MONASH University

$K \to \pi\nu\bar{\nu}$ and new physics in the neutrinos

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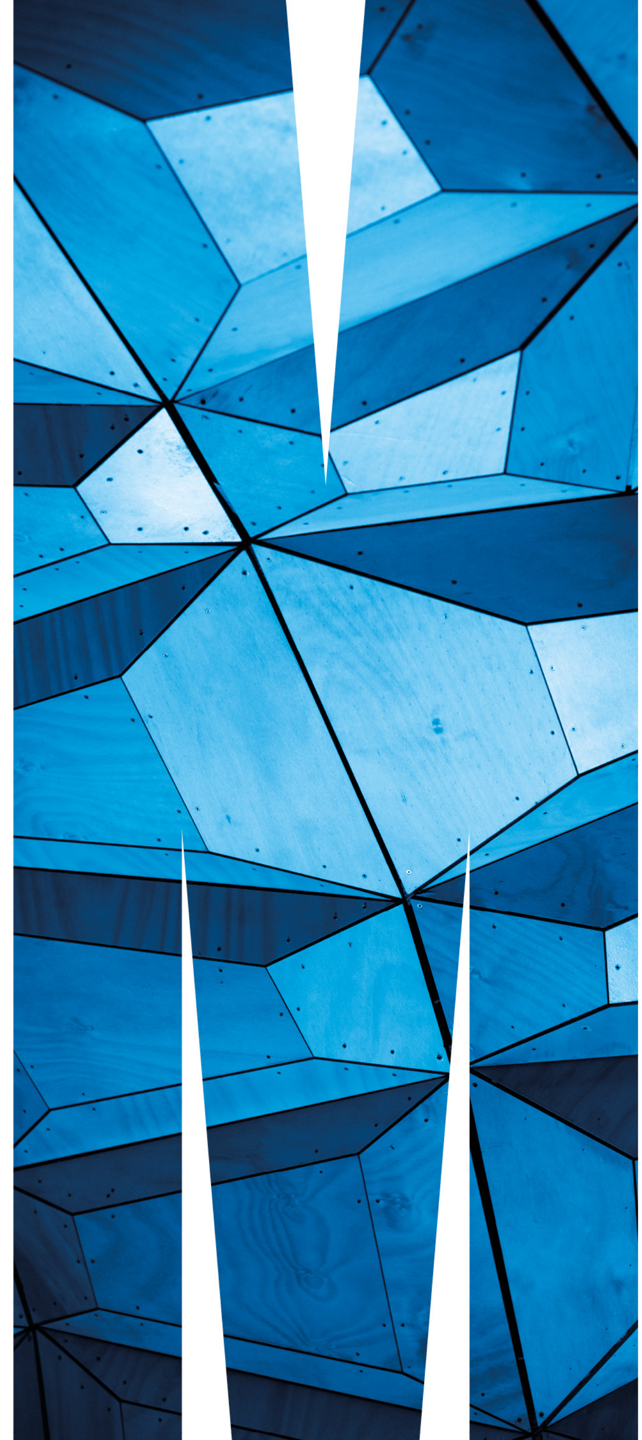
based on:
X-G He, G.V., and Keith Wong Eur.Phys.J. C78 (2018) no.6, 472
X-G He, J. Tandean and G.V. JHEP 1907 (2019) 022
X-G He, J. Tandean and G.V. Phys Let B (2019) 134842



GROUP OF EIGHT AUSTRALIA

new physics in neutrinos and $K \to \pi\nu\bar{\nu}$

- SM calculations of $K \to \pi\nu\bar{\nu}$ are very clean, so precise comparisons to experiment are eventually expected
- here we consider somewhat unusual extensions of the SM that may affect these rare modes through the unobserved neutrinos
- this is in part motivated by the charged B anomalies in $R(D)$, $R(D^\star)$
  - new light sterile neutrino possible explanation
- also motivated by a renewed interest in charged lepton flavour violation experiments
  - SU(2) of SM relates it to neutrino lepton flavour violation

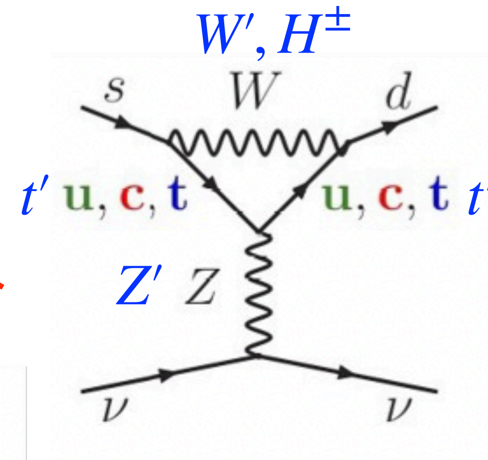
$K \to \pi\nu\bar{\nu}$: SM and 'usual' extensions

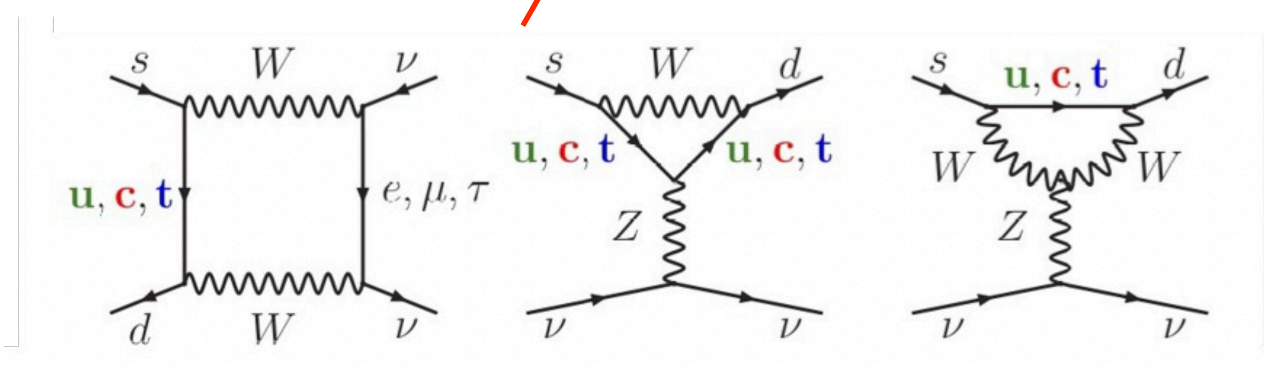
- adding NP to the SM

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi s_W^2} V_{ts}^{\star} V_{td} \bar{s}\gamma_\mu d \left((X(x_t) + X_N) \sum_{\ell} \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell \right)$$

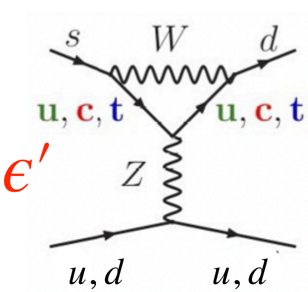
SM (top)

'usual' NP





usually related to ϵ, ϵ'



usual predictions/constraints…

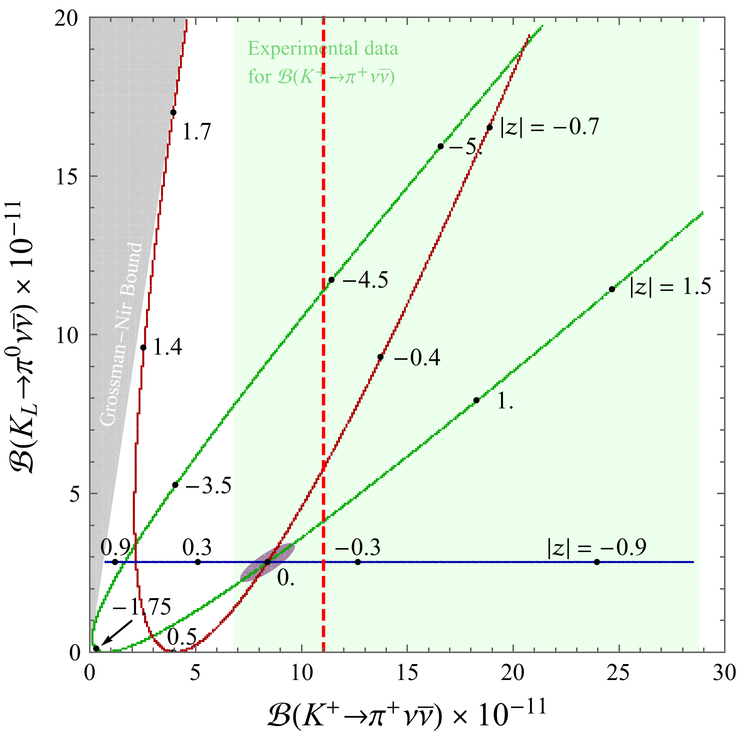


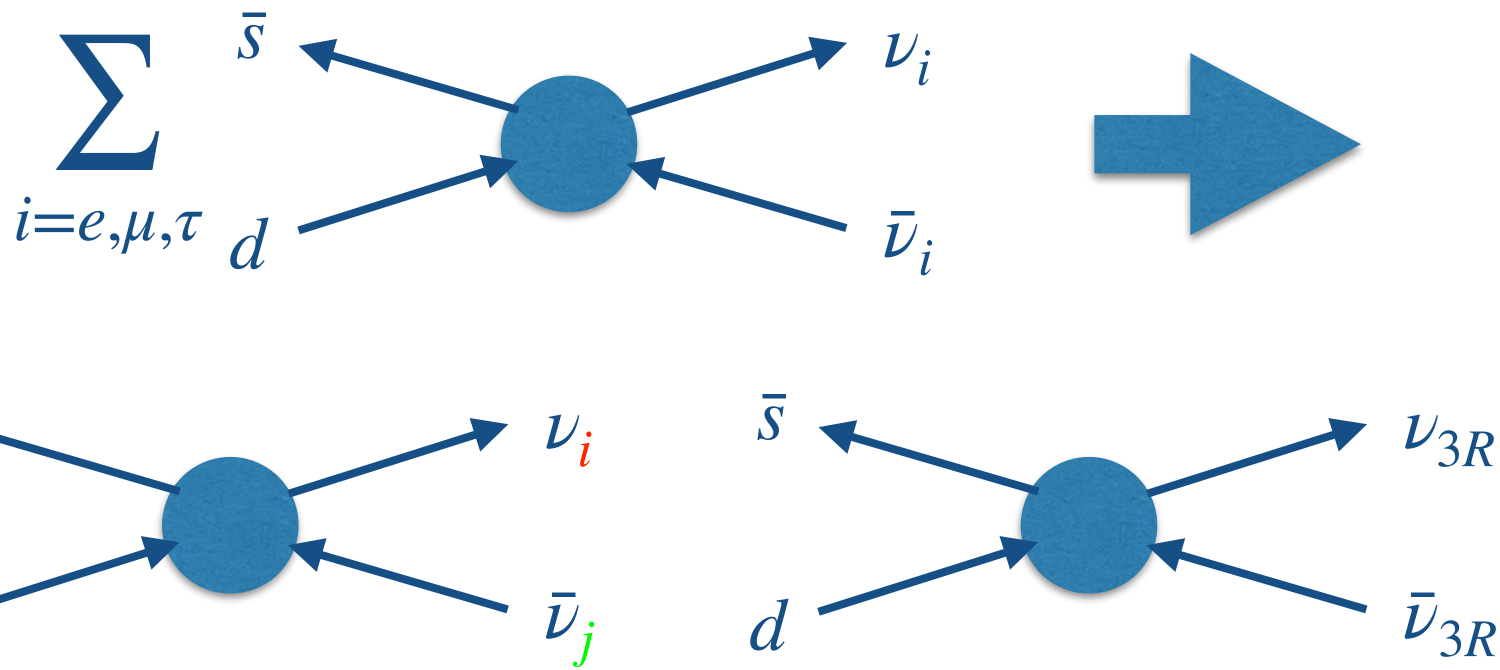
Fig. 1 New physics with lepton flavour conserving left-handed neutrinos. The green line illustrates the case X_N real, the red line corresponds to X_N having a phase equal to that of the λ_t (central value) and the blue line to X_N having a phase equal to minus that of the λ_t. For comparison the purple marks the SM 1σ region and the green marks the 90% c.l. from BNL-787 combined with BNL-949. Finally the vertical dashed red line marks a possible future limit for $\mathcal{B}_{K^+}$ at 1.3 times the SM

X-G He, G.V., and Keith Wong
Eur.Phys.J. C78 (2018) no.6, 472

- there is interference between SM and NP
- in principle can cover all the allowed window
- green curve: same phase as in SM
- other constraints limit the allowed regions and are model dependent
- this type of NP can't violate the GN bound

But the neutrinos are not seen

- can have different neutrinos
  - additional light neutrinos (right-handed - sterile in SM)
  - different flavour neutrinos (lepton flavour violation)



$K \to \pi\nu\bar{\nu}$ additional neutrino

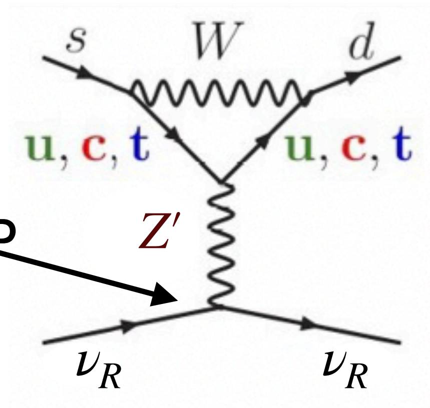
- New light sterile neutrino

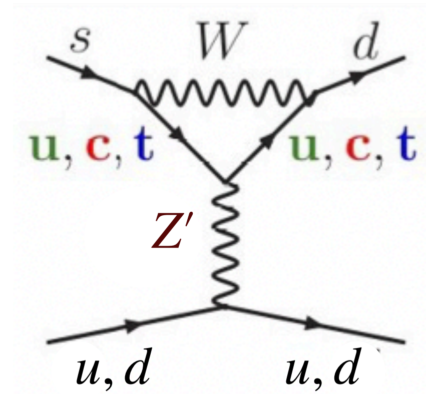
$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi s_W^2} V_{ts}^{\star} V_{td} \bar{s}\gamma_\mu d \left((X(x_t) + X_N) \sum_{\ell} \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell + \tilde{X}_N \bar{\nu}_R \gamma^\mu P_R \nu_R \right)$$

new RH ν

- No interference with SM, can only add to SM rates

sterile:
couples only to NP



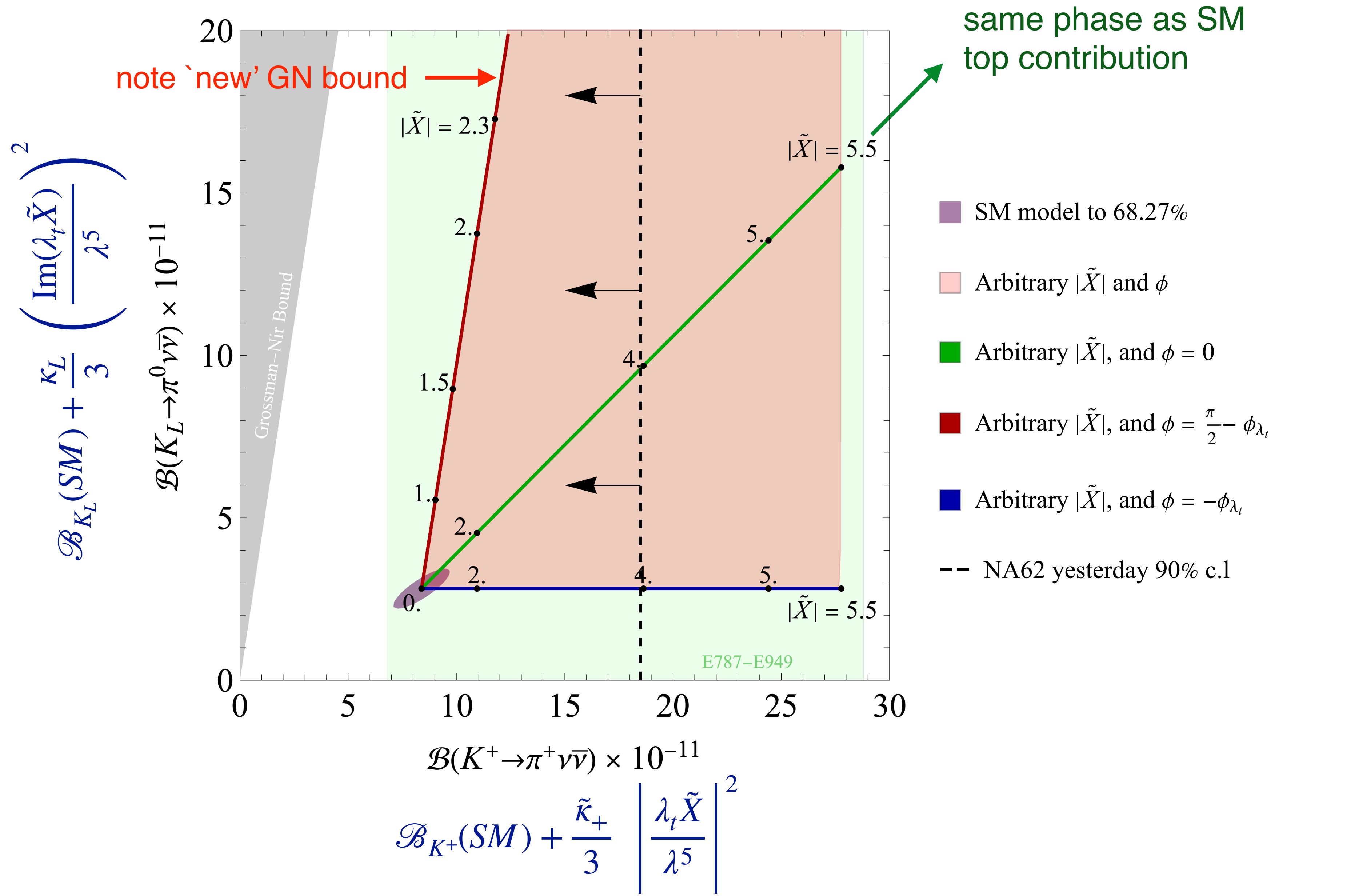


$|V_{bd}^R|^2 + |V_{tu}^R|$

NOT directly related
to $\epsilon,\ \epsilon'$

new parameters
can be tiny

Additional light (sterile) neutrino

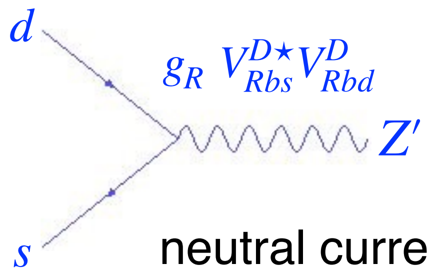


an example of a model

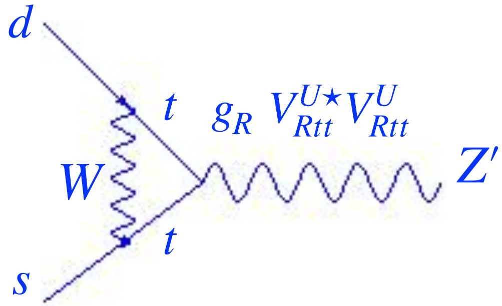
- add a new light neutrino
- needs to be sterile with respect to SM to satisfy light neutrino counts. Postulate it is part of a right-handed doublet with the τ Interacts with a W', Z'
- needs to mostly appear with a tau lepton to satisfy observed patterns of LF universality (and this helps with BBN constraints)
- W', Z' couple strongly (weakly) to the third (first two) generations: avoids LHC constraints (low σ_{prod})
- electroweak strength corrections to processes between a third generation fermion pair and one from 1st or 2nd generation
- one such neutrino already appears in models that single out the third generation

Phys.Rev. D66 (2002) 013004,
Phys.Rev. D68 (2003) 033011
Xiao-Gang He, G. V.

$(sd) \rightarrow \nu_R \bar{\nu}_R$



neutral currents quark sector



+ related $\rightarrow \dfrac{g_R}{2\cos\theta_W} \dfrac{\alpha}{2\pi \sin\theta_W} I(x_t, x_H) \; \gamma_\mu P_L$

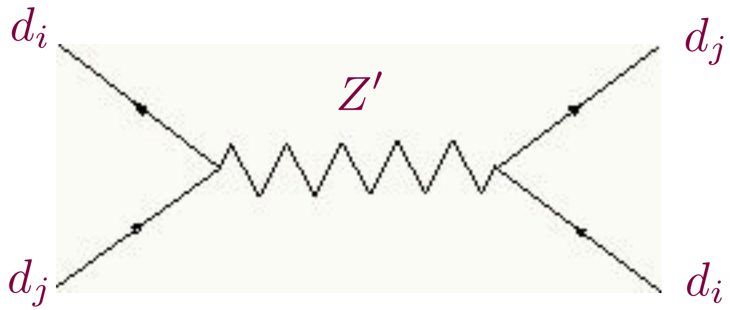
- first 2 generations couple after rotation to mass eigenstates
- three (sets) of parameters come into play
- mixing between $Z - Z'$ (tiny)
- right handed rotation angles (arbitrary but constrained)
- strength of the new interaction (can be large)

strength of g_R singles out third generation

- perturbative unitarity: $g_R \lesssim 10\ g_L$
- From $Z \to \tau^+\tau^-$ at LEP: $\left|\frac{g_R}{g_L}\xi_Z\right| \lesssim 3 \times 10^{-3}$
- From other fits to LEP data: $g_R M_Z \sim g_L M_{Z'}$
- the $Z' \quad (W')$ can be much lighter than in other models because they evade LHC searches that do not use third generation fermions
- can be made to satisfy all FCNC constraints, with room to accommodate deviations of EW strength in processes that involve a transition between a third generation fermion and a lighter one, such as $K \to \pi\nu\bar{\nu}$

Flavour constraints

- Meson mixing



for kaons

$$\propto \left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right)^2 \bar{d}_i\gamma_\mu P_R d_j \bar{d}_i\gamma_\mu P_R d_j$$

- Specifically for kaons this implies $\left|V^{D\star}_{Rbs}V^{D}_{Rbd}\right| \lesssim 1.5\times 10^{-4}$
- a combination of B_s mixing and B_d mixing with a few other assumptions leads to a stronger $\left|V^{D\star}_{Rbs}V^{D}_{Rbd}\right| \lesssim 6.7\times 10^{-7}$
- B_s mixing also limits the new loop contributions, implying for the Inami-Lim function $I(x_t, x_H) \lesssim \mathcal{O}(10)$ (this one depends on complicated details of the model, hidden in the x_H)
- FCNC constraints can be summarised by: $V^{D}_{Rbi} \sim \delta_{bi}$

collecting for $K \to \pi\nu\bar{\nu}$

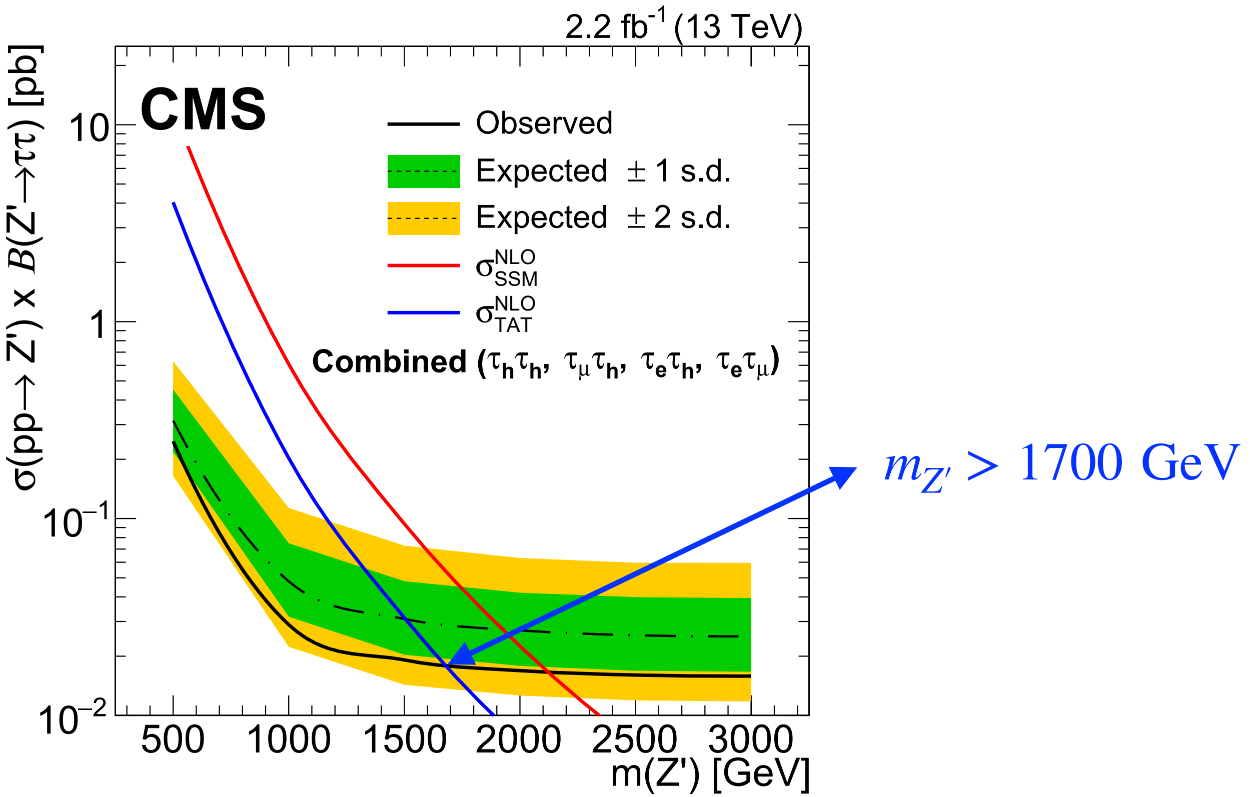
- the effective coupling is

$$\tilde{X} = -\left(\frac{M_Z^2}{M_{Z'}^2}\frac{g_R^2}{g_L^2}\right)\left(\frac{s_W^2}{2}I(\lambda_t, \lambda_H) + \frac{\pi s_W^4}{\alpha}\frac{V_{Rbs}^{d\star}V_{Rbd}^{d}}{V_{ts}^{\star}V_{td}}\right)$$

- loop term in second bracket can be $\sim \mathcal{O}(1)$
  - by construction this one has the same phase as the SM top-quark contribution
  - its magnitude is very model dependent (details of the scalar sector and symmetry breaking)
- FCNC tree-level term at most a few percent
  - too small to contribute when made to satisfy B mixing constraints
- first bracket can be order 1 from LEP constraints, has it been improved? (no)

third generation limits on Z'

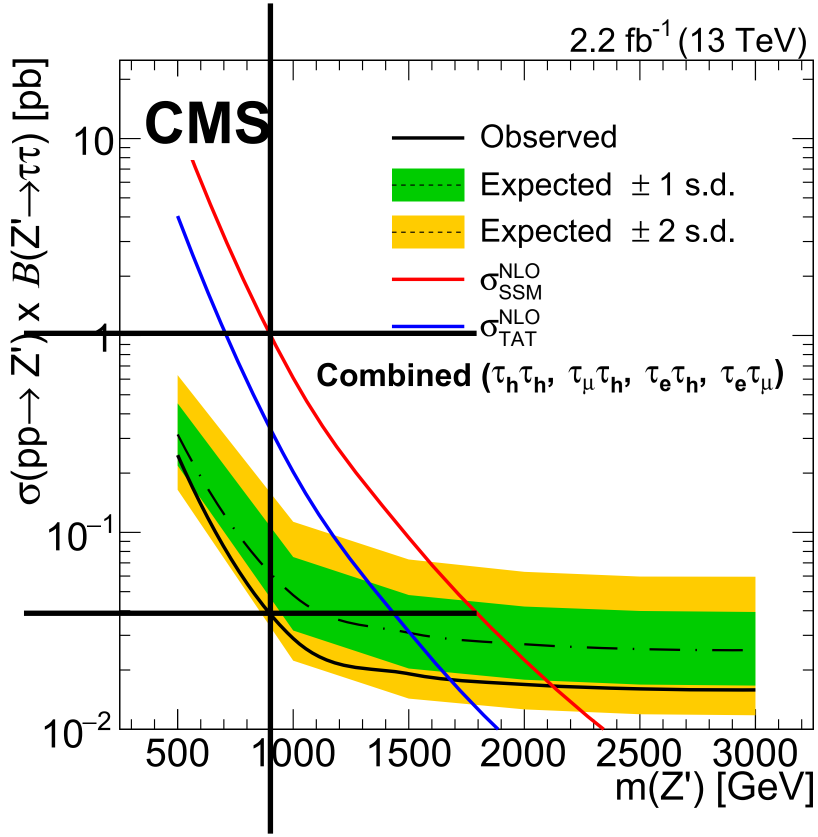
- CMS uses 'TAT' (topcolor assisted technicolor) model with
- $\sigma(pp \to Z')\mathscr{B}(Z' \to \tau\tau)_{TAT} \sim \frac{1}{3}\sigma(pp \to Z')\mathscr{B}(Z' \to \tau\tau)_{SSM}$



V.Khachatryanetal.,CMSCollaboration.JHEP**1702**,048(2017). https://doi.org/10.1007/JHEP02(2017)048.

are these limits on Z' mass general? (no)

- can it be 900 GeV? need $(\sigma\mathscr{B}) \sim 3 \times 10^{-2}\ (\sigma\mathscr{B})_{SSM}$



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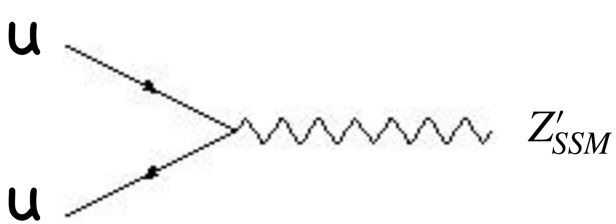
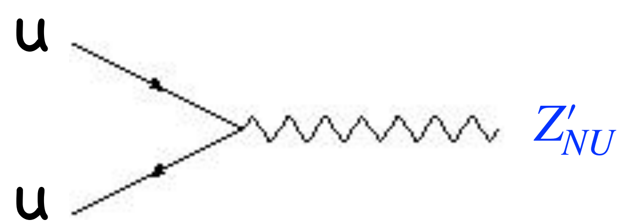
adapting the bound

- at TeV masses the $Z' \to t\bar{t}$ channel is open
- if third generation dominates then $\mathcal{B}(Z' \to \tau^+\tau^-) \to 1/8$
- however production cross section is very suppressed





$$\frac{g_L}{2\cos\theta_W}\gamma_\mu(g_V + g_A\gamma_5) \qquad \frac{g_R}{2\cos\theta_W}\sin\theta_W \; V^{U\star}_{Rtu}V^{U}_{Rtu}\;\gamma_\mu(1+\gamma_5)$$

$$\sigma \times B(Z' \to \tau\tau) \sim \big(\sigma \times B(Z' \to \tau\tau)\big)_{SSM}\,\frac{12.5\,\%}{3.37\,\%}\left(\left|\frac{g_R}{g_L}\,|\,V^U_{Rtu}\,|^2\right|^2 \text{ or } \xi_Z^2\right).$$

$$V^U_{Rtu} \sim V_{ub}$$

- likely dominated by terms not calculated, but very small

Number of light neutrinos

- there is one light right handed neutrino! why not seen at LEP?
  - LEP standard result n = 2.9840 ± 0.0082
    - assumes Lepton universality and no new particles
  - direct limit n = 3.00 ± 0.08
- basically it has to couple through $Z - Z'$ mixing

$$\Gamma(Z \to \nu_{R3}\bar{\nu}_{R3}) = \frac{1}{24}\frac{\alpha}{\cos^2\theta_W}\frac{g_R^2}{g_L^2}\xi_Z^2 M_{Z'}$$

$$\Gamma(Z \to \nu_{R3}\bar{\nu}_{R3}) < 3 \times 10^{-4}\ MeV$$

- the limit on new physics from the invisible Z width
  - there is 13.3 MeV error in this measurement so our right handed neutrino is unobservable by LEP

number of light neutrinos: cosmology?

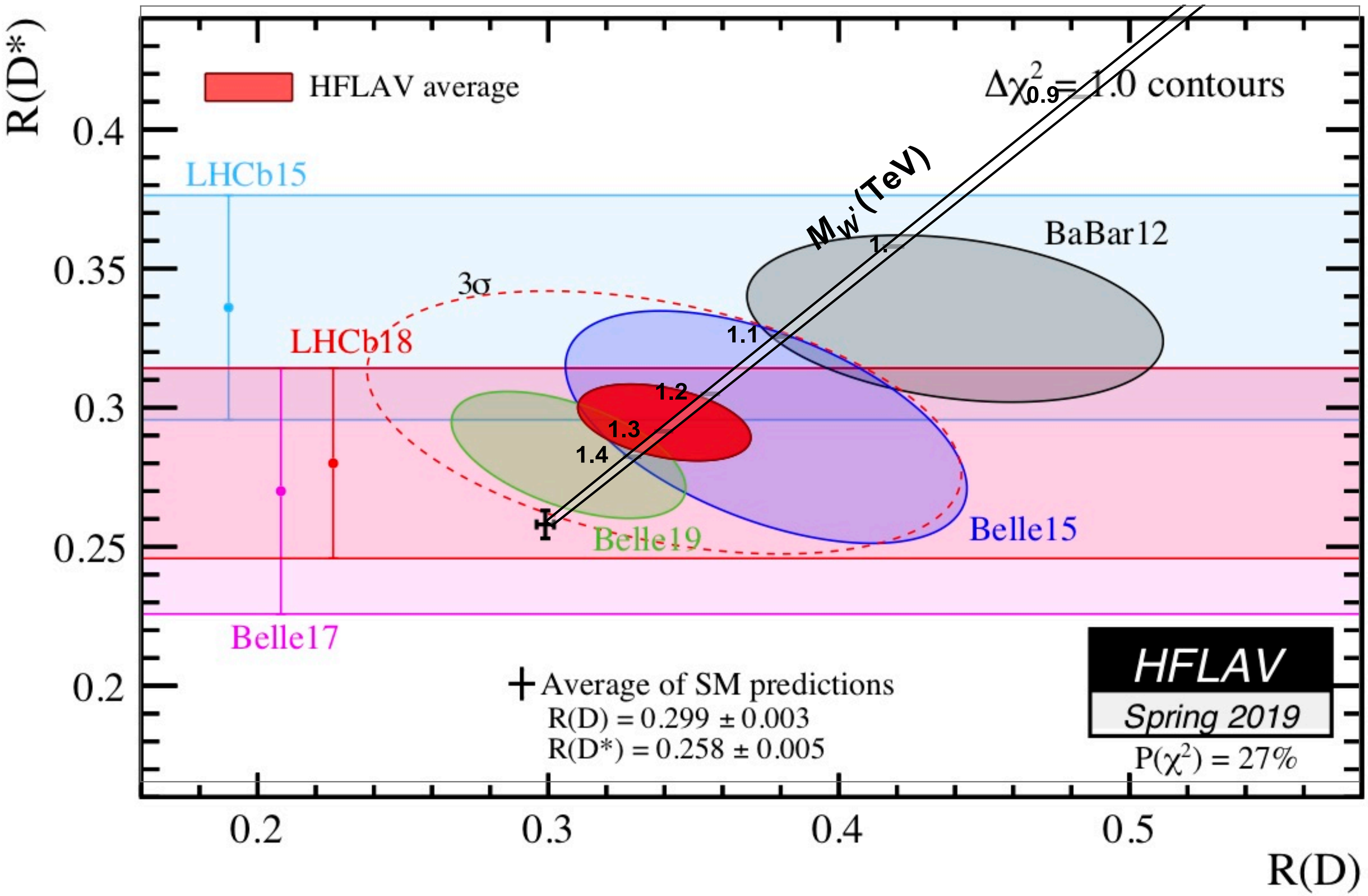
- it is known that

$$\Delta N_{eff} < \begin{cases} 0.28 & \text{for } H_0 = 68.7^{+0.6}_{-0.7} \text{ km/s/Mpc} \\ 0.77 & \text{for } H_0 = 71.3^{+1.9}_{-2.2} \text{ km/s/Mpc}. \end{cases}$$

- the new right handed interaction is stronger that weak, at least for third generation
- The Z', W' can scatter with the new light neutrino and bring it to thermal equilibrium with SM particles that could give $\Delta N_{eff} \sim 1$
- our model only lets them scatter with tau so the decoupling temperature is m_τ whereas T_{BBN} is of order 1 MeV, so there is a suppression factor
- also known that neutrinos that decouple above the QCD phase transition (200 MeV) only contribute an effective 0.1 per species

this neutrino could explain charged B anomalies

Xiao-Gang He, G. V.: PLB779 (2018), 52



$K \to \pi\nu\bar{\nu}$ LFV

- Lepton flavour conserving

$$\mathscr{H} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi s_W^2} V_{ts}^{\star} V_{td} \bar{s}\gamma_\mu d \left((X(x_t) + X_N) \sum_{\ell} \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell + \tilde{X}_N \bar{\nu}_R \gamma^\mu P_R \nu_R \right)$$

SM (top) ‘usual’ NP new RH ν

- Lepton flavour violating (e.g. leptoquark exchange) will in general also produce LFC couplings

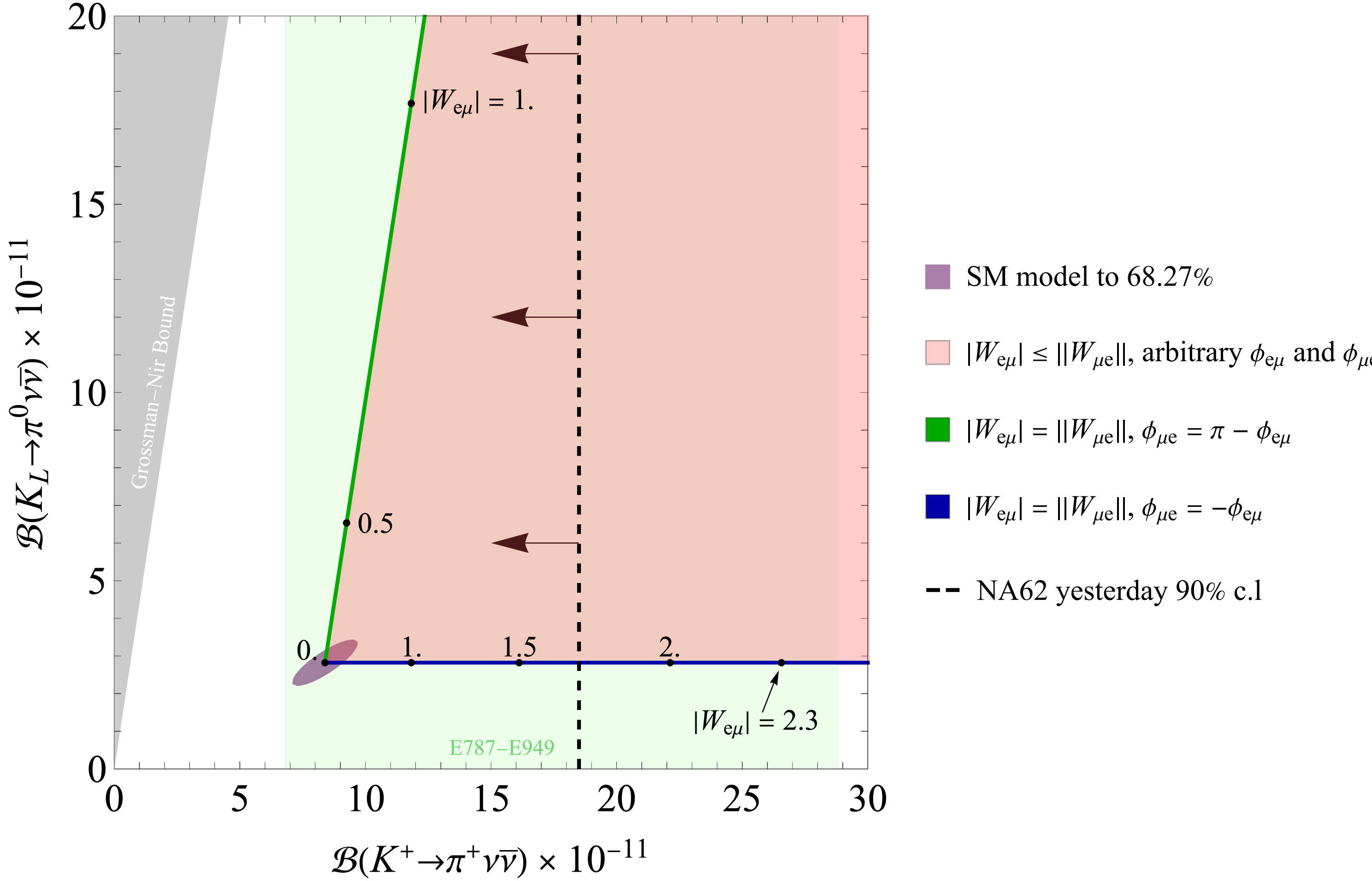
$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi s_W^2} \bar{s}\gamma_\mu d \left(\sum_{\ell} \left(V_{ts}^{\star} V_{td} X_t + \lambda^5 W_{\ell\ell} \right) \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell + \lambda^5 \sum_{i \neq j} W_{ij} \bar{\nu}_i \gamma^\mu P_L \nu_j \right)$$

SM (top) LFC LFV

- no interference between LFV and SM

$K \to \pi\nu\bar{\nu}$ constraints on LFV new physics

$$\mathcal{B}_{K_L}(SM) + \frac{\kappa_L}{3}\sum_{i\neq j}\left|\frac{(W_{ij} - W^\star_{ji})}{2}\right|^2$$



$$\mathcal{B}_{K^+}(SM) + \frac{\tilde{\kappa}_+}{3}\sum_{i\neq j}\left|W_{ij}\right|^2$$

Charged lepton flavour violation

- New physics at some high scale that respects the symmetries of the SM
- Effective theory at the electroweak symmetry breaking scale is written in terms of left-handed doublets
- So left handed leptons enter as $l = \begin{pmatrix} \nu \\ \ell \end{pmatrix}$ into operators

such as: $\mathscr{L} \supset c_4 \;\; \bar{s}\gamma^{\mu}P_R d \;\; \bar{l}\,\gamma_{\mu}P_L l \; + \; \mathrm{h.c.}$

- Which can give rise to both types of LFV decays
  - $K_L \to \mu^{\pm}e^{\mp}$ or $\Omega^{-} \to \Xi^{-}\mu^{\pm}e^{\mp}$
  - $K^{+} \to \pi^{+}\nu_{\mu e}\bar{\nu}_{e\mu}$

Dimension 6 effective Lagrangian

- LFV transitions between down-type quarks

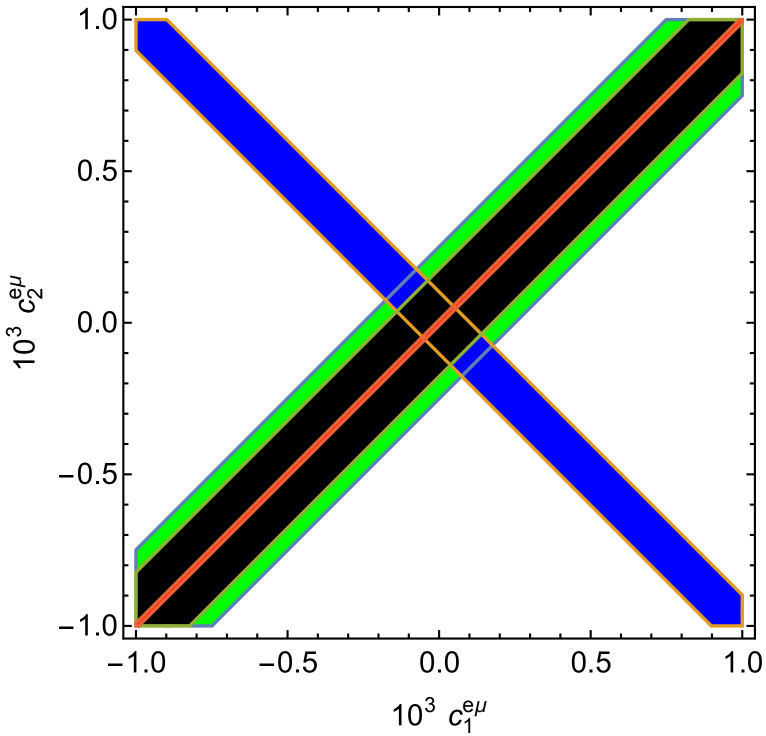
$$\mathscr{L}_{\rm NP} = \frac{1}{\Lambda^2_{\rm NP}}\left(\sum_{k=1}^{5}\mathscr{C}_k^{ijxy}\mathscr{Q}_k^{ijxy} + (\mathscr{C}_6^{ijxy}\mathscr{Q}_6^{ijxy} + {\rm H.c.})\right)$$

- $\mathscr{Q}_1^{ijxy} = \overline{q}_i\gamma^\eta q_j\,\overline{l}_x\gamma_\eta l_y$ $\quad\mathscr{Q}_2^{ijxy} = \overline{q}_i\gamma^\eta\tau_I q_j\,\overline{l}_x\gamma_\eta\tau_I l_y$ $\quad\mathscr{Q}_3^{ijxy} = \overline{d}_i\gamma^\eta d_j\,\overline{e}_x\gamma_\eta e_y$
- $\mathscr{Q}_4^{ijxy} = \overline{d}_i\gamma^\eta d_j\,\overline{l}_x\gamma_\eta l_y$ $\quad\mathscr{Q}_5^{ijxy} = \overline{q}_i\gamma^\eta q_j\,\overline{e}_x\gamma_\eta e_y$ $\quad\mathscr{Q}_6^{ijxy} = \overline{l}_i e_j\,\overline{d}_x q_y$

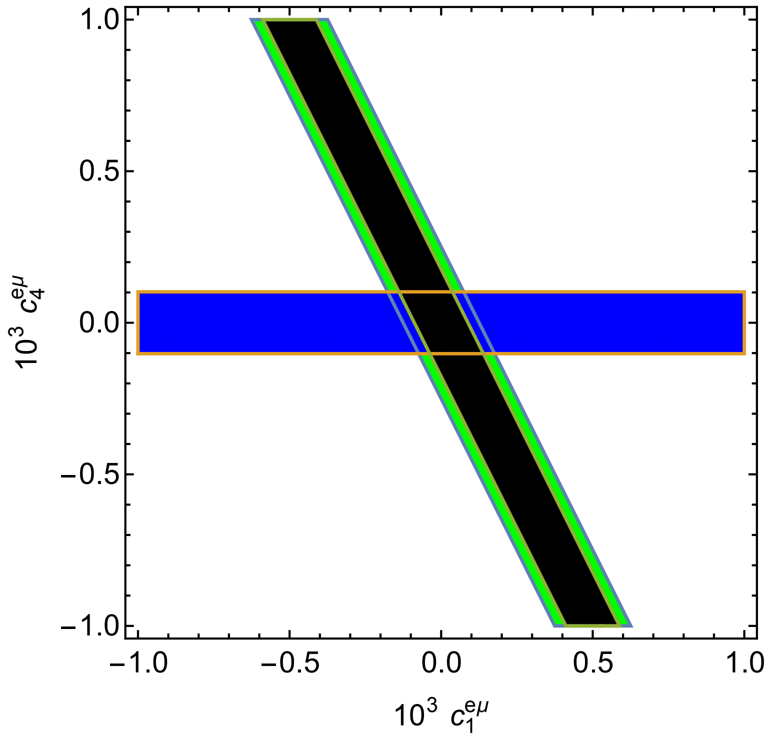
- Several structures appear:
  - $\mathscr{Q}_{1,4} \sim (\bar\nu\Gamma\nu + \ell\bar\Gamma\ell),\quad \mathscr{Q}_2 \sim (\bar\nu\Gamma\nu - \ell\bar\Gamma\ell)$
  - in terms of previous notation: $W_{\ell\ell'} \simeq 9727\left(\frac{1\ \rm TeV}{\Lambda_{NP}}\right)^2\left(c_1^{\ell\ell'} - c_2^{\ell\ell'} + c_4^{\ell\ell'}\right)$
  - $\mathscr{Q}_{3,5,6}$ do not produce neutrino pairs
  - generically different processes are complementary

LFV $K^+ \to \pi^+$ transitions

$c_i^{e\mu} = c_i^{\mu e}, c_4 = 0$



$c_i^{e\mu} = c_i^{\mu e},\ c_2 = -c_1$



$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \leq 2.88 \times 10^{-10}$ (BNL 787 – 949)

$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \leq 1.85 \times 10^{-10}$ (NA62 yesterday)

SM + NP (NP can only add to SM in this case)

$\mathcal{B}(K^+ \to \pi^+ e^- \mu^+) < 1.3 \times 10^{-11}$ (BNL 865)

μ^- Au $\to e^-$ Au $< 7 \times 10^{-13}$ (SINDRUM II)

comments

- $K^+ \to \pi^+ e^- \mu^+$ depends on $(c_1 + c_2 + c_4)^{e\mu,\mu e}$
- whereas $K^+ \to \pi^+ \nu\bar{\nu}$ depends on $(c_1 - c_2 + c_4)^{e\mu,\mu e}$
    - for these operators the charged LFV mode is more restrictive by a factor of about 4
    - a measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ at the SM level with 10% uncertainty will already make this mode more restrictive
    - of course even with current experimental limits the two are complementary

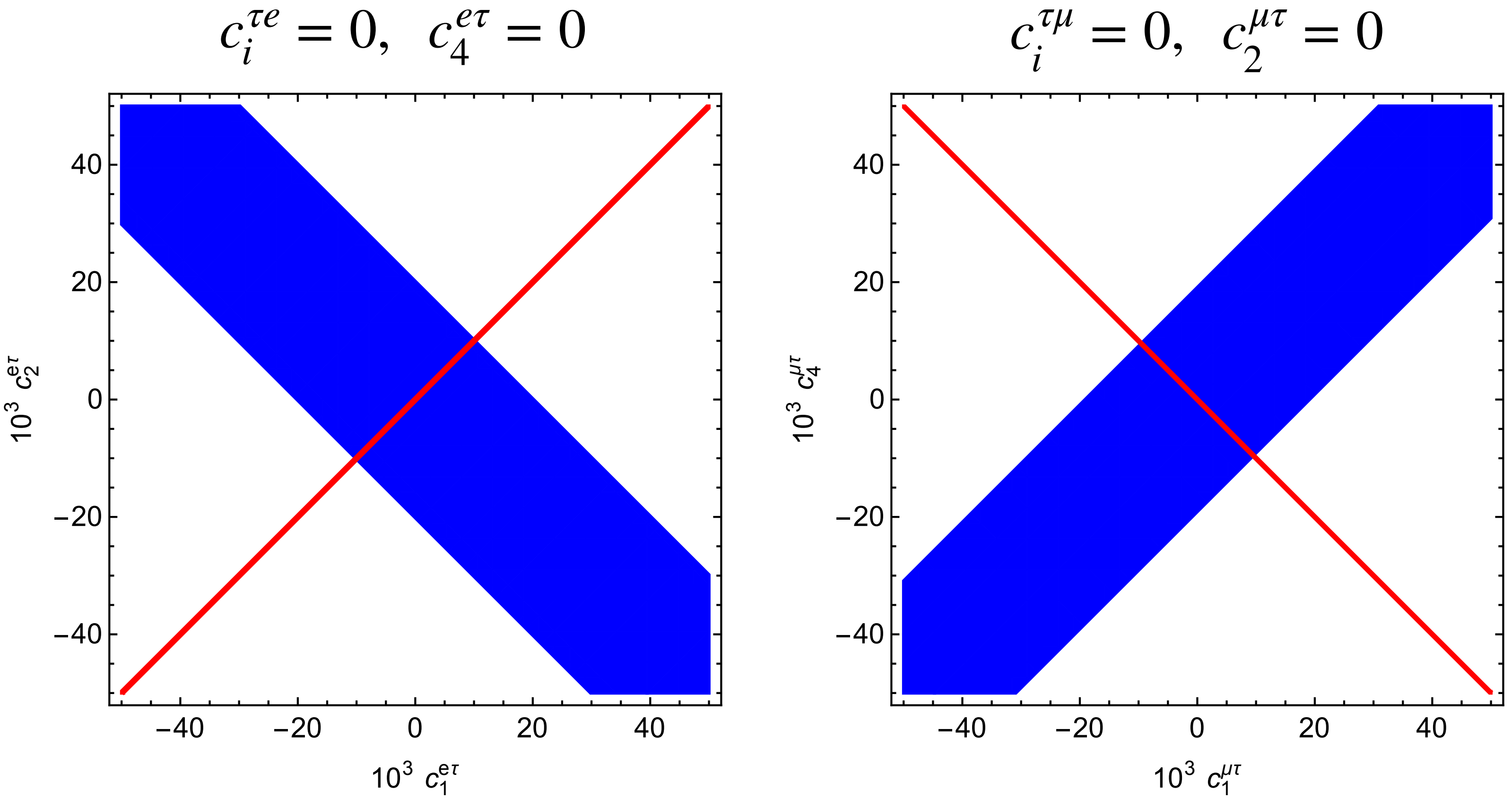
Charged lepton flavour violation

- lepton flavour indices include the third generation
- in this case left handed leptons enter as $l_3 = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$
- The LFV lagrangian can have terms such as

$$\mathscr{L} \supset c_4 \;\; \bar{s}\gamma^\mu P_R d \;\; \bar{l}_3 \gamma_\mu P_L l_{1,2} \; + \; \mathrm{h.c.}$$

- Which can give rise to both
    - $\tau^- \rightarrow e^- K_S$
    - $K^+ \rightarrow \pi^+ \nu_e \bar{\nu}_\tau$
- golden rare kaon modes can also compete with charged LFV tau-decay modes

$K \to \pi\nu\bar{\nu}$ vs CLFV τ decay



$\mathscr{B}(\tau^- \to e^- K_s) < 2.6 \times 10^{-8}$ (Belle) $\mathscr{B}(\tau^- \to \mu^- K_s) < 2.3 \times 10^{-8}$ (Belle)

$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) \leq 2.88 \times 10^{-10}$ (BNL 787 − 949)

Conclusions

- we studied the effects of new physics affecting the neutrinos on the rare decay modes $K \to \pi\nu\bar{\nu}$
- these modes can provide significant constraints on new light sterile neutrinos that avoid LEP counts and BBN bounds
- these modes also provide constraints on lepton flavour violating new physics that are complementary to bounds from CLFV experiments
  - these extend to CLFV involving tau leptons
- both of these scenarios can only increase the $K \to \pi\nu\bar{\nu}$ rates as they don't interfere with the SM