BSM PHYSICS IN THE HIGGS COUPLINGS AND FLAVOUR SYMMETRIES

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FLAVOUR IS ESSENTIALLY A BEYOND THE SM CONCEPT

AND A NEW PHYSICS SCALE RELEVANT FOR THE

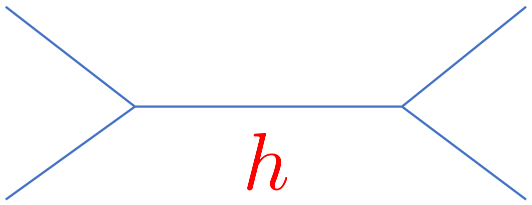
FLAVOUR SECTOR MAY BE DIFFERENT FROM THE SCALE

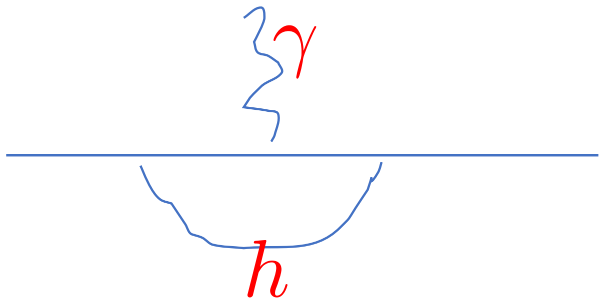
OF THE BSM PHYSICS LINKED TO THE BROUT-ENGLERT-HIGGS MECHANISM IN THE SM AND ITS HIERARCHY PROBLEM

SEVERAL SOURCES OF INFORMATION ON THE BSM PHYSICS IN YUKAWAS:

- HIGGS BOSON PRODUCTION AND DECAYS, DIRECTLY DEPENDENT ON THE YUKAWA COUPLINGS (COLLIDERS) **TESTING SO FAR DIAGONAL COUPLINGS**

- VERY HIGH PRECISION LOW ENERGY FLAVOUR OBSERVABLES, INCLUDING MAGNETIC AND ELECTRIC DIPOLE MOMENTS AND A VARIETY OF FCNC PROCESSES, DEPENDENT ON THE YUKAWA COUPLINGS VIA HIGGS EXCHANGE CONTRIBUTIONS TO THEIR AMPLITUDES (**TESTING NON-DIAGONAL)**





I'LL FOCUS ON THE CP VIOLATION IN YUKAWA COUPLINGS AND THE POTENTIAL FOR THE BSM PHYSICS DISCOVERY IN THE HIGGS DECAYS, GIVEN THE HIGH PRECISION OF THE FCNC DATA

SM: $y_{h\bar{\psi}\psi} = \frac{\sqrt{2}}{v} m_\psi$

IN THE SMEFT FRAMEWORK, INCLUDING DIM 6 OPERATORS, THERE IS ONLY ONE OPERATOR CONTRIBUTING TO YUKAWA COUPLINGS:

$$L = -\bar{L}_L^J H Y_e'^{JK} e_R^K - \bar{L}_L^J H C_e'^{JK} e_R^K \frac{H^\dagger H}{\Lambda^2} + h.c$$

Y', C' ARE 3x3 COMPLEX MATRICES IN THE FLAVOUR SPACE

(AND SIMILARLY FOR THE UP AND DOWN FERMIONS)

FLAVOUR STRUCTURE OF THE BSM PHYSICS CONTRIBUTING TO YUKAWA COUPLINGS, THAT IS THE FLAVOUR STRUCTURE OF THE MATRICES C' ?

WHAT CAN WE EXPECT FOR SUCH A FLAVOUR STRUCTURE ?

MOTIVATED BY CONTROL ON THE FCNC

G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia (0207036)

A Flavour Model (1/2)

Minimal Flavour Violation

The Model

- **SM**: accidental symmetry $U(3)^5 = U(3)_q^3 \times U(3)_l^2$ broken solely by Yukawas
- **MFV**: the only source of flavour and CP-violation in the SM comes from the Yukawas

- The Yukawas are promoted to **spurion fields** transforming as bi-triplets of the flavour symmetry

$\Longrightarrow$ **all** higher dimensional flavour-violating operators must be **controlled by Yukawas**!

Consequences

$$\mathcal{L} \subset - \bar{F}'_L C'_f \overset{(\sim)}{H} f'_R \frac{H^\dagger H}{\Lambda_f^2} + \text{h.c.} \qquad C'_f = c'_f Y'_f \longrightarrow$$

No flavour-violating terms!
Only one c'_f for each fermion sector!

Family blind complex number

IN THE LINEAR IN YUKAWAS APPROXIMATION

MOTIVATED BY THE STRUCTURE OF MASSES AND MIXING

C.D.Froggatt, H.B.Nielsen (1979)

A Flavour Model (2/2)

Froggatt-Nielsen

The Model

- New $U(1)$ **symmetry** and **SM-*singlet* scalar field** ϕ (conventionally, with charge $n_\phi = -1$)
- **Fermions** and ϕ **transform** under the new symmetry and the Yukawa terms are made invariant adding powers of ϕ/Λ_F

$$\mathcal{L} \subset -\left[y'_{f,ij} \bar{F}'_{i,L} \overset{(\sim)}{H} f'_{j,R} + c'_{f,ij} \bar{F}'_L \overset{(\sim)}{H} f'_R \frac{H^\dagger H}{\Lambda_f^2} \right] \left(\frac{\phi}{\Lambda_F} \right)^{n_{F_i}+n_{f_j}} + \text{h.c.}$$

Consequences

- Once the ϕ takes **VEV**, each term is **suppressed** by powers of $\epsilon \equiv \langle \phi \rangle / \Lambda_F$

$$Y_f = \text{diag}\left(y_{f_1} \epsilon^{n_{F_1}+n_{f_1}}, y_{f_2} \epsilon^{n_{F_2}+n_{f_2}}, y_{f_3} \epsilon^{n_{F_3}+n_{f_3}} \right) \qquad C_{f,ij} \approx \mathcal{O}(1) \epsilon^{n_{F_i}+n_{f_j}} e^{i\theta_{f,ij}}$$

Similarly for MFV with higher order terms in the Yukawa spurion

A UV COMPLETE MODEL AS THE ORIGIN OF THE EFT OPERATOR:

2HDM WITH Z_2 symmetry in the electroweak basis,
after integrating out the heavier states

The Yukawa couplings of the physical higgs similar as above,
with Lambda= m_Heavy

$$Y_F = \frac{m_F}{v}[1 - g_F(\tan\beta)\lambda_6^* \frac{v^2}{m_H^2}] \quad \frac{1}{v}\lambda_{3h} = -\frac{3m_h^2}{v^2} + 6|\lambda_6|^2 \frac{v^2}{m_H^2}$$

$$g_{hVV} = \frac{2M_V^2}{v}[1 - \frac{1}{2}|\lambda_6|^2 \frac{v^4}{m_H^4}] \qquad \lambda_6 H_1^\dagger H_1 H_1^\dagger H_2$$

THE EFFECTIVE COUPLING MATRICES IN THE FERMION MASS EIGENSTATE BASIS:

$$\hat{Y}_F = Y_F + \frac{v^2}{\Lambda^2} C_F \qquad Y_F = diag(m_{F,i})/v$$

MFV: $$C_F = c_F Y_F$$

2HDM: $$C_F = g_F(\tan\beta)\lambda_6^* \frac{v^2}{m_H^2} Y_F$$

NO NON-DIAGONAL COUPLINGS

FN: $$C_{F,ii} = \mathcal{O}(Y_{F,ii}) e^{i\theta_{F,ii}} \quad C_{F,ij} = \mathcal{O}(1)\epsilon^{n_{Q_i}+n_{Fj}} e^{i\theta_{F,ii}}$$

MORE COMMON NOTATION FOR DIAGONAL COUPLINGS

$$\mathcal{L}_{eff} = -\frac{m_f}{v}(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f)h$$

TWO KINDS OF PREDICTIONS:

1) NEW MASS SCALE INDEPENDENT CORRELATIONS BETWEEN DIFFERENT OBSERVABLES, E.G. CORRELATIONS BETWEEN ELECTRON AND TAUON OBSERVABLES

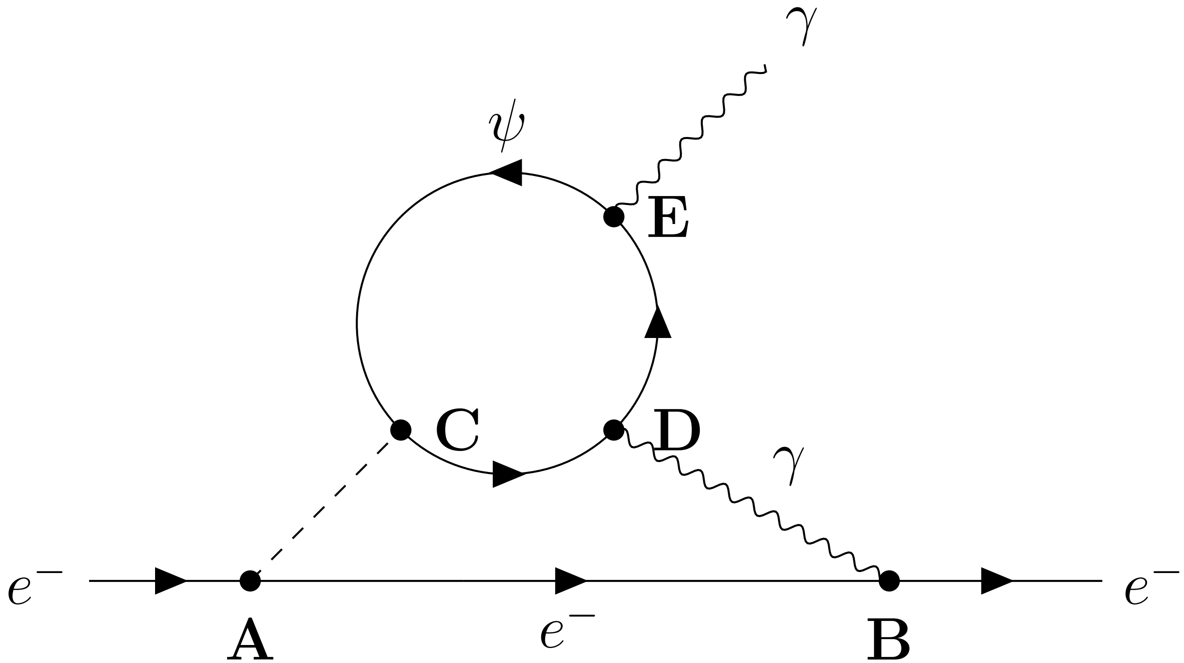
BOUNDS ON CP VIOLATION IN YUKAWAS

2) NEW BOUNDS ON THE BSM MASS SCALES; DIRECT LHC BOUNDS FROM HIGGS PRODUCTION AND DECAYS COMPARED TO FCNC BOUNDS

EXAMPLE 1

EXPERIMENTAL BOUNDS ON $|\tilde{\kappa}|$ WITHOUT AND WITH FLAVOUR STRUCTURE OF THE WILSON COEFFICIENTS OF THE DIM 6 OPERATORS

COME FROM THE ELECTRON EDM, WHICH IS GIVEN BY THE TWO-LOOP BARR-ZEE DIAGRAM



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BARR-ZEE DIAGRAM CONTRIBUTION TO THE ELECTRON EDM:

$$\frac{d_e}{e} \sim [\kappa_e \tilde{\kappa}_f f_1(x) + \tilde{\kappa}_e \kappa_f f_2(x)] \qquad x = \frac{m_f^2}{m_h^2}$$

$$|d_e| < 1.1 \times 10^{-29} e\ cm$$

WITHOUT ANY FLAVOUR STRUCTURE, FOR THE THIRD GENERATION FERMIONS RUNNING IN THE LOOP ONE GETS THE BOUNDS (E. FUCHS, M. LOSADA, Y. NIR, Y. VIERNIK, arXiv:2003.00099)

$$|\tilde{\kappa}_t| \leq 0.0012 \qquad |\tilde{\kappa}_b| \leq 0.27 \qquad |\tilde{\kappa}_\tau| \leq 0.3$$

ONE CAN ALSO FIND THAT $\tilde{\kappa}_e \leq 0.0017$

SINCE IN GENERAL

$$\tilde{\kappa}_e = \frac{v^2}{\Lambda^2}\frac{ImC_{11}}{y_e} \qquad \tilde{\kappa}_\tau = \frac{v^2}{\Lambda^2}\frac{ImC_{33}}{y_\tau}$$

WITH THE BOUND $\tilde{\kappa}_e \leq 0.0017$ ONE GETS

$$\tilde{\kappa_\tau} < 0.0017\frac{m_e}{m_\tau}\frac{ImC_{33}}{ImC_{11}}$$

HENCE, WITH FLAVOUR STRUCTURE

MFV, 2HDM: $\tilde{\kappa}_\tau \leq 0.0017$

FN: $\tilde{\kappa}_\tau \leq \mathcal{O}(1) \times 0.0017$

FOR SEVERAL NP CONTRIBUTIONS TO THE BARR-ZEE DIAGRAM

$$\tilde{\kappa}^{eff} = 2.68\tilde{\kappa}_e + 3.82\tilde{\kappa}_t + 0.019\tilde{\kappa}_b + 0.015\tilde{\kappa}_\tau < 0.0045|_{exp}$$

FOR

$$\tilde{\kappa}_e \approx \tilde{\kappa}_\tau \approx 0.3$$

ONE NEEDS CANCELLATIONS 1:1000

ELECTROWEAK BARYOGENESIS: TO EXPLAIN THE BARYON ASYMMETRY OF THE UNIVERSE WITH A SINGLE COMPLEX YUKAWA COUPLING ONE NEEDS (FUCHS ET AL)

$$|\tilde{\kappa}_t| \approx 0.06 \qquad |\tilde{\kappa}_b| \approx 3 \qquad |\tilde{\kappa}_\tau| \approx 0.12$$

NO FLAVOUR STRUCTURE FOR DIM 6 OPERATORS-→ COMPLEX TAU YUKAWA COULD SAVE BARYOGENESIS

EXP BOUNDS: $|\tilde{\kappa}_t| \leq 0.0012$ $|\tilde{\kappa}_b| \leq 0.27$ $|\tilde{\kappa}_\tau| \leq 0.3$

BUT….with flavour structure about two orders of magnitude are missing

EXAMPLE 2: DIAGONAL VS NONDIAGONAL

COMPARISON OF THE LOWER BOUNDS ON THE SCALE OF BSM

PHYSICS CONTRIBUTING TO THE $\bar{f} f h$ EFFECTIVE COUPLINGS

OBTAINED FROM THE COLLIDER DATA AND THE VARIETY OF

FCNC DATA (SEE G. BLANKENBURG, J. ELLIS, G. ISIDORI,
arXiv: 1202.5704, FOR BOUNDS ON THE OFF-DIAGONAL $\bar{f} f h$

THIS IS MUCH MORE MODEL DEPENDENT AS A GIVEN UV COMPLETION MAY ALSO GENERATE DIM 6

FOUR-FERMION OPERATORS.

In the EFT approach one can consider one operator at the time (all of them consistent with the assumed flavour structure) and compare the limits for the new scale

For the UV complete model (2HDM) one can use the calculable Wilson coefficients

FIRST, TAKE FN MODELS

ASSUMPTION: THE ONLY SOURCE OF 4-FERMION OPERATORS CONTRIBUTING
TO THE FCNC IS THE HIGGS EXCHANGE

FROM HIGGS PRODUCTION AND DECAYS AT THE LHC (diagonal couplings)

$\Lambda > 0.6\ TeV$ ALMOST INDEPENDENT OF THE FLAVOUR STRUCTURE

$\Lambda > 0.7\ TeV$ FROM THE BOUNDS ON THE ABSOLUTE VALUES OF $|\hat{Y}_{ds}\hat{Y}^*_{sd}|$

(from K-K mixing)

IN PARTICULAR, THOSE ARE THE ONLY BOUNDS IF THE IMAGINARY PARTS OF THE COUPLINGS ARE SUPPRESSED BY SMALL PHASES AND NOT BY THE LARGE SCALE (APPROXIMATELY CP CONSERVING SCENARIO)

SURPRISINGLY LOW BOUNDS FROM FCNC?

ADDING 4-FERMION OPERATOR GENERATED BY TREE LEVEL HIGGS
EXCHANGE WITH GENERIC NONDIAGONAL WILSON COEFFICIENTS OF THE DIM 6 OPERATOR

$$\frac{v^2}{\Lambda^2}\bar{f}_i f_j h \to \Lambda > \mathcal{O}(60) TeV$$

ADDING 4-FERMION OPERATOR GENERATED BY TREE LEVEL HIGGS EXCHANGE WITH NONDIAGONAL WILSON COEFFICIENTS OF THE DIM 6 OPERATOR CONTROLLED BY FROGGATT-NIELSEN MODELS

$$C_{ij}\frac{v^2}{\Lambda^2}\bar{f}_i f_j h \quad C_{ij} \approx \mathcal{O}(1)\epsilon^{n_{Q_i}+n_{d_j}} e^{i\theta_{ij}}$$

n_{Q_i}, n_{d_j} -FERMION CHARGES GIVING GOOD DESCRIPTION OF FERMION MASSES AND MIXING

$$\epsilon = 0.23 \quad (Cabibbo \quad angle)$$

THEREFORE

$$\hat{Y}_{sd}\hat{Y}_{ds} \sim \frac{m_d m_s}{v^2}\frac{v^4}{\Lambda^4} \quad \to \Lambda > 0.7\ TeV$$

WHAT ABOUT GENUINE 4-FERMION OPERATORS GENERATED IN THE PRESENCE OF A FN SYMMETRY?

$$\frac{1}{\tilde{\Lambda}^2} = \frac{v^4}{\Lambda^4}\frac{1}{m_h^2} \quad \rightarrow \tilde{\Lambda} > 1TeV$$

SUMMARY FOR FN MODELS:

$$\rightarrow \Lambda > O(1)\ TeV$$

FITS TO DIAGONAL COUPLINGS (LHC)
HIGGS EXCHANGE CONTRIBUTION TO FCNC
DIM 6 FOUR-FERMION OPERATORS

2HDM WITH Z_2 symmetry in the electroweak basis,
after integrating out the heavier states

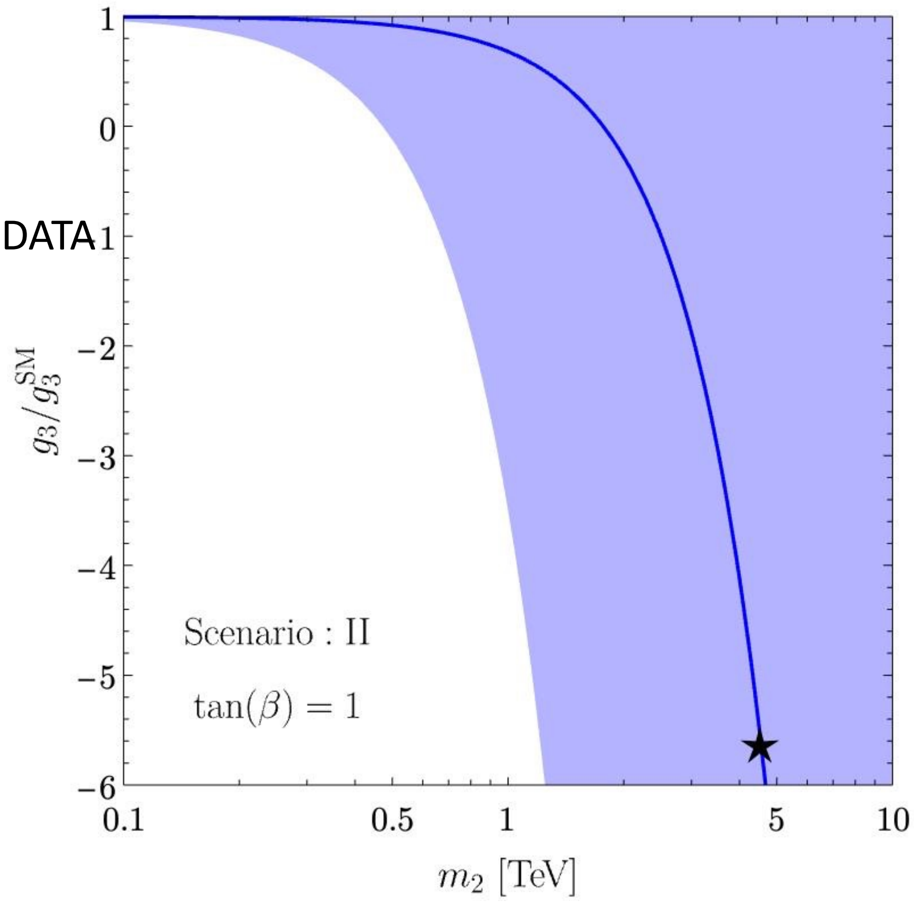
The Yukawa couplings of the physical higgs similar as above,
with Lambda= m_Heavy

$$Y_F = \frac{m_F}{v}[1 - g_F(\tan\beta)\lambda_6^* \frac{v^2}{m_H^2}] \qquad \frac{1}{v}\lambda_{3h} = -\frac{3m_h^2}{v^2} + 6|\lambda_6|^2 \frac{v^2}{m_H^2}$$

$$g_{hVV} = \frac{2M_V^2}{v}[1 - \frac{1}{2}|\lambda_6|^2 \frac{v^4}{m_H^4}] \qquad \lambda_6 H_1^\dagger H_1 H_1^\dagger H_2$$

FOR $\dfrac{\lambda_6}{m_H^2}$ FIXED

BY THE BEST FIT TO THE
HIGGS PRODUCTION AND DECAY DATA



EFFECTIVE 4-FERMION OPERATORS COMING FROM CHARGED HIGGS EXCHANGE

GIVE LOWER BOUND ON THE HEAVY MASS (TO BE CHECKED)

EFT APPROACH WITH MFV HYPOTHESIS INCLUDEs NON-HIGGS EXCHANGE 4-fermion FCNC OPERATORS LEADING TO MUCH STRONGER BOUNDS ON THE SCALE OF NEW PHYSICS THAN THE BOUNDS ON NEW PHYSICS SCALE IN THE YUKAWA FROM HIGGS PRODUCTION AND DECAY

SUMMARY FOR MFV

LHC FITS TO THE. HIGGS DECAYS $\Lambda > 0.6\ TeV$

HIGGS EXCHANGE TO FCNC. --→. NO CONTRIBUTION

DIM 6 FOUR FERMION OPERATORS $\Lambda > 6\ TeV$

LOW BOUNDS- INTERESTING PROSPECTS FOR FUTURE EXPERIMENTS

$\Lambda > \mathcal{O}(1)TeV$

--→ DEVIATIONS UP TO O(5)% IN THE HIIGS COUPLINGS STILL POSSIBLE (GOOD NEWS FOR THE FUTURE PRECISION HIGGS MEASUREMENTS IN COLLIDERS)

IN 2HDM, THE TRIPLE HIGGS COUPLING IS LINKED TO THE FAMILY SYMMETRY (VIA THE FIT TO YUKAWAS)

SUMMARY

I HAVE SHOWN TWO EXAMPLES OF THE ROLE OF THE FLAVOUR STRUCTURE IN THE BSM PHYSICS

1) CONSTRAINTS ON CP VIOLATION IN THE TAU YUKAWA COUPLING

2) GOOD NEWS FOR COLLIDERS: A COUPLE OF PER CENT DEVIATIONS FROM THE SM PREDICTIONS IN THE HIGGS COUPLINGS TO FERMIONS ARE STILL POSSIBLE, CONSISTENTLY WITH VERY HIGH PRECISION FCNC DATA.

ELECTROWEAK BARYOGENESIS NEEDS NEW SOURCES OF

CP VIOLATION (BEYOND THE CKM MATRIX)

THE MOST NATURAL SCENARIO (ALTHOUGH NOT THE ONLY ONE) IS THAT YUKAWA COUPLINGS HAVE A CP VIOLATING COMPONENT.

CP VIOLATING INTERACTIONS ACROSS THE EXPANDING WALLS OF THE

BUBBLES OF THE VEVs OF THE HIGGS FIELD WOULD CREATE A CHIRAL ASYMMETRY,

THEN CONVERTED TO A BARYON ASYMMETRY BY THE WEAK SPHALERON PROCESS.

(VERY RICH LITERATURE ON THIS SUBJECT:
most recent E. FUCHS, M.Losada, Y. Nir and Y. VIERNIK)