Violation of lepton universality: impact of new physics for R_K and R_π

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Probing the Standard Model and New Physics at Low and High Energies

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Lepton flavour universality (LFU)

- **Lepton Flavour Universality:** couplings of SM **gauge bosons** to **leptons** are

  independent of lepton flavours

- **Violation of LFU** offers precise **tests of the Standard Model**

  deviations from SM $\leftrightsquigarrow$ **evidence for New Physics**

- Many **observables to test LFU:** gauge boson decays, leptonic meson decays, ...

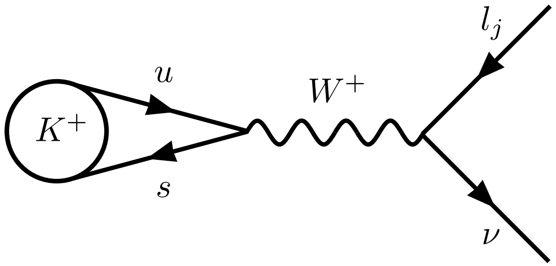
- **LFU violation** in **light meson decays** - kaons, pions

  Decay amplitudes plagued by QCD uncertainties; consider ratios

$$R_P \equiv \frac{\Gamma(P \to e\nu)}{\Gamma(P \to \mu\nu)} \qquad P = K, \pi, \ldots \quad \text{(pseudoscalar)}$$

Lepton flavour universality: R_K

- R_K **in the Standard Model**



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

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

[Cirigliano et al, '07]

- **Experimental** measurements: **NA62** (kaon beam from CERN SPS)

$$R_K^{\text{exp}} = (2.488 \pm 0.010) \times 10^{-5}$$

[Goudzovski, '11]

future sensitivity $\delta R_K / R_K \sim 0.1\%$

- **New Physics contributions (?):** $\Delta r_K = \dfrac{R_K^{\text{exp}}}{R_K^{\text{SM}}} - 1$ $\quad \Delta r_K = (4 \pm 4) \times 10^{-3}$

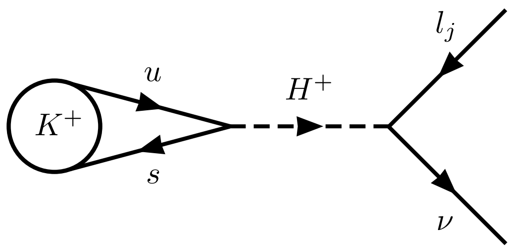
Compatible with **SM** **or** with New Physics contribution $\sim \mathcal{O}(10^{-2})$

Similar prospects for R_π and Δr_π

LFU violation: deviations from the SM

- **New Physics violation** of **LFU** in ***K* decays:**

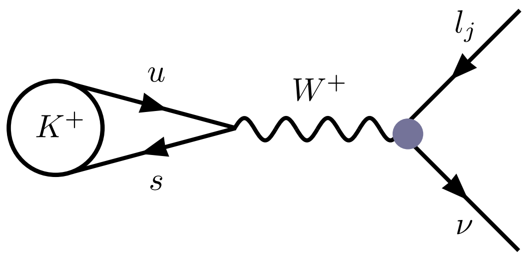
(i) New Lorentz structure in the 4-fermion interaction



(new fields, new $X\ell\nu$ coupling)

Multi-Higgs doublet models, Supersymmetry, ...

(ii) Corrections to the $W\ell\nu$ vertex of the SM



(new states, higher-order effects)

models with additional (light) leptons: νSM,

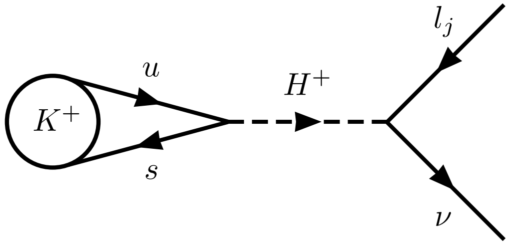
low-scale seesaw, inverse seesaw, ...

- **Recall** - **severe constraints** on **New Physics models:**

direct searches; indirect bounds (flavour physics, cosmology, ...); precision tests, ...

Δr_K - new Lorentz structure

- Two Higgs Doublet models (2HDM):



$$\Gamma^{\text{2HDM}}(K^\pm \to \ell^\pm \nu) = \Gamma^{\text{SM}} \times \left(1 - \tan^2\beta \, \frac{m_K^2}{m_{H^+}^2} \, \frac{m_s}{m_s + m_u}\right)^2$$

Tree-level correction is **lepton universal** $\Rightarrow \Delta r_K^{\text{2HDM}} \sim 0$

[Hou, '93]

- Supersymmetry: charged Higgs exchange identical to 2HDM $\Rightarrow \Delta r_K^{\text{SUSY-tree}} \sim 0$

higher order, flavour violating corrections are required!

[Masiero, Paradisi, Petronzio, '05-'08]

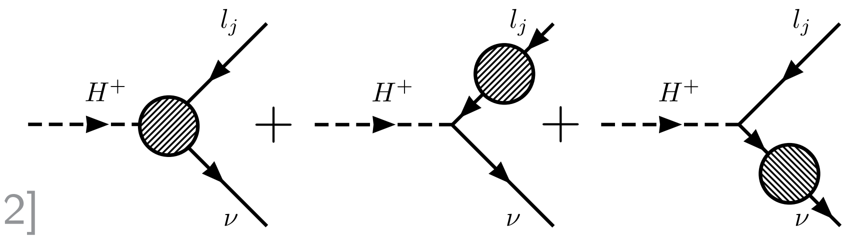
[Girrbach and Nierste, '12]

R_K in SUSY models

- Supersymmetric contributions to Δr_K:

  full 1-loop corrections to the $H^{\pm}\ell\nu$ vertex

  [Fonseca, Romão, AMT, '12]



$$\Delta r_K^{\text{SUSY}} \sim \left[1 + X\left(1 - \frac{9}{10}\frac{\delta}{m^2_{\text{SUSY}}}\right)\left(m^2_{\tilde{L}}\right)_{e\tau}\right]^2 - 1 + X^2\left[-\mu^2 + \delta\left(3 - \frac{3}{10}\frac{\mu^2+2M_1^2}{m^2_{\text{SUSY}}}\right)\right]^2$$

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

in agreement with Mass Insertion Approx. limit [Masiero et al, '05]

- Survey of different SUSY models: cMSSM, NUHM, general MSSM,

  seesaw-related, LR models, ...

- Imposing available experimental constraints:

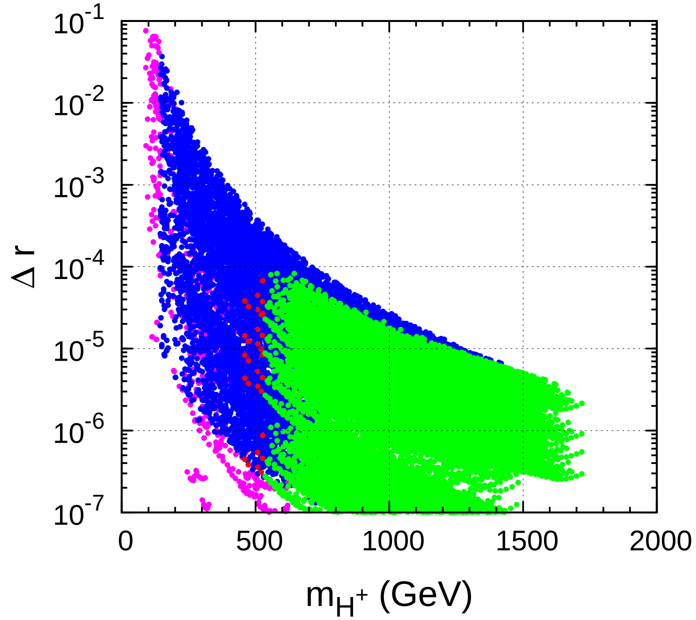
  LHC (direct searches & Higgs mass), flavour violation (lepton & hadron), ...

Δr_K in SUSY models: NUHM

- **Non-Universal Higgs Mass: universal** $M_{1/2}$, A_0, $m^2_{\tilde{F}}$ at GUT **except** $\boldsymbol{m^2_{H_i}}$**!**

  Light $H^\pm$ and large $\tan\beta$ $\Rightarrow$ enhance **SUSY contributions** to $\Delta r_K \propto \frac{\tan^6\beta}{m^4_{H^+}}$

  [typically for $m^2_{H_1} \approx m^2_{H_2} \sim -(2.2\,\mathrm{TeV})^2$]



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

- No cuts
- Mass bounds (LEP & LHC)
- All bounds **but** BR($B_u \to \tau\nu$)
- All bounds

[Fonseca, Romão, AMT, '12]

- **Semi-constrained regimes** - in principle $\boldsymbol{\Delta r_K \sim \mathcal{O}(10^{-2})}$
- Imposing **collider and low-energy bounds: at most $\Delta r_K \lesssim 10^{-4}$** (for $m_{H^+} \gtrsim$ 500 GeV)

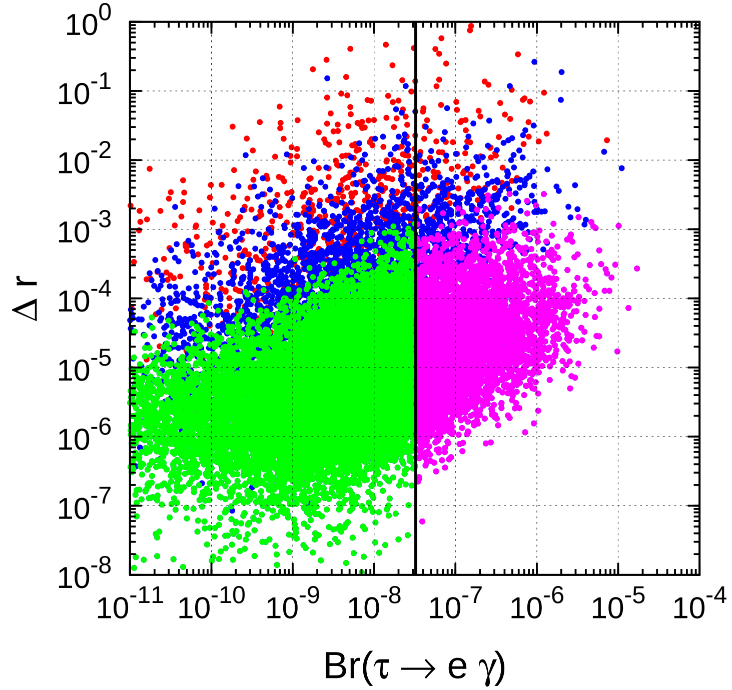
  [Negative interference of SUSY and SM contributions to BR($B_u \to \tau\nu$)]

- Worse prospects for other constrained SUSY models: mSUGRA-like (seesaw), LR-symmetric, ...

Δr_K in SUSY models: unconstrained MSSM

- **General MSSM: “free” SUSY parameters** at the low-scale

  Explore parameter space to **maximize SUSY contributions** to $\boldsymbol{\Delta r_K}$ [no FV in $\tilde{q}$ sector]



	μ	m_A	$M_{1,2}$	M_3	A_0	$m_{L,R}$	$m_{Q,U,D}$	$\tan\beta$	δ^{RR}_{31}
Min	100	50	100	1100	-1000	100	1200	30	0.5
Max	3000	1500	2500	2500	1000	2200	5000	60	0.5

- Mass bounds (LEP & LHC)
- All bounds BUT BR($B_u \to \tau\nu$) and BR($\tau \to e\gamma$)
- All bounds BUT BR($\tau \to e\gamma$)
- All bounds

- **General case** - $\boldsymbol{\Delta r_K \sim \mathcal{O}(10^{-1,-2})}$ [Masiero et al, ’05-’08; Ellis et al, ’08; Girrbach and Nierste, ’12]

- **Imposing flavour constraints: BR($B_s \to \mu\mu$) and $\tau \to e\gamma \Rightarrow \Delta r_K \lesssim 10^{-2}$**

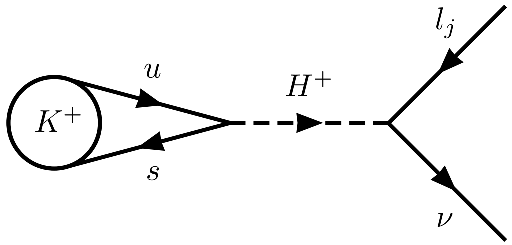
  BR($B_u \to \tau\nu$) $\Rightarrow \Delta r_K < 10^{-3}$

  [Fonseca, Romão, AMT, ’12]

LFU violation: deviations from the SM

- **New Physics violation** of **LFU** in K **decays:**

(i) New Lorentz structure in the 4-fermion interaction

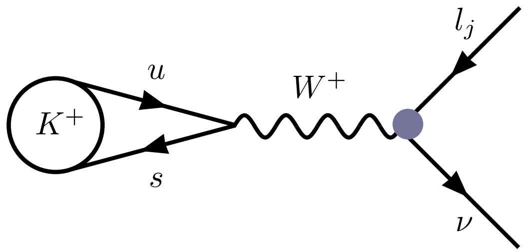


(new fields, new $X\ell\nu$ coupling)

Multi-Higgs doublet models, Supersymmetry, ...

SUSY models: $\Delta r_K^{\text{SUSY}} < 10^{-3}$

(ii) Corrections to the $W\ell\nu$ vertex of the SM



(new states, higher-order effects)

models with additional (light) leptons: νSM,
low-scale seesaw, **inverse seesaw, ...**

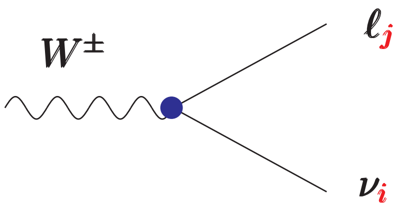
Interesting prospects!

- **Recall** - **severe constraints** on **New Physics models:**

  direct searches; indirect bounds (flavour physics, cosmology, ...); precision tests, ...

Δr_K: corrections to the $W\,\ell\,\nu$ vertex

- **Tree level corrections:** naturally present when leptonic mixing is incorporated into SM



SM: $\bullet \propto g P_L \delta_{ij}$ $\rightsquigarrow$ **SM**$^{\text{fermion singlets}}$**:** $\bullet \propto g P_L U^\nu_{ji}$

$j = e, \mu, \tau$; $i = 1 \ldots 3 \ldots n_\nu$ neutrinos

- **Impact for LFU violation:** dependent on the New Physics scenario!

  SM$_\nu$: $n_\nu = 3$ $\rightsquigarrow$ $U^\nu_{ji} = U^{\text{PMNS}}$ $\Rightarrow \Delta r_K \approx 0$

  New sterile states: $n_\nu > 3$ $\rightsquigarrow$ $U^\nu_{ji} \neq U^{\text{PMNS}}$ ($\tilde{U}^{\text{PMNS}}_{3\times 3}$ non-unitary block of $3 \times n_\nu$ matrix)

  If small active-sterile mixing $\leftrightsquigarrow$ $\tilde{U}^{\text{PMNS}} \approx U^{\text{PMNS}}$ $\Rightarrow$ $\Delta r_K \approx 0$

  e.g. high scale type I & III seesaw, ...

  If sizable active-sterile mixing, light steriles $\leftrightsquigarrow$ corrections to $W\ell\nu$ vertex

  e.g. νSM, low-scale type I, inverse seesaw, ...

  non-unitarity of $\tilde{U}^{\text{PMNS}}$ $\Rightarrow$ sizable Δr_K (?) [Shrock, '80-'81]

- **Higher order corrections:** $\mathcal{O}(m_W^2/\Lambda^2_{\text{NP}}) \to$ below exp. sensitivity [Masiero et al, '08]

Δr_K: corrections to $W\,\ell\,\nu$ from sterile neutrinos

- **Sterile neutrinos:** abundant **experimental and observational motivations**

  LSND & reactor anomaly, cosmology, "warm" dark matter, ...

- **Constraints on ν_s** dependent on m_{ν_s} regime and $\nu_L - \nu_s$ mixing $\theta_i^{\nu_s}$

  Laboratory bounds: **direct searches** (e.g. $\pi^\pm \to \mu^\pm \nu$) [Atre et al, '09; Kusenko, '09]

  Non-Unitarity constraints: $\tilde{U}^{\text{PMNS}}_{3\times3} = (1-\eta)\, U^{\text{PMNS}}_{3\times3}$; stringent in $m_{\nu_s} > m_W$ regime [Antusch et al, '09]

  Lepton flavour violating processes: in particular **BR($\mu \to e\gamma$)** [Deppish and Valle, '05]

  B physics: compatibility with **BR($B \to \ell\nu$)** data

  LHC data: **indirect** bounds from $H \to \nu_L \nu_s$ searches; relevant for $m_{\nu_s} \sim$ **100 GeV** [Bhupal et al, Cely et al, Bandyopadhyay et al, '12]

  EW precision tests: sensitive to leptonic mixing for $m_{\nu_s} \gtrsim$ **1 TeV** [Del Aguila et al, '08]

  Cosmological bounds: Large scale structure; Lyman-α limits; BBN; CMB; X-ray, ... [Smirnov et al, '06; Kusenko, '09]

  ... can be evaded with non-standard cosmology (example low T_{reheat}) [Gelimini et al, '09]

Sterile neutrinos and Δr_K

- **Sizable deviations for Δr_K : hierarchy of ν_s and mixings $\nu_L - \nu_s$**

[Abada, Das, AMT, Vicente, Weiland, '13]

$$\Delta r_P = \frac{m_\mu^2 (m_P^2 - m_\mu^2)^2}{m_e^2 (m_P^2 - m_e^2)^2} \frac{\sum_{m=1}^{N_{\max}^{(e)}} F^{m1}\, G^{m1}}{\sum_{n=1}^{N_{\max}^{(\mu)}} F^{m2}\, G^{n2}} - 1 \qquad P = K, \pi$$

$$F^{ij} = |U_\nu^{ji}|^2 \qquad G^{ij} = \left[m_P^2 (m_{\nu_i}^2 + m_{l_j}^2) - (m_{\nu_i}^2 - m_{l_j}^2)^2 \right] \left[(m_P^2 - m_{l_j}^2 - m_{\nu_i}^2)^2 - 4 m_{l_j}^2 m_{\nu_i}^2 \right]^{1/2}$$

- **Illustrative mass regimes for new sterile states (n_s)**

  (A) *all* ν_s lighter than decaying meson but heavier than active states

  $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_P \Rightarrow$ sum over $3 + n_s$ states; phase space enhancement

  (B) *all* ν_s heavier than decaying meson $\quad m_{\nu_s} \gtrsim m_P$

- **LFU-impact wise: (A) and (B) in general experimentally indistinguishable**

Sterile neutrinos and Δr_K: Inverse Seesaw

- Concrete example of **SM extended by (light) sterile neutrinos:** Inverse Seesaw

[Mohapatra, Valle '86]

- **Inverse seesaw:** extend SM by n_R generations of ν_R and n_X **singlet fermions** X

$$\mathcal{L}_{\text{ISS}} = \mathcal{L}_{SM} + Y_\nu^{ij} \bar{\nu}_{Ri} L_j \tilde{H} + M_{R ij}\, \bar{\nu}_{Ri} X_j + \tfrac{1}{2} \mu_{X ij} \bar{X}_i^c X_j + \text{h.c.}$$

$$n_R = n_X = 3$$

- **In the inverse seesaw limit** $\mu_X \ll v Y_\nu \ll M_R$

$$\nu \text{ spectrum: } \begin{cases} m_\nu \simeq v^2\, Y_\nu^T\, M_R^{T^{-1}}\, \mu_X\, M_R^{-1}\, Y_\nu \\ m_{\nu_s} \simeq M_R \end{cases}$$

[μ_X suppression: large Y_ν for "low" M_R]

- **Corrections to the $W\ell\nu$ vertex:** *all states* participate via LH component

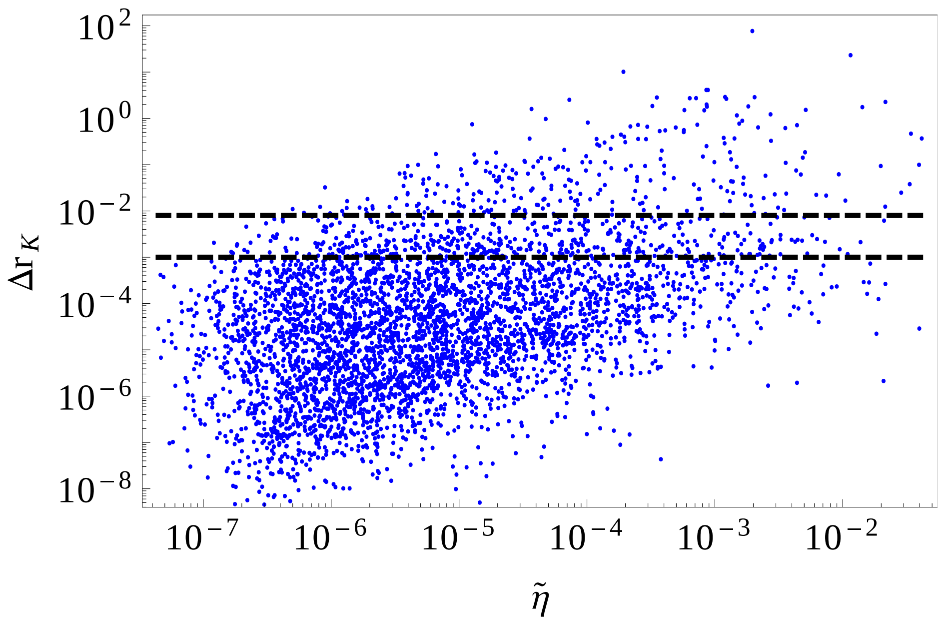
large active-sterile mixings; **"light"** sterile **states $\Rightarrow$ potentially large** Δr_K

[Shrock, '80-'81; Abada, Das, AMT, Vicente, Weiland, '13]

Inverse Seesaw - one illustrative example; other possibilities!

Δr_K in the Inverse Seesaw

- **Numerical results:** Δr_K vs $\tilde{\eta} = 1 - |\mathrm{Det}(\tilde{U}_{\mathrm{PMNS}})|$



Case (A):

$$m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$$

$M_R \in$ [0.1 MeV, 200 MeV]

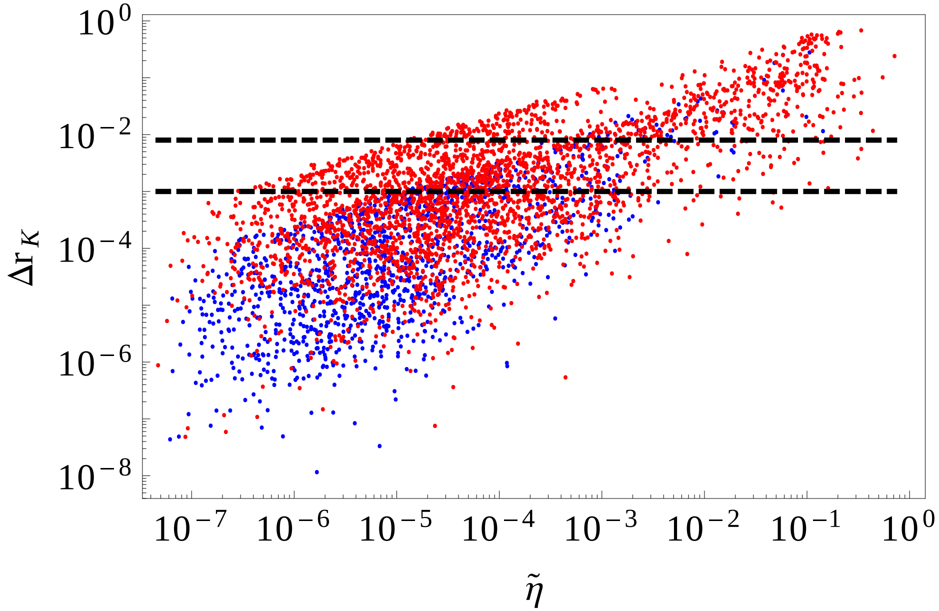
$\mu_X \in$ [0.01 eV, 1 MeV]

- **Sizable LFUV possible:** $\Delta r_K \gtrsim 0.01$ (still avoiding non-unitarity bounds)
- **No LFV** signatures expected (due to the smallness of Y_ν in (A) regimes)
- Scenario (A) **excluded** due to CMB and X-ray constraints

(**but viable** if non-standard cosmology considered)

Δr_K in the Inverse Seesaw

- **Numerical results:** Δr_K vs $\tilde{\eta} = 1 - |\text{Det}(\tilde{U}_{\text{PMNS}})|$



Case (B):

$$m_{\nu_s} \gtrsim m_K$$

$M_R \in$ [1 GeV, 10^6 GeV]

$\mu_X \in$ [0.01 eV, 1 MeV]

• $Y_\nu \gtrsim 10^{-2}$; • $Y_\nu \lesssim 10^{-2}$

- **Large LFUV:** $\Delta r_K \sim \mathcal{O}(1)$ (despite very stringent non-unitarity bounds!)
- (B) exhibits peculiar **features of Inverse Seesaw:**

  large Δr_K for singlet states considerably heavier than pseudoscalar $m_{\nu_s} \gg m_K$

  large $Y_\nu \sim 10^{-1} \Rightarrow$ BR$(\mu \to e\gamma)$ within MEG reach

- **Similar prospects for pion decays!** $\Delta r_\pi \sim \Delta r_K \sim \mathcal{O}(1)$

R_K and New Physics: concluding remarks

- **Violation of Lepton Universality** provides an excellent **SM testing ground**,

  good **theoretical** precision and **experimental prospects!**

- **New Physics models** can provide new contributions to **LFU violation,** e.g. R_K, R_π
- Considered deviations from the **SM prediction for R_K from**

  New Lorentz structure in 4-fermion operator - **SUSY models**

  Corrections to the $W\ell\nu$ vertex - **Inverse Seesaw**

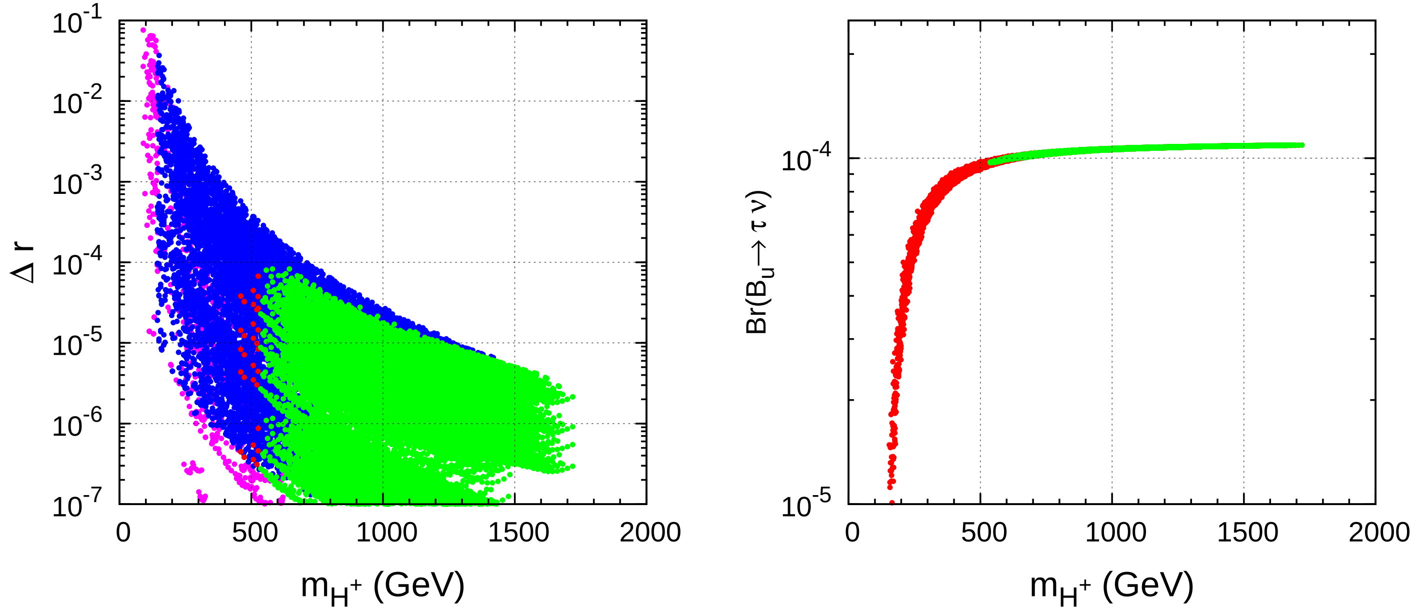
- Prospects of **broad class of SUSY models:** at most $\Delta r_K \lesssim 10^{-3}$

  below current experimental sensitivity... conflict with B and τ decays

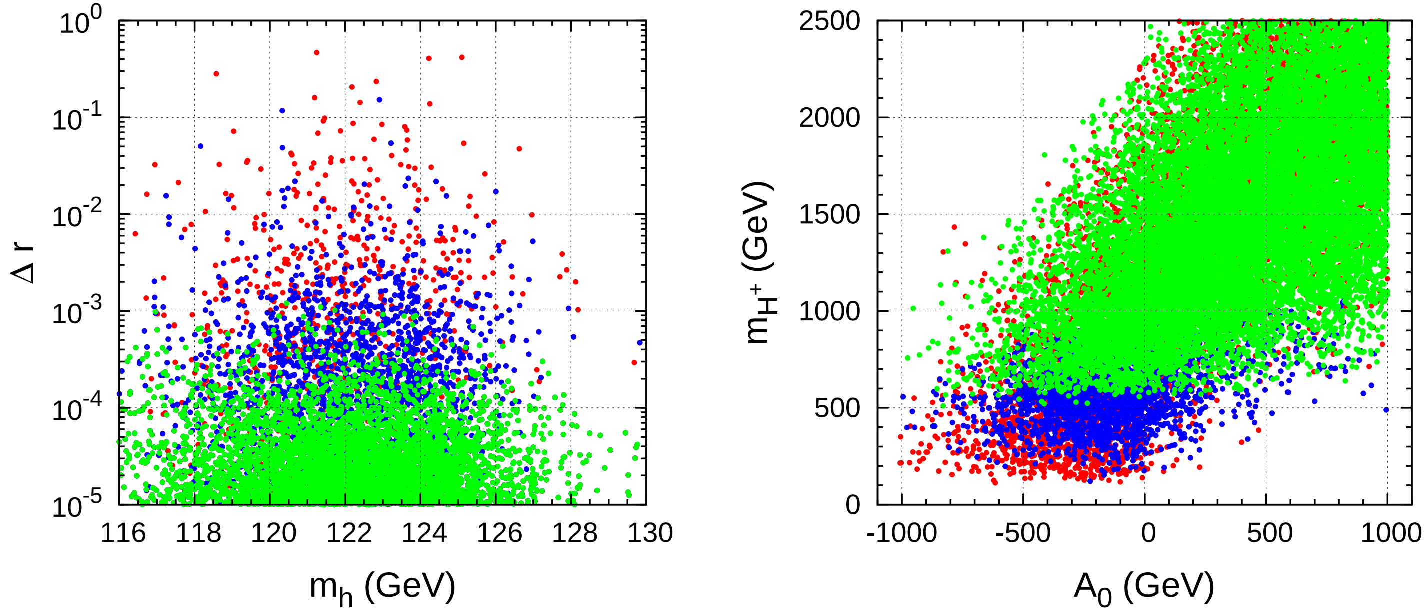
- **Corrections to $W\ell\nu$** from **sterile neutrinos** (sizable mixings) $\Rightarrow$ **LFU violation**
- **Illustrative example** of **Inverse Seesaw** - **excellent prospects!**

  $\Delta r_K \sim \Delta r_\pi \sim \mathcal{O}(1)$ in agreement with **observational bounds**

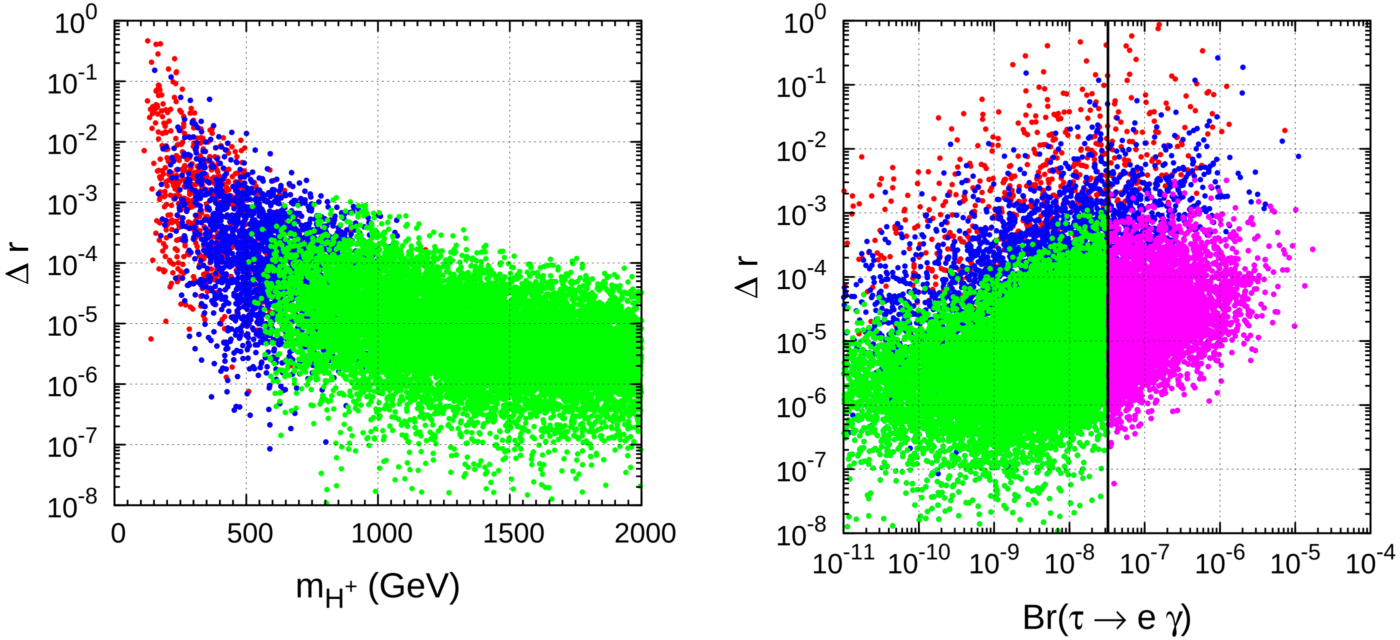
Additional slides



Left panel: Δr as a function of the charged Higgs mass, m_{H+} (in GeV). Magenta points have been subject to no cuts, blue points comply with the bounds on the masses (LEP+LHC), red points satisfy all bounds except BR($B_u \rightarrow \tau\nu$) and green points satisfy all bounds. Right panel: BR($B_u \rightarrow \tau\nu$) versus m_{H+}. Red points satisfy only the bounds on the masses (LEP+LHC) while green points comply with all bounds.



Left panel: Δr as a function of the lightest Higgs boson mass m_h (in GeV). Red points satisfy the bounds on the spectrum (LEP+LHC), blue points satisfy all bounds except $\mathrm{BR}\,(B_u \to \tau\nu)$ and green points satisfy all bounds. Right panel: m_{H^+} versus A_0 (both in GeV), with the same colour code.



Ranges of variation of Δr in the unconstrained MSSM as a function of m_{H^+} (left panel), and as a function of BR($\tau \to e\gamma$) (right panel). (Notice that $\delta_{31}^{RR} = 0.5$). On the left panel red points satisfy the bounds on the masses (LEP+LHC), blue points satisfy all bounds except $\mathrm{BR}\,(B_u \to \tau\nu)$ and green points comply with all bounds. Similar colour code on the right panel, except that blue points now comply with all bounds except $\mathrm{BR}\,(B_u \to \tau\nu)$ and BR($\tau \to e\gamma$) while magenta denotes points only failing the bound on BR($\tau \to e\gamma$).