Last time I was in Slovenia ...

Killing the ρ, the $K^\star$, and their ugly cousins

Towards a coherent approach for B decays to unstable particles

Javier Virto

Universität Bern

Brda - Slovenia – October 20th, 2016

Based on collaborations with S. Kränkl, T. Mannel, A. Khodjamirian, S. Cheng, T. Huber and K. Vos

UNIVERSITÄT BERN

Last time I was in Slovenia ...

It is great to be in Slovenia

The home country of the next first lady...

Javier Virto (Uni Bern) B decays to unstable particles October 20th, 2016 2 / 18

The CKM Matrix in the SMEFT

Descotes-Genon, Falkowski, Fedele, González-Alonso, Virto, **arXiv:1812.08163 [hep-ph]**

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Massachusetts Institute of Technology

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Portoroz 2019 —– April 17th 2019

Marie Skłodowska-Curie Actions

Simple example: Leptonic Tau decay

Consider using $\Gamma(\tau \to e\nu\bar{\nu})$ to constrain a Lepton-Universal BSM scenario:

$$\mathcal{L}_{BSM} = \sum_{i,j\in\{e,\mu,\tau\}} \left[C_{H\ell}^{(3)}\right](\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{\ell}_i\sigma^I\gamma^\mu\ell_i) + \left[C_{\ell\ell}\right](\bar{\ell}_i\gamma^\mu\ell_j)(\bar{\ell}_j\gamma_\mu\ell_i)$$

Then: $\mathcal{A}(\tau \to e\nu\bar{\nu}) \propto \frac{1}{v^2} + 2\, C_{H\ell}^{(3)} - C_{\ell\ell}$

Going to the PDG, $v = 246.21965(6)\text{GeV}$

A measurement of $\Gamma(\tau \to e\nu\bar{\nu})$ then constrains $[2\, C_{H\ell}^{(3)} - C_{\ell\ell}]$

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Then: $\quad \mathcal{A}(\tau \to e\nu\bar{\nu}) \propto \dfrac{1}{v^2} + 2\, C_{H\ell}^{(3)} - C_{\ell\ell}$

Going to the PDG, $\quad v = 246.21965(6)\text{GeV}$

A measurement of $\Gamma(\tau \to e\nu\bar{\nu})$ then constrains $[2\, C_{H\ell}^{(3)} - C_{\ell\ell}]$

WRONG : The PDG value of v comes from the measurement of τ_μ, which in this scenario is strictly speaking a determination of exactly $\tilde{v}$, with

$$\frac{1}{\tilde{v}^2} \equiv \frac{1}{v^2} + 2\, C_{H\ell}^{(3)} - C_{\ell\ell}$$

Simple example: Leptonic Tau decay

How to do it properly?

1. Reinterpret the PDG value: $\tilde{v} = 246.21965(6)\text{GeV}$

with $\quad \dfrac{1}{\tilde{v}^2} \equiv \dfrac{1}{v^2} + [C_{H\ell}^{(3)}]_{\mu\mu} + [C_{H\ell}^{(3)}]_{ee} - [C_{\ell\ell}]_{\mu ee\mu}$

2. Rewrite the $\tau \to e\nu\bar{\nu}$ amplitude:

$$\begin{aligned}\mathcal{A}(\tau \to e\nu\bar{\nu}) \quad &\propto \quad \frac{1}{v^2} + [C_{H\ell}^{(3)}]_{\tau\tau} + [C_{H\ell}^{(3)}]_{ee} - [C_{\ell\ell}]_{\tau ee\tau} \\ &= \quad \frac{1}{\tilde{v}^2} + [C_{H\ell}^{(3)}]_{\tau\tau} - [C_{H\ell}^{(3)}]_{\mu\mu} - [C_{\ell\ell}]_{\tau ee\tau} + [C_{\ell\ell}]_{\mu ee\mu}\end{aligned}$$

3. Substitute $\tilde{v} = 246.21965(6)\text{GeV}$ and use $\Gamma(\tau \to e\nu\bar{\nu})$ to constrain C_i.

Fixing $D \leq 4$ couplings in the SMEFT

The procedure to fix the “SM” couplings in NP scenarios is well known and has been discussed extensively.

But...

> “ In the context of the SMEFT, experimental extractions and fits to the CKM matrix elements get corrections due to $\mathcal{L}^{(6)}$ operators. Such corrections define a difference between “bar” and “hatted” CKM quantities that are neglected here. The reason we have neglected these effects on the CKM inputs is that to our knowledge, no complete analysis in the SMEFT defining such corrections to the global fit to Wolfenstein parameters exists in the literature. Analyses that build up results central to the effort to determine such corrections include Refs. [40, 44, 64–66]. When such results are available they will be included in the SMEFTsim package as an update.

Brivio, Jiang, Trott 1709.06492

The CKM Matrix, Unitarity and the Wolfenstein Parameters

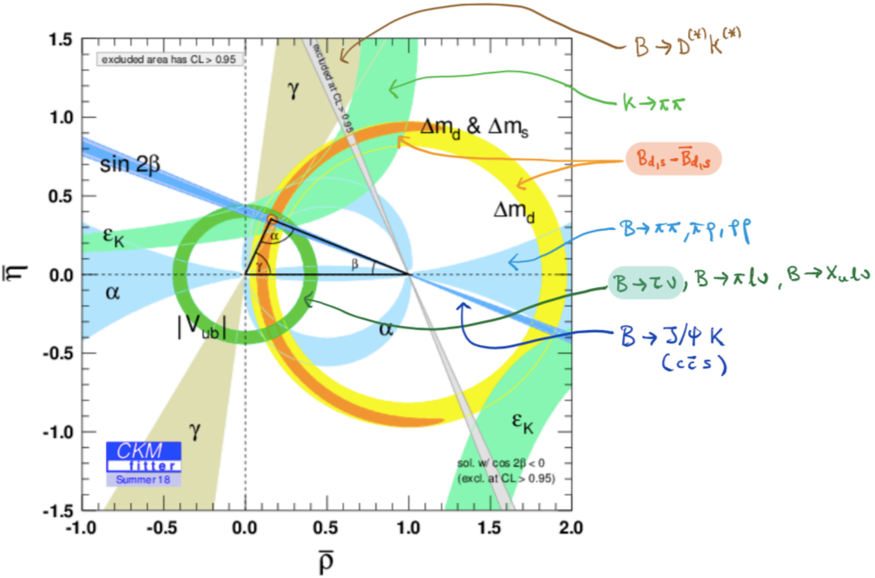
- $\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{D>4} = \mathcal{L}_{\rm SM} + \sum_i C_i\, Q_i^{(6)} + \cdots\ ,$
- In the broken phase, $\mathcal{L}_{m_\psi} = - \sum_{\psi=u,d,e} \overline{\psi}_{R,i}\, [M_\psi]_{ij}\, \psi_{L,j} + \text{h.c.}$
- $\exists$ a weak basis s.t. $M_e = \text{diag},\ M_u = \text{diag},\ M_d = \text{diag} \cdot V^\dagger$

$$V \;=\; \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \text{CKM Matrix}$$

$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(1+\frac{1}{2}\lambda^2)(\bar\rho-i\bar\eta) \\ -\lambda+A^2\lambda^5(\frac{1}{2}-\bar\rho-i\bar\eta) & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2+A\lambda^4(\frac{1}{2}-\bar\rho-i\bar\eta) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)\,.$$

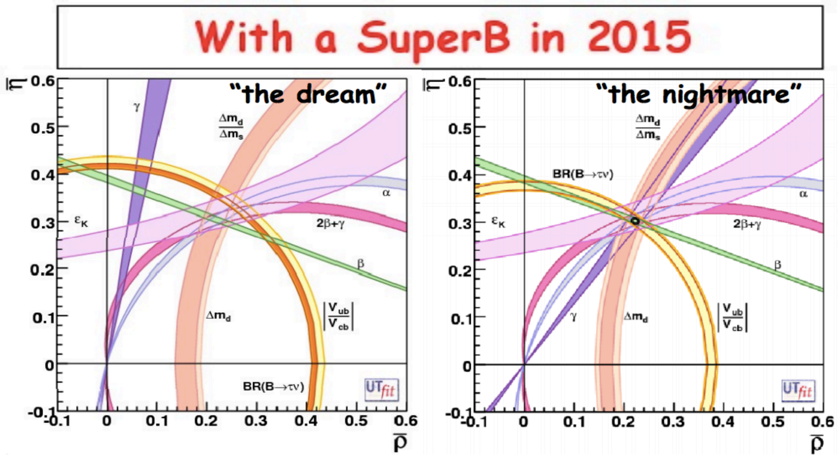
- Wolfenstein Parameters : $W_i = \{\lambda, A, \bar\rho, \bar\eta\}$

The SM CKM fit



The SM CKM fit

L.Silvestrini, Lattice'2008



How to translate this into BSM constraints / a BSM pattern ?

Beyond The SM: Two paths

Path 1. Global fit to NP including the CKM parameters as free parameters.

Path 2. Take the model-independent determination of some “effective CKM parameters” from precise measurements (independent on the ones you use in your analysis) and use them as inputs.

2 has some advantages (if you are looking at individual observables, or your analysis is very different from flavor and at a different scale [i.e. collider, top, higgs, ...]) and works very well under certain conditions (hierarchy of precisions, etc).

We do 2.

The Strategy

We do:

1. Choose 4 "optimal" observables that depend on 4 orthogonal combinations of Wolfenstein parameters.
2. Absorb NP contributions into "effective" Wolfenstein parameters $\widetilde{W}_j$.
3. Extract numerical values for $\widetilde{W}_j$, and quote $W_j = \widetilde{W}_j - \delta\, W_j(C_k^{D=6})$.

$$O_i^{\rm exp} \stackrel{!}{=} O_i^{\rm th}(W_j) = \underbrace{O_i^{\rm SM}(W_j)}_{\sim 1} + \underbrace{O_i^{\rm NP}(W_j)}_{\sim 1/\Lambda^2} \equiv O_i^{\rm SM}(\widetilde{W}_j) \quad \Rightarrow \quad \widetilde{W}_j = \#_j$$

You do:

4. To calculate your observables $P_i(W_j, C_k^{D=6})$, you substitute $W_j \to \widetilde{W}_j - \delta\, W_j(C_k^{D=6})$, and re-expand in $1/\Lambda$.

Example: $\widetilde{V}_{us}$ from $K_{\mu 3}$

From now on it is convenient (not necessary) to define $\widetilde{V} \equiv V(\tilde{\lambda}, \tilde{A}, \tilde{\rho}, \tilde{\eta})$

$$\Gamma(K^- \to \mu^- \bar{\nu}_\ell) = \underbrace{|V_{us}|^2 \left(1 + \Delta_{K\mu 2}\right)}_{|\widetilde{V}_{us}|^2} \frac{f_K^2\, m_P m_\mu^2}{16\pi \tilde{v}^4} \left(1 - \frac{m_\mu^2}{m_K^2}\right)^2 (1 + \delta_{K\mu})$$

$$\Delta_{K\mu 2} = 2\,\mathrm{Re}(\epsilon_A^{\mu us}) - \frac{2\, m_P^2}{(m_u + m_q) m_\mu} \mathrm{Re}(\epsilon_P^{\mu us}) + 4\, \frac{\delta v}{v} + \mathcal{O}(\Lambda^{-4})$$

$$\epsilon_A^{\mu us} \equiv -1 - \frac{v^2}{2\, V_{us}} \left(\left[L_{\nu edu}^{V,LL}(\mu_s)\right]^*_{\mu\mu su} - \left[L_{\nu edu}^{V,LR}(\mu_s)\right]^*_{\mu\mu su} \right),$$

$$\epsilon_P^{\mu us} \equiv -\frac{v^2}{2\, V_{us}} \left(\left[L_{\nu edu}^{S,RR}(\mu_s)\right]^*_{\mu\mu su} - \left[L_{\nu edu}^{S,RL}(\mu_s)\right]^*_{\mu\mu su} \right),$$

A number for $|\widetilde{V}_{us}|$ can be used by trading $|V_{us}| \to |\widetilde{V}_{us}|(1 - \Delta_{K\mu 2}/2 + \cdots)$ in the observable of interest.

Choice of Observables

X **CP Asymmetries in Non-leptonic Decays :** (Matrix Elements)

$$B \to \pi\pi, \rho\pi, \rho\rho \quad \text{(for } \alpha\text{)} \qquad B \to J/\psi K^{(*)}, (c\bar{c})K \quad \text{(for } \beta\text{)}$$

$$B \to D^{(*)}K^{(*)} \quad \text{(for } \gamma\text{)} \qquad B_s \to J/\psi\phi, \psi(2S)\phi \quad \text{(for } \beta_s\text{)}$$

X $b \to c\ell\nu$ **transitions :** (inclusive vs. exclusive)

X **Semi-leptonic Decays :** (momentum dependence)

$$K \to \pi\ell\nu \; (V_{us}),\; D \to K\ell\nu \; (V_{cs}),\; B \to \pi\ell\nu \; (V_{ub}), \ldots$$

✓ **Leptonic Decays :**

→ For λ, $K_{\ell 3}$ better than $D_{\ell 3}$ – (precision).

→ $K_{\ell 3}/\pi_{\ell 3}$ (f_K/f_π) better than $K_{\ell 3}$ (f_K) – (precision, lattice scale).

→ $B_{\ell 3}$ necessary.

✓ $\Delta M_{d,s}$ **:** All Matrix Elements known from Lattice

Choice of Observables

Our subjective and time-dependent choice is :

$$\boxed{\begin{array}{cc} \dfrac{\Gamma(K\to\mu\nu_\mu)}{\Gamma(\pi\to\mu\nu_\mu)} & \Gamma(B\to\tau\nu_\tau) \\ \\ \Delta M_d & \Delta M_s \end{array}}$$

This choice is based on some criteria which are not universal, and on some circumstances that are local in time (e.g. precision, tensions, theory, ...)

These observables fix the combinations

$$\boxed{\begin{array}{cc} |\widetilde{V}_{us}/\widetilde{V}_{ud}| & |\widetilde{V}_{ub}| \\ |\widetilde{V}_{tb}\widetilde{V}_{td}| & |\widetilde{V}_{tb}\widetilde{V}_{ts}| \end{array}}$$

Extraction of the Wolfenstein Parameters

$$
\begin{aligned}
|\widetilde{V}_{us}/\widetilde{V}_{ud}| &= 0.23131 \pm 0.00050 &&= \tilde{\lambda} + \frac{1}{2}\tilde{\lambda}^3 + \frac{3}{8}\tilde{\lambda}^5 + \mathcal{O}(\lambda^7)\,, \\
|\widetilde{V}_{ub}| &= 0.00425 \pm 0.00049 &&= \tilde{A}\sqrt{\tilde{\rho}^2 + \tilde{\eta}^2}\left[\tilde{\lambda}^3 + \frac{1}{2}\tilde{\lambda}^5 + \mathcal{O}(\lambda^7)\right] \\
|\widetilde{V}_{tb}\widetilde{V}_{td}| &= 0.00851 \pm 0.00025 &&= \tilde{\lambda}^3\tilde{A}\sqrt{(1-\tilde{\rho})^2 + \tilde{\eta}^2} + \mathcal{O}(\lambda^7)\,, \\
|\widetilde{V}_{tb}\widetilde{V}_{ts}| &= 0.0414 \pm 0.0010 &&= \tilde{\lambda}^2\tilde{A} - \frac{1}{2}\tilde{\lambda}^4\tilde{A}(1-2\tilde{\rho}) + \mathcal{O}(\lambda^6)\,.
\end{aligned}
$$

$$
\begin{pmatrix} \tilde{\lambda} = \lambda + \delta\lambda \\ \tilde{A} = A + \delta A \\ \tilde{\rho} = \bar{\rho} + \delta\bar{\rho} \\ \tilde{\eta} = \bar{\eta} + \delta\bar{\eta} \end{pmatrix} = \begin{pmatrix} 0.22537 \pm 0.00046 \\ 0.828 \pm 0.021 \\ 0.194 \pm 0.024 \\ 0.391 \pm 0.048 \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & -0.16 & 0.05 & -0.03 \\ \cdot & 1 & -0.25 & -0.24 \\ \cdot & \cdot & 1 & 0.83 \\ \cdot & \cdot & \cdot & 1 \end{pmatrix}.
$$

Comparison to SM fits

Comparing apples and oranges:

CKMfitter (SM) [1]	UTfit (SM) [2]	This work (SMEFT)
$\lambda = 0.224747^{+0.000254}_{-0.000059}$	$\lambda = 0.2250 \pm 0.0005$	$\tilde{\lambda} = 0.22537 \pm 0.00046$
$A = 0.8403^{+0.0056}_{-0.0201}$	$A = 0.826 \pm 0.012$	$\tilde{A} = 0.828 \pm 0.021$
$\bar{\rho} = 0.1577^{+0.0096}_{-0.0074}$	$\bar{\rho} = 0.148 \pm 0.013$	$\tilde{\rho} = 0.194 \pm 0.024$
$\bar{\eta} = 0.3493^{+0.0095}_{-0.0071}$	$\bar{\eta} = 0.348 \pm 0.010$	$\tilde{\eta} = 0.391 \pm 0.048$

[1] CKMfittler collaboration, http://ckmfitter.in2p3.fr/www/html/ckm results.html

[2] UTfit collaboration, http://www.utfit.org/UTfit/Results

NP contributions to Wolfenstein Parameters

The NP contributions to the Wolfenstein Parameters are:

$$\begin{pmatrix} \delta\lambda \\ \delta A \\ \delta\bar{\rho} \\ \delta\bar{\eta} \end{pmatrix} = M(\tilde{\lambda}, \tilde{A}, \tilde{\rho}, \tilde{\eta}) \begin{pmatrix} \Delta_{K/\pi} \\ \Delta_{B\tau 2} \\ \Delta_{\Delta M_d} \\ \Delta_{\Delta M_s} \end{pmatrix} .$$

Numerically,

$$M(\tilde{\lambda}, \tilde{A}, \tilde{\rho}, \tilde{\eta}) = \begin{pmatrix} 0.1070(2) & 0 & 0 & 0 \\ -0.786(20) & -0.0040(9) & 0.0167(6) & 0.402(10) \\ 0.286(24) & 0.094(22) & -0.390(10) & 0.296(23) \\ -0.385(18) & 0.200(19) & 0.184(10) & -0.384(19) \end{pmatrix}$$

where the correlations can & should be included (see paper).

Pion decay :

$$\Gamma(\pi \to \mu\nu) = \left|1 - \frac{\tilde{\lambda}^2}{2} - \frac{\tilde{\lambda}^4}{8}\right|^2 \frac{f_{\pi^\pm}^2 m_{\pi^\pm} m_\mu^2}{16\pi\tilde{v}^4} \left(1 - \frac{m_\mu^2}{m_{\pi^\pm}^2}\right)^2 (1 + \delta_{\pi\mu}) \left[1 + \widetilde{\Delta}_{\pi\mu 2}\right]$$

$$\widetilde{\Delta}_{\pi\mu 2} = 2\,\mathrm{Re}(\epsilon_A^{\mu ud}) - \frac{2 m_{\pi^\pm}^2}{(m_u + m_d) m_\mu} \mathrm{Re}(\epsilon_P^{\mu ud}) + 4\frac{\delta v}{v} + 2\tilde{\lambda}(1 + \tilde{\lambda}^2)\delta\lambda + \mathcal{O}(\Lambda^{-4}, \tilde{\lambda}^6)$$

$$\left.\begin{array}{l} \mathcal{B}(\pi \to \mu\nu) = 0.9998770(4) \\ \tau_\pi = 2.6033(5) \cdot 10^{-8} s \end{array}\right\} \Rightarrow \quad \widetilde{\Delta}_{\pi\mu 2} = 0.004 \pm 0.013$$

Applications I : Leptonic Decays

D meson decay :

$$\Gamma(D \to \ell\nu) = |\tilde{\lambda}|^2 \frac{f_{D^\pm}^2\, m_{D^\pm}\, m_\ell^2}{16\pi \tilde{v}^4} \left(1 - \frac{m_\ell^2}{m_{D^\pm}^2}\right)^2 (1 + \delta_{D\ell}) \left[1 + \widetilde{\Delta}_{D\ell 2}\right]$$

$$\widetilde{\Delta}_{D\ell 2} = 2\,\mathrm{Re}(\epsilon_A^{\ell cd}) - \frac{2\, m_{D^\pm}^2}{(m_c + m_d) m_\ell}\,\mathrm{Re}(\epsilon_P^{\ell cd}) + 4\frac{\delta v}{v} - 2\frac{\delta\lambda}{\tilde{\lambda}} + \mathcal{O}(\Lambda^{-4}, \tilde{\lambda}^4)$$

$$\left.\begin{array}{l} \mathcal{B}(D \to \mu\nu) = 3.74\,(17) \cdot 10^{-4} \\ \tau_{D^\pm} = 1.040(7) \cdot 10^{-12}\, s \end{array}\right\} \quad \Rightarrow \quad \widetilde{\Delta}_{D\mu 2} = -0.089 \pm 0.043$$

Applications II : Exclusive Hadronic W Decays

Corrections to W couplings in the SMEFT:

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{\tilde{g}_L}{\sqrt{2}} W^{\mu+} \bar{u}_{Lj} \gamma_\mu \left(V_{jk} + \left[\delta g_L^{Wq}\right]_{jk} \right) d_{Lk} + \text{h.c.}$$

with

$$\begin{aligned} \left[\delta g_L^{Wq}\right]_{jk} \quad = \quad & [C_{Hq}^{(3)}]_{jl} V_{lk} + \frac{\tilde{g}_L^2 \tilde{v}^2}{\tilde{g}_L^2 - \tilde{g}_Y^2} \Bigg[-\frac{\tilde{g}_Y}{\tilde{g}_L} C_{HWB} - \frac{1}{4} C_{HD} + \frac{1}{4} [C_{\ell\ell}]_{e\mu\mu e} \\ & + \frac{1}{4} [C_{\ell\ell}]_{\mu e e \mu} - \frac{1}{2} [C_{H\ell}^{(3)}]_{ee} - \frac{1}{2} [C_{H\ell}^{(3)}]_{\mu\mu} \Bigg] V_{jk} + \mathcal{O}(\Lambda^{-4}) \end{aligned}$$

Taking $V_{jk} \to \tilde{V}_{jk} - \delta V_{jk}$, we have

$$\frac{\Gamma(W \to u_j d_k)}{\Gamma(W \to u_j d_k)_{\text{SM}}} = 1 + 2\,\text{Re} \left(\frac{\left[\delta g_L^{Wq}\right]_{jk} - \delta V_{jk}}{\widetilde{V}_{jk}} \right),$$

Applications II : Exclusive Hadronic W Decays

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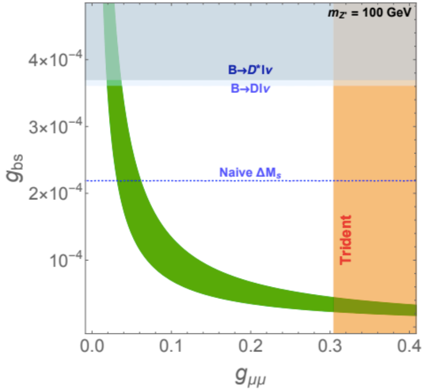
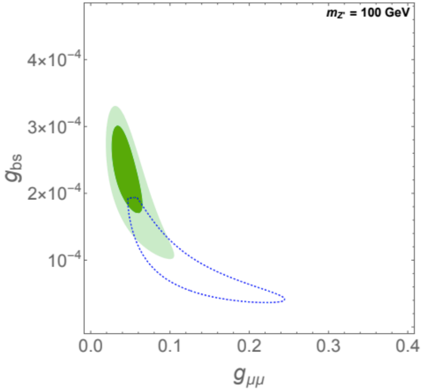
Where the result of our analysis gives:

$$\begin{aligned}
\delta V_{ud} &= \delta V_{cs} = -\tilde{\lambda}\,\delta\lambda + \mathcal{O}(\tilde{\lambda}^4)\ ,\\
\delta V_{us} &= -\delta V_{cd} = \delta\lambda + \mathcal{O}(\tilde{\lambda}^5)\ ,\\
\delta V_{ub} &= 3\tilde{A}\tilde{\lambda}^2(\tilde{\rho} - i\tilde{\eta})\,\delta\lambda + \tilde{\lambda}^3(\tilde{\rho} - i\tilde{\eta})\,\delta A + \tilde{A}\tilde{\lambda}^3(\delta\rho - i\delta\eta) + \mathcal{O}(\tilde{\lambda}^5)\ ,\\
\delta V_{cb} &= 2\tilde{A}\,\tilde{\lambda}\,\delta\lambda + \tilde{\lambda}^2\,\delta A + \mathcal{O}(\tilde{\lambda}^6)\ .
\end{aligned}$$

Applications III : $b \to s\ell\ell$ Anomalies

$$\mathcal{L}_{BSM} = g_{bs} Z'_\rho \left(\bar{q}_2 \gamma^\rho q_3 + \text{h.c.}\right) - g_{\mu\mu} Z'_\rho \bar{\ell}_2 \gamma^\rho \ell_2$$





Imagine having NP contributions to $b \to c\ell\nu$ transitions also.

Summary

- My prediction about Melania at Brda'2016 was confirmed.
- Determination of CKM parameters affected by $D = 6$ ops in the SMEFT
- Cannot use SM fit. We set up a consistent strategy.
- We identify a set of 4 good observables to extract the "tilde" Wolf Pars:

$$\Gamma(K \to \mu\nu_\mu)/\Gamma(\pi \to \mu\nu_\mu)\ , \quad \Gamma(B \to \tau\nu_\tau)\ , \quad \Delta M_d\ , \quad \Delta M_s$$

- Our results are : (with a given correlation matrix)

$$\tilde{\lambda} = 0.22537(46)\ , \quad \tilde{A} = 0.828(21)\ , \quad \tilde{\rho} = 0.194(24)\ , \quad \tilde{\eta} = 0.391(48)\ .$$

- Also necessary are the NP contributions $\delta W(C_i) = \{\delta\lambda, \delta A, \delta\rho, \delta\eta\}$ depending on the SMEFT Wilson coefficients C_i at the matching scale Λ.

Any observable can now be written as $Obs = Obs(W, C_i) = Obs(\widetilde{W}, C_i)$

- We have seen a few applications.

1st Workshop on Tools for Low-Energy SMEFT Phenomenology

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