SEARCHING FOR BSM PHYSICS IN YUKAWA COUPLINGS AND FLAVOUR SYMMETRIES

Based on:

- J. Alonso-Gonzales, L. Merlo and SP, JHEP 06(2021) 166
  - J.Alonso-Gonzales, A. de Giorgi, L.Merlo and SP, arXiv:2109.07490 [hep-ph]

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

MOTIVATION

FLAVOUR IS ESSENTIALLY A BEYOND THE SM CONCEPT

AND A NEW PHYSICS SCALE RELEVANT FOR THE FLAVOUR

SECTOR MAY BE DIFFERENT FROM THE SCALE

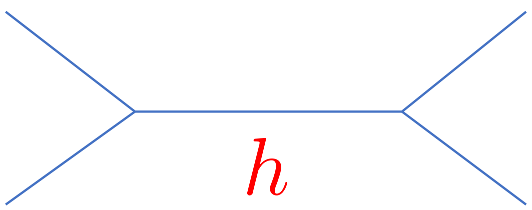
OF THE BSM PHYSICS LINKED TO THE BROUT-ENGLERT-HIGGS

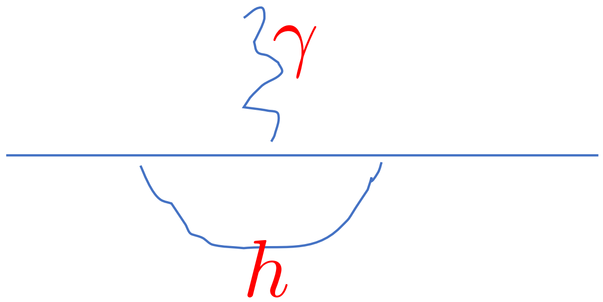
MECHANISM IN THE SM AND ITS HIERARCHY PROBLEM

SEVERAL SOURCES OF INFORMATION ON THE BSM PHYSICS IN YUKAWAS:

- HIGGS BOSON PRODUCTION AND DECAYS, DIRECTLY DEPENDENT ON THE YUKAWA COUPLINGS (COLLIDERS)

- 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





WHAT IS THE SENSITIVITY OF DIFFERENT OBSERVABLES TO THE BSM PHYSICS IN YUKAWA COUPLINGS?

ITS DEPENDENCE ON THE FLAVOUR STRUCTURE OF THE BSM PHYSICS CONTRIBUTING TO YUKAWA COUPLINGS, IF PRESENT?

WHAT CAN WE EXPECT FOR SUCH A FLAVOUR STRUCTURE ?

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

$$L = -\bar{Q}_L^J \bar{H} Y_u'^{JK} u_R^K - \bar{Q}_L^J H Y_d'^{JK} d_R^K - \bar{L}_L^J H Y_e'^{JK} e_R^K$$

$$-(\bar{Q}_L^J \bar{H} C_u'^{JK} u_R^K - \bar{Q}_L^J H C_d'^{JK} d_R^K - \bar{L}_L^J H C_e'^{JK} e_R^K)\frac{H^\dagger H}{\Lambda^2} + h.c$$

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

TWO INTERESTING HYPOTHESES FOR THE FLAVOUR STRUCTURE OF THE WILSON COEFFICIENTS:

MINIMAL FLAVOUR VIOLATION OR THEY RESPECT A FLAVOUR SYMMETRY OFTEN INVOKED TO EXPLAIN FERMION MASSES AND MIXINGS (U(1) SYMMETRY FROGGATT-NIELSEN MODELS ARE TAKEN AS EXAMPLES)

IN BOTH CASES THE YUKAWA MATRICES Y' AND THE WILSON COEFFICIENT MATRICES C' ARE RELATED TO EACH OTHER.

STRONG IMPLICATIONS FOR THE EMERGING PICTURE OF BOUNDS ON THE BSM PHYSICS IN THE HIGGS COUPLINGS

IN THE FERMION MASS EIGENSTATE BASIS THE FERMION-HIGGS COUPLINGS READ

$$L = -[\bar{u}_L(Y_u + \frac{v^2}{\Lambda^2}C_u)u_R + \bar{d}_L(Y_d + \frac{v^2}{\Lambda^2}C_d)d_R$$

$$+\bar{e}_L(Y_e + \frac{v^2}{\Lambda^2}C_e)e_R]\frac{h}{\sqrt{2}} + h.c$$

$$Y_u = \sqrt{2}/v \; diag(m_u, m_c, m_t) \;\; and \;\; similarly \;\; for \;\; Y_d, Y_e$$

$$C_F = V_F^\dagger C_F' U_F$$

V_F, U_F ARE THE MATRICES WHICH DIAGONALIZE THE MASS TERMS

THE EFFECTIVE COUPLING MATRICES

$$\hat{Y_F} = Y_F + \frac{v^2}{\Lambda^2} C_F$$

MFV: $C'_F = c'_F Y'_F \qquad |c'_F| = \mathcal{O}(1) \qquad C_F = c'_F Y_F$

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

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

THE MATCHING WITH THE EFFECTIVE $\kappa_f, \tilde{\kappa}_f$ GIVES, E.G

$$K_u = diag(\kappa_u, \kappa_c, \kappa_t)$$

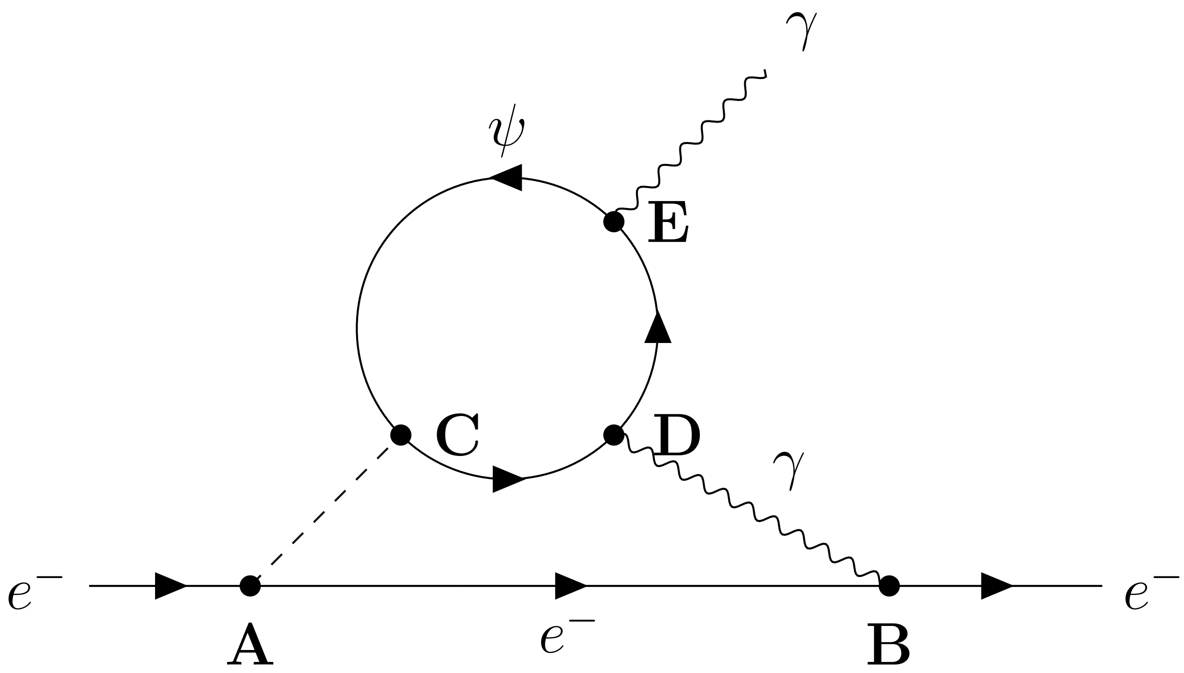
$$YK = Y + \frac{v^2}{\Lambda^2} diag(ReC), \qquad Y\tilde{K} = \frac{v^2}{\Lambda^2} diag(ImC)$$

AND THE NON_DIAGONAL COUPLINGS (IF PRESENT) ARE GIVEN BY THE NON-DIAGONAL ENTRIES IN THE MATRICES C

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

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

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

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

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

BUT….

IN TYPICAL FLAVOUR SCENARIOS, THE ELECTRON EDM BOUNDS MAKE SUCCESSFUL ELECTROWEAK BARYOGENESSIS UNLIKELY

SEARCHING FOR CP VIOLATION IN

$$h \to \tau\tau$$

IS CRUCIAL FOR TESTING THE VIABILITY OF THE ELECTROWEAK BARYOGENESISIS AND FLAVOUR SYMMETRY IN SMEFT

EXAMPLE 2:

COMPARISON OF THE LOWER BOUNDS ON THE SCALE OF BSM

PHYSICS CONTRIBUTING TO THE $\bar{f}fh$ 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 $\bar{f}fh$

A COMPLEX PICTURES OF BOUNDS ON Λ_q AND Λ_l OBTAINED FROM DIFFERENT OBSERVABLES EMERGES FROM SUCH AN ANALYSIS (SEE arXiv:2109.07490 [hep-ph])

BOTTOM LINES FOR Λ_q : THE BOUNDS THAT DO NOT DEPEND ON THE PHASES OF THE EFFECTIVE COUPLINGS

$\Lambda_q > 0.6\ TeV$ FROM HIGGS PRODUCTION AND DECAYS AT THE LHC

$\Lambda_q > 1\ TeV$ 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?

CONSIDER BOUNDS ON NP COMING FROM FCNC PROCESSES

ADDING TO THE SM A GENERIC
4-FERMION OPERATOR

$$\frac{1}{\Lambda^2}(\bar{s_R} d_L)(\bar{s_L} d_R) \to \Lambda > \mathcal{O}(10^4) TeV$$

ADDING 4-FERMION OPERATOR GENERATED BY THREE 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

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

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

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

THERFORE

$$\hat{Y}_{sd}\hat{Y}_{ds} \sim \frac{m_d m_s}{v^2}\frac{v^4}{\Lambda^4} \quad \rightarrow \Lambda > 1\ TeV$$

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)

$$0.88 < \kappa_q < 1.12 \qquad \kappa = \frac{\hat{Y}}{Y_{SM}}$$

BOTTOM LINES FOR Λ_q : IMAGINARY PARTS ARE SUPPRESSED ONLY BY LARGE SCALES, WITH MAXIMAL PHASES

$\Lambda_q > 3\ TeV$ FROM ϵ_K ASSUMING PURELY IMAGINARY hds COUPLING (FCNC)

$\Lambda_q > 7\ TeV$ FROM ELECTRON EDM (DIAGONAL COUPLINGS)

SUMMARY

THE SCALE OF BEYOND THE SM PHYSICS CONTRIBUTING TO THE HIGGS FERMION COUPLINGS MAY BE DIFFERENT FROM E.G. ELECTROWEAK BSM PHYSICS

IF IN THE EFT APPROACH THE WILSON COEFFICIENTS OF THE RELEVANT OPERATORS RESPECT SOME FLAVOUR STRUCTURE, LIKE MINIMAL FLAVOUR VIOLATION OR A FLAVOUR SYMMETRY RESPONSIBLE FOR THE FERMION MASSES AND MIXING, THERE ARE BAD AND GOOD NEWS:

BAD NEWS: ELECTROWEAK BARYOGENESIS LOOKS UNLIKELY $(h \to \tau\tau?)$

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.

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Understanding the Early Universe:
interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen

BACKUP

FOR SEVERAL NP CONTRIBUTIONS TO THE BARR-ZEE DIAGRAM

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

MOTIVATION (SPECIFIC)

ELECTROWEAK BARYOGENESIS NEEDS NEW SOURCES OF

CP VIOLATION (BEYOND THE CKM MATRIX)

THE MOST NATURAL SCENARIO (IF 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)