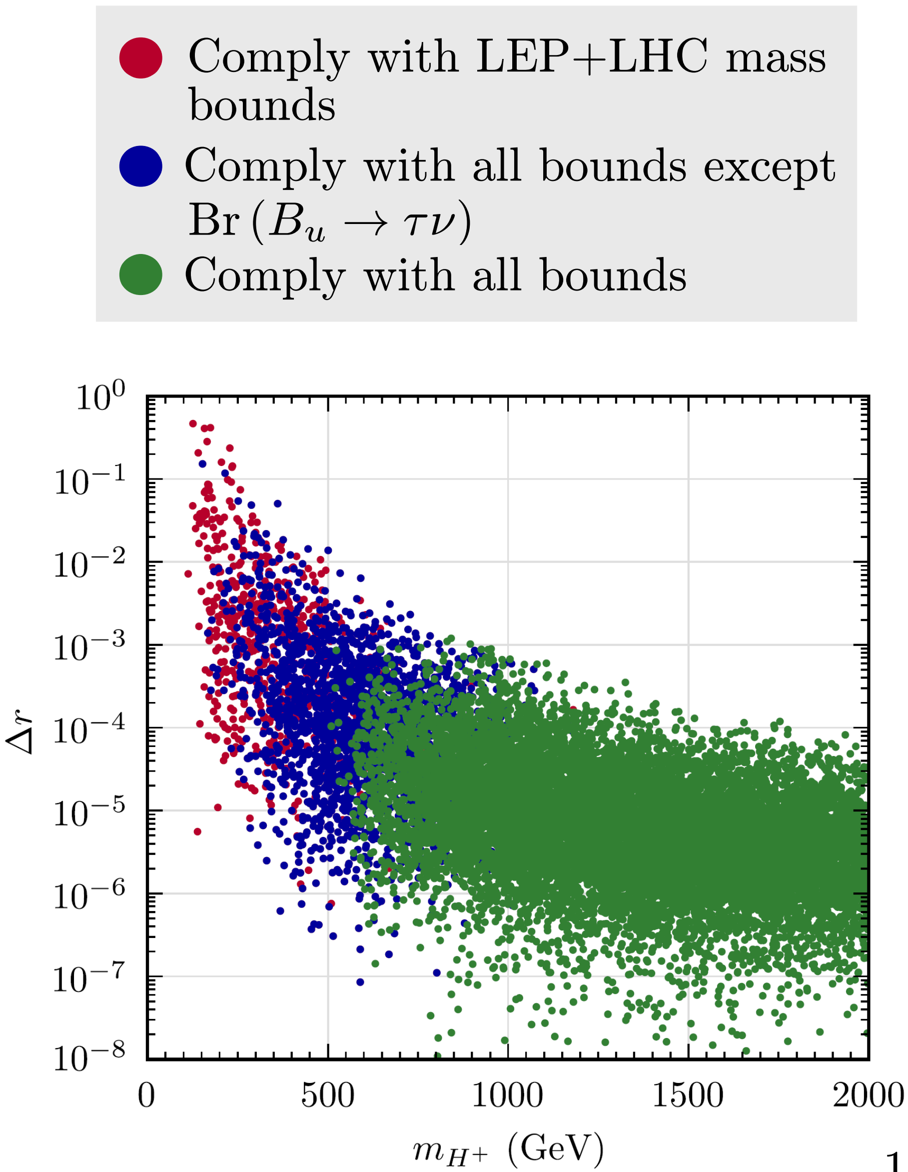
The Higgs mass is easily accommodated

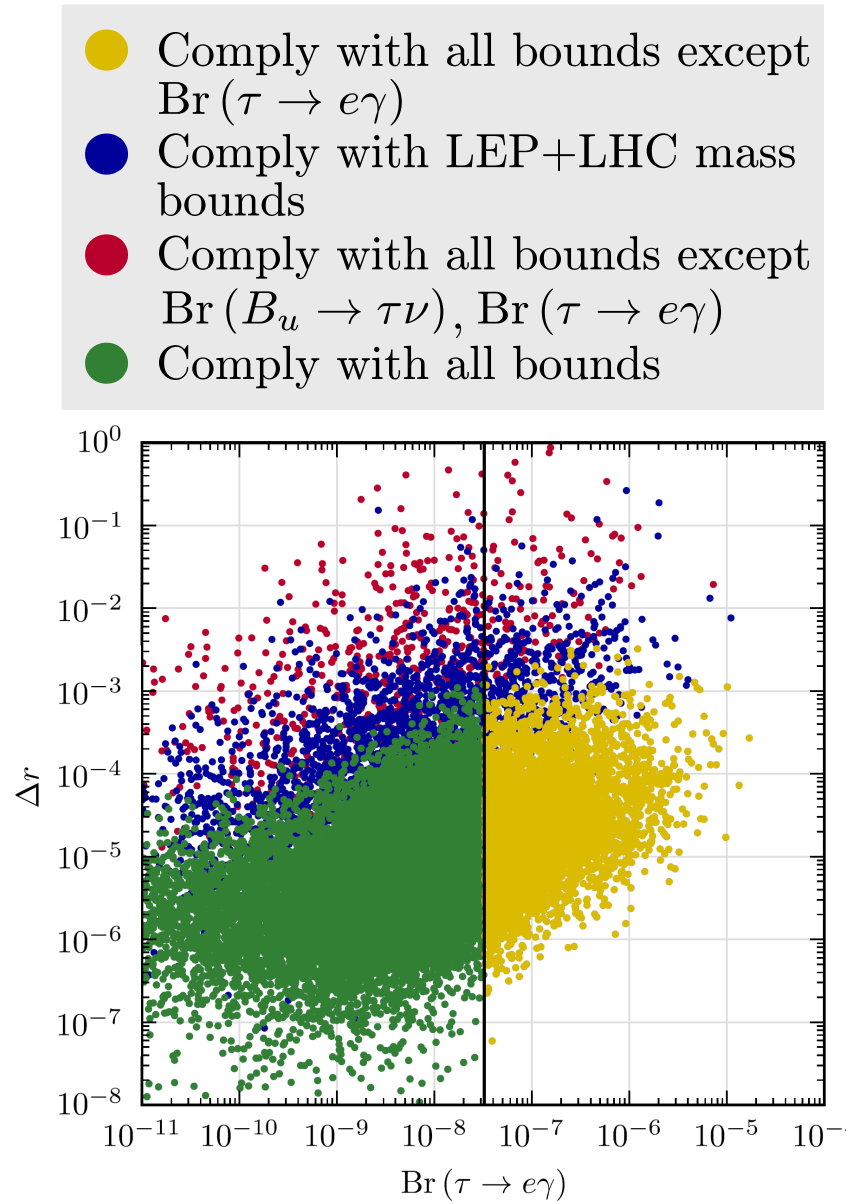


- Comply with LEP+LHC mass bounds
- Comply with all bounds except $\mathrm{Br}\,(B_u \to \tau\nu)$
- Comply with all bounds

Results

Unconstrained MSSM





Conclusions

- We have computed supersymmetric contributions to $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ by including the one-loop corrections to the $\nu \ell H^+$ vertex
- The modified cMSSM with $\delta_{\tau e}^{RR} \neq 0$ at the GUT scale leads to a small effect on R_K
- A LR model we tested also did not produce a sizable effect
- In the NUHM, the charged Higgs mass can be controlled, leading to a larger Δr
- Finally, we tested the unconstrained MSSM; Δr can be as large as $\sim 10^{-3}$, which is still smaller than the current experimental sensitivity $\sim 10^{-2}$
- $\mathrm{Br}(B_u \to \tau\nu)$ and $\mathrm{Br}(\tau \to e\gamma)$ preclude larger SUSY contributions to R_K

Thank you for your time