Lepton Universality and Lepton Flavour Violation

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UK Strategy on Flavour Changing Physics and QCD

Outline

- Motherhood and Apple Pie.
- Experimental Measurements by decay
  - muon anomalous magnetic moment, a_μ
  - $\mu \to e\gamma$ and $\mu N \to eN$ conversion
  - Kaon decays
  - τ decays
  - Charm decays
  - $\Upsilon(nS)$ and B decays
- Not discussed in any depth
  - V_{us}, Form Factors, $\alpha_s(M_\tau)$
  - Experimental details (see following talks)

Declaration of Interest

- I am a member of BaBar (R.I.P.) and LHCb.
- I've signed SOIs for SuperB and LHCb upgrade.
- I've participated in discussions on UK NA62 involvement.

The importance of Charged LFV

- Charge Lepton Flavour Violation (CLFV) is not a fundamental symmetry of the Standard Model (SM).
- Even with neutrino oscillations, SM LFV BF is ~ $(M_\upsilon / M_W)^4 \sim 10^{-54}$. Compare with Quark Flavour Violation (QFV) which scales with $\log(m_q)$.
- Nearly all BSM theories have a LFV component.
- Even Minimal Quark Flavour Violating models (QFV comes from the SM sector only) have a LFV component.
- Experiments are already eliminating models and/or parameter space e.g. in $\tau^+ \to l^+ l^- l^+$ MFV BF predictions $<10^{-8}$, experimental upper limits $<10^{-8}$.
- CLFV decays are much cleaner theoretically and experimentally than QFV:
  - Lepton decays (very few hadrons to worry about).
  - Final state is often all charge tracks.
  - Minimal non-perturbative QCD calculations needed.

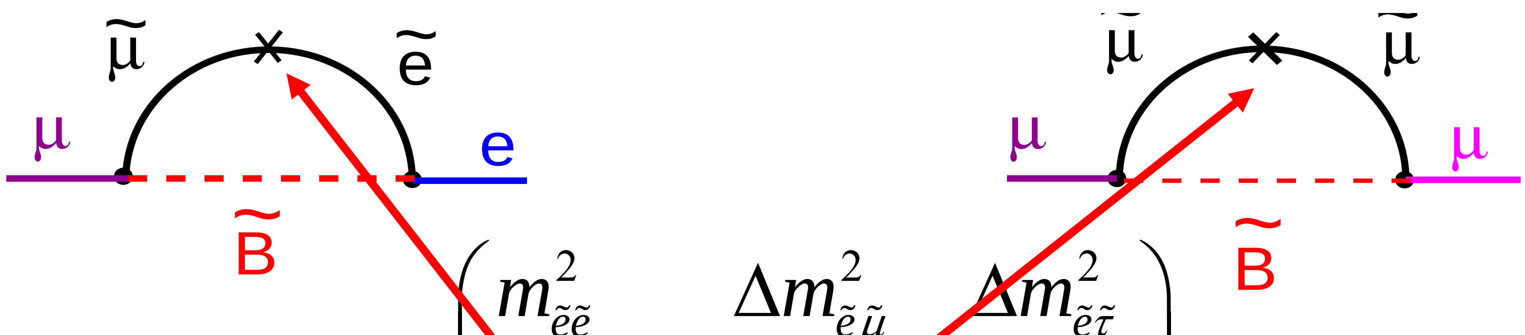
The importance of Charged LFV

- Very high precision in some theory and experiment e.g. muon g-2 at 0.5ppm.
  - A driver to improve theoretical calculations and Lattice QCD.
  - A driver of experimental and accelerator techniques.
- Essential to understand the flavour properties of the Higgs and SUSY. A vital cross-check and complementary measurement to the LHC.
- If the Higgs/SUSY not found (or find hierarchy of new particles beyond 1TeV) then need to look at loop processes to probe higher mass scales (1-100 TeV).
- LFV is can also effected by GUT-scale processes e.g. heavy ν in SeeSaw models.
- All BSM models have a different hierarchy of predictions for various LFV decays. It is therefore vital to make as wide a range of LFV measurements as possible.

g-2

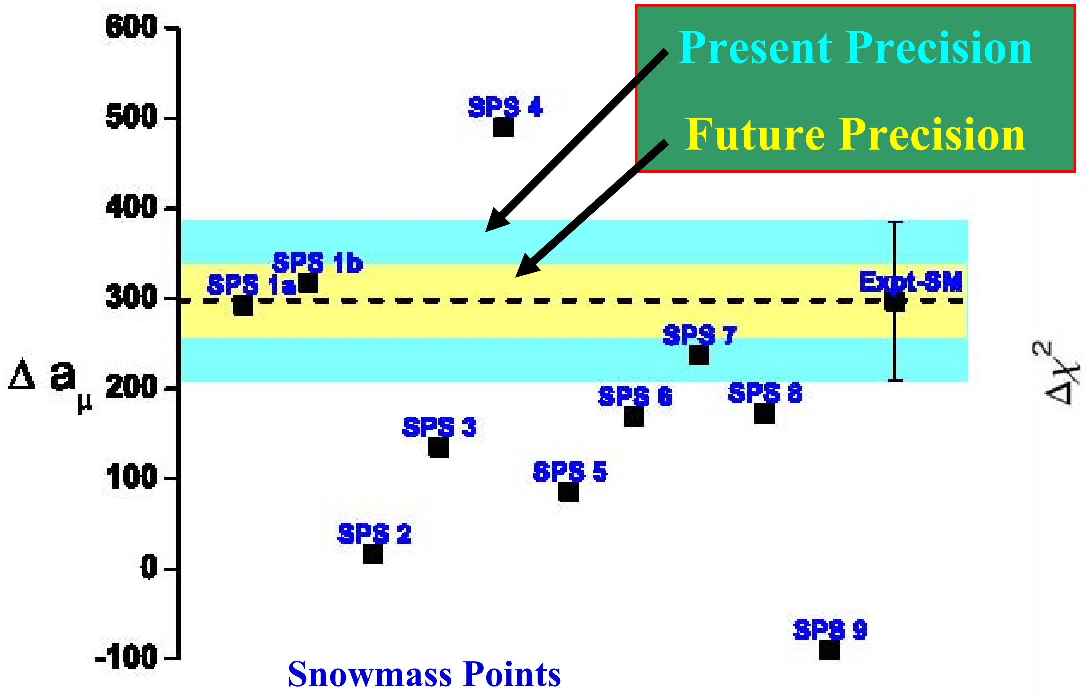
g-2: Anomalous μ Magnetic Moment a_μ

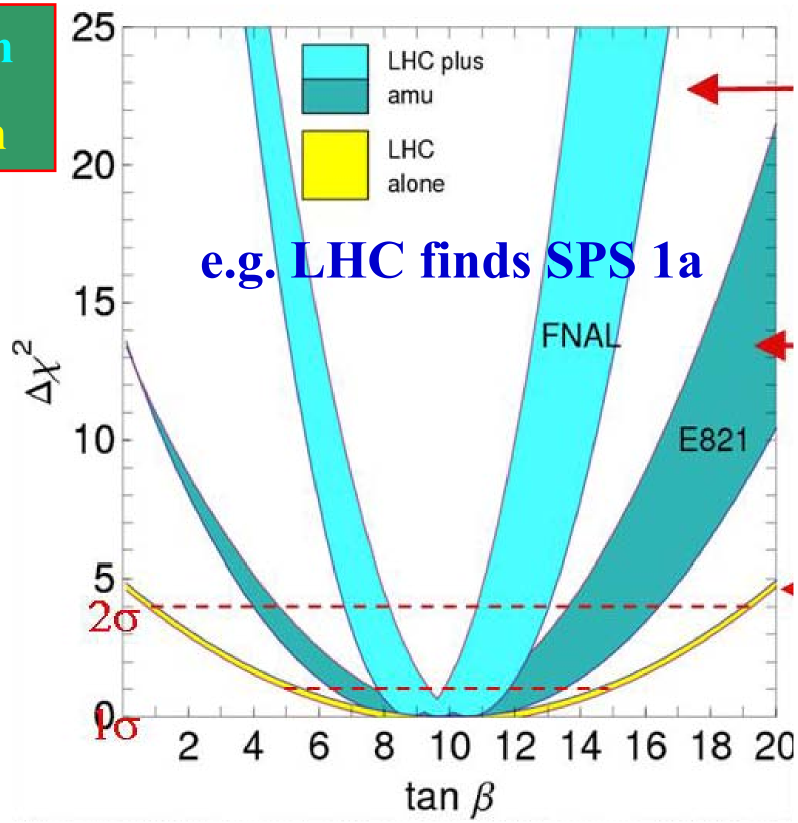
- Muon $a_l \neq 0$ due to radiative corrections; could come from BSM particles.
- Muon anomaly ~750 x e anomaly but more susceptible to heavy virtual particles ~ $(m_l/M)^2$.
- Connection to LFV in SUSY slepton mixing



$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

g-2: BSM models and LHC





- Can already discriminate between various models and parameter space.
- Can be combined with LHC measurements to constrain parameter space

g-2: Predictions and Results

$$a_l^{SM} = a_l^{QED} + a_l^{had,LO} + a_l^{had,HO} + a_l^{weak}$$

$$a_\mu^{QED} = (116584718.09 \pm 0.14) \times 10^{-11}$$

$$a_\mu^{had,LO} = 6901 \pm 42 \pm 19 \pm 7$$

$$a_\mu^{had,HO} = -97.9 \pm 0.9 \pm 0.3$$

$$a_\mu^{weak} = 154 \pm 2 \pm 1$$

$$a_\mu^{had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{R(s)\hat{K}(s)}{s^2} ds$$

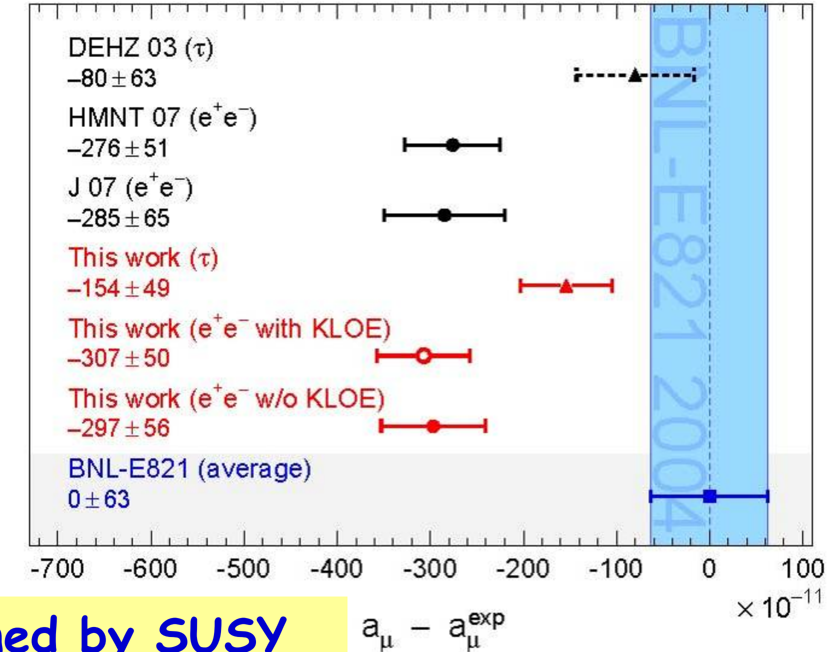
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$a_\mu^{SM}[\tau] = 11659192.6 \pm 4.1 \pm 2.6 \pm 0.2$$

$$a_\mu^{SM}[e^+e^-] = \begin{cases} 11659177.3 \pm 4.3 \pm 2.6 \pm 0.2 \\ 11659178.3 \pm 5.0 \pm 2.6 \pm 0.2 \end{cases}$$

$$a_\mu^{exp} = 11659208.0 \pm 6.3$$

$$a_\mu^{exp} - a_\mu^{SM} = \begin{cases} 15.4 \pm 8.0 (\tau) \\ 30.7 \pm 8.1 \text{ (e}^+\text{e}^- \text{ with KLOE)} \\ 29.7 \pm 8.5 \text{ (e}^+\text{e}^- \text{ w/o KLOE)} \end{cases}$$



1.7-3.0σ deviation: Δa could be explained by SUSY

g-2: The Future

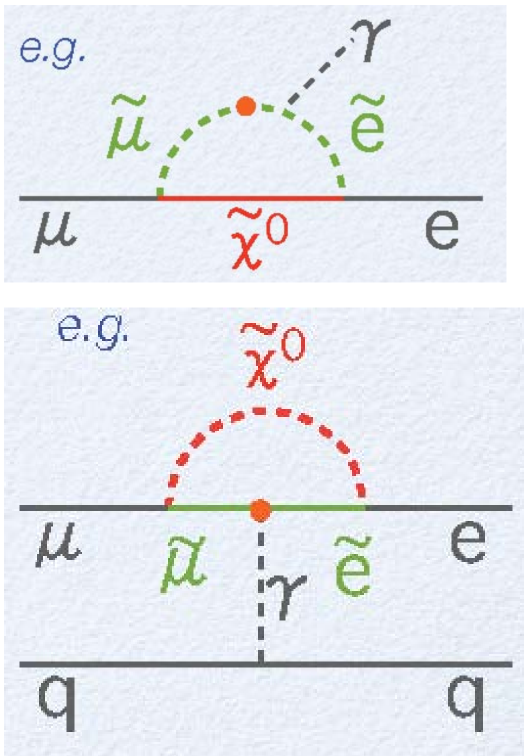
- Currently
  - Experimental accuracy 0.46 (stat)+/- 0.28 (syst)= 0.54 ppm (4.4×10^{-10})
  - Theory accuracy ~0.6 ppm (~6×10^{-10})
  - Lattice accuracy ~1.5 ppm: $a_\mu^{(had,LO)} = (715\pm15)\times 10^{-10}$ (from 2007, MILC)
- Near Future 2012:
  - ISR analyses from BaBar/Belle (see EPS09 possibly)
  - Resonance scans BaBar/Belle
  - KLOE-2
  - VEPP-2000: up to sqrt(s) = 2 GeV
  - BES III tau-charm factory
  - Total error by 2012: Reduce error by factor 2 to 3.0×10^{-10}?
- Further Future:
  - SuperB/BelleII
    - ISR and resonance scans.
  - E821->E989
    - Double statistics but then need more muons to be feasible.
  - JPARC/E989/Project X
    - Aim for 0.1(stat) +/-0.07 (syst) ppm
    - Reduce total error by another factor 2 -> 1.5×10^{-10}
    - Need more muons -> MICE
    - Possiibility to measure muon EDM. Sensiitivity 10^{-19} e cm $\rightarrow$ 10^{-22}-10^{-24} e cm

$\mu \rightarrow e\gamma$ and $\mu N \rightarrow eN$

μ→eγ and μN→eN conversion

- CLFV very rare in SM ~ 10^{-54}
- SUSY-GUT models etc… can enhance this in μ→e to 10^{-15} – 10^{-11}

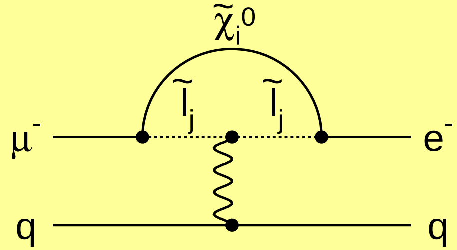
$$B^{GUT}(\mu \to e\gamma) = \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$



- Experimental Advantages
  - High Muon Flux
  - Leptonic Decay process

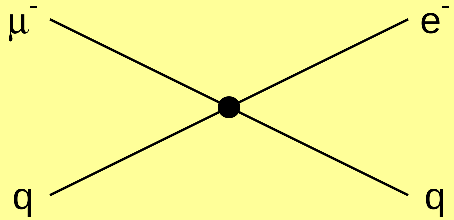
μN→eN: Sensitive to many sources of New Physics

Supersymmetry



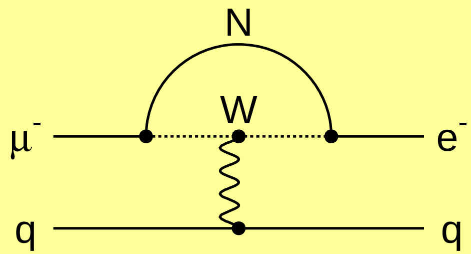
Predictions at 10^{-13}

Compositeness



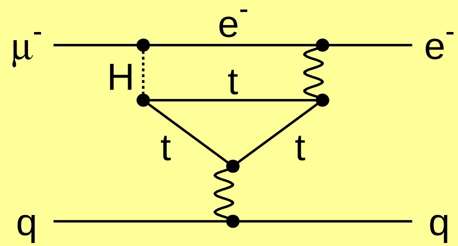
$$\Lambda_c \approx 3000\ \text{TeV}$$

Heavy Neutrinos



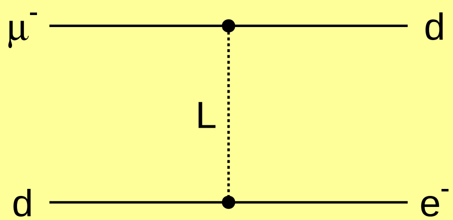
$$\left|U^*_{\mu N} U_{eN}\right|^2 \approx 8 \times 10^{-13}$$

Second Higgs doublet



$$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$$

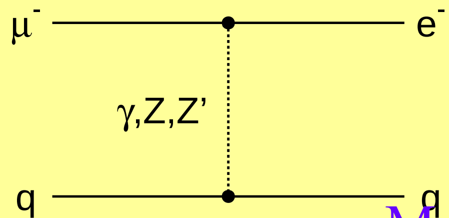
Leptoquarks



$$M_L \approx 3000 \sqrt{\lambda_{\mu d} \lambda_{ed}}\ \text{TeV/c}^2$$

Heavy Z'

Anomalous Z coupling



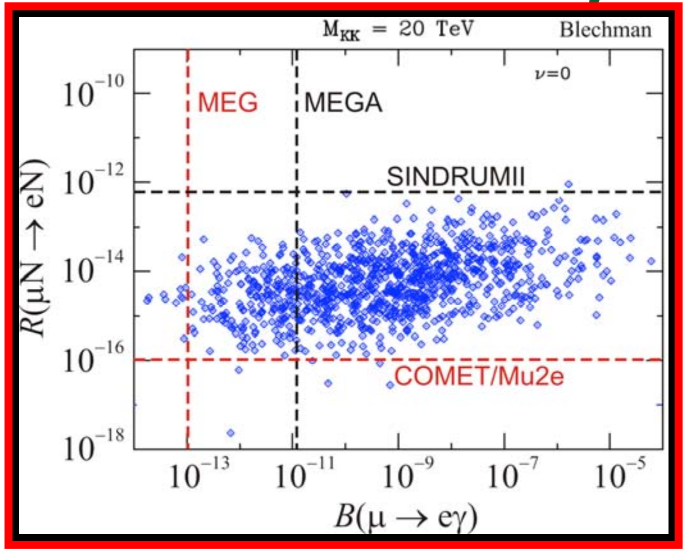
$$M_{Z'} \approx 3000\ \text{TeV}/c^2$$

$$@\ B(Z \to \mu e) < 10^{-17}$$

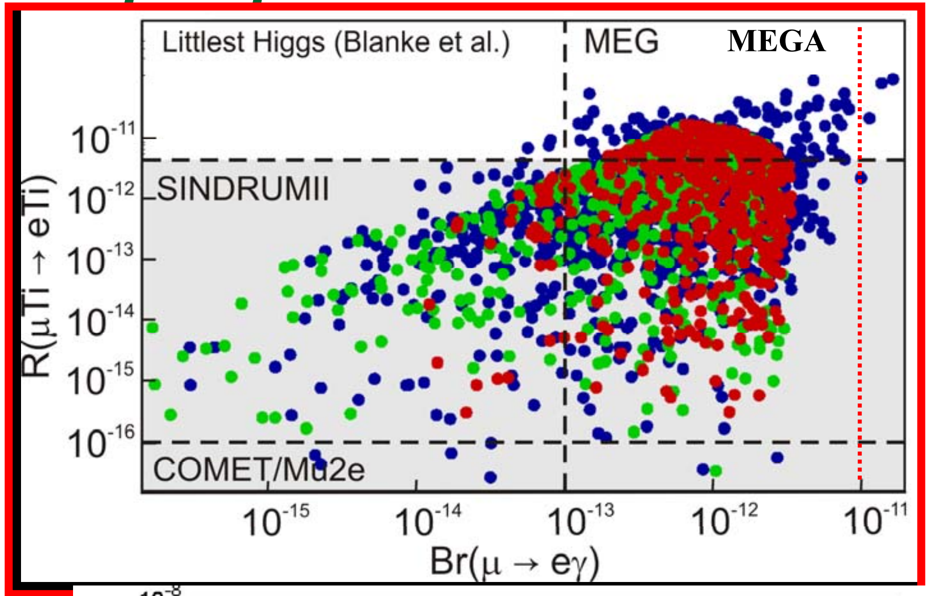
(a la Marciano)

μ→e : already challenging BSM

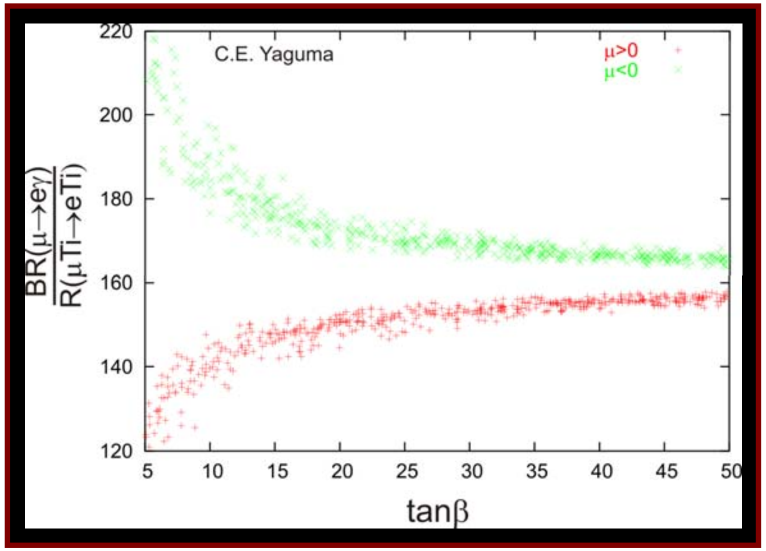
Randall-Sundrum



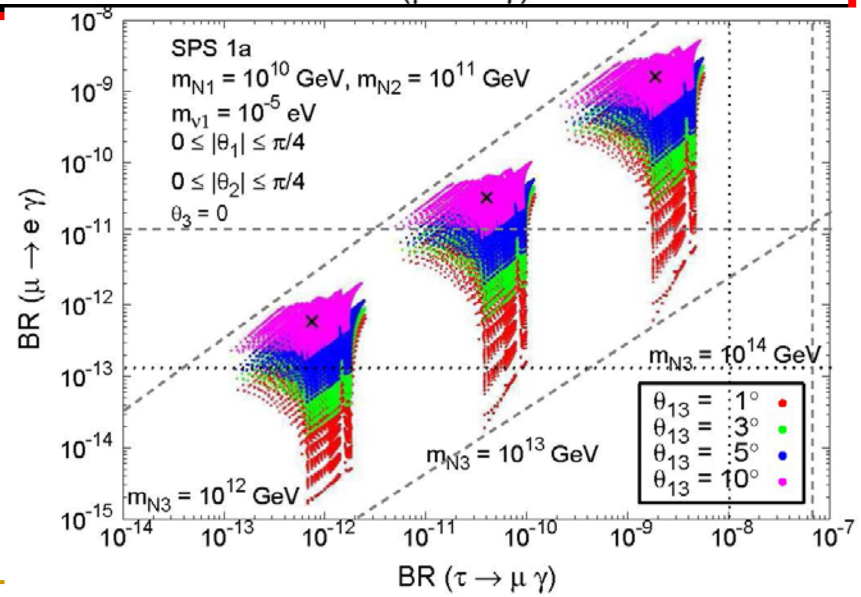
Littlest Higgs w T-parity



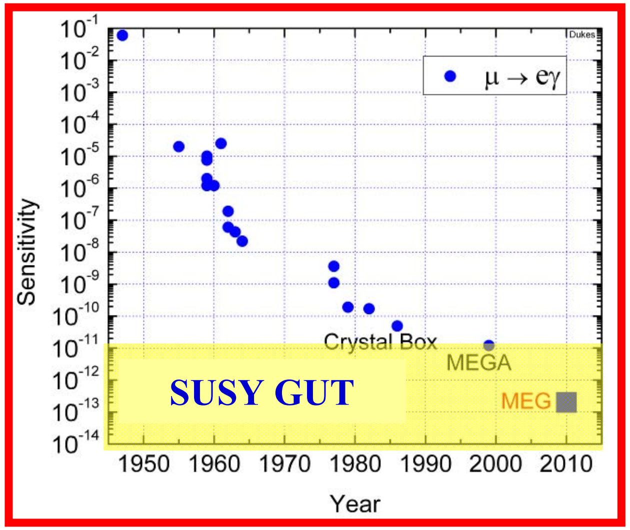
MSSM w mSUGRA bc



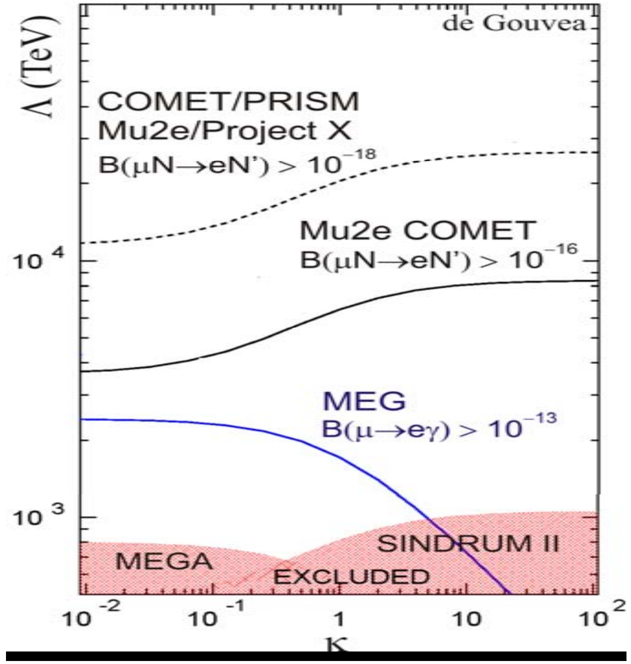
CMSSM-seesaw

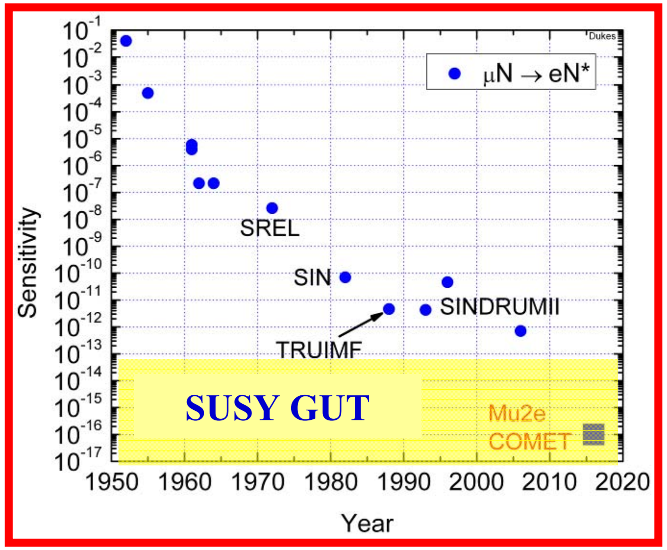


μ→e : Future precision

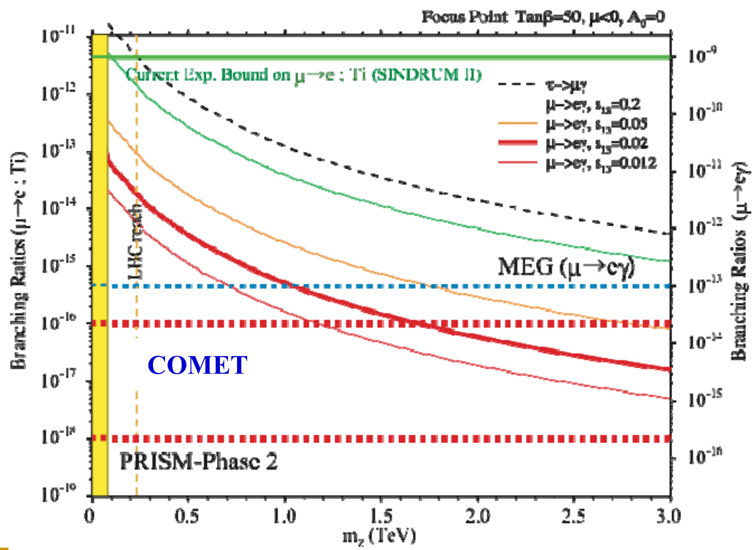


Rates indicate type of interaction e.g. new particle in a loop versus a four-fermion point interaction.





Sensitive to scales above LHC



μ→e: The Future

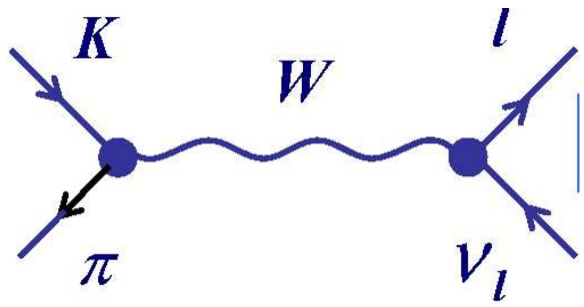
Experiment	Where	Mode	Limit	Date	Status
SINDRUMII	PSI	$\mu^- Au \to e^- Au$	$< 7.0 \times 10^{-13}$	2001	Finished
MEGA	LAMPF	$\mu^- \to e^- \gamma$	$< 1.2 \times 10^{-11}$	1999	Finished
MEG	PSI	$\mu^- \to e^- \gamma$	$< 10^{-13}$	2009 – 2011	Starting
COMET	JPARC	$\mu^- Al \to e^- Al$	$< 10^{-16}$	2016 – ?	Proposed
Mu2e	FermiLab	$\mu^- Al \to e^- Al$	$< 10^{-16}$	2018 – ?	Approved
PRISM	JPARC	$\mu^- Ti \to e^- Ti$	$< 10^{-18}$	2018 – ?	Proposed

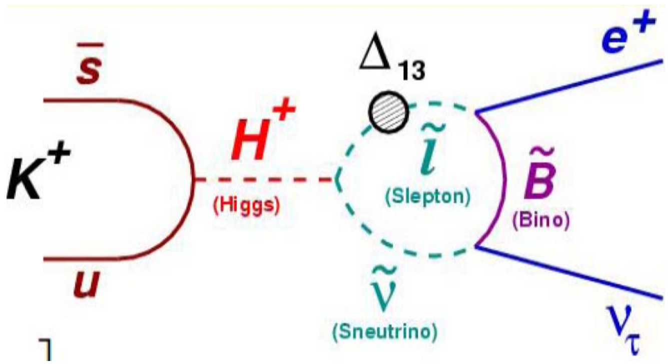
- MEG starting to take data.
- Mu2e approved (but long-term funding uncertain?).
- UK interest:
  - COMET has CDR before JPARC PAC (June 09).
  - PRISM after COMET but has UK accelerator interest (muon, FFAG etc...)

Kaon decays

Kaon decays and ratios

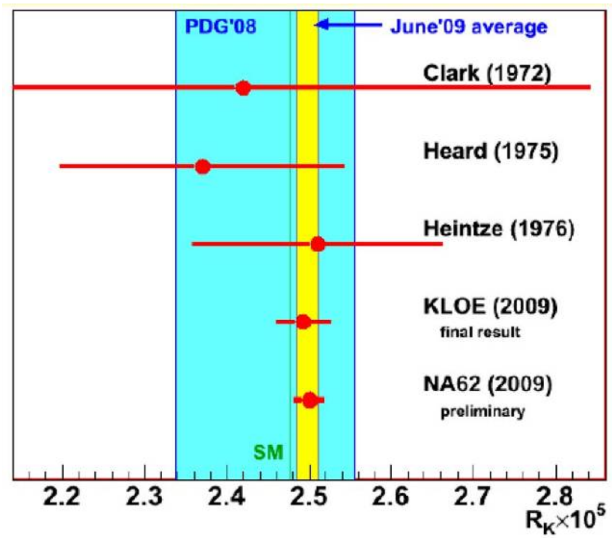
- SM predictions (plus theoretical input and corrections) exist for:
  - $BF(M^- \to l^- \upsilon)$
  - $BF(K \to l \pi \upsilon(\gamma))$
  - $BF(K^-, \pi^- \to l^- \upsilon(\gamma))$
- *Charged Higgs will change the BF.*
- LFV of a few % possible with reasonable parameters.
- Measure BF and ratios (ratios eliminate many theoretical uncertainties);
  1. $R = K_{\mu 2(\gamma)} / \pi_{\mu 2(\gamma)} \to V_{us} / V_{ud}$
  2. $R_K = K_{e2(\gamma)} / K_{\mu 2(\gamma)} \to LU$
     - $\Delta r = R_K(exp) - R_K(SM) \to$ New Physics?
  3. $r_{\mu e} = K_{\mu 3} / K_{e3} \to LU$
  4. $R_{l23} = K_{\mu 2} / K_{\mu 3} \to LU$

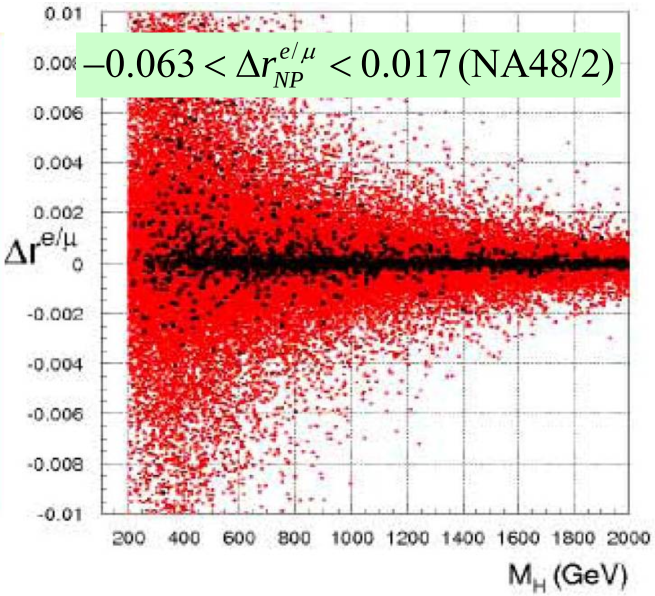




K: Status

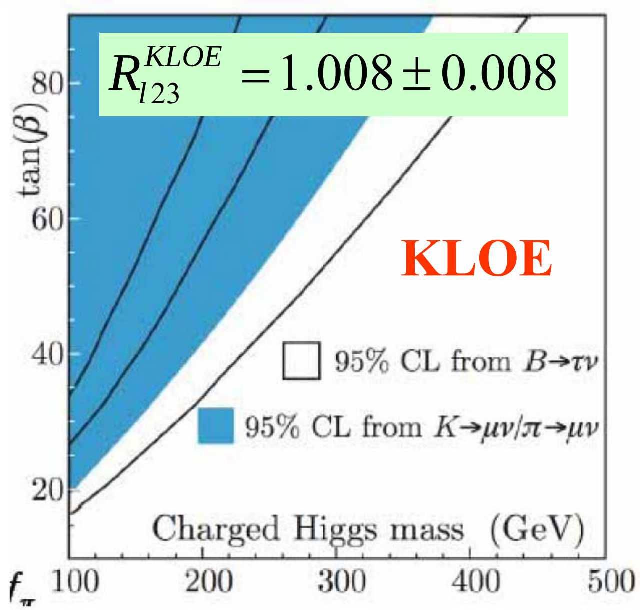
$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$
$$R_K^{NA62} = (2.500 \pm 0.016) \times 10^{-5}$$
$$R_K^{KLOE} = (2.493 \pm 0.032) \times 10^{-5}$$

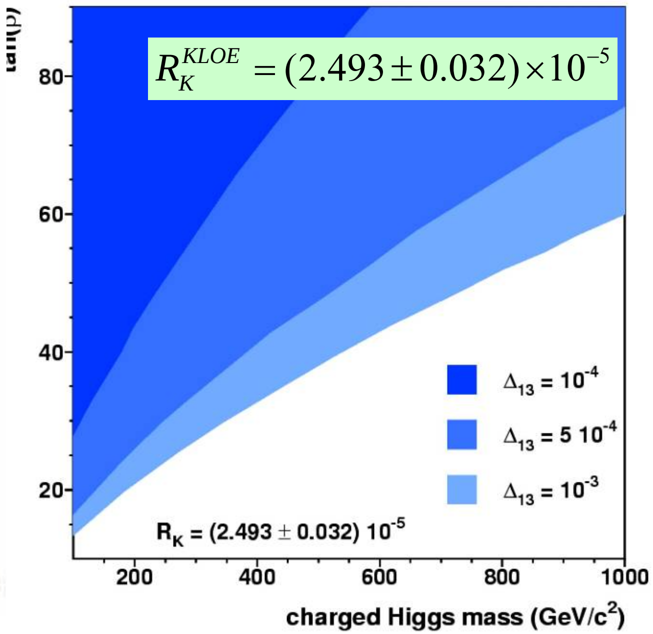




$$r_{\mu e}^{SM} = 1$$

$$r_{\mu e} = \left(\frac{G_\mu}{G_e}\right)^2 = 1.008 \pm 0.005$$





$$1\text{-}V_{ud}^2 - V_{us}^2 = (4 \pm 7) \times 10^{-4}$$

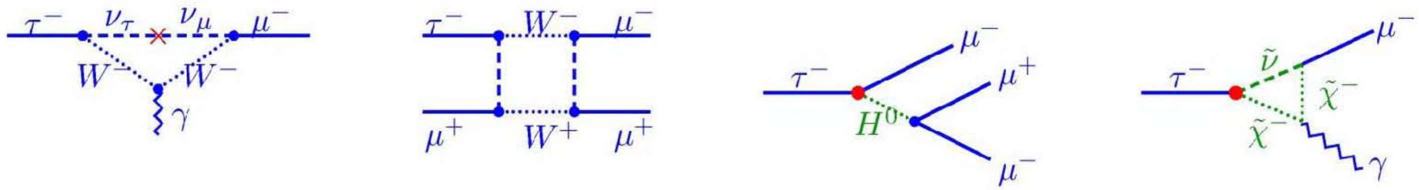
Kaon: The Future

- KLOE 2 Step 0 (5-10 fb^{-1})
  - Run with increased lumi from now.
  - V_{us} error: 0.3% (now) $\rightarrow$ 0.17%
  - $1-|V_{us}|^2-V_{ud}|^2$ error: 7×10^{-4} (now) $\rightarrow$ $3\text{-}4\times10^{-4}$
  - R_K error: 1.3% (now) $\rightarrow$ 0.6% (in 5 fb^{-1})?
- NA62-I
  - Data already in hand
  - R_K error: 0.7% (now) $\rightarrow$ 0.4% (full dataset)
- NA62-II
  - Construction 2009-2012
  - Run 2012-2015
  - R_K error: 0.4% (NA62-I) $\rightarrow$ 0.2%

τ decays

τ : LFV in τ decays

- Many different BSM models and predictions to test
- Predicted rates are several orders of magnitude higher than μ rates



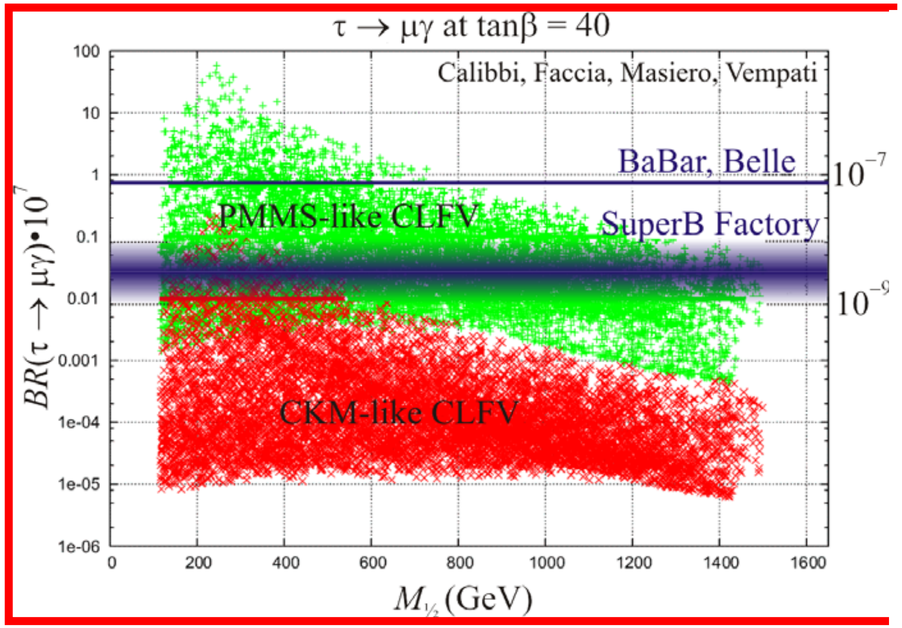
Model	$\tau \to \ell\gamma$	$\tau \to \ell\ell\ell$	Ref.
SM + lepton mixing	10^{-40}	10^{-14}	hep-ph/9810484
SM + left-h. heavy Dirac neutrino	$< 10^{-18}$	$< 10^{-18}$	SJNP25(1977)340
SM + right-h. heavy Majorana neutrino	$< 10^{-9}$	$< 10^{-10}$	PRD66(2002)034008
SM + left and right-h. neutral singlets	$< 10^{-8}$	$< 10^{-9}$	PRD66(2002)034008
mSUGRA + seesaw	$< 10^{-7}$	$< 10^{-9}$	hep-ph/0206110, hep-ph/9911459, etc
SUSY $SU(5)$	$< 10^{-4}$		hep-ph/0303071
SUSY flipped $SU(5)$	$< 10^{-7}$		hep-ph/0304130
SUSY $SO(10)$	$< 10^{-8}$	$< 10^{-10}$	hep-ph/0209303, hep-ph/0304190
SUSY anomalous $U(1)$	$< 10^{-7}$		hep-ph/0308093
neutral SUSY Higgs	$< 10^{-10}$	$< 10^{-7}$	hep-ph/0304081
charged SUSY Higgs triplet		$< 10^{-7}$	hep-ph/0209170
MSSM+nonuniversal soft SUSY breaking	$< 10^{-10}$	$< 10^{-6}$	hep-ph/0305290
Non universal Z' (technicolor)	$< 10^{-9}$	$< 10^{-8}$	PLB547(2002)252
two Higgs doublet III	$< 10^{-15}$	$< 10^{-17}$	hep-ph/0208117
extra dimensions	$< 10^{-11}$		hep-ph/0210021

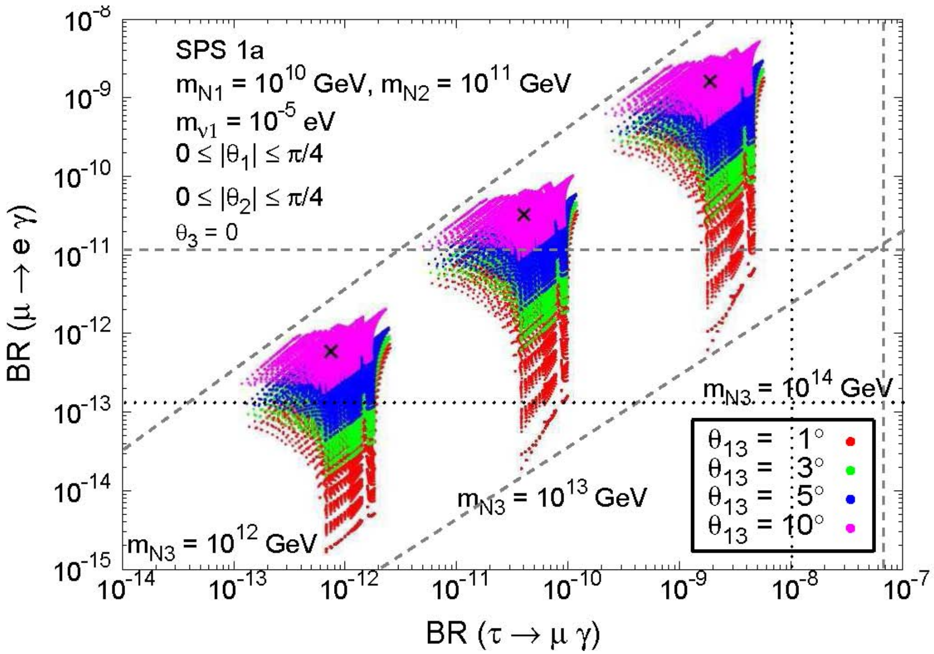
τ : Why look at τ LFV as well as μ?

- Rates are higher than μ
- Many BSM predictions already at experimental precision e.g. 31 decays measured at B Factories at ~ 10^{-8} level
- The τ and μ LFV predictions are often coupled

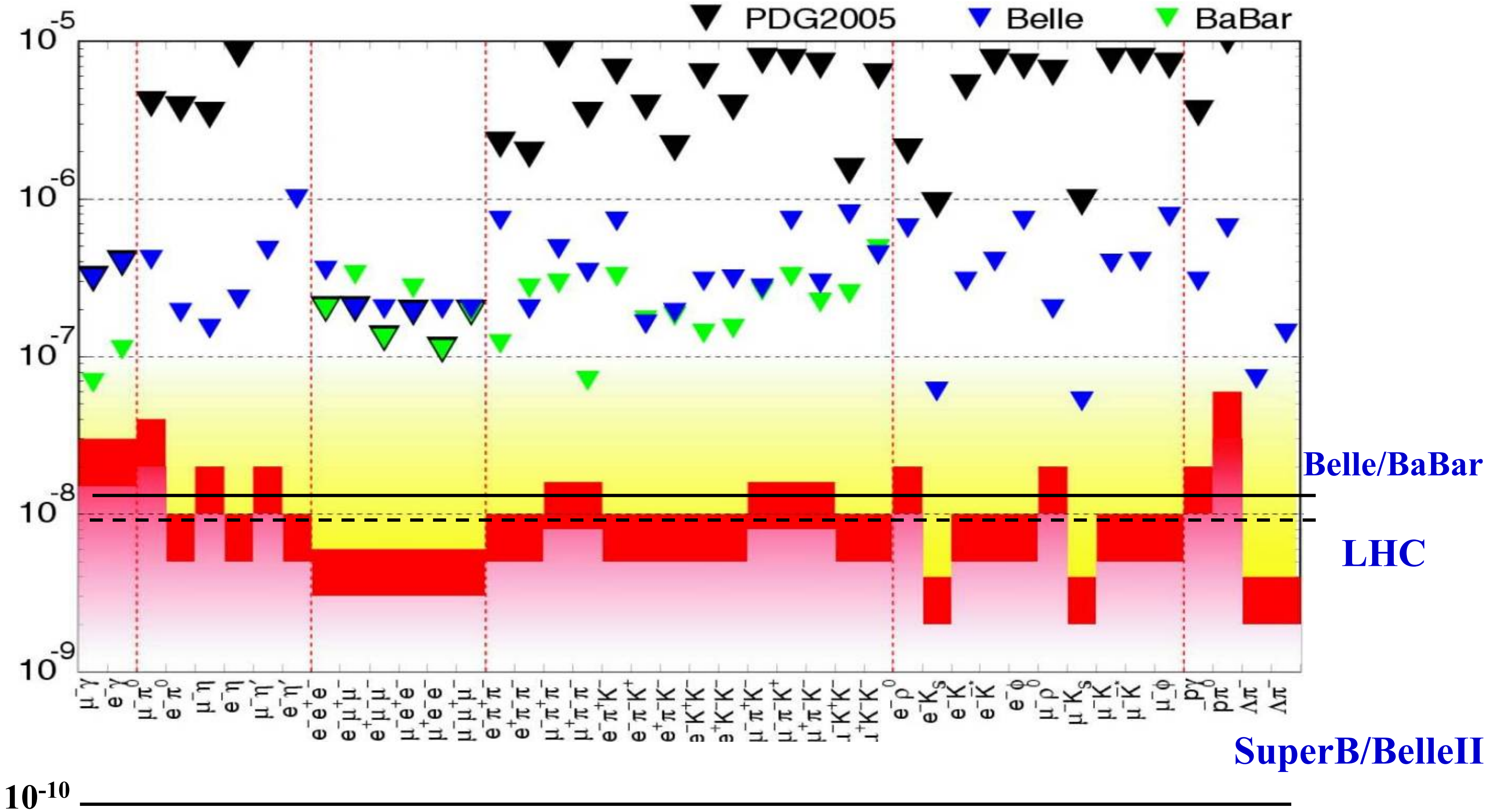
Some B-Factory τ LFV measurements

Channel	UL (90%)	Channel	UL (90%)
$\mathcal{B}(\tau^+ \to e^+e^-e^+)$	2.9×10^{-8}	$\mathcal{B}(\tau^- \to \mu^- K^0_S)$	4.0×10^{-8}
$\mathcal{B}(\tau^+ \to e^+e^-\mu^+)$	2.2×10^{-8}	$\mathcal{B}(\tau^- \to e^- K^0_S)$	3.3×10^{-8}
$\mathcal{B}(\tau^+ \to e^+e^+\mu^-)$	1.8×10^{-8}	$\mathcal{B}(\tau^- \to \mu^-\omega)$	1.0×10^{-7}
$\mathcal{B}(\tau^+ \to e^+\mu^-\mu^+)$	3.2×10^{-8}	$\mathcal{B}(\tau^- \to e^-\omega)$	1.1×10^{-7}
$\mathcal{B}(\tau^+ \to e^+\mu^+\mu^+)$	2.6×10^{-8}	$\mathcal{B}(\tau^- \to \mu^-\gamma)$	4.5×10^{-8}
$\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+)$	3.3×10^{-8}	$\mathcal{B}(\tau^- \to e^-\gamma)$	12.0×10^{-8}
		$\mathcal{B}(\tau^- \to e^-\eta)$	9.2×10^{-8}
		$\mathcal{B}(\tau \to \mu^-\eta)$	6.5×10^{-8}
$\mathcal{B}(\tau \to e\phi)$	3.1×10^{-8}	$\mathcal{B}(\tau \to \mu\phi)$	19.0×10^{-8}
$\mathcal{B}(\tau \to e\rho)$	4.6×10^{-8}	$\mathcal{B}(\tau \to \mu\rho)$	2.6×10^{-8}
$\mathcal{B}(\tau \to eK^*)$	5.9×10^{-8}	$\mathcal{B}(\tau \to \mu K^*)$	17.0×10^{-8}
$\mathcal{B}(\tau \to e\overline{K}^*)$	4.6×10^{-8}	$\mathcal{B}(\tau \to \mu\overline{K}^*)$	7.3×10^{-8}





τ : The experimental landscape



τ : Lepton Universality and Charged Higgs

Compare to LU from Kaon decays, page 19

About factor 2 more accurate than Kaon modes.

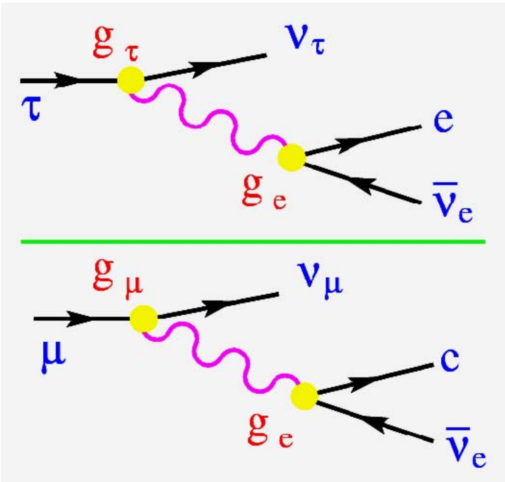
$$\left(\frac{g_e}{g_\mu}\right)^2 = \frac{B(\tau \to e\nu\nu)}{B(\tau \to \mu\nu\nu)} \frac{(1+C^{rad}_{\tau e})}{(1+C^{rad}_{\tau\mu})}$$

$$\left(\frac{g_e}{g_\tau}\right)^2 = \frac{(1+C^{rad}_{\tau\mu})}{(1+C^{rad}_{\tau e})} \frac{\tau_\tau}{\tau_\mu} \left(\frac{m_\tau}{m_\mu}\right)^5 B(\tau \to \mu\nu\nu)$$

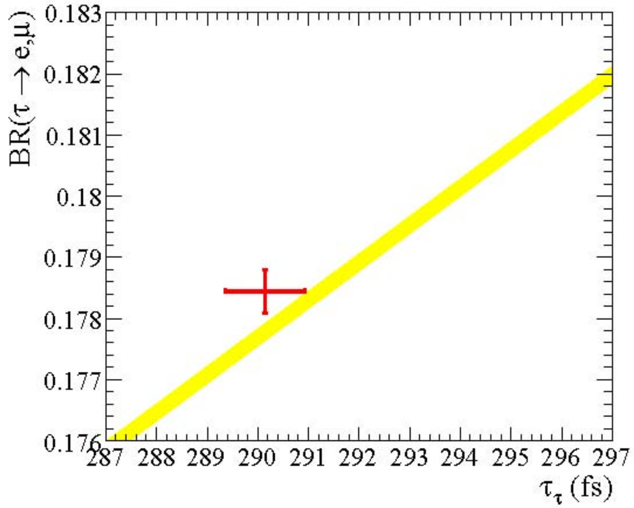
$$r_{\mu e} = \frac{\Gamma(\tau \to \mu\nu\bar{\nu})}{\Gamma(\tau \to e\nu\bar{\nu})}$$

$$\approx 1 - 10^{-3} \left(\frac{\tan\beta}{50}\right)\left(\frac{200GeV}{M_{H^+}}\right)^2$$

	$\lvert g_\mu/g_e \rvert$
$B_{\tau\to\mu}/B_{\tau\to e}$	1.0000 ± 0.0020
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	1.004 ± 0.007
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.002 ± 0.002
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.010
	$\lvert g_\tau/g_\mu \rvert$
$B_{\tau\to e}\,\tau_\mu/\tau_\tau$	1.0006 ± 0.0022
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.996 ± 0.005
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.979 ± 0.017
$B_{W\to\tau}/B_{W\to\mu}$	1.039 ± 0.013
	$\lvert g_\tau/g_e \rvert$
$B_{\tau\to\mu}\,\tau_\mu/\tau_\tau$	1.0005 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.036 ± 0.014

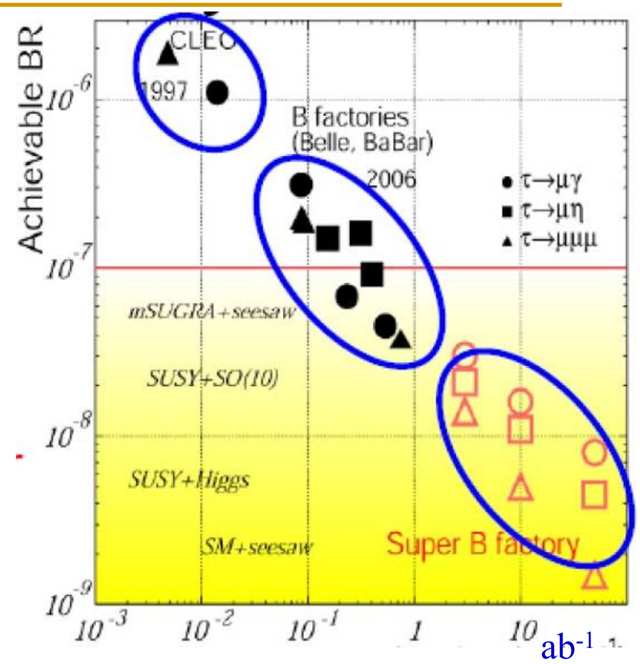


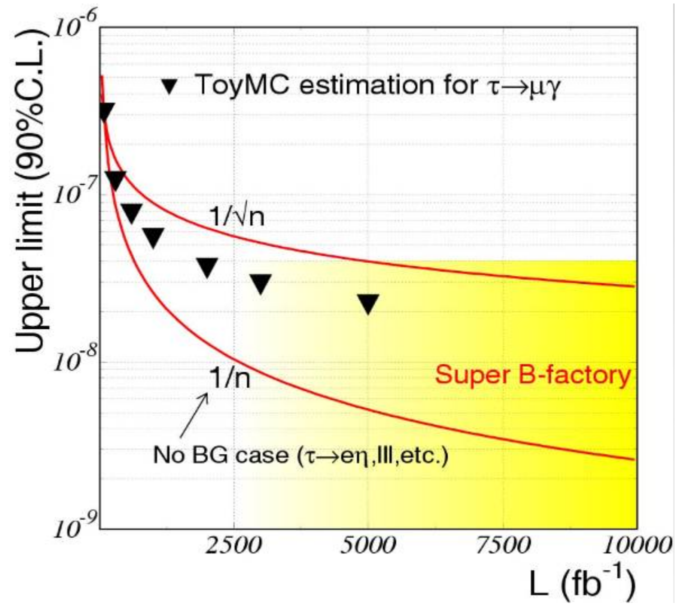
Tests LU at 0.2%



τ : The Future

- Next 1-2 years
  - BaBar, Belle (~1.5×10^{9} tau pairs).
  - LHCb:
    - $\tau\to\mu\mu\mu < 1.2\times10^{-7}$ in 2 fb^{-1}
- Next ~5 years
  - ATLAS/CMS
    - $\tau\to\mu\mu\mu$ (W-source) $< 3.8\times10^{-8}$ in 30 fb^{-1}
    - $\tau\to\mu\mu\mu$ (W+Z-source) $<$ 1-2×10^{-8} in 300 fb^{-1}
  - LHCb
    - $\tau\to\mu\mu\mu < 2.0\times10^{-8}$ in 10 fb^{-1}
- Next 10 years
  - SuperB/BelleII (~7.5×10^{10} tau pairs, 50-75 ab^{-1})
    - $\tau\to\mu\mu\mu < 1\times10^{-9}$ -1×10^{-10}
    - $\tau\to l\gamma < 1\times10^{-8}$ -1×10^{-9}
    - $\tau\to l\upsilon\upsilon$ LU at 0.02% (statistical).
  - LHC upgrade
    - LHCb: $\tau\to\mu\mu\mu < 1\times10^{-8}$ in 100 fb^{-1}
    - ATLAS: Improved trigger + detector should extend $\tau\to\mu\mu\mu$ but work not yet complete
- Next 20 years
  - GLC and GigaZ



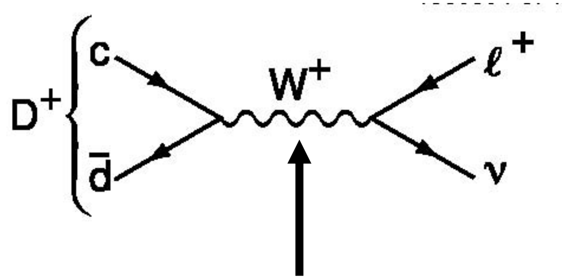


Charm

$D^+_{(s)} \to l^+ \upsilon$ and Charged Higgs

$$\Gamma(D^+_{(s)} \to l^+\upsilon) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} m_l^2 M_{D^+_{(s)}} \left(1 - \frac{m_l^2}{m^2_{D^+_{(s)}}}\right)^2 \left|V_{c(d,s)}\right|^2$$

$$R^{\tau/\mu}_{D_{(s)}} = \frac{\Gamma(D^+_{(s)} \to \tau^+\upsilon)}{\Gamma(D^+_{(s)} \to \mu^+\upsilon)} = \frac{m_\tau^2\left(1 - m_\tau^2 / m^2_{D^+_{(s)}}\right)^2}{m_\mu^2\left(1 - m_\mu^2 / m^2_{D^+_{(s)}}\right)^2}$$



Charged Boson can contribute

SM Predictions

$$BF(D^+ \to e^+\nu) < 9.2\times10^{-9}$$

$$BF(D_S^+ \to e^+\nu) < 1.3\times10^{-7}$$

$$R_D^{\tau\mu} = 2.65$$

$$R_{D_S}^{\tau\mu} = 9.76$$

CLEO results:

$BF(D^+ \to \mu^+\upsilon) = (3.93 \pm 0.35 \pm 0.10)\times10^{-4}$

$BF(D^+ \to e^+\upsilon) < 8.8\times10^{-6}$

$BF(D^+ \to \tau^+\upsilon) < 2.1\times10^{-3}$

$BF(D_S^+ \to \mu^+\upsilon) = (6.57 \pm 0.90 \pm 0.34)\times10^{-3}$

$BF(D_S^+ \to \tau^+\upsilon) = (6.29 \pm 0.78 \pm 0.52)\times10^{-2}$

$R_{D_S}^{\mu,\tau} = 11.74 \pm 1.7 \pm 0.2$

$BF(D_S^+ \to e^+\upsilon) < 1.2\times10^{-4}$

Belle:

$BF(D_S^+ \to \mu^+\upsilon) = (6.44 \pm 0.76 \pm 0.57)\times10^{-3}$

Charm: The Future

- Lattice QCD
  - Already have high precision D and D_s decay constants (error lower than experiment).
- BES-III $D \rightarrow l\upsilon$
  - Goal 12x (4x) Cleo-c D (D_s) dataset
  - Factor 2-3 improvement in statistical error
  - Statistical error should then equal current Cleo-c systematic error.
- BES-III $D \rightarrow h\ l^+l^{-\prime}$ (e.g. $D \rightarrow K^- \mu^+ e^-$)
  - UL on LFV decays improve by 100-1000 over CLEO/FOCUS/D0 etc… with 20 fb^{-1}
- Super B factories $D \rightarrow l\upsilon$
  - Factor 10 improvement in statistical error
  - But needs to work on systematics

B and Υ(nS) decays

$B^0 \to l^+l^-$, $B^0 \to l^+\tau^-$, $B^+ \to l^+\upsilon$

Standard Model:

$$\mathrm{BF}(B^+ \to l^+\upsilon) = \frac{G_F^2 m_B m_l^2}{8\pi}\left[1 - \frac{m_l^2}{m_B^2}\right]\tau_B f_B^2 |V_{ub}|^2$$

SM Prediction:

$$\mathrm{BF}(B^+ \to e^+\upsilon_e) \sim (1.2 \pm 0.3)\times 10^{-11}$$

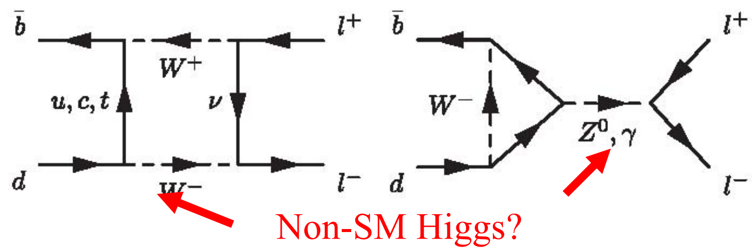
$$\mathrm{BF}(B^+ \to \mu^+\upsilon_\mu) \sim (5.2 \pm 1.3)\times 10^{-7}$$

$$\mathrm{BF}(B^+ \to \tau^+\upsilon_e) \sim (1.59 \pm 0.40)\times 10^{-4}$$

Charged Higgs Effect:

$$BF = BF_{SM} \times r_H, \quad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

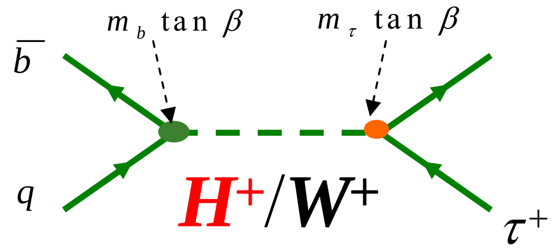
Channel	BF (UL 90%)
$B^0 \to \mu^+\mu^-$	$< 5.2\times 10^{-8}$
$B^0 \to e^+e^-$	$< 11.3\times 10^{-8}$
$B^0 \to e^\pm\mu^\mp$	$< 9.2\times 10^{-8}$
$B^+ \to e^+\upsilon$	$< 1.9\times 10^{-6}$
$B^+ \to \mu^+\upsilon$	$< 1.0\times 10^{-6}$
$B^0 \to e^+\tau^-$	$< 2.8\times 10^{-5}$
$B^0 \to \mu^+\tau^-$	$< 2.2\times 10^{-5}$

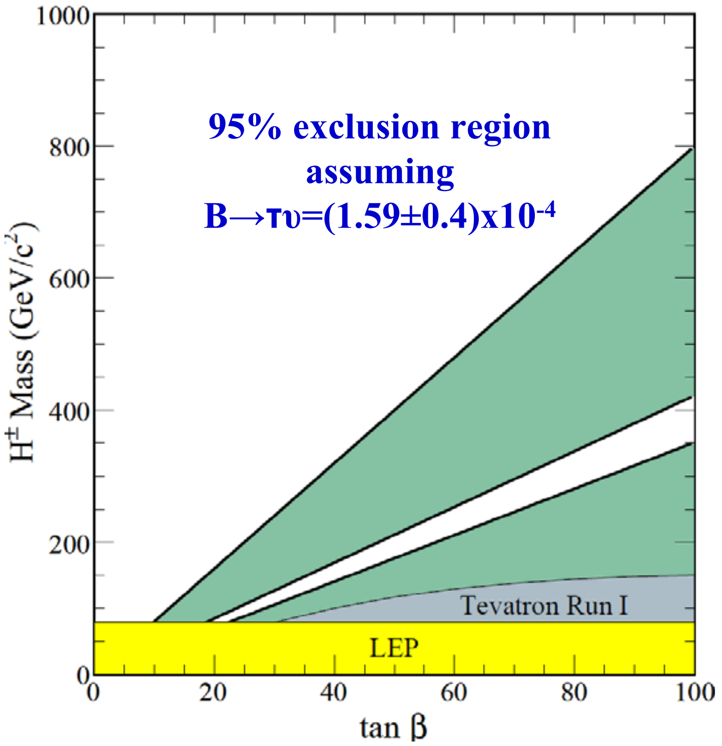


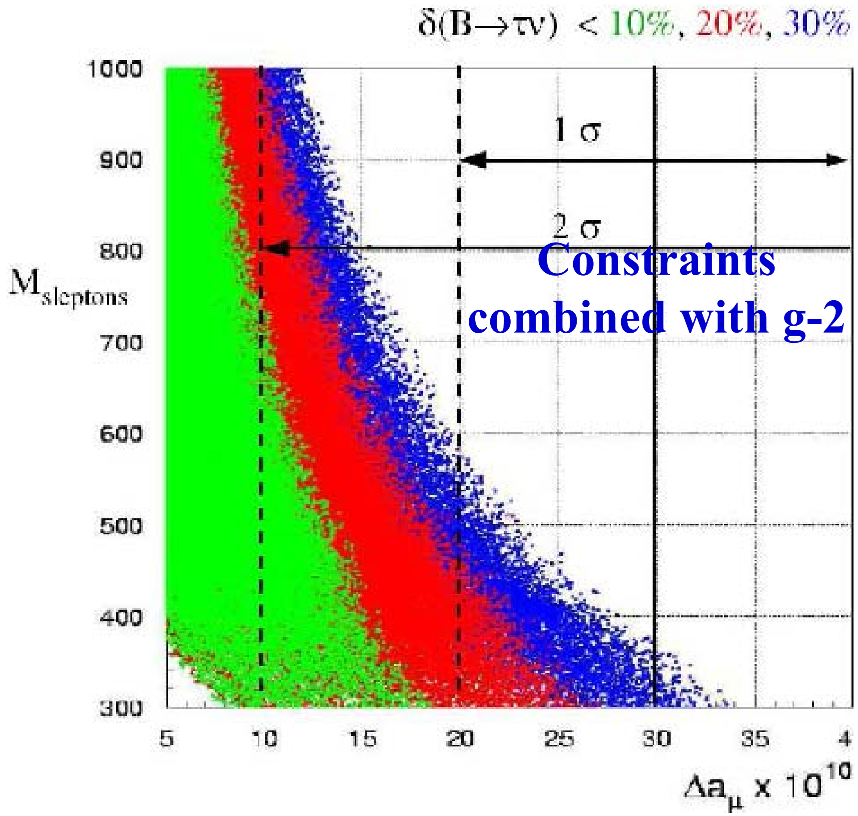
- Error on BF prediction from V_{ub} (~10%) and f_B (~10%)
- $B^+ \to \mu^+\upsilon$ experimental Upper Limit approaching SM prediction
- $B^+ \to \mu^+\upsilon$ with $B^+ \to \tau^+\upsilon$ leads to LU test

$B^- \to \tau^- \upsilon$

- HFAG Average BF($B \to \tau\upsilon$) = (1.73±0.35) x 10^{-4}
- BF on edge of current experimental reach
- Need to reduce error







Lepton Universality and LFV in Υ(nS) decays

- BF(Y(ns)→l+l-) should be independent of flavour l.

$$e^+e^- \to \gamma^* \to \Upsilon^* \to \tau\mu$$

- Υ(nS) and τ LFV decays are related:

$$\frac{B(\Upsilon \to \mu\tau)}{B(\Upsilon \to \tau\tau)} \propto \left(\frac{\alpha_N}{\alpha}\right)^2 \left(\frac{M_\Upsilon}{\Lambda}\right)^4$$

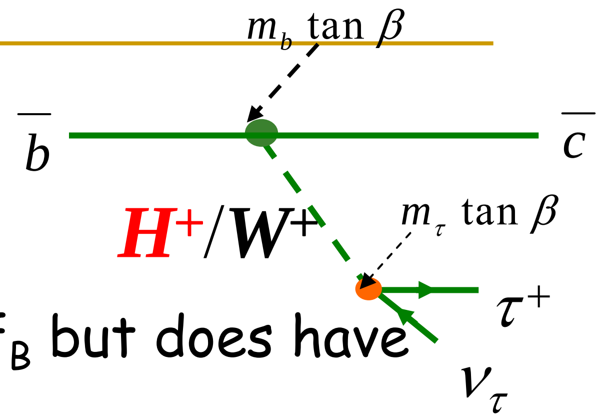
- Sensitive to a low mass CP-odd Higgs, A^0.
- LU Cleo results for R(ττ/μμ):

Mode	$R(\tau\tau / \mu\mu)$
$\Upsilon(1S)$	$= 1.02 \pm 0.02 \pm 0.05$
$\Upsilon(2S)$	$= 1.04 \pm 0.04 \pm 0.05$
$\Upsilon(3S)$	$= 1.07 \pm 0.08 \pm 0.05$

- LFV B Factory UL on R(τμ/μμ):

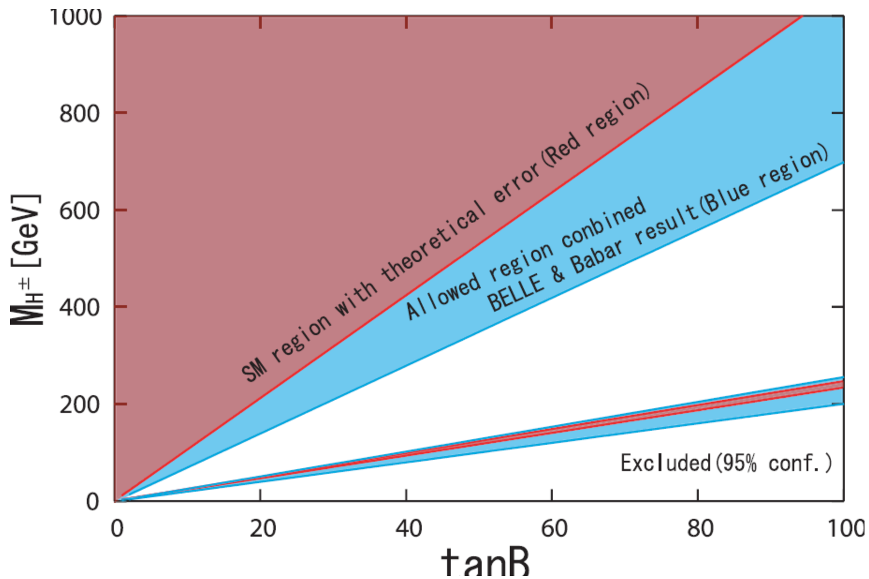
$$\begin{array}{ll} Mode & B(\tau\mu)/B(\mu\mu) \\ \Upsilon(1S) & \left.\begin{array}{l} < 0.023\% \\ < 0.17\% \\ < 0.13\% \end{array}\right\} \Rightarrow \Lambda > 1.5\ \text{TeV} \\ \Upsilon(2S) & \\ \Upsilon(3S) & \end{array}$$

B→Dτυ



- Also sensitive to charged Higgs
- Different theory systematics (no V_{ub} and f_B but does have B→D form factors).
- q^2 and τ polarisation also affected by different BSM.
- Universality between b → cH, b → uH, b→ tH (LHC).

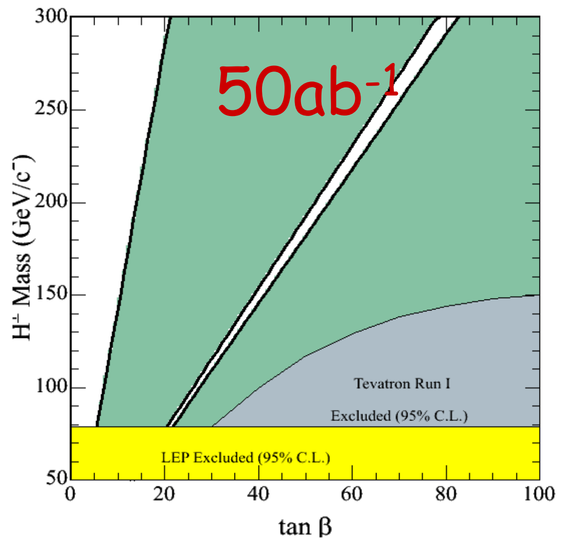
$$BF(B^+ \to D^0\tau^+\upsilon_\tau) = (1.51^{+0.41+0.24}_{-0.39-0.19} \pm 0.15)\%$$
$$BF(B^0 \to D^-\tau^+\upsilon_\tau) = (1.01^{+0.46+0.13}_{-0.41-0.11} \pm 0.10)\%$$
$$BF(B^+ \to D^{*0}\tau^+\upsilon_\tau) = (3.04^{+0.69+0.40}_{-0.66-0.47} \pm 0.22)\%$$
$$BF(B^0 \to D^{*-}\tau^+\upsilon_\tau) = (2.56^{+0.75+0.31}_{-0.66-0.22} \pm 0.10)\%$$



- Deviation from SM: 0.5σ (B^0) and 1.6 σ (B^+)

B decays: The Future

- Need improvement on V_{ub} and f_B.
- LHCb
  - BF($B_s \to e^+\mu^-$) < 6.5×10^{-8} in 2 fb^{-1}; <0.4×10^{-8} in 100 fb^{-1}
  - BF($B \to \tau X$) < 10^{-8} in 10 fb^{-1}
- B factories are a natural place to do this
  - BF($B \to \tau\nu$) ±2%
  - BF($B \to \tau X$) < 10^{-8-9}
  - BF($B \to \mu\nu$) 5σ discovery with 5 fb^{-1}
  - BF($D_s \to \tau\nu$) ±1.5% (charm factory better for $D \to l\nu$).
  - BF($B \to D\tau\nu$) ±2.5%



Effect of H^+ :

- $B \to l\nu$ O(10-30)%
- $B \to D\tau\nu$ O(3-10)%
- $K \to l\nu$ O(0.1-0.3)%

(see Isidori talk)

Lattice QCD : possible 5 - year plan

- Lattice QCD (Form Factors, V_{CKM}, masses) is an important input to some LFV measurements.
- Alternatively, assuming LF conservation, improved experimental precision will drive LQCD.

Process	$K \to \pi l \nu$	$\dfrac{K \to l\nu}{\pi \to l\nu}$	$D, D_s \to l\nu$	$B, B_s \to l\nu$
Lattice Parameter	$f_+(0)$	f_K / f_π	$f_{D_{(s)}}$	$f_{B_{(s)}}$
Current Lattice Error	0.5%	0.6%	2%	6%
Current Exptl. Error	0.2%	0.2%	4%	30%
Future Lattice Error	0.2%	0.3%	0.5%	2%

Concluding Remarks

- There is no one "LFV experiment".
- Highly interconnected set of measurements.
- Many measurements are still statistics dominated but will become theory-dominated with next generation experiments.
- Many SUSY models are already being challenged by LFV and LU measurements.
- We can expect many measurement errors to improve as *luminosity*^{1}.
- Flavour is essential to the understanding of the Higgs (SM and BSM) and SUSY.
- It is important to measure LFV in tau and muon decays as different models predict different relative levels of tau and muon LFV.

Concluding Remarks

- g-2 is still a benchmark measurement. Hadronic uncertainties can be understood from tau, charm, beauty and hadron experiments.
- BSM models can be confirmed/excluded by measuring a set of golden-mode flavour decays.
- The UK has built up a huge expertise in flavour physics over the last decade (both experimental and theoretical).
- Flavour has a successful track record on flavour (on-time, on-budget).
- *A large fraction (30%?) of our community is interested in flavour physics.*
- Flavour is essential for the breadth of the field in the UK.
- Without flavour physics, LHC discoveries will not be complete.