MONASH University

Additional neutrinos and the B anomalies

Corfu Summer Institute:
Workshop on the Standard Model and Beyond

German Valencia

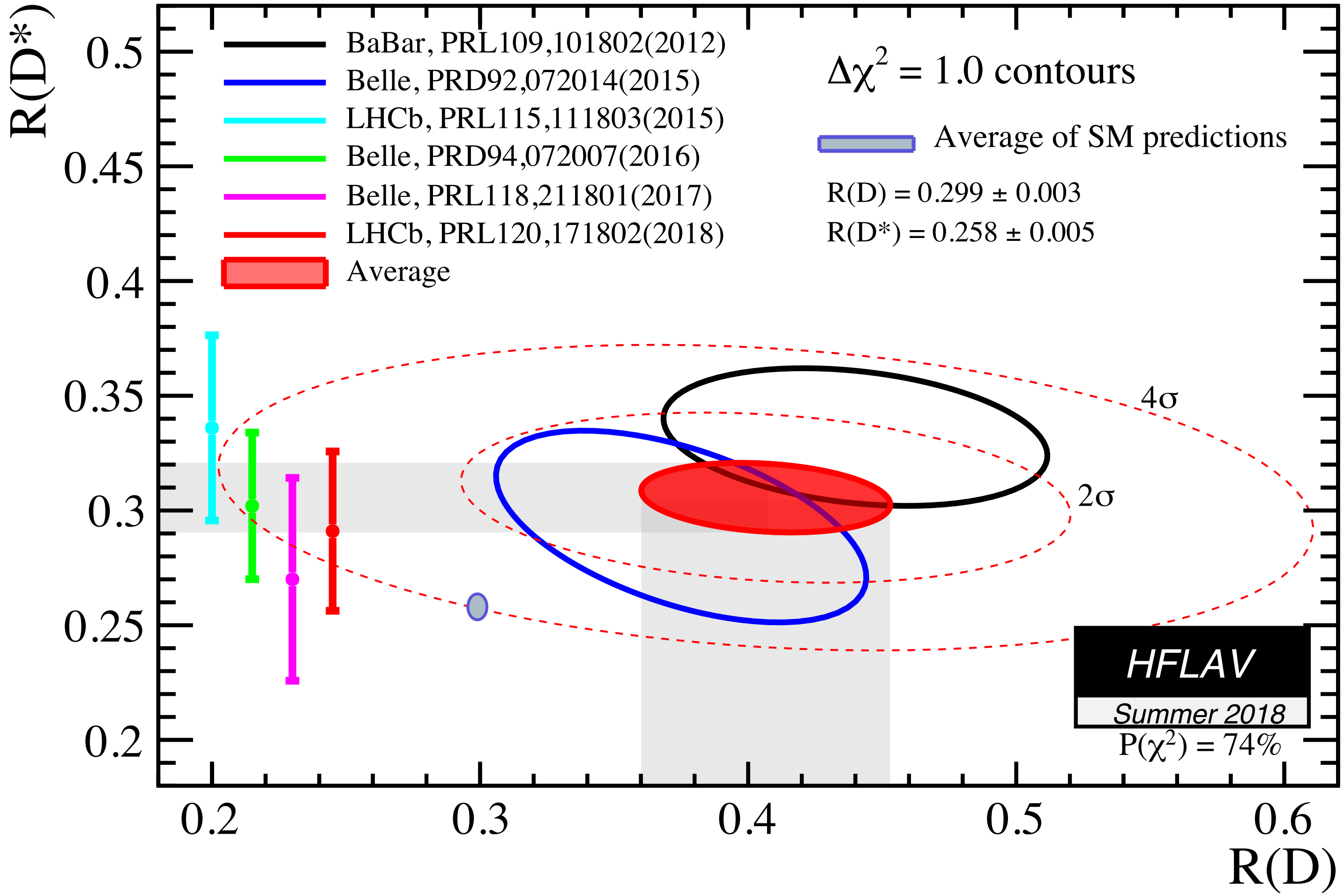
based on:
Xiao-Gang He, G. V. PRD87 (2013) no.1, 014014
PLB779 (2018), 52
arXiv:1706.07570

GROUP OF EIGHT AUSTRALIA

one that works

problems with lepton universality
in B decay to τ?

Semileptonic B decay to τ



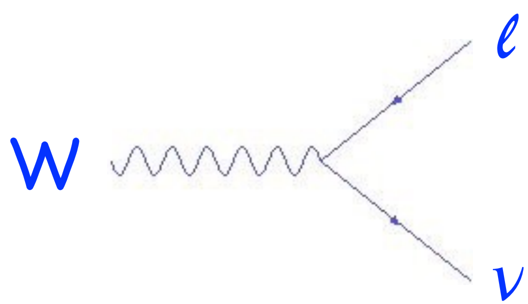
$$R(D^\star) = \frac{B(\bar{B} \to D^\star \tau^- \bar{\nu}_\tau)}{B(\bar{B} \to D^\star \ell^- \bar{\nu}_\ell)}$$

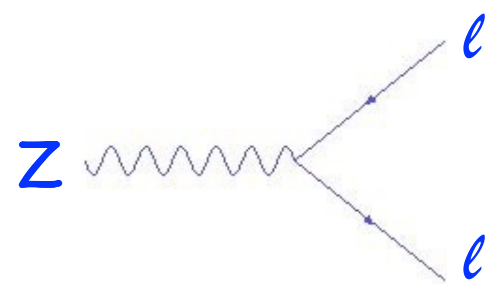
about 4σ away from SM

$$R(D) = \frac{B(\bar{B} \to D \tau^- \bar{\nu}_\tau)}{B(\bar{B} \to D \ell^- \bar{\nu}_\ell)}$$

Lepton Universality

- lepton couplings to gauge bosons in the SM are all the same
- very well tested, PDB averages:





$$\frac{B(W^+ \to \mu^+ \nu)}{B(W^+ \to e^+ \nu)} = 0.991 \pm 0.018$$

$$\frac{B(W^+ \to \tau^+ \nu)}{B(W^+ \to e^+ \nu)} = 1.043 \pm 0.024$$

$$\frac{B(W^+ \to \tau^+ \nu)}{B(W^+ \to \mu^+ \nu)} = 1.070 \pm 0.026$$

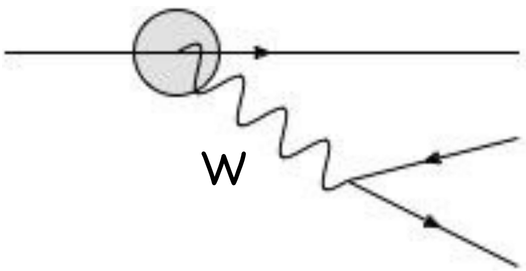
$$\frac{B(Z \to \mu^+ \mu^-)}{B(Z \to e^+ e^-)} = 1.0009 \pm 0.0028$$

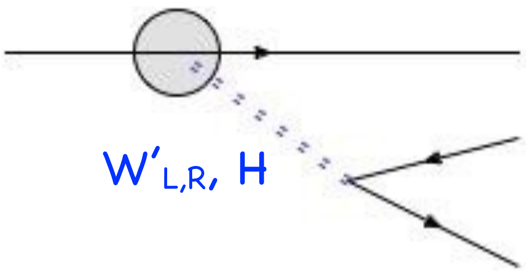
$$\frac{B(Z \to \tau^+ \tau^-)}{B(Z \to e^+ e^-)} = 1.0019 \pm 0.0032$$

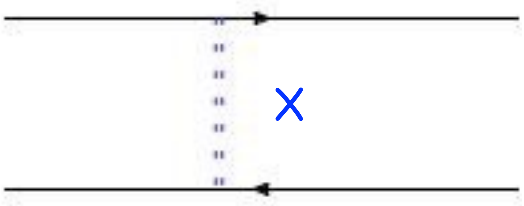
.9977 (SM)

first surprise in $b \to c\ \tau\ \nu$

- apparently the τ has a stronger coupling
- at tree level, several possible other couplings







  - new W gauge boson with non-universal couplings
  - leptoquark - need very specific flavour structure
  - charged Higgs, seems a natural explanation but the simple models do not work

Nothing seen in other meson decay

	Exp. (PDB)	SM
$\frac{B(K^+ \to \pi^0 \mu^+ \nu)}{B(K^+ \to \pi^0 e^+ \nu)}$	0.6608±0.0029	0.6631±0.0042 (Cirigliano et al)
$\frac{B(K^+ \to e^+ \nu)}{B(K^+ \to \mu^+ \nu)}$	2.488±0.009(10^{-5})	2.477±0.001 (10^{-5}) (Cirigliano et al)
$\frac{B(\pi^+ \to e^+ \nu(\gamma))}{B(\pi^+ \to \mu^+ \nu(\gamma))}$	1.2327±0.0023(10^{-4})	1.2352±0.0005(10^{-4}) (Marciano, Sirlin)

- no simple models
- need to arrange the flavour structure to single out third family: b, τ

proposal

- add a new light neutrino
- needs to be sterile with respect to SM to satisfy light neutrino counts
- needs to mostly appear with a tau lepton to satisfy observed patterns of LF universality
- 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.

Model: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- the third generation has an additional $SU(2)_R$
- fermion content

$$Q_L^{1,2} : (3,2,1)(1/3)\ , \quad U_R^{1,2} : (3,1,1)(4/3)\ , \quad D_R^{1,2} : (3,1,1)(-2/3)\ ,$$
$$L_L^{1,2} : (1,2,1)(-1)\ , \quad E_R^{1,2} : (1,1,1)(-2)\ .$$

$$Q_L^3 : (3,2,1)(1/3)\ , \quad Q_R^3 : (3,1,2)(1/3)\ ,$$
$$L_L^3 : (1,2,1)(-1)\ , \quad L_R^3 : (1,1,2)(-1)\ .$$

- one additional light neutrino compared to SM ν_{R3}
  - light to address anomalies
  - can have other heavy neutrinos but these will not play a role here.

Model: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- scalar content:
  - H_R (1,1,2)(-1) breaks $SU(2)_R$,
  - H_L (1,2,1)(-1) or ϕ (1,2,2)(0) breaks SU(2) to SM
  - both H_L and ϕ needed to give all fermions mass
  - additional scalars with (small) vevs to generate neutrino masses
  - it is possible to have a scalar sector that gives an acceptable neutrino mass spectrum and mixing
- W and W' mix

$$W_L = \cos\xi_W W - \sin\xi_W W' ,$$
$$W_R = \sin\xi_W W + \cos\xi_W W' .$$

charged weak interaction

$$\mathcal{L}_W = -\frac{g_L}{\sqrt{2}}(\bar{\nu}_L\gamma^\mu U^{\ell\dagger}\ell_L + \bar{\nu}^c_{R3}\gamma^\mu U^{\ell*}_{RLj3}\ell_{Lj})(\cos\xi_W W^+_\mu$$
$$- \sin\xi_W W'^+_\mu) - \frac{g_R}{\sqrt{2}}(\bar{\nu}^c_{Li}\gamma^\mu U^\ell_{LRij}\ell_{Rj} + \bar{\nu}_{R3}\gamma^\mu U^\ell_{R3j}\ell_{Rj})$$
$$\times (\sin\xi_W W^+_\mu + \cos\xi_W W'^+_\mu) + \text{h. c.}, \qquad (8)$$

$$\mathcal{L}_W = -\frac{g_L}{\sqrt{2}}\bar{U}_L\gamma^\mu V_{KM}D_L(\cos\xi_W W^+_\mu - \sin\xi_W W'^+_\mu)$$
$$-\frac{g_R}{\sqrt{2}}\bar{U}_R\gamma^\mu V_R D_R(\sin\xi_W W^+_\mu + \cos\xi_W W'^+_\mu) + \text{h. c.}, \qquad (6)$$

Single out tau-lepton - and b-quark

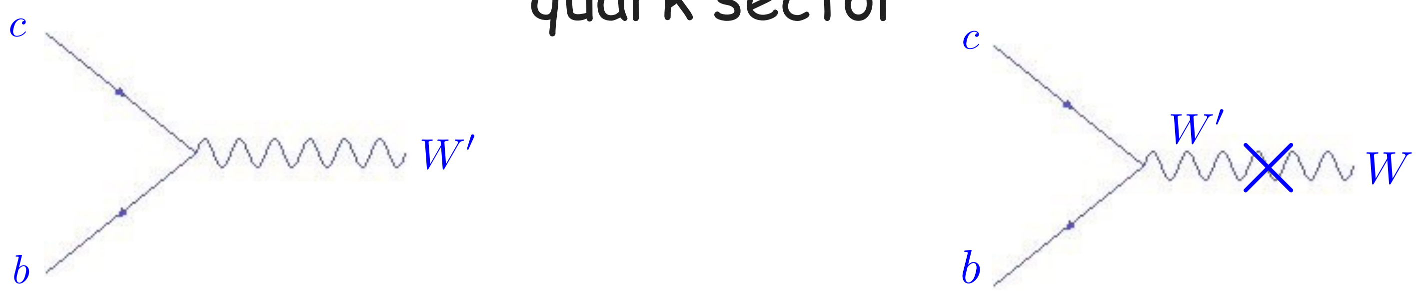
- enhance third generation with $g_R > g_L$
  - perturbative unitarity: $g_R \lesssim 10\ g_L$
- can accommodate $A_{FB}{}^b$
  - From LEP: $g_R M_W \lesssim g_L M_{W'}$

$$\left|\frac{g_R}{g_L}\xi_Z\right| \lesssim 3 \times 10^{-3}$$

- Z′ and W′ can be much lighter than in other models because they evade 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.

W´and semileptonic B decay to tau

quark sector



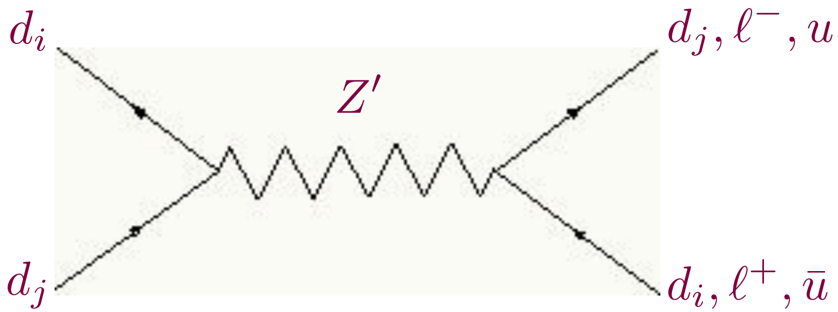
$$\mathcal{L}_W = -\frac{g_L}{\sqrt{2}}\bar{U}_L\gamma^\mu V_{KM} D_L(\cos\xi_W W^+_\mu - \sin\xi_W W'^+_\mu) \\ -\frac{g_R}{\sqrt{2}}\bar{U}_R\gamma^\mu V_R D_R(\sin\xi_W W^+_\mu + \cos\xi_W W'^+_\mu) \ + \ \text{h. c.},$$

- two (sets) of parameters come into play
- mixing between W and W′
- right handed analog of CKM matrix

previously worked out constraints

*HFAG-2012

*From b → s γ = (3.55±0.25) × 10^{-4} $$-0.0013 \leq \frac{g_R}{g_L}\xi_W \leq 0.0027$$



strongest constraints from meson mixing

FCNC constraints can be summarised by $V^d_{Rbi} \sim \delta_{bi}$

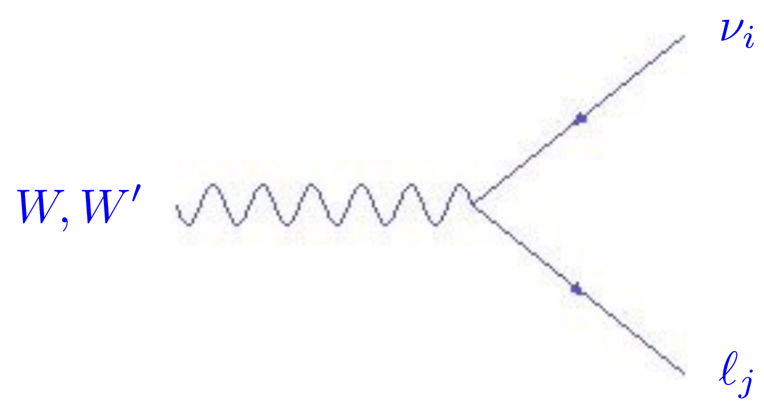
with $V_L^{u,d} = V_R^{u,d}, \; V_L^{u\dagger} V_L^d = V_{CKM}$ this allows us to predict

$$V_R = (V_{Rij}) = (V^{u*}_{Rti} V^d_{Rbj}) \qquad V_R \sim \begin{pmatrix} 0 & 0 & A\lambda^3 \\ 0 & 0 & A\lambda^2 \\ 0 & \lambda^4 & 1 \end{pmatrix}$$

$$V^u_{Rtc} \sim V_{cb}, V^u_{Rtu} \sim V_{ub}$$

W´and semileptonic B decay to tau

lepton sector



no interference if neutrino mass << charged lepton mass

$$\sum_i |M_{\text{lepton}}|^2 \propto \begin{cases} 1 & \text{for } \ell_L \\ |V^\ell_{R3j}|^2 & \text{for } \ell_R. \end{cases}$$

~ 1 for j = τ

rotates RH charged lepton to mass eigenstate

Predictions for b to c τ

In terms of the parameter combinations

$$F^q_{W'} = \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^4 \frac{|V^\ell_{R3\ell}|^2 |V_{Rqb}|^2}{|V_{qb}|^2}\right)$$

$$F^q_{\rm Mix} = \xi_W \frac{g_R}{g_L} \frac{{\rm Re}\left(V^\star_{qb} V_{Rqb}\right)}{|V_{qb}|^2} \left(1 - \left(\frac{M_W}{M_{W'}}\right)^2\right) \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^2 |V^\ell_{R3\ell}|^2\right)$$

$$\frac{R(D)}{R(D)_{SM}} = F^c_{W'} + 2\ F^c_{\rm Mix}$$

$$\frac{R(D^*)}{R(D^*)_{SM}} = F^c_{W'} - 1.77\ F^c_{\rm Mix}$$

$$\frac{R(J/\psi)}{R(J/\psi)_{SM}} = F^c_{W'} - 1.94\ F^c_{\rm Mix}$$

$$\frac{\Gamma(b \to c\tau^-\nu)}{\Gamma(b \to c\tau^-\nu)_{SM}} = F^c_{W'} - 0.8\ F^c_{\rm Mix}$$

$$\frac{\Gamma(B^-_c \to \tau^-\nu)}{\Gamma(B^-_c \to \tau^-\nu_\tau)_{SM}} = F^c_{W'} - 2\ F^c_{\rm Mix}$$

note this is ok!

In principle all different, after b $\to$ s γ all are very similar

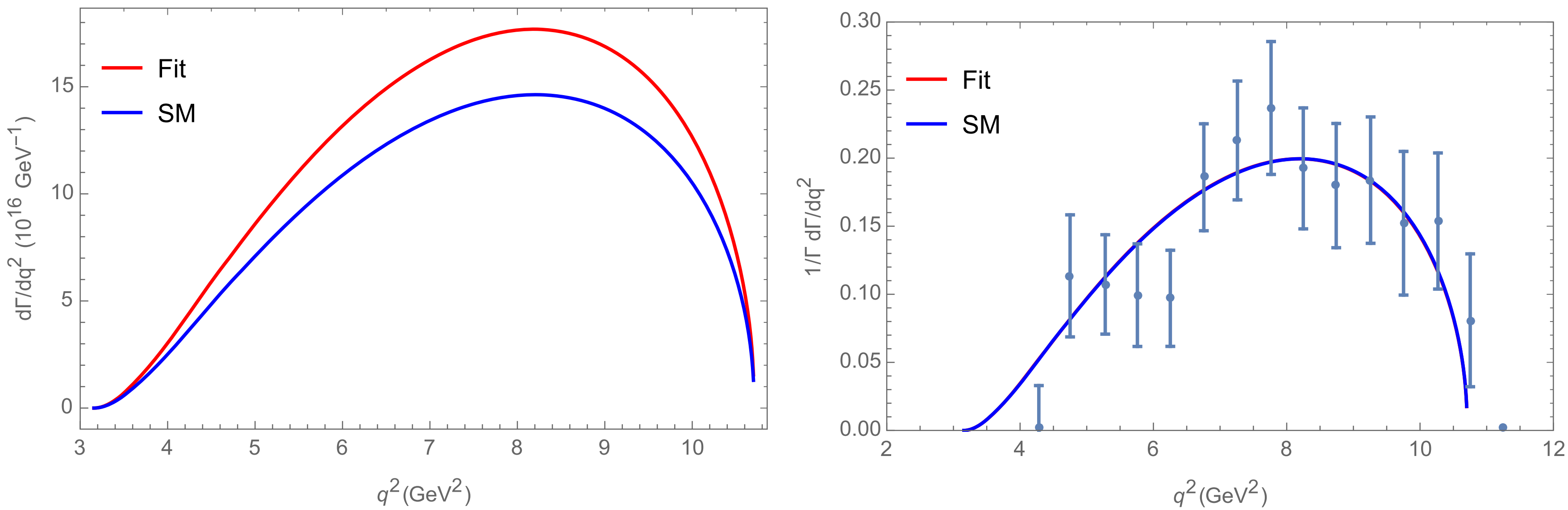


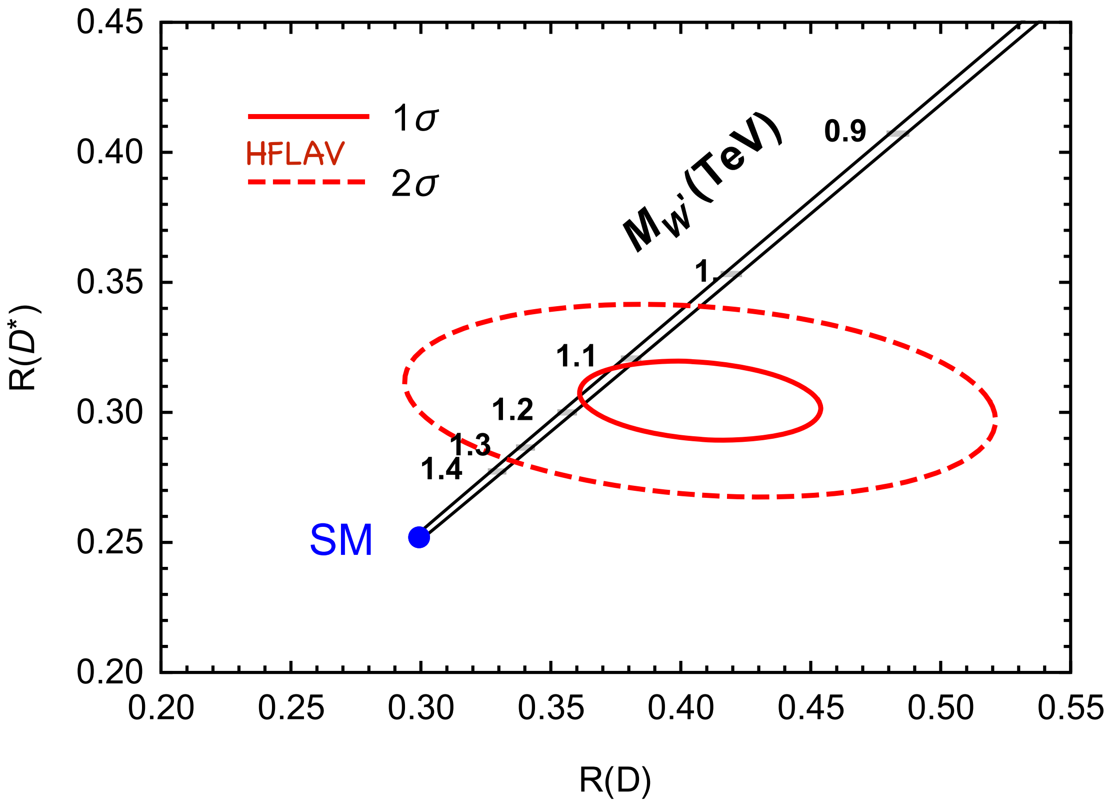
Fig. 2. Differential decay distribution $d\Gamma/dq^2$ in the SM and the fit with the NP contributions as in Eq. (23) for $B \to D^\star \tau \nu$ (left panel). Normalized distributions compared to the BaBar data [2] (right panel). Note how the model prediction for the shape of the distribution (red) is indistinguishable from the SM (blue) in the right panel because the mixing contribution is very small. (The red curve on the left panel is above the blue curve. In the right panel the red and blues curves are almost indistinguishable.)

- q^2 distributions do not differentiate the models
- fit R(D), R(D*) $F^c_{W'} = 1.28, \ F^c_{\rm Mix} = 0.04$
- predict R(J/ψ) = 0.34 vs LHCb

$$R(J/\psi) = \frac{B(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{B(B_c^+ \to J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17 \pm 0.18 \, .$$

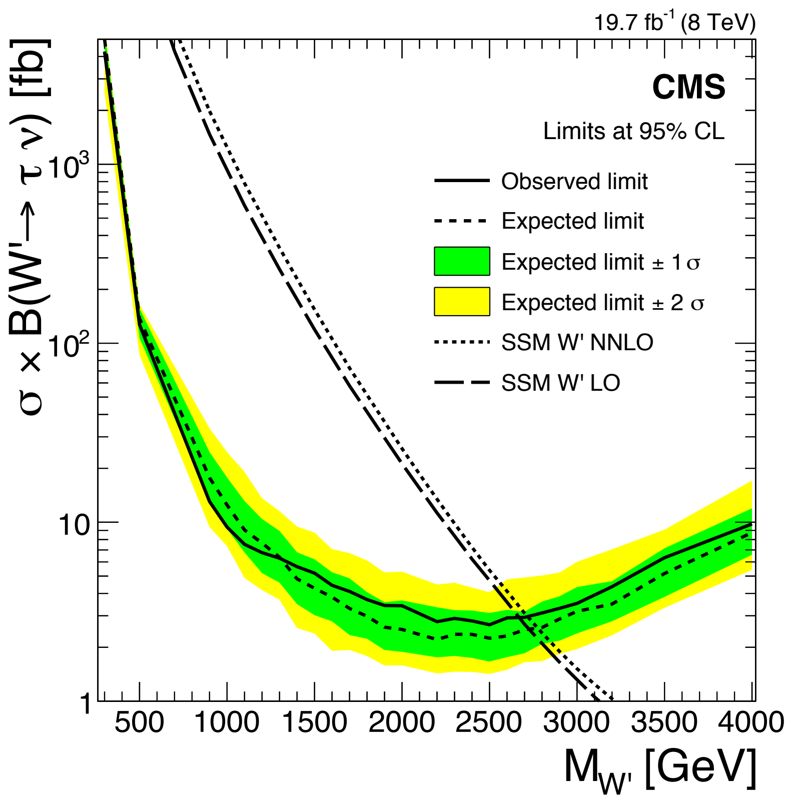
imposing $b \to s\,\gamma$ $\quad -2.1\times 10^{-3} \lesssim F^{bc}_{\rm mix} \lesssim 2.7\times 10^{-3}$,

56 *X.-G. He, G. Valencia / Physic*



also predict in this case $\quad \frac{R(D)}{R(D)_{SM}} \approx \frac{R(D^\star)}{R(D^\star)_{SM}} \approx \frac{R(J/\psi)}{R(J/\psi)_{SM}}.$

The W′

- for the model to address these asymmetries it needs a W′ with mass near one TeV
- CMS, Phys. Lett. B 755 (2016) 196 search for W′ decaying to tau-lepton, 8TeV, 19.7 fb-1,
- 

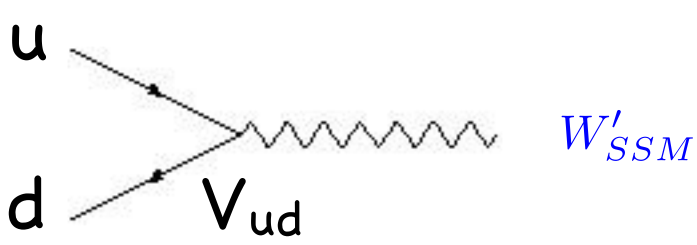
$M_{W'}(SSM) \gtrsim 2.7$ TeV

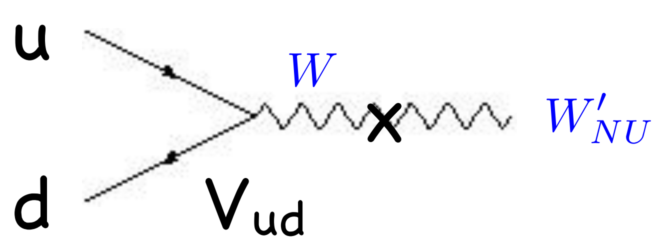
$\sigma B(W' \to \tau\nu) \lesssim 3$ fb^{-1}

- NUGIM benchmark
- $M_{W'} > (2\text{–}2.7$ TeV$)$

adapting the bound

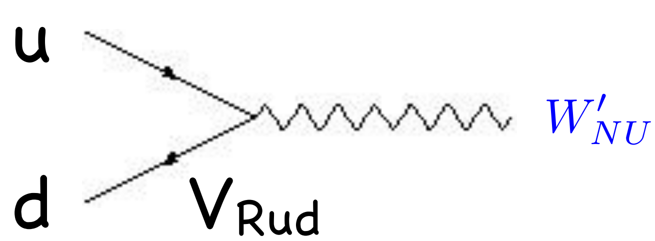
- at TeV masses the tb channel is open $B(W' \to \tau\nu)_{SSM} \sim 8.5\%$
- in non-universal case $B(W' \to \tau\nu)_{NU} \sim 25\%$
- production cross section is very suppressed





$$\left(\left|\frac{g_R}{g_L}\frac{V_{Rud}}{V_{ud}}\right|^2 \text{ or } \xi_W^2\right)$$

$(10^{-6})^2$ $(10^{-3})^2$



- NUGIM production cross section similar to SSM

Number of light neutrinos

- there is one light right handed neutrino! why not seen at LEP?
- basically it has to couple through mixing with Z′

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

- from Z $\tau\tau$ results at LEP we find $\left|\frac{g_R}{g_L}\xi_Z\right| \lesssim 2\times 10^{-3}$
  - and this makes $\Gamma(Z \to \nu_{R3}\bar{\nu}_{R3}) < 3\times 10^{-4}\ MeV$
- the limit on new invisible Z decay
  - LEP standard result n = 2.9840 ± 0.0082
    - assumes Lepton universality and no new particles
  - direct limit n = 3.00 ± 0.08
  - implies 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 $$\Delta N_{eff} < \begin{cases} 0.28 & \text{for } H_0 = 68.7^{+0.6}_{-0.7} \text{ km/s/Mpc} \\ 0.77 & \text{for } H_0 = 71.3^{+1.9}_{-2.2} \text{ km/s/Mpc} . \end{cases}$$
- to explain the anomalies we use an interaction is not much weaker than weak
- The W′ can scatter with the new light neutrino and bring it to thermal eq. 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 at least 0.1

$$r = \left(\frac{g_*(T_{BBN})}{g_*(T_R)} \right)^{4/3}$$

- safe!

$K \to \pi\,\nu\,\nu$ on the other hand

Eur. Phys. J. C (2018) 78:472

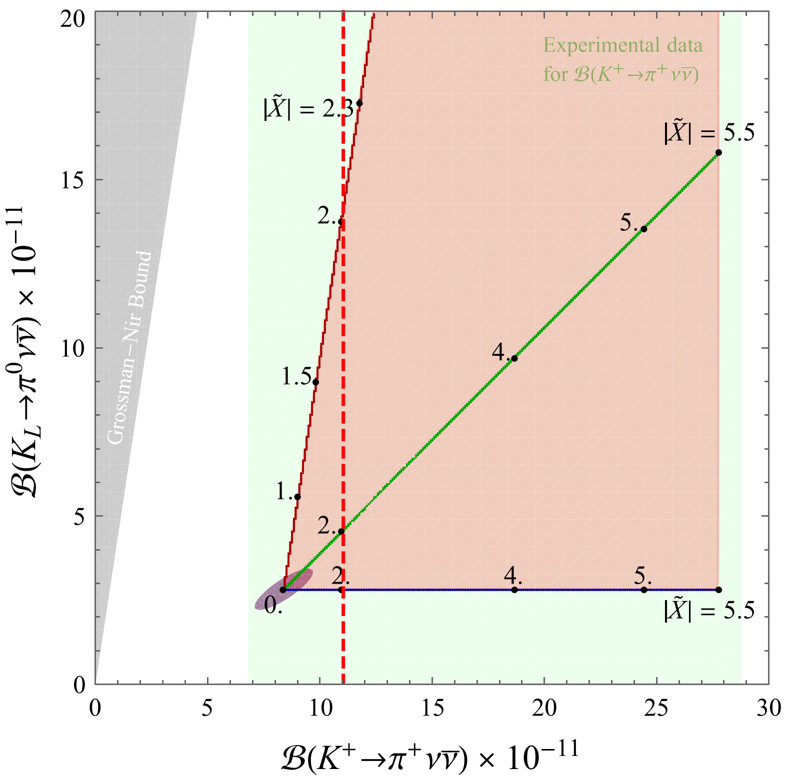


Fig. 2 New physics with one light right-handed neutrino. The green line illustrates the case $\tilde{X}$ real and the pink region illustrates the case $|\tilde{X}| \leq 5.5$. The purple marks the SM 1σ region and the green marks the 90% c.l. from BNL-787 combined with BNL-949. The red and blue lines on the boundary of the pink region correspond to a new physics phase given by $\phi + \phi_{\lambda_t} = (\pi/2 \text{ or } 3\pi/2)$ and $\phi + \phi_{\lambda_t} = (0 \text{ or } \pi)$ respectively. Finally the vertical dashed red line marks a possible future limit for $\mathcal{B}_{K^+}$ at 1.3 times the SM

Eur. Phys. J. C (2018) 78:472

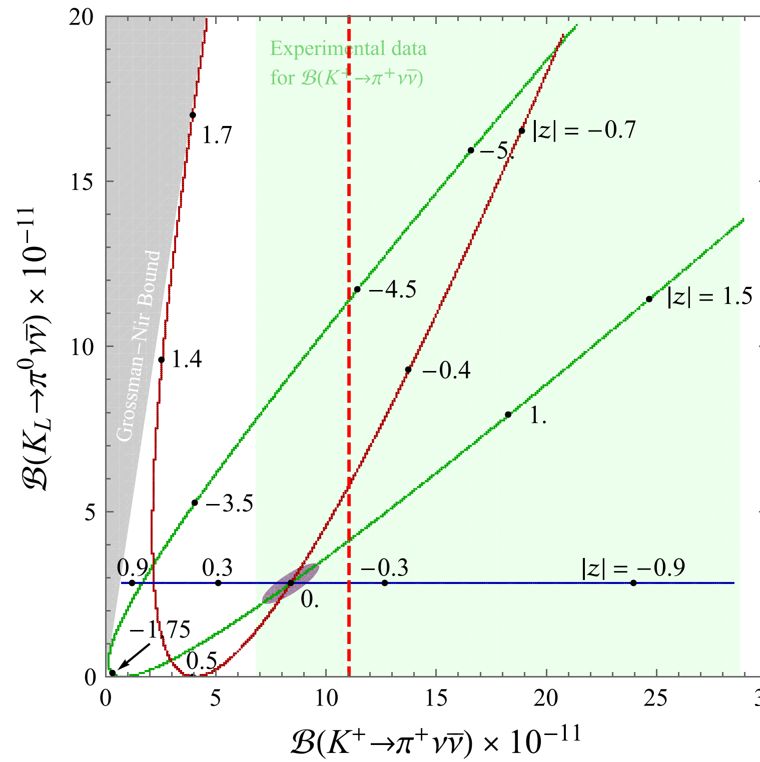


Fig. 1 New physics with lepton flavour conserving left-handed neutrinos. The green line illustrates the case X_N real, the red line corresponds to X_N having a phase equal to that of the λ_t (central value) and the blue line to X_N having a phase equal to minus that of the λ_t. For comparison the purple 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

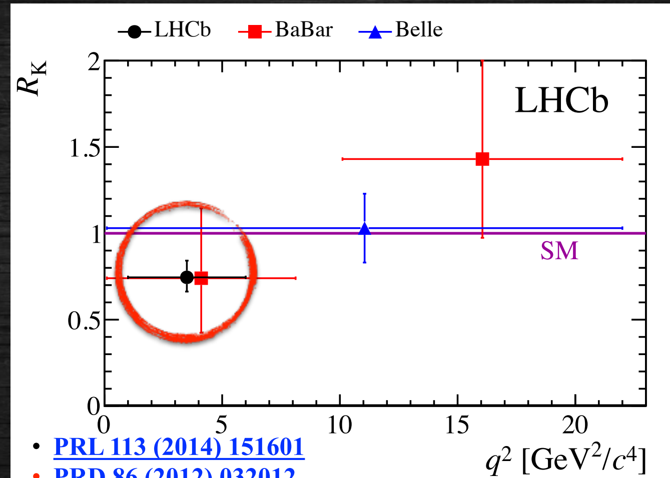
and one that doesn't quite work

problems with μ in B decay?

Once upon a time …

› LHCb tested Lepton Universality using **$B^+ \to K^+ll$** decays and observed a **tension with the SM at 2.6σ**

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}$$



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

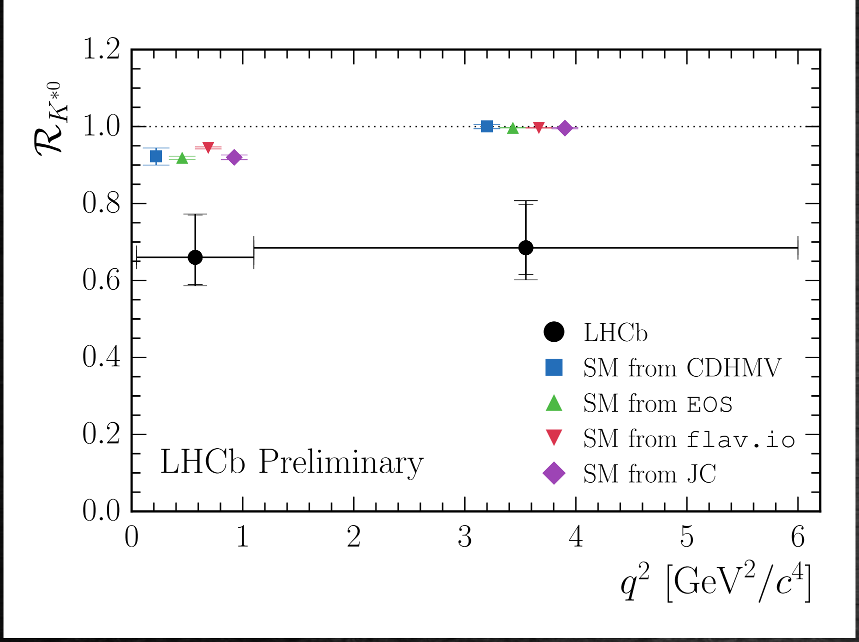
› Consistent with observed BR($B^+ \to K^+\mu\mu$) if NP does not couple to electrons

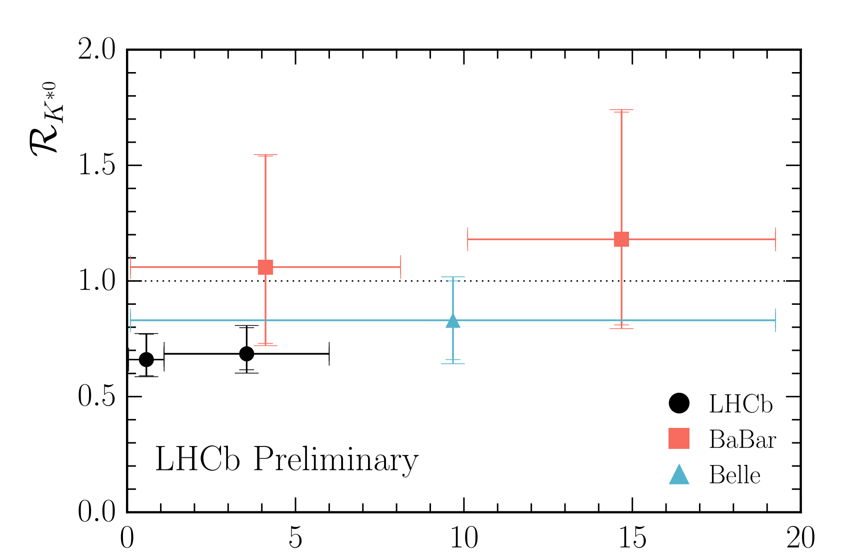
› **Observation of LFU violations would be a clear sign of NP**

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

vs 1.00 ± 0.01 in SM

Results – II



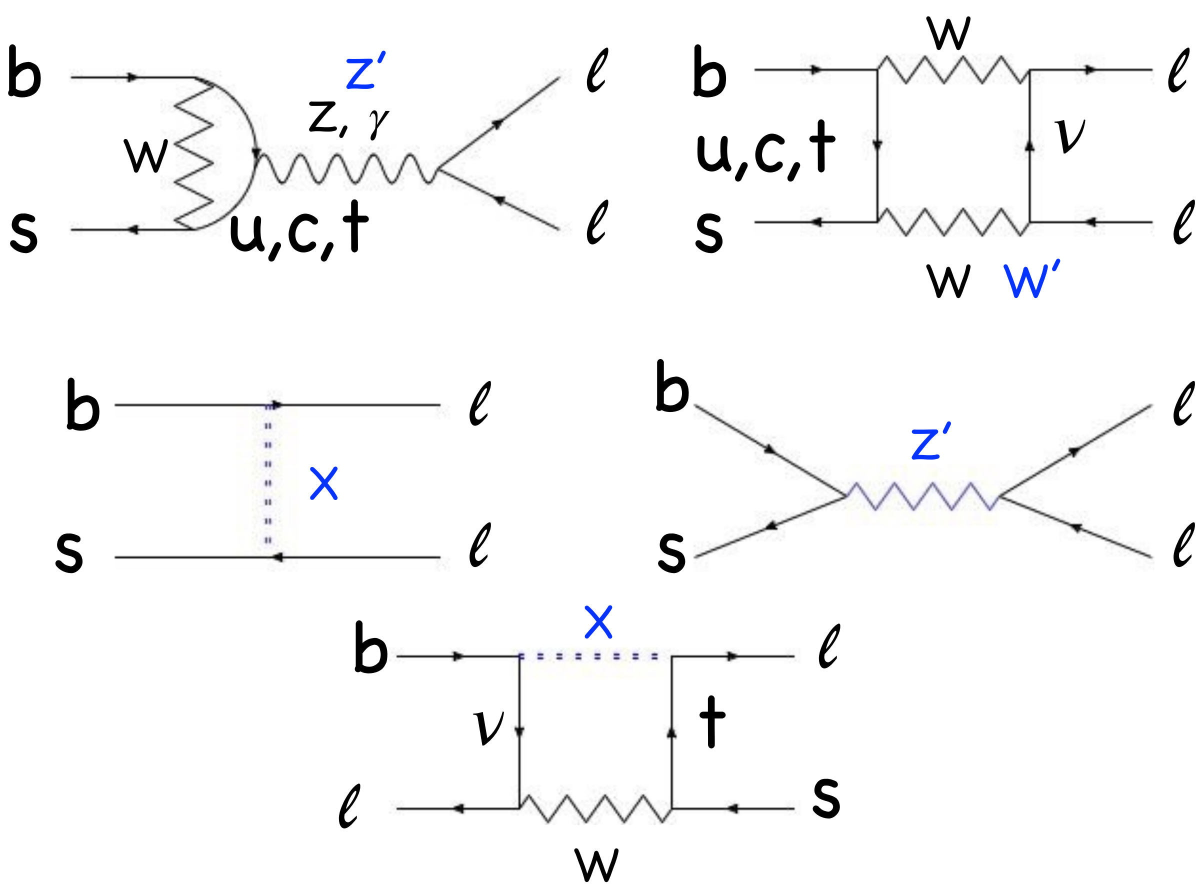


- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

second surprise in b → s μ μ

- apparently the μ has a weaker coupling that the electron
- at tree and loop level, many possible other NP couplings



effective hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i O_i$$

possible NP + ...

SM

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}_{9'} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10'} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

- assume matrix elements ok, new physics encoded in the Wilson coefficients, the C_i
- perform a global fit to the C_i
- C_i can be different for different leptons to break universality

Global fits

- from J. Matias, Moriond EW 2017:

Global analysis of $b \to s\mu\mu$ anomalies

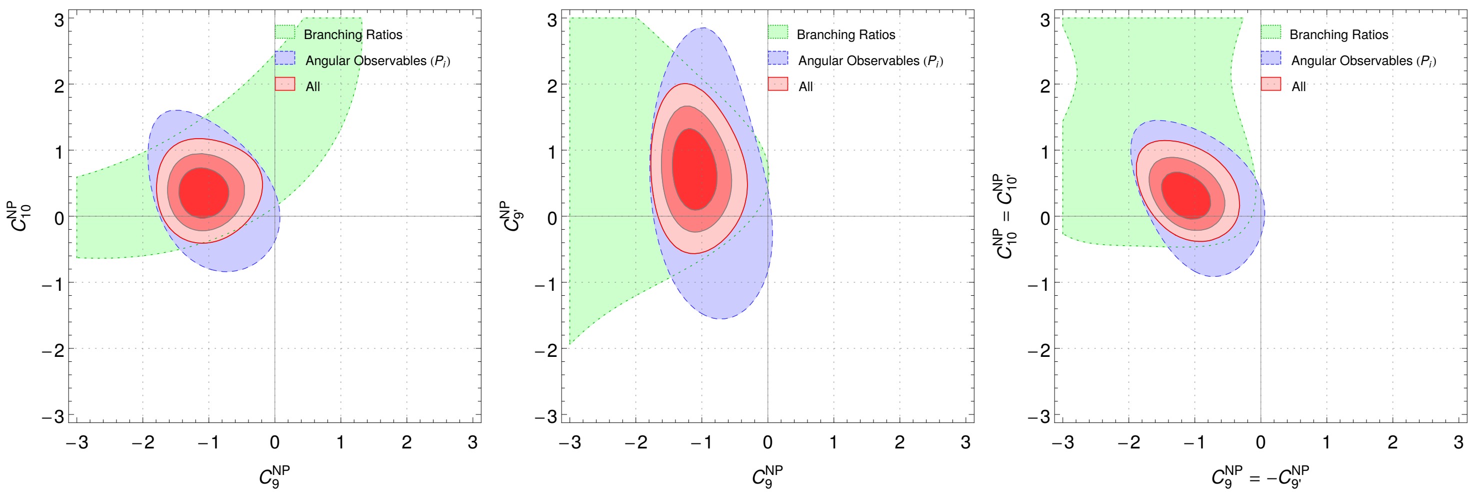
[Descotes, Hofer, JM, Virto]

96 observables in total (LHCb for exclusive, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.
- $B_s \to \phi\mu\mu$ (P_1, $P'_{4,6}$, F_L in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR), $B \to K^*\gamma$ (A_I and $S_{K^*\gamma}$)

Beyond 1D several favoured scenarios

Allowing for more than one Wilson coefficient to vary different scenarios with pull-SM beyond 4σ pop-up:



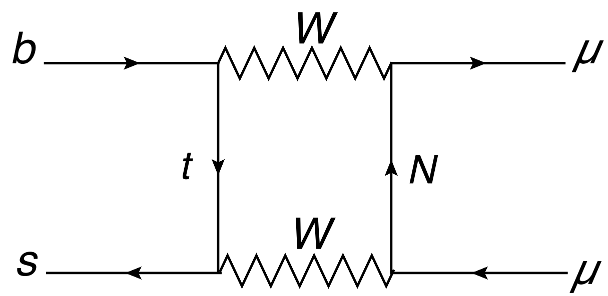
(C_9, C_{10}) (C_9, C'_9) ($C_9 = -C'_9$ & $C_{10} = C'_{10}$)

- BR and angular observables both favour $C_9^{\rm NP} \simeq -1$ in all 'good scenarios'.

benchmark

$$C_{9\mu}^{NP} = -C_{10\mu}^{NP} \in (-0.73, -0.48) \text{ at } 1\sigma$$

- notice that if we have heavy neutrinos N then

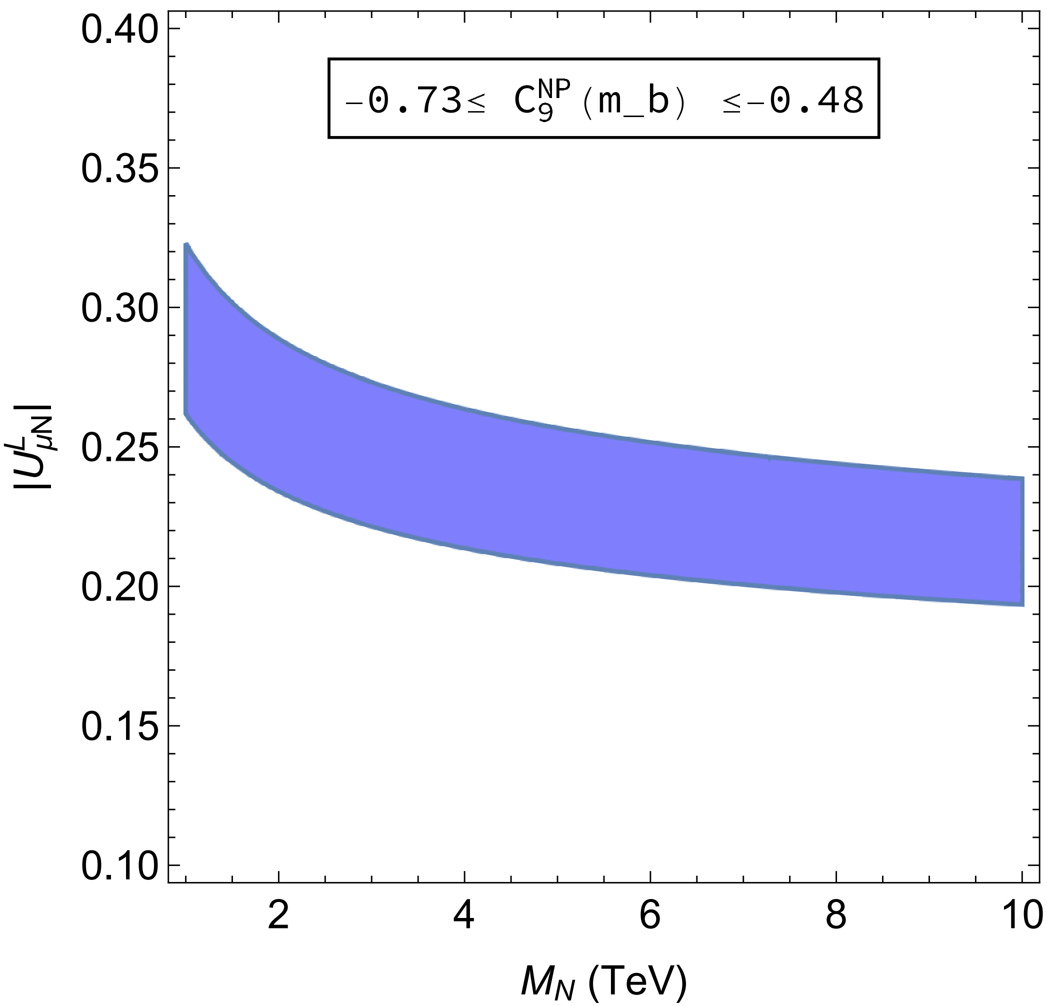


- produces the right pattern in $C_{9,10}$, resulting in

$$C_9^{NP}(M_W) = -C_{10}^{NP}(M_W) = -\frac{1}{4s_W^2}\sum_N U_{\mu N}^{L\star} U_{\mu N}^{L} E(\lambda_t, \lambda_N).$$

numerics

- to get into the 1σ range one needs



in conflict with global fits

10.1007/JHEP08(2016)033, Enrique Fernandez-Martinez, Josu Hernandez-Garcia, Jacobo Lopez-Pavon

- for example conclude that this mixing angle is a few % at most from LFC constraints
  - basic vertices like $W \to \mu\nu$ pick up the same angles
  - constrained from G_F ...
- simplest see-saw model doesn't work
- there are other models that introduce additional particles into the box-diagram (heavy vector like quarks) Francisco J. Botella, Gustavo C. Branco, Miguel Nebot, arXiv:1712.04470 which may work.